

REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

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ABSTRACT—This paper reviews published conservation research that utilizes digital image analysis of petrographic thin sections. Examples involve quantifying quartz microcrack patterns to analyze stone deterioration, conducting porosimetric studies of stone, examining grain-size distribution and grain shape in stone, comprehensively evaluating deterioration mechanisms of stone, studying conservation treatments of stone, characterizing cementitious materials, analyzing ceramic materials, and measuring layer thickness on a variety of materials. Background issues that must be understood before undertaking or evaluating image analysis include experimental design and statistical validity, calibration, image quality, and image enhancement (preprocessing of images). Early work often required in-house computer programs; recent studies make use of new comprehensive image analysis packages. With the emergence of these packages that provide fast preprocessing and measurement of a wide range parameters, we can expect increasing use of image analysis of petrographic thin sections as an analytical tool in the future.

TITRE—Un compte-rendu des recherches dans le domaine de la conservation concernant l'analyse d'images numériques de plaques minces pétrographiques. **RÉSUMÉ**—Cet article fait le compte-rendu des recherches déjà publiées dans le domaine de la conservation concernant l'analyse d'images numériques de plaques minces pétrographiques. Ces analyses d'images peuvent servir à identifier des réseaux de microfissures sur le quartz, ce qui indiquerait une détérioration de la pierre. Elles peuvent aussi permettre des études sur la porosité de la pierre, l'examen de la distribution et de la forme des constituants de la pierre, l'évaluation des mécanismes de détérioration de la pierre, l'analyse des traitements de restauration de la pierre, la caractérisation des matériaux de cimentation, l'analyse des céramiques, et enfin la mesure de l'épaisseur des couches d'une grande variété de matériaux. Certains principes fondamentaux doivent être compris avant d'évaluer ou d'entreprendre l'analyse d'images numériques, par exemple le design expérimental, la validité statistique, la calibration, la qualité de l'image et l'accentuation d'image (pré-traitement d'image). Au début, l'analyse d'images numérique requérait des programmes informatiques spécifiques, alors que les études récentes utilisent de nouveaux programmes sophistiqués, mais courants, d'analyse d'images. Avec l'arrivée de ces nouveaux programmes qui permettent

un pré-traitement rapide et facilitent la mesure d'une vaste gamme de paramètres, l'analyse d'images numériques des plaques minces pétrographiques devrait devenir pratique courante dans le futur.

TITULO—Reseña del análisis de imagen digital de secciones delgadas petrográficas en la investigación en conservación. **RESUMEN**—Este artículo reseña los trabajos de investigación publicados sobre conservación que utilizan análisis de imagen digital de secciones delgadas petrográficas. Los ejemplos incluyen la cuantificación de patrones de microfisuras de cuarzo para analizar el deterioro de la piedra, los estudios de porosimetría de la piedra, el examen de la distribución del tamaño y la forma del grano en la piedra, la evaluación exhaustiva de los mecanismos de deterioro de la piedra, el estudio de los tratamientos de conservación de la piedra, la caracterización de los materiales cementosos, el análisis de los materiales de cerámica y determinaciones del grosor de las capas de una variedad de materiales. Problemas de fondo que deben ser comprendidos antes de asumir el análisis de la evaluación de la imagen incluyen diseños experimentales y validación estadística, calibración, calidad de la imagen, y mejoramiento de la calidad de la imagen ("preproceso" de la imagen). Los primeros estudios frecuentemente requerían de programas de computación desarrollados por el investigador; estudios recientes hacen uso de nuevos paquetes de software comerciales detallados de análisis de imagen. Con la aparición de estos paquetes que proveen procesamiento rápido y medición de un amplio rango de parámetros, podemos esperar un incremento del uso del análisis de la imagen de secciones delgadas petrográficas como una herramienta analítica en el futuro.

TÍTULO—Revisão das imagens digitais das análises petrográficas de camada fina para a pesquisa em conservação. **RESUMO**—Este artigo revê trabalhos publicados sobre pesquisa em conservação que utilizam imagens digitais de análises petrográficas de camada fina. Os exemplos envolvem a quantificação de padrões de microfissuras de quartzo para a análise da deterioração da pedra, estudos sobre a microcondutividade porosa da pedra, exames sobre a distribuição dimensional do grão da pedra e sobre o seu formato, ampla avaliação dos mecanismos da deterioração da pedra, estudo de tratamentos de conservação da pedra, caracterização de materiais de cimentação,

análise de materiais cerâmicos e a medição da espessura das camadas de uma variedade de materiais. Algumas questões que devem ser entendidas antes da realização ou avaliação das análises das imagens incluem projeto experimental e validação estatística, calibração, qualidade de imagem e realce da imagem ("pré-processamento" de imagens). Os trabalhos anteriores frequentemente requeriam programas de computador desenvolvidos de forma doméstica; estudos recentes fazem uso de pacotes de imagens analíticas mais novos e mais completos. Com o surgimento destes pacotes que proporcionam mais rápidos pré-processamento e medição de uma variedade alargada de parâmetros, pode-se esperar um aumento do uso de imagens digitais das análises petrográficas de camada fina como uma ferramenta analítica no futuro.

1. INTRODUCTION

Petrographic thin-section analysis is an important tool for materials characterization and for studying deterioration and treatment effects on stone, cementitious materials, and ceramics. Combining thin-section examination with computer programs that analyze digital images is a standard procedure in geology (Petruk 1989). Such programs allow rapid measurement and quantitative analysis of thin-section features. In recent years, a variety of image analysis packages for personal computers have been released. These packages provide major advantages over traditional methods of analyzing thin sections (visual estimation, individual measurement of features seen under the microscope, or use of point counting or similar approaches). Although pioneers of computerized image analysis wrote their own in-house programs for each application, comprehensive packages are commercially available today for virtually all potential applications. Use of these packages with digital images captured at the microscope facilitates efforts to characterize, classify, and compare images by using quantitative data. Image analysis makes it possible to rapidly and accurately measure particles or features within a thin section and to quantify parameters such as area percentage, length, width, distance between features, roundness, size distribution, and clustering of features. Digital image analysis techniques also are used for other types of materials characterization applications pertinent to conservation research (such as metallurgical analysis, analysis of fibers, analysis of pigment particles or cross sections,

scanning electron microscope analysis, etc.).

Section 2 provides a brief background on traditional methods for analyzing petrographic thin sections. Section 3 discusses background issues that must be understood before undertaking or evaluating image analysis work, including experimental design and statistical validity, calibration, image quality, and image enhancement. Section 4 reviews conservation research literature reporting image analysis of petrographic thin sections for quantifying quartz microcracks to analyze stone deterioration, conducting porosimetric studies of stone, examining grain-size distribution and grain shape in stone, comprehensively evaluating deterioration mechanisms of stone, studying conservation treatments of stone, characterizing cementitious materials, analyzing ceramic materials, and measuring layer thickness on a variety of materials.

2. PETROGRAPHIC THIN-SECTION ANALYSIS

This technique usually involves specimens 30 μm thick of stone, ceramic, or cementitious materials examined under a transmitted-light microscope, in plane polarized and crossed-polarized light, usually at magnifications ranging from 4x to 400x (Kerr 1977). Thin-section analysis is used to characterize the mineralogical and textural features of archaeological artifacts, works of art, or building materials; identify the susceptibility of materials to weathering; determine the degree and mechanisms of deterioration; and study the effectiveness of consolidation and other conservation treatments (Kempe and Harvey 1983; Reedy 1994). Although other methods of analysis of inorganic materials may be used in conjunction with this technique, petrographic thin sections often provide crucial basic information not available through other methods of analysis (Peacock 1970; Rossi-Manaresi 1982; Williams 1983; Jones 1986; Whitbread 1989; Reedy 1991, 1994; Freestone 1995; Velde and Druc 1999).

Traditional methods of quantifying and analyzing thin sections involve measuring features with a micrometer or eyepiece graticule; doing visual estimations with the aid of published estimation charts (Williams et al. 1982; Matthew et al. 1991); and using variations on point counting, where the relative proportion of different minerals or features are counted by recording what appears at the intersections along a superimposed grid (Stoltman 1989; Goins and Reedy 2000).

REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

Visual estimation has the advantage of being relatively fast, so that it is feasible to include more thin sections, and thus improve the statistics regarding variation within and between thin sections of a single object and between objects of the same category. Visual estimation charts specific to cultural materials such as archaeological ceramics have been developed, which improves the usefulness of this approach (Matthew et al. 1991). However, a great weakness is that not all researchers are adept at visual estimates, and thus accuracy and reproducibility may not be very high.

In point counting, a grid, or system for systematic sampling, is established. At fixed intervals, any grain that falls at that point is counted, and attributes such as size and shape may be recorded. Variations in approaches include the counting intervals selected, and different researchers may differ on whether or not a grain will be counted more than once if it is large enough to intersect more than one point on the grid. Other methods include counting the grain nearest a grid point if no grains fall exactly on the point (Streeten 1982). Variations include line, ribbon, or area counting. The main purpose of all of these counting methods is to obtain an unbiased estimate of the constituents of the sample, expressed as an area or volume percentage, or as percentage of individual grains.

Early work by geologists (Chayes 1954) validated that areal measurements produce good estimates of the relative volume of rock constituents, so they have been standard in geology for decades for rocks and soils (Daniels et al. 1968). Similarly, point counting is a standard method for studying thin sections in archaeology (Kempe and Harvey 1983; Stoltman 1989). However, making many individual measurements is very time-consuming and tends to limit the number of specimens that can be analyzed in a reasonable period of time, reducing statistical reliability or making a rigorous project too impractical to undertake. Measurement of 50–200 grains is often needed in order to adequately characterize a thin section (Middleton et al. 1985).

Other measurement parameters of interest with cultural materials also involve either time-consuming individual measurements or faster but less reliable visual estimation methods. For example, length of many individual grains can be measured with a stage micrometer, to arrive at an average length of a specific mineral in the sample. Shape (such as rounded, subrounded, subangular, or angular) is often estimated

for quartz grains using visual guides for estimating degree of roundness (Pettijohn 1975; Scholle 1979; Pettijohn et al. 1987). Selection of grains to measure or estimate can be done rigorously by point counting, or faster but less accurately by trying to identify grains typical for the thin section.

3. IMAGE ANALYSIS: BACKGROUND ISSUES

Identification of specific minerals and textures present must be done mainly through petrographic training and experience. However, quantitative parameters such as area percent, length, width, and roundness measurements can now be accomplished with computerized analysis of digital images taken at the microscope. Even automatic identification of rocks in thin sections has succeeded for some rock types using image analysis of textural characteristics to classify specimens (Wang 1995). Image analysis systems incorporate many of the same measurements that have been used by petrographers for decades using manual methods; however, a considerable savings in time is achieved by using analysis algorithms in conjunction with a computer. The earliest systems often required in-house programming, were instrument-specific, or were limited by computer memory and processing speeds. Today, a variety of comprehensive image analysis packages are available that make use of advances in microcomputers and software library developments. User interfaces simplify the application of complex operations (Hetzner 1998; Goins and Reedy 2000).

In computerized analysis of digital images taken through the microscope, one can highlight or mark for analysis certain minerals or features of a specific size range, shape, color, or contrast. A wide variety of data on those highlighted minerals or features then can be collected rapidly and simultaneously (e.g., number of grains, range and average size, degree of roundness, range and average length of axes, length of perimeter).

For each type of material and research application, specific protocols for differentiating (or segmenting) the components and/or features of interest are needed. For example, a mineral might vary in size, color, and shape within a thin section or it may be very close in size, color, and shape to another mineral in the thin section. A good image analysis software package easily allows one to manip-

ulate image contrast and brightness and apply a variety of different filters and algorithms to the images in order to enhance features of interest. Once the features of interest can be separated reliably by the software, decisions then need to be made regarding what data should be collected in order to answer specific research questions.

There are now a variety of image analysis packages available to the researcher. Some digital microscope cameras come equipped with an analysis package, other more comprehensive packages are available commercially, and some packages are available as free downloads on the World Wide Web. There are advantages to the use of widely available packages over a variety of in-house computer programs. Without the need to spend time writing in-house programs, more time and focus can go towards the actual analysis of thin sections and interpretation of results. The image analysis work of each laboratory can more readily be duplicated by others if it uses a program that is easily available, written to run with standard systems and equipment, and includes detailed documentation and avenues for technical assistance.

Three comprehensive packages (two commercial packages, Image-Pro Plus and Clemex Vision Professional Edition, and one free downloadable package, NIH's ImageJ) were recently evaluated regarding applications pertinent to research involving thin sections of cultural materials (Reedy and Kamboj 2003). Some of those results are incorporated in the following discussions.

3.1 EXPERIMENTAL DESIGN AND STATISTICAL VALIDITY

As with traditional methods of estimation and point counting, in digital image analysis a study should be designed to ensure that samples are representative of the material being examined, and that the analysis is done in such a way as to ensure that the results have statistical validity. For example, samples must be large enough that they include any variation present. The number of specimens taken, their size, whether or not sampling is random or systematic, the number of areas within each sample where images are analyzed, the method of selecting those areas, etc., will all vary depending upon the type of material being studied and the research questions of interest. However, for all studies, these details need to be carefully considered and reported. For example, grain size

and the amount of each component of interest will influence the number of grains counted. If the component of interest is a minor one, present in low amounts, more grains may have to be counted overall to give a high enough level of confidence for that rarely-occurring particle type (Goins and Reedy 2000). Typically, pilot studies with a specific material will help in planning further research and identifying the best sampling approach.

3.2 CALIBRATION

With computer analysis of digital images taken at the microscope, the images are represented in the form of picture elements, or pixels, which are small dots making up the image. In order to perform measurements, the image analysis tools need to know how many pixels there are in one unit length of the image. The unit length may be in millimeters, micrometers, or any other unit chosen according to the overall size of the image and its important components. The process of assigning the number of pixels per unit length to an image is known as calibration. Before undertaking any analysis, a system setup must be calibrated so that measurements such as length, perimeter, or area are calculated in a specific unit, rather than as number of pixels measured (Reedy and Kamboj 2004a).

The calibration for each setup depends on the magnification of the objective lens that is used to view the image under the microscope, the resolution under which the image is stored, and the digital camera/microscope combination that is being used to acquire the image. This calibration measure will then apply to all images taken with that combination. The appropriate calibration measure must be imported and applied to each image at the time of analysis, so it is crucial to store that information on the image itself, in the filename, or in an image database.

Most digital microscope cameras include the capability of marking each image directly at the time of image capture with a scale bar. Where this was not done, a scale bar can be inserted after the fact with most image analysis software packages. It is important to include the scale bar in published reports rather than listing a magnification. Calculated magnifications apply to what the eye sees when looking into the microscope lens. In traditional work, magnifications had to be recalculated to adjust for publication size of photomicrographs. In image analysis work there are also many intermediate steps in which the digital image may be resized, which also would affect magni-

REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

fication. The original image as viewed under the microscope can be thought of as a rubber band being extended or contracted during photography, analysis, and final publication, making magnifications impossible to track. Thus most journals require scale bars in thin-section images, but do not list magnifications.

3.3 IMAGE QUALITY

The photography is a crucial step for successful image analysis, which requires a high quality image with which to work. The digital camera used for image capture at the microscope must provide resolution appropriate for the type of image and magnifications of interest; there are many cameras available today that meet the needs of thin-section petrography of cultural materials. Most analyses require uncompressed file formats such as tagged image file format (TIFF) to prevent loss of image quality.

What is considered a good quality image can vary. For published descriptions of a material, an image that closely resembles what one sees when looking in the microscope is often desirable. However, image analysis may require enhancement of certain features, exaggeration of contrast, etc. Multiple versions of the same image may be produced during preprocessing as discussed below, during various phases of analysis, and as publications are prepared; the original uncompressed image must always be retained. In order to keep all versions of an image organized and annotated, a good image database software package is a prerequisite for serious image analysis work, such as IQbase, published by MediaCybernetics.

3.4 IMAGE ENHANCEMENT OR PREPROCESSING

It is often necessary to enhance features of interest in order to perform an analysis. When a new project is initiated, identifying a reliable protocol for enhancement may be somewhat time-consuming. Once done, however, the same procedure can be applied routinely to similar materials undergoing the same analysis, and often routines can be set up to perform image enhancement or preprocessing steps automatically.

One often needs to separate two or more different particle types, phases, or components, and then count or measure specific features of one or both populations. Before any measurement and analysis can be done, particles must be clearly visible, with high

contrast between particles and matrix or between the components of interest. There are a variety of approaches to preprocessing to correct potential problems. For example, image contrast and brightness can be manipulated to emphasize particular features, and various algorithms can be applied such as an edge enhancement filter that highlights all edges and ignores particle masses (Schmitt 1993; Goins and Reedy 2000). Most comprehensive image analysis packages include all tools needed for preprocessing. For many thin sections, contrast enhancement is sufficient to improve the image enough for successful analysis. Some initial experimentation will help identify optimal preprocessing procedures for the material under study and the goals of the analysis.

4. APPLICATIONS OF IMAGE ANALYSIS TO CONSERVATION RESEARCH PROBLEMS

4.1 QUANTIFYING QUARTZ MICROCRACKS IN STUDIES OF STONE DETERIORATION

In studies of the deterioration of granite (sculpture or architecture), the presence of microcracks in quartz grains is related to degree of weathering (Dearman and Irfan 1978; Ordaz et al. 1978; Pérez-Ortiz et al. 1994; Rainey and Whalley 1994; Fiora et al. 1996; Hernández 1996; Molina et al. 1996). Typically, researchers count the number of microcracks encountered while moving along a linear transverse area on a thin section of standard size. The length of each crack is measured, and for the thin section as a whole the overall length (total length of all cracks combined) and the average fracture length are computed. Multiple thin sections, usually at least five for each building, monument, or sculpture to be characterized, are analyzed and the data combined. These multiple specimens are also used to check for differences between external surfaces and interior areas, as presumably the interior represents more closely the original character of the fresh stone. For relatively wide cracks, the width of the crack may also be assessed. The number of cracks that extend into multiple grains, and the number and length of offshoots within cracks may also be recorded.

Most cracks within quartz grains are curving and wandering lines, so traditional methods of measure-

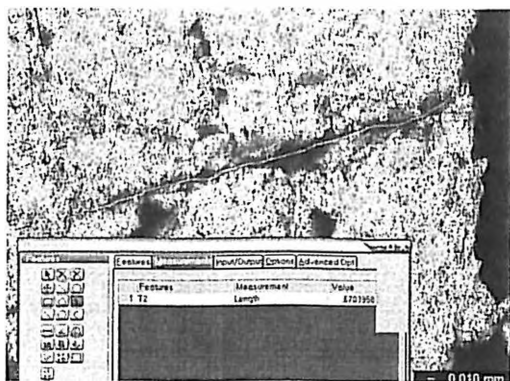


Fig. 1. A crack within a quartz grain in granite; the length of the main crack was traced using the trace tool in Image-Pro Plus, and the length was identified as 0.67 mm.

ment are problematic. With digital image analysis, using a tracing tool one can simply trace along the crack. Length will be calculated automatically in whatever units were used for the calibration (Reedy and Vallamsetla 2004a). For example, figure 1 illustrates the use of a trace tool in Image-Pro Plus to highlight a crack within a quartz grain in granite. Once traced, the crack length can be viewed (0.67 mm in the case of figure 1). The ease of this method is apparent especially for complex cracking patterns.

Microfissuring due to salt crystallization was examined on a granite from northwest Spain in a study by Pérez-Ortiz et al. (1994). Thin sections showed cracks in quartz grains, accompanied by alteration of plagioclase feldspars to sericite and chlorite. Using an image analysis package modified and adapted for petrographic work, the authors calculated the specific surface of fissures (total internal surface of fissures, expressed in microns); the loss of material (in percentage of voids volume, proportional to the area occupied by the voids in a uniform plane section); the fractal dimension (profiles of the crack walls in cross-section); and the linear crack density (the average number of cracks intersecting a predetermined length, which they measured as the number of cracks per millimeter).

4.2 POROSIMETRIC STUDIES OF STONE

Digital image analysis is used to characterize the pore structure of a stone and evaluate the effects of that structure. Fitzner (1988, 1990) focused on the fact that stone weathering modifies structure and

phase, with changes often occurring at the interfaces of minerals, making pore spaces the location of a variety of weathering processes. Thus, measuring pore space and characterizing pore systems are important for any study of stone weathering. Fitzner utilized both thin-section microscopy involving image analysis, and mercury porosimetry. He compared naturally deteriorated building stones with those used in accelerated aging studies, focusing on three sandstones quarried in Germany and used in the construction of historic buildings.

All three sandstones show a high total porosity in the nonweathered state. In comparing image analysis results with those for mercury porosimetry, Fitzner found that for one sandstone both methods gave nearly the same results. For another stone with a large number of small macropores, these could only be evaluated by mercury porosimetry. For another stone with large macropores, these could not be registered by mercury porosimetry, and could only be studied with thin sections. Two of the stones are shown to have pore spaces connected by small pore channels called "ink-bottle" pores. By combining the two approaches, mercury porosimetry and image analysis of thin sections, a better estimate of the proportion of the ink-bottle pores in the rock is provided and, ultimately, a more reliable pore space description is possible.

Rodríguez-Navarro et al. (1994) conducted porosimetric studies of calcitic limestones from Jaén Cathedral, a Spanish Renaissance building of the 16th–17th centuries. They used digital image analysis of petrographic thin sections to elicit information on macropores in deteriorated building stones compared with undeteriorated quarry samples. These data were complemented by mercury intrusion porosimetry for pores of very small size (0.01–5.0 μm). Rodríguez-Navarro et al. found that mercury-intrusion porosimetry had great limitations for biomicritic limestone, and that the image analysis of thin sections provided the most reliable data, allowing the exact dimensions of each pore type to be measured.

4.3 EXAMINING GRAIN-SIZE DISTRIBUTION AND GRAIN SHAPE IN STONE

Poschlod and Grimm (1988) characterized two granites from Bavaria (Nannering-Gelb and Kösseine) and two marbles from Italy (Carrara and Laas) as part of research on the weathering behavior

REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

of crystalline natural stones. An image analysis program (not specified, apparently an in-house program) calculated grain area, perimeter, equivalent diameter, and equivalent sphere volume and compared patterns for the four stones. This was done solely as a supplement to porosity studies done by mercury intrusion porosimetry and water buoyancy. The most frequent grain diameter was found to vary significantly among the four stones analyzed. The four stones also varied in total porosity and most frequent pore diameter, as well as in weathering behavior.

Germann et al. (1988) used image analysis of thin sections to differentiate between two marble-producing sites of the Cycladic Islands, Paros and Naxos, important sources of marble for Greek sculpture and architecture. They were particularly interested in being able to identify Greek mainland architectural stone that had been imported from the Cyclades, as an indicator of close connections at crucial time periods. A total of 104 samples from marble deposits and ancient quarry sites at Paros and Naxos were studied, and compared with samples taken from buildings at Delos and from the treasuries at Delphi. Germann et al. found that the average grain size as determined from 100 calcite grains was an especially useful discriminating criterion.

Perez (1995) developed a procedure for using digital image analysis for automatic classification of marbles. The marbles studied include those from a wide variety of sources from Italy, Greece, Asia Minor, Portugal, Spain, and France. The step of preprocessing to develop an image with maximum contrast was crucial to this work, so that the boundaries of individual grains could be discerned. Parameters analyzed included grain roundness, squareness, elongation, and size. These data were used in a discriminant analysis, which appeared to be successful in separating the sources and correctly classifying specimens to their actual source.

As part of their research on methods for determining the geographic origin of ornamental stone used in the Roman period, Lumbreras and Serrat (1996) wrote a computer program to aid in segmentation of grains in digital images of marble thin sections, so that individual grains could be better differentiated from each other for measuring. They found that fractures within grains can look similar to actual grain boundaries, making some edge detection tools inaccurate; and intensity variations within grains may prevent segmentation by uniform gray-level region detection. To better distinguish grains, they

first captured an image without using a polarizer, then captured two images with different polarizer-analyzer angles. Information was then assembled regarding the characteristic pattern of intensity variation of each grain.

Schmid et al. (1999) undertook a quantitative fabric study by image analysis to compare white marbles from different ancient quarries. The fabric study included variables such as grain size and shape; the quantitative approach aided by image analysis has the goal of defining quantifiable parameters based on geometrical features observed in thin section. In this example, they analyzed 63 thin sections from 14 quarries in Greece, Italy, France, and Turkey. Analyzing grain-boundary networks with a comprehensive image analysis package (NIH Image), they computed axial difference (major axis minus minor axis) and perimeter divided by area for each grain; grain distribution within a thin section; and the PARIS factor, which describes the ratio between convexity and concavity of a particle outline.

Best discrimination between quarries was achieved with two variables: mean (logarithmic) major axis and PARIS factor. Where there were overlaps, cathodoluminescence provided additional data useful for characterizing marble source. They note that the color and pattern of luminescence depends mainly on trace elements, whereas the fabric of the marble is a marker of the history of deformation and recrystallization of the rock, so the two types of data represent very different and independent sources of information.

4.4 COMPREHENSIVE EVALUATIONS OF DETERIORATION MECHANISMS OF STONE

One advantage of image analysis is that it facilitates rapid collection of a wide range of data pertinent to studies of stone deterioration measures. For example, Ebert and Montoto (1986) used digital image analysis of thin sections of building stone (limestone, sandstone, and granite) to study macroporosity, to identify the relative proportions of mineral components, and to characterize fractures, as an aid to studying mechanisms of deterioration. In order to highlight original pores and microcracks for deterioration and durability studies of monumental stones, Ebert and Montoto recommend using polished

sections of varying thickness impregnated in fluorescent resin, so porosity can be characterized by fluorescent microscopy. They emphasize that care must be taken to prevent the development of new cracks or pits during specimen preparation. The digital image analysis (with in-house software) was used mainly to better discriminate grain boundaries, to map pores and cracks, and to conduct granulometric and microfractographic analyses.

For the porosity and granulometric analyses, pores and grains were characterized by perimeter, area, diameter, and shape factor (which compares the shape of a region of interest with that of a circle). For the microfractographic analysis, fissures were characterized by first applying an algorithm that reduced every fissure to its medial line. Then the lengths and directions of the lines were calculated and reduced to total length of fissures and an orientation histogram giving fissure percentages for orientations at 10° intervals. Using this wide array of quantitative data, Esbert and Montoto were successful in being able to characterize the deterioration state of each rock type for a variety of parameters.

Weiss et al. (1999) reported that different marble types used for building the eighteenth-century Marmorpalais in Potsdam, Germany, showed variation in degree of deterioration. They studied grain fabric and texture to see if there was a connection between those features and weathering susceptibility. Understanding such connections is important because restoration of deteriorated areas involves replacement with fresh marble from the same sources, but rapid degradation can occur with some types of materials. In addition to the weathered building stones, they examined fresh marble specimens from Poland, the Czech Republic, and Italy (sources of marble for the building's construction, and where restoration materials are obtained).

Differences were found in average grain size, grain boundary geometry, and texture. The research incorporates digital image analysis to quantify the data, to compare marble types, and to look for correlations with other parameters such as mechanical strength. Weiss et al. concluded that different grain fabrics and textures and their combinations lead to different types of weathering mechanisms (such as powdering versus breakouts along microcracks). Knowledge of these relationships can help in the selection of appropriate restoration materials.

4.5 STUDYING CONSERVATION TREATMENTS OF STONE

Conservation treatments of granite were the focus of a study by O'Brien and Cooper (1994) that incorporated image analysis of thin sections. Two methods for cleaning granite were compared, hydrofluoric acid (HF) and grit blasting. Thin sections were examined before and after cleaning, and revealed that quartz was fractured by both conservation treatments.

Photomicrographs of thin sections were digitized for calculation of quantitative fracture statistics. Image analysis gave fracture length per unit area of quartz. Although fracture lengths were somewhat lower for HF than for grit-blasting, both cleaning methods caused an increase in fractures of a factor of three or four compared to the uncleaned surface and the stone interior.

4.6 CHARACTERIZING CEMENTITIOUS MATERIALS

Berlucchi and Corradini (1995) used a variety of laboratory tests to compare standard mortars of known components with historic mortars found in the masonry walls of 16 historic monuments. The goal was to reconstruct historic mortar recipes, so that restoration materials would correspond as closely as possible to original building materials. Digital image analysis of thin sections helped to determine binder/aggregate ratios.

Hansen (2000) used thin sections in research on Maya burnt-lime technology (stucco, plaster, and mortar). His main interest was in better understanding complex technological styles. He needed to resolve the problem of the binder and aggregate being mineralogically and chemically similar, as both were derived from limestones. He prepared thin sections from archaeological materials, from raw materials that might have been used in their preparation, and from laboratory replicates of known formulations of a variety of components and recipes.

Two types of thin-section images were used for mineralogical and textural analysis: images captured directly at the microscope, and images obtained by scanning thin sections as if they were slide transparencies. The advantage of scanning slides is that the resulting images cover a more extensive area of the thin sections than can be obtained from a microscope, facilitating studies of macrotexture.

REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

Goins (2002; see also Goins and Reedy 2000) also used digital image analysis of thin sections for characterizing components of historic cementitious materials. She presents a protocol in which she outlines the steps needed for a successful analysis of such materials, including characterizing aggregate, relict cement grains and hydration products, matrix, and voids or pores. She describes how the relative proportions of the constituents of cementitious materials can be estimated by traditional methods of point counting or linear traverse, or by area estimation using image analysis. She notes that an advantage of image analysis software is that information on grain sizes and textures is acquired simultaneously with acquiring of photographic images.

Mueller and Hansen (2001) used digital image analysis to study historic building materials. Their primary goal was to characterize pore texture using thin sections. They note that with cultural materials, there may not be enough sample material available for performing some tests found in ISO or ASTM standards. In contrast, thin sections require only a small amount of material, and can be used for measuring multiple parameters. Thin sections can also show the progression of deterioration from surface to interior. Mueller and Hansen used Image-Pro Plus to characterize macropores, focusing on pores at or above an area of $400 \mu\text{m}^2$. By mounting samples in a blue-dyed epoxy resin, they could use a hue-saturation-intensity segmentation procedure to separate the blue-dyed pores from other components of the thin sections.

Thompson and Jerram (2003) also used thin sections impregnated with blue epoxy resin to quantify porosity, although they were studying sand and lava cemented by calcite. They wrote a macro plug-in for a freeware image analysis program (Scion Image) to automatically recognize the blue hues representing porosity (from the blue epoxy) and calculate a percentage abundance for the thin section. They compared the results with results for optical point counting, and found them comparable, but requiring much less time to complete than the older method.

Others have used novel sample preparation protocols to help improve visibility of components of interest for image analysis work. For example, Herwegh (2000) used a two-step etching technique (using 0.37% hydrochloric acid and 0.1% acetic acid) to produce topographic relief that reflects grain boundary geometry for fine-grained carbonate materials (in this case, nylonites). Calcite grain boundaries

were more intensely dissolved than their grain interiors, while other minerals were not affected by the acid, and thus form topographic peaks.

Carò and Di Giulio (2004) did in-depth experiments on the reliability of image analysis for morphological and textural characterization (especially quantity and assortment of aggregate) in studies of ancient plasters and mortars. They prepared a series of mortars of pre-determined textural features and composition for analysis, then compared the results of mechanical sieving and thin section petrography. To improve grain boundary discrimination, uncovered thin sections were stained with Alizarin Red S, giving the lime binder a pink or red color and distinguishing it from other fine-grained components.

The thin sections were analyzed both by manual point counting (100 grains per thin section) and by digital image analysis using Image-Pro Plus, collecting data for six images per thin section. Carò and Di Giulio note that for image analysis, choice of magnification and image resolution are crucial and affect the precision and reliability of the results. The field of view must be large enough to see the largest features and pixel size has to be small enough to detect the smallest details. They characterized aggregate percentages and grain size distribution, using area percent and Feret's diameter (width of rectangles enclosing an object). The latter was chosen because of robustness and similarity to the geological application of sieve aperture.

They note that whichever approach is used, calibration with standards is important. For both point counting and image analysis of coarse aggregates, bias can be introduced by the size of the field of view; for fine aggregates, by image resolution and grain detection. Blurring in images of fine fractions can be problematic. If image acquisition results in more blurring along the edges of the image, an area of interest can be outlined for counting, selecting the best part of the image. (Alternatively, Image-Pro Plus has a depth-of-field correction procedure that reduces or eliminates any blurring along edges.) Staining the thin sections with Alizarin Red S improved consistency in analysis with aggregates ranging from fine to coarse. Image analysis results were similar to those of point counting, but the procedure was much faster and more reproducible. Conversion to volume percentage allowed comparison between the thin section data and sieving data.

Casadio et al. (2005) also compared digital image analysis of mortars with results obtained by other

analytical approaches. They too prepared mortars of known composition containing carbonate aggregates of different origin (travertine and Bath limestone) for analysis by wet chemistry, manual disaggregation, and digital image analysis of thin sections and cross sections stained with Alizarin Red S. Binder/aggregate ratio was the main focus of analysis, since that is the parameter that most affects the working and use properties of a cementitious material. They note that acid dissolution of the binder fraction is problematic because concentrated acidic solutions dissolve any calcareous aggregate present, while dilute solutions may dissolve the binder only partially. Mechanical methods used as an alternative are also problematic because they tend to give unreliable values for the binder/aggregate ratio. Petrographic methods that focus on point counting are very time consuming, so digital image analysis is a promising alternative.

Casadio et al. tried different approaches to separating the binder and aggregate for analysis, checking reproducibility and accuracy through replicated analysis of specimens of known composition. Both the thin sections and cross sections of prepared mortars were embedded in blue-dyed epoxy resin so that pores were visible and aggregate boundaries were sharpened. The sections were then stained with Alizarin Red S to highlight the carbonate components. Rather than use digital images acquired at the microscope, the sections were scanned at maximum resolution on a flat-bed scanner to improve contrast. Cross sections were included because they are easy to prepare and can be larger than standard thin sections (they used diameters of up to 5 cm) to improve the statistical validity of results.

They found that image contrast needed to be optimized in the original image so that objects of interest stand out clearly from other components and from the background. Staining with Alizarin Red S and acquiring the thin section images in reflected rather than transmitted light best accomplished that objective. They also found that precision in quantitative analysis was improved by using an image of very high resolution but reducing the number of colors down to 16. By avoiding the array of pixels showing subtle color variations, a sharpened contrast was obtained around grain boundaries. Using this procedure they were able to obtain, with good reproducibility, percentage area estimates for components of mortar with travertine aggregate, used to calculate binder/aggregate ratios. Problems were encountered in using this procedure for mortars prepared with

Bath limestone, because the porosity and microtexture of the microcrystalline aggregate made it difficult to separate from the binder (it did not respond well to selective staining).

Casadio et al. concluded that, overall, digital image analysis was accurate, applicable to many different mortars, less time consuming than point counting, and gave representative results provided more than one thin section was analyzed. Adding the image analysis enhanced the optical microscopy that was already used qualitatively to identify mineral composition and mortar texture; adding quantitative data on binder/aggregate ratio is especially important where carbonate aggregates are present, as in that case traditional analytical methods are not adequate.

4.7 ANALYZING CERAMIC MATERIALS

There are many research questions pertaining to ceramics that are addressed through thin-section petrography (Peacock 1970; Williams 1983; Jones 1986; Freestone 1995; Velde and Druc 1999). Often, analysis of a large selection of sherds from a site or region provides information not available from analysis of a few sherds in isolation. For quantitative studies involving statistical analysis, ten or more specimens per group may be needed (Freestone 1995). The availability of image analysis packages for developing routines and protocols for quantitatively characterizing large numbers of specimens is clearly advantageous.

The time-consuming and tedious methods of quantitative petrography for characterizing wares lend themselves well to digital image analysis (Reedy and Vallamsetla 2004b). For example, Forte (1994) incorporated image analysis of thin sections in characterization studies of Etruscan bucchero ceramics, and found it helpful in addressing a variety of questions on technology and identification of production areas.

Schmitt (1993) used image analysis to characterize thin sections of Roman amphoras found in Lyons, France. She focused on quantifying grain-size distribution and on identifying the percentages of each type of grain constituting the non-clay component. Ceramic data were compared to geological data in efforts to identify production locales.

Velde and Druc (1999) presented results of digital image analyses of common-ware sherds from central France. The goals were to count grains of

REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

specific types, estimate the amount of non-clay material present, and estimate grain sizes and relative amounts of different-size grains. Photomicrographs of thin sections were scanned and then the quartz and feldspar grains enhanced through a binary conversion process that converts those grains to black and the clay matrix background to white. An image analysis program (not specified) was then used to compute surface area of the particles, perimeters, and length over width; frequency histograms were produced with the data by use of a separate spread sheet.

Since sands and sandstones have many similarities to ceramic materials, some work on image analysis performed by sedimentary geologists is relevant to ceramic studies. Schäfer and Teyssen (1987) used an image analysis system to determine grain-size distribution, grain shape, and grain orientation in thin sections of sands and sandstones. Protz and VandenBygaert (1998) developed a protocol for using image analysis to differentiate voids, organic matrix, clay coatings, and carbonate and iron concretions in thin sections of soils. Francus (1998) showed how image analysis (using a binary conversion process) to study grain size variation in thin sections of soft clastic sediments can be done relatively quickly and quantitatively.

Cenozoic aquifer sands in Belgium were analyzed by traditional sieving as well as by digital image analysis of thin sections (Lagrou et al. 2004). The authors note that the image analysis approach gives an overestimate of smaller grain sizes, mainly due to random sectioning of the grains in thin section. This difference between sieving and thin section data is a well-known phenomenon, and conversion equations exist if the two data types need to be compared (Harrell and Eriksson 1979; Johnson 1994). However, some of the difficulties encountered by Lagrou et al. could be improved by better preprocessing procedures to prevent the artificial splitting of inhomogeneous grains into several smaller grains, and by making a composite image so that large grains that exceed the field of view of the image are not cut off.

For ceramics, statistical analysis of grain-size distribution may help identify the presence of deliberate non-clay additives (temper). Natural sediments tend to have a unimodal, continuous distribution of grain sizes. In contrast, when an additive is present, there tends to be a bimodal distribution of grain sizes, with the finer grain sizes coming in with the clay and coarser ones with the added temper material. Another approach that is used is to compare the total surface

area of the larger grains with that of the smaller grains, keeping in mind that there will be a range of diameters for both added and naturally-occurring grains. The two statistical approaches combined can be used to characterize the amount of temper additive (Velde and Druc 1999).

A similar approach was taken by Bouchain and Velde (2001) in a study of grain-size distribution by image analysis of thin sections from Gaulo-Roman common wares excavated in France. All specimens studied have a similar mineralogy of quartz, potassium feldspar, muscovite, and biotite with occasional accessory minerals. A two-mica granite was suggested as a precursor, with a common origin for both the clay and grit resources, probably coming from sandy micaeous deposits found along a river bed near the site. An in-house program was used for a binary conversion process, so the brown clay was converted to white background while the translucent grit was converted to black. Estimation of grain size for the grit particles was done by computing the percentage of the area of the photograph occupied by various size categories. Grain-size distribution curves were then plotted.

They concluded that three types of grain distribution could be seen. In one, grain sizes are evenly and symmetrically distributed on plots that compare log size to area percent, indicating a single origin for sediments used to make the paste. In the second, the same regular distribution is seen, but there are also some very large grains with a clear size cut-off, as might result from sieving of the river sediment to produce the grit. The third is similar to the second but the large grains include some that are much larger than the others, which Bouchain and Velde interpret as indicating the addition of a temper of varying grain size rather than from sieving of the original material. Thus different methods of preparing paste were used for a single ceramic ware.

Using Image-Pro Plus with a sandy ceramic thin section, it is fast and easy to focus on the non-clay sand fraction and look at its size distribution. Once calibration and preprocessing steps have been completed, one can use a procedure in which the bright objects (the sand) within the darker clay matrix are highlighted and measured. Histograms can then be viewed for visual evaluation of size distribution. Figures 2, 3, 4, and 5 compare results for two different sherds. For figures 2 and 3, the results indicate a continuous distribution of sand grain sizes, ranging from 0.002 to 0.09 mm with the largest

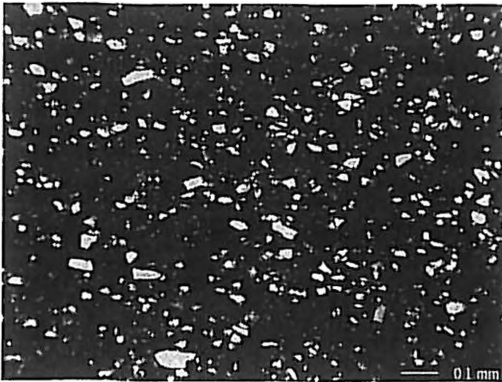


Fig. 2. A ceramic thin section analyzed using Image-Pro Plus' "automatic bright objects" procedure to select the bright sand grains within a dark clay matrix.

number of grains falling between 0.003 and 0.02 mm. The results for figures 4 and 5 point instead to the presence of two distinct populations. One population has a similar spread as that of figure 3, although with a somewhat larger starting size. This population ranges from 0.006 to just above 0.09 mm, with most grains falling between 0.008 and 0.05 mm. The second population consists of a concentration of larger grains at or above 0.10 mm in size. The first population of grains may be a natural constituent of the clay, with the second representing a separate temper additive.

Since larger grains are often much fewer in number than smaller grains, an accurate analysis of size distribution generally requires characterization of multiple areas within a thin section, with the data

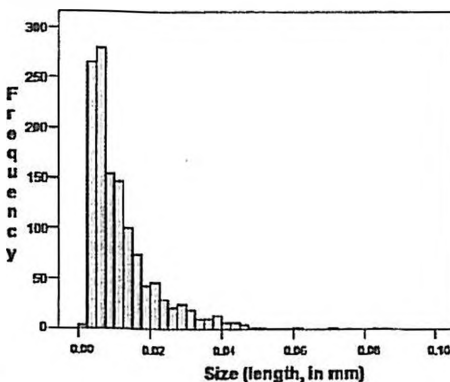


Fig. 3. The histogram accompanying the "automatic bright objects" analysis of figure 2 shows a continuous distribution of sand grain sizes, ranging from 0.002 to 0.09 mm, with the largest number of grains falling between 0.003 and 0.02 mm.



Fig. 4. A second ceramic thin section analyzed using Image-Pro Plus' "automatic bright objects" procedure to select the larger grains within a fine-grained dark clay matrix.

combined for statistical analysis. It is also important to exclude any grains that are touching the boundaries of the area of analysis, as otherwise large grains that are cut off from the edge of the field of view will be given an artificially small size. Most comprehensive image analysis packages such as Image-Pro Plus can exclude such grains from the count automatically.

Along with histograms, Image-Pro Plus produces a variety of statistical data that can be used to characterize ceramic materials. For example, one can view data on the total areal percentage of the sand component; the minimum, maximum, and mean length of the sand particles; and minimum, maximum, and mean quartz roundness (perimeter divided by area). Data such as these can be exported to a statistical package for multivariate statistical analyses.

Whitbread (1991) wrote an image analysis program called Grain-Size Analysis (GSA) to help in distinguishing particles to be measured. He found that in crossed-polarized light, ceramic fabrics tend to be rather dark, limiting the ability of automatic image analysis to identify boundaries of some components. For example, composite inclusions such as lithic fragments can present problems in differentiating between boundaries of the lithic fragment and those of individual grains within the fragment. Thus Whitbread used a combination of conditions including plane polarized light, crossed-polarized light, and crossed-polarized light with a gypsum plate, in order to clarify the boundaries of some features.

Modern comprehensive image analysis packages help to overcome some of these limitations by providing a variety of approaches to separating the components of interest. For example, with Image-Pro

REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

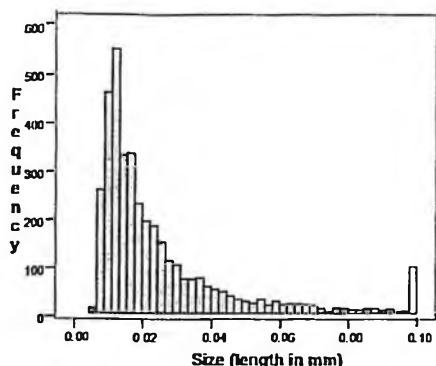


Fig. 5. The histogram accompanying figure 4 shows two distinct populations of grain size rather than one continuous distribution. Most of the grains are small, a few are larger. One background population shows the same continuous distribution of grain sizes as seen in figure 3, although with a starting point of larger grains. This group ranges from 0.006 to just above 0.09 mm, with most grains falling between 0.008 and 0.05 mm. A second group is concentrated at larger sizes of 0.10 mm or larger. The first population of grains may be a natural constituent of the clay, with the second representing a separate temper additive.

Plus the user can convert the image to gray scale or not, use an automatic bright object or automatic dark object marking protocol, or use a dropper tool for manual highlighting of gray-scale gradations or color variations that represent the full range of visual appearances of the component of interest. Selections can be restricted further according to specific grain sizes, shapes, or other parameters. In addition, careful attention to lighting conditions at image capture and to preprocessing steps can significantly improve separations.

With Clemex Vision Professional Edition, one can choose gray thresholding to separate features of interest. A gray-level histogram shows clearly defined peaks indicating distinct phases on gray levels, and the distribution of pixels within each gray level. One can then manually select at which points to assign a gray level to a specific phase. For example, the gray-level histogram in figure 6, produced for a ceramic thin section, has the lower levels (indicated by brackets) defined as belonging to the clay matrix and the higher levels as belonging to the sand component. Each selected phase will be highlighted in a distinct color or shade (fig.7). That image can be inspected visually to confirm that the marking procedure correctly highlighted all of the sand grains within the clay matrix. If so, the grains are now ready for counting and measuring.

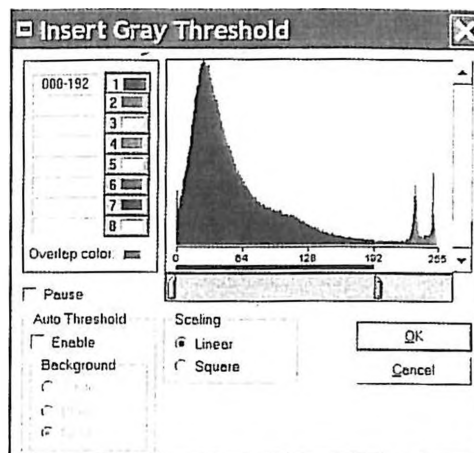


Fig. 6. A gray-level histogram (from an analysis using Clemex Vision PE) with clearly defined peaks indicating distinct phases in a ceramic thin section, and distribution of pixels within each gray level. The lower levels of the gray threshold histogram, delineated by the brackets, are defined here as belonging to the clay matrix, with the higher levels belonging to the sand component.

Additional operations can exclude particles of a certain size, shape, or other defined attribute. In some cases the gray thresholding procedure may not work satisfactorily due to too many subtle gradations between phases of interest. A shading calibration option in the Clemex software may help, as may use

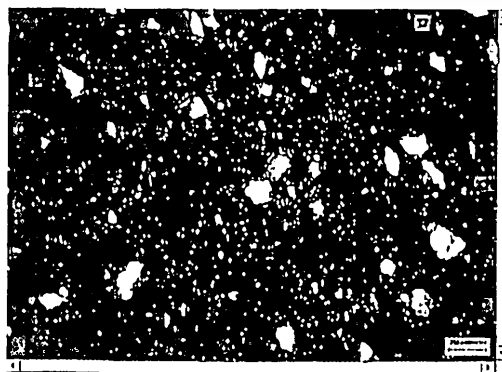


Fig. 7. The phases delineated in the gray-level histogram are then highlighted with a distinct color or shade for each phase. Visual inspection of the resulting image confirms that the marking procedure in figure 6 correctly highlighted all of the sand grains within the clay matrix. The grains are now ready for counting and measuring.

of a color thresholding option. As with Image-Pro Plus, there are tools available in Clemex to select manually a color range to highlight for each phase. Again, exclusions can be made based on size, shape, or other defined attributes.

Another approach is seen with the ImageJ package. One of its procedures that tends to work well much of the time with ceramic thin sections is to convert the thin section image to gray scale first (fig. 8), then to a binary threshold image as shown in figure 9. The sand fraction now appears as black particles against a white background (the clay matrix). The particles can be processed further in a variety of ways before counting and measuring, including separating joined particles or excluding particles of a certain size or shape from counting and measurement. This procedure is similar to the binary thresholding discussed by Velde and Druc (1999) and by Bouchain and Velde (2001).

Middleton et al. (1991) developed computer programs for image analysis of ceramic thin sections for a study of Romano-British relief-patterned flue tiles. Relief patterning was applied to the tiles using wooden rollers, not primarily for decoration, but to provide a key for the application of plaster. A variety of patterns, or dies, were used. An unanswered question was whether or not the appearance of the same die pattern at different sites implies that the tiles were made at centralized production sites and then transported to other sites, or whether instead it implies the presence of itinerant tile makers who traveled with their own tool kit of roller dies. Middleton et al. wanted to answer this question for two sites in Surrey, England.

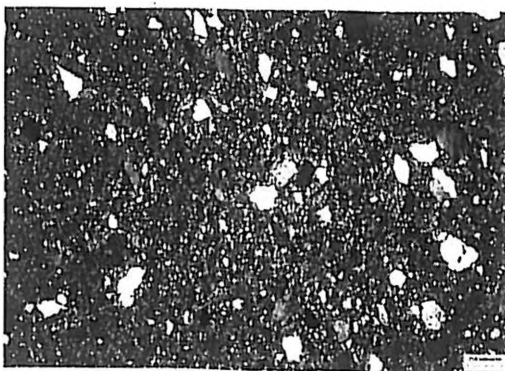


Fig. 8. A ceramic thin section comprised of a fine clay plus a sand temper, in crossed polarized light, converted to gray scale using the ImageJ package.

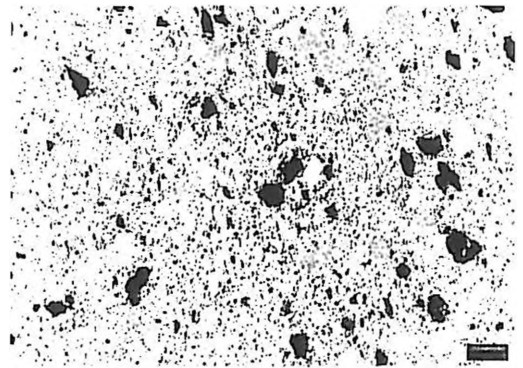


Fig. 9. Using ImageJ, the gray-scale image in figure 8 is converted to a binary threshold image. The black components (the sand fraction) are now ready for counting and measuring.

Two main fabric groups could easily be distinguished in thin section, but subdivision of the first group was difficult because there were so many similarities and so many samples to analyze (about 60 tiles). They therefore developed a computer-based procedure to establish fabric groupings. They wrote their own preprocessing programs, and used existing statistical packages for cluster analysis and multidimensional scaling. Images were then compared with each other, and a similarity index developed using a scale of 1–5. Ultimately, they concluded that the relief-patterned tiles were made at one of the sites, where kilns were also found, and were used there as well as transported to the other site for use in construction.

With ceramic materials, porosity data can be used to study deterioration and to design preservation approaches. For example, in a study of Central American earthen materials, Mueller and Hansen (2001) examined porosity to characterize water transport capability, as a way of predicting problems from uprising damp and fluctuations in relative humidity. Thin sections were used to quantify pore size distribution and to create a porosity profile from surface to interior, using Image-Pro Plus. Color differences between matrix grains (less than 30 microns in size), sand grains, and macropores helped in separating and quantifying the components.

4.8 MEASURING LAYER THICKNESS

Image analysis can be used to measure deterioration layers on stone as an assessment of weathering.

REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

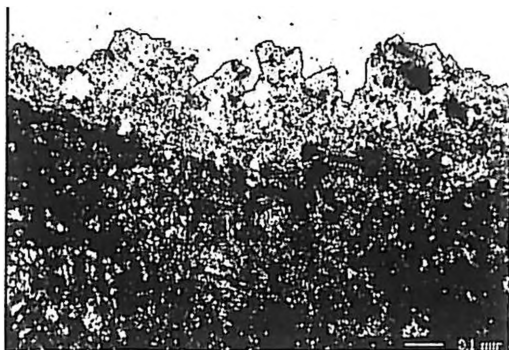


Fig. 10. A thin section taken from a Gandharan phyllite sculpture (plane polarized light) shows an outer weathering layer of altered material. With Image-Pro Plus, a tracing tool is used to mark the upper and lower boundaries of the layer. The software can then calculate the minimum (0.11 mm), maximum (0.32 mm), and average layer thickness (0.20 mm), as a measure of deterioration.

The range and average thickness of layers can be measured quickly and with great accuracy. For example, a thin section of an ancient Gandharan stone sculpture made of phyllite is shown in figure 10. It has an outer layer of altered material, different in appearance under the microscope from the layer below. Using a tracing tool in Image-Pro Plus, lines are traced along the upper and lower boundaries of the layer, and the distance between them automatically measured. Usually we are interested in knowing the average width, or distance between the two lines, as well as the minimum and maximum distance. This automatic process easily allows us to examine variation in the outer weathering layer, to compare this layer to those found on other Gandharan phyllite sculptures, and to layers on known forgeries. Here the minimum layer thickness was found to be .11 mm, the maximum .32 mm, and the average .20 mm.

Other image analysis packages take different approaches to identifying a layer. For example, with the Clemex package, gray or color thresholding is applied in a manner similar to that used to highlight different phases or components in ceramics. Once the underlying stone material, the layer, and the epoxy background have all been assigned to bitplanes, or colors, automatic measurement sampling can take place at parallel lines all along the layer. Figure 11 shows how this process can be used to highlight for measurement the same stone layer as seen in figure 10. This process also results in data on the minimum, maximum, and average distance, which were com-

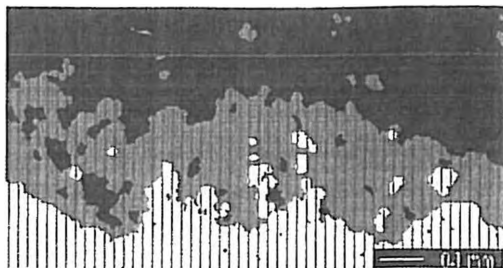


Fig. 11. The Clemex software uses a gray or color thresholding procedure to separate layers. The matrix material, the layer, and the epoxy background have all been assigned to bitplanes, or colors. Automatic measuring is then done at a series of parallel lines all along the layer, giving minimum, maximum, and average distance of the layer. The procedure is being applied here to the same stone specimen shown in figure 10, and the measurement results are comparable.

parable to the results obtained by the procedure of figure 10.

The same procedures can also be used to measure layers that mark technological processes. For example, figure 12 shows a glaze layer on a ceramic thin section. Any image analysis package can easily measure distance at a single point along the layer. In figure 12, measurements were taken at six separate points, giving layer thicknesses of 34.39, 54.75, 36.29, 62.01, 72.89, and 99.16 μm moving from left to right across the field of view. However, with the degree of varia-



Fig. 12. The thickness of a glaze layer on a ceramic thin section (plane polarized light) can be measured at a single point using an image analysis package. Here six points were measured, giving layer thicknesses of 34.39, 54.75, 36.29, 62.01, 72.89, and 99.16 μm moving from left to right across the field of view. Alternatively, a software package capable of automatically calculating the minimum, maximum, and average thickness can be used in order to study technological style or surface deterioration.

tion present, the ability to automatically calculate a minimum, maximum, and average width is crucial if one is interested in characterizing a technological style or quantifying surface deterioration. Thus selecting an analysis package capable of this more detailed work would be important (Reedy and Kamboj 2004b).

5. CONCLUSIONS

There are many more potential ways in which digital image analysis can aid in characterizing and studying petrographic thin sections of inorganic materials for conservation research applications. The existence of extensive image analysis computer 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 selection of appropriate choices at each step of analysis. Recent innovations in petrographic microscope equipment (Fueten 2006) are helping to maximize the usefulness and success of image analysis of petrographic thin sections.

Effective analysis depends upon the quality of the images being analyzed. Image capture must provide even lighting conditions and a sharp image, and preprocessing must ensure that the components of interest are distinctly visible. However, the ability to rapidly obtain quantitative data from petrographic thin sections makes digital image analysis packages highly advantageous for conservation research.

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REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

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REVIEW OF DIGITAL IMAGE ANALYSIS OF PETROGRAPHIC THIN SECTIONS IN CONSERVATION RESEARCH

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