Scanning Microscopy

Volume 2 | Number 3 Article 4

3-9-1988

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W. Petruk
CANMET

Scanning Microscopy, Vol. 2, No. 3, 1988 (Pages 1247-1256)
Scanning Microscopy International, Chicago (AMF O'Hare), IL 60666 USA

0891-7035/88$3.00+.00

THE CAPABILITIES OF THE MICROPROBE KONTRON IMAGE ANALYSIS SYSTEM : APPLICATION TO MINERAL BENEFICIATION

W. Petruk

CANMET
555 Booth Street,
Ottawa, Ont. Canada K1A 0G1

Phone: 613 992 1376

(Received for publication June 16, 1987, and in revised form March 09, 1988)

Abstract

Image analysis is a technique for determining quantities, grain size distributions, grain orientations, intergrowths, associations, liberations and degrees of alteration of minerals or phases in naturally occurring and processed materials. It is performed by analysing images of polished or thin sections of the material under study. To obtain accurate results the images must be faithful reproductions of the material, and each mineral or phase displayed in the images must be distinct enough to be automatically discriminated and identified without operator interaction. An image analysis system that meets these requirements was developed in the Process Mineralogy Section at CANMET by interfacing a microprobe, an energy dispersive X-ray analyser (EDXA), and an image analyser with communication in both directions between the units. The analytical procedure involves transferring a backscattered electron image (BSE) from the microprobe to the image analyser. The minerals or phases are discriminated and identified on the basis of their grey levels in the image. If the grey levels of two or more minerals or phases are too close for discrimination and identification, the minerals or phases are identified by scanning each grain with the electron beam of the microprobe under control of the image analyser, and analysing the grains with the EDXA. To perform the analysis a binary image is produced for each mineral displayed in the BSE image and prepared for analysis by using a variety of image analysis routines. The binary images are analysed and the data are classified, summarized and output in simple tables and graphs.

Key Words: image analysis, automatic image analyser, backscattered electron image, energy dispersive X-ray analysis, mineral quantities, size distribution, mineral discrimination, mineral association, mineral dressing, grain boundary reconstruction.

Introduction

Image analysis is a technique used in applied mineralogy to mineral beneficiation to determine mineral quantities, grain size distributions, grain orientations, mineral intergrowths, mineral associations, degrees of liberation, and degrees of alteration of minerals in naturally occurring and processed materials. The technique involves analysing an image of a polished or thin section of the material, by (1) producing an image with an imaging instrument such as an optical microscope, scanning electron microscope (SEM), or microprobe, (2) transferring the image to an image analyser, (3) digitizing the image, (4) processing the digitized image and preparing it for measurement, (5) measuring appropriate parameters, and (6) classifying and summarizing the data and outputting it in a simple format.

The combination of the imaging instrument plus the image analyzer will be referred to in this paper as an image analysis system. For automatic image analysis the image analysis system must be capable of discriminating and identifying every mineral or phase in every field of view although the operator may wish to analyse only the phases of interest. The optical microscope was the standard imaging instrument during the initial applications of image analysis to mineral beneficiation (Oosthuyzen, 1983, Petruk, 1976). The image was transferred to the image analyser via a black and white TV camera. Unfortunately many minerals cannot be discriminated from each other in such an image. By contrast, most minerals can be discriminated from each other by their grey levels in the backscattered electron (BSE) image produced with a scanning electron microscope (SEM) or microprobe. (Jones and Smith, 1978, Lebiedzik and Gouda, 1981). Furthermore, the computer control of the electron beam and digital image processing of the backscattered electron output (Byers et al, 1971, Troutman et al, 1974, and Lebiedzik et al 1979) has made it possible to (1) scan each particle with the electron beam of the SEM or microprobe (2) sort the X-ray spectrum of each particle with the energy dispersive X-ray analyser (EDXA) (3) compare the resulting spectrum to spectra in reference mineralogy or phase files, and thereby identify each particle.

An image analysis system was developed at CANMET by interfacing a JEOL 733 microprobe, a Tracor Northern 2000 EDXA and a Kontron SEM-IPS image analyser in such a manner that communication in both directions is possible between the units. To integrate the instruments in this manner the manufacturers wrote special programs according to the author's design, and the author tested them. The system is referred to as a microprobe SEM-IPS image analyser (MP-SEM-IPS), and is described in this paper. CSIRO have developed a comparable image analysis system, the QEM*SEM (Miller et al, 1982). Its mode of operation is different and a description of it is beyond the scope of this paper. A Cameca microprobe image analyser, using a line scan technique, has been developed at Royal School of Mines (Jones, 1985).

The advantages of the MP-SEM-IPS image analysis system are (1) accurate mineral identification in the automatic mode, (2) high speed of mineral identification using grey levels in the BSE image, (3) automatic identification of particles that cannot be discriminated on the basis of their grey level, (4) most of the image analysis capabilities that are available on the market have been incorporated into the system, and (5) data are output in summary tables (Petruk, 1985).

General Operation of the MP-SEM-IPS Automatic Image Analysis System

During set-up for analysis a BSE image is obtained on the microprobe and transferred to the image analyser via an interface (Fig. 1A). Each mineral is discriminated on the basis of its grey level in the image (Figs. 1B, 1D-1H), and a separate binary image is produced for the mineral. Each mineral is first identified off-line with the EDXA. If several minerals are found to have the same grey level, they are identified during analysis by scanning the particles from the image that represents these minerals (multi-mineral grey level image) (Fig. 1C) with the electron beam. Each particle displayed in this grey level is therefore individually identified. Images of mineral grains that have been identified, on the basis of grey level, as well as by scanning individual particles are stored in a separate image memory for each mineral (Figs. 1D-1H). The grains in each image memory are then analysed to determine the required properties, such as mineral quantities, size distributions, etc., and the data are output in appropriate tables and graphs. When the analysis of a field is completed the sample is automatically moved to a new field, and the process is repeated. Generally a sufficient number of fields is analyzed to measure about 5000 particles. The operation is performed unattended.

The image transferred to the image analyser is normally 512 by 512 pixels, although images of 1024 by 1024 and 256 by 256 pixels can be obtained. The magnification is selected by the SEM or microprobe. The most common magnification is 200 to 400X, with minimum and maximum magnifications being 60 and 1000X, respectively. When the magnification is less than 60X the grey level from top to bottom of the field is not uniform enough for analysis, and at magnifications greater than 1000x the resolution is too poor for analysis.

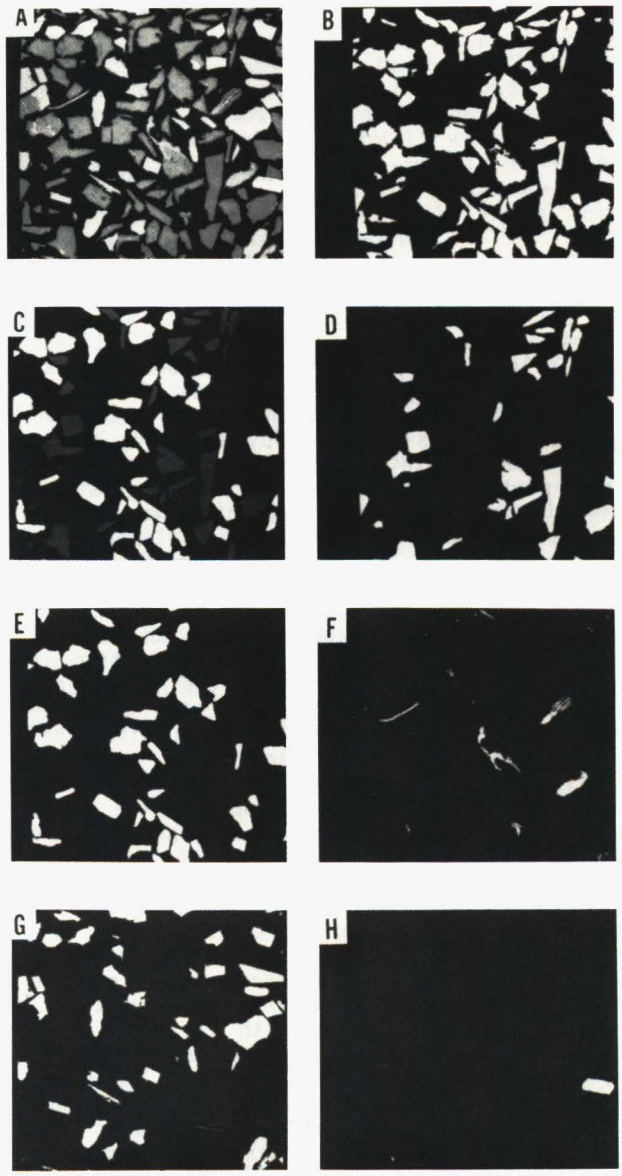

Fig. 1. Images on image analyser. (A) Electron backscattered (BSE) image transferred to the image analyser. The grey grains are quartz and albite, the medium grey are microcline, the light grey are orthoclase and the white are apatite. (B) Binary image of quartz plus albite (undifferentiated). (C) The quartz and albite of image 1B have been identified with the EDXA (differentiated). The quartz is dark grey and albite is white. (D -H) Binary images: D = quartz, E = albite, F = microcline, G = orthoclase and H = apatite.

The image analysis system contains several hundred image analysis programs. The analysis is performed by stringing appropriate image-analysis programs in series to build an operator's program for the required task. The system operates in such a manner, that during set-up, image-analysis programs are entered into the operator's program whenever they are tried. When the operator has developed a workable operator's program he can save it to disk, edit it, and recall it as required.

Image Input

For automatic image analysis it is of utmost importance that the image transferred to the image analyser be a faithful reproduction of the image under study, and that each mineral displayed in it can be discriminated. The grey levels of minerals in the BSE image from a SEM or microprobe relate to the average atomic number of the minerals, with the lowest atomic number mineral being darkest grey, and the highest atomic number mineral being white. This property enables mineral or phase identification. For automatic image analysis the image must be produced with a fast scan high resolution BSE module, and not a standard BSE module. The grey level for each mineral produced with a fast scan BSE module stays constant as the sample is moved from field to field, and as the magnification is changed, providing that the accelerating voltage, the beam current on the Faraday cup, the amplifier brightness and contrast from the BSE detector are held constant. Therefore, a primary requisite is that the SEM or microprobe be equipped with a fast scan BSE module and have meters for monitoring these above conditions. All the meter readings must remain constant during the period of analysis, which could be several hours. To maintain a constant current, a beam stabilizer is a necessary module on a microprobe or SEM. To verify that the beam current has not drifted the operator checks the meter readings periodically. If the beam current has changed, the analysis is repeated. It has been found that the beam current remains constant after the microprobe has operated four hours. Consequently the microprobe is left on all the time, and successful unattended overnight runs are routinely carried out.

The window for the grey level can be modified during set-up by adjusting the BSE amplifier brightness and contrast on the microprobe or SEM. A narrow window permits good discrimination between minerals, but the window needs to be wide enough to include all the minerals that need to be analysed. It has been found that quartz can be readily discriminated from K-feldspar in an image produced at a setting of 20kV and 15 na, with a window that is wide enough to include all the silicate and metallic minerals in a base metal ore. By contrast quartz cannot be discriminated from Na-feldspar on the basis of grey level because both minerals have a similar average atomic number.

Mineral Identification

Grey Level From BSE Image

It is possible to discriminate about fifteen to twenty different phases in the BSE image that has been transferred to the image analyser. The BSE image includes all minerals that fall within the window selected by the fast scan BSE module on the microprobe or SEM. The minerals are discriminated manually by fixing the threshold settings for their gray levels at the beginning of analysis of each polished section. The settings remain fixed during automatic analysis, and if desired during all future analysis of the same type. The mineral represented by each grey level can be identified off-line by focusing the electron beam of the microprobe on a representative particle. An X-ray spectrum is collected from the particle and identified manually with the EDXA. A mineral name is then assigned to particles within each grey level, and this mineral identity remains constant as long as the operating conditions on the microprobe remain constant.

EDXA

If more than one mineral is represented by a particular grey level, each particle in such a multi-mineral image (Fig. 1C) is scanned automatically with the electron beam and identified on the basis of its chemical composition. The above-mentioned Na-feldspar (albite) and quartz are discriminated and identified in this manner.

To automatically identify particles by scanning with an electron beam, a number of conditions must be met. Firstly the windows on the EDXA must be set to define the elements that will be used to identify the minerals. Secondly a computer routine that will label the element peaks and calculate the relative peak intensities must be written. Mineral compositions are normally determined by counting the X-rays from each particle for a set period of time. The Kontron classification in the MP-SEM-IPS, however, works by scanning each particle at a speed defined by the operator, and counting gross intensities in the selected windows during the entire scanning period for each particle. When the scan is completed for one particle the electron beam automatically moves to the next particle. Since it takes a longer period of time to scan a large particle than a small particle the total counts will be greater for the large particle than for the small particle. Consequently a relative peak intensity that is independent of scan time is calculated by computer for each peak in each window. Thirdly a reference file of minerals or phases must be prepared by scanning standards to obtain relative peak intensities in each window for each reference mineral or phase. Only the mineral or phase that is in the reference file will be identified. The particle will be rejected if (1) the mineral or phase is not in the reference file, (2) if the particle is composed of two or more minerals, or (3) the particle is too small (<1μm). Images of the rejected particles can be recalled and analysed separately.

Discrimination of Minerals

The transition from one grey level to another in a multi-level BSE or optical microscope image occurs over a distance of one to several pixels, and this is reflected in the detected binary image, which is the image that is analysed. Consequently, the initial binary image is a poor representation of the area covered by the grey level in the original BSE image. The transitions are referred to as halo effects, artifacts from other minerals, electronic noise, overlapping grey levels, etc. (Fig. 2A). The binary image can, however, be filtered and enhanced so that the binary image for the mineral or phase is an exact or nearly exact representation of the grey level in the original BSE image (Fig. 2B). The enhancement is achieved by a variety of methods, including an erosion-dilation technique to remove small unwanted binary features and a restoration technique to restore the remaining features to their original size and shape. For an exact overlay of binary image on the original image, boolean and markobject (See glossary) operations are used in conjunction with the erosion-dilation technique. These operations retain the boundaries of the particles in the original image.

If a mineral is poorly detected because of overlap of grey level with another mineral the detected binary image can be enhanced to represent the mineral. This is done by an image enhancement (median) routine that determines the density of pixels in the detected binary image and creates mineral outlines (Figs. 3A-3H). This computer-generated outline is not a true outline of the mineral (Figs. 3D, 3F, and 3H), but is a relatively accurate representation. The enhanced image of each mineral is then stored in a separate image memory.

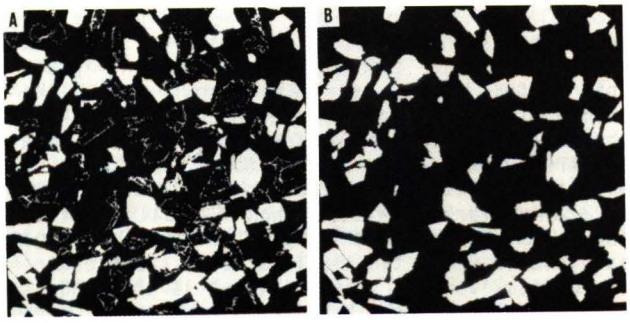

Fig. 2. (A) An unfiltered digitized image for quartz plus albite showing artifacts from other minerals. (B) Enhanced binary image of Figure 2A. It was enhanced by erosion to remove small unwanted features and by restoration to bring the grains to the original grain sizes and shapes by using the markobject operation.

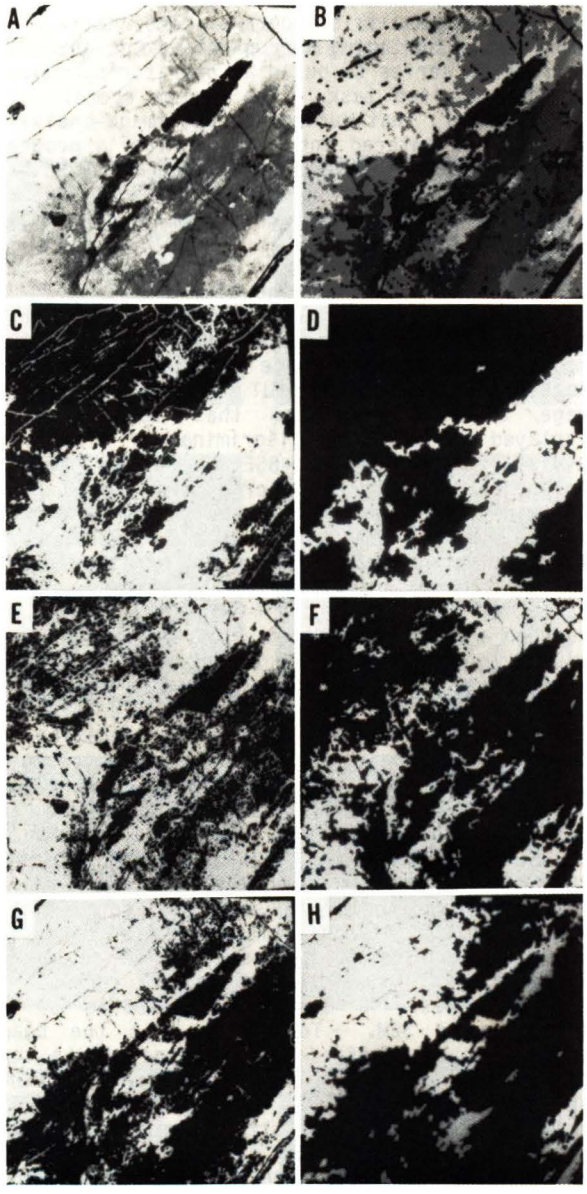

Fig. 3. Detection of compositional zones in an allanite grain where the grey levels for the zones are close and overlap. (A) BSE image transferred to image analyser. (C) Detection of darkest grey zone plus artifacts from other grey zones. (D) Enhanced binary image of Figure C using the density of pixels routine. (E) Detection of second zone plus artifacts from other zones. (F) Enhanced binary image of Figure E using the density of pixels routine. (G) Detection of third zone plus artifacts. (H) Enhanced binary image of third zone. (B) Binary images D, F and H combined. For presentation, image 3D was given an artificial dark grey colour, image F a light grey, and image H white.

Grain Boundary Reconstruction

In some instances it may be necessary to determine the size distributions or orientations of grains in a massive piece of mineral or monophase material. This operation requires that each grain be outlined. Unfortunately the grain boundaries are generally absent in an image obtained from a polished or thin section of a mass composed of one mineral or phase. However, incipient outlines of the mineral grains may be seen (Fig. 4A). It is possible to reconstruct the grain boundaries in the image of the mineral from these incipient outlines by combining the erosion, dilation, boolean operation, binary thinning, and markobject operations (See glossary) into an appropriate operator's program (Figs. 4B and 4C).

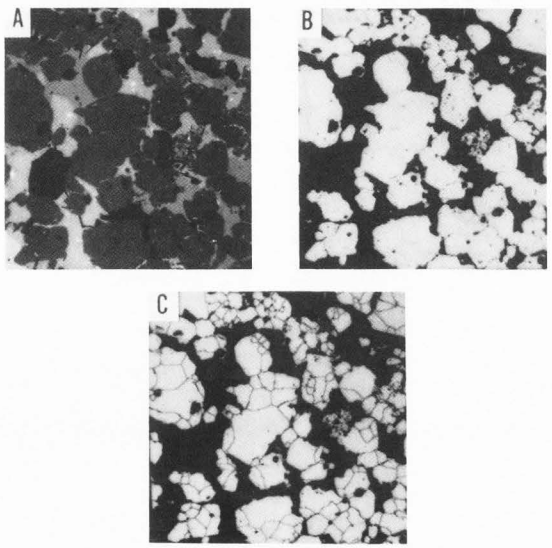

Fig. 4. (A) BSE image of massive pyrite with interstitial sphalerite, transferred to the image analyser. (B) Detected binary image of pyrite. (C) Grain boundaries are reconstructed. Incipient lines in Figure 4B were used to reconstruct grain boundaries.

Analysis

Mineral or Phase Quantities

Mineral quantities can be determined by measuring either the chord length fractions or the areal fractions for the particles in binary images of the minerals or phases. The measurement can be directly converted to the relative volume per cent for each mineral since the stereological relationship is that the relative chord length or the relative areal fraction is equal to relative volume per cent. The relative mineral volumes can be converted to relative weight per cent by using the specific gravity for each mineral. Mineral quantities are routinely determined for all samples studied in connection with mineral beneficiation to provide background information on the nature of the material being studied (Petruk and Mainwaring, 1985).

Size Distributions

Several types of size distributions can be performed by using different parameters and making appropriate measurements for each particle in the binary images. One involves measuring the intercept lengths across the particles, and another measuring the area covered by the particles in the polished section. When the area of the particle is measured the size distribution can be reported on the basis of the number of particles in each size range (Fig. 5B), or the areal fraction covered by the particles in each size range (Fig. 5A). The latter type of size analysis provides an apparent size distribution that can be converted to an apparent volume per cent and hence to an apparent weight percent (Petruk, 1981). A variety of descriptors can be used to define the particle diameters. The descriptors are maximum, minimum, mean, equivalent circle (Serra, 1982), and edge length of equivalent square. Equivalent circle diameter and edge length of equivalent square are determined by measuring the area covered by each particle in the polished section and calculating the diameter of the particle from its area. It is noteworthy that the mean diameter is nearly equal to the equivalent circle diameter, whereas the edge length of equivalent square is close to the size of particle that would pass through screen openings which are square. Empirical tests give good correlations between screen analysis and size distributions as determined by using edge length of equivalent square as the grain diameter (Petruk, 1981). Consequently in applied mineralogy to mineral beneficiation size distributions are determined by using the edge length of equivalent square. At CANMET analyses are performed routinely on grains and particles that range from 1.0 to about 500 μm in diameter. For mineral beneficiation, size analyses are performed for minerals in both unbroken ores and in mill products. The analyses on unbroken ores are made to determine size distributions of mineral grains in order to predict how finely the ore must be ground to liberate the minerals (King, 1979, Klimpel, 1984, Finch and Petruk, 1984). After the ore has been ground, images of liberated grains are isolated from images of unliberated grains, and size distributions are determined for both free and unliberated grains.

Aspect Ratios

The aspect ratios of the particles in the binary images can be determined by using an algorithm that calculates the values for the maximum diameter divided by the minimum diameter. The grains can be classified as aspect ratio vs grain size (Figs. 5C and 5D). The aspect ratio is measured for prismatic grains to determine whether they would be classified as asbestiform.

Grain Orientations

The angle between horizontal and the maximum diameter is a standard measurement that is available on most image analyzers. This measurement can be made for all particles in each binary image; and as pointed out in the discussion on size distributions the measurement can be based on either number of individuals at

each orientation or areal fraction covered by particles of each orientation (Fig. 5E). In addition the results can be classified as grain sizes vs grain orientation (Fig. 5F). Grain orientations would be measured for ores that have highly oriented minerals, since pronounced grain orientations may affect the breakage of a rock during grinding.

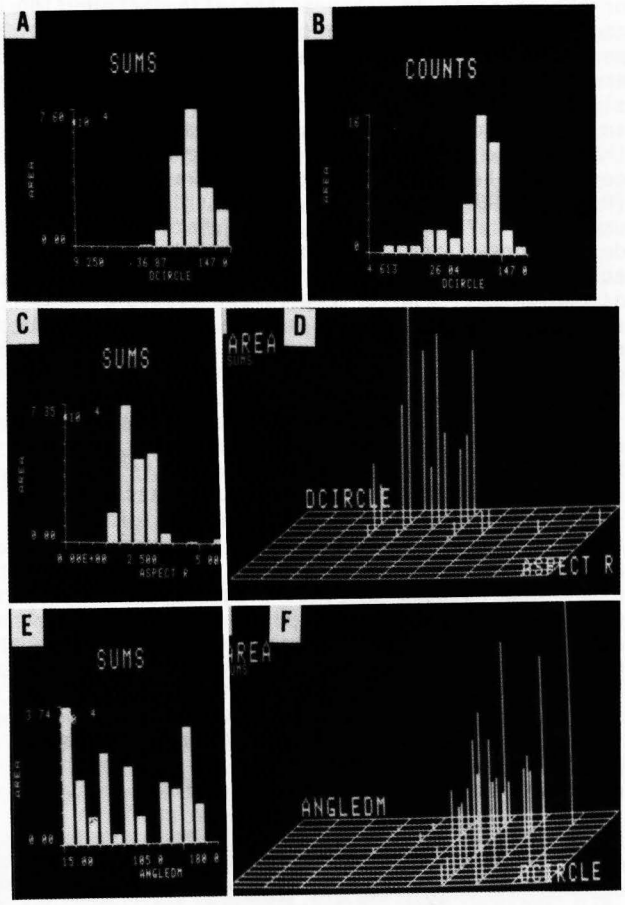

Fig. 5. Graphic output from the image analyser for the orthoclase shown in figure 1G. (A) Size distribution using the area of each grain and equivalent circle diameter (Dcircle). (B) Grain counts for grains of each size. (C) Distribution of aspect ratio, using the area of each grain to determine the relative quantity of mineral that is represented by grains which have a certain aspect ratio. (D) Double classification of aspect ratio vs grain diameter using the area of each grain to define the relative amount in each category. (E) Distribution of orientation of maximum grain diameter with respect to horizontal. Areas of mineral grains were used to determine the relative quantity of mineral in each category. (F) Double classification of grain orientation vs grain diameter.

Mineral Associations

To determine mineral associations it is necessary to prepare the binary images for analysis. The following example is given to show the logic. The problem is to determine the proportion of K-feldspar (orthoclase) that is adjacent to quartz and albite, respectively (Fig. 6A). To solve this problem it is necessary to find the common boundaries between the orthoclase and albite and the orthoclase and quartz (Fig. 6B). The percentage of orthoclase touching the orthoclase-albite boundary is the percentage of orthoclase associated with albite (Fig. 6C), and the percentage touching the orthoclase-quartz boundary is the percentage associated with quartz (Fig. 6D). It is obvious that if two free particles are touching, due to sample preparation, they will be measured as associated particles. This problem can be overcome by preparing the image for analysis with a grain boundary reconstruction technique which has been recently developed, or by a sample preparation technique such as the one used by CSIRO (Reid pers. comm.). The author does not use any special

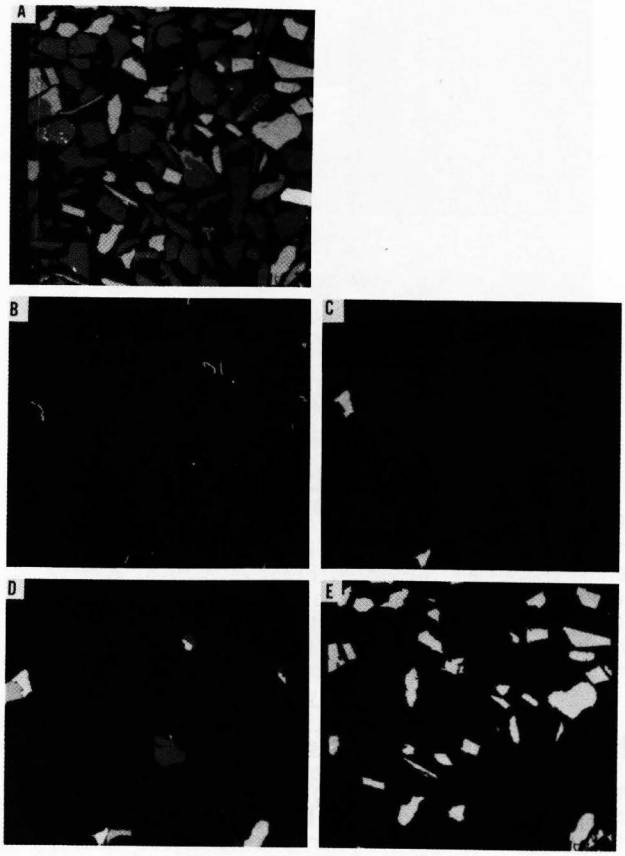

Fig. 6. Procedure to obtain mineral associations (A) BSE image of field. (B) Common boundaries between orthoclase and albite and between orthoclase and quartz. (C) Orthoclase grains associated with albite. (D) Combined grains showing orthoclase (white), albite (light grey) and quartz (grey). (E) Orthoclase that is not associated with albite.

sample preparation techniques. Size distributions and other parameters of the associated grains can be determined. The property of mineral associations is used in mineral beneficiation to define the characteristics of unliberated grains.

Percentage of Mineral Occurring as Inclusions

To determine the proportion of mineral occurring as inclusions in another mineral it is necessary to prepare the binary images for analysis by finding the common grain boundaries between the different minerals. The mineral occurring as inclusions must have a common boundary with the host mineral but not with any other mineral. The procedure is to first select those grains that have a common boundary with the host mineral, then reject any that have a common boundary with another mineral. The remaining grains are inclusions (Figs. 7B and 7C). The image of the inclusions can be stored in a separate image memory and measured and classified as required. This property is used in mineral beneficiation to determine the degree of locking of unliberated grains. Moderately locked grains might be recovered in concentrates, whereas intensely locked grains would be lost to tailings.

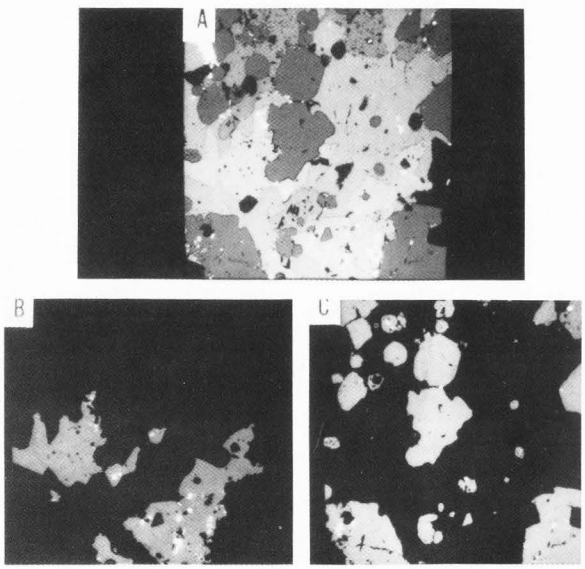

Fig. 7. Inclusions in a host mineral. (A) BSE image of a base metal ore transferred to image analyser. It shows galena (white) in sphalerite (light grey), chalcopyrite (med. grey) and pyrite (dark grey). (B&C) Restored binary images to two shades of grey in each image. B = galena inclusions (white) in sphalerite (grey), C = galena inclusions (white) in pyrite.

Separating Interconnecting Grains

In many instances the grains in a product may be interconnected with veinlets. It may be desirable to find the relative quantities and sizes of the large grains and the relative quantities and widths of the interconnecting veinlets. To do this it is necessary to modify the binary image by separating the large grains from the interconnecting veinlets and thereby produce two images (Fig. 8). The procedure for separating the large grains from the interconnecting veinlets is done by using the erosion, dilation, boolean operation, markobject, binary thinning and image enhancement techniques in an appropriate operator's program. This routine is used in mineral beneficiation to define the distribution of narrow veinlets, since such veinlets produce zones of weakness which affect rock breakage during grinding. Size distributions are performed on the large grains that are interconnected by the veinlets to predict liberations that would be obtained at a particular grind.

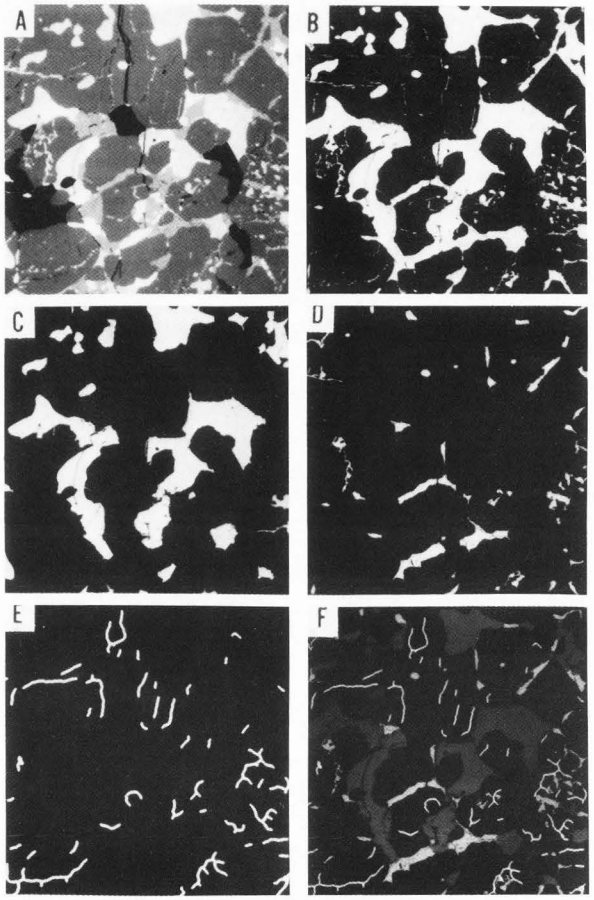

Fig. 8. Separating interconnecting grains. (A) BSE image of a base metal ore showing sphalerite (light grey) and chalcopyrite (med. grey) in pyrite (grey). (B) Sphalerite and chalcopyrite were detected together to produce a binary image of interconnecting large grains. (C) Large grains are separated. (D) Interconnecting veinlets. (E) Narrow veinlets are isolated. (F) Images D, E and F are combined using artificial grey colours for each image.

Application of Image Analysis to Mineral Dressing

Image analyses associated with mineral dressing generally involves studying crushed mill products. The most common requirement is (1) to measure mineral or phase quantities (2) to measure the proportion of mineral that is present as free grains and (3) to classify the unliberated grains.The procedure for determining mineral quantities is to identify each mineral and to measure the area covered by it in a statistically valid number of fields of the polished section. If a mineral grain does not have a common boundary with any other mineral it is assumed to have been liberated during grinding and is a free grain. The proportion of mineral that occurs as free grains, and the size distributions of the free grains can be measured. The unliberated grains are studied in more detail. The binary image of the unliberated grains is combined with the binary images of other minerals which touch the unliberated grains to reconstruct the host particle. The percentage that the unliberated grain contributes to each host particle, and the size of the host particle are measured. The particles are then classified as containing different amounts of the unliberated mineral. The data are output on a percentage basis as quantity of mineral present in each size range and the particles are classified according to the amount of unliberated mineral that they contain (Fig. 9).

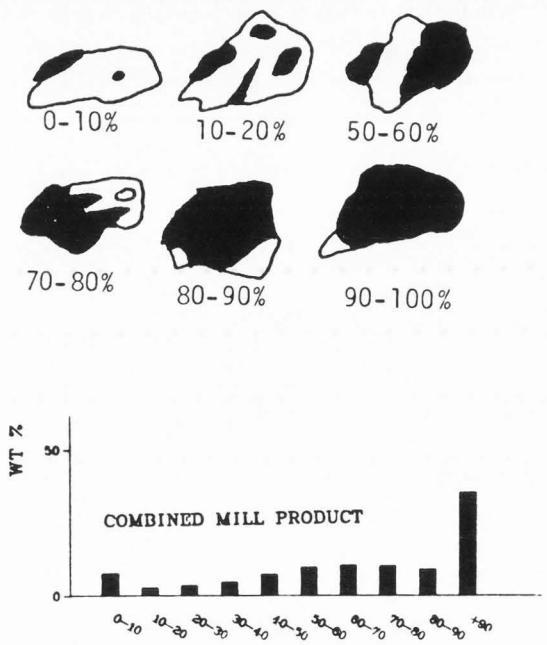

Fig. 9. Classification of particles into categories that contain 0-10, 10-20, 20-30, etc.,% mineral of interest. The X-axis shows the classified particles, and Y-axis the quantity in each class (Photograph from Petruk, 1985).

Concluding Remarks

The most important considerations with respect to image analysis applied to mineralogical studies are that the binary image be a faithful reproduction of an image of the material under study, and that the image analysis system have the capabilities of performing the required analyses. In general, when an image is obtained from an optical microscope, many minerals cannot be discriminated from each other, and hence their image cannot be digitized. By contrast most minerals can be discriminated and digitized in a BSE image from a SEM or microprobe. Therefore, an image analysis system for studying minerals must use a SEM or microprobe as the imaging instrument.

An image analysis system that uses a microprobe as an imaging instrument was developed at CANMET to perform the required analyses of applied mineralogy to mineral beneficiation of ores containing either metallic minerals or industrial minerals. The system automatically identifies minerals or phases on the basis of their grey level in the BSE image, or by scanning each particle with the EDXA to determine mineral compositions. The major benefits of the system are high speed of analysis, ability to obtain accurate data, high-versatility and ability to output data in appropriate summary tables.

Glossary

Boolean operators - This function correlates two binary images according to the logical operator OR = add images, AND = retain common parts of both images, and XOR= subtract one image from another.

Markobject - A routine that sorts objects by comparing an original binary image to a reference image. If at least one pixel of the reference image coincides with the object in the original binary image the full size of the object in the original image will be retained. If the reference image has no coincident pixels the object will be rejected from the original binary image.

Erosion - Erodes a number of pixels from an object (like peeling an onion).

Dilation - Dilates an object by several pixels.

Median - A rank order filter.

Binary thinning - Skeletonization, i.e., thins white linear structure in binary images.

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Discussion with Reviewers

D. Sutherland: How long does it take to carry out analysis of a new sample say of a complex Cu, Pb, Zn ore? How is the time divided, typically, between sample preparation, primary image collection, manipulation of images to bring out the required features, and analysis and presentation of results?

Author: Analysis time is variable depending upon (1) purpose of analysis, (2) desired statistics, (3) number of mineral associations to be determined, (4) whether the analysed minerals are major, minor or trace, (5) required magnification to see the features, and others. For example if only major minerals are analysed 10 fields will provide adequate statistics. If data required is for minor minerals 50 fields need to be analysed. Trace mineral analysis requires looking at 500 to 5000 fields, and is usually performed on overnight runs. Our standard program for a mill product of base metal ore takes two minutes to analyse a field of 100 to 200 particles and to tabulate the data into tables and graphs. The program identifies 12 minerals on the basis of grey level, does a modal analysis, determines size distribution of the particles, determines percent liberated for pyrite, sphalerite, galena and chalcopyrite, and classifies particles containing unliberated pyrite, sphalerite, galena and chalcopyrite. In contrast a program that determines only the quantities of twelve minerals, and the size distributions of the major mineral grains takes 30 seconds per field.

D. Sutherland: What comparisons have been made between the measurements of say modal analysis by convential methods and by image analysis?

Author: Several hundred comparisons have been made between modal analysis determined with the MP-SEM-IPS image analysis system and calculated modal analyses from chemical assays. The results are generally within 8% of the amount present, but with poor sample preparation may be up to 25 % of the amount present. In contrast during the period of 1960 to 1972 we performed many point count analyses using an optical microscope and compared them to chemical assays. The results were usually 20 to 60% of the amount present.

D. Sutherland: No mention is made of analysing specific size fractions of the sample in the liberation analysis. Also no mention is made of stereological corrections to the liberation results. Both factors can be very important, and if they are not considered, why not?

Author: Liberation analyses that are made on a series of narrow size range fractions are more accurate than liberation analyses made on unsized fractions (Petruk at al, 1985). On the other hand when a series of sized samples is analysed the data must be recombined into data for the sample, and this means more work. In some cases, such as for base metal ores, the product is largely in the minus 400 mesh size range. The increased accuracy that would be achieved by screening is too small to warrant sizing the product. On the other hand, coarse grained products, such as an iron ore, must be screened. Every second screen in the Tyler series can be used to reduce the number of screened products.

Mathematical concepts and computer modelling indicate that stereological corrections should be made to observed liberations, but it is difficult to test these concepts. Empirical tests by the author (Petruk, 1981) initially indicated that a correction of 15% should be applied, but subsequent materials balances, using the corrected data, gave poorer results than

using uncorrected data. Further tests (unpublished) suggest that the required stereological corrections can vary from 0 to 35%, depending upon the liberation size of the mineral in the ore, and on the sizes of the particle and inclusion. Preliminary results suggest that the required corrections are small for grains that are nearly free and for particles that are close to the liberation size of the inclusion. Since most liberation analyses are performed on particles that are close to the liberation size of the inclusions, the stereological corrections would be small and can be disregarded for most image analysis studies related to mineral beneficiation.

N. Rowlands: How are samples prepared to ensure that random distributions and homogeneity necessary for quantitative analysis is attained?

Author: To ensure homogeneity the powder is mixed well before sample preparation. To minimize the effect of heavy minerals settling in araldite, a small amount of powder is mixed with a small amount of araldite and the mixture is allowed to harden. Clear araldite is used to make the rest of the briquette. A minimum of grinding is done during preparation for polishing to reduce the chances of grinding away the heavy minerals.

N. Rowlands: When a polished section of a mineral aggregate is presented for particle size analysis in the image analyser the size distribution is underestimated due to stereological effects. How is this compensated for in your data?

Author: Stereological effects are complex and produce a variety of problems. The effect on size distribution of single-sized particles mounted to different depths in araldite can be calculated and modelled. The problem is insoluble when particles of different shapes and sizes are mounted in a polished section. The stereological effect is minimized at some conditions, and image analyses should be performed only at such conditions. It was found, empirically, that when the size range of particles exceeds 5 Tyler mesn sizes, the size distribution of the particles in the polished section is close to the size distribution of the particles in the sample (Petruk, 1981). Size distributions, are therefore, performed in the CANMET laboratory only for samples that are known to have a wide size range of particles.