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THE APPLICATION OF THE GENERAL IMAGE PROCESSING SYSTEM (GIPSY) TO MINERAL BENEFICATION STUDIES

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The General Image Processing System (GIPSY) is being employed for the quantitative textural analysis of complex sulfide ores from the Southern and Central Appalachians and for the determination of liberation characteristics of the mineral constituents during grinding. Optical images from a microscope-mounted TV camera or from 35mm film are converted into digital images which are subsequently analyzed by GIPSY, a transportable image processing software package. Properties measured by GIPSY include spatial distribution of mineral constituents, grain sizes, grain shapes, grain orientation and mineral co-occurrences.

Applications of Image Processing to Mineral Benefication

Automated to semiautomated image processing systems have in recent years begun to prove valuable in supplying and analyzing mineralogical and liberation data for ores and their beneficiation products (1,6,7,8). These systems will become increasingly important because they offer the capability of compiling and analyzing more data more rapidly than the manual methods employed here-to-fore. Such data are necessary to optimize the efficiency of extraction of metals from the larger volumes of lower grade ores which will be used to provide the nation's and world's metal needs in the future.

The present paper attempts to describe the utility of the General Image Processing System (GIPSY) to the characterization and analysis of ore samples and beneficiation products. This description demonstrates some of the general capabilities of the system; more detailed applications will be described in subsequent papers.

The General Image Processing System (GIPSY)

GIPSY is a general interactive image processing software package designed to be easily used, easily learned, easily modified, and easily transported from one computer to another. It operates with single or multi-band images, in integer or real format, and includes more than 180 operations to do image filtering, classification, geometric spatial transformations, numeric and symbolic recursive neighborhood operations, spatial clustering, region growing and property file generation. GIPSY is user friendly and has all its documentation on-line and available through GIPSY commands.

The physical setup for the application of GIPSY includes: a Leitz Orthoplan microscope; a Hamamatsu C-1000 television camera; an optic fibre system for image transmission; modems to converse with the computer; a color television monitor; and a VAX 11/780 computer. The image is either generated directly from the microscope or from a 35mm negative of an image previously seen in the microscope. Film images are digitized by a laser scanner and microscopic images are digitized on-line by a Hamamatsu C-1000 camera; the data are stored on magnetic disk or tape. The investigator converses with the VAX computer from any point on campus via a modem using a hard wired setup or an acoustic coupler and a standard telephone. At the direction of conversational commands typed into the modem, GIPSY displays up to a 512 X 512 image on the television monitor. The investigator may then process the image in a very large number of ways and receive data on the modum, on the TV screen, or on a high speed printer. The attachment of a Matrix graphics camera system to the television monitor allows the generation of 35mm color slides or 8 X 10 inch color prints of any image seen on the TV monitor.

In order to carry out image analysis GIPSY, like most other systems, subdivides the original image into an N by N (N in the range 100 to 5000) array of individual squares pixels as shown in figure 1. The original image, derived from a 35mm film negative or directly from a TV camera mounted on a microscope, is digitized and stored on magnetic tape or disk. Individual grains are generally differentiated on the basis of their differing reflectances (gray-levels). In most other systems presently operational, the pixels are classified on a pixel by pixel basis depending

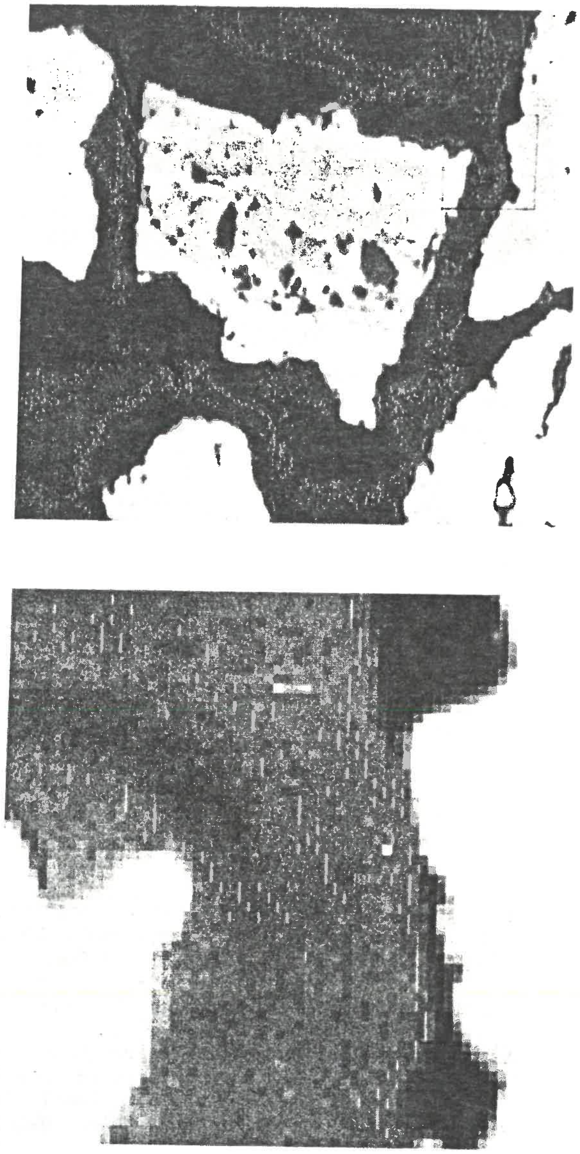


Figure 1. (A) GIPSY generated image of locked mineral particle (light phase is pyrrhotite; dark phase is sphalerite) of Ducktown ore in an epoxy matrix. (B) Enlarged portion of the boxed region of Figure 1(A) showing individual pixels which comprise the image.

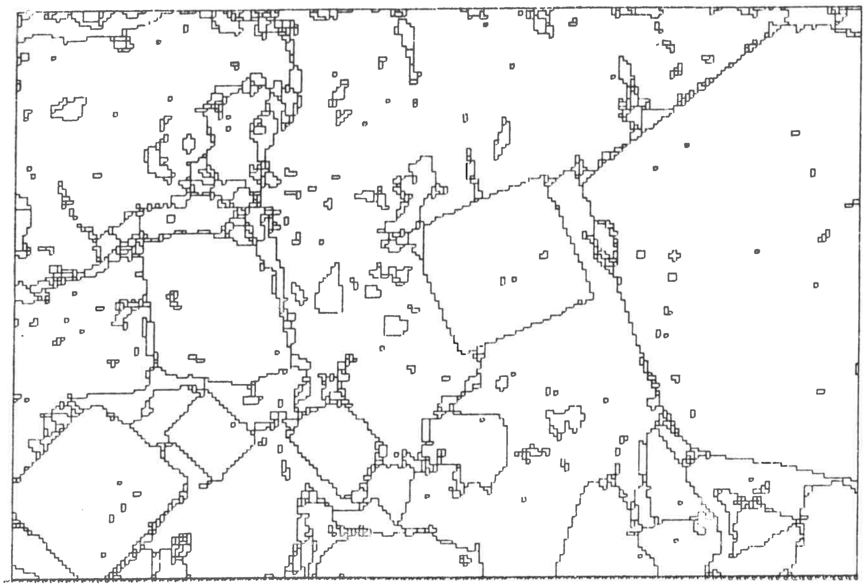


Figure 2. Segmentation of image shown in Figure 5 showing the individual segments identified by GIPSY for classification and analysis. The minimum size of individual segments can be adjusted to eliminate surface imperfections within a sample.

upon their reflectance. In contrast, the GIPSY system subdivides each image into discrete segments or areas of similar nature by determining the edge boundary surrounding each homogeneous region (Fig. 2).

The edge operator and its functions have been defined and described in rigorous mathematical terms by Haralick (4) and are only treated in a qualitative sense here.

The facet model is used to accomplish step edge detection. The essence of the facet model is that any analysis, made on the basis of the pixel values in some neighborhood, has its final authoritative interpretation relative to the underlying grey tone intensity surface of which the neighborhood pixel values are observed noisy samples.

Pixels which are part of regions have simple grey tone intensity surfaces over their areas. Pixels which have an edge in them have complex grey tone intensity surfaces over their areas. Specifically, an edge moves through a pixel if and only if there is some point in the pixel's area having a zero crossing of the second directional derivative taken in the direction of a non-zero gradient at the pixel's center.

To determine whether or not a pixel should be marked as a step edge pixel, its underlying grey tone intensity surface must be estimated on the basis of pixels in its neighborhood. For this, we use a functional form consisting of a linear combination of the tensor products of discrete orthogonal polynomials of up to degree three. The appropriate directional derivatives are easily computed from this kind of a function. Once edge pixels have been marked, the homogeneous areas are determined as the largest connected areas of pixels which are entirely surrounded by edge pixels.

These connected areas are called segments and they correspond to grains or portions of grains.

Once an image has been segmented it can be processed in terms of phase identification. The individual segments are assigned a gray-level representing the average of all pixels included within them. Gray level discrimination is routinely based on a scale of 255 recognized levels; however the averages of individual segments are reported to a percision of 0.001 of a gray level. The sizes of individual segments may be derived in terms of number of pixels contained, percent of total image area, or percent of area identified as that phase. Shapes of segments are based upon the boundaries recognized by the edge operator relative to the boundaries expected of ideal shapes. The locations of segments in terms of x-y space is determined on the basis of the centers of gravity of the segments.

Examples of Property Measurements by GIPSY

At the time of the preparation of this manuscript GIPSY routinely provides 30 discrete pieces of data for each segment in an image (Table 1). The investigator has the option of visual presentation of as much or as little of the data as desired on the console screen or in hard copy from an on-line printer. In the following pages are presented some examples of the application of the GIPSY program to studies of the fine-grained complex massive sulfide ores of the Central and Southern Appalachians. The samples considered are massive copper- and zinc-bearing pyrrhotite-pyrite ores of the Ducktown, Tenn. and Great Gossan Lead, Va. Districts. Samples of the raw ores and of carefully ground and sized beneficiation products have been cast in cold-setting epoxy and polished according to the procedures outlined in Craig and Vaughan (2).

Table 1. Selected Parameters Determined For Each Segment by GIPSY

1. Area = the number of pixels
2. Maximum gray level
3. Minimum gray level
4. Mean gray level
5. Gray level variance

6-7. Center of Mass - Row + Column

8. Elongation (ratio of minor to major axis of best fitting ellipse)
9. Circularity (ratio of radius standard deviation to mean radius)
10. Azimuth of major axis of best fitting ellipse to horizontal or vertical
11. Perimeter
12. Gradient of a region (measure of inhomogeneity)
13. Slope facet error

Mineralogical Identification

The application of image analysis to most mineralogical studies requires that there be a reliable means of distinguishing between the individual mineral types present. Most techniques rely upon the differences in reflectance to separate one phase from another. Such separation is readily accomplished if there are broad differences between the reflectances of minerals (e.g. pyrite, R% ≃ 53; pyrrhotite, R% ≃ 37; sphalerite, R% ≃ 17; gangue, R% ≃ 5), but become difficult if the R% differences are small and/or variable (e.g. due to differences in polishing, in bireflectance, or high density of inclusions or fractures). Thus the present workers, as well as others, have found that chalcopyrite, although distinct to the human eye because of its yellow color, is difficult for image analysis systems (operating in black and white) to separate from pyrrhotite because the reflectances when averaged across the white light spectrum are similar. The nature of and solution to the problem may be seen in figures 3 and 4 which present the reflectance curves for pyrite, pyrrhotite, chalcopyrite, magnetite, and sphalerite from 400 to 700 nm and an example of phase discrimination using monochromatic light. The distinct differences between pyrite, pyrrhotite, and magnetite at all wavelengths are apparent; these differences allow for relatively easy discrimination in reasonably well polished samples. The reflectance curve for chalcopyrite lies below that for pyrrhotite at wavelengths less than 460 nm but above the pyrrhotite curve at wavelengths above about 500 nm. It is apparent that if monochromatic light in the ranges 440-460 nm or 560-620 nm is used for illumination phase separation of pyrrhotite and chalcopyrite should be most readily accomplished. In the range 440-460 nm the chalcopyrite will appear darker than the pyrrhotite whereas in the range 560-620 the chalcopyrite will appear lighter. The present investigators have found monochromatic light of approximately 580 nm to work well in most applications of GIPSY to chalcopyrite-bearing pyrrhotite-rich ores.

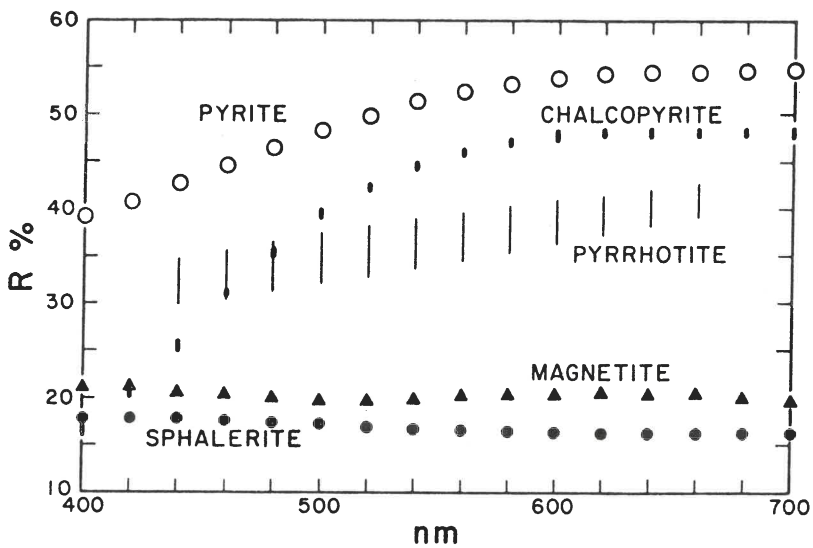


Figure 3. Reflectance curves for the common ore minerals encountered in massive sulfide ores of the Central and Southern Appalachians. Data are taken from Henry (5).

Although mineralogic identification is generally accomplished by means of differences in reflectance (gray-level), the GIPSY program also allows identification on the basis of size, shape or surface texture (eg. degree of pitting or numbers of inclusions).

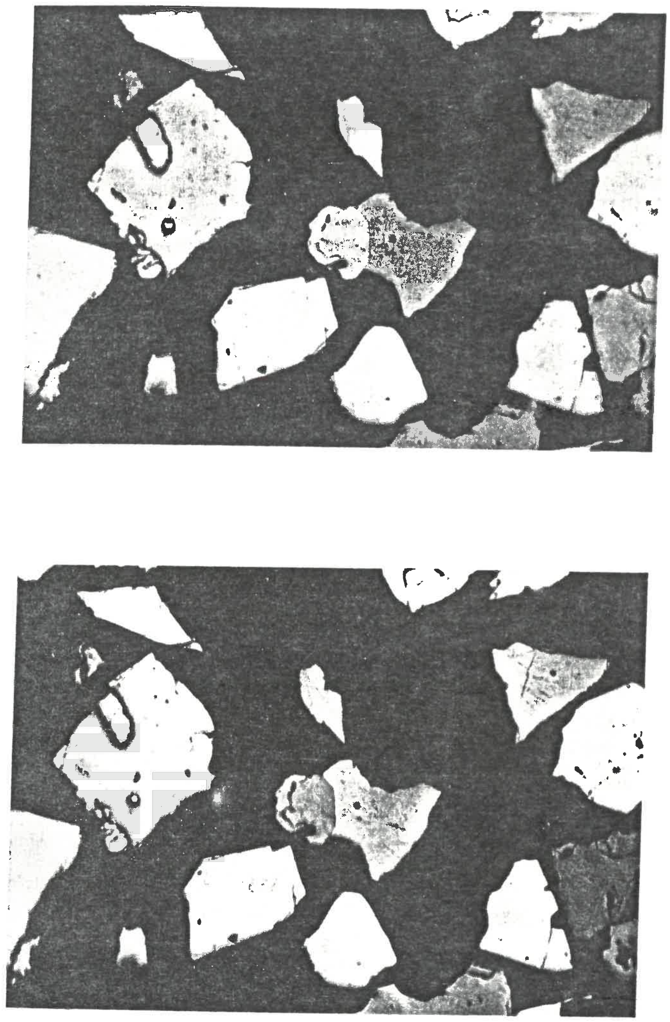


Figure 4. Effect of using monochromatic light to effect phase distribution. (A) Central locked particle consisting of chalcopyrite (light) and pyrrhotite, with adjacent monomineralic grains, as perceived by GIPSY when monochromatic illumination at 578 nm is employed. Width of field is 0.6 mm. (B) Same field of view as above, but note that with monochromatic illumination at 446 nm the chalcopyrite is now darker than the adjacent pyrrhotite.

Shape Analysis

Mineralogical shape in an ore or rock is a function of the growth characteristics of the mineral (i.e. some minerals such as pyrite and garnet have a strong "force of crystallization" and characteristically assume euhedral shapes), the environment of initial formation (i.e. open voids vs crystallizing melts etc.), and their post-depositional history (i.e. recrystallization or fracturing due to metamorphism). The shape of a mineral grain may in turn affect the manner in which it responds to crushing, grinding, and liberation. GIPSY currently allows the quantitative determination of particle shape in terms of elongation and circularity. Elongation is the ratio of the length of the minor axis to the length of the major axis of the best fitting ellipse of the grain. Circularity is calculated after rotating and scaling the grain so that its best fitting ellipse becomes a circle. This is done to separate the effect of elongation from circularity. Circularity is the ratio of the standard deviation of the transformed grain's radii to the mean radius where the radii are taken from the center of mass of the transformed grain. Rigorous mathematical definitions of these parameters are presented in Haralick (3). Examples of elongation and circularity measurements are demonstrated for ideal shapes and for real grain in complex sulfide ores in figure 5 and table 2. The shape analysis can also be applied to particles at various stages of mineral beneficiation.

Table 2. Circularity and elongation parameters for ideal and real figures. The ideal figures were generated by one of GIPSY's commands. The real figures correspond to the numbered grains in Figure 5.

Shape or grain number in figure	Circularity	Elongation
equilateral triangle	3.110	0.984
square	1.745	1.000
pentagon	1.149	0.995
hexagon	0.696	0.999
septagon	0.555	0.992
octagon	0.388	1.000
nonagon	0.386	0.993
decagon	0.271	0.995
circle	0.140	0.999
1	2.141	0.609
2	2.532	0.862
3	6.537	0.347
4	1.349	0.837
5	2.831	0.706
6	3.181	0.707
7	2.743	0.212

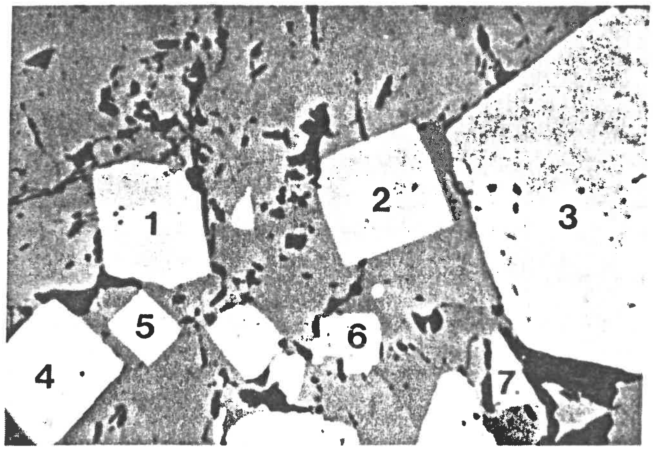


Figure 5. Typical example of pyrrhotite-pyrite ore from Ducktown, Tennessee showing subhedral to euhedral pyrite porphyroblasts (white) in a matrix of pyrrhotite (gray), black areas are holes. The numbered grains have been defined by GIPSY in terms of shape parameters (see text and Table 2). Width of field is 1 mm.

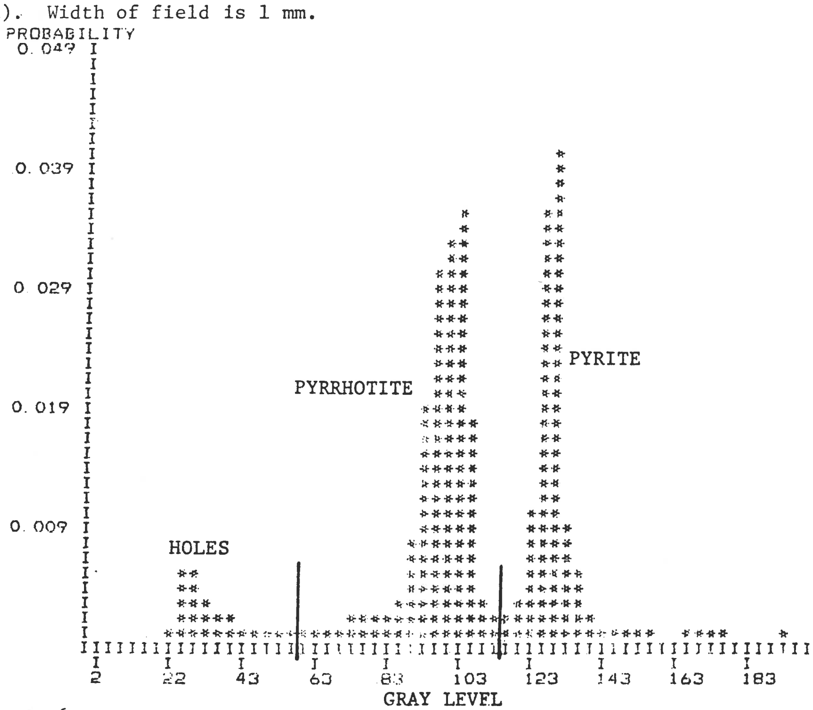


Figure 6. GIPSY histogram of mineralogical content of image in Figure 5 in terms of reflectance. The reflectance levels corresponding to pyrite, pyrrhotite, and holes are noted.

Areal Distribution

The mineralogical composition of an ore or beneficiation product is measured in terms of the area occupied by each mineral in a polished section or thin section. Ideally every portion of a given mineral phase will have the same reflectance, hence simple summation of the pixels possessing a reflectance within designated limits defines the area occupied by a mineral. In reality, variable polishing effects at the edges of grains and internal imperfections (due to scratches, inclusions etc.) often create significant differences in reflectance and hence misidentification of pixels in those systems processing in a pixel-by-pixel manner. The GIPSY system minimizes these errors by calculating an average reflectance for each region (grain or portion of a grain) thus allowing small improperly polished areas to be properly designated. Furthermore GIPSY possesses smoothing operations such as median filtering and peak noise removal which allow for the removal of scratches from images before processing and edge expanding operations to delete shadow effects at grain edges due to polishing or to relief on the polished surface. Figure 6 represents a typical histogram of mineral reflectance versus abundance for the image shown in figure 5; once limits are specified, the program readily also lists the areal percentages of each phase. A real distribution of individual mineral types may be color or texture coded and may be displayed as histograms or merely presented in percentages. Furthermore, non-random distribution of any given phase can be defined in terms of x-y coordinates in the image or in terms of relationship to another phase (i.e. tendency to co-occur or to be mutually exclusive).

Co-occurrence measurements are especially important because they permit determination of: (i) the percentage of a phase which occurs as locked particles (ii) the percentage of particles which are locked (iii) the correlation of each mineral species with each other mineral species.

Grain Size Measurements

The measurement of the size of an individual mineral grain and/or the distribution of grain sizes in a sample is extremely important. GIPSY accomplishes such measurements by the area of the pixels within the segment identified as the grain in question; individual segments are pinpointed on the video screen by a cursor controlled at the keyboard of the modum. The distribution of grains in an image (either all grains or only those of a pre-selected reflectance) may be displayed on the video screen and/or printed in histogram form.

Azimuth Measurement

Ore forming processes or post depositional metamorphism may leave a pronounced linear or planar fabric to ores. In addition, different grinding methods may include different fracture patterns in the mineral grains. The GIPSY program allows the measurement of both length and orientation of any linear feature. This clearly demonstrated in figures 7 & 8 which illustrate respectively an essentially unidirectional strain pattern in pyrrhotite and orthogonal sets of fractures in pyrite. The (B) portions of these figures present the azimuth data in terms of frequency histograms.

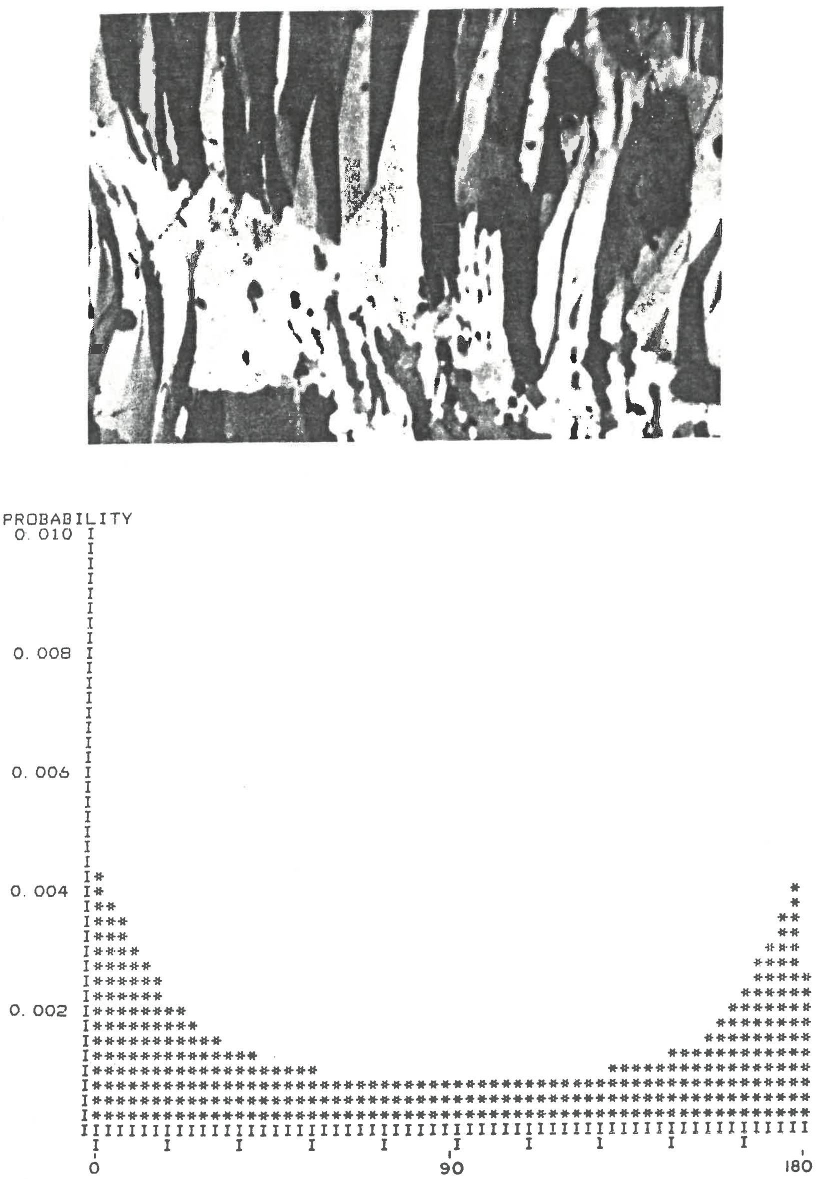
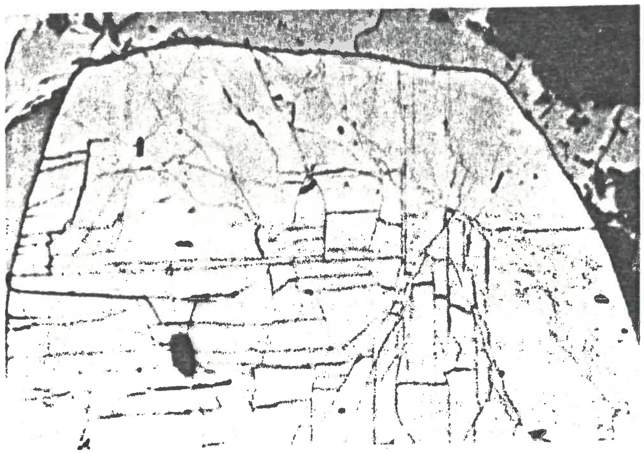


Figure 7. (A) Photomicrograph of strained pyrrhotite as viewed under crossed nicols; note unidirectional nature to twin lamallae. Width of field is 1 mm. (B) GIPSY histogram showing unimodal distribution of pyrrhotite lamellae. 0° is taken as vertical on page and 90° is taken as horizontal.



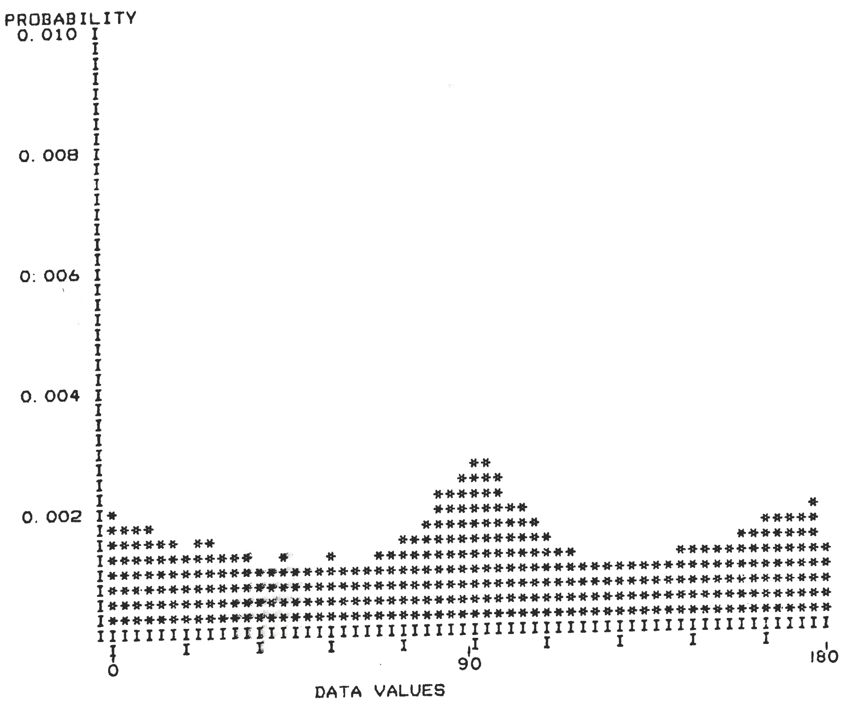
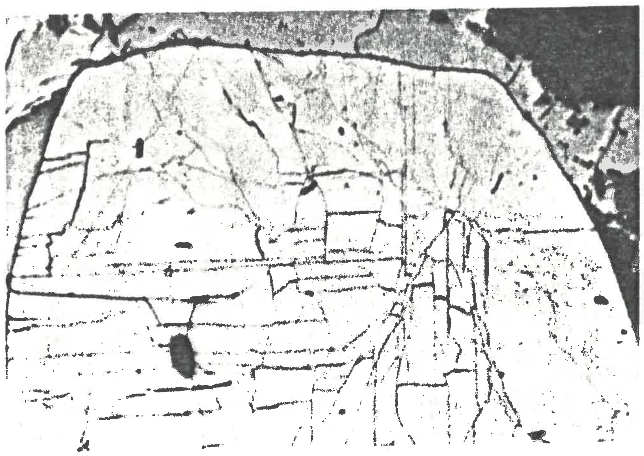


Figure 8. (A) Photomicrograph of pyrite which contains a nearly orthogonal set of fractures. Width of field is 2 mm. (B) GIPSY histogram showing bimodal distribution of fractures. 0° is taken as vertical on page and 90° is taken as horizontal.



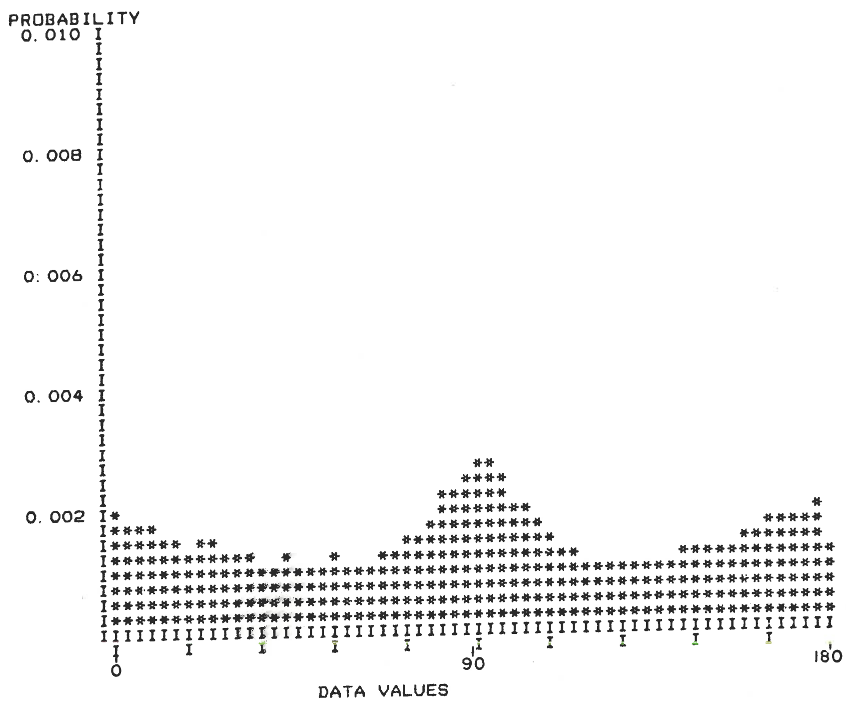


Figure 8. (A) Photomicrograph of pyrite which contains a nearly orthogonal set of fractures. Width of field is 2 mm. (B) GIPSY histogram showing bimodal distribution of fractures. 0° is taken as vertical on page and 90° is taken as horizontal.

Grain Distribution

The non-random distribution of one or more types of grains, either in terms of x-y space or in terms of coexisting minerals, can be extremely important. GIPSY permits ready determination of the spatial distribution of grains based upon their centers-of-gravity. The distribution data may be obtained for all grains of all types, for all grains of only one type, for all grains which lie within imposed size limits, etc. Furthermore, GIPSY permits the determinations of the degree to which the distribution of one mineral type correlates with the distribution of another mineral type.

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