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Objective Procedures for Lineament Enhancement and Extraction

A five-step digital convolution procedure extracts edge and line segments or produces directionally enhanced images.

Abstract: *Rock fractures commonly are indicated by edge and line segments that form lineaments on remotely sensed images. Manual methods of mapping lineaments are subjective, and the results are always controversial. A long-term research goal at* EROS *Data Center is to develop automated, objective procedures for lineament mapping. In support of this goal, a five-step digital convolution procedure has been used to produce directionally enhanced images, which contain few artifacts and little noise. The main limitation of this procedure is that little enhancement of lineaments occurs in dissected terrain, in shadowed areas, and in flat areas with a uniform land cover.*

The directional enhancement procedure can be modified to extract edge and line segments from an image. Any of various decision rules can then be used to connect the line segments and to produce a final lineament map. The result is an interpretive map, but one that is based on an objective extraction of lineament components by digital processing.

Introduction

Faults and joints in rocks commonly provide keys to occurrence of ground water, minerals, and petroleum. The locations, patterns, and densities of these fractures also are important for studies of earthquakes, landslides, dam safety, foundation integrity, and pollution susceptibility.

Rock fractures commonly are indicated by lineaments on remotely sensed images. Lineaments can be defined (O'Leary and others, 1976, p. 1467) as "mappable, simple or composite linear features of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon." Lineaments on the land surface are formed by a variety of landscape elements, including topographic, drainage, vegetation, and soil tonal alignments. Some lineaments are continuous, and many others appear to be continuous because closely spaced edge and line segments are merged by the human eye. A careful examination of images, however, shows that nearly all lineaments are discontinuous.

During the usual lineament interpretation process, a scientist examines an image for closely spaced linear segments that appear to be aligned. This process is subjective, and results depend mostly on the scientist and on the purpose for the interpretation. Comparison of results in one study (Podwysocki *et al.*, 1976, Figure 4) showed that "only 0.4 percent of the total 785 linears were seen

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by all four operators, 5 percent by three operators, and 18 percent by two operators." The same study also found significant differences in the average lengths of lineaments mapped by different scientists. The patterns obtained by different operators should be similar, but wide variations occur in lineament locations and densities. Thus, lineament maps that have not been field-checked are always controversial.

Various objective approaches to lineament enhancement, extraction, or delineation are possible with digital processing of image-format data (Ehrich, 1979; Burdick and Speirer, 1980; and Podwysocki *et al.*, 1976). These approaches include directional filters (ordinarily implemented by a convolution procedure), derivative images, edge enhancement algorithms, filtering Fourier transformed data, and various line-detection and line-follower algorithms. Line-detection algorithms eventually may prove to be the best approach to objective lineament mapping.

The long-range research plan for the EROS Data Center includes lineament enhancement, detection, delineation, mapping, and interpretation. The goal is to develop automated objective procedures for the extraction of lineaments from remotely sensed data and to determine the geologic and hydrologic significance of the results. Some research on these tasks was begun in 1980; the purposes of this work are to evaluate the convolution method of producing directionally enhanced images and to determine the best procedure to achieve the enhancement. Convolution is the movement (pixel by pixel and line by line) of a filter window through an image. Successive elements of the original image are multiplied by values within the window, and the products are summed to form the resulting filtered image.

Various edge and gradient detection algorithms in the literature were tested as were the effects of changing weights in the filter windows. The procedure that was finally selected has proven to be an effective method of lineament detection and enhancement in a wide variety of Landsat scenes. However, this procedure was derived empirically and has not been subjected to mathematical theory.

Lineament Enhancement

Landsat-image data commonly are used for analysis of regional geologic structure. Any multispectral scanner (MSS) or return beam vidicon (RBV) band of digital data can be directionally enhanced, but MSS band 7 (0.8 to 1.1 micrometres) generally is selected for this purpose. Bare rock, soil, and vegetation all have a relatively uniform gray tone on band 7 images (Figure 1). Thus, topographic shadows tend to have a fairly uniform contrast with the background, and the interpreter is not distracted by sharp tonal or color contrasts at land-cover boundaries. Band 7 images also may show the sharpest detail, because atmospheric haze penetration is better in this part of the electromagnetic spectrum.

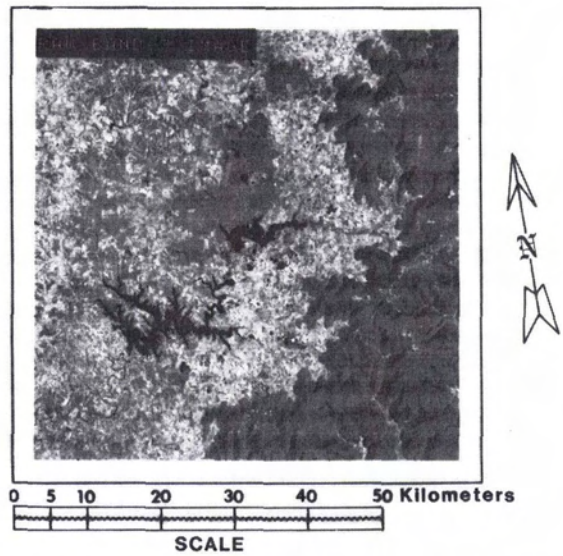

Fig. 1. Landsat MSS band 7 images are most often used for lineament analysis and mapping. This image (1265-15501; 14 April 1973) shows Elk River Reservoir, Tims Ford Lake, and parts of the Eastern Highland Rim and Cumberland Plateau in south central Tennessee.

Low sun-elevation images are best for a manual detection of lineaments because most geologically significant lineaments are formed by topographic depressions and because depressions are enhanced by shadowing. Widespread and dark shadows are a disadvantage, however, for the procedures described in this report. A directional filter oriented parallel to the trend (length) of the shadows does not produce any enhancement of lineaments. If the directional algorithm is oriented near normal to the shadows, artifacts are introduced, the image breaks apart, and results are impossible to interpret. Light or subtle shadowing of topographic depressions is desirable, but shadows should not be pronounced or even obvious on a film image. The best sun-elevation depends on the dissection of the terrain. A sun-elevation of 35° to 45°, for example, is near optimum for slightly rolling terrain.

A five-step convolution procedure (Table 1) can be used for lineament enhancement. The first step in the procedure is to generate a low-pass image (Figure 2) using a 3 by 3 averaging function. This step is not essential, but it aids in subsequent processing.

When an image containing high spatial frequencies is used for step 2, the resulting line segments are numerous, thin, and relatively short. Con-

TABLE 1. A FIVE-STEP PROCEDURE FOR PRODUCING DIRECTIONALLY ENHANCED IMAGES.

Step 1: Generate low-pass image.
Remove the highest spatial frequency components from an MSS band 7 image by use of a 3 × 3 moving window. The digital value of each central pixel is replaced by an average of the nine pixels in the window.

B	C	D
E	A	F
G	H	I

$$A_1 = (A_0 + B + \ldots + I)/9$$

Step 2: Derive directional components from the low-pass image.
The digital value of each pixel in the low-pass image is replaced with the value produced by the windows. Each pixel in the window is multiplied by the indicated number; the final value for the central pixel is a sum of these products.

East-West

-1	-2	-1
2	4	2
-1	-2	-1

North-South

-1	2	-1
-2	4	-2
-1	2	-1

NW-SE

2	-1	-2
-1	4	-1
-2	-1	2

NE-SW

-2	-1	2
-1	4	-1
2	-1	-2

WNW-ESE

1	-2	-2
1	4	1
-2	-2	1

NNW-SSE

1	1	-2
-2	4	-2
-2	1	1

ENE-WSW

-2	-2	1
1	4	1
1	-2	-2

NNE-SSW

-2	1	1
-2	4	-2
1	1	-2

Step 3: Smooth directional component images.
A 3 × 3 moving window is used to reduce extraneous noise in the directional images. The digital value of each central pixel is replaced by an average of the nine pixels in the window.

B	C	D
E	A	F
G	H	I

$$A_3 = (A_2 + B + \ldots + I)/9$$

Step 4: Extract the longer and more prominent line segments from the directional component images.
Scale the directional component images into a 0-255 range (for 8-bit resolution data), and obtain cumulative histograms of the scaled images. Scaling is a procedure in which the lowest digital value is set to 0, the highest digital value is set to 255, and all intermediate values are linearly distributed within this range. Finally, extract the line segments:

TABLE 1.—Continued

Original value	New value
0 to X	0 to 127
(X + 1) to (Y − 1)	128
Y to 255	129 to 255

The values of X and Y are selected from the cumulative histogram. For most Landsat subscenes, X is the 10-15 percentile value and Y is the 85-90 percentile value. This step results in considerable additional smoothing of the directional components.

Step 5: Add directional components to original band 7 image and rescale for display.
First, scale the original band 7 image to a 0-255 range. Separately add the eight directional component images from step 4 to the original image. Finally, rescale the sums to a 0-255 range. The result is a group of directionally enhanced images.

versely, when progressively lower pass images (from 3 by 3, 5 by 5, and 7 by 7 windows) are used for the second step, resulting line segments are fewer, thicker, and longer. The longer lineaments are more likely to indicate important structures. The line segments resulting from step 2 processing of very low-pass images, however, also represent only prominent spectral trends and contrasts. There is not necessarily any correlation between image contrast and geologic significance. A low-

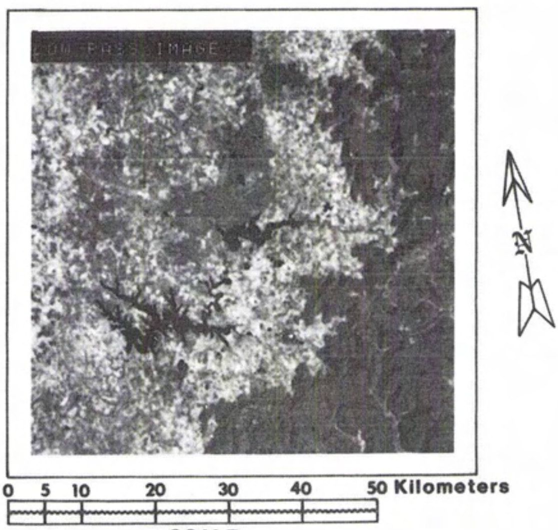

FIG. 2. An averaging function was used to generate this low-pass image. The image has a lower resolution and a slightly blurred appearance because lines and edges with a high spatial frequency have been removed.

pass image obtained with a 3 by 3 window seems to produce good results.

The second step in the procedure increases the contrast of edge and line segments that have trends in approximately the desired direction. The dark side of an edge segment is made darker, and a light line segment is made lighter, relative to the background (Figure 3). Secondary effects are blurring of the background image, the introduction of harmonic noise, and the introduction of artifacts, caused by residual Landsat image striping. Other numbers could be used in the convolution windows, but those shown in Table 1 have proven at least as effective as several others that were tested. Undesirable secondary effects are increased with the use of some algorithm variations. Convolution algorithms for the top four compass directions (Table 1) probably are sufficient for most Landsat scenes and for most objectives, because intermediate trends are also enhanced on the final image products.

In the third step, an averaging function is used to reduce the secondary effects of directional convolution: artifacts, harmonics, and noise. A maximum reduction of undesirable image features with minimum change of the desired edge and line segments is obtained by use of a 3 by 3 window. The result in Figure 4 is visually not very different from Figure 3, but omission of this step is apparent in the final directional enhancement. An alternative to steps 3 and 4 is a tangent function, which is described later.

The fourth step consists of processing the image

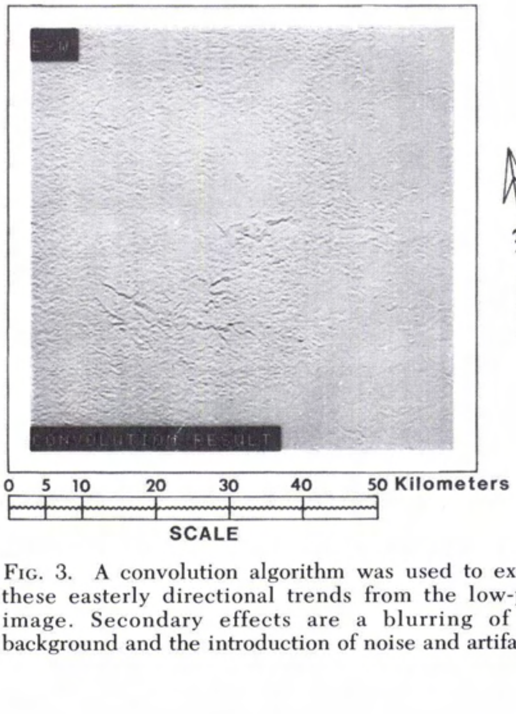

FIG. 3. A convolution algorithm was used to extract these easterly directional trends from the low-pass image. Secondary effects are a blurring of the background and the introduction of noise and artifacts.

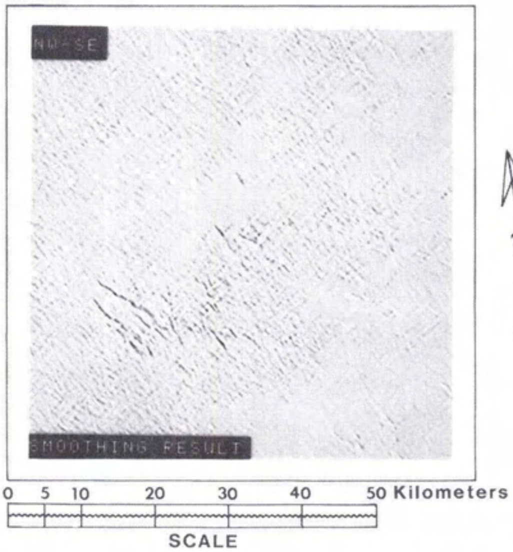

FIG. 4. A low-pass filter or averaging function was used to reduce noise and artifact prominence in these northwesterly directional trends.

data to obtain a better separation of directional trends and noise. As previously noted, the enhanced edge and line segments have high contrast with their surroundings. This observation is confirmed by examining slices of the image histogram. Image slices near the histogram tails contain virtually all of the directional information in the image. As slices are taken closer to the histogram center, the orientation of edge and line segments becomes more random, the segments become shorter, and the alignments of these segments become more obscure.

Step 4 is implemented by setting the digital values of pixels near the histogram center equal to 128 (medium gray) and by stretching the histogram tails to fill the intervals 0 to 127 and 129 to 255. Tail ranges are selected from a cumulative histogram. This selection affects both the appearance of the final directionally enhanced images and the interpretive results: (a) 5 and 95 percentile digital values produce a very smooth-textured image in which only the most prominent lineaments are enhanced, (b) 10 and 90 percentile digital values produce a less smooth texture and an enhancement of both the prominent and some of the more obscure line segments, and (c) 20 and 80 percentile digital values produce a somewhat rough texture and an enhancement of virtually all line segments. The result (Figure 5) is an image showing dark and light line segments in a medium-gray background.

The application of a tangent function to image data creates a strong compression of digital values near the histogram center and a stretch of values in

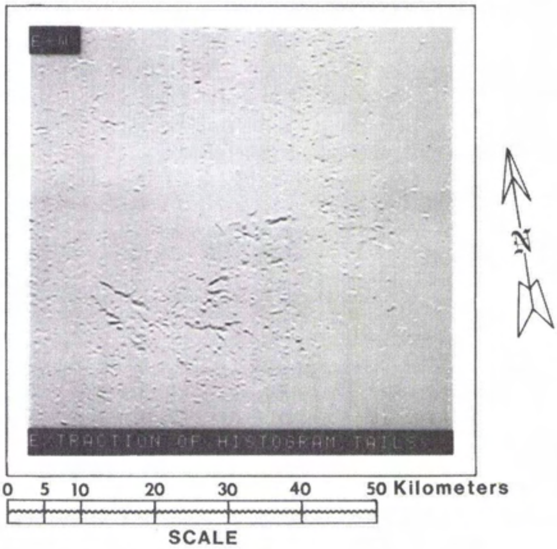

FIG. 5. Additional smoothing was obtained by extracting easterly directional data in the histogram tails from noise near the histogram center.

the histogram tails. Thus, a tangent function is an effective alternative to the smoothing and noise reduction procedures used in steps 3 and 4. Possible directional information near the histogram center is preserved, but a fairly rough texture is produced in the final directionally enhanced image. A tangent function is implemented by first scaling the image data into a range slightly less than 0 to 255. Otherwise, tangent values would range from minus to plus infinity. An appropriate trial range is 11 to 244; resulting tangent values range from −7.3 to +7.3: i.e.,

$$Y = \tan(180X/255 - 90).$$

The multiplier for X adjusts a data range of 0 to 255 to an angular range of 0° to 180°; the additive factor sets a digital value of 0 equal to −90°. After Y is obtained, the data are rescaled into a 0 to 255 range.

The fifth step consists of adding the enhanced line segments to the original image and of rescaling the sum into a 0 to 255 range for display. The result (Figure 6) is a directionally enhanced image. Experience has shown that it generally is necessary to truncate about 1 percent of the lower end of the rescaled histogram in order to obtain an average gray tone similar to that of the original image.

When the procedure described above is followed, the directionally enhanced images contain few, if any, artifacts and a minimum amount of noise. The texture of these images can be controlled as can the number and intensity of enhanced line segments. If additional enhanced line segments are added to the image, however, the result is a rougher texture.

There are definite limitations to the results that can be obtained with lineament enhancement by convolution. In the final products (1) some edge and line segments are enhanced in directions other than the one desired; (2) little if any enhancement of lineaments occurs in very dissected terrain, lightly shadowed areas, and flat areas with a uniform land cover; (3) all spectral lines and edges are enhanced, not just those having geologic significance; and (4) landmarks are less apparent on directionally-enhanced images. In addition, directionally-enhanced images are relatively less interpretable when scan lines are prominent in the original MSS image.

Lineament Extraction

The fourth step (Figure 5) of the lineament enhancement procedure displays dark and light line segments against a medium-gray background. The relative darkness or lightness of these segments represents the contrast of edges and lines in the original Landsat scene. The image thus represents an automated directional extraction of lineament segments.

The line segments on Figure 5 are longer when 20 and 80 percentiles of the cumulative histogram (the dark and light tails) are displayed than when 10 and 90 percentiles or 5 and 95 percentiles are displayed. These results suggest that level slices of the image in Figure 5 could be used to aid in determining which line segments should be extended and merged for lineament mapping. Nine

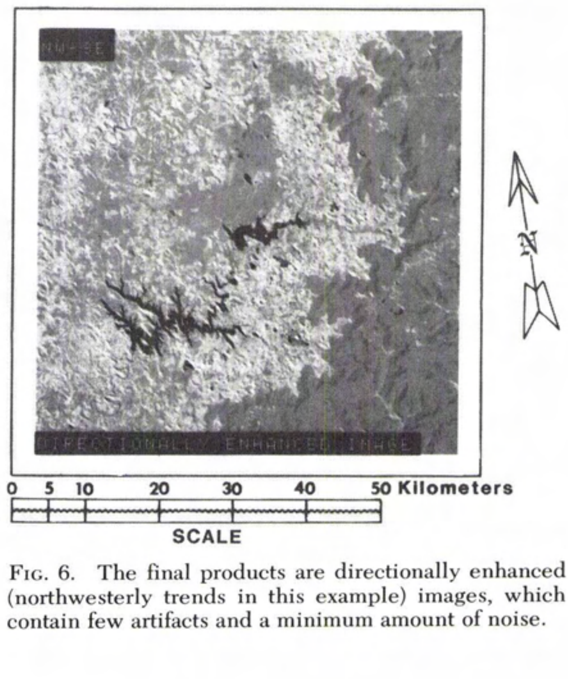

FIG. 6. The final products are directionally enhanced (northwesterly trends in this example) images, which contain few artifacts and a minimum amount of noise.

level slices (Figure 7) can be implemented by the algorithm and values below.

Algorithm: Set range in original digital value, as indicated by the cumulative histogram, equal to the sliced digital value.

Histogram percentile	Sliced digital value
0–2.5	0
2.5–5.0	32
5.0–7.5	64
7.5–10.0	96
10.0–90.0	128
90.0–92.5	160
92.5–95.0	192
95.0–97.5	223
97.5–100.0	255

The effects of including more of the histogram are to slightly lengthen the desired line segments, but noise and short, randomly oriented segments are added to the display.

Edge segments in the original image are represented by adjacent dark and light lines (Figure 7) in the extraction image. Line segments in the original image vary from single dark or light lines to a series of alternating dark and light segments in the extraction image. This effect is caused partly by the complexity of contrasts in the original image and partly by the processing procedure. Virtually all line segments in the extraction image can be related easily to particular lines, edges, and spectral contrasts in the original image.

All line segments are longer, wider, and more obvious on the extraction image than on the original image. The increases in length and contrast are intended results, but the increase in width is a byproduct of the averaging function, as is the slight separation of dark and light lines. An aesthetically more pleasing result (Figure 8) can be obtained by using a tangent function instead of an averaging filter for image smoothing.

The extraction image in Figure 8 was obtained by first applying a tangent function to scaled data from step 2. When the data then were rescaled to a 0 to 255 range, the histogram was truncated by 1 percent at both the upper and lower ends. This truncation decreases the undesirable compression of data in the transition zone between histogram center and the tails. Finally, 5 percent of the data at each end of the cumulative histogram was set equal to 0 and 255; the remaining 90 percent of the data was set equal to 128.

The directional line segments extracted from a tangent stretch are uniformly dark or light on the medium-gray background (Figure 8). The output data from a tangent function and rescaling cannot be level sliced easily because of the data compression that occurs in the use of this algorithm. Otherwise, the length, location, and orientation of line segments extracted by the tangent-function procedure are virtually identical to those obtained by the first procedure.

Any of various subjective decisions can be used to connect the extracted line segments for a final lineament map. Little objectivity is gained by computer processing, because the decision rules for a line-connection algorithm are themselves subjective. The best procedure may consist of

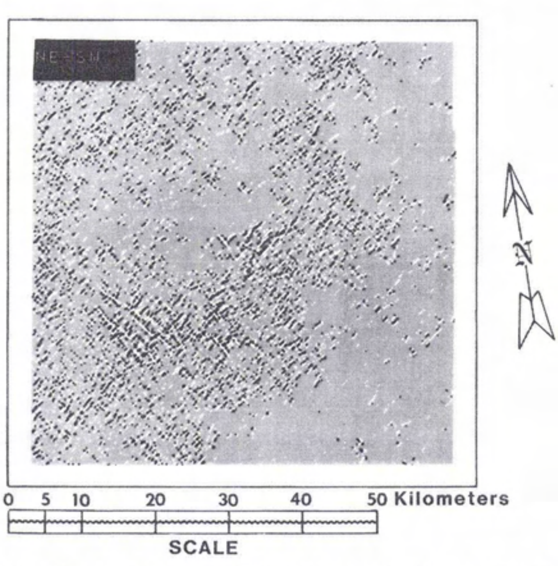

FIG. 7. Northeast trending line and edge segments have been extracted from the image and enhanced. Products of this type can be used for lineament mapping.

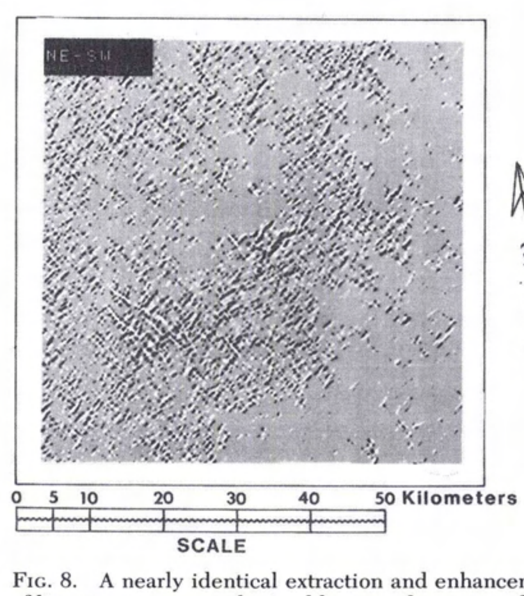

FIG. 8. A nearly identical extraction and enhancement of line segments was obtained by use of a tangent function for data smoothing. The resulting line segments are thinner and more nearly adjacent.

comparing the extracted line-segment image with the original image and then manually connecting the lines that may have geologic significance because of location, topographic position, and orientation. The result would be an interpretive map but one that is based on an objective determination of lineament components. If field checking proves the lineament map to be deficient in one or more respects, modified decision rules can be used to revise the map.

The extracted line segments, obtained by procedures described in this report, have not been checked in the field to determine their relationships to rock fractures. It has been confirmed that some line segments represent land-cover boundaries, drainage lines, and shadows along topographic depressions. Thus, these extracted line segments represent parts of lineaments.

Conclusions

Faults and joints in rock are important features in geologic and hydrologic studies. These rock fractures commonly are indicated by the discontinuous edge and line segments that form lineaments on remotely sensed images. Lineaments generally are mapped with a manual analysis and interpretation procedure. A manual procedure is subjective, however, and results are always controversial.

Various objective approaches to lineament enhancement are possible with digital processing. The digital convolution procedure described in this report consists of five steps: (1) generating a low spatial frequency image with an averaging function, (2) extracting directional data with a convolution filter, (3) smoothing the directional data with an averaging or tangent function, (4) further smoothing the data by extracting directional trends in the tails of the image histograms, and (5) adding the enhanced directional trends to the original image.

Directionally enhanced images contain few, if any, artifacts and a minimum amount of noise. The roughness of image texture is determined by the spatial frequency of the enhanced edge and line segments that are added to the image. Little enhancement of lineaments occurs, however, in dissected terrain, lightly shadowed areas, and flat areas with a uniform land cover. Also, all spectral lines and edges are enhanced, not just those with geologic significance.

The directional enhancement procedure can be modified to extract edge and line segments from an image. These segments represent land-cover boundaries, drainage lines, and the shadowing of topographic depressions in the original image; all extracted segments can be related easily to lines and edges in the original image. Any of various decision rules can be used to connect the extracted line segments for a final lineament map. The best method may consist of comparing the extracted segments with the original image and of manually connecting the segments that may have geologic significance.

Acknowledgments

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