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A STUDY OF THE TYRONE - MOUNT UNION LINEAMENT BY REMOTE SENSING TECHNIQUES AND FIELD METHODS

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16. Abstract Field work was combined with satellite imagery and photography to study the Tyrone - Mount Union lineament in Blair and Huntingdon Counties, central Pennsylvania. This feature, expressed as the valleys containing the Little Juniata and Juniata Rivers, transgresses the nose of the southwest-plunging Nittany Anticlinorium in the western extremity of the Valley and Ridge Province. Field data collection involved mapping faults and folds; orientation and density of joints; and the thickness, attitude, and juxtaposition of stratigraphic units. It was demonstrated that the lineament is a zone of high fracture density crossed by numerous structural anomalies and stratigraphic offsets. Increased joint density and disruption of structural elements extends over a zone approximately 3.2 km (2 miles) wide. Base metal sulfide deposits and a transverse Bouguer anomaly suggest extension of these manifestations to Precambrian basement rocks.

Comparison of lineament, fracture trace, and joint orientations with data from other areas in southeastern United States shows a similarity of orientations on all scales and suggest a formerly active pervasive stress field. Conversely, a disagreement of fracture trace orientations between the Valley and Ridge and Allegheny Plateau provinces raises questions concerning the age and mechanics of formation of these features. Fractures on the three scales investigated were related geometrically: lineaments and joints were parallel (dominant peak at 310°) and fracture traces were oblique to, and oriented as a conjugate set, about them.

The technique of lineament enhancement of LANDSAT image data with a digital high-pass filter was evaluated: lineaments mapped on enhanced and unenhanced images were "real" topographic expressions and their dominant orientation was 310°.

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INTRODUCTION

An alignment of stream and river valleys, wind and water gaps, and tonal variations on LANDSAT-1 imagery is apparent for approximately 150 km (90 miles) through central Pennsylvania. This linear feature, known as the Tyrone-Mount Union lineament (Gold et al. 1974), extends from the Blue Ridge physiographic province northwestward across the Appalachian Fold mountain belt and into the Allegheny Plateau. The northwestern portion of this lineament (see Figs. 1 and 2), expressed mainly as valleys containing the Little Juniata and Juniata rivers, was selected for study because of the relative abundance of outcrops and quarry sites, the presence of anomalous structures, and its accessibility from State College. The purpose of this study was to investigate the general nature of this lineament, characterize the geologic features associated with it, and map its extent.

In addition to mapping bedding attitudes and stratigraphic contacts, and measuring the attitude and frequency of imposed fractures (joints and faults) within and adjacent to the lineament expression, this study attempts to characterize the parameters on a vastly different scale, of a feature sensed in only two dimensions. The parameters to be measured were deduced mainly from theoretical arguments pertaining to the relationship of shear fractures of different orders to stress on different scales. The importance of this study is emphasized by the paucity of documented observations of bedrock features associated with lineaments. A field study of the Tyrone-Mount Union lineament would yield information on its bedrock character and demonstrate whether or not the lineament exhibits a third dimension.

Location and Regional Setting

The study area encompasses a 9 km (5.5 mile) wide and 16 km (10 mile) long swath, centered on the Little Juniata River between Tyrone and Petersburg, in Blair and Huntingdon Counties (see Fig. 1 and Plate 1). A number of active quarries are located within the valley expression of the lineament, and a serviceable county road network provides access to most of the area. The lineament crosses the Sinking Valley anticline, a southwest plunging anticlinal domain of the Nittany Anticlinorium in the westernmost first-order anticline of the Valley and Ridge Province of central Pennsylvania (see Plate 2).

Stratigraphic units from Cambrian to Silurian age are exposed. The oldest, the Pleasant Hill Limestone, is located near Huntingdon Furnace; the youngest unit, the Wills Creek Formation, is located in the eastern part of the study area near Petersburg (see Plate 2). The stratigraphic column shown in Fig. 3 does not distinguish the Lower Ordovician Larke Dolomite, as noted by Butts et al. (1939) and Donaldson (1959), nor is it mapped as a separate unit on the geologic map (Plate 2). Donaldson, who has developed detailed sections near Honest Hollow and Spruce Creek along the Little Juniata River, has shown that the Larke Dolomite intertongues with the Stonehenge Limestone. Discriminating the tongues of the Larke Dolomite from the Mines member of the Gatesburg Formation, below the Stonehenge Limestone, and the Nittany Dolomite, above, is difficult and only of academic interest. Because its precise position has little bearing on this paper it has been mapped with the dominant adjacent dolomite unit: either with the overlying Nittany Dolomite or the underlying Mines member of the Gatesburg Formation.

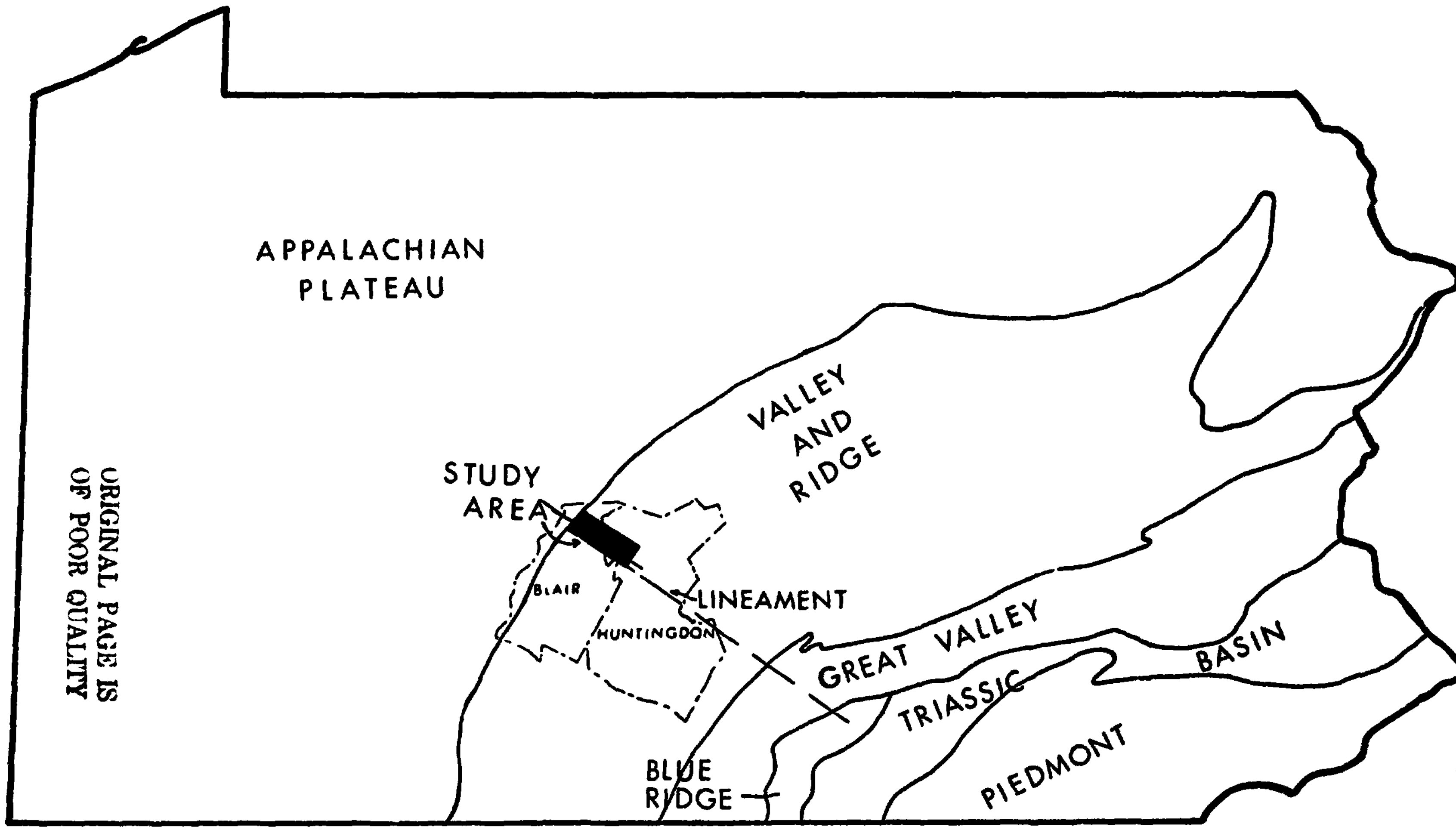

Figure 1. Location of study area. The Tyrone - Mount Union lineament is shown by the dashed line. Note the en echelon segments in the study area.

Figure 2. LANDSAT-1 image (1:230,000) showing the location of the study area. White arrows indicate the position of two *en echelon* segments of the Tyrone - Mount Union lineament. The northern segment was investigated during this study.

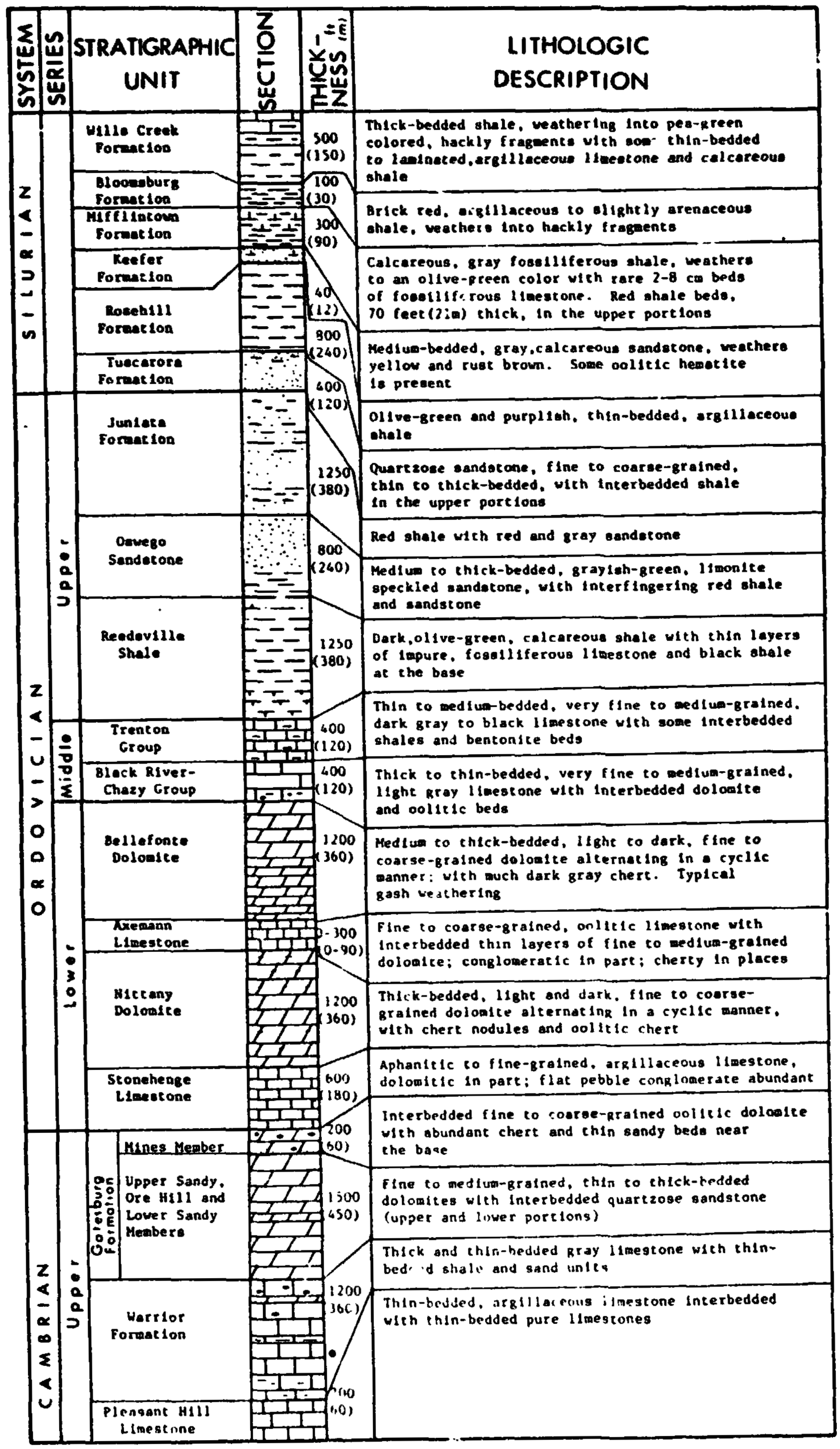

Figure 3. Stratigraphic column of the Tyrone area.

Fracture Studies

Fractures are apparent on LANDSAT-1 imagery, low altitude aerial photography, and in field outcrops. These are referred to as mega-, macro-, and meso-scopic fractures, respectively. The worldwide pervasiveness of fractures has been demonstrated by the compilations of Gay (1973). The orthogonal fracture patterns, which Gay termed "pairsets," are thought to be genetically related to basement fractures. Of the studies compiled by Gay, those pertaining to the eastern United States were of greatest interest to the author. These included the works of Fisk (1947), Vernon (1951), Trainer and Ellison (1967), Sonderegger (1970), and Powell et al. (1970). Orthogonal fractures (pairsets) are reported in all of the studies; some involve lineaments and/or fracture traces in a structural setting similar to that of central Pennsylvania. Therefore, a comparison of data from a study area in central Pennsylvania to that of the above mentioned authors seems logical and will be one objective of this paper.

Fortunately, a local comparison of data is possible because of the availability of fracture trace and joint orientation data compiled by Matzke (1961) in western Centre County, only 32 km (20 miles) northeast of the present study area in the same valley (Nittany Valley). In addition, Lattman and Nickelsen (1958) measured joint orientations on the Allegheny Plateau, and these results have been compared to lineament orientations measured on SKYLAB and LANDSAT imagery by Kowalik (1975).

One of the side issues of this study is to explore possible relationships between fractures on different scales. If such relationships could be quantified then, using current sensing systems, a method of inferring small scale structures from larger features would be available and parameters could perhaps be identified and incorporated in the design of the next generation of remote sensing devices.

Previous Work

With the launching of ERTS-1 (now LANDSAT-1) in 1972 and SKYLAB in 1973, multispectral scanner (MSS) images and photographs of large areas of the earth on a scale of 1:250,000 and 1:1,000,000 became available for scientific study. Many applications have been found for these data in a varied assortment of fields. Geologically, the imagery has been useful in providing a megascopic view of features previously not visible, or imperfectly seen, on mosaics of aerial photographs. Lineaments of varying length and expression have been detected on satellite images and mosaics of Pennsylvania, and have been classified according to quality and type of expression (Kowalik and Gold 1976). Although many such linear features are apparent on topographic maps, and have been the subject of debate since the turn of the century (Hobbs 1904), their surface and subsurface nature has not been well understood.

Geologists, particularly in the United States, are interested in these lineaments, as is shown by the recent increase in the number of research papers on this topic (refer, for example, to the 1976 Proceedings of the First International Conference on the New Basement Tectonics held in 1974). Lineaments are being studied to determine their relationships to factors such as mineral occurrences, increased water yields, and terrane instability. Studies of this type in the Appalachian region include the works of Drahovzal et al. (1973), Drahovzal (1976), Powell et al. (1970), Krohn (1976), Parizek (1976), Kowalik and Gold (1976), and Hunter (1977). Others have chosen to investigate the general nature of a lineament, including origin, extent, and geometric relationship to features on the same and smaller scales. In West Virginia, Wilson and Wheeler (1974), Wheeler et al. (1974), and Werner (1976) have been investigating the nature of structural disontinuities (lineaments) by a number of methods, including non-parametric statistical tests of bedding strike, bedding dip, deviation from regional attitude and fracture density. A similar field-oriented approach, with a greater emphasis on photogeologic mapping, has been undertaken by the New York State Geological Survey (Isachsen et al. 1973, Isachen 1976).

Many recent works on fracture traces (lineaments less than 1.6 km long) and lineaments in Pennsylvania involve photointerpretative techniques (Gold et al. 1973, Kowalik and Gold 1976) and applications to groundwater exploration (Parizek 1976). These studies have been based on earlier work by Lattman and Nickelsen (1958) and Nickelsen and Hough (1967). Kowalik (1975) mapped the regional distribution of lineaments on LANDSAT-1 imagery throughout Pennsylvania, addressing problems in selected areas. One of these areas was on the Allegheny Plateau, where comparison was made between lineament spatial data and the joint orientations measured by Nickelsen and Hough (1967). Kowalik's conclusion, that the lineaments, fracture traces, and joints were parallel to sub-parallel in strike, did not support the hypothesis of Gold et al (1973) that minor lineaments, and perhaps fracture traces, were a result of the second and higher-order shear mechanisms discussed by McKinstry (1953) and Moody and Hill (1956).

Perhaps the most prominent transgressive geomorphic feature in central Pennsylvania passes through Tyrone and Mount Union, expressed topographically as the valleys of the Little Juniata and Juniata Rivers. Although a linear base-metal mineral trend had been recognized along this valley (Smith et al. 1971), it was not until LANDSAT-1 imagery became available in 1972 that the feature was mapped and named the Tyrone - Mount Union lineament (Gold et al. 1973). The area around the northern segment of this lineament has been the focus of geological investigations for some time. Although the various geological maps differ only in detail, interpretations of their subsurface significance differ greatly.

The history of work in this area dates back to the mapping of Rogers (1858), followed by Platt (1881), Lesley (1885), Butts (1918), and Butts et al. (1939). These were regional studies, conducted by The Pennsylvania Geological Survey. More recently, detailed studies of an area where a window exposes Late Ordovician to Early Silurian units near Birmingham, have been made by Zeller (1949), Fox (1950), Moebs and Hoy (1959), and Schmiermund and Palmer (1973). Besides the above reports, in which cross-sections are presented by all except Rogers (1858) and Butts (1918), subsurface interpretations have been published by Stose (in Butts et al. 1939) and Gwinn (1964 and 1970). Each cross-section exhibits a different subsurface configuration and presupposes a different kinematic and dynamic model for the Nittany Arch.

It is apparent that the subsurface interpretations of geology near this lineament are ambiguous. The present study was intended to test whether the structural complexity is related to the presence of the lineament. A detailed analysis should clarify some of the ambiguity in interpretations of the structure of this section of the Nittany Arch and also give some insight into the nature of lineaments. Discordance of structural elements across the lineament zone would give credence to the concept that some lineaments are domain boundaries (see Kowalik and Gold 1976) and that, at least in the Appalachian fold belt, they may represent a zone of decoupling between segments (see Fig. 4).

Definitions

A new technology can provide a new perspective of a feature, often calling for the redefinition of existing terms and/or the introduction of new terms and concepts to match the new scale of observation. It is not surprising then, with so many investigations of the application of remote sensing data to geology, that there are increasing numbers of vaguely defined and inappropriately used terms. Therefore, the intended meaning of the terms used in this paper are listed below, grouped according to topic.

Photo-linear features are linear features seen on terrain photographs or on images sensed from airborne or satellite platforms. They appear as alignments of elements such as stream segments, sinkholes, wind gaps, water gaps, and vegetation tonal variations, or as combinations of these, and also include cultural features such as roads, railroads, and power lines.

Fracture traces are photo-linear features (exclusive of cultural features) less than 1.6 km (1 mile) long (Lattman 1958), but longer than 600 m (2000 ft) (R. R. Parizek, pers. comm. 1976). In central Pennsylvania they are frequently expressed as shallow depressions, zones of increased moisture content and more vigorous vegetation growth, and alignment of springs and sinkholes. Many have been shown to overlie zones of increased fracture density, with an attendant increase in the porosity and permeability of the rocks beneath the fracture trace.

Photo-lineaments are photo-linear features greater than 1.6 km (1 mile) long. Their field expression is subtle, mainly because of the size difference between the observer and the feature being viewed, but they appear on the imagery as an alignment of stream segments, topographic sags, wind gaps, and tonal variations.

Lineaments are alignments of natural topographic or tonal expressions greater than 1.6 km (1 mile) long. They include photo-lineaments that exhibit topographic expression(s) and linear features apparent on topographic and raised relief maps.

Fracture refers to a breakage plane or parting in a rock, without appreciable displacement. Specific terminology is developed with scale, e.g., joints, fracture traces (?), faults, lineaments (?).

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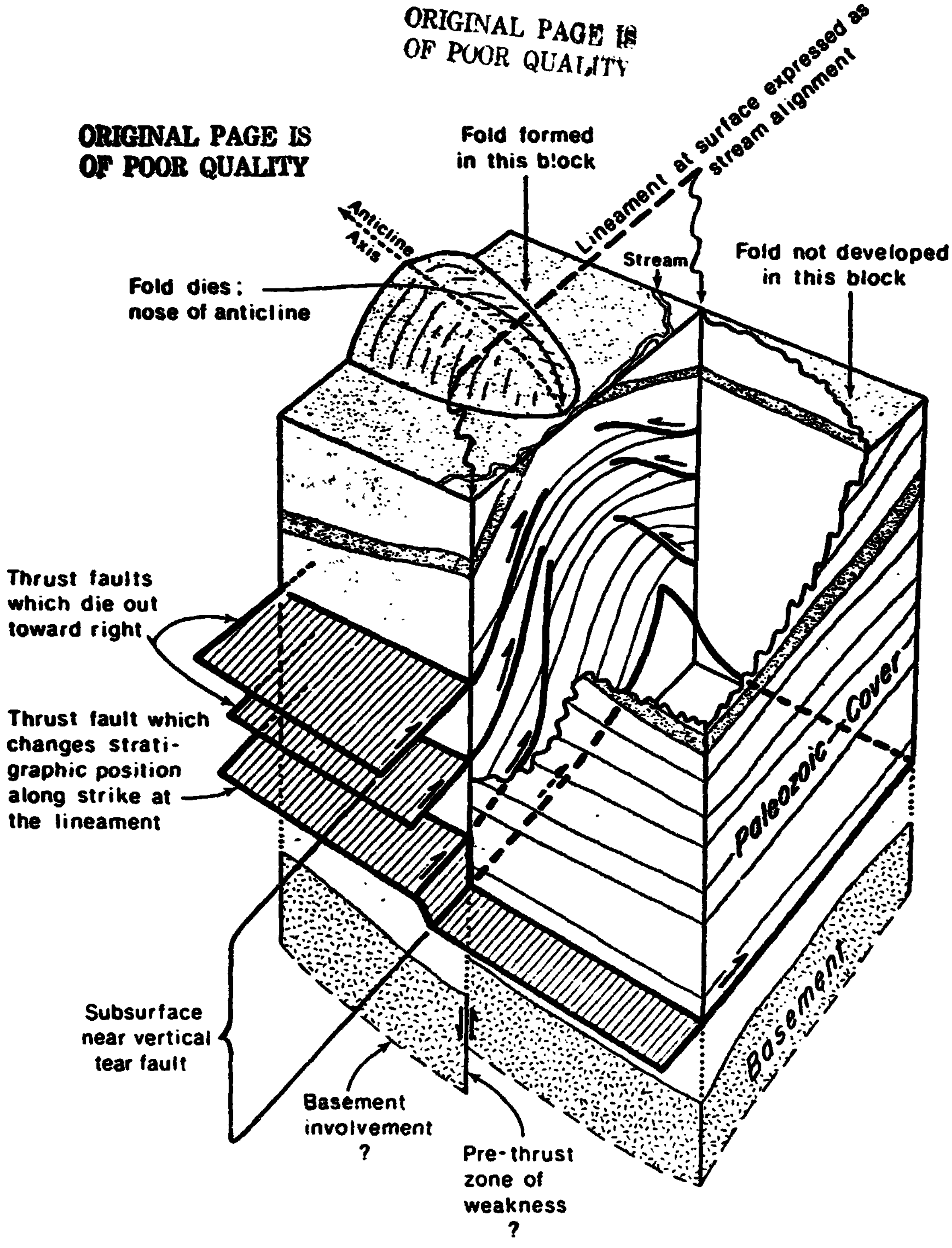

Figure 4. Conceptual view of a lineament as a domain boundary, with termination or ramping of thrust faults at depth. (After Kowalik and Gold 1976.)

Joint refers to a surface of actual or potential fracture or parting in a rock, essentially without displacement. The orders of scale, mesoscopic, macroscopic, and megascopic are used to indicate the scales, respectively, of third-and fourth-order folds and joints; second-order folds, fracture traces, and short lineaments; and first-order folds and lineaments (Turner and Weiss 1963).

An image is the photographic form of data from a multispectral scanner (MSS) sensor. These data are recorded in digital form on magnetic tape, and are usually machine processed to remove geometric distortions and other artifacts of the sensing system. The resultant product is marketed as digital data on tape, or as photographic transparencies and prints, termed images. These standard products are referred to as unenhanced, even though the data have been through a machine processing stage. They may be processed further to enhance specific features (edge enhancement) or aspects (contrast enhancement).

Edge enhancement techniques emphasize feature edges by a computational procedure that compares the brightness value of each pixel with the average value of nearby pixels to determine edge presence. The brightness difference of those pixels defining the edge is then enhanced.

A pixel is the reflectance value integrated over a specific scan area on the ground. For LANDSAT systems, the pixel area is 4,520 m^2 (48,400 ft^2).

Methodology

In order to determine the bedrock nature of a lineament, mesoscopic and macroscopic features along the Tyrone - Mount Union lineament were mapped and analyzed.[1] Field data were obtained from road and railroad cuts, quarries, and natural outcrops. Each outcrop was investigated for composition, stratigraphic position, bedding thickness, location with respect to second-order folds, and various structural elements of interest, such as bedding and joint orientations, joint density, fault planes with associated slickenlines, sense of movement on slickenlines, and attitude of fold axes and axial planes. Station numbers were assigned to the outcrops, the formations exposed at each station were identified, and the structural elements present were measured according to the criteria listed in Table 1.

It can be seen from the table that the measurement of joint density imposed some special requirements not inherent to the other data collected. Because joint density varies with bedding thickness and lithology, measurements

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[1] The photographs and images used were as follows--
Low Altitude: AQL-6V 50-53 and AQH-6V 31-35, 54-56, 115-124, 138-146, 206-212, from 7 June 1958.
High Altitude U-2: Mission 74-060A, Roll 17, Frame 8127, from 25 April 1974.
LANDSAT-1: Scene 1297-15252, from 16 May 1973.

Table 1. Criteria for Measurement of Structural Elements

Structural Element	Parameters	Restrictions on Measurement
Joint	Orientation	None
	Dominance or type	None
	Density	Only in similar lithologies where orthogonal faces could be sampled
Fault	Orientation	None
	Direction of motion	None
	Sense of motion	None
	New movement	None
Fold	Orientation of axial line	None
	Orientation of axial plane	None
	Order	None
	Sense of rotation	None
Bedding	Orientation	One reading for each cell at each sample site

were made only in areas of similar lithologies and where two or more roughly orthogonal cuts were available for a three-dimensional determination of joint spacing. This latter criterion was necessary because it has been shown (Turner and Weiss 1963) that the obliqueness of uniformly spaced joints to the sampling face is proportional to the number of joints imposed on that face. Therefore, if the strike of the outcrop face is varied, a less biased joint density can be determined. Quarry faces are preferred because they yield 360° coverage of an area and provide a test for comparing density results from opposite walls. The joint densities were determined by applying a two-meter-square grid every 10 meters to the quarry wall rock surface (bedding or fracture plane) and recording the orientation and number of each joint or joint set. Between 50 and 100 stations were established in each quarry site, providing a meaningful population for analysis (Griffiths 1967) in the grid area (i.e., 4 m^2).

For frequency determination, the joints were described as being systematic or non-systematic, according to a modified version of joint description developed by Hodgson (1961). Although this terminology is useful in describing joint frequencies, it was not practical in the joint orientation studies here because the systematic joints varied greatly in definition and frequency. Thus for orientation data, a three-fold classification was used, where joints were referred to as dominant, subordinate, and rare. This ordinal quality scale can be equated to the systematic and non-systematic terminology by considering the dominant and subordinate joints as the former and the rare joints as the latter. The number of joint orientations was determined by an intergraded count of frequency from the entire outcrop. This value was then applied to the local setting in order to filter out, where necessary, localized joint sets induced by blasting. By contrast, the dominance quality was determined by inspection of the entire outcrop to compensate for very localized zones of high joint density.

The selection of joints to be measured was as random as possible, considering the bias of outcrop availability. Sample points were located at equal intervals along the outcrop and all joints present at each site were measured. The presence, attitude, and sense of calcite-or quartz-filled joints and tension cracks or gashes were also noted.

As shown in Table 1, the attitudes of faults and associated slickenlines were measured. If the sense of motion could be determined by inspection of the jogged slickenlines, the direction of motion of the hanging wall was given by an arrow symbol in the stereographic plots. For many faults the sense of motion and the net slip were not apparent, but both parameters were readily observable for wedge faults[2] (described by Cloos, 1964) on the mesoscopic scale. For these, the sense of motion and amount of slip were determined from slickenlines and the geometry of the competent beds comprising the wedge (Fig. 5). Consistent with Cloos' observation, wedge faults were found to occur preferentially in the cores of anticlines. The attitudes of the axial planes and axial lines were measured for these anticlines as well as for all other folds observed. To determine the geometric compatibility of the different orders of folds, the scale and sense of folds were noted.

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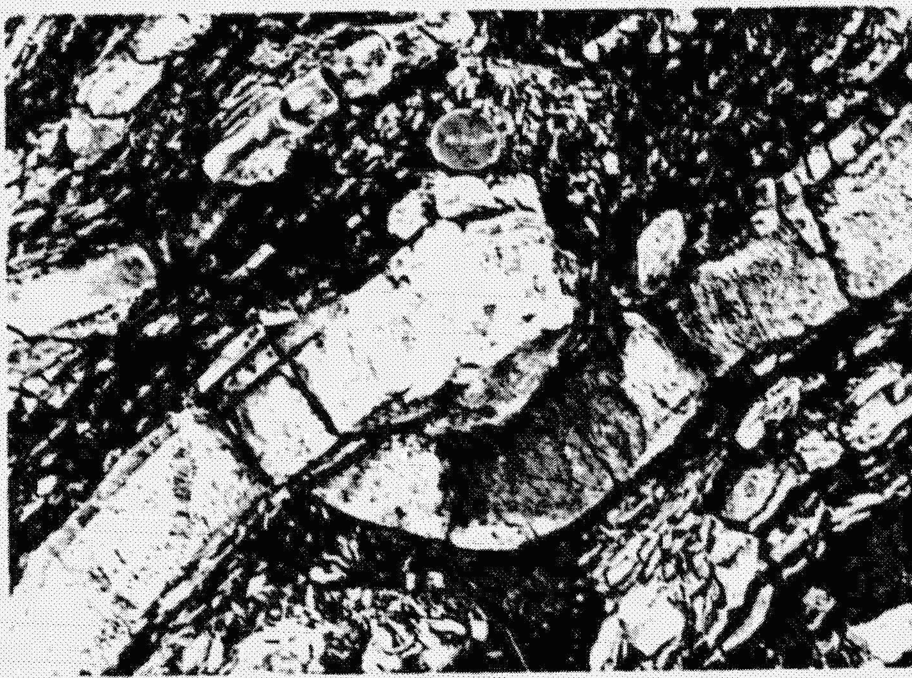
[2]Local duplication of beds in compressional faults at a low angle to the bedding surface.

a.



b.

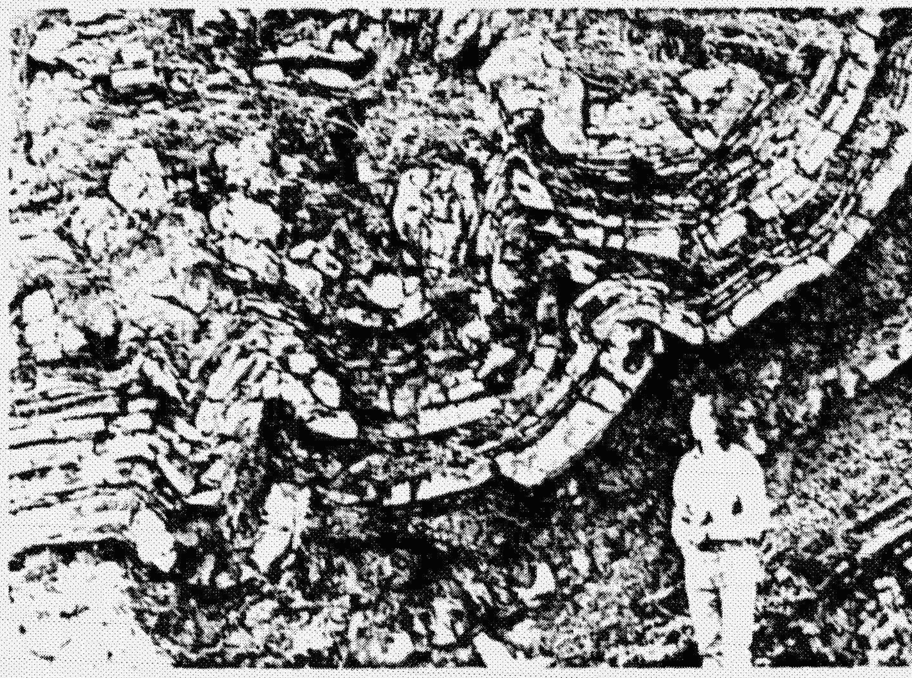


Figure 5. Mesoscopic wedge faults in the Mifflintown formation.
a) Wedge fault showing net displacement.
b) Wedge fault with associated fold.
Both faults are located 450 m (1500 ft) southeast of Barree, along the railroad tracks.

Six 1:24,000 7.5 minute USGS quadrangle maps were compiled for a topographic base map and the Tyrone quadrangle geologic map by Butts et al. (1939), on a scale of 1:65,000, was enlarged to 1:24,000 to give a general geologic reference base. Low altitude aerial photographs (1:20,000), U-2 photographs (1:135,000) and LANDSAT-1 imagery (1:230,000) were used in conjunction with the field work. Positional data from all scales were plotted on the 1:24,000 topographic map to produce a fracture trace and lineament map (Plate 1) and a detailed geological map (Plate 2), and cross section profiles of the structure and geology either side of the Tyrone - Mount Union lineament were drawn (Plate 3).

The fracture trace map was developed from linear features mapped on stereographic pairs of low altitude photographs (1:20,000), using conventional photo-geologic techniques. The fracture traces mapped represented linear features from 600 m to 1600 m (2000 ft to a mile) in length. Their expression took the form of characteristics such as a sag in topography, a tonal variation due to moisture along a more porous zone, and differential growth of vegetation. Linear features less than 600 m (2000 ft) long were not mapped, for many of these represent the surface expressions of joints and joint sets (R. R. Parizek, pers. com. 1976). In some places fracture traces can be shown to be surface expressions of fracture zones and/or faults (Parizek 1976). The fracture traces were mapped on individual aerial photographs, which were joined in an uncontrolled mosaic. They were then projected from the photographs onto the 1:24,000 topographic base map. The x and y coordinates of the end points of the fracture traces were finally digitized to permit computer calculation of azimuths and frequencies per azimuth class, using the TRANSFORM and AZMAP programs originally written by Podwysocki (1974). The TRANSFORM program processes the raw digitized data, making it compatible for final processing by the AZMAP program, which generates the histograms of frequency and length per azimuth class.

The megascopic data were mapped on monoscopic ortho-images, with a time limit set for each map section. The LANDSAT image was enlarged and cropped[3], yielding a 1:230,000 image of central Pennsylvania, encompassing the Nittany Anticlinorium and a portion of the Allegheny Plateau and the Broadtop Synclinorium (see Fig. 2). In order to test operator variability, photo-linears greater than 1.6 km (1 mile) long were mapped by three operators, transferred to a topographic base (Plate 1), and processed and analyzed in the same manner as the fracture traces.

It was found that the number of photo-linears mapped increased with the time spent on each scene, and that the length varied as operator objectives changed. In order to reduce bias in the size distribution analysis, a selected area was subjected to saturation mapping, by removing the time limits and allowing the operator to set specific size objectives each time he analyzed the scene. These photo-linears were measured for orientation and length, making it possible to determine if discrete length groupings were present.

[3]Enlargement provided by Dr. M. H. Podwysocki, NASA/Goddard Space Flight Center, Greenbelt, Maryland.

Initially, only the LANDSAT MSS-7 image[4] was mapped, but in an attempt to increase the number of lineaments perceived the MSS-5 image was included. Both of these images were edge-enhanced by the digital high-pass filter system described by Podwysocki et al. (1975). A description of this enhancement process and discussion of the results obtained are presented in the next section.

[4] The LANDSAT-1 MSS-7 image represents the 0.8 to 1.1 μ wavelength; MSS-5 is the image of the 0.6 to 0.7 μ data.

LINEAMENT ENHANCEMENT TECHNIQUES: AN EVALUATION

A portion of the detailed study conducted on the Tyrone - Mount Union lineament in central Pennsylvania involved mapping photo-lineaments in a 40 by 48 km (21 by 30 mile) area centered on the Little Juniata River (see Fig. 2). The mapping was done on both edge-enhanced and standard LANDSAT-1 images, at an approximate scale of 1:230,000. Such a lineament map was prepared to:

a) obtain a megascopic view of fracture systems and any structural variants present in this area;

b) determine whether photo-lineaments, particularly those with subtle or vague expression, could be accentuated by high pass filters in an edge enhancement technique; and

c) determine if the photo-lineaments apparent in edge-enhanced images were "real" or artifacts of the enhancement process.

Procedure

Computer compatible tapes (CCT's) for MSS bands 5 and 7 of the appropriate portion of LANDSAT scene 1297-15252 were processed by Dr. M. H. Podwysocki on the VICAR-SMIPS data processing systems at NASA/Goddard Space Flight Center, Greenbelt, Maryland. In addition to contrast enhancement and geometric correction for each MSS band, the digital data were processed through high-pass filters (as discussed by Podwysocki et al. 1975) for edge enhancement. This study is concerned with the edge enhancement aspect of the digital processing procedures. Both line and column (horizontal and vertical, respectively) filters were applied, thus creating two edge-enhanced images for each MSS band. The function of the filter is to preferentially enhance those photo-lineaments oriented 15-30° to the filter direction (Podwysocki et al. 1975). Although several orientations of the filter are required to enhance all possible photo-lineament directions, only two were used in this study. The digitally processed, edge-enhanced, data were recorded on photographic film by means of a DICOMED digital-analog recorder.

To minimize individual bias, six images were mapped by three operators, using the following criteria:

Operator Guidelines

1. Aligned linear segments are joined if the gap between them is shorter than the length of any individual segment.

2. Known or obvious lithologic contacts are not mapped; questionable contacts are mapped and deleted in a later comparison with the geologic maps.

3. Obvious cultural features are not mapped (roads, powerlines, etc.); questionable features are mapped and deleted in a later comparison with the topographic maps.

Time Element and Quality Control

1. Each image is mapped in a one-hour time period.

2. The mapping period is divided into four fifteen-minute segments; the most obvious photo-lineaments are mapped first, progressing with time to the least obvious.

3. Lineaments drawn during the respective time segments are labelled 1,2,3,4.

After each image was mapped, the end points of the photo-lineaments were digitized. That is, their coordinates were punched on cards in a form suitable for computer analysis of lineament orientation, frequency, and density. The programs used, TRANSFORM, AZMAP, and ROSE were modified after Podwysocki (1974).

TRANSFORM converts the digitized data into a form compatible with AZMAP. At this stage any errors present in the punched deck of digitized data will be flagged by the computer and corrections can be made. AZMAP calculates the frequency and length distributions of the vectors (photo-lineaments) with an option of performing a Chi-square test for randomness of density and frequency with respect to direction. The resulting distributions are displayed in histogram form. (For this study the category increment of 10° was selected.) Rose diagrams can be generated using the ROSE program.

The azimuth orientations were of primary interest in this study. These are displayed in Figs. 6 and 7, as frequency histograms for the individual operators, and in Figs. 8 and 9, as rose diagrams of the combined frequencies. The bias imposed by a single operator is minimized in the combined frequency plot, yielding a more valid representation of the megascopic fracture pattern in central Pennsylvania.

To verify whether this pattern and the photo-lineaments seen on enhanced images were free of artifacts of machine processing, a comparison was made with photo-lineaments mapped on standard (un-enhanced) LANDSAT-1 images, and on aircraft photography. Such comparisons minimize the effect of scan line and sun azimuth bias (Kowalik 1975) and improve the planimetric map plot of LANDSAT photo-lineaments.

It would have been desirable to also use lineaments mapped on SKYLAB photography for this comparison. However, the SKYLAB coverage for this area was limited. An attempt was made to use the one available scene by enlarging just the portion containing the study area, but the quality of the enlargement was too poor for photo-lineament recognition and mapping. Although cloud cover posed a problem with the high altitude U-2 aircraft coverage, some photo-lineaments could be mapped. None of these problems were encountered with the 38 low-altitude aerial photographs available. These were analyzed for fracture traces by the technique developed by Lattman (1958). The fracture traces ranged in length from 0.6 km (2000 ft) to 1.6 km (5240 ft). They were the dominant linear features visible on this scale (1:20,000) of photograph.

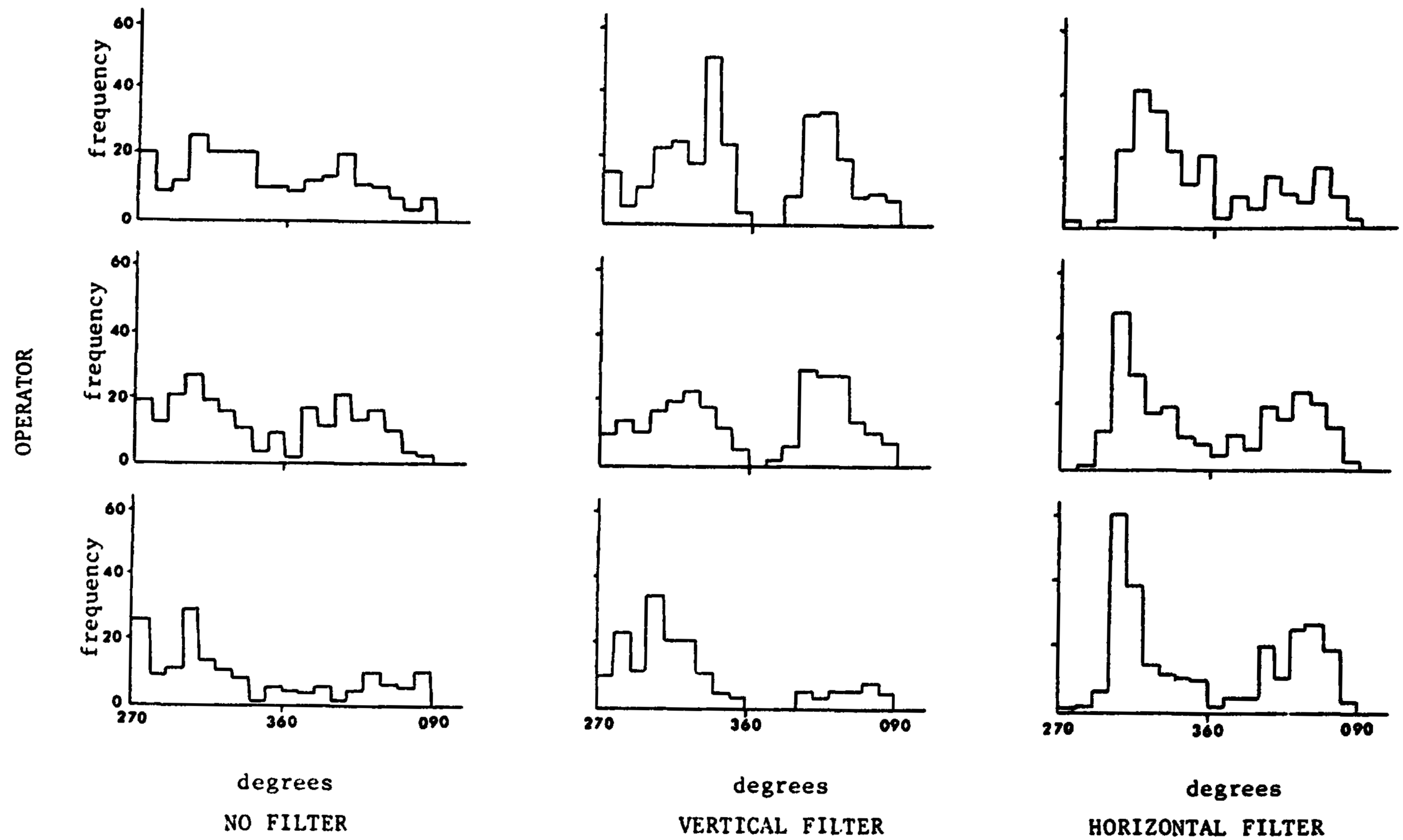


Figure 6. Bar histograms of frequency-per-azimuth-class for individual operators, MSS-5.

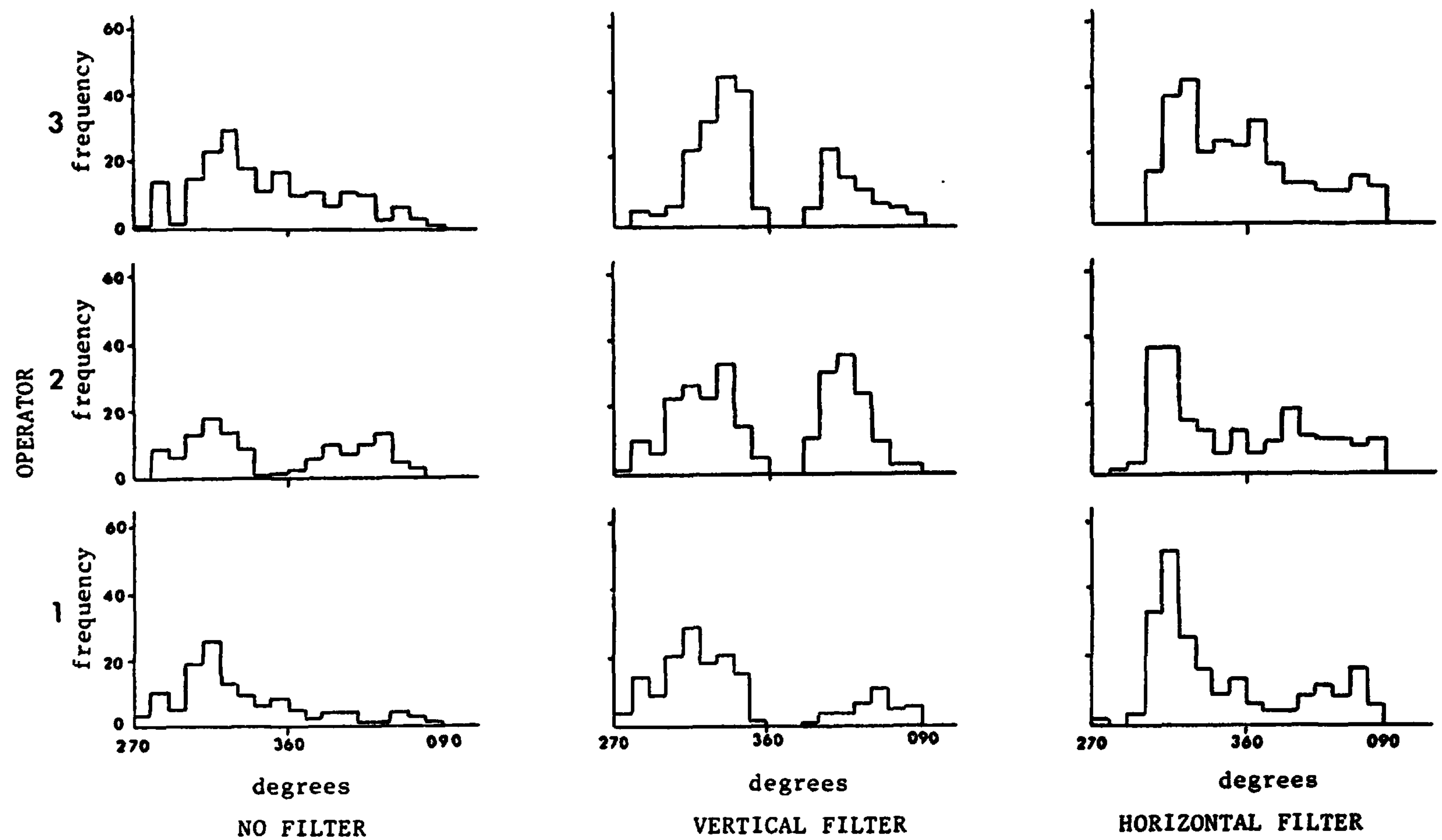
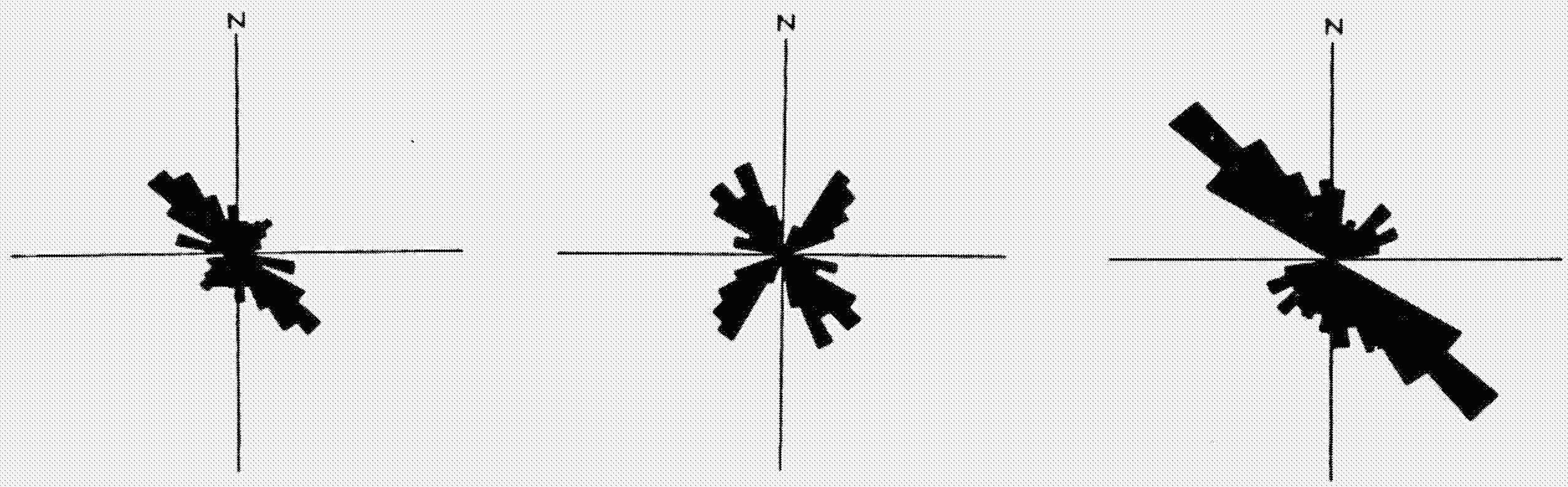


Figure 7. Bar histograms of frequency-per-azimuth-class for individual operators, MSS-7.

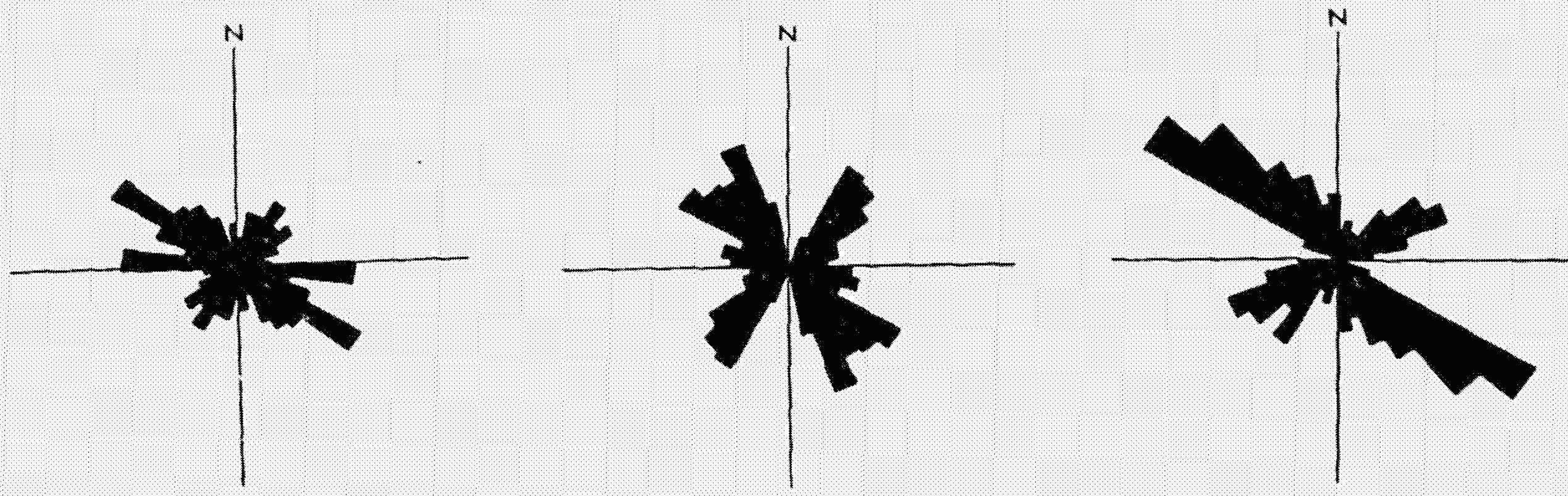


a. Unenhanced

b. Vertically edge enhanced

c. Horizontally edge enhanced

Figure 8. Rose diagrams exhibiting frequency of photo-linear orientations for MSS-7. Each diagram is a combination of data from the three operators for the respective images.



a. Unenhanced

b. Vertically edge enhanced

c. Horizontally edge enhanced

Figure 9. Rose diagrams exhibiting frequency of photo-linear orientations for MSS-5. Each diagram is a combination of data from the three operators for the respective images.

Overlays of the photo-lineaments mapped on the low-altitude and U-2 photographs, and on the LANDSAT images, were superimposed and visually compared for orientation, position, and pattern. Photo-lineaments with up to 5° rotation and 12.7 mm (0.5 in.) translation, at a map scale of 1:24,000, were considered as coincident. The tolerance limits may seem high, but they are in line with the degree of error involved in mapping and transferring photo-lineaments from LANDSAT-1 images to 7.5 minute topographic quadrangle maps. The increase in scale by a factor of 10 means that an 0.8 mm (0.03 in.) error of positioning a photo-lineament on the LANDSAT image, a common error due partly to the "shadowing" effect (Wise 1968), magnifies to at least 8 mm (0.3 in.) on the topographic base map. Optical distortion also introduces error in the transfer of data. These azimuthal errors, introduced by optical distortion, positioning, and orientation, are contained by a 5° rotation tolerance.

All the LANDSAT photo-lineaments were numbered and their expression at the three scales compared (Table 2). (The numbers on lineaments in Plate 1 correspond to those in Table 2.) Photo-lineaments common in all formats were given the same number; the presence of the additional lineaments was noted. Of these, 38 photo-lineaments were field checked to investigate their nature and surface expression. An evaluation could then be made of each photo-lineament in terms of degree (field and photographic) and nature of expression of the feature. The degree of expression was referred to as "definite," "probable," or "possible," in decreasing order of confidence. The nature of expression was described as "a small stream," "a line of trees," etc., with an additional note concerning fracture density, if possible.

Results and Discussion

Histograms of the photo-lineaments mapped are shown in Figs. 6 and 7. Each histogram shows the frequency distribution per azimuth class for each operator for the two LANDSAT images. A statistical comparison of operators was made using the CHISQUARE option of MINITAB-2, a library program at The Pennsylvania State University (Ryan et al. 1974). The Chi-square contingency table (3 by 18) produced as output from MINITAB-2 showed that, based on a .05 level of rejection, the operators were not mapping the same population of photo-lineaments. The original histograms for edge-enhanced images demonstrated the effect of the directional filters. The filters were horizontal and vertical with respect to the edges of the image. Because these were parallel and perpendicular, respectively, to the orbit (which tracked approximately 9° east of north), a correction had to be included in the histograms.

The combined operator photo-linear orientations, including the 9° orbit correction, are presented in the rose diagrams of Figs. 8 and 9. Figure 8 shows the maximum number of unenhanced photo-lineaments with a strike centered approximately at 315°. This orientation is compatible with that of the major lineament between Tyrone and Mount Union. It should be noted that all of the lineaments oriented at 315° may not be seen on a LANDSAT image due to the sun azimuth bias, as discussed by Kowalik (1975). On the other hand, some cultural features inadvertently were included, but they comprised less

Table 2. Ground Truth Correlations of Linear Features Mapped from Three Scales of Remote Sensing Data

Lineament Number	LANDSAT	U-2	Low Altitude Aircraft	Expression Degree	Expression Nature
1	N,H,V[a]	x[b]	x	Definite	Gap on Bald Eagle Mountain, alignment of hollows, fracture zone
2	N,H,V	-	x	Possible	Gap on Bald Eagle Mountain
3	V	-	x	Possible	Sags and hollows
4	N,H	-	x	Definite	Sags, hollows, fracture zones
5	N,H,V	-	x	Possible	Sags in Oswego Ridge, Canoe Mountain, and fields
6	N,H	-	x	Possible	Fracture zones, fault, breccias, alignment of sags and hollows
7	H,V	-	x	Possible	Sags near Route 453
8	N,H	-	-	Possible	Alignment of hollows, parallels lithology
9	N,H	-	-	Possible	Alignment of sags and hollows
10	N,H,V	-	x	Definite	Fault and stream
11	N	-	x	Possible	Sags and hollow
12	N	-	x	Probable	Straight valley
13	H	x	x	Probable	Sags in Plummer Hollow, Oswego Ridge, and Grandview Hill
14	N,H,V	-	x	Definite	River segment
15	H,V	-	-	Probable	River segment
16	H	-	-	-	Fence line
17	H	-	-	Possible	Sags
18	H	-	x	Possible	Hollow with road
19	N,H	-	Outside mapped area	Possible	Sags, valley and road
20	H	-	x	-	Lithologic contact

(Continued)

Table 2 (Continued)

Lineament Number	LANDSAT	U-2	Low Altitude Aircraft	Expression Degree	Expression Nature
21	N,H	-	-	Probable	Portion of stream, fracture zone
22	H	-	-	Possible	Sag and river alignment
23	V	-	-	Possible	Hollow and sag alignment
24	N,H,V	x	x	-	Lithologic contact
25	H,V	-	x	-	Field-woods contact
26	H,V	-	x	Possible	Subtle swales, fracture zone, breccias
27	H	-	-	Probable	Fracture zone, stream sinking into cave, breccias
28	N,H,V	x	-	Probable	Portion of river, alignment of hollows and sags
29	H	-	-	Possible	Small hollow
30	V	x	-	-	Telephone line right-of-way
31	N,H,V	x	-	Probable	River segment
32	N,H,V	-	-	-	Probably Route 22
33	H,V	x	x	Probable	Hollow alligment
34	H	-	x	Possible	Hollow, subparallel to lithology
35	V	-	-	-	Cloud
36	V	-	-	Probable	Sags, stream alignment
37	V	x	-	Probable	Hollow, fractured areas, faults
38	N,V	-	-	Possible	Hollow

[a] N = no filter, H = horizontal filter, V = vertical filter

[b] x = coincidence of lineament with that mapped on the LANDSAT imagery.

than two percent of the total observations. Therefore, the peak centered around 315° is a reasonable representation of the general trend of the megascopic fracture pattern. The two smaller peaks in the histogram are attributed to scan lines (at 280°) and bedding strike (at 045°), respectively.

As in Figs. 6 and 7, one can see the effect of the digital filters on the perception of linear features in Figs. 8b and 8c. For example, in Fig. 8b, the filter is oriented vertically with respect to the image, thus there is a complete suppression of photo-lineaments in this direction. A partial and somewhat less obvious suppression occurs in a horizontal direction with respect to the image. The increase of lineaments measured in a zone from 10° to 30° ± 5° on either side of the vertical filter direction is apparent, sustaining the rationale for the edge-enhancement process. A similar effect for the horizontal filter is apparent in Fig. 8c, where a definite increase in photo-lineaments is seen in the direction of maximum frequency evident in Fig. 8a.

The results for the MSS-5 data were similar to those for the MSS-7 data (see Fig. 9). In general, more cultural features can be seen on the MSS-5 images, therefore a larger percentage of photo-linear features tend to be non-geologic in origin. Even with this in mind, the peak of linear features is centered around 315° and is consistent with the orientation of peaks in Fig. 8.

The ground truth data for some photo-linear features mapped on unfiltered and directionally filtered images are presented in Tables 2 and 3. Table 2 shows the correspondence of photo-lineaments mapped on LANDSAT-1 images to those mapped on U-2 and low-altitude photographs. In the column headed "LANDSAT," the letters N, H, and V represent "no filter," "horizontal filter," and "vertical filter," respectively. As stated previously, only one photo-lineament was drawn and numbered for those that were coincident. In the columns headed "U-2" and "Low Altitude," an x indicates the coincidence, within the established tolerance limits, of the photo-lineaments mapped on the aircraft photography with those mapped on the LANDSAT imagery. The number of low altitude photo-lineaments was so large, compared to those from the U-2 photographs, that a greater chance of coincidence existed in the former case. as is evident in the table.

The heading, "Expression," in Table 2, contains two sub-headings: "Degree" and "Nature." The nature of a photo-lineament was determined by a field check of its geomorphologic and structural characteristics. A number of photo-linear features were determined to be non-geologic in origin and were noted accordingly. For the natural (geologic) linear features, a correlation of their nature with their detectability in the three scales reflects their degree of expression. For example, LANDSAT Photo-Lineament 1 was found to have a definite expression in the field as well as on the photographs and images. This can be contrasted with LANDSAT Photo-Lineament 13, which has good expression on the images and photographs but is not so definite in the field. Thus, its degree of expression is termed "probable." The term "probable" is also applied to the inverse situation, where the field expression is better than the remotely sensed expression. The term "possible" was used for photo-linear features not easily recognized in the field and/or on all three scales of photographs and images.

Table 3. Time Comparison for Photo-Lineament Plots on Standard and Edge-Enhanced Images, MSS-7

Photo-Lineament Number	No Filter	Horizontal Filter	Vertical Filter
1	3[a]	2	3
2	2	2	2
3	-	-	1
4	1	1	-
5	2	3	2
6	4	2	-
7	-	3	1
8	1	4	-
9	1	1	-
10	1	1	2
11	1	-	-
12	3	-	-
13	-	2	-
14	2	1	2
15	-	2	3
16	-	3	-
17	-	4	-
18	-	4	-
19	2	2	-
20	-	4	-
21	4	3	-
22	-	4	-
23	-	-	1
24	2	3	1
25	-	3	3
26	-	4	3
27	-	2	-
28	2	3	1
29	-	2	-
30	-	-	3
31	2	1	3
32	1	1	1
33	-	2	1
34	-	4	-
35	-	-	4
36	-	-	2
37	-	-	1
38	2	-	3

[a]Each time period, 1 through 4, represents tne first, second, third, or fourth quarter, respectively, of a one-hour mapping period.

From Table 2, one can be confident that all of the linear features mapped on the edge-enhanced images, whether of geologic origin or not, are not artifacts of machine processing, and that this is true of the linear features seen on the standard images as well. These results do not support the conclusions of Gillespie and Goetz (1976), who show that artifacts are introduced into the final image if a high pass filter system is used. Their conclusion may be true for other geographic areas, but it was not found to be true for the area of this study.

In Table 3, the time periods (1,2,3, or 4), in which the LANDSAT-1 photo-lineaments were mapped are shown for the standard and edge-enhanced images. Grades of coincidence for photo-lineaments range from mapped on all three images to mapped on only one image. There was no consistent trend of improved perception rate apparent by enhancing the images, i.e., there was no improvement in the mapping-time category of linear features detected on the edge-enhanced images over the standard image. Although the "rate of perception," in this case, exhibits no definite trend, the number of photo-lineaments perceived has definitely increased for the edge-enhanced images. This is illustrated by the addition of 21 photo-lineaments mapped solely on edge-enhanced images.

Conclusions

The following conclusions can be derived from this evaluation of lineament enhancement techniques:

1. The megascopic lineament pattern is dominated by a peak oriented at 315°.

2. The operators mapped similar photo-lineament directions.

3. Most photo-lineaments mapped on edge-enhanced images are "real," i.e., not artifacts of the machine processing.

4. Except for scan lines, most of the photo-linear features on standard images are real.

5. Photo-linear features mapped on edge-enhanced images are not necessarily perceived more rapidly than those on standard images.

6. More photo-linear features can be mapped on edge-enhanced images than on standard images in an equal time period.

7. Because of the orthogonal nature of the filter and the limited test of directions conducted here (vertical, 009°, and horizontal, 279°), the full potential of the digital filtering technique has not been evaluated.

A STUDY OF STRUCTURES ALONG THE NORTHWESTERN SEGMENT OF THE TYRONE - MOUNT UNION LINEAMENT

The writer started developing a cross-sectional profile along the northern part of the Juniata River valley during the summer of 1975. This was followed by detailed structural and stratigraphic mapping along the northwestern part of the Tyrone - Mount Union lineament during the fall of 1975 and the winter and spring of 1976.

Procedure

Field observations and measurements were made on a number of stratigraphic and structural parameters (see Table 1), and compared for on-lineament and off-lineament sites in the study area. The objective was to determine the features, and characteristics unique to the lineament zone. Most of the comparisons were made as orientation and frequency diagrams and in tables; some statistical tests for significance were also made. New data on the geology were recorded on the geological map (Plate 2) and in detailed maps and photographs.

All orientation data were plotted on an equal-area, lower hemisphere spherical projection, and contoured by the SNAP program (Jeran and Mashy 1970), modified for use on The Pennsylvania State University computer system. The general contour interval used was 3, 6, and 9% per 1% area. However, to accommodate the large number of observations, contour values of 2, 3, 4, and 6% per 1% area were used for the synoptic, density contoured, S-pole diagrams of joint orientations. Values of 2, 4, and 6% per 1% area were used for synoptic diagrams of fault planes and slickenlines.

Results

The S-pole diagram of Fig. 10 contains all of the joint orientations measured. It exhibits a point maximum of 045° and a subsidiary peaked cluster at 130°C. These maxima correspond, respectively, to a subvertical plane set centered on 130° strike, and a predominantly northwest dipping set striking about 045°. The former joint set is generally dominant in expression and frequency in the field. However, this does not imply that it is the dominant joint or joint set at each outcrop. Variations are apparent in the individually contoured S-pole diagrams for some of the locations shown in Plate 2. These diagrams reveal how joint orientations vary with location on the second and third order folds present, as well as across the lineaments.

The pole representing the mean bedding plane for an outcrop is included on the individual contoured joint diagrams in Plate 2. The strike orientation is nearly constant within most of the outcrops but the dip angle varies. Therefore, the mean bedding plane was determined by finding the arithmetic average of dip angles and using the approximate strike orientation. In view of the contorted nature of the beds, this pole could not be included for some localities. The geometry of the joints with respect to an assumed horizontal bedding attitude before folding was determined by rotating measured joint orientations about the bedding strike and through the dip angle of the beds to a horizontal attitude. Because joints in flat-lying strata are commonly parallel and perpendicular to the bedding planes (De Sitter 1956),

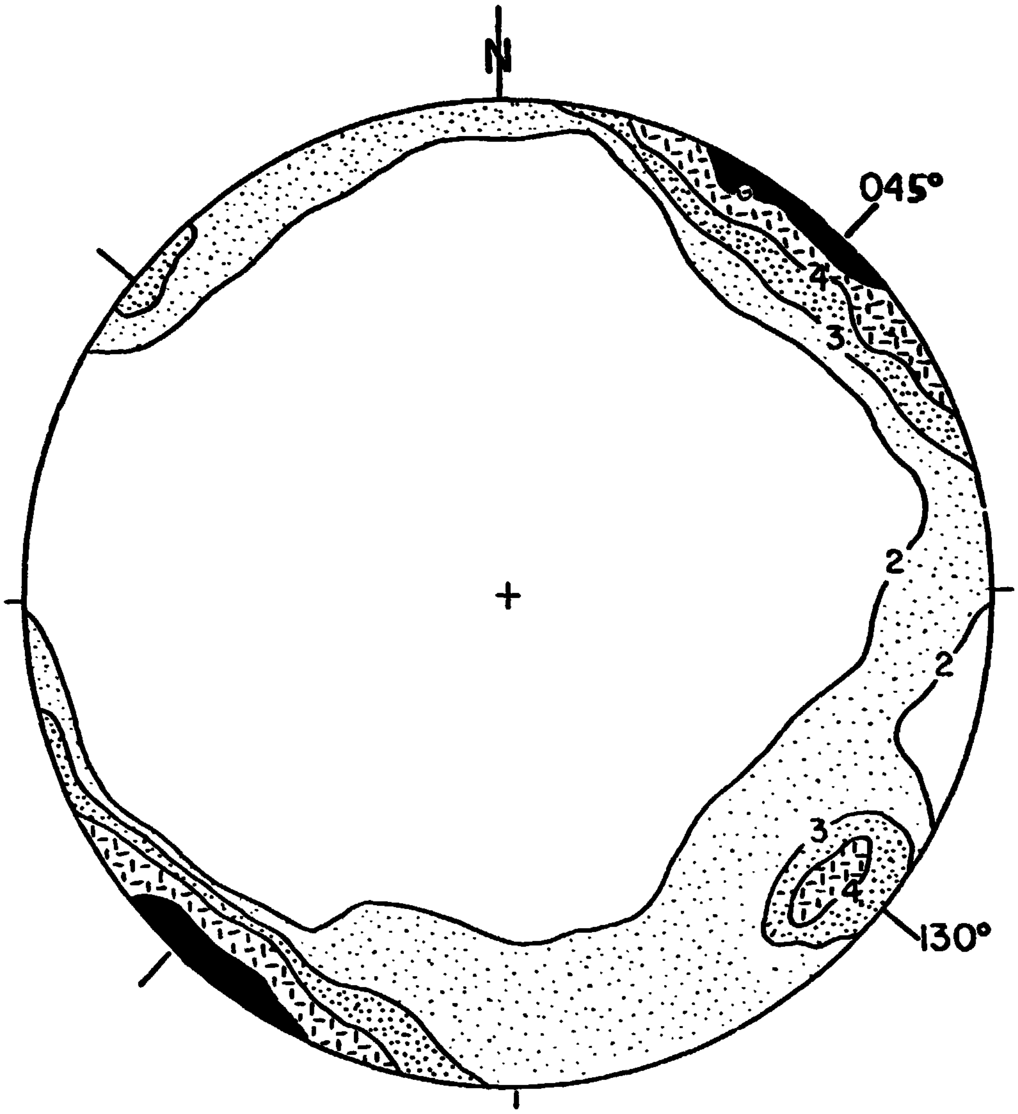


Figure 10. Synoptic S-pole diagram of 2316 joint attitudes, contoured at 2, 3, 4, and 6% per 1% area. Planes associated with the peak concentrations are indicated at 045° and 130°.

those sets parallel or orthogonal to bedding planes were interpreted as joints inherited from pre-Alleghenian orogenic events, and the others were interpreted as superimposed. This assumption, however, cannot be used to unambiguously sort out pre- or post-folding joint sets nearly perpendicular to bedding strike (i.e., the axis of rotation). Determination of the age of origin for each joint set should be made in an area of through-going joints, oblique to the bedding strike. For example, nearly vertical joints oriented at 103° are observed in most outcrops regardless of the bedding attitude. From geometric considerations, the age of this joint set is ambiguous for outcrops with a bedding strike of 040° but definitely is post-folding for other bedding orientations.

Joint density data for four locations are compiled in Table 4, and the nature of the beds, formation name, station number, and locality are listed in Table 5. A comparison of average frequencies for individual azimuth classes (Table 4, last column), suggests the presence of four broadly defined peaks (indicated by brackets), two of which coincide with the 130° and 045° preferred joint orientations apparent from the synoptic S-pole diagram (Fig. 10). The absence of the other two peaks in Fig. 10 indicates that these preferred orientations exist just for the formations sampled at the four locations and not for the entire study area. The four peaks shown in Table 4 represent the sum of the average frequencies per azimuth class for systematic and non-systematic joints from the four sampling localities in the region, and do not necessarily represent the preferred directions and density of joints from individual quarry sites. For example, only the peaks for the 81°-100°, 111°-140°, and 151°-170° class intervals for Location 18 exhibit a general coincidence with the regional frequency distribution.

It was noted during this study that joint density decreases with an increase of bedding thickness; thus comparisons are valid only between units of similar thickness. In order to reduce the variability due to lithology and bedding thickness, a comparison was made between Locations 18 and 25, in which the bedding aspects and lithology are the most similar of the four quarries. There is an increase of 24 and 278%, respectively, of average frequency per cell for systematic and non-systematic joints between Locations 18 and 25 (Table 4, subtotals) and a 44% increase of total frequency per cell. An analysis of variance test was performed on these data to determine if the difference in joint frequency distributions between sampling localities was significant, i.e., if the variance of joint direction-frequency (density) between the quarry sites is greater than between sample sites within any given quarry. The AOVONE (Analysis of Variance One Way) option of the MINITAB-2 library program at The Pennsylvania State University (Ryan et al. 1974) was used to test the null hypothesis, H_o, that no significant difference in joint density exists between sample locations. An F-test of these data rejected this hypothesis at the .05 level for all four sampling localities, and yielded a similar result for a comparison between sampling Locations 18 and 25. The indicated 44% increase in joint density in Location 18 over 25 is, therefore, statistically significant.

Note that the subtotals (Table 4) of systematic and non-systematic joints do not decrease systematically away from the lineaments, even though the overall totals do decrease proportionately with distance from the lineament. This could be due to differences in lithology, bedding thickness, tectonic

Table 4. Joint Density Data for Four Locations

The average frequencies[a] per 4 m^2 cell for each 10^o azimuth class are plotted. Location 18 is on the lineament; the other locations are, respectively, 2.5, 3.0, and 3.8 km (1.4, 1.9, and 2.4 miles) from it. Brackets indicate distribution peaks.

Location #:	18		3		24		25		Totals per
Azimuth	S[b]	NS	S	NS	S	NS	S	NS	Azimuth Class
0-10	0.65	0.20	--	--	0.40	0.08	--	--	1.33
11-20	--	--	--	--	0.20	0.72	--	--	0.92
21-30	--	--	0.11	--	0.52	--	0.59	0.06	1.28
31-40	0.25	--	0.34	0.66	0.12	0.40	--	--	1.77
41-50	0.65	0.05	0.51	0.37	0.20	0.20	--	--	1.98
51-60	--	--	0.37	0.23	0.52	0.04	1.41	--	2.57
61-70	0.15	0.15	0.71	0.09	--	0.28	1.00	0.18	2.56
71-80	0.80	--	0.40	--	0.12	0.08	--	--	1.40
81-90	0.70	0.15	0.34	--	0.20	1.08	0.12	--	2.59
91-100	1.20	0.70	0.31	0.31	0.52	0.20	0.12	--	3.36
101-110	0.15	--	--	0.17	0.56	--	--	0.24	1.12
111-120	1.30	1.10	0.49	0.40	0.28	--	0.71	--	4.28
121-130	0.50	--	0.40	0.09	1.12	1.60	1.65	--	5.36
131-140	3.05	0.70	2.69	--	1.84	0.28	0.06	--	8.62
141-150	0.70	--	0.43	0.06	0.96	0.08	0.65	--	2.88
151-160	1.15	--	1.06	0.06	0.08	0.28	1.29	0.12	4.04
161-170	0.85	0.15	0.54	--	0.20	--	1.88	0.29	3.91
171-180	--	--	0.29	0.09	0.64	0.24	0.29	--	1.55
Subtotals	12.10	3.20	8.99	2.53	8.48	5.56	9.77	0.89	
Totals	15.30		11.52		14.04		10.66		

[a] $\text{Average frequency} = \frac{\text{Total joints per azimuth class}}{\text{Number of cells}}$

[b] S = systematic joints, NS = non-systematic joints

Table 5. Bedding Characteristics of Geologic Fc.mations at Four Joint Sampling Sites

Location	Sampling Site	Formation(s)	Bedding Characteristics
Warners Quarry, Union Furnace	18	Black River formation	Predominantly thick-bedded rocks; some thin-bedded strata in upper portion
Narehood Bros. Quarry, Stover	3	Upper Black River formation; some Lower Trenton group	Equal amounts of thick and thin-bedded strata
Colerain	24	Trenton group	Thin-bedded strata
One mile north of Colerain	25	Upper Black River formation	Predominantly thick-bedded strata

setting, localized stresses, operator inconsistency during data collection, or unknown causes. Whatever the reason, the 44% increase in overall joint density is significant and cannot be attributed solely to operator error or the other possible factors. This leaves a possible correlation between the increase in joint density and the lineament position.

The width of anomalous fracture frequency cannot be determined unambiguously from the data in Table 4 because the ambient joint density elsewhere in Nittany Valley is not known. In addition, Location 25 is coincident with a fracture trace and the other two locations, 3 and 24, are positioned 150 m (500 ft) and 300 m (1000 ft), respectively, from other fracture traces (see Plate 1). Therefore, it is not clear whether the joint density values at Locations 3, 24 and 25 reflect proximity to the Tyrone - Mount Union lineament, the presence of local fracture traces, or other factors. Future studies of joint densities throughout Nittany Valley are needed to clarify this point.

High angle faults with small displacements are ubiquitous throughout the study area, and some appear to form conjugate sets. A synoptic, contoured S-pole diagram of 159 of these fault orientations yielded maxima with strikes of 110° and approximately 140° (Fig. 11). In conjugate sets of faults, the σ_2 axis (intermediate principal stress axis) is defined by the attitude of the line of intersection, and the position of the maximum principal stress axis, σ_1, coincides geometrically with the perpendicular bisector of the acute dihedral angle between the fault planes, shown in Fig. 11 as the line x-y, the bisector of the obtuse dihedral angle between poles to the fault planes. The plunge of the slickenlines associated with these faults forms a broad girdle about the 120° plane, and most of the slickenlines plunge to the southeast and northwest at moderate angles (Fig. 12).

The polarity of slickenlines on the fault planes from a few well exposed localities along the lineament are portrayed in Figs. 13 and 14. The stereographic plots show not only the plunge of the slickenlines, but also a short segment of the fault plane through it and the sense of motion of the hanging-wall block. The sampling locations are, Tyrone Gap (Locations 1 and 2), a roadcut near Union Furnace (Location 17), and two Locations (30 and 31) in an area 150 m (500 ft) east of the railroad tunnel in Spruce Creek Gap (see Plate 2). The data from Tyrone Gap are plotted in Fig. 13 and those from locations 17, 30, and 31 are plotted in Fig. 14.

At Tyrone Gap, the general trend of motion to the northwest and southeast differs from the north-south motions recorded in the west limb of the Scotch Valley syncline near Union Furnace (Location 17 and Diagram 17 on Plate 2). Most of this difference can be reconciled if the beds are rotated to a horizontal attitude; the difference may also be attributed to redistribution of stresses in the nose of the syncline. The former solution is favored because, by rotating the bedding attitudes at Location 17 back to horizontal through the dip angle the slickenlines correspondingly rotate to a shallow northwest-southeast plunging orientation. This orientation is consistent with those measured in Tyrone Gap (Fig. 14), as well as with the overall trend in the synoptic slickenline diagram (Fig. 12).

The interpretation of fault type from slickenline polarity requires a knowledge of fault chronology, since the slickenlines generally represent only the latest movement(s). The initial attitude of the fault plane must also be known because it may have changed as a result of folding. For example,

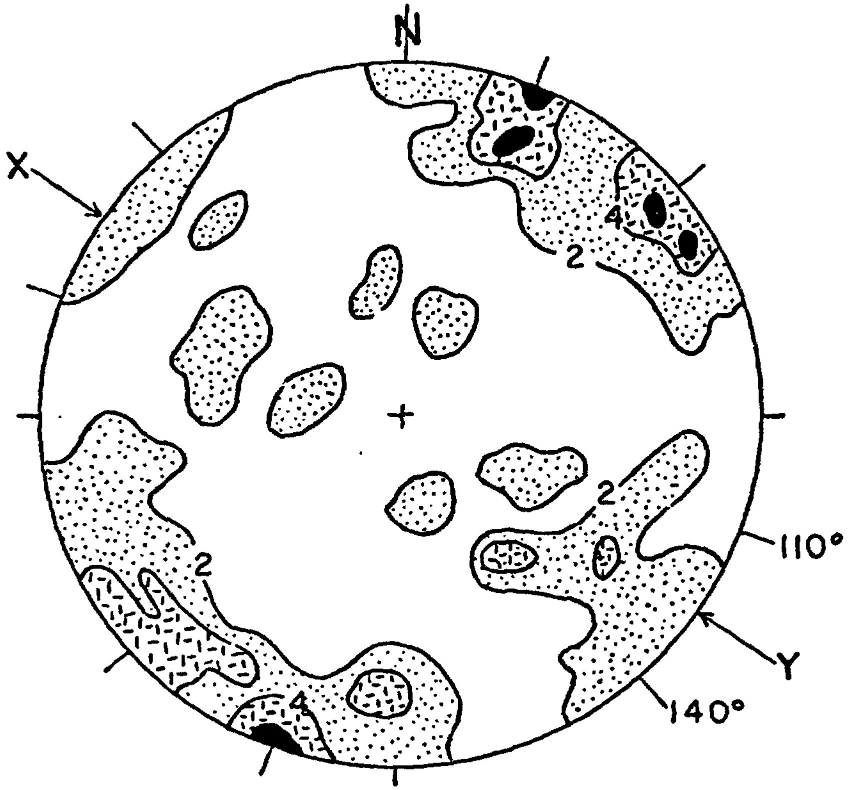


Figure 11. Synoptic S-pole diagram of 159 fault planes, contoured at 2, 4, and 6% intervals per 1% area. The pole maxima represent strike directions of 110° and 140°, respectively. Line X-Y is the perpendicular bisector of the acute dihedral angle between the dominant fault attitudes.

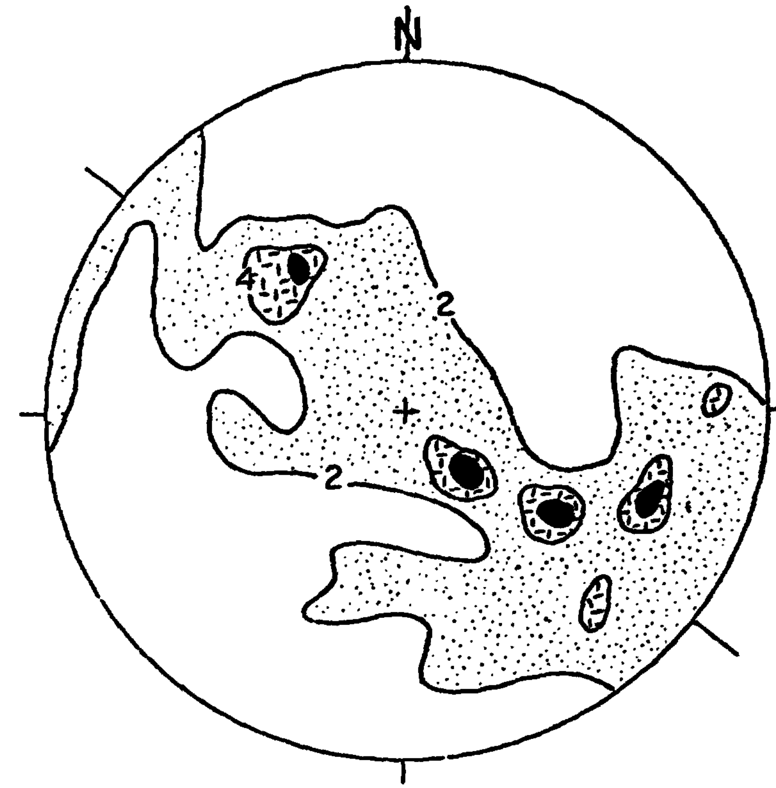


Figure 12. Orientation diagram of 136 slickenlines contoured at 2, 4, and 6% per 1% area.

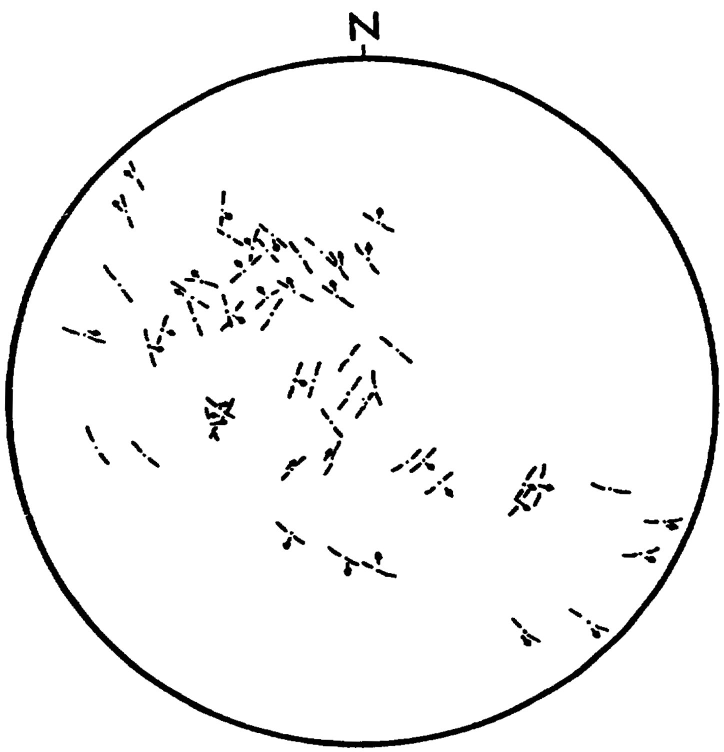


Figure 13. Stereographic plot of slickenline polarity in Tyrone Gap. Fifty seven observations are plotted. A segment of the fault plane (←·→) and the sense of motion of the hanging wall (→) are shown.

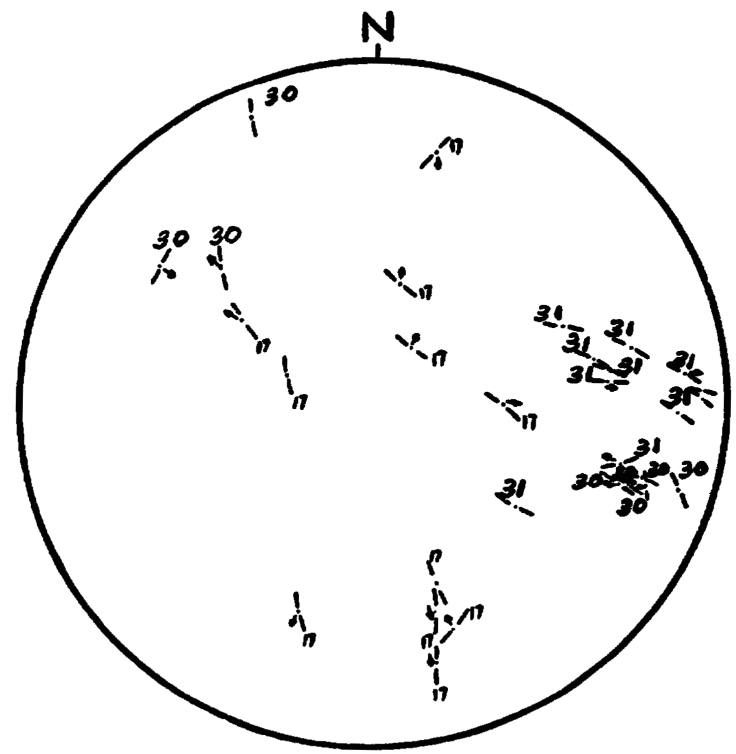


Figure 14. Stereographic plot of slickenline polarity at Locations 17, 30, and 31. A segment of the fault plane (←·→) and the sense of motion of the hanging wall (→) are shown.

many conjugate faults exposed in the Tyrone Gap section exhibit non-unique slickenline directions on their planes. Most of these fault sets, developed in the sandstone planes and shale beds of the Oswego formation, have a subhorizontal line of intersection oriented about 140°. Other fault planes in the same outcrop contain two sets of slickenlines, with a subhorizontal set superimposed on a steeply inclined set.

Slickenlines on the fault near the butt of the hammer in Fig. 15 are subparallel to the nearly vertical bedding surface (indicating a dip-slip movement), whereas the set of subhorizontal striae on the fault near the hammer head indicates that the fault is essentially strike-slip in nature. This variation in slickenline attitude may have resulted from a southeast-northwest directed stress acting intermittently on a fault plane rotated by folding. It may also be the result of rotation of the stress field, producing early dip-slip faults and later strike-slip faults, both with small displacements. The former hypothesis is favored, mainly because (a) dip separations on either side of the lineament are not apparent from the detailed lithologic mapping, and (b) many mesoscopic right and left strike-slip faults with compensating displacements were mapped in the lineament zone. Thus the dip-slip fault depicted in Fig. 15 as nearly perpendicular to the bedding surface probably developed as a strike-slip fault prior to folding, when the beds were subhorizontal. Reactivation of the conjugate fault plane after the folding episode, by similar compressive stresses, would account for its current, *in situ* strike-slip mode.

In the area 150 m (500 ft) east of the railroad tunnel in Spruce Creek Gap (Sites 30 and 31), the plunge directions of slip lines vary by at least 20° from one side of the gap to the other, a distance of approximately 180 m (600 ft). Possible reasons for this variation in plunge will be discussed later in this section.

Mesoscopic scale folds are ubiquitous, and seem to occur preferentially where competent and relatively incompetent units are intercalated, such as the Oswego Sandstone in Tyrone Gap and the Mifflintown Formation near Barree. Where the competent unit is dominant, folds tend to be larger, from 3 to over 30 m (10 to over 100 ft), than in the areas where the incompetent unit is dominant, where the folds range from 0.03 to 3 m (0.1 to 10 ft). All of the fold axes measured are compatible with a northwest direction of transport, which is consistent with the orientations of slickenlines and fault planes and the general geometry of the Nittany Anticlinorium. Not all of the minor folds are consistent in drag sense with their location on higher order folds. These minor folds may be disharmonic, with scale-related decoupling between the third and higher-order folds, i.e., where a decollement in the stratigraphic section separates folds of different scale and style (Nickelsen 1963). For example, a fourth-order kink fold in Tyrone Gap is incompatible in drag sense with its location in the west limb of a first-order anticline, the Nittany Anticlinorium. Slickenlines on the bedding surface perpendicular to the fold axis suggest a flexural slip mechanism for these kink folds. A nearly vertical fault plane, obliquely transecting the fold, contains subhorizontal slickenlines. These relationships suggest that an early flexural slip-folding event preceded the transgressive strike-slip faults of small displacement.

The entire study area, 9 by 16 km (5.5 by 10 miles), was covered by photogeologic studies at different scales. A strip 3.2 km (2 miles) wide, centered on the Tyrone - Mount Union lineament, was mapped in detail in the field. With

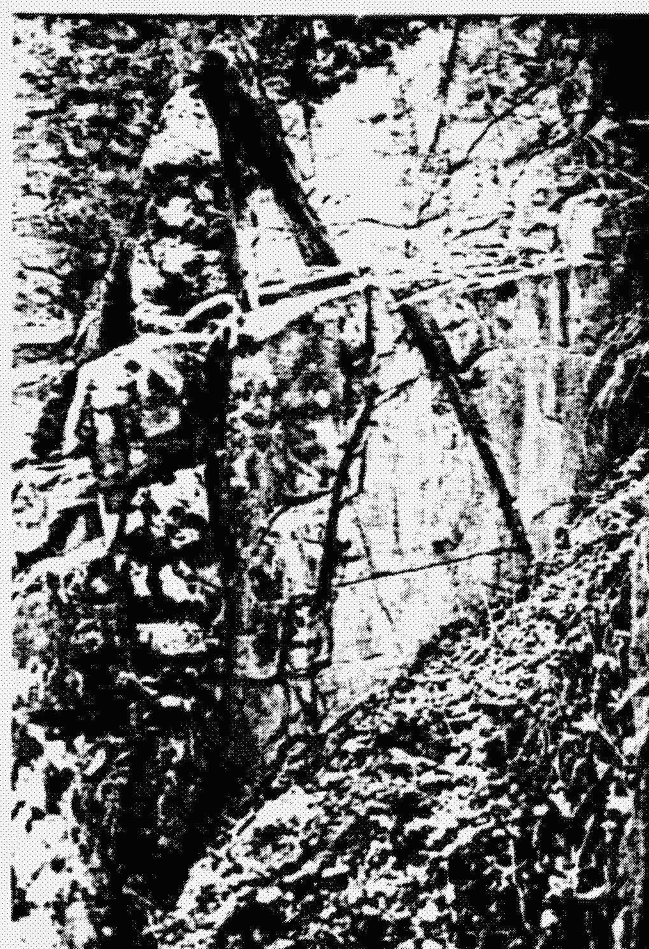


Figure 15. Two sets of inclined, intersecting, faults with different slip line orientations. The fault near the butt of the hammer shows motion sub-parallel to the bedding surface (vertical and parallel to the plane of the photograph) and the fault near the head of the hammer shows sub-horizontal motion.

the improved data base (aerial photographs and satellite imagery) the author was able to extend coverage of units into areas of limited or poor exposure. These mapping methods proved to be complementary and enabled the author not only to extend in detail the geological and structural mapping of Butts et al. (1939) with additional faults and folds, but also to correct the positions of subsequently mapped faults and lithologic contacts. This new data base has spurred new interpretations and necessitated a reinterpretation of the earlier data.

The following list of observations and interpretations are considered to be the more important contributions of this paper:

1. The trace of the Shoenberger fault, which Butts et al. (1939) showed to terminate in the Nittany Formation, is seen on LANDSAT imagery to extend into a N 80° E trending lineament that passes through Brush Mountain at Skelp Gap. This lineament probably represents the trace of a fault, because right lateral displacements of the Middle Ordovician section are apparent near Skelp. This movement is compatible with the reverse sense proposed by Butts et al. (1939) for the Shoenberger fault. Indeed, the latter fault may terminate on the former.

2. The reversal of dips in beds of the Juniata Formation exposed in Plummer Hollow, south of Tyrone Gap (Plate 2), probably reflects the presence of a third-order fold confined to this formation. This fold does not project across Tyrone Gap to the north (Plate 3). Its presence would account not only for increase in the thickness of this formation south of the river, but also for the development of the strike valley in Plummer Hollow.

3. Mesoscopic scale strike faults that duplicate beds occur singly or in conjugate pairs in the Tyrone Gap exposures (Krohn 1976). Although their present attitude requires them to be classified as normal dip-slip faults, they have been interpreted as pre-folding compressive or wedge faults (Cloos 1964). On some of the faults, superimposed slickenlines attest to a late strike-slip movement, consistent with the motions on mesoscopic dip and oblique faults that cut the earlier "wedge" faults. The late strike-slip faults also occur in conjugate sets, in which adjacent faults may exhibit right and left lateral displacements, respectively. The apparent lack of offset across the lineament in Tyrone Gap indicates that the mesoscopic scale strike-slip displacements are compensatory.

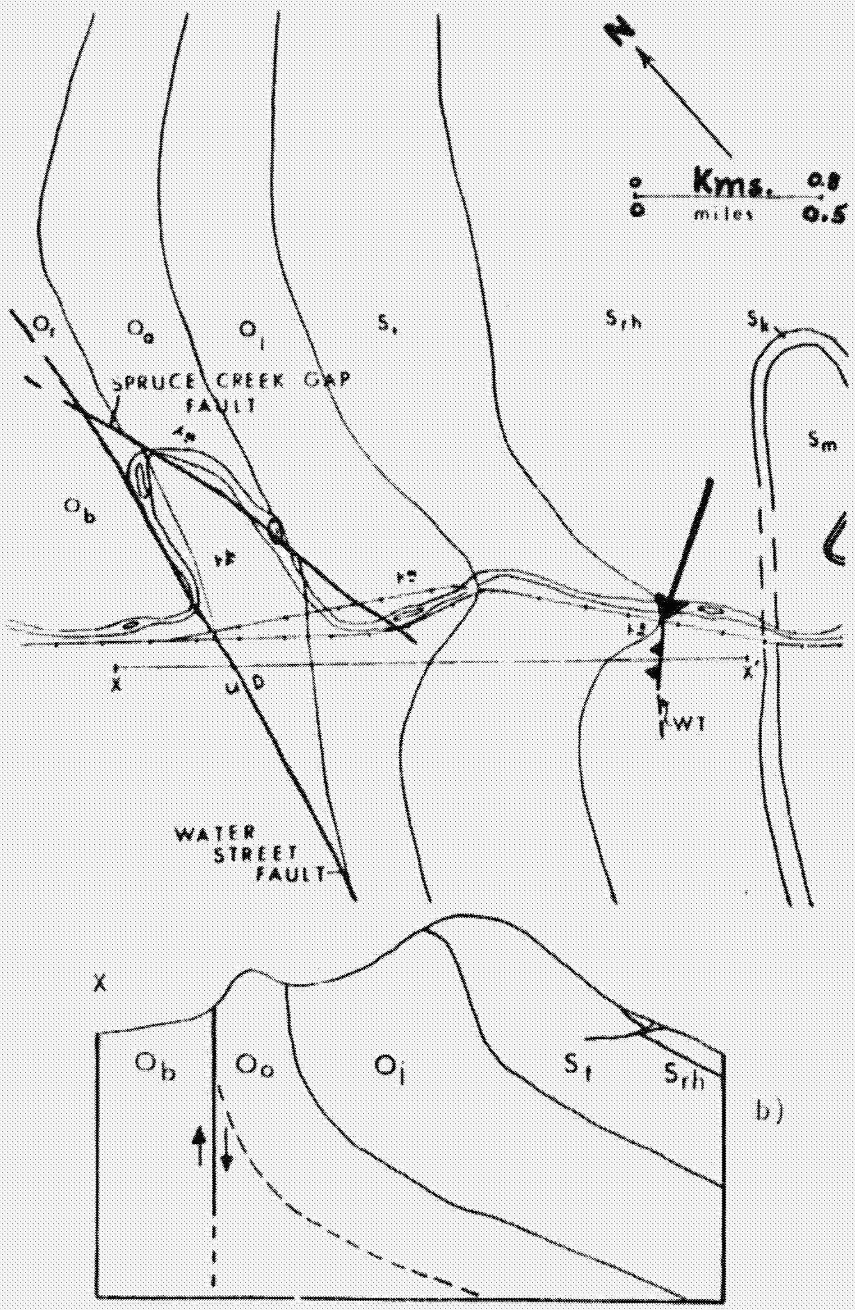
4. The area around Birmingham has long been recognized for its structural complexity (Butts et al. 1939, Fox 1950), with anomalous thinning in overturned beds of the Upper Ordovician and Lower Silurian formations in a local fenster called the Birmingham window. The Knarr window, 2.4 km (1.5 miles) to the northeast, exposes Ordovician rocks within Cambrian formations. Detailed mapping of the Birmingham window by Moebs and Hoy (1959), Schmiermund and Palmer (1973) and the author (see Plate 2) show the juxtaposition of overturned Reedsville, Oswego, Juniata, and Tuscarora beds against upright Black River-Chazy Group beds south of the river. Cross sections drawn by Moebs and Hoy (1959) from

drill core data, imply varying thickness or attitude of the Upper Ordovician Juniata and Reedsville units beneath the Sinking Valley fault, even though no mention was made of these variations in their text. The subsurface configuration shown here (Plate 3) is inferred from an analysis of the drill data presented by Mcebs and Hoy (1959) and from projections of the outcrop mapping done by the author. The "surprising difference in the beds exposed" (Fox 1950) and the absence elsewhere of any of the units present in the Birmingham window, even though equivalent and lower topography is developed on the southwest side of the river, suggests the presence of a ramp in the thrust plate coincident with the river. A fault of sufficient displacement to fit the observed geometry is inconsistent with the outcrop pattern of the Birmingham and Honest Hollow faults.

5. A thrust fault of undetermined displacement is exposed in the north wall of Warner's Main Quarry at Union Furnace, and is expressed as a fracture trace on aerial photographs (1:20,000). Its reverse sense of motion is compatible with the compressional regime in the core of the Scotch Valley syncline above the intrados surface.

6. The Water Street fault (Butts et al. 1939), a high angle fault with a downthrown east side, may be genetically associated with a fracture zone and anomalous bedding orientations along the Little Juniata River in Spruce Creek Gap (Fig. 16 and Plate 2). Farther east, a low angle thrust fault (marked WT in Fig. 16), gently inclined to the northwest, has a measured stratigraphic separation of 30 m (100 ft). The photographic inset in Fig. 16 shows rotated strata in a thrust slice between the main fault (lower) and an associated splay fault (upper). An increase in the dips of beds close to the Water Street fault suggests that the local thrust fault (WT) may have formed in response to flexures induced by movement on the Water Street fault (see cross section in Fig. 16).

The acute downstream junction of Spruce Creek with the Little Juniata River and the diversion of the iver around a spur of Oswego Sandstone are anomalous. High level gravels preserved on this spur above the railroad tunnel (Butts et al. 1939) indicate that the river in Spruce Creek Gap at one time followed a more linear course, subparallel to the Tyrone - Mount Union Lineament. The saddle 0.5 km (0.31 mile) east of the village of Spruce Creek (Plate 2), which is part of the Spruce Creek Gap, is at the same elevation as the gravel deposits on the opposite spur, and may represent the fossil course of the Spruce Creek. The abrupt change in the Little Juniata River course is probably a result of capture along the fossil Spruce Creek drainage, which is controlled by a fracture zone through the sandstone ridge (see the diagram in Fig. 16). Structural evidence for a fault in Spruce Creek Gap is seen (a) in the alignment of highly fractured rocks on the northern tip of the Oswego Spur, with disturbed beds exhibiting highly variable slip line orientations 150 m (500 ft) to the east of the Spruce Creek Gap railroad tunnel; (b) a slight offset in the projection of



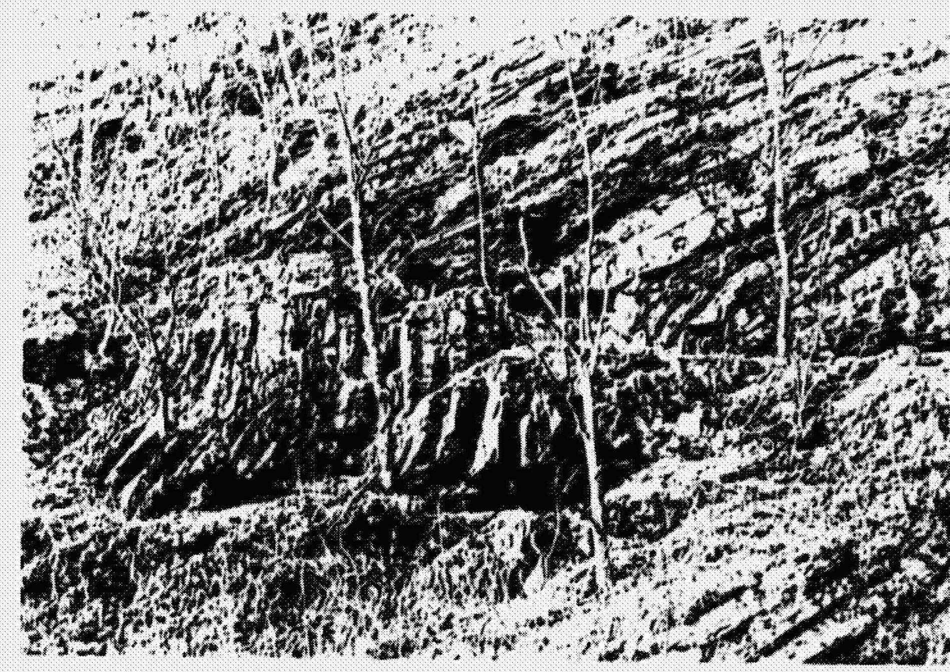


Figure 16. Geologic map and cross section of a low-angle, westerly dipping, thrust fault and the Water Street fault. The photograph shows rotated strata in a thrust slice between the main Water Street fault and an associated splay. (The site of the photo is shown by an arrow on the map --the view is southwest, across the railroad tracks. A key to the formation symbols may be found on Plate 2.)

geologic contacts across the river; and (c) a variation in bedding attitude in the Oswego Sandstone, from 70° to 85° SE on the spur to 15° to 25° S on the north side of the river. The author interprets these data to indicate that a fault, the Spruce Creek Gap fault (see Plate 2), intersects the Water Street fault near Spruce Creek and exerts structural control over the present diversion of the Little Juniata River.

Other manifestations of the Water Street fault may be seen in the steep dip of the Tuscarora beds exposed in the ganister quarry on Short Mountain, 1.1 km (0.7 mile) northeast of Water Street (Location 26). Elsewhere, along Short and Tussy Mountains these beds have a dip of 15° to 20° S. Drag flexures associated with eastside downward movement (Fig. 16b) on the fault plane would account for the anomalous dips in the vicinity of the fault.

7. Field follow-up studies on two fracture traces mapped on aerial photographs showed them to be underlain by highly jointed zones up to 45 m (150 ft) wide. The mesoscopic fractures in one of these zones, exposed in the railroad cut between Spruce Creek and Union Furnace (see Plate 2), are seen to dip approximately 60° SE. However, a vertical dip is implied by the essentially linear trace of this zone, which suggest an en echelon disposition of the inclined mesoscopic fractures in a vertical macroscopic fracture zone. The other fracture trace is located on the western limb of the Barree syncline, where the Keefer formation is offset by a fault with a vertical throw of approximately 6 m (20 feet). This fault zone is exposed only in an abandoned mine pit, and no fracture density studies were attempted.

8. A curve in the trace of Bald Eagle mountain (Fox 1950) is evident on the LANDSAT imagery as a sharply bounded segment from Tyrone Gap to south of the village of Bald Eagle. This salient may represent the movement of a small thrust plate bounded by tear zones (Gwinn 1964, Kowalik 1975), expressed as lineaments on the LANDSAT images. (The northernmost of these two lineaments is outside the study area, and therefore not plotted on Plate 1.) These boundaries are envisaged as diffused zones of structural decoupling, i.e., the domain boundary concept of Gold and Parizek (1976), rather than as discreet tear faults.

9. Landslides which developed during and after construction of the Route 220 Bypass near Tyrone appear to be related to lineaments. Two slumps flanking Tyrone Gap, and another 8 km (5 miles) to the north, near Bald Eagle, are on lineaments mapped by Krohn (1976) and Kowalik (1975). An increase in pore pressure along the lineament near Bald Eagle was monitored in a drill hole in the road bed during the spring of 1975. Local slumps occurred high in the road cut, and "quick" conditions developed near the base, disrupting the road bed for approximately 100 m (300 ft) and delaying the opening of this section of highway (Gold and Krohn, 1976). These observations support the concept that some lineaments and fracture traces are the surface expression of secondary structural zones of increased porosity and permeability (Parizek and Gold 1976).

10. A discordance of 15° in the strike of the Tuscarora and Oswego beds with the ridge crest trend of Brush and Bald Eagle mountains between Skelp Gap and Vail Gap (John Way and M. Dennis Krohn, pers. comm.) is largely accommodated by right lateral offsets of small displacement (Krohn 1976). Some larger faults with the same right lateral sense of displacement have been mapped (see Plate 2), e.g., the fault mapped by Butts et al. (1939) east of Vail. The reason for the pattern of small displacement faults in the competent beds is not known, but they appear to be more common in the vicinity of lineaments, particularly the Tyrone - Mount Union lineament.

11. The only outcrops of the Axemann Limestone in the study area are between Union Furnace and Spruce Creek, in the core of the Eden Hill School Anticline (Plate 2). The general absence of this unit in the southwestern portion of the Nittany Anticlinorium was attributed by Butts et al. (1939) to sedimentary processes (non-deposition or a facies change to dolomite).

Discussion

The Tyrone - Mount Union lineament is a cross-strike topographic feature that appears to be the locus of structural and topographic anomalies such as a high density of mesoscopic scale faults and fractures, truncation of tectonic windows, termination of folds, and juxtaposition of beds of contrasting attitude and thickness. Gold and Parizek (1976) suggested, from gravity and seismic data, that this lineament is underlain by a fracture zone that acts as a domain boundary, separating blocks of different strain (structural style) even though stresses in each may have been similar. Conceptually, this zone would act as a buffer, enabling folds of different magnitude and style to develop in neighboring blocks, or attenuating fold forms across from one block to another. For example, the Scotch Valley syncline extends at least 16 km (10 miles) south of its intersection with the Tyrone - Mount Union lineament, but it terminates just north of its intersection with the lineament, as does the Eden Hill School anticline. Many third- and fourth-order folds in the Silurian shales near Alexandria do not extend north of the southern branch of this lineament. The Shoenberger and Birmingham faults also appear to terminate in the vicinity of the lineament (see Plate 2). The former extends from Skelp Gap eastward for 6.5 km (4 miles) and dies out about 1.6 km (1.0 mile) north of the lineament, whereas the latter extends approximately 48 km (30 miles) to the north in Nittany Valley and terminates in Sinking Valley anticline 2.3 km (1.5 mile) south of the lineament.

Estimates of northwestward lateral shortening in the Appalachian fold belt during the Alleghenian orogeny range from 32 km (20 miles) by Chamberlain (1910) to 80 km (50 miles) by Gwinn (1970). Manifestations of the northwest transport direction are seen in the map area by (a) a northwest-southeast girdle of slickenlines in the synoptic orientation diagram (Fig. 12); (b) fold axes coincident with the pole of the slickenline girdle; (c) a strike of 110° to 140° for the slickenline plunges of most faults (Fig. 11); and (d) the northwest-southeast compression implied by the geometry of the Nittany Anticlinorium. Greater foreshortening north of the lineament than south of it is indicated by the pattern of the Water Street and Yellow Springs faults.

These faults extend individually for some distance to the south of the lineament. However, to the north they converge with a number of smaller faults, associated with another thrust and a high angle reverse fault shown in cross-section A-A' on Plate 3.

Other indicators of differential foreshortening are the salient in Bald Eagle mountain north of the Tyrone - Mount Union lineament and the Round Top and Leading Ridge anticlines south of the lineament and east of Tussey mountain. Additional folds in these second-order anticlines expose more Tuscarora ridges on the north side, and imply greater crustal foreshortening, than on the south side of the lineament. Much of the differential foreshortening on the north side may have been taken up in the Scotch Valley syncline to the southwest. The misalignment of structural features caused by differential foreshortening across part of the lineament has led to the domain boundary or strain boundary concept, a zone along which local foreshortened segments or displacements in the cover rocks compensate over a longer distance. This subvertical zone of superimposed structural discontinuities is interpreted as a decoupling zone to Alleghenian deformation as well as the locus of late deformations, such as small displacement right and left lateral strike-slip faults.

The formation of wedge faults and kink folds early in the deformation process has been noted by Cloos (1964) and Faill (1973). The curved fault surfaces and superimposed sets of slickenlines of mesoscopic wedge faults attest to their early formation. Such faults are particularly abundant in Silurian shales. Compressional slip motions are indicated by wedge faults, and by the bedding slip lines in the kink folds. The Sinking Valley, Birmingham, and Honest Hollow faults, and some kink bands which have a sense of rotation incompatible with their location on lower order folds and/or have anomalous plunges, are examples of structures formed early and geometrically altered as deformation continued.

Evidence for the additional motion of the crustal block north of the lineament was mentioned earlier. The mechanism causing this differential motion includes participation of the Birmingham fault in the formation of the Nittany Anticlinorium. The salient in Bald Eagle mountain could have been a result of the overriding thrust plate of the Birmingham fault, north of the lineament, moving farther to the northwest than in the adjacent areas due to basement "uncoupling."

Another possible model (see Fig. 4, after Kowalik 1975) involves a ramp in the Sinking Valley fault with differential movement of thrust plates. This model is preferred because a ramp in the Sinking Valley fault is implied by the stratigraphic offset and structural anomalies present in the Birmingham window area. This differential motion was followed by continued folding, evident in the present geometry of the Nittany Anticlinorium. The late formation of the high angle and/or westerly dipping faults is indicated by the apparent truncation of the Birmingham fault by the Shoenberger fault in the Sinking Valley anticline.

It is concluded that the Tyrone - Mount Union lineament originated not later than late Paleozoic time, and the presence of a dominant pervasive joint set parallel to it infers a continuation of influence of the lineament until at least the termination of the Alleghenian orogeny. The 130° joint orientation (parallel to the lineament) was noted in each outcrop, with joints ranging in number from one or two to many per outcrop (sufficient to apply a quality of "subordinate" to it), regardless of the orientation of the rotation axis (strike of beds). Therefore, in the areas where the strike of the beds is presently neither parallel nor perpendicular to 130°, vertical joints, particularly those oriented at 130°, must be superimposed after folding (i.e., in the post-Alleghenian orogeny) because it is unlikely that this unique geometry would be preserved through folding rotations. Post-tectonic joints may be very young, and may even be forming today as a result of earth tides (Blanchet 1957, Gold et al. 1973) causing various size blocks, determined by the location of lineaments, to react with a slightly different amount of vertical motion. Such diurnal motions might activate fractures in fossil fracture zones (dormant lineaments) and thus enhance degradation processes and topographic expression of lineaments relative to other structures in the area.

Although the morphological expression of the Tyrone - Mount Union lineament is confined to a narrow belt between 0.5 to 2 km (0.35 to 1.2 miles) wide, its structural manifestations may be more extensive. However, its limits cannot be determined unambiguously from the data currently available. Not only do the two segments of the lineament overlap <u>en echelon</u> between Alexandria and Barree, but the short lineaments and fracture traces (Plate 1), which occur throughout the area, influence the local joint density. In addition, some segments bounded by fracture zones within the major lineament are essentially free of deformation effects. It can be seen, therefore that the size of the sample area is important. It is apparent from the data and these discussions that the nature of the surficial bedrock character of this lineament is difficult to establish for three major reasons: 1) the lack of continuous exposure across the lineament; 2) the size of the feature; and 3) a lack of experience with similar features.

The key question, and an even more difficult problem on which to gather data, is the subsurface nature and extent of the lineament. However, localization of base metals and geophysical data permit some inferences regarding its nature at depth. The location of five base metal sulfide occurrences and one formerly productive lead-zinc mine (the Keystone Mine near Birmingham, circa 1795) (Smith et al. 1971) along the Tyrone - Mount Union lineament, suggests the migration of ore fluids in a zone of increased porosity and permeability. The Bouguer anomaly gravity map of Pennsylvania, compiled by Peter M. Lavin (pers. comm., 1976) shows a truncation of the regional anomalies coinciding with the Tyrone - Mount Union lineament. A steep gradient near and perpendicular to the lineament implies an involvement of basement rocks in its location and expression. Disturbed contour patterns in the aeromagnetic maps are interpreted to represent changes in the basement topography coincident with the Tyrone - Mount Union lineament. A structural link from the basement structure through the Paleozoic cover rocks to the surface is suggested by the attenuation of seismic waves (Alexander and Abriel 1976) across this zone, and by evidence that the lineament is the locus of current microseismic activity (Shelton S. Alexander, pers. comm., 1976).

Summary and Conclusions

Field data combined with investigation of the geologic map (Plate 2), supports the domain boundary hypothesis for the Tyrone - Mount Union lineament. Stratigraphic offsets and structural anomalies exist along the lineament and the author feels these are genetically linked to an underlying fracture zone. Thus, the lineament is thought to represent the surface expression of basement fractures modified in various ways through the stratigraphic column and through time.

A model of the lineament requires that it (a) be a zone of fractures but not a fault, (b) be controlled by a feature in Precambrian rocks of the "basement" beneath 3000 to 4000 m (10,000 to 13,000 ft) of sediments, and (c) be currently active (at least seismically). This model is consistent with constraints on other lineaments mapped in Pennsylvania which transgress the metamorphosed Precambrian and Paleozoic rocks of the Piedmont, Mesozoic sediments in the Triassic Basin, Paleozoic strata in the Appalachian fold belt, and recent sediments of the Coastal Plain (Gold et al. 1973). The model accommodates a fracture zone through the Nittany Anticlinorium that locally influenced the "Valley and Ridge" deformation during the Alleghenian orogeny (Root 1974). The sequence of events during late Paleozoic Alleghenian deformation is envisaged as (a) initial compression and lateral shortening in a northwesterly direction with the development of wedge faults and kink folds, followed by (b) the main episode of folding and thrusting and development or reactivation of a decoupling zone with local differential displacement, and (c) contemporaneous development of high angle faults with downthrown east sides along with low angle westerly-dipping thrust faults during the late folding stage, and, finally, (d) development of late strike-slip faults of small displacement in the lineament fracture zone.

The observations discussed here lead to the following conclusions:

1. The dominant joints in the region (130° and 045°) are related geometrically to the Tyrone - Mount Union lineament.

2. There is a general increase in fracture density as one approaches the lineament.

3. The joint density is influenced by lithology and bedding thickness, and by proximity to fracture traces.

4. The σ_1 - σ_2 plane trends approximately 320° and has been constant throughout the Alleghenian orogeny.

5. The Tyrone - Mount Union lineament is linked to a basement fracture, acted as a domain boundary during the Alleghenian orogeny, and may still be a slightly active stress relief zone.

GEOMETRIC RELATIONSHIP OF LINEAMENTS, FRACTURE TRACES, AND JOINT TRACES

From a field study of joints, from fracture trace mapping on low altitude aerial photographs using stereoscopic photogeologic techniques (Lattman 1958), and from lineament mapping on enlargements of LANDSAT images in both normal and edge-enhanced modes, orientation data on three different scales were collected for linear phenomena assumed to be associated with fractures. In the portion of the study described here the dominant orientations of these features of different size were compared for possible geometric relationships which could have genetic significance in fracture theories. Some of these data were in a form that permitted additional comparisons, e.g., the orientation and frequency of features of similar length (short lineaments and fracture traces) mapped on bases developed from different sensing systems, and the distribution of lineaments by size and direction. These results were compared with those from other sites in eastern United States, to test for regional pervasiveness and consistency in orientation.

Results and Discussion

The attitude and density of joints were recorded as part of the field work for a structural study of the Tyrone - Mount Union lineament. Orientation diagrams summarizing the results from 38 sites are plotted on Plate 2, and the strike directions were compiled into a composite histogram (Fig. 17) for comparison with the two-dimensional orientation data on fracture traces and lineaments. There are three peaks, at 315°, 045°, and 065°, in the joint-strike histogram, with a maximum at 315°. It is apparent from the position of concentration of joint poles in Fig. 10, that the 065° peak is actually part of the 045° peak, and is the result of degrading the combined strike and dip data to strike alone. Accordingly, the 045° strike direction is used in the discussion here.

In Fig. 17, the peaks for the strike of joints and photo-lineaments coincide at 315° and 045°, whereas the strike of fracture traces differ, with the main peak at 270° and a minor peak at 352°. The minor peaks at 284° and 356° in the photo-lineament strikes coincide, respectively, with the scan line direction and a low amplitude swell in the fracture trace strikes. The former is discounted as an artifact introduced by the scanning system, and the latter is attributed to subtle lineament expressions that might prove to be more numerous if more time were allotted in the lineament mapping procedure.

The results for the second stage mapping of linear features on LANDSAT imagery are shown by length and azimuth in Fig. 18. The two longer lineaments occur around 310°, the lineament maximum in Fig. 17. The clustering of the shorter lineaments around 270° and 340° nearly matches the peaks for fracture traces, suggesting that these subtly expressed short lineaments on the LANDSAT imagery overlap with the fracture traces discernable on the low altitude aerial photographs.

If the above arguments are valid, the parallelism of joint traces and lineaments at 315° and 045° and the symmetrical disposition of the fracture trace peaks at 270° and 352° should have geometric significance. The dominant orientations of lineaments, fracture traces, and joint traces from other eastern

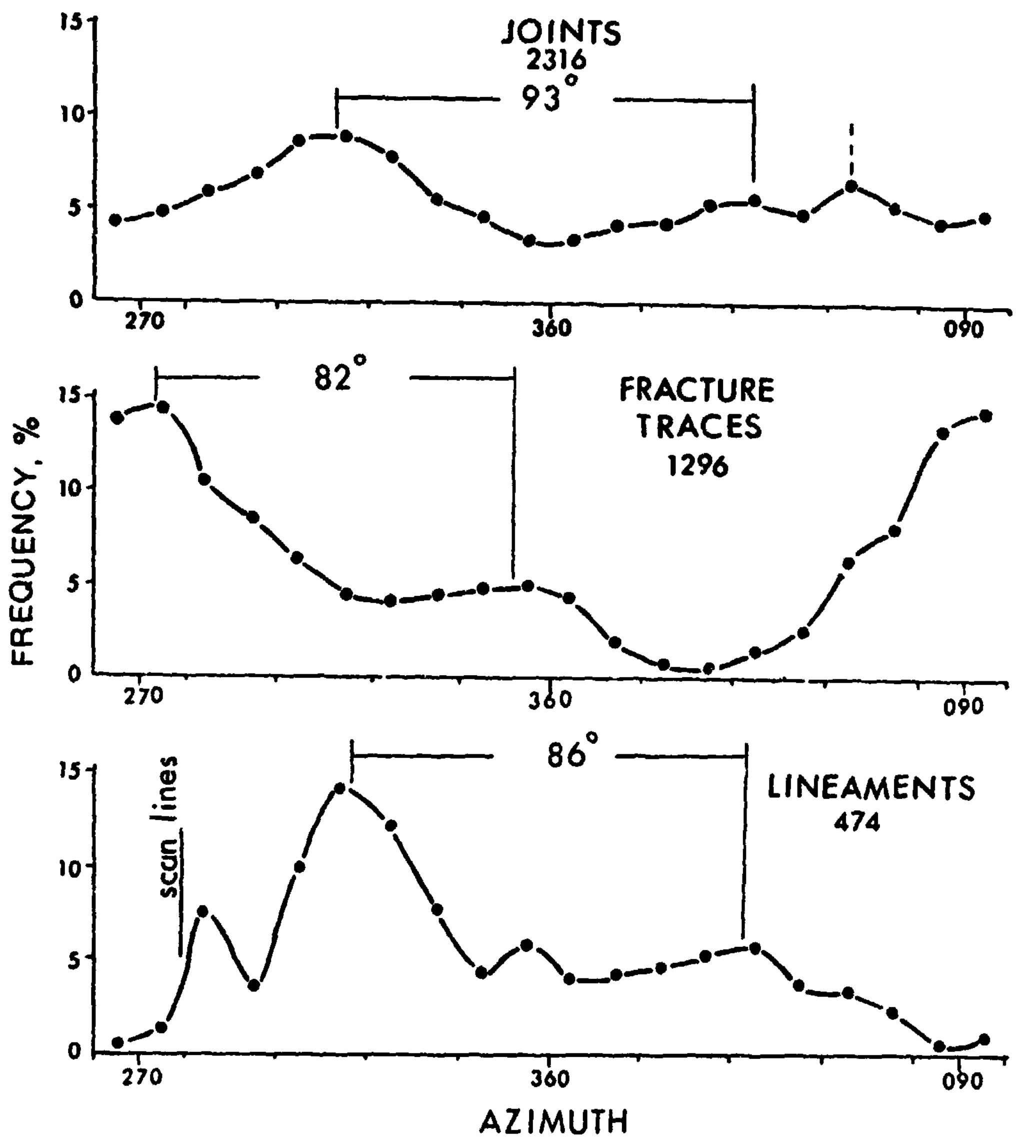


Figure 17. Smooth-curve cartesian histograms of joint trace, fracture trace, and lineament orientations, showing frequency per 10° azimuth class. (Data not averaged.)

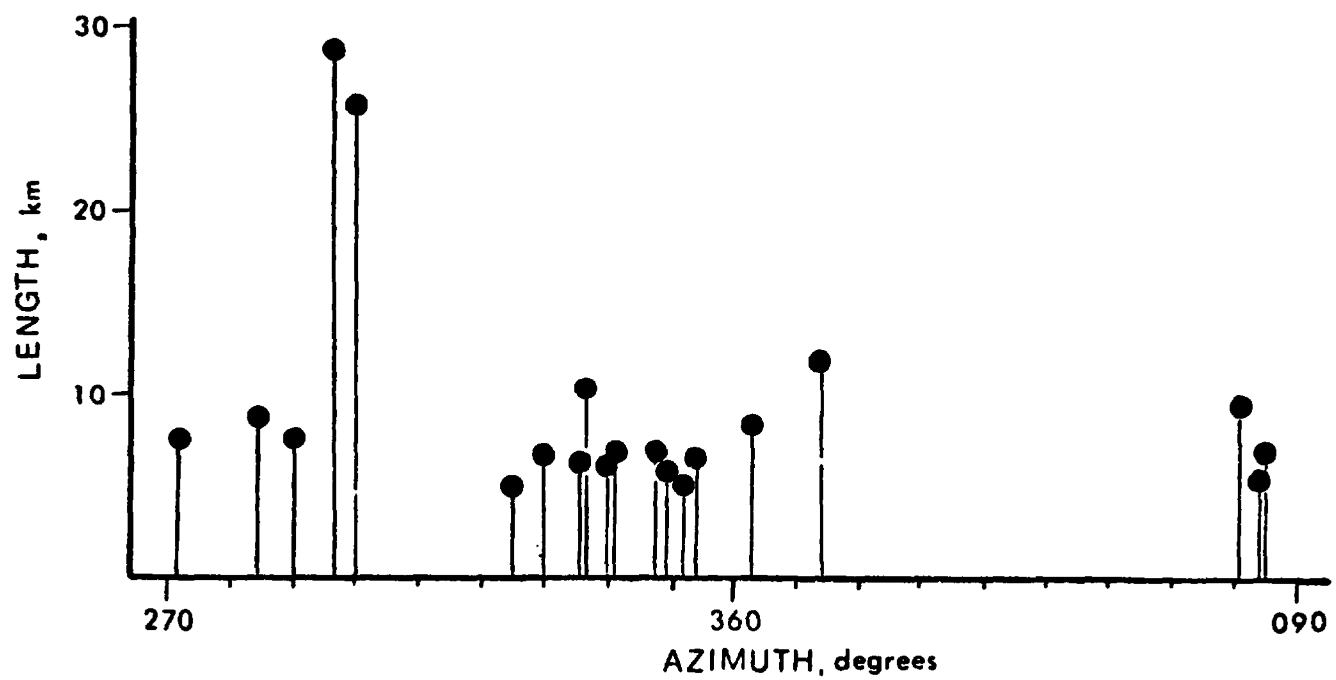


Figure 18. Histogram showing natural grouping of 20 photo-lineaments with respect to length, mapped on a LANDSAT-1 image.

United States sites are summarized in Table 6. Some of these data were gleaned from a secondary source (Gay, 1973) where they were presented in histogram form. Although the linear features reported by Powell et al. (1970) were mapped on photographs taken by the Apollo 9 crew, they are included as "fracture traces" because the authors state that the east-west trending linears were the "shortest" and those trending north-south were "moderately long to relatively short," without defining the terms. An estimated scale of these latter features would classify them in the 2-5 km range. Some workers (Powell et al. 1970, Kowalik and Gold 1976) have applied filters in the direction of the dominant fold trend and bedding strike, which suppressed or eliminated the 046° photo-linear orientation from their data. Except for the joint orientations measured by Sonderegger (1970) there is remarkable consistency in the general orientation of all categories of features over a wide area.

The similarity in orientation and a 45° angular relationship between fracture traces and joint traces in the State College area (Matzke 1961) and Tyrone area (discussed earlier) apparently does not hold across the Allegheny Front into the Allegheny Plateau terrain, where the data of Lattman and Nickelsen (1958) and Nickelsen and Hough (1967) indicated a slight rotation of joint directions and a subparallel relationship between the joints and fracture traces. Kowalik (1975) found a 10° to 20° difference in orientation between long (315°-325°) and short (325°-335°) lineaments mapped in the Allegheny Plateau, but it is not certain if the latter would qualify as fracture traces. The dominant direction of fracture traces reported by Matzke (1961) coincides with the minor direction reported here, and vice versa. This difference may be due to operator and flight line biases, introduced when more than one flight line is used. More likely, it could be due to a preferred orientation of fracture traces near a major lineament. The nearly orthogonal disposition of each category, except the joint orientations of Sonderegger (1970), support the pervasive orthogonal fracture theory (Gay 1973).

A possible geometric configuration for the three categories of linear features mapped in the Tyrone - Alexandria area is shown in Fig. 19. This implies a heirarchial relationship between lineaments, fracture traces, and joint traces. It also implies that joint zones would give expression to fracture traces and that concentrations of these would be expressed as lineaments. Although the distribution of short lineaments and fracture traces is fairly uniform in this region (see Plate 1), there tends to be a concentration, particularly of 140° short lineaments, on the major lineament. This distribution and the increase in joint density close to the lineament is in keeping with the concept for the pervasive development of fractures at discrete scales at an interval of approximately 0.4 time their length (Gold et al. 1973). If this concept is valid for this region, the map area should cover the secondary features associated with the Tyrone - Mount Union lineament. This supposition could be tested by mapping the distribution of short lineaments and fracture traces in an area in Nittany Valley not located on or near a major lineament.

Deformation Model

Of all the known theories of failure, only the second-order shear theory developed by McKinstry (1953) accommodates a hierarchial size and distribution of fractures. This theory was modified and applied to major strike-slip faults in a classical paper by Moody and Hill (1956). The theory requires that the

Table 6. Dominant Directions of Lineaments, Fracture Traces, and Joint Traces in Eastern United States

Location	Lineaments			Fracture Traces			Joint Traces		Reference
Tyrone-Alexandria, PA	315	055	L[a]	355 356	093 104	CAP L	312	045	Canich (this study)
State College area, PA				000	090	CAP	320	060	Matzke 1961
Allegheny Plateau, central PA							325	070	Lattman and Nickelsen 1958
Allegheny Plateau, central PA	315-325 325-335		L S						Kowalik 1975
Mississippi embayment	321	049[b]	M						Fisk 1947
Florida	312	048[b]	M						Vernon 1951
Northern Alabama	319	056[b]	M				100-120 150-170		Sonderegger 1970
Alabama	326	046[b]	A	358	092[b]	CAP			Powell et al. 1970
Shanandoah Valley, VA				355	089[b]	CAP			Trainer and Ellison 1967

[a]The mapping base is indicated by the following letters:
- A - Apollo 9 photographs
- L - LANDSAT-1 MSS images
- M - Mosaic of low-altitude aerial photographs
- S - SKYLAB photographs
- CAP - Conventional aerial photographs

[b]These data were recast in histogram form by Gay (1973).

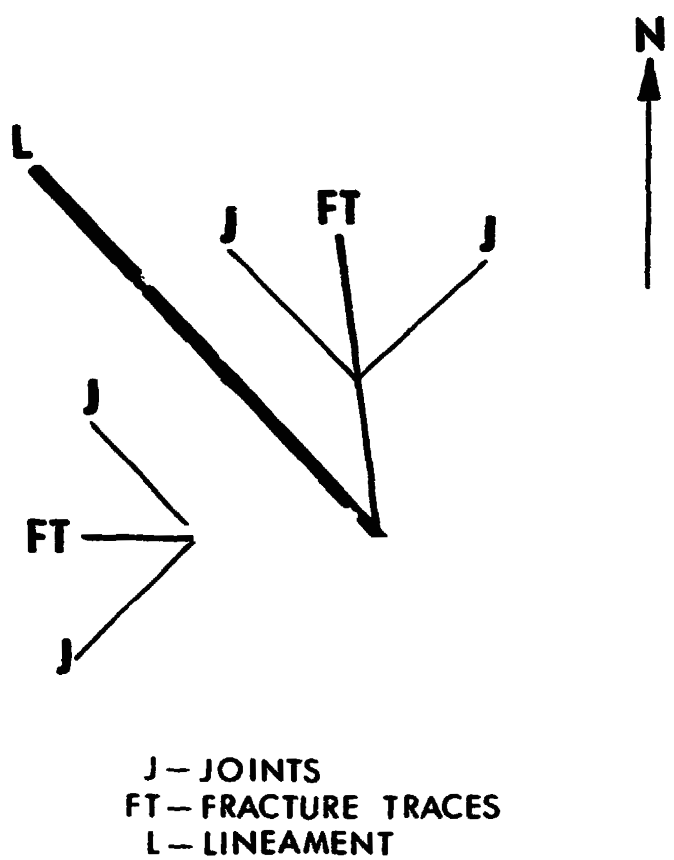


Figure 19. Possible geometric relationship between lineaments, fracture traces, and joints in the Tyrone - Alexandria area of central Pennsylvania.

normal stress across a first-order shear plane be sufficient to create its own set of conjugate fractures in the shear mode, i.e., the second-order shear. Likewise, the normal stress across the second-order shear planes might induce even more third-order shear fractures, and possibly continue to higher orders if the stress at this level is sufficient to overcome the strength of the rocks. The number of potential fractures in successively higher orders in an isotropic medium would increase by 2^{2n-1}, where n is the order number. This has been shown by Gold et al. (1973), who also showed that the angular relationship between conjugate sets would be 60° and that alternate order shear sets would have common directional elements.

Although lineaments, fracture traces, and joint traces fit the hierarchical and frequency schemes of the second-order shear theory, the nearly orthogonal patterns and the lack of strike-slip displacements on the features are anomalous. Moody and Hill (1956) note that a maximum of 90° between conjugate shear planes is possible theoretically, but that a 60° angle is more typical. In the absence of pre-existing planes of weakness to influence fracture development, the angle between the maximum principal stress axis and the shear plane should be 45° - $\theta/2$, where θ is a property of the material, termed the "angle of internal friction." Clearly the smaller the value of θ, the greater the angle between the resulting shear planes. In natural situations these angles vary from 40° to 90° (De Sitter 1956).

Perhaps the orthogonal fracture pattern is the imprint of a relict basement fracture pattern propogated through cover rocks by oscillating vertical motions resulting from gravitational forces. If so, the condition of the early crust could possibly have been one of low "internal friction," providing a nearly orthogonal second-order shear pattern. Such a scheme would account for the lack of strike separations on the features. However, this lack could also be accounted for by frictional forces greater than the shearing stress, particularly at high confining pressures, generating a set of "locked" fractures (Bombolakis 1976). The initial low internal friction model calls for superimposed events, a condition demanded by the transgression of some lineaments across tectonic province boundaries and their persistence in rocks from Precambrian to Recent (Gold et al. 1974). The inclined and parallel disposition of higher order fractures (macroscopic fracture traces and mesoscopic joints and faults) within the lineament zone are typical of a locked or aborted shear zone (Gramberg 1965, 1966). Perhaps each condition prevailed at a different time, in response to different crustal stress regimes.

Regardless of the correctness of our understanding of these features, their patterns are consistent and too well established on a world-wide basis to be disregarded. If the conceptual characterization of lineaments and fracture traces as zones of fracture concentration is incorrect, then the geometric relationships in scale would be fortuitous. Perhaps some of these questions could be resolved by additional study in an area where the patterns appear to be anomalous. By piecing together a number of independent studies (Lattman and Nickelsen 1958, Nickelsen and Hough 1967, and Kowalik 1975) a composite pattern of subparallel lineaments, fracture traces, and joint traces is apparent for the relatively flat-lying rocks of the Allegheny Plateau. If this relationship is not an artifact of data collection, then the cause of the variation in patterns across the Allegheny Front from the Valley and Ridge province to the Allegheny Plateau structural province could supply clues to their origin.

Conclusions

Some of the tentative conclusions from this study of the geometric relationship of linear features follow:

1. Linear features in the Tyrone - Alexandria area exhibit nearly orthogonal and bimodal orientation concentrations at each scale.

2. Both dominant joint traces and lineaments trend approximately in the directions of 315° and 045°, whereas fracture trace trends peak at 270° and 352°.

3. Linear features have a discrete (stepped) rather than a continuous length distribution.

4. The frequency and spatial distribution of linear features of different scale can be accommodated in a second-order shear theory, provided special conditions for non-displacive fracturing and near orthogonality of the conjugate fracture directions are invoked.

5. The remarkable regional consistency in the trends of linear features at different scales, suggests a uniform regional stress regime over a large portion of the eastern United States.

6. A test area should be established in the Allegheny Plateau to study an apparently anomalous pattern of linear features.

SUMMARY AND CONCLUSIONS

The objectives of this study were to investigate the nature of a major lineament, characterize the geological features associated with it, and attempt to establish criteria, other than morphological, that might give a three-dimensional meaning to similar linear features. In order to help solve the problem of applying the results of mesoscopic scale deformation experiments to a feature more than 150 km (90 miles) long and 1 to 3 km (0.6 to 2 miles) wide, mapping was undertaken at three different scales. Because of the paucity of similar studies, a normal background situation has not been established and the distribution, lengths, and orientations of the linear features mapped cannot be adequately compared for uniqueness. Perhaps expanding the map area to include terrane such as Nittany Valley, to the north and removed from the influence of the Tyrone - Mount Union lineament, would help establish the necessary background parameters and provide a better base for new interpretations of the surface geology (Hunter and Parizek 1976).

This study has shown that with five months of field work and a geological base map of the detail published by Butts et al. (1939) subtle variations in fold axes, fold form, and stratigraphic thickness can be delineated. Many of the conclusions are based on extrapolation in similitude to different scales. They must, therefore, be considered as tentative, pending additional field work to develop regional background parameters. Moreover, the megascopic scale of the Tyrone - Mount Union lineament necessitates the development of concepts in the synthesis of the mesoscopic observations, and these concepts may not be ameanable to testing by experiment.

A conceptual model has been derived for the Tyrone - Mount Union lineament. In this model, the lineament is the morphological expression of a zone of fracture concentrations which penetrates basement rocks and may have acted as a curtain to regional stresses or as a domain boundary between uncoupled adjacent crustal blocks. This model is supported by:

1) the transgressive nature of the Little Juniata River across anticlinal structures and resistant beds, in a terrain of interbedded sedimentary rocks of markedly different erosional competency;

2) the coincidence with displacements in the Bouguer gravity anomaly map and with deep-seated magnetic intensity patterns;

3) the coincidence with the locus of microseismic earthquakes;

4) the coincidence with the locus of base metal sulfide occurrences;

5) the termination of third- and fourth-order folds and faults near the lineament;

6) changes not only in bedding attitude, but also locally in thickness across the lineament;

7) the ramping or termination of a thrust plate locally along the lineament;

8) the increased density of mesoscopic faults and joints in the lineament;

9) the similar preferred orientations of joint traces and lineaments, with the dominant trend at 315° and the subsidiary trend at 045°, and the symmetrical clustering of fracture traces about the dominant lineament trend at 270° and 352°;

10) the fact that more linear features can be mapped on edge-enhanced images than on standard images in equivalent time;

11) the mapping of linear features, on both "enhanced" and "unenhanced" LANDSAT images, which could be characterized on the ground as valley segments, sag alignments, and growth anomalies in the vegetation;

12) the characterization of some fracture traces in road cuts as the surface expression of narrow zones of increased fracture density;

13) the fact that the frequency and spatial distribution of linear features of different scales can be accommodated in a second-order shear model, provided some special conditions for fracturing without displacement and the near orthogonality of the conjugate fracture directions are invoked; and

14) the remarkable regional consistency in the trend of linear features of different scales, suggesting the possibility of a uniform regional stress regime over a large portion of the eastern United States.

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