Paper G 2

ANALYSIS AND APPLICATION OF ERTS-1 DATA FOR REGIONAL GEOLOGICAL MAPPING

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ABSTRACT

Combined visual and digital techniques of analysing ERTS-I data for geologic information have been tried on selected areas in Pennsylvania. The major physiographic and structural provinces show up well. Supervised mapping, i.e. following the imaged expression of known geologic features on ERTS band 5 enlargements (1:250,000) of parts of eastern Pennsylvania, delimited the Diabase Sills and the Precambrian rocks of the Reading Prong with remarkable accuracy.

From unsupervised mapping, transgressive linear features are apparent in unexpected density, and exhibit strong control over river valley and stream channel directions. They are unaffected by bedrock type, age, or primary structural boundaries, which suggests they are either rejuvenated basement "joint" directions on different scales, or they are a recently impressed structure possibly associated with a drifting North American plate. With ground mapping and underflight data, 6 scales of linear features have been recognized, viz., joints (10's of feet), fracture traces (several 100's feet to 1 mile), short lineaments (1 to 5 miles), intermediate lineaments (5 to 50 miles), long lineaments (>50 miles) and megalineaments (several 100's of miles). Their numbers decrease with increase length, suggesting they are related in mechanism through 1st, 2nd, 3rd and possibly higher order shears. The smaller linear features are important economically in terms of foundation engineering projects, ground water exploitation, mining, tunneling, etc., while the larger lineaments appear to exert some control over the emplacement of some base metal deposits.

1 INTRODUCTION

Although the association of scale to structural elements and geologic features is implicit in the detailed, regional, or compiled geologic maps, and in the division of some disciplines (Structural Geology versus Tectonics) only in Structural Analysis is there a conscious interplay between scales of the fabric or structural elements characteristic of each scale (Turner and Weiss, 1963). Apart from the direct measurements and observations made in man-size scale (mesoscopic), most of the data gathered on other scales is sensed remotely and integrated into a composite or mosaic for viewing in the mesoscopic scale.

Painstaking synthesis or the integration of data on one scale to provide information on the next smaller scale over many years has provided our regional,State, National, and Global maps. However, the synthesis of features on one scale does not guarantee that a larger feature will necessarily be apparent on the smaller scale map generated, because of artifacts in mosaicing, poorly known scaling laws, and the inconsistent conditions (variable sun angle, albedo, seasons, etc), of data collection, are more likely to obscure than enhance subtle features. Hence the value of the ERTS imagery.

Unfortunately, most remote sensed data are surficial in nature, and the features displayed are but the trace on the surface exposed of 3-dimensional structural elements. Interpretation and correlation of subsurface features and parameters requires a background knowledge of the geometry and nature of the parameter sought. Proving utility and production from a remotely sensed class of feature may take years of detailed "ground truth" data gathering by drill holes, geophysical probes, and pumping tests (Parizek, 1971a).

2. OBJECTIVES

Although our goals are broader based we have concentrated on (a) testing the utility of Regional Geological Mapping by studying a few well known areas in detail, and (b) in classifying the linear transgressive features apparent on all scales of overflight imagery. We feel that the latter study will have the best and quickest economic pay-off (hydrogeology, engineering geology, ore deposits) because we have considerable ground data for establishing correlations, and because there is a theoretical base for possibly linking linear features through scale (McKinstry, 1953; Moody and Hill, 1956; Price, 1966).

3. METHODOLOGY

The methodology, is continually developing as we gain experience in interpreting the imagery and learn to recognize the real signals. The criteria used in mapping like areas (visual similarity in tone, spatial patterns, or texture) are classified according to whether they represent a direct or indirect manifestation of the bedrock condition. In forested areas such as in Pennsylvania a knowledge of the indirect indicators is important for geologic interpretations even though their relationship to the bedrock conditions may not be understood.

The main parameters (criteria) used are:

(a) Boundaries or interfaces that seperate areas of different tone, texture, or pattern. Whereas irregular boundaries generally result from differences in land use (arable land versus forests), smooth and regular boundaries commonly reflect geologic control, expecially where layered rocks are involved. Combinations of these two habits, e.g., forest cover over untillable rocky areas, enhance the contrast and the interpretability if the correlation can be made and the cause identified from the ground truth data. The diabase sills in eastern Pennsylvania show up best on band 5 because of their overlaying forest cover in contrast with the surrounding cultivated fields.

(b) Linear transgressive features (lineaments) that shows as a narrow band contrasting in tone, topography, or displacing areas of like tone or pattern. These are generally long features (5 to several hundred miles) and some morphologically represent the alignment of wind and water gaps: others represent the surface expression of dikes, faults, zones of fracture concentrations, etc., without any apparent displacement.

The main stages in analysing ERTS data are:

(a) Primary correlation with the available ground truth geologic boundaries on 1:1X10^6 scale and enlargements (1:250,000) of ERTS imagery using combinations of channels.

(b) Mapping and classification of anomalous features.

(c) Computerized mapping of selected areas using cluster analysis on digital data, with the parameters controlled (supervised) from training areas.

(d) Unsupervised computer mapping, to bring out any latent features that might have geologic significance.

4. RESULTS OF MAPPING PRIMARY STRUCTURES

Although the necessary programs have been developed for stages (c) and (d), we have not yet progressed beyond the basic correlations and classifications. The contacts of some lithologic boundaries in eastern Pennsylvania, e.g., the Conestoga Formation, the Diabase Sills, and the Precambrian inliers of the Reading Prong, can be placed, using band 5 imagery at a scale of 1;250,000 with an accuracy of 400m(1/4 mile) with respect to the Geological Map of Pennsylvania(Figure 1). Much of this error may be in transferring boundaries from the ERTS imagery to the base map.

The physiographic provinces in Pennsylvania show up well, particularly the "Folded Appalachian Belt" in bands 5 and 7. However, little new geology can be added to the existing geological maps, but the remarkable correlation between the imaged and the ground truth boundaries demonstrates the feasibility of locating geologic contacts in unmapped areas. An example of the combined use of tone, boundary shape, vegetal cover, and characteristic spectral response is in the mapping of the diabase sills and flows in eastern Pennsylvania (Fig. 1). Some of the ore deposits associated with the diabase are aligned along a possible transgressive linear zone that is not apparent on the images.

5. LINEAR FEATURES (see Figure 2a, b, c, and d).

Introduction

Perhaps the most encouraging and unexpected features on the ERTS imagery are the number, distribution and patterns of unspecified linear features. Geologists have long recognized the presence of straight to slightly curved linear features on the earth's surface. These vary in size from 10's to 100's of feet for the systematic and non-systematic joints to "lineations" 10's of miles long that commonly had no obvious field expression and were visible on aerial airphoto mosaics. To distinguish among features recognizable on aerial photographs, Lattman (1958) defined a "fracture trace" as a "natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs, and expressed continuously for less than one mile". Those greater than one mile he termed "lineaments". Wise (1968) termed these regional and sub-continental sized fracture systems "linears", and noted their independence of regional structure. A considerable amount of work has been done with joint traces, and joint orientation studies in the field, and more recently (since 1957) with fracture traces. Including ground based and aircraft overflight data we now recognize at least 6 scales of linear features, and while there is a link between joints and fracture traces, theory suggests (McKinstry, 1953; Badgley, 1965; Moody and Hill, 1956; Price, 1966) that the same mechanism may link all scales.

Recognition and Characteristics

In addition to the criteria listed above, fracture traces may be revealed by straight valley segments, abrupt changes in valley alignment, gaps in ridges, gulley development, aligned sink holes and swallow holes, localized springs and diffuse seepage areas, localized vegetational differences, etc.,(Fig. 2a, 2b),(Parizek, 1971a and b). Fracture traces and lineaments are commonly straight, unaffected by topography, and hence are considered surface manifestations of vertical to near-vertical zones of fracture concentration (Mollard, 1957a and 1957b; Hough, 1960; Lattman and Parizek, 1964; Parizek and Voight, 1970, Parizek 1971a and 1971b). In carbonate terranes, surface sags and depressions 2-10 ft. deep may develop along fracture traces or open sinkholes 10 to 50 ft. deep may occur. The width of these depression appears to vary with the thickness of weathered mantle above bedrock and the width of the zone of fracture concentration. Calkins (1966) found that fracture traces in granite represent linear depression 2-8 ft. deep and 15 to 200 ft. wide. Parizek (1971b) has measured zones from 10 to over 100 ft. wide in various rock types in the United States, and locally in Pennsylvania, has found zones 20 to 40 ft. wide in folded and faulted carbonate rocks. In silt-stones and shales of northeastern Pennsylvania they varied from 15 to over 60 ft. wide, and average 39 ft. There, zones of fracture concentration maybe inclined only 2 tp 3 degrees from vertical (Parizek, 1971a). Individual joints may be closely spaced, 5 to over 60 in number, sub parallel to parallel, and cut all beds equally well, or be concentrated in selected bedrock units without vertical continuity.

Relationship to Structure

Parallelism has been recognized between fracture traces orientation and joints in relatively undeformed bedrock of Pennsylvanian age of the Appalachian Plateau (Lattman and Nickelson, 1958) and flat-lying rocks elsewhere (Hough, 1960; Boyer and McQueen, 1964). In folded rocks fracture traces and joints have been found to have different trends (Lattman and Matzke, 1961; Keim, 1961). These authors found that joint sets are parallel and perpendicular to the strike of bedding in Nittany Valley, and that fracture traces are unrelated to local fold and fault structures. Dominant trends of fracture traces and joints differ; fracture traces appear to be unaffected by tight folds and tend to lie at a constant (52°) angle to regional structure in Central Pennsylvania. (Fig. 2b). This work, together with that of Calkins (1966) and Lattman and Segovia (1961), supports the conclusion that fracture traces are not controlled by local structure but rather by regional features.

Application to Hyrogeologic and Engineering Studies

Lattman and Parizek (1964) established the important relationship between the occurence of ground water and fracture traces for carbonate aquifers, and in particular that fracture traces are underlain by zones of localized weathering, increased permeabilityand porosity, Highly productive wells used in their study were intentionally located by Parizek on one fracture trace or at fracture-trace intersections; the low producing wells more commonly proved to be off fractures traces. Siddiqui (1969), Siddiqui and Parizek (1969, 1971a, and 1971b) further demonstrated that fracture traces are the surface expression of zones of increased permeability and porosity. Moreover fracture zones form an interlaced network in most terranes (Fig.2b) serve as local ground-water feeder routes from more massive blocks of rock in inter-fracture areas; and supply water to regional conduits, which inturn may be localized by these same features.

Incorrect location of fracture traces probably accounts for the lack of correlation between well yields and fractures traces (Meisler, 1963) for carbonate rocks in the Lebanon Valley, near Harrisburg (Parizek, 1971b). Favorable relationships between well yields and fracture traces have been reported from as far afield as Sao Paulo, Brazil (Setzer, 1966). Wobber (1967) suggested that fracture traces may be useful in locating zones of increased permeability in bedrock in Illnois, overlain by glacial drift. He found an association between fracture trace orientations, and that of bedrock joints buried by up to 150 ft. of drift.

Parizek and Voight (1970) showed that fracture traces could be used in geotechnical investigations to predict zones of increased weathering in advance of foundation exploration; areas of potential roof collapse and excess water in mining and tunneling operations; and leakage beneath dams and into excavations within bedrock. Zones of fracture concentration also could be mapped to account for seepage pressure variation, risk of blowouts and piping, and strength variations within bedrock. Detailed knowledge of the significance and distribution of zones of fracture concentration also is useful in planning, designing, and conducting grout or cutoff wall operations, and in locating highly-effective pressure and drainage wells. Parizek, (1971a); and Parizek and Tarr, (1972); Koppe and Thompson, (1972), showed how they can be employed in acid mine drainage abatement projects.

Faults

High angle faults and fault zones are common in the Appalachian folded rocks. Stratigraphic separations of only a few feet are generally sufficient to concentrate ground water flow, and hence solution and weathering. Exposures in caves and quarries reveal that other fault zones are tight and do not facilitate weathering. In Nittany Valley the presence of major springs on fault zones indicates their regional influence in the valley hydrogeology (Parizek, 1971b). Thrust faults in the Appalachian folded rocks tend to be several miles to tens of miles in length. They have the potential of exerting regional controls on permeability and may localize ground-water drains. Warman and Causey (1962) indicate that thrust faults in Alabama form the principal reservoirs and conduits along which ground water from deep and distant sources reaches the surface.

Lineaments (linears)

Much less is known about linear features a mile or more in length. Hobbs, (1905, 1911), and more recently Lattman, Parizek, Wise and others have noted their presence in Pennsylvania,(see figure 2 e and d).

Several lineaments that transgress regional structural grain and also physiographic province boundaries have been discovered from visual examination of the ERTS MSS images. Four tentative scales of lineaments have been recognized, viz., 1 to 5 miles long features, 5 to 50 features, 50 to a few hundred miles, and megalineaments on a subcontinental scale. Little is known about the length, frequency, and relationship to fracture traces and joints, but there appears to be an inverse relationship of length to abundance and density. Lineament mapping from ERTS tapes is cumbersome because of their variability in length, and unreliable because of their variation in expression along strike (e.g., between ridges and valleys, or even from one valley to another), and the difficulty of distinguishing man-made effects (roads, field boundaries, etc.), and machine artifacts.

Lineaments have the same morohological characteristics as fracture traces except in that they are wider, longer, are not at all obvious in the field, and exert a major influence on topography. Years of airphoto mapping and field work in central Pennsylvania did not reveal many of the lineaments so obvious on the ERTS images, although it was known that the wind gaps and water gaps in the ridges may be aligned.

Although most of the lineaments are straight, some are gently curved and appear to be independent of regional structural trends. However, some of the long lineaments, spaced about 10 miles apart are approximately perpendicular to the Appalachian trend, and fan with the Appalachian orocline. Offsets and drag features are associated with the east-west striking line lineaments, e.g., north of Harrisburg, and through the South Mountains near Gettysburg, and must represent the trace of faults. In the test area east of Harrisburg, the intermediate and short lineaments appear to be conjugate with an angle of about 30° to a northwesterly trending axis. Likewise these shorter lineaments cut across regional primary structure and even the major physiographic province boundaries. Generally, they are spaced less than a mile apart. Except for lineaments coincident with known faults, their physical nature in 3 dimensions is not known, but by analogy with the fracture traces we speculate they are underlain by zones of fractured and joined rocks and represent zones of deformation or movement between "jostling" blocks. They transgress rocks from Precambrian to Triassic age in Pennsylvania, and though they are blanketed by the Pleistocene glacial drift in part of the State they are not obscured by it. They must be either a rejuvinated crustal fracture system impressed on the younger rocks and in a sense are a reflection through the cover rocks of active crustal "joints", or they represent the deformation in response to a wide-spread and pervasively imposed stress field as would be expected from a drifting North American plate.

Potential Applications; Research Directions

There is urgent need for a genetic classification of "linears" and the development of an appropriate descriptive terminology. Lineaments with associated offsets most probably are the trace of faults or fault zones; others are the trace of dikes. For the majority of lineaments, displacements are not apparent, but because of a correlation in mines to zones of poorer rock condition and increased density of joints (broken ground), and also an increase in density of joints in the wind and water gaps that define the longer lineaments, we predict they are surface manifestations of imposed mechanical breaks with little or no displacement, i.e., scaled up fracture traces.

It is obvious from a comparison of figures 2a, b, c, and d, that the density of linear features (fractures) is related to scale, but this relationship has yet to be quantified. By analogy with fracture traces and joints (Parizek, 1971a,1971b; Parizek and Voight, 1970) it is reasoned that most lineaments are approximately vertical zones of joint concentration. Although the relationship of joint frequency to (a) residual stress after faulting, (b) strain energy of lithology, (c) thickness of beds, and (d) degree of tectonic deformation, are recognized (Price, 1966), no model has yet been proposed linking "joints" and fractures on different scales.

Because most joint and fracture traces are essentially vertical, the intermediate principal stress axis of the associated stress field should also be vertical. We suggest that the 2nd order shear mechanism (McKinstry, 1953) applied to a wrench fault model (Moody and Hill, 1956; Badgley, 1965) as a working hypothesis for genetically relating certain "linears" of different size and density. Anderson (1951) showed that under these conditions (σ 2 vertical), the stresses near the center of the fault were relieved by fault movement but that the original level of stress is equalled or exceeded at a distance of 0.4 times the length of the fault, perpendicular to the fault plane. This gives a theoretical distribution of faults or zones of fracture, for stress can also be relieved by the development of joints (Price, 1966).

For a very simple model that assumes fractures (joints) to develop along the planes of maximum shear stress oriented symmetrically at 30° to each successive order of normal stress and that each order "shear" will be separated by a distance of 0.5 the length of its associated higher order shear, then the number of joint bounded blocks per unit area increases by 2^{2n-1}, where n is the order number. The unit area chosen may vary in size, but for each area the longest "fracture" is assigned to order 1. This model neglects the asymmetry of the (n+1)th "shears" to the normal of the nth "shear" (McKinstry, 1953) and yields only 3 directions of fracture instead of 8 (Moody and Hill, 1956). However, this should affect the pattern and not the size of the resulting "fracture" blocks.

This model at least predicts fracture density, which should be ameanable to testing using ERTS, underflight, and ground mapping data. If the thickness to joint interval relationship (Price, 1966) holds for the larger lineaments, then the roots to the lineaments must be deep and represent a neglected element in Global tectonics.

There can be little doubt that lineaments must have a subsurface control similar to that of fracture traces, because in out study areathey exhibit a similar strong control over the position and direction of river valleys. Streams once established may be trapped in their present position controlled by these vertical "zones of weakness", and underscores the role of lineaments in the evolution of river valleys and topography.

We are on the verge of many exciting discoveries which is inevitable whenever a new research tool improves on the resolution of features that were previously rather obscure. Hardware of the ERTS program provides us with such a tool.

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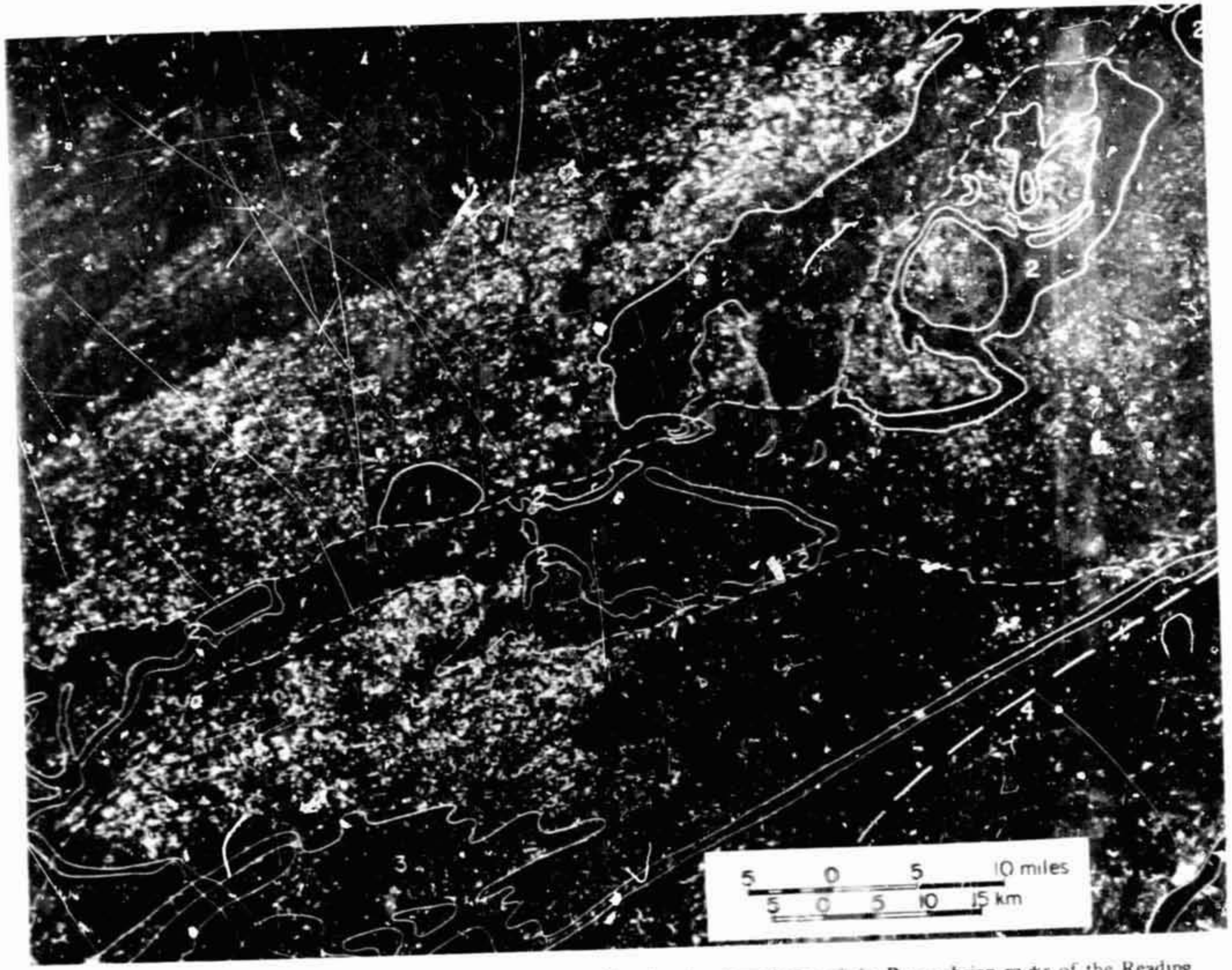

Figure 1. ERTS image of an area east of Harrisburg, Pa. showing boundaries of the Precambrian rocks of the Reading Prong (1), the Triassic Basin (in dashed lines), the Diabase Sills (2), and the Conestoga Formation (3) and Martic Line (4) in the Piedmont province. (Enlargement of ERTS image 1080-15185 band 5; October 11, 1972).

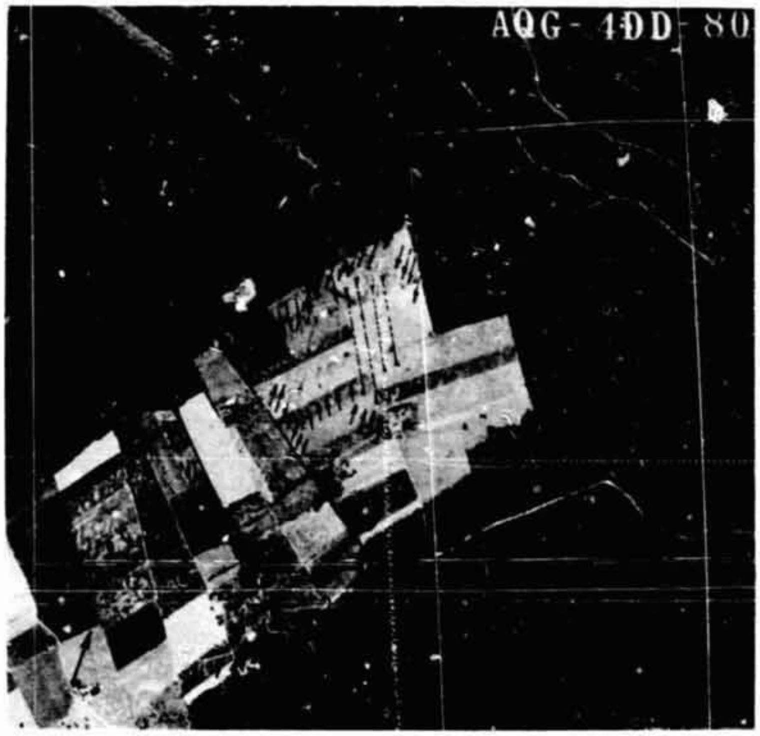

Figure 2(a). Fracture traces (large arrows) faintly visible in cultivated fields and forest in Pennsylvania, underlain by 5 to more than 100 feet of residual soils derived from folded limestone, dolomite, and sandy dolomite. Systematic joint sets account for the mottled tonal patterns in the cultivated areas (small arrows). (Modified after Parizek, 1969. USDA aerial photograph AQG-4DD-80).

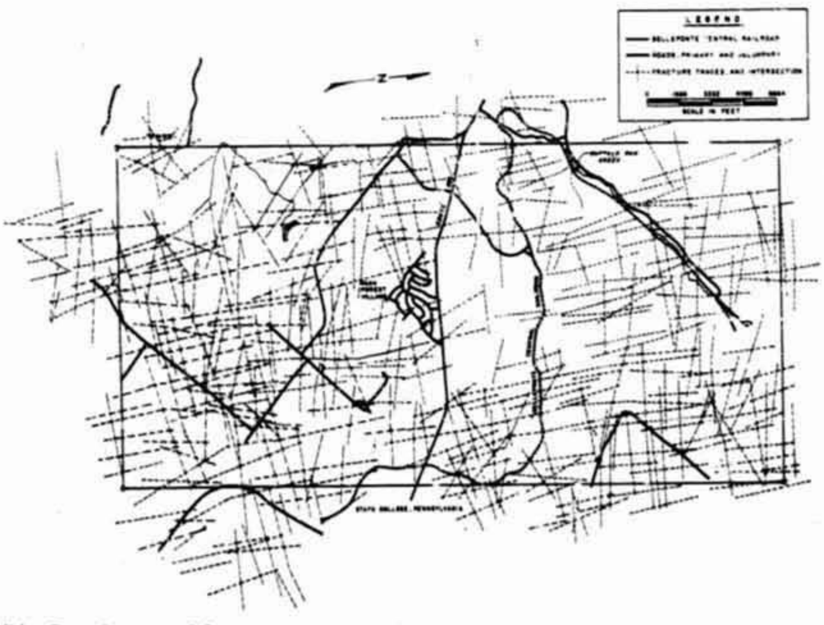

Figure 2(b). Distribution of fracture traces near State College, Pennsylvania. Note that the fracture traces are generally less than 1 mile long, are straight even in folded rocks, are not necessarily uniformily distributed, and may display two or more prominent orientations. (After Parizek and Drew, 1966).

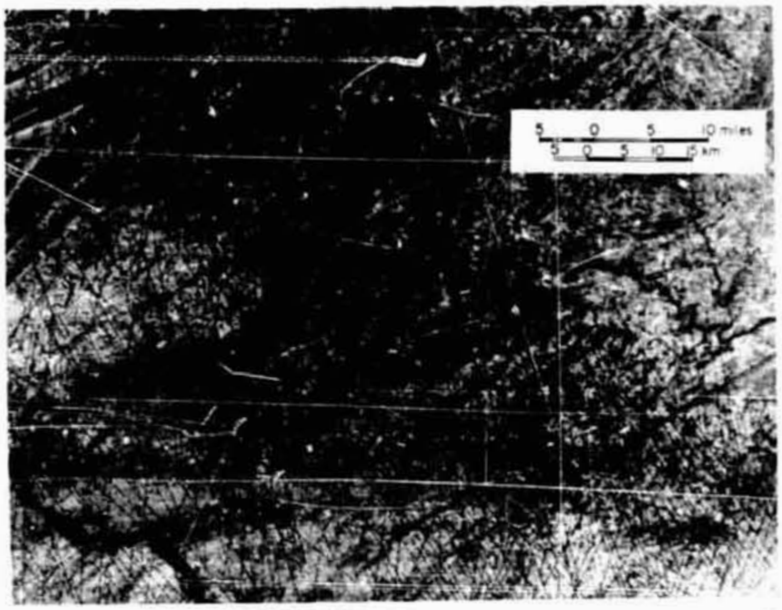

Figure 2(c). "Short" to "intermediate" lineaments crossing the Valley and Ridge, Great Valley, Triassic Basin, and Piedmont structural provinces east of Harrisburg, Pa. The Susquehanna River appears in the lower left, and the Schuylkill River in the northeast half of the figure. Reading is located on the Schuylkill near the center of the figure. (Enlargements of ERTS image 1116-15192 band 7, November 16, 1972).

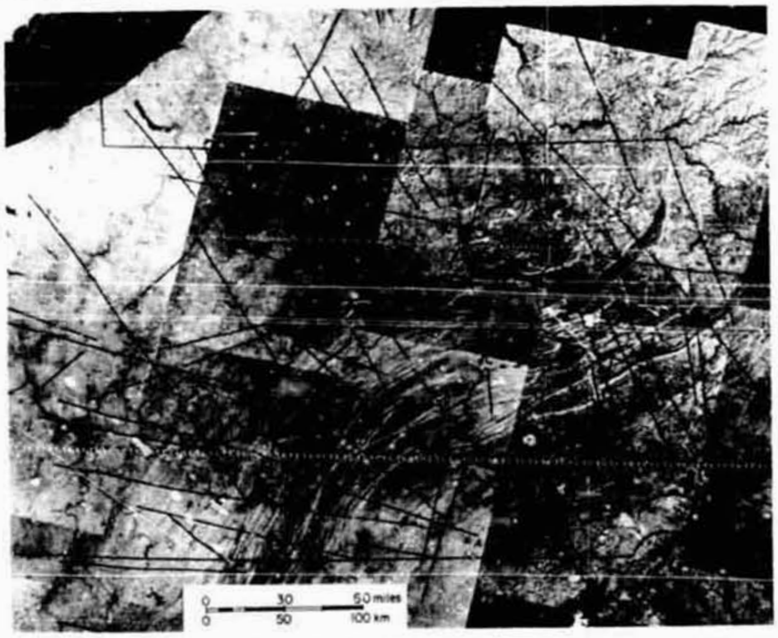

Figure 2(d). "Longer" Lineaments in Pennsylvania. Dashed lines represent known faults that exhibit displacements on this scale of the ERTS imagery: solid lines are lineaments (without genetic implications). The physiographic provinces, the Allegheny plateau to the north and west, the curved Appalachian folded belt through the central section, and the Piedmont to the southeast, show up well. The dark crescentric area in the northeast part of the State in the "anthracite basin" around Scranton and Wilkes-barre.