X-923-75-183
PREPRINT

NASA TM X- 70951

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(NASA-TM-X-70951) QUANTIFICATION OF GEOLOGIC LINEAMENTS BY MANUAL AND MACHINE PROCESSING TECHNIQUES (NASA) 28 p HC $3.75 CSCL 08G
N75-30702
Unclas
G3/46 34739

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JULY 1975

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QUANTIFICATION OF GEOLOGIC LINEAMENTS BY MANUAL AND MACHINE PROCESSING TECHNIQUES*

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ABSTRACT

An on-going study is being carried out at Goddard Space Flight Center to study the effect of operator variability and subjectivity in lineament mapping and to examine methods to minimize or eliminate these problems by use of several machine preprocessing methods. LANDSAT scenes from the Anadarko Basin of Oklahoma and the Colorado Plateau were analyzed as test cases.

Four geologists mapped lineaments on an Anadarko Basin scene, using transparencies of MSS bands 4-7 and their results were compared statistically. The total number of fractures mapped by the operators and their average lengths varied considerably, although comparison of lineament directions revealed some consensus. A summary map (785 linears) produced by overlaying the maps generated by the four operators showed that only 0.4 percent were recognized by all four operators, 4.7 percent by three, 17.8 percent by two, and 77 percent by one operator. Similar results were obtained in comparing these results with another independent group. This large amount of variability suggests a need for the standardization of mapping techniques, which might be accomplished by a machine aided procedure.

Two methods of machine aided mapping were tested, both simulating directional filters. One consists of computer (digital) processing of CCT's using edge enhancement algorithms. The other employs a television (analog) scanning of an image transparency which superimposes the original image and one offset in the direction of the scan line. Both methods created similar products, producing many more linear features than were observed by the geologists in the original work. This suggested some processing artifacts may have been introduced, either in the machine processing or the original LANDSAT image. Various tests were performed which downgraded the possibility of such artifacts.

*Paper to be published in Proceedings of NASA Earth Resources Symposium, Houston, Texas, 1975.

Comparison with published data for the Colorado Plateau indicates that numerous directions of the edge enhanced linears do correspond with known directions of jointing and airphoto linears. Further study is required to determine the implications of these machine methods of fracture mapping before operator interpretations and automated machine mapping may be attempted.

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ILLUSTRATIONS (Continued)

QUANTIFICATION OF GEOLOGIC LINEAMENTS BY MANUAL AND MACHINE PROCESSING TECHNIQUES

INTRODUCTION

As part of an on-going research program at Goddard Space Flight Center into the evaluation of linears as observed on satellite and aerial photograph images, the geologists of the Earth Resources Branch (ERB) have analyzed in detail a LANDSAT-1 image of a portion of the Anadarko Basin, Oklahoma, an area studied by the Eason Oil Co. in its LANDSAT-1 investigations. Their study attempted to evaluate the usefulness of space imagery for petroleum exploration through morphotectonic and fracture analysis. For this reason ERB chose the same scene for the purposes of 1) further investigation of anomalous structural features by spectral enhancement techniques, 2) extraction and classification of lineaments, and 3) comparison of results of the two independent groups. In addition, this same scene, as well as one of the Colorado Plateau of New Mexico, was processed by several automatic methods in order to determine the feasibility of linears enhancement. These processes will be discussed in detail later.

This paper has two purposes: 1) To point out the subjectivity and variability involved in mapping linear features by different interpreters, particularly in low relief terranes, and 2) to propose some automatic enhancement techniques, which with some reservations, may aid in eliminating some of this operator variability.

Lineaments are naturally occurring linear features observed on small scale remote sensing imagery. They are manifest in the imagery as various combinations of stream, tonal, vegetational, and topographic alignments. Lineaments may be either continuous or discontinuous in nature, and can vary from several to several hundreds of kilometers in length. They are usually regarded as the surface manifestations of fault and fracture zones, or with zones of increased jointing, have been linked in one fashion or another with local or regional tectonics, and have been used on occasion as a tool for oil, gas,[1-3] and minerals exploration.

The features discussed in this paper are unverified in the field and some are inevitably related to anthropogenic activity. Consequently, the more general terms "linears" or "linear features" will be used, however, it should be noted that a good many of these features would fall into the category of lineaments.

ANALYSIS OF OPERATOR VARIABILITY

Four geologists of the ERB mapped lineaments on MSS bands 4 - 7 over a period of several days in order to minimize mapping fatigue. A maximum of six hours was spent by individuals in examining the scene. Each geologist, within the constraints of the definition, mapped what he determined to be a lineament, and it was agreed that cultural features should be ignored. A lack of communications resulted in only three of the four operators ignoring the cultural features. This will be evident in the ensuing illustrations.

All four MSS bands were analyzed, beginning with five and seven, followed by the two remaining bands. Composite maps of linears were generated for each operator, summarizing each individual's results for all four bands onto one overlay. A summary map was then created, comparing the results of all four operators by overlaying their results and checking for coincidence of linears. All linears which fell within approximately 1 km (1 mm on the 9 x 9-inch LANDSAT image) of each other and deviated by no more than approximately 3 degrees were considered contiguous. Where two linears overlapped by more than half their length, they were considered to be coincident.

Figure 1 shows the Anadarko Basin scene, an area underlain mainly by gently dipping (less than 2 degrees) sedimentary rocks of Pennsylvanian and Permian ages. Figure 2 illustrates the results of the individual mapping efforts by the four operators. Very little information was added to the analysis by the use of MSS bands 4 and 6, so that they were not included in the analysis. Furthermore, if a linear feature was noted in one band, it could usually be found on the other, but some of the linears were more apparent on one.

A wide disparity in the number of linears mapped and their average lengths is noted in Figure 3, which is a frequency (number of linears)/azimuth class and density (summed length of linears)/azimuth class plot for each of the four operators. There was a tendency for the operators to map linears of differing average lengths as well as total numbers. Moreover, some operators, in varying degrees, mapped features which were associated with the north-south and east-west boundaries of the midwestern land-grid system. This is particularly evident in the results of operator 4. Operator 2 picked very few linear features in the northwesterly directions. This may be partially the result of unfamiliarity with these features and because of the sun's southeasterly position, which preferentially enhances the northeasterly trending linear features.

Variability due to illumination is not discussed in this paper, but is noted by Wise[4] and Siegal,[5] and is another major factor to be considered. Generally, the northeast and northwest directions, corresponding to Sonder's "regmatic shear"[6] are found by the majority of operators. Operators 1 and 3 show the closest correspondence. This result may be attributed to the fact that they both had considerable prior industrial and/or academic experience in lineament mapping. A Chi Square test (4 operators x 18 azimuth classes contingency table) shows that the operators did not map the same directions based on a .01 level of rejection. Elimination of operator 2 (3 x 18 contingency table) produced results which show no cause to reject the hypothesis that the remaining three operators picked the same directions based on a .05 rejection level.

A comparison of the linears picked by the four operators is summarized in Figure 4. It can be seen that only a very minor amount of the total was seen by all four operators. Only 22.9 percent was seen by at least two operators. In defense of the operators, it should be stated that the area chosen was less than ideal for this type of test, because of 1) the dominating effect of man's activities and 2) the relatively low relief of the terrain. Analysis of more rugged terrain would likely show better agreement.

A comparison of the work performed by the Eason Oil Co.[7] with the ERB geologists (Figure 5) shows only 20 percent of the linears were seen by both groups, using the combined linears map of the ERB group. This lack of coincidence is further reinforced in the Eason Oil study, where their comparsion of Skylab and LANDSAT mapping resulted in only a 30-percent agreement between the two sets of imagery.[7] Figure 6 illustrates the frequency/azimuth and density/azimuth histograms for the Eason Oil and ERB groups. Besides those linear features which are in agreement, a Chi Square test (2 x 18 contingency table) comparing linears directions seen by each of the two groups, gives no reason to reject the hypothesis that they are mapping the same directions, even though the individual linear features do not agree.

The above comparisons show that selection of individual linears is highly subjective, but that with training, a regional pattern suitable for tectonic interpretation may be possible, particularly within a closely knit group of geologists. However, any attempt to reach agreement among the members of the whole geologic community would prove more difficult, as interpretations of lineaments will vary.

AUTOMATED PROCESSING FOR LINEARS EXTRACTION

It therefore seems imperative that in order to minimize differences both between operators and between institutions, some truly objective standardization criteria are required. This is particularly important when analysis is made to define minor changes in lineament density, a factor which some have claimed as a geologic exploration tool for structures suitable for petroleum accumulation.[1,8,9]

Several philosophies exist, two of which are discussed here. One would entail rigorous training of operators to pick the same features and might prove successful at least within one or several closely cooperating institutions. This technique, unfortunately, does not eliminate other factors such as changes in operator acuity due to fatigue or mental attitude. Another approach is through machine processing: one involving either a completely automated procedure of pattern recognition and mapping or a semi-automated one in which linears are enhanced for ease of operator interpretation. Machine methods still require some interaction to eliminate cultural effects. Goetz (pers. comm.) found that a fully automated method requires an inordinate amount of computer processing of the image and would still not produce an accurate map devoid of cultural effects.

Several methods for semi-automated mapping of linear features are presently available. One involves the use of an analog television system, which scans an image with a vidicon camera, electronically producing a positive and negative version of the image offset from each other by a minute amount along the scan line direction. This is analogous to a masking technique discussed by Wier and Wobber,[10] where positive and negative transparencies are superposed to produce a product from which linears could be mapped. A single image developed by this electronic offsetting gives only part of the information, as the technique selectively enhances only certain directions. However, the problem is easily circumvented by a stepwise rotation of the image through 180 degrees, thus enhancing all possible directions of linears. A final product would involve creating a composite of a number of these images, taken at different rotations to the television scan lines. The method is advantageous, because it allows for a rapid inspection of the image, but it produces a somewhat spatially degraded result.

The second method uses digital image processing techniques. High-pass digital filtering is used to enhance linear features employing an interactive variant of the Jet Propulsion Laboratory VICAR system implemented at Goddard Space Flight Center. Both directional and non-directional filters were tested. Thus far, most success has been achieved with the directional filters and these will be discussed herein. Although this system does not have the real-time quick image rotation and display, it excells in giving the best possible resolution and variety of filter possibilities.

Both systems produced many more linears for a given direction than had previously been detected by the unaided eye. Consequently, many of the features became suspect as machine artifacts.

Both systems enhanced those linear features which were inclined at a relatively low angle either to the television scan line or filter direction in the digital case. Figure 7 shows the results of edge enhancing a star test pattern on the analog system. It can be seen that the finest lines which are preferentially enhanced are inclined at small angles (15°-30°) to the horizontal or scan line direction of the system.

Rotation of a LANDSAT image on the television system produced sets of linears which were enhanced when brought within this critical angle, which would rotate with continued image rotation, and would then disappear as these features passed out of the critical angular field. Thus, the television image was not continuously occupied by linears, but only when a set would come into the critical field, suggesting that the features were real.

The possibility of an electronic "ringing" (i. e., spurious linears generated when a set of linears fell within the critical angle) induced by the techniques was examined for the analog system. This would be manifested as a repetition of a pattern on the screen beyond the actual confines of the pattern. A grid of progressively closer spaced lines was examined on the television system, and no ringing effects were noted.

It was also suggested that the digital LANDSAT data or its resultant image might contain some systematic processing or electronic artifact unrelated to the sensed image. However, examination of the Skylab S-190B photography, free of digital processing, produced similar patterns of linears directions when processed with the television system.

A comparison between the LANDSAT digitally processed data and the high-resolution S-190B photography showed that in many instances, linears could be correlated between the two, although some were of obvious man-made origin. This observation is exemplified in Figure 8. These features have yet to be field-checked to determine their origin.

In order to determine if these detected linears processed from LANDSAT imagery could be related to lineaments, a comparison was made with the detailed lineament mapping of Kelley and Clinton[11] for a portion of the Colorado Plateau of New Mexico. Both analog and digital techniques were investigated and the enhanced images were qualitatively compared using an optical transferring device. The processed LANDSAT images reveal coincident lineament directions, but again, many more features can be isolated from the image compared to the map. Figures 9 and 10 illustrate the comparisons.

CONCLUSIONS

Studies of operator variability in the mapping of fracture patterns and lineaments has shown that:

- Operators have differing concents as to the average lengths of lineaments.

- There is little reproducibility between operators or groups in the selection of individual linears, although with some training, they may pick the same directions.

Processing of imagery by both digital and analog methods indicates that:

- There are many more linear features than are detected by the unaided eye.

- There is agreement between the two processing techniques, and the features seen are related to linear features on the ground; in some cases they are of obvious man-made origin.

- A comparison of a processed LANDSAT image and a map of lineaments created from relatively large-scale photography indicates a concurrence in directions of individual lineaments, although many more features are seen by the enhancement

- The analog television system allows a reconaissance inspection of the imagery, but suffers from degraded resolution. Ultimate detail and greater processing flexibility can be achieved by using digital processing of the LANDSAT computer compatible tapes. The effect of filter size, direction, and shape must be investigated to determine optimum criteria for quantification. These factors are being investigated at this time.

- The data must still be interpreted by the operator to eliminate cultural effects. Although the large number of linear features enhanced will most likely lead to operator variability, it may fall within more tolerable limits.

- Ultimately, automatic recognition techniques must be developed to allow complete quantification.

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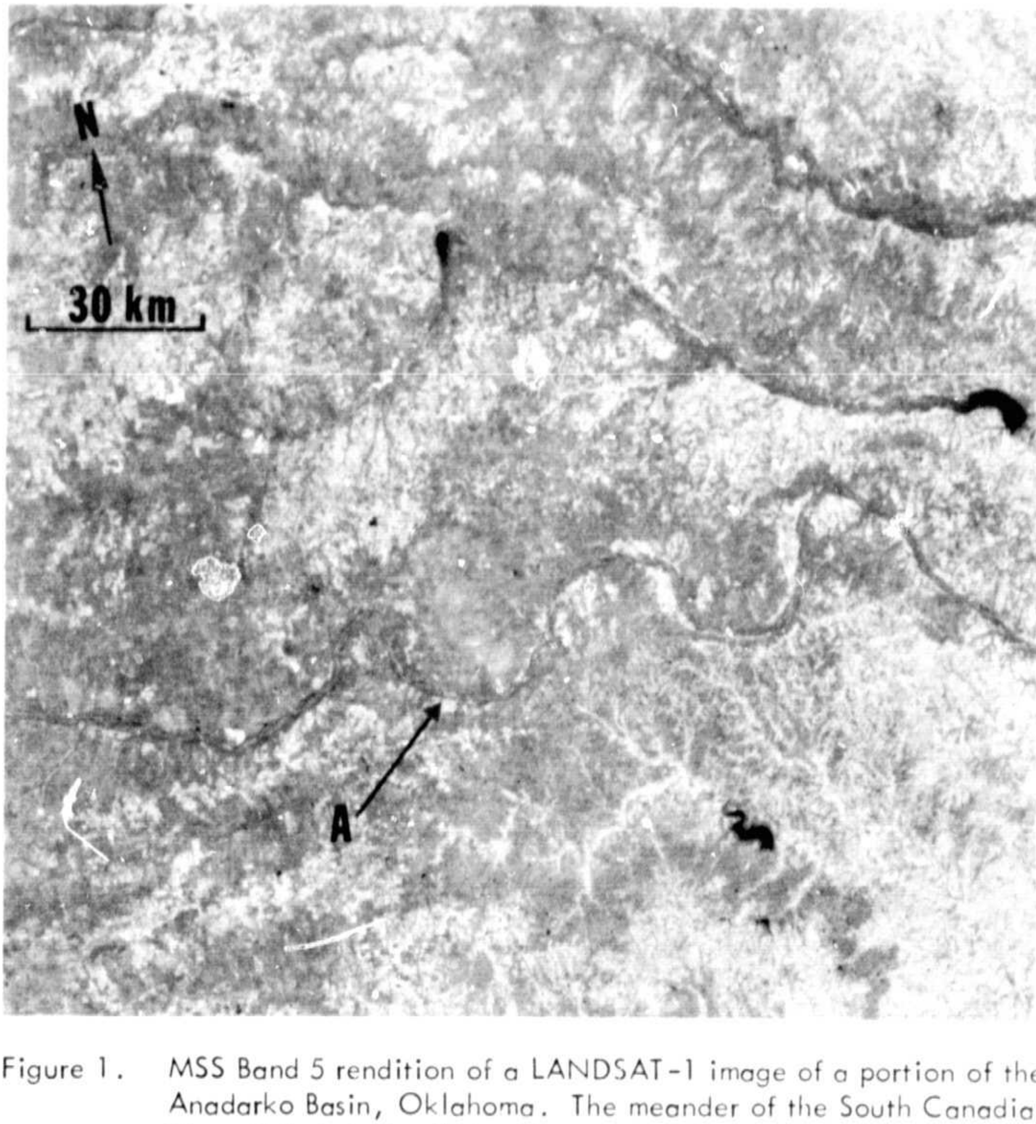

Figure 1. MSS Band 5 rendition of a LANDSAT-1 image of a portion of the Anadarko Basin, Oklahoma. The meander of the South Canadian River (labeled A) will be illustrated in later figures.

INDIVIDUAL OPERATOR LINEARS MAP: ANADARKO BASIN

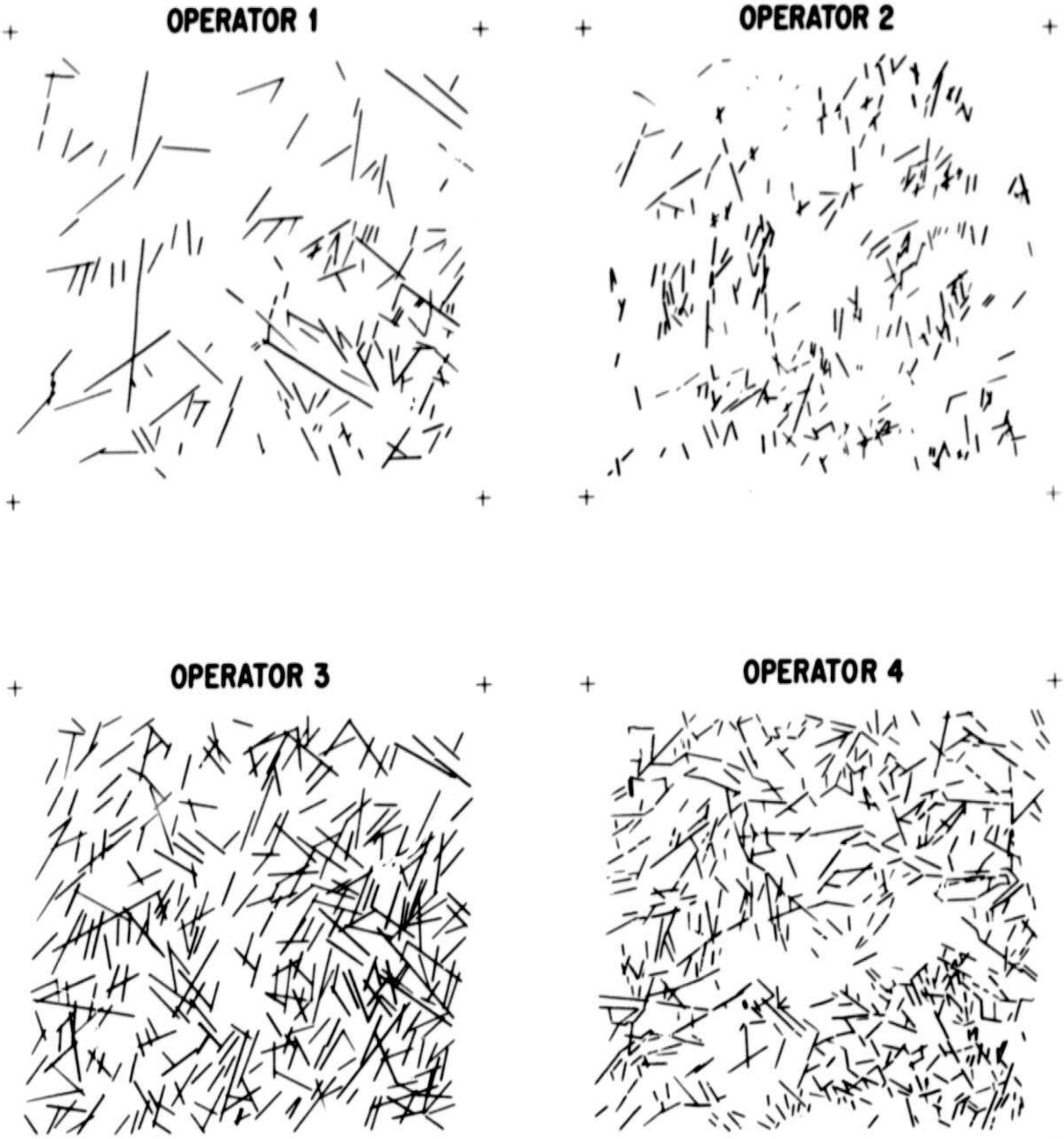

Figure 2. A comparison of linear features mapped by the four operators. MSS Bands 5 and 7 are included in this composite. The tic marks correspond with the registration marks on the LANDSAT image.

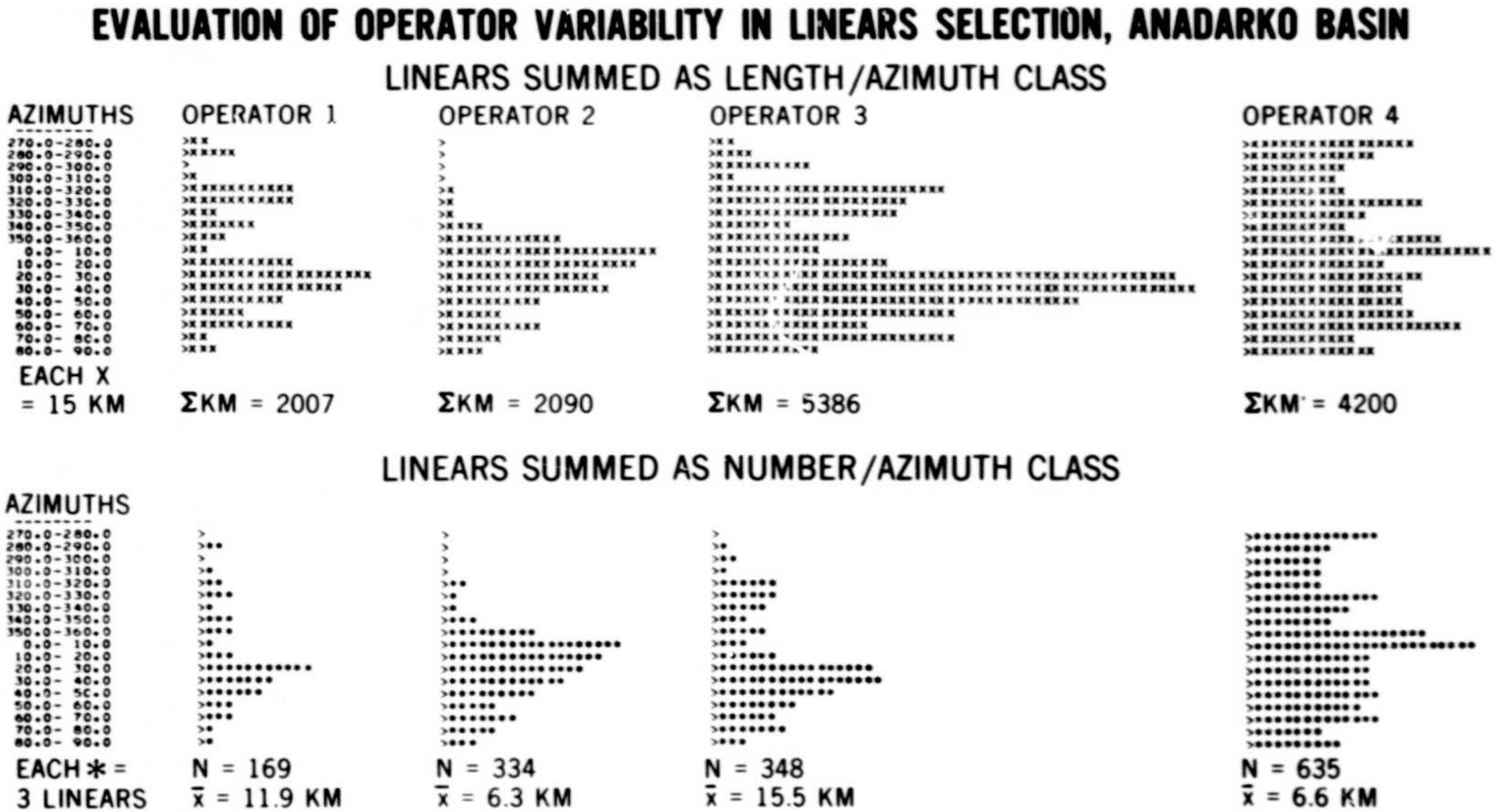

Figure 3. A comparison of density (total length of linears mapped) and frequency (number of linears mapped) per azimuth class for each of the operators. A Chi Square contingency table (4 x 18) showed that the operators were not mapping the same population of linears based on a .01 level of rejection. Removal of operator 2 from the analysis indicates that there is no reason not to believe the remaining 3 operators were mapping the same population based on a .05 level of rejection.

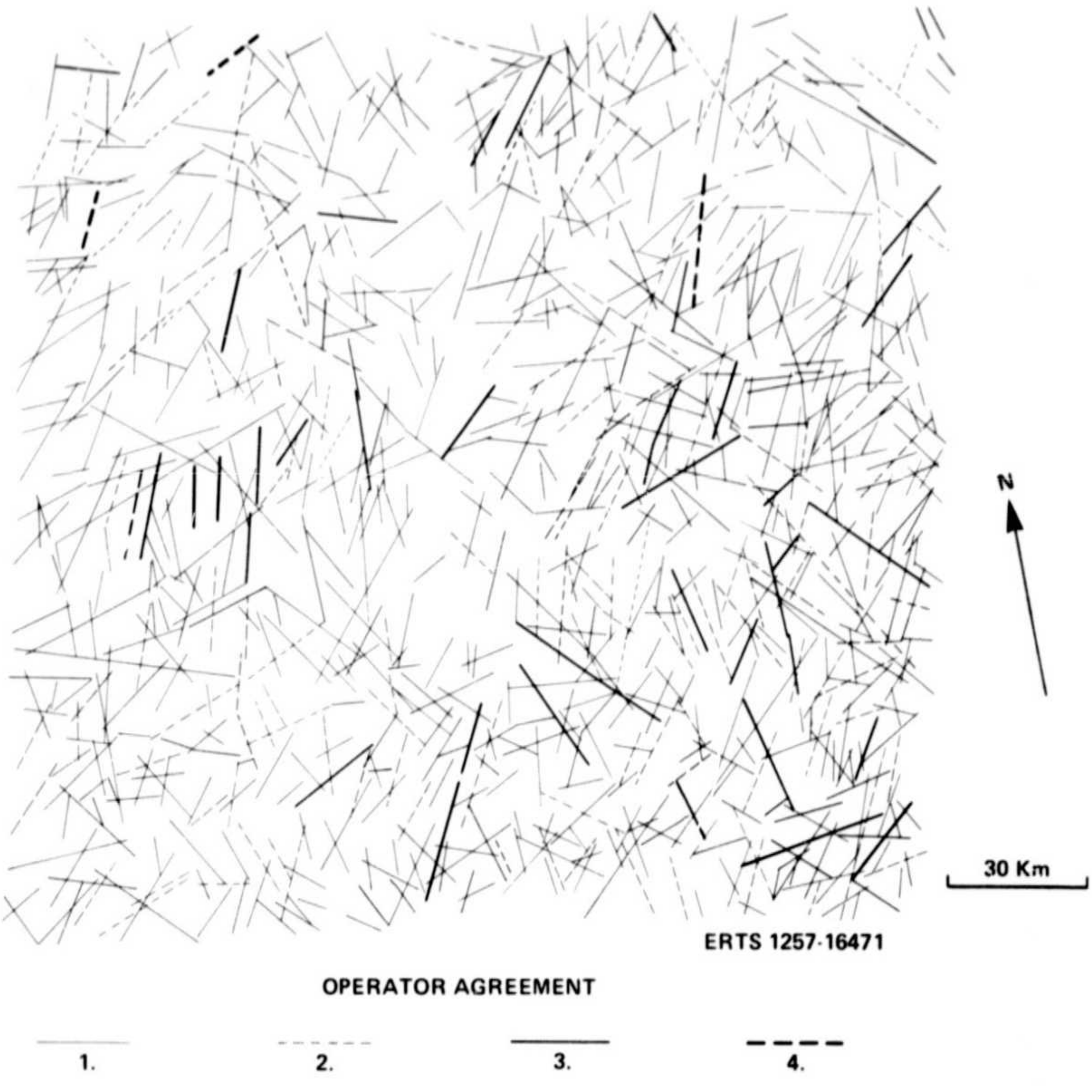

Figure 4. Composite map of coincident linears for the four ERB geologists. Only 3 (0.4%) of the total 785 linears were seen by all four operators, 37 (4.7%) by three, 140 (17.8%) by two, and the remainder by one of the four.

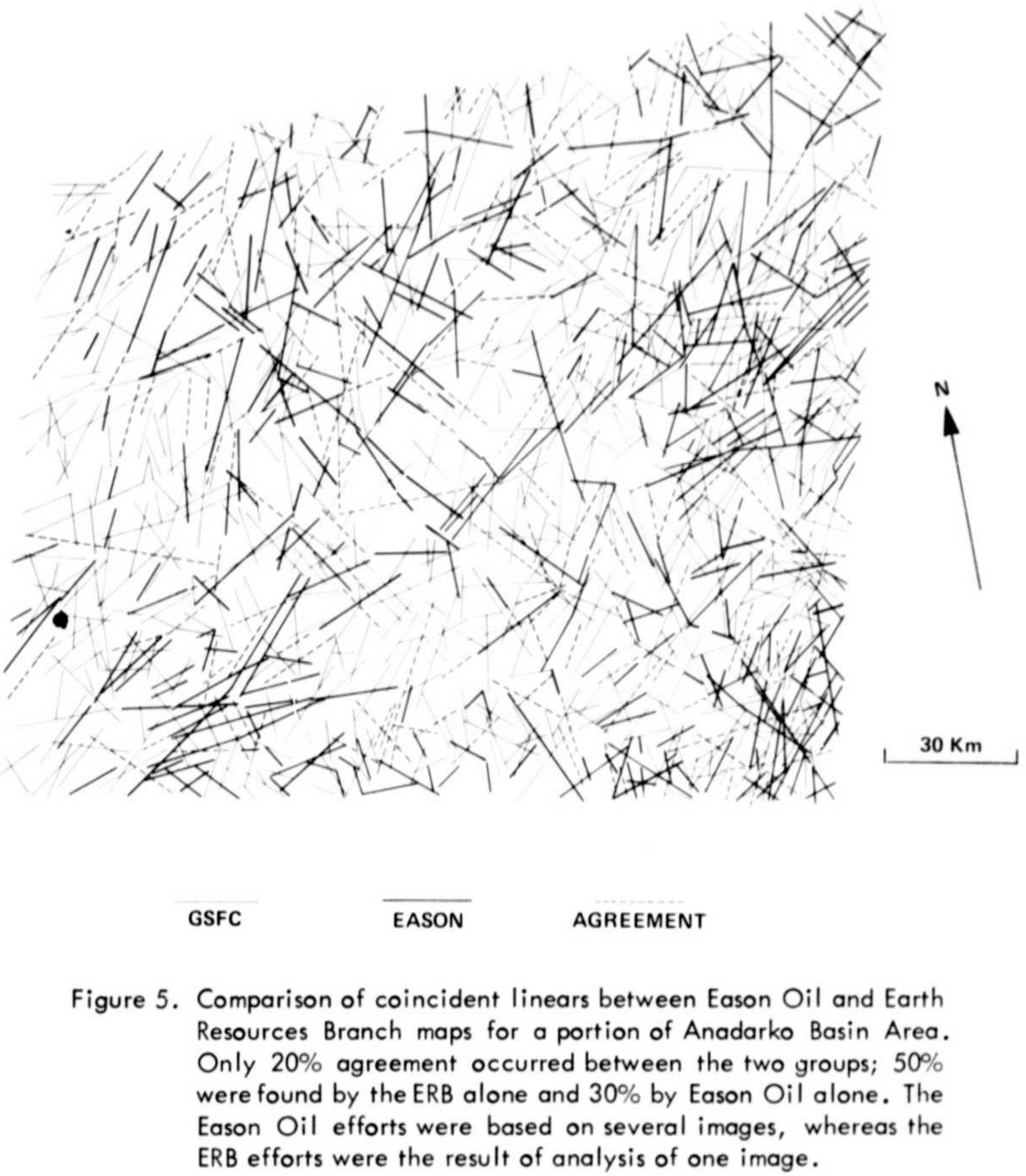

Figure 5. Comparison of coincident linears between Eason Oil and Earth Resources Branch maps for a portion of Anadarko Basin Area. Only 20% agreement occurred between the two groups; 50% were found by the ERB alone and 30% by Eason Oil alone. The Eason Oil efforts were based on several images, whereas the ERB efforts were the result of analysis of one image.

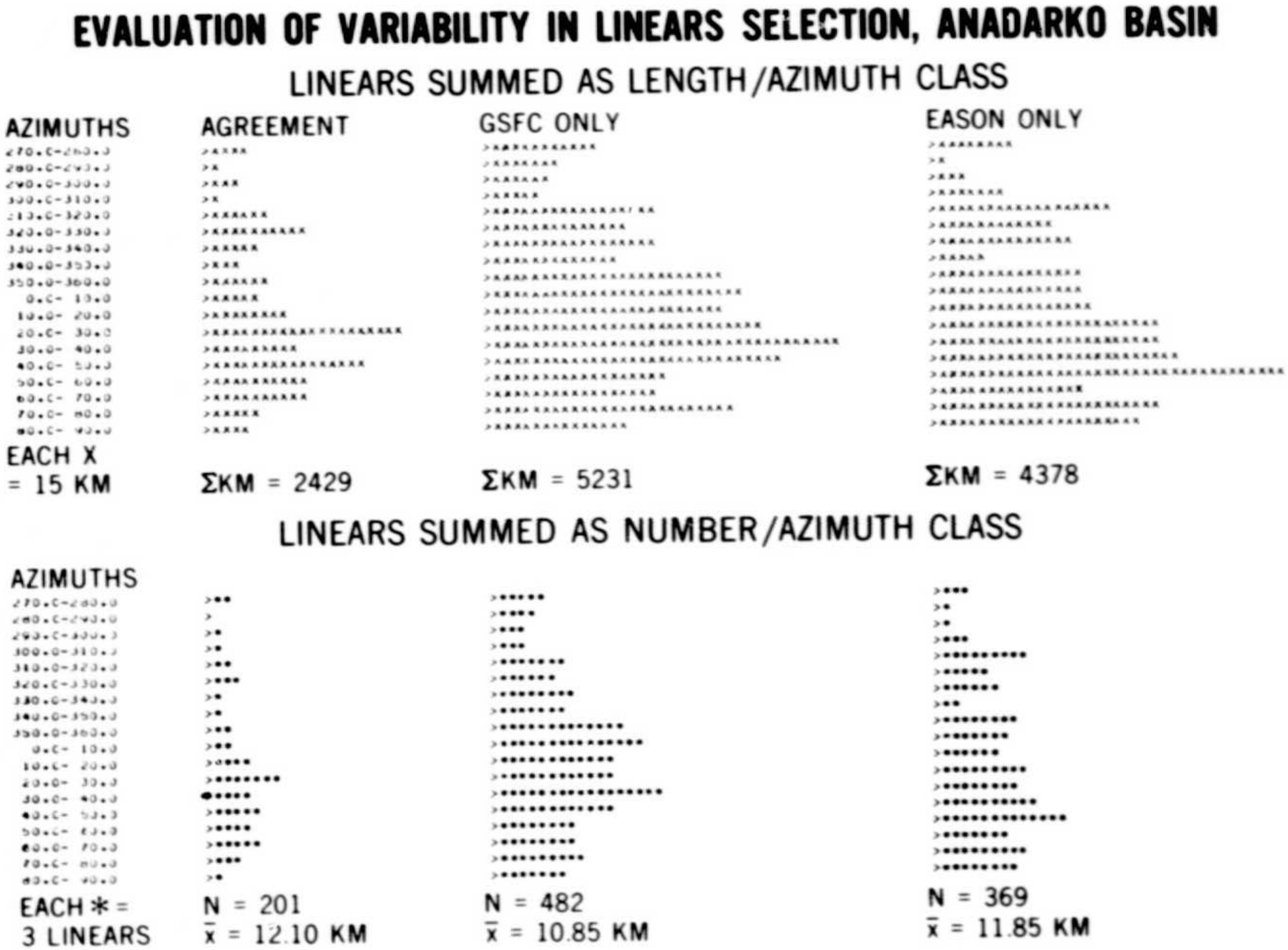

Figure 6. A comparison of density and frequency per azimuth class for the Eason Oil and ERB (4 operators) maps of linear features. Although only 20% of the linears were in agreement, a Chi Square test of those mapped by the two organizations and not in coincidence (2 x 18 contingency table), gave no reason to reject the hypothesis that the two groups were mapping the same directions of features based on a .05 level of rejection.

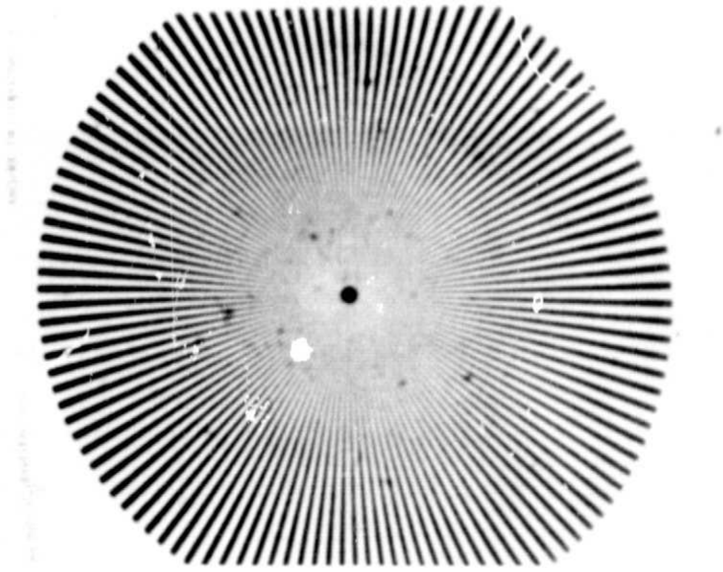

Figure 7a. Unenhanced version of the star test pattern as viewed on the television screen (analog process). Note that as the lines become finer towards the center of the pattern, they become less distinguishable.

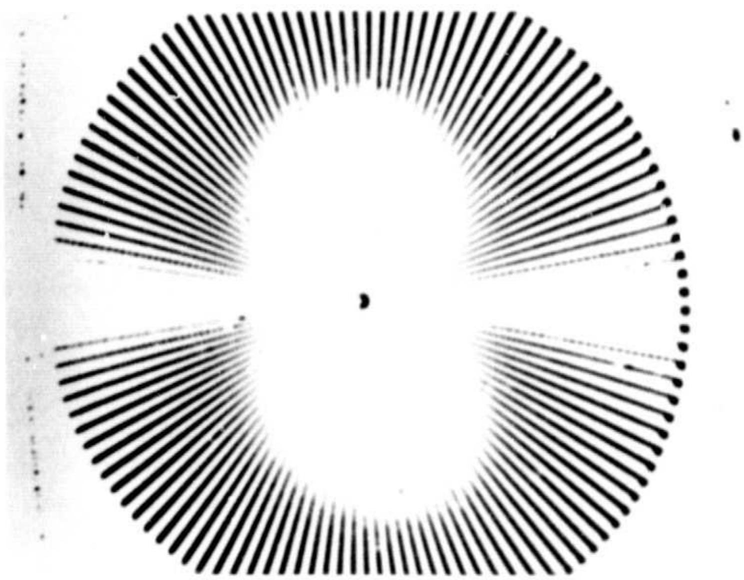

Figure 7b. Enhanced version of the same pattern. The lines are preferentially enhanced (their fine detail is seen closer to the center of the pattern) in the area inclined at a relatively shallow angle (15° - 30°) to the horizontal scan line. Note also that those lines parallel to the scan line direction are not visible.

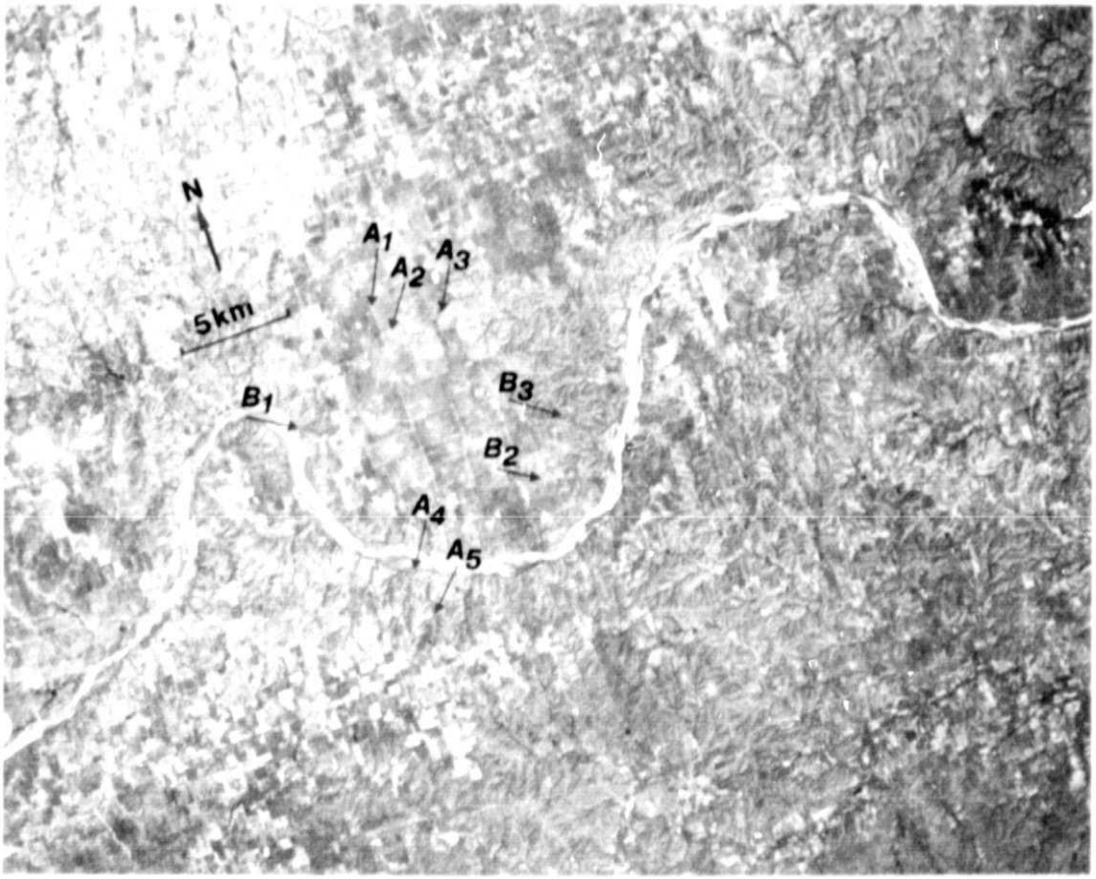

Figure 8a. Comparison of a Skylab S-190B photograph (8a) of the South Canadian River meander and the digital high-pass filtered LANDSAT-1 images for the same areas (8b & 8c). A filter oriented nearly due north (perpendicular to the MSS scan line direction) was applied in Figure 8b. Arrows marked A1-A5 (Fig. 8a & 8b) mark the northern extent of representative linear features observable on the Skylab photograph. Linear A1 is most likely due to culture. A filter oriented parallel to the MSS scan line was applied to the image illustrated in Figure 8c. Arrows B1-B3 mark the westernmost extent of representative linear features in Figures 8a & 8c.

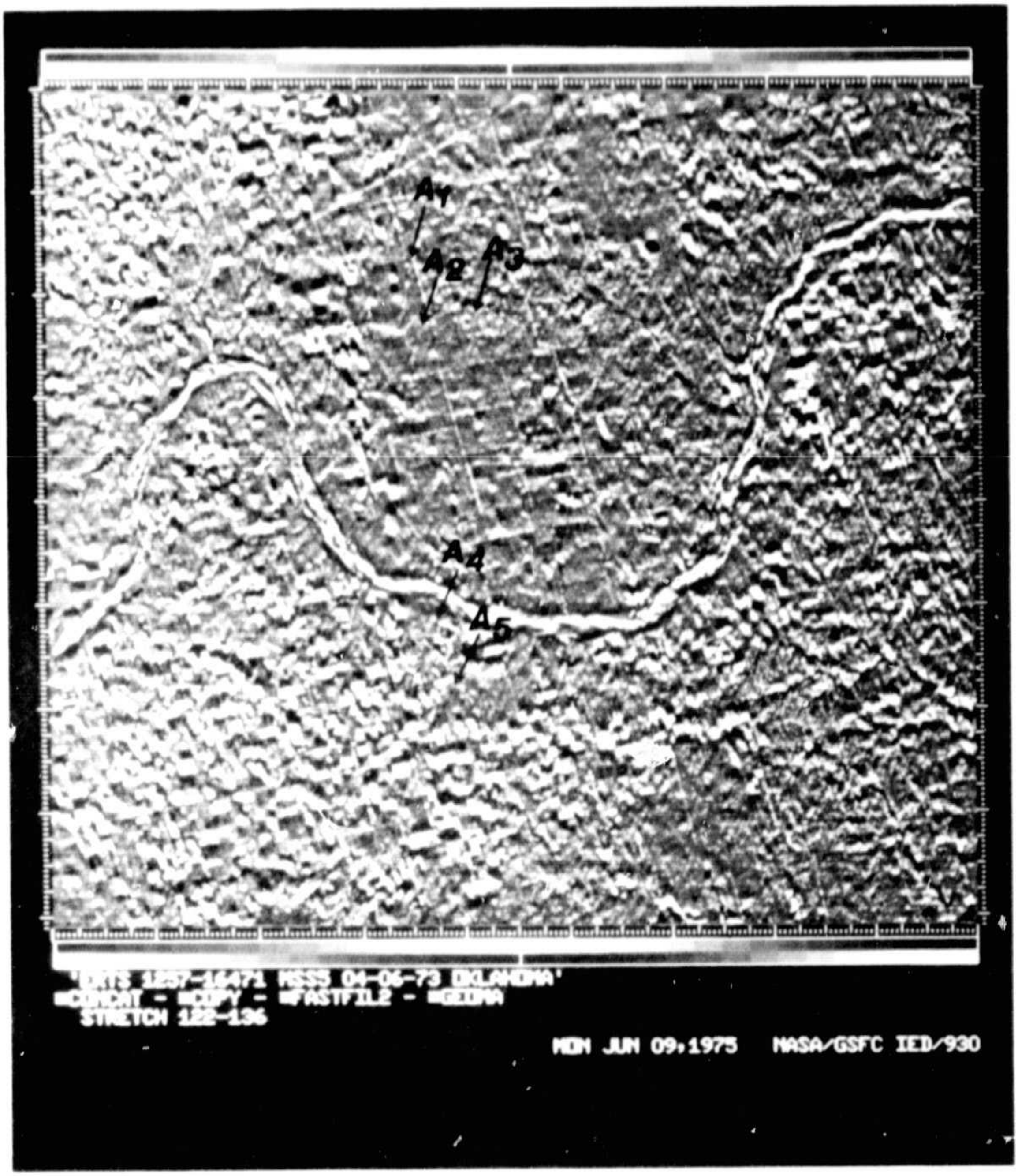

Figure 8b. See figure caption, page 16.

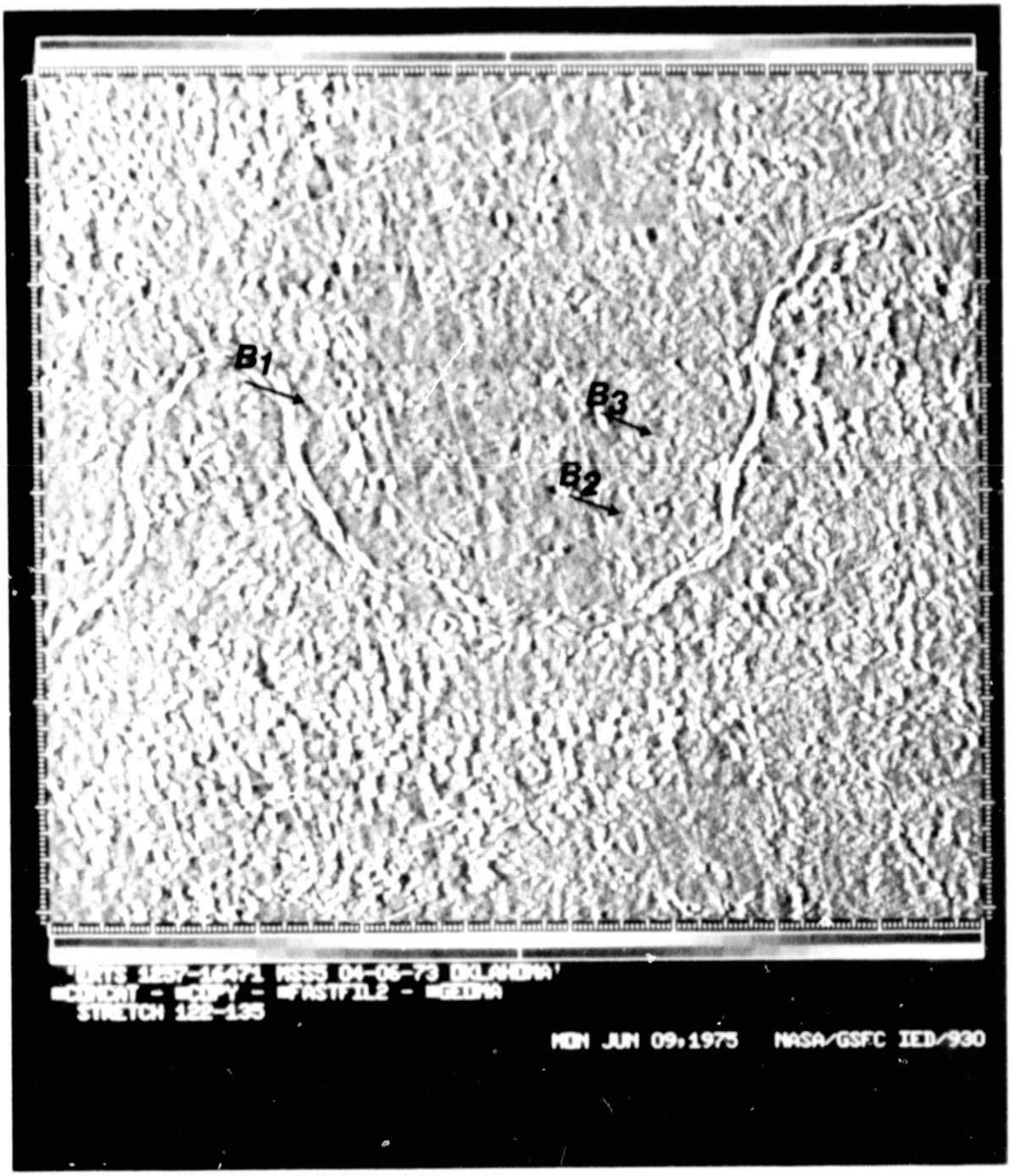

Figure 8c. See figure caption, page 16.

Figure 9. A non-enhanced version of MSS Band 5 of a portion of the Colorado Plateau test area (Figure 9a) and its corresponding part from the fracture map of Kelley and Clinton [11] (Figure 9b). Figures 9c and 9d represent high pass digital line filters respectively oriented normal and parallel to the scan line direction

KEY TO MAP SYMBOLS

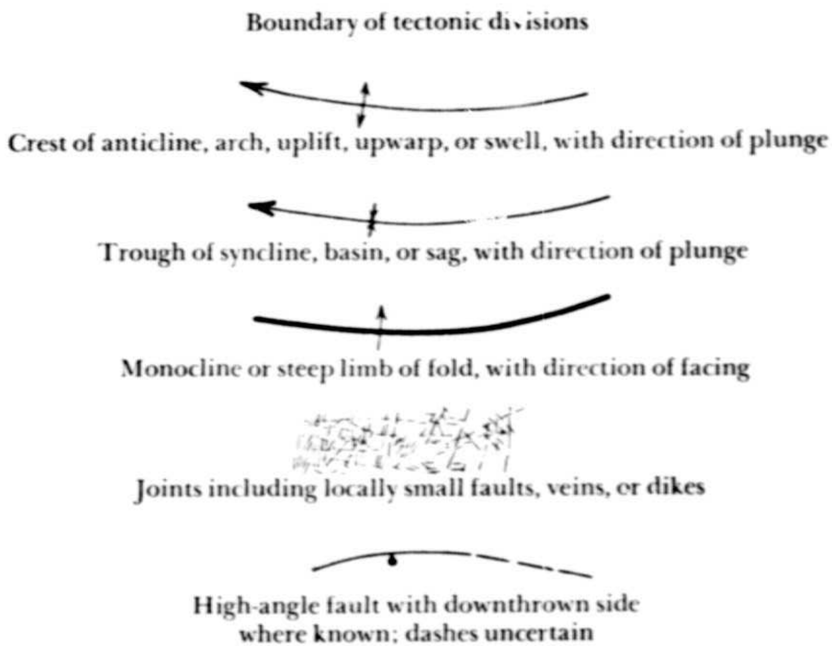

Figure 9a

Figure 9b

Figure 9c. See figure caption, page 20.

Figure 9d. See figure caption, page 20.

Figure 10a

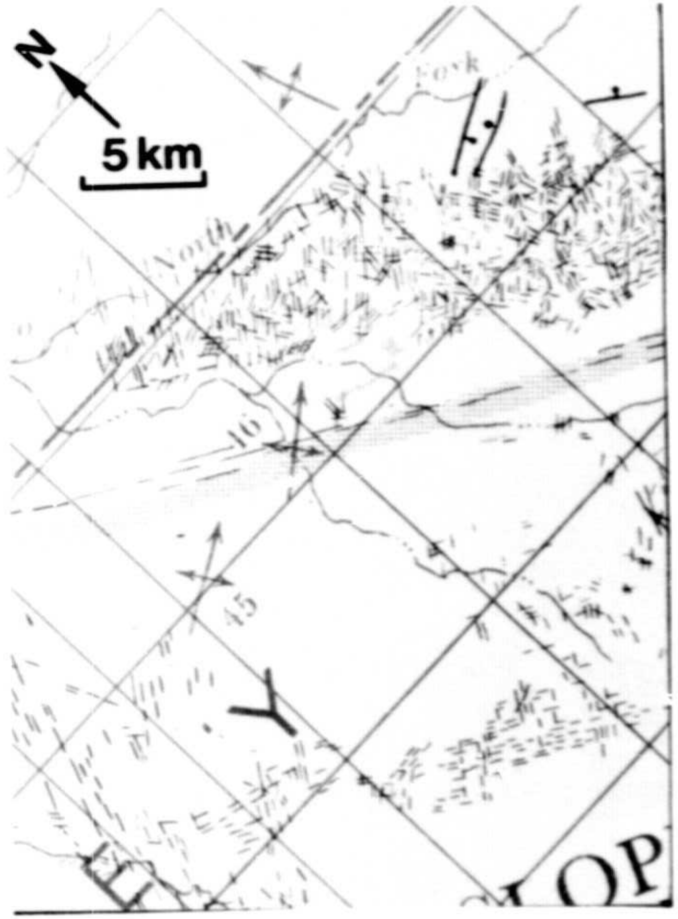

Figure 10b

Figure 10a. A television (analog) enhancement of a portion of the area covered in Figure 9a.

Figure 10b. Fracture Map from Kelly and Clinton[11] corresponding to area covered in Figure 10a. Arrows labeled A and B are representative of the directions of enhanced linear features. Arrow M is the direction of the MSS scan lines whereas T represents the television scan line direction.