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ERTS-I IMAGERY USE IN RECONNAISSANCE PROSPECTING

Evaluation of the commercial utility of ERTS-I Imagery in structural reconnaissance for minerals and petroleum

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16. Abstract

This study was performed to investigate applications of ERTS-I imagery in commercial reconnaissance for mineral and hydrocarbon resources. ERTS-I imagery collected over five areas in North America (Montana; Colorado; New Mexico-West Texas; Superior Province, Canada; and North Slope, Alaska) has been analyzed for data content including linears, lineaments, and curvilinear anomalies. Locations of these features were mapped and compared with known locations of mineral and hydrocarbon accumulations. Results were then analyzed in the context of a simple-shear, block-coupling model.

Data analyses have resulted in detection of new (and extension of known) lineaments, some of which may be continental in extent, detection of many curvilinear patterns not generally seen on aerial photos, strong evidence of continental regmatic fracture patterns, and the realization that all geological features in the test areas can be explained reasonably in terms of a simple-shear, block-coupling model. Cost analysis has shown that using ERTS-I imagery for regional structure investigations is about 1/500 as expensive as using conventional aerial photos.

The conclusions are that ERTS-I imagery is of great value in photogeologic/geomorphic interpretations of regional features, and that the simple-shear, block-coupling model provides a means of relating data from ERTS imagery to structures that have controlled emplacement of ore deposits and hydrocarbon accumulations, thus providing the basis for a new economical approach to reconnaissance for lode mineral and uranium deposits and favorable oil or gas structures.

17. Key Words	18. Distribution Statement	
ERTS-I imagery, reconnaissance, mapping structural lineaments, commercial application, mosaics, curvilinear anomalies, simple-shear, block-coupling model, minerals, petroleum.		
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PREFACE

A. OBJECTIVE

The objective of this study was to evaluate the feasibility of using ERTS-I imagery for interpreting and mapping large-scale structural lineaments and other geomorphic features in order to determine the commercial utility of this imagery for mineral and petroleum reconnaissance prospecting.

B. SCOPE OF WORK

Five geographic areas (Figure 1) were included in this study. Government-furnished ERTS prints were studied in mosaic form to determine the relative utility of ERTS-I imagery as compared to aerial photography for lineament and geomorphic interpretations in mining and petroleum reconnaissance exploration applications. Seasonal and wavelength effects on application of ERTS imagery and the economics of using ERTS imagery for regional structure investigations were also studied.

C. CONCLUSIONS

The general conclusion is that there is a great advantage in photogeologic interpretation from the satellite viewpoint to provide a truly synoptic examination of regional geologic features. In this study, for example, many large lineaments and other geomorphic features with dimensions of tens to hundreds of miles which are not generally detected on aerial photographs were mapped. Many of these lineaments appear to be continental in scale in that they extend across the entire test areas shown on the index map. (Trend distribution studies of these major lineaments show strong evidence of a continental regmatic fracture pattern.) Other features detected on ERTS imagery but not on aerial photos include many large circular or curvilinear tonal or dissection pattern anomalies that outline calderas, intrusive bodies, basins, etc.

Comparison studies showed that smaller features such as fracture traces (lineaments less than 1 mile long) and lineaments up to 4 or 5 miles long are not as detectable on the 1:1,000,000 scale ERTS imagery as they are on aerial photos. The use of 1:250,000 scale enlargements of ERTS scenes permits most of the smaller lineaments to be mapped, but aerial photos should be used for fracture trace studies.

Cost analysis showed that the use of ERTS-I imagery for regional scale structural studies is about 1/500 as expensive as using conventional aerial photography.

The various MSS bands were compared to determine the best ones for use. In general, the combined use of bands 5 (red) and 7 (infrared) as separate images will provide adequate information for most interpretations. The best single band and the best season of coverage depends on the problem to be solved and the region to be studied.

Experience with color composite images was very limited. However, the simulated false color infrared composite of bands 4, 5, and 7 was used, and large tonal variations were found because of processing differences between prints. This, combined with the necessity of using

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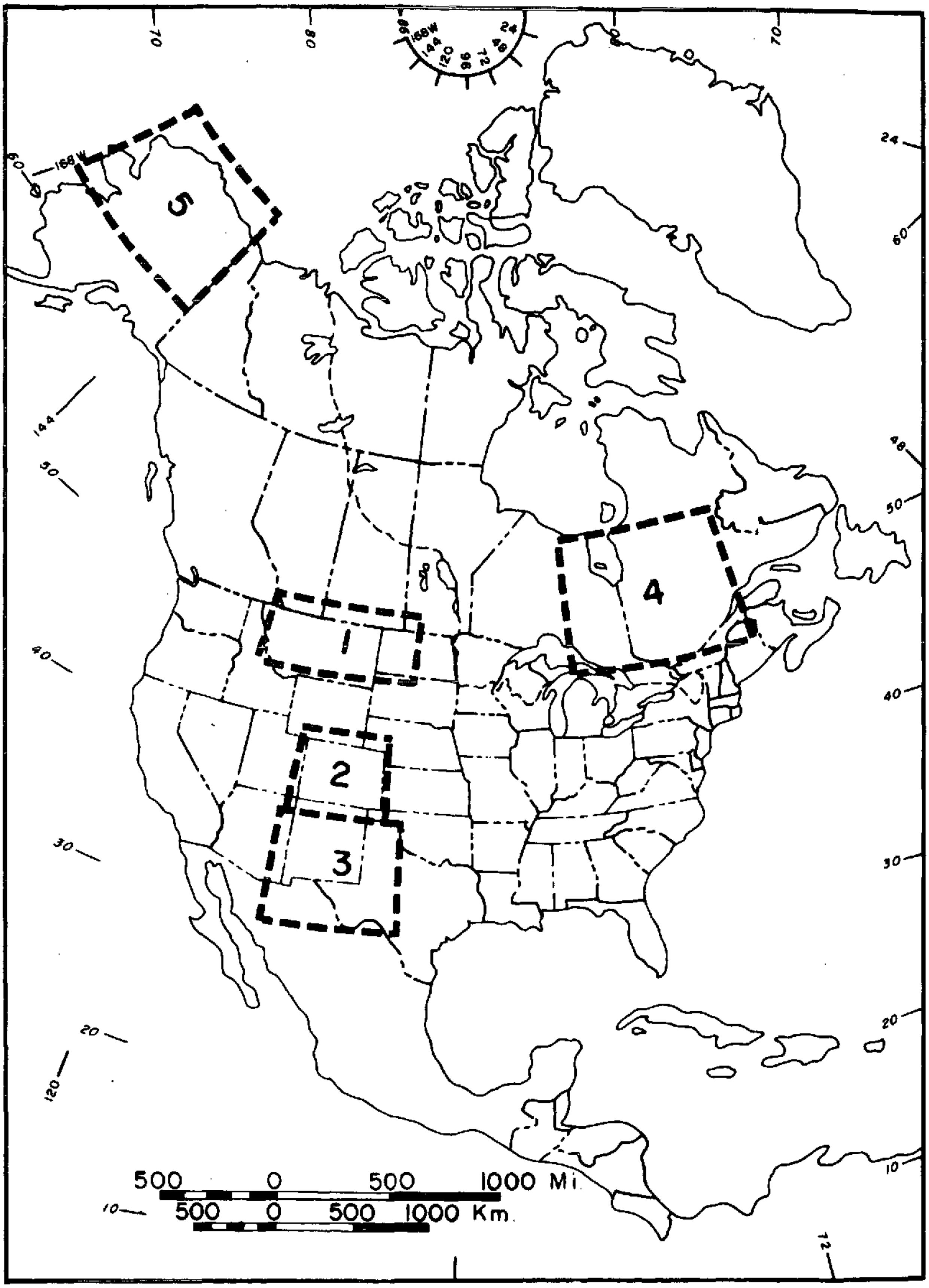

Figure 1. ERTS Study Areas, Investigation MMC-083

different seasonal coverages to get cloud-free images, caused the final mosaics to be such a mix of tones that they were difficult to use. With constant tone processing, the color composites probably would be superior to any single-band black and white prints for both lineament and tonal interpretation. However, single-band black and white mosaics are believed to be more cost-effective and easier to use until more uniform color products become available.

In the process of interpreting lineaments and curvilinear tonal or dissection anomalies, close empirical relationships were found between these features and both mineral deposits and the structure of sedimentary basins. It is believed that this type of broad-scale geomorphology coupled with simple-shear, block-tectonic structural interpretations and regional geologic and geophysical studies can provide a radically improved approach to reconnaissance prospecting for new mining and petroleum districts.

D. SUMMARY OF RECOMMENDATIONS

It is recommended that commercial applications of ERTS data be initiated utilizing both 1:1,000,000 and 1:250,000 or 1:500,000 scale mapping of lineaments and curvilinears with data analysis to provide first step broad reconnaissance guides to potential new mining districts and petroleum regions. This should be accompanied by further research studies including more detailed ERTS data analysis with annotation at 1:250,000 or 1:500,000 scale, and analysis of Skylab or high-altitude photography in conjunction with geologic interpretations over a series of known mining and oil or gas localities to more fully exploit the available information in the ERTS images and develop methods for defining individual prospects for detailed exploration. These studies should include field studies to verify the usefulness of ERTS imagery in reconnaissance prospecting for minerals and petroleum.

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LIST OF ABBREVIATIONS AND SYMBOLS

EROS–Earth Resources Observatory Systems
ERTS–Earth Resources Technology Satellite
MSS–Multispectral Scanner
NASA–National Aeronautics and Space Administration
OZ–Ounce
USGS–United States Geologic Survey

SECTION I
INTRODUCTION

A. STUDY OBJECTIVE

The general objective of this study was to evaluate the utility of ERTS-I imagery at 1:1,000,000 scale in commercial reconnaissance exploration for minerals and petroleum, and to begin to develop its role in helping to solve present and future resource problems. Specifically, this was to be accomplished by determining the feasibility of using ERTS-I imagery as a medium for interpreting and mapping large-scale structural lineaments as compared to using conventional aerial photos for this purpose. Other specific objectives included determining the optimum wavelength bands to be used and the best seasonal coverage to provide the necessary topographic, water feature, and tonal contrasts for lineament and geomorphic studies.

The eventual desired end product is the development of methods and approaches for future large-scale commercial utilization of ERTS imagery in mineral and petroleum reconnaissance.

B. BACKGROUND FOR THE INVESTIGATION

1. General

In recent years, increased attention has been given to considering continental-scale structural processes and their possible relationships to the formation of mineral and petroleum deposits. These include the new concepts of sea-floor spreading and plate tectonics as well as the older continental-drift theories. Details of interpretations and conclusions vary from one investigator to another, but one additional approach, lineament tectonics, seems to be emerging: the concept of a series of major zones of weakness in the continental basement rocks expressed as lineaments at the surface which have been sites of recurrent structural activity throughout much of geologic time. The recurrent activity along these weakness zones and the resultant stresses generated in the areas between the zones have produced folding and fracturing which can have a controlling effect on mineral and hydrocarbon deposit emplacement. A good understanding of the details of these relationships promises to offer a radically more effective reconnaissance prospecting tool.

For many years, "linears" or lineaments* detected visually or in geophysical data have been interpreted by geologists to represent the surface expression of buried faults or fracture zones. Hobbs in his description of the Atlantic border region was among the earlier writers to use the term "lineament" (Hobbs, 1911); however, the study of linear features and their geologic significance was pursued by John Phillips as early as 1828 (Umgrove, 1947). The methodology of mapping these features using aerial photography was described by Lattman (1958), and their use in geologic photointerpretation was summarized by Tator (1960). Until the advent of ERTS, it was not economically feasible to gather wide imagery coverage in the form of aerial photos in several wavelength bands at several seasons of the year, which is necessary for mapping these linear features with optimum detectability. An additional disadvantage in using aerial photos has been the very large number of photographs necessary for continental-scale coverage. The work is

*For the purposes of this study, linear or gently curved alignments of topographic features or tones identified on ERTS imagery are termed "linears," and those linears or groups of aligned linears which are interpreted to have geologic structural significance are termed "lineaments."

very tedious, and the large number of edges between photos can be misleading or can obscure the surface lineament indications needed for mapping. ERTS imagery is providing a unique opportunity to obtain the necessary coverage and viewpoint to adequately evaluate this new prospecting approach.

Before ERTS-I was launched, studies of the geologic significance of imagery from satellite altitudes were pursued using Gemini and Apollo photography and degraded aerial photography. These experiments demonstrated the advantages of the satellite viewpoint in presenting synoptic coverage for regional tectonic studies and geologic mapping (Lowman and Tiedemann, 1971). It was suggested that the study of major wrench fault systems is especially susceptible to attack with orbital photography (Lowman, 1968; 1971). Studies utilizing aerial photography degraded to resolutions of about 100 meters illustrated the potential improvements in recognizing and characterizing very large features in ERTS imagery because of the loss or reduction of distracting details (Short and McLeod, 1972). Studies using Nimbus imagery showed that even with the very low resolution obtainable (2 to 5 nautical miles) regional geologic features could be discerned (Sabantini *et al.*, 1971; Lathram, 1972).

2. Structural Reconnaissance for Minerals

a. Introduction

Many mineral deposits have been observed to occur along and adjacent to such prominent lineaments as the well-known Texas Lineament of the southwestern United States (Wertz, 1970). Stokes (1968) noted the genetic relationship of most ore deposits in Utah with relatively obscure, generally northeast-trending fractures that cut diagonally across the presently outlined mountain blocks. The deposits also are concentrated along well-recognized belts which trend in a generally easterly or northeasterly direction. Landwehr (1967, 1968) observed that with few exceptions, the centers of intrusion which produce minerals in the western United States lie in seven northeasterly-trending belts which he interprets to reflect early Precambrian zones of crustal weakness. Crockett and Mason (1968) describe the use of "megastructural" elements in the "basement complex" and unmetamorphosed "cover" rocks as essential guides in future exploration for diamonds and nickel in South Africa. They consider these to be zones of crustal weakness related to major lineaments which have served as foci of mantle disturbances over long periods of geologic time.

The details of the relationship of deposits to lineaments or belts have remained somewhat obscure, and prospecting applications have been limited mostly to searching along these trends. However, a new interpretive technique which applies to continental tectonics was developed recently (Thomas, 1971) and was based on observations published by Sales (1968). Combined with the new general theories of plate tectonics (Dewey and Bird, 1970; Isacks, Oliver, and Sykes, 1968) and continental drift (Morgan, 1968; LePichon, 1968; Carey, 1958), it seemed to offer a promising means of applying lineaments to fuel and mineral resource exploration.

This new concept is based on lateral movement on lineaments during orogenic stress, thereby coupling the interlineament continental plates or blocks* by simple shear producing deformational features which include folding and faulting.

*Blocks are considered to be lineament-defined divisions of the large continental plates.

Before publication of Sales' simple-shear concept, the prevailing lateral fault theory was based on pure-shear mechanics as conceived by Moody and Hill (1956). Figure 2 shows the difference between pure shear and simple shear. In pure shear, the compressional force is in line; that is, the incoming compressional force is directly opposed by a buttress effect. Resulting fold axes are perpendicular to the primary force direction, which is the bisectrix of the shear fractures shown on the strain ellipsoid. In simple-shear conditions, the strain model is deformed by secondary compressional forces generated within the block by the rotational action of the couple produced by the differential horizontal movement. Resulting fold axes occur at regular characteristic angular relationships to the bounding lineaments.

Moody and Hill postulated in their wrench-fault theory that basement zones of weakness are produced as master conjugate shear fractures during pure-shear, Precambrian orogenies. Subsequent orogenic stress reactivated these master shears laterally to form drag folds and faults which, in turn, gave rise (when laterally reactivated) to still higher orders of drag folds and faults. Eight orders of drag folds and faults were postulated. Today, the many orders of Moody and Hill wrench-fault tectonics above the first and second order are being questioned. With the publication of Sales' simple-shear mechanics, pure-shear mechanics, long considered as the basic mountain-building process, is now being reexamined.

b. Simple-Shear, Block Coupling

In the following paragraphs, the various degrees of lineament simple-shear, block coupling are briefly examined and some recognition characteristics for simple-shear tectonics are pointed out as a prerequisite to understanding the structural significance of lineaments as used in this study.

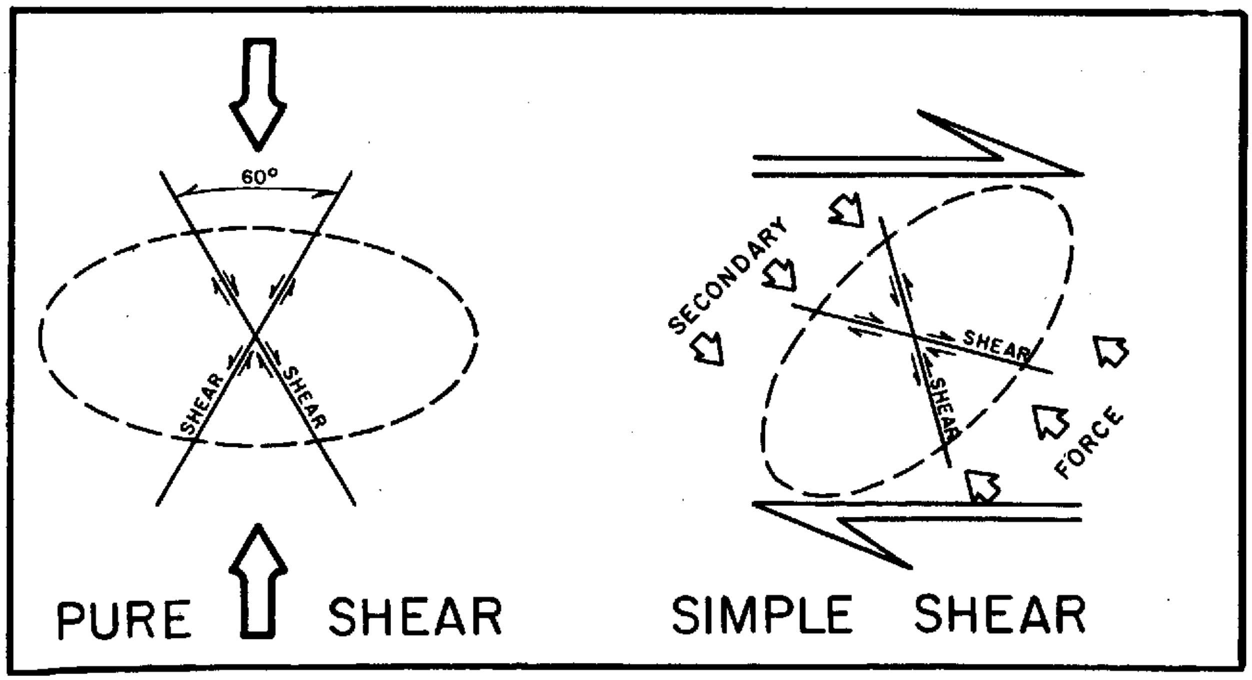

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Figure 2. Comparison Between Pure Shear (In-Line Compression) and Simple Shear (Differential Horizontal Movement)

Figure 3 illustrates three general stages of block coupling as a function of increased simple shear on the block-bounding lineaments which causes rotation of the couple-generated uplifts, faults, and fractures. The three general stages (incipient, moderate, and advanced) are used more for the convenience of discussion than for any precise classification. This is because couple deformational results occur as continuous responses to stress intensity. It is common to recognize advanced coupling near the block-bounding lineament and incipient to moderate coupling in the block proper.

As is evident from Figure 3, the drag fold uplift generated by coupling is characterized as being confined between the major lineaments along which the simple-shear adjustment took place. Flank faults ("step" faults), and cross-fold tensional fractures or faults are also confined between the lineaments. Conjugate shearing is generally of secondary importance. During greater coupling intensity, previously formed flank or cross-fold faults can become local shear zones.

A fourth coupling stage (extreme coupling) is recognized in zones where simple shear reaches a maximum. As shown in Figure 4, the characteristic *en echelon* drag folds of advanced coupling begin to override one another during extreme coupling, thrusting out the intervening syncline or Z-fold connection.

c. *Applications in Minerals Reconnaissance*

In minerals reconnaissance, one of the problems is to delineate those tension zones that can act as mineral conduits or depositional sites. The trends and general locations of these zones can be defined, utilizing the premises of the simple-shear, block-couple theory (Thomas, 1971) and the locations of the known major lineaments. For example, Figure 5 shows a preliminary map of the major lineaments on the Superior Plate of the Canadian Shield, along with the "greenstone belts" and inferred tension zones. The sites of commercial mineral localities are shown by triangles. The major lineaments are indicated at the surface by abrupt structural-trend changes or by major lithologic changes such as those occurring along the Grenville Front lineament or the Thompson-Cape Smith lineament. Lineament control of the deposits is suggested by the proximity of some of the deposits to major lineaments (especially Grenville Front) and by the fact that the favorable host rock "greenstone belts" occur in trends that intersect the major lineaments at angles ranging from 35 to 45 degrees. This angular range of intersections suggests coupling in the areas between the major lineaments, since right-lateral incipient coupling would (as illustrated by the strain ellipsoid diagrams, Figure 5) produce similar fracture trends as tensional features. Such mechanics may very well have produced Precambrian horsts and grabens in the Superior Plate, or Block, at 35- to 45-degree angles to the major lineaments. Deposition in the grabens, subsequent orogenesis, and metamorphism of and mineral emplacement in the graben sediments followed by long periods of erosion could explain the geologic picture seen today: highly mineralized greenstone belts, crossing ancient granite terrain in remarkably consistent trends, all of which terminate at major northeast lineaments. Using this kind of analysis to find tensional zones could guide prospectors to general areas with good possibilities for undiscovered deposits. (See Subsection III.D.)

3. Structural Reconnaissance for Fluid Hydrocarbons

a. *Introduction*

The same general approach in structural analysis (using a series of basement blocks subjected to coupling by simple shearing along basement weakness zones) can be applied in analyzing and predicting potential oil structures in the sedimentary basins.

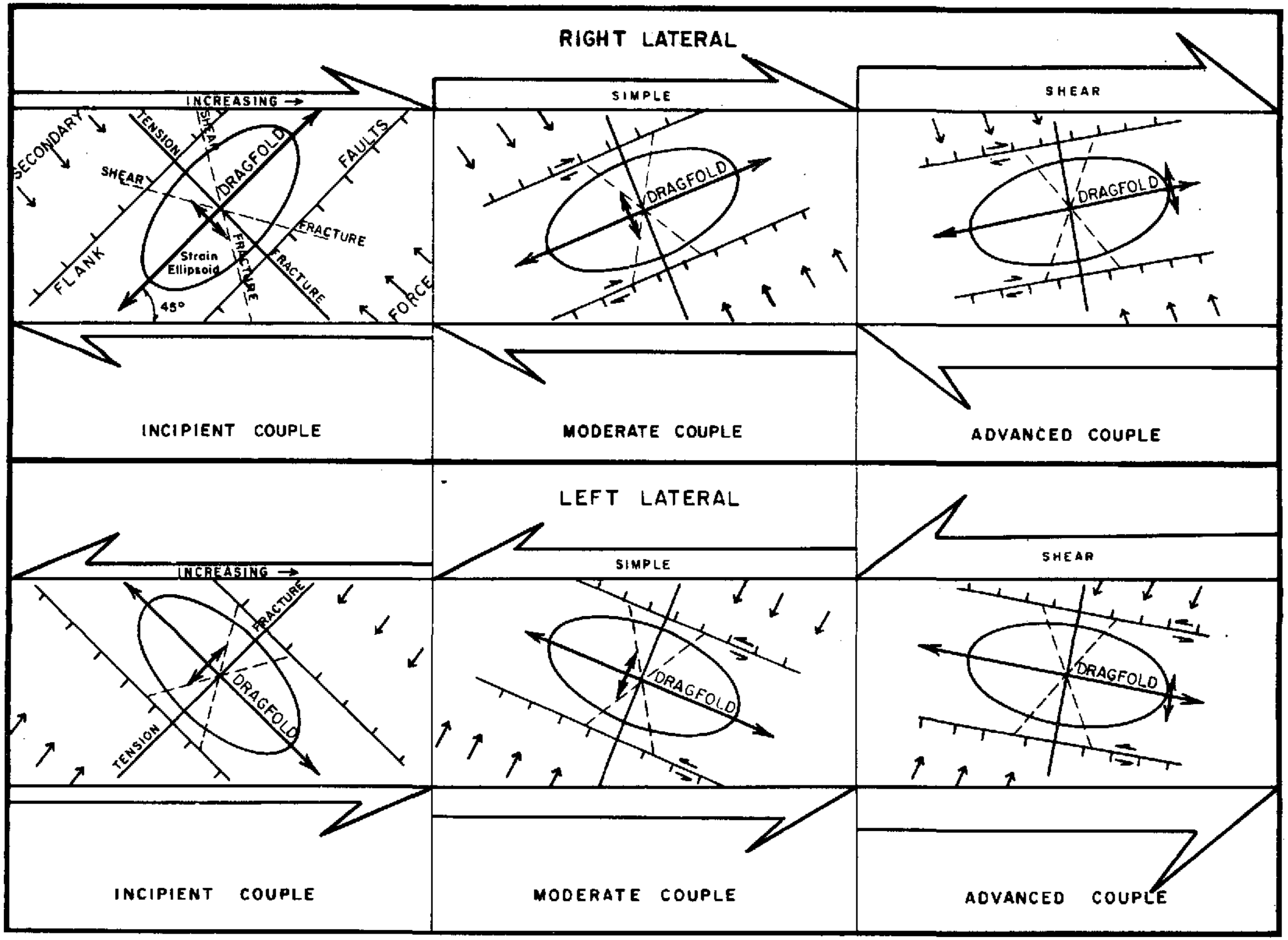

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Figure 3. Simple-Shear, Block-Coupling Mechanics

b. Applications in Petroleum Structural Reconnaissance

Basement weakness zones which pass beneath sedimentary basins may be represented at the surface as linears or lineaments in the form of:

- Tonal alignments brought about by vegetation or moisture conditions unique to the lineament zone
- Physiographic alignments produced by erosion
- Straight stream courses, also a product of erosion.

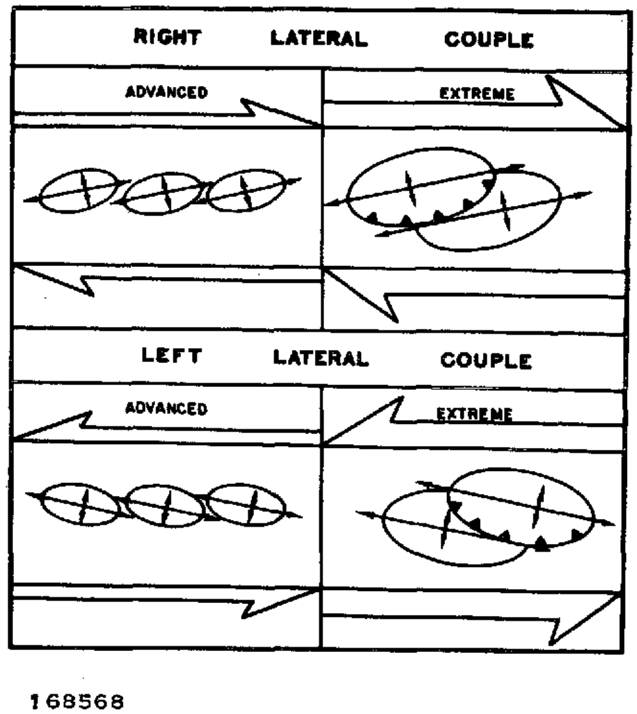

Figure 4. Simple-Shear Block Couple (Advanced to Extreme Stages)

All of these criteria for lineaments generally depend on one common condition: increased rock fracturing in the sedimentary rock (Lattman and Matzke, 1961) above the basement weakness zone because of lateral reactivation of the basement feature in response to orogenic stress. By itself, increased rock fracturing along linears and lineaments in a sedimentary basin can have a pronounced effect on rock porosity and permeability and on the ultimate recovery of hydrocarbons.

Another means of applying lineament mapping and subsequent structural analysis in a sedimentary basin involves recognizing the effects of simple shear in sedimentary rocks above a basement weakness zone. Figure 4 shows the characteristic *en echelon* arrangement of drag folds that can be expected to be produced in the sedimentary section if the basement weakness zone has adjusted laterally to an advanced stage of simple-shear coupling. The Piceance Basin of western Colorado and the Williston-Blood Creek Basin of eastern Montana display such structural effects (Figure 6). Both sets of anticlines [Figures 6(A) and 6(B)] are marked by their *en echelon* arrangement. Each succeeding fold occurs slightly offset to the southwest, similar to the effects in the left-lateral advanced coupling diagram of Figure 6. Quite often, folds of this type which cross sedimentary basins contain hydrocarbons, and are primary target localities in a basin-wide search for hydrocarbons. Since the basement weakness zone which is the cause of the folding can be represented as a surface lineament on aerial photographs or ERTS imagery, basin lineament mapping should be a first step in defining more favorable zones for hydrocarbon accumulation.

Besides using lineaments and subsequent structural analyses of the lineaments to define localities of increased fracturing and structural drag folds in sedimentary basins, it has been recognized (Sikabonyi and Rodgers, 1959) that lineaments, as reflections of basement weakness zones, may indicate where the weakness zones have affected paleotopography and thereby influenced paleodepositional conditions. Since fluid hydrocarbon accumulations require proper lithologic conditions, it is of the utmost importance in the search for hydrocarbons to be able to define zones or localities of changing lithologic conditions. Sikabonyi and Rodgers (1959)

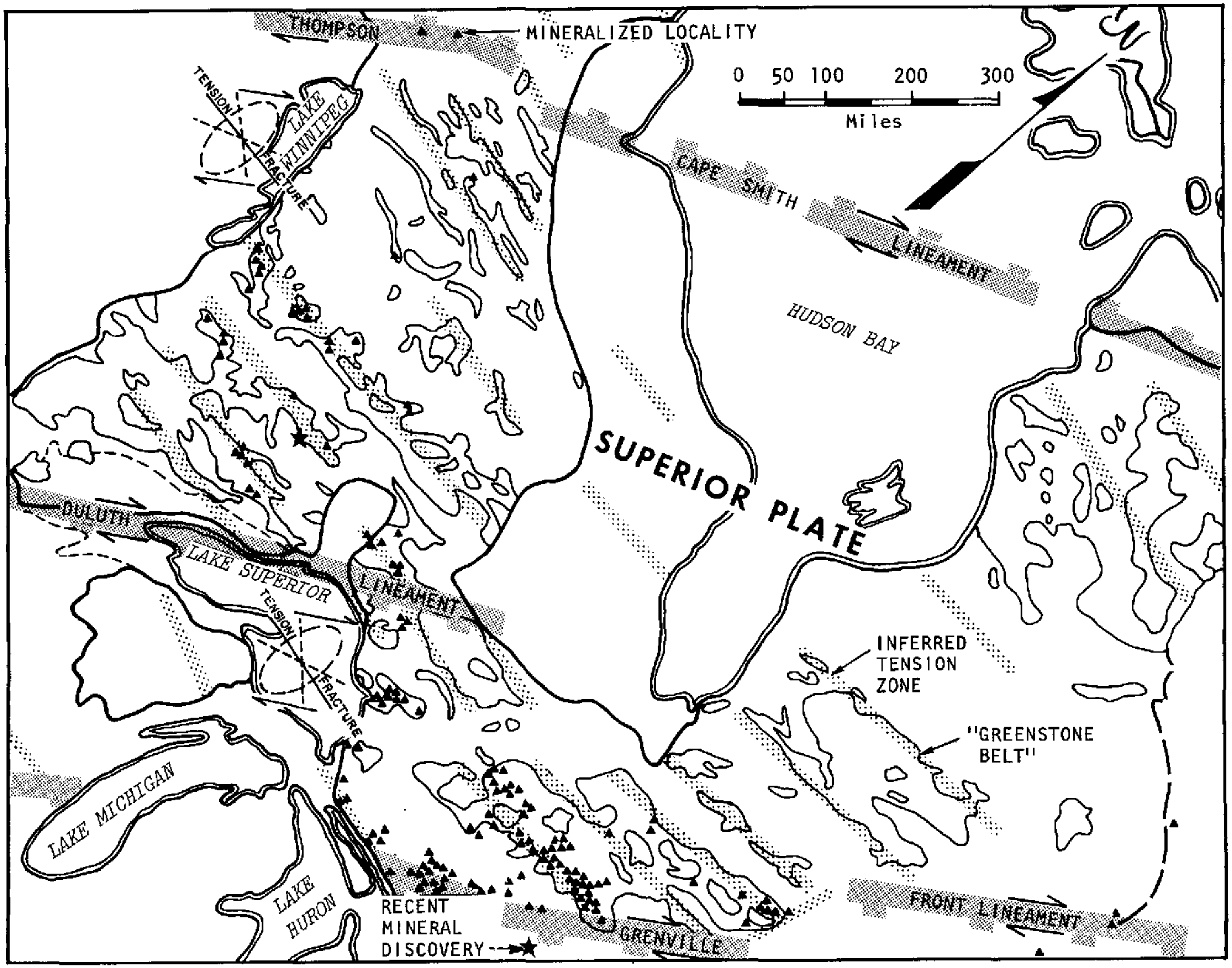

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Figure 5. Major Lineaments and Tensional Zones in Superior Plate

where vertical changes in the paleotopography would be more likely, thereby providing control for ancient shelf development. In either case, the mapping of the lineaments would be helpful in the initial reconnaissance of sedimentary basins for petroleum prospecting sites.

SECTION II
TECHNICAL APPROACH

A. STUDY AREA AND SPECTRAL BAND SELECTION

The five study areas (see Figure 1) were chosen to provide a representative variety of types of economic geology, physiography, and climates which included portions already mapped by Texas Instruments personnel so that conclusions could be drawn in comparing ERTS imagery with aerial photography as lineament mapping media. A good cross section of known deposits of gold, base metals, uranium, and petroleum are included. Area 1 contains many major Laramide mineral deposits (including Butte, Montana) and the petroliferous Williston-Blood Creek Basin. Area 2 includes the Colorado Mineral Belt, the uranium areas of Utah and Colorado, the oil and gas deposits of the San Juan and Piceance Basins and the sedimentary region east of the Front Range. Area 3 covers the southern Basin and Range Province, important porphyry copper deposits, the Ambrosia Lake uranium region, and the prolific oil fields of the Permian Basin in West Texas. Area 4 provides a sampling of Precambrian (Archean) gold and base metal deposits as well as the Blind River uranium area. Area 5 is largely a prospective area with large oil reserves (Prudhoe Bay) and great potential for both new petroleum and mineral prospects.

Originally, it was intended to prepare seasonal mosaics for each test area in each of the available spectral bands to evaluate variations in data quality. Experience soon demonstrated that only partial coverage could be obtained for each season because of areas of persistent cloud cover and poor image quality. It was found to be more practical to evaluate variations in data quality due to seasonal changes and different spectral bands by comparing individual images of representative scenes within the "master" mosaic of each area. The master mosaics were constructed from the best quality MSS band 6 (near-infrared band) images available regardless of the collection season. Band 6 was chosen as the best single band for data annotation based on comparisons of the preliminary mosaics of separate bands and on general experience in comparing large quantities of individual prints. This choice is supported by studies of multi-spectral photographic images which simulate ERTS observations where the contrasts of geologic features were optimized in the red band equivalent to MSS band 5 (Short and MacLeod, 1972). The best tonal contrasts were also observed in this study in MSS band 5; however, haze penetration and contrast of water features were best in MSS band 7. Band 6 (in the middle) provided all these adequately.

It was originally planned to select small regions within each area for comparing ERTS data with known mineral or petroleum deposits and with previous mapping based on aerial photos. Preliminary inspections and interpretations of the mosaics showed that the most significant advantage of ERTS imagery was in mapping very extensive lineaments which were not discernible on aerial photos. This was because their extensiveness cannot be seen due to the limited area coverage of individual photos. The decision was made to interpret the entire coverage of each area in terms of known mineral and petroleum deposits to better demonstrate the regional extent and significance of many of the lineament zones.

B. DATA PREPARATION AND METHOD OF ANALYSIS

The 9- by 9-inch positive prints of band 6 were made into a mosaic for each area, using the best and most cloud-free images available. As each shipment was received from NASA, the prints were inspected and compared with the mosaics to ensure that optimum quality coverage was obtained. The microfilm and Cumulative Standard Catalogs of ERTS images were inspected to try to find coverage for all gaps and cloud-covered areas. Where possible, these were filled by reordering.

When complete, each mosaic was photocopied to produce 1:1,000,000-scale prints for interpretation. The linears in each area were mapped separately and independently by three experienced interpreters who used transparent overlays and colored drafting tapes. The three linear maps were then superimposed and a final map was constructed using heavy dashed tapes for those linears agreed upon by the three interpreters, medium tape for those mapped by any two interpreters, and light dashed tape for those mapped by only one interpreter. This procedure was adopted to maximize objectivity in picking out these sometimes very subtle features. Anomalies indicated by curvilinear tonal and dissection patterns were then mapped by the interpreters.

Aligned patterns of linears which appeared to have regional structural significance were then sought, and these "lineaments" or "lineament zones" were connected by stippled patterns. Names were assigned to the most prominent ones and to those recognized as being previously reported in the literature.

Transparent overlays were prepared showing the mineral localities and oil or gas fields at the same scale. Data on gold and base metal deposits in the conterminous United States were obtained from Kinkle and Peterson (1962), McKnight, et al. [1962 (a) and (b)], and Koschmann and Bergendahl (1962). Uranium data for that area were obtained from Finch, et al. (1959), and Schnabel (1955). Oil and gas locations were taken from Vlissides and Quirin (1963) and Petroleum Information (1972). In Alaska, uranium mineral localities were taken from Cobb (1970), and the data on gold and base metals was from Cobb (1960, 1962). Both oil and gas occurrences and mineral deposits in Canada were taken from Geological Survey of Canada (1969). Mexican mineral deposits were obtained from Reyna (1956). These and all available geologic and tectonic maps at scales between 1:500,000 and 1:5,000,000 were used to evaluate the significance of the lineaments and geomorphic anomalies in the five areas. The detailed structures associated with selected major mineral occurrences were studied to determine their relationships to the regional structural patterns.

SECTION III
RESULTS OF THE INVESTIGATION

A. AREA 1 (MONTANA REGION)

1. General Observations

The "master" band 6 mosaic for Area 1 is shown in Figure 8. The observation identification number index of images is given in the appendix. For convenience in handling illustrations, the original 1:1,000,000 scale mosaic has been photo-reduced to 1:2,500,000 scale for this report. Because of degradation due to reduction and reproduction processes, some of the more subtle features are slightly less discernible on the reduced version than they were on the original; however, most major features can be readily identified. Figure 9 shows the mapped linears and curvilinear anomalies displayed as an overprint on the mosaic, and Figure 10 presents the lineament interpretation of aligned and continuous zones of linears as stippled patterns on a base map showing the oil and gas deposits and the major mining districts. This map has served as the primary basis for data interpretation. Methods of annotation and data analysis are described in Section II.

Area 1 was chosen for this study because it contains the only oil basin area known to the investigators in which detailed photogeologic studies have resulted in a proprietary regional lineament map of the Williston-Blood Creek Basin. Geophoto Services of Texas Instruments has allowed this information to be used as an aid in evaluating the ERTS data. This lineament map was produced from the interpretation of 1:20,000 scale aerial photographs and 1:48,000 scale mosaics and is based on linear geomorphic and/or structural trends. The proprietary map was reduced to 1:1,000,000 scale to match the ERTS lineament overlay so that a direct comparison of coincidence of the two data sets could be made. A distinct similarity of overall pattern was found in that both sets of data show a prominent NE "grain" and a less prominent NW series of lineaments. For comparison purposes, a criterion of coincidence was chosen whereby an ERTS-derived linear or lineament had to be coincident with at least half of a photo-derived lineament to be counted as a positive correlation. Table 1 summarizes the results.

TABLE 1. COMPARISON OF LINEAMENTS DERIVED FROM ERTS IMAGERY AND AERIAL PHOTOS

Lineaments	Results
ERTS major lineaments coincident with photo lineaments	27
ERTS linears coincident with photo lineaments	16
Total	43
Total number of photo lineaments	62
Coincidence (percentage)	70
New lineaments derived from ERTS data and *not* found on photos	10

Although minor "fracture traces" (linears less than a mile long) are not readily mappable on ERTS because of the small (1:1,000,000) scale, and minor linears up to 10 miles long are more easily mapped on the aerial photomosaics in most cases, the fact that 30 percent of the photo-derived lineaments were not detected on the ERTS imagery is not due to more detailed data

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obtainable from the photos but rather to cloud cover and poor tonal quality of some of the ERTS images used in the Area 1 mosiac. When better quality ERTS images of the region become available, the coincidence of lineaments should be significantly greater.

Even though some 30 percent of the photo lineaments were not detected on ERTS imagery, the comparison of the two types of data clearly indicates that ERTS lineament data compares favorably with that obtained from more costly conventional photos. Furthermore, because of the scale of ERTS imagery, the more extensive lineaments of continental scale can be mapped best (or perhaps only) on ERTS imagery.

It is concluded that the ERTS lineament interpretation is essentially equivalent in utility to the much more costly and time-consuming regional lineament mapping as done by photointerpretation, and in addition, provides continental-scale information that photos cannot. Exact figures on the cost of production of the photo lineament map are not available, but a reasonable estimate indicates that the effort involved was at least several orders of magnitude greater than that involved in the ERTS interpretation. (See Subsection III.H. for economic analysis data.) A study comparing ERTS lineaments with known faults in western Montana and northern Idaho is under way at Montana University (Weidman, *et al.*, 1973).

Identification and mapping of linears and curvilinear anomalies on the ERTS mosaic was done without any comparison with the geologic, mineral, or petroleum deposit maps of the area so that a maximum degree of objectivity could be maintained. After the major lineaments had been interpreted, comparisons were made with published structural maps as well as the Geophoto Services map of the Williston-Blood Creek Basin. Names for the major lineaments were adopted from the literature or the previous Geophoto map, or are new names chosen from topographic or planimetric names shown on the standard USGS 1:250,000 topographic maps of the area. In general, previously published local structural names were avoided to prevent confusion between well-defined known structural features and lineaments of more uncertain origin. Probably the best-defined lineament trends in Area 1 are the NW-striking Lewis and Clark Zone and the Coeur D'Alene-Nye-Bowler lineaments. These have long been recognized as structural shear zones (Sales, 1968; Stone, 1968).

All the inferred major lineaments in Area 1 are listed in Table 2 with the azimuths of trend. Figure 11 shows the major lineament trend distribution. It should be emphasized that Table 2 and Figure 11 relate only to the lineament zones inferred to be major lineament zones on the basis of extent and continuity. Other mapped linears are not included in the trend distribution.

Major NE (N 62° E), ESE (N 105° E) and NW (N 125° E) trends are obvious in Figure 11 as are subordinate NNW (N 150° E) and NNE (N 35° E) trends. These general trends have been observed by many workers around the world, and the NE and NW sets, in particular, have been referred to as the "global regmatic fracture pattern" (Lathram, 1972).

In addition to the linear features, prominent circular or curvilinear tonal or dissection patterns were annotated and are shown by the dotted lines in Figures 9 and 10. These features are thought to indicate intrusive bodies, caldera, uplifts, basins, and so forth. Their interpretive significance is discussed in the following sections.

TABLE 2. AREA 1 (MONTANA REGION) MAJOR LINEAMENTS

Name	Trend*	References
Pincher Creek	N 69 E	
Kootenai	N 70 E	
Cypress Hills	N 64 E	
Missoula	N 64 E	
Missouri River	N 63 E	Geophoto Services (1972)
Great Falls	N 47 E	Geophoto Services (1972)
Bitterroot	N 60 E	
Helena	N 57 E	
Butte	N 60 E	
Deer Lodge	N 64 E N 55 E	
Musselshell River	N 75 E N 69 E	Geophoto Services (1972)
Beaverhead	N 30 E	
Wheatland	N 56 E	Geophoto Services (1972)
Weldon	N 63 E	Stone (1968)
Roscoe-Billings–Fromberg	N 53 E	Geophoto Services (1972)
Hardin	N 13 E	Geophoto Services (1972)
Yellowstone River	N 58 E	Geophoto Services (1972)
Croff-Foxholm	N 57 E	Geophoto Services (1972)
Tongue River	N 35 E	Geophoto Services (1972)
Dickinson	N 59 E	Geophoto Services (1972)
Knife River	N 62 E	Geophoto Services (1972)
Powder River	N 35 E	Geophoto Services (1972)
Bell Creek	N 70 E	
Standing Rock	N 67 E	
Moreau River	N 70 E	
Box Elder	N 57 E	Geophoto Services (1972)
Brockton-Froid	N 74 E	Stone (1968)
Souris	N 61 E	
Lake Darling	N 153 E	
Weyburn	N 145 E N 124 E	
Missouri-Couteau	N 120 E	
Radville	N 140 E	
Bredette	N 135 E	Geophoto Services (1972)
Brorson	N 128 E	Geophoto Services (1972)
Watford City	N 107 E	Geophoto Services (1972)
Garrison	N 110 E	Geophoto Services (1972)
Mobridge	N 128 E	
Glasgow	N 131 E	Geophoto Services (1972)
Cedar Creek	N 150 E	Stone (1968)

*When more than one trend is present in a lineament, the dominant trend is indicated by underlining.

TABLE 2. AREA 1 (MONTANA REGION) MAJOR LINEAMENTS (Continued)

Name	Trend*	References
Cat Creek	N 134 E N 153 E N 143 E	Stone (1968)
Judith Mountains	N 107 E	Geophoto Services (1972)
Lethbridge	N 102 E	
Milk River	N 104 E	Geophoto Services (1972)
Marias	N 103 E	Geophoto Services (1972)
Shawmut	N 112 E N 118 E	Geophoto Services (1972)
Lake Basin	N 102 E	Stone (1968)
Harlowtown	N 107 E	
Big Belt Mountains	N 158 E	
Four Mile Coulee	N 148 E	
Nye-Bowler	N 106 E N 120 E	Sales (1968); Stone (1968)
Clark Fork	N 120 E	
Coeur d'Alene	N 110 E	Sales (1968); Stone (1968)
Lewis and Clark Zone	N 120 E	Contains the Flathead, Shawmut, Lake Basin, Coeur d'Alene and Clark Fork Lineaments (Smith, 1965).

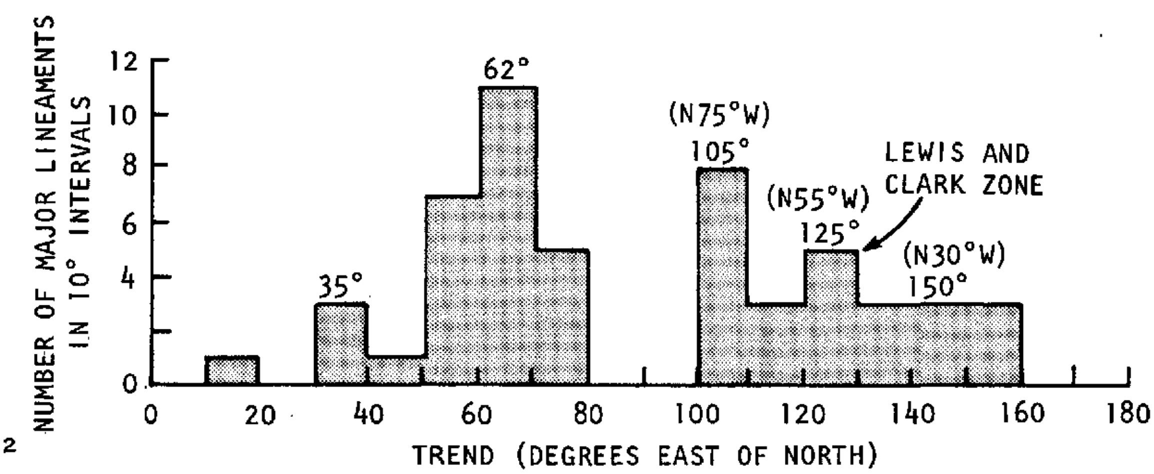

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Figure 11. Area 2 (Montana Region) Major Lineament Trend Distributions

2. Correlation of ERTS Data With Economic Deposits

a. *Preliminary Conclusions About the Structural Nature of ERTS Lineaments*

When a total area as large as the one included in this program is studied, it is necessary to limit detailed study of the lineaments to a few spot checks in each of the study areas where the structures are reasonably exposed. A conclusion from this phase of the work is that the major lineaments generally appear as zones of faulting, shearing, dike swarms, etc., up to several miles wide and with an average strike about the same as the lineament.

As an example in Area 1, the MISSOURI RIVER* lineament passes through the Bearpaw Mountains south of Havre, Montana, where it coincides with the "arch" of the intrusive uplift and consists of a strip 2 to 8 miles wide of deformed and metamorphosed sedimentary rocks accompanied by a swarm of thousands of dikes (Pecora *et al.*, 1957) with trends generally parallel to the strike of the lineament. This zone also produces a distinct aeromagnetic lineament of similar strike where it crosses the Warrick quadrangle (Balsey *et al.*, 1957). As indicated in later sections, in nearly all the areas where such studies of the detailed geology of the lineament could be made, it was similarly found that ERTS major lineaments are more likely to be relatively broad zones of weakness rather than single faults or fractures detectable as surface features. Consequently, unlike single faults or fractures which can be easily groundchecked and are common on large-scale "mine-type" maps, lineaments cannot be readily groundchecked. Indeed, many individual mine-map areas appear to be entirely included within a lineament zone which may be represented merely as a general structural grain over the entire map area. Maps showing the regional setting of mining districts rather than detailed mine maps are usually more useful in evaluating the possible relationship of the districts to the linear features.

Based on this view of the nature of the ERTS lineaments, the spatial correlation with mining districts must be approached in such a way that the probable relatively broad width of the potential zone of shearing or tension at the surface is taken into account as well as the possible composite errors in annotating the lineaments and in the positioning of mines at 1:1,000,000 scale. In this work, a mine is considered as probably being assiciated with a lineament if it is located within 4 miles of the center of the lineament. Similarly, the possibility of structural influence on oil accumulations is inferred if the mapped field is aligned with or appears to be bounded by a lineament within a margin of error of about 4 miles.

b. Gold and Base Metal Deposits

As a general observation, the gold and base metal deposits tend to be associated with the highest density of linears in the region where the Lewis and Clark Zone intersects the NE trending zone of lineaments between the MISSOULA-MISSOURI RIVER and the WHEATLAND-WELDON lineaments or on these zones. Control of the ore deposits in this region by the Lewis and Clark "line" has been recognized by Hobbs (1968), who suggested that other similar structural zones had been postulated but not documented.

Sixty-seven percent of all the deposits in Area 1 and 62 percent of the major mining centers are either on or within 4 miles of a linear as mapped from the ERTS imagery at 1:1,000,000 scale. If the annotation had been done at 1:250,000 scale, it is expected that the degree of correlations would be even higher due to the addition of many minor lineaments not mappable at the smaller scale. The high degree of association between the linears and the mining districts is clearly indicated by inspection of Figure 10. It can be observed that the center regions of the blocks are relatively devoid of deposits except within the Lewis and Clark Zone where the Lincoln, McClellan, Stemple and Marysville districts are located.

The Butte district lies close to a prominent ESE-trending linear between the NE-trending BUTTE and DEER LODGE lineaments. Meyer *et al.* (1968) shows a lineament approximately in the position of the ESE linear but shows no evidence for NE-trending lineaments in the area. If right-lateral, simple-shear coupling on the block between the BUTTE and DEER LODGE lineaments is hypothesized, a consideration of the strain ellipsoid indicates that the expected strike of incipient

*Names called out on the data interpretation maps are presented in text in all capital letters. Initial capitals are used to name those lineaments defined in previous literature by other authors.

cross-fold tension faulting would be ESE or at approximately 45 degrees to the NE lineaments. Similarly, the NE lineaments are generally along the strike of tensional faulting for left-lateral coupling between plates bounded by lineaments trending WNW to NW, such as the Lewis and Clark Zone (see Subsection III.B.2). Vein and fault systems at Butte show both NE- and ESE-striking swarms (Meyer *et al.* 1968) which may indicate structural control by right-lateral coupling on NE zones and left-lateral on NW zones at different times, that is, pre-Laramide Jurassic coupling on the NE zones and Laramide-post-Laramide on the NW zones.

The Warm Springs and North Moccasin districts lie on the ESE-striking JUDITH MOUNTAINS lineament, suggesting that right-lateral coupling between the HELENA and WHEATLAND-WELDON lineaments may have provided a tensional opening for those mineralizing solutions. This possible type of control of mineralization is more strongly evident in Areas 2, 3, and 4, and is discussed more thoroughly in the following sections dealing with economic deposits in those areas.

It is suggested that more detailed follow-on studies in this area should include evaluation of this ore control hypothesis in the other mining districts indicated in Figure 10. Figure 12 shows a simplified presentation of the major NE lineaments and the ESE lineaments and linears which would most likely be tension zones under the two types of coupling mentioned previously. It also shows the "Transverse Porphyry Belt" of Jerome and Cook (1967) in relation to our lineaments.

The only major mining districts apparently related to curvilinear anomalies are the Flint Creek, First Chance, Nine-Mile Creek, and Cedar Creek districts. A much more striking relationship was noted in Area 2 (see Subsection III.B.2.a).

c. Uranium Deposits

Two types of uranium deposits are found in Area 1: vein-type deposits in the Rocky Mountain area and in the Bearpaw Mountains, and uraniferous lignites and minor sandstone type deposits in the southeastern part of the area.

Sixty-five percent of the vein type deposits are found on or within 4 miles of ERTS linears, whereas only 46 percent of the lignite deposits are seen to be apparently related to linears. These results seem reasonable in light of the probable different origins of the deposits. The veins are most probably hydrothermal types with structural control generally similar to the other vein-type deposits. Conversely, the lignites are thought to derive their uranium content by leaching of overlying volcanics by ground waters and subsequent reprecipitation by reduction in the presence of the lignite beds. Thus, these latter deposits should be more stratigraphically than structurally controlled.

The curvilinear anomalies in the Slim Buttes area (103°W 45°30'N) are probably due to topography; the apparent control of the uranium is suspected to be due to the position of the outcrops of the lignite.

d. Hydrocarbon Occurrences

There are a few relatively striking examples of controls of oil and gas accumulations by lineaments in Area 1 (Figure 10). One of these is the series of small fields along the CAT CREEK linear; this is interpreted to be *en echelon* folding, as described in Subsection I.B.3. Another is

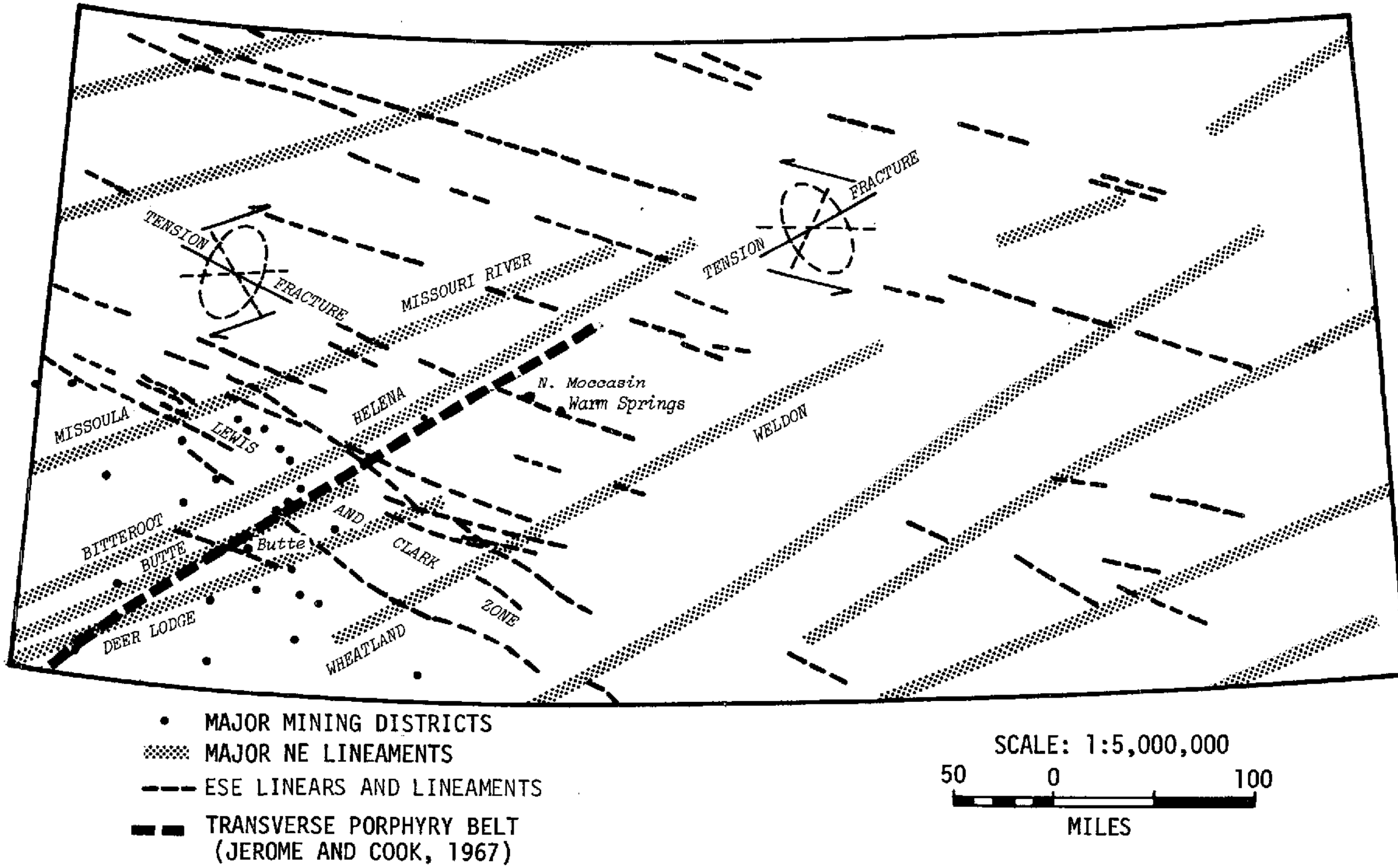

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Figure 12. Area 1 (Montana Region) Hypothetical Tension Zones and Major Mining Districts

the long, narrow field along the CEDAR CREEK lineament. This field, however, is the result of an anticline apparently associated with the lineaments.

In many cases, the oil and gas fields show apparent structural control by the lineaments in the form of narrowing or widening where crossed by a lineament or by one side or end being bordered or cut off by the lineament. Most of the fields lie in the blocks between lineaments but nearer to the lineaments than to the centers of the blocks. This sort of distribution would be expected if the lineament defined the edges of the basins or uplifts where conditions are generally more favorable for the formation of oil or gas traps by structural adjustment, reef growth during sedimentation, facies changes, development of pinchouts, etc. It should be noted, however, that in much of the Williston-Blood Creek Basin of Area 1, tonal quality of the imagery is too poor to adequately define a complete picture of surface lineaments. Thomas (1974) discusses in more detail the structural and stratigraphic significance of surface lineaments in this area as based on previous studies.

It is generally concluded that lineament interpretation can be best used for petroleum reconnaissance in Area 1 as a guide for seismic surveys to predict the best general areas and indicate the most fruitful profile directions.

B. AREA 2 (COLORADO REGION)

1. General Observations

Figure 13 shows the master mosaic prepared for Area 2. The images are the best available in band 6 as selected for regional lineament interpretation, regardless of season of coverage. The image observation identification numbers are given in the appendix.

Many of the more subtle linears cannot be easily discerned on Figure 13 because of degradation in the reduction and reproduction process, although they were easily visible on the original mosaic. However, an example of a strong linear can be seen trending southwest from Denver. This has been named the INDEPENDENCE PASS–NORTH FORK lineament because it is closely coincident with strong Precambrian shear zones reported in those areas (Tweto and Sims, 1963, Plate I, localities 6 and 4). This and all other linear features of the mosaic were mapped and graded as described in Section II. The resulting linears are shown in Figure 14 as an overprint on the mosaic.

The most prominent lineaments–those which are inferred as major lineaments and those which have been reported previously in the literature–are named in Figure 15. The inferred major lineament trends are also accented by a stippled pattern. Names of previously reported lineaments in the area (Stone, 1968; Kelley, 1955; Mayo, 1958; etc.) were used where lineaments of this study coincided in some degree with these previous features. Other lineament names (Figure 15) were taken from topographic or planimetric features in the region.

Because Area 2 consists principally of mountains displaying high relief and well-developed drainage systems, an abundance of lineaments were mapped. Note in Figure 15 in the eastern third where the High Plains occur, how lineament frequency becomes less. The general pattern of lineaments in Area 2 is strongly characterized by a northeasterly grain, even though the majority of mountain uplifts trend north-northwesterly. The possible reason for this is discussed in Subsection III.B.2. The WNW trend common to such continental lineaments as the TEXAS (to

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the south in Area 3) and LEWIS-CLARK (Area 1) are not readily apparent in Figure 15, ex for the WICHITA and NORTH PLATTE lineaments. Furthermore, the WICHITA ZONE is readily traceable into the mountains. Similar left-lateral adjustment effects as those found on WICHITA (Sales, 1968) are found, however, along such features as the GUNNISON PARADOX lineaments, which may indicate a left-lateral *en echelon* continuation of the efl of the WICHITA ZONE. Our preliminary investigations (Saunders, *et al.*, 1973) suggested connection of the WICHITA ZONE with the UINTA-UINTA MOUNTAINS lineament via LEADVILLE-WET MOUNTAINS feature. Further study indicates, however, that the sugge alternative *en echelon* explanation is probably more correct for the WICHITA ZONE.

For the most part, those lineaments trending NNW, such as the FRONT RAN LEADVILLE and WET MOUNTAINS, are prominent on the ERTS imagery as linear flank mountain uplifts, and in some cases coincide at least in part with known faults displaying ver adjustment effects. Such features as the Gunnison and Paradox lineaments appear to con both vertical and lateral adjustment effects and are as prominent on the ERTS imagery as previously mentioned mountain flank lineaments. Lineaments in the southwest corner of Ar (UTE, HENRY and ZUNI) appear to coincide approximately with Kelley's (1968) intru trends but are nowhere as prominent on ERTS imagery as those features described previously

Figure 15 also displays numerous circular or curvilinear tonal anomalies and dissec patterns evident in the mountainous terrain. As previously discussed in Subsection III.A (Are Montana), these circular features are believed to represent plutons and/or calderas in mount ous areas, since several of the patterns coincide with these features. In some cases, the patt coincide with basins such as the southern part of the Piceance Basin (Figure 15, immediately of Grand Junction) or uplifts such as the White River uplift (Figure 15, immediately north of Piceance Basin pattern). The well-defined circular outline of the White River uplift sugges very extensive buried intrusive body as the cause of the uplift. Note again, as in the case of lineaments, that curvilinear patterns are not frequent in the High Plains region (Figure 15).

The major named lineaments are listed in Table 3 with the directions of their trends cases where more than two trends are evident because of lineament curvature or branching, t are given. An inspection of Figure 15 shows that there are several apparent series of paralle subparallel lineaments. Figure 16 shows the trend distribution of the major lineaments. M peaks in the distribution occur at about N 60° E (NE) and N 135° E (NW) with less pronour peaks at about N 105° E, and N 155° E. The peak at N 135° E appears to represent the m

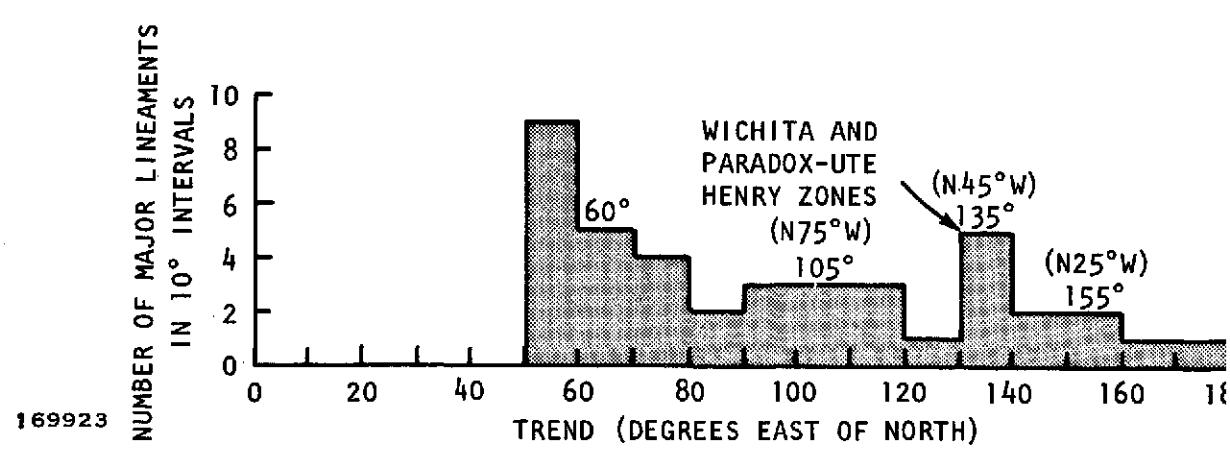

Figure 16. Area 2 (Colorado Region) Data Interpretation Map

TABLE 3. AREA 2 (COLORADO REGION) MAJOR LINEAMENTS

Name	Trend*	Reference
Evanston	N 56 E	
Wamsutter	N 73 E	
Hartville	N 51 E	Stone (1968)
Miller Hill–Flat Top	N 58 E	Stone (1968)
Little Bear	N 70 E	
Steamboat Springs	N 65 E	
Pierce–Black Hollow	N 73 E	Stone (1968)
South Platte	N 50 E N 55 E	
Colorado River	N 59 E	
Denver	N 70 E N 80 E	
Independence Pass–North Fork	N 58 E	Tweto and Sims (1963)
San Juan	N 64 E	
Navajo	N 58 E N 64 E	
La Veta	N 54 E N 61 E	
Jemez	N 63 E	Mayo (1958)
Green River	N 139 E	
Uinta Mountains	N 87 E N 97 E	
Uinta	N 107 E	Stone (1968)
North Platte	N 114 E N 66 W	
Gunnison River	N 135 E N 145 E	
Leadville	N 152 E	Mayo (1958), Central Colorado Belt lineament
Front Range	N 160 E	Mayo (1958), Laramie lineament
Paradox	N 130 E N 140 E	
Pueblo	N 102 E	
Lamar	N 102 E	
Ute	N 133 E	Kelley (1955)
Henry	N 133 E	Kelley (1955)
Apishapa	N 119 E	Stone (1968)
Nacimento	N 179 E	(near Mayo's 1958 Cordilleran Front Belt lineament)
Wichita Zone	N 115 E N 126 E	Sales (1968); Schmitt (1966)
Purgatoire River	N 42 E	
Clear Creek	N 94 E	
Dillon	N 93 E	
Wet Mountains	N 150 E	

*When more than one trend is present in a lineament, the dominant trend is indicated by underlining.

WNW lineament zones considered to have dominant left-lateral shearing during the Laramide orogeny (Thomas, 1971; Sales, 1968).

The strong northeast lineament "grain" which crosses the generally NNW trend of the mountain ranges may be explained in terms of tensional fracturing which would be produced by large-block, simple-shear, left-lateral coupling between the major WNW trending lineament zones such as the LEWIS-CLARK, WICHITA, and TEXAS (see Figures 12 and 24). Such tensional features exert stronger control on the direction of stream channels than would other types of faults or shear zones, and therefore would tend to emphasize the lineaments defined by them.

The predominant NE lineament trend and the less strong ESE trends are similar to the predominant direction of strike of mineralized veins in Colorado (Landwehr, 1967) and to the hypothesized Precambrian structural "grain" thought by many to be a controlling influence on the Precambrian and the younger ore deposits in the Western U.S. (Landwehr, 1967, 1968; Schmitt, 1966; Stokes, 1968; and others). The visibility of these Precambrian weakness zones through the younger covering rocks is explained as being caused by recurring adjustments along the zones which control the jointing and faulting directions in the overlying rocks (Lattman and Matzke, 1961; Hodgson, 1965). These, in turn, control the tonal and erosional patterns visible on ERTS imagery. Thus, for the first time there is large-scale visible evidence of the strong NE trending "grain." This may very well be the key to a much better understanding of the structural history of our major mining and petroleum producing districts.

2. Correlation of ERTS Data with Economic Deposits

a. Gold and Base Metal Deposits

A study of the gold and base metal deposits in Figure 15 showed that 100 percent of the major deposits and 95 percent of all of these mines are located within 4 miles of one of the linears. This, coupled with the observed greater density of linears in the mineral zones, indicates particularly strong lineament control of these deposits.

Tweto and Sims (1963) showed several surface-mapped, basement-shear zones in the central Colorado Rockies. They expressed the opinion that these zones not only localized the mineral belt but played an active part in its origin. To test the hypothesis that ancient and deep-seated zones of crustal weakness can be expressed as linears or lineaments in the ERTS imagery, a detailed comparison of Tweto and Sims' map of the Precambrian shear zones was made with the linear features shown in Figure 15 (see Figure 17). Their Idaho Springs-Ralston shear zone (① in Figure 17) is seen to be coincident with the NE-trending linear crossing just east of the center of the CLEAR CREEK lineament. One of the shear zones near Berthoud Pass (② in Figure 17) is seen as the linear which is nearly coincident. Tweto and Sims' North Fork fault (④ in Figure 17), Independence Pass shear zone (⑥ in Figure 17), and a small zone of faulting to the southwest fall directly on the strong Texas Instruments INDEPENDENCE PASS–NORTH FORK lineament, as noted previously. Tweto and Sims' zone of NE lineations in the River Portal Schist of the Black Canyon of the Gunnison (⑨ in Figure 17) is approximately on strike with that lineament just beyond its southwest end. Tweto and Sims' Homestake shear zone (⑤ in Figure 17) appears to be related to the nearby group of linears. Inspection of Figure 17 shows very close association of Tweto and Sims' mapped faults and shear zones with the FRONT RANGE, WET MOUNTAINS, LEADVILLE, and DILLON lineaments, as well as several of the linears.

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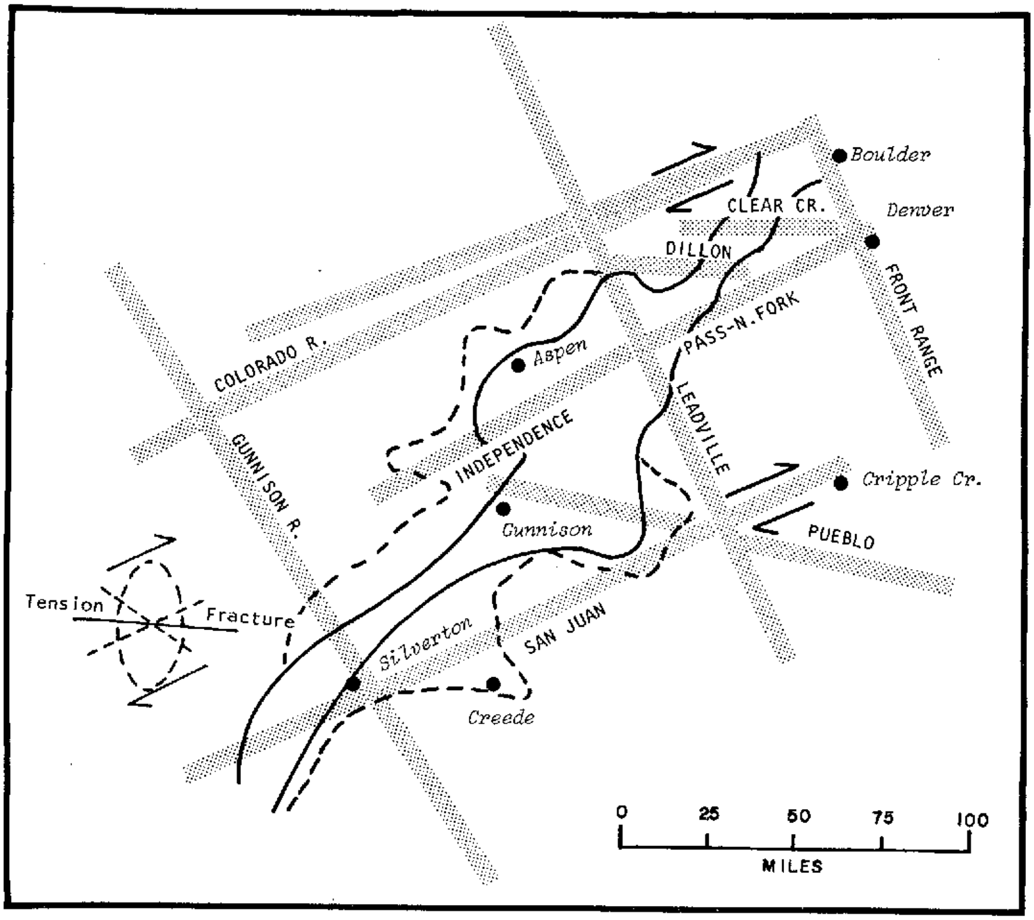

Mineral belt boundaries as defined by principal mining districts of Laramide age

Maximum boundaries as defined by all intrusive porphyry bodies and mineralized areas of Laramide age, and mining districts of Tertiary age in the San Juan Mtns.
(After Tweto and Sims, 1963)

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Figure 18. Major Lineaments and the "Colorado Mineral Belt"

This coincidence between the linear features and the mapped Precambrian shear zones provides strong support for using ERTS imagery in extending and connecting local shear patterns to provide a regional interpretation of the mineralization control by Precambrian crustal weakness zones.

Examination of Figures 17 and 18 in relation to the Colorado Mineral Belt (as defined by Tweto and Sims, Figure 18) and the major lineaments of this study shows a possible significant relationship of minerals and lineaments not previously recognized in Colorado. Like most regional "mineral belts," the Colorado belt has been defined by "connecting" known deposit localities into a regional trend. Locally, the inferred trend may be supported by field-observed shear zones, but inspection of Figure 17 shows that all these with a NE trend are essentially parallel to the major mapped lineaments rather than to the inferred trend of the Colorado

Mineral Belt. These data support a "connection" of the Aspen-Clear Creek-Central City mineralized localities rather than a "connection" between the Clear Creek-Central City region and Silverton, via the Aspen and Gunnison Areas (Figure 18). A glance at Figure 15 shows that there are no lineaments of any magnitude, suggesting a generic "connection" between the latter two regions, as would be indicated by the inferred trend of the Colorado Mineral Belt; and consequently, there is cause to wonder about the validity of any generic inferences drawn from the trend of the mineral belt as it is usually shown. Rather, it is suggested that all the available data as shown in Figures 15, 17, and 18 indicate that it is reasonable to conclude that the proper "connection" of the Silverton-San Juan Mountains area is with the Cripple Creek area via the Bonanza locality along the SAN JUAN lineament.

Such "connections" of mining districts along ERTS-derived lineaments and linears is felt to be a truer correlation than "connections" based only on observed linear arrangements, inasmuch as there is strong evidence that the linears are related to actual structural features. This, in turn, suggests localities of exploration interest perhaps not previously recognized. These would include, for example, localities along the SAN JUAN lineament, especially those where curvilinear anomalies occur. Parallel major lineaments such as the NAVAJO, LA VETA and JEMEZ should also be examined for localities of interest.

In general, the mapping of ERTS lineaments in the Colorado region may very well provide a greater understanding of basement framework control of mineral emplacement than any other media available to date, and with greater understanding will come increased success in exploration.

From the regional viewpoint, the prolific mineralized areas in Colorado are bounded on the north by the COLORADO RIVER lineament zone and on the south by the SAN JUAN lineament zone, as indicated in Figure 18. In the central and northern part of the belt, many of the mineral deposits mapped in Figure 15 appear to be associated with (or on strike with) east-west lineaments such as the CLEAR CREEK, DILLON, PUEBLO and many small linears of similar strike. If it is hypothesized that right-lateral, simple-shear coupling is imposed on the blocks included between the major NE lineaments, the incipient cross-fold tensional fracturing would strike essentially east to west, as shown by the strain ellipsoid in Figure 18.

Left-lateral coupling on the continental lineament zones trending WNW leads to generally NE-trending tensional features. Such tensional features should provide good channelways for mineralizing solutions. An inspection of Figure 15 shows a close association of the major mineral occurrences with both northeast or generally east-west trending lineaments. Predominant NE strikes of mineralized veins in Colorado (Landwehr, 1967) were discussed earlier. Thus, the ERTS data, the field observations, and the block tectonics/simple-shear theory all seem to agree that the generally east-west and northeast directions are preferred for mineralized structures in this region. This indicates that linears and lineaments with these general strike directions should be the most productive for prospecting.

Figure 15 also shows the curvilinear tonal or dissection pattern anomalies as dotted lines. As a general observation, the precious and base metal mines of Colorado tend to be located around the edges of these features, particularly where a linear crosses the curvilinear anomaly. This relationship is particularly striking in the San Juan Mountains where many studies have illustrated the localization of most known ore deposits around the youngest subsidence caldera in the complex (Steven, 1968). These caldera or "caldrons" are nearly circular features and comprise part of a large area of complexly overlapping volcanic subsidence structures of middle Tertiary age. Steven reports that exploration for concealed ore deposits in the Creede Mining District has already been successfully guided by the relationship of the known deposits to the edges of the youngest caldera, and that this approach should be helpful in judging the potential of other areas nearby. He states that although several of these caldera are known, undoubtedly many others remain undetected.

Figure 19 shows the relationship of the ERTS-mapped caldera which appear as circular dissection anomalies with the major ore deposits in the Western San Juan Mountains. The well-known Silverton and Lake City caldera (Burbank and Luedke, 1968) are easily seen in the ERTS imagery, along with many other apparently similar structures. The previously undetected caldron northwest of the Silverton feature shows a close relationship to the deposits in the Telluride area. The Rico district, while not apparently related to any caldron structure, does show an apparent relationship to a mapped linear. On the basis of these observations, it is concluded that ERTS data should prove very useful in helping to guide further exploration for concealed deposits in the San Juan volcanic field. This is further supported by the relationships of the Creede and Summitville deposits (Figure 15) with linears and curvilinear features. The Creede caldron is known and a similar type feature has been reported previously for the Summitville area (Lipman and Steven, 1970). The San Luis caldron reported north of Creede (Steven, 1968) was not found by ERTS imagery on the initial interpretation, but a circular structure was detected there on close reexamination.

A comparison of the ERTS data with the reported mineralization in the Red River Area, New Mexico (near center bottom of Figure 15), shows a strikingly good correlation of the circular anomaly with the "Precambrian Gold Hill positive caldera block" (Carpenter, 1968). The northern-most NE-trending linear intersecting the circular anomaly on Figure 15 coincides with the Red River fault, and the Questa molybdenum mine (not shown in Figure 15) is located at the intersection of the Red River fault and the circular anomaly. Further, Carpenter shows a large number of precious and base metal prospects and mines scattered generally around the intersections of the two NE-striking linears and the circular anomaly. If this area is viewed in terms of a "simulated" remote reconnaissance prospect based on the ERTS data and the observed relationship between linears, curvilinear anomalies, and known mines in other areas, it is reasonable to predict success in an ensuing detailed exploration of the area.

b. Uranium Deposits

The uranium deposits of the Colorado region include vein-type deposits generally associated with the Colorado mineral belt (Walker *et al.*, 1963) and the sandstone-type deposits of the Colorado Plateau region (Fischer, 1968). The vein deposits appear to be correlated with the ERTS data in essentially the same way as are the precious and base metal deposits (see Subsection III.B.2.a). About 82 percent of these deposits are located within 4 miles of a linear.

The sandstone-type deposits are more scattered and do not show such a close relationship to the linear and curvilinear features. About 55 percent of these deposits are located within 4 miles of a linear, and inspection of Figure 15 shows that those in the southwest Colorado region appear to be loosely associated with the NW-trending lineaments, including the UNCOMPAHGRE FAULT, PARADOX, UTE, and HENRY lineaments, as well as other nearby linears of varying strike. This is partly due to the relatively linear distribution of the outcrops of

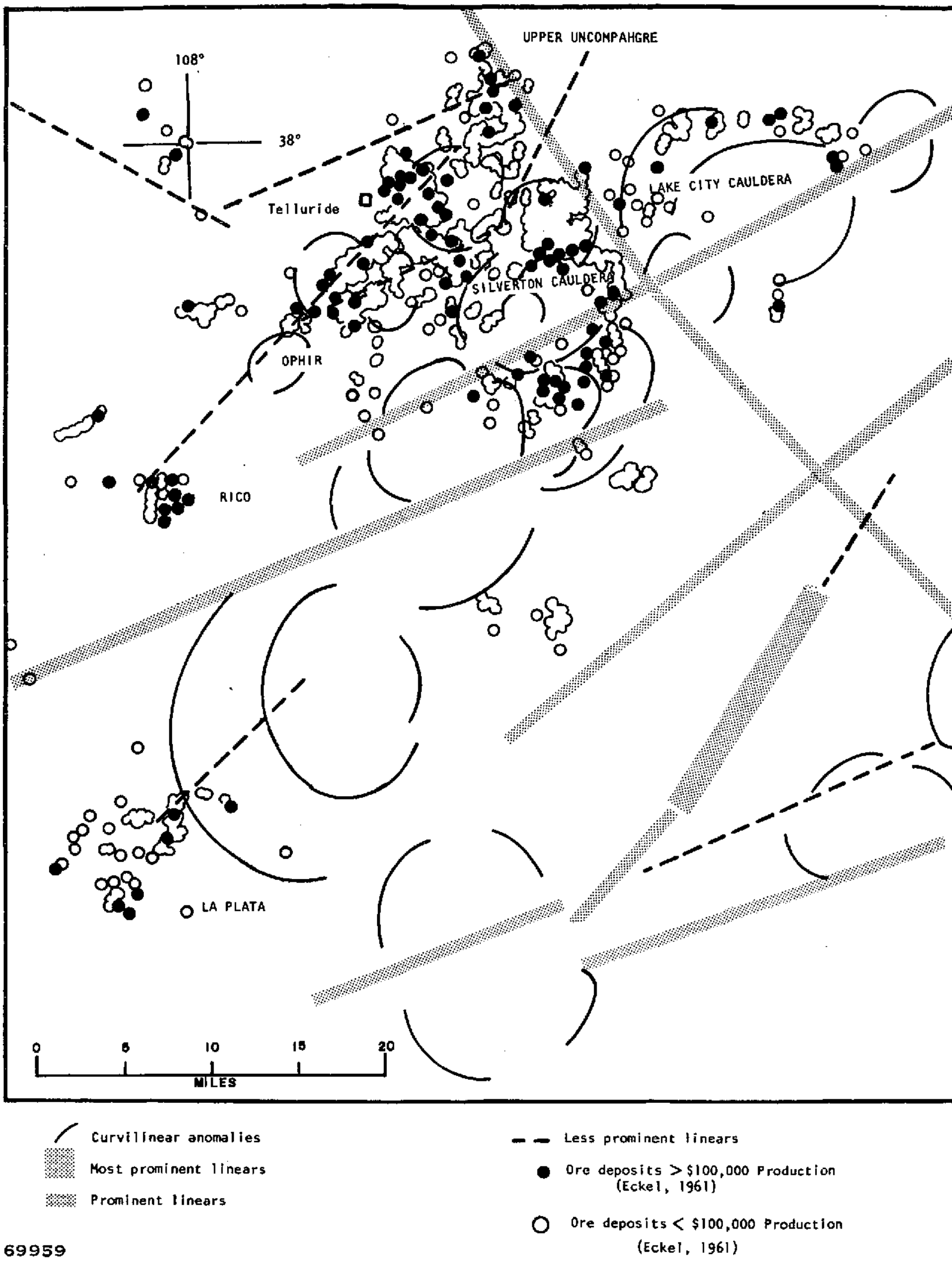

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Figure 19. ERTS Data and Ore Deposits of the Western San Juan Mountains

the uranium-bearing formations as they are controlled by the structure of the salt anticlines in the area (Finch, 1955). Wood (1968) ascribes the apparent spread of the uranium deposits along the Lisbon Valley fault to a flattening of the angles of nonconformity between the Cutler and Chinle beds and a flattening of the dip of these beds at each end of the Lisbon anticline. (This area is located just south of the PARADOX label on that lineament in Figure 15.) He also suggests that the stratigraphic limitations of the uranium ore belt (which contain the Big Indian ore deposit) may have been controlled by the water table or by a water-oil-gas interface. If water tables or water-oil-gas interfaces are structurally controlled, this suggests the possibility of utilizing lineament structure analyses to attempt to predict locations where similar conditions might be found to be favorable for uranium deposition from the ground waters. The approach might be generally patterned after the application of lineament analyses in the search for favorable petroleum structures.

Many of the uranium deposits of the Colorado Plateau region also appear to be distributed around the laccolithic intrusive centers in the area including the La Sal Mountains and the Ute Mountains (Fischer, 1968). This association is reasonable in light of either general theory for the origin of the deposits, that is:

1. Groundwater leaching of slightly uraniferous volcanics followed by deposition in favorable sites by reducing agents such as carbonized wood, hydrogen sulfide, etc. (Harshman, 1968)
2. Telethermal transport from the intrusive centers via faults, permeable sediments, etc., to be deposited as in 1, above.

In the first theory, the source of the volcanics could have been the intrusive center. Lineaments could be related to this process if they were the controlling influence on the intrusive either by providing the weakness point for intrusion or by initiating intrusion by drag folding to produce centers of uplift in the crust. In the second theory, the lineaments could serve as channelways for the telethermal solutions. Further study of the details of the origins of uranium deposits as they may relate to simple-shear, block-couple mechanics might lead to an improved reconnaissance guidance to new uranium prospects.

It has also been observed that many of the uranium ores are associated with paleostream channels. It is suggested that the linears may serve as guides to locating paleostream channels on the basis that the same zones of weakness which influence today's drainage must have also influenced the paleodrainage in a similar manner. Thus, the linears should be useful as guides for reconnaissance prospecting in those covered areas some distance back from the outcrops of the mineralized formations. This possibility should be investigated using 1:250,000 scale imagery and a more detailed interpretation than was possible during this study.

c. *Hydrocarbon Occurrences*

Lineament control on the location of oil and gas fields is particularly striking in the San Juan basin (southwest portion of Area 2) where the known gas accumulations appear to be confined between the PARADOX and UTE lineaments and the oil field zone (Aneth trend) is bounded by the UTE and HENRY lineaments. In general, the basins are roughly outlined by many of the lineaments or curvilinear anomalies, and the edges of some of the fields appear to be defined by linears. The STEAMBOAT SPRINGS lineament has a series of five oil and two gas fields on it, or adjacent to it. Other oil and gas occurrences appear to cluster around the

WAMSUTTER, GREEN RIVER, UINTA MOUNTAINS, MILLER HILL-FLAT TOP, PIERCE-BLACK HOLLOW, DENVER, COLORADO RIVER, GUNNISON, UTE and LA VETA lineaments. The Florence field is located at the junction of the PUEBLO and WET MOUNTAINS lineaments. This general close association supports the genetic relationships described in Subsection I.B.3 in that regions on or near lineaments should be favorable for petroleum accumulations by providing:

Zones of increased porosity and permeability by fracturing

More intensive drag folding by advanced coupling near the lineament

Shelf areas near the edges of the basins

Zones favorable for reef growth.

Of interest also in the lineament role of hydrocarbon control is that in defining basins and shelf areas, lineaments often appear to "offset" deposits when actually the lineament is merely defining two sub-basins within a larger basin. Such may be the case in the Denver Basin east of Denver (Figure 15). The NE, SOUTH PLATTE lineament appears to "interrupt" the production trends, entering Colorado from Wyoming. These trends are related to a shelf paleodepositional environment, but it is interesting to note that producing localities diverge from a general north-south strike whenever a NE lineament is encountered (PIERCE-BLACK HOLLOW, SOUTH PLATTE, and DENVER lineaments). It may very well be that each of these lineaments affected the development of subtle paleosubbasins in which favorable stratigraphic conditions follow to some extent the position of the lineaments. If such is the case, the areas of the continuation of the SAN JUAN and LA VETA lineaments into the Denver Basin may be sites of similar hydrocarbon accumulations.

These observations lead to the conclusion that ERTS lineament studies can be used to guide more detailed search methods in virgin areas. It is recommended, however, that these be performed using 1:250,000 scale imagery to obtain more detail than can be easily annotated at the 1:1,000,000 scale.

C. AREA 3 (NEW MEXICO–WEST TEXAS REGION)

1. General Observations

Subsequent to the preliminary reporting (Saunders *et al.*, 1973), the mosaic for this area was reconstructed with improved imagery and reinterpreted completely. The observation identification numbers for the MSS band 6 images of the final mosaic are given in the appendix.

The mosaic is shown in Figure 20. Due to degradation in the reduction and reproduction process, many of the more subtle linears visible on the original mosaic cannot be as easily discerned in the figure, but a particularly striking NE-trending example can be seen west of Roswell, New Mexico, passing along the north edge of the bright playa near the center of the mosaic. This and other linears aligned with it have been named the CHIRICAHUA lineament (Figures 21 and 22) which cuts diagonally through the regional basin and range structure and extends across the entire map area. This area contains a striking parallel to subparallel series of NE-trending lineaments shown in Figure 22, providing further evidence for a wide-spread NE-trending structural "grain" of basement weakness zones already noted in Areas 1 and 2. Other lineaments in the area vary in strike from nearly due north-south (the NACIMIENTO

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lineament) and NNW (the general basin and range trend) to a NW and WNW parallel to subparallel series.

The Texas "lineament," long inferred to be a major weakness zone (Kelley, 1955; Schmitt, 1966; Wertz, 1970 and others), appears as a very diffuse zone of 12 major lineaments and many linears with an aggregate width of about 100 to 150 miles extending from the Rio Grande region of Texas and Mexico through the area generally north of Tucson, Arizona.

The WICHITA ZONE passes through the NE corner of the area (see Subsection III.B.). The UTE, HENRY, and ZUNI lineaments are located approximately coincident with the Ute and Henry Porphyry lines and the Zuni lineament described by Kelley (1955); his nomenclature has been adopted.

Inspection of Figure 22 shows a NW-trending set of linears, including the LUBBOCK and LAMESA lineaments. As was suggested in Subsection III.B., this may be a major weakness zone of continental extent between the TEXAS and WICHITA zones. On projection northwestward, the LUBBOCK-LAMESA trend appears coincident with the Uncompahgre lineament described by Kelley (1955), which lies between the UTE and PARADOX lineaments of this study (see Figure 15). Unlike the TEXAS and WICHITA lineaments, however, the LUBBOCK-LAMESA zone does not appear to have had the same intensity of lateral adjustment.

Table 4 lists the inferred major lineaments identified in Figure 22, along with their trends. This distribution of trends is shown in Figure 23 and shows maxima at about N 62° E, N 78° W, and N 52° W. The maximum at N 62° E represents the prevailing NE "grain." That at N 78° W is interpreted, for the most part, to be the tension fracture direction for right-lateral coupling of the plates included between the NE shear zones (Figure 24), although locally the TEXAS ZONE is nearly parallel to this direction. The other maximum at N 52° W represents mountain flank lineaments. The three major NW lineament zones–Texas, LUBBOCK-LAMESA and the WICHITA–are nearer a N 60° W trend and are part of the broad maximum of values surrounding the N 52° W direction. Throughout its long extent the TEXAS lineament is reported to have an average azimuth of N 75° W (Schmitt, 1966).

It is extremely interesting to compare the mapped lineaments of Areas 1 (Figure 10), 2 (Figure 15), and 3 (Figure 22) to see just how consistent the lineament trends are in the Rocky

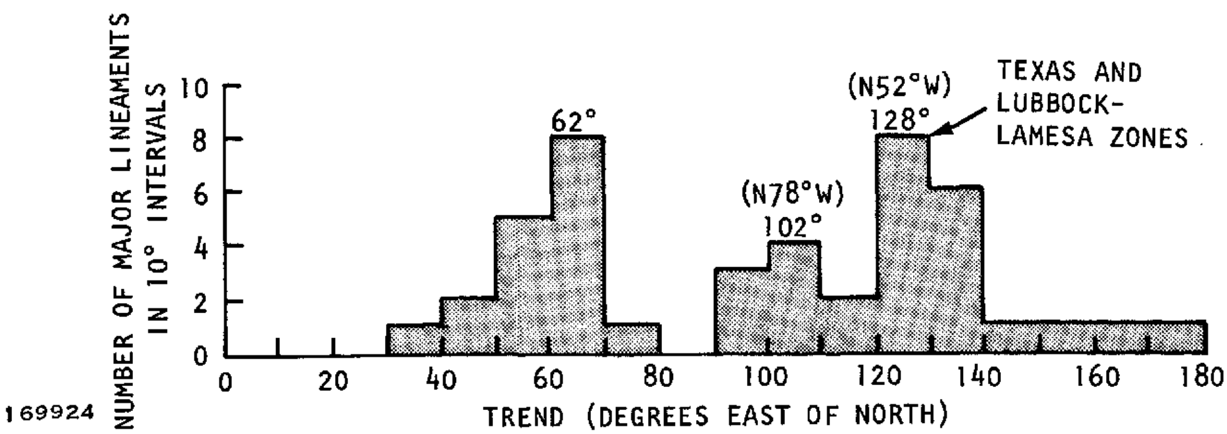

Figure 23. Area 3 (New Mexico–West Texas Region) Major Lineament Trend Distribution

TABLE 4. AREA 3 (NEW MEXICO-WEST TEXAS REGION) MAJOR LINEAMENTS

Name	Trend*	References
Navajo	N 56 E	
LaVeta	N 58 E	
Jemez	N 54 E	Mayo (1958)
Apache	N 63-69 E	Geophoto Services (1972a)
Tucumcari	N 60 E	
Papago	N 48 E	Geophoto Services (1972a)
Burro	N 62 E	
Lordsburg	N 45 E	
Chiricahua	N 60 E	
Roswell	N 55 E	
	N 37 E	
Mex-Tex	N 60 E	
Andrews	N 60 E	
Sautomkin	N 65 E	
	N 51 E	
	N 77 E	
Presidio	N 32 E	
Alpine	N 62 E	
Zuni	N 135 E	Kelley (1955)
Henry	N 123 E	Kelley (1955)
Ute	N 133 E	Kelley (1955)
Wichita Zone	N 125 E	Sales (1968)
Nacimiento	N 179 E	Near Mayo, 1958 Cordelleran Front Belt
Gila-San Simon	N 137 E	
Lubbock	N 121 E	
Lamesa	N 128 E	
	N 150 E	
Huachuca	N 163 E	
Pecos	N 120-128 E	
Chihuahua	N 118 E	

*When more than one trend is present in a lineament, the dominant trend is indicated by underlining.

TABLE 4. AREA 3 (NEW MEXICO-WEST TEXAS REGION) MAJOR LINEAMENTS (Continued)

Name	Trend*	References
Odessa	N 132 E N 161 E	
Val Verde	N 117 E	
Sonora	N 100 E	
Sahuaripa	N 98 E	
Texas Zone Segments	T-1 N 102 E T-2 N 103 E T-3 N 97 E T-4 N 118 E N 140 E T-5 N 90 E T-6 N 134 E T-7 N 129 E T-8 N 120 E N 106 E N 125 E T-9 N 130 E T-10 N 104 E T-11 N 123 E	Kelley (1955); Schmitt (1966); Wertz (1970); *et al.* Average trend = ~N 116° E

*When more than one trend is present in a lineament, the dominant trend is indicated by underlining.

Mountain region (Figure 44). Also, the spacing between major lineaments, especially the northeast features, is consistent to a point where a regular NE and NW pattern of lineaments is common. As basement weakness zone indicators, the lineament pattern attests to a basement fault-fracture pattern of hitherto unrecognized regularity.

2. Correlation of ERTS Data with Economic Deposits

a. Gold and Base Metal Deposits

(1) General

Inspection of Figure 22 shows that nearly all the major and most of the minor deposits appear to be related to linears and/or curvilinear anomalies, as was observed in Areas 1 and 2. Based on U.S. data only (Mexican locations are not believed to be comparatively accurate), 89 percent of the major deposits and 70 percent of all deposits are located within 4 miles of a linear. In essential agreement with earlier reporting (Saunders *et al.*, 1973), 15 of the major mining districts are associated with major NE-trending lineament zones and 11 of the major districts are close to ESE-trending linears. Six of the major districts are close to the intersections of NE and ESE linears. Only the Magdalena, Santa Rita Mountains, and Gleeson-Tombstone Hills districts do not show any apparent connection with either a prominent linear or a curvilinear anomaly or both.

Figure 24 shows only the major NE and ESE-trending lineaments and the ESE linears of Area 3. Application of simple-shear theory indicates a parallel situation to that described for Areas 1 and 2. Right-lateral coupling of the blocks between the NE lineaments (possible early Laramide) produced ESE-striking tension zones (possibly reactivating Precambrian tensional zones) and dominant left-lateral coupling along the NW zones during Laramide and Tertiary caused tensional fracturing with a NE strike along the ancient Precambrian weakness zones. Note the parallelism of the ESE and NE lineaments with the strain ellipsoid diagrams of Figure 24.

If the hypothesis that the major lineaments have existed as weakness zones since the Precambrian (Cloos, 1948; Meinesz, 1947 and others) is accepted, it is not unreasonable to conclude that there has been recurring mineralization control by them since that time. Landwehr (1967) has suggested that these NE belts reflect deep crustal ruptures that were formed simultaneously in the early Precambrian in response to a common regional stress. Mesozoic or early Tertiary ages are generally accepted for most of the ore deposits in this area (Anderson, 1968) and a preponderance of the veins strike in a general NE direction (Landwehr, 1967). Precambrian ore deposits of the Superior Province in Canada are seen to be associated with generally EW-trending tensional features due to right-lateral coupling on the NE-trending major lineaments (see Subsection III.D.). The Coeur d'Alene district in Idaho, the largest silver deposit of the U.S., is Precambrian in age and shows a predominant ESE trend to its mineral belts (Hobbs and Fryklund, 1968).

Based on these observations, there is the possibility that many of the deposits in Area 3 (and perhaps the entire Rocky Mountain area) are reworked Precambrian deposits originally emplaced along the ESE tensional zones caused by continental-scale Precambrian simple-shear coupling of the blocks between the major NE-striking lineaments. During the Mesozoic and Tertiary, the regional stresses caused left-lateral shearing along the NW zones and tensional fracturing along the NE lineaments with emplacement of ores remobilized from deeply buried Precambrian deposits. This type of ore genesis would explain the apparent association of several deposits with both the NE and ESE-trending lineaments and linears. Many of the deposits in New Mexico appear to be related also to the curvilinear anomalies; however, the relationship is not as pervasive as was noted in Area 2 (see Subsection III.B.).

For most of the major deposits, the detailed structures, which have been described in the literature as related to the emplacement of the ore deposits, are similar in strike to the lineaments mapped from ERTS data, which are apparently related to those deposits as shown in Figure 22.

(2) Discussion of Selected Deposits

Major deposits at Cananea (Mexico), Bisbee (Arizona), Lordsburg, Tyrone and Santa Rita (New Mexico) all appear to be associated with the LORDSBURG lineament which coincides essentially with the southern portion of the New Mexico mineral belt as described by Jerome and Cook (1967) and which is illustrated in Figure 24. The deposits along the northern part of the New Mexico mineral belt appear to be related to other linears, as shown in Figure 22.

In the Bisbee area, Bryant and Metz (1966) describe the ore occurrences as being intimately associated with a series or more than 20 fault zones, mostly trending NE. These authors refer also to the Dividend Fault as a major ESE-trending break that splits the prophyry body and

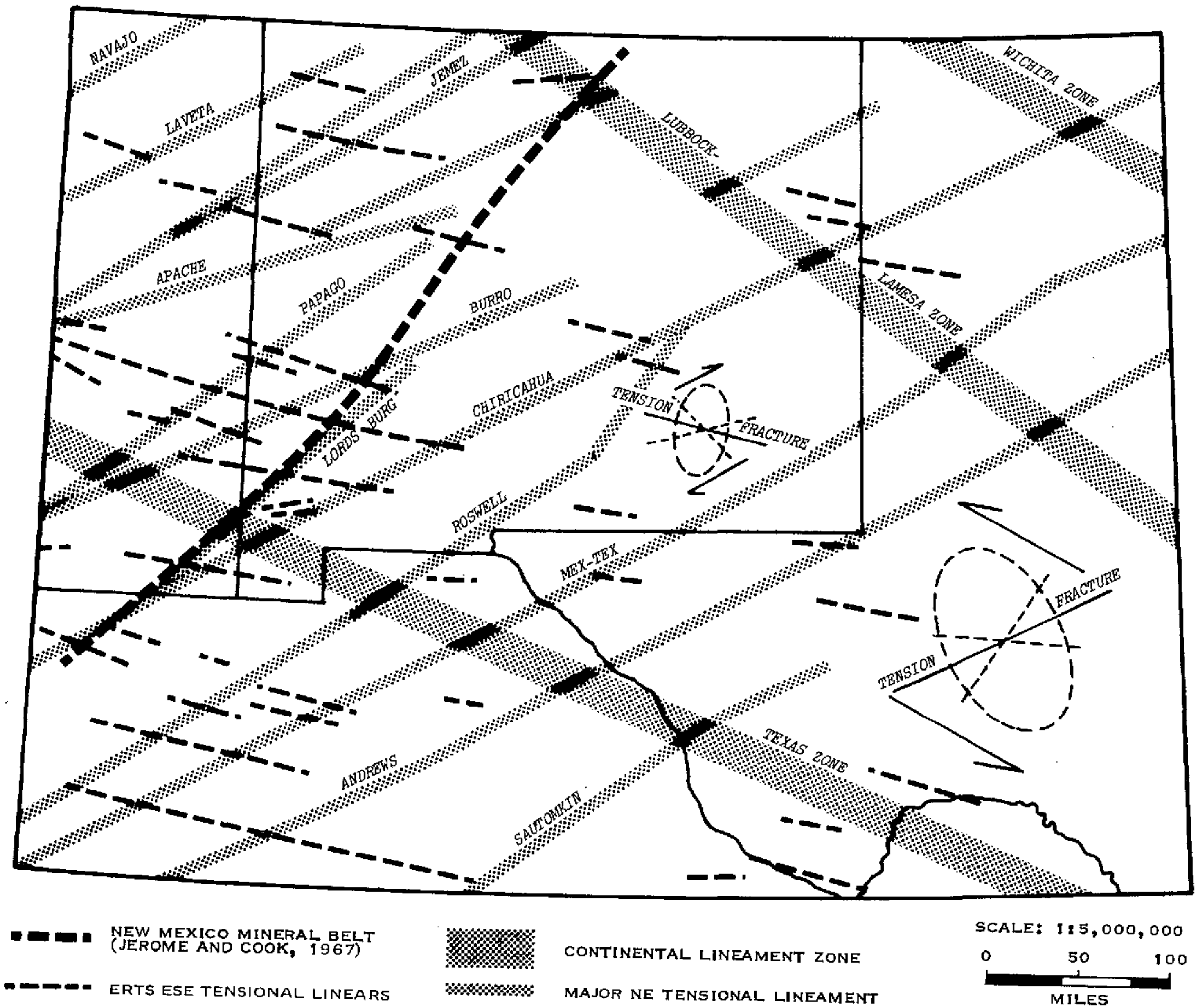

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Figure 24. Simple-Shear, Block-Coupling Analysis of the "New Mexico Mineral Belt"

limits the ore to the north. A second fault system, essentially parallel to the Dividend, limits the ore about 8000 feet to the south. This description would fit the hypothesis described previously in which the ore was originally emplaced along an ESE zone during the Precambrian, and then reworked and redeposited in NE tension zones during the Laramide orogeny. The Dividend fault was not detected during 1:1,000,000 scale mapping of this study, but detailed mapping at 1:250,000 scale would be more likely to detect it.

The Cananea deposit in Mexico lies generally along one of the branches of the NE-trending CHIRICAHUA lineament. Velasco (1966) describes a general ESE alignment of the associated quartz porphyry bodies and refers to the similarly striking Ricketts Fault. He also mentions "late, generally north-south-trending, steeply dipping wide-shear and fracture zones as controlling structural features in the deposition of better grade secondary ore." These essentially north-south shear fractures may be represented by the HUACHUCA lineament of this study (Figure 22) which is believed to be either part of the basin and range mechanics common northwest of Area 3 and/or part of the San Andreas system immediately west of Area 3. Velasco does not describe any NE-trending local structures which could be correlated directly with the CHIRICAHUA lineament.

Rose and Baltosser (1966) describe the regional structure of the Santa Rita area as including an "older" northeast-trending lineament which passes southwest from the Santa Rita area through the Tyrone, Lordsburg, Bisbee, and Cananea mining districts and to the northeast through the Kingston and Hillsboro districts. Locally this is expressed as a zone of faults trending from N 40° E to N 75° E which Rose and Baltosser think to be controlled by a basement feature. Thus the LORDSBURG lineament is confirmed locally at Santa Rita. The presence of a NW-trending structural control in the Santa Rita area is indicated by the Mimbres and Silver City faults which border the district on the NE and SW sides, respectively, as shown by Hernon and Jones (1968), who state:

> The directions of faulting and fracturing conform to the regional pattern in the southwestern United States. These patterns may have existed in Precambrian time and have been imposed on the veneer of Paleozoic and later rocks by reactivation.

In the Lordsburg district most of the veins strike NE while a few strike nearly E-W (Lingren *et al.*, 1910, p. 333).

Lynch (1966) describes the Esperanza mine in the Pima district where ore mineralization has a definite NW trend and the prominent structural features have a NE trend. This deposit lies on the prominent NE-trending PAPAGO lineament. Following the PAPAGO to the NE one encounters the Safford district where Robinson and Cook (1966) describe the mineralization as having been controlled by strong NE faulting and shearing, and the Morenci district where Moolik and Durek (1966) state that the dominant trend of the main intrusive, associated dikes, veins, and early faults is NE.

In all the districts where sufficient information could be obtained in the time available, local structures were generally in accord with what might be expected based on the lineament analysis.

b. Uranium Deposits

The uranium deposits of Area 3 include both the sandstone types in the Colorado Plateau and a few vein-type deposits in the base metal mining regions. Overall, some 52 percent of the deposits lie within 4 miles of a linear shown on Figure 22. This agrees quite well with the comparative figure for sandstone deposits in Area 2 and reflects the stratigraphic control of the Area 3 sandstone deposits which predominate in number over the vein deposits.

The most important producing area is located between 35° and 36°N and between 107° and 108°W and contains the Ambrosia Lake, Jackpile, Poison Canyon and Laguna districts. This area is traversed by the JEMEZ lineament zone. Kelley *et al.* (1968) show a generally NE-trending fault zone in this region, including the San Mateo, San Rafael, and Ambrosia faults, which may be related to the lineament zone.

The axis of the Ambrosia Lake anticline is approximately on strike with a SSE-trending linear [just north of the ZUNI label on that lineament (Figure 22)]. The Ambrosia deposit appears to be indicated by a curvilinear anomaly, as are some of the deposits to the south in the Poison Canyon area. Other deposits are found along the westward extension of this linear, and the Laguna deposits are found along the eastern extension of the ESE-striking linear to the south.

It is suggested that a detailed study of the ERTS lineaments in this area at 1:250,000 scale might shed some additional light on the structural analysis of the area. Both faulting and tectonic folding are thought to play important roles in ore localization (Kelley *et al.*, 1968), and the new lineament information might lead to the discovery of new favorable structures.

c. Hydrocarbon Occurrences

Area 3 contains the prolific oil-producing areas of West Texas and New Mexico and the huge Panhandle gas and oil fields northeast of Amarillo, Texas. The Panhandle field is clearly structurally controlled by the WICHITA lineament zone in this map area (Figure 22). Lineament control of the major structures in the Permian Basin area was also evident in the preliminary studies (Saunders *et al.*, 1973; Thomas *et al.*, 1973).

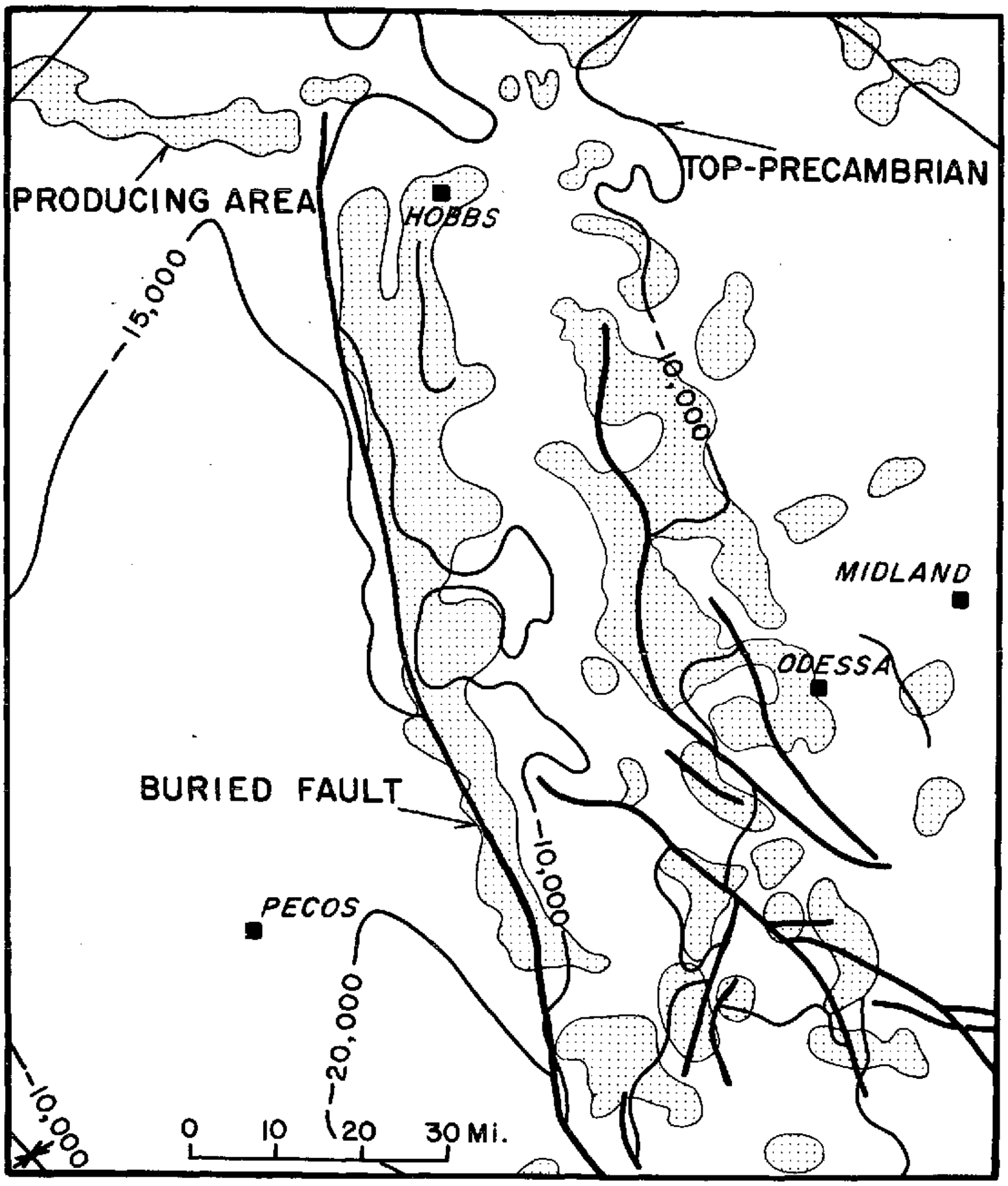
As was indicated earlier, Area 3 was completely reinterpreted with improved imagery after the preliminary work. The results in the Central Basin Platform area were generally the same as before with the following significant differences:

The major lineaments were better defined (more linears were mapped).

A new major lineament was found: the ODESSA, which was not evident in the earlier mapping. This feature correlates well with an indicated subsurface fault shown on the U.S. Tectonic Map.

In addition to the previously reported geomorphic indication of a positive area on the south end of the platform, additional curvilinear features were found in the basin areas on both sides of the platform.

Comparison of the preliminary report illustrations (Figures 25, 26, and 27) with Figure 22 shows the added features and demonstrates the excellent repeatability of two interpretations performed at widely separated times with no planimetric or economic information present to



(FROM SAUNDERS, ET AL, 1973)

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Figure 25. Central Basin Platform, West Texas–Known Features

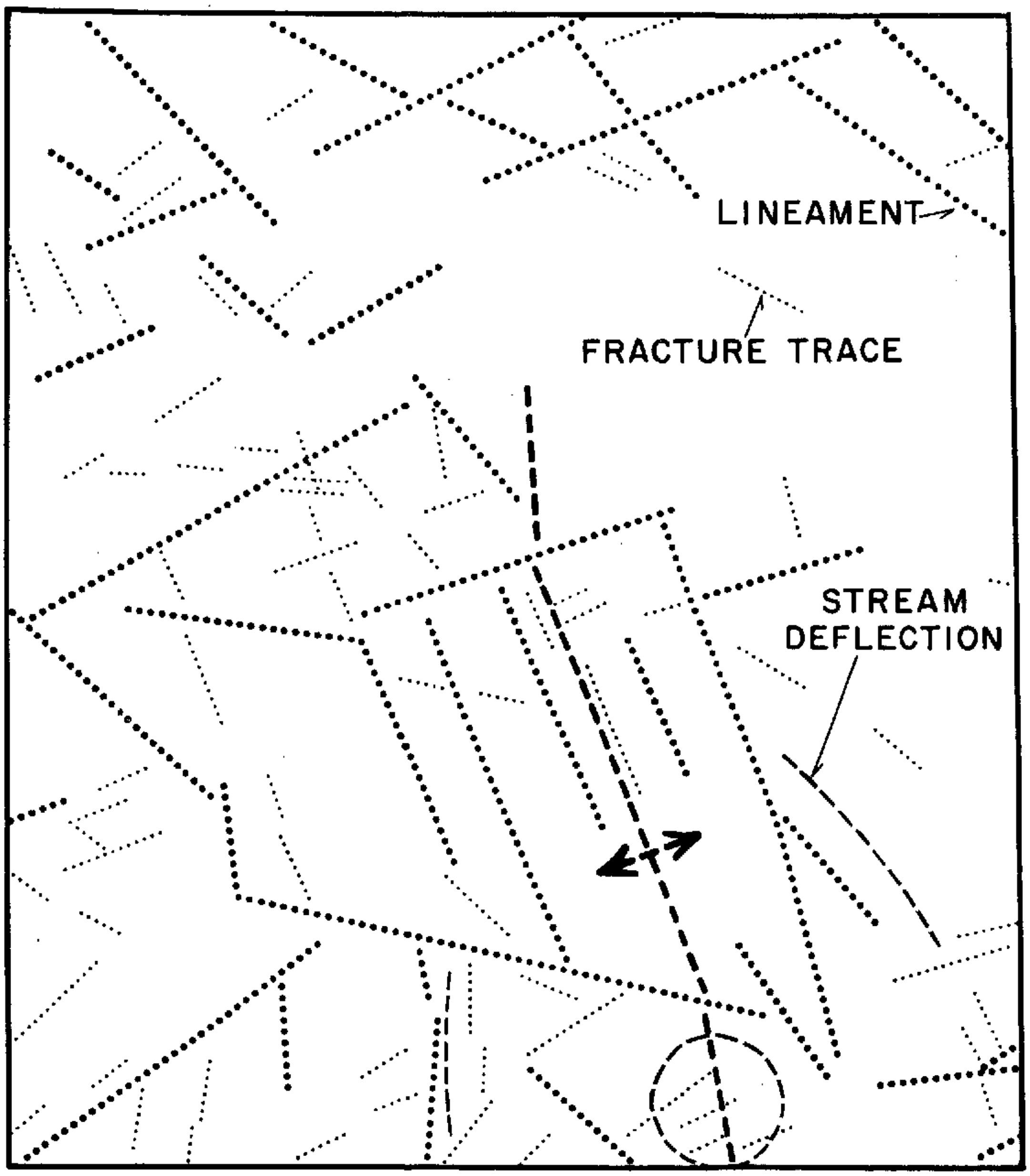

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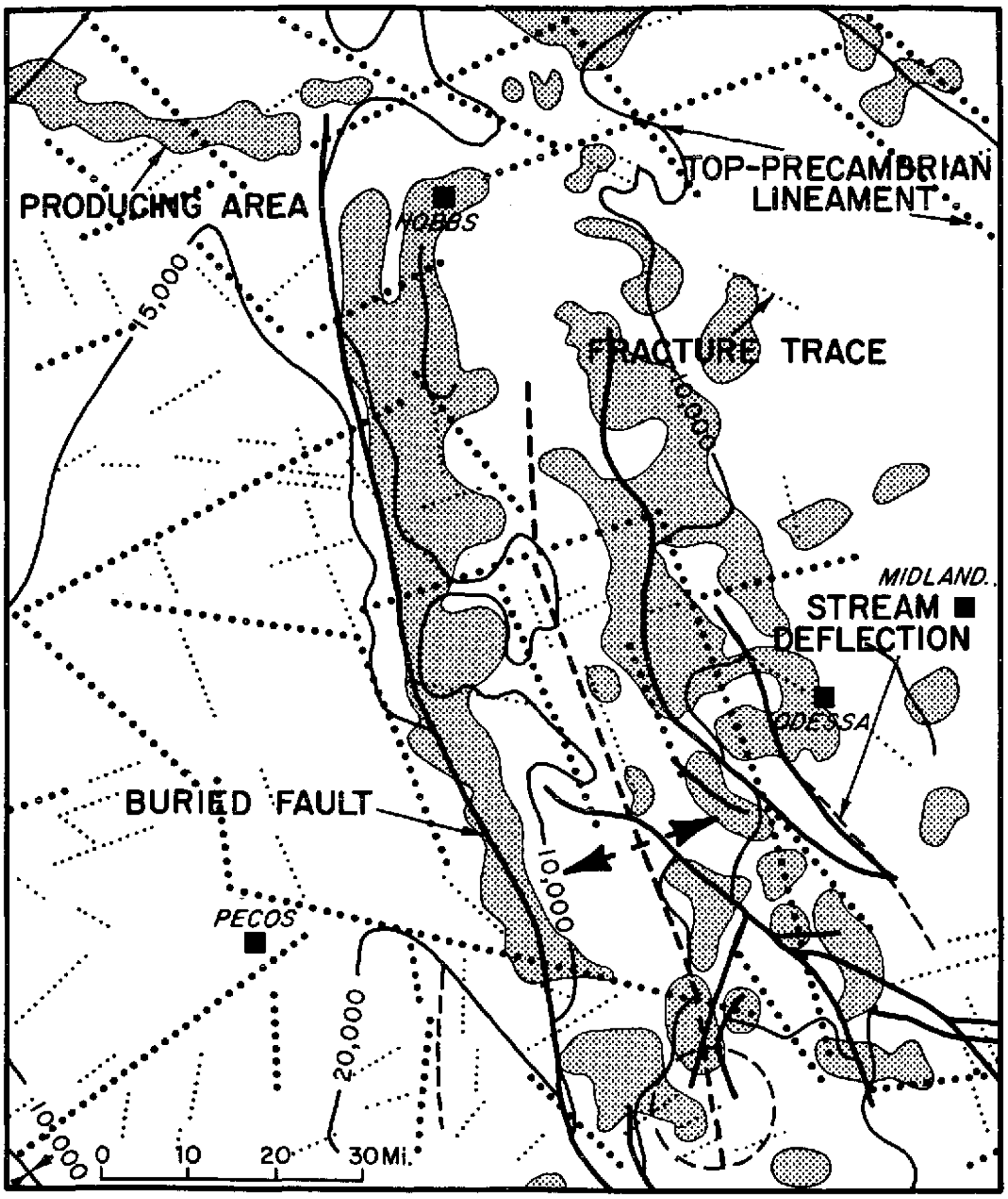
Figure 26. Central Basin Platform, West Texas--New ERTS Data



(FROM SAUNDERS ET AL, 1973)

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Figure 27. Central Basin Platform, West Texas–Known Features and New ERTS Data

prejudice the findings.* Not all of the preliminary linears were found again in the second interpretation. (No attempt was made to repeat the preliminary detailed annotation of faint features in this area and only the prominent features were mapped.) Several new prominent linears were identified and an increased effort was made to identify curvilinear features the second time. In spite of these differences, the two sets of data provide essentially the same interpretation.

The Tectonic Map of the U.S. (1962) shows the Central Basin platform as defined by a series of buried flank faults that offset structural contours on the top of the Precambrian surface (Figure 25). The axis of this large structure with its associated flank producing areas and indicated faults trends about N 20° W. Immediately north of Hobbs, New Mexico, the platform loses its identity as indicated by the structure contours, the lack of flank faults, and the trend change of producing areas (Figures 22 and 25).

Linears, "fracture traces," and geomorphic evidence were mapped, as shown in Figure 26, using the preliminary ERTS mosaic. Combining the linear-fracture data with the geomorphic evidence of stream deflections, it is possible to infer an anticlinal axis which appears to be truncated at the north end, as indicated by the NE-trending lineament pattern at the top of Figure 26. Inspection of Figure 22 indicates essentially the same features, but with better definition.

Combining Figures 25 and 26 (see Figure 27) allows a direct comparison between the known structure and the new lineament data obtained from ERTS photos. In several localities, the new lineaments nearly coincide with the known or inferred faults or with the flank-producing areas. The inferred axis (Figure 26) coincides approximately with the crest of the platform, as defined in Figure 25. Other more detailed comparisons can be made, but an extremely interesting one is in the locality of Hobbs, New Mexico, where the loss of platform identity and the change in production trend coincides well with the major MEX-TEX lineament (Figure 22). This was indicated by an abrupt change in the linear trends in the more limited preliminary study.

Detailed study of Figure 22 shows an apparent clustering of oil fields along several linears such as the PECOS, LUBBOCK, and LAMESA lineaments. The Scurry Reef field just south of the LUBBOCK label on that lineament is truncated by it on the NE and by a parallel linear which borders it on the SW end. Other producing areas are clearly bordered by linears, as can be noted in Figure 22.

The isolated gas field adjacent to the LA VETA lineament at about 35° N and 109° 30′ W shows an apparent curvilinear anomaly and is the only field that shows such a coincidence in this area. It must be noted, however, that the High Plains and basin areas of Area 3 (just as in Areas 1 and 2) contain ERTS imagery of too dark tonal quality to map adequately any curvilinear patterns other than very large features. ERTS imagery at 1:250,000 scale in the area, when properly processed, does show numerous curvilinear patterns, some of which coincide with known structures and producing reefs. Collins *et al.* (1973) reported an apparent strong correlation between crudely circular geomorphic structural and hazy anomalies in the Anadarko basin and known structurally controlled oil and gas fields. This suggests that a regional reconnaissance study at 1:1,000,000 scale, followed by a detailed study of ERTS imagery at 1:250,000 scale, in Areas 1, 2, or 3 should provide another means of applying geomorphology to petroleum exploration.

*It should be noted that a much more generalized oil field map was used for reference in the preliminary work.

It is concluded that the large-scale photogeologic and geomorphic data discernible in ERTS imagery in West Texas allows reconnaissance mapping of surface effects caused by major basement features as much as 10,000 feet below the surface and which appear to control basin shape, shelf areas and major uplifts. In addition, detailed interpretation of curvilinear and tonal features should provide valuable additional data on potential oil structures.

D. AREA 4 (SUPERIOR PROVINCE, CANADA)

1. General Observations

The band 6 "master" mosaic for Area 4 is shown in Figure 28. The image observation identification index map is presented in the appendix.

A very large amount of photogeologically significant information is visible in this mosaic—much more than can be annotated practically at the 1:1,000,000 scale. This study has been limited to the major features appropriate in a reconnaissance approach, and it is believed that follow-up studies at the 1:250,000 scale would be most appropriate as a next step and should be quite productive.

Four very large prominent lineaments are easily identified on Figure 28. Reference to Figures 29 and 30 will identify these as the SAINT LAWRENCE lineament (also known as Logan's Line Fault; King, 1969), the HUDSON BAY lineament (about 25 miles east of and parallel to Kutina's Hudson Bay Paleolineament as previously mapped; Kutina, 1971), and the JAMES BAY and RUPERT RIVER lineaments (not reported previously). Less prominent, but indicated by a zone of linears, is the well-recognized GRENVILLE FRONT (King, 1969b; Douglass, 1969).

The RUPERT RIVER lineament appears to be a major crustal weakness zone which coincides with linear structures and a linear series of ultrabasic intrusives along its eastern portion, as seen on the Tectonic Map of Canada (Geol. Surv. of Canada, 1969a). Along its western portion it lies on a linear positive gravity anomaly (Geol. Surv. of Canada, 1969b) and an aeromagnetic lineament (Geol. Surv. of Canada, 1969c). Both of the geophysical anomalies extend southwestward out of the map area toward, and aligned with, the linear northwest shore of Lake Superior. Eastward out of the map area it is aligned with the major structural break between the Grenville and Nain structural provinces of Canada (Douglass, 1969; Geol. Surv. of Canada, 1969a).

The JAMES BAY lineament is aligned with an anticline west of James Bay and appears as a zone of general disruption of lithologic trends and as a gravity "lineament"* to the southeast (Geol. Surv. of Canada, 1969a, b, d). There is no apparent magnetic expression of this lineament.

The HUDSON BAY lineament is suggested to be the surface expression of the major N-S-trending "geofracture" described by Kutina (1971), although it does not coincide with Kutina's feature as mapped. The north-south straight stretch of the Turgeon River described by Kutina as part of his Hudson Bay Paleolineament is seen on Figure 29 about 25 miles west of the central part of the HUDSON BAY lineament, but the lineament as mapped in this study is much

*A gravity "lineament" as referred to here is a linear trend of gravity features such as apparent steep gradients, or an aligned series of small disconnected highs which appears to interrupt the larger regional trends.

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more prominent and extensive on the ERTS imagery than Kutina's feature. It seems reasonable to accept his arguments that the northern extension of this feature probably forms the eastern boundary of the Paleozoic sediments in the Hudson Bay Basin and that it may be a very old feature offset by younger faults at several places. Observation of Figure 30 does *not* support his claim of close association of the major ore deposits in the Abitibi belt with his paleolineament (*or* the HUDSON BAY feature of this study either). In this the authors agree with Allcock (1973).

In general, most of the mapped fault and gabbro dike trends are represented by one or more linears. There are many more mapped dikes on the Tectonic Map of Canada than were indicated by linears, but it must be noted that only major features were mapped in this study and it is highly probable that many more will be found by mapping at a more detailed scale. As would be expected, nearly all of the major mapped faults appear as linears in this area due to the high degree of erosion and bedrock exposure, as well as the large number of lakes and streams following the fracture zones. Table 5 lists the major lineaments with their trends, and Figure 31 illustrates the trend distribution.

Strongly evident are the strong NE "grain" (N 65° E) and the ESE (N 102° E) theoretical tensional direction for right-lateral coupling of the blocks between the NE lineaments. It is felt that this close similarity to the trend distributions in the Rocky Mountain region (Areas 1, 2, and 3) provides strong evidence of a continental regmatic fracture pattern which has existed since the earliest Precambrian. (See also Figure 44, Subsection IV.B, for comparison of all trend distributions.) The presence of such a continental pattern appears to be a fundamental key to the effective use of ERTS lineament interpretations in predicting favorable structures for both potential new mining districts and petroleum provinces.

The area contains many curvilinear anomalies, at least one of which has been identified as the Manicouagan meteor impact structure (shown near the eastern edge of Figure 30). Two other much smaller shock metamorphic structures, the Charlevoix and Brent, are known in Area 4 (Douglass, 1969), but were not large enough to be mapped as a major curvilinear anomaly. The Sudbury irruptive is also listed by Douglass as a possible impact structure. Many of the other large curvilinear features mapped from ERTS imagery show the concentric "ring" structure described by Baldwin (1949) as being characteristic of the probable structure beneath a meteoritic crater caused by a hypervelocity* impact. It is suggested that some of these may be

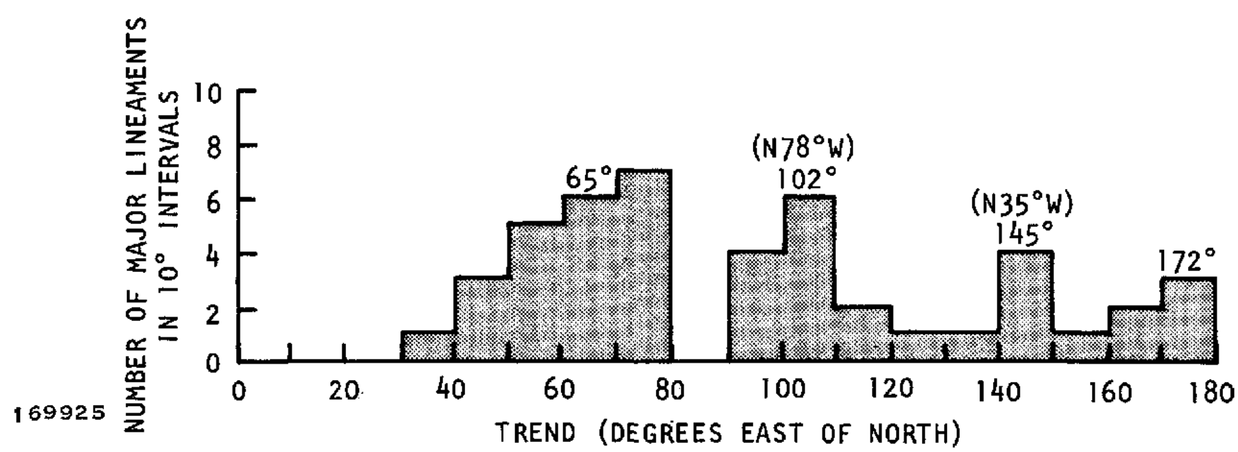


Figure 31. Area 4 (Superior Province, Canada) Major Lineament Trend Distribution

*Hypervelocity means the velocity of the object is greater than the velocity of sound in the impacted medium.

TABLE 5. AREA 4 (SUPERIOR PROVINCE, CANADA) MAJOR LINEAMENTS

Name	Trend*	References
Albany River	N 65 E	
Kenogami River	N 58 E	
Rupert River	N 69 E	
Moose River	N 48 E N 43 E	
Kapuskasing	N 64 E	
Michipicoten River	N 56 E	
Timmins	N 56 E	
Montreal River	N 78 E N 100 E	
Sault St. Marie	N 62 E	
Lac St. Mard	N 72 E	
Grenville Front	N 65 E N 40 E	King (1969); Douglass (1969)
Baskatong	N 48 E	
St. Lawrence	N 39 E N 53 E	Logan's Line Fault (King, 1969)
Lac a La Croix	N 52 E	
Burton Lake	N 78 E	
Yasinski Lake	N 75 E	
East Main River	N 68 E	
Boatswain Bay	N 77 E	
Matagami Lake	N 72 E	
Chibougamau	N 78 E	
Waswanipi Lake	N 79 E	
Nicobi Lake	N 58 E	
Lac Quevillon	N 69 E	
Waswanipi River	N 101 E	
Bell River	N 103 E	
Normetal	N 109 E	
Val D'Or	N 107 E N 116 E	
North Bay	N 96 E	
North Channel	N 101 E	
Saguenay River	N 110 E	
Tiniscouata Lake	N 134 E	
Rupert Bay	N 99 E	
Akimiski	N 110 E	
Attawapiskat River	N 99 E	
Dabeat	N 92 E	
Kaniapiskau River	N 142 E	
Wawa Lake	N 146 E	

*When more than one trend is present in a lineament, the dominant trend is indicated by underlining.

TABLE 5. AREA 4 (SUPERIOR PROVINCE, CANADA) MAJOR LINEAMENTS (Continued)

Name	Trend*	References
Kinsautom	N 142 E	
Kelvin Lake	N 125 E	
Windigo River	N 162 E	
James Bay	N 143 E	
Sloan's	N 150 E	
Tamiskaming Lake	N 145 E	
Londonderry	N 173 E	
Smuts	N 160 E N 177 E	
Hudson Bay	N 178 E	(About 25 miles east of Kutina's "Hudson Bay" lineament and with the same strike; Kutina, 1971).

*When more than one trend is present in a lineament, the dominant trend is indicated by underlining.

relict impact structures. Such an interpretation would be consistent with observations of the much less eroded surfaces of Mars and the Moon which show vast numbers of such apparent structures. However, such "ring" structures may also represent igneous intrusive bodies or caldera as is evident in Colorado (Area 2).

The linear patterns were compared with mapped glacial grooving (Geol. Surv. of Canada, 1969f) to see if there was any correlation. The area east of James Bay was the only region where the lineaments and grooving showed strongly similar strikes. Minor parallelism was found in the extreme northwest corner of the area and in the south-central to southwest portions. Generally, the linear strikes were discordant to the grooving and may be attributed to structural activity with relative confidence.

2. Correlation of ERTS Data with Economic Deposits

a. Gold and Base Metal Deposits

In Figure 30, some 73 percent of the mapped gold and base metal deposits lie within 4 miles of a linear indicating strong structural control on emplacement. The gold deposits of the Canadian Shield show a close relationship to the generally E-W-trending belts of Archean volcanic rocks. The largest producers lie in the rocks of the Abitibi belt (Douglass, 1969). This area includes the Timmins, Kirkland Lake, and Noranda regions and deposits to the east along the VAL D'OR lineament, as shown in Figure 30. The formation of the ore bodies and the distribution of ore shoots within them is clearly controlled by faults and other local structures (Douglass, 1969). The regional distribution of the deposits of gold and base metals along and near generally E-W-trending major faults is apparent on the Mineral Map of Canada (Geol. Surv. of Canada, 1969e) and was illustrated in Subsection I.B.2., Figure 5. This relation is even more apparent when mapped at about 1:250,000 scale (Dugas *et al.*, 1966). The Larder Lake, Cadillac, and associated fault and fold zones appear to be several miles wide and contain the major mining centers of Kirkland Lake, Larder Lake, Noranda, Malartic, Bourlamaque, and Val D'Or. In Figure 30, these are seen as the prominent ESE linear just below the Kirkland Lake label, the

ENE less prominent linear leading from the Noranda region to the VAL D'OR lineament, and the central portion of the VAL D'OR lineament. The association of the deposits appears strongest with the ESE-trending linears in Figure 30. Again, this is the theoretical strike of tension fracturing as a result of simple-shear, right-lateral coupling of the blocks between the major NE-trending lineaments just as hypothesized in Areas 1, 2, and 3. Thus, it appears that simple-shear mechanics may be applicable also in the shield area to provide a reasonable model for mineral deposit emplacement. This conclusion is discussed at greater length in Subsection III.D.3.

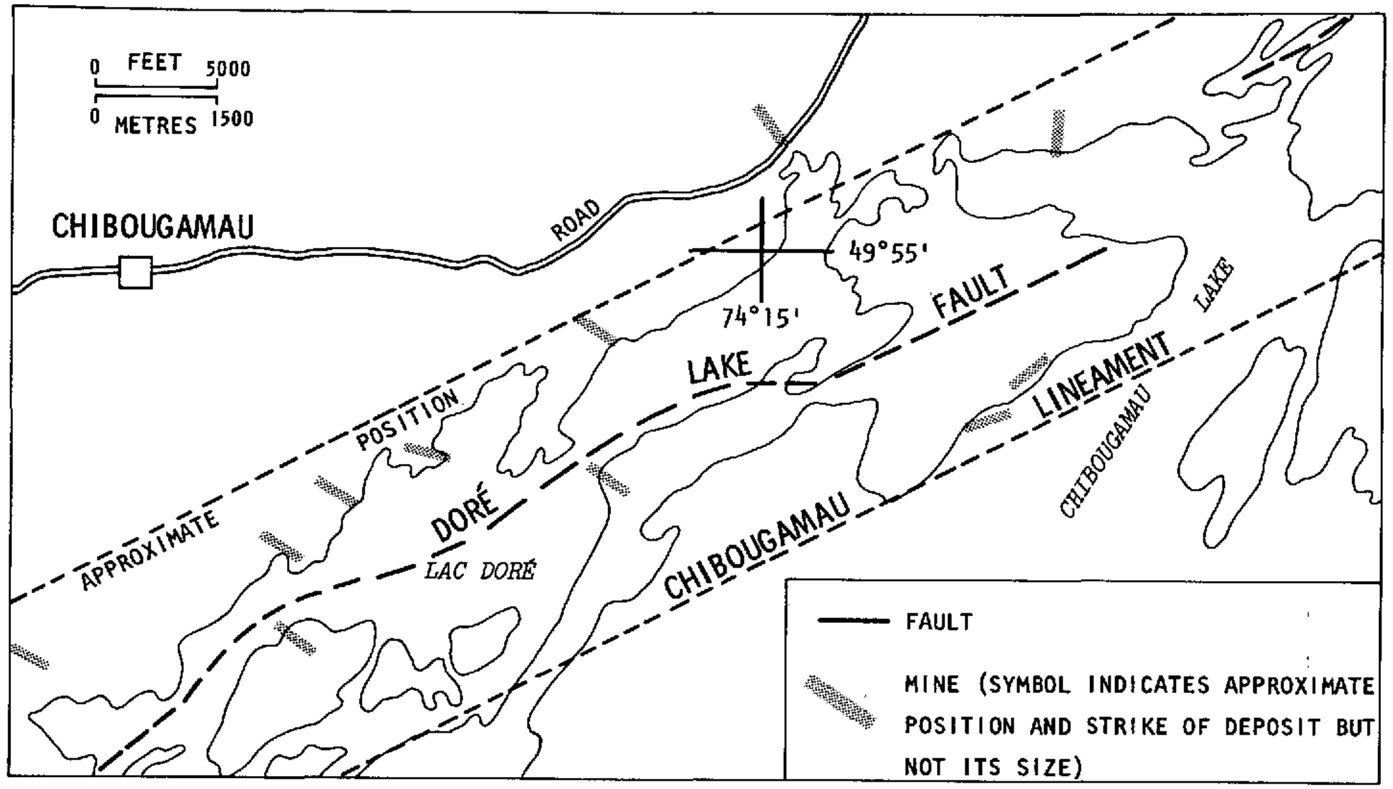
In the Timmins area, Figure 30 shows a clustering of ore deposits on a concentric curvilinear anomaly, associated with an intersection of NE- and NW-trending linears. The northernmost deposit in this cluster is the Kidd Creek mine, the largest producer in the group. This mine is apparently associated with the ESE linear just to the north and trending toward the VAL D'OR lineament and may be related in origin to the deposits along that lineament to the southeast. The deposit shown in the center of the Timmins curvilinear is a porphyry copper deposit; the curvilinear may be related to the intrusive body. As discussed later in this section, both the ESE and SE linears in this region may have been tensional to act as mineralizing conduits.

The central concentric curvilinears in the Sudbury area outline the Sudbury eruptive and show a clear association with the mineral deposits, as would be expected since the area between the two inner curvilinears roughly represents the outcrop region of the ultrabasic rocks. A lead-zinc and a copper deposit are apparently associated with the outer concentric curvilinear to the north, which may be related to the outcrop of the Quirke Lake group on the north edge of the Sudbury basin as described in Douglass (1969).

The Chibougamau and Matagami Lake mining districts appear to be closely related to the lineaments of the same names (Figure 30).

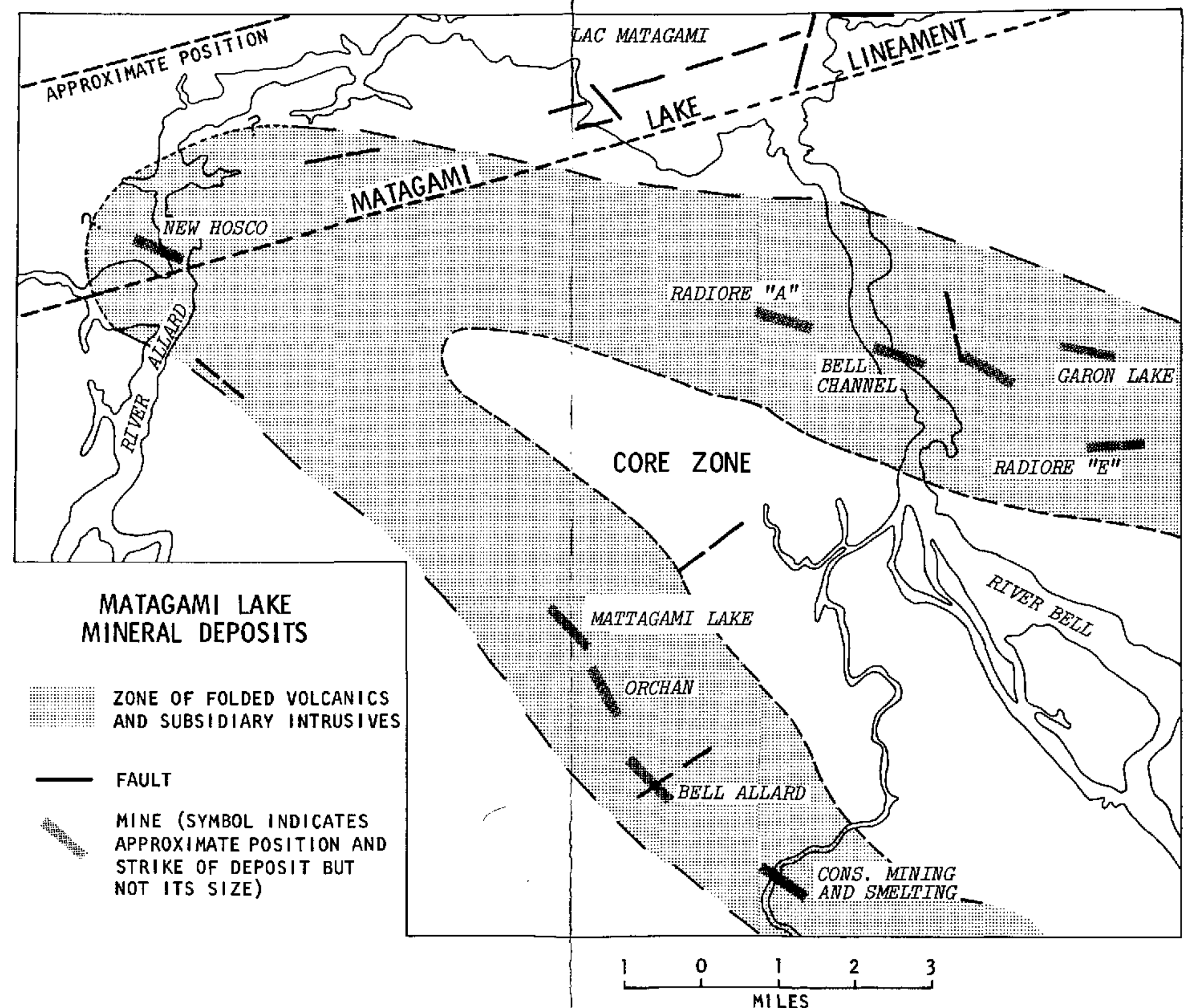
The Chibougamau deposits are distributed along and close to the Dore Lake Fault a shear zone, which strikes approximately N 70° E and appears to be a local expression of the CHIBOUGAMAU lineament, as shown in Figure 32(A). The ore bodies themselves are mainly in shear zones striking either approximately WNW or generally parallel with the Dore Lake Fault.

Deposits at Matagami Lake lie along two structural zones bordering an intrusive core zone, as shown in Figure 32(B): (1) the Radiore "A", Bell Channel, Garon Lake, and Radiore "E" ore bodies in a zone trending about ESE; and (2) the Mattagami Lake, Orchan, Bell Allard and Consolidated Mining and Smelting ore bodies in a zone trending about SE with the New Hosco ore body approximately at the intersection of the two zones (Sharpe, 1968, Figure 4). The two zones consist of folded volcanics and subsidiary intrusives. The MATAGAMI LAKE lineament, as illustrated in Figure 32(B), shows as a linear portion of Lake Matagami with parallel fault zones on the south shore of the lake, directly on strike with the intersection of the two zones of ore bodies (Sharpe, 1968, Figure 2). Other zones of NE faulting lie to the NE of the Mattagami Lake mine, the largest in the area, and at the Bell Allard deposit. These may be part of the MATAGAMI LAKE lineament. In this area, the favorable ore zones strike ESE and NW and were not mapped as ERTS linears. At least some of the ore bodies apparently lie on or near intersections of the favorable zones with segments of the MATAGAMI LAKE lineament. In both areas, the general location of the mining districts appears to be controlled by the major lineaments, but the emplacement of the ore bodies is in intersecting shear or tension zones striking generally ESE or SE.



CHIBOUGAMAU MINERAL DEPOSITS

A. CHIBOUGAMAU MINING AREA (ADAPTED FROM DOUGLASS, 1969, FIGURE V-25)



B. MATAGAMI LAKE MINING AREA (ADAPTED FROM SHARPE, 1968, FIGURES 2 AND 4)

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Figure 32. Chibougama and Matagami Lake Mineral Deposits

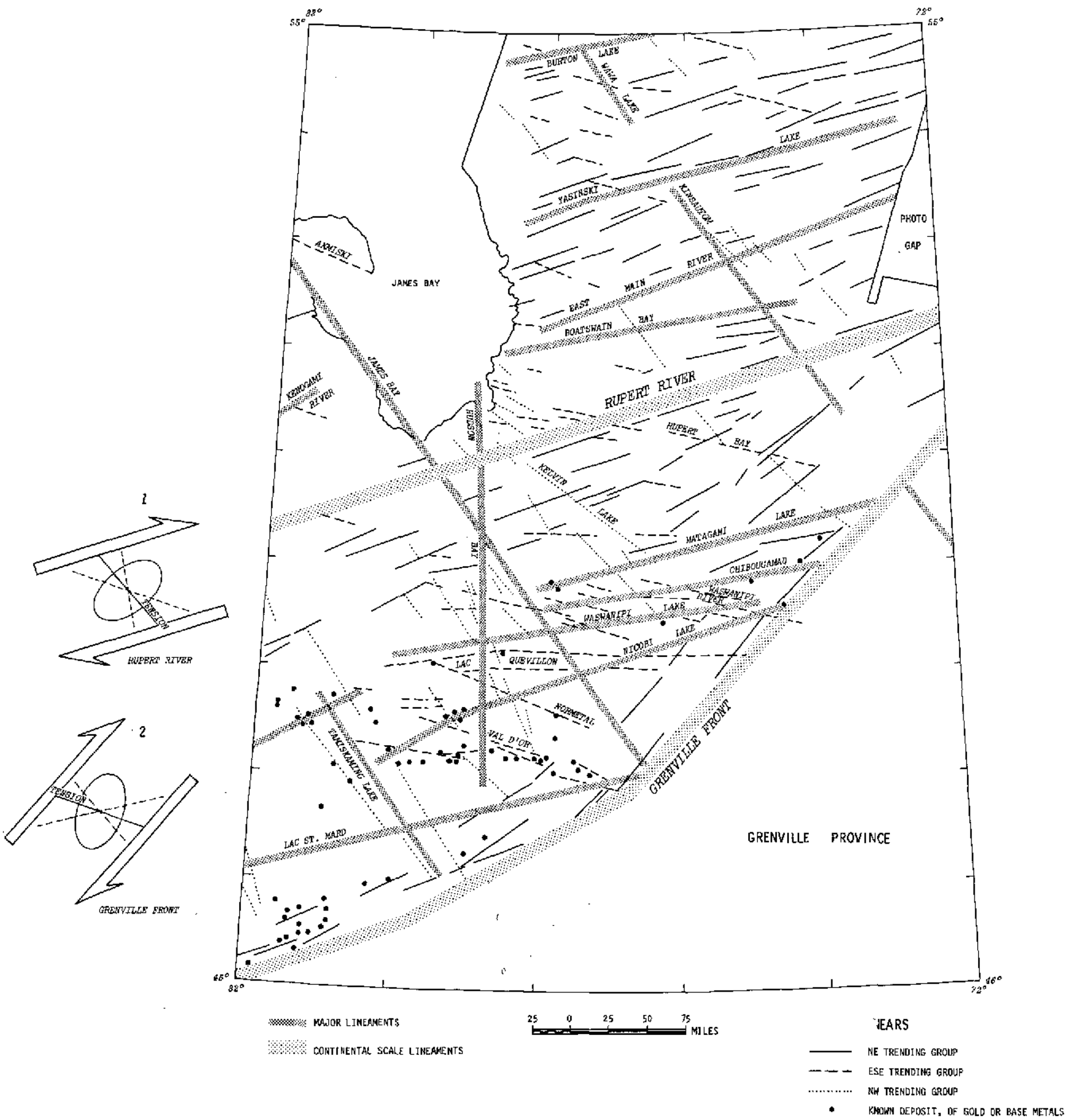

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Figure 33. Simple-Shear, Block-Coupling Analysis of Favorable Prospecting Areas in a Portion of Area 4

The geology of the greenstone belts of the Superior Province is quite complex, and there is evidence that ore deposits which were emplaced during the Archean may have been remobilized one or more times due to periods of orogenic activity subsequent to their emplacement. This complexity renders it very difficult (or perhaps impossible) to analyze the structural history in detail. Instead, an empirical approach, including an analog model study (Subsection III.D.3), has been adopted to explain the gross aspects of the distribution and trends of the ore deposits.

The regional distribution and the general attitudes of the ore deposits in the Abitibi and Chibougamau belts (to the limited extent to which the investigators have been able to study them) appear to fit a general model of right-lateral coupling of the blocks between the generally NE-trending major lineaments. For example, if one assumes moderate right-lateral coupling along the RUPERT RIVER and GRENVILLE FRONT lineaments as shown in Figure 33 (covering the center portion of Area 4), the tensional directions in the included block will vary from ESE to SE, depending on the strike the lineament of primary influence (see strain ellipsoids in Figure 33). It might be expected that the SE tension will predominate near the GRENVILLE FRONT lineament and the ESE will predominate in the vicinity of the RUPERT RIVER and other near-parallel lineaments. In any case, it appears reasonable to use this type of model to predict generally that the ESE, SE, and NW linears and lineaments should be preferred for prospecting, both on the basis of the observed relationships of the mining districts to these linears and on characteristics of the structural model. (See Subsection III.D.3 for the analog model study.) Figure 33 shows the linears and lineaments with these trends, as well as the major mining localities. It is suggested that the intersections of two or more of these linears in areas of favorable host rock types should be prime areas to search. The next step would be to study these areas in more detail at 1:250,000 scale to further delineate the best possibilities for photogeologic, geophysical, and surface geologic studies. Potentially favorable greenstone belts lie in the region east of James Bay as well as in the Matagami Lake-Chibougamau region.

b. Uranium Deposits

The Elliot Lake area in the southwest corner of Area 4 contains the largest uranium reserves of Canada. These are quartz-pebble conglomerates containing "brannerite," uraninite, and uraniferous monazite (Douglass, 1969, pp. 163–166). The ores are in the basal conglomerate of the Huronian, the Matinenda (lower Mississagi) formation, located in the Quirke Lake syncline. This structure is roughly indicated by the small curvilinear anomaly just to the right of the Elliot Lake label in Figure 29.

It is concluded that although these deposits are apparently stratigraphically controlled, ERTS imagery at 1:250,000 scale might be used for detailed photogeologic mapping that could help greatly in elucidating the structural relationships of the ore bearing strata.

3. Ice Model of Block Coupling

During the lineament interpretation of Area 4, a remarkable similarity was noted between the fracture pattern in Arctic Ocean ice seen on ERTS image 1266-20543 and the mapped lineaments of Area 4. Figure 34 shows the band 7 image, and Figure 35 illustrates a simple-shear structural interpretation where the ice fractures and pressure ridges have been named for their analog lineaments in Area 4. Comparison of Figures 30 and 34 shows the striking similarity in strike and relative spacing of the lineaments and the corresponding ice fractures. Assuming right-lateral coupling of the blocks between the ST. LAWRENCE, GRENVILLE FRONT, and

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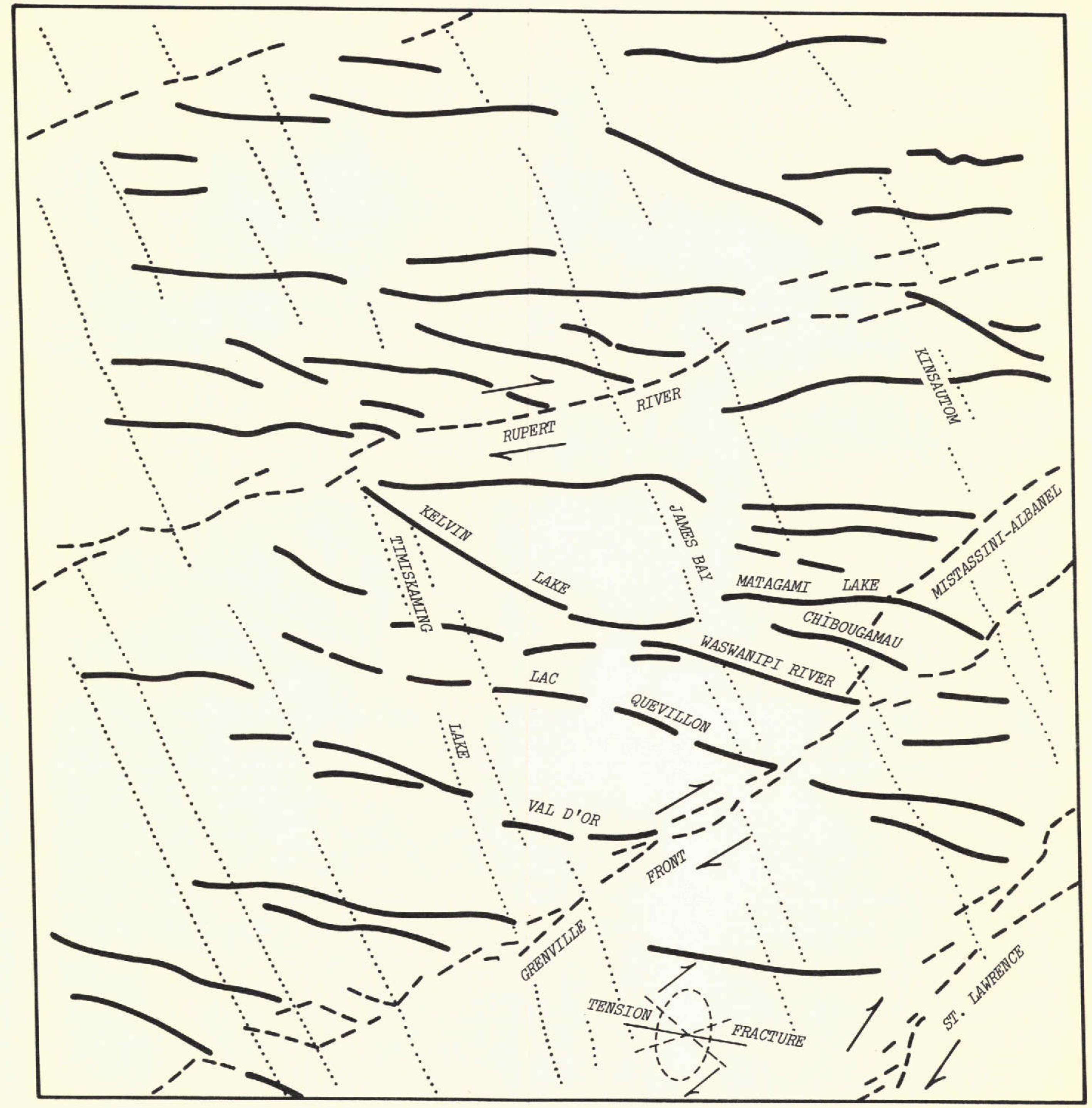
Figure 34. ERTS Image of Analogous Ice Structure



1266-20543

SCALE: 1:1,000,000

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Figure 35. Lineament Interpretation of Analogous Ice Structure

RUPERT RIVER lineaments on both the Canadian Shield and the ice analog, the obvious tensional fractures in the ice are in reasonably close accord with the strain ellipsoid shown in Figure 35. These observations suggest that those lineaments or faults of similar relative strike on the Canadian Shield may well have been the tensional openings which acted as channelways for the solutions which formed the vast mineral deposits which are spatially associated with them.

The dangers in drawing model analogies are appreciated in regard to both scale extrapolations and material property differences. It is important not to be carried away by coincidence; however, it is suggested that the opportunity to use ERTS images of ice to study these types of structures should be further pursued on the chance that significant insight might be gained bearing on block tectonics problems.

E. AREA 5 (NORTHERN ALASKA)

1. General Observations

The northern Alaska region differs from the other areas considered in this study in that it has relatively few known mineral or petroleum-producing localities. However, the area is thought to contain vast reserves of petroleum, oil shale and coal, and has many promising prospective areas for minerals (Berg and Cobb, 1967). The approach has been to evaluate the applicability of ERTS data in finding new potential prospects based on the known prospects as well as the experience and theoretical structural models developed in the other areas.

The master MSS band 6 mosaic for Area 5 is shown in Figure 36, and the observation identification index of images is in the Appendix. In this region it was difficult to obtain enough cloud-free coverage, and it was necessary to use a mixture of winter and summer imagery. Generally, the snow-covered ground with low sun angle provided strong enhancement of minor surface topography which could not be seen as well in the other seasons.

Major known structures that are easily detected on Figure 36 (see Figures 37 and 38) include:

- The Kobuk trench which is expressed as two essentially parallel zones of linears
- The Kaltag fault zone
- The Tintina fault zone
- The Yukon-Porcupine lineament
- The Brooks Range, bounded on the north by the BROOKS RANGE lineament
- The Cretaceous fold belt (north of the DE LONG lineament).

The major lineaments identified are listed in Table 6 along with their trends. The trend distribution is plotted in Figure 39.

The plotted data and inspection of Figure 38 provides reasonably strong evidence for a set of generally NW- and NE-trending shears as reported by Lathram, Tailleur, Patton and Fischer (1973) and as observed in all the other areas covered by this investigation (see Figure 44, Subsection VI.A). The peaks in Figure 39 appear to be displaced 5 to 10 degrees to the east when compared to the other areas but the relative spacing and the presence of the generally NE, NW and ESE trends as found in the other areas suggests a truly continental-scale regmatic fracture pattern in North America.

TABLE 6. AREA 5 (NORTHERN ALASKA) MAJOR LINEAMENTS

Name	Trend*	References
Pittalukrliak Lake	N 76 E	
Meade River	N 77 E N 102 E	
Horse	N 97 E	
De Long	N 62 E N 81 E N 72 E	
Colville River	N 65 E	
Eagle Creek	N 75 E	
Brooks Range	N 87 E N 67 E	
Junjik River	N 95 E N 69 E	
Kobuk Zone	N 91 E N 82 E N 68 E	Lathram (1972) Kobuk trench
Ikpek	N 54 E	
Sinuk River	N 69 E	
Gisasa River	N 33 E N 52 E N 66 E	
Kaltag Zone	N 65 E	Lathram (1972) Kaltag Fault
Yukon-Porcupine	N 60 E N 67 E	Lathram (1972) Porcupine lineament
Cascaden Ridge	N 57 E	
Hot Springs	N 70 E N 87 E	
Goldstream Creek	N 43 E	
Teklanika River	N 42 E	
Chena	N 68 E N 76 E	
Tomsaukin	N 67 E	
Tintina	N 112 E N 118 E	Lathram (1972) Tintina Fault and Trench
Sheenjek	N 22 E	
Your Creek	N 141 E	
Alatna River	N 140 E	
Kotzebue	N 127 E N 142 E N 5 E	

*When more than one trend is present in a lineament, the dominant trend is indicated by underlining.

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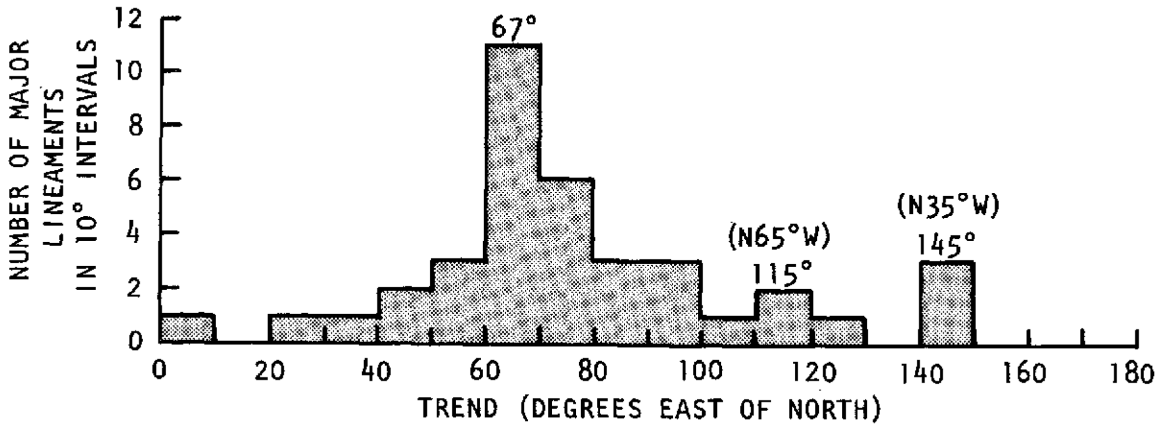

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Figure 39. Area 5 (Northern Alaska) Major Lineament Trends

2. Correlation of ERTS Data with Economic Deposits

a. Lode Mineral Deposits

The small number of producing mines in this area led to the inclusion of all prospects in the analysis as well as those shown in Figure 38, which have some known production either primary or by product (Cobb, 1960; 1962). Fifteen out of 22 (68 percent) of the known gold, silver, or base metal producers shown on Figure 38 were located within 4 miles of a linear. Of these, 80 percent were associated with linears trending NE to ESE. A similar analysis of all the known prospects for gold, silver or base metals showed 79 out of 113, or 70 percent located, within 4 miles of a mapped linear; 77 percent of those were associated with the NE- to ESE-trending linears.

Many of the NNE linears and lineaments in Figure 38 are believed to be flank faults on basement uplifts, while those with ESE trend are inferred to be tensional zones. Both sets of linears in most of the map area are believed to have been generated by right-lateral coupling on the NE block sets (see Subsection III.G.3). In the SE corner of the area, however, the "master" Tintina shear zone trends NW rather than NE, as do the other major shear zones of the region. Tensional trends here vary from NW to NE, depending on the intensity of the coupling. Flank faults display the same sort of variance in direction.

It is concluded that both observation and theory indicate that the linears varying in strike from NNE to ESE are preferred directions for lode mineralization and should be sought first in any reconnaissance prospecting program in northern Alaska. Uranium mineral localities are shown in Figure 38 (Cobb, 1970), but there is not enough available information concerning them to draw any valid conclusions about structural control.

b. Hydrocarbon Occurrences

The oil and gas fields of the North Slope include the vast new discoveries near Prudhoe Bay (shown north of the east end of the COLVILLE RIVER lineament in Figure 38) and the Naval Petroleum Reserve No. 4 in the region south of Point Barrow. The general area south of Prudhoe Bay is interpreted to be a single large asymmetric basin with the long axis parallel to the Brooks Range and the deepest part in the Arctic Foothills province, that is, the area labeled "FOLD BELT" in Figure 38 (Woolson, *et al.*, 1962).

The structures in the fold belt are well defined on the ERTS images and could be mapped in much more detail than is indicated by the curvilinear anomalies shown in Figure 38. Observations in the Arctic coastal plain to the north confirm, in general, those of Fischer and Lathram (1973) and Lathram *et al.*, (1973) in that both linear and curvilinear features are identifiable in the distribution and structures of lakes and streams on the Gubik formation. In particular, a specific curvilinear anomaly shown by Lathram *et al.* (1973), was not detected in this study because the image used had cloud cover in that region. As indicated in Figure 38, a curvilinear anomaly was found over the Prudhoe Bay field, suggesting that those observed to the southeast and southwest of Prudhoe Bay deserve close attention. Three curvilinears south of Barrow trend NE toward the oil field shown southeast of Barrow. The two northernmost anomalies coincide with gravity anomalies (Woolson *et al.*, 1972) and the one just south of the HORSE lineament is on trend with the West Meade anticline. The HORSE lineament is immediately to the north of and parallel to the series of anticlines trending toward the Umiat oil field and the Gubik gas field shown adjacent to the COLVILLE RIVER lineament. The EAGLE CREEK lineament lies between and parallel to the Kuparuk and Aufeis anticlinal axes and adjacent to a small gasfield on the parallel Kemik structure (Woolson *et al.* 1962). The PITTALUKRLIAK LAKE lineament lies on distinctive magnetic and gravity slopes and is interpreted as a zone of faulting in the pre-Cretaceous seismic sections at its west end; and also just south of the Simpson oil field (Woolson *et al.* 1962).

It is concluded that the ERTS data in the Arctic coastal plain reflect concealed geologic structures which may control the accumulation of oil and gas. A detailed study of this area at 1:250,000 scale should provide much new reconnaissance information to guide follow-up seismic studies.

F. SEASONAL AND BAND STUDY

Representative scenes were chosen from each area, and all cloud-free coverage was laid out to compare for ease of interpretation of linears, tonal anomalies, and water features in terms of wavelength bands and seasons of coverage. This allowed a choice to be made of the best single bands and seasons for each type of feature. The results are summarized in Table 7.

In general, the combined use of bands 5 and 7 as separate images will provide adequate information for most interpretations of geologic features in all the areas studied, and the best seasons are in the spring and fall with moderate sun angles (40 to 50 degrees). The best single band and season varies, depending on the features being sought and the region to be studied. Subtle topographic features are best emphasized on winter coverage with light snow and low sun angle.

The greater inherent information content of color composite products would indicate that these should be superior to single-band black and white images for geologic interpretation. The limited experience with the color products tends to bear this out, except for the difficulty in obtaining uniform hue and tonal qualities from print to print in large mosaics. This appears to be due to both processing difficulties and the necessity to mix seasonal coverages to obtain cloud-free images. When this problem is solved, the greater cost of the color products may be offset by the advantages of greater information content. However, at this time the single bands are easier to use and quite satisfactory for the purposes for which they are being used.

TABLE 7. SUMMARY OF WAVELENGTH AND SEASONAL STUDY RESULTS*

Region	Features Sought	Best Band	Best Time Of Year	Remarks
Montana	Linears	5 or 7	Fall	
	Tonals	5	Fall	
	Water	7	Fall	
Colorado	Linears	7	Winter	Band 5 fall coverage also good
	Tonals	5	Fall	
	Water	7	Fall	
New Mexico	Linears	5	Winter	Band 7 spring coverage also good
	Tonals	5	Spring or fall	
	Water	7	Spring or fall	
Canada (Eastern)	Linears	5	Spring	Band 7 in the summer also good
	Tonals	5	Summer	Band 7 early fall coverage also good
	Water	7	Summer	Band 5 in winter also good
	Roads and Trails	5	Summer	
Alaska (Northern)	Linears	7	Late summer	Early winter also good
	Tonals	7	Late summer	
	Water Features	7	Late summer	

*Imagery collected after the spring in 1973 was not included in this study.

G. ERTS DATA/BLOCK TECTONICS INTERPRETATIONS OF MAJOR GEOLOGIC FEATURES

1. Introduction

A critical part of demonstrating the feasibility of using any new tectonic theory in the reconnaissance for economic deposits involves its compatibility with the known geologic structure of the area. In this section, the major geologic features of each of the test areas are examined in light of the mapped major lineaments, and simple-shear, block mechanics. For this analysis, the data interpretation maps for each area were reduced to 1:5,000,000 scale transparencies and were studied as overlays on the Tectonic Map of North America (King, 1969).

Areas 1, 2, and 3 are considered together as parts of the Rocky Mountain Region, and Area 5 is considered separately because of the fundamental differences in its geologic history. Area 4 is unique in that it lies entirely within the Precambrian shield of North America and has such exceedingly complex and fragmentary structural and sedimentary history that it was not feasible to attempt a detailed interpretation of the structure there at this time.

2. Rocky Mountain Region

a. General

Areas 1 (Montana), 2 (Colorado), and 3 (New Mexico–West Texas) include the northern, central, and southern parts of the Rocky Mountains within the United States. Also included are portions of the contiguous High Plains displaying a lesser degree of Laramide deformation (late Cretaceous to early Tertiary) than the Rocky Mountains. Because of the relatively large region included, this study provides an opportunity to observe the probable role of ERTS-derived lineaments in a major orogeny.

The Rocky Mountains of Laramide development have long been considered to be the result of pure compressional forces directed from a WSW direction (Curtis, 1960). In Colorado, Badgley (1960) advocates a N 100° W direction for the Laramide compression. Similar directions are recognized in the literature for the Montana and New Mexico regions. Badgley also recognizes for the Laramide deformation in Colorado a controlling, basement tectonic framework consisting of ancient NE-trending fault, shear, and foliation zones. In the other two areas, basement control factors for Laramide deformation have not been as well recognized as in Colorado, but as described in Subsection III.B.2., a Precambrian northeast basement "grain" has been recognized as a controlling factor in mineral deposits (Anderson, 1966; Landwehr, 1967; *et al.*).

The compression mechanism for the formation of the Rocky Mountains evolved as a theory before the recognition of numerous and widespread lineaments in the region, as is evident on ERTS imagery. Many of the more extensive of these lineaments are believed to be surface fracture zones representing deep-seated basement weakness zones, as previously pointed out in this report and in the literature on lineaments (Brock, 1957; Cloos, 1948; Hills, 1956; Mayo, 1958; Moody and Hill, 1956; O'Driscoll, 1971; Vening Meinese, 1947). Based on the widespread presence of major basement weakness zones in the Rocky Mountain region, the question must be asked as to their role in the deformational process. Do they remain passive to regional compression so that pure-shear, compressive mechanics are the cause of mountain building, or do they play an active role in the development of mountains?

J.K. Sales (1968) argues that lineament-basement weakness zones played a dominant role in the development of the Wyoming Rockies. According to Sales, left-lateral adjustment on the major NW-trending weakness zones in response to regional Laramide compression produced a region-wide left-lateral couple in which such major uplifts as the Big Horn Mountains, the Black Hills, and the Wind River Mountains developed as couple-generated drag folds. Sales' model studies are extremely persuasive in arguing his point that coupling mechanics rather than pure compressional mechanics were dominant in the formation of the Rocky Mountains. Thomas (1971) concurred with the Sales' theory but included the additional effect of NE-trending weakness zones on the structural and stratigraphic conditions of southwest Wyoming.

Based on these considerations and the ERTS data already presented, it is believed that the regional compressive forces, when encountering the system of NW- and NE-trending weakness zones, were deflected along them as lateral adjustment forces, thereby producing mountain building by means of lineament simple-shear, block-couple mechanics. It is the thesis of this report that lateral simple shear along weakness zones is the primary and dominant characteristic of an orogeny rather than a subordinate role, as generally considered in conventional, compression mechanics.

The basic phases of the simple-shear, block-couple theory (see Figure 3) are visualized to be:

1. Regional compressive forces first initiate lateral adjustment along weakness zones and preliminary spatial adjustment on blocks, resulting in epeirogenic uplift and downwarp of block sets.

2. Intensification of essentially equal lateral adjustment on NW and NE weakness zones produces local drag folding in sedimentary rocks above the weakness zones. Gradually the stress direction relationship to the weakness zone trends favors one direction over the other, thereby producing a dominant coupling direction. In the Rocky Mountains, the Laramide approximately N 100° W stress direction favored the NW weakness zones,

thereby producing left-lateral dominant coupling on the NW block sets (as indicated by the predominance of NW-trending uplifts in the Rocky Mountains region); NE weakness zones became subordinate in drag folding as NW dominant coupling increased and eventually became the NE tensional part of dominant NW coupling.

3. An incipient drag-fold phase begins in response to further lateral adjustment, and basement rocks become involved if the stress is great enough. Dominant coupling produces most of the drag folds, but subordinate coupling may also produce incipient drag folds locally. Igneous intrusive activity may occur along axes and flank faults of basement uplifts in response to decompression gradients along uplifts, causing melting of the lower crustal materials by a process similar to that described by Kay *et al.* (1970) for the origin of oceanic ridge volcanics.

4. Further intensification of lateral adjustment accentuates the dominant couple direction, and rotation of drag folds through moderate, advanced, or extreme drag-fold phases can occur depending upon total stress intensity and resistence of the rocks to rotation (Figure 4). Rotation of drag folds produces local shearing on previously formed flank faults; further rotation results in high-angle reverse faulting along flank faults in this path of rotation and down dropping along flank faults away from the path of rotation. Igneous activity would probably decrease in response to greater shearing and reverse faulting unless cross-fold tensional activity is established to produce conduits (see phase 5 below). If incipient or other drag fold phases occur in or along depositional trough or shelf, gravity sliding of sediments will be initiated as the uplifts gain relief.

5. The last phase is believed to have predominantly tensional effects. Increasing dominant coupling on one block set produces increased shearing on weakness zones in the direction of the dominant couple and increased tensional activity along other weakness zone directions. In the Rocky Mountains, NW weakness zones became part of the dominant shear direction during the Laramide while NE weakness zones, because of their near parallelism to the cross-fold tensional direction in the left-lateral incipient to moderate phases (see mechanics diagrams, Figures 40, 41, or 42), became increasingly subjected to tension. Intrusive and extrusive activity during the later stages of the Laramide orogeny and following it is inferred to have been controlled to a large extent by the NE tensional conduits. Whether the tensional fracturing occurs during or at the conclusion of the incipient, moderate, advanced, or extreme phases of drag folding would depend upon the resistence of the basement rocks to further rotation.

In the specific structural analyses to follow, two basic premises have been used: first, the mapped major lineaments are regarded as the surface expression of basement weakness zones; and second, the curvilinear patterns evident on ERTS imagery are believed to represent, for the most part, outlines of intrusive plutons or volcanic calderas. In some cases, larger curvilinear patterns appear to outline basins or parts of basins but these are readily recognized. The pluton or caldera features are believed to have been intruded or extruded along axes or flank faults of drag-fold uplifts. The rationale behind the latter premise lies in the fact that many of the mapped curvilinears or calderas have been identified as intrusives. Examples include such plutons as the Pikes Peak, Silver Plume, and Boulder batholiths and such calderas as those of the San Juan Mountains and the Jemez Caldera (northern New Mexico) which are indicated on the ERTS imagery as curvilinear patterns. In areas where geologic information is lacking, other curvilinear patterns have been used in this study as a guide in inferring drag-fold uplifts.

In the following analysis, the figures illustrating the interpretation are presented as a 1:5,000,000 scale, which is the same scale as the Tectonic Map of North America (King, 1969b). While this allows ready comparison of the interpretations with the known structural features of each area, the small scale unfortunately does not allow the defining of each mapped lineament or every curvilinear pattern.

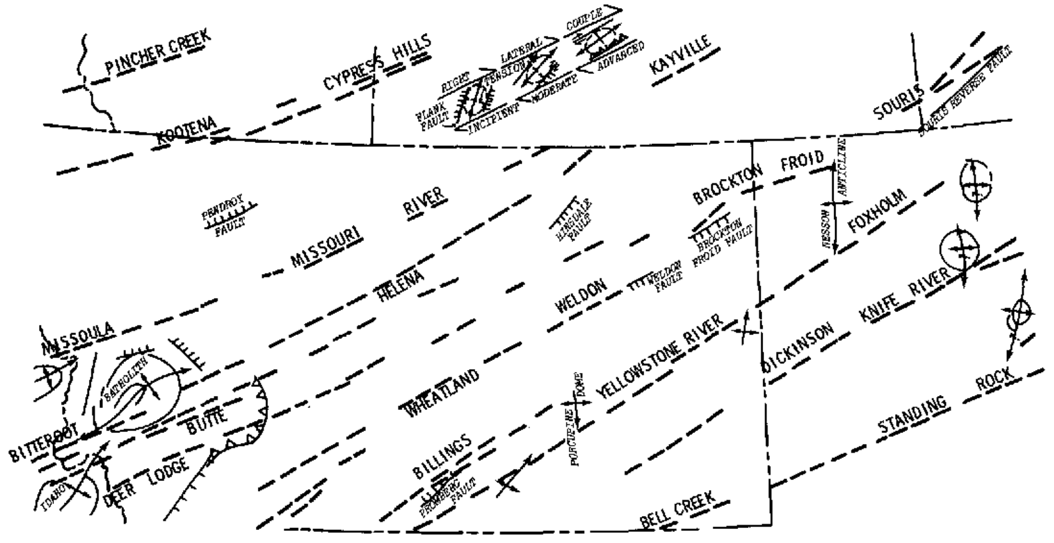
To best match the scale of this interpretation of major structures, the ERTS lineaments and curvilinear patterns were high graded for the analysis; i.e., only the major features are retained. In the figures, those lineaments believed to be flank faults are shown by hachures. (Many of these original normal flank faults eventually became shear zones or high-angle reverse faults in the southern Front Range of Area 2 (Colorado); some retain their normal, flank-fault origin along part of their length, but have evolved into a high-angle reverse fault along other parts.) Many of the smaller lineaments, not used in this structural analysis, are thought to be cross-fold tensional features if they are nearly at right angles to an uplift or flank fault. If they are near parallel to the dominant shear direction they probably are minor flank faults or secondary shear features.

In the Rocky Mountain region the most obvious, extensive lineaments discernible on ERTS imagery are the NE lineaments; NW lineaments are more difficult to map and seldom show the continuous extent of the NE features. Ironically, however, it is the NW lineament system in the Rocky Mountains which is thought to have controlled the dominant coupling during the Laramide orogeny while the NE features played a subordinate role. The reason for their difference of expression is believed to be that the NW lineaments were part of the dominant shear system while the NE lineaments were part of the subordinate tensional system during the latter phases of the orogeny. As shear zones, the NW features were "tight;" that is, both sides of the weakness zone were sheared tightly together, thereby minimizing subsequent erosional activity. Without this subsequent erosion, the NW lineaments do not show up as prominent geomorphic features.

The extensive NE lineaments, however, were subjected to greater and greater tension during the latter stages of the Laramide orogeny (again note the near parallelism of the incipient-to-moderate drag-fold tensional directions with the NE lineaments in Figures 40, 41 and 42). Such tensional activity along the NE lineaments easily controlled subsequent stream erosion; consequently, today the NE lineaments are easily seen as prominent geomorphic features on ERTS imagery.

b. Area 1 (Montana)

During the Laramide orogeny, the NW and NE lineaments of the Montana region are interpreted to have defined a series of basement blocks, rectangular or rhombohedral in shape which subsequently controlled the events and resultant features of the orogeny in that area [Figure 40(C)]. The NW weakness zones because of their directional relationship to regional WSW compression were favored as lateral adjustment zones over the NE weakness zones which were more parallel to the incoming forces. Consequently, dominant left-lateral coupling on the NW block sets in the Montana region produced a predominance of drag-fold uplifts and downwarps trending NW at various degrees [compare parallelism of these features to the theoretical stress diagrams for left-lateral coupling, Figure 40(B)].



LEWIS-CLARK NW LINEAMENT CONTROLLING DOMINANT LEFT-LATERAL COUPLING DURING LARAMIDE OROGENY

HELENA NE LINEAMENT, SUBORDINATE TO DOMINANT COUPLE SYSTEM DURING LARAMIDE OROGENY

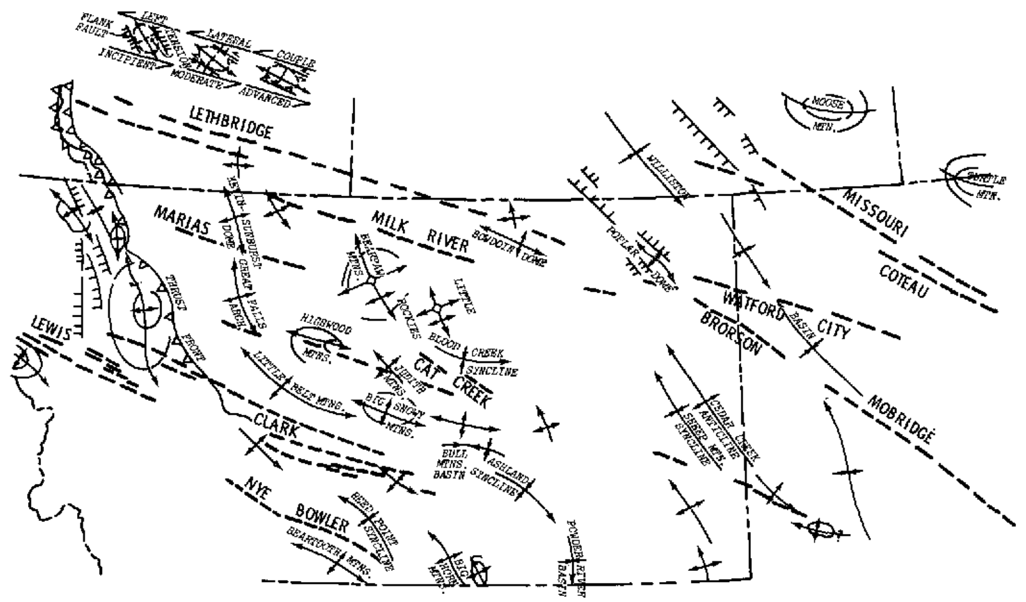
PUBLISHED FAULT

INFERRED FLANK FAULT

DRAG FOLD, ANTICLINE, SYNCLINE OR UNKNOWN TYPE

CURVILINEAR PATTERN DEFINING UPLIFT AND/OR INTRUSIVE/CALDERA FEATURE

A



LEWIS-CLARK NW LINEAMENT CONTROLLING DOMINANT LEFT-LATERAL COUPLING DURING LARAMIDE OROGENY

HELENA NE LINEAMENT, SUBORDINATE TO DOMINANT COUPLE SYSTEM DURING LARAMIDE OROGENY

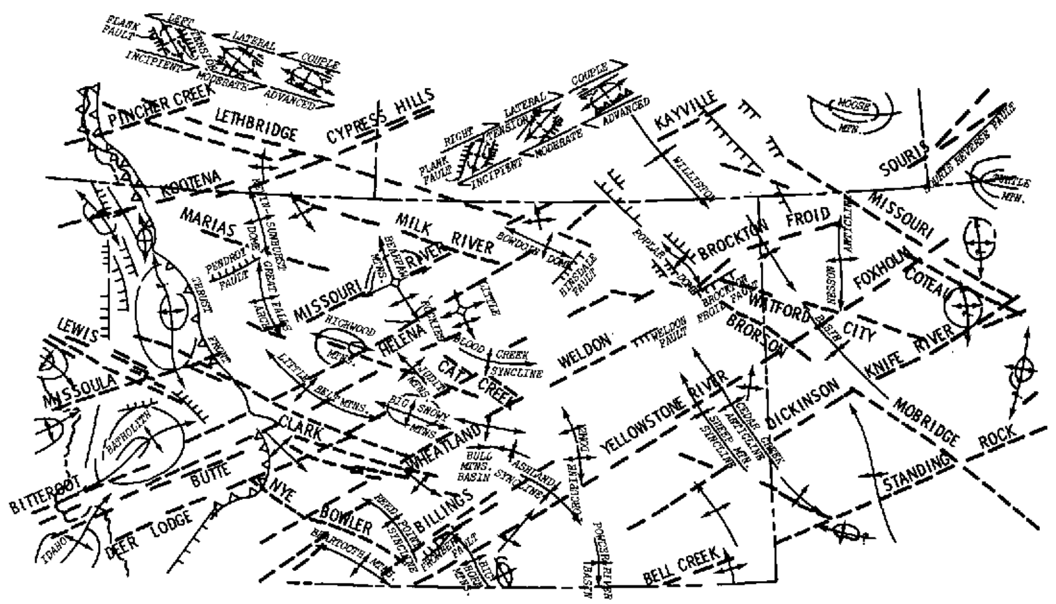
PUBLISHED FAULT

INFERRED FLANK FAULT

DRAG FOLD, ANTICLINE, SYNCLINE OR UNKNOWN TYPE

CURVILINEAR PATTERN DEFINING UPLIFT AND/OR INTRUSIVE/CALDERA FEATURE

B



LEWIS-CLARK NW LINEAMENT CONTROLLING DOMINANT LEFT-LATERAL COUPLING DURING LARAMIDE OROGENY

HELENA NE LINEAMENT, SUBORDINATE TO DOMINANT COUPLE SYSTEM DURING LARAMIDE OROGENY

PUBLISHED FAULT

INFERRED FLANK FAULT

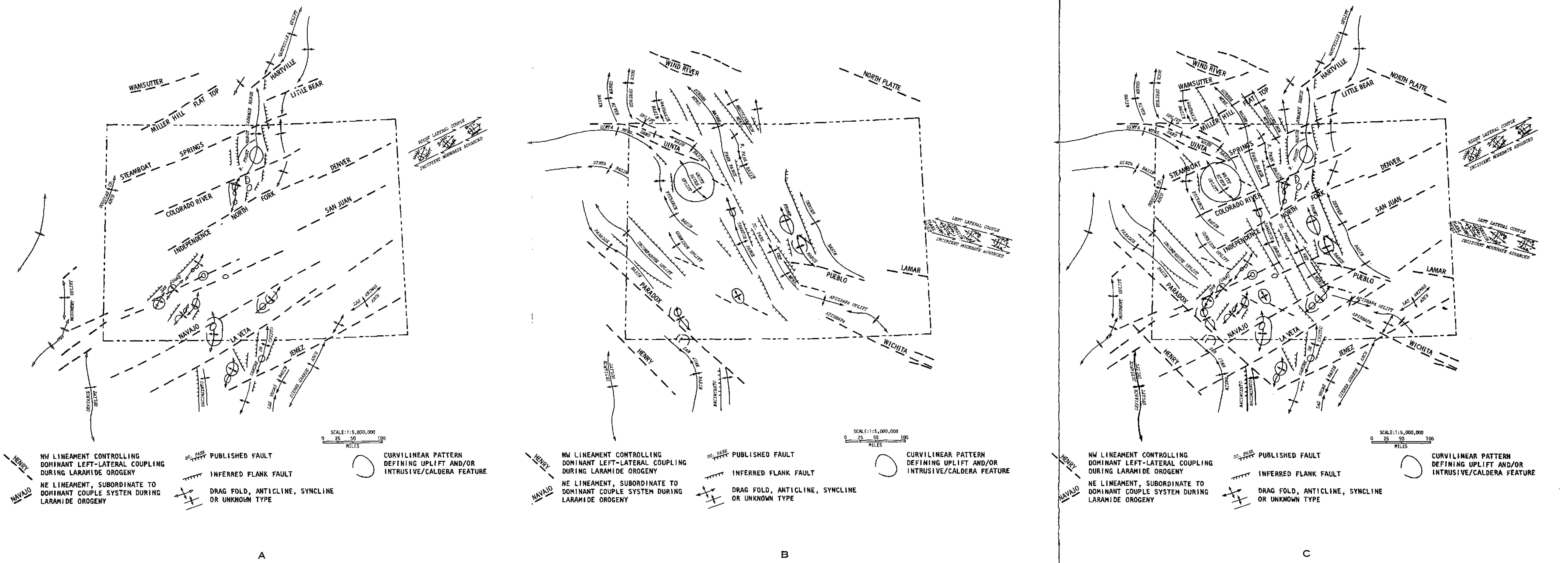
DRAG FOLD, ANTICLINE, SYNCLINE OR UNKNOWN TYPE

CURVILINEAR PATTERN DEFINING UPLIFT AND/OR INTRUSIVE/CALDERA FEATURE

C

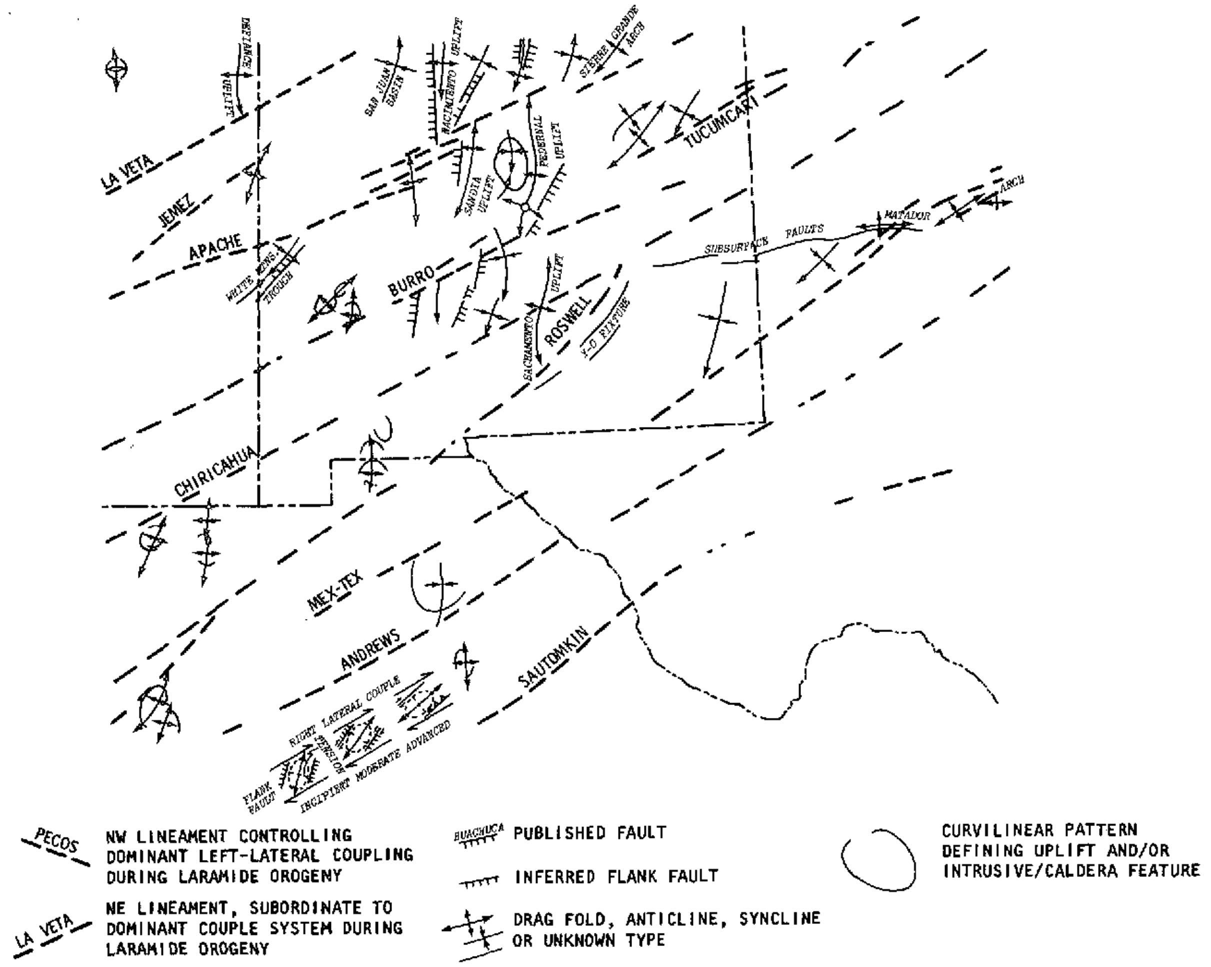
169971

Figure 40. Area 1 Lineament System

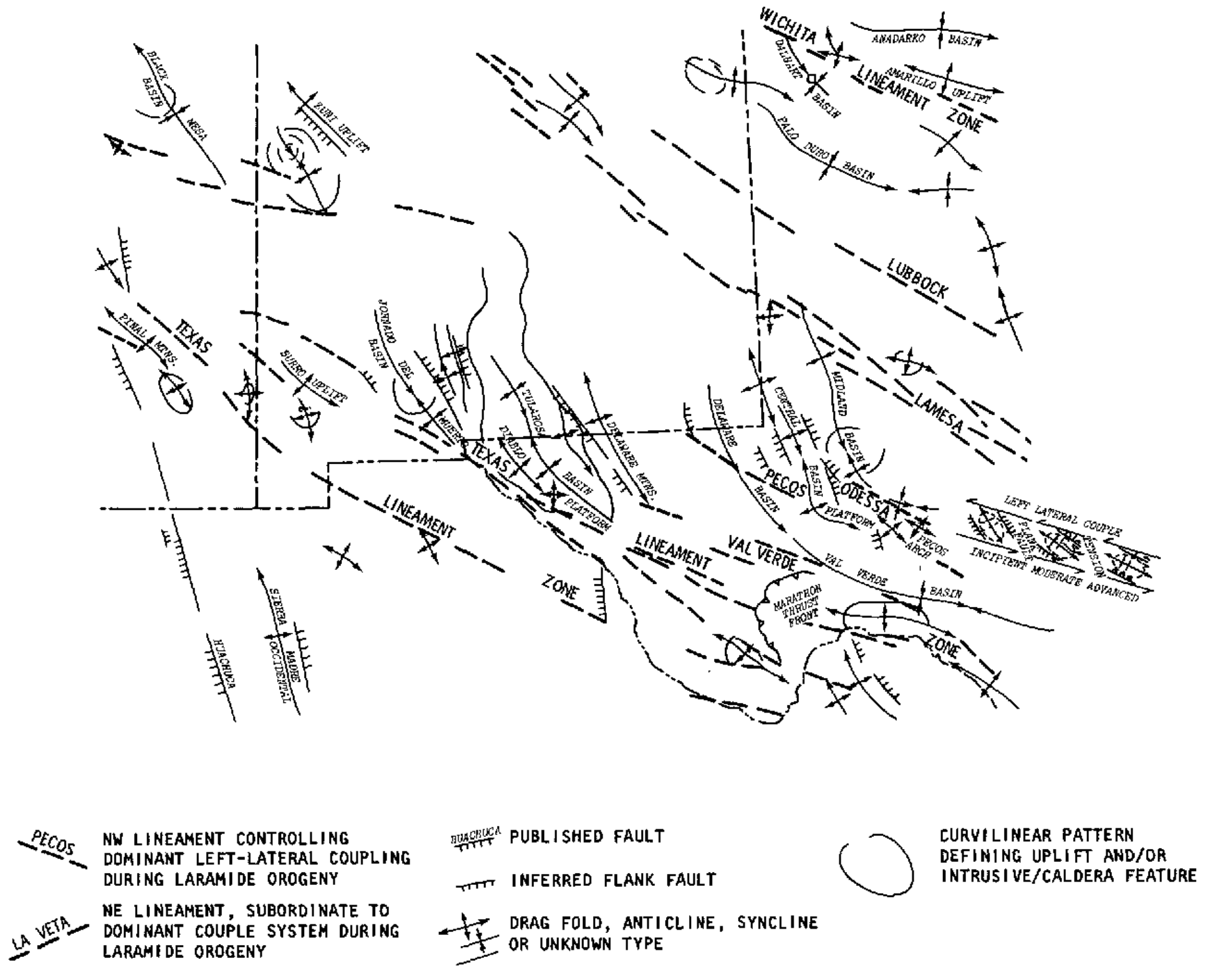


169972

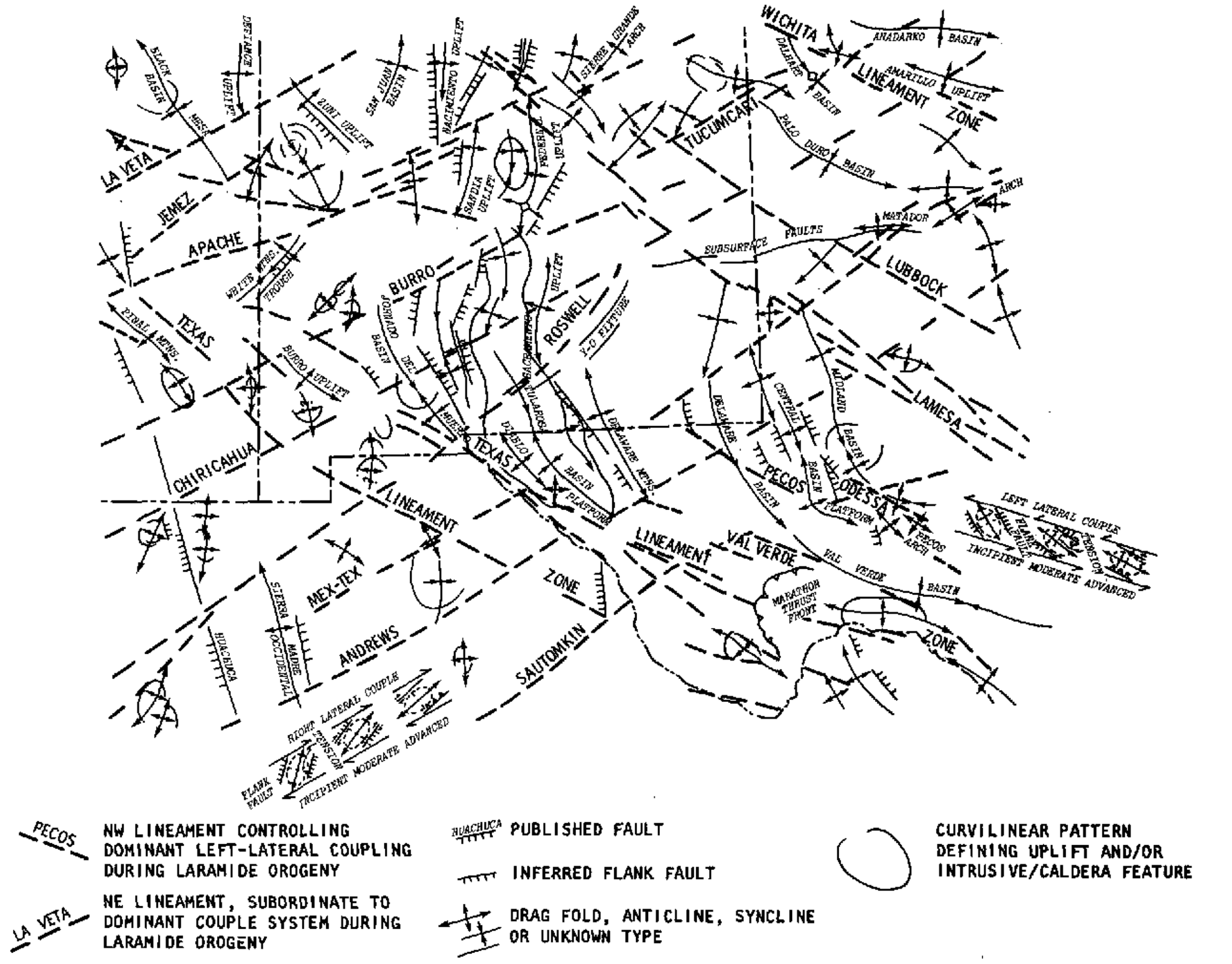
Figure 41. Area 2 Lineament System



A



B



C

169973

Figure 42. Area 3 Lineament System

Where the NW-trending uplifts are in proximity to the three major NW weakness zones of the region (NYE-BOWLER, LEWIS-CLARK and CAT CREEK lineaments), a significant amount of drag-fold rotation has taken place, as indicated by the near parallelism of the drag folds to the major shear zones. Farther away from these major zones, to the north and east the NW drag folds display trends suggestive of incipient to lower moderate coupling.

The NE weakness zones [Figure 40(A)], because of a subordinate role in lateral adjustment during the Laramide orogeny, did not produce many NNE drag folds during the orogeny in most of the Montana region. The Nesson anticline and the few questionable inferred uplifts of central North Dakota may have been buried basement features reactivated somewhat by the Laramide forces acting on the NE weakness zones. The questionable uplifts, however, are based on curvilinear patterns, and may be buried Paleozoic or basement highs evident only because of surface tonal patterns on the ERTS imagery.

In any case, NE drag folds indicative of right-lateral adjustment on the NE zones are not discernible in mid-central Montana where NW folds appear predominant. However, a large possible NE drag-fold uplift, intruded by numerous plutons, may be the extensive Idaho Batholith trend (including the Boulder Batholith), the northeastern end of which is shown in Figures 40(A) and 40(C). There several prominent NE lineaments occur in association with several curvilinear patterns. The individual curvilinear patterns suggest a multitude of intrusive bodies along a major NE-trending uplift that is better defined to the southwest of Figure 40. The major basement weakness zone responsible for the development of the Idaho Batholith drag fold would be the Snake River lineament zone (also to the southwest of Figure 40), a NE-trending feature presently consisting of a large belt of volcanic rocks, but believed by the investigators to have been a prominent NE shear zone during the Nevadan and early Laramide events.

The reason for the present accumulation of volcanic rocks along the Snake River Weakness zone and the predominant occurrence of NE-striking surface normal faults through most of Area 1 [Figure 40(A)] is also the probable cause for the NE elongation of many of the intrusive plutons in such mid-central Montana uplifts as the Bearpaw, Little Rocky, and Judith Mountains. As the dominant northwest block set coupling increased in intensity, the NE weakness zones became increasingly subjected to tension with consequent intrusion, extrusion, and normal faulting. The exact age of this phenomenon varied from area to area within the region due to variations in the response of the basement rocks to further coupling; but it probably occurred generally near the end of the Laramide orogeny or post-Laramide and accounted for the post-Laramide intrusive and extrusive activity in the area as well as the surface normal faults, some of which cut post-Laramide Tertiary rocks. This tensional phase must still be active in some parts of the western United States as evidenced by the Quaternary volcanics in the Snake River downwarp and other recent volcanic activity such as the Jemez center in New Mexico, which is thought to be associated with the NE-trending JEMEZ lineament.

In general, as regards the phases of a simple-shear, block-couple orogeny, Area 1 can be classified as an incipient-to-lower-moderate (in coupling intensity) drag-fold orogeny decreasing to the north and east with a strong NE-trending tensional phase near the end of the lower moderate phase of northwest coupling. Thomas (1974) has a more extensive discussion of simple-shear, block-coupling tectronics in this region.

c. *Area 2 (Colorado)*

In contrast to Areas 1 and 3, which contain large areas of plains-type topography, the Colorado area consists of about two-thirds mountains where more extensive relief and erosion has made many of the lineaments relatively easily detectable. This has aided in the structural analysis of the area.

As the combined version [Figure 41(C)] shows, the Laramide simple-shear, block-couple orogeny in Colorado consisted of coupling along both the NW and NE weakness zones in response to increasing stress. The following phases can be inferred:

Initial adjustment of weakness zones and blocks to regional compression, causing epeirogenic uplift and downwarp of blocks or block sets now only preserved in the Colorado Plateau.

Increasing lateral adjustment on both NW and NE weakness zones. Ancient Precambrian, right-lateral deformational "grain" (drag folds, flank faults, cross-fold tensional fractures, intrusive cores, etc.) originally controlled by the NE lineament system was reactivated where strongest by initial Laramide right-lateral adjustment on NE weakness zones. Those features shown in Figure 41(A) are considered to be part of this phase. Ancient intrusive plutons associated with this system were reactivated by uplift and fracturing. New Laramide uplifts in the NE system are believed to have been controlled in location by the ancient "grain." At the same time the NW Laramide structural system was beginning to develop.

Lateral adjustment increased on the NW weakness zones as the compressional stress intensified from the N 100° W direction. [If, for example, the compressive stress direction had been N 50° W, the Laramide dominant coupling would have been along NE block sets as demonstrated by model studies (Thomas 1974; in press)]. Dominant NW coupling is believed to have created NW incipient drag folds with flank fault complexes [Figure 41(B)]. Igneous intrusive activity is considered to have taken place along NW uplifts in addition to the reactivation of ancient plutons by uplift and fracturing.

With further increased lateral adjustment on NW weakness zones, some rotation of NW drag folds to an early moderate phase is believed to have occurred and produced high-angle reverse faults and constriction of intervening synclinal downwarps. NE weakness zones were subjected to tension, probably serving as early Tertiary conduits for eventual emplacement of plutons or volcanic activity with caldera formation along lineament zones where the geology and geochemistry were favorable. Intrusive or extrusive activity may also have occurred in the vicinity of ancient plutons in the reactivated NE drag fold system [Figure 41(C)].

Local advanced-to-extreme drag folding is considered to have taken place where the lithology was favorable, as in the case of the Paradox Basin salt deposits. *En echelon* advanced-to-extreme drag folding is believed to have occurred in the basin controlling salt emplacement along anticlines where the pressure gradient decreased. After the initial salt injection, development of anticlinal relief through coupling probably was aided by salt emplacement. Advanced to extreme coupling in incompetent Paradox Basin rocks may have produced deformational inducement for greater rotation of drag folds in both the Uncompahgre and

Gunnison uplifts. Both these uplifts and the Uinta and Apishapa uplifts are unique in Colorado for being closely parallel to major NW shear lineaments. This is taken to be an indication of maximum rotation.

Although the structural analysis of the Colorado region was based on known structural and lithologic information while incorporating the ERTS data, it should be emphasized that similar analyses could be carried out in regions of sparse geologic information utilizing only the ERTS data and a knowledge of simple-shear, block-couple mechanics. The angular relationships between various uplifts, flank faults, and cross-fold faults (all of which can be detected on ERTS imagery) are so consistent in coupling mechanics that a reasonably accurate structural picture can be constructed. In addition, curvilinear patterns on ERTS imagery give a reasonably accurate indication of probable plutons and caldera. Both sets of ERTS data make possible an economical and rapid means of defining regional as well as local mineral prospects. A similar approach can be used to define hydrocarbon prospects in a sedimentary basic utilizing only ERTS lineaments and curvilinears (see Section IV).

d. Area 3 (New Mexico-West Texas)

Area 3 is unique in that it contains part of what has been thought to be perhaps the largest simple-shear zone of adjustment in the world: the TEXAS lineament. This lineament zone has been described as bearing an average of N 75° W from the Santa Barbara Channel west of Los Angeles to the edge of the Gulf Coast fault zone (Schmitt, 1966), a distance of some 1,280 miles. In most places the zone of lineaments appears to be 100 to 125 miles wide. Although no one is quite certain of the amount of left-lateral adjustment along the TEXAS lineament zone since its possible Precambrian origin (Albritton and Smith, 1956), Schmitt (1966) speculated that the TEXAS zone has moved a total of 150 miles just since the Miocene. However, if the left-lateral offset of the offshore shelf along the Santa Barbara Channel can be used as a measure of the total accumulated movement of the TEXAS zone, 80 miles may be more correct.

In any event, the effect of the TEXAS lineament zone on the structures in Area 3 can be plainly seen in Figure 42(B). From the Pinal Mountains of southeast Arizona to the Val Verde Basin of southern Texas, a linear zone of drag folds, faults, and lineaments is evident. Equally evident are the incipient-to-moderate drag folds believed to have been generated by the left-lateral adjustment immediately north of the zone. These large folds are considered to include the Jornada del Muerto Basin, Tularosa Basin, Delaware Mountains, Delaware Basin, Central Basin Platform, and the Midland Basin. (The latter two features are believed to have been locally modified by the subordinate PECOS and ODESSA lineaments.) Westward, the TEXAS lineament zone passes through the Arizona copper porphyry belt on its way toward the coast.

Another NW lineament zone which has had a strong structural influence in Area 3 is the WICHITA lineament zone in the northeast part of the area. Paleozoic simple-shear movement on the WICHITA lineament zone, also a left-lateral zone, is believed to have produced large drag folds such as the Anadarko Basin, the Amarillo Mountains, the Wichita Mountains (immediately east of Figure 42), and the Dalhart and Palo Duro Basins. Judging from the parallelism of the drag folds to the lineaments, rotation of the drag folds along the Wichita Zone has apparently reached the advanced phase. (The *en echelon* ancient Wichita and Amarillo uplifts also support this contention).

The greater amount of rotation associated with the WICHITA zone than the TEXAS zone may be due to the resistence of the basement to rotation, or may be due to the fact that no major uplift southwest of the WICHITA zone impeded rotation. The structural complex of Mexico along with the Sierra Madre Occidental may have limited rotation of drag folds generated along the TEXAS zone, except in such local areas as the Diablo Platform where conditions are presumed to have favored greater rotation. It is interesting to note in conjunction with apparent rotation in the WICHITA zone that the Anadarko Basin may be considered to be a couple-generated downwarp to a depth in excess of 40,000 feet, a figure comparable to many of the oceanic trenches believed by many to be a result of subduction zone downwarp. It is conjectured that the oceanic trenches might be explained as simple-shear, coupled downwarps rather than as a part of a convection current subduction system.

Throughout most of the rest of Area 3, the NNE uplifts and basins suggest that they are a part of the right-lateral adjustment system along the NE lineament-weakness zones [Figure 41(A)]. Since many of these features are older than the Laramide orogeny (the Sierre Grande Arch is believed to have been initiated in the Pennsylvanian, which may also be true for the Pedernal and Sacramento uplifts), it is suggested that the northeast lineaments may have been reactivated as right-lateral adjustment zones as early as the Pennsylvanian. The fact that the left-lateral WICHITA zone disturbance has also been dated as a Pennsylvanian event (King, 1969a, p. 64) suggests that the entire basement weakness zone system in the general region of Area 3 was probably activated during the Pennsylvanian. Both the Ouachita fold belt and the Marathon deformation may have been formed during this earlier reactivation of the weakness zones. Subsequent Laramide stress could have reactivated the weakness zone system, forming new drag folds and reactivating old features where conditions were favorable.

A further structural complexity in Area 3 occurs in the southwest part of the region where NNW lineaments such as the HUACHUCA, parallel the basin and range fault system of the western United States north of the TEXAS lineament zone. It is believed that lineaments with these trends are related to the basin and range system and probably are void of mineralization. Stokes (1968) has recognized this to be the case for the basin and range faults which apparently were formed after the main periods of mineralization.

As in Areas 1 and 2, it is believed that the NE lineaments of Area 3 (especially in the western half) were subjected to an early period of right-lateral adjustment during the Laramide orogeny and subsequently became increasingly tensional as the dominant NW block set coupling increased in intensity. The parallelism of the tensional direction of incipient-to-moderate coupling with the NE weakness zones may be noted in Figure 42. This activity is believed to have opened the NE weakness zones, including local NE fractures and foliations to provide emplacement conduits and depositional sites for intrusives and mineralization during the later phases of the Laramide orogeny and post-Laramide Tertiary events. The same NE tensional activity occurring after the Laramide is believed to have controlled the large outpourings of post-Laramide volcanics in Area 3.

3. Area 5 (Northern Alaska)

Of the five areas studied for this report, only northern Alaska is part of the continental margin deformation of North America. As such, it provides a unique opportunity to investigate lineaments and their role in the structural development of such an area. Also unlike the other areas, Alaska has long been recognized to contain extensive fault zones with right-lateral adjustments as their principal mode of movement (Tectonic Map of North America; King, 1969b). These lateral faults define a great arc in the southern part of Alaska from the northeasterly Aleutian Islands trend to the southeasterly fault-mountain trends of the extreme southeastern part of Alaska. This great arc of faults and mountain trends has been labeled the Alaskan Orocline by Carey (1958). Its origin is in dispute.

Carey interprets the orocline as being the result of North America swinging to the southwest around a pivot point in the McKenzie Delta area (immediately east of Alaska) in response to the opening of the Arctic-Atlantic oceans. With this mechanism, the Aleutian Islands chain remained stationary while the western coast of North America moved WSW, thus producing the great oroclinal bending in southern Alaska. An alternate postulate in terms of the new "Global Plate Tectonics" suggests that the bend might be the result of the North Pacific Plate and its associated mid-Pacific Gordo ridge complex being pushed northward into the continental margin like the bow of a battleship thrust into a large, flat sheet of steel.

Whatever the correct interpretation of the orocline is, the northern part of the orocline proper is represented in Figure 43(A) by the KALTAG-TINTINA fault complex, both recognized as right-lateral shear complexes. North of these faults the characteristic arc-like fault-mountain trends of the orocline disappear. Instead, the major structural features, such as the Brooks Range, trend essentially E-W. It has been questioned whether the structural mechanics north of the orocline proper are different from the right-lateral mechanics within the orocline.

In general, the formation of the Brooks Range has long been considered geosynclinal in nature, that is, an ancient E-W geosyncline, the Colville, was filled with Paleozoic eugeosynclinal deposits and marginal miogeosynclinal deposits, and later uplifted by compressive stress oriented in a N-S direction during later Paleozoic and Mesozoic orogenies in the regions. Carey (1958), however, has offered a different reason for the structural trend change north of the orocline. He believes that the Yukon Sphenocasm* [Figure 43(A)], formed between the orocline proper and the Brooks Range area and that it gradually widened, forcing the western half of the Brooks Range Area northward, presumably setting up the N-S compressive stress deforming the range at the same time. A lateral adjustment break at the mouth of the Sphenocasm [the Kotzebue lineament, Figure 43A], resulted in the separation, left-laterally, of the Brooks Range proper and its formerly western extension, the Seward Penisula. The similarity of rock types between the two areas suggests the validity of the sphenocasm theory.

Lineament mapping in Area 5 tends to support Carey's theory in that the Yukon Sphenocasm contains numerous lineaments paralleling the Kobuk and Kaltag lineament zones, thereby emphasizing the triangular nature of the feature. In addition, a more or less extensive lineament trend, the Kotzebue, is evident on ERTS imagery where Carey proposed a lateral adjustment zone. Further possible support of the theory lies in the presence and position of several major curvilinear patterns within the Brooks Range. The elongation of these patterns suggest a series of right-laterally coupled *en echelon* uplifts cored by buried intrusive bodies. [The same type of patterns have been found in Colorado (Area 2) coincident with major uplifts.] If these inferences are correct, the Brooks Range, instead of being deformed by compressive stress, may actually have been deformed by right-lateral coupling which produced *en echelon* uplifts within an ancient depositional trough. Concomitant with the uplifting would be gravity sliding of the water-filled sediments down the north flanks of the broad uplift. If a

*The Yukon Sphenocasm is a triangular opening in the continental crust floored with oceanic crust in response to the regional structural mechanics.

right-lateral mechanism deformed the Brooks Range, it might indicate that the right-lateral movements of the Alaskan orocline to the south extended northward through the Yukon Spenochasm and into the Brooks Range. This possibility, of course, would negate the need of a sphenocasm to provide compressive force.

Another interpretation is possible, however: incorporating the existence of a sphenocasm that began to form *after* the Brooks Range had been essentially deformed and not *before* as Carey postulates. Figure 43(B), shows the same area, but this time without the Yukon Sphenocasm. Such a sketch map clearly shows that the Brooks Range inferred structure is very compatible with the orocline structures to the south. Further, it reconnects the Brooks Range and the Seward Peninsula complex as Carey postulated. Presumably, this is a pre-Cretaceous situation. With the opening of the sphenocasm, Cretaceous sediments and volcanics infilled the gradually widening sphenocasm and also infilled the Colville syncline north of the range whose northward movement during the Cretaceous period produced an asymmetric downwarp adjacent to the mountains in which over 15,000 feet of Cretaceous sediments were deposited.

The compatibility of the trend and structures of the Brooks Range with the southern orocline when the sphenocasm is closed [Figure 43(B)], suggests to the investigators that Carey is correct in his sphenocasm theory but that it is a post-Brooks Range feature for the most part rather than a pre-Brooks Range feature.

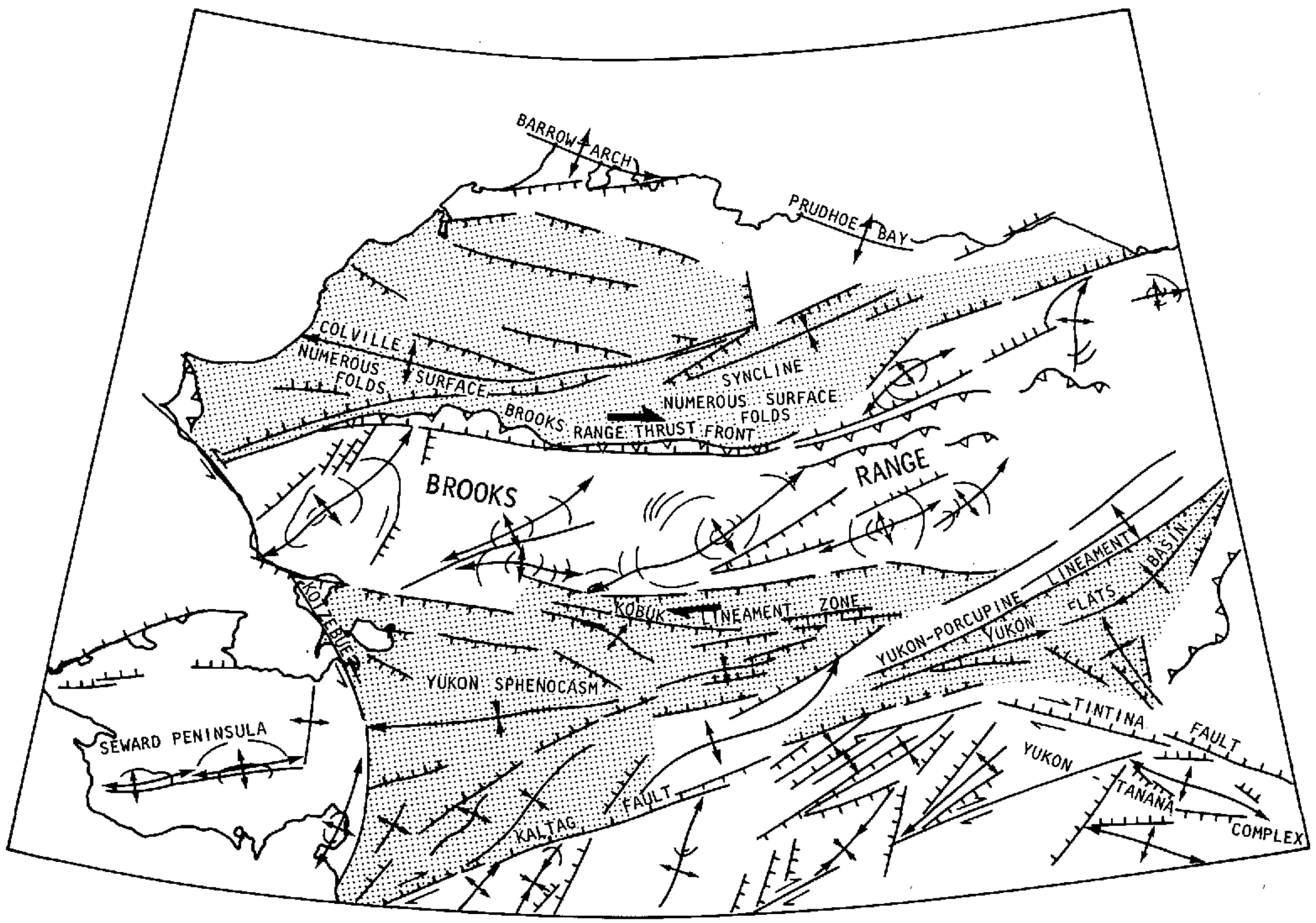
The Area 5 interpretation incorporating ERTS data clearly shows that the use of ERTS imagery in regional structural analyses can add much to the tectonic data already known for any area. Combination of ERTS data with that shown on regional maps should provide a greater understanding of the structural relationships in any area. It follows, of course, that a greater understanding of structural relationships leads eventually to a greater understanding of the mineral emplacement and hydrocarbon trapping mechanisms which is fundamental in resource exploration.

H. ECONOMICS OF ERTS IMAGERY APPLICATION

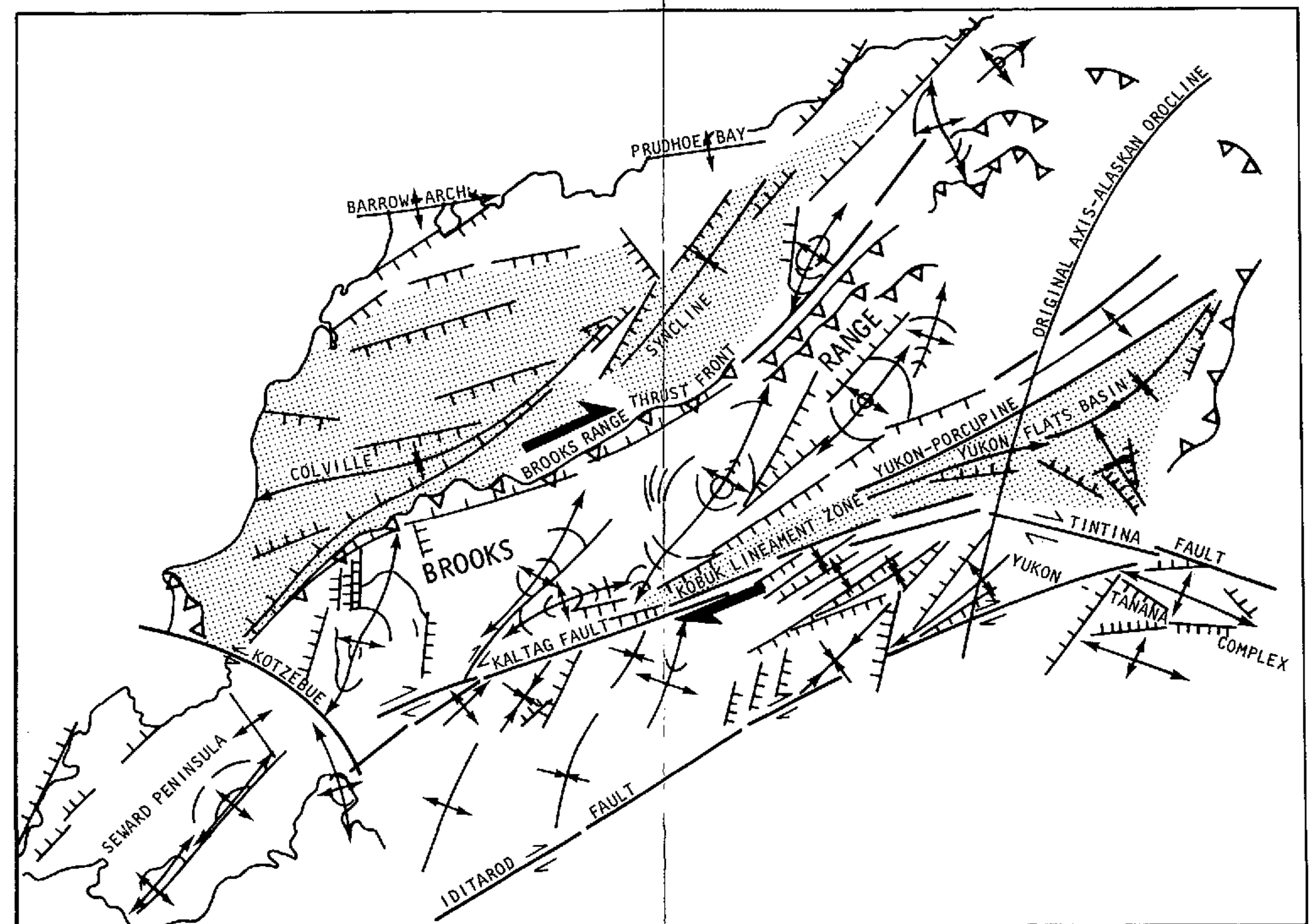
1. Introduction

For many years aerial photography has been used for photogeologic and geomorphic interpretations to guide petroleum and minerals exploration. In recent years it has served as the data base for detection and mapping of lineaments (Lattman, 1958). This experience allowed a comparative economic analysis to be made between ERTS imagery and aerial mosaics as used for the same general type of data analysis. The results of this study are presented in the following subsections.

There are limitations in the accuracy of the comparison; they are based on differences in scale, resolution, availability of coverage, etc., that result in basic differences in the capabilities of the two media in lineament data analysis. ERTS imagery exhibits unique characteristics, such as large area coverage with near-vertical look angles, relatively constant solar angles, and coincidental multispectral images, all on a relatively short time base as compared with aerial photography. On the other hand, aerial photography has a much higher resolution which allows



A. YUKON SPHENOCASM PRESENT: RIGHT–LATERAL SIMPLE SHEAR ON KALTAG–TINTINA FAULT SYSTEMS PRODUCES A SERIES OF DRAG–FOLD, FLANK–FAULT COMPLEXES ADJACENT TO FAULTS. SIMILAR RIGHT–LATERAL MOVEMENT ACROSS BROOKS RANGE PRODUCES RIGHT–LATERALLY EN ECHELON SERIES OF DRAG FOLDS



B. YUKON SPHENOCASM ABSENT: WITH SPHENOCASM NOT YET IN EXISTENCE, BROOKS RANGE–SEWARD PENINSULA COMPLEX DEFORMED AS PART OF RIGHT–LATERAL ADJUSTMENT SYSTEM IN WEST FLANK OF ALASKAN OROCLINE.

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Figure 43. Lineament-Block Tectonics, Northern Alaska

much more follow-on detailed work to be done using the same data base; however, this can be a disadvantage in the lineament data analysis because of the small area coverage, which necessitates many individual photos in a large-area mosaic. This very large number of photo edges and unnecessary detail can effectively obscure large-scale features such as major lineaments. Thus, technically, the two media are not equivalent, and care must be exercised in drawing conclusions from direct economic comparisons between them.

This analysis is based on practical work experience using ERTS imagery in this study and on previous work using aerial mosaics to accomplish essentially the same result primarily in Montana and Arizona (Geophoto Services, 1972, 1972a). Following this approach, the following factors become important:

Costs were compared, based on a single ERTS-I image at 1:1,000,000 scale (100 nautical miles on a side), the Area 2 (Colorado Region) ERTS mosaic, and on the aerial photography required to provide 1:48,000 scale mosaics of equivalent areas.

It was assumed that both aerial photos and ERTS-I imagery are available for public purchase over any area of interest. Therefore, costs associated with data collection were not considered in this analysis.

No attempt was made to quantize the admitted differences in information content of broadband aerial photography and multispectral ERTS imagery, or the differences in lineament mapping capability based on resolution differences. It was assumed that there is an equivalent technical tradeoff in this area, inasmuch as the applications of both types of products are in their infancy and there is insufficient data available to judge any differences in eventual overall success. In the same vein, differences in interpreter experience and ability with the two media were not considered.

2. Costs of Data Reduction

a. *Approach*

The following tasks were established as those normally associated with producing a salable lineament interpretation based on aerial photos:

1. Select area of interest
2. Select desired scale of photos
3. Determine availability and order photos
4. Construct mosaic
5. Perform data analysis (annotate data).
6. Perform data interpretation
7. Translate data and interpretations to common map base.

A review of these tasks revealed that only tasks (3), (4), and (5) would be materially affected by using ERTS imagery rather than standard aerial photos. Thus cost comparisons were limited to these three tasks.

b. *Costs Associated with Imagery Source Location*

Locating and ordering aerial photographs can be a very time-consuming and laborious task. For example, Geophoto Services of Texas Instruments has spent years establishing a photo source library which is constantly being updated as information on new photo coverage becomes available.

Sources of photo coverage are extremely diverse but generally fall in two categories: Government agencies or commercial organizations. Within the U.S. Government, photos (where available) can be ordered from various agencies such as the U.S. Forest Service, U.S. Coast and Geodetic Survey, U.S. Geological Survey, and the Soil Conservation Service (Department of Agriculture). These agencies periodically publish information on their holdings, a service which is very beneficial to potential users; but in many cases local offices do not provide all available coverage from a given agency. Thus, it often becomes a time-consuming task to review Government agency holdings and find the specific photos required.

Recently, a major step has been undertaken to assist users of Government photography. The EROS Processing Center in Sioux Falls, South Dakota, is expanding its holdings to include those of the following Government Agencies: U.S. Geological Survey, U.S. Bureau of Reclamation, U.S. Forest Service, U.S. Bureau of Land Management, NASA, U.S. Navy, U.S. Air Force, and the holdings of the University of Michigan. This does not include the U.S. Coast and Geodetic Survey or the Soil Conservation Service holdings, which are also major sources of standard photography. However, this consolidation of holdings, along with computer-aided inventory updates, automated screening, and retrieval systems, and an open procurement policy will be a great aid to all groups working with photography. Once this system is fully implemented, photo users will have to interface with only two or three source locations to procure photos taken by all Government agencies.

The problems of interfacing with two or three Government sources becomes trivial by comparison with the problems that may be encountered in locating and ordering photos from private flying contractors. A recent experience by Geophoto Services illustrates this difficulty. Library sources indicated that a particular company had flown and collected certain aerial photos of interest. It was recognized that the company had made these photos available for sale in the past but now had divested themselves of their holdings. After numerous phone calls, Geophoto was informed that a second company now held these photos. Direct contact with them established that they had only part of the desired coverage and the remaining holdings had been distributed to various universities around the country. Unfortunately, experiences like this are not uncommon.

In contrast, all ERTS imagery is available from central Government facilities, such as the USGS Sioux Falls EROS Processing Center. Since various customer services such as computer printouts of coverage are available at these facilities, the problem reduces itself to a standard ordering procedure; and thus, much of the time-consuming task of locating the imagery is eliminated. The time in preparing the order is much less for ERTS, corresponding to the much smaller number of images necessary to cover a given area. It is concluded that it generally is more costly to locate and order aerial photos than ERTS imagery. While it is recognized that this cost ratio can vary widely, from experience it is estimated that this ratio probably is at least 2:1; that is, on the average it is twice as costly to locate aerial photos than to locate standard ERTS imagery.*

*This ratio could be low, particularly for large area coverage, when scale, season, and date-of-coverage restrictions are important. However, this may be offset at least partly by many years of experience in photo source selection.

c. *Costs Associated With Preparing a Mosaic*

Mosaics are generally considered to be either controlled and uncontrolled; however, there are varying degrees of control. Mosaics commonly used for petroleum and mineral exploration purposes are tied to a few prominent geographic locations established on published maps with survey control. There is no attempt to eliminate completely all sources of errors such as that caused by lens distortions, but minimal use is made of data near the edges of photos where maximum distortions occur. Dimensional accuracies achieved in this manner are considered to generally match those of an ERTS image. This type of mosaic construction was taken as a basis of comparison with ERTS usage.

The following assumptions were made in comparing costs of making mosaics:

The purchase prices of single photos and ERTS-I images are essentially equivalent ($1.75 per print)

One photo at 1:48,000 scale covers 22.3 square nautical miles

One ERTS image at 1:1,000,000 scale covers 10,000 square nautical miles

One man-day of labor is required to produce one 15-minute quadrangle mosaic at 1:48,000 scale.

On this basis, the material and labor costs are shown in Table 8. Thus, the cost ratio of providing a photo mosaic to that of one ERTS image is approximately 1881:1.

TABLE 8. COMPARISON OF COSTS IN PREPARING A MOSAIC

	ERTS	Photos
Images		
Number images required	1	448
Cost at $1.75 per image	$1.75	$784
Labor		
Number of 15-minute quadrangles included	44	44
Number of man-days required	0	44
Cost at $57/day	0	$2,508
Total Cost	$1.75	$3,292

The Area 2 (Colorado Region) ERTS-I mosaic required about 0.75 man-day for its construction and included an equivalent of about 768 15-minute quadrangles. Based on these figures, the comparative material and labor costs are given in Table 9. On the basis of this ERTS mosaic, the aerial photo-to-ERTS cost ratio is about 500:1.

TABLE 9. COMPARATIVE COSTS FOR AREA 2 MOSAIC

	ERTS	Photos
Materials		
Number images required	~34	7,820
Cost at $1.75 per image	$59.50	$13,684
Labor		
Number of 15-minute quadrangles	768	768
Number of man-days required	0.75	768
Cost at $57/day	$42.75	$43,776
Total Cost	$102.25	$51,596

d. Costs Associated With Imagery Interpretations

Any difference in cost between performing a lineament interpretation on an ERTS image or an equivalent area photo mosaic at 1:48,000 scale would be a function of the time required to extract the same level of information from each data source. Since the level of information extraction is controlled by resolution on the ground, the comparative lineament interpretation base was established as that which could be extracted from an ERTS emage.*

Factors which will control the time to perform an interpretation are quantity, quality, and distribution of data. All of these factors (within assumptions of this report) will dictate a longer time to interpret the aerial photo mosaic. In terms of quantity, there is more data on the photo mosaic, so the interpreter is likely to spend more time extracting the lineament data from other confusing data. In terms of quality, the ERTS image is likely to exhibit a more uniform density than a photo mosaic covering the same area. Not only is there likely to be overall density variations among large numbers of prints, but there will be subtle confusions associated with the edges of the photos. It requires time to separate such features from the real data. In terms of distribution, an interpreter's eye must cover a far larger area to deal with the photo mosaic than with a single ERTS image. This is far more important in picking out lineaments than in many other types of interpretations because the eye must pick up a subtle linear pattern that covers many miles on the ground. If these linear patterns require a major shift of the interpreter's eye, it will require double and triple checks to ensure that the same frame of reference is being used in all eye positions.**

No one, to the authors' knowledge, has performed an actual time study on this specific task; hence, it became necessary to estimate these time requirements based on general experience. It is recognized that time differences can vary widely from one specific data set to another, but on the average it takes approximately 3 days to perform a lineament interpretation on 1:48,000 aerial photo mosaics that would be approximately equivalent to a 1-day interpretation on a single ERTS image. Thus, the cost ratio for interpretation is concluded to be about 3:1.

*The assumption here is that there are ground details which can be seen on the 1:48,000 photo mosaic but not on the 1:1,000,000 ERTS image. On the other hand, any feature observed on the ERTS image should be observable on the photo mosaic. Any comparison, therefore, must be done on the ERTS imagery base.

**This is why many interpreters will "back off" from large mosaics when they perform lineament interpretations.

e. Conclusions on Cost Ratios

From this analysis it is concluded that costs associated with three tasks in preparing large-area lineament interpretation products would be much less through the use of ERTS imagery rather than standard aerial photography. The cost ratios of imagery source location and imagery interpretation have been estimated at 2:1 and 3:1, respectively. The cost of using ERTS imagery for the preparation of mosaics is concluded to be about 1/500 of the cost in using aerial photography; this is clearly dominant over the other savings. Thus, within the errors inherent in these estimates, the overall cost ratio associated with using ERTS imagery versus aerial photos for large area interpretation products is about 1:500 in favor of ERTS.

3. Marketability

To come to grips with the economics of using ERTS imagery for lineament interpretations, it is not sufficient to consider only the costs; one must also consider the larger question of salability of the end product.

Salesmanship is never unimportant, but it is less important in a mature market than in a new potential market. In a mature commercial market, the salability of a product is governed by the price of the product, increased profits attributable to the product, and other acceptance measures such as economic need for the user's end product, convenience of use, and availability.

The market for ERTS lineament interpretations must be considered a new potential market. This type of market is controlled by salesmanship, promising expectations and judgments of the buyer (user). Since there is no historical evidence of increased profits associated with the use of the product, the buyer makes his decision based on the price to him versus the appeal of information presented to him regarding reasons to expect increased profits. Thus cost (or price) of an ERTS lineament interpretation map does not completely control its salability, but it becomes one important factor.

Some lineament interpretation maps have been prepared and sold at prices dictated by costs associated with using aerial photographs. Applications of these types of maps characteristically are for a "first look" in unexplored regions, for aids to guide other exploration activities (such as establishing seismic lines), or for an additional data set used in combined interpretations of a region where seismic, magnetic, gamma ray, geochemistry and/or other types of data are used in concert. These limited sales indicate there is some potential market for lineament interpretation maps. The reduced costs (about 500 times reduction as established in this analysis) for large area ERTS maps plus the empirical relationships between linear and curvilinear patterns and known mineral deposits established in this study should positively influence the judgments of potential buyers toward ERTS lineament map utilization. In support of this argument, Geophoto Services of Texas Instruments in recent months has sold six area interpretations of this type to various oil companies, and at least one or two other companies are beginning to offer similar services.

Thus it is concluded that at least a small potential market for lineament maps based on ERTS imagery currently exists. Initially, salesmanship will be a dominant factor controlling the expansion of this market, but ultimately new petroleum or mineral discoveries will have to be made where ERTS data played an important identifiable role before this market becomes mature and valuable in itself.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A. INTRODUCTION AND SUMMARY

The feasibility of using ERTS-I imagery in commercial reconnaissance exploration involves technical and economic questions as well as customer acceptance. In this study all these facets have been considered to varying degrees. The bulk of the work has been in the area of technical evaluation with minor effort in economic comparison with aerial photography as a data source. Through limited experience, some insight has been gained in the area of customer acceptance, but a thorough evaluation of that will be possible only after an extended period of commercial use.

Specific conclusions and recommendations are presented in the following subsections. In summary, it is concluded that the mapping and application of ERTS data at 1:1,000,000 scale will provide a workable and economically advantageous new reconnaissance prospecting approach for gold, base metals, uranium, and fluid fossil fuels. Used in the context of a simple-shear, block-coupling model, the data can be used to predict potential new mining districts and trends of favorable petroleum structures, at least in the study areas. It is also concluded that a more detailed analysis with annotation at 1:250,000 scale or 1:500,000 scale should provide the basis for taking the next step in exploration, that is, defining individual prospects within the favorable districts or trends. It is recommended that this next step be tested over known and prospective areas to determine the best methods to be used and the extent to which individual prospects can be defined using the ERTS data.

Texas Instruments is routinely using ERTS imagery in all photogeologic reconnaissance programs to the extent allowed by its availability, thus demonstrating faith in these conclusions. Much client interest has been shown in the applications of this new medium to date.

B. TECHNICAL EFFECTIVENESS

1. General

Reconnaissance for minerals or petroleum involves a series of steps which sequentially and progressively reduce the area to be searched by eliminating those areas most likely to be barren. Methods used for reconnaissance may be based on:

Pure empiricism—where known deposits are statistically demonstrated to be spatially related to structural or geological elements

Geological reasoning—where structural and petrological hypotheses are employed to determine areas potentially favorable for deposits to form

Combinations of empiricism and theory—which are most effective where reliable measurements or observations are combined with well-founded geological relationships.

The practical utilization of ERTS imagery in prospecting requires proved models to tie the observed data to the formation of favorable structures. Simple-shear mechanics in a block-coupling framework have been applied as the structural model in this study, and this has been found to be convenient, flexible, and plausible in reconciling observations and theory. There may be other structural models which will work as well, and it is not implied that simple-shear mechanics is the only recommended approach. Others are encouraged to investigate alternatives.

When the study was initiated, the problem of technical applicability was approached in terms of using ERTS imagery as conventional aerial mosaics had been used to map large-scale structural features. The actual ability to see regional lineaments and curvilinear anomalies was not anticipated, and when this advantage was realized, it was necessary to reexamine the planned approach so that it could be best evaluated. This required interpreting the entire areas of interest rather than selected portions, as was proposed, and concentrating on the regional search for mining districts and petroleum provinces rather than reconnaissance for individual prospects.

2. Regmatic Fracture Pattern

To be of practical commercial value, any new tool must be widely applicable, and of primary interest in this regard is the observed regularity of trend distributions for the major lineaments as illustrated in Figure 44. All areas show peaks in the northeast region (N 60°–67° E) and in the east-southeast region (N 102°–115° E). This implies a continent-wide regmatic fracture pattern which probably originated in the Precambrian era with interpreted recurrent right-lateral coupling on plates between northeast lineaments, producing a pervasive tensional "grain" with a general ESE trend. NW-trending lineaments are less frequent and well-defined but are found in all areas and are interpreted to have been coupled generally in a left-lateral sense, producing NE tensional fractures. NW lineament peaks on Figure 44 include segments of the major lineament zones (LEWIS-CLARK, WICHITA and TEXAS), Laramide uplift flank faults and the WNW (ESE) tensional trends. It should be noted that many of the individual linears defining the major lineament zones have trends more nearly NW than the zones themselves which are overall WNW, suggesting *en echelon* arrangement of the defining linears. It is generally concluded that ERTS has provided a new key to unravelling the complex structural history of the earth on a continental scale by allowing the ancient major zones of crustal weakness to be detected effectively and mapped.

3. Reconnaissance for Minerals

Lode minerals such as gold, base metals, and vein-type uranium show close correlation with linears. Inspection of the data interpretation maps shows a higher density of linears where the lode deposits are located and high percentages of the deposits are found within 4 miles of linears, as summarized in Table 10.

In all areas it was possible to analyze the lineament and curvilinear patterns in terms of simple-shear block-coupling so that predictions of the most favorable linear trends could be made as a guide to prospecting. In all areas, ESE linears appear to be favorable. In the Laramide areas NE trends appear favored, while SE trends are mineralized in the Precambrian.

Sandstone-type uranium deposits are interpreted to have an element of lineament control through presumed control of paleostream drainage and on observed lineament control on surface outcrops of ore-bearing formations. In general, the control on deposition appears to be predominantly stratigraphic, and this is evidently even stronger in the uraniferous lignites, as would be expected. This is shown in Table 10 by the relatively lower correlation with linears.

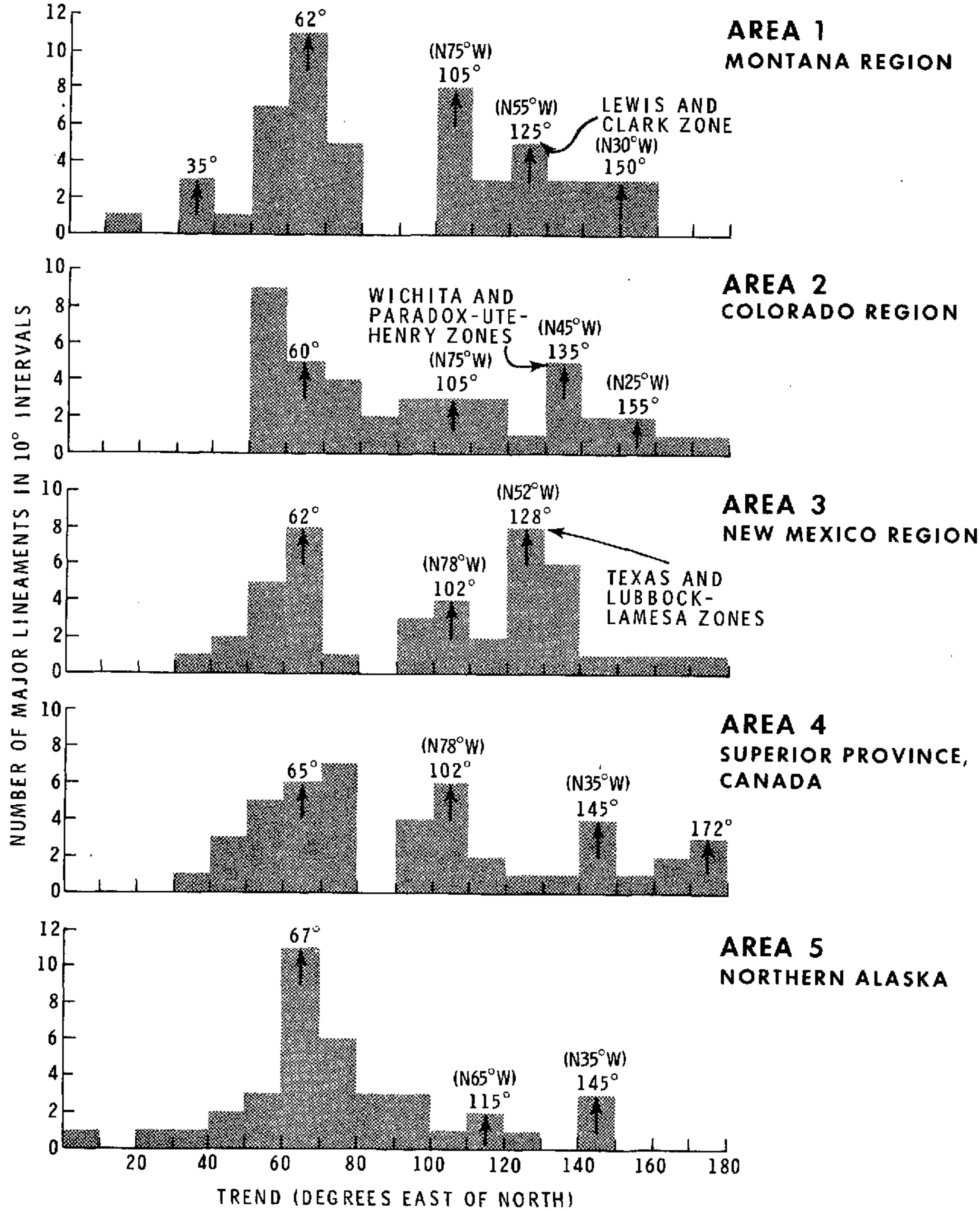

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Figure 44. Comparison of Major Lineament Trend Distribution

TABLE 10. SUMMARY OF ERTS DATA CORRELATION WITH MINERAL DEPOSITS

	Percent of Mines Within 4 Miles of Linears				
	Area 1	**Area 2**	**Area 3 (U.S. Only)**	**Area 4**	**Area 5**
Gold and Base Metals					
Majors	62	100	89	–	–
Total	67	95	70	73	68
Total Mines Plus Prospects	–	–	–	–	70
Uranium					
Veins	65	82	–	–	–
Lignites	46	–	–	–	–
Sandstones	–	55	–	–	–
Total	–	–	52	–	–

The data suggest that there may have been one or more possibly continent-wide Precambrian periods of mineralization in the Archean producing ore deposits such as are exposed in Area 4. It is inferred that these may have been caused by right-lateral coupling along the major NE-trending weakness zones with emplacement primarily in ESE tension zones.

In the Rocky Mountain region (Areas 1, 2 and 3), it is inferred that the Precambrian deposits formed by this continent-wide process became the "roots" of the present ore deposits which are thought to have been formed in large part by reworking of the Precambrian ores. In this concept the Precambrian ores at Coeur d'Alene are thought to be one of the few deposits of that age that were not reworked.

In the pre-Laramide and early Laramide, the NE lineaments are considered to have been reactivated right-laterally to produce reworked deposits which trend generally ESE to SE (as is the case with one of the vein systems at Butte). Later the predominant adjustments were along the NW lineament systems left-laterally to emplace ores in the NE-trending tension zones (as in the Santa Rita porphyry copper deposit and others).

The situation in Alaska is somewhat more complex because of the suspected rotation of parts of the area with respect to the major continental plate, but it is believed that the same general structural concepts may apply and should be investigated as a prospecting guide.

Follow-up research is recommended to include detailed studies of ERTS at 1:250,000 scale to find methods of defining individual prospects.

4. Reconnaissance for Hydrocarbons

Linears and large curvilinears are found to roughly outline sedimentary basins and large uplift structures. The major lineaments often show strong evidence of being the surface expression of basement weakness zones which have controlled depositional conditions in such a manner as to provide favorable structures for petroleum accumulation including:

En echelon folding due to advanced or extreme coupling immediately adjacent to the lineament (Cat Creek–Area 1; Pieeance Basin--Area 2)

Favorable conditions for reef growth (Scurry Reef *et al.,* Area 3).

Hinge lines for pinchouts and facies changes (flanks of Central Basin Platform–Area 3)

Zones of increased permeability through fracturing (Florence Field–Area 2).

Many lineaments show a clustering of fields along them or appear to be production boundaries.

Lineament analyses can be used in petroleum reconnaissance to predict the most productive seismic profile directions and to indicate generally the regions with most potential in a basin.

Follow-up studies should use ERTS imagery at 1:250,000 to evaluate the possibilities of locating individual prospects through dissection or tonal anomalies.

C. ECONOMIC EFFECTIVENESS

1. Costs

Subsection III.H. of this report has shown that there is at least a 500:1 cost advantage in using ERTS imagery rather than standard aerial photography for large-area lineament interpretations. This cost reduction should lend added impetus to the sale of large-area lineament interpretations.

2. Profits

While it is possible to estimate how many dollars ERTS imagery will save in preparation of lineament interpretations, it is not possible to realistically estimate how many dollars it will make for its users. The financial "carrot" that is placed before us is that empirical correlations have been established in this study between certain patterns observed on the ERTS imagery and known petroleum and mineral deposits, and it has been reported, for example, that 70 percent of the known western hemisphere copper deposits range in value between 600 million and 10 billion dollars per deposit (De Geoffroy, 1972).

3. Market

The current market for lineament interpretations is young and just beginning to emerge. Any new market will be dominated by the effects of salesmanship, and, because of its tender nature, such a market can be killed by either overselling or underselling. This market is not expected to take on the characteristics of a mature and valuable market in itself until new discoveries of petroleum or mineral deposits are made in which ERTS lineament interpretations played an important role. Therefore, every reasonable effort should be made to verify the significance of ERTS lineament interpretations in finding new deposits.

4. Timeliness

Some comment should be made regarding the timeliness of a new product like ERTS lineament interpretation maps, for if a good product is introduced at the wrong time, it may not survive. On the other hand, if a good product is introduced at the right time, it may succeed beyond expectations.

The United States and many other countries around the world are facing a resource crisis. This not only includes energy resources such as gas and petroleum but other minerals such as tungsten, tin, copper, lead and zinc (Szego, 1971). New sources of these materials are being sought at an ever increasing rate, and ERTS lineament interpretation maps, if developed properly, could provide another needed tool to aid in this search.

SECTION V
NEW TECHNOLOGY

No new technology was developed under this contract.

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APPENDIX

Figure A-1. Observation Identification Index, Area 1

Figure A-2. Observation Identification Index, Area 2

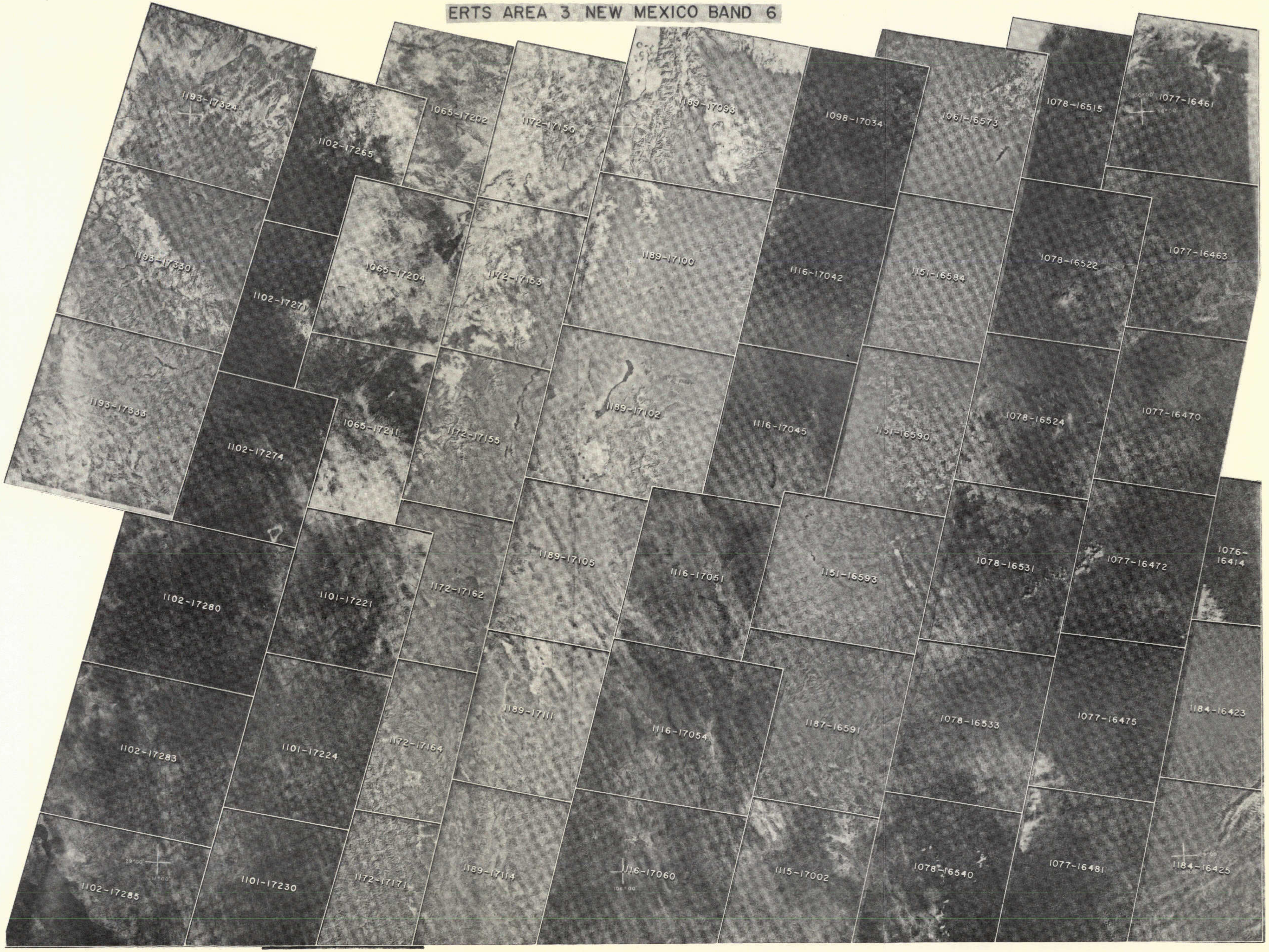

Figure A-3. Observation Identification Index, Area 3

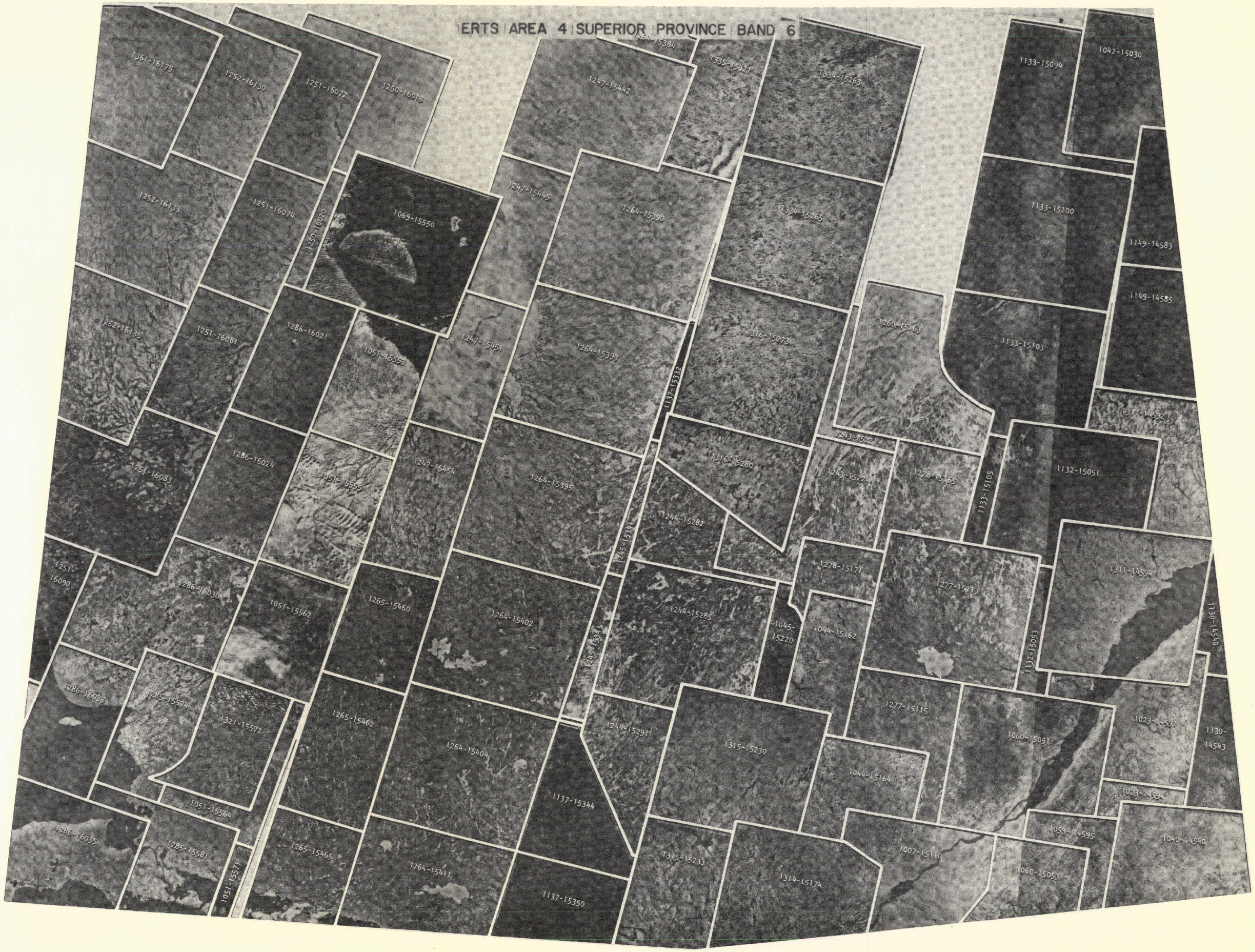

Figure A-4. Observation Identification Index, Area 4

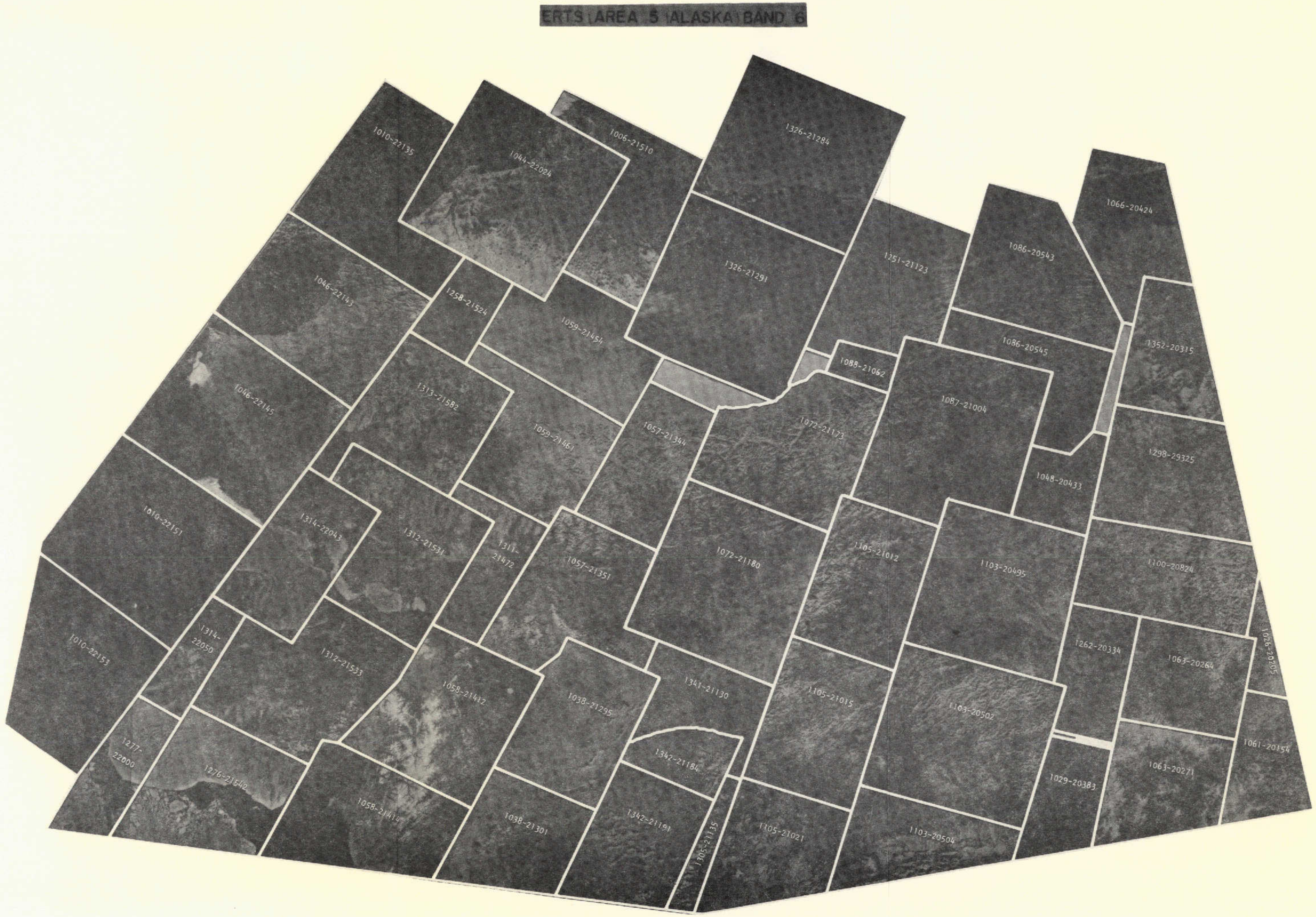

Figure A-5. Observation Identification Index, Area 5