This is to certify that the

thesis entitled

A STUDY OF LANDSAT LINEAMENT
DATA OBSERVED IN MICHIGAN

presented by

Kevin Todd Campbell

has been accepted towards fulfillment
of the requirements for

M.S. degree in Geology

C. E. Prouty
Major professor

Date August 13, 1981

A STUDY OF LANDSAT LINEAMENT

DATA OBSERVED IN MICHIGAN

By

Kevin Todd Campbell

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTERS OF SCIENCE

Department of Geology

1981

ABSTRACT

A STUDY OF LANDSAT LINEAMENT
DATA OBSERVED IN MICHIGAN

By

Kevin Todd Campbell

Lineaments previously measured by Prouty in 1976 from LANDSAT imagery printouts were studied by the writer to determine the relationship, if any, that exists between length of lineaments, azimuth direction, number of lineaments observed, and age of bedrock in which they reside.

The number of lineaments and average length of lineaments was found to be primarily independent of lithology, location, and age of bedrock.

Due to the diversity of movement along basement faults, the associated lineament azimuths did not fit a wrenching deformation model as proposed by Prouty (1976). The calculation of the chi square statistic however, suggested a low order relationship between number of lineaments and azimuth direction. No apparent relationship between length of lineaments and azimuth direction exists.

Using harmonic analysis and Fisher's test of significance on the resultant harmonic data, it was found there appears to be an association between the azimuths of the lineament data and those of inferred linear trends extracted from SURFACE II generated structure maps of selected Michigan Basin oil fields.

Dedicated to Harold and Joan Campbell

ACKNOWLEDGEMENTS

The author wishes to sincerely thank Dr. C. E. Prouty, Chairman of the Guidance Committee, for his advice, patience, and devotion of his time during the preparation of this study. Dr. J. W. Trow and Dr. F. W. Cambray were also greatly appreciated for their helpful suggestions and constructive criticisms, which led to the successful completion of this manuscript.

Appreciation and gratitude is also extended to Mary Campbell and Ann Stephens for the typing of this work, also to Dick Sheets for help with the drafting of some of the figures.

Special thanks goes to my wife, Janet, for her support and faith in me and for presenting me with a daughter, Megan, who made this all worthwhile.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

Figure		Page

INTRODUCTION

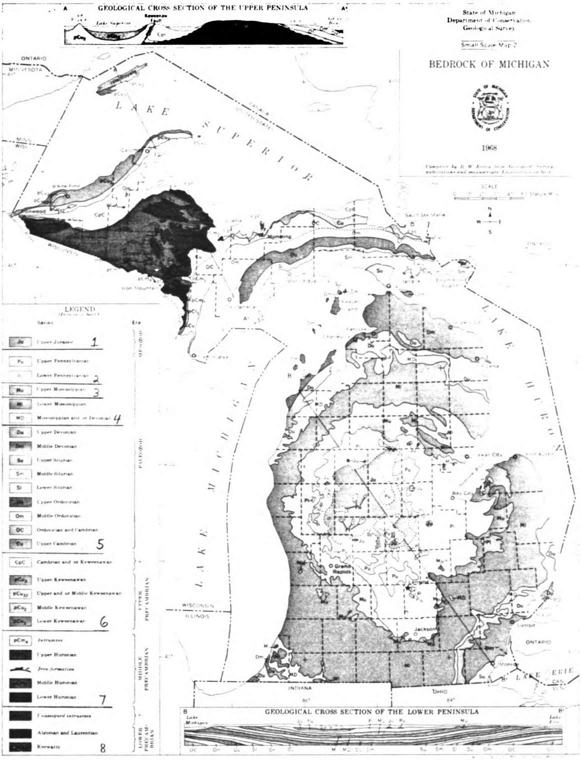
Purpose of the Study

This study was performed to provide a better understanding of the nature of lineaments (alignments) observed through LANDSAT imagery. By checking the relationship, if any, that exists between length, azimuth, and geologic occurrence, these features may yield information as to the times and types of deformation of the Michigan Basin and Upper Peninsula. It is also the purpose to test in as quantitative a manner as practicable, the proposal by Prouty (1976), that lineaments of the Michigan Basin are indeed shear faults, essentially strike-slip, formed under a wrenching model with stress derived from a general southeastwardly direction.

A statistical comparison of the azimuth directions and number of lineaments in the Lower Peninsula to linear trends obtained from selected Michigan Basin oil fields, may suggest that there may be a relationship between the lineaments and linear structures in the Basin.

Methodology

The azimuths of the lineament data were measured by hand using a protractor and T square directly off of a base map, compiled by Prouty in 1976, which contained all of the



GEOLOGICAL CROSS SECTION OF THE UPPER PENINSULA
State of Michigan
Department of Conservation
Geological Survey
Small Scale Map 2
BEDROCK OF MICHIGAN
1968
LEGEND
Series
Era
Upper Jurassic 1
Upper Pennsylvanian
Lower Pennsylvanian 2
Upper Mississippian 3
Lower Mississippian
Mississippian and or Devonian 4
Upper Devonian
Middle Devonian
Upper Silurian
Middle Silurian
Lower Silurian
Upper Ordovician
Middle Ordovician
Ordovician and Cambrian
Upper Cambrian 5
Cambrian and or Keweenawan
Upper Keweenawan
Upper and or Middle Keweenawan
Middle Keweenawan
Lower Keweenawan 6
Intrusives
Upper Huronian
Iron formation
Middle Huronian
Lower Huronian 7
Unassigned intrusives
Algoman and Laurentian
Keewatin 8
MESOZOIC
PALEOZOIC
UPPER PRECAMBRIAN
MIDDLE PRECAMBRIAN
LOWER PRECAMBRIAN
ONTARIO
MINNESOTA
LAKE SUPERIOR
LAKE MICHIGAN
LAKE HURON
LAKE ERIE
WISCONSIN
ILLINOIS
INDIANA
OHIO
Ironwood
White Pine
Iron Mountain
Munising
Sault Ste Marie
Grand Rapids
Lansing
Jackson
Bay City
Detroit
Monroe
GEOLOGICAL CROSS SECTION OF THE LOWER PENINSULA

Figure 1

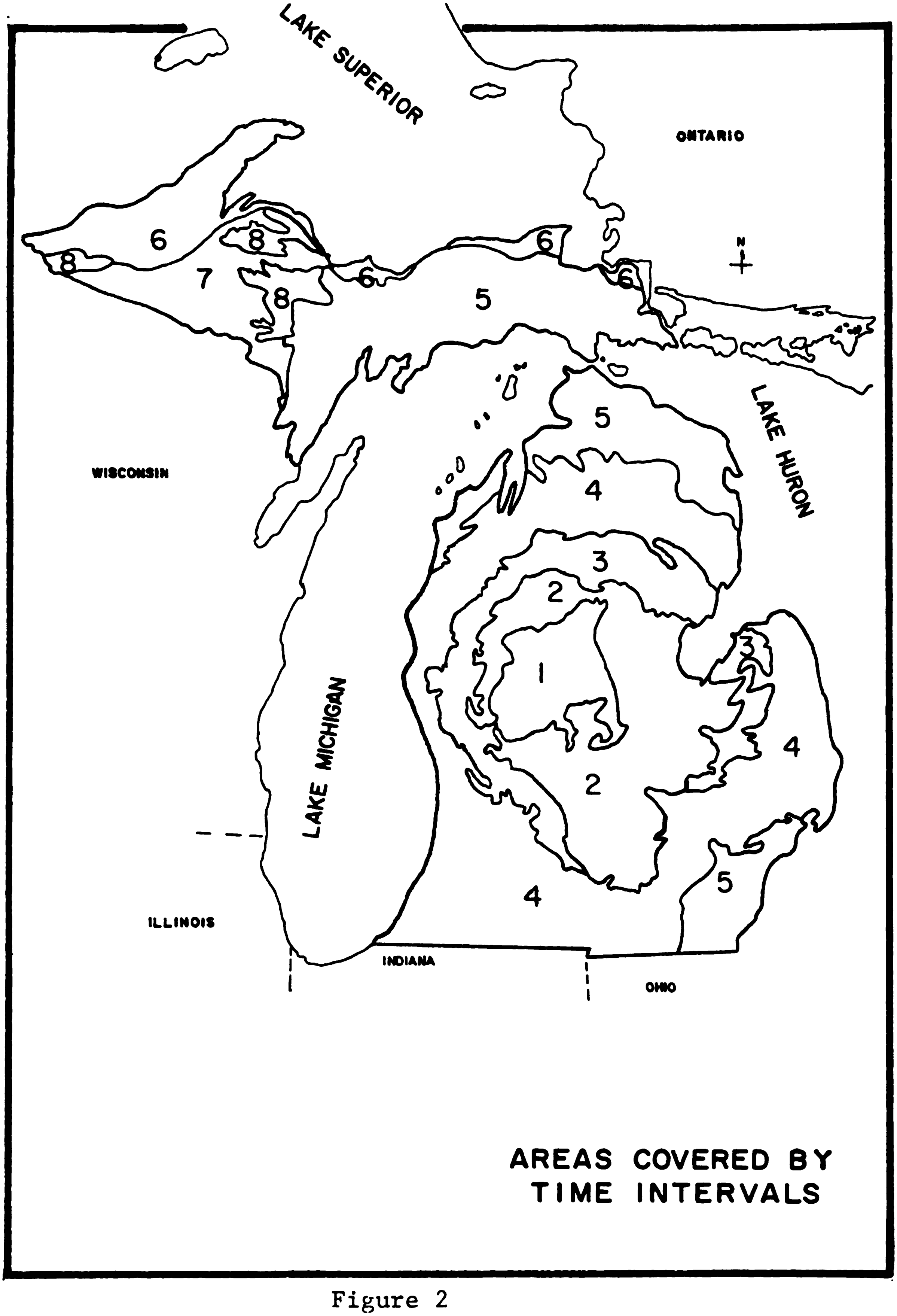

LAKE SUPERIOR
ONTARIO
N
6
8
7
8
6
6
6
5
5
LAKE HURON
WISCONSIN
4
3
2
1
3
4
2
LAKE MICHIGAN
5
4
ILLINOIS
INDIANA
OHIO
AREAS COVERED BY
TIME INTERVALS

Figure 2

lineaments he had recorded from LANDSAT imagery printouts until that time. It was decided not to display a figure of the original lineament map because the loss of detail and distortion that would accompany the drastic reductions necessary for the map to be included in the thesis.

Access to the lineament map may be obtained by consulting C. E. Prouty, Department of Geology, Michigan State University. All lineament measurements performed by the writer can be seen in the appendices.

Using the Bedrock of Michigan map (Figure 1), Prouty's base map was divided into areas corresponding to eight different geologic time intervals (Figure 2). These intervals were chosen primarily according to age of the rocks and areal extent. Time interval number four was created in the hope that differences between this and subsequent time intervals might reflect the proposed timing (Prouty, 1972) of the Appalachian orogeny.

The length of each lineament was digitized on the MICRO DATATIZER and a file was created which consisted of azimuth, length of lineament, and geologic time interval in which the lineament was observed. Lineaments shared by two or more categories were placed in the category in which the greatest fraction of its length rested. Line segments which occupied the same vector and were less than four miles (¼ inch on the original base map) apart were recorded as one lineament. All E-W and N-S trending lineaments were listed as N 90 E and N 0 E respectively.

From this file, rose diagrams and histograms were created on the CALCOMP plotter using standard FORTRAN commands. The rose diagrams (Figures 5-13) portrayed the number of lineaments observed per degree from N 90 W to N 90 E for each separate geologic category and for all categories combined. The histograms (Figures 15-23) portray average length of lineaments for each category and a summary of all categories through the simple mean equation (sum of length of lineaments/total number of lineaments) per five degree intervals.

A planimeter was used to measure the area covered by each time interval. These results were then used to correct the differences, due to areal extent, that would arise in the total number and average length of lineaments observed in each interval.

Statistical tests were run on the lineament azimuths to determine randomness of the data and overall goodness of fit to a wrenching deformation model (Moody and Hill, 1956).

Well data for the oil fields studied were obtained from drillers logs from the Geology Division of the Michigan Department of Natural Resources. Oil fields were selected on the basis of the number of well sites, their location in the Basin, and the nature of the surrounding township and range baselines and meridians (see appendix B). Geologic horizons were picked out for each oil field according to their position in the stratigraphic column, the formations present in the area and the constancy with which the drillers and/or geologists had been able to identify the target formation.

A FORTRAN computer program developed for the mathematical conversion from township and range notation to Cartesian coordinates (Good, 1964) was modified and used as a location identifier for subsequent use on the SURFACE II computer mapping program. This program also featured a scaling routine that fit data with any range of X and Y extremes into a 12" by 12" area.

SURFACE II is a computer software system used for the creation of displays of spatially distributed data. A contour map is the basic form of graphic display produced by this program. Data input is required to be in the X, Y, Z form, where X and Y are location identifiers and Z is a finite value or identification number associated with that point. The only restrictions are that the coordinate variables must be orthogonal and the Z variable must be single valued.

Portrayal of the data as a contoured surface requires either the data to be read in neatly spaced on a regular pattern or, for randomly spaced data, the creation of a grid by the program. In the latter case size and shape of the grid and methods used in estimating values at grid nodes can be performed automatically or can be specified by the user.

The resultant maps can be drawn by either the CALCOMP plotter or a line printer. Maps created on the plotter are more accurate and are the more aesthetically pleasing of the two. Various other capabilities such as posting of data points, manipulation of gridded data, perspective block diagrams, stereographic projections, map overlays, trend surface analysis, histogram generation, error analysis and first derivative calculation are also available through SURFACE II.

Linear trends were extracted from the SURFACE II generated contour maps and these were compared to the lineament data through harmonic analysis. A FORTRAN computer program was used to perform the harmonic analysis on Lower Peninsula LANDSAT data and on the oil field linear trend data respectively. Results of the tests were then graphed to see if a possible correlation between the two exists.

Previous Work

Several studies have been made regarding the relationship between known faults and lineament data. Although there was some apprehension as to the reliability of the early data gathering process (ERTS-1 and aerial photographs) and the fact that some lineaments do not coincide with known faults, it is generally agreed that a positive correlation between the two does exist.

Kaiser (1950) observed lineaments associated with zones of close-spaced random joints, with swarms of parallel joints, and with abrupt but minor changes in the strike of sedimentary beds. He suggested those lineaments not directly related to faults or lithologic changes may reflect structures having a common origin with echelon fault belts, transcurrent fault zones and related structures. Kaiser believed lineaments were passive structures produced by recurrent movements of basement blocks.

Hoppin (1974) reported in many cases lineaments have been demonstrated to be very old deep faults that have a history of repeated activity. Attempts to fit lineaments of the Central Rocky Mountains into a simple wrench-fault model did not work because of the overall complexity of the region and failure of the researchers to take all variables into account.

Werner (1975), studying lineaments ranging in length from 50-1000 kilometers mapped from ERTS mosaics and supplemented by other photography, found that lineaments were frequently sites for termination or offset of structural axes in the Appalachian Plateau region and in the Valley and Ridge province. Except for the Mid-Continent region, no known faults were found to coincide with the lineaments. He suggested lineaments are deep fracture zones in the sedimentary column which might be inherited from basement structure.

Prouty (1976) performed frequency analysis using LANDSAT lineament azimuths in a transect from eastern Pennsylvania to Iowa (including the Michigan Basin) and found cluster tendencies whose orientations were similar to major Michigan Basin structures. He believes lineaments are faults and their related structures. These faults and their related structural patterns are attributed to periodic reactivation along Precambrian lines of weakness. Prouty concluded these faults fit a wrenching deformation model with the shearing stresses coming from a general eastward direction with the dominant stress occurring in Post-Osagean, Mississippian time.

Cassinis (1977), through the use of satellite data, studied the correlation between lineaments and faults in Italy and found, in general, there was a close agreement between their azimuth directions. He also discovered that the number of lineaments exceeded that of the observed faults by many times. Cassinis further observed that the older tectonic patterns were very often rejuvenated by subsequent periods of orogeny.

The harmonic analysis performed by the writer on the relationship between linear trends observed in oil fields and on lineament data azimuths is based on studies explaining structure according to patterns of facies changes in carbonates. Jackson (1958), Ells (1962), Dastanpour (1977), Hamrick (1978), Hyde (1979), and Ten Have (1979) have all inferred faults in oil fields based on the geometry of dolomite-fracture porosity fields.

GENERAL STRATIGRAPHY

This study encompassed the entire time stratigraphic sequence of rocks present in Michigan. Lineaments were found to exist in the oldest Precambrian rocks right up through to sediments that are Upper Jurassic in age. Lithologic descriptions are generalized.

Major revisions in Precambrian nomenclature have occurred since Figure 1 was produced (James, 1972). Precambrian W refers to the period of earth history prior to 2.5 Ga, also known as the Archean. This replaces such terms as Keewatin and Laurentian, the period terminated with what is referred to as the Algoman Orogeny in the U.S.A. (Kenoran in Canada). The period post 2.5 Ga before present (B.P.) up to the beginning of the Cambrian, 0.6 Ga B.P., is referred to as the Proterozoic and is divided into three parts.

Precambrian X, formerly Middle Precambrian and Huronian as shown on Figure 1 ranges from 2.5 Ga to 1.6 Ga and in Michigan it was represented by the Marquette Range Supergroup (Cannon and Gair, 1970) which contains the well-known banded iron formations.

Precambrian Y ranges from 1.6 Ga B.P. to 0.8 Ga B.P. and contains the Keweenawan rocks of Michigan which are thought to be associated with an approximately one billion year old intracontinental rift system (Chase and Gilmer, 1973; Halls, 1978; and Fowler and Kuenzi, 1978).

Precambrian Z covers the period of time from 0.8 Ga B.P. to 0.57 Ga B.P. The only unit which may belong to this period in Michigan is the Jacobsville sandstone. Placement of the Jacobsville formation in this time frame has been contested as some prefer to classify it as defining the base and middle of the Cambrian system (Figure 3). Whether it truly belongs with the Cambrian or Precambrian is a matter of conjecture but for the purpose of this study it shall be termed Precambrian Z.

The Precambrian W in oldest to youngest order, consists of schists, greenstones, granite gneiss, metasedimentary and metavolcanic rocks and a gneissic granite.

The Precambrian X succession goes from dolomite and quartzites on the bottom; iron formations, slate, and quartzites in the middle; and graywackes, slate, basic volcanics and local iron formations at the top.

Precambrian Y is represented by sandstones, conglomerates and extrusive volcanics.

The general lithology of Precambrian Z, as has already been discussed, is a sandstone.

Cambrian rocks were comprised of sandstones and dolomite.

Ordovician rocks in Michigan are primarily carbonates and shales that have roughly the same gross characteristics throughout the Basin. The St. Peter sandstone, a clean white sand found mostly in western Michigan, is a notable exception.

STRATIGRAPHIC SUCCESSION IN MICHIGAN

PALEOZOIC THROUGH RECENT

PLEISTOCENE NOMENCLATURE

ERA	SYSTEM	SERIES		STAGE
OZOIC	QUATERNARY	RECENT		
		PLEISTOCENE	Wisconsin Glaciation	Valders Stade Two Creeks Interstade Mankato Stade (Pt Huron?) Cary Stade Tazewell Stade

Figure 3

Early Silurian time was characterized by dolomite and shale. Middle Silurian time is marked by the growth of large reefs, followed by a series of evaporites in Late Silurian time.

Early Devonian rocks consisted of carbonates which were periodically upwarped and eroded. An evaporite basin formed in Middle Devonian time and was followed by extensive carbonate deposition. Black shales blanketed the Michigan area during Late Devonian time.

The Mississippian is composed primarily of shales, siltstones, and sandstones. Some carbonate and anhydrite units occur in Late Mississippian time.

Pennsylvanian rocks are cyclothemic in nature and this sequence is characterized by sandstones, black shales, gray and buff limestones, light underclays, and thin coal seams. Surfaces of unconformity are frequent in this section.

Jurassic age sediments are generally termed as "Red Beds". These consist of poorly consolidated sands and shales. Gypsum is present at various intervals.

GENERAL STRUCTURE

The Michigan Basin is a roughly circular depositional province that consists of the entire Lower Peninsula of Michigan, the eastern half of the Upper Peninsula the area overlain by Lake Michigan and Lake Huron and small portions of Ontario, Ohio, Indiana, Illinois, and Wisconsin. It contains sediments from almost all of the Paleozoic systems and these are overlain in the central area of the Basin by Mesozoic sediments that are Upper Jurassic in age.

There are several major frame structures bordering the Basin (Figure 4). These are thought to have defined the overall shape of the Basin and may have been factors in the formation of some intrabasinal structures (Ells, 1969). The majority of these intrabasinal structures trend generally northwest-southeast.

The Basin is bounded on the west by the Wisconsin Arch, to the northwest by the Wisconsin Highlands, and on the north and northeast by the Canadian Shield. The Algonquin Arch lies to the east in Ontario, the Findlay Arch borders the Basin to the southeast in northern Ohio and the Kankakee Arch is to the southwest in northern Indiana and northeastern Illinois.

The intrabasinal structures are anticlinal in nature and were contributing factors in the development of some theories regarding the origin of the Michigan Basin.

Pirtle (1932) and Newcombe (1933) believed the origin of the basin was related to the Keweenawan disturbance

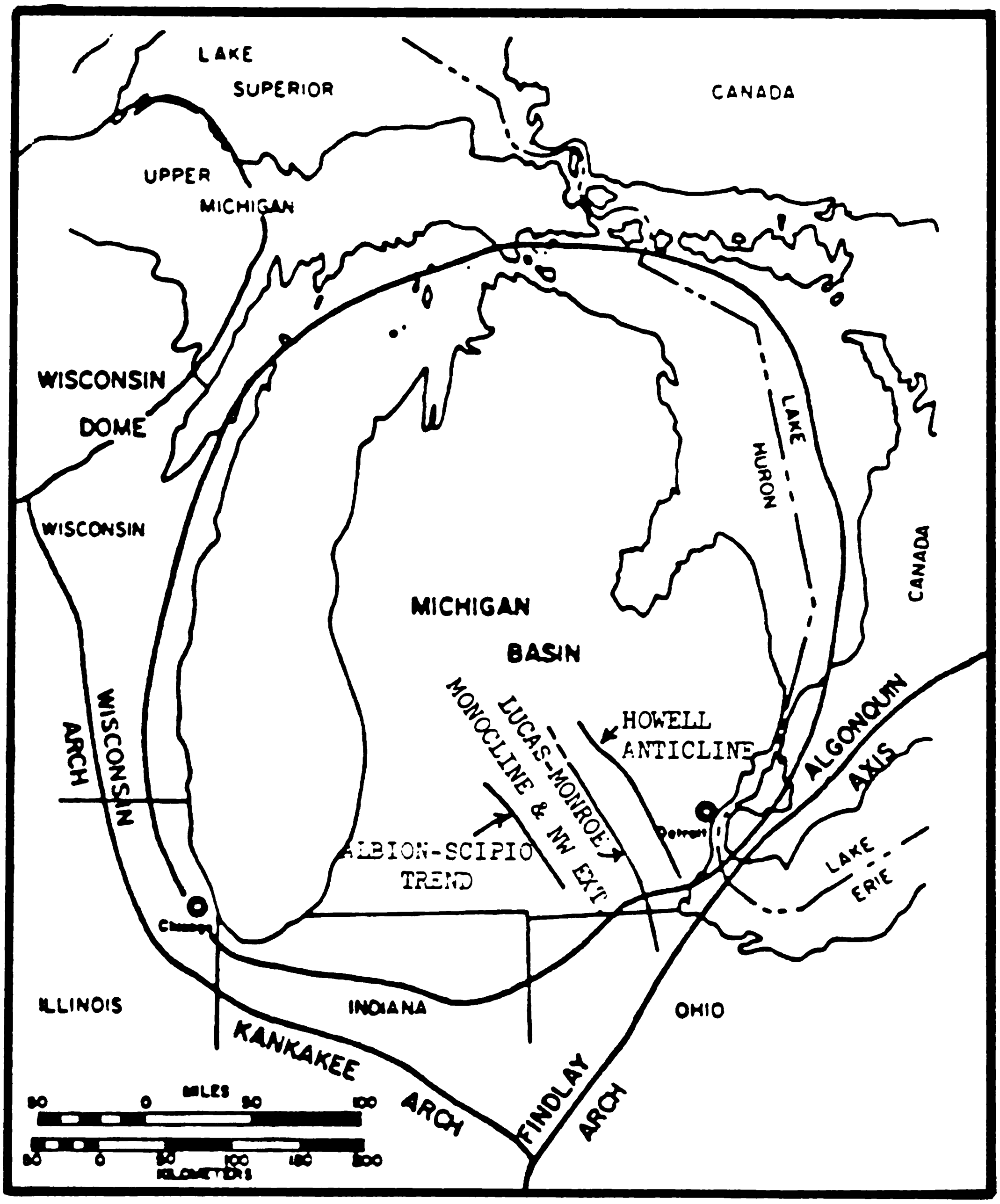

LAKE SUPERIOR
CANADA
UPPER MICHIGAN
WISCONSIN DOME
WISCONSIN
LAKE HURON
CANADA
MICHIGAN BASIN
WISCONSIN ARCH
LUCAS-MONROE MONOCLINE & NW EXT
HOWELL ANTICLINE
ALGONQUIN AXIS
ALBION-SCIPIO TREND
LAKE ERIE
ILLINOIS
INDIANA
OHIO
KANKAKEE ARCH
FINDLAY ARCH
MILES
KILOMETERS

Figure 4

acting against the Wisconsin Arch causing a compressional downwarp in Michigan. Evolution of the Basin to its present form was controlled by subsequent periods of stress. The anticlinal fold trends were suggested to have been controlled by zones of weakness in the basement rocks and formation of structures continued relative to these zones of weakness during successive periods of compression through geologic time.

Kirkham's (1937) concept of the origin of the Michigan Basin was that of a compound graben caused by collapse of magma chambers. He theorized that bodies of magma moving from one part of the earth's crust to another was accompanied by subsidence of the crust in a primarily vertical direction. The Precambrian surface was said to be marked by a pattern of joints, shear zones, faults, and rifts which Kirkham described as zones of weakness. The anticlinal folds were believed to have been formed by vertically acting forces along these zones of weakness.

Lockett (1947) claimed the subsidence of the basin was due to the mass of sediments deposited from the positive structural features that surround it. He postulated these positive structures are underlain by the cores of Precambrian mountains.

Orogenic forces were discounted as a cause in basin formation and as a factor in forming the anticlinal structural trends. Lockett believed the system of fractures or lines of weakness and the associated anticlinal folds were a result of simple subsidence.

Hinze and Merritt (1969), using data from gravity and magnetic studies of the Michigan Basin, suggested a rift zone had a dominant role in its origin. Isostatic sinking of the Basin could have been a result of additional mass caused by the outpouring of Keweenawan mafic rocks in the basement complex. Subsequent deformation was associated with movements along lines of weakness in the basement related to the rift zone.

LINEAMENT STUDY

LANDSAT Imagery

The LANDSAT satellites carry two types of sensor systems: three Return Beam Vidicon (RBV) television cameras and a Multispectral Scanner (MSS). The MSS system is a mechanical line scanning device using an oscillating mirror to simultaneously scan, in four separate regions or bands, the earth's landscape passing beneath the spacecraft. The scanner detects electromagnetic radiation (or the intensity of reflected light) from the earth's surface. A summary of the wavelength used and spectral range for each band and sensor type is listed in Table 1.

Table 1 - Spectral Bands (from Enslin, 1977)

Band	Sensor	Wavelength (nanometers)	Spectral Range
1	RBV	475-575	blue-green
2	RBV	580-680	red
3	RBV	690-830	near infrared
4	MSS	500-600	green
5	MSS	600-700	red
6	MSS	700-800	near infrared
7	MSS	800-1100	near infrared

The above wavelengths fall into the reflected infrared range. Fault zones or other cracks in the bedrock are believed to be detected by differences in reflected radiation caused by the presence of moisture in the cracks (Rudd, 1974). Water absorbs infrared more effectively than it does the visible wavelength so a land/water boundary becomes evident. Data observed by the scanners can be affected by the time of day in which it is recorded and by atmospheric conditions.

One LANDSAT scene covers an area of 115 by 115 miles. An arbitrary forward overlap of approximately 10% occurs between consecutive LANDSAT images. Sidelap between adjacent orbits is about 37% for Michigan.

Definition

There is a considerable amount of controversy over the meaning of the term LINEAMENT. The main points of debate center around the scale and or continuity of the features.

Hobbs (1904) defines the term as nothing more than a generally rectilinear earth feature.

Kaiser (1950) notes that a lineament is a straight linear feature many hundreds of feet and commonly many miles long.

Lattman (1958) stated a lineament is a feature extending greater than one mile. Any linear feature expressed continuously for less than a mile was termed a fracture trace.

Hoppin (1974) identified lineaments as being lines or zones of structural discordance of regional (100 kilometers or longer) extent. They are expressed at the surface by alignment of combinations of single rectilinear elements less than 100 kilometers in length called linears.

Werner (1977) suggested the term be modified to indicate the source and type of features which are aligned. He offered for example the terms photolineament, structural lineament, aeromagnetic lineament, topographic lineament, and geologic lineament.

The tectonic definition from a geologic dictionary (Matthews, 1976) states a lineament is a straight or gently curved lengthy feature on the earth's surface. For the purpose of this study, this definition will suffice.

Lineament Relationships

General

This study attempts to measure the amount and types of relationships that may exist between four variables: number of lineaments, age of bedrock in which they are observed, length of lineaments and azimuth direction.

It is hoped these relationships may provide information as to the timing and type of deformation of the Michigan Basin and its surrounding area.

Past studies have indicated an association between zones of weakness in the basement complex and lineaments (Kaiser, 1950; Hoppin, 1974; Werner, 1975; Prouty, 1976; Cassinis, 1977). It is upon this premise which much of the following discussion, experimentation, and statistical analysis is based.

Number of Lineaments vs. Age

As seen in Table 2, the number of lineaments observed per geologic time interval increases until Middle Mississippian time, after which (except for the large number in Pennsylvanian time) it generally decreases. Controlling factors which could be responsible for this phenomenon are areal size covered by each time interval, lithology (rupture strength of bedrock), orogeny, basinal settling, and data gathering limitations.

Table 2 - Number of Lineaments Per Time Interval vs. Area

Interval	Number of Lineaments	Area	Number of Lineaments per unit area
1	34	1.6	21.25
2	206	5.4	38.15
3	69	1.7	40.59
4	397	14.1	28.16
5	142	11.9	11.93
6	41	3.0	13.67
7	33	2.1	15.71
8	15	.9	16.67

Mean = 23.27

Standard deviation = $\pm$11.15

Referring to Figure 2, a positive correlation seems to exist between the areal extent of a particular time interval and the number of lineaments recorded for that interval. Logically, the greater the area covered by a time interval the greater the number of lineaments. To test this the number of lineaments per unit area was obtained by dividing the total number of lineaments for a particular time interval, by the area it covered on a large scale version of Figure 1. If the number of lineaments seen in each interval is indeed controlled by areal size, the number of lineaments in each interval when corrected for area should be roughly the same.

Results of this test (Table 2) show that corrected values for five of the eight time categories fall within one standard deviation of the mean, indicating areal size is indeed a major factor in controlling the number of lineaments observed in each time interval.

The rupture strength of the rock beds may determine the amount and type of fracturing likely to be produced when the rock is subjected to stress. Unfortunately, any attempt at determining the rupture strength of the rocks in question is beyond the scope of this study.

Recurrent stresses, produced by orogenic episodes or basinal settling, act upon basement faults and cause movement along these old lines of weakness. Transferral of these stresses causes fracturing in the overlying beds and some of these effects are depicted at the surface as lineaments.

It has been suggested (Prouty, 1976) this fracturing would occur according to the wrenching-deformation model.

Stresses produced by basinal settling and changes in depocenter location might also account for a difference in lineament occurrence. Effects of these stresses would be observed primarily in the basin area. There is some debate as to when the basin actually began to subside. Sufficient well control is available to show a well defined depocenter in Ordovician time (Cohee, 1948). This depocenter was located in the middle eastern part of the state covering the Thumb area, Saginaw Bay, and part of Lake Huron. The depocenter switched back and forth on a North-South axis prior to Mid Mississippian time. At this point the depocenter moved to a location roughly in the middle of the Lower Peninsula (Prouty, 1972).

Increased stresses caused by this shifting and by regular subsidence could have reactivated the basement faults or could have possibly created new ones. This would result in a more diffuse orientation seen in the lineaments.

The greatest stress (from the Appalachians) and the time most folded structures are believed (Prouty, 1972) to have occurred in the Basin was Post-Osage Mississippian time. This also is believed to be the time of shifting of the depocenter to the present central position in the Lower Peninsula. This compares favorably with the high number of lineaments seen in that time interval. The high number of lineaments occurring in Pennsylvanian time may reflect the continued orogenic stresses in Late Paleozoic time.

A general factor that affects the number of lineaments observable from LANDSAT imagery is the extent of cloud cover. During the mapping procedures in which the basic lineament map was developed, Prouty (1981) indicates that by use of several different passes by the LANDSAT satellite in the same path (18 day intervals) it was generally possible to observe cloud-free conditions. The most notable exception to this was in a small area of the north central Lower Peninsula, in parts of the time interval designated number 4.

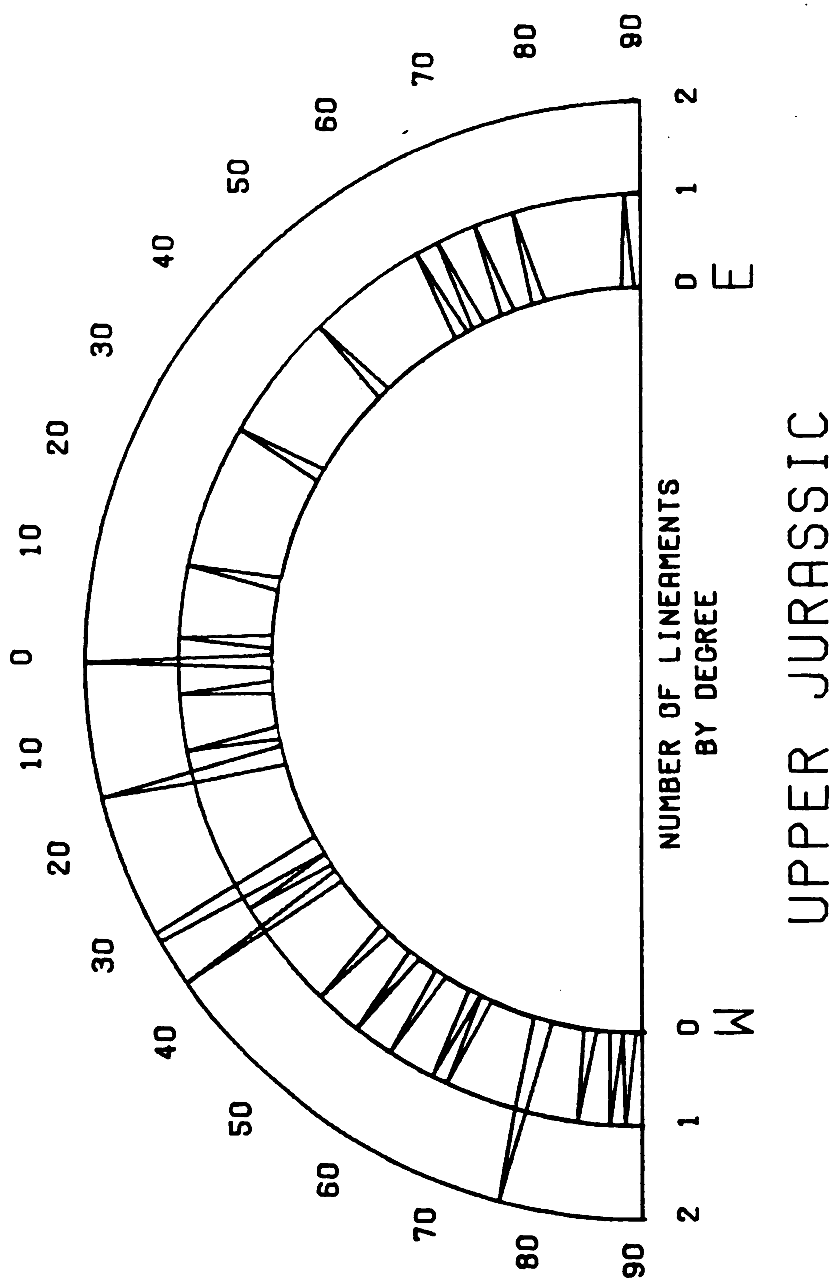
Azimuth Directions Vs. Number and Age

Tests and graphic displays were made to determine if a preferred orientation of the lineaments was evident for each time interval and for all intervals combined. Rose diagrams were constructed and a statistical analysis that attempted to fit the observed number of lineament azimuths to a wrenching-deformation model was performed.

The Rose diagrams (Figures 5-13) were prepared to give a rough generalization as to the directions of preferred orientation. It was hoped clustering tendencies (a succession of azimuth directions containing a higher concentration of lineaments) would readily become apparent. Unfortunately no definite set of preferred orientations presents itself.

Using the wrenching deformation model (of Moody and Hill, 1956, Figure 14) a more precise method of determining the extent of preferred orientation was attempted. Ideally, according to this model there are twelve principle directions along which fractures and their associated folds would be likely to develop. Primary 1st-order wrenches would be defined in two directions, primary folding in one direction, 2nd-order wrenches in four directions, 2nd-order drag folds in two directions, 3rd-order wrenches along four directions, and 3rd-order drag folds occur in one direction. This adds up to fourteen directions, but two of the four azimuth trends for 3rd-order wrenches are parallel to the primary 1st-order wrenches, hence only 12 directions are represented. This model also assumes the material which is being fractured is homogenous, isotropic, and that the faulting stresses and motions are essentially horizontal.

Direction of the primary stress controls the azimuth at which a particular structural feature would appear. The same azimuth numbers reoccur with every 15 degree rotation from a base point. For example, the exact same set of azimuth directions would occur at N 0 E as there would be at N 15 E, N 30 E, N 15 W, etc. The only variables are the type of deformational structure defined by a particular azimuth. An example of this is in a primary stress from N 90 E a primary 1st-order wrench would occur at N 60 E, while rotating the primary stress to S 75 E the feature described at N 60 E would be a 2nd-order drag fold.



0
10
20
30
40
50
60
70
80
90
0
1
2
E
W
NUMBER OF LINEAMENTS
BY DEGREE
UPPER JURASSIC

Figure 5

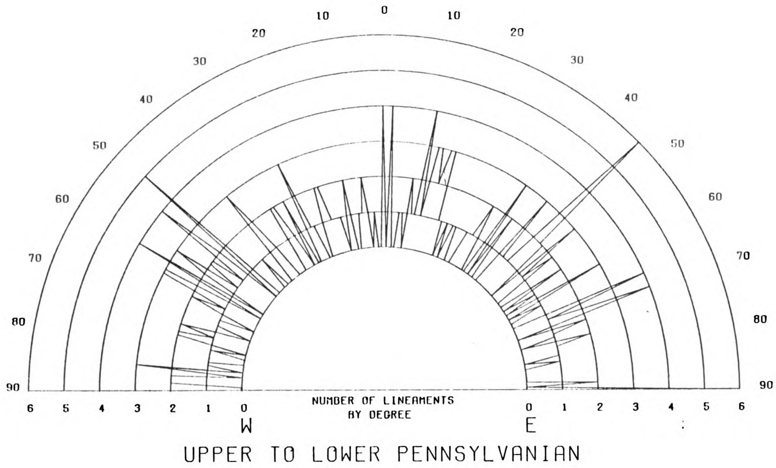

0
10 10
20 20
30 30
40 40
50 50
60 60
70 70
80 80
90 90
6 5 4 3 2 1 0
NUMBER OF LINEAMENTS
BY DEGREE
0 1 2 3 4 5 6
W
E
UPPER TO LOWER PENNSYLVANIAN

Figure 6

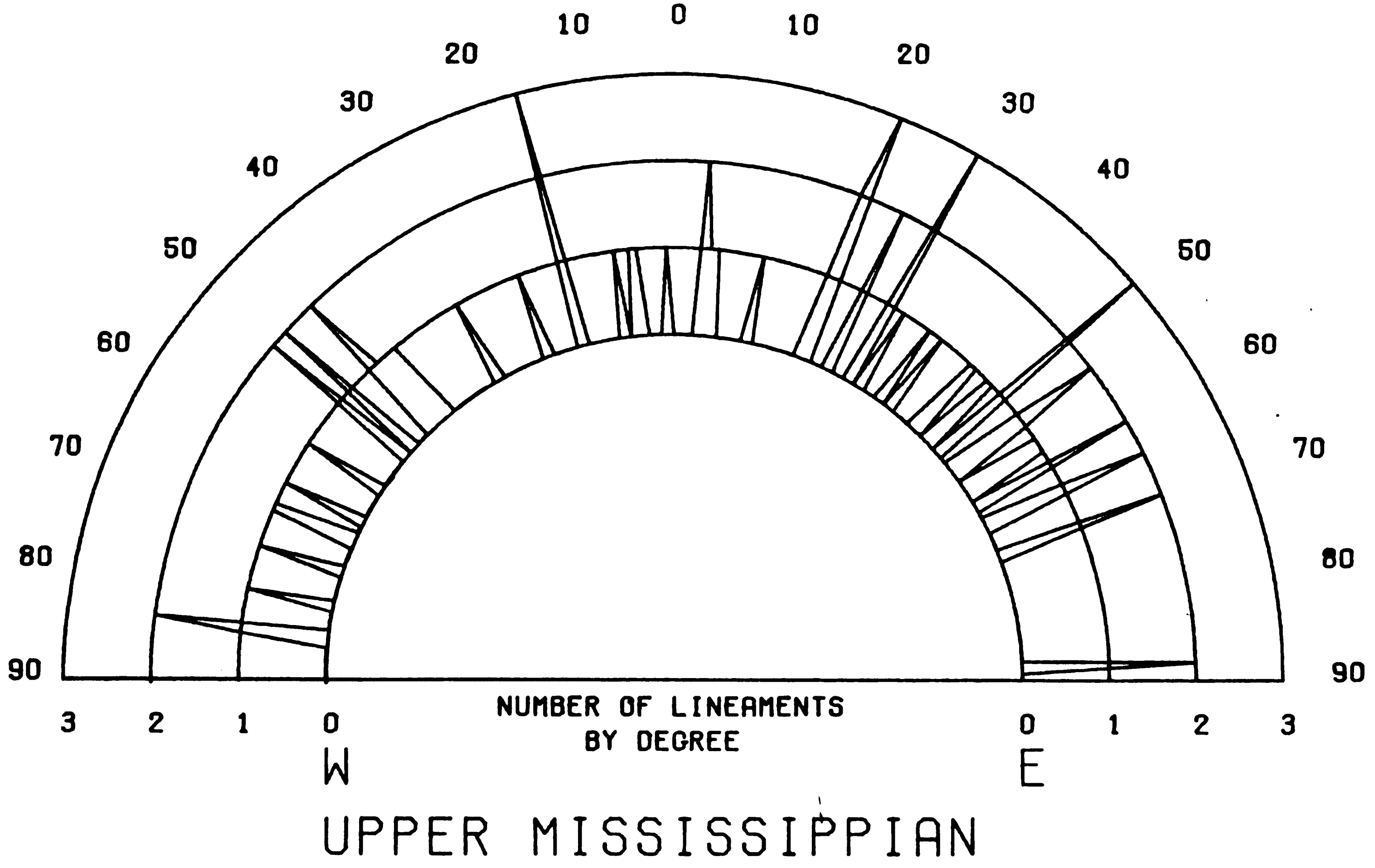
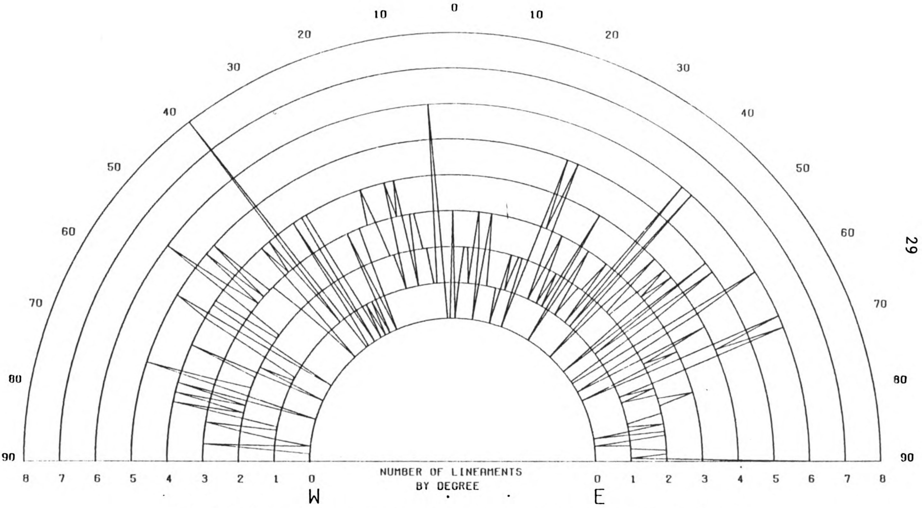
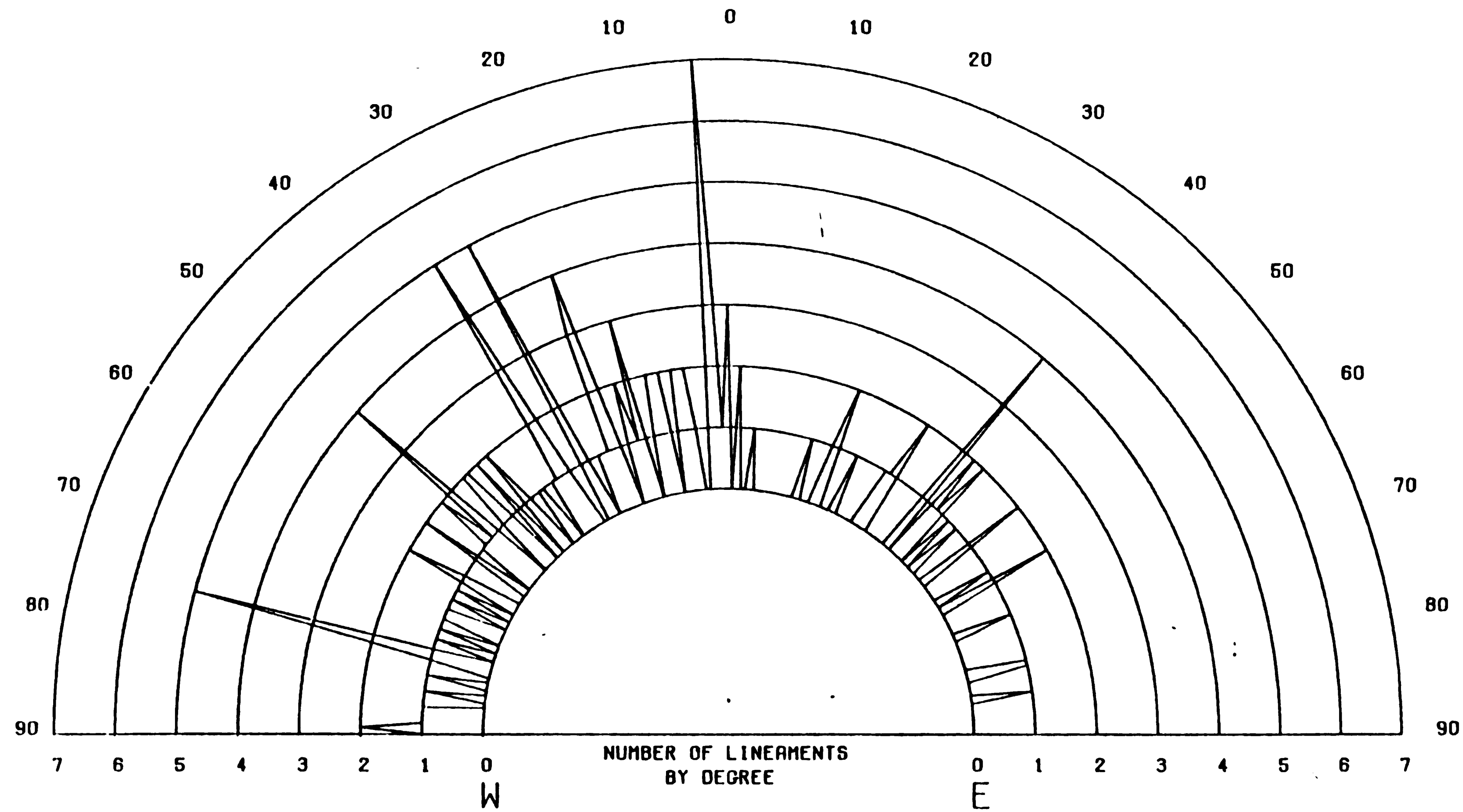

0
10
20
30
40
50
60
70
80
90
3 2 1 0
0 1 2 3
W
E
NUMBER OF LINEAMENTS
BY DEGREE
UPPER MISSISSIPPIAN

Figure 7



LOWER MISSISSIPPIAN MISS. AND/OR DEVONIAN

Figure 8



TOP OF UPPER DEVONIAN TO BOTTOM OF UPPER CAMBRIAN

Figure 9

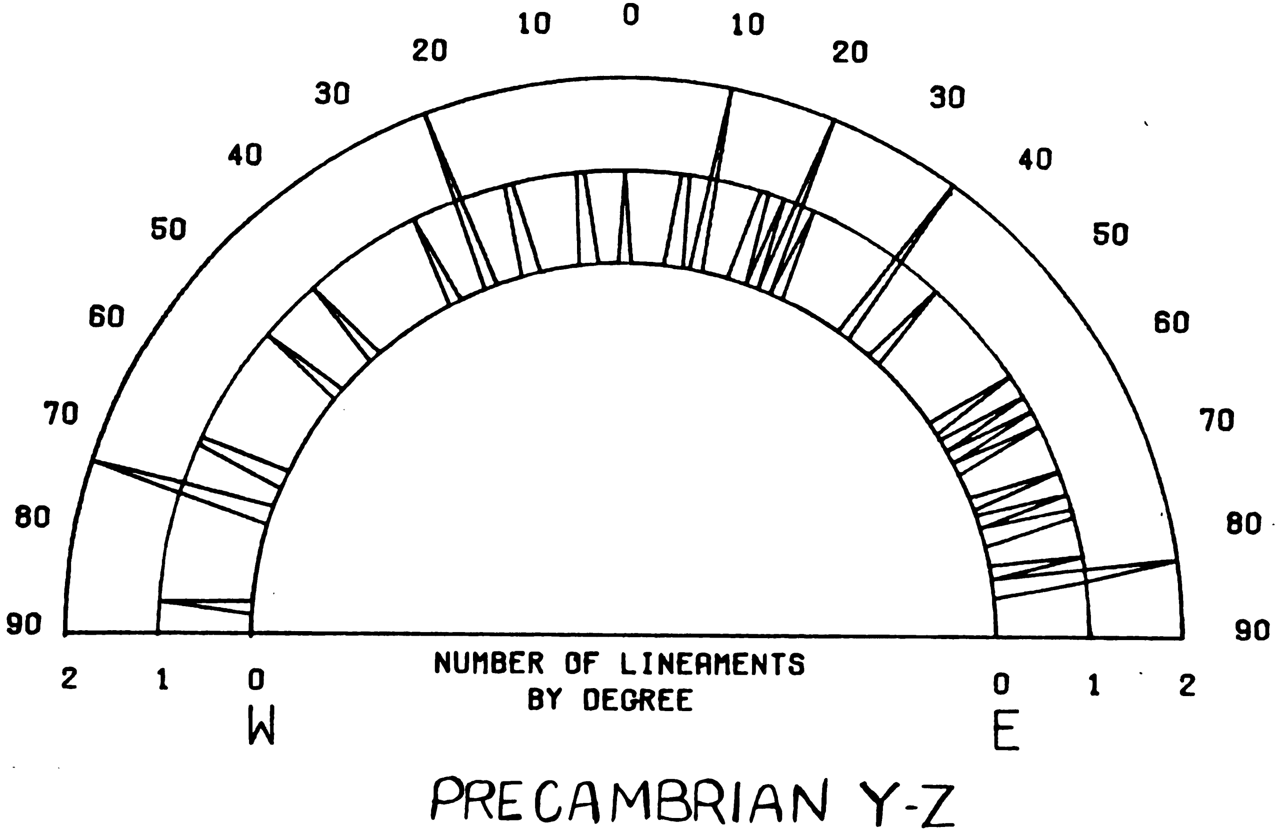

0
10
10
20
20
30
30
40
40
50
50
60
60
70
70
80
80
90
90
2
1
0
0
1
2
NUMBER OF LINEAMENTS
BY DEGREE
W
E
PRECAMBRIAN Y-Z

Figure 10

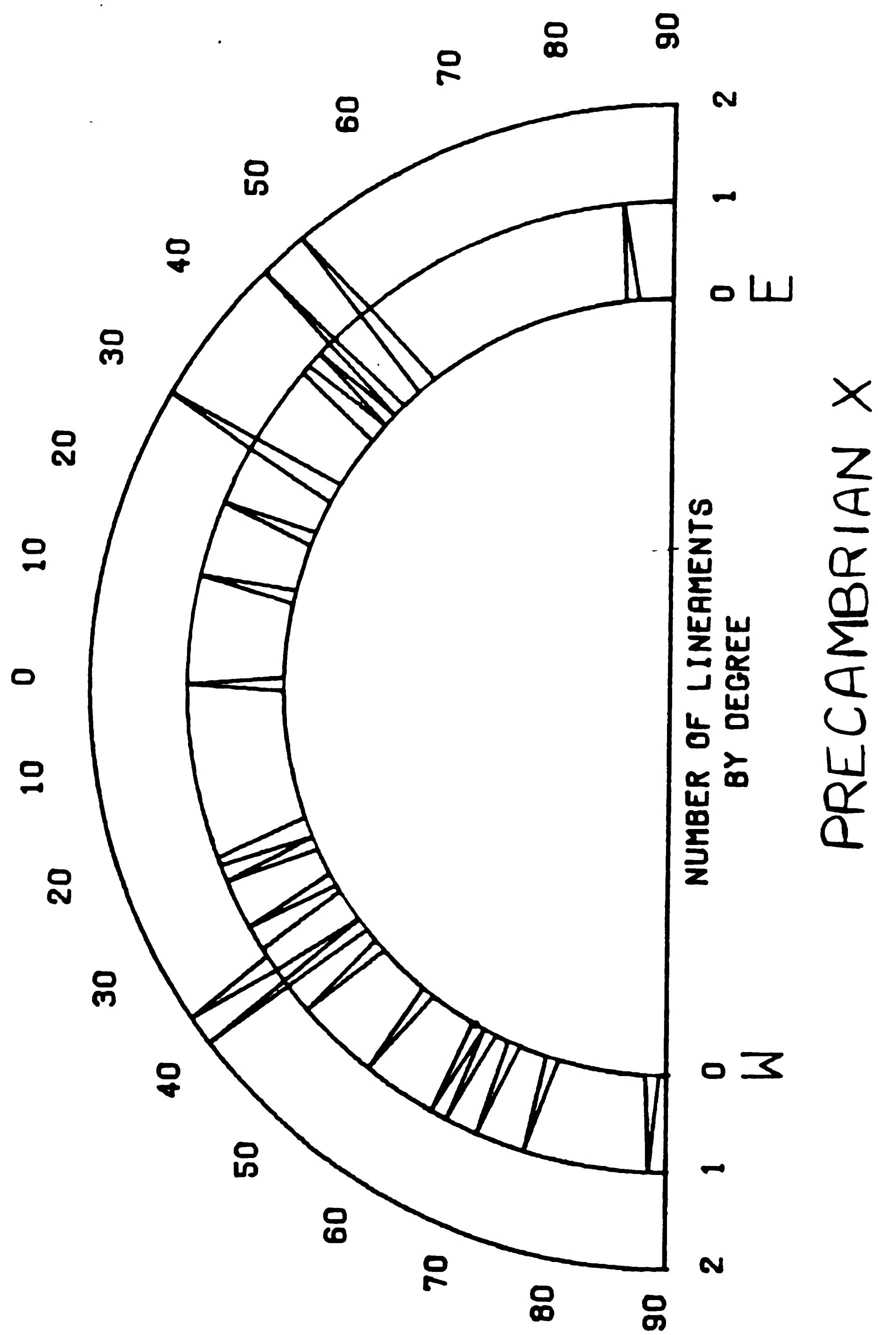
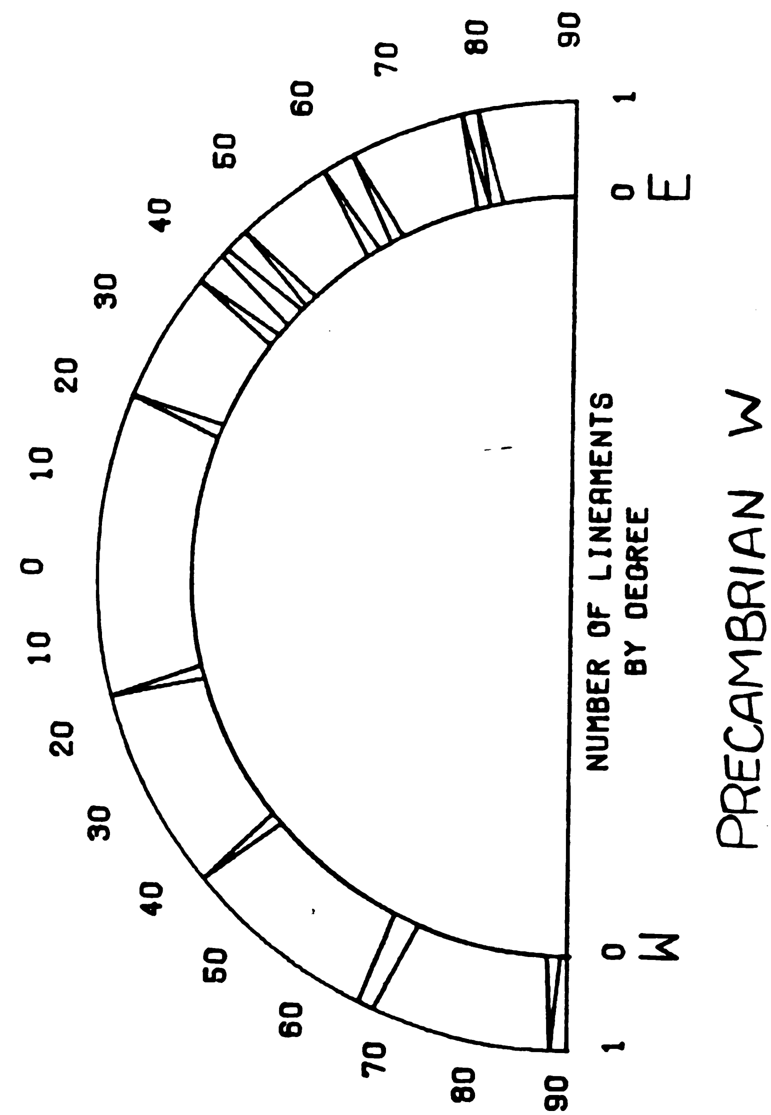

90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
2
1
0
0
1
2
W
E
NUMBER OF LINEAMENTS
BY DEGREE
PRECAMBRIAN X

Figure 11



90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
0
1
E
0
1
W
NUMBER OF LINEAMENTS
BY DEGREE
PRECAMBRIAN W

Figure 12

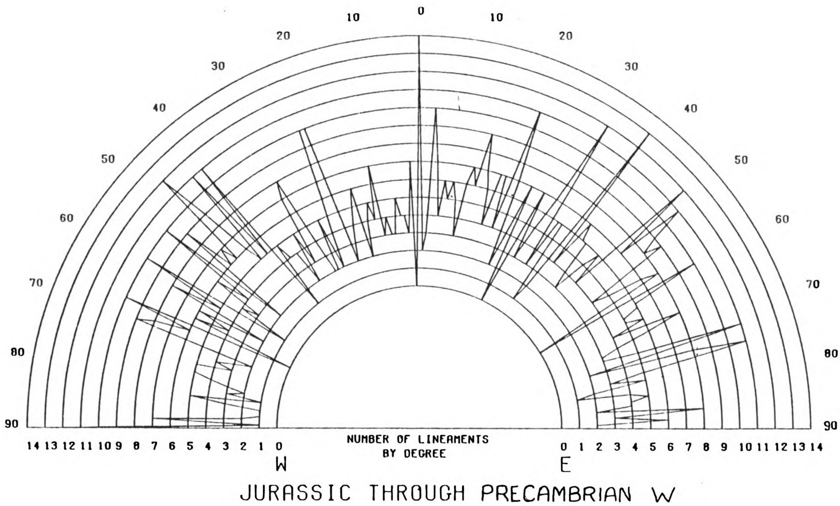
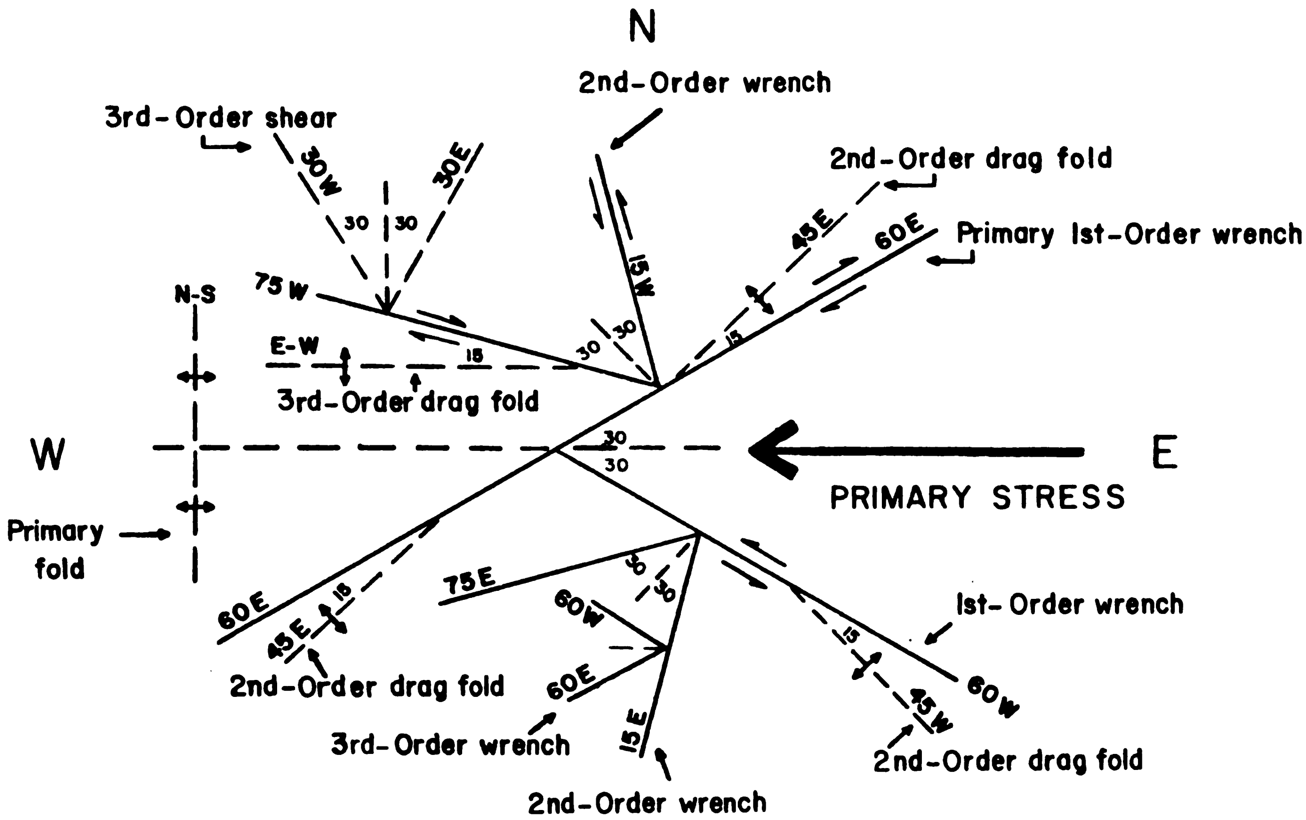

0
10
20
30
40
50
60
70
80
90
14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
NUMBER OF LINEAMENTS BY DEGREE
W
E
JURASSIC THROUGH PRECAMBRIAN W

Figure 13



PLAN OF WRENCH SYSTEM UNDER EAST-WEST SIMPLE SHEAR

Figure 14

Method

The percentage of lineaments observed in a $\pm$ 3 degree standard deviation around a direction of proposed preferred orientation under the wrenching-deformation model was compiled for five different principle stress azimuths. Each principle stress direction was rotated 3 degrees from the previous example. In this way, along with the margin of standard deviation, a representative sample of the goodness of fit to the wrenching model for all possible primary directions was obtained.

From the equation:

E(1)=((standard deviation x 2)+1)/180

the expected percentage (E) of lineaments to be observed at each azimuth direction if the sampling was random can be obtained. In this case a random sampling of 4% of the lineaments would be expected to fall in each set.

To measure the percentage of lineaments expected to fit the wrenching deformation model for a random sampling the equation:

E(2)=(((standard deviation x 2)+1)x12)/180

is used. In this study a random sample of 47% of the total lineaments would be expected to fit the model.

Three equations were used to compute the percentage of the actual number of lineaments observed (A) that fit the wrenching deformation model. These represented percentages for goodness of fit for overall direction, time interval, and total time combined.

$$A(1) = \frac{\text{total number of lineaments in one direction}}{\text{total number of lineaments in Michigan}}$$

$$A(2) = \frac{\text{total number of lineaments in a time interval that fit model}}{\text{total number of lineaments contained in that time interval}}$$

$$A(3) = \frac{\text{total number of lineaments overall that fit model}}{\text{total number of lineaments in Michigan}}$$

The compilation of these data (Tables 3-7) shows the percentage of lineaments that fit the wrenching model per geologic time interval and overall time for each primary stress direction. Percentage of overall number of lineaments that fit a proposed direction of preferred orientation is also given.

Interpretation

According to these tests there is nothing to definitely indicate that the lineaments observed in Michigan fit into a wrenching deformation model. None of the precentages recorded for overall fit, time interval, or any particular direction of preferred orientation are significantly above what would be expected for a random sampling.

Hoppin (1974), reported attempts to fit lineaments from the Central Rocky Mountain region into a wrenching deformation pattern meet with a similar lack of success. The wrench-fault hypothesis requires that each lineament set have the same sense of horizontal slip. Hoppin stated because lineaments are ancient faults that have been reactivated many times with differing resultant styles of deformation and senses of fault slip, attempts to equate them with a simplified wrench-fault system are unsatisfactory.

Considering the diversity of modes of stress extant in the Michigan Basin (differential basinal settling, depocenter relocation, orgenic episodes), this explanation might apply to the failure of this endeavor.

Table 3 - Wrenching deformation model, Principle stress from N 0 E

	Time Interval									A(1)
	1	2	3	4	5	6	7	8	Tot.	%
N 75 W	3	8	2	21	8	2	1	0	45	5
N 60 W	2	13	2	17	4	0	2	0	40	4
N 45 W	1	6	6	18	7	1	1	0	40	4
N 30 W	5	7	1	10	14	1	2	0	40	4
N 15 W	3	7	3	19	11	2	0	1	36	4
E-W	3	9	1	8	16	1	1	0	39	4
N 15 E	1	16	1	8	1	2	1	0	30	3
N 30 E	1	6	4	13	4	0	3	0	31	3
N 45 E	1	16	4	20	7	1	3	3	55	6
N 60 E	1	5	5	17	3	3	0	2	36	4
N 75 E	1	7	0	14	2	3	0	2	29	3
N-S	2	11	2	11	5	0	1	1	32	3
Tot.	24	111	31	176	82	16	15	9	464	
N	34	206	69	397	142	41	33	15	937	
A(2)%	71	54	45	44	58	39	45	60	50% A(3)	

Table 4 - Wrenching deformation model, Principle stress from N 3 E

	Time Interval									A(1)
	1	2	3	4	5	6	7	8	Tot.	%
N 87 W	2	14	1	10	7	1	1	1	37	4
N 72 W	3	9	1	18	8	3	1	0	43	5
N 57 W	1	12	1	19	5	0	0	0	39	4
N 42 W	0	4	6	15	7	1	1	1	35	4
N 27 W	4	7	1	6	8	1	2	0	29	3
N 12 W	4	5	3	19	9	2	0	1	43	5
N 3 E	3	10	4	12	6	1	1	0	37	4
N 18 E	0	11	2	12	4	3	0	0	32	3
N 33 E	1	7	5	13	4	1	2	0	33	3
N 48 E	1	17	5	19	2	0	5	1	50	5
N 63 E	2	8	5	16	2	2	0	1	26	3
N 78 E	0	7	0	10	2	2	0	2	23	2
Tot.	21	111	34	169	64	17	13	7	436	
N	34	206	69	397	142	41	33	15	937	
A(2)%	62	54	49	43	45	41	39	47	47% A(3)	

Table 5 - Wrenching deformation model, Principle stress from N 6 E

	Time Interval									A(1)
	1	2	3	4	5	6	7	8	Tot.	%
N 84 W	2	9	3	10	4	1	0	0	29	3
N 69 W	0	6	3	20	5	4	1	1	40	4
N 54 W	2	15	1	25	6	0	1	0	50	5
N 39 W	0	6	3	20	5	1	4	1	40	4
N 24 W	0	5	1	11	11	3	3	0	34	4
N 9 W	1	7	2	16	11	1	0	0	38	4
N 6 E	1	5	4	13	1	2	0	0	26	3
N 21 E	0	5	5	19	3	5	1	1	39	4
N 36 E	0	5	2	14	2	1	0	1	25	3
N 51 E	0	8	8	22	3	0	3	0	44	5
N 66 E	2	11	5	22	1	2	0	0	43	5
N 81 E	0	3	0	8	1	4	1	1	18	2
Tot.	7	85	37	200	53	24	14	5	432	
N	34	206	69	397	142	41	33	15	937	
A(2)%	21	41	54	50	37	59	42	33	45%	A(3)

Table 6 - Wrenching deformation model, Principle stress from N 9 E

	Time Interval									A(1)
	1	2	3	4	5	6	7	8	Tot.	%
N 81 W	1	5	4	12	2	0	0	0	24	3
N 66 W	2	7	3	13	4	2	2	3	36	4
N 51 W	1	16	4	28	9	1	1	0	60	6
N 36 W	2	6	0	14	6	0	7	0	35	4
N 21 W	0	7	1	17	12	2	3	0	42	4
N 6 W	1	6	3	17	14	2	0	0	43	5
N 9 E	1	10	2	12	0	4	0	0	29	3
N 24 E	0	3	7	21	3	3	1	1	39	4
N 39 E	0	6	2	21	6	2	2	1	40	4
N 54 E	0	5	6	14	2	1	1	0	29	3
N 69 E	1	14	2	22	1	2	0	0	42	4
N 84 E	0	1	0	8	1	3	1	0	14	1
Tot.	9	86	34	199	60	22	18	5	433	
N	34	206	69	397	142	41	33	15	937	
A(2)%	26	42	49	50	42	54	55	33	46% A(3)	

Table 7 - Wrenching deformation model, Principle stress from N 12 E

	Time Interval									A(1)
	1	2	3	4	5	6	7	8	Tot.	%
N 78 W	2	4	1	17	7	0	0	0	31	3
N 63 W	2	10	2	14	5	2	2	3	40	4
N 48 W	1	11	4	24	12	1	0	0	53	6
N 33 W	5	5	1	13	10	0	6	0	40	4
N 18 W	0	8	4	18	11	3	1	1	46	5
N 3 W	3	7	3	13	15	3	1	0	45	5
N 12 E	1	15	1	9	0	2	1	0	29	3
N 27 E	1	4	5	12	1	1	3	0	27	3
N 42 E	0	9	2	20	9	1	5	2	28	3
N 57 E	0	6	6	19	3	2	0	1	37	4
N 72 E	2	10	2	13	0	4	0	0	31	3
N 87 E	1	7	2	13	1	0	1	0	25	3
Tot.	18	96	33	185	74	19	20	7	452	
N	34	206	69	397	142	41	33	15	937	
A(2)%	53	47	48	47	52	46	61	47	48% A(3)	

Test for Randomness

Having concluded there is no relationship between azimuth direction and number of lineaments according to the wrenching model, the data must be tested to see if it is truly random. A common measure of the discrepancy between two variables, that is, how far the observed data differs from what would be expected under no association, is the chi square(χ^2) statistic.

Method

The number of lineaments per five degree interval was recorded from N 90 E to N 90 W. These values were then substituted into the equation:

$$\chi^2 = \sum_{1}^{36} \frac{(Obs-Exp)}{Exp}$$

where the expected value (Exp) is equal to:

$$Exp = \frac{\text{Total number of lineaments}}{\text{Number of 5 degree intervals}}$$

The probability if there is no association, of getting a χ^2 at least as large as the one calculated is called the level of χ^2. This is given approximately by the following formula:

$$\text{Level of } \chi^2 = 2H(\sqrt{\chi^2})$$

Thus the level of the calculated χ^2 in this case is:

$$2H(\sqrt{72.425}) = 2H(8.51)$$

This value is higher than 4.45, which is the highest number listed for $\sqrt{\chi^2}$ in the available Normal Distribution table. $H(\chi^2)$ for 4.45 is .00000429.

Interpretation

If there were no association between number of lineaments and azimuth direction the chance of getting a sample at least as far from the expected value, as measured by χ^2 , would be less than .00000429. This test confirms that a relationship does exist but it does not indicate what kind of relationship it is. It merely states the observed pattern of lineament number to azimuth direction is not random.

Discussion

The preceding tests indicate that the number of lineaments observed and their orientations are independent of lithology, time, and location.

These findings are compatible with those of Holst and Foote (1981 b), who found upon measurement of close to 5,000 joints in Devonian age rocks from Charlevoix, Michigan, to Alpena, Michigan, that fluctuations in mean orientation of joint sets were independent of formation, lithology, and distance between sample stations.

This is not to infer that in actuality LANDSAT lineaments represent joints. However, Prouty (1975) suggests, upon favorable comparison of frequency analyses performed on lineament azimuths to those on joint patterns from outcrop measurements, that a relationship between the orientations of the two does exist.

Length vs Age

Possible factors controlling the length of a lineament are rupture strength of the rock and areal size covered by the time interval.

Rupture strength, as previously mentioned, could not be ascertained in this study. Areal size however, through use of a planimeter, was determined. Because of the method of placing lineaments that crossed interval boundaries into the interval in which the majority of the lineament length rested, length of lineaments per time interval is biased towards the intervals which cover a larger amount of area (i.e. the larger the area, the greater the probability of having the longer lineaments placed in that interval). An attempt was made to remove some of this bias by dividing the average length of the total number of lineaments observed per time interval by the total area covered by that interval. When corrected for area, it would be expected that all average lengths would be very nearly the same.

The results of this test (Table 8) show that seven of the eight time intervals are within one standard deviation of the mean indicating that areal size is a major factor in controlling the average length of lineament per time interval.

Table 8 - Average Length Per Time Interval vs. Area

Interval	Average Length (in miles)	Area	Length per Unit Area
1	5.28	1.6	3.3
2	4.9	5.4	.91
3	7.52	1.7	4.42
4	6.72	14.1	.48
5	4.9	11.9	.41
6	6.08	3.0	2.03
7	4.64	2.1	2.21
8	1.6	.9	1.78

Mean = 1.94

Standard deviation = $\pm$1.40

Length vs Azimuth Direction and Age

Histograms showing the average length of all lineaments occurring within five degree intervals were prepared for each geologic time interval and for all time intervals combined (Figures 15-23). Generally, the length was affected by the number of lineaments used to calculate the average. As a whole, length does not appear to be related to azimuth direction.

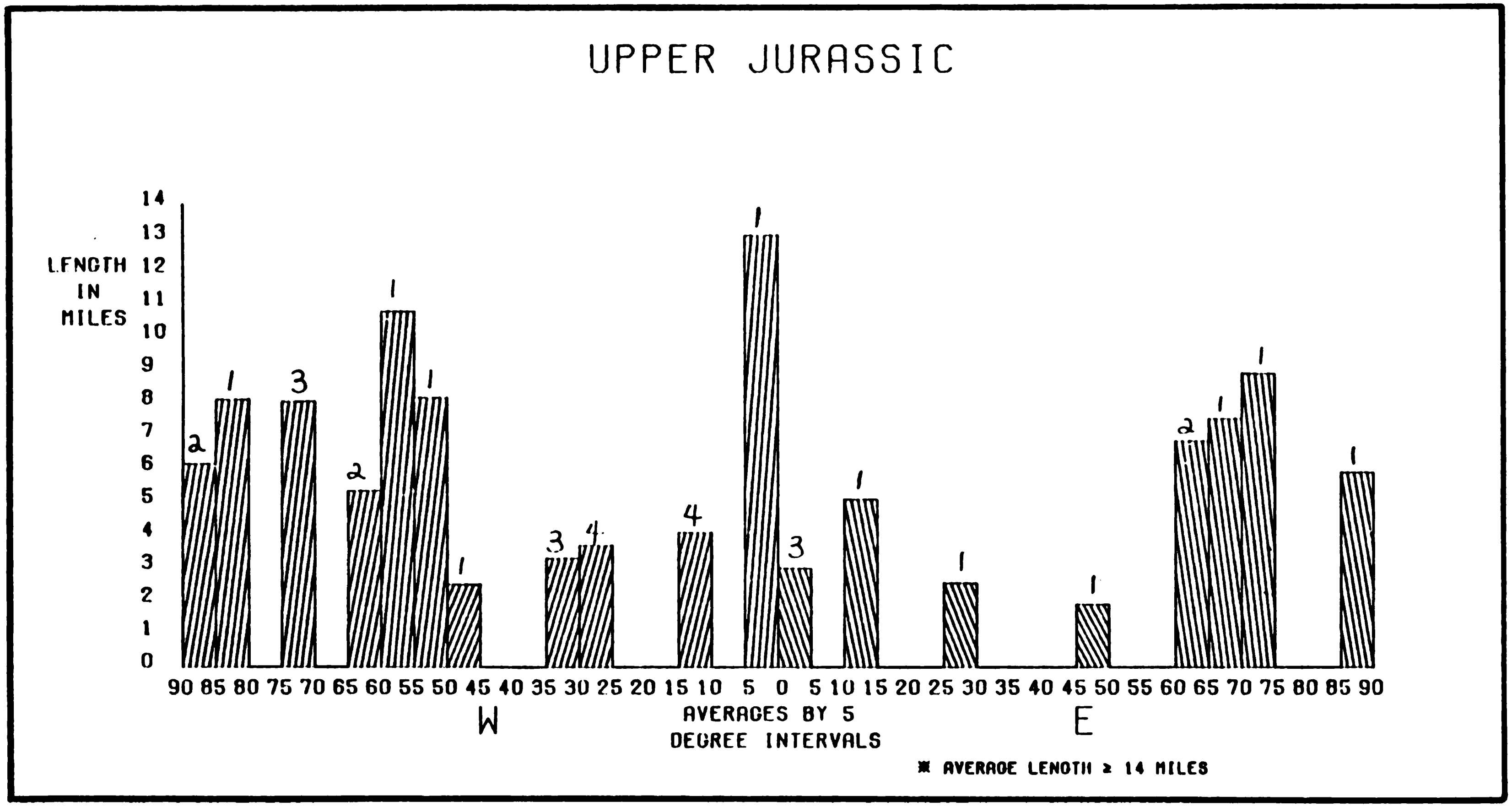

UPPER JURASSIC
LENGTH IN MILES
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
W
AVERAGES BY 5 DEGREE INTERVALS
E
✱ AVERAGE LENGTH ≥ 14 MILES

Figure 15

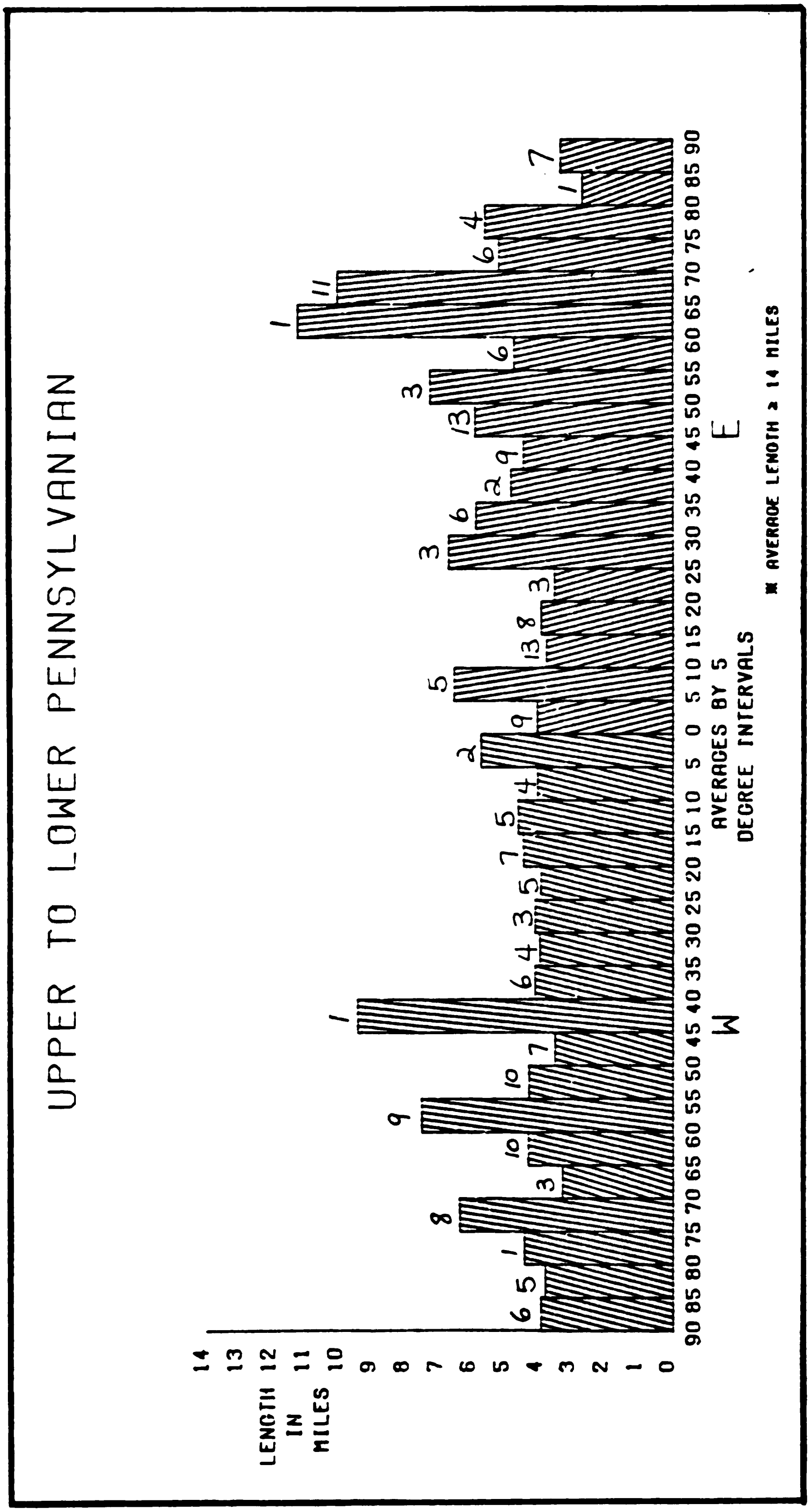

UPPER TO LOWER PENNSYLVANIAN
LENGTH IN MILES
14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
W
E
AVERAGES BY 5 DEGREE INTERVALS
* AVERAGE LENGTH ≥ 14 MILES

Figure 16

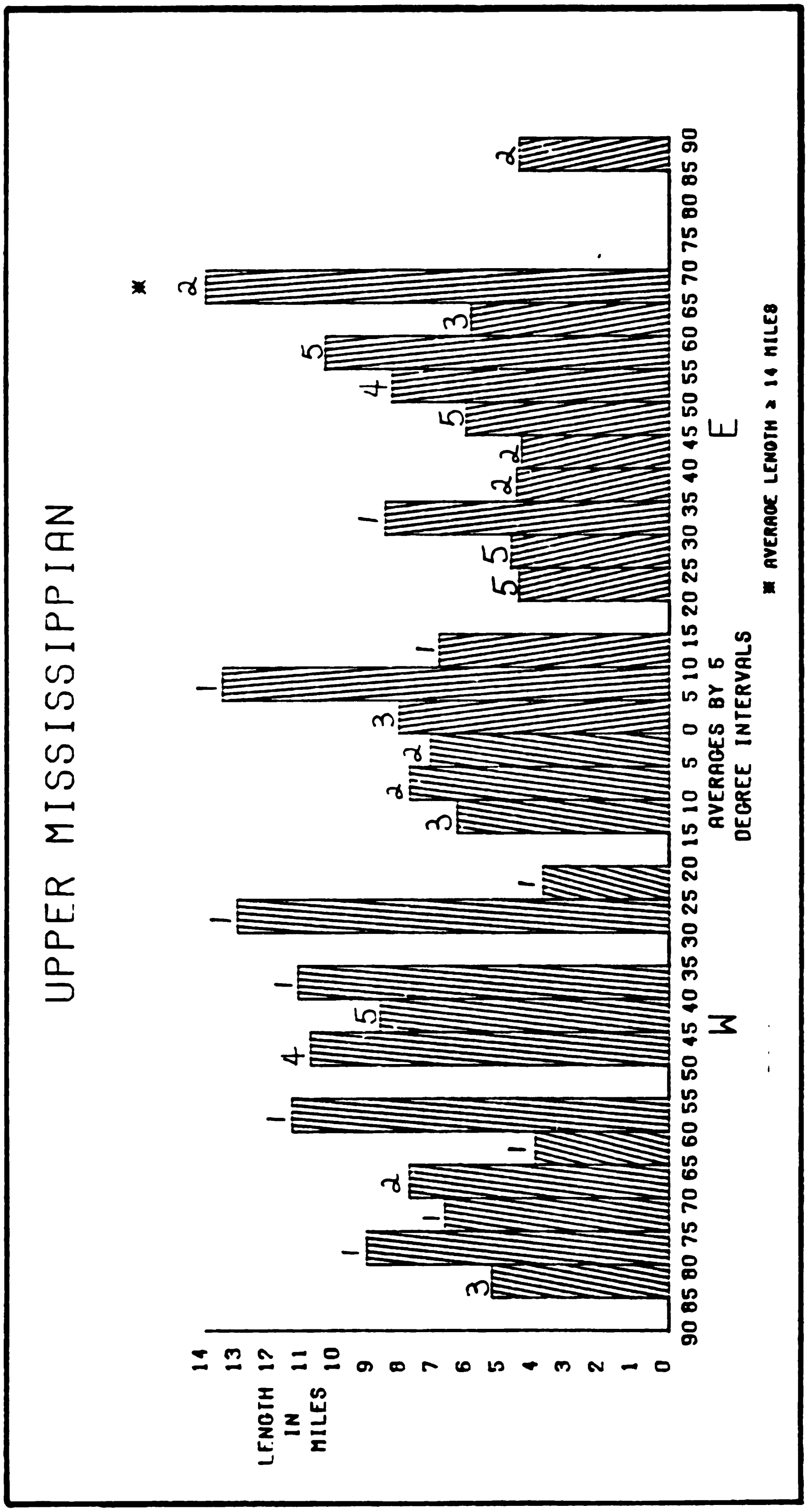

UPPER MISSISSIPPIAN
LENGTH IN MILES
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
AVERAGES BY 5 DEGREE INTERVALS
W
E
* AVERAGE LENGTH = 14 MILES

Figure 17

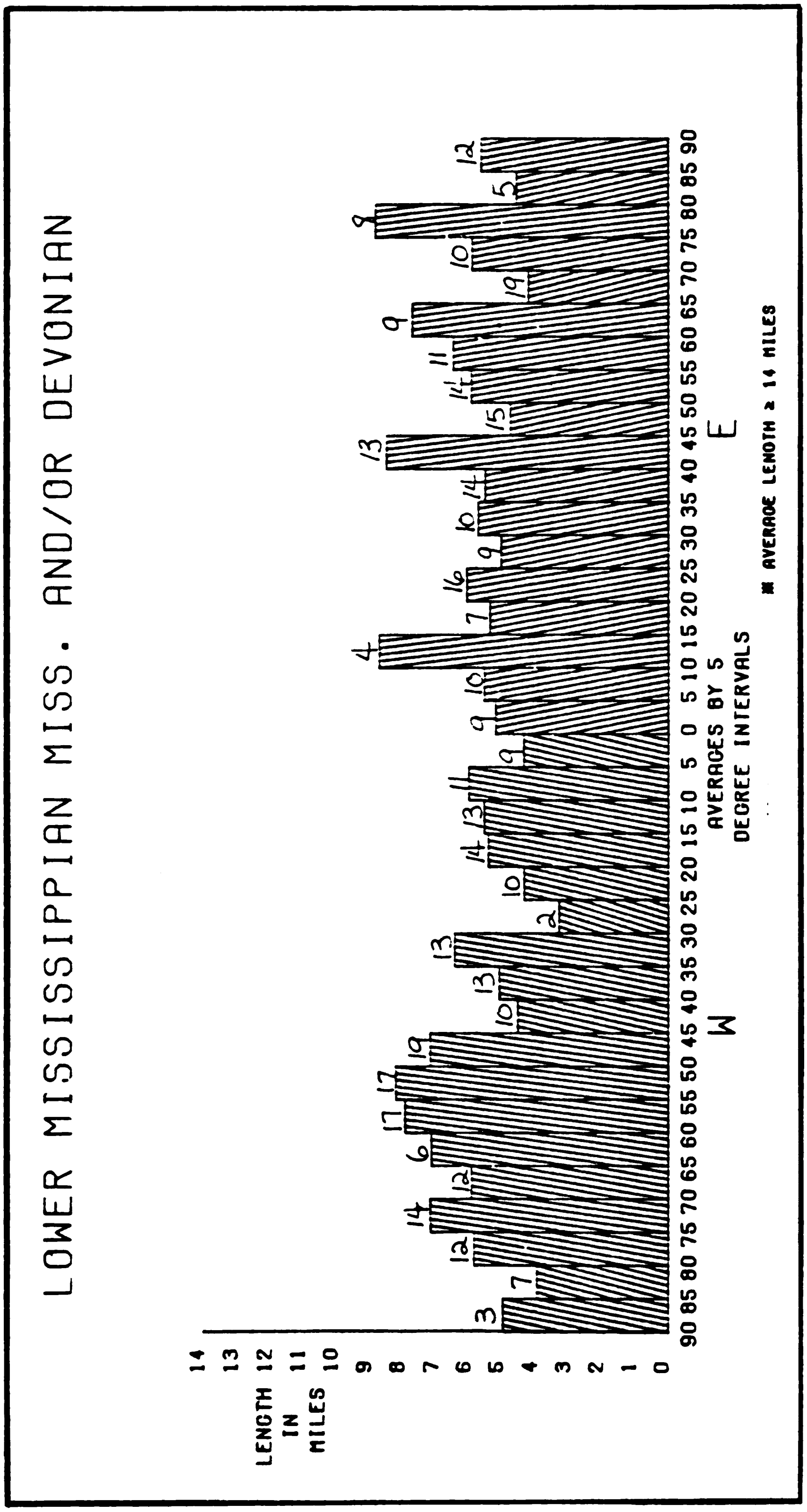

LOWER MISSISSIPPIAN MISS. AND/OR DEVONIAN
LENGTH IN MILES
AVERAGES BY 5 DEGREE INTERVALS
W
E
* AVERAGE LENGTH ≥ 14 MILES

Figure 18

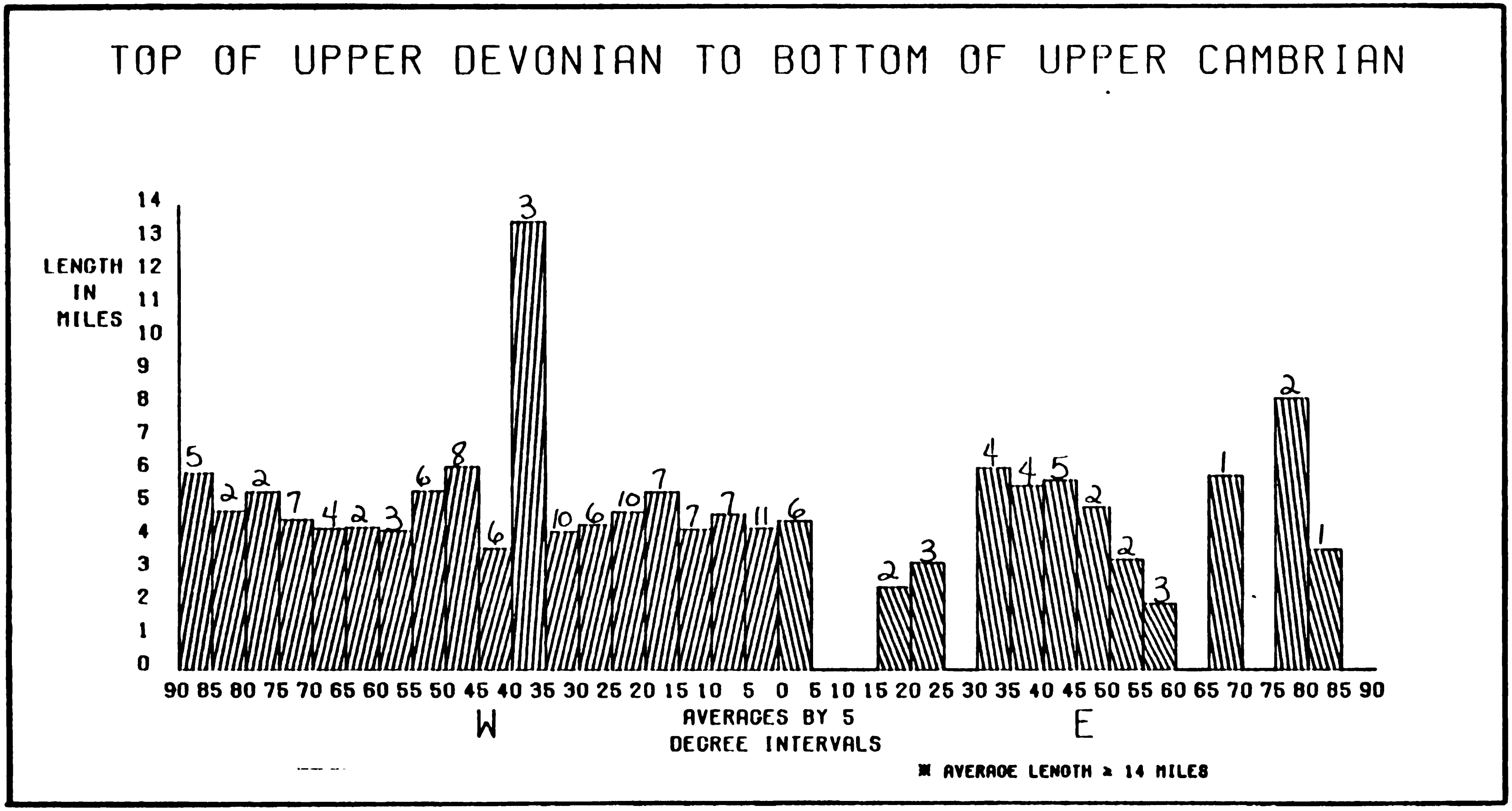

TOP OF UPPER DEVONIAN TO BOTTOM OF UPPER CAMBRIAN
LENGTH IN MILES
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
W
E
AVERAGES BY 5
DEGREE INTERVALS
* AVERAGE LENGTH ≥ 14 MILES
5
2
2
7
4
2
3
6
8
6
3
10
6
10
7
7
7
11
6
2
3
4
4
5
2
2
3
1
2
1

Figure 19

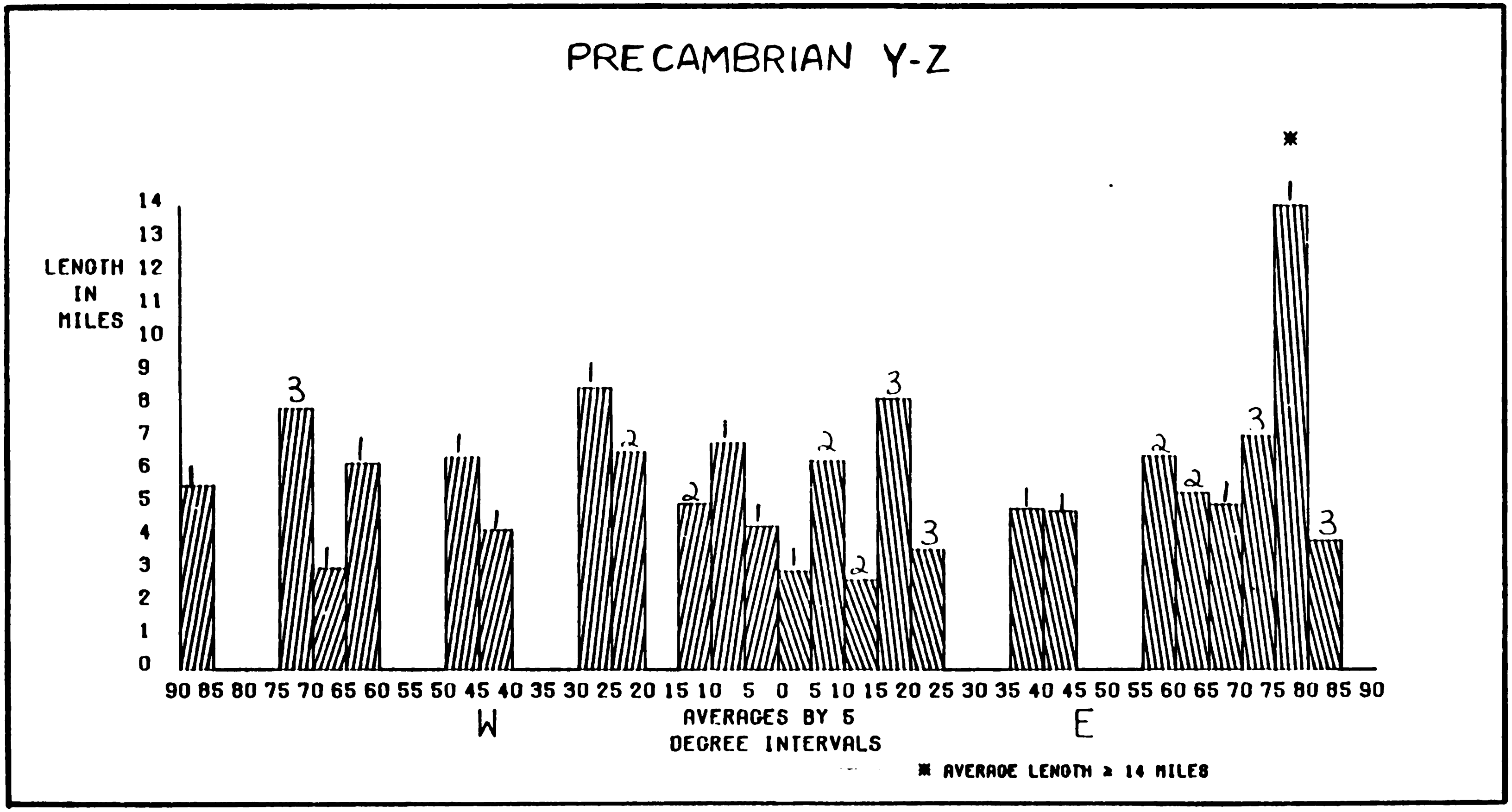

PRECAMBRIAN Y-Z
LENGTH IN MILES
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
W
E
AVERAGES BY 5 DEGREE INTERVALS
* AVERAGE LENGTH ≥ 14 MILES

Figure 20

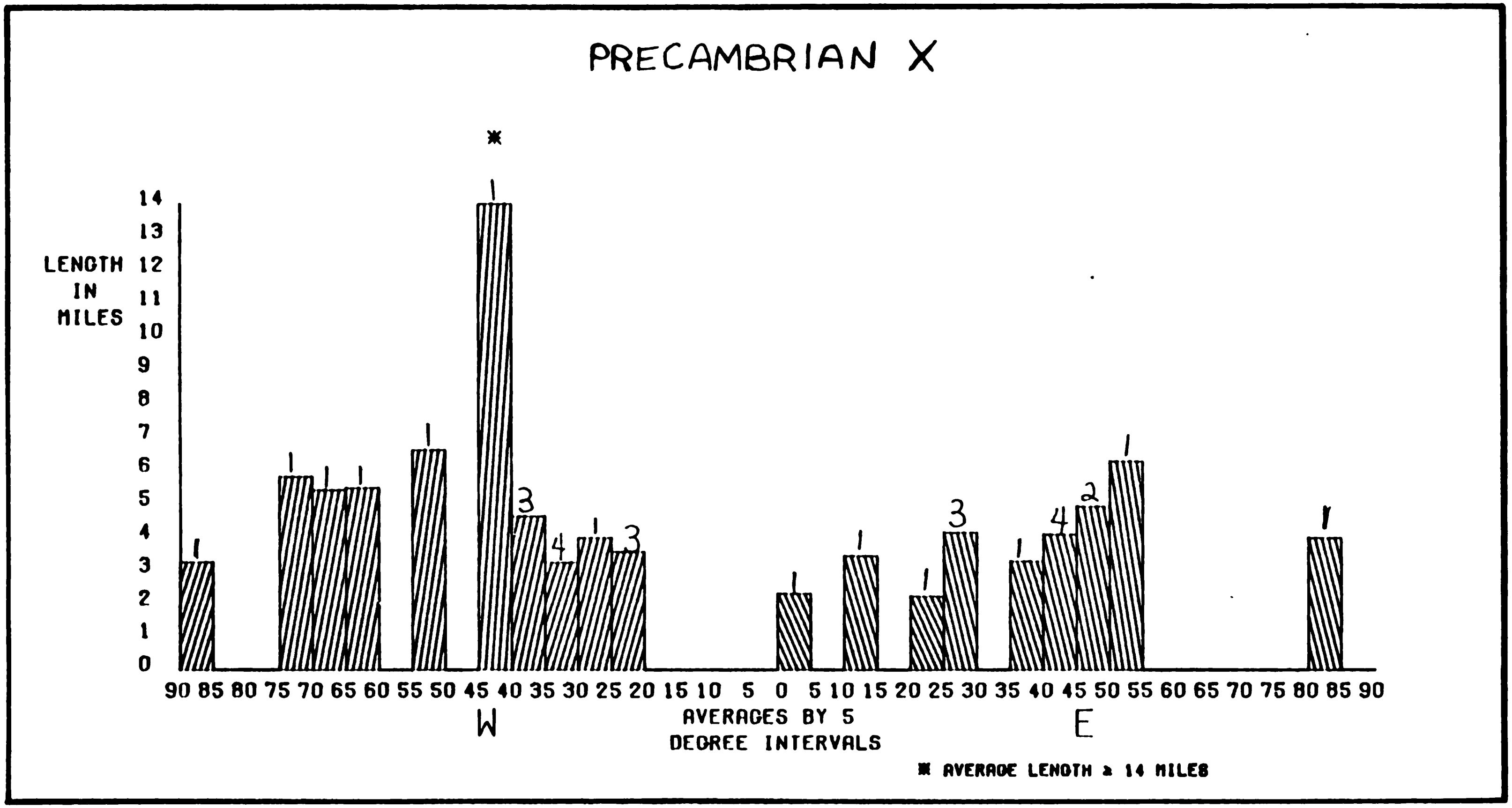

PRECAMBRIAN X
LENGTH IN MILES
14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
W
E
AVERAGES BY 5 DEGREE INTERVALS
* AVERAGE LENGTH ≥ 14 MILES

Figure 21

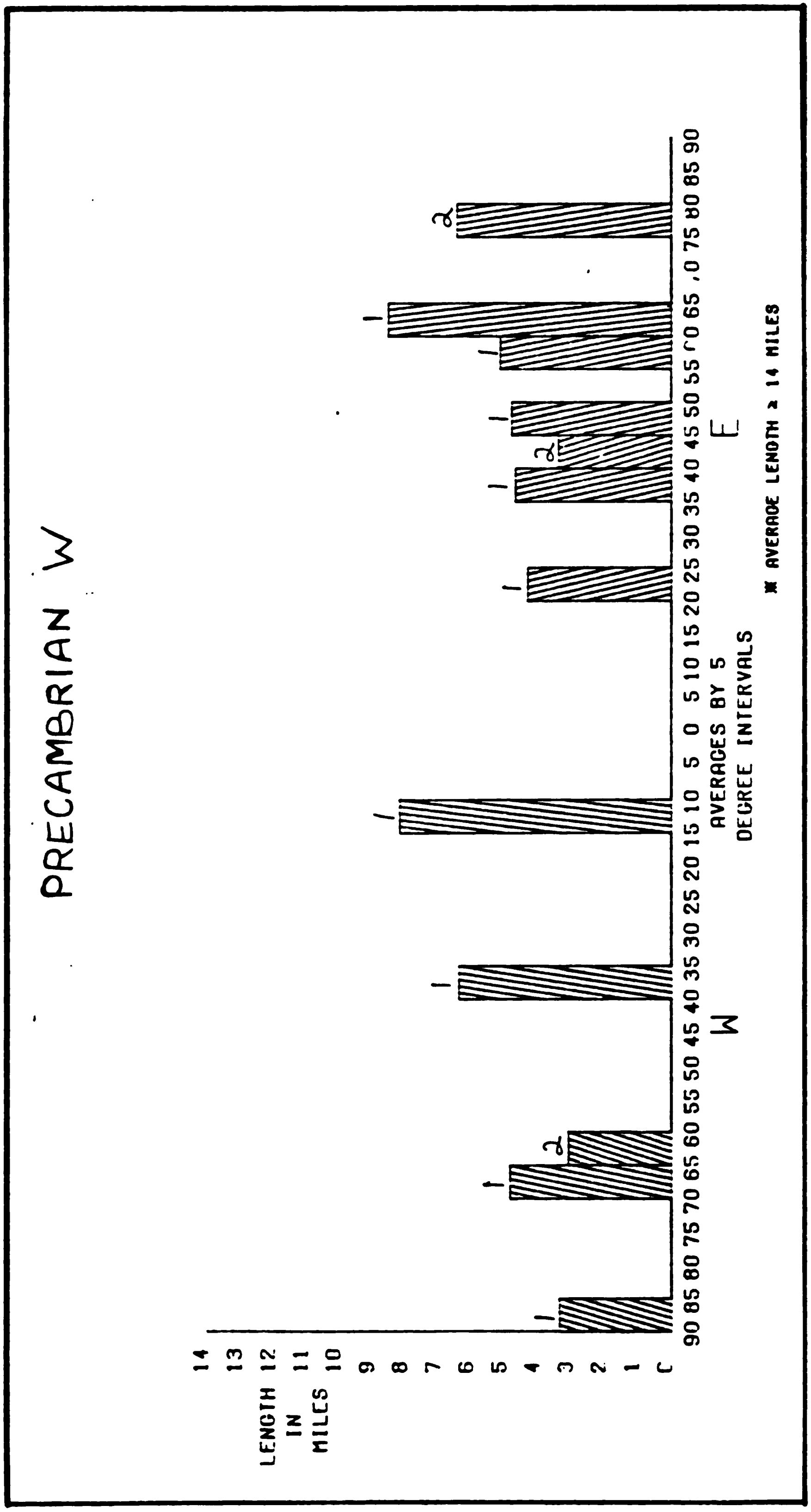

PRECAMBRIAN W
LENGTH IN MILES
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
W
E
AVERAGES BY 5 DEGREE INTERVALS
* AVERAGE LENGTH ≥ 14 MILES

Figure 22

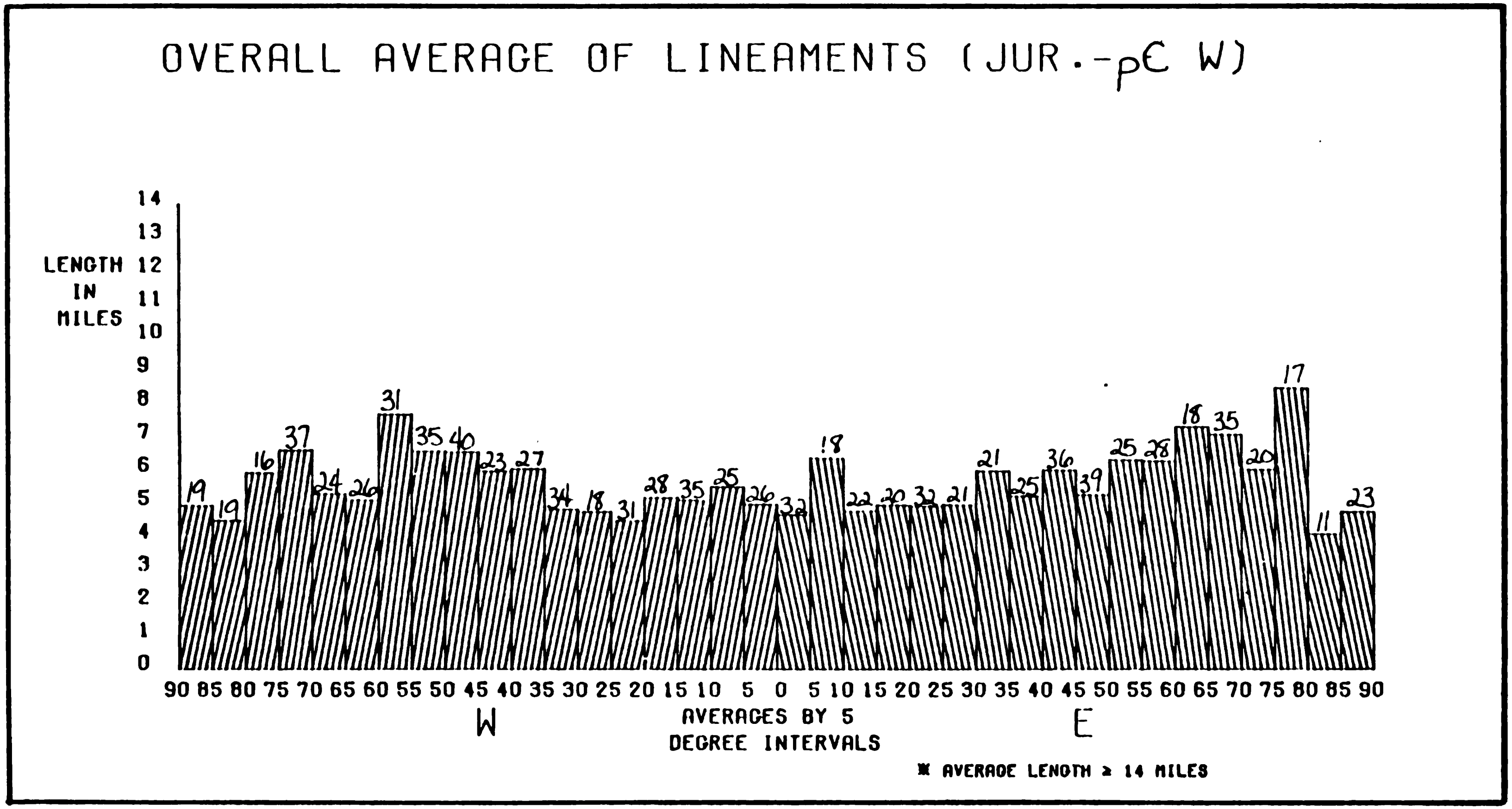

OVERALL AVERAGE OF LINEAMENTS (JUR.-pЄ W)
LENGTH IN MILES
14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
19 19 16 37 24 26 31 35 40 23 27 34 18 31 28 35 25 26 32 18 22 20 32 21 21 25 36 39 25 28 18 35 20 17 11 23
90 85 80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
W
E
AVERAGES BY 5
DEGREE INTERVALS
* AVERAGE LENGTH ≥ 14 MILES

Figure 23

LINEAMENTS VS OIL FIELD TRENDS

Past studies, as referenced earlier, have suggested many, perhaps all, of the linear oil fields in Michigan are fault related. It was hoped that since lineaments are proposed faults, a correlation would exist between lineament azimuths of the Lower Peninsula and those of inferred linear trends extracted from oil field structure maps.

Ten oil fields were selected for this study on the basis of number of wells drilled, nature of its surrounding township and range baselines, and their position in the Basin (Figure 24). These regulations were set to provide a good amount of well control in the creation of structure maps, an accurate conversion from township and range notation to Cartesian coordinates, and a representative sampling from as many areas as possible in the Michigan Basin.

Geologic horizons from these oil fields were picked mainly on the constancy with which driller/geologist logs had been able to pick contact boundaries.

Efforts centered on getting a sample to coincide chronologically with one of the five Phanerozoic time intervals created for this study. Additional horizons were picked for some oil fields in the hope that their lithology might better show a linear trend than other formations of that same field.

Criteria used in extracting likely structural trends from the contour maps were largely threefold:

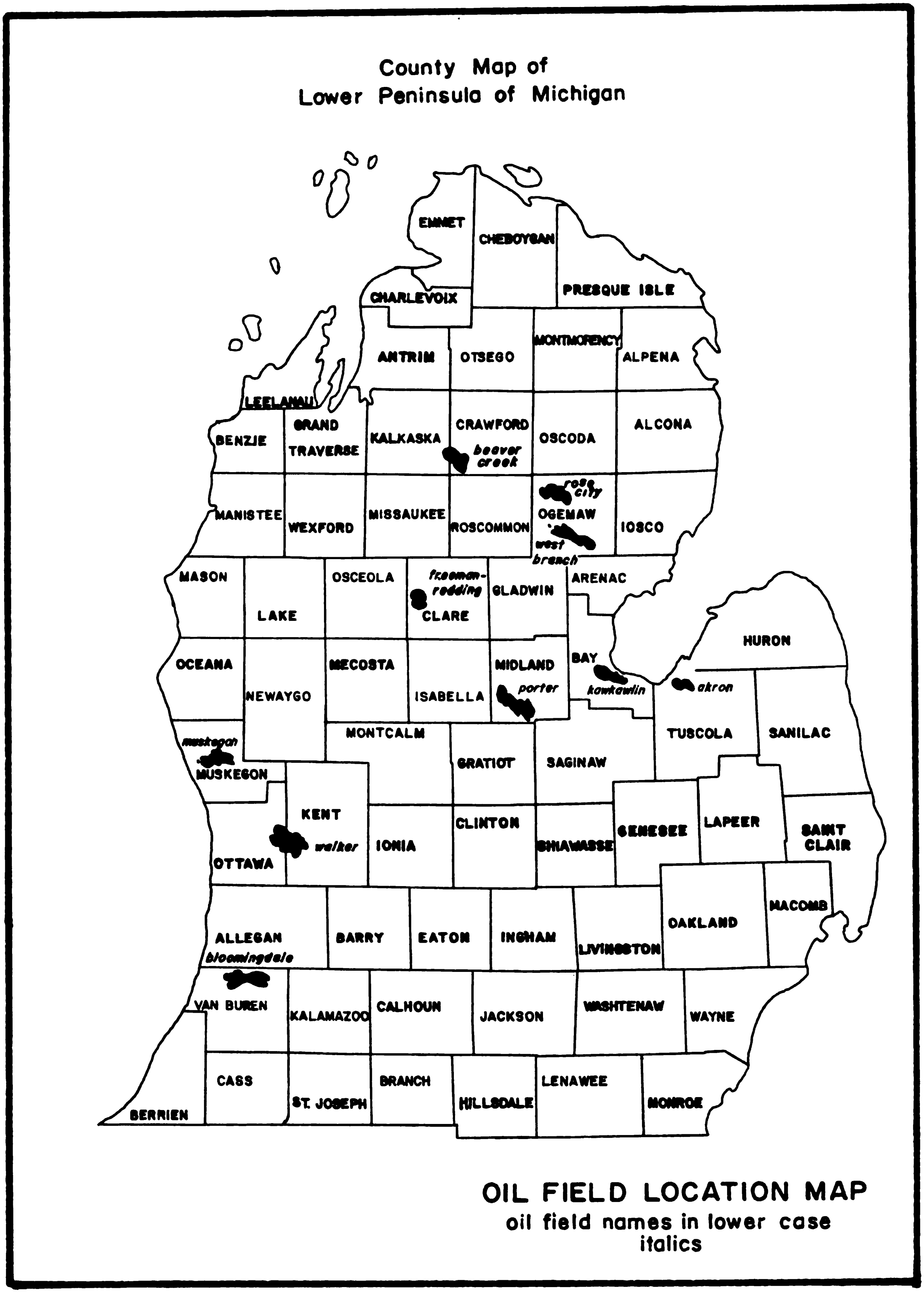

County Map of
Lower Peninsula of Michigan
EMMET
CHEBOYGAN
CHARLEVOIX
PRESQUE ISLE
ANTRIM
OTSEGO
MONTMORENCY
ALPENA
LEELANAU
BENZIE
GRAND TRAVERSE
KALKASKA
CRAWFORD
beaver creek
OSCODA
ALCONA
MANISTEE
WEXFORD
MISSAUKEE
ROSCOMMON
rose city
OGEMAW
west branch
IOSCO
MASON
LAKE
OSCEOLA
freeman-redding
CLARE
GLADWIN
ARENAC
HURON
OCEANA
NEWAYGO
MECOSTA
ISABELLA
MIDLAND
porter
BAY
kawkawlin
akron
TUSCOLA
SANILAC
muskegon
MUSKEGON
MONTCALM
GRATIOT
SAGINAW
KENT
walker
OTTAWA
IONIA
CLINTON
SHIAWASSEE
GENESEE
LAPEER
SAINT CLAIR
ALLEGAN
bloomingdale
BARRY
EATON
INGHAM
LIVINGSTON
OAKLAND
MACOMB
VAN BUREN
KALAMAZOO
CALHOUN
JACKSON
WASHTENAW
WAYNE
BERRIEN
CASS
ST. JOSEPH
BRANCH
HILLSDALE
LENAWEE
MONROE
OIL FIELD LOCATION MAP
oil field names in lower case italics

Figure 24

1) Alignment and configuration (elongation) of structural high points (likely fold axes) were connected.

2) Alignment and configuration of depressed areas (likely "karsting" which appears related to faults) were connected.

3) A succession of contours elongated in a particular direction (low or high points included) were connected.

Density of well control was also an important factor. Especially on the flanks of the oil fields, where the edge effects created by the gridding method used by the SURFACE II mapping program were magnified.

Despite efforts towards providing uniformity of method in data gathering, interpretation of these linear trends was largely subjective. Hence, the lines depicting the linear trends (Figures 25-55) are dashed to show they are inferred.

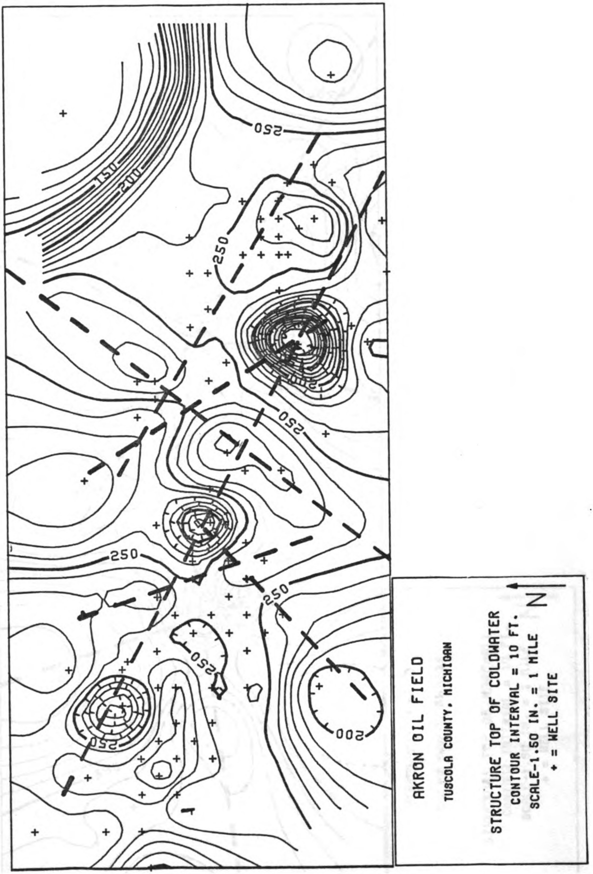
Statistical Method

The number of lineaments and inferred linear trends per five degree intervals was recorded from N 90 W to N 90 E and a harmonic analysis was run on each set of data. The program used for this analysis required the data to be read in as x and y coordinates. The data was converted to the Cartesian system through the use of the equations:

$$x = \cos(d) \times \text{number of lineaments or trends}$$

$$y = \sin(d) \times \text{number of lineaments or trends}$$

where d = the midpoint of a five degree interval starting with N 90 E as 0 and N 90 W equaling 180. It was also necessary to



AKRON OIL FIELD
TUSCOLA COUNTY, MICHIGAN
STRUCTURE TOP OF COLDWATER
CONTOUR INTERVAL = 10 FT.
SCALE-1.50 IN. = 1 MILE
+ = WELL SITE
N
150
200
250

Figure 25

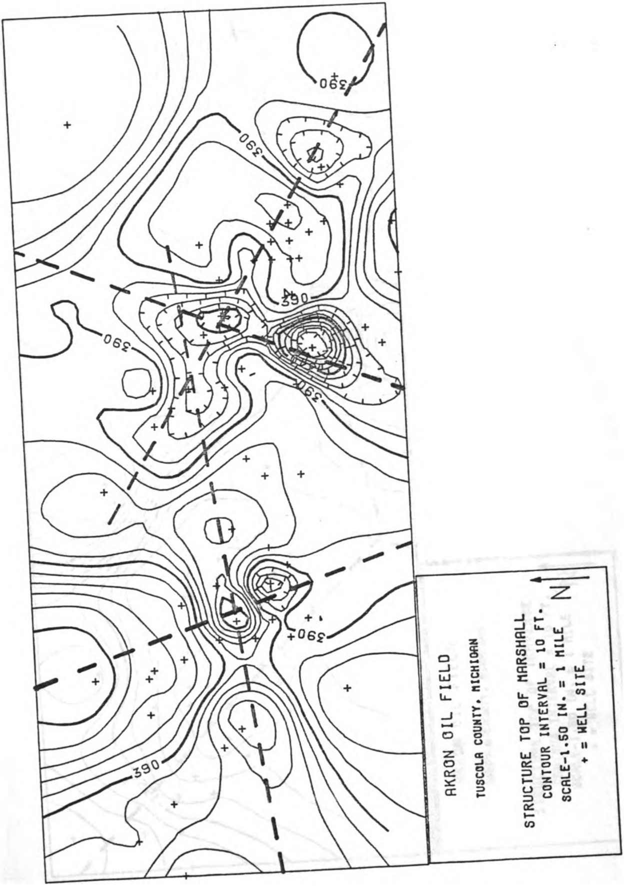

AKRON OIL FIELD
TUSCOLA COUNTY, MICHIGAN
STRUCTURE TOP OF MARSHALL
CONTOUR INTERVAL = 10 FT.
SCALE-1.50 IN. = 1 MILE
+ = WELL SITE
N
390

Figure 26

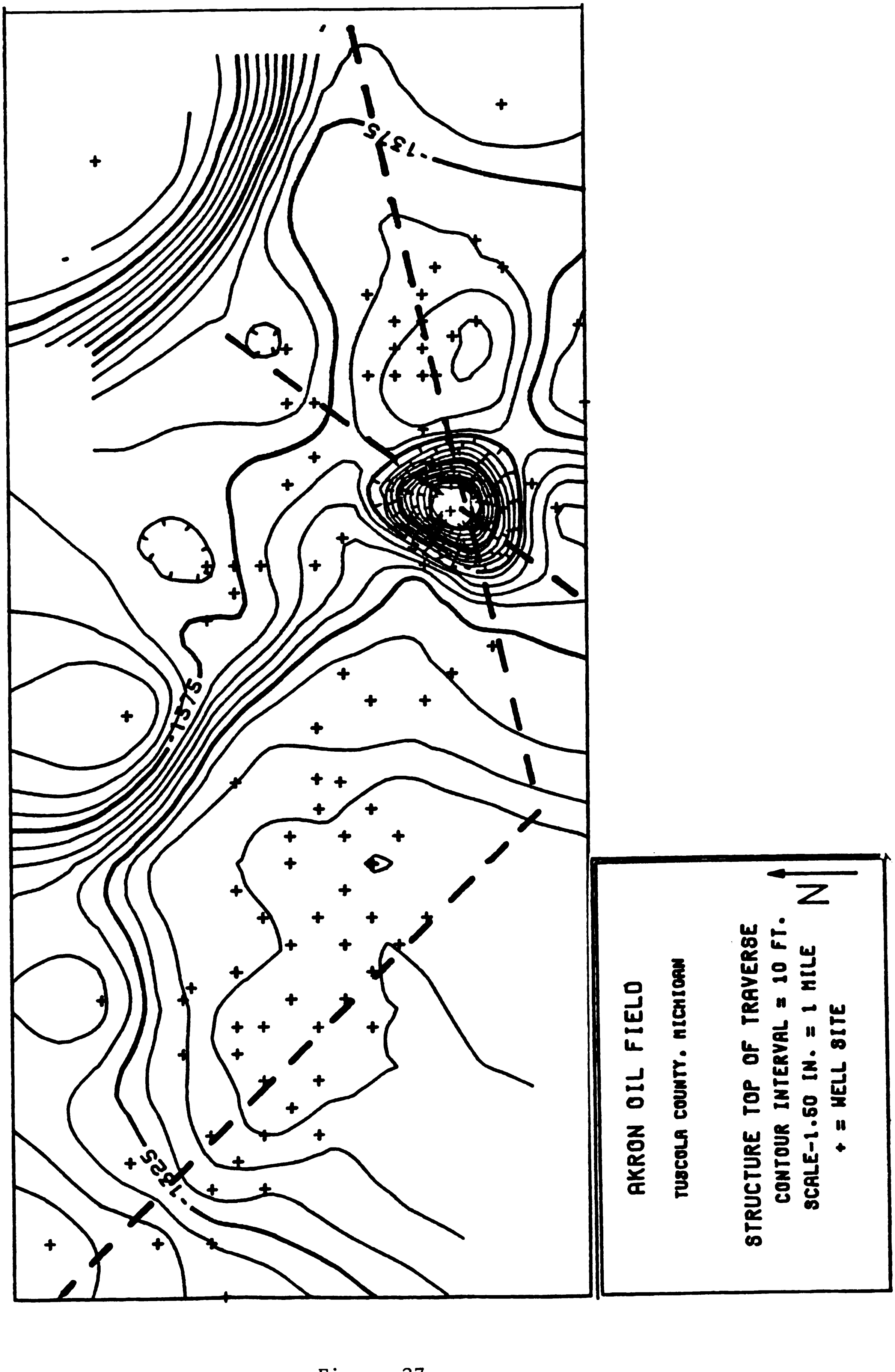

AKRON OIL FIELD
TUSCOLA COUNTY, MICHIGAN
STRUCTURE TOP OF TRAVERSE
CONTOUR INTERVAL = 10 FT.
SCALE-1.60 IN. = 1 MILE
+ = WELL SITE
N
-1375
-1375
-1325

Figure 27

Figure 28
Page 64

Figure 29
Page 65

Figure 30
Page 66

Figure 31
Page 67

Figure 32
Page 68

Figure 33
Page 69

Figure 34
Page 70

Figure 35
Page 71

Figure 36
Page 72

Figure 37
Page 73

Figure 38
Page 74

Figure 39
Page 75

Figure 40
Page 76

Figure 41
Page 77

Figure 42
Page 78

Figure 43
Page 79

Figure 44
Page 80

Figure 45
Page 81

Figure 47
Page 83

Figure 48
Page 84

Figure 38
Page 74

Figure 39

Figure 40
Page 76

Figure 41
Page 77

Figure 42
Page 78

Figure 43
Page 79

Figure 44
Page 80

Figure 45
Page 81

Figure 47
Page 83

Figure 48
Page 84

Figure 49
Page 85

Figure 50
Page 86

Figure 51
Page 87

Figure 52
Page 88

Figure 53
Page 89

Figure 54
Page 90

Figure 55
Page 91

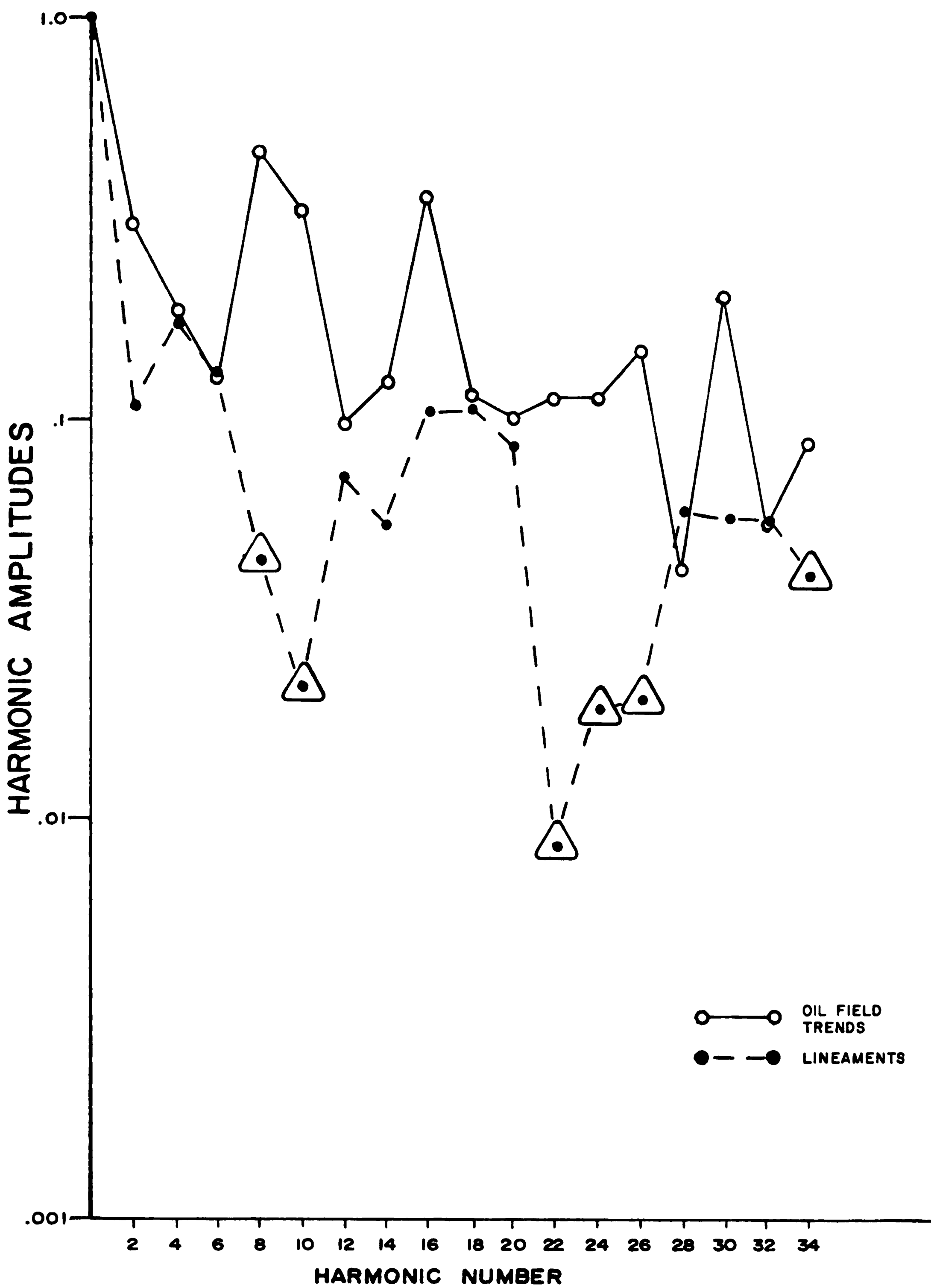
calculate the x and y coordinates from 180-360 degrees because the definition of a closed shape was needed. In addition, all values had to be normalized to occur in the northeast quadrant of the Cartesian system before the harmonic analysis could be performed.

The technique utilized in this analysis yields a mathematical model that will regenerate the shape of the outline of the data. An explanation of this method is given by Erlich and Weinberg (1970).

The results of each analysis were plotted on semilogarithmic graph paper with harmonic amplitude on the ordinate scale and harmonic number on the abscissa (Figure 56).

To determine the power of each amplitude peak Fisher's test of significance in harmonic analysis was used. This test determines the probability that the largest of the amplitudes, given in a normalized form with respect to the data, is the result of the randomness of the data. Shimshoni (1971) suggests the proper application of Fisher's test would be to extend its use to encompass all amplitudes to ascertain which of them are meaningful.

Using tables provided by Shimshoni, it was found that all peaks observed for the inferred oil field trends attained a 95% level of significance. While only the spectral peaks observed for harmonic numbers 4, 6, 2, 16, 18, 20, 12, 28, 30, 14, and 32 achieved 95% significance for the lineament data. Points due to the randomness of the data on Figure 56 are encompassed by triangles.



GRAPH OF HARMONIC ANALYSIS

Figure 56

Interpretation

Differences in the two equations (each graphed line) may arise from the size of the data, the areal extent of the data, and data compilation procedures.

The problem of data size deals with the number of features used in each analysis. There are 937 lineaments, while there are only 152 linear trends. The larger number of lineaments allows a great deal of noise through randomness to affect the shape equation.

Areal extent of the data pertains to source area from which the data were drawn. The lineament data are regional in nature while the oil field trends are local. Due to the diversity of stress propagation and intensity throughout the Michigan Basin, a regional set of data would contain many features not present in a more localized area.

Finally, data compilation procedures can result in differences in the data. Lineaments were measured directly off a map prepared from LANDSAT imagery printouts. Linear trends, as mentioned previously, were "inferred" from computer generated contour maps. The former method is objective while the latter is subjective. The number of linear trends and their azimuth directions would probably vary from one interpretation to another.

Excluding all points due to randomness in the lineament data and those of their corresponding harmonic numbers for the oil field data, it is found that 7 of the 11 remaining pairs of harmonic amplitudes are within close proximity of one another. In view of this fact, despite the overall difference in the equations defining the outline shape of each set of data, it must be concluded the relationship between oil field linear trends and lineaments is more than coincidental.

FURTHER STUDY

Retesting of the relationship between oil field structural trends and lineaments may yield more positive results by changing two factors, areal size of study and contour interval, or by performing digital filtering.

1) Areal size could be changed so that instead of testing all lineaments against a group of oil fields, the number of lineaments within a prescribed radius around an oil field could be compared to linear trends observed in that oil field.

2) The contour interval used in constructing the structure maps could be reduced to 5' for all maps. In this way subtle linear trends might become more evident and larger trends could be enhanced. Attempts to do so resulted in overcrowding of the contours as drawn by the plotter on the preferred scale of the maps. If the scale were enlarged sufficiently this overcrowding would not be evident.

3) Digital filtering offers a potential for selection of linear trends in a more objective manner by decreasing background (i.e. weak structural trends) thereby making the major trends more pronounced.

CONCLUSIONS

Certain conclusions can be advanced with respect to the results of the tests made in this study:

1) The number of lineaments observed per geologic time interval is primarily independent of lithology, location and age of rocks.

2) The lineament azimuths do not fit the wrenching deformation model for any direction of principle stress.

3) The chi square statistic suggests a relationship between azimuth direction and number of lineaments observed. Preferred orientation probably exists in a low ordered state.

4) Length of lineaments is primarily independent of lithology, location and age of rocks.

5) There is no apparent relationship between length and azimuth direction of the lineaments.

6) Although there are differences in the graphed harmonics, there appears to be sufficient evidence to conclude a relationship between lineaments and inferred trends from oil fields does exist.

APPENDIX A LIST OF LINEAMENT DATA

Length is in inches, one inch = 16 miles

All azimuth measurements are in degrees divergent from north

LIST OF LINEAMENT DATA

UPPER JURASSIC (#1)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
0 E	.21	29 W	.22
0 E	.22	30 W	.23
3 E	.13	30 W	.22
12 E	.32	32 W	.32
30 E	.14	35 W	.07
46 E	.12	35 W	.20
61 E	.41	46 W	.14
64 E	.43	52 W	.50
69 E	.47	57 W	.66
74 E	.55	63 W	.18
88 E	.35	65 W	.49
4 W	.79	74 W	.44
11 W	.18	75 W	.43
13 W	.32	75 W	.57
14 W	.31	82 W	.50
14 W	.17	86 W	.33
29 W	.21	88 W	.41

LIST OF LINEAMENT DATA

UPPER TO LOWER PENNSYLVANIAN (#2)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
0 E	.15	16 E	.18
0 E	.21	16 E	.26
0 E	.35	16 E	.28
0 E	.28	17 E	.30
2 E	.10	17 E	.42
2 E	.20	17 E	.18
2 E	.18	18 E	.21
2 E	.19	19 E	.20
5 E	.60	21 E	.18
6 E	.39	23 E	.32
8 E	.26	24 E	.16
8 E	.15	28 E	.67
9 E	.13	29 E	.32
10 E	1.08	30 E	.28
11 E	.23	31 E	.53
11 E	.13	31 E	.65
11 E	.28	32 E	.30
11 E	.13	35 E	.33
12 E	.11	35 E	.28
13 E	.19	35 E	.13
13 E	.22	37 E	.29
13 E	.17	37 E	.30
14 E	.12	41 E	.13
14 E	.48	41 E	.20
14 E	.18	41 E	.12
15 E	.37	42 E	.19
15 E	.23	43 E	.53

LIST OF LINEAMENT DATA

UPPER TO LOWER PENNSYLVANIAN (#2)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
44 E	.13	66 E	.48
45 E	.37	66 E	.36
45 E	.42	66 E	.93
45 E	.39	66 E	.78
46 E	.63	67 E	1.07
46 E	.17	68 E	.19
46 E	.23	68 E	.23
46 E	.17	69 E	.30
46 E	.22	69 E	.43
46 E	.30	69 E	.21
47 E	.23	69 E	.33
47 E	.28	71 E	.56
48 E	.21	71 E	.27
48 E	.58	72 E	.16
50 E	.22	73 E	.61
50 E	1.22	75 E	.20
50 E	.11	75 E	.08
51 E	.23	76 E	.35
52 E	.97	77 E	.17
52 E	.18	78 E	.80
56 E	.34	79 E	.17
56 E	.24	81 E	.17
58 E	.13	88 E	.19
60 E	.65	88 E	.23
60 E	.12	90 E	.30
60 E	.13	90 E	.23
62 E	.68	90 E	.11

LIST OF LINEAMENT DATA

UPPER TO LOWER PENNSYLVANIAN (#2)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
90 E	.34	30 W	.40
90 E	.13	31 W	.17
3 W	.38	31 W	.38
5 W	.30	32 W	.20
6 W	.28	32 W	.23
6 W	.13	37 W	.19
7 W	.25	38 W	.33
8 W	.32	38 W	.37
11 W	.23	39 W	.32
11 W	.60	39 W	.18
12 W	.12	39 W	.15
14 W	.17	43 W	.59
15 W	.38	48 W	.27
16 W	.22	48 W	.15
17 W	.26	48 W	.33
18 W	.23	48 W	.15
18 W	.30	48 W	.70
19 W	.29	50 W	.18
19 W	.27	50 W	.37
20 W	.38	51 W	.32
23 W	.29	51 W	.23
24 W	.18	51 W	.42
25 W	.20	51 W	.33
25 W	.34	52 W	.20
25 W	.20	53 W	.27
28 W	.23	53 W	.26
28 W	.15	54 W	.20

LIST OF LINEAMENT DATA

UPPER TO LOWER PENNSYLVANIAN (#2)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
54 W	.30	68 W	.23
55 W	.16	69 W	.33
56 W	.43	71 W	.15
56 W	.27	72 W	.31
56 W	.42	72 W	.26
57 W	.98	73 W	.14
57 W	.20	74 W	.45
59 W	.31	74 W	.66
59 W	.26	75 W	1.02
59 W	.38	75 W	.18
59 W	.08	77 W	.27
61 W	.35	81 W	.23
61 W	.42	82 W	.22
61 W	.20	84 W	.33
62 W	.33	84 W	.20
62 W	.15	84 W	.23
62 W	.27	86 W	.13
63 W	.22	86 W	.14
64 W	.31	87 W	.21
64 W	.28	87 W	.18
65 W	.18	88 W	.20
67 W	.22	88 W	.41

LIST OF LINEAMENT DATA

UPPER MISSISSIPPIAN (#3)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
4 E	1.04	53 E	1.24
4 E	.28	54 E	.29
5 E	.18	56 E	.28
6 E	.85	57 E	.34
12 E	.43	58 E	.27
21 E	.31	60 E	.17
21 E	.29	60 E	2.10
22 E	.17	63 E	.62
22 E	.38	64 E	.30
22 E	.26	64 E	.22
26 E	.24	69 E	.32
26 E	.30	69 E	2.08
30 E	.45	88 E	.37
30 E	.28	88 E	.20
30 E	.19	1 W	.38
32 E	.53	5 W	.34
36 E	.33	6 W	.26
38 E	.26	8 W	.60
43 E	.32	15 W	.23
44 E	.24	15 W	.70
46 E	.18	15 W	.23
47 E	.38	21 W	.24
49 E	.23	30 W	.98
49 E	.75	40 W	.69
49 E	.33	41 W	.36
52 E	.33	42 W	.49
53 E	.23	43 W	.64

LIST OF LINEAMENT DATA

UPPER MISSISSIPPIAN (#3)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
44 W	.93	66 W	.12
44 W	.22	67 W	.85
48 W	1.35	72 W	.43
48 W	.25	78 W	.57
50 W	.83	83 W	.31
50 W	.24	83 W	.52
57 W	.71	84 W	.15
63 W	.23		

LIST OF LINEAMENT DATA

LOWER MISSISSIPPIAN, MISS. AND/OR DEVONIAN (#4)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
0 E	.39	18 E	.30
0 E	.30	19 E	.20
0 E	.72	19 E	.50
2 E	.33	21 E	.39
3 E	.30	21 E	.42
3 E	.10	21 E	.23
4 E	.13	21 E	.17
4 E	.34	21 E	.14
5 E	.32	22 E	.85
6 E	.29	22 E	.46
6 E	.31	22 E	.17
6 E	.12	23 E	.41
7 E	.22	23 E	.18
7 E	.44	23 E	.66
9 E	.66	23 E	.56
9 E	.23	23 E	.41
9 E	.28	24 E	.17
10 E	.65	24 E	.20
10 E	.26	25 E	.66
11 E	.58	26 E	.37
12 E	.79	26 E	.24
13 E	.58	26 E	.22
14 E	.23	27 E	.29
16 E	.19	27 E	.11
16 E	.28	28 E	.27
17 E	.79	29 E	.79
18 E	.10	29 E	.21

LIST OF LINEAMENT DATA

LOWER MISSISSIPPIAN, MISS. AND/OR DEVONIAN (#4)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
30 E	.34	42 E	.34
31 E	.52	42 E	.45
31 E	.45	42 E	.98
31 E	.24	42 E	.54
31 E	.44	42 E	.21
33 E	.25	44 E	.46
33 E	.17	44 E	2.28
33 E	.31	45 E	.27
34 E	.43	45 E	.37
34 E	.34	45 E	.15
35 E	.44	45 E	.33
36 E	.39	46 E	.30
36 E	.43	46 E	.10
37 E	.18	47 E	.26
37 E	.12	47 E	.85
38 E	.11	48 E	.24
38 E	.35	48 E	.26
38 E	.29	48 E	.31
39 E	.38	48 E	.50
40 E	.23	49 E	.13
40 E	.18	49 E	.16
40 E	1.18	49 E	.25
40 E	.31	50 E	.58
40 E	.37	50 E	.17
40 E	.31	50 E	.13
41 E	.27	50 E	.24
42 E	.24	52 E	.39

LIST OF LINEAMENT DATA

LOWER MISSISSIPPIAN, MISS. AND/OR DEVONIAN (#4)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
52 E	.24	62 E	.31
52 E	.27	63 E	.16
52 E	.12	63 E	.29
52 E	.90	64 E	.22
53 E	.34	64 E	2.01
54 E	.26	64 E	.39
54 E	.23	66 E	.30
54 E	.31	66 E	.24
54 E	.23	66 E	.35
54 E	.58	66 E	.21
55 E	.88	66 E	.87
55 E	.29	66 E	.17
55 E	.17	67 E	.40
58 E	.27	67 E	.15
58 E	.45	67 E	.08
58 E	.41	67 E	.12
58 E	.31	68 E	.19
58 E	.20	68 E	.17
58 E	.36	68 E	.28
59 E	.76	68 E	.27
59 E	.76	68 E	.26
59 E	.19	68 E	.20
59 E	.11	69 E	.35
60 E	.67	70 E	.23
62 E	.51	70 E	.21
62 E	.24	71 E	.16
62 E	.22	72 E	.34

LIST OF LINEAMENT DATA

LOWER MISSISSIPPIAN, MISS. AND/OR DEVONIAN (#4)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
72 E	.41	90 E	.18
73 E	.38	90 E	.26
73 E	.40	90 E	.16
74 E	.24	90 E	.34
74 E	.30	90 E	.28
74 E	.23	90 E	.16
75 E	.42	3 W	.22
75 E	.83	3 W	.18
76 E	.23	4 W	.10
76 E	.15	4 W	.19
77 E	.87	4 W	.28
77 E	.41	4 W	.25
78 E	.38	4 W	.30
79 E	1.38	4 W	.62
80 E	.37	5 W	.32
80 E	.62	6 W	.68
82 E	.23	7 W	.26
82 E	.38	7 W	.67
83 E	.23	8 W	.20
83 E	.30	8 W	.52
85 E	.28	9 W	.32
86 E	.23	9 W	.26
87 E	.78	9 W	.61
87 E	.48	10 W	.22
88 E	.35	10 W	.23
88 E	.62	10 W	.17
89 E	.39	11 W	.56

LIST OF LINEAMENT DATA

LOWER MISSISSIPPIAN, MISS. AND/OR DEVONIAN (#4)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
12 W	.29	21 W	.46
12 W	.70	21 W	.24
12 W	.09	22 W	.14
12 W	.40	22 W	.47
13 W	.49	22 W	.29
13 W	.19	24 W	.19
13 W	.25	25 W	.17
14 W	.20	25 W	.09
14 W	.44	25 W	.23
14 W	.28	27 W	.23
14 W	.20	29 W	.19
15 W	.43	31 W	1.15
16 W	1.02	31 W	.31
16 W	.17	31 W	.20
17 W	.22	31 W	.33
17 W	.21	32 W	.53
18 W	.19	32 W	.43
18 W	.36	32 W	.40
18 W	.77	32 W	.15
19 W	.31	34 W	.60
19 W	.18	34 W	.15
19 W	.34	34 W	.21
19 W	.10	34 W	.55
20 W	.32	35 W	.23
20 W	.22	38 W	.13
20 W	.35	38 W	.40
21 W	.45	38 W	.13

LIST OF LINEAMENT DATA

LOWER MISSISSIPPIAN, MISS. AND/OR DEVONIAN (#4)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
38 W	.18	48 W	.28
38 W	.27	48 W	.27
38 W	.16	48 W	.15
38 W	.15	48 W	1.38
38 W	1.05	49 W	.67
39 W	.42	49 W	.69
40 W	.19	49 W	.36
40 W	.55	50 W	.20
40 W	.26	50 W	.20
40 W	.27	50 W	.38
41 W	.27	50 W	.50
41 W	.13	50 W	.35
41 W	.87	51 W	.20
42 W	.19	51 W	.57
42 W	.16	51 W	.30
42 W	.12	52 W	.66
42 W	.50	52 W	.51
44 W	.25	52 W	.17
45 W	.16	52 W	.33
45 W	.19	53 W	.17
46 W	.26	53 W	.21
46 W	.64	53 W	.65
46 W	.53	53 W	.69
47 W	.47	53 W	1.42
47 W	.62	53 W	.40
47 W	.35	54 W	.61
48 W	.22	54 W	.42

LIST OF LINEAMENT DATA

LOWER MISSISSIPPIAN, MISS. AND/OR DEVONIAN (#4)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
55 W	.25	66 W	.23
55 W	1.18	66 W	.30
56 W	.19	67 W	.28
56 W	.23	67 W	.19
56 W	.31	68 W	.33
56 W	.80	68 W	.12
57 W	.42	69 W	.51
57 W	.34	69 W	.24
57 W	.25	70 W	1.00
57 W	.52	70 W	.34
59 W	.66	71 W	.25
59 W	.52	71 W	.30
59 W	.25	71 W	.98
59 W	1.86	72 W	.23
59 W	.42	72 W	.50
60 W	.88	72 W	1.77
60 W	.16	72 W	.12
60 W	.34	72 W	.16
60 W	.30	74 W	.20
61 W	.51	74 W	.62
61 W	.44	74 W	.46
62 W	1.05	74 W	.24
63 W	.18	75 W	.30
64 W	.22	75 W	.19
64 W	.28	76 W	.57
66 W	.38	76 W	.20
66 W	.54	76 W	.26

LIST OF LINEAMENT DATA

LOWER MISSISSIPPIAN, MISS. AND/OR DEVONIAN (#4)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
76 W	1.00	81 W	.15
77 W	.56	81 W	.22
77 W	.40	81 W	.28
78 W	.30	82 W	.21
78 W	.17	82 W	.30
78 W	.22	83 W	.40
78 W	.26	85 W	.19
79 W	.20	86 W	.61
80 W	.26	86 W	.15
		86 W	.18

LIST OF LINEAMENT DATA

UPPER DEVONIAN (TOP) TO UPPER CAMBRIAN (BOTTOM) (#5)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
0 E	.21	52 E	.27
0 E	.17	58 E	.19
0 E	.57	60 E	.10
2 E	.21	60 E	.08
2 E	.30	67 E	.36
5 E	.22	76 E	.40
16 E	.15	77 E	.62
20 E	.16	82 E	.23
21 E	.22	1 W	.30
21 E	.16	2 W	.30
25 E	.21	2 W	.22
31 E	.21	2 W	.26
32 E	.18	3 W	.23
33 E	.85	3 W	.16
33 E	.27	3 W	.18
40 E	.41	3 W	.17
40 E	.32	3 W	.31
40 E	.42	3 W	.44
40 E	.23	3 W	.35
42 E	.73	6 W	.38
42 E	.25	7 W	.25
43 E	.25	7 W	.25
44 E	.27	8 W	.18
44 E	.28	8 W	.46
46 E	.40	9 W	.25
48 E	.21	9 W	.27
52 E	.14	11 W	.24

LIST OF LINEAMENT DATA

UPPER DEVONIAN (TOP) TO UPPER CAMBRIAN (BOTTOM) (#5)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
11 W	.33	28 W	.24
12 W	.37	28 W	.23
12 W	.22	31 W	.13
13 W	.27	32 W	.32
13 W	.21	32 W	.30
14 W	.21	32 W	.23
16 W	.17	32 W	.55
16 W	.22	32 W	.35
16 W	.97	33 W	.25
17 W	.25	33 W	.16
18 W	.28	34 W	.13
18 W	.28	35 W	.18
19 W	.17	37 W	.21
21 W	.34	38 W	1.84
21 W	.26	40 W	.48
21 W	.23	41 W	.08
21 W	.30	41 W	.25
22 W	.31	43 W	.33
22 W	.29	43 W	.26
22 W	.33	45 W	.16
23 W	.30	45 W	.29
24 W	.18	46 W	.25
25 W	.42	46 W	.13
27 W	.41	47 W	.12
28 W	.18	49 W	.95
28 W	.30	49 W	.23
28 W	.28	49 W	.20

LIST OF LINEAMENT DATA

UPPER DOVONIAN (TOP) TO UPPER CAMBRIAN (BOTTOM) (#5)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
49 W	.27	72 W	.26
50 W	.89	74 W	.41
51 W	.31	75 W	.39
51 W	.36	75 W	.16
52 W	.19	75 W	.14
53 W	.35	75 W	.20
55 W	.43	75 W	.41
55 W	.46	76 W	.45
59 W	.22	79 W	.21
60 W	.32	82 W	.36
60 W	.25	85 W	.24
62 W	.15	86 W	.72
64 W	.39	87 W	.26
66 W	.17	88 W	.27
67 W	.36	89 W	.38
68 W	.14	89 W	.27
70 W	.39	89 W	.31

LIST OF LINEAMENT DATA

PRECAMBRIAN Y-Z (#6)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
0 E	.19	75 E	.26
7 E	.11	80 E	1.35
8 E	.67	82 E	.41
11 E	.25	82 E	.12
11 E	.09	83 E	.20
17 E	.31	5 W	.27
18 E	.89	6 W	.43
20 E	.34	14 W	.43
22 E	.12	15 W	.20
22 E	.27	21 W	.26
24 E	.29	21 W	.57
36 E	.39	27 W	.53
36 E	.22	42 W	.26
42 E	.30	50 W	.40
56 E	.39	65 W	.39
59 E	.41	66 W	.19
61 E	.32	71 W	.39
63 E	.35	72 W	.89
69 E	.31	72 W	.21
72 E	.30	86 W	.35
74 E	.77		

LIST OF LINEAMENT DATA

PRECAMBRIAN X (#7)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
0 E	.14	24 W	.16
13 E	.22	30 W	.25
22 E	.14	33 W	.20
29 E	.30	34 W	.24
30 E	.35	35 W	.20
30 E	.13	35 W	.18
40 E	.21	36 W	.19
41 E	.32	38 W	.32
43 E	.21	38 W	.36
45 E	.25	42 W	1.17
45 E	.24	52 W	.41
50 E	.32	61 W	.29
50 E	.30	63 W	.40
51 E	.39	67 W	.34
84 E	.25	73 W	.36
21 W	.24	88 W	.20
22 W	.27		

LIST OF LINEAMENT DATA

PRECAMBRIAN W (#8)

AZIMUTH	LENGTH	AZIMUTH	LENGTH
22 E	.27	78 E	.45
38 E	.29	15 W	.51
42 E	.24	40 W	.40
43 E	.18	64 W	.28
46 E	.30	65 W	.10
58 E	.32	66 W	.30
62 E	.53	88 W	.21
76 E	.35		

APPENDIX B FORTRAN PROGRAM FOR COORDINATE CONVERSION

FORTRAN PROGRAM FOR COORDINATE CONVERSION

```
C  This program is designed to mathematically convert data
C  from Section, Township and Range notation into Cartesian
C  Coordinates (Good, 1964).  It has been modified so as to
C  pinpoint the data location within the section by using the
C  quarter section notation, the distance in feet from the
C  North or South line of the quarter section and the distance
C  in feet from the East or West line of the quarter section.
C  Prior to input of data, all Township and Range numbers
C  should be normalized so they fit into the Northeast quadrant
C  of the Cartesian Coordinate system.
C  Because it is assumed the area being studied is perfectly
C  square, use of this program should be reserved for small
C  scale maps and should not be used in areas where Township
C  and Range baselines are offset.
C  In reality few, if any, areas defined by Township and
C  Range notation are perfectly square.  However this method
C  provides a much closer approximation of the data point
C  location than does the conventional ¼ section, ¼ of a ¼
C  section and ¼ of a ¼ of a ¼ section nomenclature (i.e.
C  NW SE SW, SW NE NW, ect.).
C
         Program Towr(input,output,tape1=input,tape2=output,
         +tape8,tape20)
         Dimension st(36),sr(36)
         Integer tshp,ran
         tt=5.5
         Do 10 nn=1,36
         st(nn)=tt
         If(nn/6)*6.NE.nn) Go To 10
         tt=tt-1.0
   10    Continue
         rr=5.5
         nr=1
         Do 11 jr=1,3
         Do 12 jc=1,6
         sr(nr)=rr
         rr=rr-1.0
         nr=nr+1
   12    Continue
         rr=rr+1.0
         Do 13 kc=1,6
         sr(nr)=rr
         rr=rr+1.0
         nr=nr+1
   13    Continue
         rr=rr-1.0
   11    Continue
```

FORTRAN PROGRAM FOR COORDINATE CONVERSION (continued)

```
C  The preceeding sequence of commands sets the values needed
C  to define the coordinates of the centers of each of the 36
C  sections.
C
         iob=0
   17    Read(1.14)tshp,ran,nsec,a,b,ft1,dir1,ft2,dir2,elev
         +h1,he,h3
   14    Format(-----)
C
C  Reads in input data.  Format is variable.  tshp=Township #,
C  ran=Range #, nsec=Section #, a=the N or S component and
C  b=the E or W component of the quarter section.  ft1 and ft2
C  are the distance in feet from the N or S (dir1) and the
C  E or W (dir2) quarter section lines respectively.  elev=feet
C  above sea level and h1,h2,h3,..., are the drilling depths
C  at which each target formation was encountered.
C
         If(EOF(1).NE.0) Go To 15
C
C  Checks for end of input data
C
         iob=iob+1
         If(h1.EQ.0) h1=elev
         If(h2.EQ.0) h2=elev
         If(h3.EQ.0) h3=elev
C
C  The above If statements check for missing data
C
         ts=Float(tshp)-1.0
         ra=Float(ran)-1.0
         r1=6.0*ra
         t1=6.0*ts
         If(a.EQ.1hN.AND.dir1.EQ.1hN) y1=.5-((ft1/2640.)/2.)
         If(a.EQ.1hN.AND.dir1.EQ.1hS) y1=(ft1/2640.)/2.
         If(a.EQ.1hS.AND.dir1.EQ.1hS) y1=(ft1/2640.)/2.-.5
         If(a.EQ.1hS.AND.dir1.EQ.1hN) y1=-(ft1/2640.)/2.
         If(b.EQ.1hE.AND.dir2.EQ.1hE) x1=.5-((ft2/2640.)/2.)
         If(b.EQ.1hE.AND.dir2.EQ.1hW) x1=(ft2/2640.)/2.
         If(b.EQ.1hW.AND.dir2.EQ.1hW) x1=(ft2/2640.)/2.-.5
         If(B.EQ.1hW.AND.dir2.EQ.1hE) x1=-(ft2/2640.)/2.
         x=x1+r1+sr(nsec)
         Y=y1+t1+st(nsec)
C
C  The preceeding sequence converts the data from Township
C  and Range notation to Cartesian (X,Y) Coordinates.
```

FORTRAN PROGRAM FOR COORDINATE CONVERSION (continued)

```
          If(iob.NE.1) Go To 19
          xmin=x
          xmax=x
          ymin=y
          ymax-y
          Go to 21
   19     If(xmin.GT.x) xmin=x
          If(xmax.LT.x) xmax=x
          If(ymin.GT.y) ymin=y
          If(ymax.LT.y) ymax=y
   21     Continue
C
C  Checks for minimum and maximum X and Y values to be used
C  in 9 scaling routine.
C
          z1=elev-h1
          z2=elev-h2
          z3=elev-h3
C
C  Determines the feet relative to sea level at which each
C  target formation occurs.
C
          Write(8,16)x,y,z1,z2,z3
   16     Format(-----)
C
C  Creates a file on which the converted coordinates and
C  associated formation values are saved.
C
          Go to 17
   15     Continue
          Rewind 8
          xdif=xmax-xmin
          ydif=ymax-ymin
          If(xdif.GE.ydif) cnstan=xdif
          If(ydif.GE.xdif) cnstan=ydif
   24     Read(8,22)x,y,z1,z2,z3
   22     Format(-----)
          If(EOF(8).NE.O) Go To 23
          xscal=(x-xmin)*(12/cnstan)
          yscal=(y-ymin)*(12/cnstan)
C
C  The above sequence is used to scale the converted
C  coordinates to fit into an area 12" by 12".
C  (area size is variable and is subject to the discretion
C  of the user)
C
```

FORTRAN PROGRAM FOR COORDINATE CONVERSION (continued)

```
          Write (20,25)xscal,yscal,z1,z2,z3
  25      Format(-----)
C
C  Creates a file on which the scaled coordinates and
C  associated formation values are written.
C
          Go to 24
  23      Continue
          Write(2,18)iob,xmin,xmax,ymin,ymax
  18      Format(-----)
C
C  Lists values needed to define parameters on subsequent
C  SURFACE II runs.
C
          End
```

APPENDIX C LOCATION OF OIL FIELDS

LOCATION OF OIL FIELDS

AKRON OIL FIELD	**TUSCOLA COUNTY**
Akron Township	T 14 N, R 8 E
Sections 19,20,21,28,29,30,32,33	
Wisner Township	T 14 N, R 7 E
Sections 22,23,24,25,26	
BEAVER CREEK OIL FIELD	**CRAWFORD-KALKASKA COUNTIES**
Beaver Creek Township	T 25 N, R 4 W
Sections 7,8,16 through 21,27,28,29	
Garfield Township	T 25 N, R 5 W
Sections 12,13	
BLOOMINGDALE OIL FIELD	**VAN BUREN COUNTY**
Bloomingdale Township	T 1 S, R 14 W
Sections 1,2,3,6 through 18,24	
Columbia Township	T 1 S, R 15 W
Sections 1,2,10 through 16,23,24	
Pine Grove Township	T 1 S, R 13 W
Section 18	
FREEMAN-REDDING OIL FIELD	**CLARE COUNTY**
Freeman Township	T 18 N, R 6 W
Sections 3,4	
Redding Township	T 19 N, R 6 W
Sections 27,28,29,32,33,34	
KAWKAWLIN OIL FIELD	**BAY COUNTY**
Monitor Township	T 14 N, R 4 E
Sections 1,2,3,11,12	
Kawkawlin Township	T 15 N, R 4 E
Sections 26,27,28,29,33,34,35,36	
Bangor Township	T 14 N, R 5 E
Sections 4,5,6,7,8,9	

LOCATION OF OIL FIELDS (continued)

MUSKEGON OIL FIELD	MUSKEGON COUNTY
Muskegon Township	T 10 N, R 16 W
Sections 3 through 10,15,16,17,21,22	
Laketon Township	T 10 N, R 17 W
Sections 1,11,12,13,14	
PORTER OIL FIELD	MIDLAND COUNTY
Porter Township	T 13 N, R 1 W
Sections 7,8,9,10,14 through 23,26,27,28	
Jasper Township	T 13 N, R 2 W
Sections 1,2,3,11,12	
Greendale Township	T 14 N, R 2 W
Sections 34,35	
ROSE CITY OIL FIELD	OGEMAW COUNTY
Foster Township	T 24 N, R 1 E
Sections 14,20,21,23,24,25	
Foster Township	T 24 N, R 2 E
Sections 19,20,21,27 through 35	
Rose Township	T 24 N, R 2 E
Sections 27,34,35	
Klacking Township	T 23 N, R 2 E
Sections 2,3,11	
WALKER OIL FIELD	KENT-OTTAWA COUNTIES
Walker Township	T 7 N, R 12 W
Sections 19,20,27 through 34	
Walker Township	T 6 N, R 12 W
Sections 3,4,5,6	
Wyoming Township	T 6 N, R 12 W
Sections 2,3,4,7,8	

LOCATION OF OIL FIELDS (continued)

WALKER OIL FIELD (CONT.)

Tallmadge Township T 7 N, R 13 W
Sections 14,15,22 through 28,33,34,35,36

Tallmadge Township T 6 N, R 13 W
Sections 1,12

Georgetown Township T 6 N, R 13 W
Sections 1,2

Georgetown Township T 7 N, R 13 W
Section 35

WEST BRANCH OIL FIELD OGEMAW COUNTY

West Branch Township T 22 N, R 2 E
Sections 18,19,20,21,26,27,28,29,34,35,36

Ogemaw Township T 22 N, R 1 E
Sections 10,13,14,23,24

Churchill Township T 22 N, R 3 E
Section 31

Horton Township T 21 N, R 2 E
Sections 1,2

Mills Township T 21 N, R 3 E
Sections 5,6

APPENDIX D OIL FIELD LINEAR TREND

OIL FIELD LINEAR TRENDS

West Branch:

Coldwater - N 41 E, N 44 W, N 53 W, N 77 E, N 57 E, N 84 E, N 74 E, N 44 W.

Sunbury - N 43 E, N 61 W, N 62 W.

Traverse - N 88 E, N 14 E, N 44 E, N 64 W, N 66 W.

Walker:

Coldwater - N 20 E, N 28 W, N 45 E.

Traverse - N 48 W, N 61 W, N 69 W, N 78 W, N 69 E.

Bloomingdale:

Coldwater - N 24 E, N 63 E, N 40 W, N 58 E, N 63 E, N 85 E, N 88 E, N 76 W, N 17 W.

Traverse - N 41 E, N 46 E.

Muskegon:

Coldwater - N 2 W, N 84 E, N 74 W.

Traverse - N 9 W, N 41 E, N 67 E, N 50 W, N 86 W.

Freeman-Redding:

Saginaw - N 54 W, N 1 E, N 56 W, N 1 E, N 1 E, N 3 E, N 75 E, N 82 W, N 82 E, N 89 W, N 66 E.

Bayport - N 44 E, N 67 E, N 88 W, N 88 W, N 35 W, N 55 E, N 90 E.

Marshall - N 48 W, N 45 E, N 41 E, N 25 E, N 88 W.

Coldwater - N 26 W, N 59 E, N 90 E, N 75 E, N 88 W.

Traverse - N 37 W, N 53 W, N 66 W.

Akron:

Marshall - N 85 E, N 57 W, N 22 E, N 17 W.

Coldwater - N 61 W, N 49 E, N 15 W, N 30 W, N 38 E, N 57 W.

OIL FIELD LINEAR TRENDS (continued)

Akron (cont.):

Traverse - N 44 W, N 38 E, N 77 E.

Rose City:

Coldwater - N 41 W, N 10 W, N 32 E, N 42 E, N 64 W.

Sunbury - N 58 W, N 84 W.

Traverse - N 89 E, N 57 W.

Porter:

Saginaw - N 78 E, N 89 E, N 26 W, N 58 W.

Bayport - N 50 E, N 43 E, N 47 W, N 66 W, N 41 E, N 33 E, N 47 E, N 30 W, N 53 W, N 42 E, N 8 E, N 87 E.

Coldwater - N 54 W, N 57 E, N 4 W, N 45 W, N 33 E, N 70 E.

Traverse - N 16 E, N 52 W, N 58 E, N 7 E, N 53 E, N 35 E, N 41 W, N 89 E, N 33 W, N 44 W.

Kawkawlin:

Saginaw - N 0 E, N 2 W, N 3 W, N 22 E, N 65 W, N 87 W, N 44 W, N 73 E.

Coldwater - N 13 E, N 28 W, N 68 E, N 69 E, N 66 E, N 50 E, N 46 E, N 61 W, N 27 W.

Sunbury - N 79 E, N 48 E, N 50 W.

Traverse - N 45 W, N 62 W, N 50 E, N 80 E.

Beaver Creek:

Marshall - N 10 E, N 54 W, N 88 E.

Coldwater - N 2 E, N 52 W, N 40 E, N 88 E.

Traverse - N 51 W, N 43 E, N 90 E, N 81 E, N 85 E, N 3 E.

BIBLIOGRAPHY

BIBLIOGRAPHY

Blackwell, David, 1969, Basic Statistics, McGraw-Hill, Inc., New York, New York, 143 p.

Cambray, F. W., 1981, Personal Communication.

Cannon, W. F., and Gair, J. E., 1970, A Revision of Stratigraphic Nomenclatures for Middle Precambrian Rocks in Northern Michigan: Geol. Soc. Amer. Bull., v. 81, pp. 2843-2846.

Cassinis, R., 1977, Applications of Satellite Studies for Structural Geology in Italy: Remote Sensing of the Terrestrial Environment, The Colston Papers, v. 28, pp. 169-182.

Chase, C. G. and Gilmer, T. H., 1973, Precambrian Plate Tectonics- the Mid-Continent Gravity High: Earth Planet. Sci. Let., v. 21, pp. 70-78.

Cohee, G. V., 1948, Cambrian and Ordovician Rocks in Michigan Basin and Adjoining Areas: Amer. Assoc. Pet. Geol. Bull., v. 32, n. 8, p. 1434.

Coons, R. L., Wolland, G. P., and Hershey, G., 1967, Structural Significance and Analysis of Mid-Continent Gravity High: Am. Assoc. Pet. Geol. Bull., V. 51, pp. 2381-2399

Dastanpour, Mohammad, 1977, An Investigation of the Carbonate Rocks in the Reynolds Oil Field, Montcalm County, Michigan: Unpublished Master's Thesis, Michigan State University.

Dorr, J. A., and Eschman D. F., 1971, Geology of Michigan: University of Michigan Press, Ann Arbor, Michigan, 476 p.

Eicher, D. L. and McAlester, A. L., 1980, History of the Earth: Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 413 p.

Ells, G. D., 1969, Architecture of the Michigan Basin: Mich. Basin Geol. Soc. Ann. Field Excursion, pp. 60-88.

_____________, 1962, Structures Associated with the Albion-Scipio Oil Field Trend: Mich. Geol. Survey.

Enslin, W. R. and Hill-Rowley, R., 1977, Guide to Aerial Imagery of Michigan: Michigan Agricultural Experiment Station Research Report, n. 340.

Erlich, R. and Weinberg, B., 1970, An Exact Method for Characterization of Grain Shape: Jour. Sed. Pet., v. 40, n. 1, pp. 205-212.

Fowler, J. H. and Kuenzi, W. D., 1978, Keweenawan Turbidites in Michigan (Deep Borehole Red Beds): A Foundered Basin Sequence Developed During Evolution of a Protoceanic Rift System: Jour. Geophs. Res., V. 83, n. B12, pp. 5833-5843.

Good, D. I., 1964, Mathematical Conversion of Section, Township and Range Notation to Cartesian Coordinates: Kan. St. Geol. Sur. Bull., n. 170, part 3, 30 p.

Grigoryev, A. A., 1973, Direction of Lineaments from the Nimbus-III Infrared Data Derived in the 0.7 to 1.3 Spectral Region: Rem. Sens. Earth Res., v. 2, pp. 997-1003.

Hamrick, R. J., 1978, Dolomitization Patterns in the Walker Oil Field, Kent and Ottawa Counties, Mich: Unpublished Master's Thesis, Michigan State University.

Halls, H. C., 1978, The Late Precambrian Central North American Rift System-A Survey of Recent Geological and Geophysical Investigations in Tectonics and Geophysics of Continental Rifts: Eds. Ramberg, I. B., and E. R. Newman, Pub. D. Reidel Pub, Comp., Dordrecht, Holland.

Hinze, W. J. and Merritt, D. W., 1969, Basement Rocks of the Southern Peninsula of Michigan: Mich. Basin Geol. Soc. Ann. Field Excursion, pp. 28-59.

Hobbs, B. E., Means, W. D., and Williams, P. F., 1976, An Outline of Structural Geology, John Wiley & Sons, Inc., New York, New York, 571 p.

Hobbs, W. H., 1904, Lineaments of the Atlantic Border Region: Geol. Soc. Amer. Bull., v. 15, pp. 483-506.

Holst, T. B., 1981a, Joint Orientation Analysis in the Northern Michigan Basin: Abstracts & Proceedings, 27th Annual Meeting, Institute on Lake Superior Geology.

Holst, T. B. and Foote, G. R., 1981b, Joint Orientation in Devonian Rocks in the Northern Portion of the Lower Peninsula of Michigan: Geol. Soc. Amer. Bull., Part 1, v. 92, n. 2, pp. 85-93.

Hoppin, R. A., 1974, Lineaments: Their Role in Tectonics of Central Rocky Mountains: Amer. Assoc. Petr. Geol. Bull., v. 58, n. 11, pp. 2260-2273.

Hyde, M. K., 1979, A study of Dolomite/Calcite Ratios Relative to the Structures and Producing Zones of the Kawkawlin Oil Field, Bay County, Michigan: Unpublished Master's Thesis, Michigan State University.

Jackson, R. P., 1958, Dolomitization and Structural Relations of the Deep River, North Adams and Pinconning Oil Fields, Michigan: Unpublished Master's Thesis, Michigan State University.

James, H. L., 1955, Zones of Regional Metamorphism in the Precambrian of Northern Michigan: Geol. Soc. Amer. Bull., v. 66, pp. 1455-1487.

James, H. L. 1972, Note 40-Subdivision of Precambrian: an Interim Scheme to be used by U.S. Geological Survey: Amer. Assoc. Pet. Geol. Bull., v. 56, pp. 1128-1133.

Kaiser, E. P., 1950, Structural Significance of Lineaments: Geol. Soc. Amer. Bull., v. 61, pp. 1475-1476.

Kirkham, V. R. D., 1937, Theory of Origin of the Oil and Gas Bearing Folds in Michigan and Theory of Origin of Oil and Gas: Mich. Oil and Gas News, May 15.

Lattman, L. H., 1958, Techniques of Mapping Geologic Fracture Traces and Lineaments on Aerial Photographs: Photogramm. Eng., v. 24, n. 4, pp. 568-576.

Lockett, J. R., 1947, Development of Structures in Basin Areas of Northeastern United States: Amer. Assoc. Pet. Geol. Bull., v. 31, pp. 429-446.

Michigan Basin Geological Society, 1969, Stratigraphic Cross Sections, Michigan Basin.

Michigan Geological Survey, 1978, Michigan's Oil and Gas Field's 1977: Mich. Geol. Survey Ann. Stat. Summary n. 28.

__________, 1968, Bedrock of Michigan: Mich. Geol. Survey Small Scale Map n. 2.

__________, 1964, Stratigraphic Succession in Michigan: Mich. Geol. Survey, Chart 1.

Moody, J. D. and Hill, M. J., 1956, Wrench Fault Tectonics: Bull. Geol. Soc. Amer., v. 67, n. 9, pp. 1207-1246.

Moody, J. D., 1973, Petroleum Exploration Aspects of Wrench Fault Tectonics: Amer. Assoc. Pet. Geol. Bull., v. 57, n. 3, pp. 449-476.

Newcombe, R. S., 1933, Oil and Gas Fields of Michigan: Mich. Geol. Survey, Publ. 38, G. Ser. 32.

Nowroozi, A. A., 1966, Table for Fishers Test of Significance in Harmonic Analysis: Geophys. J. R. astr. Soc., v. 12, pp. 517-520.

Paris, R. M., 1977, Developmental History of the Howell Anticline: Unpublished Master's Thesis, Michigan State University.

Pirtle, G. W., 1932, Michigan Structural Basin and its Relationship to Surrounding Areas: Amer. Assoc. Pet. Geol. Bull., v. 16, pp. 145-152.

Prouty, C. E., 1970, Michigan Basin Paleozoic Evolutionary Development: Geol. Soc. Amer. Abst. with Programs, v. 2, n. 7, pp. 657-658.

Prouty, C. E., 1972, Michigan Basin Development and the Appalachian Foreland: Abst. Int. Geol. Cong., 24th Session, p. 97.

Prouty, C. E., 1975, An Interpretation of Major Intrabasinal Structures-Michigan Basin: Mich. Acad. Sci. Arts, 79th Annual Meeting, Ann Arbor, Michigan.

______, 1976, Michigan Basin-A Wrenching Deformation Model?: Geol. Soc. Amer. Abst. with Programs, v. 8, n. 4, pp. 505.

______, 1976, Implications of Imagery Studies to Time Origin of Michigan Basin Linear Structures: Abst. Amer. Assoc. Pet. Geol., 61st Ann. Meeting, pp. 102.

Prouty, C. E., 1981, Personal Communication.

Rudd, R. D., 1974, Remote Sensing: A Better View: Duxbury Press, North Scituate, Mass., 135 p.

Sampson, R. J., 1978, SURFACE II Graphics System (Revision One): Kansas Geol. Survey, Lawrence, Kan., 234 p.

Shimshoni, Michael, 1971, On Fishers Test of Significance in Harmonic Analysis: Geophys. J. R. astr. Soc., v. 23, pp. 373-377.

Syrjamaki, R. M., 1977, The Prairie du Chien Group of the Michigan Basin: Unpublished Master's Thesis, Michigan State University.

Ten Have, L. E., 1979, Relationship of Dolomite/Limestone Ratios to the Structure and Producing Zones of the West Branch Oil Field, Ogemaw County, Michigan: Unpublished Master's Thesis, Michigan State University.

Trow, J. W., 1981, Personal Communication.

Walters, R. F., 1969, Contouring by Machine: A User's Guide: Amer. Assoc. Pet. Geol., v. 53, n. 11, pp. 2324-2340.

Werner, E., 1975, Long Lineaments of the Appalachians and their Geologic Relations: Geol. Soc. Amer. Abst. with Programs, v. 7, n. 4, p. 548.

_______, 1977, Photolineament Mapping in the Appalachian Plateau and Continental Interior Geological Provinces- A Case Study: Remote Sens. Earth Res., v. 5, pp. 403-417.

Withington, C. F. and Jacobeen, F. H., Jr., 1973, Possible Implication of Lineaments in the Atlantic Coastal Plain as seen by Satellite Imagery: Remote Sens. Earth Res., v. 2, pp. 981-996.