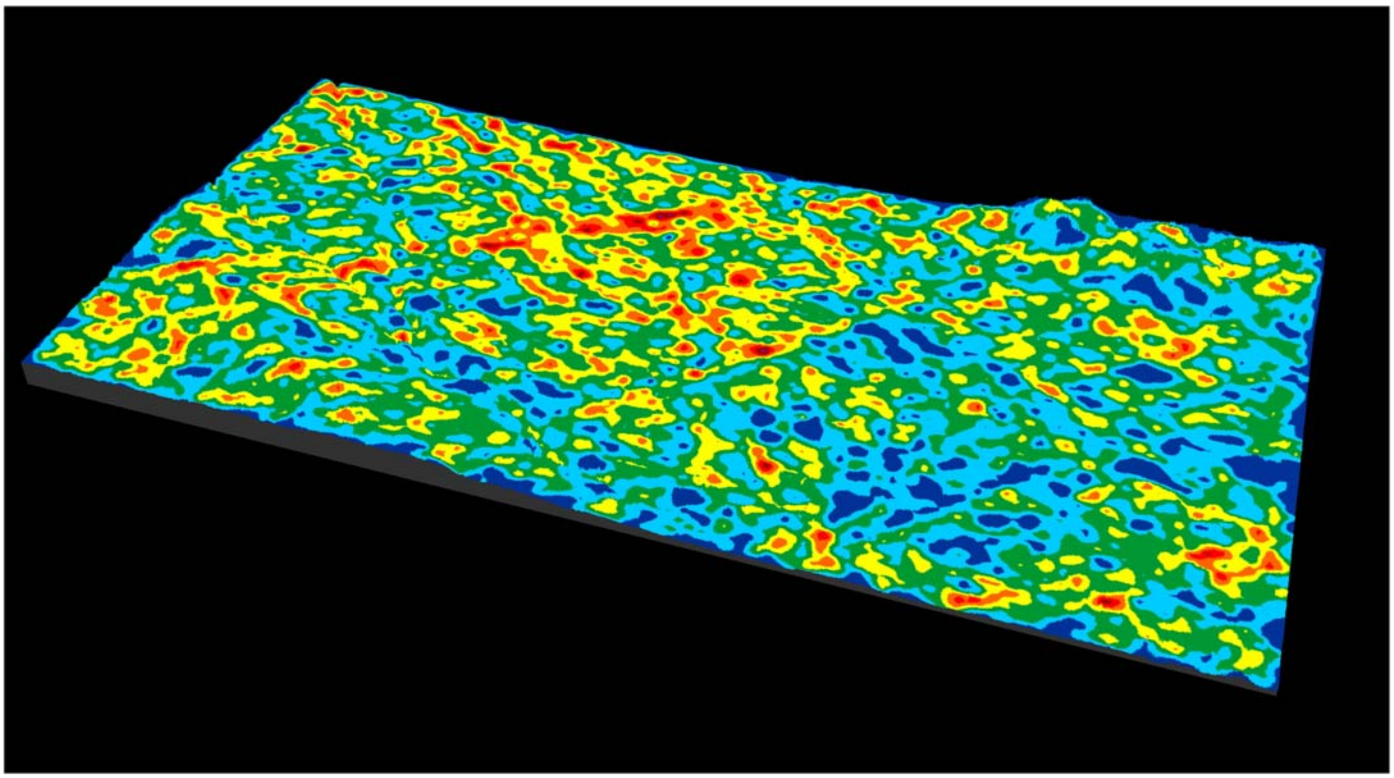
LINEAMENT MAPPING AND ANALYSIS IN THE NORTHEASTERN WILLISTON BASIN IN NORTH-CENTRAL NORTH DAKOTA

By

Fred J. Anderson



GEOLOGIC INVESTIGATIONS NO. 145
NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
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On the cover: Three-dimensional perspective view from the southeast towards the northwest across the Minot 1:250k sheet map area displaying the lineament density map created from this investigation overlain onto a digital elevation model of the land surface.

Abstract

A lineament mapping and analysis investigation of a 6,344 square mile area, located in the northeastern portion of the Williston Basin in north-central North Dakota, was conducted at a scale of 1:250,000 to potentially identify and characterize surficial lineaments and relate these features to areas of current and historical oil and gas exploration and production and to support future petroleum geologic investigations seeking to identify surface expression of deeper buried subsurface folds, faults, and stratigraphic structures that may influence the generation, migration, accumulation, and production of petroleum hydrocarbons. Lineaments were identified and mapped by successive visual and manual inspection at various scales, ranging from 1:24,000 to 1:1,000,000, from four sources: previous studies (historical lineaments), digital shaded relief data, aerial imagery, and LANDSAT-7 ETM+ data and imagery. Lineaments were mapped and characterized based on data source and further combined into a single compilation for overall characterization and analysis. The lineaments identified and analyzed in this investigation are the interpreted lineament features derived from the various imagery and mapping data sources and were not field verified. Dominant lineament trends were found in NW to SE and NE to SW orientations, generally consistent with previous lineament studies in the region and currently accepted knowledge of regional tectonic stress regimes and fracture development within the Williston Basin. The distributions of lineament line lengths follow generally lognormal relationships within each data source and in compilation. Qualitative spatial relationships between mapped lineaments and areas of current oil and gas production and development, were examined by visual comparison of mapped lineament intersection, lineament density via domain mapping, degree of lineament interconnectivity, the evaluation of preferred lineament directional trends, and overall lineament density. Evaluation of these relationships revealed several areas of generally higher lineament density in the northwestern and north-central portions of the map area that correspond with areas of current oil and gas production and field development. Areas with a high degree of overall lineament density and low degree of oil and gas exploration and development in the central and east-central portions of the map area were identified that may be favorable for future potential exploration. Further, producing wells appear to be located in areas of greater lineament development where non-producing wells appear distributed throughout areas of lesser lineament development.

Acknowledgements

The author would like to acknowledge the continued work of Mr. Elroy Kadrmas, GIS Specialist at the NDGS, for his contributions to cartographic design and overall support for spatial analysis and map production and Ms. Shannon Heinle, for her work in the compilation of previous lineament studies in the Williston Basin, while a graduate student at the University of North Dakota.

Author's Note

The continuing intent of this and other recently completed lineament investigations (Anderson, 2008 & 2011), is to combine information contained in previous lineament studies, with the results of larger scale contemporary lineament mapping investigations, in order to identify and evaluate relationships between mapped lineaments and current oil and gas production and development trends, and to support the identification of the surface expression of subsurface geologic structures that have the potential to influence the accumulation of petroleum hydrocarbons. As before, in order to maintain objectivity during the mapping of lineaments, the evaluation of the relationships between currently producing wells and current oil and gas field development and exploration trends were not conducted until after lineament mapping was completed.

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BACKGROUND

Introduction

Lineaments have been defined as extended mappable linear or curvilinear features of a surface whose parts align in straight or nearly straight relationships that may be the expression of folds, fractures, or faults in the subsurface (Sabins, 2000). These features are mappable at various scales, from local to continental, and can be utilized in minerals, oil and gas, and groundwater exploration studies. The NDGS recently completed a lineament mapping and analysis investigation of the area within the Minot 1:250k map sheet located in the northeastern Williston Basin in north-central North Dakota. This investigation was conducted in order to potentially identify any linear or linear-like surface features that may be linked to deeper, buried basinal and stratigraphic structures that may have an influence on the generation, migration, accumulation, and production of petroleum hydrocarbons. Lineaments mapped and analyzed in this study are the interpreted lineament features derived from the various imagery and mapping data sources and were not field verified.

Description of the Study Area

The area within the Minot 1:250k map sheet is within the standard 1:250,000 scale (1^o x 2^o) quadrangle that covers an approximate 6,344 square mile area from 48^o to 49^o N. Latitude and 100^o to 102^o W. Longitude. This quadrangle contains most of the lower Souris River Basin and contains all of the Souris River that is present in the U.S. as it traverses its way from the northwest to the southeast and back around and up toward the northwest again to the Canadian border. This 1:250k quadrangle study area is bounded to the north by the border with Canada, the west by the Williston 250k quadrangle, the east by the Devils Lake 1:250k quadrangle, and the south by the McClusky 1:250k quadrangle. Some of the larger oil fields found in the northwestern portion of the sheet include the Newburg, South Westhope, Glenburn, and Mouse River Park fields (Figure 1). The Eckman SE, Newburg SW, Deering, and Granville NW quadrangles are the four 1:24,000 scale (7.5’ series) quadrangles that are located at the center of the study area.

Previous Lineament Studies Conducted at Various Scales

Several continental to regional scale lineament studies have been completed by several authors over the last four decades at regional to continental scales (Figure 2) and include the works of: Penner and Cosford (2006), Gibson (1995), Brown and Brown, (1987), Downey, et. al. (1987), Gerhard, et. al. (1987), Oglesby (1987), Peterson and MacCray (1987), Anna (1986), Maughan and Perry (1986), Hayes (1984), Cooley (1983), Haman (1975), Kent (1974), Thomas (1974), and Erickson (1970), (Plate I).

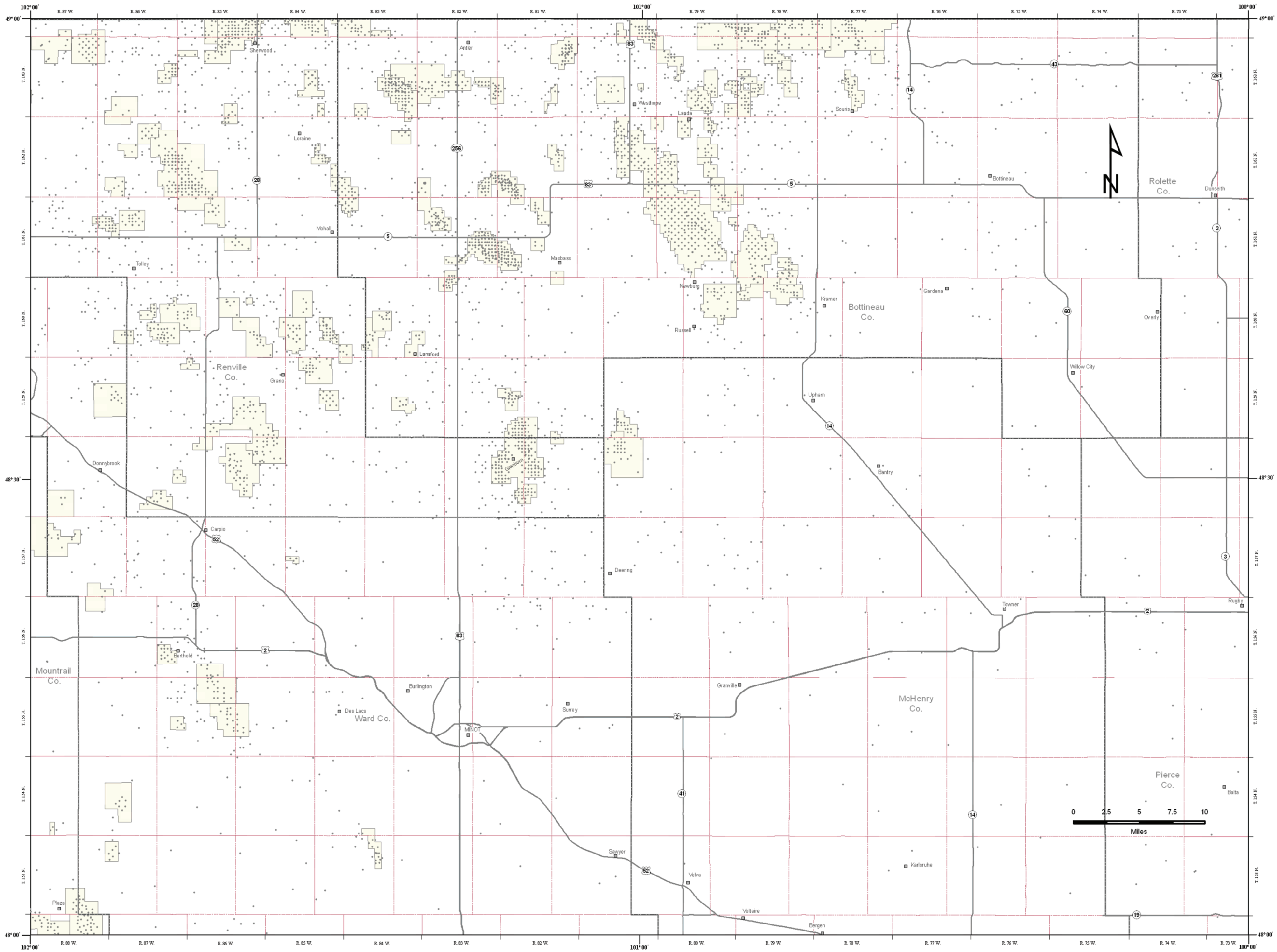


Figure 1. Area of investigation in Minot 1:250k map sheet located in the northeastern Williston Basin in north-central North Dakota. Locations of oil and gas fields are shown in yellow. Locations of oil and gas wells are shown in gray.

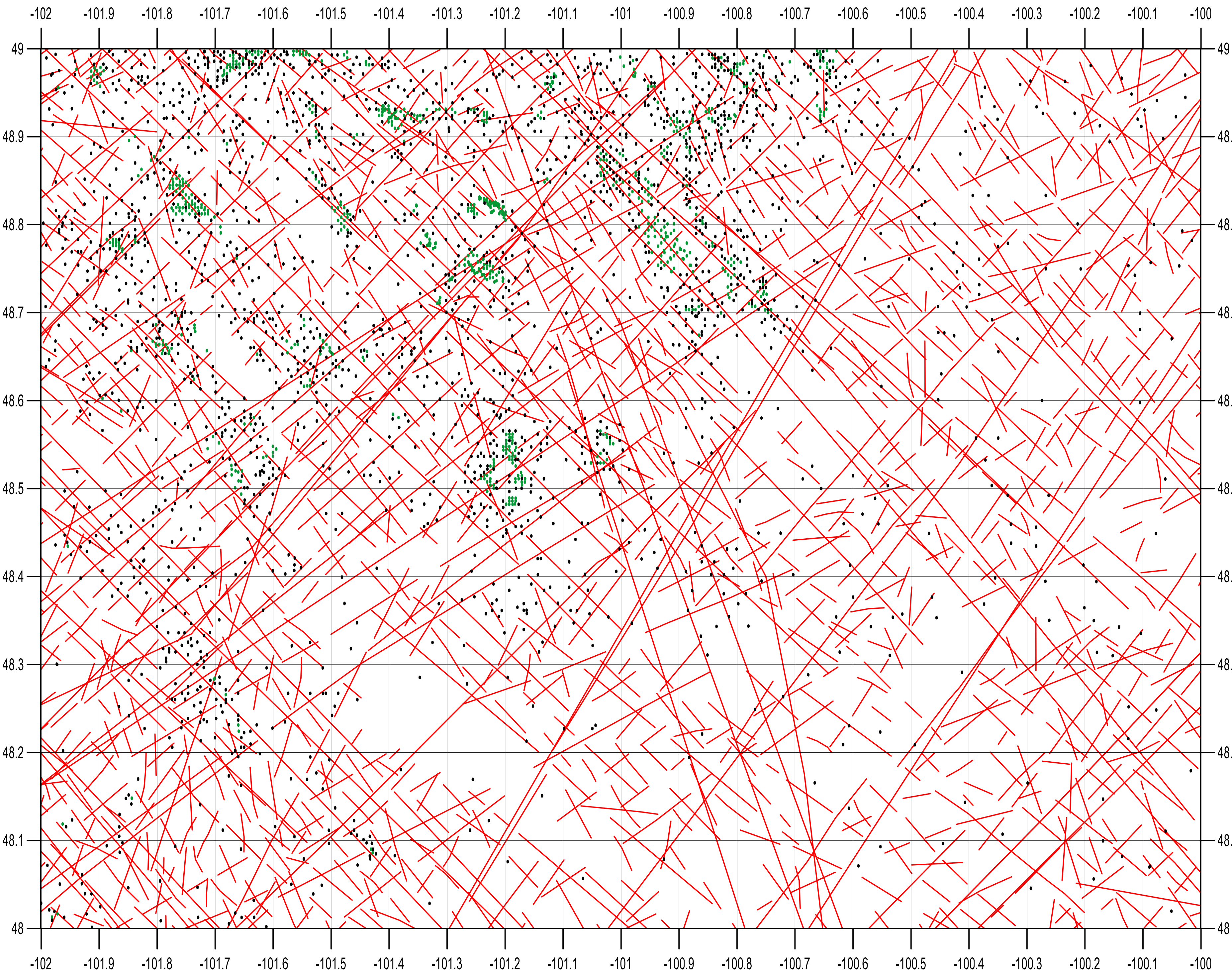


Figure 2. Historical (i.e. previously published) lineaments mapped in the Minot 1:250k sheet. Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

LINEAMENT MAPPING AND ANALYSIS METHODOLOGY

Description of Data and Imagery Sources

Lineaments in the Minot 1:250k map sheet were identified, and progressively derived from four primary data and imagery sources (Table 1): lineaments mapped from previous studies, lineaments mapped from digital shaded relief data, lineaments mapped from aerial imagery, and lineaments mapped from LANDSAT data and imagery. Images and data from the ambient thermal band (band 6) of the LANDSAT data suite, along with ASTER data, as a replacement, were also considered as a part of this investigation. However, limited availability of data covering the study area and the amount of cloud cover existing on available images negated their use.

Table 1. Summary of Data and Imagery Sources used for Lineament Mapping

Data Type	Original Data Creation/Acquisition	Description/Author	Data Source Location (URL address)
Historical Lineaments	1970 - 2006	Compiled from Various Published Sources	https://www.dmr.nd.gov/ndgs//
Shaded-Relief Data	1997	USGS National Elevation Dataset (NED)	http://ned.usgs.gov/
Aerial Imagery	Summer, 2010	National Agricultural Imagery Program (NAIP)	http://165.221.201.14/NAIP.html
Satellite Imagery Data	Summer, 2000	LANDSAT-7 ETM+	http://eros.usgs.gov/products/satellite/landsat7.php

Historical (Previously Published) Lineaments

Lineaments published in previous studies and determined to be present, as mapped in the Minot sheet (Figure 2), were digitally extracted from their original published sources (Heinle, 2007) as is, compiled, and merged into a single "historical" lineament coverage for the Minot 1:250k map sheet area (Plate I).

NED Shaded Relief Data

Lineaments were also mapped and digitized (Figure 3) from a digital, shaded-relief image created from 1997 USGS National Elevation Dataset (NED) data set, with a vertical exaggeration of 9X (Plate II).

National Agricultural Imaging Program (NAIP) Imagery

Imagery data sources were also utilized for lineament mapping in this investigation. Lineaments were interpreted from digital aerial imagery and digitized from a digital aerial image mosaic of the study area (Figure 4), compiled as is from 2010 USDA National Agricultural Image Program (NAIP) imagery (Plate III).

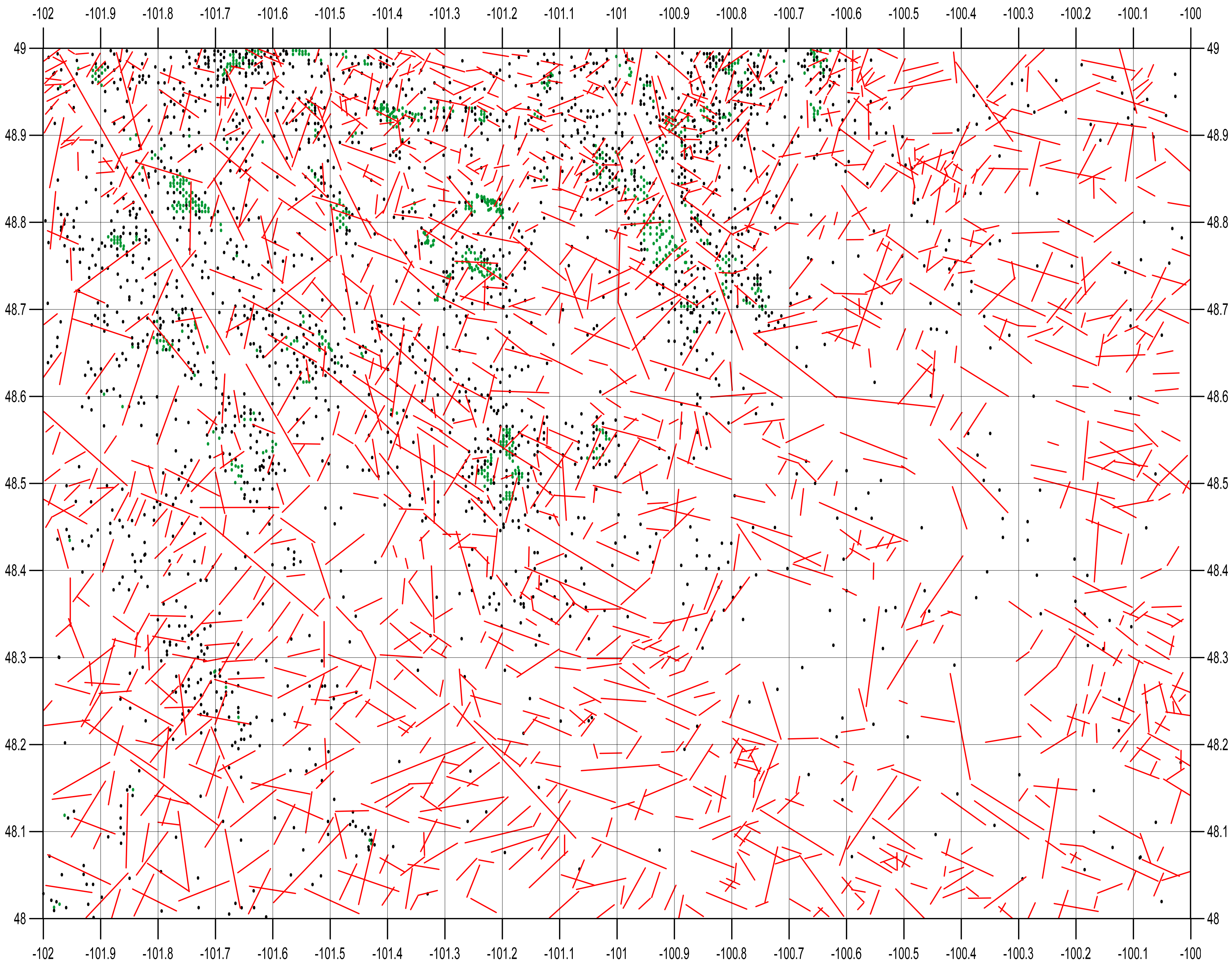


Figure 3. Lineaments mapped from USGS NED shaded relief data in the Minot 1:250k sheet. Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

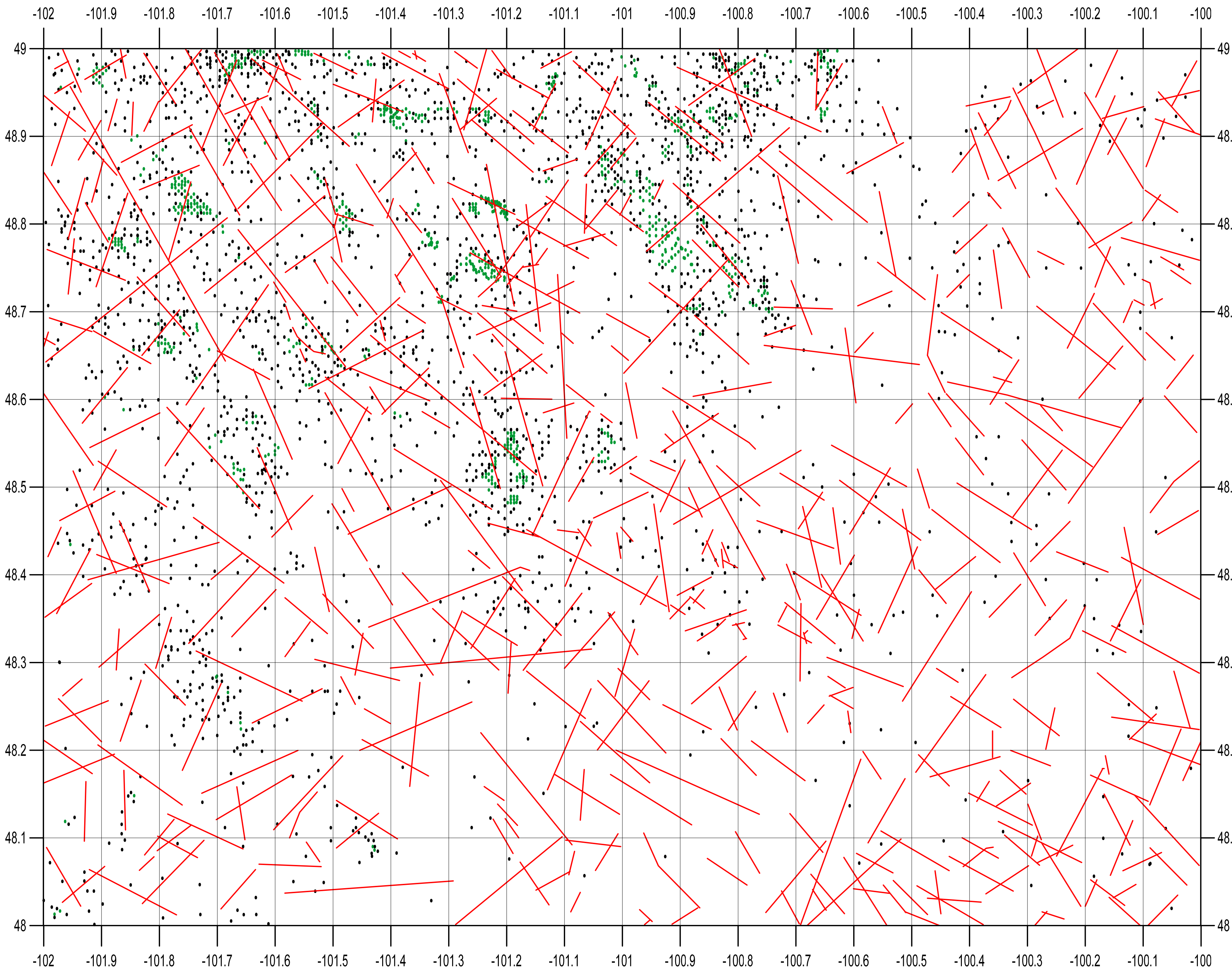


Figure 4. Lineaments mapped from 2010 USDA NAIP aerial imagery in the Minot 1:250k sheet. Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

LANDSAT-7 Enhanced Thematic Mapper (ETM) Imagery

In addition to the traditional data and image mapping sources, lineaments were also digitally mapped and digitized from a digital image mosaic compiled from 2000 LANDSAT-7 Enhanced Thematic Mapper Plus (ETM+) data (Figure 5). This digital image mosaic was created from four available scenes in a blue, green, red (BGR) false color combination of spectral bands 2, 4, and 7 for enhanced visual lineament mapping and analysis (Plate IV).

Merged (Compiled) Lineaments

All lineaments mapped from previously described data sources in this investigation, were combined into a single compilation (Figure 6) for an additional comprehensive characterization and analysis (Plate V).

Lineament Mapping and Analysis Methodology

Lineament identification and mapping was conducted by successive visual and manual inspection of each of the data and imagery layers at various scales (most commonly 1:24,000, 1:100,000, 1:250,000 and 1:1,000,000). Lineaments were identified and manually digitized on screen using the drawing and mapping tools in Surfer v. 9.0 and exported to ArcGIS for final digitizing, georeferencing, and ESRI shape file (.shp) creation. All lineaments mapped are presented at a scale of 1:250,000 in Plates I-V. Individual lineament orientations were analyzed for directional trends in RockWorks using the rose diagrams tool in the utilities module. Full rose diagrams were created from the lineaments mapped from each data source (i.e. LANDSAT, shaded relief, etc.) and presented as directional trends on 10^{o} orientation intervals (Figure 7). Individual lineament line lengths were also statistically analyzed and plotted on frequency distributions of lineament length per lineament length class for each of the data sources (Figure 8) that best characterized the data. The qualitative relationships between mapped lineaments and current oil and gas production from wells in the Minot sheet was also explored by comparing the spatial relationships of mapped lineament intersections (Plate I-Figure 4), lineament density via domain mapping (Plate II-Figure 4), degree of lineament interconnectivity (Plate III-Figure 4), evaluation of “preferred” lineament directional trends (Plate IV-Figure 4), and overall lineament density (Plate V-Figure 4). The locations of currently producing and non-producing oil and gas wells were also included in each of these qualitative comparisons in order to identify any observable potential spatial relationships.

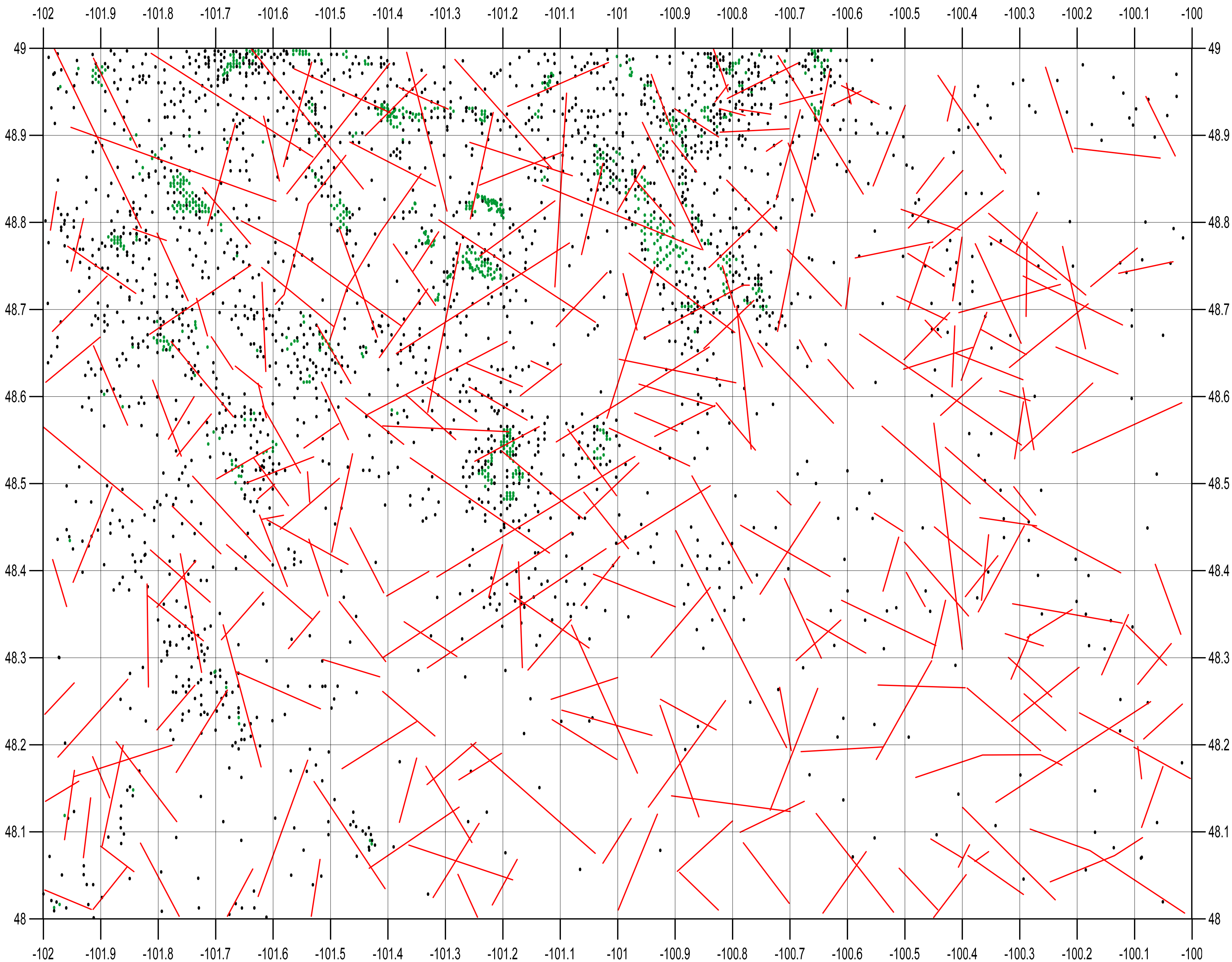


Figure 5. Lineaments mapped from 2000 LANDSAT-7 ETM+ data (bands 2, 4, and 7) in the Minot 1:250k sheet. Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

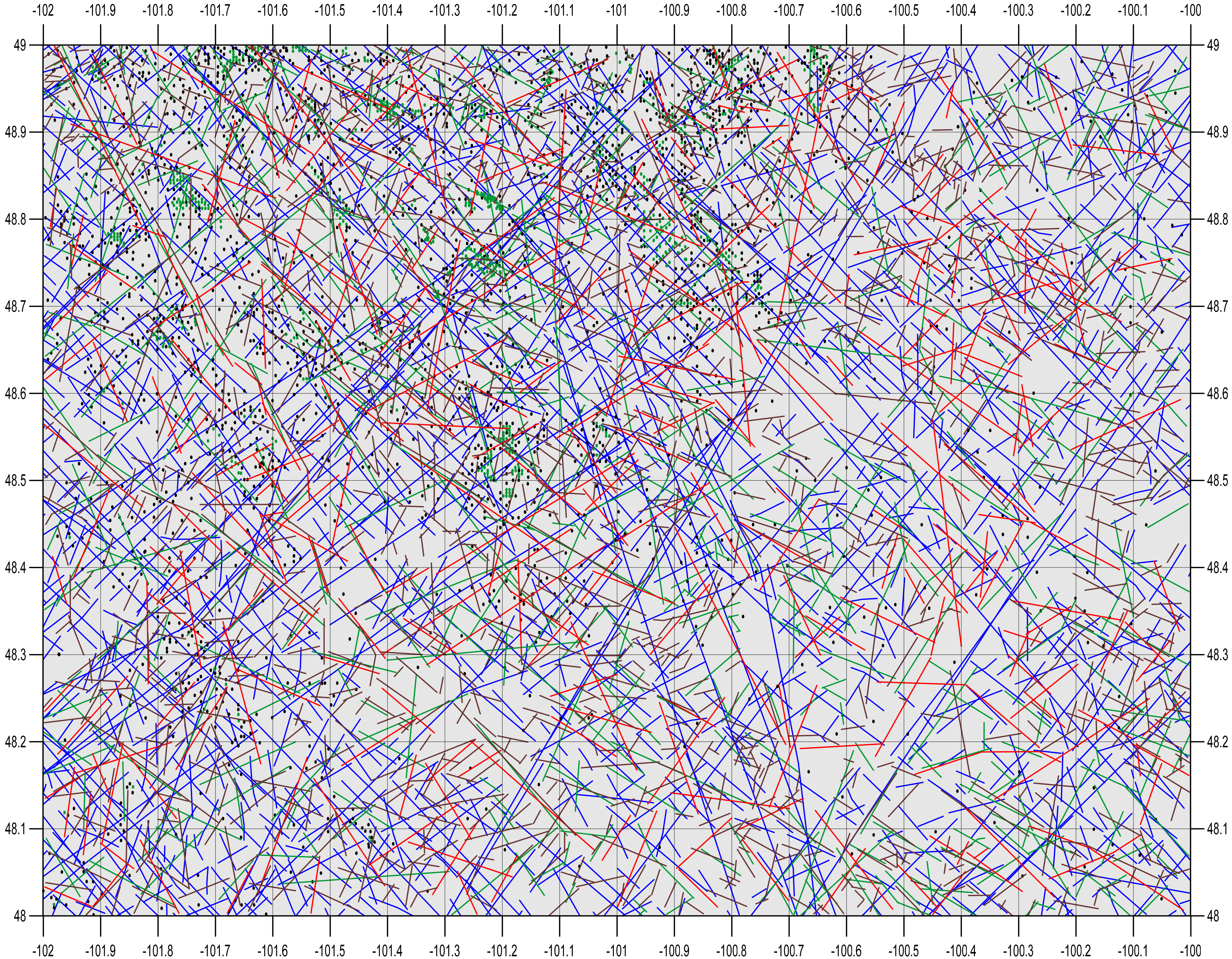


Figure 6. Compilation of lineaments mapped in the Minot 1:250k sheet. Historical lineaments (blue), lineaments mapped from shaded relief data (brown), NAIP imagery (green), and LANDSAT-7 ETM+ data (red). Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

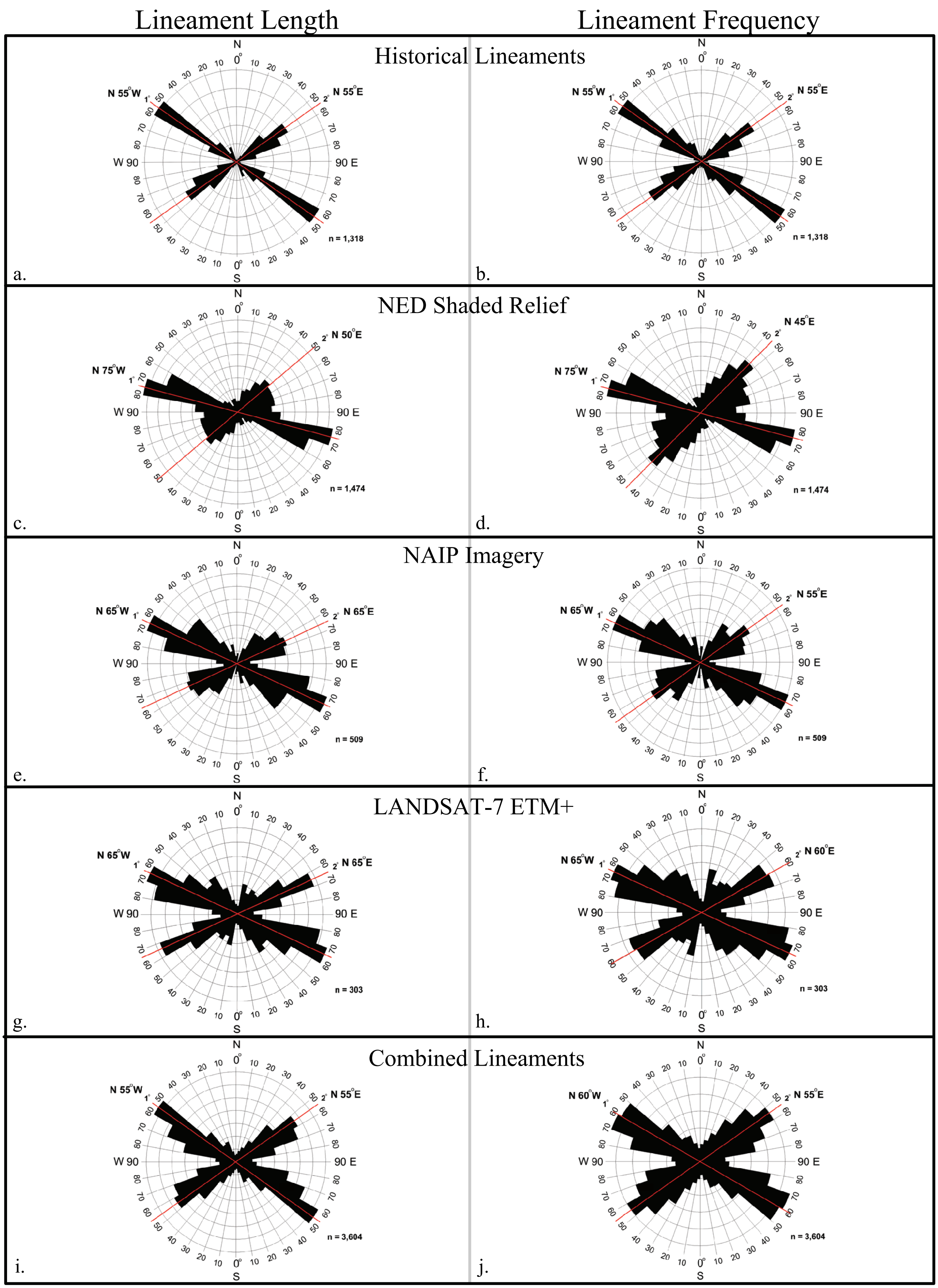
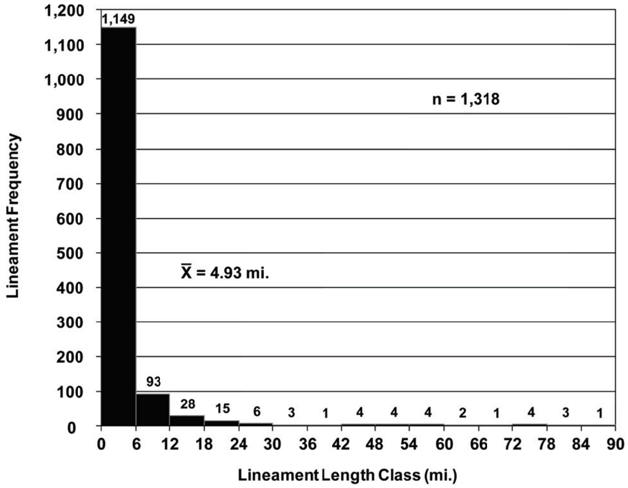
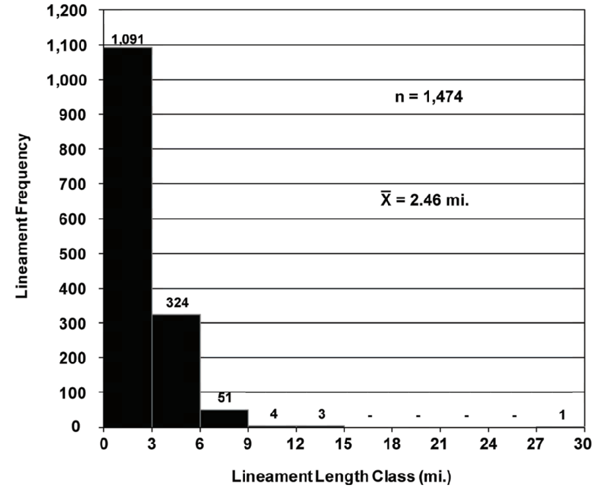


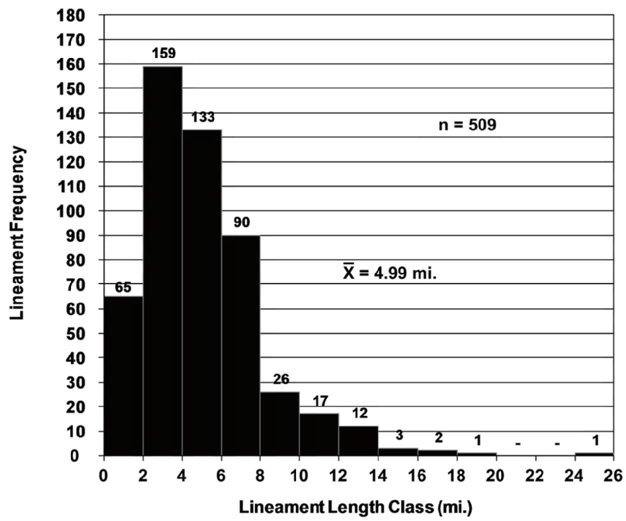
Figure 7. Summary of rose diagrams depicting dominant lineament orientation trends in each set of mapped lineaments, based on data/image source (a.- j.). Strike trends of compiled lineaments (i. & j.) show trends extracted from all mapped lineaments combined.



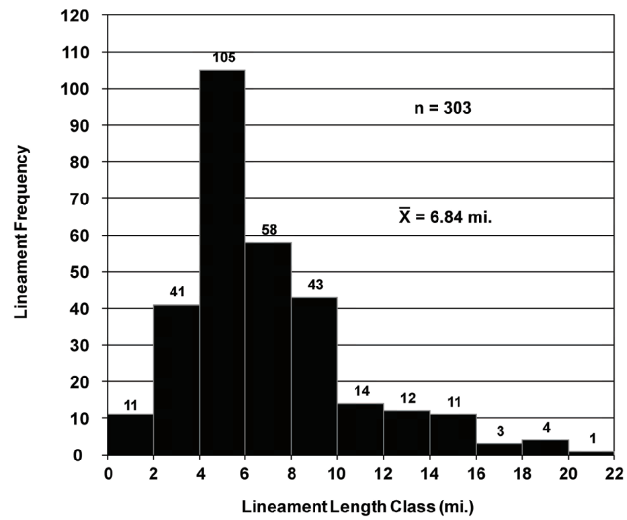
a. Distribution of lineaments mapped from historical data.



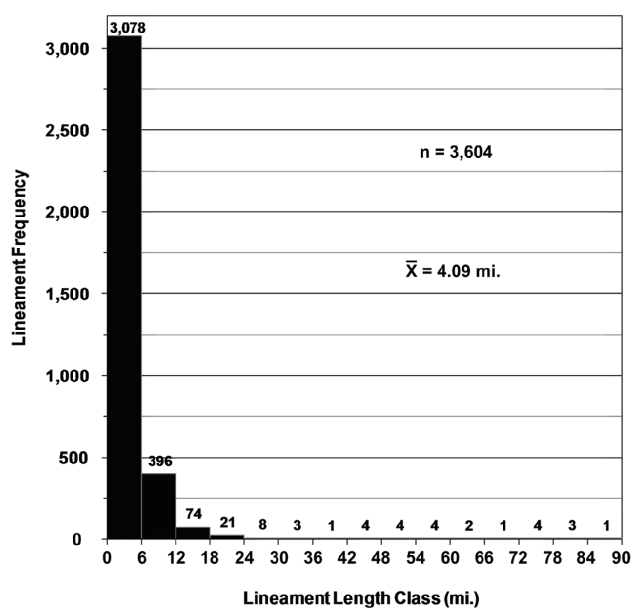
b. Distribution of lineaments mapped from shaded relief data.



c. Distribution of lineaments mapped from NAIP imagery.



d. Distribution of lineaments mapped from LANDSAT imagery.



e. Distribution of lineaments mapped from combined data.

Figure 8 (a-e). Frequency distributions of mapped lineaments per data and image source. All of the lineaments sets mapped follow generally lognormal distributions.

Lineament Density Mapping

Compiled lineaments (Figure 6 & Plate V) were merged into a 1 mile (5,280-ft) by 1 mile grid that corresponds to the actual Public Land Survey System (PLSS) sections found within the map area. Lineament densities were calculated for each section or "cell" using the sum of lineament(s) lengths contained within each unit section.

Nodes were determined at the center points of each of the sections in ArcGIS for extraction of geographic coordinates and data file assignment of corresponding lineament density values.

The resulting X,Y,Z data file was taken in to Surfer v. 9.0 for density mapping and contouring (Figure 9) using an ordinary kriging interpolation algorithm. The interpolated density contours were exported from Surfer as shape files (.shp, etc.) and imported back into ArcGIS for final compilation of spatially correct projected mapping (Plate VI). The resulting density map shows several areas of generally higher lineament density in the northwestern portion of the map area that generally corresponds to areas of current oil and gas production and field development. Density mapping also shows some areas in the eastern portion of the map area with a high degree of overall lineament density and low degree of oil and gas exploration and development as evidenced by sparse drilling in these areas (Figure 10). These areas may be favorable for future potential exploration in the Minot sheet.

3D visualization of lineaments mapped in the Minot 1:250k sheet and interpolated lineament densities draped over a digital elevation model of the map area, created from the USGS NED, provides an enhanced view of the relationships between the occurrence of lineaments and areas of relatively higher lineament density and existing oil and gas fields (Figures 2 & 3, Plate VII).

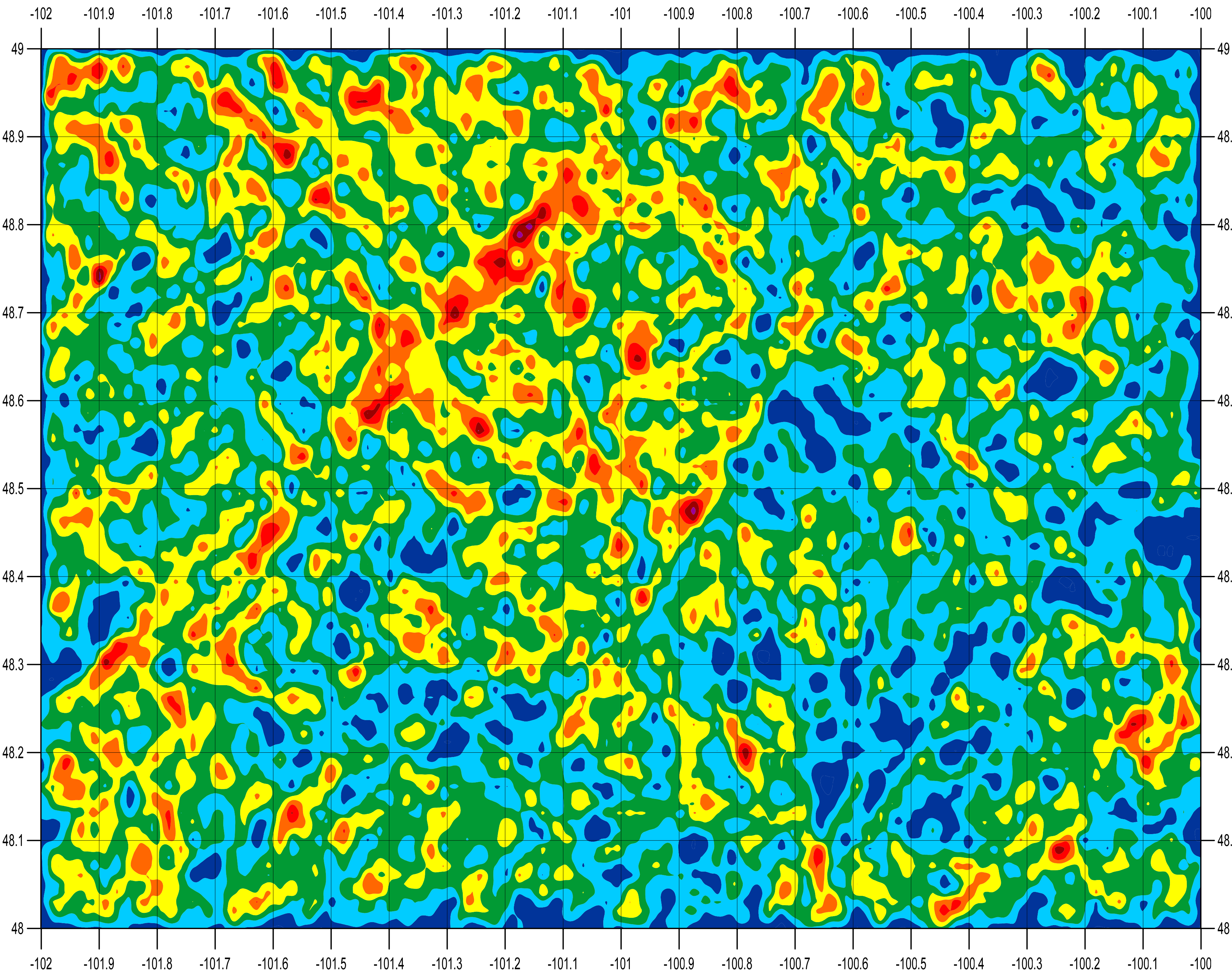


Figure 9. Lineament density map of the Minot 1:250k sheet located in the northeastern Williston Basin in north-central North Dakota. Increasing lineament density per unit area (i.e. length of lineaments within each square mile unit section) is depicted across eight intervals: 0-5,000 feet (dark blue), 5,000-10,000 (pale blue), 10,000-15,000 (green), 15,000-20,000 (yellow), 20,000-25,000 (orange), 25,000-30,000 (red), 30,000-35,000 (dark red), and 35,000 - >40,000 (purple).

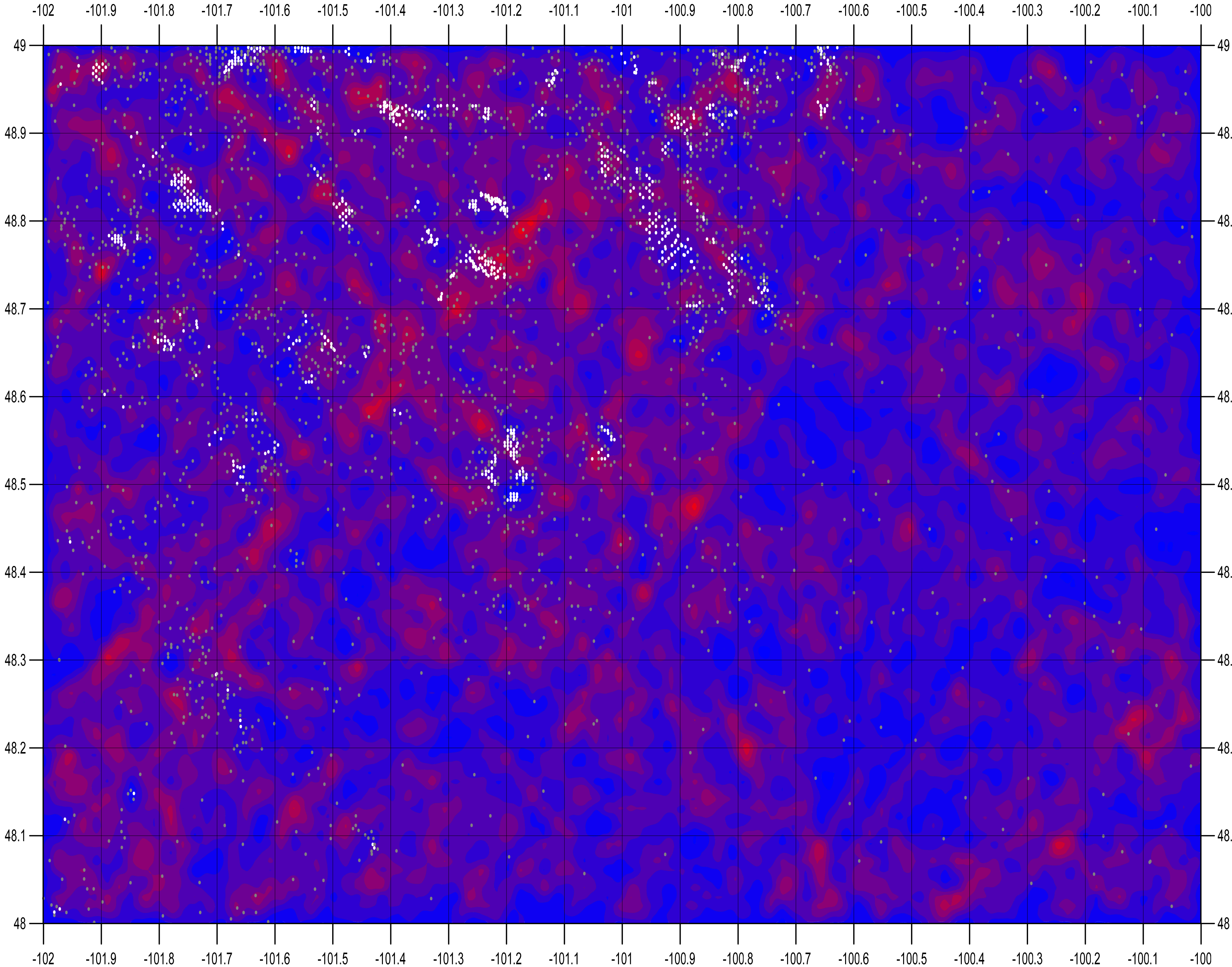


Figure 10. Lineament density map of the Minot 1:250k sheet located in the northeastern Williston Basin in north-central North Dakota. Areas of higher relative lineament density are shown as warmer (reds) colors. Areas of lower relative lineament density are shown as cooler (blues) colors. The locations of currently producing wells (white) and non-producing wells (gray) are shown.

RESULTS AND CONCLUSIONS

Lineament Orientations

Lineament orientations based on the contributions of lineament line length and frequency components to the orientation trends (Figure 7) are dominantly found in orthogonal NE to SW and NW to SE orientations (Table 2) consistent with previous lineament studies in the region and currently accepted knowledge of regional tectonic stress regimes and fracture development in the Williston Basin of North Dakota (Besler, 2008).

Table 2. Lineament Orientation Trends Determined within Individual Data Sources

Data Type	No. of Trends	Orientation Description			Basic Relationship
		1^{o}	2^{o}	3^{o}	
Historical Lineaments	2	N 55^{o} W	N 55^{o} E	--	1^{o} and 2^{o} trends Conjugate.
NED Shaded-Relief Data	2	N 75^{o} W	N 50^{o} E	--	1^{o} and 2^{o} trends Conjugate.
2003 NAIPAerial Imagery	2	N 65^{o} W	N 60^{o} E	--	1^{o} and 2^{o} trends Conjugate.
2002 LANDSAT-7 ETM+ Satellite Imagery Data	2	N 65^{o} W	N 60^{o} E	--	1^{o} and 2^{o} trends Conjugate.
Combined\Merged Lineaments	2	N 55^{o} W	N 55^{o} E	--	1^{o} and 2^{o} trends Conjugate.

[1]Trends determined and summarized from lineament length and frequency based methods.

A primary (1^{o}) trend of N 55^{o} W along with a conjugate (as measured against the regional tectonic NE-SW maximum stress direction) secondary (2^{o}) trend of N 55^{o} E were identified (Figure 7a & b) within the historical lineaments mapped (Plate I-Figure 2) and are consistent with most continental to regional scale lineament mapping studies completed over the last 40 years.

These orientations are heavily influenced numerically by the inclusion of the LANDSAT lineaments mapped by Cooley (1983) which contained a strong NW-NE orthogonal trend as well as a relatively high number of smaller length lineaments. Removing the Cooley (1983) data from the analysis, in this instance, would not likely reorient the dominant directional trends.

Within the shaded relief data two directional trends were found within the lineaments mapped (Figure 7c & d). A 1^{o} trend of N 75^{o} W along with conjugate 2^{o} trend of N 50^{o} E was found (Plate II-Figure 2).

Since it has been found that is possible to map a greater amount of lineaments from shaded relief data and imagery (Penner and Cosford, 2006), due to the high resolution of surface features and geomorphological influence inherent in the data, it is not surprising that additional trends are revealed that may be indicative of surficial geomorphological influence related to Pleistocene glaciation in the region and subsequent drainage development (Lemke, 1960).

Lineaments mapped from the 2010 NAIP aerial imagery also exhibited two dominant directional trends (Figure 7e & f). A 1^o trend of N 65^o W along with a conjugate 2^o trend of N 60^o E was found (Plate III-Figure 2). Lineament mapping from this image and data source was found to continue to be somewhat challenging as land use in the region results in less natural tonal contrast and variation across relatively larger land areas, which has an overall homogenization effect on individual pixel contrast (Plate III-Figure 1).

Mapping of lineaments from LANDSAT derived satellite imagery afforded a different look at the aerial image data and also revealed two dominant orientation trends within the lineaments mapped (Figure 7g & h). A 1^o trend of N 65^o W along with a conjugate 2^o trend of N 60^o E was revealed (Plate IV-Figure 2). A significantly less prominent 3^o trend around N 15^o W, nearly orthogonal to the 1^o trend could also be interpreted to exist within the data. It is likely that the 2-4-7 (BGR) band combination simply accentuated the tonal contrasts associated with these lineaments, which permitted a more discernable tonal expression (Plate IV-Figure 1).

Combining all of the lineament directional data into one set and analyzing it for orientation trends resulted in the recognition and strengthening of the two dominant NW-SE and NE-SW orientations (Figure 7i & j) found within the individually mapped data sources. A 1^o trend of N 55^o W along with a conjugate 2^o trend of N 55^o E was found (Plate V-Figure 2). It is apparent that the approximate 1^o and 2^o orientation trends within the historical lineaments data set are strengthened by additional lineament mapping from other data and imagery sources. The 3^o trend identified from the lineaments mapped from LANDSAT (Plate IV-Figure 2) imagery disappears when merged into the compiled lineament data set.

Distribution of Lineament Lengths

The descriptions of lineament line lengths mapped (Table 3) are consistent with statistically valid distributions commonly found in lineament mapping studies and generally follow log-normal type distributions (Figure 8).

Table 3. Characteristics of Lineaments Mapped in the Minot 1:250k sheet.

Data Type	No.	Lineament Length Characteristics (miles)				Lineament Density (Lpsm/Lpst)
		Min	Max	Mean	1 Std. Dev.	
Historical Lineaments	1,318	0.12	84.15	4.93	8.71	0.21/7.5
NED Shaded-Relief Data	1,474	0.39	27.37	2.46	1.72	0.23/8.3
2009 NAIP Aerial Imagery	509	0.28	24.85	5.00	3.05	0.08/2.9
2000 LANDSAT-7 ETM+ Satellite Imagery Data	303	1.35	21.08	6.85	3.59	0.05/1.7
Merged\Combined Lineaments	3,604	0.12	84.15	4.09	5.78	0.57/20.4

(Lpsm/Lpst): Lineaments per square mile/Lineaments per standard township (36 mi^2).

A total of 1,318 lineaments were mapped in the Minot 1:250k sheet as compiled from previous works (Figure 2). Lineament lengths tend to follow a lognormal distribution (Figure 8a) with the majority of lineaments falling within the 0 to 12 mi. lineament length class. Minimum lineament length was 0.12 miles (mi.) with a maximum length of 84.15 mi. The mean lineament length was 4.93 mi. with a standard deviation of 8.71 mi. Lineament density across the entire 1:250k map sheet area of investigation was 0.21 lineaments per square mile (Lpsm) which translates to approximately 7.5 lineaments per township (i.e. 36 square miles).

A total of 1,474 lineaments were mapped in the Minot 1:250k sheet as mapped from shaded relief data (Figure 3), considerably less than previous studies in the Parshall and Dickinson areas, which is reflective of the modifying influence of Pleistocene glaciation on the landscape. Lineament lengths in this data set also tended to follow a lognormal distribution (Figure 8b) with the majority of lineaments falling within the 0 to 6 mi. lineament length class. Minimum lineament length was 0.39 mi. with a maximum length of 27.37 mi. The mean lineament length was 2.46 mi. with a standard deviation of 1.72 mi. Lineament density across the entire 1:250k area was 0.23 Lpsm which translates to approximately 8.3 lineaments per township (Lpst).

A total of 509 lineaments were mapped in the Minot 1:250k sheet as mapped from NAIP aerial imagery (Figure 4). Lineament lengths in this data set also tend to follow a lognormal distribution (Figure 8c) with the majority of lineament lengths falling within the 2 to 8 mi. lineament length class. Minimum lineament length was 0.28 mi. with a maximum length of 24.85 mi.

The mean lineament length was 5.00 mi. with a standard deviation of 3.05 mi. Lineament density across the entire 1:250k area was 0.08 Lpsm which translates to approximately 2.9 Lpst.

A total of 303 lineaments were mapped in the Minot Area as mapped from LANDSAT-7 ETM+ data and imagery (Figure 5). Lineament lengths in this data set also follow a lognormal distribution (Figure 8d) with the majority of lineament lengths also falling within the 2 to 10 mi. lineament length class. Minimum lineament length was 1.35 mi. with a maximum length of 21.08 mi. The mean lineament length was 6.85 mi. with a standard deviation of 3.59 mi. Lineament density across the entire 1:250k map sheet was 0.05 Lpsm which translates to approximately 1.7 Lpst. The data characteristics of lineaments mapped from both the NAIP and LANDSAT data are similar and suggest a scale effect for the identification of lineaments mapped at the 1:250,000 scale.

A total of 3,604 lineaments were mapped in the Minot 1:250k sheet as compiled from all data and imagery sources (Figure 6) used. Lineament lengths continue to follow a lognormal distribution (Figure 8e) with the majority of lineament lengths falling well within the 0 to 12 mi. lineament length classes. Minimum lineament length was 0.12 mi., with a maximum length of 84.15 mi. The mean lineament length was 4.09 mi. with a standard deviation of 5.78 mi. Lineament density across the entire 1:250k map area was 0.57 Lpsm which translates to approximately 20.4 Lpst.

Lineament Density Mapping

Lineament densities were calculated for each square mile within the area of investigation as the sum of the lineament line lengths occurring within each unit grid cell (i.e., $\Sigma L_1 + L_2 + L_3 ....$). Each unit cell was assigned a nodal value at the cell center in true geographic coordinates. The data was interpolated using an ordinary kriging algorithm and contoured over nine lineament density classes (Figure 9). The resulting lineament density map shows increased lineament density dominantly towards the northwest with lessening lineament density moving towards the south and east.

The total area covered by the Minot 1:250k map sheet is 6,344 square miles. Of this total, the largest Lineament Density Area (LDA) is the Class-VII LDA (sky blue) which is dispersed throughout the entire map area (Table 4) but is more common in the eastern portion of the map area. The Class-V (yellow) to Class-I LDAs (purple) are highly visually correlative to currently producing oil and gas wells. The Class-VI (green) to Class-VIII (dark blue) LDAs are conversely highly visually correlative to non-producers (Plate VI).

Table 4. Map Surface Area Covered by Lineament Density Class

Lineament Density Class	Lineament Density Range (Lpsm)	Map Area Covered (mi^2)
Class-I	6.6 – 7.6	0.62
Class-II	5.7 – 6.6	8
Class-III	4.7 – 5.7	67
Class-IV	3.8 – 4.7	386
Class-V	2.8 – 3.8	1324
Class-VI	1.9 – 2.8	2,348
Class-VII	0.95 – 1.9	1,733
Class-VIII	0 – 0.95	478
		Total = 6,344

(Lpsm): Total of all lineament lengths (mi) per square mile (mi^2).

Overlaying the interpolated lineament density map with current producing and non-producing oil and gas wells in the area (Figure 10) shows a fair qualitative correlation between areas of producing wells and areas of high lineament density, particularly in the northwestern portion of the map area. There are some areas where producers are clearly located in areas of lower relative lineament density, which may be explained by wells be within a defined reservoir "block", bounded by structure. It does become more visually apparent, as one moves towards the southeast, that the distribution of non-producing wells tend to be scattered throughout areas of relatively low lineament density.

DISCUSSION

Consistent with previous lineaments studies in the region (e.g., Penner and Cosford, 2006) it was found that it continues to be possible to map a considerably greater number of lineaments from shaded relief data than other data sources due to the resolution and refinement of detail at mappable scales. Conversely, unique lineament expression was found within each data source used in mapping which added to the complexity of the overall mapped interpretation and enhanced the comprehensive nature of the data coverage. Generally and qualitatively, it appears that wells that have produced oil and gas appear to be located in areas of greater lineament density (Figure 11); particularly when lineament density is determined as the total *length* of lineaments found to occur within each unit cell or section, which further results in a higher amount of lineament intersection and connectivity. Non-producing wells were generally found to be disbursed throughout areas of lesser lineament density. Further quantitative investigation into this relationship will follow this work.

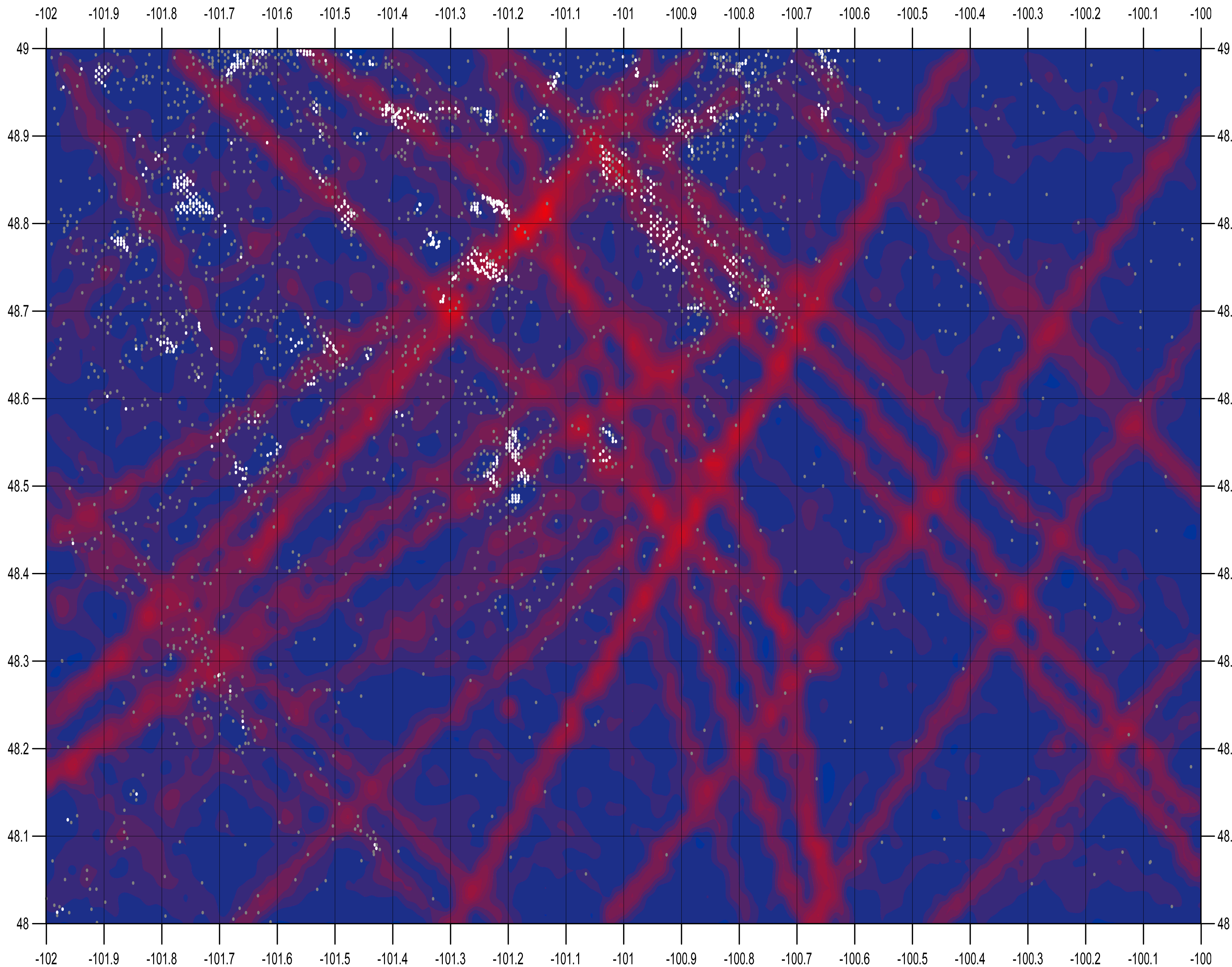


Figure 11. Lineament length-based density map of the Minot 1:250k sheet located in the northeastern Williston Basin in north-central North Dakota. Areas of higher relative lineament density are shown as warmer (reds) colors. Areas of lower relative lineament density are shown as cooler (blues) colors. The locations of currently producing wells (white) and non-producing wells (gray) are shown.

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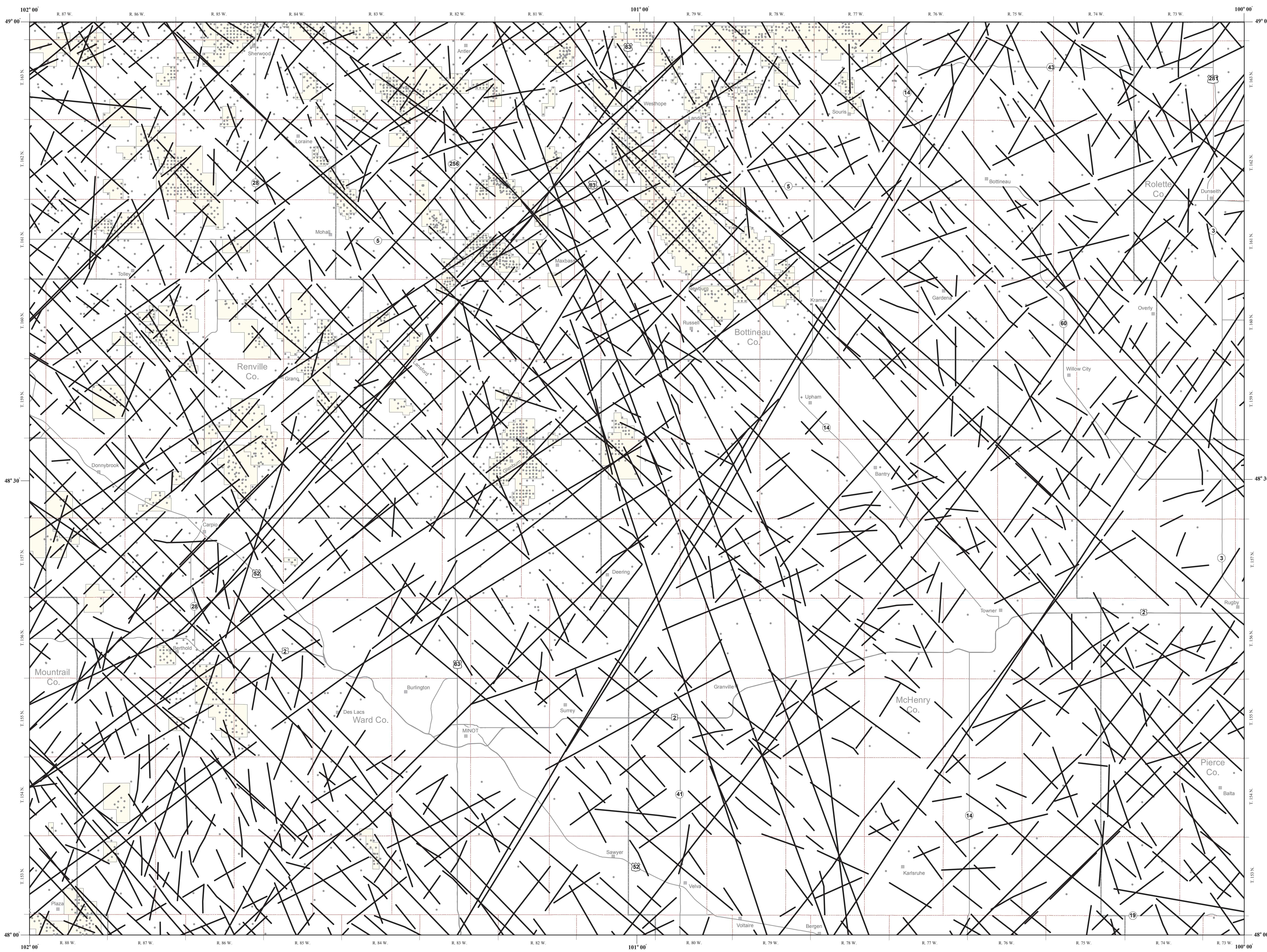
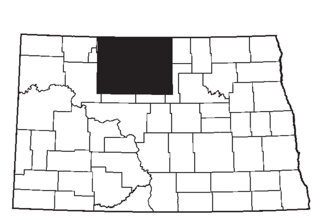
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE I - HISTORICAL LINEAMENTS MAPPED IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

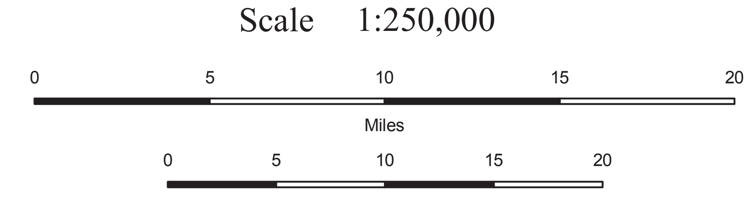
2011





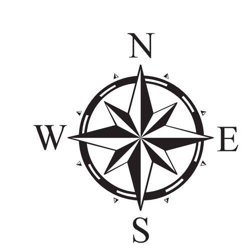
Minot 250K Sheet, North Dakota

Scale 1:250,000



Mercator Projection
Standard parallel 48° 00′

1927 North American Datum
Central meridian 101° 00′



HISTORICAL LINEAMENTS IN THE MINOT 1:250K SHEET COMPILIED AND MERGED FROM PREVIOUS STUDIES

This map presents the results of a segment of a contemporary lineament mapping investigation for the Minot 250k sheet. The Minot 250k sheet is located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineaments mapped from previous studies (i.e., historical lineaments) by several authors over the last four decades, include: Penner and Cosford, 2006, Gibson, 1995, Brown and Brown, 1987, Downey, et. al., 1987, Gerhard, et. al., 1987, Oglesby, 1987, Peterson and MacCray, 1987, Anna, 1986, Maughan and Perry, 1986, Hayes, 1984, Cooley, 1983, Kent, 1974, Thomas, 1974, and Erickson, 1970, (Figure 1).These lineaments were digitally extracted from a compilation of original published sources (Heinle, 2007), compiled, and merged into a single historical lineament coverage for the Minot 250k sheet (Figure 1). Previously mapped lineament centerline traces are presented here at a scale of 1:250,000, independent of their original mapped scales. Lineament directional analysis of the strike of 1,318 individual lineaments in this compliation reveals two distinct trends; a primary (1°) orientation of N 55° W (S 55° E) and a secondary (2°) orientation of N 55° E (S 55° W) (Figure 2). The distribution of lineament lengths follow a general log-normal distribution with the majority of lineaments (87%) falling within the zero to six mile lineament length range. Over 98% of the lineaments mapped were less than 30 miles in length (Figure 3). The overall density of lineaments within the sheet (i.e. lineaments mapped per unit area) is 0.21 lineaments per square mile, approximately 7.5 lineaments per township. Lineament density is generally greater in the northeastern portion of the study area, but overall is relatively uniform in character, particularly for shorter lineaments. This may be partially attributed to scale factors, as most of these lineaments were originally mapped at much smaller scales (e.g., 1:1,000,000 or greater). On this map, several of the lineaments are coincident with areas of current oil and gas field development and current exploration and production trends, particularly in eastern Renville and western Bottineau County. Lineaments mapped are likely influenced by subsurface geological (i.e., basement faulting) and surface geomorphological conditions resultant from Pleistocene glaciation. Lineament intersections are also shown (Figure 4) as an example of a variation of lineament density and are generally coincident with currently producing and developing oil and gas fields. Areas with a higher relative lineament intersection density, and a corresponding small drilling exploration footprint, include most of the area within the southern half and eastern third of the sheet. Several fields have several lineaments occurring within the field boundries, which may provide hints to deeper structure.

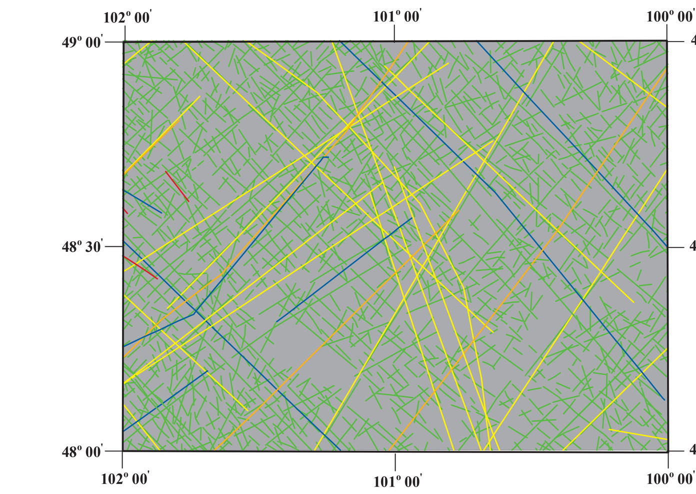
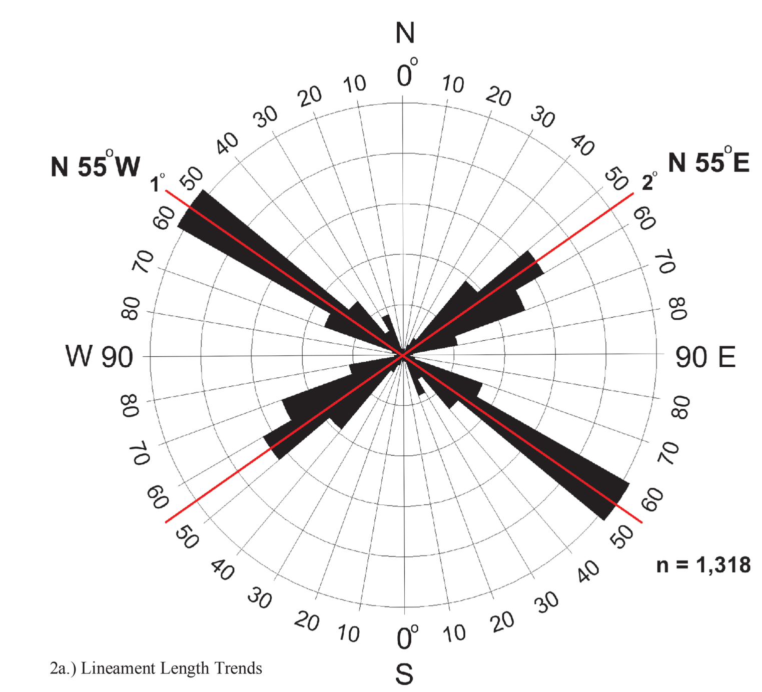
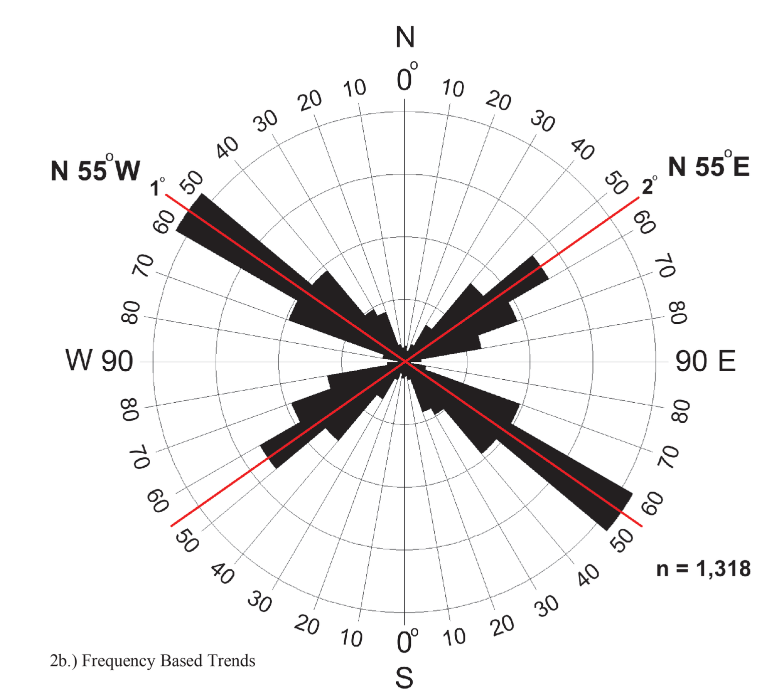


Figure 1. Index map of historical (i.e. previously published) lineaments, grouped by color by the decade in which they were mapped, in the Minot 1:250k sheet in the northeastern portion of the Williston Basin in north central North Dakota. Lineaments by Penner and Cosford, 2006 are shown in red, Gibson, 1995, in orange, Brown and Brown, 1987, Downey, et. al., 1987, Gerhard, et. al., 1987, Oglesby, 1987, and Peterson and MacCray, 1987 in yellow, Anna, 1986, Maughan and Perry, 1986, Hayes, 1984, and Cooley, 1983 in green, and Kent, 1974, Thomas, 1974, and Erickson, 1970 in blue.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 1,318 individual lineament orientations mapped from previous lineament studies in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. The two dominant lineament orientations(1° and 2°), are N 55° W (S 55° E), and N 55° E (S 55° W) based on orientational analysis of lineament length (2a) and lineament frequency (2b).

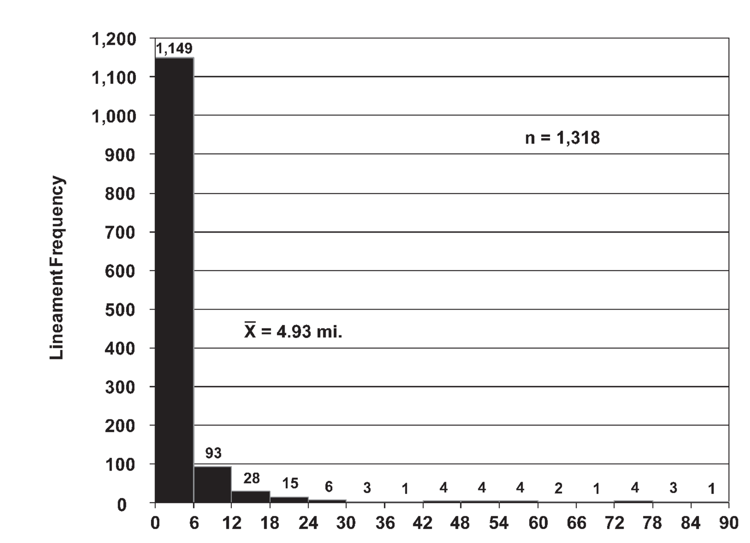


Figure 3. Frequency distribution of 1,318 individual lineament lengths from previously mapped lineaments in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for fifteen lineament length classes from zero to 90 miles in six mile intervals or classes. This distribution is heavily influenced by the inclusion of the Cooley (1983) LANDSAT derived lineaments as a part of this compilation, as the majority of lineaments mapped were less than 20 miles in length.

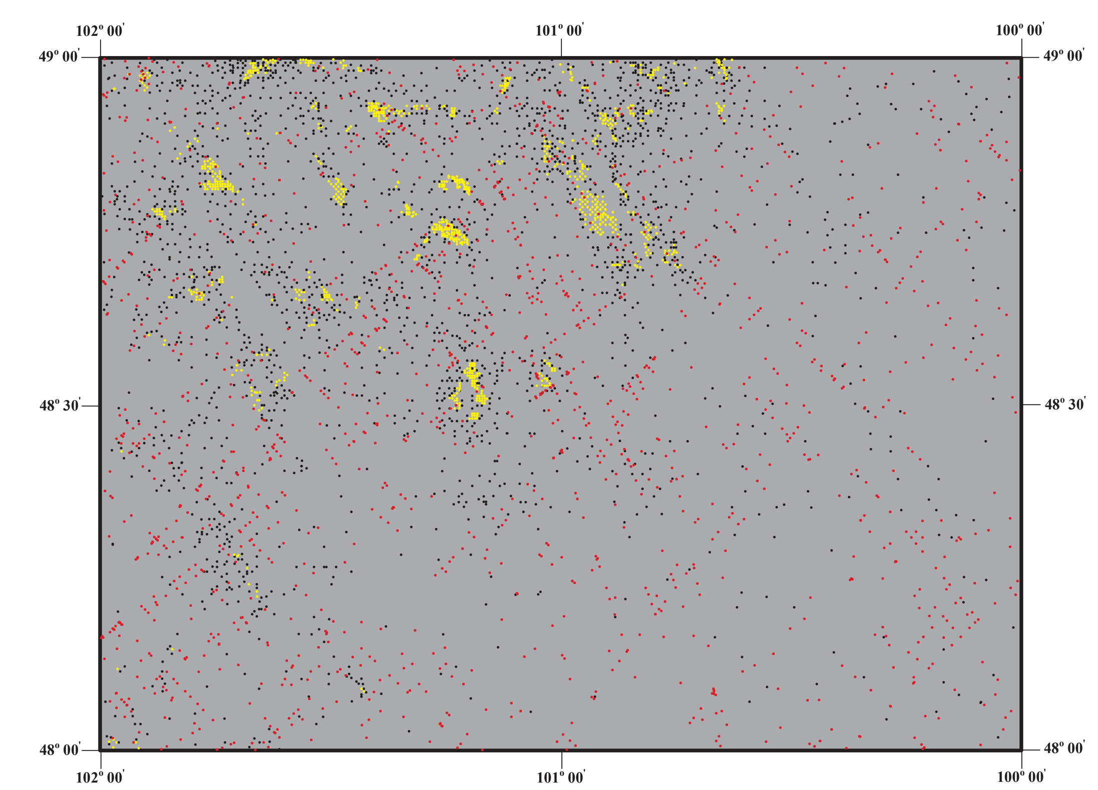


Figure 4. Map of lineament intersections (shown in red) overlain with currently producing wells (shown in yellow) and dry holes (shown in black) displaying the relationship between areas where lineament intersections are prevalent or lacking and areas of current production and field development. Nearly all of the wells shown here were completed vertically.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways

Cartographic Compilation: Elroy L. Kadrmas

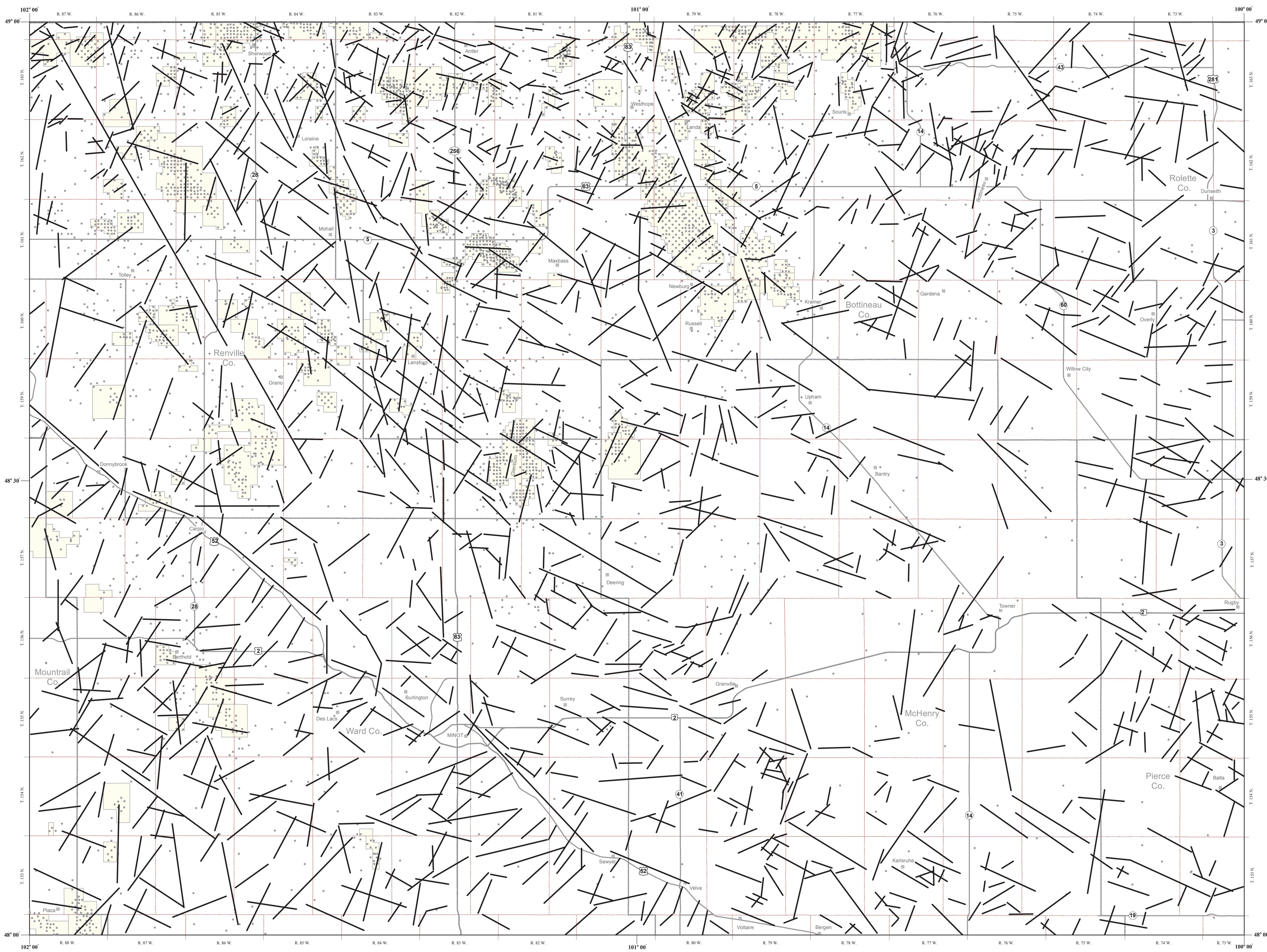
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate II

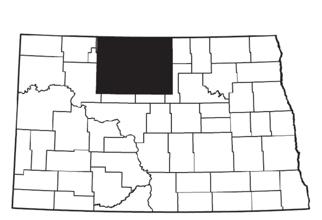
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE II - LINEAMENTS MAPPED FROM SHADED RELIEF DATA IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

2012





Minot 250K Sheet, North Dakota

Scale 1:250,000

0 5 10 15 20
Miles

0 5 10 15 20
Kilometers

Mercator Projection
Standard parallel 48° 00′

1927 North American Datum
Central meridian 101° 00′

Cartographic Compilation: Elroy L. Kadrmas

LINEAMENTS IN THE MINOT SHEET DERIVED FROM SHADED RELIEF MAP INTERPRETATION

This map presents the results and discussion of a segment of a contemporary lineament analysis of the Minot 1:250k map sheet in north-central North Dakota. The Minot 1:250k map area is located in the northeastern portion of the Williston Basin, in the north-central portion of the state. Lineaments were mapped and digitized from a digital, shaded-relief image, constructed from a USGS National Elevation Data (NED) set with a vertical exaggeration of 9X (Figure 1). Mapping of lineaments was conducted digitally by successive visual and manual inspection at various scales (most commonly 1:24,000, 1:100,000, 1:250,000, and 1:1,000,000). Lineaments mapped are presented here at a scale of 1:250,000. Lineament orientation analysis of 1,474 individual lineaments reveal two distinct orientation trends (Figures 2a. and b.). A primary (1°) trend of N 75° W (S 75° E), and a secondary (2°) trend of approximately N 45° E (S 45° W), The distribution of lineament lengths follows a general log-normal distribution with nearly all lineaments (99%) falling within the 0-9 mile lineament length range interval (Figure 3). The density of lineaments (i.e. lineaments mapped per unit area) is generally greater in the western portion of the map area with an overall lineament density of 0.23 lineaments per square mile (8.3 lineaments per township). In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 4). These lineament density areas (LDAs) exhibit similar lineament character (i.e. lineament density, length, degree of connectivity) and may be influenced by subsurface geology (e.g., basement faulting) but are more likely surface geomorphology ice features related to Pleistocene glacial processes. Lineament density is observed to be greatest in the northern (LDAs I, II, and III) portion of the map area, and is generally coincident with current oil and gas field development, and current exploration and production trends. LDA-V is located in the eastern portion of the map area where limited oil and gas drilling and field development has occurred. LDAs-I, II, and III, contain areas of significant oil and gas field development. Overall, lineament density appears greater in areas of currently producing wells and relatively lower in areas of limited or no production.The Souris River is the largest hydrologic feature present in the study area, but is not shown on this map.

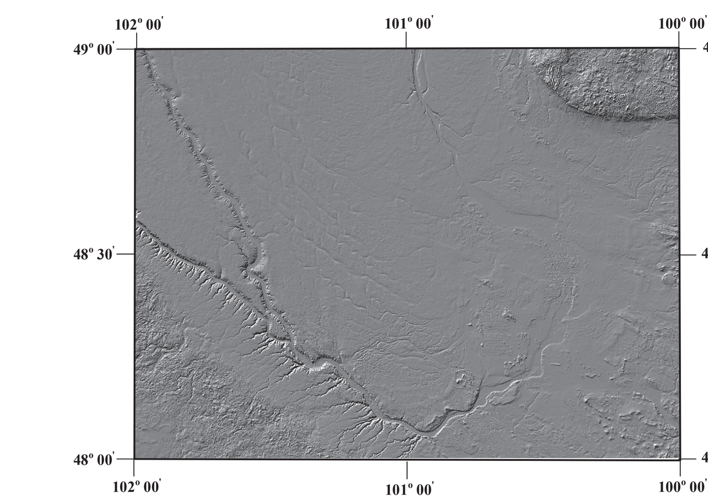
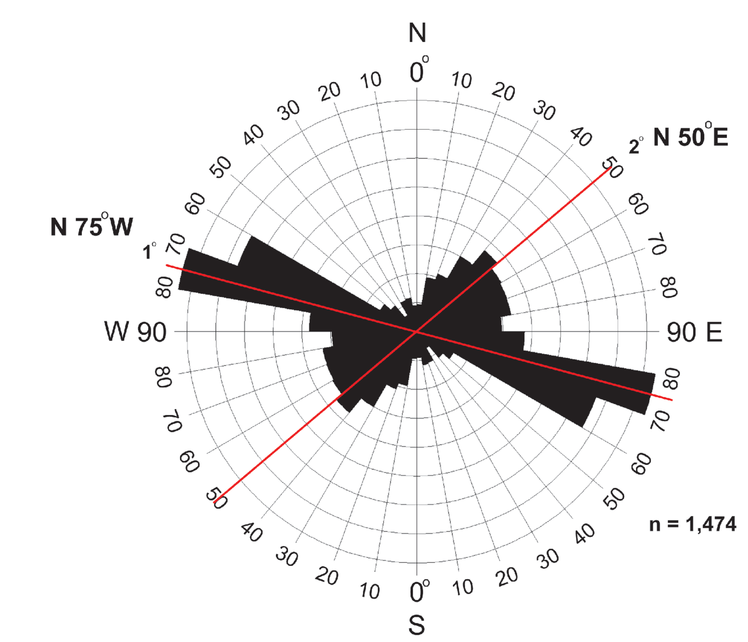
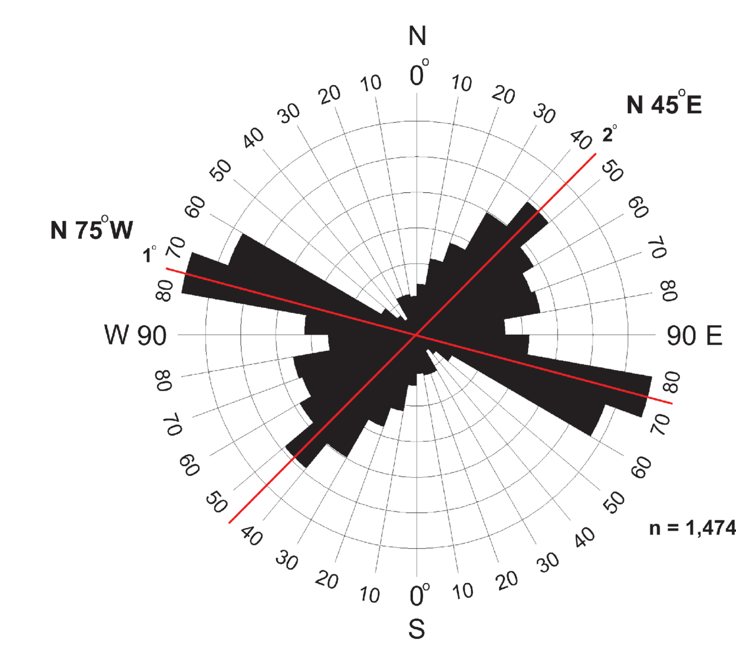


Figure 1. Index map of USGS NED shaded relief data for the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 1,474 individual lineament orientations mapped from shaded relief data in the Minot 1:250k sheet located in the northeastern portion of the Willison Basin in north-central North Dakota. The two dominant orientations (1° and 2°) are N 75° W (S 75° E) and approximately N 45° E (S 45° W), based on directional analysis of lineament line length (2a) and lineament frequency (2b).

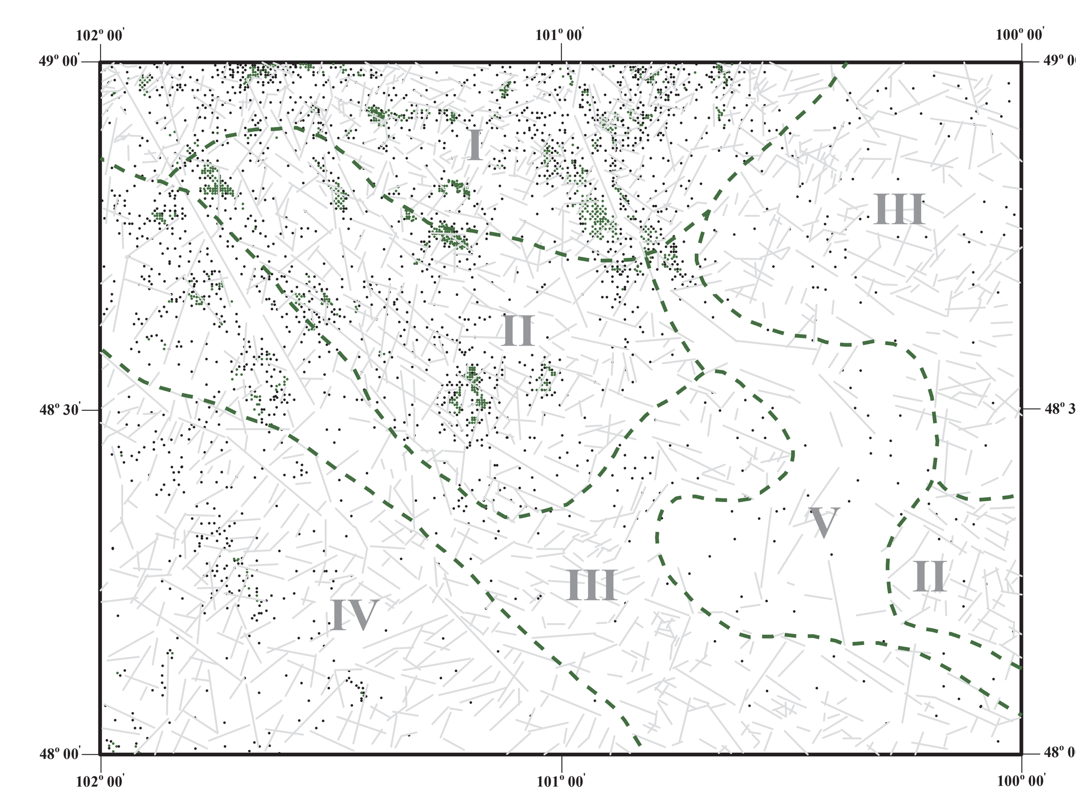


Figure 4. Diagram of Lineament Domain Areas (LDAs I-V) mapped in order of decreasing relative lineament densities (i.e. lineaments per unit area). Mapped LDAs generally encompass areas coincident with areas of current production and non-production. Currently producing wells (green) and dry holes (black) are shown. LDA boundaries are approximately delineated by the dashed green line.

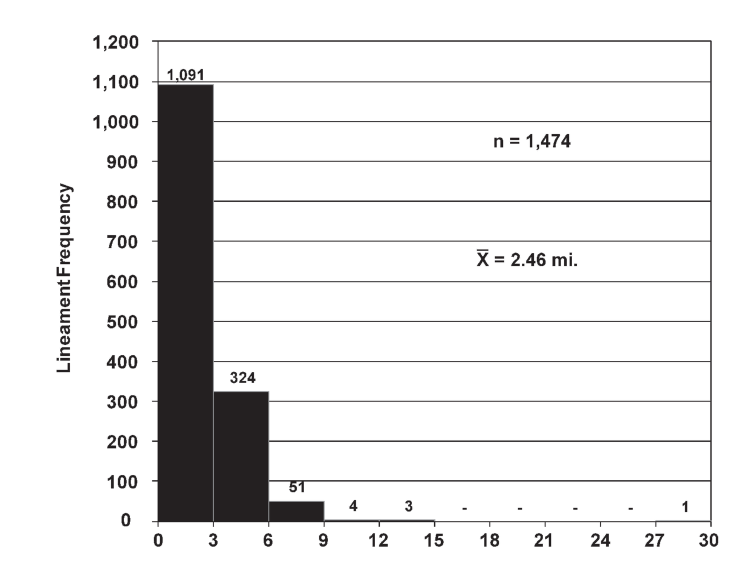


Figure 3. Frequency distribution of 1,474 individual lineament lengths from lineaments mapped from shaded relief data in the Minot1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for ten lineament length classes from zero to 30 miles in 3 mile intervals or classes.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways

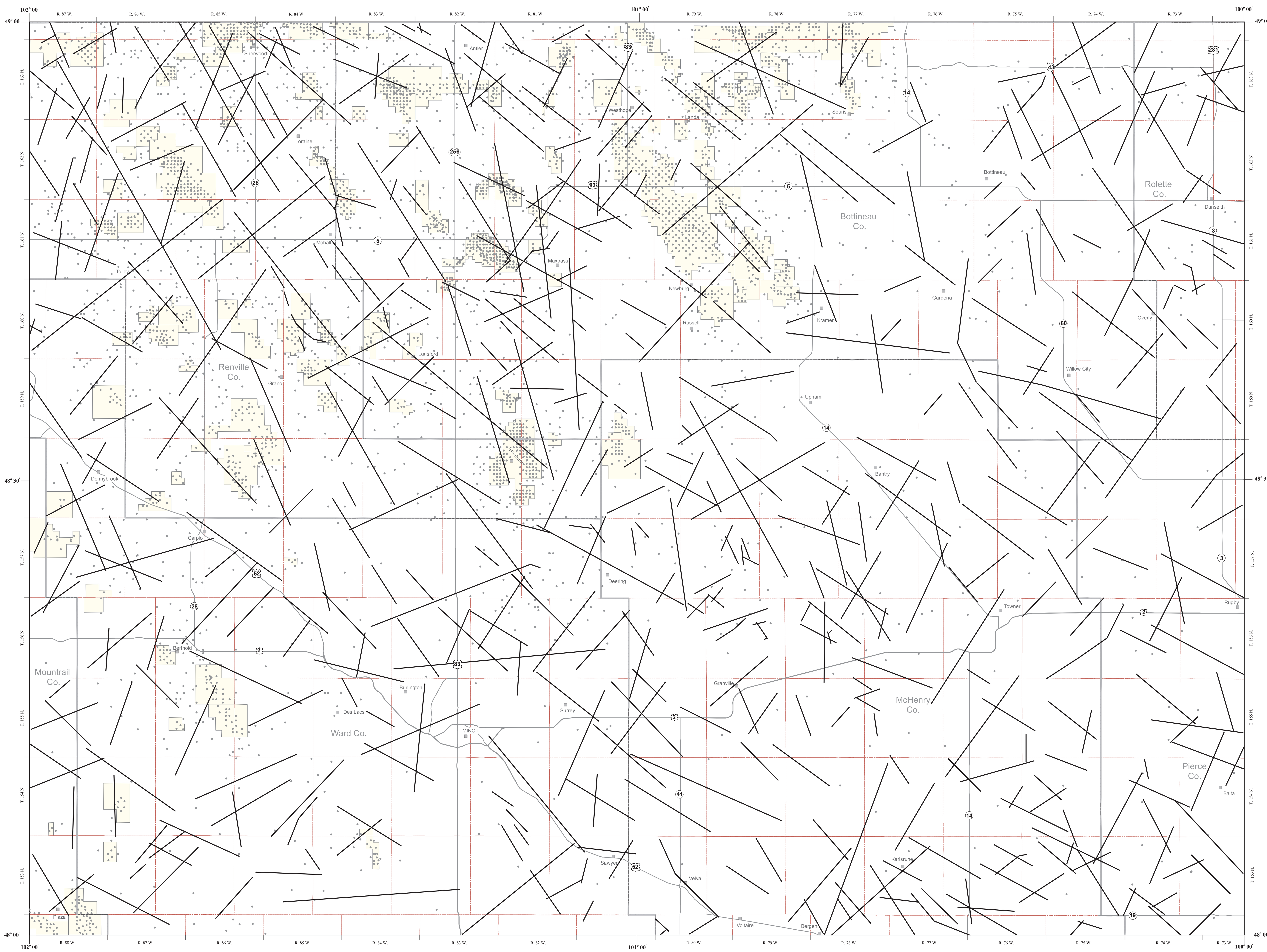
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate III

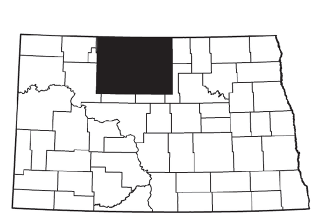
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE III - LINEAMENTS MAPPED FROM NAIP IMAGERY IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

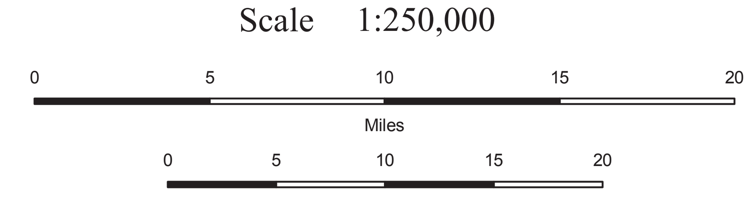
2011





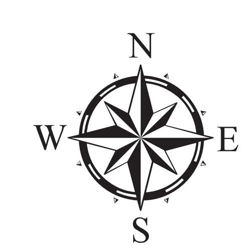
Minot 250K Sheet, North Dakota

Scale 1:250,000



Mercator Projection
Standard parallel 48° 00' 00"

1927 North American Datum
Central meridian 101° 00' 00"



LINEAMENTS IN THE MINOT 1:250K SHEET DERIVED FROM AERIAL IMAGE MAP INTERPRETATION

This map presents the results and discussion of a segment of a contemporary lineament mapping and analysis study in the Minot 250k sheet. The Minot 250k sheet is located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineaments were digitally mapped and digitized from a digital aerial image mosaic of the study area, complied from 2010 USDA National Agricultural Imagery Program (NAIP) imagery (Figure 1). Lineament Mapping was conducted by successive visual and manual inspection at various scales (most commonly 1:24,000, 1:100,000, 1:250,000, and 1:1,000,000). Lineaments mapped are presented here at a scale of 1:250,000. Directional analysis of the length (Figure 2a) and frequency (Figure 2b) of the orientation (i.e. strike) of 509 individual lineaments reveals two distinct trends; a primary (1°) orientation of N 65° W (S 65° E) and a secondary (2°) orientation of approximately N 60° E (S 60° W). The distribution of lineament lengths follow a general log-normal distribution with the majority of lineaments (88%) falling within the zero to eight mile lineament length range. Over 98% of the lineaments mapped were less than 14 miles in length (Figure 3). The overall density of lineaments within the sheet (i.e. lineaments mapped per unit area) is 0.08 lineaments per square mile, approximately 2.9 lineaments per township. Lineament density is generally greater in the northeastern portion of the study area, but overall is relatively uniform in character, particularly for shorter lineaments. On this map, several of the lineaments are coincident with areas of current oil and gas field development and current exploration and production trends, particularly in eastern Renville and western Bottineau County. Lineaments mapped are likely influenced by subsurface geological (i.e., basement faulting) and surface geomorphological conditions resultant from Pleistocene glaciation. Lineament intersections are also shown (Figure 4) as an example of a variation of lineament density and are generally coincident with currently producing and developing oil and gas fields. Areas with a higher relative lineament intersection density, and a corresponding small drilling exploration footprint, include most of the area within the southern half and eastern third of the sheet. Several fields have several lineaments occurring within the field boundries, which may provide hints to deeper structure.

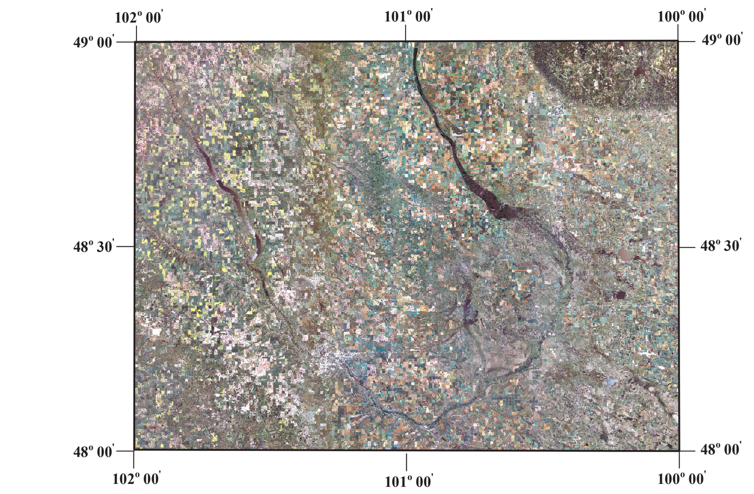
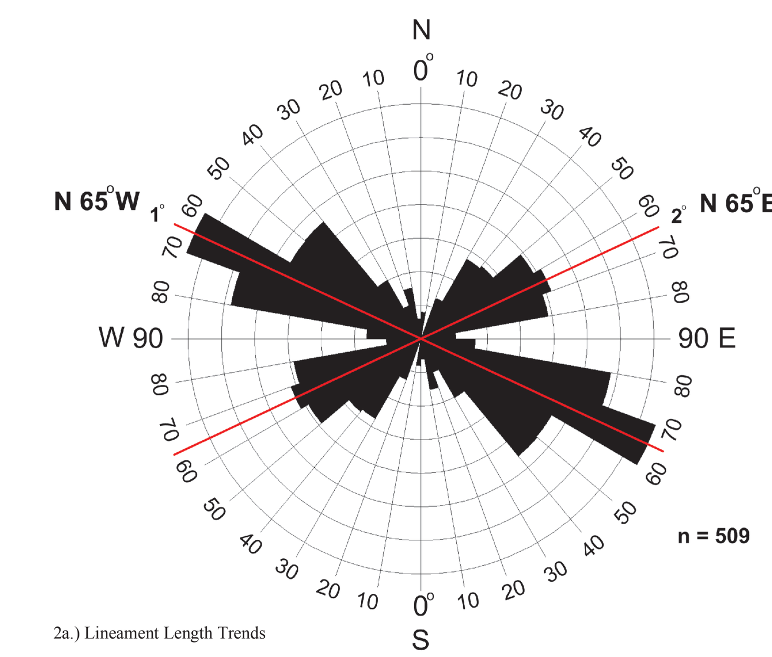
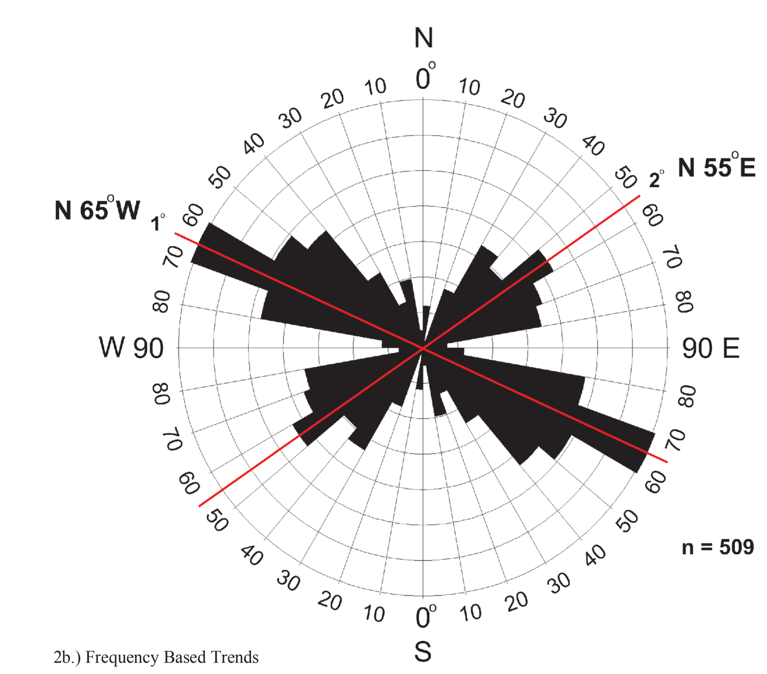


Figure 1. Map of 2010 NAIP aerial imagery used for lineament mapping in the Minot 1:250k sheet in the northeastern portion of the Williston Basin in north-central North Dakota.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 509 individual lineament orientations mapped from 2010 NAIP imagery in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. The two dominant lineament orientations (1° and 2°), are N 65° W (S 65° E), and N 55° E (S 55° W) based on orientational analysis of lineament line length (2a) and lineament frequency (2b).

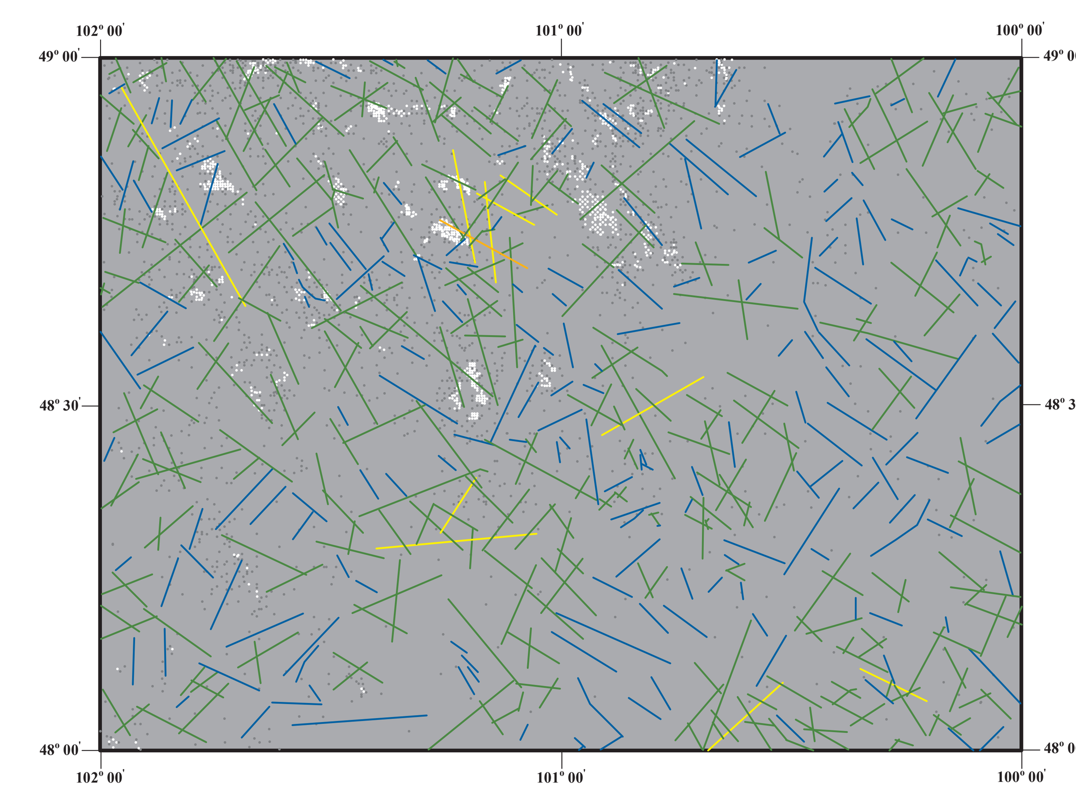


Figure 4. Lineament intersection map displaying the amount of lineament interconnectivity. Discontinuous lineaments (i.e. lineaments that do meet or intersect another lineament along the path of the lineament) are shown in blue, lineaments with intersections of 1 - 3 intersections per lineament path are shown in green, 4 - 6 yellow, and 7 - 9 orange. Producing wells (shown in white) display linear trends similiar to mapped lineament orientations. The distribution of dry holes (shown in gray) tend to be in areas where no mapped lineaments occur.

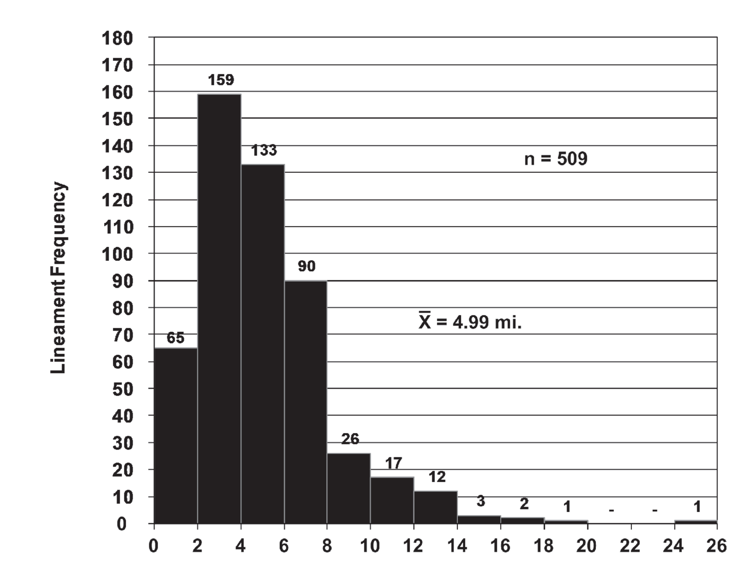


Figure 3. Frequency distribution of 509 individual lineament lengths mapped from 2010 NAIP imagery in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for 13 lineament length classes from zero to 26 miles in two mile intervals or classes.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways

Cartographic Compilation: Elroy L. Kadrmas

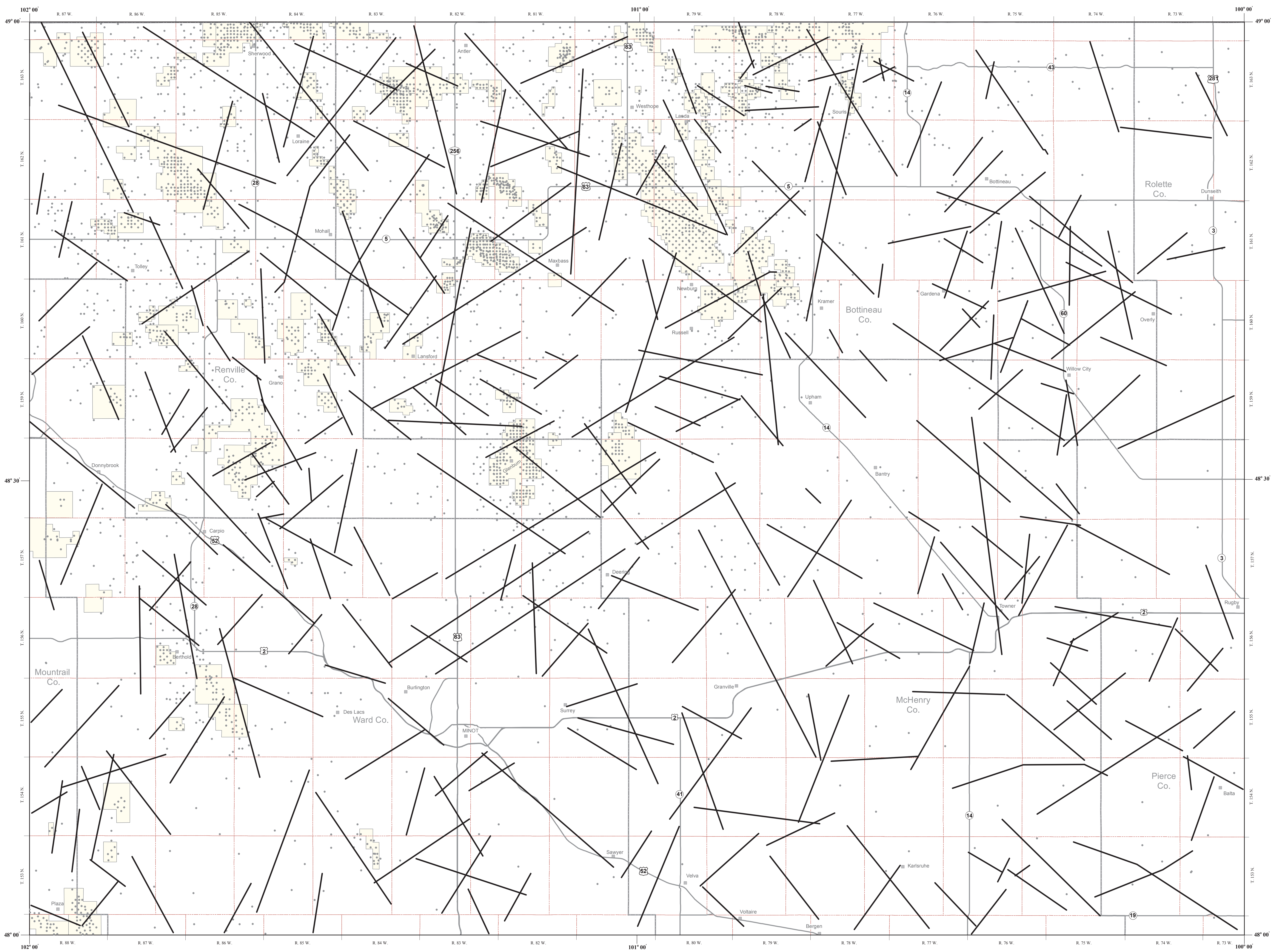
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate IV

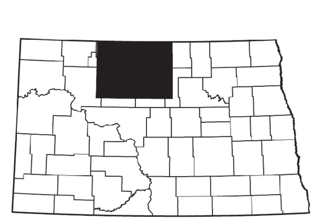
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE IV - LINEAMENTS MAPPED FROM LANDSAT DATA IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

2012





Minot 250K Sheet, North Dakota

Scale 1:250,000

0 5 10 15 20
Miles

0 5 10 15 20
Kilometers

Mercator Projection
Standard parallel 48° 00' 00"

1927 North American Datum
Central meridian 101° 00' 00"

Cartographic Compilation: Elroy L. Kadrmas

LINEAMENTS IN THE MINOT SHEET DERIVED FROM LANDSAT 7-ETM IMAGERY MAP INTERPRETATION

This map presents the results and discussion of a segment of a contemporary lineament mapping and analysis study of the Minot 1:250k map sheet in north-central North Dakota. The Minot 1:250k map area is located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineaments were digitally mapped and digitized from a digital image mosaic of the study area, compliled from 2000 LANDSAT 7 Enhanced Thematic Mapper (ETM) data. A digital image mosaic was created from four available scenes in a blue, green, red (BGR) false color combination of spectral bands 2, 4, and 7 for analysis (Figure 1). Lineament mapping was conducted by successive visual and manual inspection at various scales (most commonly 1:24,000, 1:100,000, 1:250,000, and 1:1,000,000). Lineaments mapped are presented here at a scale of 1:250,000. Lineament orientation analysis of 303 individual lineaments reveal two distinct orientation trends (Figures 2a. and b.). A primary (1°) orientation of N 65° W (S 65° E), and a secondary (2°) orientation of approximately N 60° E (S 60° W). The distribution of lineament lengths follows a general log-normal distribution with the majority of lineaments (82%) falling within the two to ten mile lineament length range. Overall, 85% of the lineaments mapped were less than 10 miles in length (Figure 3). The overall density of lineaments within the study area (i.e. lineaments mapped per unit area) is 0.05 lineaments per square mile (approximately 1.7 lineaments per township). Lineament density is generally greater in the northwestern portion of the study area but overall is relatively uniform in character. This may attributed partially to the existence of large tracts of agricultural land (i.e., cultivated crops) where image tonal constrasts are reduced. On this map, several of the lineaments are coincident with areas of current oil and gas field development and current exploration and production trends. Lineaments mapped from this imagery source may be influenced by subsurface geological (e.g., basement faulting) conditions but are likely more heavily influenced by Pleistocene glacial processes. Lineaments are generally coincident with currently producing and developing oil and gas fields and areas where exploratory oil and gas drilling has been completed. Lineament density appears to be generally greater in areas of currently producing wells and less in areas of non-producing wells. Horizontal drilling and production trends have suggested more successful preferential horizontal leg completions along a NW trend throughout the Williston Basin of North Dakota. Visual analysis of lineaments mapped perpendicular to sub-perpendicular of this trend suggest a relatively higher amount of lineament frequency (i.e., lineaments encountered per path) normal to the preferred NW trend (Figure 4). The Souris River is the major surface water feature found in the map area. The southwestern portion of the Turtle Mountains are present in the northeastern corner of the map area. These features are not displayed on the 1:250,000 scale lineament map shown at the left.

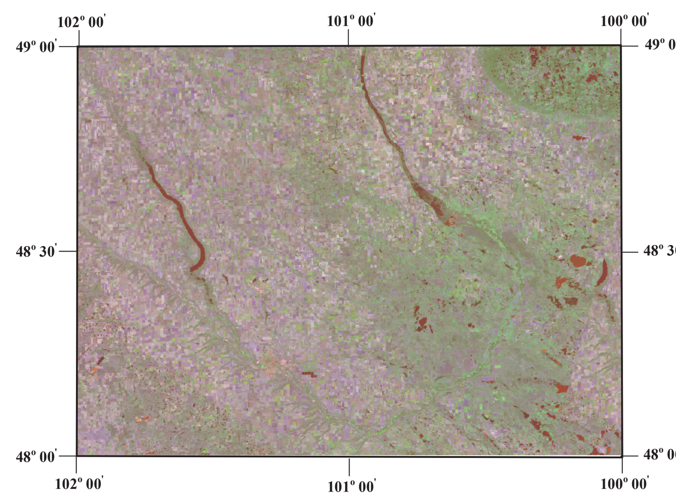
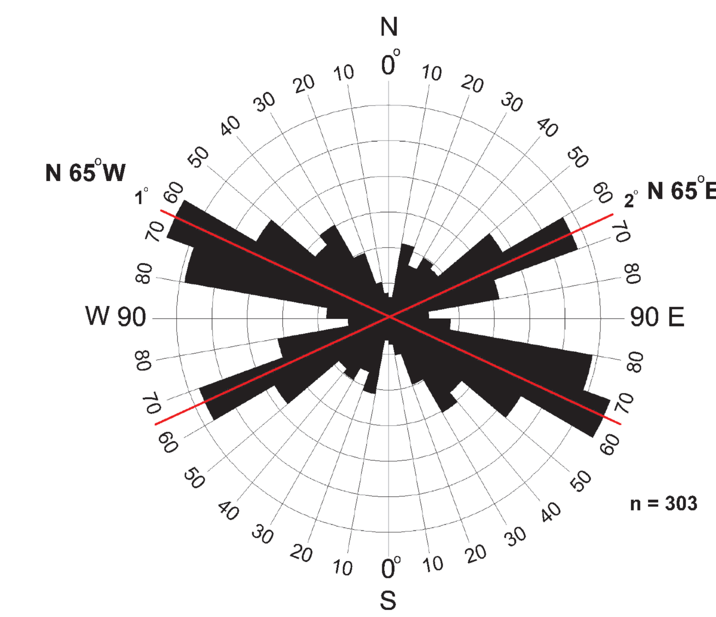
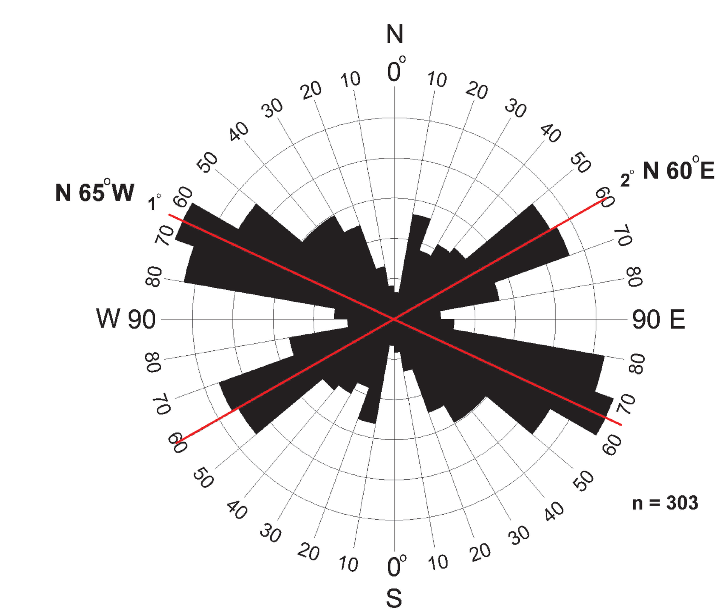


Figure 1. Map of 2000 LANDSAT 7-ETM false color (2-4-7) imagery used for lineament mapping in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Agricultural land use can again be seen as the patchwork pattern (green) throughout the central and eastern two-thirds of the study area.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 303 individual lineament orientations mapped from 2000 LANDSAT 7-ETM imagery in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. The two dominant lineament orientations (1° and 2°), are N 65° W (S 65° E), and approximately N 60° E (S 60° W) based on orientational analysis of lineament length (2a) and lineament frequency (2b).

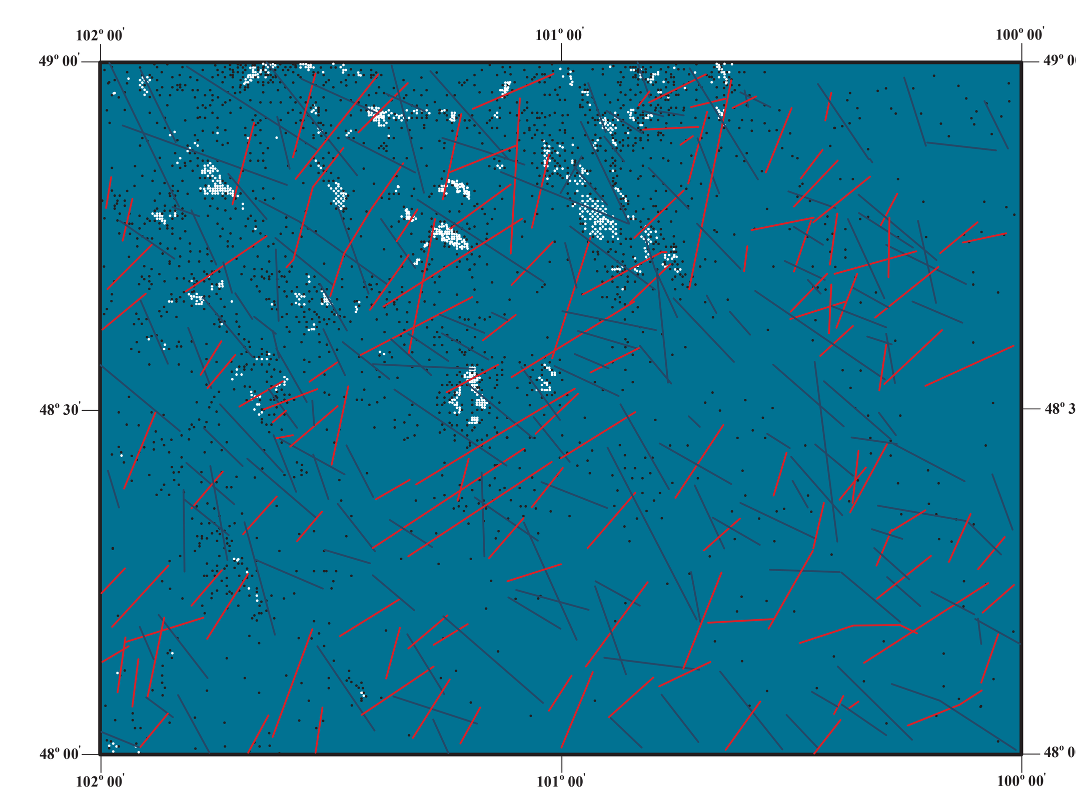


Figure 4. Lineament map displaying lineaments in two classes of lineament orientation. Lineaments oriented along a N-NE or S-SW orientation are showin in red, lineaments oriented along a N-NW or S-SE orientation are shown in blue. Producing wells (shown in white) tend to be located near areas of relatively higher lineament density. The distribution of dry holes (shown in black) tend to be in areas where lineament density is relatively low.

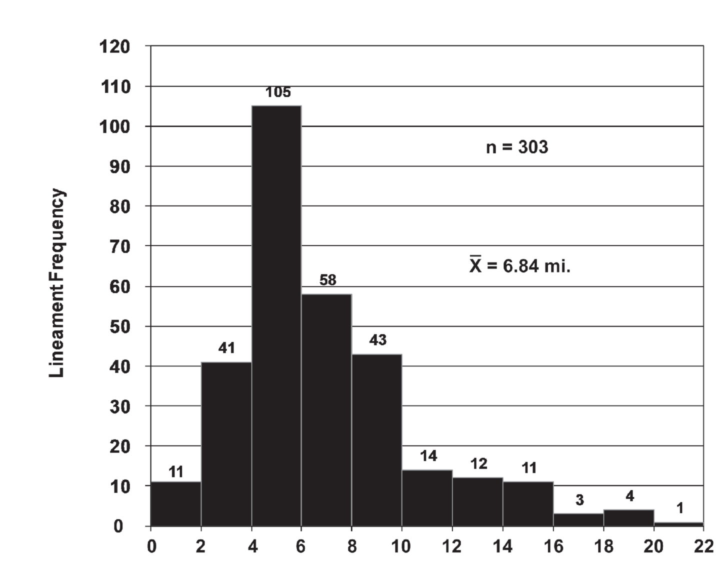


Figure 3. Frequency distribution of 303 individual lineament lengths (distance in miles) mapped from 2000 LANDSAT 7-ETM false color (2-4-7) imagery of the Minot 1:250k map sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for 11 lineament length classes from zero to 22 miles in two mile intervals or classes.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways

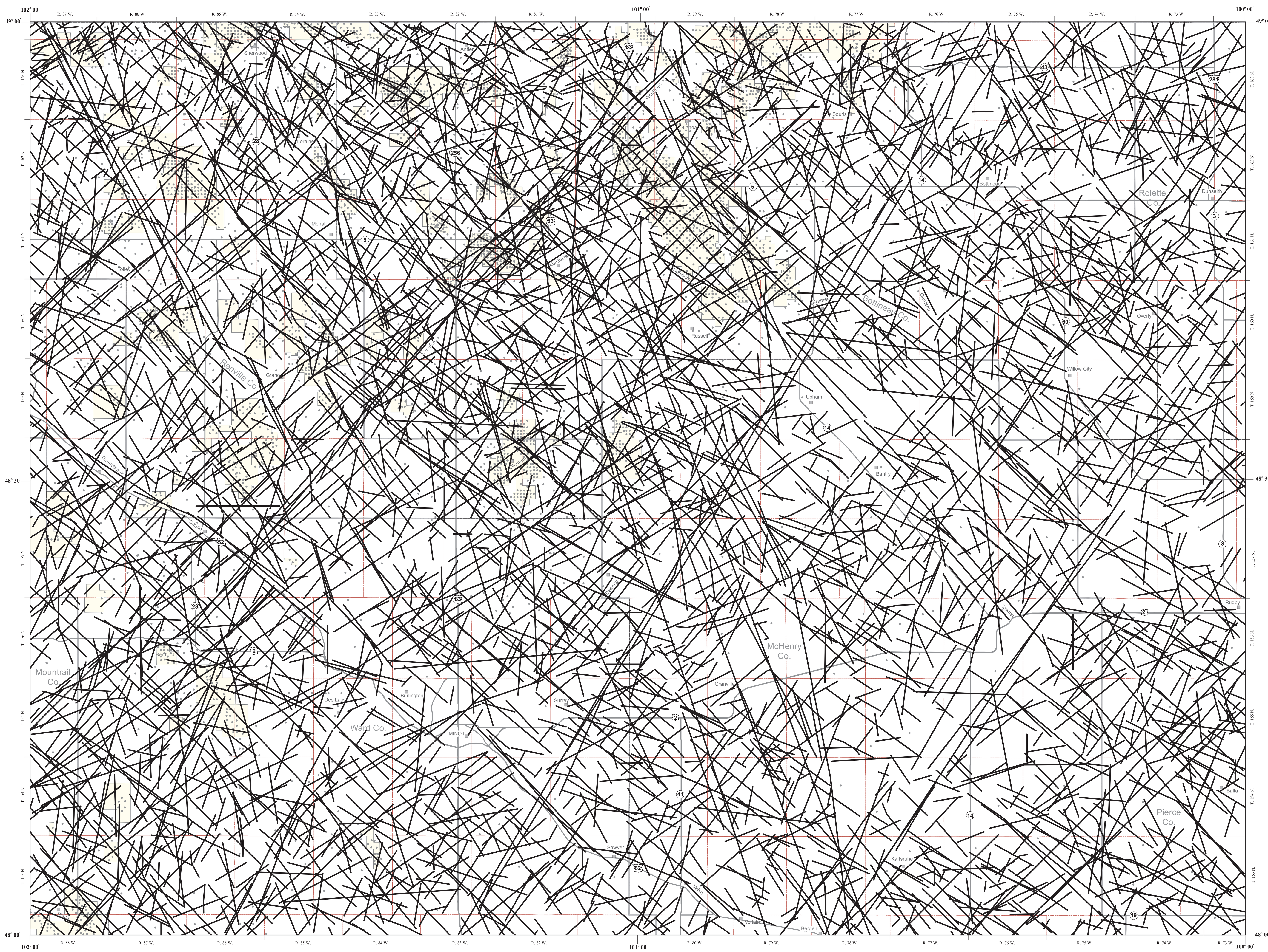
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate V

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE V - COMPILED LINEAMENTS MAPPED IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

2012



COMPILED LINEAMENTS IN THE MINOT SHEET

This map presents the results and discussion of a segment of a contemporary lineament analysis study of the Minot 1:250k map sheet in north-central North Dakota. The Minot 1:250k map area is located in the northeastern portion of the Williston Basin in the north-central part of the state. Lineaments were compiled from Plates I - V for this map (Figure 1). Lineaments compiled are presented here a scale of 1:250,000. Lineament orientation analysis of 3,604 mapped lineaments reveal two dominant orientation trends (Figures 2a. and b.). A primary (1°) orientation of approximately N 60° W (S 60° E) and a secondary (2°) orientation of N 55° E (S 55° W). The distribution of lineament length follows a sharp log-normal distribution with the majority of lineaments (96%) falling within the 0-12 mile lineament length size range (Figure 3). The density of lineaments (i.e. lineaments mapped per unit area) is generally greater in the northwestern and southwestern portions of the map area with an overall linement density of 0.57 lineaments per square mile (~20 lineaments per township). In this map, the general distribution of lineaments is likely more influenced by surface geomorphology and to a lesser degree by subsurface geologic conditions. Lineament density is observed to be greatest and generally coincident with current oil and gas field development, and current exploration and production trends. Overall, lineament density appears to be greater in areas of currently producing wells and relatively lower in areas of limited or no production (Figure 4).

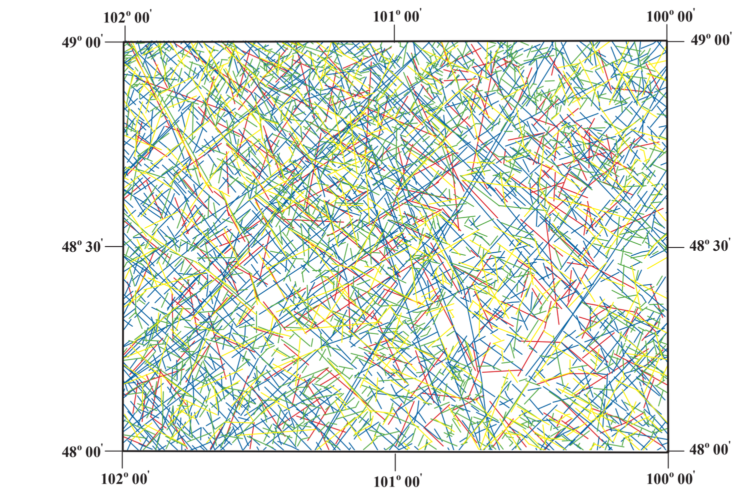
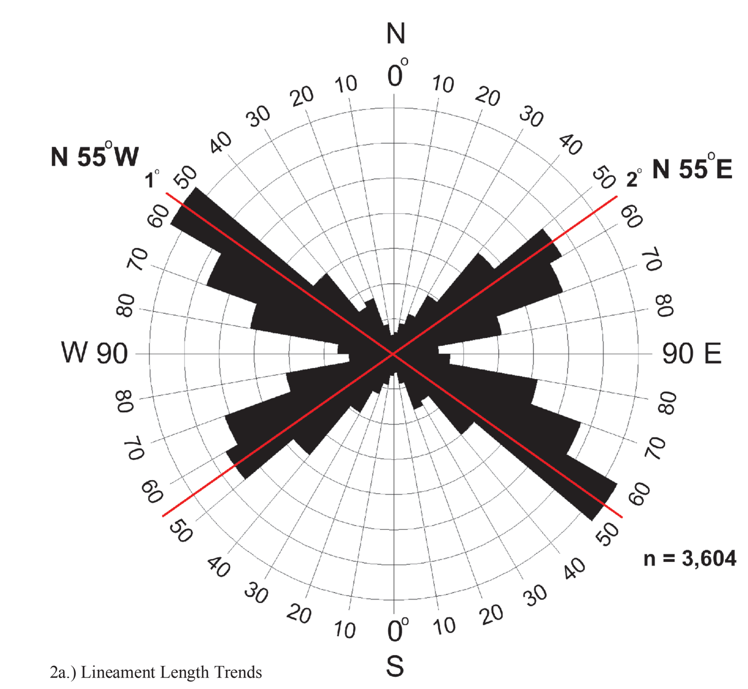
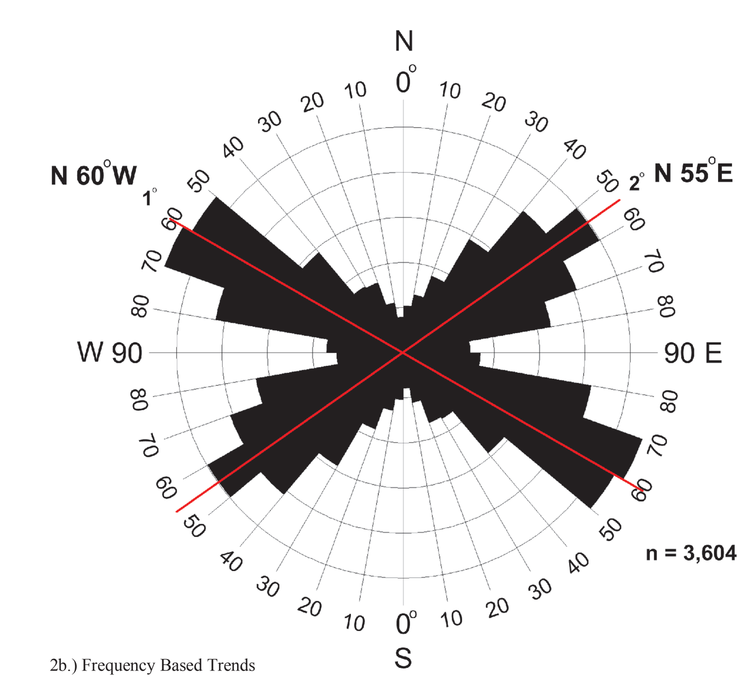


Figure 1. Index map of compiled lineaments in the Minot 1:250k map sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Historical or lineaments compiled from previous studies, are shown in blue. Lineaments mapped from shaded relief data are shown in green. Lineaments mapped from aerial imagery are shown in yellow. Lineaments mapped from LANDSAT imagery are shown in red.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 3,604 individual lineament orientations compiled from all lineaments mapped in the the Minot 1:250k sheet located in the northeastern portion of the Willison Basin in north-central North Dakota, analyzed for trends in strike orientation by lineament length (2a) and frequency based (2b) methods. There are two dominant orientation trends (1° and 2°) displayed within the data of approximately N 60° W (S 60° E) and N 55° E (S 55° W).

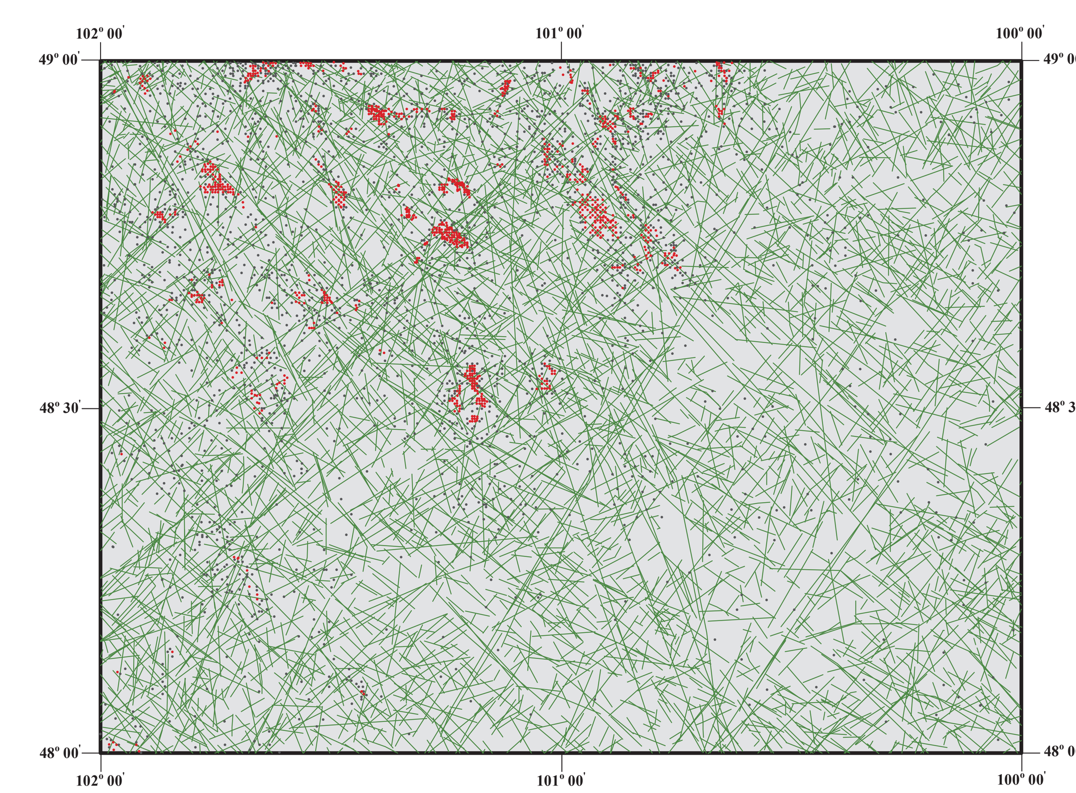


Figure 4. Map of compiled lineaments (green) with currently producing wells (red) and non-producing wells (dark gray) displaying the general relationships between overall lineament trends and densities and oil and gas production and development in the Minot 1:250k Sheet.

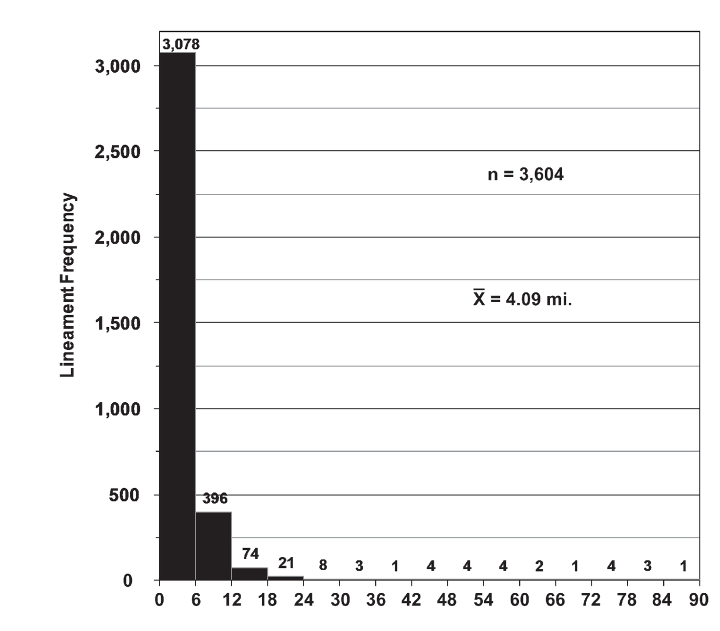


Figure 3. Frequency distribution of 3,604 individual lineament lengths (distance in miles) compiled from lineaments mapped in the Minot 1:250k map sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for 15 lineament length classes from zero to 90 miles in 6 mile intervals.

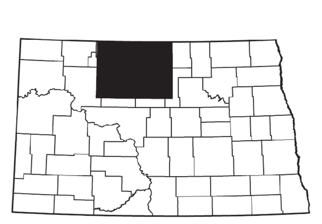
EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways



Minot 250K Sheet, North Dakota

Scale 1:250,000

0 5 10 15 20
Miles

0 5 10 15 20
Kilometers

Mercator Projection
Standard parallel 48° 00' 00"

1927 North American Datum
Central meridian 101° 00' 00"

Cartographic Compilation: Elroy L. Kadrmas

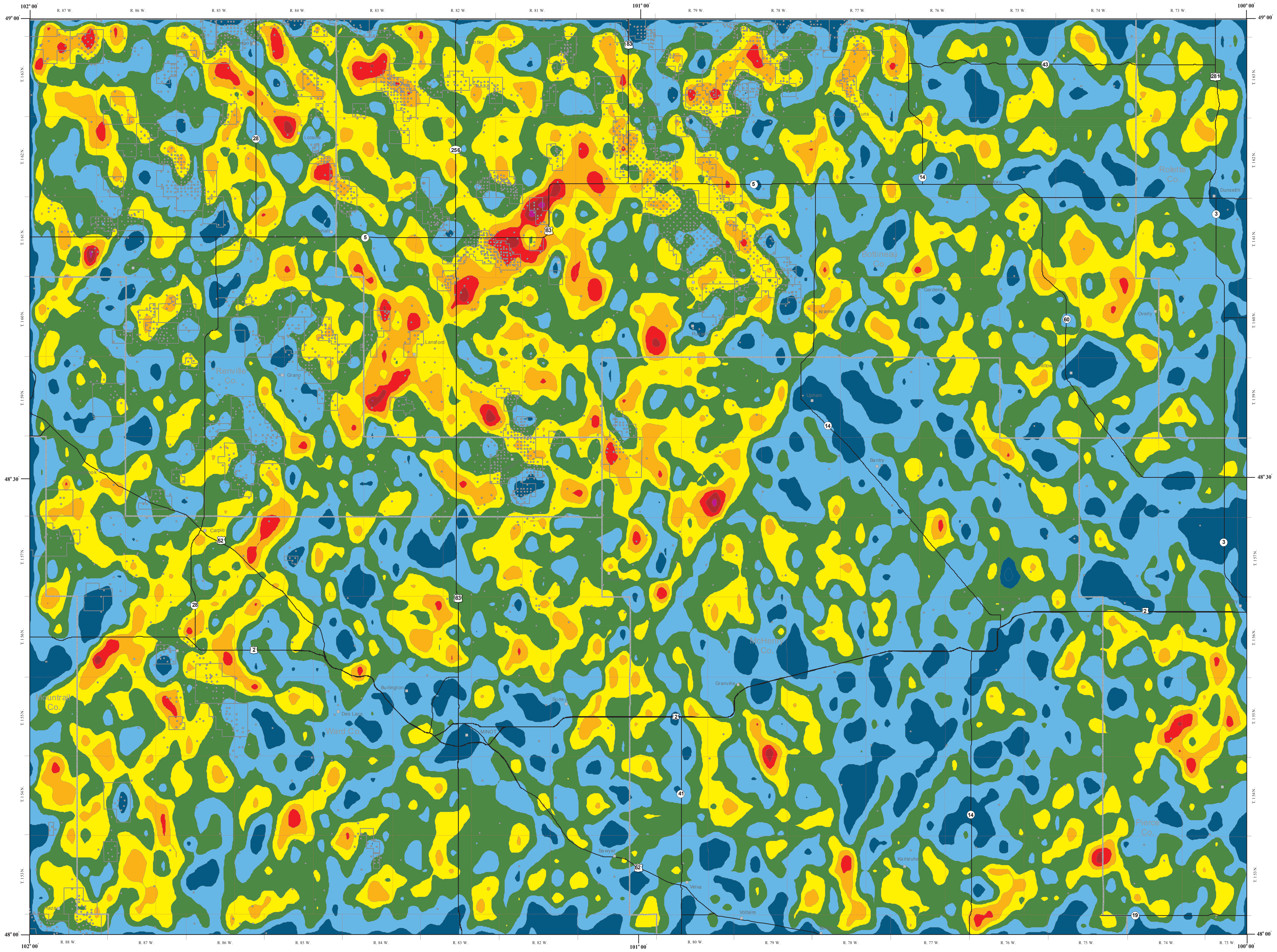
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate VI

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE VI - LINEAMENT DENSITY MAP OF THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

2012



LINEAMENT DENSITY MAPPING IN THE MINOT SHEET

This map presents the results and discussion of a segment of a contemporary lineament analysis of the Minot 1:250k sheet located in the northeastern Williston Basin in north-central North Dakota.The density of lineaments for this map was determined from the compliled lineaments extracted from Plate V of this report. Lineament density was calculated across the map area by automated analysis of all lineament lengths found to occur within a 1 mile x 1 mile grid cell coincident with actual Public Land Survey System (PLSS) sections. Cellular lineament density values (i.e., lineament line length within each unit cell) were assigned to nodal values for the centers of each of the grid cells (sections). The resulting x,y,z data file was contoured across the determined data range in 5,000-ft intervals from 0 to >40,000-ft/mi^2. Lineament density classes are depicted on this map as ranging from areas of lower lineament density, shown as cooler colors, to areas of higher lineament density, shown as warmer colors. This map shows areas of higher lineament density in the northwestern portion of the map area and lower lineament density towards the southeast. Overall, lineament density appears to be greatest and relatively coincident with areas where producing oil and gas wells and fields are commonly located, and lower in areas where non-producing wells have been drilled (Figure 1). This suggests a relationship between overall production and areas of relatively higher lineament density.

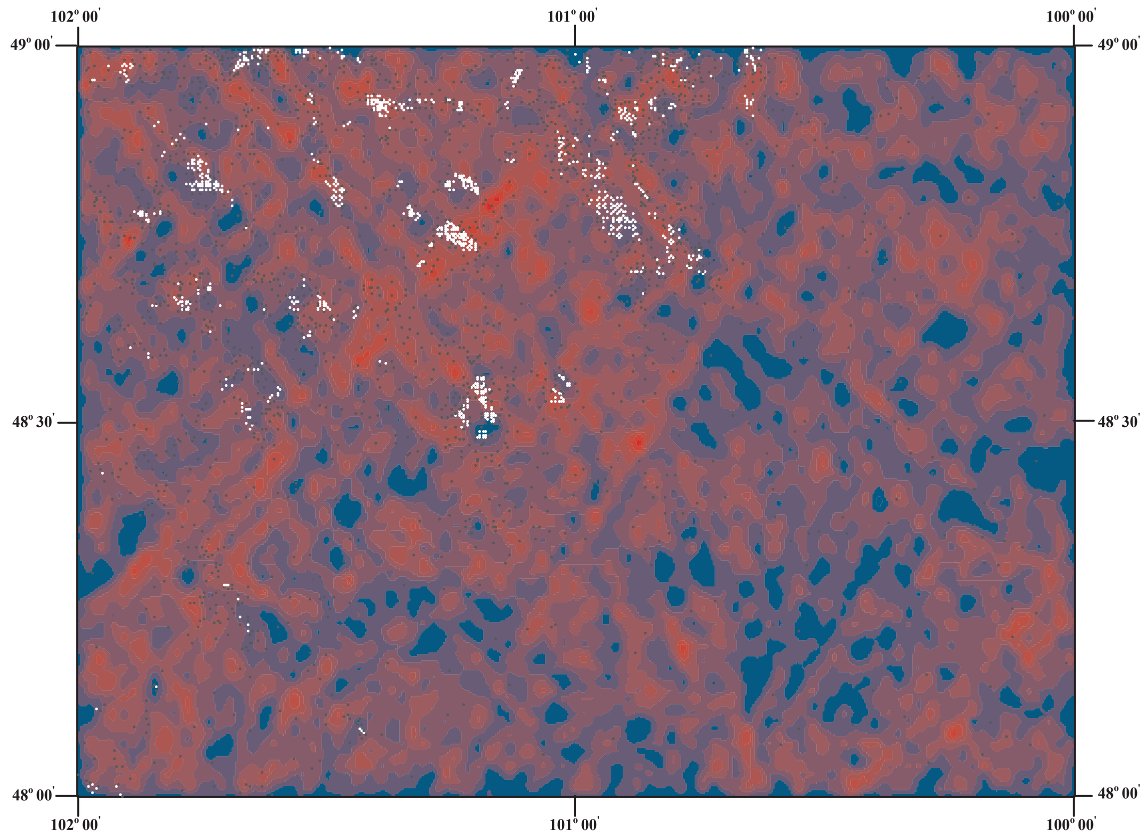


Figure 1. Lineament density map displaying lineament density with currently producing (white) and non-producing (dark gray) wells in the Minot 1:250k sheet. Producing wells tend to be located near areas of relatively higher lineament density (shown in red). The distribution of dry holes or non-producing wells tend to generally be distributed throughout areas where lineament density is relatively low (shown in blue).

Lineament Density (ft/mi^2)

- 35,000 - >40,000
- 30,000 - 35,000
- 25,000 - 30,000
- 20,000 - 25,000
- 15,000 - 20,000
- 10,000 - 15,000
- 5,000 - 10,000
- 0 - 5,000

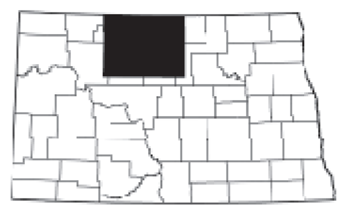
EXPLANATION

Geologic Features

- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways



Minot 250K Sheet, North Dakota

Scale 1:250,000

0 5 10 15 20
Miles

0 5 10 15 20
Kilometers

Mercator Projection
Standard parallel 48° 00'
1927 North American Datum
Central meridian 101° 00'

N
W E
S

Cartographic Compilation: Elroy L. Kadrmas

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE VII - 3D VISUALIZATION OF LINEAMENTS MAPPED IN THE MINOT 1:250K SHEET, NORTH DAKOTA

Fred J. Anderson

2012

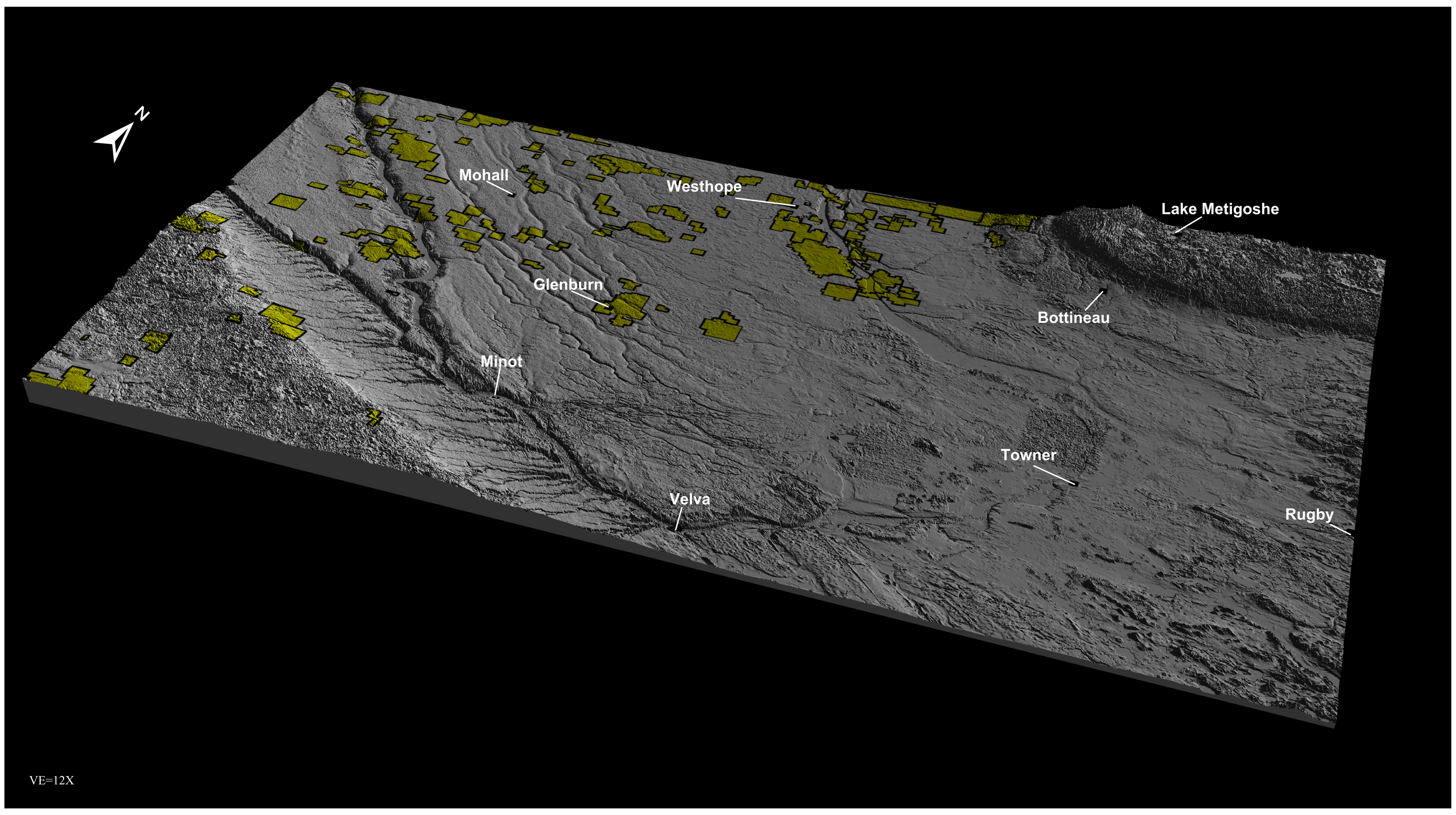


Figure 1. Three-Dimensional (3D) perspective view, from the southeast towards the northwest, across a digital elevation model (DEM) of the Minot 1:250k map sheet located in the northeastern Williston Basin in north-central North Dakota. This DEM was created from a 30 meter resolution digital elevation dataset extracted from the USGS 1997 National Elevation Dataset (NED) and is shown here at a vertical exaggeration of 12X.

For the rendering of this DEM, the lighting direction is from the northeast at 45° with an angle of inclination of 30°. The Minot 1:250k map sheet covers the majority of the lower Souris River Basin in North Dakota. The northeastern edge of the Max Moraine portion of the Missouri Escarpment is present in the southwestern-most corner of the map area. The confluence of the Des Lacs and Souris Rivers above Minot can also be found in the southwest portion of the map area just northeast of the escarpment. The southeastern corner of the Turtle Mountains is present as the area of highest elevations found in the northeastern corner of the map. The areas covered by current oil and gas field boundaries are highlighted in yellow on the surface of the DEM.

EXPLANATION

ELEVATION m (ft msl)

750	(2,461)
700	(2,297)
650	(2,132)
600	(1,968)
550	(1,804)
500	(1,640)
450	(1,476)

Oil & Gas Field Boundary

Cities and Towns

Westhope

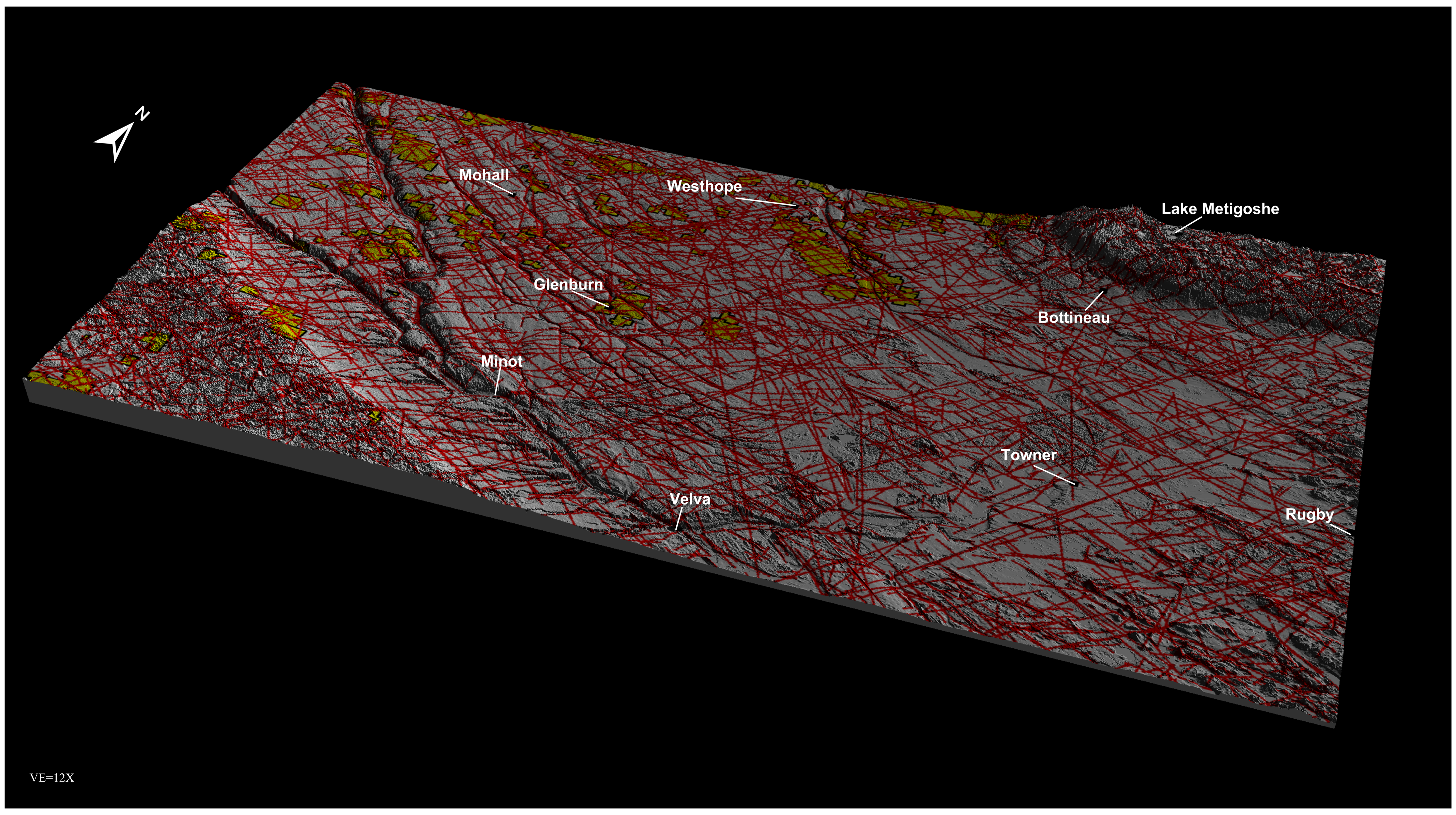


Figure 2. Lineaments mapped from selected imagery and data sources (i.e. historical, NED shaded relief, NAIP Imagery, and Landsat-7 ETM+ data) throughout the Minot 1:250k map sheet are shown in red overlain onto the land-surface DEM created from the USGS 1997 NED. In this view, the relationships between the locations of the current boundaries of current oil and gas fields and mapped lineaments is shown. Mapped lineaments are shown to be present within or traverse across every oil and gas field in the map area and many are found to intersect within field boundaries. A high degree of lineament intersection suggests a higher amount of overall structural geologic development within a given rock volume and may be suggestive of relatively higher reservoir porosity and permeability due to greater amounts of naturally occurring structures (i.e. faults and fractures) within the reservoir. The areas covered by current oil and gas field boundaries are highlighted in yellow on the surface of the DEM displayed beneath the lineaments.

EXPLANATION

Lineaments

Oil & Gas Field Boundary

Cities and Towns

Westhope

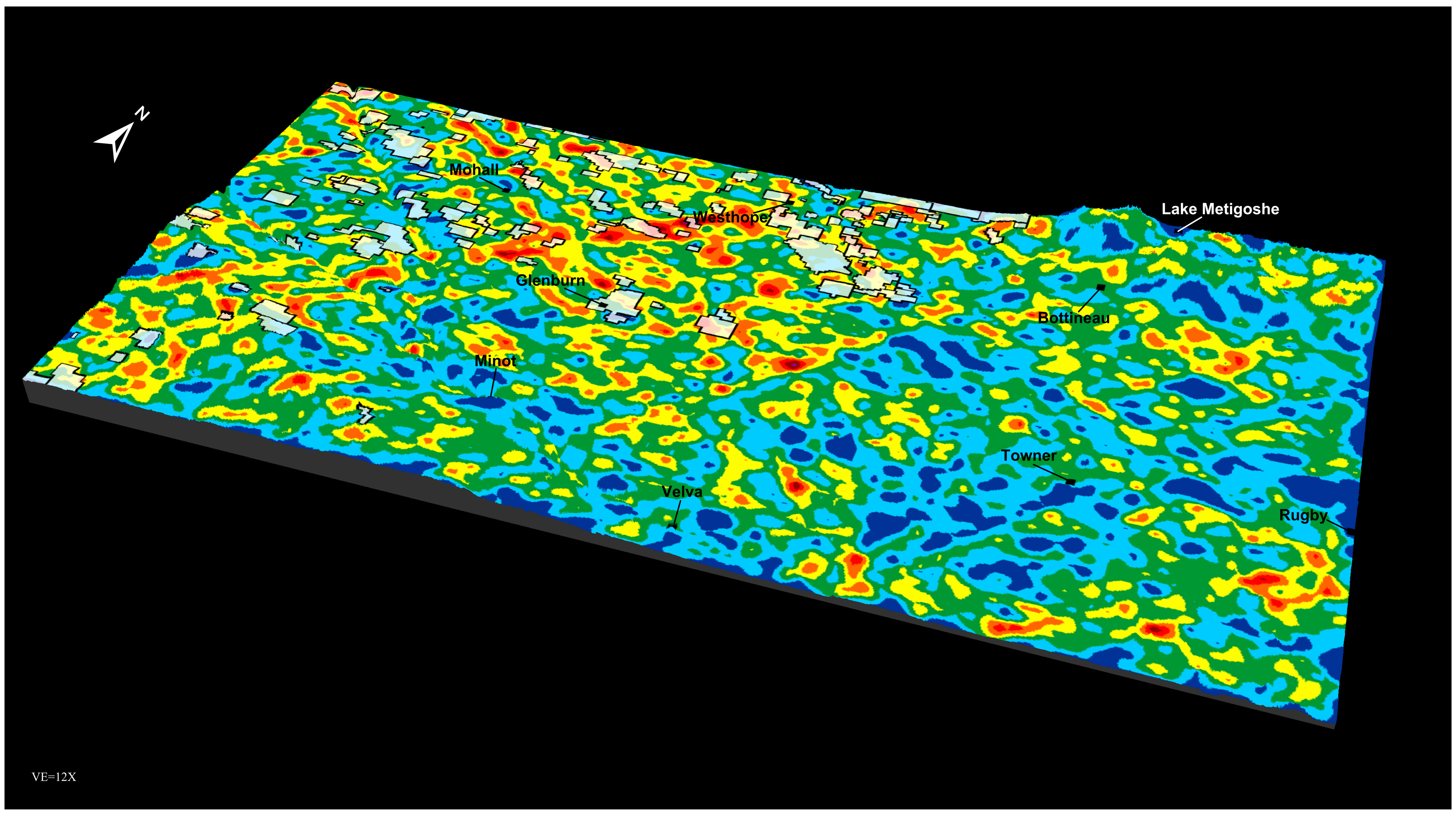


Figure 3. Interpolated lineament density map of compiled lineaments mapped within the Minot 1:250k map sheet overlain on the surface DEM created from the USGS 1997 NED. Areas of higher lineament density are depicted as warmer colors (yellow, orange, red, purple) and areas of lower lineament density are shown as cooler colors (blues and green). Lineament densities are higher in the western and northern portions of the map area generally coincident with the locations of existing oil and gas field boundaries. A high degree of lineament density suggests a higher amount of overall structural geologic development which may be related to areas of increased oil and gas production or can also be suggestive of the existence of subsurface structural boundary zones serving to define reservoir boundaries. The extent of current oil and gas fields are shown as black field boundaries draped over the lineament density map.

EXPLANATION

Lineament Density (ft/mi^2)

- 35,000 - >40,000
- 30,000 - 35,000
- 25,000 - 30,000
- 20,000 - 25,000
- 15,000 - 20,000
- 10,000 - 15,000
- 5,000 - 10,000
- 0 - 5,000

Oil & Gas Field Boundary

Cities and Towns

Westhope

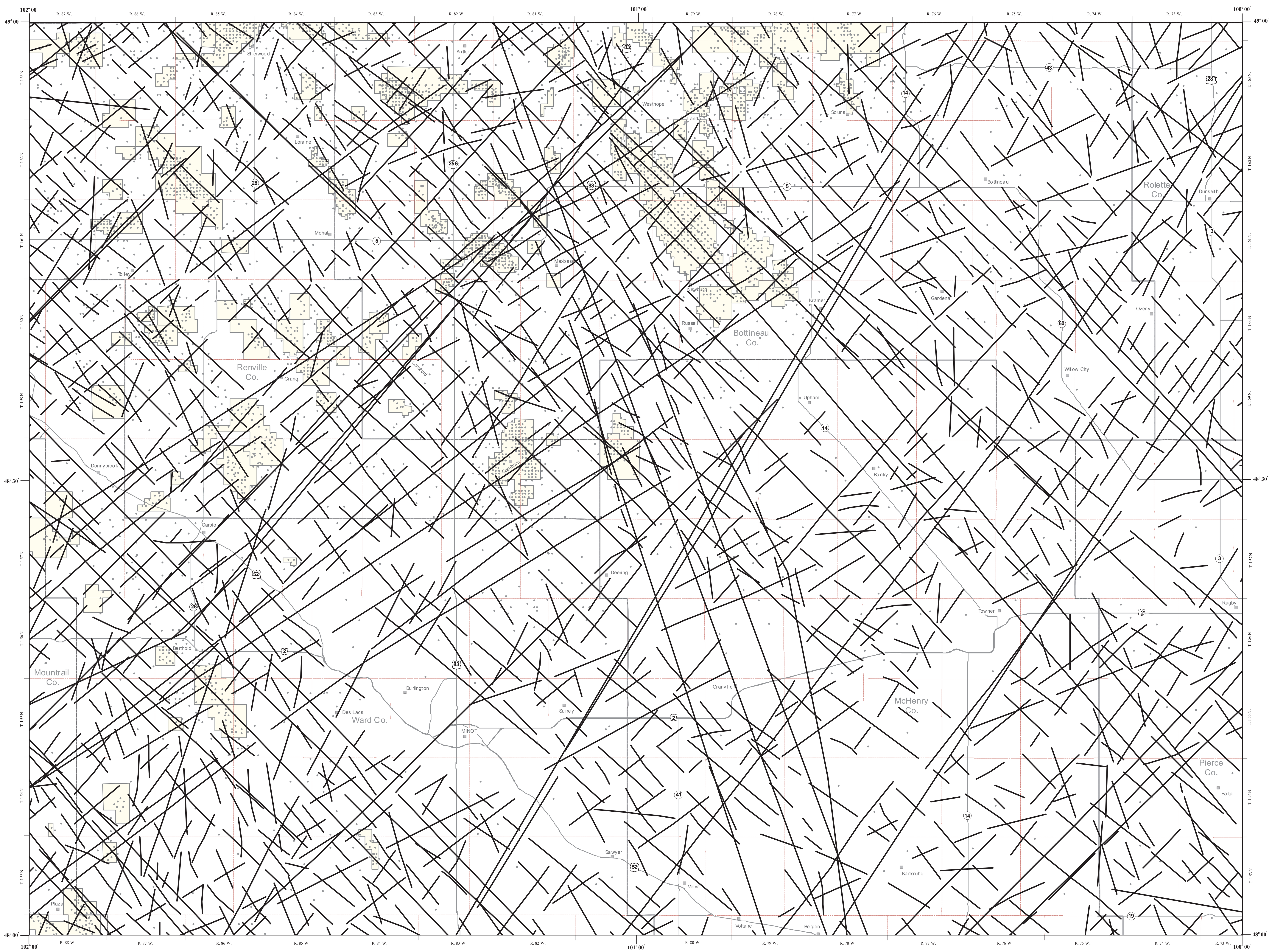
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate I

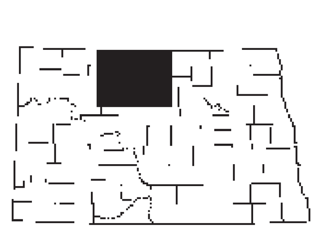
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE I - HISTORICAL LINEAMENTS MAPPED IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

2011





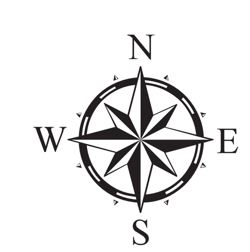
Minot 250K Sheet, North Dakota

Scale 1:250,000

0 5 10 15 20
Miles

0 5 10 15 20
Kilometers

Mercator Projection
Standard parallel 48°00'
1927 North American Datum
Central meridian 101°00'



HISTORICAL LINEAMENTS IN THE MINOT 1:250K SHEET COMPILIED AND MERGED FROM PREVIOUS STUDIES

This map presents the results of a segment of a contemporary lineament mapping investigation for the Minot 250k sheet. The Minot 250k sheet is located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineaments mapped from previous studies (i.e., historical lineaments) by several authors over the last four decades, include: Penner and Cosford, 2006, Gibson, 1995, Brown and Brown, 1987, Downey, et. al., 1987, Gerhard, et. al., 1987, Oglesby, 1987, Peterson and MacCray, 1987, Anna, 1986, Maughan and Perry, 1986, Hayes, 1984, Cooley, 1983, Kent, 1974, Thomas, 1974, and Erickson, 1970, (Figure 1).These lineaments were digitally extracted from a compilation of original published sources (Heinle, 2007), compiled, and merged into a single historical lineament coverage for the Minot 250k sheet (Figure 1). Previously mapped lineament centerline traces are presented here at a scale of 1:250,000, independent of their original mapped scales. Lineament directional analysis of the strike of 1,318 individual lineaments in this compliation reveals two distinct trends; a primary (1°) orientation of N 55° W (S 55° E) and a secondary (2°) orientation of N 55° E (S 55° W) (Figure 2). The distribution of lineament lengths follow a general log-normal distribution with the majority of lineaments (87%) falling within the zero to six mile lineament length range. Over 98% of the lineaments mapped were less than 30 miles in length (Figure 3). The overall density of lineaments within the sheet (i.e. lineaments mapped per unit area) is 0.21 lineaments per square mile, approximately 7.5 lineaments per township. Lineament density is generally greater in the northeastern portion of the study area, but overall is relatively uniform in character, particularly for shorter lineaments. This may be partially attributed to scale factors, as most of these lineaments were originally mapped at much smaller scales (e.g., 1:1,000,000 or greater). On this map, several of the lineaments are coincident with areas of current oil and gas field development and current exploration and production trends, particularly in eastern Renville and western Bottineau County. Lineaments mapped are likely influenced by subsurface geological (i.e., basement faulting) and surface geomorphological conditions resultant from Pleistocene glaciation. Lineament intersections are also shown (Figure 4) as an example of a variation of lineament density and are generally coincident with currently producing and developing oil and gas fields. Areas with a higher relative lineament intersection density, and a corresponding small drilling exploration footprint, include most of the area within the southern half and eastern third of the sheet. Several fields have several lineaments occurring within the field boundries, which may provide hints to deeper structure.

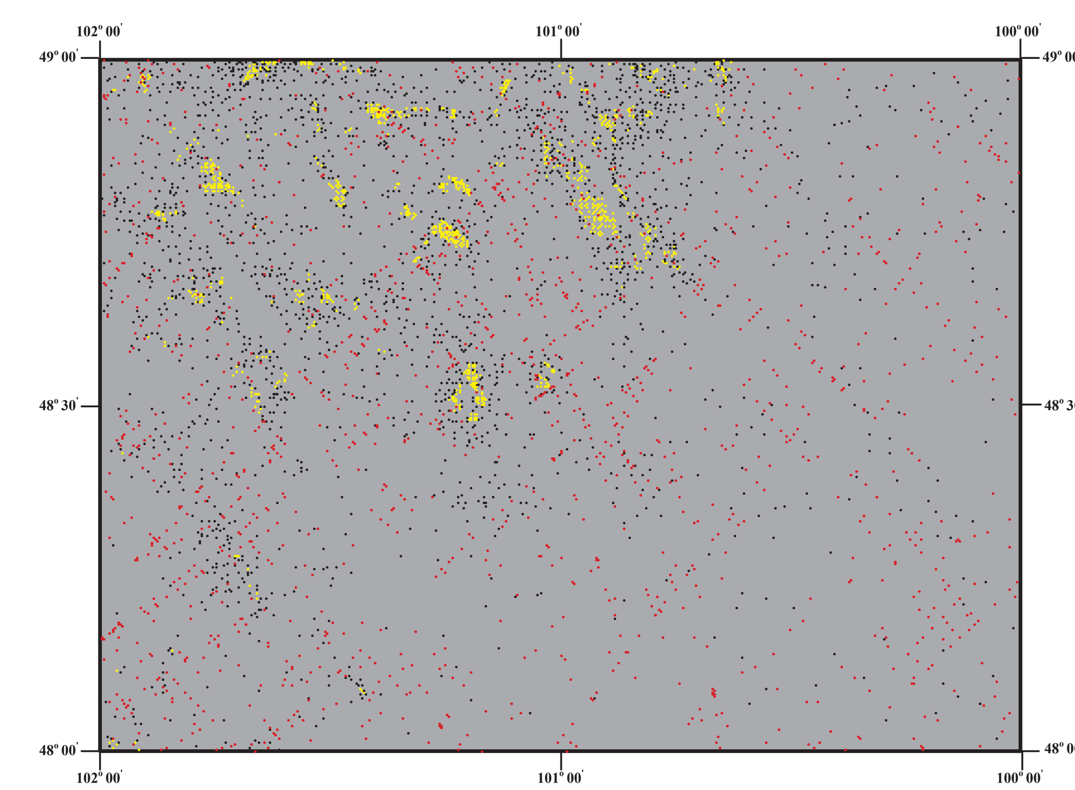
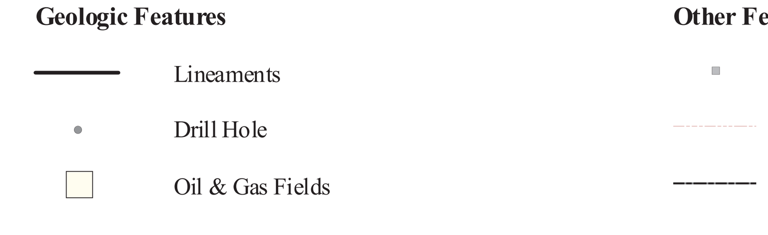


Figure 4. Map of lineament intersections (shown in red) overlain with currently producing wells (shown in yellow) and dry holes (shown in black) displaying the relationship between areas where lineament intersections are prevalent or lacking and areas of current production and field development. Nearly all of the wells shown here were completed vertically.

EXPLANATION



Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways

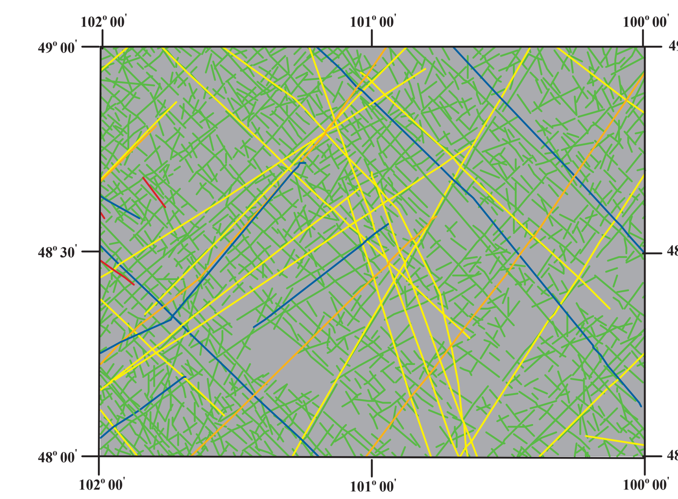
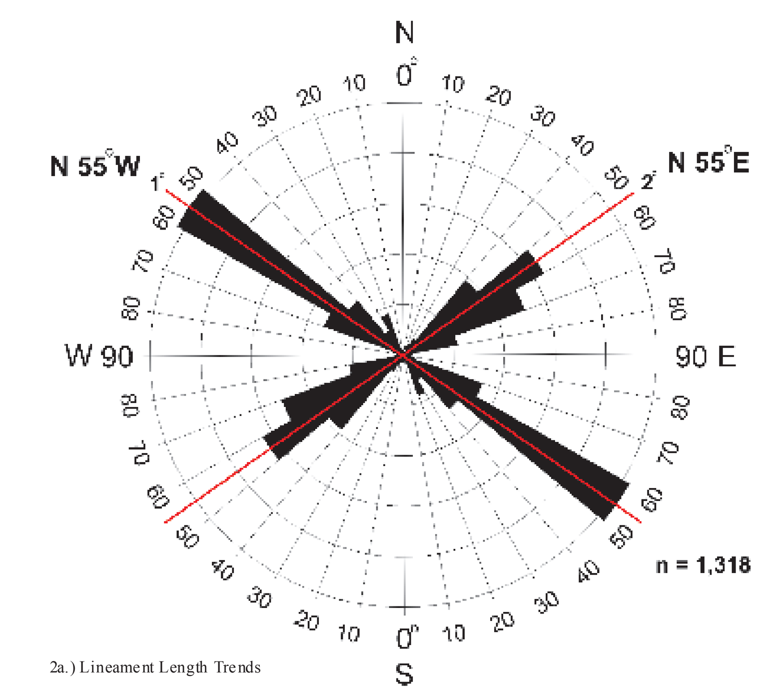
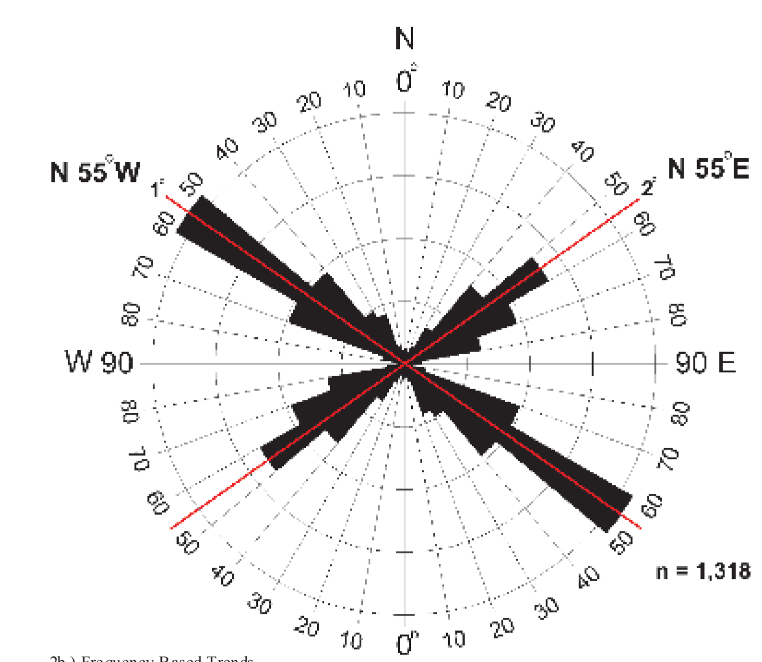


Figure 1. Index map of historical (i.e. previously published) lineaments, grouped by color by the decade in which they were mapped, in the Minot 1:250k sheet in the northeastern portion of the Williston Basin in north central North Dakota. Lineaments by Penner and Cosford, 2006 are shown in red, Gibson, 1995, in orange, Brown and Brown, 1987, Downey, et. al., 1987, Gerhard, et. al., 1987, Oglesby, 1987, and Peterson and MacCray, 1987 in yellow, Anna, 1986, Maughan and Perry, 1986, Hayes, 1984, and Cooley, 1983 in green, and Kent, 1974, Thomas, 1974, and Erickson, 1970 in blue.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 1,318 individual lineament orientations mapped from previous lineament studies in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. The two dominant lineament orientations (1° and 2°), are N 55° W (S 55° E), and N 55° E (S 55° W) based on orientational analysis of lineament length (2a) and lineament frequency (2b).

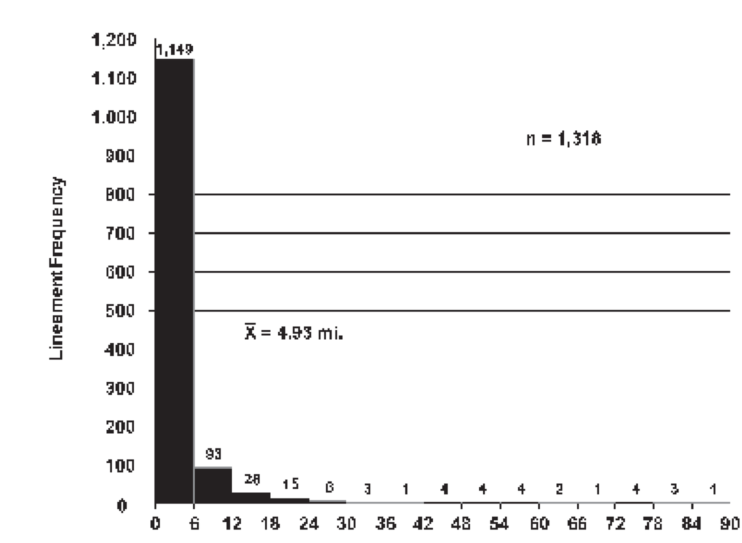


Figure 3. Frequency distribution of 1,318 individual lineament lengths from previously mapped lineaments in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for fifteen lineament length classes from zero to 90 miles in six mile intervals or classes. This distribution is heavily influenced by the inclusion of the Cooley (1983) LANDSAT derived lineaments as a part of this compilation, as the majority of lineaments mapped were less than 20 miles in length.

Cartographic Compilation: Elroy L. Kadrmas

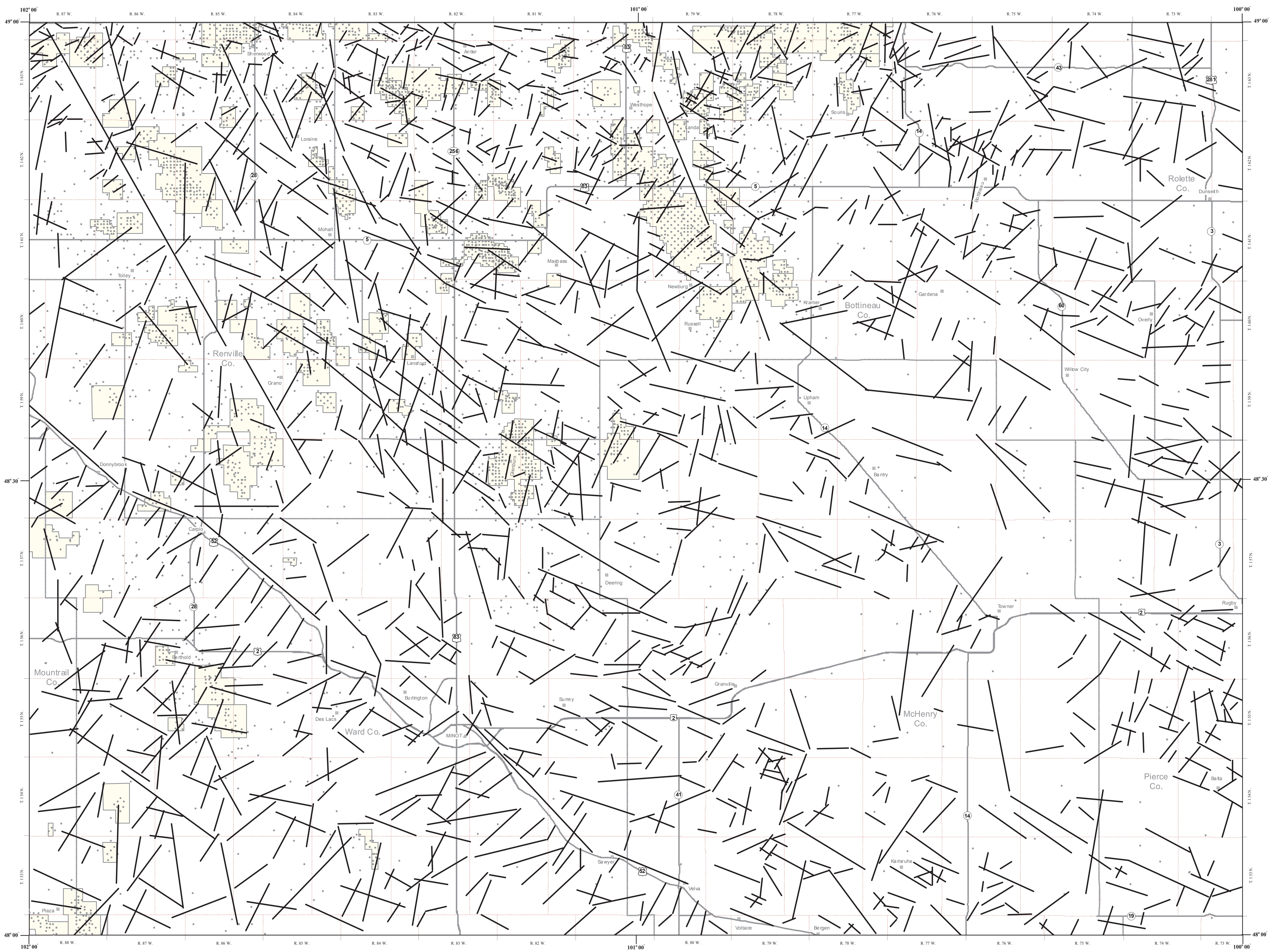
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate II

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

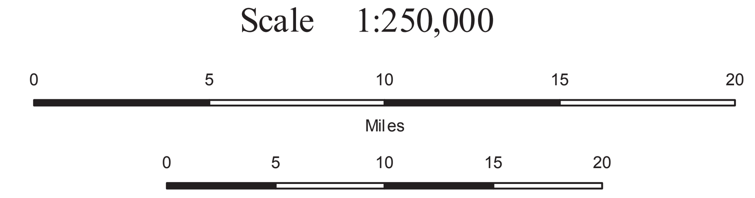
PLATE II - LINEAMENTS MAPPED FROM SHADED RELIEF DATA IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

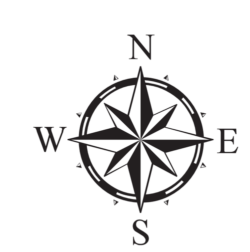
2012



Minot 250K Sheet, North Dakota



Mercator Projection
Standard parallel 48° 00'
1927 North American Datum
Central meridian 101° 00'



Cartographic Compilation: Elroy L. Kadrmas

LINEAMENTS IN THE MINOT SHEET DERIVED FROM SHADED RELIEF MAP INTERPRETATION

This map presents the results and discussion of a segment of a contemporary lineament analysis of the Minot 1:250k map sheet in north-central North Dakota. The Minot 1:250k map area is located in the northeastern portion of the Williston Basin, in the north-central portion of the state. Lineaments were mapped and digitized from a digital, shaded-relief image, constructed from a USGS National Elevation Data (NED) set with a vertical exaggeration of 9X (Figure 1). Mapping of lineaments was conducted digitally by successive visual and manual inspection at various scales (most commonly 1:24,000, 1:100,000, 1:250,000, and 1:1,000,000). Lineaments mapped are presented here at a scale of 1:250,000. Lineament orientation analysis of 1,474 individual lineaments reveal two distinct orientation trends (Figures 2a. and b.). A primary (1°) trend of N 75° W (S 75° E), and a secondary (2°) trend of approximately N 45° E (S 45° W), The distribution of lineament lengths follows a general log-normal distribution with nearly all lineaments (99%) falling within the 0-9 mile lineament length range interval (Figure 3). The density of lineaments (i.e. lineaments mapped per unit area) is generally greater in the western portion of the map area with an overall lineament density of 0.23 lineaments per square mile (8.3 lineaments per township). In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 4). These lineament density areas (LDAs) exhibit similar lineament character (i.e. lineament density, length, degree of connectivity) and may be influenced by subsurface geology (e.g., basement faulting) but are more likely surface geomorphology ice features related to Pleistocene glacial processes. Lineament density is observed to be greatest in the northern (LDAs I, II, and III) portion of the map area, and is generally coincident with current oil and gas field development, and current exploration and production trends. LDA-V is located in the eastern portion of the map area where limited oil and gas drilling and field development has occurred. LDAs-I, II, and III, contain areas of significant oil and gas field development. Overall, lineament density appears greater in areas of currently producing wells and relatively lower in areas of limited or no production. The Souris River is the largest hydrologic feature present in the study area, but is not shown on this map.

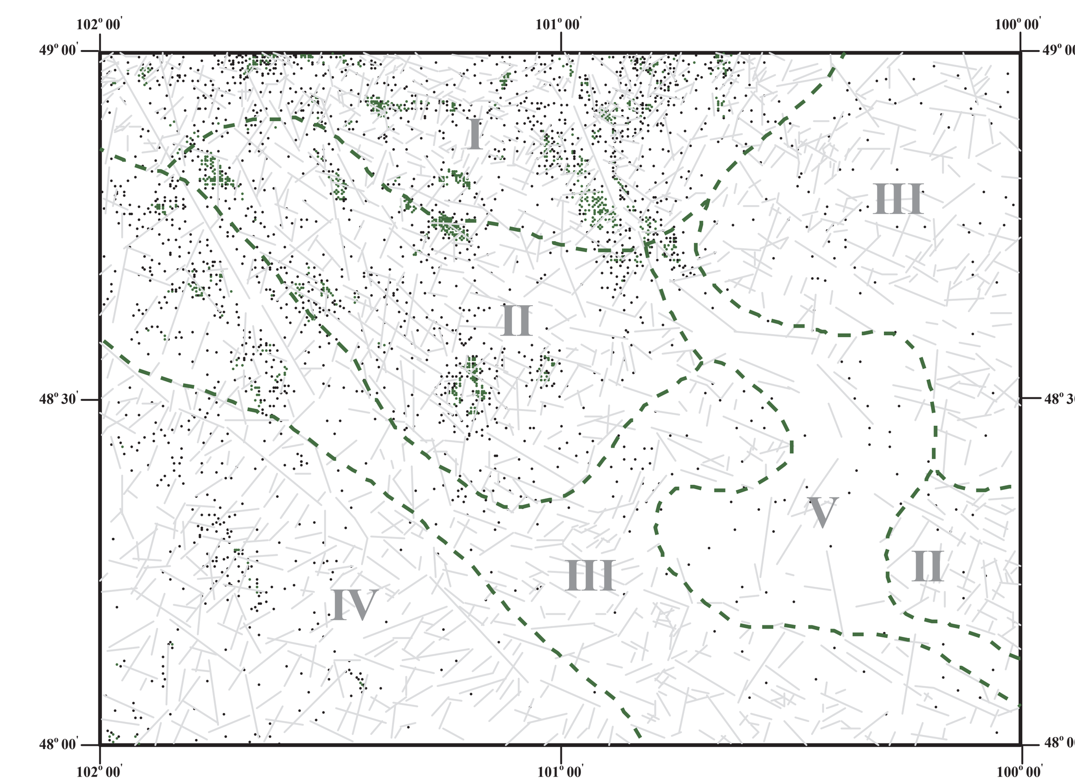


Figure 4. Diagram of Lineament Domain Areas (LDAs I-V) mapped in order of decreasing relative lineament densities (i.e. lineaments per unit area). Mapped LDAs generally encompass areas coincident with areas of current production and non-production. Currently producing wells (green) and dry holes (black) are shown. LDA boundaries are approximately delineated by the dashed green line.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways

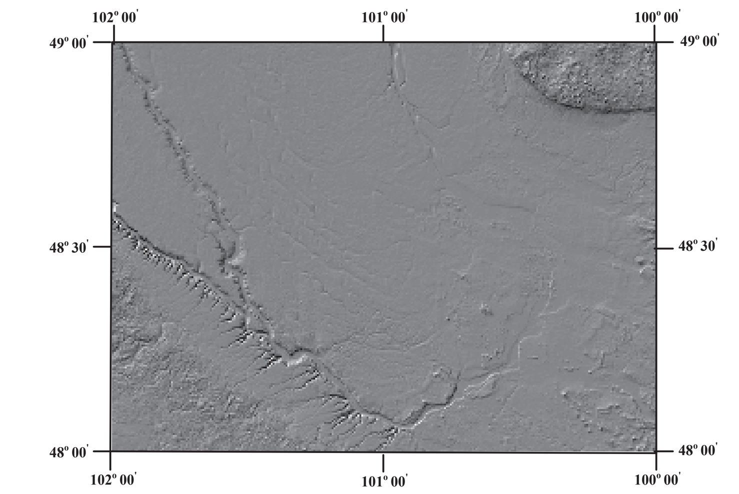
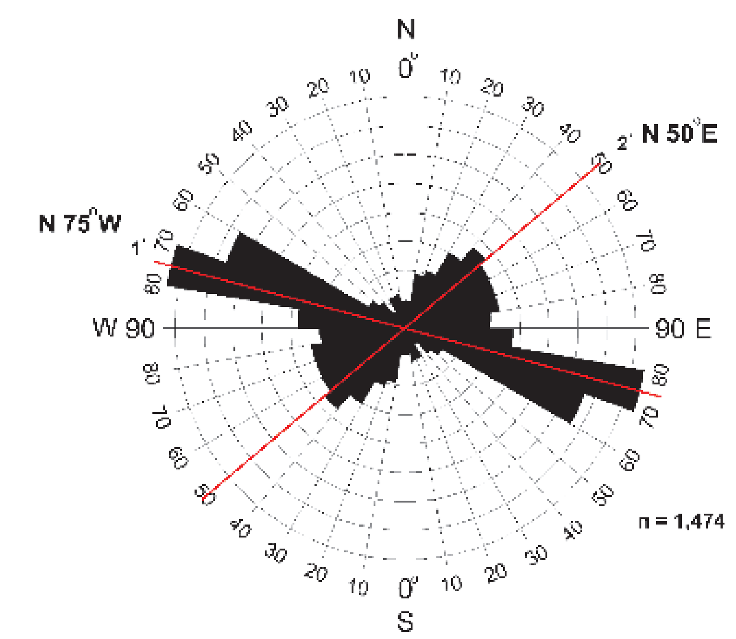
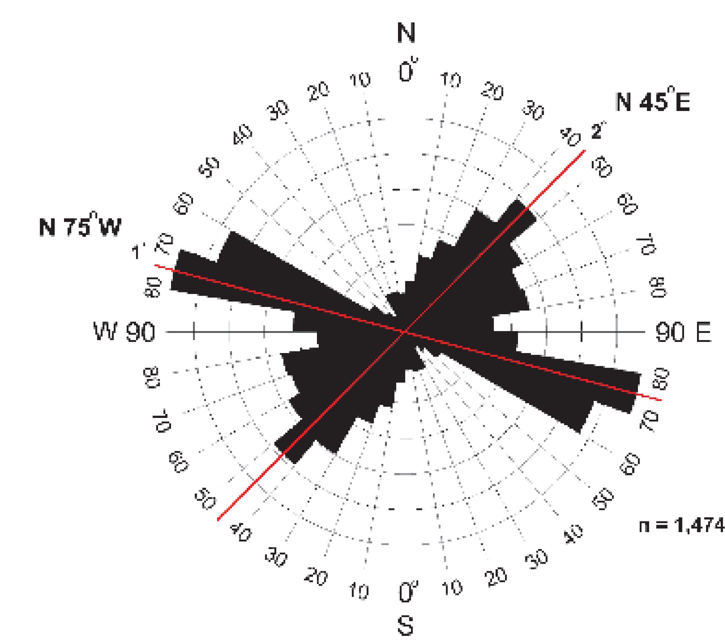


Figure 1. Index map of USGS NED shaded relief data for the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 1,474 individual lineament orientations mapped from shaded relief data in the Minot 1:250k sheet located in the northeastern portion of the Willison Basin in north-central North Dakota. The two dominant orientations (1° and 2°) are N 75° W (S 75° E) and approximately N 45° E (S 45° W), based on directional analysis of lineament line length (2a) and lineament frequency (2b).

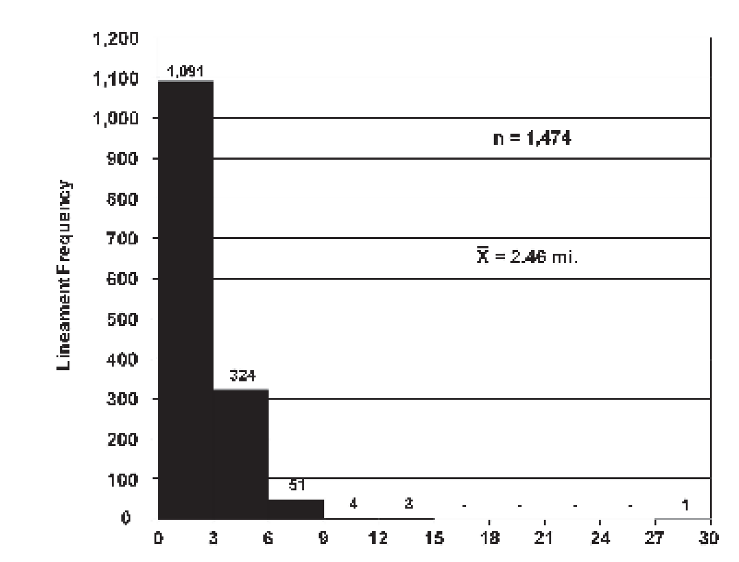


Figure 3. Frequency distribution of 1,474 individual lineament lengths from lineaments mapped from shaded relief data in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for ten lineament length classes from zero to 30 miles in 3 mile intervals or classes.

North Dakota Geological Survey
Geologic Investigations No. 145 - Plate III

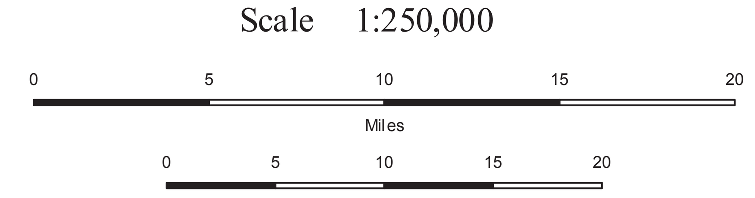
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE III - LINEAMENTS MAPPED FROM NAIP IMAGERY IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

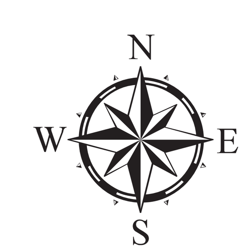
2011

Scale 1:250,000



Mercator Projection
Standard parallel 48° 00'

1927 North American Datum
Central meridian 101° 00'



Cartographic Compilation: Elroy L. Kadrmas

LINEAMENTS IN THE MINOT 1:250K SHEET DERIVED FROM AERIAL IMAGE MAP INTERPRETATION

This map presents the results and discussion of a segment of a contemporary lineament mapping and analysis study in the Minot 250k sheet. The Minot 250k sheet is located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineaments were digitally mapped and digitized from a digital aerial image mosaic of the study area, complied from 2010 USDA National Agricultural Imagery Program (NAIP) imagery (Figure 1). Lineament Mapping was conducted by successive visual and manual inspection at various scales (most commonly 1:24,000, 1:100,000, 1:250,000, and 1:1,000,000). Lineaments mapped are presented here at a scale of 1:250,000. Directional analysis of the length (Figure 2a) and frequency (Figure 2b) of the orientation (i.e. strike) of 509 individual lineaments reveals two distinct trends; a primary (1°) orientation of N 65° W (S 65° E) and a secondary (2°) orientation of approximately N 60° E (S 60° W). The distribution of lineament lengths follow a general log-normal distribution with the majority of lineaments (88%) falling within the zero to eight mile lineament length range. Over 98% of the lineaments mapped were less than 14 miles in length (Figure 3). The overall density of lineaments within the sheet (i.e. lineaments mapped per unit area) is 0.08 lineaments per square mile, approximately 2.9 lineaments per township. Lineament density is generally greater in the northeastern portion of the study area, but overall is relatively uniform in character, particularly for shorter lineaments. On this map, several of the lineaments are coincident with areas of current oil and gas field development and current exploration and production trends, particularly in eastern Renville and western Bottineau County. Lineaments mapped are likely influenced by subsurface geological (i.e., basement faulting) and surface geomorphological conditions resultant from Pleistocene glaciation. Lineament intersections are also shown (Figure 4) as an example of a variation of lineament density and are generally coincident with currently producing and developing oil and gas fields. Areas with a higher relative lineament intersection density, and a corresponding small drilling exploration footprint, include most of the area within the southern half and eastern third of the sheet. Several fields have several lineaments occurring within the field boundries, which may provide hints to deeper structure.

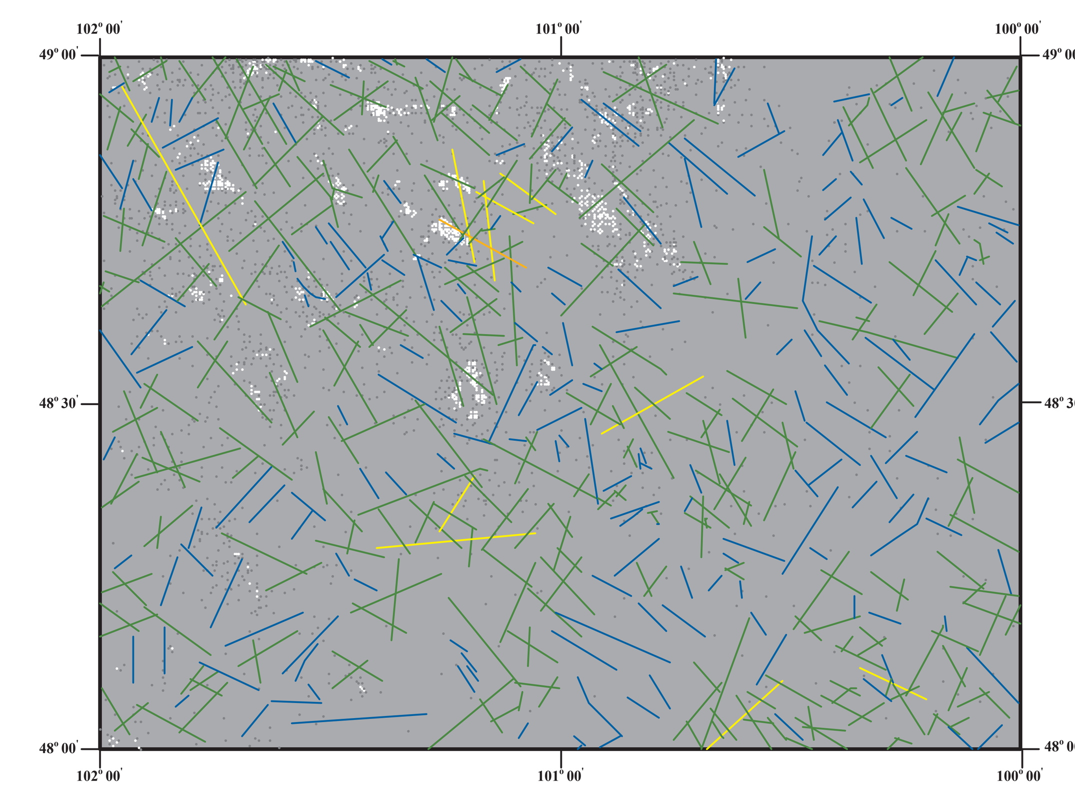


Figure 4. Lineament intersection map displaying the amount of lineament interconnectivity. Discontinuous lineaments (i.e. lineaments that do meet or intersect another lineament along the path of the lineament) are shown in blue, lineaments with intersections of 1 - 3 intersections per lineament path are shown in green, 4 - 6 yellow, and 7 - 9 orange. Producing wells (shown in white) display linear trends similiar to mapped lineament orientations. The distribution of dry holes (shown in gray) tend to be in areas where no mapped lineaments occur.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways

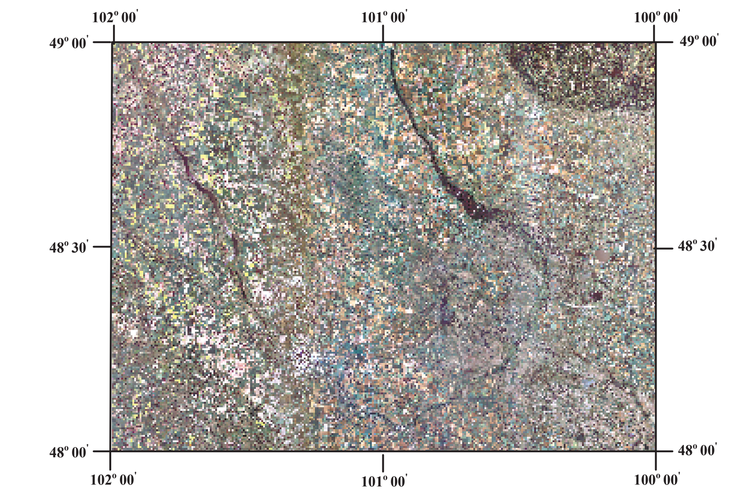
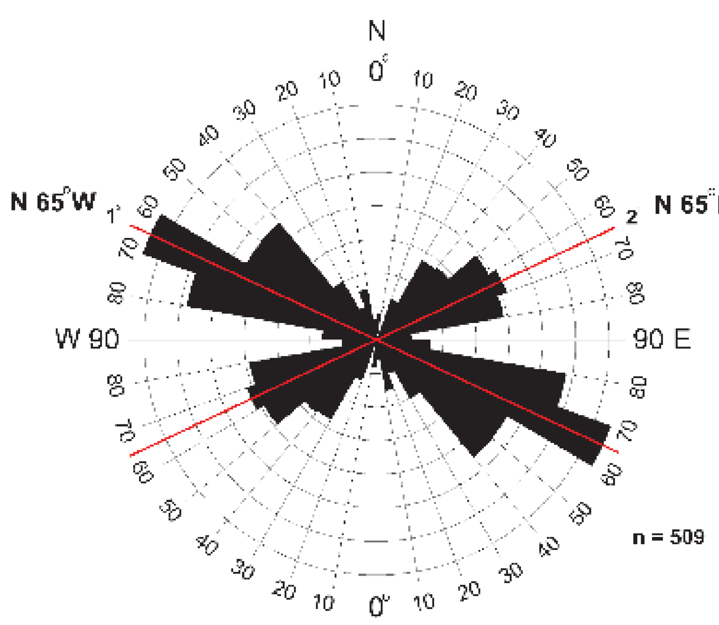
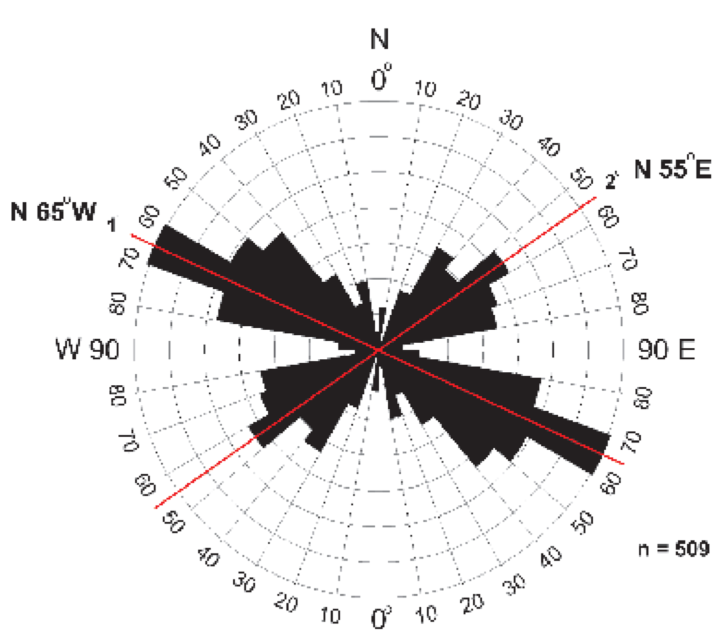


Figure 1. Map of 2010 NAIP aerial imagery used for lineament mapping in the Minot 1:250k sheet in the northeastern portion of the Williston Basin in north-central North Dakota.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 509 individual lineament orientations mapped from 2010 NAIP imagery in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. The two dominant lineament orientations (1° and 2°), are N 65° W (S 65° E), and N 55° E (S 55° W) based on orientational analysis of lineament line length (2a) and lineament frequency (2b).

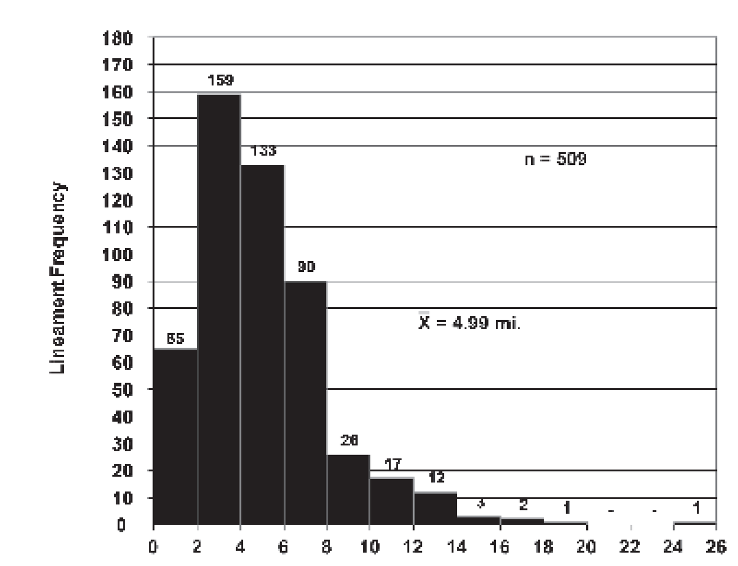


Figure 3. Frequency distribution of 509 individual lineament lengths mapped from 2010 NAIP imagery in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for 13 lineament length classes from zero to 26 miles in two mile intervals or classes.

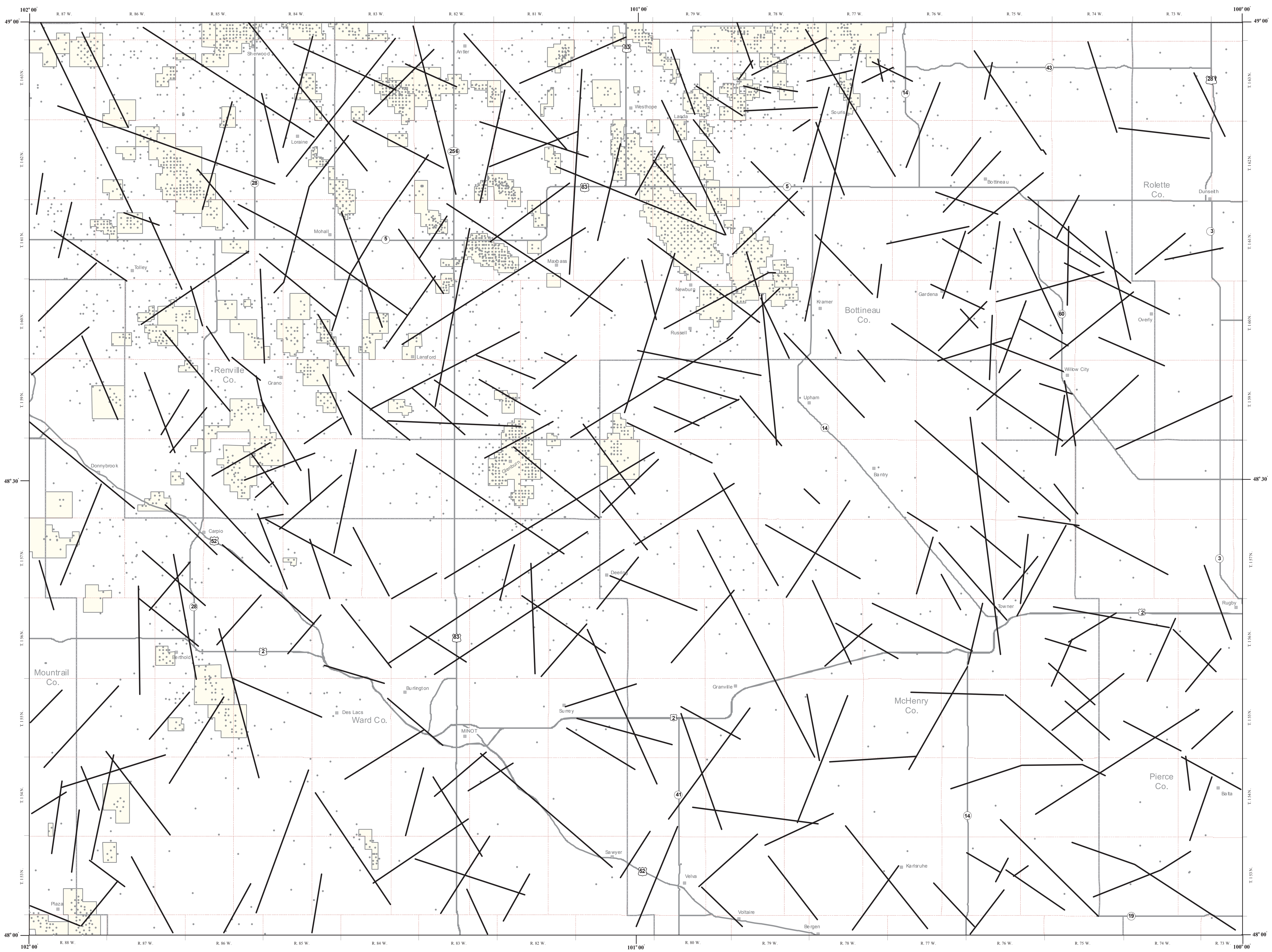
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate IV

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE IV - LINEAMENTS MAPPED FROM LANDSAT DATA IN THE MINOT 250K SHEET, NORTH DAKOTA

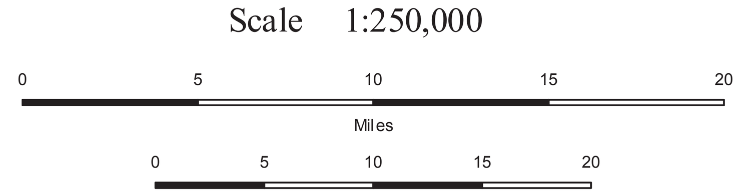
Fred J. Anderson

2012

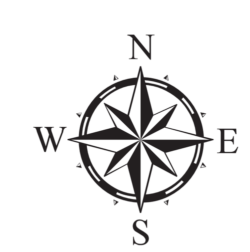


Minot 250K Sheet, North Dakota

Scale 1:250,000



Mercator Projection
Standard parallel 48° 00'
1927 North American Datum
Central meridian 101° 00'



Cartographic Compilation: Elroy L. Kadrmas

LINEAMENTS IN THE MINOT SHEET DERIVED FROM LANDSAT 7-ETM IMAGERY MAP INTERPRETATION

This map presents the results and discussion of a segment of a contemporary lineament mapping and analysis study of the Minot 1:250k map sheet in north-central North Dakota. The Minot 1:250k map area is located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineaments were digitally mapped and digitized from a digital image mosaic of the study area, compliled from 2000 LANDSAT 7 Enhanced Thematic Mapper (ETM) data. A digital image mosaic was created from four available scenes in a blue, green, red (BGR) false color combination of spectral bands 2, 4, and 7 for analysis (Figure 1). Lineament mapping was conducted by successive visual and manual inspection at various scales (most commonly 1:24,000, 1:100,000, 1:250,000, and 1:1,000,000). Lineaments mapped are presented here at a scale of 1:250,000. Lineament orientation analysis of 303 individual lineaments reveal two distinct orientation trends (Figures 2a. and b.). A primary (1^{o}) orientation of N 65° W (S 65° E), and a secondary (2^{o}) orientation of approximately N 60° E (S 60° W). The distribution of lineament lengths follows a general log-normal distribution with the majority of lineaments (82%) falling within the two to ten mile lineament length range. Overall, 85% of the lineaments mapped were less than 10 miles in length (Figure 3). The overall density of lineaments within the study area (i.e. lineaments mapped per unit area) is 0.05 lineaments per square mile (approximately 1.7 lineaments per township). Lineament density is generally greater in the northwestern portion of the study area but overall is relatively uniform in character. This may attributed partially to the existence of large tracts of agricultural land (i.e., cultivated crops) where image tonal constrasts are reduced. On this map, several of the lineaments are coincident with areas of current oil and gas field development and current exploration and production trends. Lineaments mapped from this imagery source may be influenced by subsurface geological (e.g., basement faulting) conditions but are likely more heavily influenced by Pleistocene glacial processes. Lineaments are generally coincident with currently producing and developing oil and gas fields and areas where exploratory oil and gas drilling has been completed. Lineament density appears to be generally greater in areas of currently producing wells and less in areas of non-producing wells. Horizontal drilling and production trends have suggested more successful preferential horizontal leg completions along a NW trend throughout the Williston Basin of North Dakota. Visual analysis of lineaments mapped perpendicular to sub-perpendicular of this trend suggest a relatively higher amount of lineament frequency (i.e., lineaments encountered per path) normal to the preferred NW trend (Figure 4). The Souris River is the major surface water feature found in the map area. The southwestern portion of the Turtle Mountains are present in the northeastern corner of the map area. These features are not displayed on the 1:250,000 scale lineament map shown at the left.

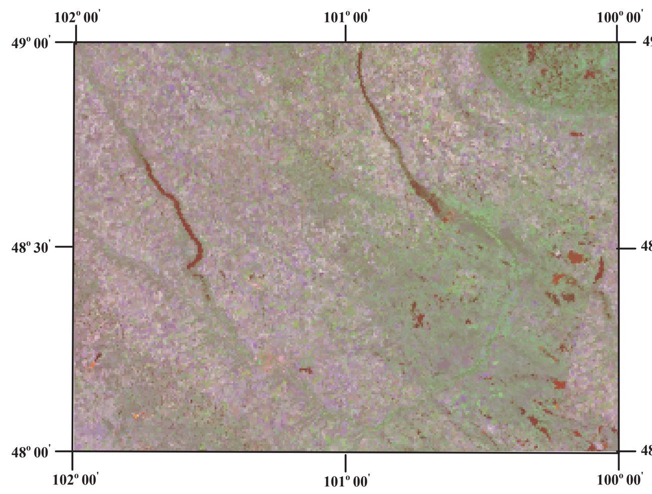
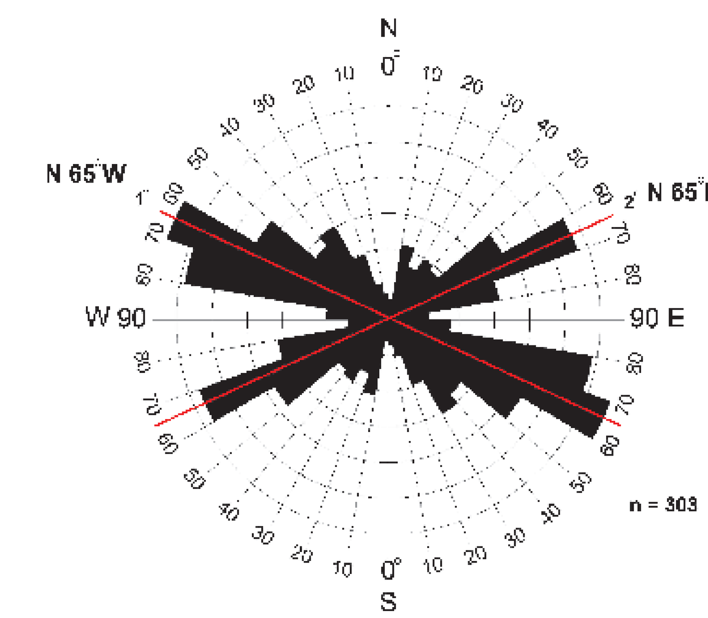
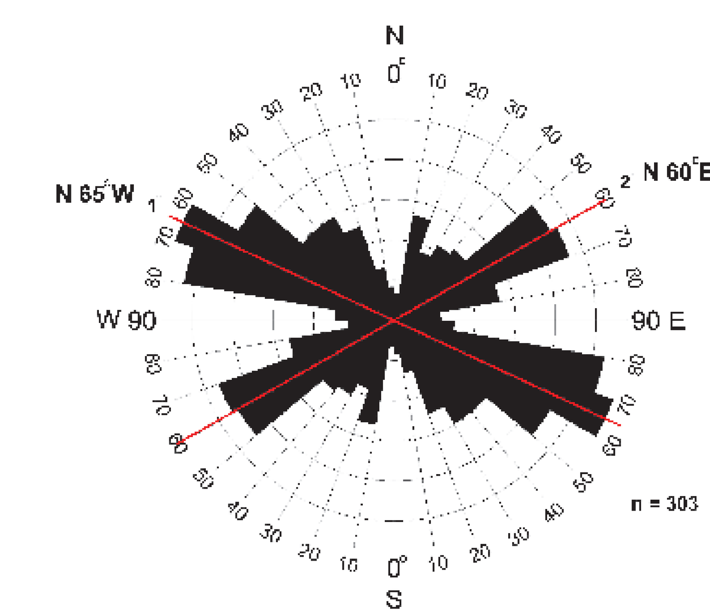


Figure 1. Map of 2000 LANDSAT 7-ETM false color (2-4-7) imagery used for lineament mapping in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Agricultural land use can again be seen as the patchwork pattern (green) throughout the central and eastern two-thirds of the study area.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 303 individual lineament orientations mapped from 2000 LANDSAT 7-ETM imagery in the Minot 1:250k sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. The two dominant lineament orientations (1^{o} and 2^{o}), are N 65° W (S 65° E), and approximately N 60° E (S 60° W) based on orientational analysis of lineament length (2a) and lineament frequency (2b).

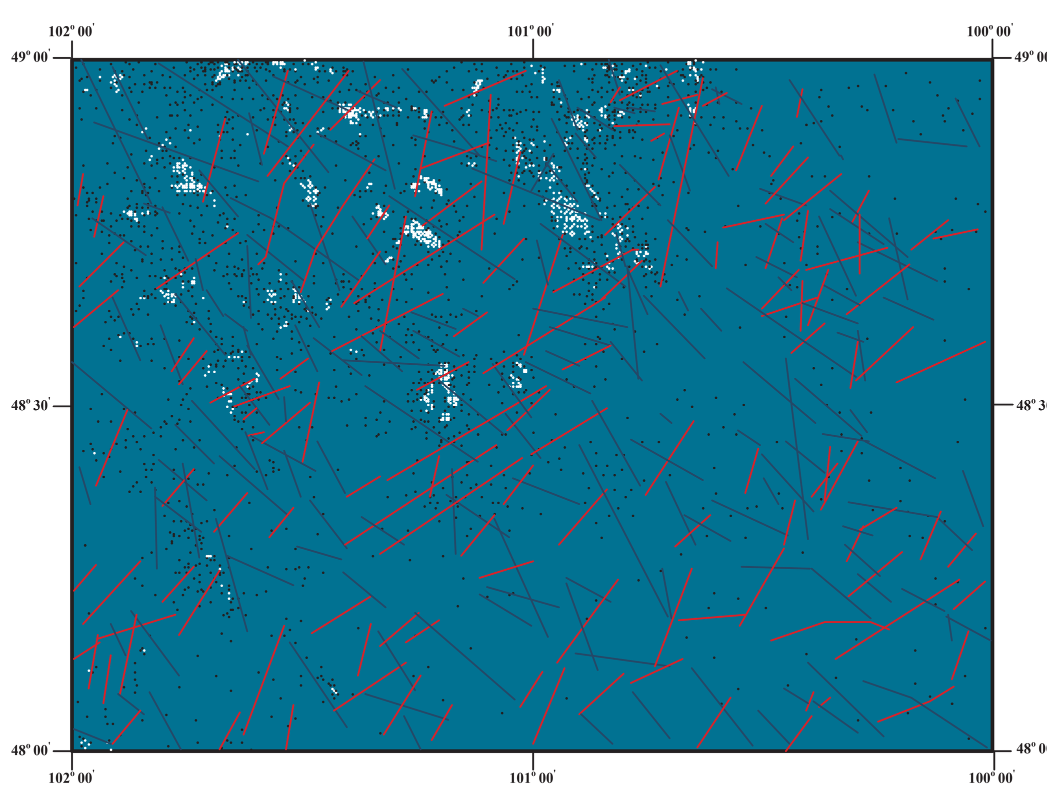


Figure 4. Lineament map displaying lineaments in two classes of lineament orientation. Lineaments oriented along a N-NE or S-SW orientation are showin in red, lineaments oriented along a N-NW or S-SE orientation are shown in blue. Producing wells (shown in white) tend to be located near areas of relatively higher lineament density. The distribution of dry holes (shown in black) tend to be in areas where lineament density is relatively low.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways

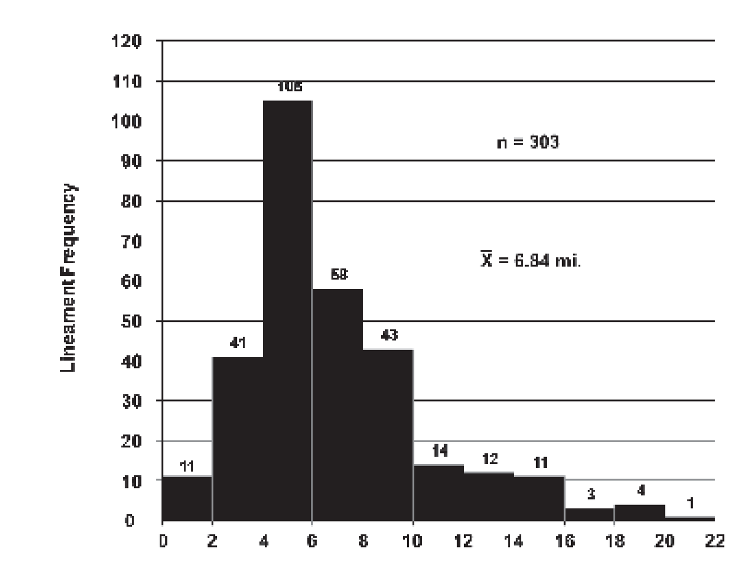


Figure 3. Frequency distribution of 303 individual lineament lengths (distance in miles) mapped from 2000 LANDSAT 7-ETM false color (2-4-7) imagery of the Minot 1:250k map sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for 11 lineament length classes from zero to 22 miles in two mile intervals or classes.

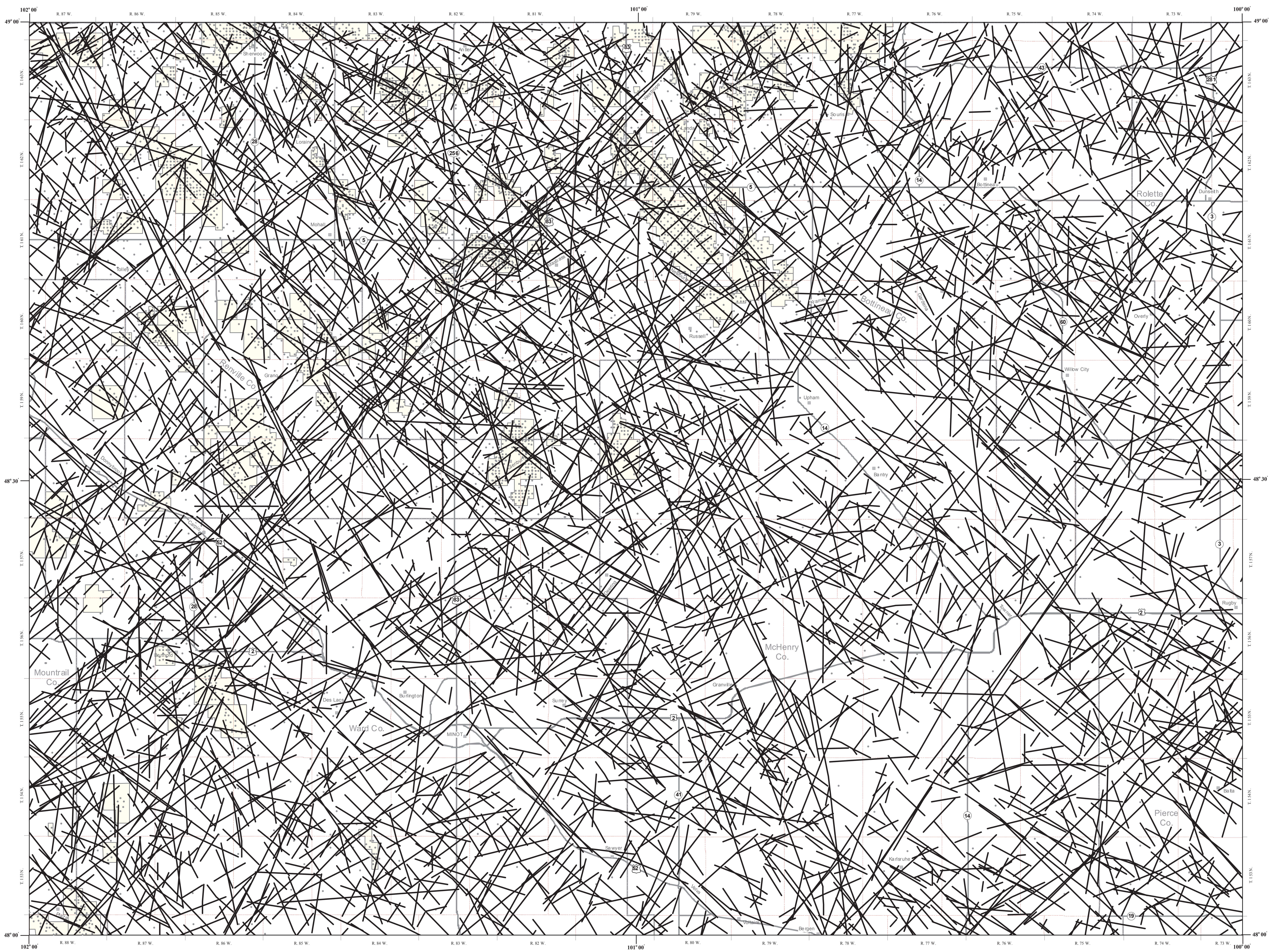
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate V

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE V - COMPILED LINEAMENTS MAPPED IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

2012



COMPILED LINEAMENTS IN THE MINOT SHEET

This map presents the results and discussion of a segment of a contemporary lineament analysis study of the Minot 1:250k map sheet in north-central North Dakota. The Minot 1:250k map area is located in the northeastern portion of the Williston Basin in the north-central part of the state. Lineaments were compiled from Plates I - V for this map (Figure 1). Lineaments compiled are presented here a scale of 1:250,000. Lineament orientation analysis of 3,604 mapped lineaments reveal two dominant orientation trends (Figures 2a. and b.). A primary (1°) orientation of approximately N 60° W (S 60° E) and a secondary (2°) orientation of N 55° E (S 55° W). The distribution of lineament length follows a sharp log-normal distribution with the majority of lineaments (96%) falling within the 0-12 mile lineament length size range (Figure 3). The density of lineaments (i.e. lineaments mapped per unit area) is generally greater in the northwestern and southwestern portions of the map area with an overall linement density of 0.57 lineaments per square mile (~20 lineaments per township). In this map, the general distribution of lineaments is likely more influenced by surface geomorphology and to a lesser degree by subsurface geologic conditions. Lineament density is observed to be greatest and generally coincident with current oil and gas field development, and current exploration and production trends. Overall, lineament density appears to be greater in areas of currently producing wells and relatively lower in areas of limited or no production (Figure 4).

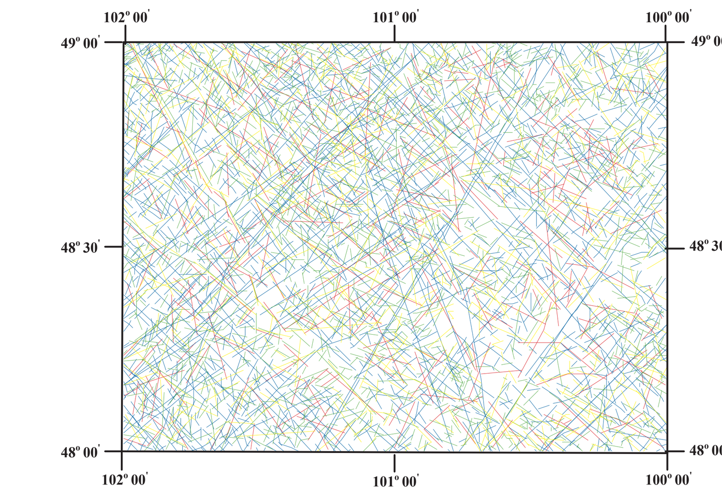
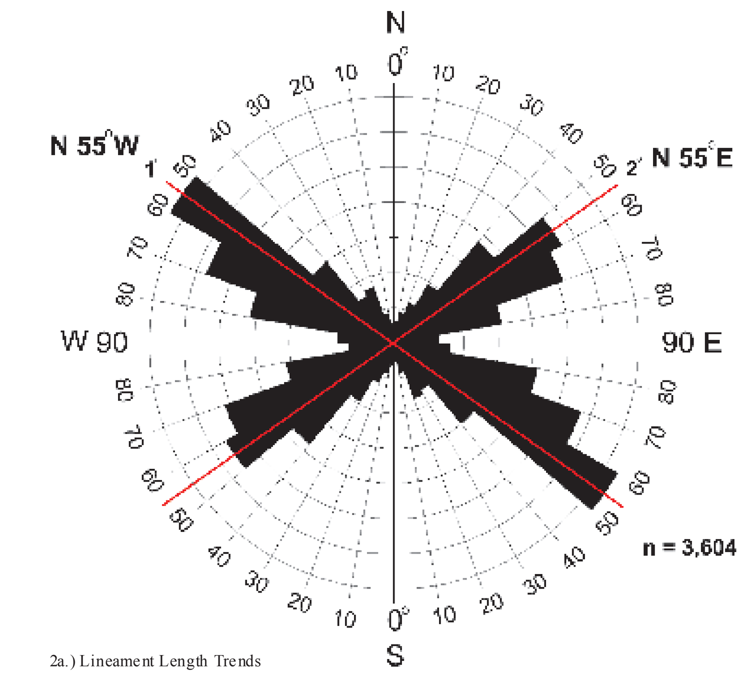
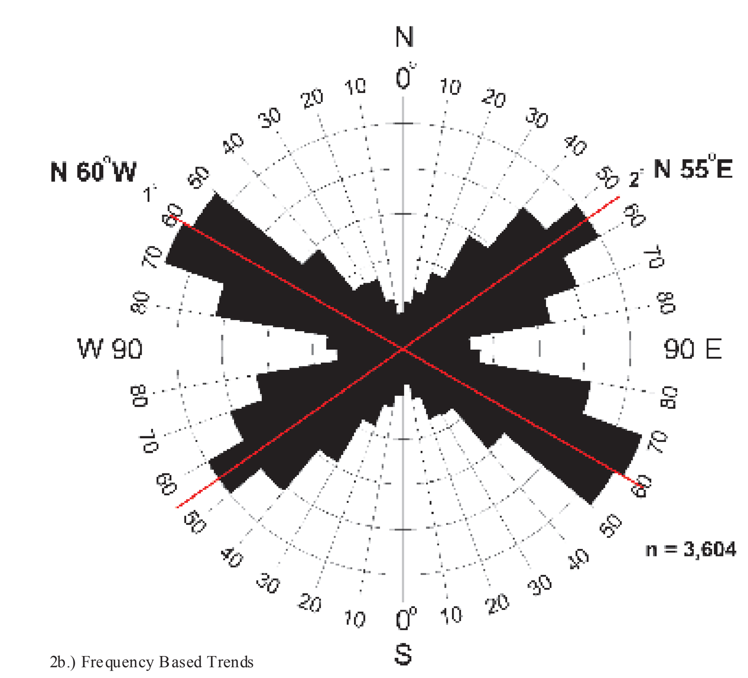


Figure 1. Index map of compiled lineaments in the Minot 1:250k map sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Historical or lineaments compiled from previous studies, are shown in blue. Lineaments mapped from shaded relief data are shown in green. Lineaments mapped from aerial imagery are shown in yellow. Lineaments mapped from LANDSAT imagery are shown in red.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 3,604 individual lineament orientations compiled from all lineaments mapped in the the Minot 1:250k sheet located in the northeastern portion of the Willison Basin in north-central North Dakota, analyzed for trends in strike orientation by lineament length (2a) and frequency based (2b) methods. There are two dominant orientation trends (1° and 2°) displayed within the data of approximately N 60° W (S 60° E) and N 55° E (S 55° W).

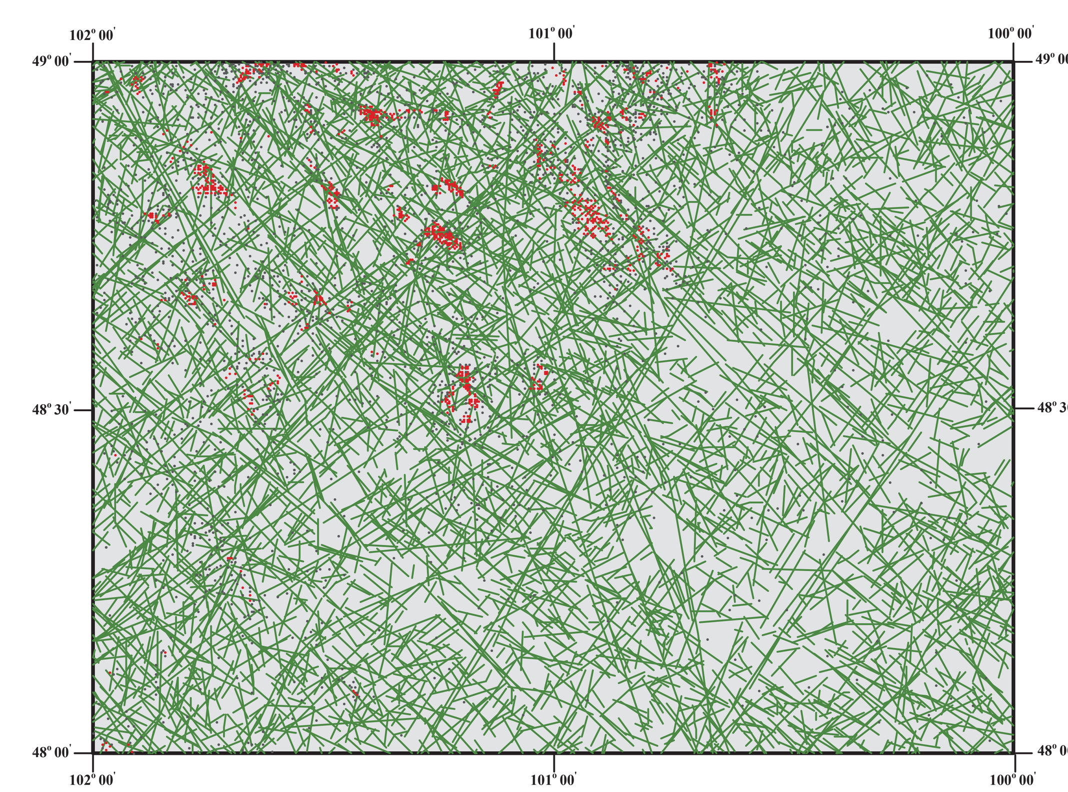


Figure 4. Map of compiled lineaments (green) with currently producing wells (red) and non-producing wells (dark gray) displaying the general relationships between overall lineament trends and densities and oil and gas production and development in the Minot 1:250k Sheet.

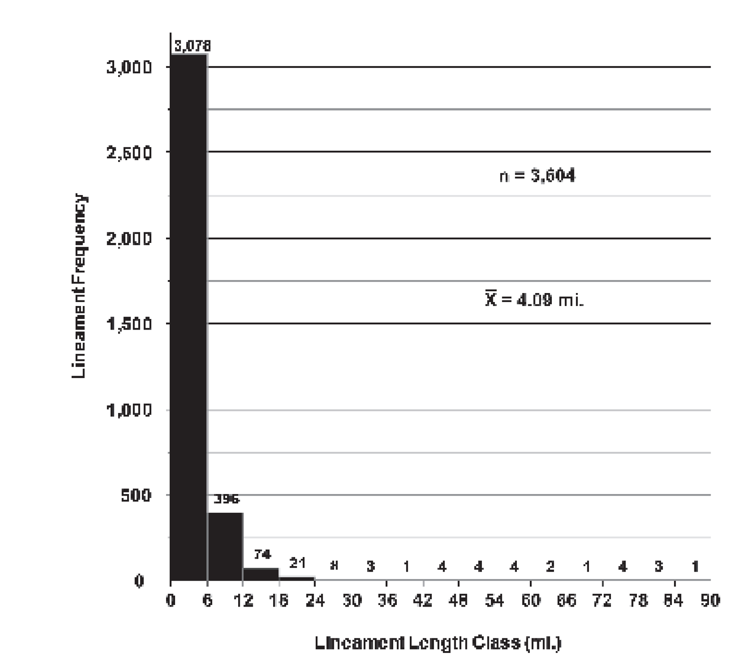


Figure 3. Frequency distribution of 3,604 individual lineament lengths (distance in miles) compiled from lineaments mapped in the Minot 1:250k map sheet located in the northeastern portion of the Williston Basin in north-central North Dakota. Lineament distributions are shown for 15 lineament length classes from zero to 90 miles in 6 mile intervals.

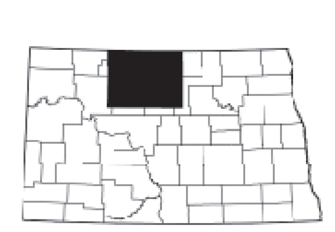
EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways



Minot 250K Sheet, North Dakota

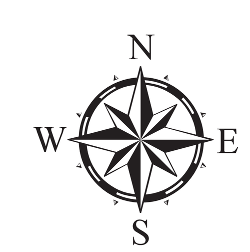
Scale 1:250,000

0 5 10 15 20
Miles

0 5 10 15 20
Kilometers

Mercator Projection
Standard parallel 48° 00' 00"

1927 North American Datum
Central meridian 101° 00' 00"



Cartographic Compilation: Elroy L. Kadrmas

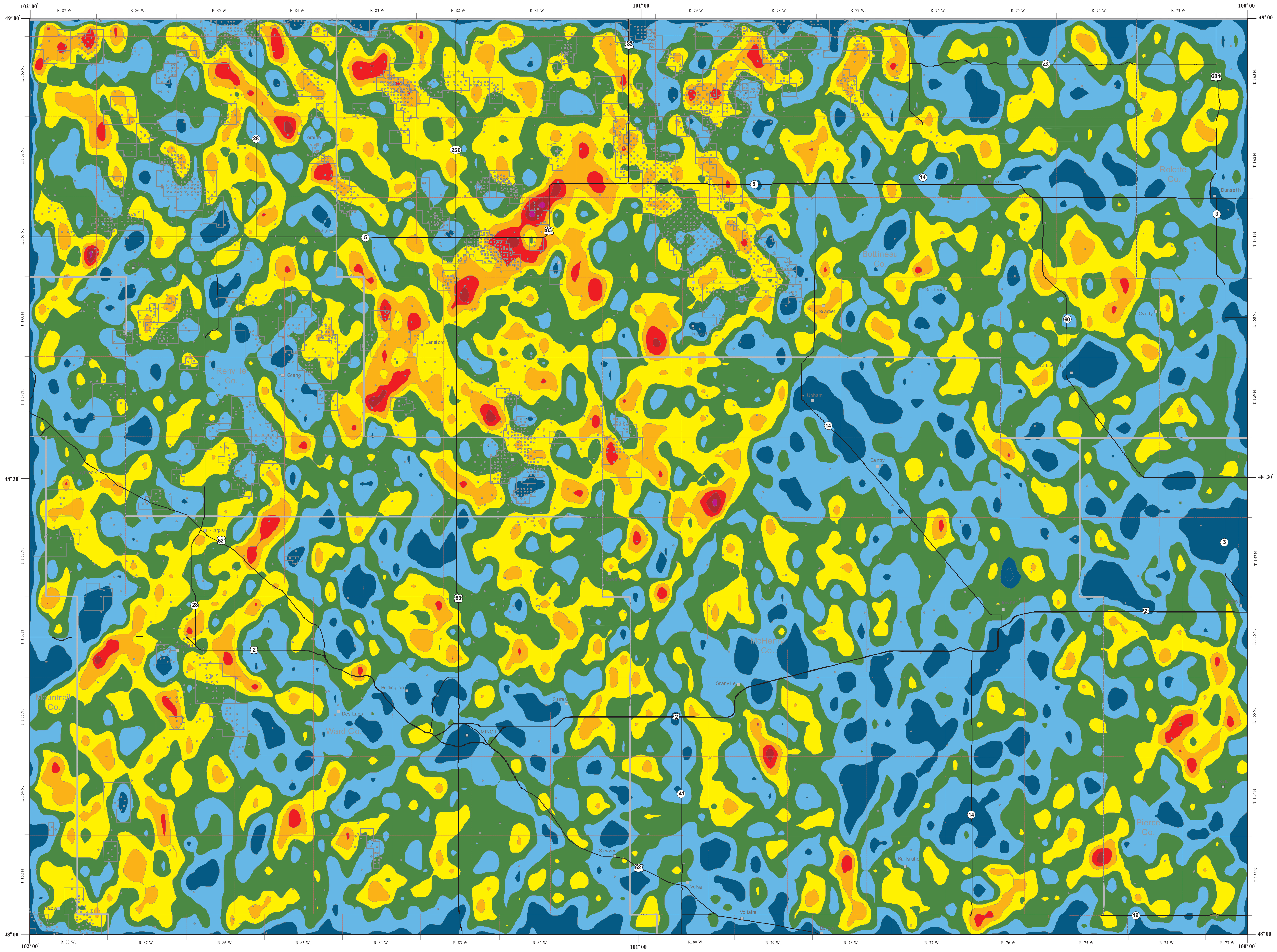
North Dakota Geological Survey
Geologic Investigations No. 145 - Plate VI

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE VI - LINEAMENT DENSITY MAP OF THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

2012



LINEAMENT DENSITY MAPPING IN THE MINOT SHEET

This map presents the results and discussion of a segment of a contemporary lineament analysis of the Minot 1:250k sheet located in the northeastern Williston Basin in north-central North Dakota.The density of lineaments for this map was determined from the compliled lineaments extracted from Plate V of this report. Lineament density was calculated across the map area by automated analysis of all lineament lengths found to occur within a 1 mile x 1 mile grid cell coincident with actual Public Land Survey System (PLSS) sections. Cellular lineament density values (i.e., lineament line length within each unit cell) were assigned to nodal values for the centers of each of the grid cells (sections). The resulting x,y,z data file was contoured across the determined data range in 5,000-ft intervals from 0 to >40,000-ft/mi^2. Lineament density classes are depicted on this map as ranging from areas of lower lineament density, shown as cooler colors, to areas of higher lineament density, shown as warmer colors. This map shows areas of higher lineament density in the northwestern portion of the map area and lower lineament density towards the southeast. Overall, lineament density appears to be greatest and relatively coincident with areas where producing oil and gas wells and fields are commonly located, and lower in areas where non-producing wells have been drilled (Figure 1). This suggests a relationship between overall production and areas of relatively higher lineament density.

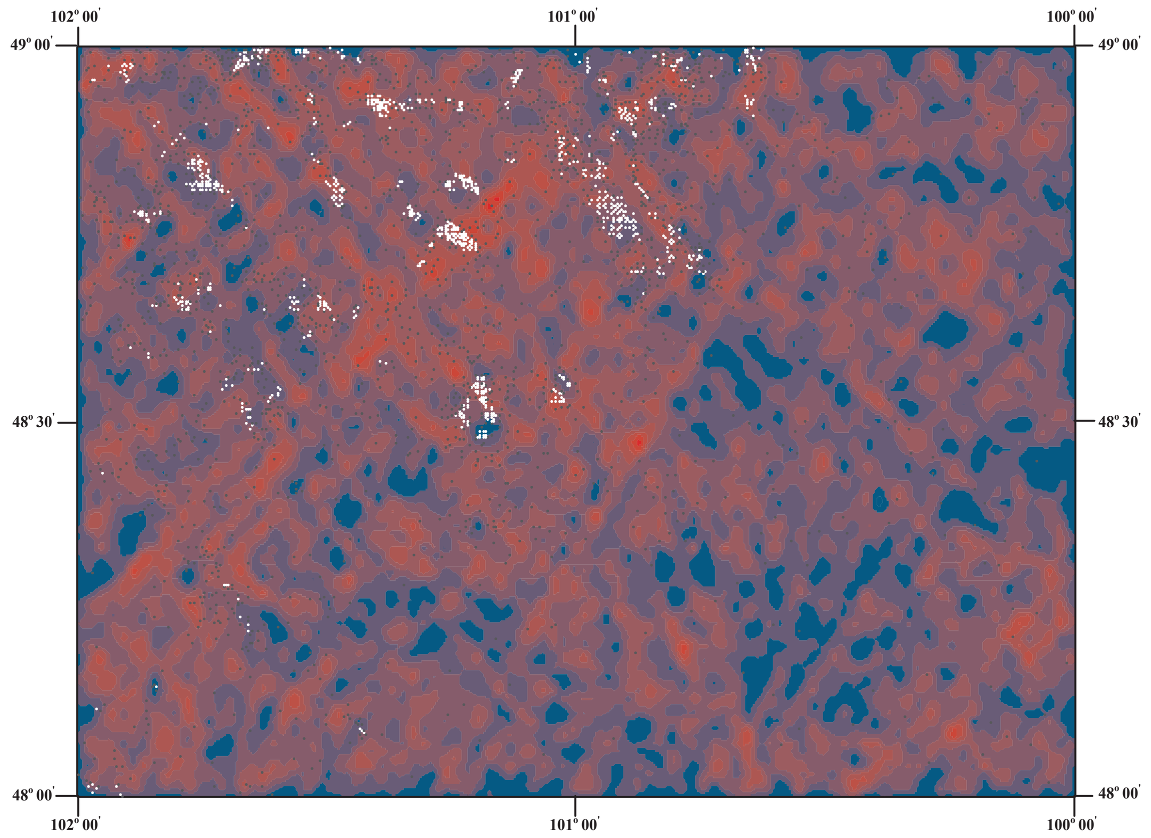


Figure 1. Lineament density map displaying lineament density with currently producing (white) and non-producing (dark gray) wells in the Minot 1:250k sheet. Producing wells tend to be located near areas of relatively higher lineament density (shown in red). The distribution of dry holes or non-producing wells tend to generally be distributed throughout areas where lineament density is relatively low (shown in blue).

Lineament Density (ft/mi^2)

- 35,000 - >40,000
- 30,000 - 35,000
- 25,000 - 30,000
- 20,000 - 25,000
- 15,000 - 20,000
- 10,000 - 15,000
- 5,000 - 10,000
- 0 - 5,000

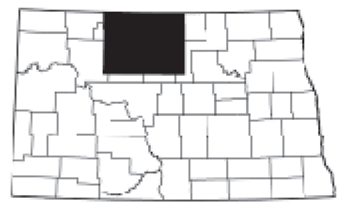
EXPLANATION

Geologic Features

- Drill Hole
- Oil & Gas Fields

Other Features

- Towns
- Township Boundaries
- County Boundaries
- State and US Highways



Minot 250K Sheet, North Dakota

Scale 1:250,000

0 5 10 15 20
Miles

0 5 10 15 20
Kilometers

Mercator Projection
Standard parallel 48° 00'

1927 North American Datum
Central meridian 101° 00'

Cartographic Compilation: Elroy L. Kadrmas

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

PLATE VII - 3D VISUALIZATION OF LINEAMENTS MAPPED IN THE MINOT 1:250K SHEET, NORTH DAKOTA

Fred J. Anderson

2012

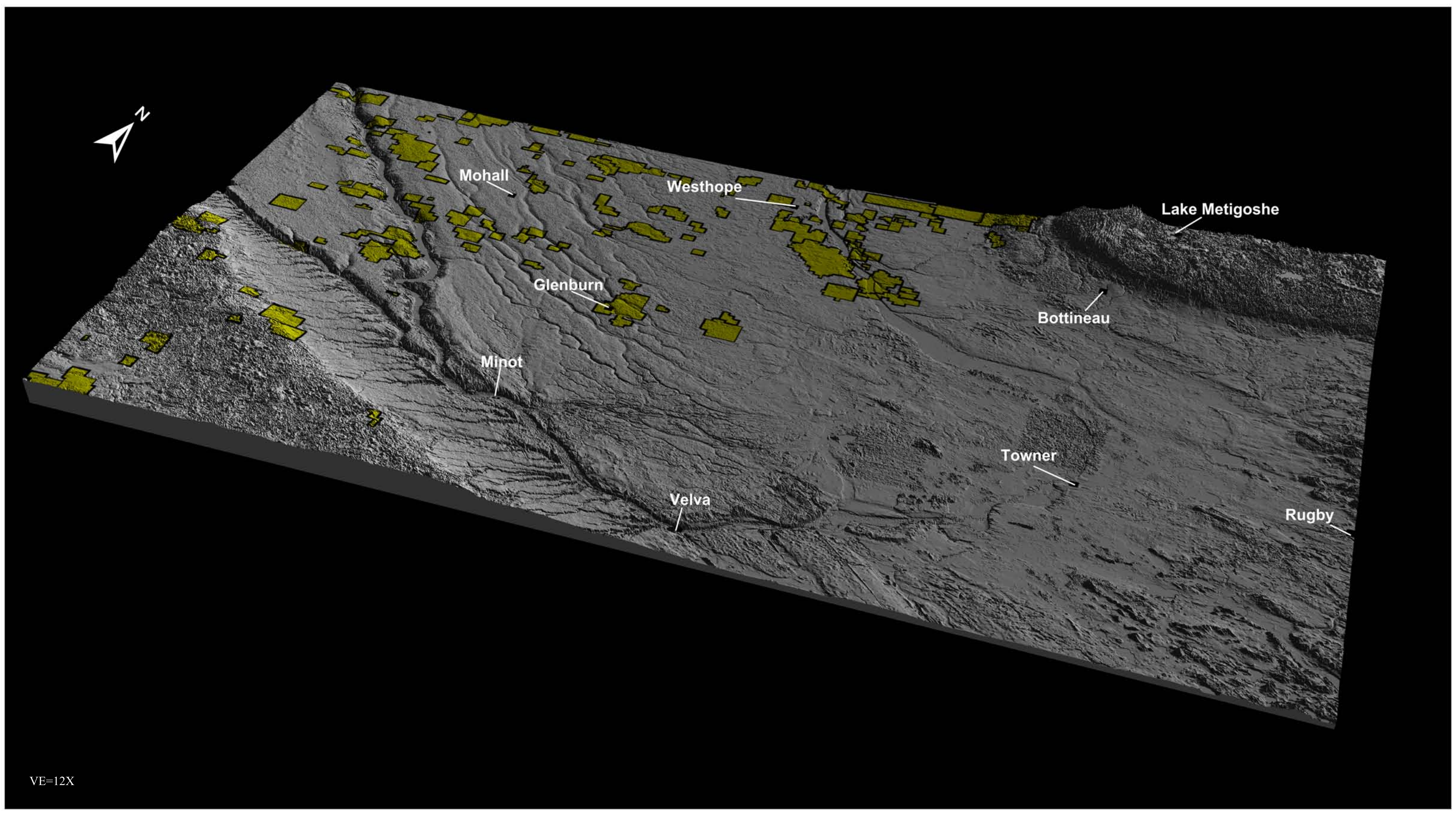
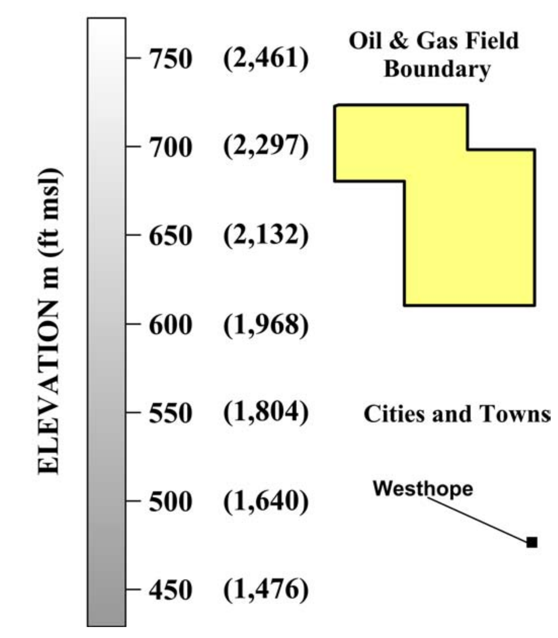


Figure 1. Three-Dimensional (3D) perspective view, from the southeast towards the northwest, across a digital elevation model (DEM) of the Minot 1:250k map sheet located in the northeastern Williston Basin in north-central North Dakota. This DEM was created from a 30 meter resolution digital elevation dataset extracted from the USGS 1997 National Elevation Dataset (NED) and is shown here at a vertical exaggeration of 12X.

For the rendering of this DEM, the lighting direction is from the northeast at 45° with an angle of inclination of 30°. The Minot 1:250k map sheet covers the majority of the lower Souris River Basin in North Dakota. The northeastern edge of the Max Moraine portion of the Missouri Escarpment is present in the southwestern-most corner of the map area. The confluence of the Des Lacs and Souris Rivers above Minot can also be found in the southwest portion of the map area just northeast of the escarpment. The southeastern corner of the Turtle Mountains is present as the area of highest elevations found in the northeastern corner of the map. The areas covered by current oil and gas field boundaries are highlighted in yellow on the surface of the DEM.

EXPLANATION



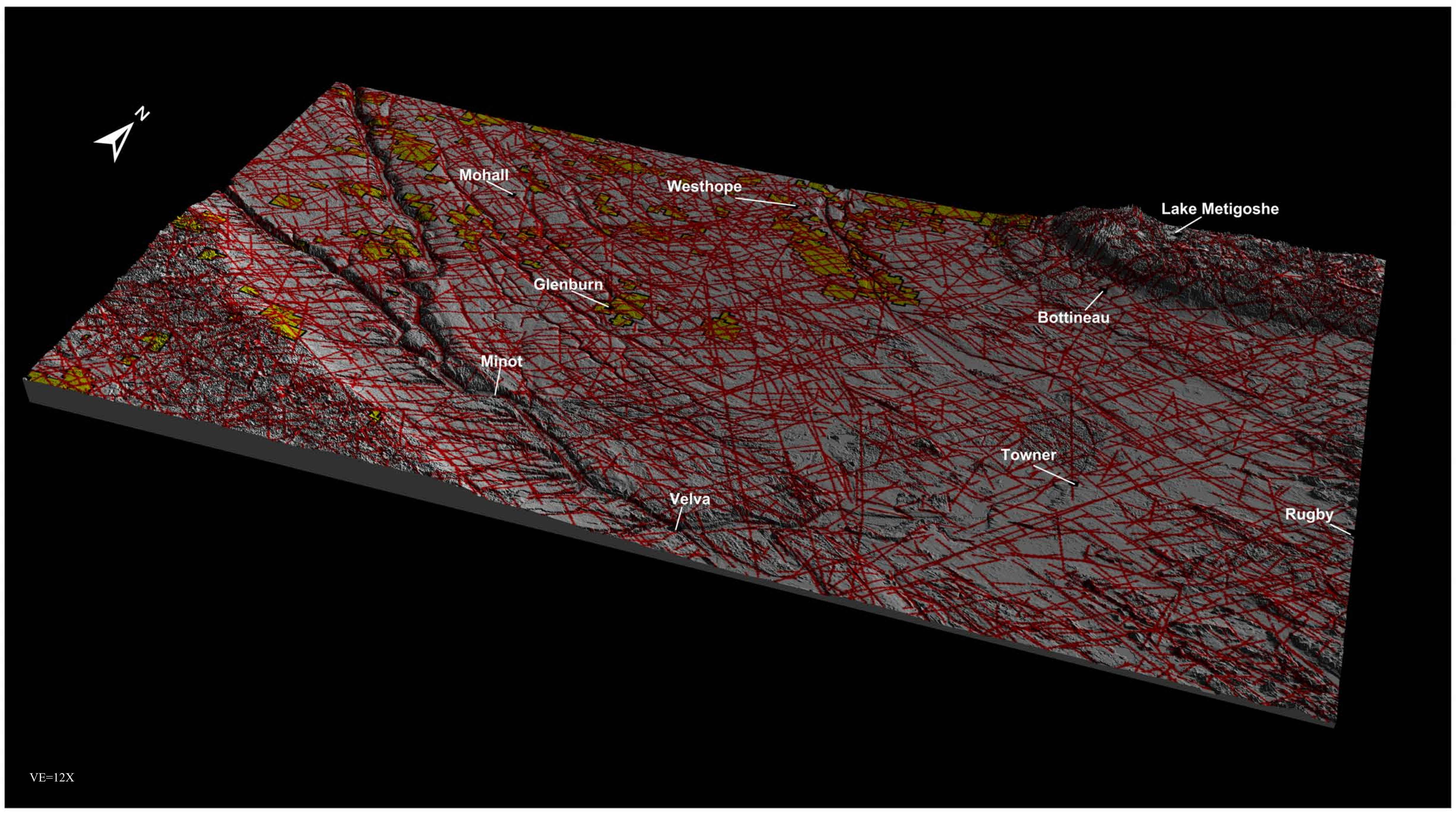
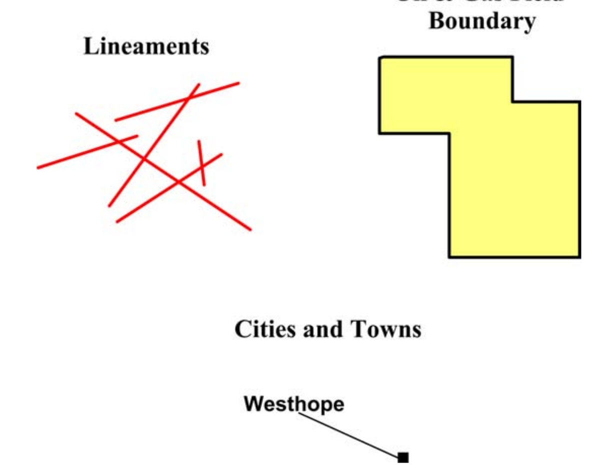


Figure 2. Lineaments mapped from selected imagery and data sources (i.e. historical, NED shaded relief, NAIP Imagery, and Landsat-7 ETM+ data) throughout the Minot 1:250k map sheet are shown in red overlain onto the land-surface DEM created from the USGS 1997 NED. In this view, the relationships between the locations of the current boundaries of current oil and gas fields and mapped lineaments is shown. Mapped lineaments are shown to be present within or traverse across every oil and gas field in the map area and many are found to intersect within field boundaries. A high degree of lineament intersection suggests a higher amount of overall structural geologic development within a given rock volume and may be suggestive of relatively reservoir porosities and permeabilities due to amounts of naturally occurring structures (i.e. faults and fractures) within the reservoir. The areas covered by current oil and gas field boundaries are highlighted in yellow on the surface of the DEM displayed beneath the lineaments.

EXPLANATION



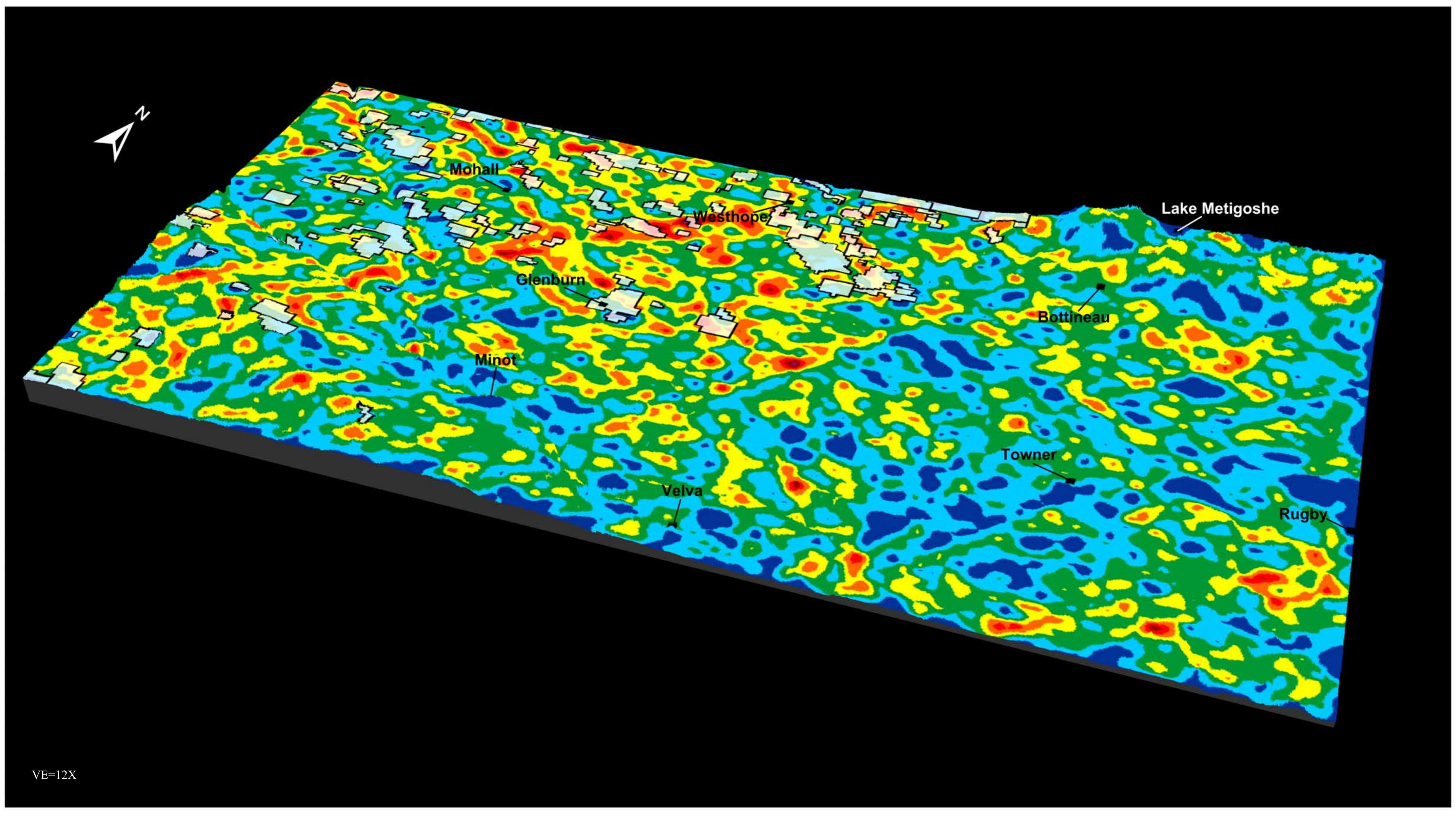


Figure 3. Interpolated lineament density map of compiled lineaments mapped within the Minot 1:2505 map sheet overlain on the surface DEM created from the USGS 1997 NED. Areas of higher lineament density are depicted as warmer colors (yellow, orange, red, purple) and areas of lower lineament density are shown as cooler colors (blues and green). Lineament densities are higher in the western and northern portions of the map area generally coincident with the locations of existing oil and gas field boundaries. A high degree of lineament density suggests a higher amount of overall structural geologic development which may be related to areas of increased oil and gas production or can also be suggestive of the existence of subsurface structural boundary zones serving to define reservoir boundaries. The extent of current oil and gas fields are shown as black field boundaries draped over the lineament density map.

EXPLANATION