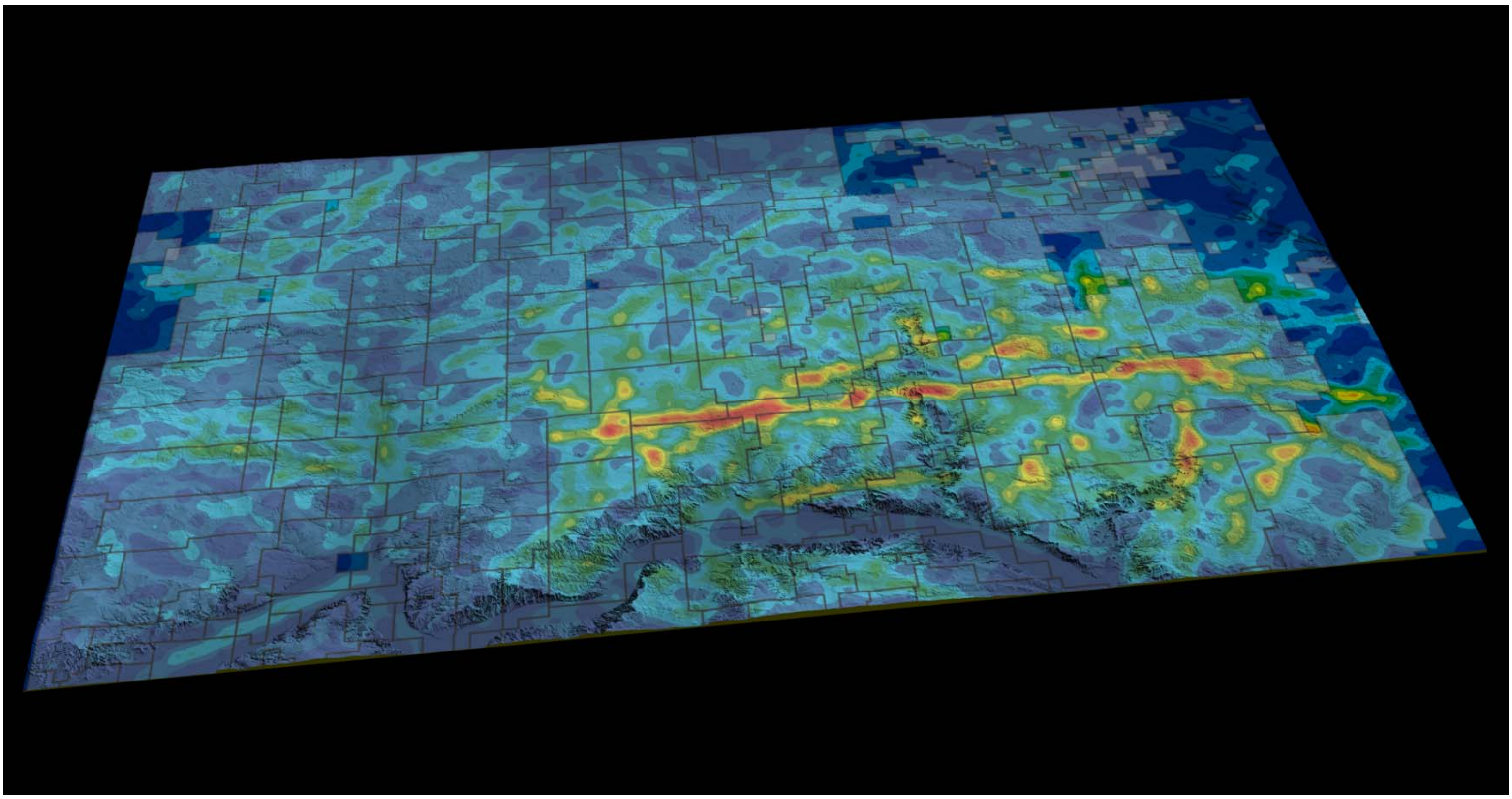
LINEAMENT MAPPING AND ANALYSIS IN THE NORTH-CENTRAL WILLISTON BASIN IN NORTHWESTERN NORTH DAKOTA

By

Fred J. Anderson



GEOLOGIC INVESTIGATIONS NO. 195
NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
2016

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

By

Fred J. Anderson

North Dakota Geological Survey

North Dakota Department of Mineral Resources

Mailing Address: 600 East Boulevard, Bismarck, ND 58505

Office Location: 1016 East Calgary Avenue, Bismarck, ND 58503

GEOLOGIC INVESTIGATIONS NO. 195
NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
2016

On the cover: Three-dimensional perspective view from the southwest towards the northeast across the Williston 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 6,490 square mile area, located in the north-central portion of the Williston Basin in northwestern 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), NED digital shaded relief data, NAIP 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, with minor expression of lineament trends in a northeasterly orientation between 5^{o} and 10^{o}, which is 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 areas of generally higher lineament density in the southeast central portion of the map area which includes most of northwestern Mountrail County. Areas with a higher degree of overall lineament density and low degree of oil and gas exploration and development in the northwestern 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, although it is evident that well locations west of the Nesson Anticline continue to be developed along uniform east-west development corridors. Some areas of non-producing wells appear distributed throughout areas of lesser lineament development, in particular in areas north and west of the Nesson Anticline.

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 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, & 2012), 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. Oil and gas well locations are shown throughout this work as the collar locations only (not the lateral traces) in order to permit observational focus on the actual mapped lineaments. Further investigation of vertical and horizontal well location, orientation, and production trends is planned to follow this work.

TABLE OF CONTENTS

Abstract ii
Acknowledgements ii
Author's Note ii

BACKGROUND 1
Introduction 1
Description of the Study Area 1
Previous Lineament Studies Conducted at Various Scales 1

LINEAMENT MAPPING AND ANALYSIS METHODOLOGY 4
Description of Data and Imagery Sources 4
Historical (Previously Mapped) Lineaments 4
NED Shaded Relief Data 4
National Agricultural Imaging Program (NAIP) Imagery 4
LANDSAT 7 Enhanced Thematic Mapper (ETM+) Imagery 7
Merged (Compiled) Lineaments 7
Lineament Mapping and Analysis Methodology 7
Lineament Density Mapping 12

RESULTS AND CONCLUSIONS 12
Lineament Orientations 12
Distributions of Lineament Lengths 16
Lineament Density Mapping 18

DISCUSSION 19

REFERENCES 20

LIST OF TABLES

Table 1. Summary of Data and Imagery Sources used for Lineament Mapping 4
Table 2. Dominant Lineament Orientations Mapped 15
Table 3. Lineament Characteristics 16
Table 4. Map Surface Area Covered by Lineament Density Class 18

LIST OF FIGURES

Figure 1. Location of the Williston1:250k Map Sheet Study Area 2
Figure 2. Historical (Previously Mapped) Lineaments in the Williston Area 3
Figure 3. Lineaments Mapped from Shaded Relief Data in the Williston Area 5
Figure 4. Lineaments Mapped from NAIP imagery 6
Figure 5. Lineaments Mapped from LANDSAT-7 ETM+ data 8
Figure 6. Merged Lineaments in the Minot Area 9
Figure 7. Summary of Lineament Orientation Trends in the Williston Area 10
Figure 8. Frequency Distributions of Lineament Lengths in the Williston Area 11
Figure 9. Lineament Density Map of the Williston Area 13
Figure 10. Lineament Density Map with Locations of Currently Producing and non-Producing Wells 14

LIST OF PLATES

Plate I. Historical Lineaments Mapped in the Williston 1:250k Sheet, North Dakota 22
Plate II. Shaded Relief Lineaments Mapped in the Williston 1:250k Sheet, North Dakota 23
Plate III. Lineaments Mapped from NAIP Imagery in the Williston 1:250k Sheet, North Dakota 24
Plate IV. Lineaments Mapped from LANDSAT Data in the Williston 1:250k Sheet, North Dakota 25
Plate V. Compilation of Lineaments Mapped in the Williston 1:250K Sheet, North Dakota 26
Plate VI. Lineament Density Map of the Williston 1:250k Sheet, North Dakota 27
Plate VII. 3D Visualization of Lineaments Mapped in the Williston 1:250k Sheet, North Dakota 28

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 Williston 1:250k map sheet located in the north-central Williston Basin in northwestern 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 have not been field verified.

Description of the Study Area

The area within the Williston 1:250k map sheet is within the standard 1:250,000 scale (1^o x 2^o) quadrangle that covers an approximate 6,490 square mile area from 48^o to 49^o North Latitude and 102^o to 104.06^o West Longitude. The study area also includes the westernmost portion of the Wolf Point 1:250k map sheet that falls within the North Dakota Boundary that lies directly adjacent to the western boundary of the Williston 1:250k map sheet. This quadrangle contains nearly all of Williams County and the northwestern two-thirds of Mountrail County in the south and all of Divide and Burke Counties in the North. A small approximately five township area of Ward County is also included in the map area in the northeast. This 1:250k quadrangle study area is bounded to the north by the border with the Province of Saskatchewan, Canada, the west by the Wolf Point, Montana 250k quadrangle, the east by the Minot 1:250k quadrangle, and the south by the Watford City 1:250k quadrangle. Most of the study area is covered by oil and gas field development (Figure 1).

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).

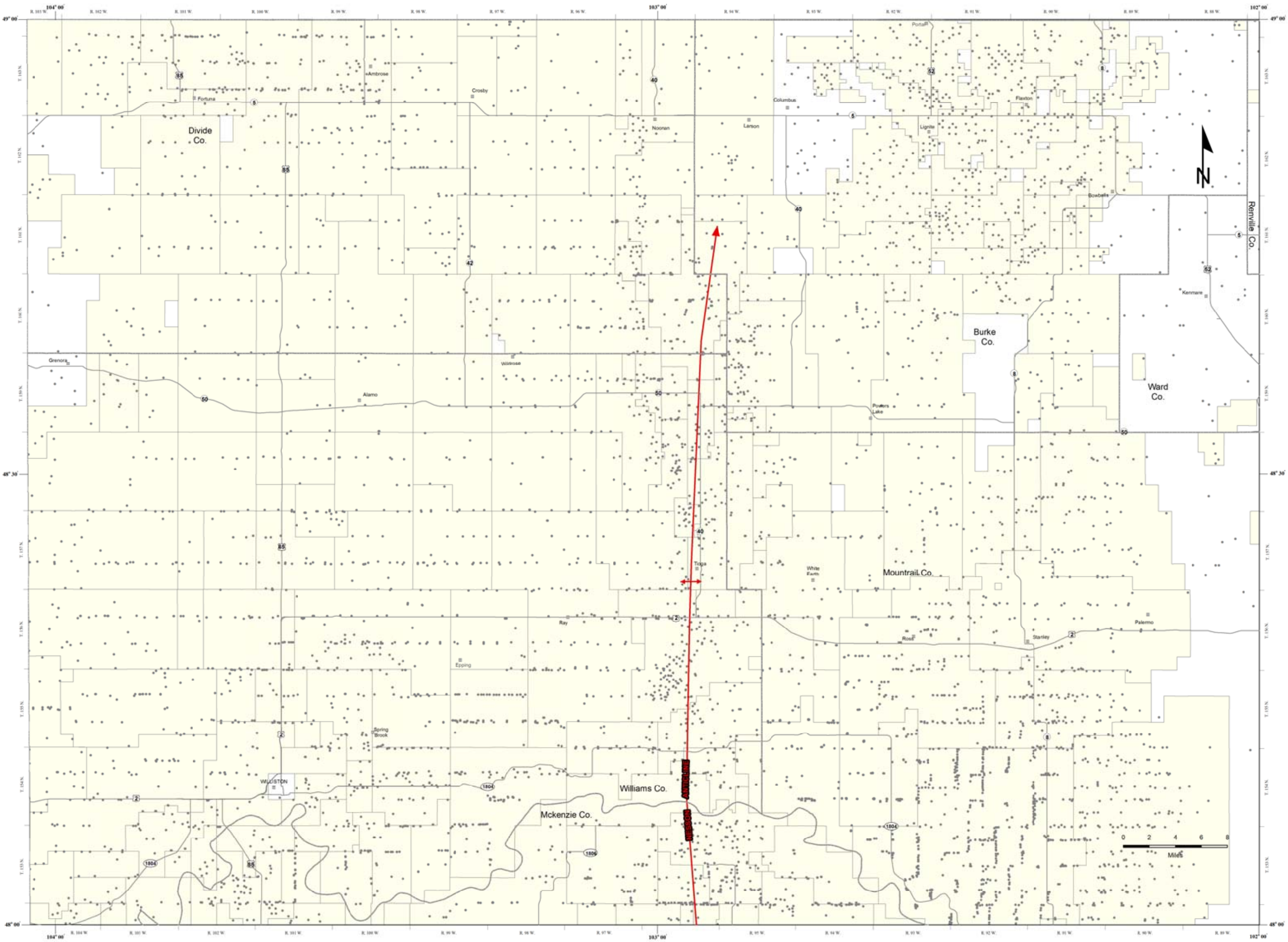


Figure 1. Area of investigation in the Williston 1:250k map sheet located in the north-central Williston Basin in northwestern North Dakota. Locations of oil and gas fields are shown in yellow. Oil and gas well collar locations are shown in gray.

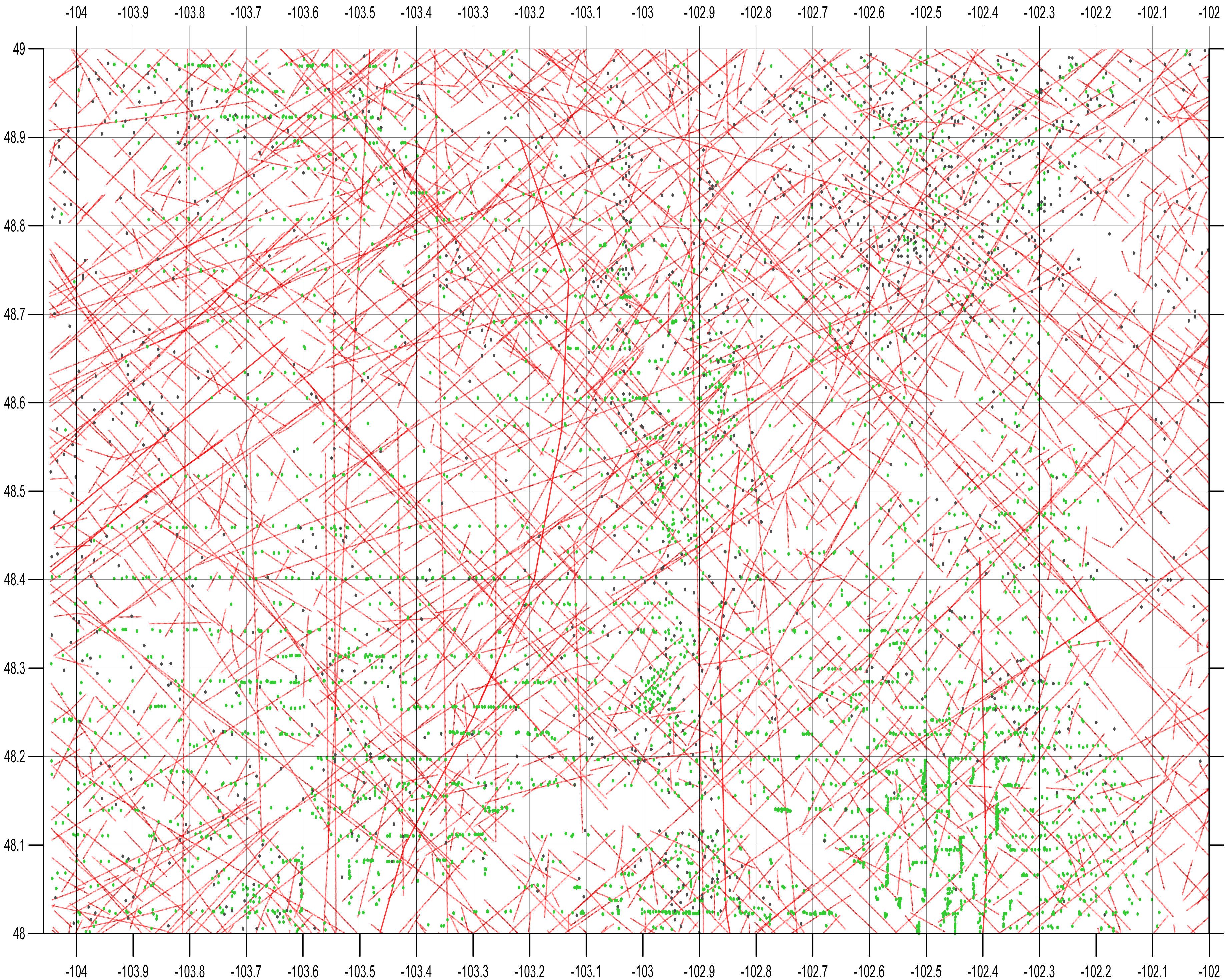


Figure 2. Historical (i.e. previously published) lineaments mapped in the Williston 1:250k sheet. Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

LINEAMENT MAPPING AND ANALYSIS METHODOLOGY

Description of Data and Imagery Sources

Lineaments in the Williston 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	2016	USGS National Elevation Dataset (NED) 10 m	http://ned.usgs.gov/
Aerial Imagery	Summer, 2015	National Agricultural Imagery Program (NAIP)	http://165.221.201.14/NAIP.html
Satellite Imagery Data	Summer, 2002	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 Williston 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 Williston 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 2016 USGS National Elevation Dataset (NED) data set, with a vertical exaggeration of 3X (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 2015 USDA National Agricultural Image Program (NAIP) imagery (Plate III).

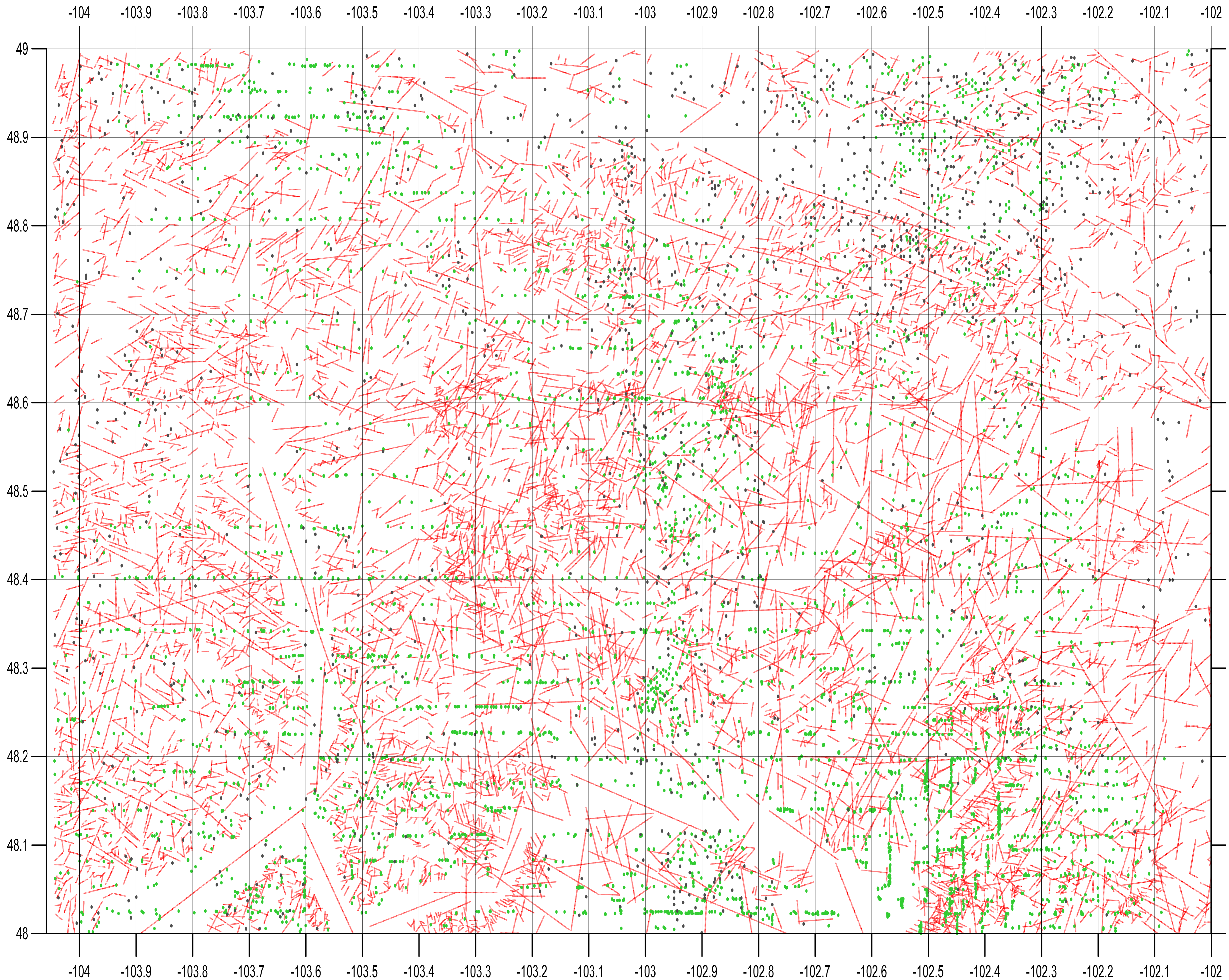


Figure 3. Lineaments mapped from USGS NED shaded relief data in the Williston 1:250k sheet. Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

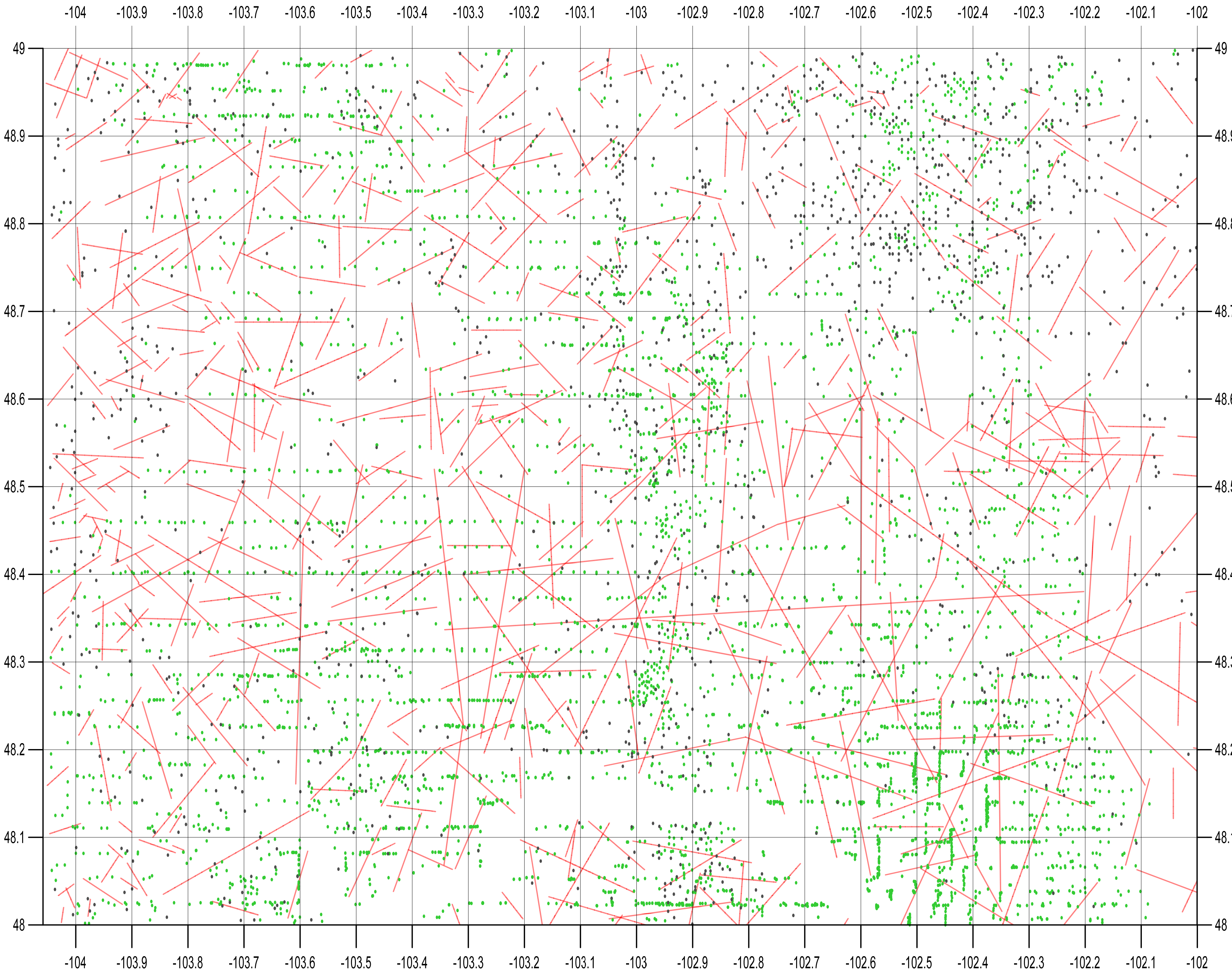


Figure 4. Lineaments mapped from 2015 NAIP aerial imagery in the Williston 1:250k sheet. Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

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 2002 LANDSAT-7 Enhanced Thematic Mapper Plus (ETM+) data (Figure 5). This digital image mosaic was created from four available scenes with zero cloud cover 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. 13 and exported to ArcGIS for final digitizing, georeferencing, and ESRI shape file (.shp) creation. Determination of lineament density values for each of the unique Sections with the Public Land Survey System (PLSS) grid were calculated using ET Geowizards and spatial joining in ArcGIS. 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 17 using the rose diagrams tool in the utilities module. Full rose diagrams were created, using length and bearing frequency based factors, 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 Williston 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 collar 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.

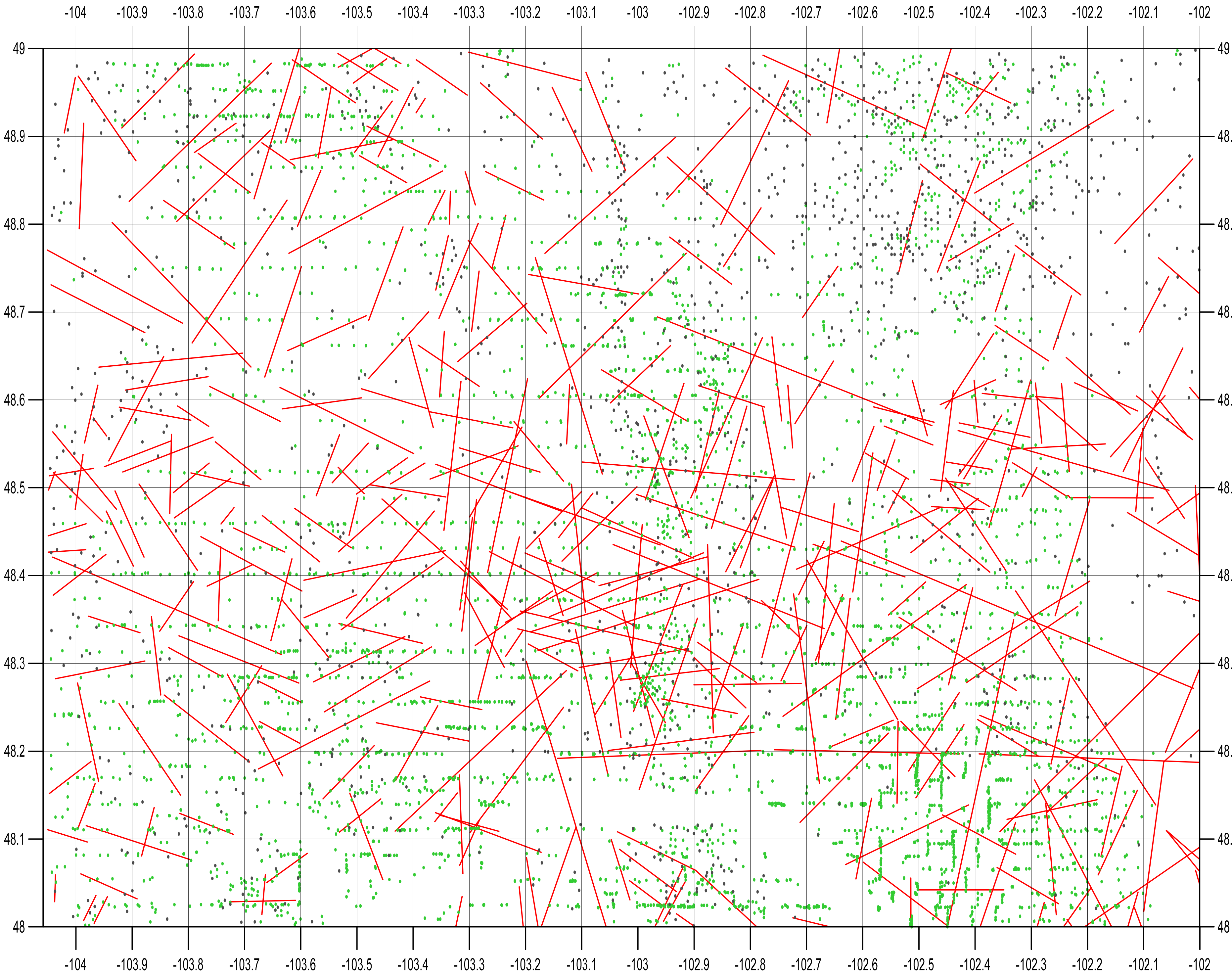


Figure 5. Lineaments mapped from 2002 LANDSAT-7 ETM+ (bands 2, 4, and 7) data in the Williston 1:250k sheet. Locations of currently producing oil and gas wells (green) and non-producing wells (black) are shown.

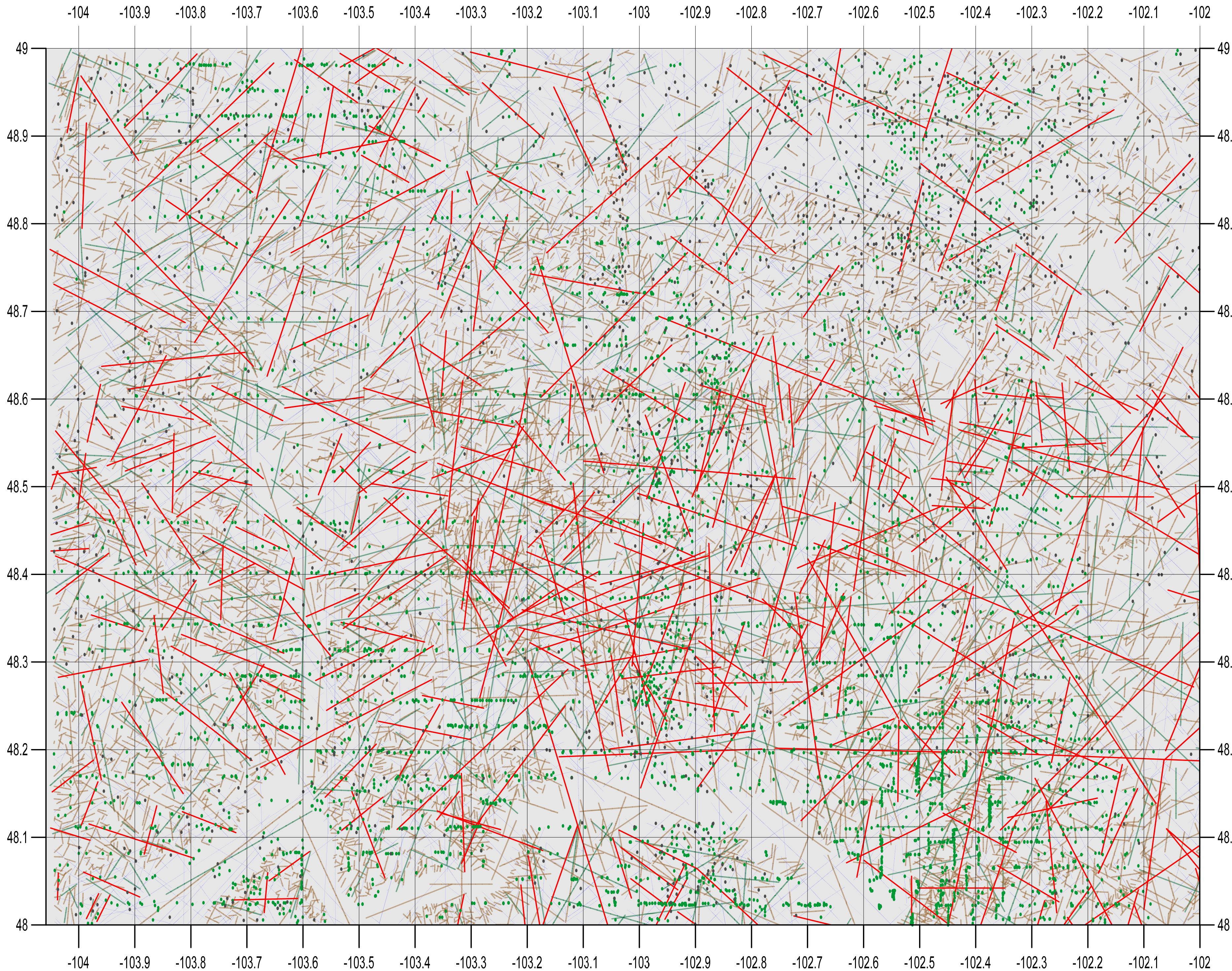


Figure 6. Compilation of lineaments mapped in the Williston 1:250k sheet. Historical lineaments (blue), lineaments mapped from shaded relief data (brown). NAIP imagery (green), and LANDSAT-7 ETM+ data (red). Locations of currently producing oil and gas wells (green) and non-producing wells (black) are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

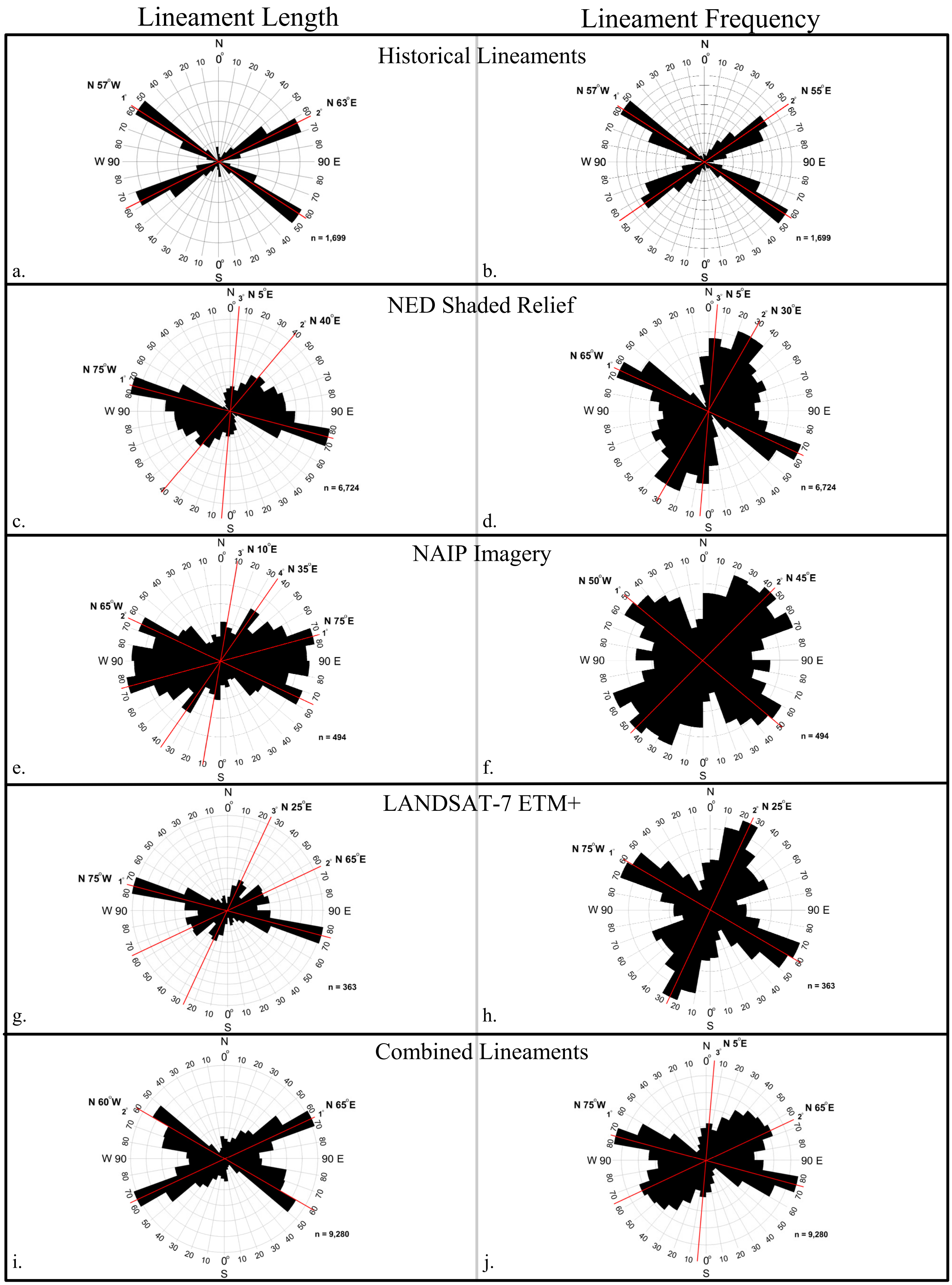
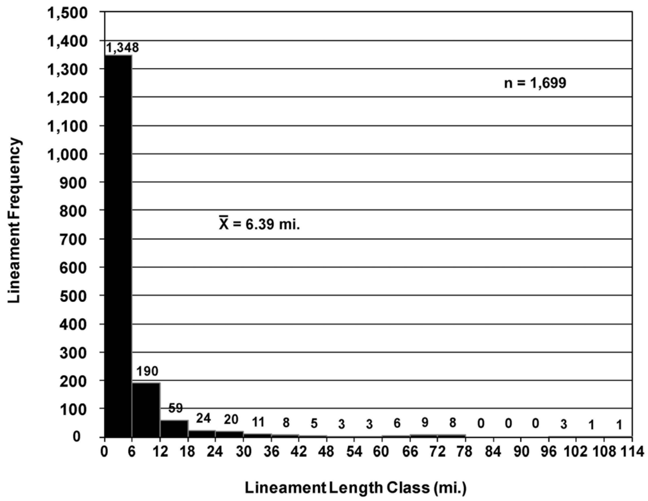
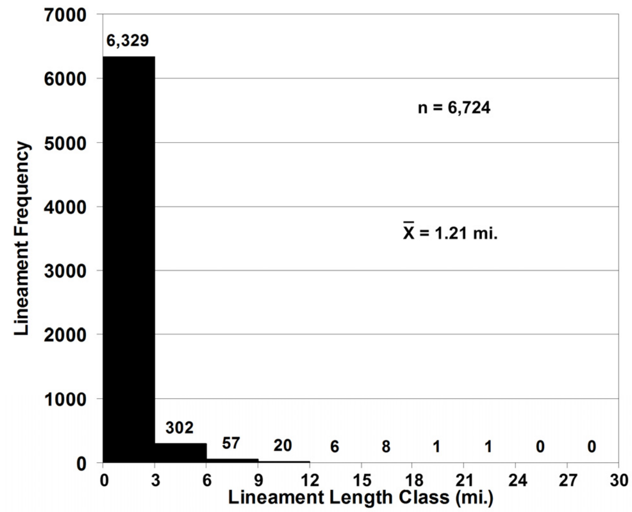


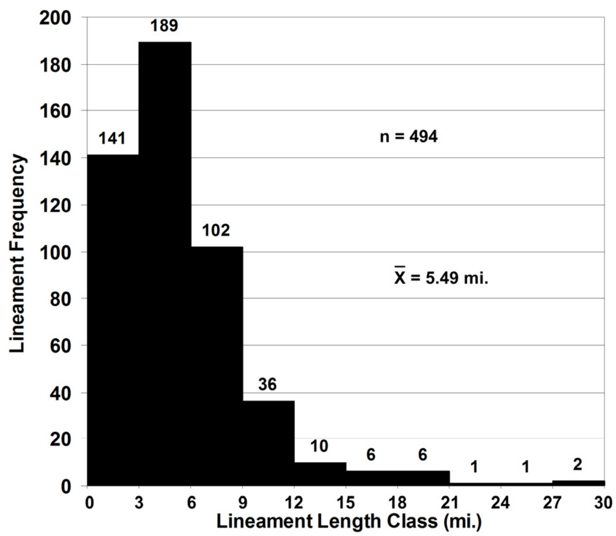
Figure 7. Summary of rose diagrams depicting dominant lineament orientation trends in each set of mapped lineaments, based on data/image source (a.- j.). Strike trends of compiled lineaments (i. & j.) show trends extracted from all mapped lineaments combined.



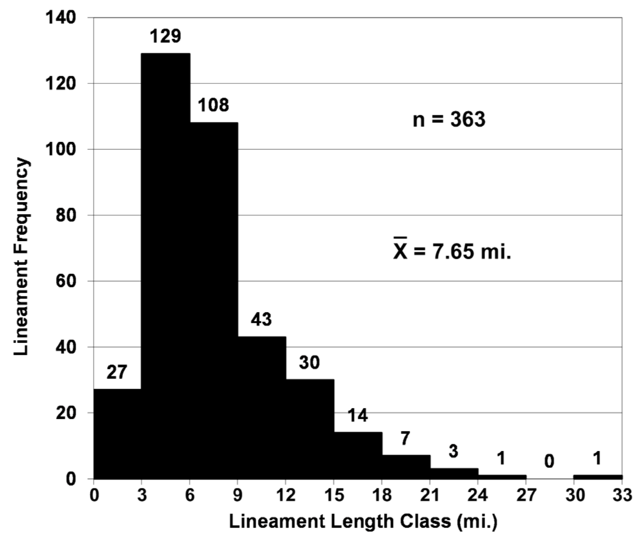
a. Distribution of lineaments mapped from historical data.



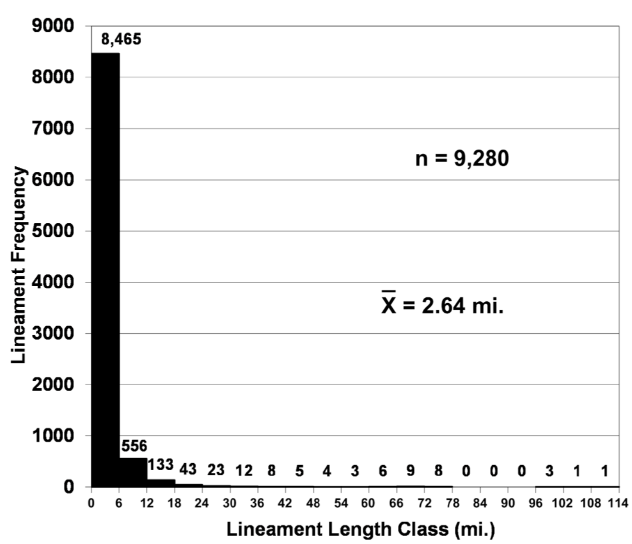
b. Distribution of lineaments mapped from NED shaded relief data.



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 lineament line length 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. 13 for density mapping and contouring (Figure 9) using an ordinary kriging interpolation algorithm. This algorithm was chosen as it is likely the easiest for others to replicate. 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 presentation (Plate VI). The resulting density map shows generally higher lineament density in the southwestern portion of the map area that generally corresponds to areas of heaviest current oil and gas production and field development. Density mapping also shows some areas in the southeastern and northeastern portions of the map area that have a high degree of relative lineament density and high degree of oil and gas exploration and development as evidenced by producing well locations that correspond generally to areas where increased lineament density is found (Figure 10). Their appears to be an area of increased lineament density following NW and NE trends where current production is lower than the surrounding areas in the northeast portion of the map area between 48.5^{o} and 48.9^{o} N Latitude. These areas may be favorable for future potential exploration and production.

3D visualization of lineaments mapped in the Williston 1:250k sheet and interpolated lineament density contours were draped over a digital elevation model of the map area, created from the USGS NED, to provide an enhanced view of the relationships between the occurrence of lineaments and areas of relatively higher lineament density and existing oil and gas well and field development (Figures 1-4, Plate VII).

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) with the emergence of some smaller sub-north to south trends. These continue to be 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, Honsberger, 2013).

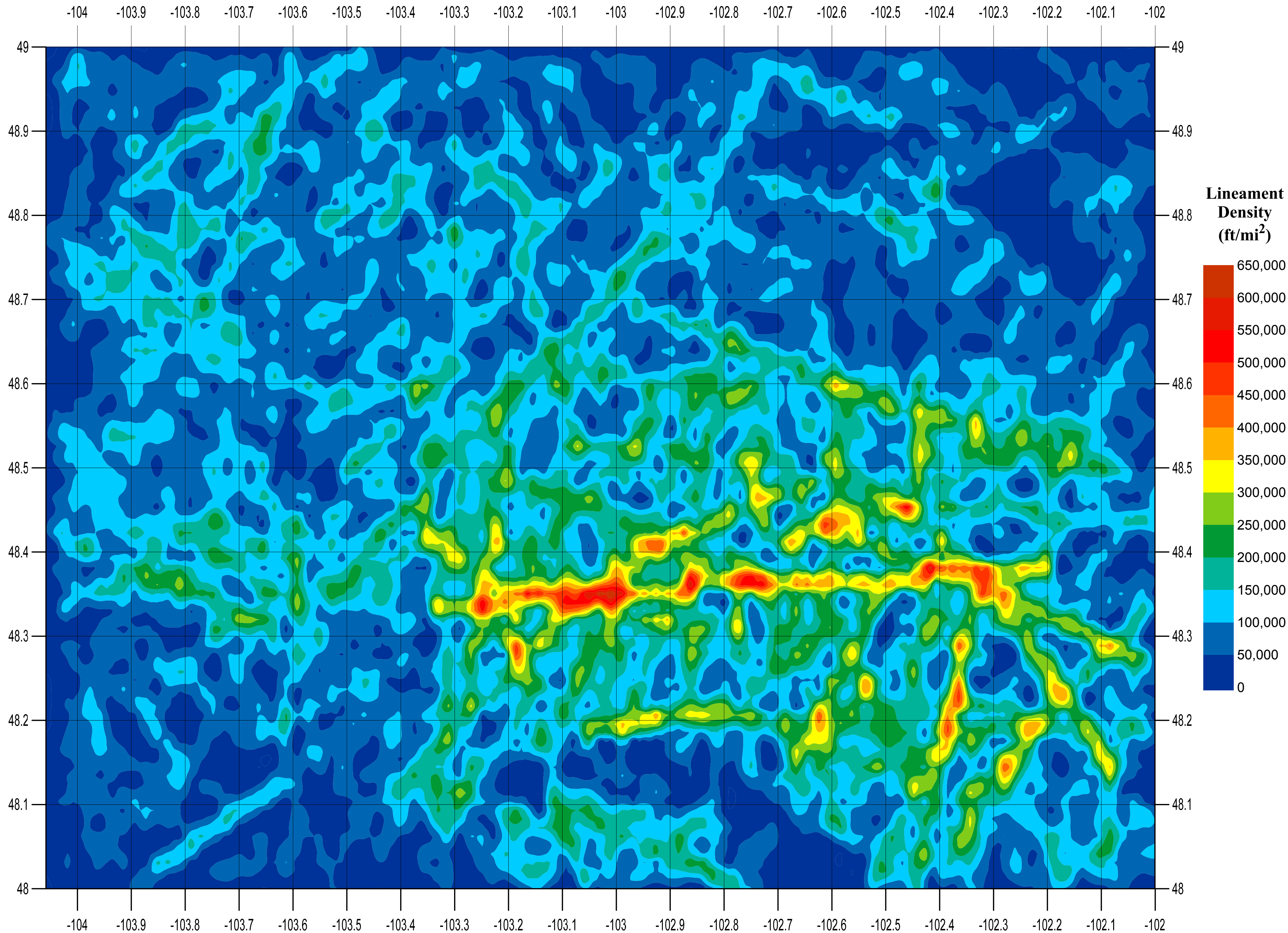


Figure 9. Lineament density map of the Williston 1:250k sheet located in the north-central Williston Basin in northwestern North Dakota. Increasing lineament density per unit area (i.e. length of lineaments within each one square mile unit section) is depicted across eleven lineament density contour intervals from low lineament density in cooler (blues and greens) to warmer (yellows and reds) colors. Lineament density is greatest in the southwestern portion of the map area and appears to be bounded by areas of lower lineament density to the northwest and northeast.

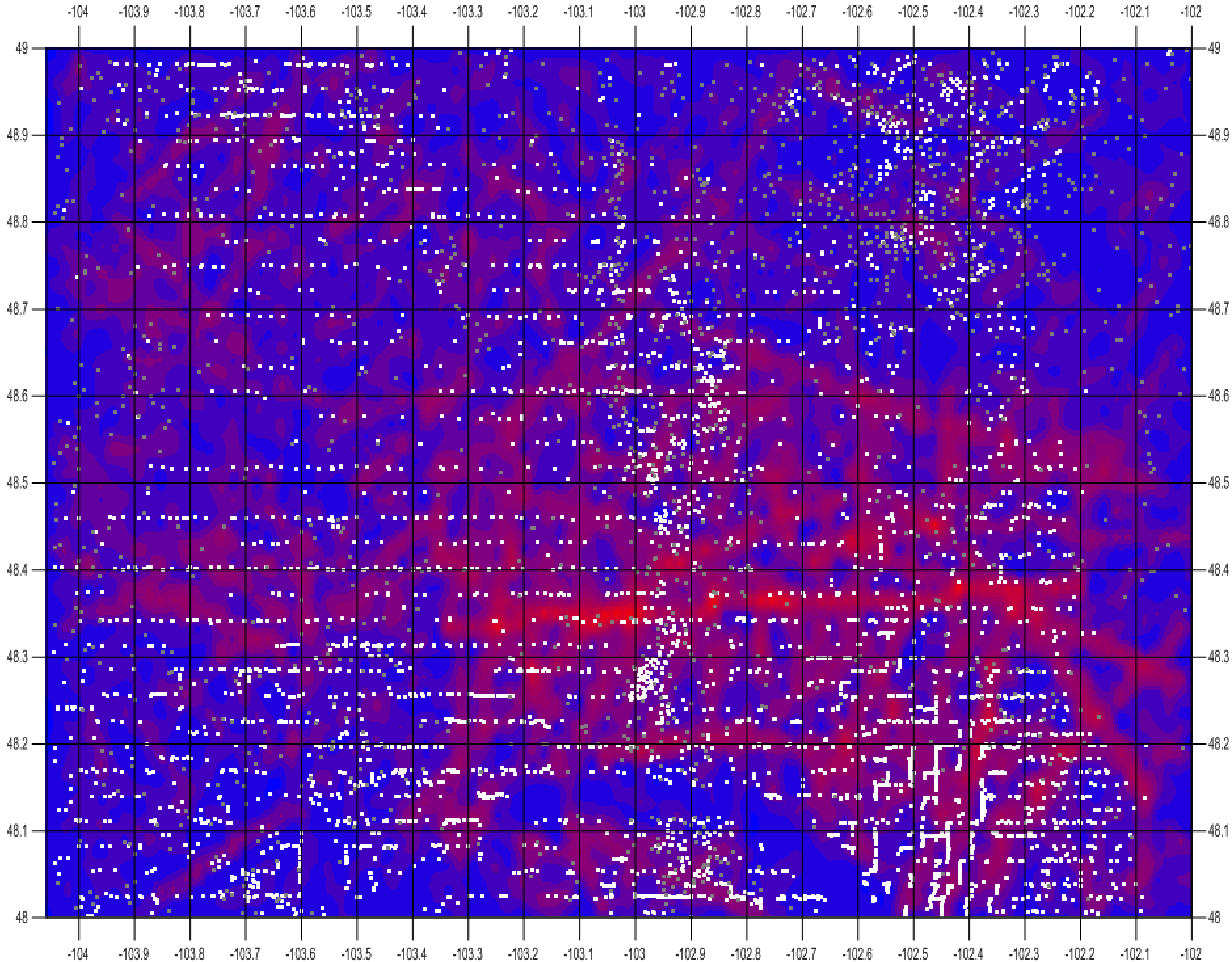


Figure 10. Lineament density map of the Williston 1:250k sheet located in the north-central Williston Basin in northwestern North Dakota. Areas of higher relative lineament density are shown as warmer (reds) colors. Areas of lower relative lineament density are shown as cooler (blues) colors. The collar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

Table 2. Lineament Orientation Trends[1] Determined within Individual Imagery Data Sources in the Williston 1:250k Sheet, North Dakota

Data Type	No. of Trends	Orientation Description				Basic Relationship
		1^{o}	2^{o}	3^{o}	4^{o}	
Historical Lineaments	2	N 57^{o} W	N 60^{o} E	--	--	1^{o} and 2^{o} trends conjugate.
NED 10m Shaded-Relief Data	2	N 70^{o} W	N 35^{o} E	N 5^{o} E		1^{o} and 2^{o} trends conjugate, 3^{o} trend orthogonal to 1^{o} trend.
2015 NAIP Aerial Imagery	2	N 50^{o} W	N 45^{o} E	N 10^{o} E	N 35^{o} E	1^{o} and 2^{o} trends approximately orthogonal, 3^{o} and 4^{o} trend approximately orthogonal to 1^{o} and 2^{o} trends.
2002 LANDSAT-7 ETM+ Satellite Imagery Data	2	N 65^{o} W	N 60^{o} E	N 25^{o} E	--	1^{o} and 2^{o} trends conjugate. 3^{o} trend approximately orthogonal to 1^{o} trend.
Combined\Merged Lineaments	2	N 65^{o} E	N 65^{o} W	N 5^{o} E	--	1^{o} and 2^{o} trends conjugate, 3^{o} trend approximately orthogonal to 1^{o} trend.

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

A primary (1^{o}) trend of N 57^{o} W along with a conjugate (as measured against the regional tectonic NE-SW maximum stress direction) secondary (2^{o}) trend of N 60^{o} E were identified (Figures 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 major and one minor directional trends were found within the lineaments mapped (Figure 7c & d). A 1^{o} trend of N 70^{o} W along with conjugate 2^{o} trend of N 35^{o} E was found. Also, a minor 3^{o} trend of N 5^{o} E was also 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, Fullerton, et.al, 2004).

Lineaments mapped from the 2015 NAIP aerial imagery also exhibited two dominant directional trends each when analyzed using length based and frequency based factors (Figure 7e & f). A 1^{o} trend of N 50^{o} W along with a conjugate 2^{o} trend of N 45^{o} E was found in addition to two minor trends at (3^{o}) N 10^{o} E and (4^{o}) N 35^{o} E (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, when analyzed by length based factors, around N 25^o E, nearly orthogonal to the 1^o trend also exists within the data and manifests as the 2^o trend when analysed by frequency based factors. 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 65^o E along with a conjugate 2^o trend of N 65^o W 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 Shaded Relief data (Plate II-Figure 2) imagery reappears 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 Williston 1:250k Sheet, North Dakota

Data Type	No.	Lineament Length Characteristics (miles)				Lineament Density (Lpsm/Lpst)
		Min	Max	Mean	1 Std. Dev.	
Historical Lineaments	1,699	0.0047	108.88	6.39	11.16	0.26/9.4
NED 2014 Shaded-Relief Data	6,724	0.99	23.96	1.21	1.37	1.04/37.3
2015 NAIP Aerial Imagery	494	0.29	52.55	5.49	4.41	0.08/2.7
2002 LANDSAT-7 ETM+ Satellite Imagery Data	363	0.02	31.11	7.65	4.40	0.06/2.0
Merged\Combined Lineaments	9,280	0.0047	108.88	2.64	5.61	1.43/51

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

A total of 1,699 lineaments were mapped in the Williston 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 18 mi. lineament length class. Minimum lineament length was 0.0047 miles (mi.) with a maximum length of 108.88 mi. The mean lineament length was 6.39 mi. with a standard deviation of 11.16 mi. Lineament density across the entire 1:250k map sheet area of investigation was 0.26 lineaments per square mile (Lpsm) which translates to approximately 9.4 lineaments per township (i.e. 36 square miles).

A total of 6,724 lineaments were mapped in the Williston 1:250k sheet as mapped from shaded relief data (Figure 3), considerably more than previous studies in the Parshall, Dickinson, and Minot areas, which is reflective of the reduction in the modifying influence of Pleistocene glaciation on the landscape in this quadrangle. 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 0.99 mi. with a maximum length of 23.96 mi. The mean lineament length was 1.21 mi. with a standard deviation of 1.37 mi. Lineament density across the entire 1:250k area was 1.04 Lpsm which translates to approximately 37.3 lineaments per township (Lpst).

A total of 494 lineaments were mapped in the Williston 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 3 to 9 mi. lineament length class. Minimum lineament length was 0.29 mi. with a maximum length of 52.55 mi. The mean lineament length was 5.49 mi. with a standard deviation of 4.41 mi. Lineament density across the entire 1:250k area was 0.08 Lpsm which translates to approximately 2.7 Lpst.

A total of 363 lineaments were mapped in the Williston 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 3 to 9 mi. lineament length class. Minimum lineament length was 0.02 mi. with a maximum length of 31.11 mi. The mean lineament length was 7.65 mi. with a standard deviation of 4.40mi. Lineament density across the entire 1:250k map sheet was 0.06 Lpsm which translates to approximately 2.0 Lpst. The data characteristics of lineaments mapped from both the NAIP and LANDSAT data continue to be similar and suggest a scale effect for the identification of lineaments mapped at the 1:250,000 scale.

A total of 9,280 lineaments were mapped in the Williston 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 0.0047 mi., with a maximum length of 108.88 mi. The mean lineament length was 2.64 mi. with a standard deviation of 5.61mi. Lineament density across the entire 1:250k map area was 1.43 Lpsm which translates to approximately 51 Lpst.

Lineament Density Mapping

Lineament densities were calculated for each unique square mile PLSS Section 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, as this algorithm is the most easily replicated, and contoured over fifteen lineament density classes with an interval of 50,000 ft/mi^2 (Figure 9). The resulting lineament density map shows increased lineament density dominantly in the southwest and in the west-northwest portion of the map area (between Grenora and Fortuna) with lessening lineament density moving towards the southwest and northeast.

The total area covered by the Williston1:250k map sheet is 6,490 square miles. Of this total, the largest Lineament Density Area (LDA) is the Class-V LDA (blues) which is dispersed throughout the entire map area (Table 4) but is more common in the northern and western thirds of the map area. The Class-IV (greens) to Class-I LDAs (dark reds and purples) are highly visually correlative to currently producing oil and gas wells. The Class-V (blues) 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)	Approximate Map Area Covered (mi^2)
Class I	113.6 - 123.1	14
Class II	85.2 - 113.6	43
Class III	56.8 - 85.2	187
Class IV	28.4 - 56.8	1,368
Class V	0 - 28.4	4,878

(Lpsm): Total of all lineament lengths (mi) per square mile PLSS Section (mi^2). Total = 6,490

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 southwestern and northeastern portions 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 being within a defined reservoir “block”, bounded by structure, but is most commonly explained by the orderly location of well collars along regulatory influenced production and development corridors, particularly west of the Nesson Anticline. It does become more visually apparent, particularly in the northeast between 48.6^o and 49^o N. Latitude, that the distribution of non-producing wells tend to be clustered throughout areas of relatively low lineament density.

DISCUSSION

Continuing to be 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 continue to appear to be generally located in areas of greater lineament density (Figure 10); when lineament density is determined as the partial *length* of lineaments found to occur within each unit cell or section. Non-producing wells were generally found to be disbursed throughout areas of lesser lineament density. Further spatial and quantitative investigation into this relationship between potential structure and production is planned to follow this work.

REFERENCES

Anderson, F.J., 2012, Lineament Mapping and Analysis in the Northeastern Williston Basin of North Dakota, North Dakota Geological Survey, Geologic Investigations No. 145, 40 p., https://www.dmr.nd.gov/ndgs/documents/Publication_List/pdf/geoinv/GI_145.pdf

Anderson, F.J., 2011, Structural Relationships between Surface Lineaments and Basement Faulting in the Northeastern Williston Basin, North Dakota, The Bakken-Three Forks Petroleum System in the Williston Basin, Rocky Mountain Association of Geologists Guidebook, p. 376-392.

Anderson, F.J., 2011, Lineament Mapping and Analysis in the Southern Williston Basin of North Dakota, North Dakota Geological Survey, Geologic Investigations No. 129, 27 p., https://www.dmr.nd.gov/ndgs/Publication_List/pdf/geoinv/GI-129.pdf

Anderson, F.J., 2008, Lineament Mapping and Analysis in the Northeastern Williston Basin of North Dakota, North Dakota Geological Survey, Geologic Investigations No. 70, 26 p., https://www.dmr.nd.gov/ndgs/Publication_List/pdf/geoinv/GI-70.pdf

Anna, L.O., 1986, Structural influences on Cretaceous sedimentation, northern Great Plains, *in* Peterson, J.A., ed., Paleotectonics and Sedimentation: in the Rocky Mountain Region, United States: AAPG Memoir 41, p. 173-191.

Besler, M, 2008, Electronic communication regarding the discussion of preferential fracture orientations and regional tectonics in the Williston Basin.

Brown, D.L., and D.L. Brown, 1987, Wrench-style deformation and paleostructural influence on sedimentation in and around a cratonic basin, *in* Peterson, J.A., Kent, D.M, Anderson, S.A., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin: Anatomy of a Cratonic Oil Province: Rocky Mountain Association of Geologists, p. 57-70.

Cooley, M.E., 1983, Linear features determined from LANDSAT imagery in North Dakota: USGS Open File Report 83-937.

Downey, J.S., Busby, J.F., and G.A. Dinwiddie, 1987, Regional aquifers and petroleum in the Williston Basin region of the United States, *in* Peterson, J.A., Kent, D.M, Anderson, S.A., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin: Anatomy of a Cratonic Oil Province: Rocky Mountain Association of Geologists, p. 299-312.

Erickson, K., 1970, Surficial lineaments and their structural implications in the Williston Basin, MS Thesis (Unpublished), University of North Dakota, 71 p.

Fullerton, D.S., Colton, R.B., Bush, C.A., Straub, A.W., 2004, Map Showing Spatial and Temporal Relations of Mountain and Continental Glaciations on the Northern Plains, Primarily in Northern Montana and Northwestern North Dakota., U.S. Geological Survey, Scientific Investigations Map 2843, 1:1,000,000 map.

Gerhard, L.C., Anderson, S.B., and J.A. LeFever, 1987, Structural history of the Nesson Anticline, North Dakota, *in* Peterson, J.A., Kent, D.M., Anderson, S.A., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin: Anatomy of a Cratonic Oil Province: Rocky Mountain Association of Geologists, p. 337-354.

Gibson, R.I., 1995, Basement tectonics and hydrocarbon production in the Williston Basin: An interpretive overview, in Hunter, L.D.V., and Schalla, R.A., eds., Seventh International Williston Basin Symposium: Montana Geological Society, p. 3-9.

Haman, P.J., 1975, A Lineament Analysis of the United States, West Canadian Research Publications of Geology and Related Sciences, Series 4, No. 1, Calgary, Alberta, 27 p.

Hayes, M.D., 1984, Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota: MS Thesis (Unpublished), University of North Dakota, 190 p.

Heinle, S., 2007, Compilation of Lineaments Mapped in the Williston Basin Region, North Dakota Geological Survey Data Compilation.

Honsberger, E., 2013, Geophysical Insights into the Bakken: Secrets from a Sleeping Giant Elm Coulee Bakken Field (Sleeping Giant), Montana USA, American Association of Petroleum Geologists, Search and Discovery Article #20187.

Kent, D.M., 1974, The relationship between hydrocarbon accumulations and basement structural elements in the northern Williston Basin, *in* Parslow, G.R., ed., Fuels: a geological appraisal: Proceedings of a Symposium held on 7-8 November 1974, p. 63-79.

Lemke, R.W., 1950, Geology of the Souris River Area North Dakota, U.S. Geological Survey, Geological Survey Professional Paper 325, 138 p.

Maughan, E.K., and W.J. Perry, Jr., 1986, Lineaments and their tectonic implications in the Rocky Mountains and adjacent plains region, *in* Peterson, J.A., ed., Paleotectonics and Sedimentation: in the Rocky Mountain Region, United States: AAPG Memoir 41, p. 41-53.

Oglesby, C.A., 1987, Distinguishing between depositional and dissolution thinning: Devonian Prairie Formation, Williston Basin, North America, *in* Carlson, C.G., and Christopher, J.E., eds., Fifth International Williston Basin Symposium: Saskatchewan Geological Society, p.47-52.

Peterson, J.A., and L.M. MacCary, 1987, Regional stratigraphy and general petroleum geology of the U.S. portion of the Williston Basin and adjacent areas, *in* Longman, M.W., ed., Williston Basin: Anatomy of a Cratonic Oil Province: Rocky Mountain Association of Geologists, p. 9-43.

Penner, L.H., and Cosford, J., 2006, Evidence Linking Surface Lineaments and Deep-Seated Structural Features in the Williston Basin, Saskatchewan and Northern Plains Oil & Gas Symposium, Saskatchewan Geological Society, p. 19-39.

Sabins, F.F., 2000, Remote Sensing: Principles and Interpretation, W.H. Freeman and Company, 494 p.

Thomas, G.E., 1974, Lineament-block tectonics: Williston-Blood Creek Basin: AAPG Bulletin, v. 58, no. 7, p. 1305-1322.

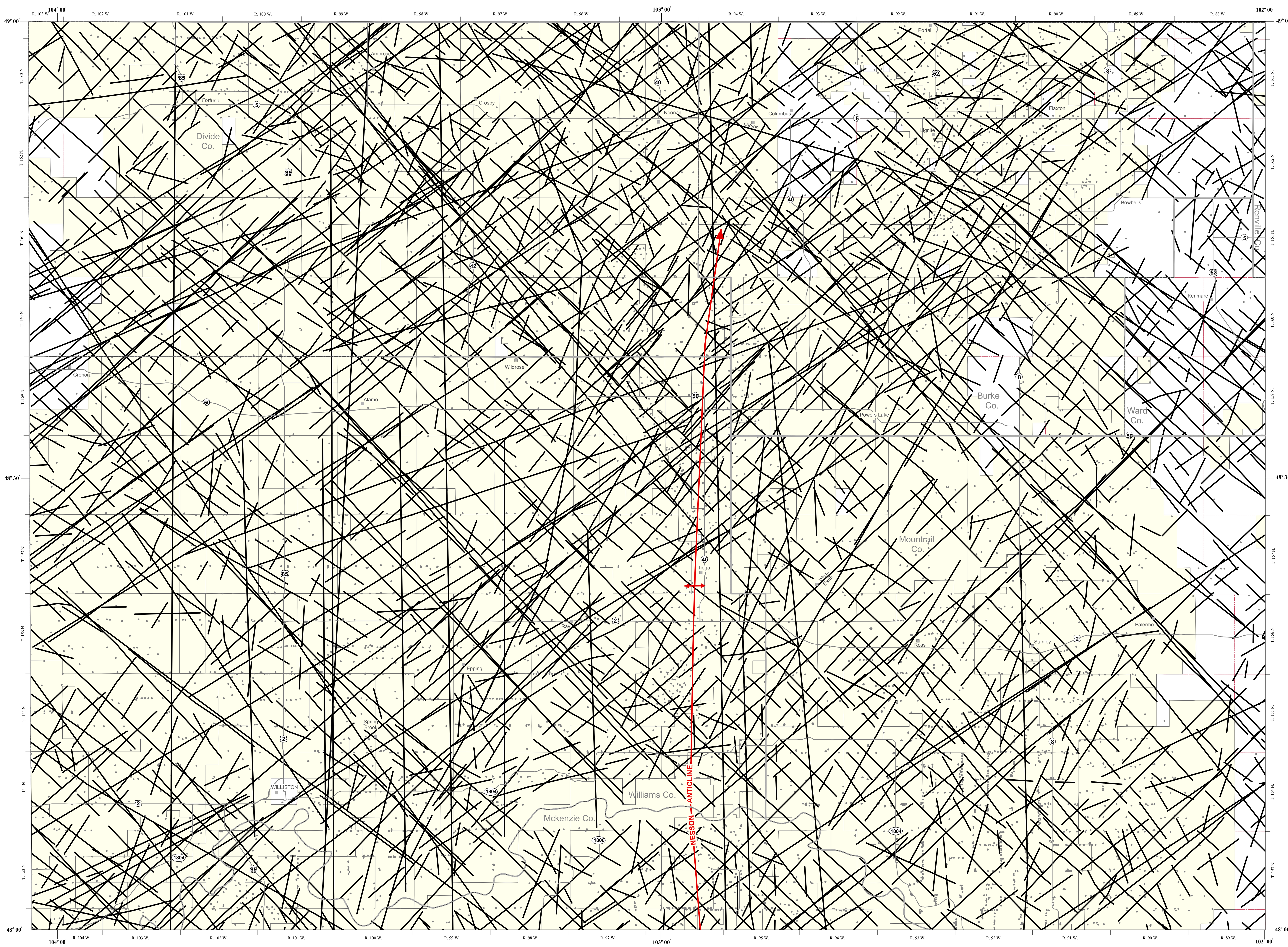
North Dakota Geological Survey
Geologic Investigations No. 195 - Plate I

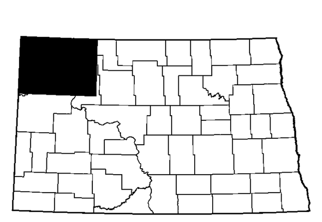
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

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

Fred J. Anderson

2016





Williston 250K Sheet, North Dakota

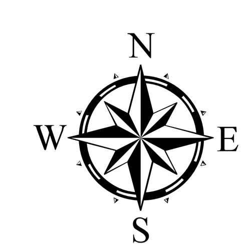
Scale 1:250,000

0 4.5 9 13.5 18
Miles

0 4.5 9 13.5 18
Kilometers

Mercator Projection
Standard parallel 48° 00′

1927 North American Datum
Central meridian 103° 00′ 00″



Cartographic Compilation: Elroy L. Kadrmas

HISTORICAL LINEAMENTS IN THE WILLISTON 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 Williston 250k sheet. The Williston 250k sheet is located in the north-central portion of the Williston Basin in northwestern North Dakota. Lineaments mapped from previous studies (i.e., historical lineaments) by several authors over the last four decades, include: Penner and Cosford, 2006, Kreis-Kent, 2000, Freisatz, 1995, Gibson, 1995, Inden-Burke 1995, Shurr, 1995, Brown and Brown, 1987, Downey, et. al., 1987, Gerhard, et. al., Mollard, 1987, Oglesby, 1987, Peterson and MacCray, 1987, Anna, 1986, Maughan and Perry, 1986, Hayes, 1984, Hindman, 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 Williston 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 1,699 individual lineaments in this compliation reveals two distinct trends; a primary (1°) orientation of approximately N 50° W (S 50° E)and a secondary (2°) orientation of approximately N 60° E (S 60° W)(Figure 2). The distribution of lineament lengths follow a general log-normal distribution with the majority of lineaments (79%) falling within the zero to six mile lineament length range. Just over 94% of the lineaments mapped were less than 18 miles in length (Figure 3). The overall density of lineaments within the sheet (i.e. lineaments mapped per unit area) is 0.26 lineaments per square mile, approximately 9.4 lineaments per township. Lineament density is generally greater in the western 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. 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 in the northwestern portion of the sheet, west of the Nesson Anticline. Several fields have several lineaments occurring within the field boundries, which may provide hints to deeper structure.

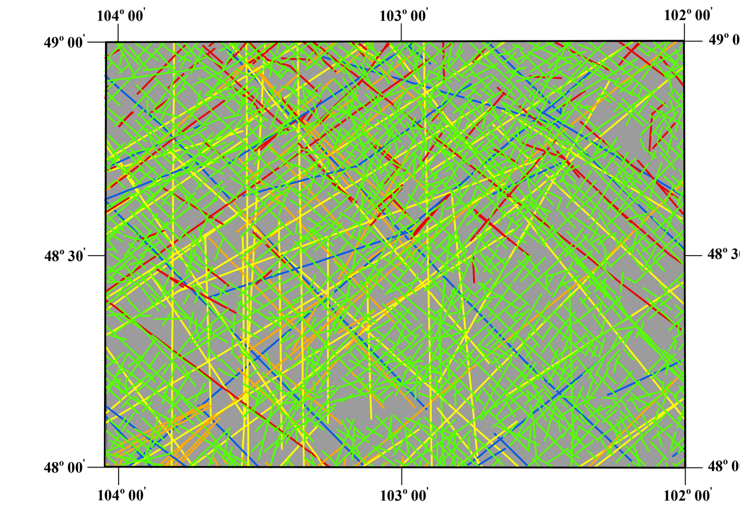
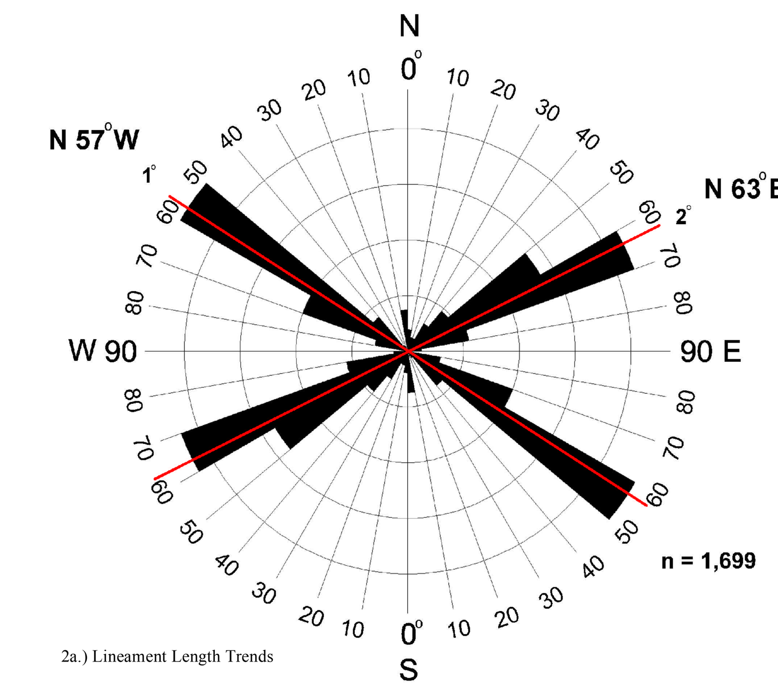
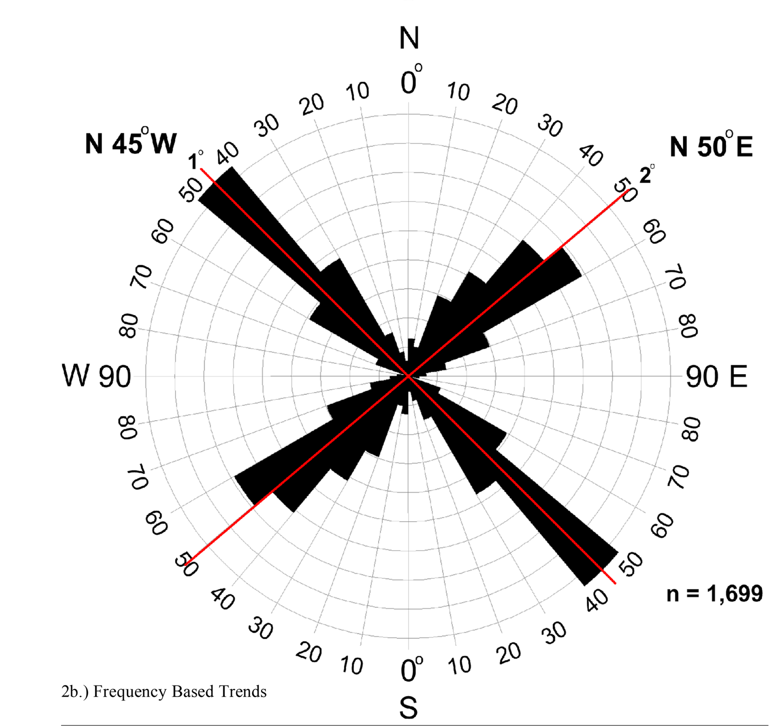


Figure 1. Index map of historical (i.e. previously published) lineaments, grouped by color by the decade in which they were mapped, in the Williston 1:250k sheet in the northcentral portion of the Williston Basin in northwestern North Dakota. Lineaments by Penner and Cosford, 2006, and Kreis-Kent, 2000, are shown in red, Freisatz, 1995, Gibson, 1995, Inden-Burke, 1995, and Shurr, 1995, in orange, Brown and Brown, 1987, Downey, et. al., 1987, Gerhard, et. al., 1987, Mollard, 1987, Oglesby, 1987, and Peterson and MacCray, 1987 in yellow, Anna, 1986, Maughan and Perry, 1986, Hayes, 1984, Hindman, 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 1,699 individual lineament orientations mapped from previous lineament studies in the Williston 1:250k sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. Two dominant trends are found: A primary (1°) trend of N 57° W and a secondary (2°) trend of N 63° E is found within the lineament orientations analyzed by length-based factors (2a), and a (1°) trend of N 45° W and (2°) trend of N 50° E is found within the lineaments orientations analyzed by frequency-based factors (2b).

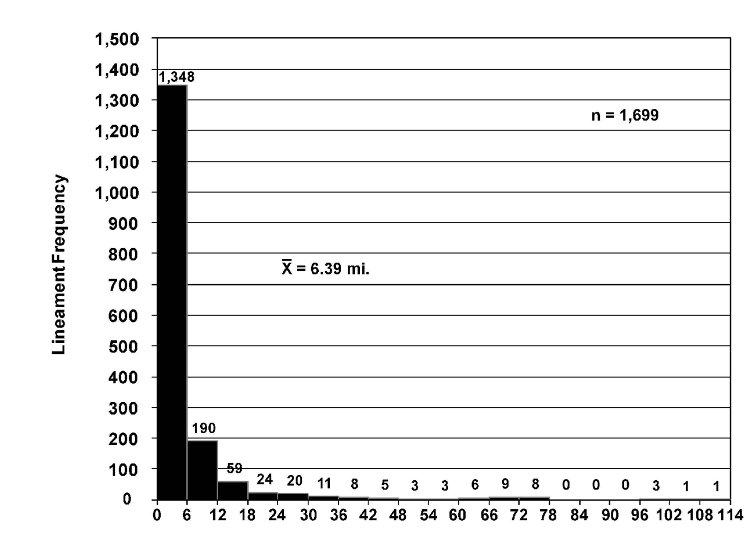


Figure 3. Frequency distribution of 1,699 individual lineament lengths from previously mapped lineaments in the Williston 1:250k sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. Lineament distributions are shown for nineteen lineament length classes from zero to 114 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.

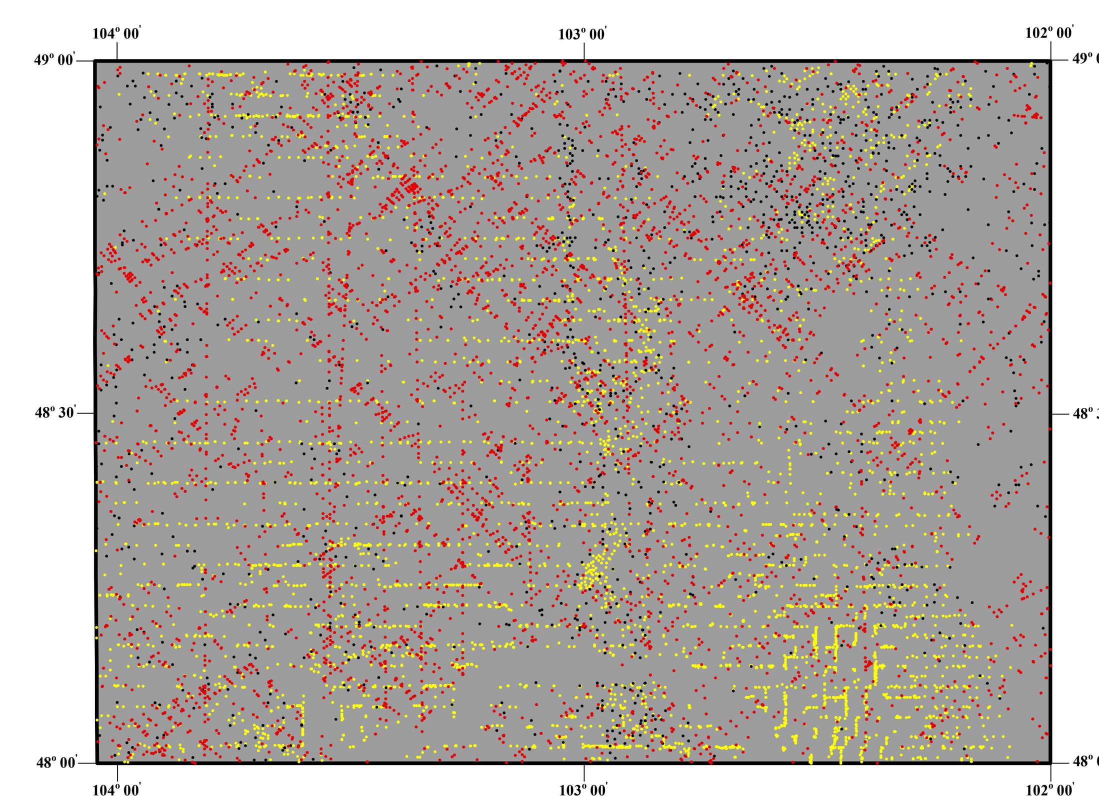


Figure 4. Map of lineament intersections (shown in red) overlain with currently producing wells (shown in yellow) and dry holes (shown in black) displaying the relationship between areas where lineament intersections are prevalent or lacking and areas of current production and field development.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields
- Nesson Anticline

Other Features

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

The Williston 250k sheet was extended into the Wolf Point 250k sheet to the North Dakota/Montana border.

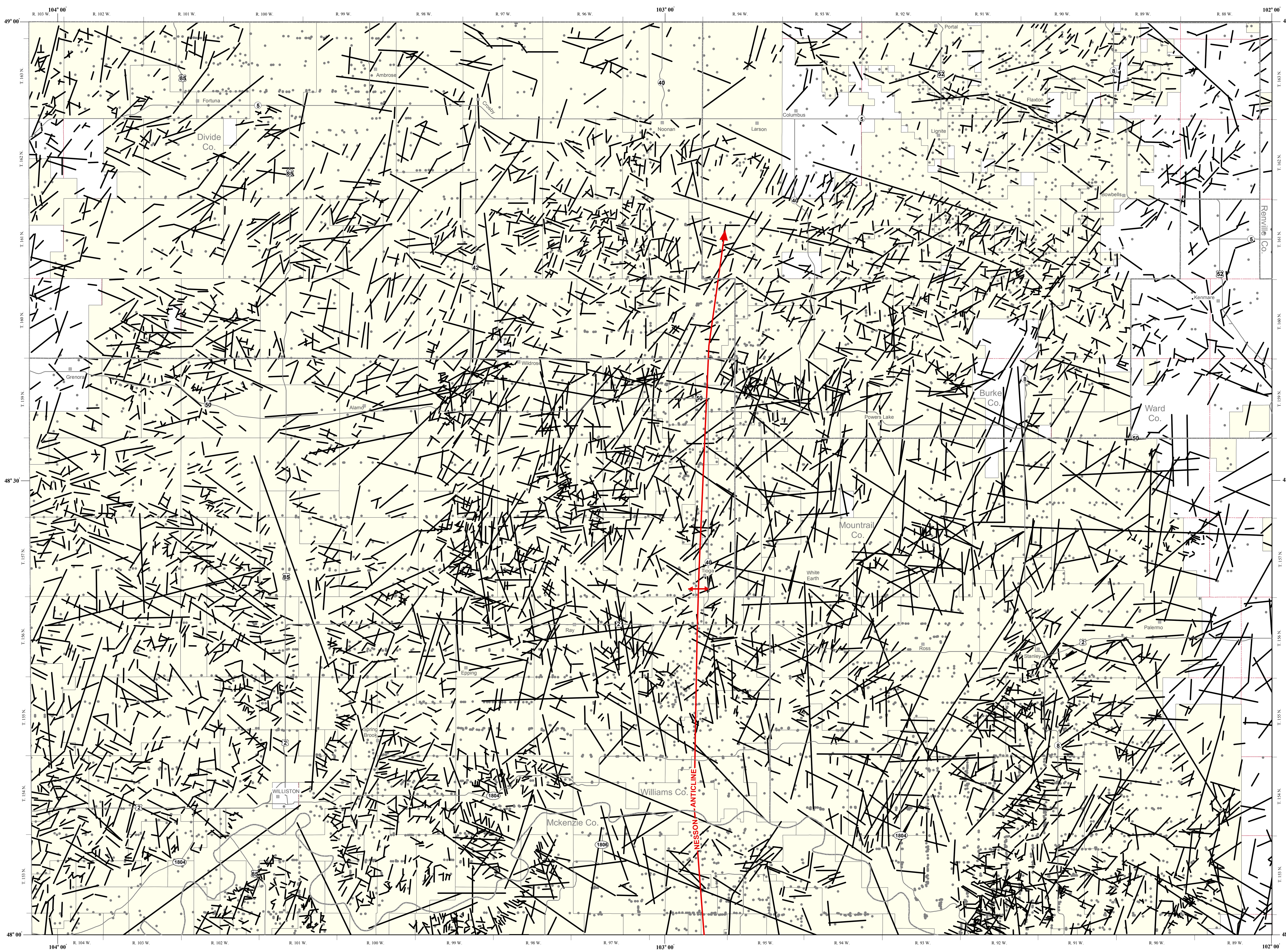
North Dakota Geological Survey
Geologic Investigations No. 195 - Plate II

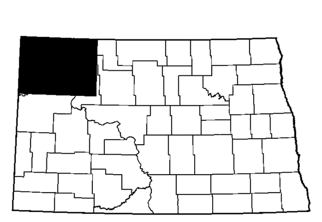
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

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

Fred J. Anderson

2016





Williston 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 103° 00' 00'

Cartographic Compilation: Elroy L. Kadrmas

LINEAMENTS IN THE WILLISTON SHEET DERIVED FROM SHADED RELIEF MAP INTERPRETATION

This map presents the results and discussion of a segment of a contemporary lineament analysis of the Williston 1:250k map sheet in northwestern North Dakota. The Williston 1:250k map area is located in the north-central portion of the Williston Basin, in the northwest portion of the state. Lineaments were mapped and digitized from a digital, shaded-relief image, constructed from a USGS National Elevation Data (10 Meter NED) set with a vertical exaggeration of 3X (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 6,724 individual lineaments reveal two distinct orientation trends (Figures 2a. and b.). A primary (1°) trend of approximately N 70° W (S 70° E), and a secondary (2°) trend of approximately N 35° E (S 35° W). The distribution of lineament lengths follows a general log-normal distribution with nearly all lineaments (99%) falling within the 0-6 mile lineament length range interval (Figure 3). The density of lineaments (i.e. lineaments mapped per unit area) is generally greater in the central portion of the map area with an overall lineament density of about one lineament per square mile (37.3 lineaments per township). In this map, the general distribution of lineaments can be grouped into six areas of 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 related to Pleistocene glacial processes. Lineament density is observed to be greatest in the north-central and southeastern portions of the map area (LDAs I and II) and is generally coincident with current oil and gas field development, The entire map area contains significant oil and gas field development. Overall, lineament density appears greater in areas of currently producing wells, particularly Area I in the southeast, Area III in the southwest, and Area V in the northeast.

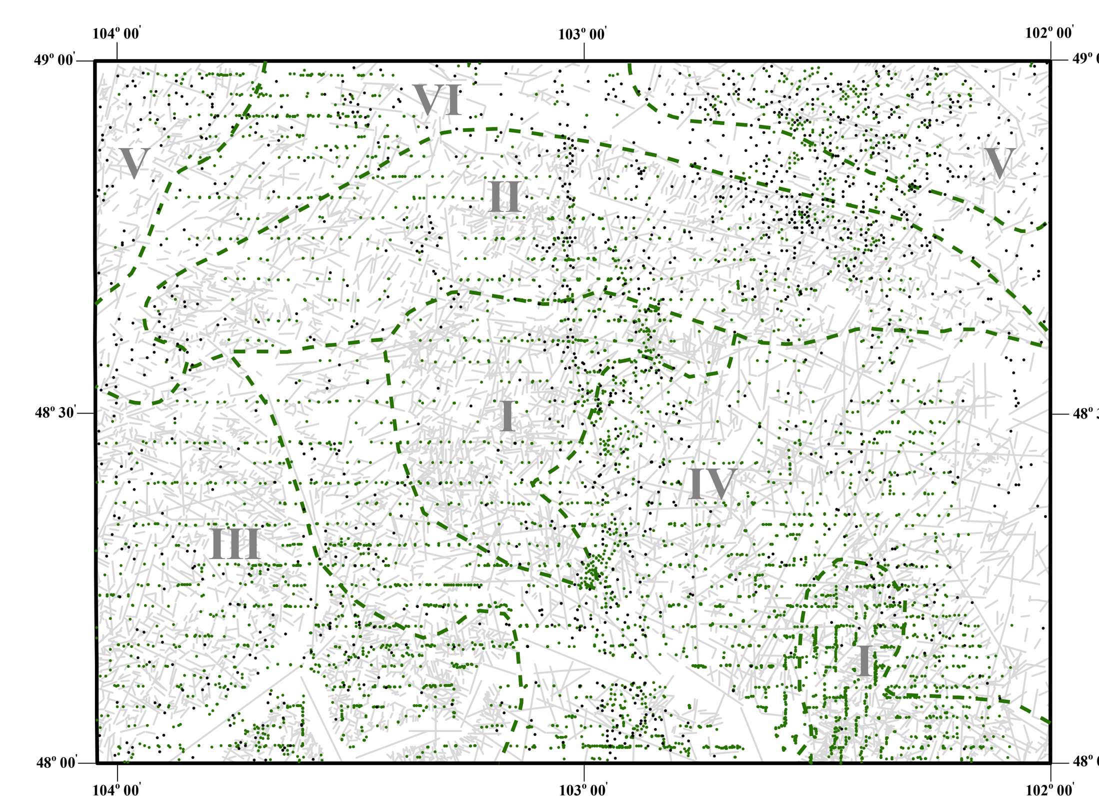


Figure 4. Diagram of Lineament Domain Areas (LDAs I-VI) mapped in order of decreasing relative lineament densities (i.e. lineaments per unit area). Mapped LDAs generally encompass areas coincident with areas of current production and non-production. Currently producing wells (green) and dry holes (black)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

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields
- Nesson Anticline

Other Features

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

The Williston 250k sheet was extended into the Wolf Point 250k sheet to the North Dakota/Montana border.

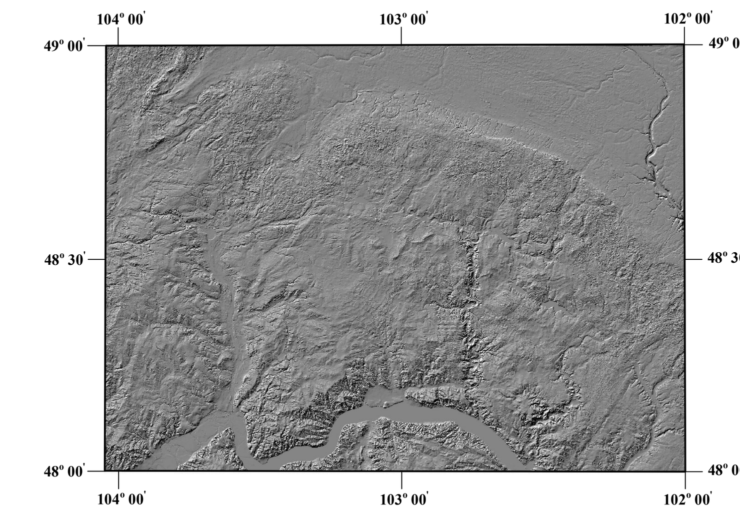
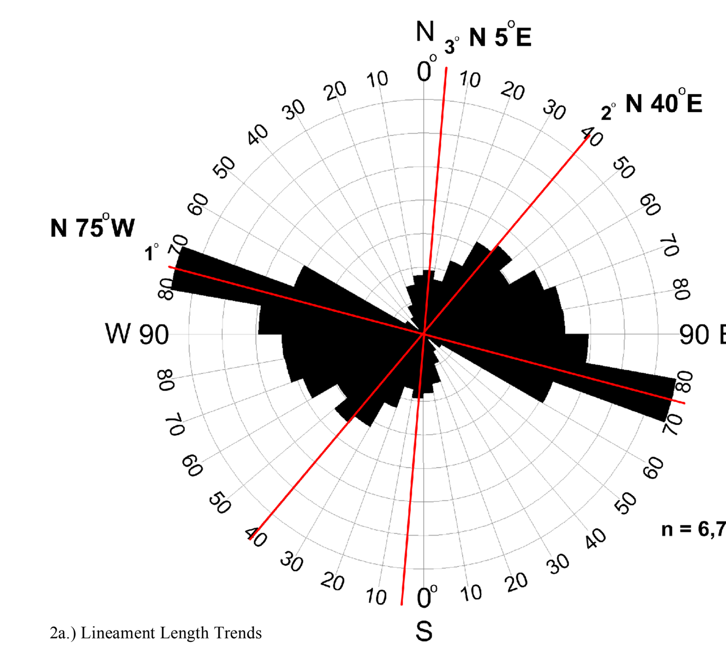
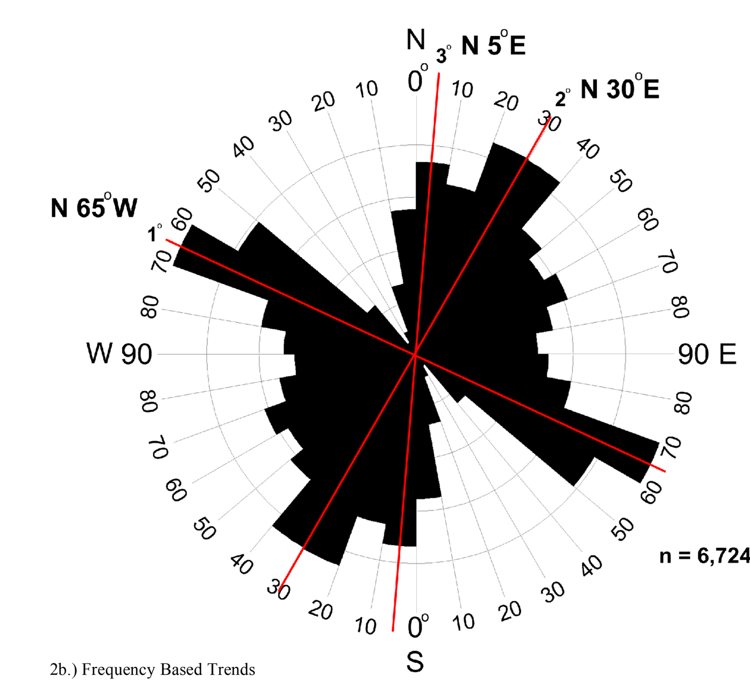


Figure 1. Index map of USGS NED shaded relief data for the Williston 1:250k sheet located in the north-central portion of the Williston Basin in northwestern North Dakota.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 6,724 individual lineament orientations mapped from shaded relief data in the Williston 1:250k sheet located in the northcentral portion of the Willison Basin in northwestern North Dakota. The two dominant approximate orientations (1°, and 2°) are N 70° W (S 70° E) and N 35° E (S 35° W), based on directional analysis of lineament line length (2a) and lineament bearing frequency (2b).

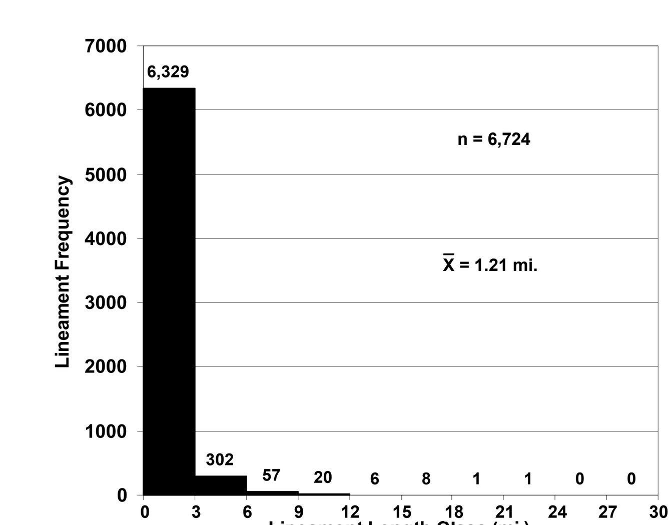


Figure 3. Frequency distribution of 6,724 individual lineament lengths from lineaments mapped from shaded relief data in the Williston 1:250k sheet located in the northcentral portion of the Williston Basin in northwestern North Dakota. Lineament distributions are shown for ten lineament length classes from zero to 30 miles in 3 mile intervals or classes.

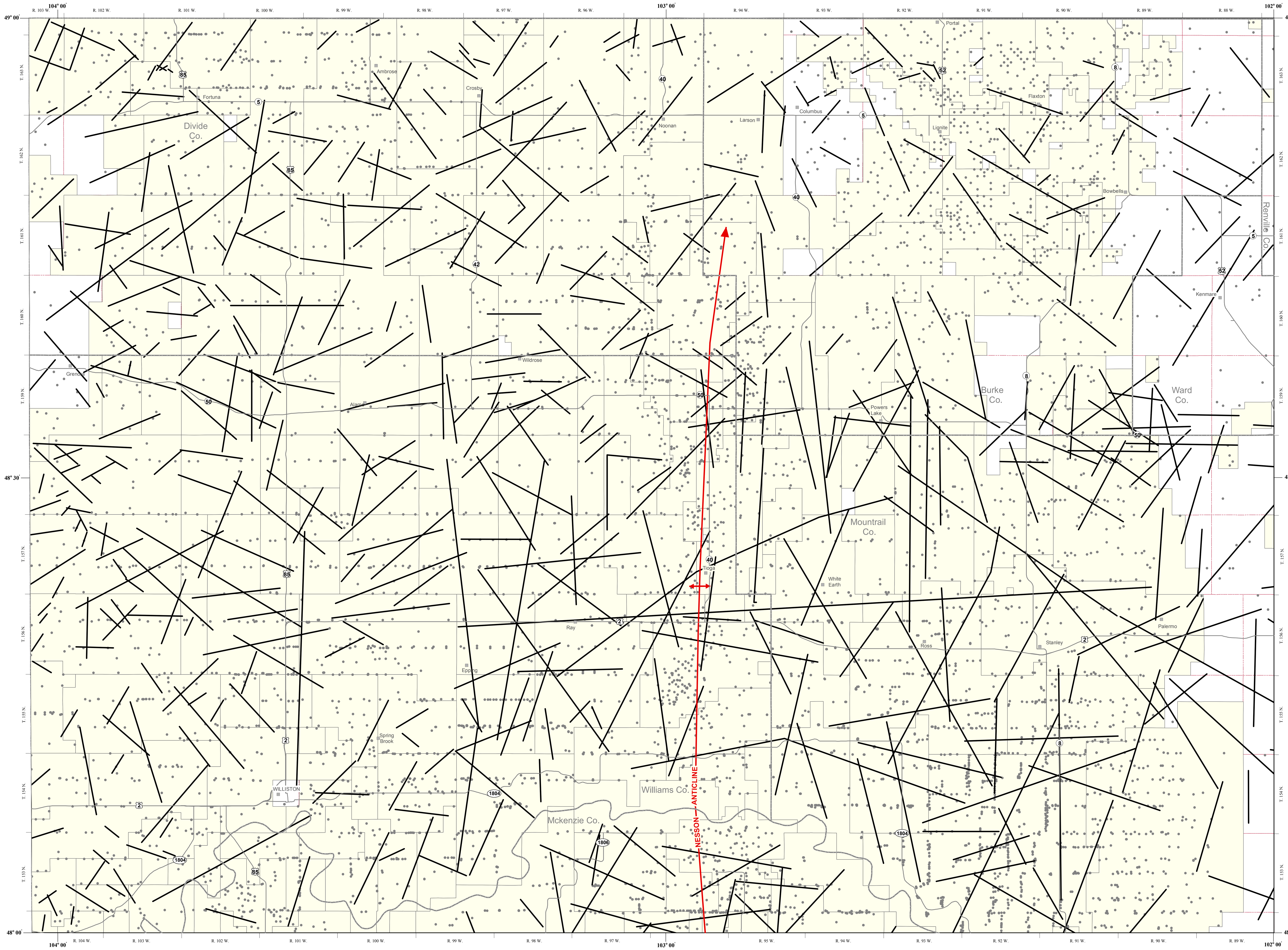
North Dakota Geological Survey
Geologic Investigations No. 195 - Plate III

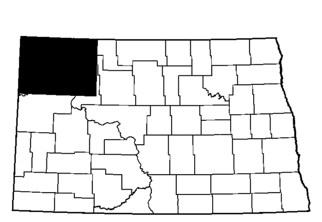
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

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

Fred J. Anderson

2016




Williston 250K Sheet, North Dakota

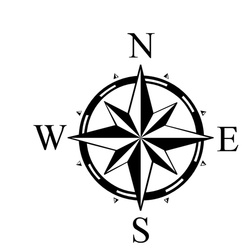
Scale 1:250,000

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 103° 00' 00'



LINEAMENTS IN THE WILLISTON 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 Williston 250k sheet. The Williston 250k sheet is located in the north-central portion of the Williston Basin in northwestern North Dakota. Lineaments were digitally mapped and digitized from a digital aerial image mosaic of the study area, complied from 2015 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 494 individual lineaments reveals two distinct trends; a primary (1°) orientation of N 60° W (S 60° E) and a secondary (2°) orientation of approximately N 45° E (S 45° W) The distribution of lineament lengths follow a general log-normal distribution with the majority of lineaments (87%) falling within the zero to nine mile lineament length range. Over 95% of the lineaments mapped were less than 12 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 2.7 lineaments per township. Lineament density is generally greater in the central and western portions of the study area, but overall is relatively uniform in character, except for the mortheast portion of the map area. 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 northwestern Mountrail County. Lineaments mapped are likely influenced by subsurface geological (i.e., basement faulting) and surface geomorphological conditions resultant from Pleistocene glaciation. Lineament interconnectivity is also shown (Figure 4) as an example of a variation of lineament density and is generally coincident with densley producing oil and gas fields. Areas with a higher degree of lineament interconnectivity, include most of the area near the Nesson Anticline and northwest Mountrail County. Several fields have several lineaments occurring within the field boundries, which may provide hints to deeper structure. Areas where no oil and gas fields are mapped tend to show areas of limited lineament occurrence.

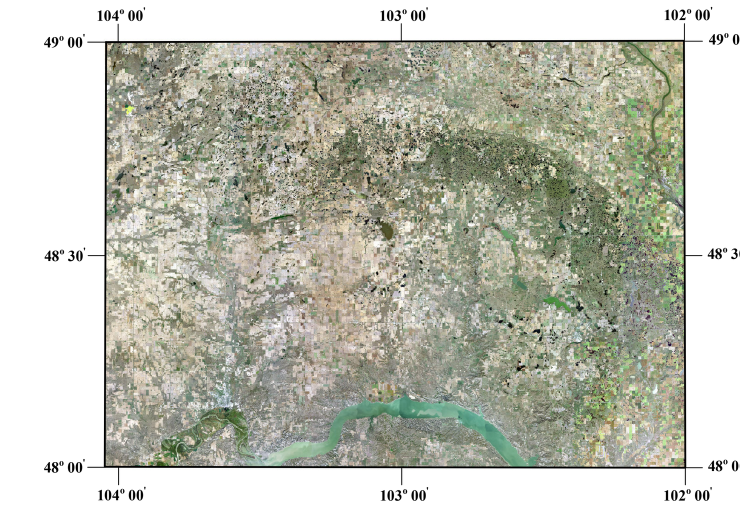
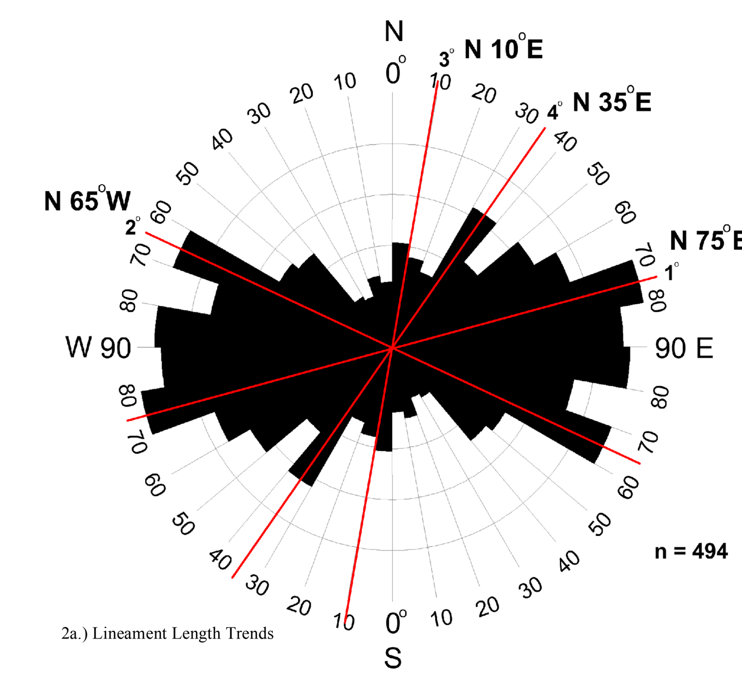
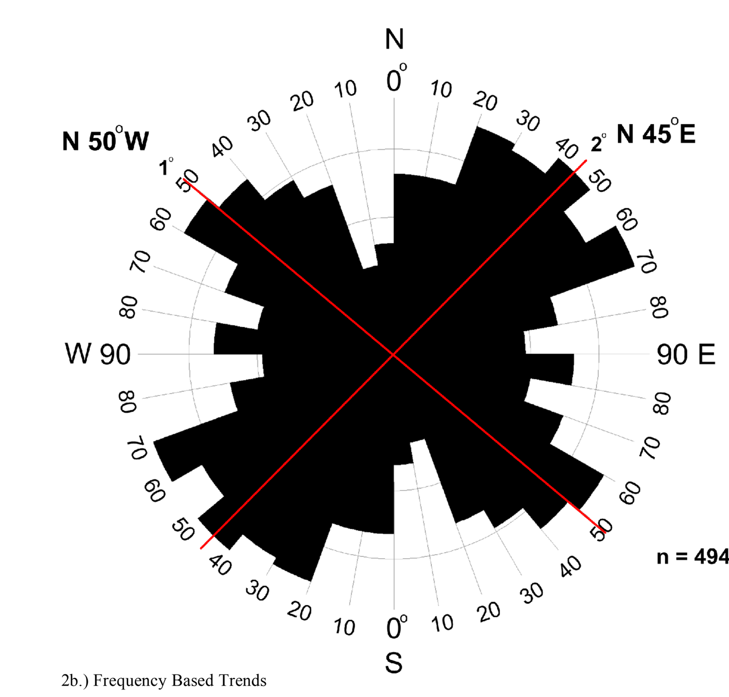


Figure 1. Map of 2015 NAIP aerial imagery used for lineament mapping in the Williston 1:250k sheet in the northcentral portion of the Williston Basin in northwestern North Dakota.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 494 individual lineament orientations mapped from 2015 NAIP imagery in the Williston 1:250k sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. Two major and two minor trends are observed in the lineaments analyzed by length based factors: A major primary (1°) trend of N 75° E (S 75° W) and a major secondary (2°) trend of N 65° W (S 65° E) and a minor tertiary (3°) trend of N 10° E (S 10° W) and a minor quaternary (4°) trend of N 35° E (S 35° W). Two major trends are observed in the lineaments analyzed by frequency base factors: A major primary (1°) trend of N 50° W (S 50° E) and a major secondary (2°) trend of N 45° E (S 45° W).

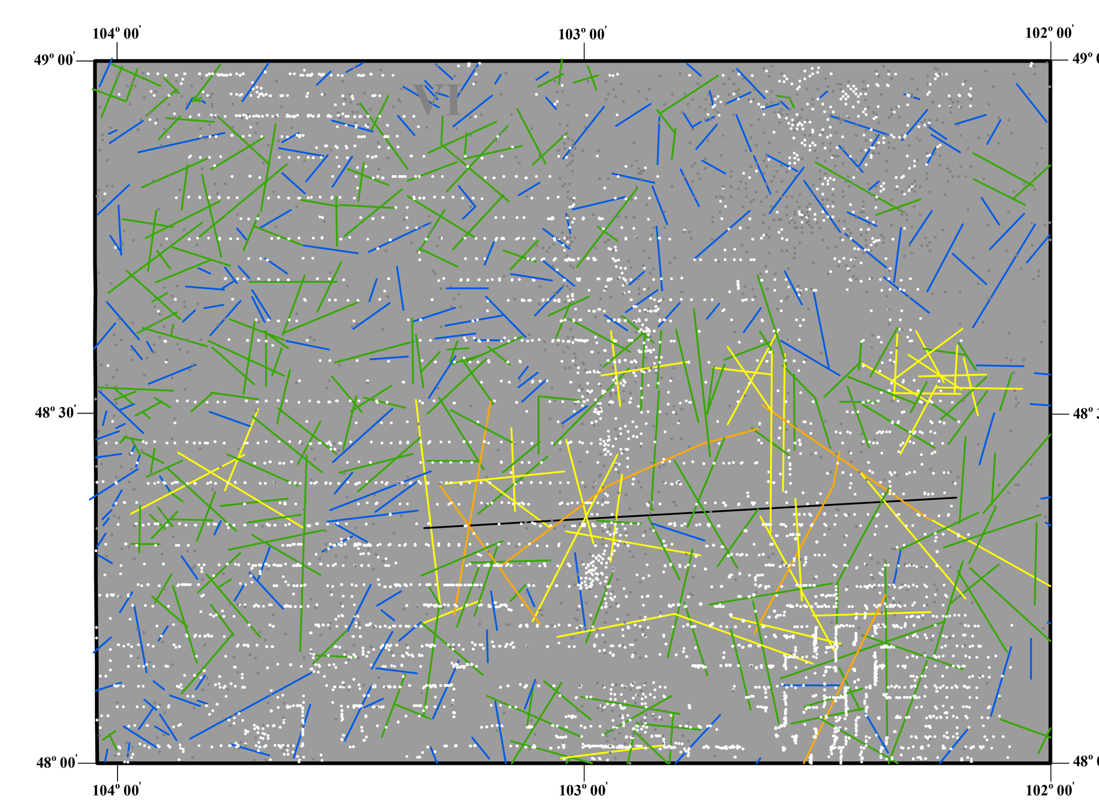


Figure 4. Lineament intersection map displaying the amount of lineament interconnectivity. Discontinuous lineaments (i.e. lineaments that do not meet or intersect another lineament along the path of the lineament) are shown in blue, lineaments with intersections of 1 - 3 intersections per lineament path are shown in green, 4 - 6 yellow, 7 - 9 orange and >9 black. 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.

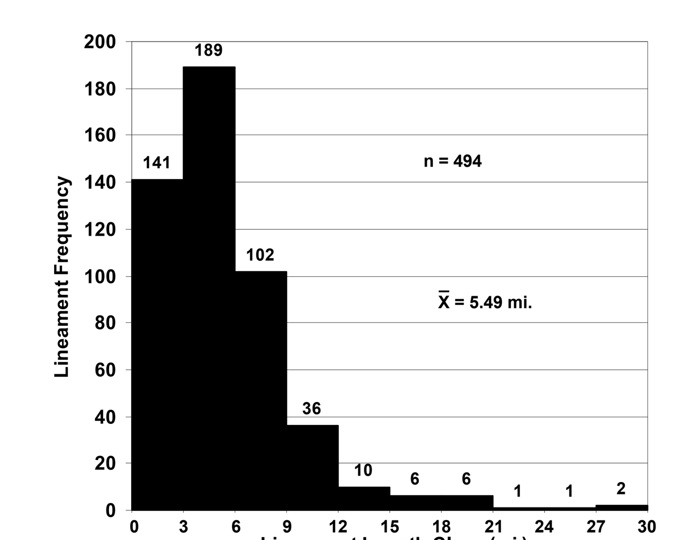


Figure 3. Frequency distribution of 494 individual lineament lengths mapped from 2010 NAIP imagery in the Williston 1:250k sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. Lineament distributions are shown for 10 lineament length classes from zero to 30 miles in three mile intervals or classes.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields
- Nesson Anticline

Other Features

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

The Williston 250k sheet was extended into the Wolf Point 250k sheet to the North Dakota/Montana border.

Cartographic Compilation: Elroy L. Kadrmas

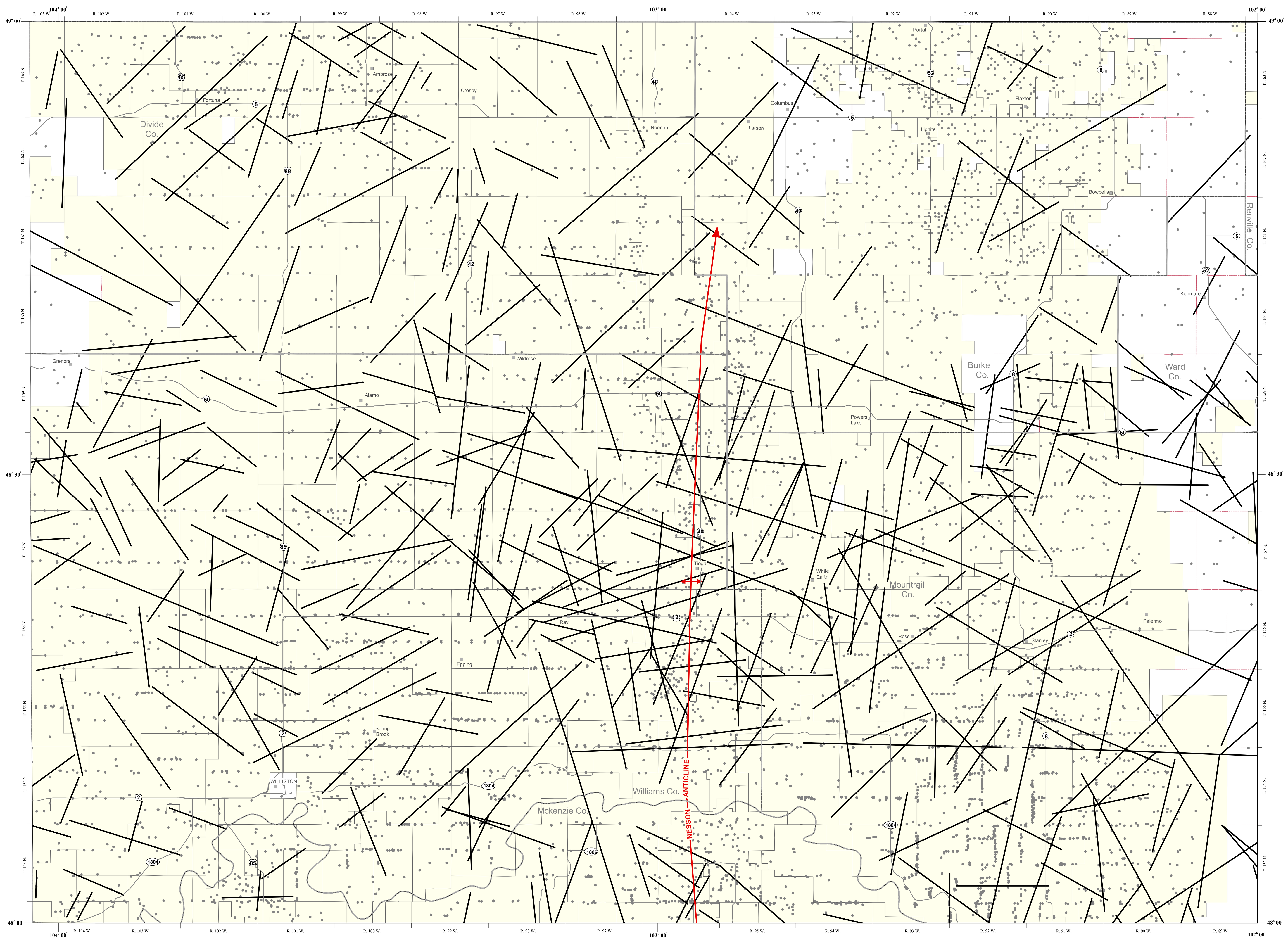
North Dakota Geological Survey
Geologic Investigations No. 195 - Plate IV

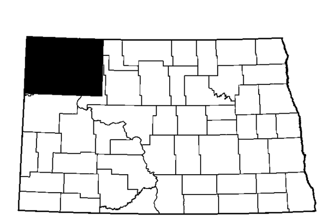
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

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

Fred J. Anderson

2016





Williston 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 103° 00' 00'

LINEAMENTS IN THE WILLISTON 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 Williston 1:250k map sheet in northwestern North Dakota. The Williston 1:250k map area is located in the north-central portion of the Williston Basin in northwestern North Dakota. Lineaments were digitally mapped and digitized from a digital image mosaic of the study area, compliled from 2002 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 363 individual lineaments reveal three general orientation trends (Figures 2a. and b.). A primary (1°) orientation of N 70° W (S 70° E), a secondary (2°) orientation of approximately N 25° E (S 25° W), and a third orientation of N 65° E (S 65° W). The distribution of lineament lengths follows a general log-normal distribution with the majority of lineaments (65%) falling within the three to nine mile lineament length range. Overall, 93% of the lineaments mapped were less than 15 miles in length (Figure 3). The overall density of lineaments within the study area (i.e. lineaments mapped per unit area) is 0.06 lineaments per square mile (approximately two lineaments per township). Lineament density is generally greater in the southern and western portion of the study area and is generlly less in the northeast. This maybe 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, particularly in the northern map area. Lineaments are generally coincident with currently producing and developing oil and gas fields and areas where exploratory oil and gas drilling has been completed. It is interesting that in areas with no field development lineaments are also sparse on this map. 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).

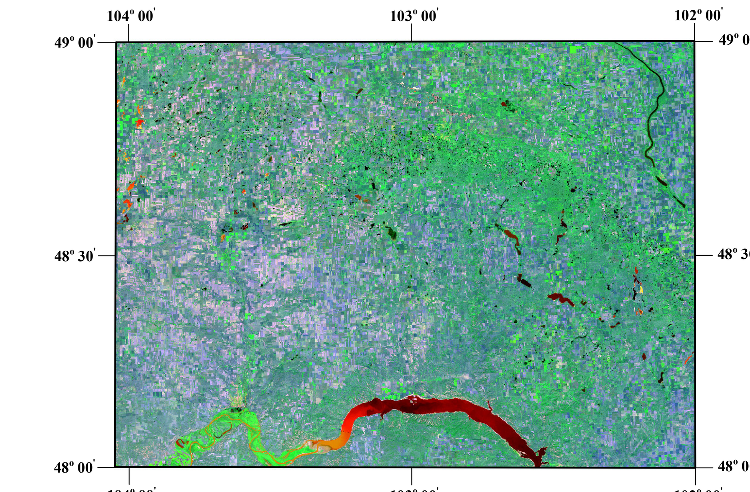
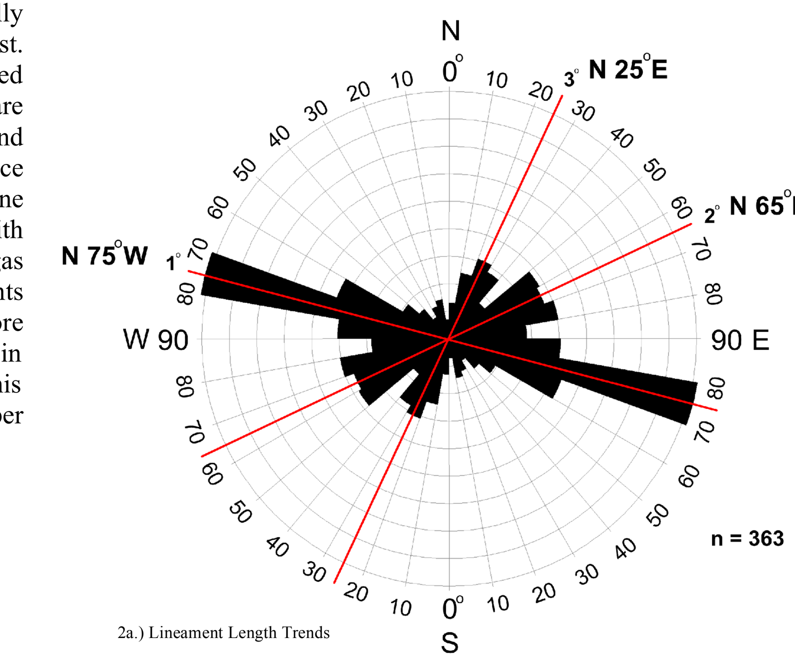
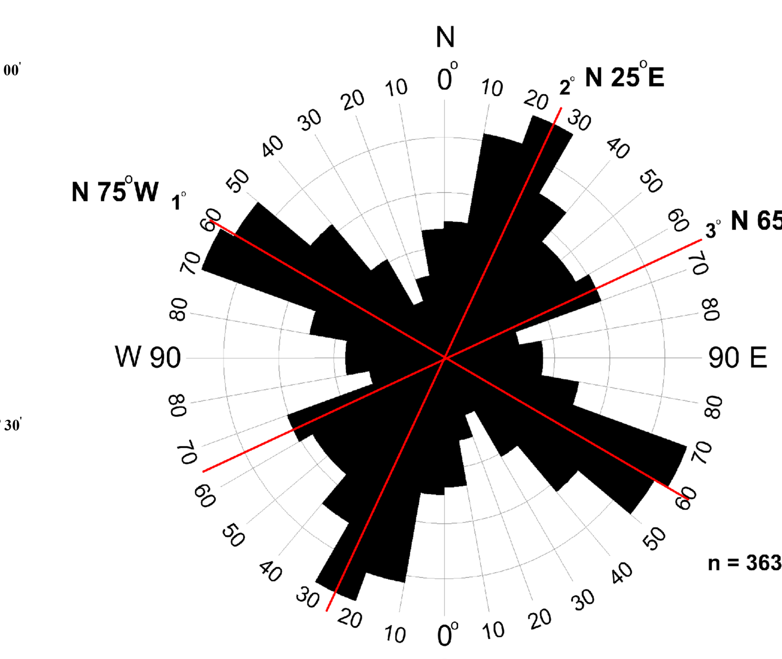


Figure 1. Map of 2002 LANDSAT 7-ETM false color (2-4-7) imagery used for lineament mapping in the Williston 1:250k sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. Agricultural land use can again be seen as the patchwork pattern (green) throughout the eastern half of the study area.



2a.) Lineament Length Trends



2b.) Frequency Based Trends

Figure 2. Rose diagrams of 363 individual lineament orientations mapped from 2002 LANDSAT 7-ETM imagery in the Williston 1:250k sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. The three dominant lineament orientations (1°, 2° and 3°), are approximately N 70° W (S 70° E), N 25° E (S 25° W), and N 65° E (S 65° W) based on orientational analysis of lineament length (2a) and lineament frequency factors (2b).

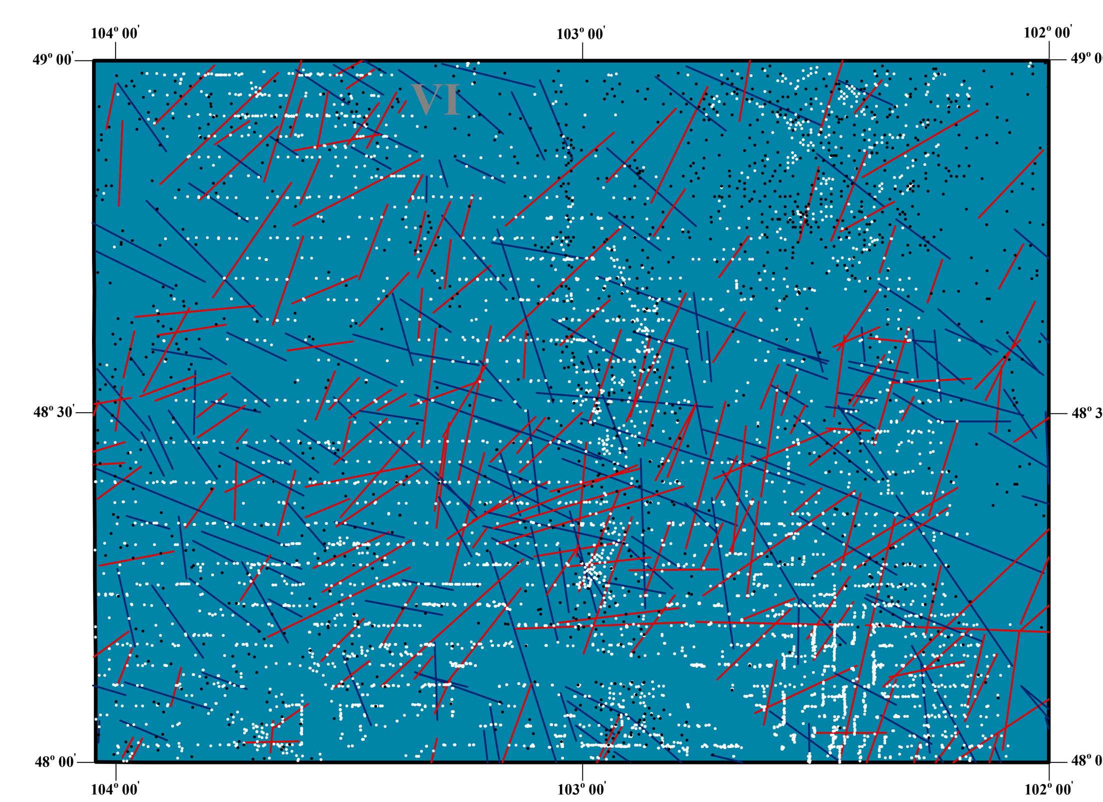


Figure 4. Lineament map displaying lineaments in two classes of lineament orientation. Lineaments oriented along a N-NE or S-SW orientation are showin in red, lineaments oriented along a N-NW or S-SE orientation are shown in blue. Producing wells (shown in white) tend to be located near areas of relatively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

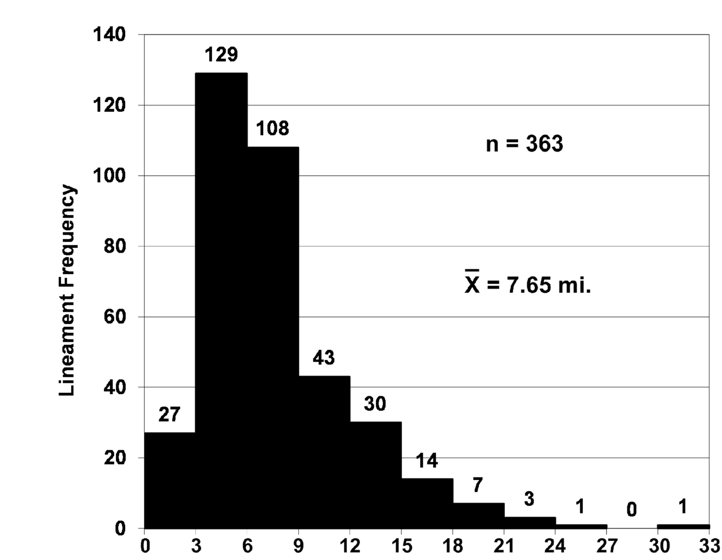


Figure 3. Frequency distribution of 363 individual lineament lengths (distance in miles) mapped from 2002 LANDSAT 7-ETM false color (2-4-7) imagery of the Williston 1:250k map sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. Lineament distributions are shown for 11 lineament length classes from zero to 33 miles in three mile intervals or classes.

EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields
- Nesson Anticline

Other Features

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

The Williston 250k sheet was extended into the Wolf Point 250k sheet to the North Dakota/Montana border.

Cartographic Compilation: Elroy L. Kadrmas

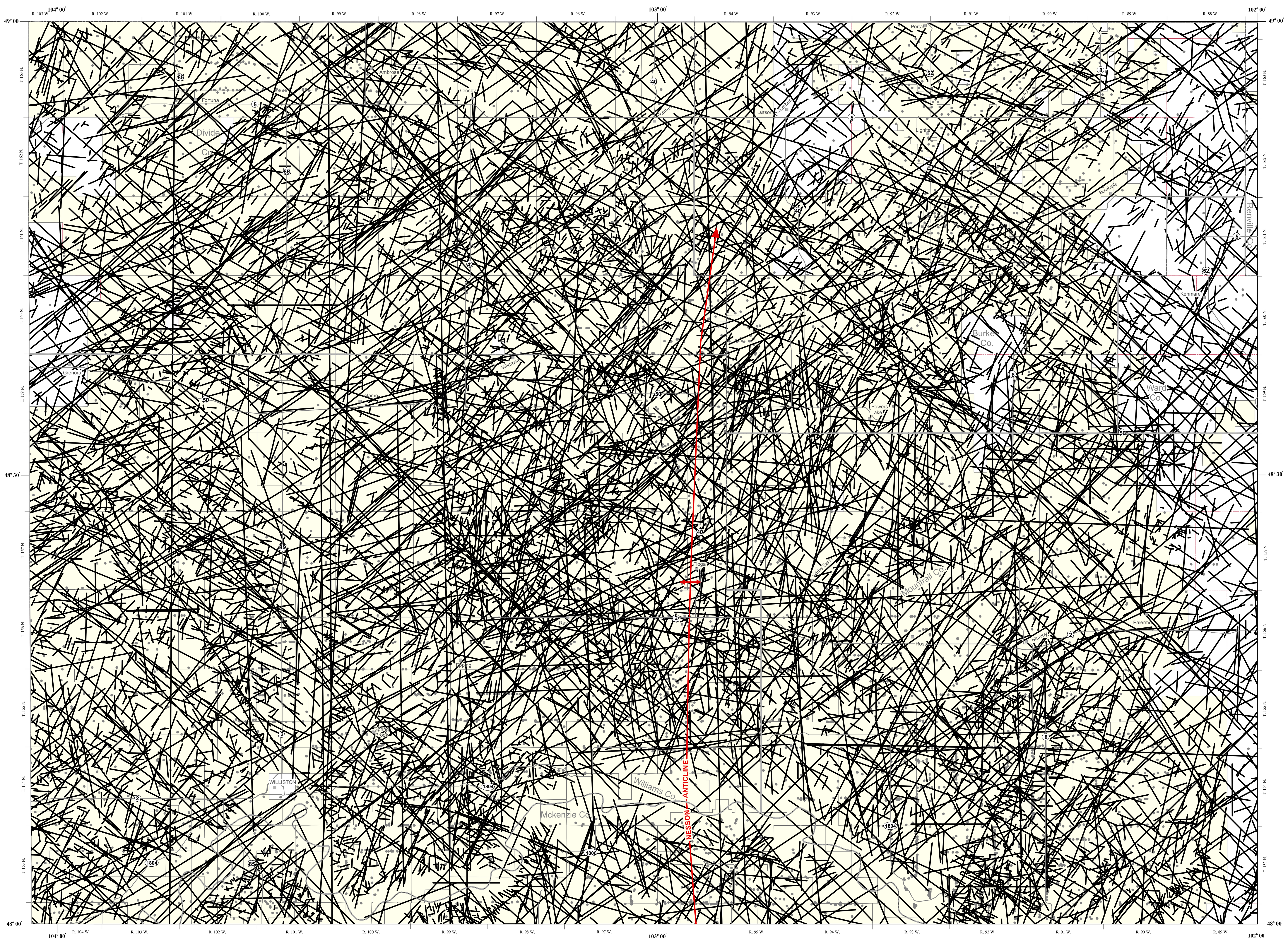
North Dakota Geological Survey
Geologic Investigations No. 195 - Plate V

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

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

Fred J. Anderson

2016



COMPILED LINEAMENTS IN THE WILLISTON SHEET

This map presents the results and discussion of a segment of a contemporary lineament analysis study of the Williston 1:250k map sheet in northwestern North Dakota. The Williston 1:250k map area is located in the north-central portion of the Williston Basin in the northwestern 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 9,280 mapped lineaments reveal two major orientation trends and one minor orientation trend (Figures 2a. and b.). A primary (1°) orientation of approximately N 70° W (S 70° E) and a secondary (2°) orientation of approximately N 65° E (S 65° W) are dominate within the data. A minor sub-north-south trend of N 5° E (S 5° W) is also observable with the data. The distribution of lineament length follows a sharp log-normal distribution with the majority of lineaments (97%) 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 southern portions of the map area with an overall linement density of 1.43 lineaments per square mile (~51 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 in the northern more extensively glaciated areas of the map. Lineament density is observed to be greatest and generally coincident with current oil and gas field development, particularly along the Nesson Anticline and southern Mountrail County. (Figure 4).

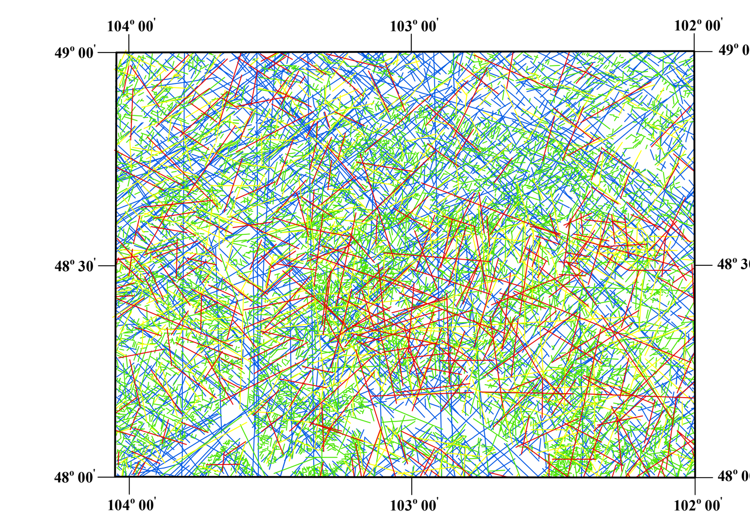
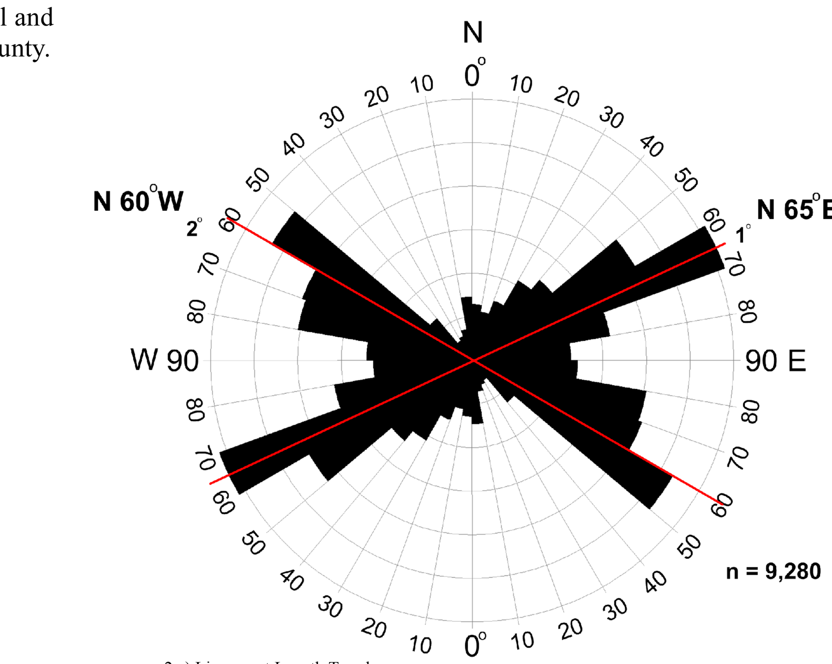
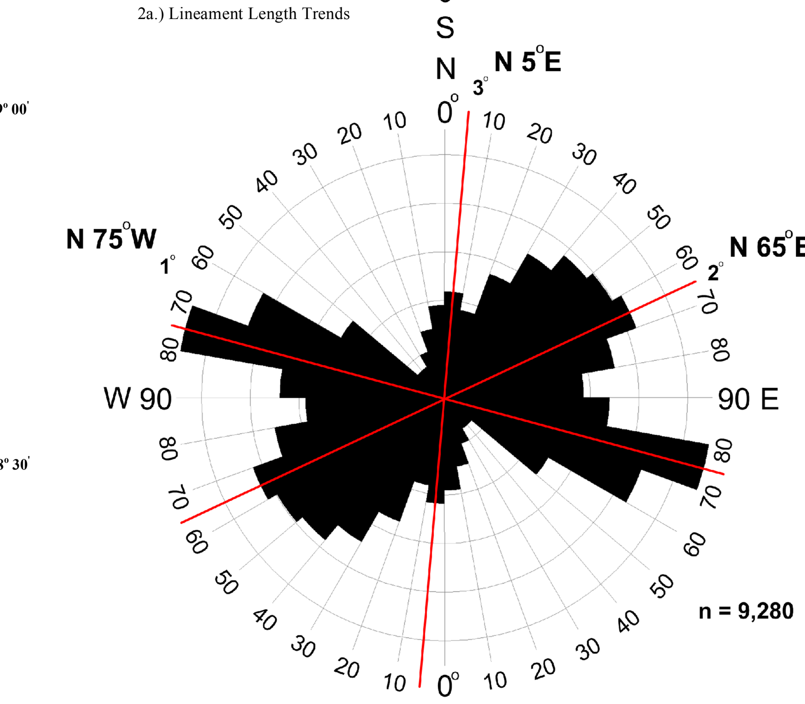


Figure 1. Index map of compiled lineaments in the Williston 1:250k map sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. Historical or lineaments compiled from previous studies, are shown in blue. Lineaments mapped from shaded relief data are shown in green. Lineaments mapped from NAIP 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 9,280 individual lineament orientations compiled from all lineaments mapped in the the Williston 1:250k sheet located in the north-central portion of the Willison Basin in northwestern 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 70° W (S 70° E) and N 65° E (S 65° W). A minor trend of N 5° E (S 5° W). is also observable within this data.

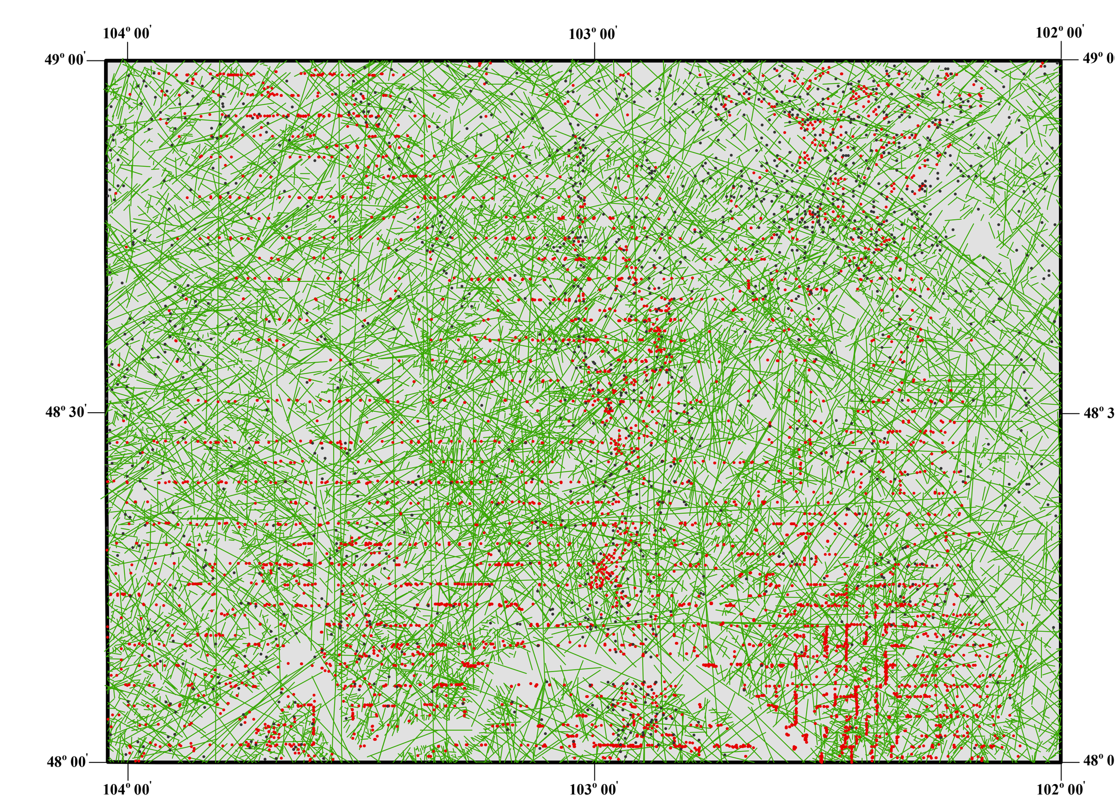


Figure 4. Map of compiled lineaments (green) with currently producing wells (red) and non-producing wells (dark gray) displaying the general relationships between overall lineament trends and densities and oil and gas production and development in the Williston 1:250k Sheet.

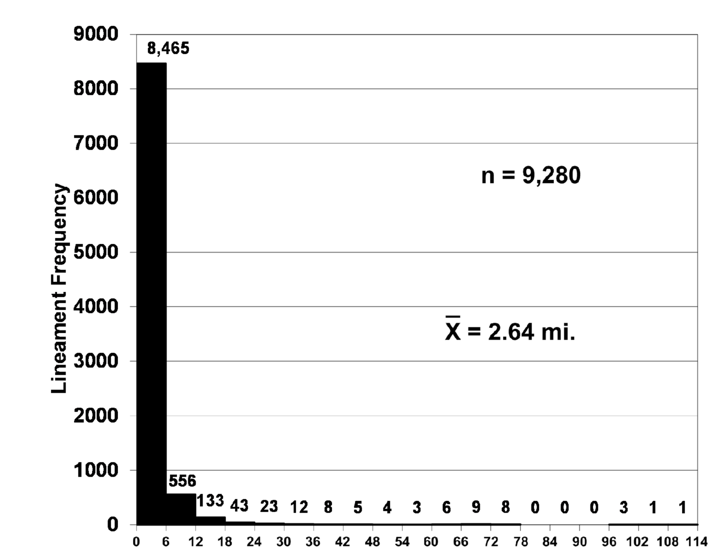
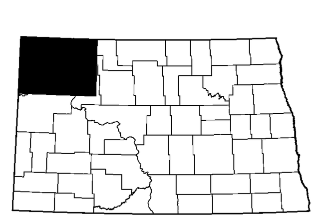


Figure 3. Frequency distribution of 9,280 individual lineament lengths (distance in miles) compiled from lineaments mapped in the Williston 1:250k map sheet located in the north-central portion of the Williston Basin in northwestern North Dakota. Lineament distributions are shown for 19 lineament length classes from zero to 114 miles in 6 mile intervals.



Williston 250K Sheet, North Dakota

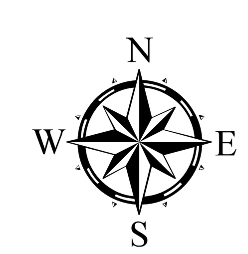
Scale 1:250,000

Miles: 0 5 10 15 20

Kilometers: 0 5 10 15 20

Mercator Projection
Standard parallel 48° 00' 00"

1927 North American Datum
Central meridian 103° 00' 00"



EXPLANATION

Geologic Features

- Lineaments
- Drill Hole
- Oil & Gas Fields
- Nesson Anticline

Other Features

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

The Williston 250k sheet was extended into the Wolf Point 250k sheet to the North Dakota/Montana border.

Cartographic Compilation: Elroy L. Kadrmas

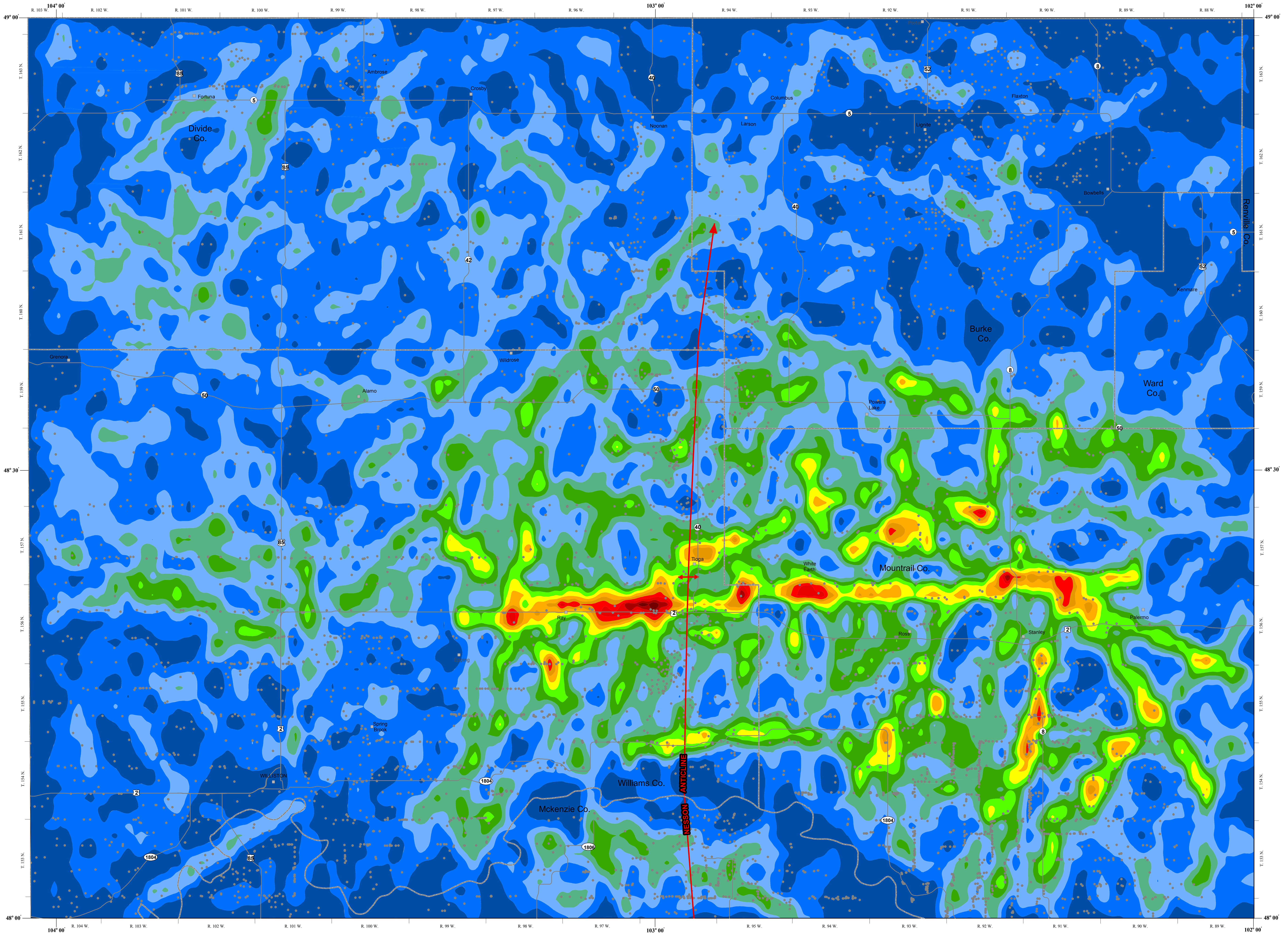
North Dakota Geological Survey
Geologic Investigations No. 195 - Plate VI

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

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

Fred J. Anderson

2016



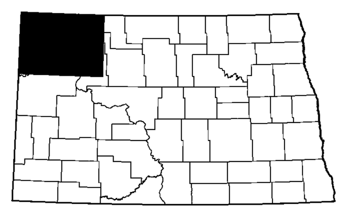
Scale 1:250,000

Miles: 0, 5, 10, 15, 20

Kilometers: 0, 5, 10, 15, 20

Mercator Projection
Standard parallel 48° 00' 00"

1927 North American Datum
Central meridian 103° 00' 00"



Williston 250K Sheet, North Dakota

LINEAMENT DENSITY MAPPING IN THE WILLISTON SHEET

This map presents the results and discussion of a segment of a contemporary lineament analysis of the Williston 1:250k sheet located in the north-central Williston Basin in northwestern 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 650,000-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 southeastern portion of the map area and lower lineament density towards the west and northeast. Overall, lineament density appears to be greatest and relatively coincident with areas where producing oil and gas wells and fields are commonly located throughout northwest Mountrail County, 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. It is apparent that regular uniform drilling and spacing along energy corridors is occuring, especially west of the Nesson Anticline.

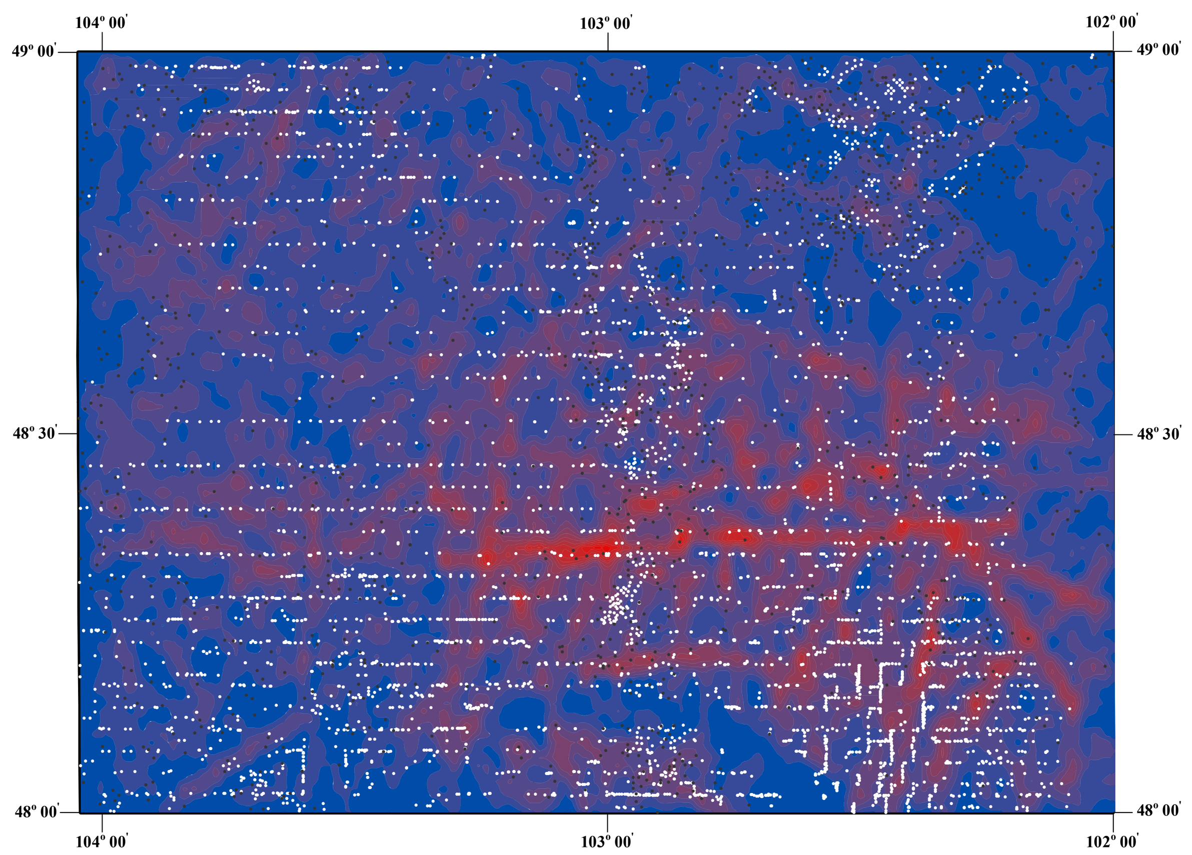


Figure 1. Lineament density map displaying lineament density with currently producing (white) and non-producing (dark gray) wells in the Williston 1:250k sheet. Producing wells tend to be located near areas of relatively higher lineament density (shown in red) in the southeast. The distribution of dry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

Lineament Density (ft/mi^2)

- 600,000 - 650,000
- 550,000 - 600,000
- 500,000 - 550,000
- 450,000 - 500,000
- 400,000 - 450,000
- 350,000 - 400,000
- 300,000 - 350,000
- 250,000 - 300,000
- 200,000 - 250,000
- 150,000 - 200,000
- 100,000 - 150,000
- 50,000 - 100,000
- 0 - 50,000

EXPLANATION

Geologic Features

- Drill Hole
- Nesson Anticline

Other Features

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

The Williston 250k sheet was extended into the Wolf Point 250k sheet to the North Dakota/Montana border.

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 WILLISTON 1:250K SHEET, NORTH DAKOTA

Fred J. Anderson

2016

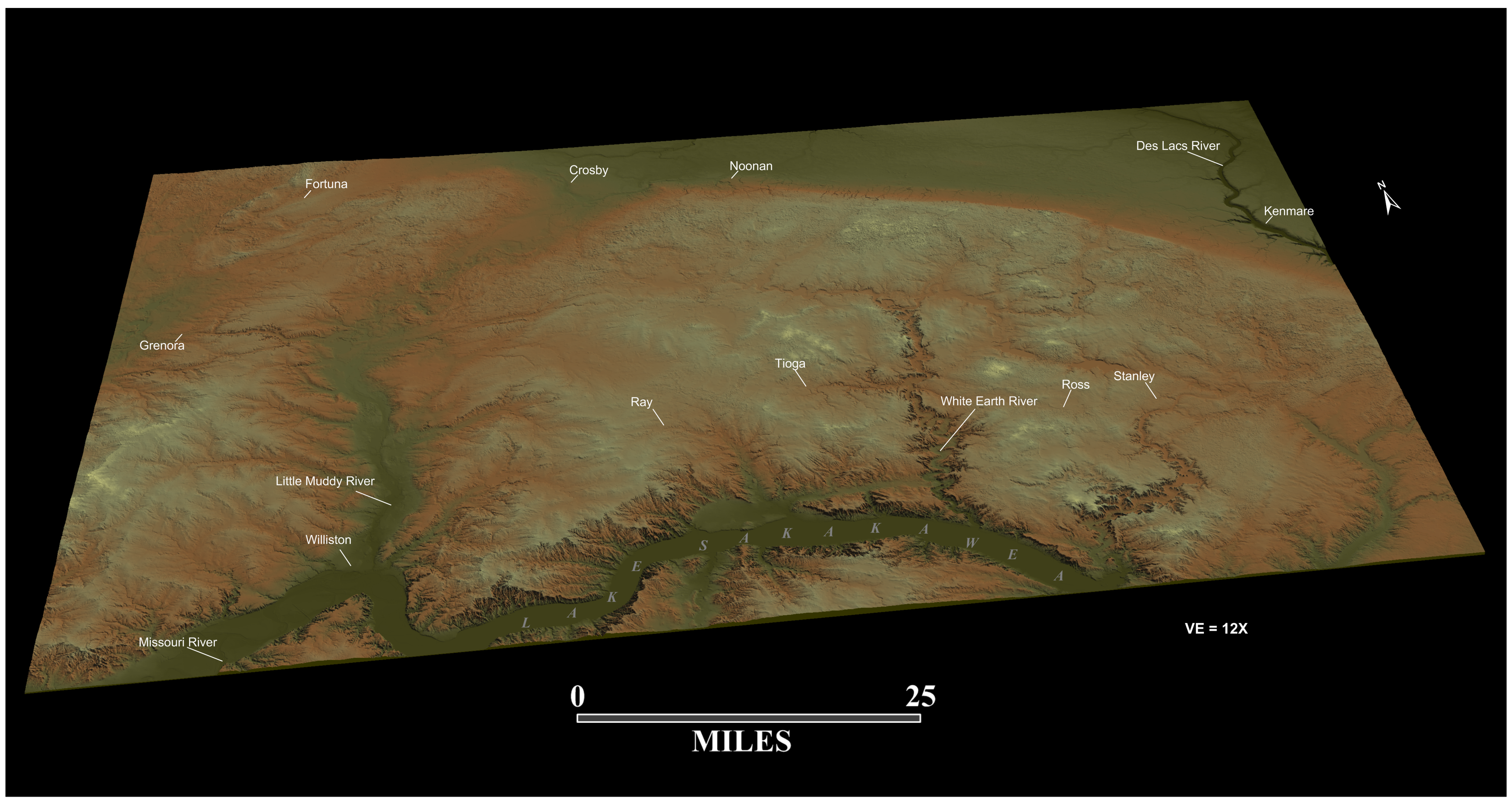
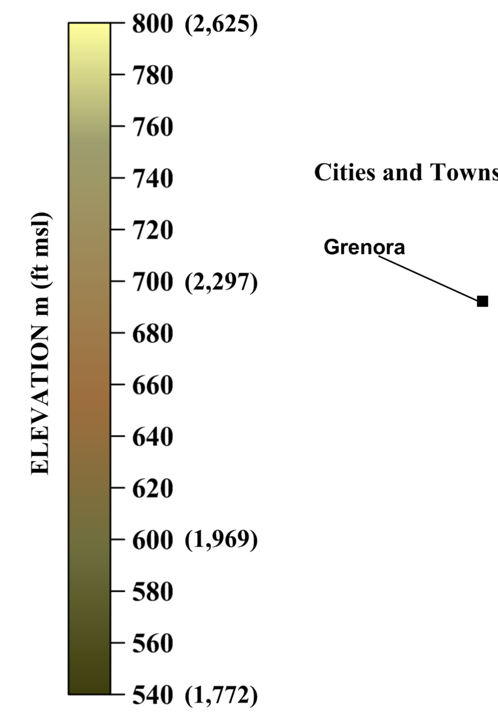


Figure 1. Three-Dimensional (3D) perspective view from the southwest towards the northeast across a digital elevation model (DEM) of the Williston 1:250k map sheet in the north-central Williston Basin in northwestern North Dakota. This DEM was created from a 10 meter resolution digital elevation dataset extracted from the USGS 2016 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 55° with an angle of inclination of 50°. The Williston 1:250k map sheet covers the northwestern portions of the (from southwest to northeast) Coteau Slope, Missouri Coteau and Escarpment, and glaciated plains physiographic regions. The northwestern portion of the Missouri Escarpment is present in the northeastern map area. The confluence of the Little Muddy and Missouri Rivers below Williston can also be found in the southwest portion of the map area just south of Williston. The upper one-third of Lake Sakakawea, from just south of Williston to the confluence with the Little Knife River is found along the southern edge of the map area.



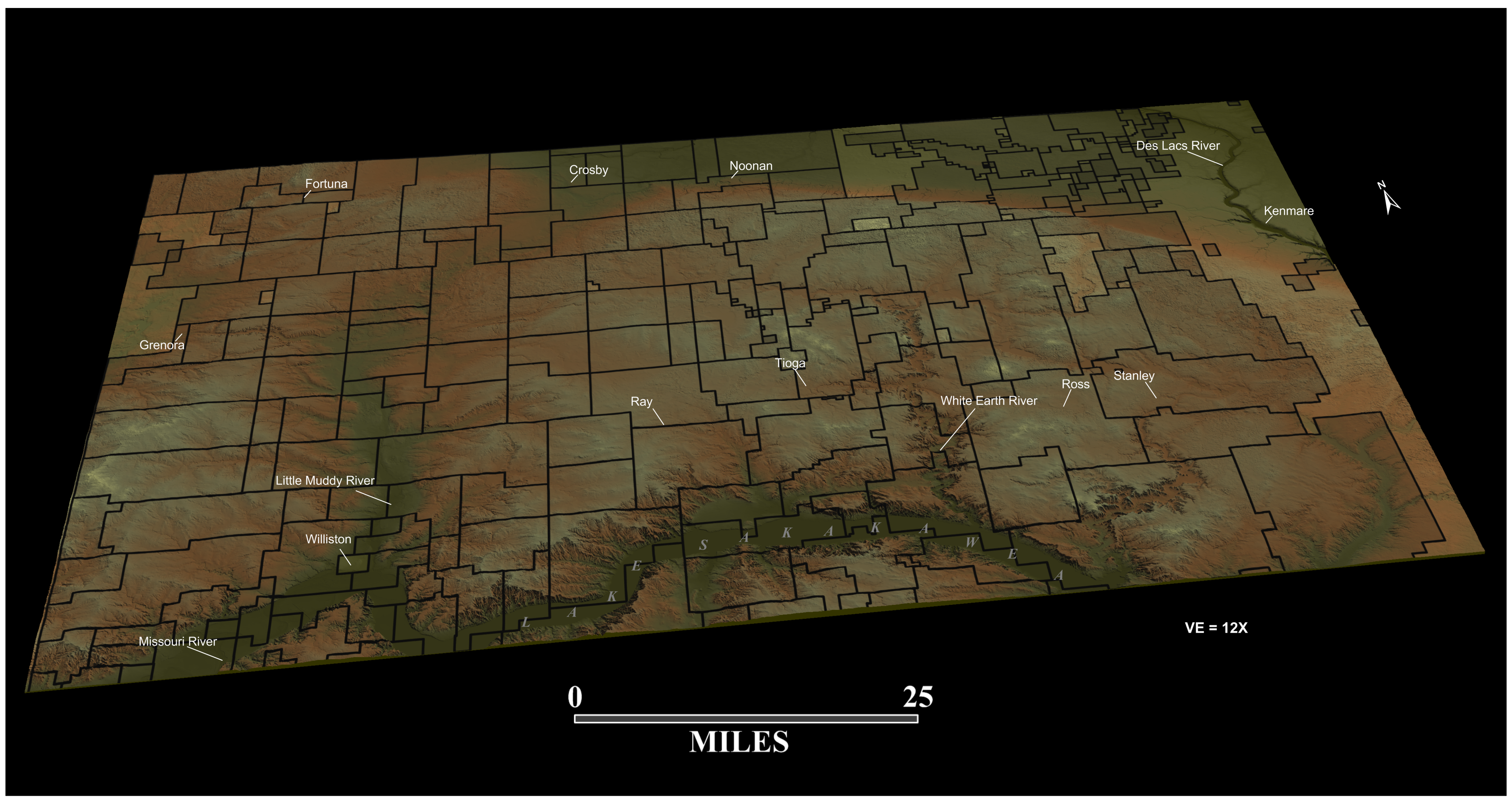
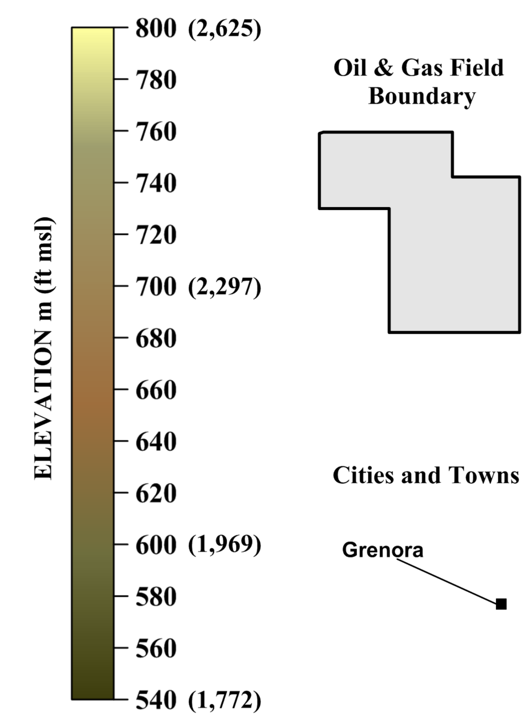


Figure 2. Three-Dimensional (3D) perspective view from the southwest towards the northeast across a digital elevation model (DEM) of the Williston 1:250k map sheet in the north-central Williston Basin in northwestern North Dakota. Current oil and gas field boundaries (shaded light gray) are overlain on the 10-meter resolution DEM. Due to the development of the Bakken in this region the majority of the map area is covered by field boundaries. Areas that are not covered by and oil and gas field boundary include the easternmost portion of the map area and a few smaller areas in the northeastern and the north-central map area.



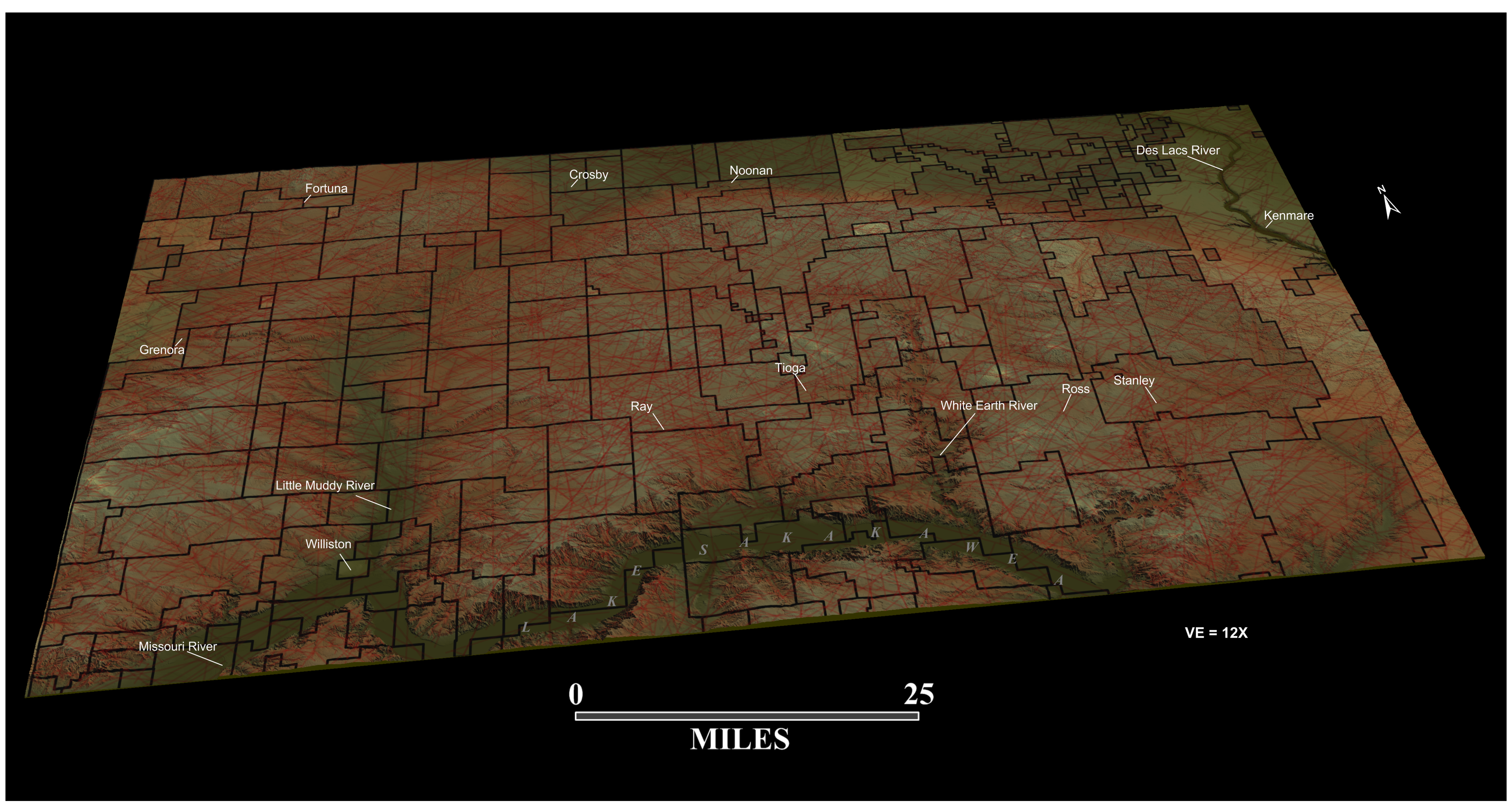
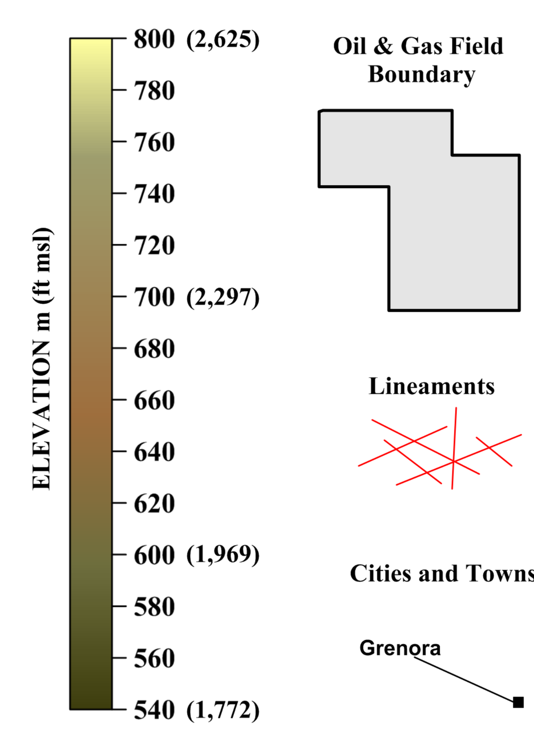


Figure 3. Lineaments mapped from selected imagery and data sources (i.e. historical, NED shaded relief, NAIP Imagery, and Landsat-7 ETM+ data) throughout the Williston 1:250k map sheet are shown in red overlain onto the surface DEM created from the USGS 2016 10-meter NED. In this view the relationships 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 traversing 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 porosities and permeabilities 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 light gray on the DEM displayed beneath the lineaments.



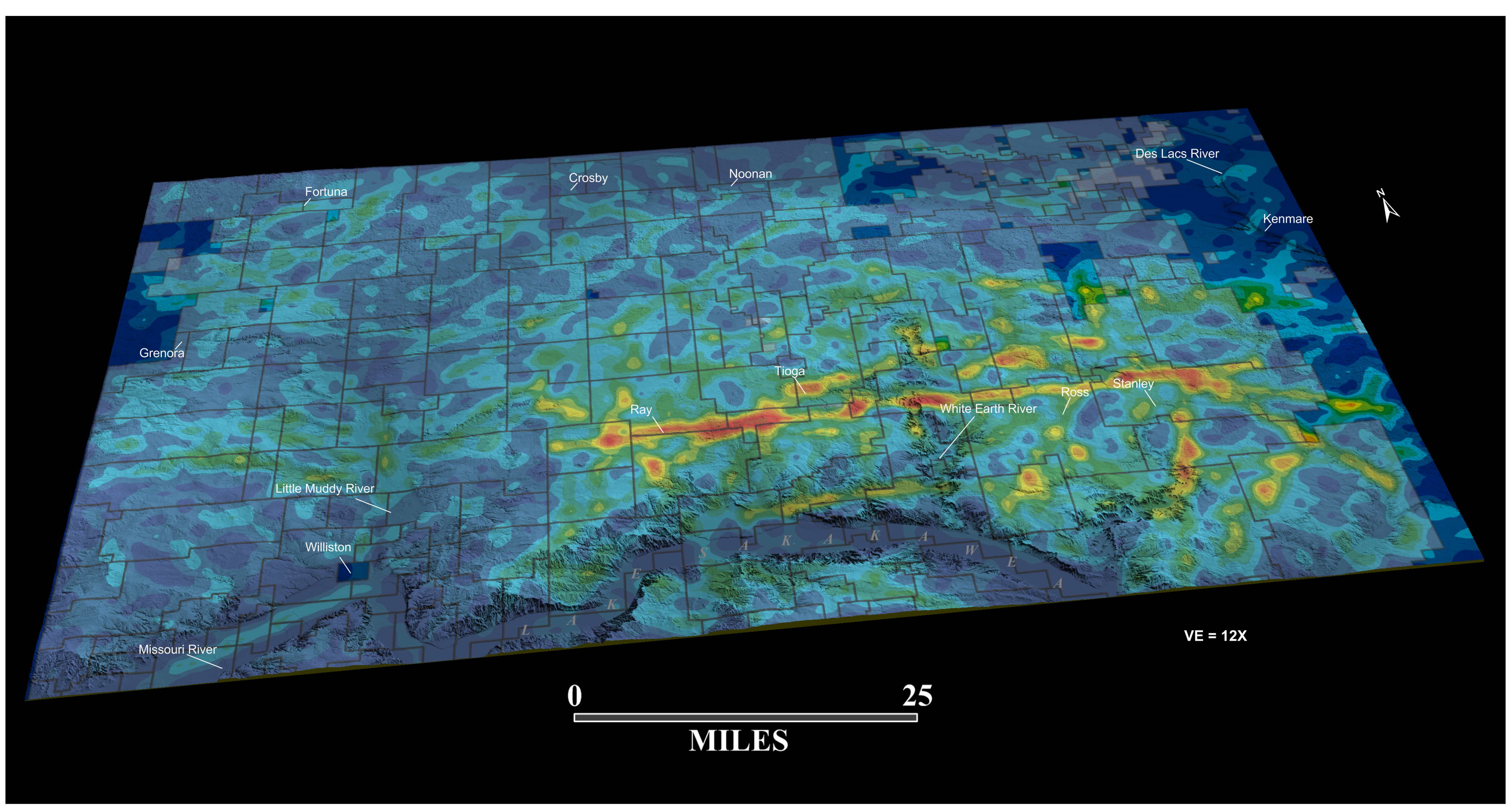


Figure 4. Interpolated lineament density map of all lineaments mapped within the Williston 1:250k map sheet overlain on the surface DEM created from the USGS 2016 10-meter NED. Areas of higher lineament density are depicted as warmer colors (yellow, orange, red) and areas of lower lineament density are shown as cooler colors (blues and green). Lineament densities are higher in the central and southeastern portions of the map area and are 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 within a given rock volume which may be related to areas of increased oil and gas production or can also be suggestive of structural boundary zones serving to define reservoir boundaries. The extent of current oil and gas fields are shown as light gray with dark gray field boundaries draped over the lineament density map.