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

By

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NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
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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

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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° x 2°) quadrangle that covers an approximate 6,344 square mile area from 48° to 49° N. Latitude and 100° to 102° 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

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Original Data Creation/Acquisition</th>
<th>Description/Author</th>
<th>Data Source Location (URL address)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical Lineaments</td>
<td>1970 - 2006</td>
<td>Compiled from Various Published Sources</td>
<td><a href="https://www.dmr.nd.gov/ndgs/">https://www.dmr.nd.gov/ndgs/</a></td>
</tr>
<tr>
<td>Shaded-Relief Data</td>
<td>1997</td>
<td>USGS National Elevation Dataset (NED)</td>
<td><a href="http://ned.usgs.gov/">http://ned.usgs.gov/</a></td>
</tr>
<tr>
<td>Aerial Imagery</td>
<td>Summer, 2010</td>
<td>National Agricultural Imagery Program (NAIP)</td>
<td><a href="http://165.221.201.14/NAIP.html">http://165.221.201.14/NAIP.html</a></td>
</tr>
</tbody>
</table>

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

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.
**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

<table>
<thead>
<tr>
<th>Data Type</th>
<th>No. of Trends</th>
<th>Orientation Description</th>
<th>Basic Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical Lineaments</td>
<td>2</td>
<td>N 55° W</td>
<td>N 55° E</td>
</tr>
<tr>
<td>NED Shaded-Relief Data</td>
<td>2</td>
<td>N 75° W</td>
<td>N 50° E</td>
</tr>
<tr>
<td>2003 NAIP Aerial Imagery</td>
<td>2</td>
<td>N 65° W</td>
<td>N 60° E</td>
</tr>
<tr>
<td>2002 LANDSAT-7 ETM+ Satellite Imagery Data</td>
<td>2</td>
<td>N 65° W</td>
<td>N 60° E</td>
</tr>
<tr>
<td>Combined/Merged Lineaments</td>
<td>2</td>
<td>N 55° W</td>
<td>N 55° E</td>
</tr>
</tbody>
</table>

Trends determined and summarized from lineament length and frequency based methods.

A primary (1°) trend of N 55° W along with a conjugate (as measured against the regional tectonic NE-SW maximum stress direction) secondary (2°) trend of N 55° 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° trend of N 75° W along with conjugate 2° trend of N 50° 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° trend of N 65° W along with a conjugate 2° trend of N 60° 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° trend of N 65° W along with a conjugate 2° trend of N 60° E was revealed (Plate IV-Figure 2). A significantly less prominent 3° trend around N 15° W, nearly orthogonal to the 1° 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° trend of N 55° W along with a conjugate 2° trend of N 55° E was found (Plate V-Figure 2). It is apparent that the approximate 1° and 2° orientation trends within the historical lineaments data set are strengthened by additional lineament mapping from other data and imagery sources. The 3° 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.**

<table>
<thead>
<tr>
<th>Data Type</th>
<th>No.</th>
<th>Lineament Length Characteristics (miles)</th>
<th>Lineament Density (Lpsm/Lpst)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Historical Lineaments</td>
<td>1,318</td>
<td>0.12</td>
<td>84.15</td>
</tr>
<tr>
<td>NED Shaded-Relief Data</td>
<td>1,474</td>
<td>0.39</td>
<td>27.37</td>
</tr>
<tr>
<td>2009 NAIP Aerial Imagery</td>
<td>509</td>
<td>0.28</td>
<td>24.85</td>
</tr>
<tr>
<td>2000 LANDSAT-7 ETM+ Satellite Imagery Data</td>
<td>303</td>
<td>1.35</td>
<td>21.08</td>
</tr>
<tr>
<td>Merged/Combined Lineaments</td>
<td>3,604</td>
<td>0.12</td>
<td>84.15</td>
</tr>
</tbody>
</table>

(L.psm/L.pst): Lineaments per square mile/Lineaments per standard township (36 mi²).

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

<table>
<thead>
<tr>
<th>Lineament Density Class</th>
<th>Lineament Density Range (Lpsm)</th>
<th>Map Area Covered (mi²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class-I</td>
<td>6.6 – 7.6</td>
<td>0.62</td>
</tr>
<tr>
<td>Class-II</td>
<td>5.7 – 6.6</td>
<td>8</td>
</tr>
<tr>
<td>Class-III</td>
<td>4.7 – 5.7</td>
<td>67</td>
</tr>
<tr>
<td>Class-IV</td>
<td>3.8 – 4.7</td>
<td>386</td>
</tr>
<tr>
<td>Class-V</td>
<td>2.8 – 3.8</td>
<td>1324</td>
</tr>
<tr>
<td>Class-VI</td>
<td>1.9 – 2.8</td>
<td>2,348</td>
</tr>
<tr>
<td>Class-VII</td>
<td>0.95 – 1.9</td>
<td>1,733</td>
</tr>
<tr>
<td>Class-VIII</td>
<td>0 – 0.95</td>
<td>478</td>
</tr>
</tbody>
</table>

Total = 6,344

(Lpsm): Total of all lineament lengths (mi) per square mile (mi²).

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 being 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.
REFERENCES


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


PLATE 1 - HISTORICAL LINEAMENTS MAPPED IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson

2011

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 northwestern portion of the Williston Basin in northwestern North Dakota. Lineaments mapped from previous studies (i.e., historical lineaments) by several authors over the last few decades, including Poore and Cordell, 1989; Dierig and Dierig, 1985; Dierig and Dierig, 1989; Peterson and MacCray, 1987, Anna, 1986, Maughan and Perry, 1986, Hayes, 1984, Cooley, 2011, and others, were included in the compilation to produce the final lineament coverage for the Minot 250k sheet (Figure 1). Previously mapped lineament control maps are presented here at a scale of 1:125,000. Contours of their density are depicted on the map. 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 root factors, as most of these lineaments were mapped at regional scales and have a broader understanding of the area. The relationship between lineaments and geology and geophysical studies in the northeastern portion of the Williston Basin is particularly in eastern Renville and western Bottineau County. Lineaments mapped are likely influenced by subcrops (geological and tectonics) and surface geological studies. Lineament maps can also show relationships between lineaments and geology, geophysical studies, and areas of 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 subcrops (geological and tectonics) and surface geological studies. Lineament maps can also show relationships between lineaments and geology, geophysical studies, and areas of oil and gas field development and current exploration and production trends, particularly in Eastern Renville and Western Bottineau County.
This map presents the results and discussion of a segment of a contemporary lineament analysis of the Minot 1:250k C-based National Elevation Data (NED) and lineament mapping from shaded relief digital elevation data. Lineament mapping was conducted digitally by successive visual and manual inspection of numerous small areas (approximately 1100 lineaments per area) to better define individual lineaments and extend their length in a leaf-base computer program (Davis and Fisher, 1996). Lineaments were converted to a two-dimensional orientation (Figure 2a and 2b) and a two-dimensional lineament density (Figure 2c) by a high resolution scan of a color digitization of the lineament analysis. Lineament length and density were determined using a range of digital lineament length measurements (2a, Figure 2a) and lineament density (2b, Figure 2b). The lineament length distributions were grouped into five similar individual lineament length classes (Figure 2c). Two dominant orientations (1°, and 2°) are N 75° W (S 75° E) and approximately N 30° E and S 30° W, based on directional analysis of lineament line length (2a) and lineament density (2b). The length and density of the lineament length interval (Figure 2a), and the density of the lineament density interval (Figure 2b), can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis. In this map, the general distribution of lineaments can be grouped into seven areas of five similar individual relative lineament density classes (Figure 2c). These lineament density areas (2b) require further lineament analysis.
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 north central part of the state and is characterized by a variety of lineament orientations. The Mineral Resources Center (MRC), in cooperation with the North Dakota Geological Survey (NDGS) and the North Dakota Oil and Gas Commission (ODGC), conducted a study to digitize and map a variety of lineament orientations from the Minot area. The study area includes a portion of MRC Quadrangle 3-8/2 and 7-6/2, and the NDGS map area 10-11/2. This map displays the results of the lineament mapping study and provides a basis for further geoscience investigations into the potential for enhanced oil and gas recovery from naturally fractured reservoirs, particularly for shorter lineaments. On this map, several of the lineaments are coincident with currently producing and developing oil and gas fields. Areas with a higher lineament density are likely influenced by subsurface geological (i.e., basement faulting) and surface processes. The distribution of lineament lengths for a given length class interval was not directly proportional to the length class interval. This may indicate that lineaments of similar length have different densities. The lineament density in the area of interest is generally greater in the north-central part of the study area. Lineaments were processed and digitized using Esri ArcGIS software, which provides tools for mapping and analysis of lineament orientations. The map provides a visual representation of lineament density and is useful for identifying potential areas of interest for further geoscience investigations. The map is available for download and use in research and development activities. The map is provided to promote understanding and awareness of the geological features and potential for enhanced oil and gas recovery in the Minot area. The map can be used by researchers, engineers, and industry professionals to identify potential areas for enhanced oil and gas recovery.
This map presents the results and discussion of a segment of a contemporary lineament mapping and analysis study of the Minot 1:250k sheet located in north-central North Dakota. The Minot 1:250k (C96) sheet is one of 22 quadrangles making up the State Geologic Map of North Dakota. Lineaments were digitally captured and digitized from a digital image mosaic of the study area, compiled from Landsat 7-ETM imagery. Digital image mosaic (DTM) data. A digital image mosaic was created from four available scenes in a blue, green, red (BGR) false color combination of special bands 5, 4, and 3 from each Landsat 7-ETO imagery file. The mosaic was generated at a scale of 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 (Figure 4a and 4b). A primary (5) orientation of 30° (N 60° W) and a secondary (5°) orientation of approximately 60° (N 30° W). The application of this methodology was to identify lineament data sets covering per path) normal to the preferred NW trend (Figure 4). The Souris River sub-perpendicular of this trend suggest a relatively higher amount of lineament frequency (i.e., distributions are shown for 11 lineament length classes from zero to 22 miles in two mile lineaments oriented along a N-NE or S-SW orientation. Overall, 85% of the lineaments are displayed on the 1:250,000 scale lineament map shown at the left. 1:250,000. Lineament density appears to be generally greater in areas of currently producing wells. Horizontal drilling and production trends have increased in the northeastern 2/3 of the Williston Basin of North Dakota. Visual analysis of lineament mapped perpendicularly to sub-perpendicular of the NW trend suggest a relatively higher amount of lineaments encountered per path) normal to the preferred NW trend (Figure 4). The Souris River is the major surface water feature located in the eastern two-thirds of the study area. Other surface and structural features are not displayed on the 1:250,000 scale lineament map shown at the left.
Trends. Overall, lineament density appears to be greater in areas of currently producing wells and coincident with current oil and gas field development, and current exploration and production relationships between overall lineament trends and densities and oil and gas production and development in the Minot 1:250k Sheet.

Figure 4. Map of compiled lineaments (green) with currently producing wells (red) and non-producing wells (dark gray) displaying the general trends.
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 compiled lineaments estimated 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 cell) were assigned to grid cell values for the areas of each of the grid cells (sections). The resulting line density was then converted to the population density range of 1:50,000 intervals (min of 1, max of 1,000). Lineament density classes were assigned to map colors, to areas of higher lineament density, shown in warmer colors. This map shows areas of higher lineament density, shown in warmer colors. Overall, lineament density appears to be greatest and relatively correlated with areas where producing oil and gas wells and fields are commonly located, and lower densities where non-producing wells have been drilled (Figure 1). This suggests a relationship between overall production and areas of relatively higher lineament density.
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 southwest 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 shown here at a vertical exaggeration of 12X. For the rendering of this DEM, the lighting direction is from the northwest 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 Blue Mountains 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 are also found in the southeastern corner of the map area just northeast of the escarpment. The northeastern 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.

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 area and many are found to intersect within field boundaries. A high degree of lineament intersection suggests a higher amount of 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.

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 shown as warmer colors (yellow, orange, red) and areas of lower lineament density are shown in 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.
HISTORICAL LINEAMENTS IN THE MINOT 250K SHEET - COMPARED AND MAPPED WITH FIELD OBSERVATIONS

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 southeastern portion of the Williston Basin in northwestern North Dakota. Lineaments mapped from previous studies (e.g., historical lineaments by several authors over the last few decades, including Foster and Cordell, 1986, Gilman, 1995, Horsley and Messers, 1967), were plotted. The lineaments were then digitized and imported into a compilation of original field-collected surveys (Hanks, 2006), compiled and mapped into a single historical lineament coverage for the Minot 250K sheet (Figure 1). Previously mapped lineament compilations (e.g., are presented here at a scale of 1:250,000, adjusted at their original level of detail). The majority of the lineaments were digitized at a level of 0.1 mile and were given a 0.1 lineament per square mile approximately 0.5 lineament per township level of resolution (approximately 1 mile). The summation of lines is generally greater than the summation portion of the original data set. The resulting lineament density is relatively uniform across the sheet, 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., lineament density is higher at 1:250,000 and 1:62,500) than at 1:1,000,000. The lineament density in the formation of new lineaments or in the reactivation of pre-existing lineaments is likely influenced by subsurface geology (e.g., basement faulting and surface geophysical analyses indicate faulting of Blaine and Pembina formations). Changes in land use and industrial activity, such as oil and gas development, have also influenced the lineament density. Areas with higher industrial activity have been reactivated and have continued to reactivate at a higher rate. Areas with a lower industrial activity have been less affected by industrial activity and have continued to reactivate at a lower rate. The map shows the lineaments that are currently active and the lineaments that are currently inactive. The lineaments that are currently active are those that are currently producing and developing oil and gas fields. Areas with a higher industrial lineament density reflect the surrounding small-level exploration and production activity, while areas of the area within the northern half and western half of the sheet, several fields have non-linear lineaments occurring within the field boundaries, which may provide better opportunities for exploration.

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

Fred J. Anderson

2011
PLATE II - LINEAMENTS MAPPED FROM SHADED RELIEF DATA IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson
2012

LINEAMENTS IN THE MINOT SHEET DERIVED FROM SHADED-RELIEF MAP INTERPRETATION

This map presents the results and discussions of a segment of a contemporary lineament analysis of the Minot 250k map sheet in northeastern North Dakota. The Minot 250k map area is located in the northeastern portion of the state, approximately at latitude 50°N and longitude 102°W. The area covers a total area of approximately 8,429 square miles (21,900 square km). Lineament data review and evaluation reveal numerous linear features, including structural lineaments, fault movements, and other forms of linear geologic expressions. The actual number of lineaments is represented in the northern part of the Minot 250k map sheet, totaling 565 lineaments, with an areal extent of approximately 3,224 square miles (8,350 square km). This is a significant portion of the map area with an overall linear density of 0.32 lineaments per square mile. 0.5 lineaments per square mile is used in this map to represent a distribution of lineaments and other geologic features. The area covers parts of the Minot area, which is a hydrogeologic feature present in the study area but is not shown on this map.

EXPLANATION

<table>
<thead>
<tr>
<th>Lineaments</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill Holes</td>
<td>Townships Boundaries</td>
</tr>
<tr>
<td>Oil &amp; Gas Wells</td>
<td>County Boundaries</td>
</tr>
<tr>
<td>Radar High Points</td>
<td>State and National Boundaries</td>
</tr>
</tbody>
</table>

Scale: 1:250,000
PLATE III - LINEAMENTS MAPPED FROM NAIP IMAGERY IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson
2011

This map presents the results of interpretation of aeriel imagery from the 2009 NAIP (National Agriculture Imagery Program) datasets of the Minot area. The data was digitized and interpreted at a scale of 1:250,000. The interpretation was done to identify linear features that are potentially important for geologic and geophysical analysis. The lineaments were mapped using a combination of visual interpretation and the lineament density analysis tool in Erdas Imagine software. The lineaments were classified based on their lineament density and their potential relationship to geologic and geophysical features. The lineaments were analyzed for their potential to indicate tectonic, sedimentary, or other geologic processes. The lineaments were also analyzed for their potential to indicate the presence of hydrocarbon or other mineral resources.
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 northeastern North Dakota. The study is based on an early 1980s lineament survey by Fred J. Anderson (1982) and a 1999 lineament reevaluation by R. H. Hogan and co-workers (1999, 2000). A digital image mosaic was created from four available scenes (a blue, green, red (BGR) false color composition of panchromatic, 2.5 m; and 7.6 m spatial resolution) from the Landsat/ETM+传感器 (TM) data (1985) and from the Landsat-7 ETM+ (2001) data (see Figure 1a). Lineaments mapped are presented here at a scale of 1:250,000. Lineament orientation and/or magnitude reveal two distinct orientation trends (Figures 2a and 3b). A primary (63') orientation of NW-SE (89.5') and a secondary (27') orientation of approximately N-S (0') are evident. The orientation of lineaments mapped here may reflect the influence of Mesozoic to Cenozoic tectonic activity. The majority of lineaments in this study are low order (1.5x10 km). The majority (68%) of lineaments are oriented within a range of 30° of a NW-SE trend (Figure 2a). The general density of lineaments within this study area is 1.1 lineaments per square mile (approximately 1.7 lineaments per square kilometer). Lineament density is generally greatest in the area surrounding the Spring River and the area to the southeast of the Minot 1:250k map sheet. Lineaments in this study are generally oriented parallel to the axis of Mesozoic to Cenozoic compression and slightly oblique to the axis of Mesozoic to Cenozoic extension. Lineaments are generally parallel to the extent that the cross-cutting geometry is consistent with a regional compressional fabric. The majority of lineaments mapped here are interpreted as structural lineaments resulting from Mesozoic to Cenozoic compressional events in the area. The following hydrogeologic systems in the area: 

- Lineament density appears to be generally greater in areas of currently producing wells and less in areas of non-producing wells. 
- Structural lineaments in the area are greater in density than their corresponding age. 
- The Spring River is the major water feature in the study area. 
- The floodplains on the Spring River and the Lake McMillan are present in the southern portion of the map area. 
- These features are not depicted on the 1:250,000 scale lineament map shown here.
PLATE V - COMPILED LINEAMENTS MAPPED IN THE MINOT 250K SHEET, NORTH DAKOTA

Fred J. Anderson
2012

This map presents the results and discussion of a segment of a contemporary lineament analysis study of the Minot 250K map sheet in northeastern North Dakota. The Minot 250K is a high-resolution map sheet that has been used for various geological studies. Published in 1979, the Minot 250K map sheet is oriented north/south with the north at the top. Published in 1979, the Minot 250K map sheet is oriented north/south with the north at the top. This map, however, is oriented as north at the left in order to provide an easy comparison to the published image. Lineaments were compiled from Plate I - V for this map (Figure 1). Lineaments oriented on a north/south 1:250K map were analyzed at the field scale of 1:250K. Lineaments oriented on 1:250K map were analyzed at the field scale of 1:250K. The majority of lineaments (97%) falling within the 0.12 mile length class range (Figure 1)). The density of lineaments (the lineaments oriented on a north/south 1:250K map) was generally greater in the northeastern and southeastern portion of the map area with an overall lineament density of 757 lineaments/km². The lineaments per square mile range from 600 lineaments per square mile to 700 lineaments per square mile. In the map, the general distribution of the lineaments is consistent with subsurface geological conditions. Lineaments closely associated with geologic features, such as fault zones, and are generally consistent with those fault zones and geologic features. Overall, lineament density appears to be greater in areas of currently producing wells and relatively lower in areas of limitation or non-production. (Figure 6).
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 compiled lineaments estimated 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 cell) were assigned to each cell based on the density of each of the grid cells (sections). The resulting data were composited across the area to yield lineament density values (degree) for each grid cell. Lineament density values between 0 and 1.69 were assigned to those areas of lower lineament density, shown in green colors. Areas of higher lineament density, shown in warmer colors, map above areas of higher lineament density. The map also shows areas of higher lineament density extending towards the southwest. Overall, lineament density appears to be greatest and relatively consistent with areas where producing oil and gas wells and fields are common or located, and lower in areas where non-producing wells have been drilled (Figure 1). The area correlates well with the overall production and areas of relatively higher lineament density.

EXPLANATION

Lineament Density (ft/mi²)

- 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

Geologic Features

- Drill holes
- Oil & Gas Fields

Other Features

- Township Boundaries
- County Boundaries
- State and US Highways

Scale 1:250,000
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 centered on the metropolitan Willmar-Hinckley area in north-central North Dakota. The 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° high angle of elevation and 30° of inclination. The Minot 1:250k map sheet covers the majority of the lower Souris River Basin in southern North Dakota. The northern edge of the Blue Mountain portion of the Missouri Escarpment is present in the southwestern portion of the map area and the Souris River valley to the north is also shown in the northeastern portion of the map area and part of the Missouri. The confluence of the Souris River above Minot is also found in the northeastern corner of the map area. The confluence area of the Souris River is present as the area of highest elevation found in the northeastern corner of the map. The southeastern corner of the Turtle Mountains is present as the area of highest elevation 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.

Figure 2. Lineaments mapped from selected imagery and data sources (i.e., aerial, NAIP shaded relief, NED shaded relief, 30 meter 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 for the purpose of illustrating structural features and gas field boundaries which are found in or near the lineament areas. Areas of higher lineament density are coincident with areas of oil and gas field boundaries. A high degree of lineament intersection suggests a higher amount of overall structural development within a given rock volume and may be related to areas of increased porosities and permeabilities due to 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.

Figure 3. Interpolated lineament density map of compiled lineaments mapped within the Minot 1:250k map sheet created from the surface DEM created from the USGS 1997 NED. In this view, lineament density is shown as a color gradient ranging from blue (lower density) to orange (higher density). The areas covered by current oil and gas field boundaries are shown as black field boundaries draped over the interpolated lineament density map. The areas covered by higher lineament density are likely to be areas with increased reservoir properties and are therefore more attractive for exploration purposes. A high degree of lineament density suggests a higher amount of overall structural development within a given rock volume which may be related to areas of increased porosities and permeabilities due to 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 lineament density map.