PHASE ONE FINAL REPORT

for

A Grant from the

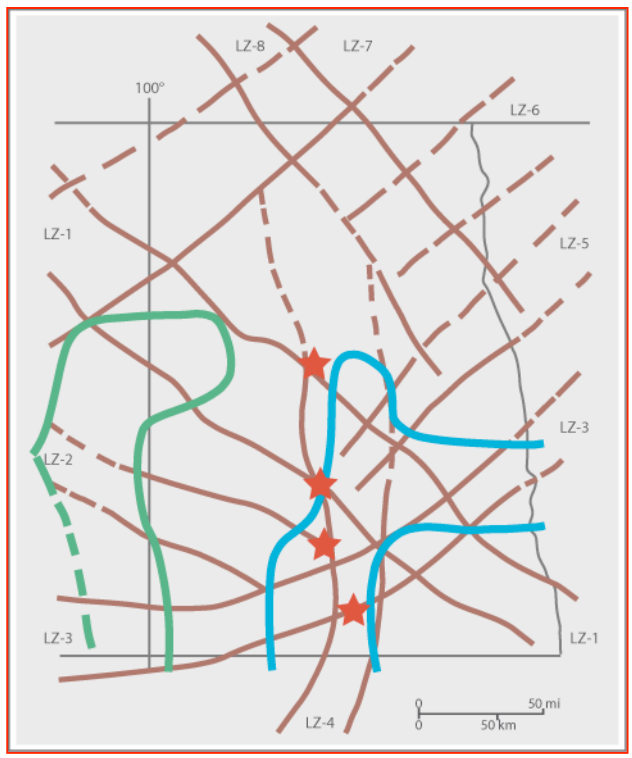
North Dakota Oil and Gas Research Council

Contract No. G019-041

through the

North Dakota Industrial Commission

IDENTIFICATION OF SHALLOW BIOGENIC GAS SYSTEMS IN EASTERN NORTH DAKOTA



Prepared and Submitted by: *George W. Shurr*

GeoShurr Resources, LLC

December 31, 2010

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<u>**PROJECT SUMMARY**</u>

The purpose of the project described in this summary is to generate information that will enhance exploration for and development of shallow biogenic gas in North Dakota east of longitude 100° W. Specifically, a five-county sweetspot with shallow biogenic gas potential is identified in the southeastern part of the state. Two important components of late generation biogenic gas systems are documented in eastern North Dakota and particularly in the multi-county sweetspot: regional fracture systems are mapped on satellite images and patterns of methane occurrences are related to the grid of lineament zones. This work was accomplished in close cooperation with the North Dakota Geological Survey (NDGS), especially their program of field screening observation wells for high levels of methane.

Linear features visible on nine scenes from the Landsat 7 satellite are the basis for interpretation of regional lineament zones within the study area. Eight distinct lineament zones generally trending northeast and northwest are mapped and related to a variety of published data sets. The lineament zone grid has expression on geophysical, stratigraphic, geologic, and structural maps. These concordant data sets provide a ranking for the eight individual lineament zones. Two particularly significant lineament zones are found in the southern two-thirds of the study area, along with three of intermediate significance. Three lineament zones in the northern one-third of the area are not well developed and the overall geologic framework in the north is definitely different than in the south.

Thousands of observation wells in more than 50 counties across North Dakota have been monitored for methane by the NDGS. Three clusters of counties are identified using information extracted from this important published record. Seven counties in the northwestern part of the state and seven counties in the central part of the state appear to be associated with migrated thermogenic and early generation "old" biogenic gas, respectively. The third cluster of counties is in southeastern North Dakota and its gas potential is believed to be based upon the existence of a late generation biogenic gas system that is currently active in the area.

The sweetspot cluster of five counties in southeastern North Dakota is clearly related to the grid of Landsat lineament zones. Zones with particularly high methane levels in a glacial outwash aquifer are concentrated in the sweetspot. An initial analysis indicates that the population of linear features within the sweetspot is different than in the surrounding counties. Along with fractures and methane, preliminary water chemistry in eastern North Dakota and data on organic carbon in Cretaceous host rocks in eastern South Dakota are important additional components of the late generation biogenic gas system currently at work in the sweetspot. A critical next step will be to document the presence of methanogenic microbes in water samples from observation wells with high methane concentrations and optimal water chemistry.

The most obvious potential application of this project is the exploration insight it provides for the entire subcrop belt of the Niobrara Formation that extends from Kansas into Canada. However, the most important exploration applications should focus specifically on the five-county sweetspot in southeastern North Dakota. Eventually, it will probably become economically viable to produce shallow gas in this area of the state where hydrocarbon development has been only minimal.

EXECUTIVE SUMMARY

This Executive Summary includes a number of illustrations that are extracted from the more detailed main body of the report. Subdivisions in this Summary follow the chapter headings of the full main report.

INTRODUCTION

Deep oil and associated gas in western North Dakota are undeniably a fundamental economic asset for the state. However, there is also a relatively unexplored and under-utilized shallow gas resource in eastern North Dakota. Shallow biogenic gas systems represent an important new potential asset in a part of the state that has traditionally experienced relatively little hydrocarbon development.

There are basically two distinct shallow biogenic gas systems: early generation is "old" gas that formed during deposition of the ancient host rocks and late generation is "new" gas that is produced by methanogenic microbes in the relatively recent geologic past. Old, early generation biogenic gas has been commercially produced from fields in southwestern North Dakota. However, it is the new gas of the late generation biogenic gas system that is thought to be the dominant system in eastern North Dakota.

Four main components have been identified for late generation biogenic gas systems: 1) organic matter to provide food for the methanogenic "bugs"; 2) fracture systems that act as plumbing systems; 3) optimal water chemistry to sustain the microbial communities; and 4) consortia of microbes, including methanogens, living in the aquifer. This current Phase I of the investigation essentially does not address the availability of organic carbon or directly document the existence of the critical microbes. Those aspects can be studied in Phase II.

The completed Phase I report emphasizes regional fracture patterns observed on satellite images and ranked on significance using published data sets. The grid of interpreted lineament zones is subsequently integrated with the results of an extensive field screening program for methane recently completed by the North Dakota Geological Survey. This integration identifies a multi-county sweetspot for shallow biogenic gas in southeastern North Dakota.

LANDSAT OBSERVATIONS AND INTERPRETATIONS

Linear features visible on Landsat satellite images can be used as the basic data for interpretations of regional lineament zones. The grid of lineament zones outlines tectonic blocks in the Precambrian basement. The blocks experience periodic reactivation and those block movements influence erosion, deposition, deformation, and fluid movement throughout geologic time.

These general concepts are applied specifically in eastern North Dakota east of longitude 100° W. Nine scenes from the thematic mapper sensors on the Landsat 7 satellite are employed in the investigation (Figure ES.1). Black and white images in spectral Bands 3 and 5 are used to map hundreds of individual linear features at a scale of 1:1,000,000 (1 in = 16 mi). The linear features observed on both Bands 3 and 5 for each scene are compiled into an uncorrected mosaic and the longest individual features are identified.

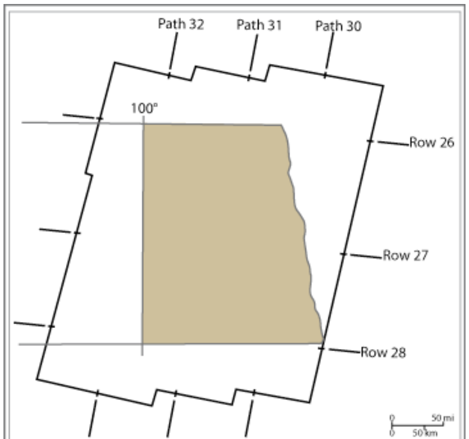

Figure ES.1. Location of the study area east of longitude 100° W relative to the footprint of nine Landsat scenes employed in the investigation.

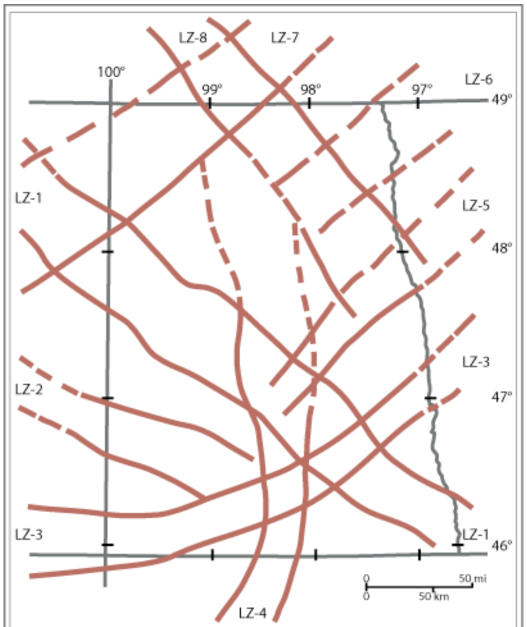

Figure ES.2. Preliminary interpretation of regional lineament zones in eastern North Dakota. See Plate 2 for a rendition at a scale of 1:1,000,000 (1 in = 16 mi).

Corridors of short linear features and the individual long linear features provide the basis for interpretation of regional lineament zones. Eight distinct lineament zones are mapped in North Dakota east of longitude 100° W (Figure ES.2). LZ-1, LZ-3, and LZ-4 are ranked as most significant. Lineament zones in the northern one-third of the study area, specifically LZ-6, LZ-7, and LZ-8, are less clearly defined. LZ-2 and LZ-5 are of intermediate significance. This preliminary ranking based on attributes of the linear features observed on Landsat images is improved by comparing the lineament zone grid with other published data sets.

Lineament Zone Significance

Four basic types of published data are used to evaluate the regional Landsat lineament zones and refine the preliminary ranking: geophysical data, stratigraphy, glacial and surface features, and geologic structure. The lineament zone grid is superimposed on published data maps to compare coincident patterns.

Geophysical data provides insight on the crystalline Precambrian basement. Compilations of magnetic and gravity data in North Dakota and surrounding areas were originally prepared by Dr Kevin Mickus of Missouri State University for a 2007 publication. These compilations are modified to focus on the study area in eastern North Dakota and are available as plates (at 1:1,000,000, 1 in = 16 mi) incorporating the lineament zone grid in the full main report.

Maps of magnetic intensity anomalies and enhanced magnetic gradient show magnetic highs co-located at the intersections of lineament zones and distributed along the trends. Maps of Bouguer gravity and polynomial residual gravity anomalies also show small anomalies along the trend of specific lineament zones as well as lineament zones bounding larger areas of similar gravity. The northern one-third of the study area has less clear expression of the lineament zones in the geophysical data.

Subsurface stratigraphic data is available from regional studies done by the US Geological Survey and from work concentrated within the state done mainly by the North Dakota Geological Survey. Regional compilations discussed in the full main report include thickness maps for the Lower Cretaceous, the Inyan Kara Group and Skull Creek Shale, the Belle Fourche Shale and Greenhorn Formation, and the Carlile Shale, Niobrara Formation, and Pierre Shale. Maps focused on North Dakota show isopach

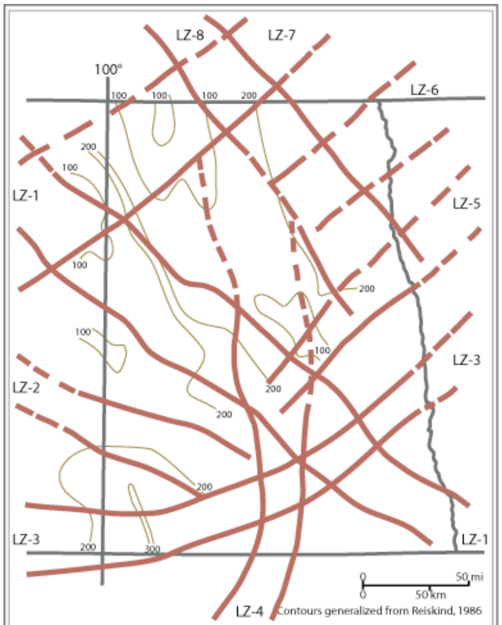

Figure ES.3. Thickness variations in the Niobrara Formation relative to Landsat lineament zones in eastern North Dakota.

patterns for the Mowry-Inyan Kara interval, the Inyan Kara Formation, and the Niobrara Formation. The thickness map for the Niobrara (Figure ES.3) is presented here to illustrate the relationships between the lineament zone grid and isopach patterns. The Niobrara does not necessarily have the most distinctive ties to the grid, but it is an important component of the late generation biogenic gas system in the study area. In addition to pattern similarities with the lineament zone grid, the stratigraphic data further emphasize differences between the northern one-third and southern two-thirds of the area.

Near surface and surface data compilations are also compared with the lineament zone grid. Buried bedrock patterns (Figure ES.4) document relationships to the grid for two important biogenic gas system components: the Niobrara subcrop belt and the distribution of a major bedrock valley. Glacial features and a digital elevation model constitute the surface data compared with the grid.

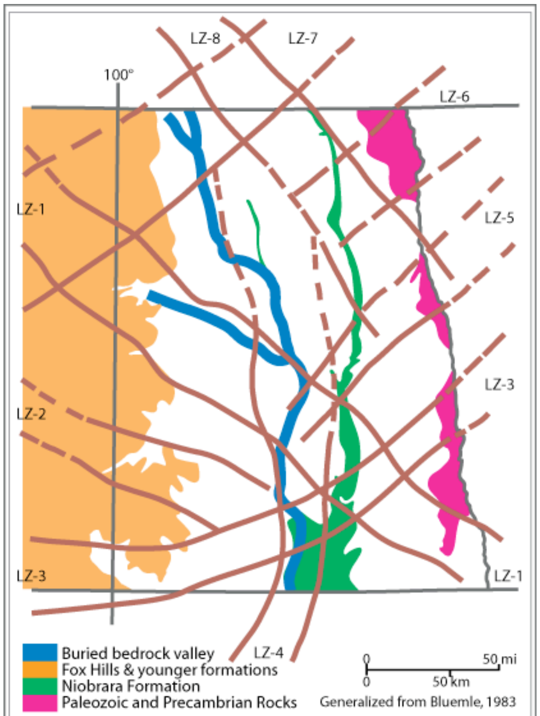

Figure ES.4. Buried bedrock geology relative to Landsat lineament zones in eastern North Dakota.

Geologic structure rarely shows clear relationships to Landsat lineament zones at scales of 1:1,000,000 (1 in = 16 mi); work is usually required at more detailed scales. However, structural contours on the top of the Inyan Kara and a compilation of published local structural features were compared with the lineament zone grid. Observations are included with stratigraphic and with near-surface and surface data to arrive at a qualitative ranking of geologic significance.

A summary ranking of the relative significance of individual Landsat lineament zones is shown in Table ES.1. Although there is not one-for-one agreement among the separate data sets, the ranks are generally the same. Clearly LZ-1 and LZ-4 are most significant and LZ-6, LZ-7, and LZ-8 in the northern part of the study area are less significant.

Table ES.1. Ranked Significance of Lineament Zones			
Lineament Zone	**Landsat Rank**	**Geophysics Rank**	**Geologic Rank**
LZ-1	1	1-2	1-2
LZ-2	4	4	5
LZ-3	2	3	3
LZ-4	3	1-2	1-2
LZ-5	5	7	4
LZ-6	8	8	8
LZ-7	6	6	6
LZ-8	7	5	7

Methane Field Screening

Over the past several years, the North Dakota Geological Survey has carried out an ambitious program to monitor methane concentrations in shallow ground water observation wells in virtually every county throughout the state. Methane measurements were made using a portable analytical instrument called a flame-ionization detector (FID). Thousands of wells in more than 50 individual counties were monitored and the published results are an important part of this investigation of shallow gas systems in eastern North Dakota.

Cross plots of the mean methane values and the percent of wells with a positive FID response in each county were prepared from the state-wide data set. The cross plots demonstrate that there are three separate clusters of counties with similar means and percent positive values. In the northwestern part of the state, seven adjacent counties (Renville, Burke, Bottineau, Ward, McKenzie, Williams, and Divide) cluster in an area that has both thermogenic and biogenic gas documented in the literature. In the central part of the state, there is a cluster of seven adjacent counties (Stark, Grant, Morton, Emmons, Burleigh, Sheridan, and Wells) in an area that is believed to have early generation "old" biogenic gas.

Southeastern North Dakota has a cluster of five contiguous counties that constitute a sweetspot for shallow, late generation "new" biogenic gas. The five counties are: Dickey, LaMoure, Barnes, Griggs, and Cass Counties. The sweetspot and the surrounding counties all have approximately the same area and population, so they constitute sampling cells with reasonably similar attributes. The outline of the sweetspot cluster closely follows LZ-4 and includes intersections and terminations of several other lineament zones (Figure ES.5). In addition, areas with particularly high methane levels (red stars, Figure ES.5) in wells completed in the Spiritwood Aquifer are concentrated in the sweetspot cluster at lineament zone intersections within LZ-4.

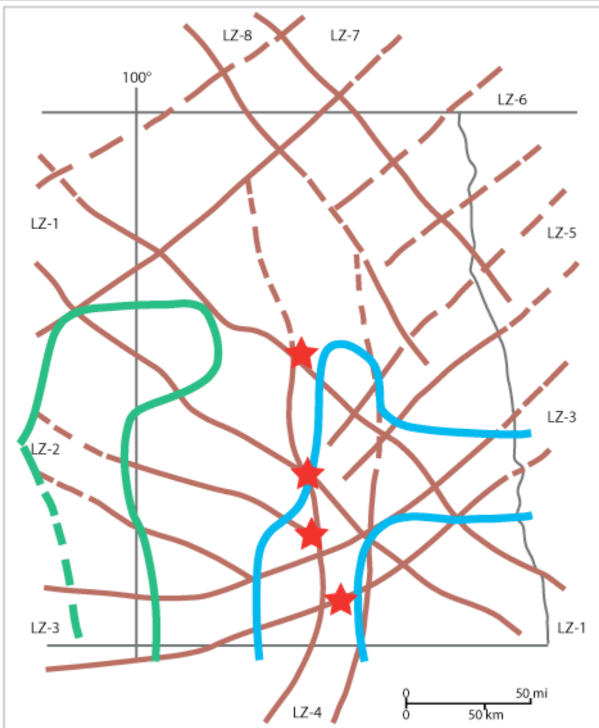

Figure ES.5. Cluster of sweetspot counties in southeastern North Dakota relative to the grid of Landsat lineament zones. Red stars show areas in the Spiritwood Aquifer with high FID values (Anderson, 2009b).

The cluster of sweetspot counties in southeastern North Dakota has distinct geologic attributes such as the shallow and subcropping Niobrara Formation. But, there are also differences in the observed Landsat linear features.

Populations of Landsat Linear Features

Populations of Landsat linear features do not follow statistically random distributions of length. Instead, the length values follow power law distributions that are similar to the statistical distributions used to characterize faults. Specifically, plots of log cumulative frequency and log length are linear and the attributes of these plots can be used to compare different populations of faults and/or linear features.

In the western part of the study area, lengths of 74 linear features within lineament zones are compared with 56 linear features measured in the blocks between lineament zones. The maximum length (49 mi versus 38 mi) and the mean length (23 mi versus 18 mi) are greater in the lineament zone than in the block. More importantly, the linear log-log plots are different for each area, but are very similar to log-log plots commonly observed for faults.

Contrasts between sweetspot counties and adjacent counties can also be described using the log-log plots of cumulative frequency and length. Approximately 60 linear features within the sweetspot counties have about the same mean and maximum lengths as almost 100 linear features in surrounding counties, but the log-log plots are distinctly different. These distributions of linear feature length give information on fractures and the plumbing system provided by the fractures is a critical component of shallow biogenic gas systems.

LATE GENERATION BIOGENIC GAS SYSTEMS IN EASTERN SOUTH DAKOTA

Recall that there are four basic components to a late generation biogenic gas system: 1) organic matter, 2) fractures, 3) optimal water chemistry, and 4) methanogenic microbes. Although the microbes have not yet been documented in eastern North Dakota, the FID field screening done by the North Dakota Geological Survey strongly suggests that they are present. Published statewide compilations of the FID results and of water quality data in the public domain provide useful comparisons with the lineament zone grid. The distribution of positive FID wells in eastern North Dakota generally follows linear outwash bodies that trend along lineament zones and are specifically focused in the multi-county sweetspot. Optimal water for the methanogens has high bicarbonate (greater than 400 mg/L) and low sulfate (less than 500 mg/L) concentrations. Wells with these values are distributed in patterns very similar to the positive FID wells.

This investigation has emphasized regional fracture systems and methane measurements, with a preliminary look at water chemistry. The availability of total organic carbon has not been directly addressed, but useful data exist just over the border in eastern South Dakota. Similarly, information on cuttings headspace gas and some isotopic measurements are available from that same project area. More significantly, laboratory experiments on water from shallow Niobrara observation wells document the presence of microbes that make methane. The geologic and hydrologic framework is basically the same all along the subcrop belt of the Niobrara Formation in the eastern Dakotas. It is highly likely that a late generation biogenic gas system is currently present and at work in North Dakota east of longitude 100° W.

CONCLUSION

Regional lineament zones interpreted from Landsat observations describe a grid of fracture corridors. Observation wells with measurable concentrations of methane are distributed in patterns very similar to the fracture gird. In particular, a cluster of five counties in southeastern North Dakota is identified as a sweetspot that warrants further studies to document the presence of methanogenic microbes. A late generation biogenic gas system could generate methane that would be a significant economic asset in North Dakota east of longitude 100° W.

CHAPTER 1

INTRODUCTION

This brief introductory chapter describes why shallow biogenic gas is important in eastern North Dakota and reviews the background for shallow biogenic gas systems. An overview of the entire report is included, as well as acknowledgment to specific people who provided assistance with the project.

IMPORTANCE

Deep oil and associated gas in western North Dakota are an important economic asset for the state. The current Bakken oil boom has resulted in all-time record highs for natural gas production. Those huge reserves are part of a national trend growing from exploitation of deep shale reservoirs. Gas prices have responded to this big supply by remaining relatively low. Locally, these conditions have led to the statement: "North Dakota shallow gas exploration is not economic at the current price." (Rocky Mountain Oil and Gas Journal, September 3, 2010).

However, hydrocarbon booms do pass and natural gas prices are changing constantly. Gas is a fundamental component in the mix of new energy sources for the twenty-first century. It has emerged as the environmental fuel of choice for new electrical generation facilities. Gas is already providing an important back up for renewable energy sources such as wind. And, even small reserves can be the basis for distributed electrical generation and local consumption.

Shallow biogenic gas, in particular, remains a relatively under-utilized resource, especially in eastern North Dakota. Before reserves can be demonstrated or documented, extensive exploration must be carried out. The investigations described in this report are intended to provide some basic tools for that exploration effort. That effort may not get rolling in the next year or two, but the long-term demand for natural gas will eventually make eastern North Dakota a significant target.

By funding this work, the North Dakota Oil and Gas Research Council is laying the groundwork for future energy development in a part of the state that has historically had little exploration activity. There is naturally excitement about the current deep oil boom in western North Dakota. But, there is also hydrocarbon potential in the eastern part of the state. Shallow biogenic gas systems are an important potential energy resource for eastern North Dakota. There is long term opportunity here.

BACKGROUND REVIEW

The concept of petroleum systems has proved to be a useful approach to exploration and development of hydrocarbon resources. For example, ten petroleum systems have recently been identified in the Williston Basin (Gaswirth et al., 2010): eight are in Paleozoic rocks that host deep oil and associated thermogenic gas and two are in Mesozoic and Cenozoic rocks that host shallow biogenic gas systems.

Substantial and significant differences exist between shallow biogenic gas systems and deep thermogenic gas systems (Figure 1). Thermogenic gas is generated in the deep, basin-centered "kitchen" where conditions below the "ceiling" are favorable. In contrast, biogenic gas is generated by anaerobic microbes in thermally immature, organic-rich source rocks. There are depth-related constraints, such as temperature and water composition, on the microbial environment. In the microbe "nursery" above the biogenic "floor", conditions support a robust methanogenic community. The resulting accumulations of biogenic gas are located at shallow depths, especially around the basin margins. This is true not only in the Williston Basin (Shurr, 1998), but also in numerous other basins in the Rocky Mountains and adjacent Great Plains (Shurr, 2001).

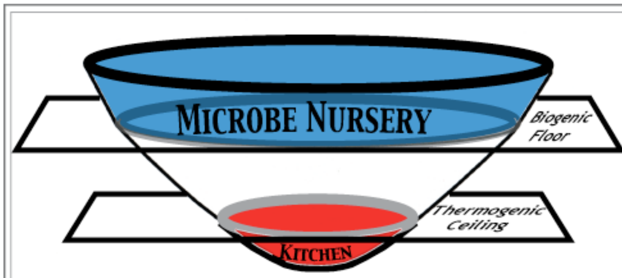

Figure 1. Sketch of an idealized basin that shows the relative locations of the deep thermogenic kitchen and the shallow microbe nursery where biogenic gas is generated. Modified from Shurr & Ridgley, 2002.

Biogenic Gas Systems

There are fundamentally two different types of shallow biogenic gas systems (Shurr & Ridgley, 2002; Rice, 1993). ***Early generation*** biogenic gas forms during or shortly after deposition and diagenesis of the source and reservoir rocks. Subsequently, gas migration and accumulation may extend over a long period of time. Examples of commercial production include Cretaceous clastic reservoirs in the Northern Great Plains (Lillis, 2007) and the Cretaceous Niobrara Chalk on the eastern margin of the Denver Basin (Rice, 1984). On the southwestern margin of the Williston Basin in North Dakota, shallow gas fields in Bowman County are in this category (Shurr, 1998).

In contrast, ***late generation*** biogenic gas forms long after deposition and diagenesis of the host rocks and methanogenesis has routinely occured in the last few million years. As a consequence, migration and accumulation are of minor importance; the gas is produced in close proximity to where it was originally generated. Examples of well known commercial production include the coal bed methane in Tertiary rocks of the Powder River Basin (Gorody, 1999; Ulrich & Bower, 2008) and the fractured Antrim Shale (Devonian) on the northern margin of the Michigan Basin (Martini et al., 2003). There is potential for this type of biogenic gas in fractured Niobrara reservoir rocks on the eastern margin of the Williston Basin in North and South Dakota (Shurr, 2008).

Early and late generation biogenic gas systems have three basic differences (Shurr & Ridgley, 2002). The first difference is in the timing of generation and the age of the gas. Early generation gas usually forms in the distant geologic past on organic material that is contemporary with the methanogens. It is "old" biogenic gas. Late generation gas forms in the recent geologic past on organic material that may be relatively ancient. It is "new" biogenic gas. In the jargon of petroleum systems, there is a difference in the timing of events including the critical moment.

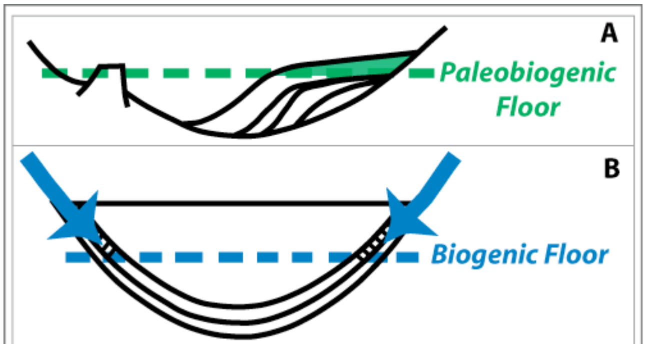

Figure 2. Contrasts between biogenic gas systems and geologic basins.
(A) Early generation gas forms above a paleobiogenic floor that covers wide areas of a depositional basin.
(B) Late generation gas forms above a biogenic floor that is an expression of modern subsurface environments around the margins of a structural basin. Shurr, 2008.

The second basic difference relates to the age of the microbial communities (Figure 2). Early generation methanogens thrived above a depth constrained paleobiogenic floor, but late generation methanogens still inhabit the favorable environments that currently exist above a modern biogenic floor.

Early generation "bugs" and their supporting environment are long gone, while late generation "bugs" are still present. These modern microbial communities can be sampled and studied and the contemporary environment that supports them can be described in real-time detail.

The third basic difference between the two biogenic gas systems is a distinction in the tectonic setting. Early generation systems were located on the margins of *depositional* basins where subsidence, deposition, and methanogenesis above the paleobiogenic floor are all three concurrent. In contrast, late generation systems are situated on the margins of *structural* basins; post-depositional tectonism pre-dates current methogenesis above the biogenic floor. The result, in the parlance of petroleum systems, is a difference in the geometry of the pod of active source rock or sediment. Specifically, the early generation system is a fairly continuous blanket, but the late generation system is more ring shaped around the edges of the basin (see Figure 2).

Both types of biogenic gas systems are probably present in North Dakota east of longitude 100° W. However, it is anticipated that the late generation system is the most significant within the study area.

Late Generation Biogenic Gas Systems

Of the three natural gas systems (viz. thermogenic, early generation biogenic, and late generation biogenic), it is the "new" gas system that is least familiar to the traditional oil and gas industry. The late generation biogenic gas system consists of modern methanogenic microbes metabolizing ancient organic material in favorable, present day, shallow subsurface environments. The system has been described by geologic, hydrologic, geochemical, microbiological investigations in the Antrim Shale in Michigan (Martini et al., 1996; McIntosh & Martini, 2008) and in the coal bed methane in Wyoming's Powder River Basin (Ulrich & Bower, 2008; Green et al., 2008; Flores et al., 2008).

Four main elements of the system have been emphasized as specific components that should guide exploration (Shurr, 2008): 1) organic matter, 2) fractured reservoirs, 3) water chemistry, and 4) methanogenic microbes. These four attributes can be represented in an agricultural analog. The microbes are like cows grazing in a pasture. Both require food, water, and a sustaining environment. Methanogenic microbes "graze" a pasture of source rock high in total organic carbon. Fractured reservoirs provide a plumbing system to carry water, gas, and the microbes throughout the host rock.

The total organic carbon (TOC) pasture must have more than 0.5% TOC which is the value commonly recognized as a minimum for methanogenesis in modern sediments (Claypool & Kaplan, 1974). The fracture plumbing may be related to individual small faults or to regional lineament zones visible on satellite images. The optimal water chemistry is high bicarbonate (greater than 400 mg/L) and low sulfate (less than 500 mg/L). The community of methanogenic microbes is diverse and complex. It can be directly documented by microcosm experiments carried out in the lab on water samples from the gas system. Alternatively, the methane generated by the microbes in the system can be measured using portable gas detectors in the field. Applications of these various exploration components have been

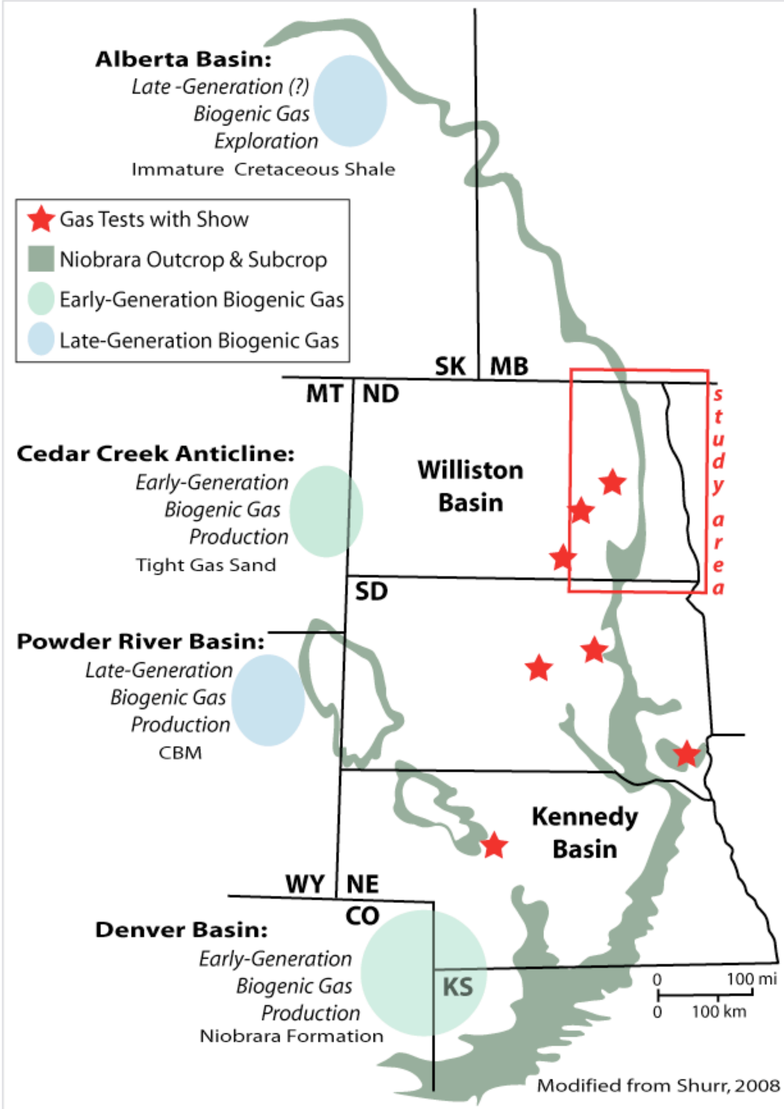

Figure 3. The location of the study area in eastern North Dakota relative to the subcrop and outcrop of Niobrara Formation which hosts biogenic gas. Areas of current commercial biogenic gas production are also shown. Modified from Shurr, 2008.

successful in eastern South Dakota (Shurr & Scheier, 2007; Gilcrease & Shurr, 2007), although commercial production remains to be demonstrated.

REPORT OVERVIEW

North Dakota east of longitude 100° W is located in a shallow biogenic gas fairway defined by the outcrop and subcrop of the Niobrara Formation (Figure 3). It is part of a fairway that stretches from Kansas northward into Canada and the lessons learned here will have applications beyond North Dakota. The first part of the investigation maps regional lineament zones from satellite images in eastern North Dakota. These lineament zones are then ranked on the basis of published data sets and integrated with field screening for methane recently completed by the North Dakota Geological Survey. A multi-county sweetspot is identified in southwestern North Dakota. It is described in a preliminary manner using linear features observed on satellite images and the exploration components for the late generation biogenic gas systems. A partial bibliography for technical publications is provided in the references cited.

ACKNOWLEDGMENTS

This investigation is a classic example of a partnership between the private and public sectors. There are a number of people in both state agencies and in the world of business who have provided significant assistance. Fred Anderson of the North Dakota Geological Survey has directed a program of field screening for methane in observation wells maintained by the state over the past several years. The results of that program are a critical part of this study of shallow biogenic gas systems. Fred also participated in early conversations that provided a framework for the study. Previous work conducted in South Dakota contributed important perspectives on the North Dakota study. Staff of the South Dakota Geological Survey, especially Tom Haggar and Sarah Chadima, were involved in that earlier work and have continued to offer advice.

Dave Fischer of Fischer Oil and Gas, Inc has been an integral part of this effort from the beginning. It is anticipated that his role will only increase when Phase II of work on the shallow biogenic gas systems continues. Marshall Crouch of White Eagle Exploration, Inc offered some initial advice and suggestions and subsequently provided financial support as a part of the matching funds.

The main financial support provided by the North Dakota Industrial Commission through its Oil and Gas Research Council is gratefully acknowledged. Karlene Fine in her role as executive director and secretary of the Commission was particularly helpful. The following legal notice complies with Paragraph 23 of the governing contract.

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CHAPTER 2

LANDSAT OBSERVATIONS AND INTERPRETATIONS

This chapter begins a discussion of the investigations focused in North Dakota east of longitude 100°W. After an introductory review of background literature and the basic concept used in mapping the satellite images, specific aspects of the work are described. These include a description of the images themselves and of the data collected from the images. Preliminary analysis and interpretation lay the groundwork for a ranking of the significance of specific structural zones that is done in the following chapter.

BACKGROUND

The idea that the earth's crust is a mosaic of discrete basement blocks was applied to structures in the Rocky Mountains and adjacent Great Plains about 40 years ago (Sales, 1968). The phrase "lineament-block tectonics" was articulated a few years later (Thomas, 1974) and it emphasized the importance of the broad zones of weakness that bound basement blocks. Block mosaics represent a fundamental tectonic architecture in continental crust under the Williston Basin (Shurr, 2000).

Relationships between basement blocks mapped on satellite images and shallow gas reservoirs have been documented in South Dakota and Montana (Shurr, 1978; Shurr & Rice, 1986). In addition to paleotectonic significance, the blocks control the development of post-depositional structural features in Montana and South Dakota (Shurr, Larson, & Watkins, 1989; Shurr, Hammond, & Bretz, 1994). Oil production from deep reservoirs such as the Bakken and Lodgepole in North Dakota is also believed to be influenced by basement block shapes and reactivation histories (Shurr, 1995; Shurr et al., 1995).

With the perspectives gained from these several decades of investigation and publication, it is possible to summarize the basic functional concept in a succinct manner.

THE CONCEPT

Satellite images can be used to map the surface expression of basement blocks that have experienced multiple reactivation. Recurrent activity along the block boundaries has produced corridors of concentrated linear features that constitute lineament zones (Figure 4).

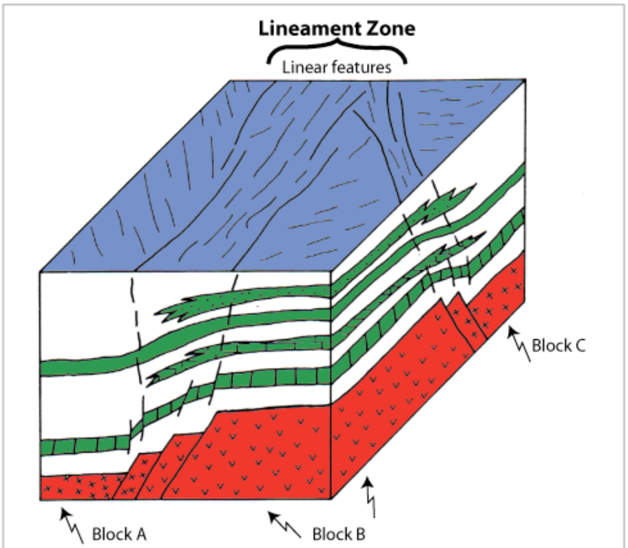

Figure 4. Idealized block diagram that shows how surface linear features and lineament zones are rooted in Precambrian block boundaries. Modified from Shurr, Larson, & Watkins, 1989.

The linear features are patterns of landscape, vegetation, and moisture that have resulted from fluid migration along the block boundaries. Block movement has enhanced fracture porosity and permeability along the boundaries and thus influenced fluid movement. In addition, very recent block movements throughout the Northern Great Plains have further facilitated the formation of linear features. The fluid migration that helps to provide surface expression of fractures as linear features, probably also has significance for hydrocarbon exploration. There are, however, several other aspects of basement block tectonics that are important for exploration.

Paleotectonic block movement has influenced erosion and deposition so that patterns of reservoir geometries, source beds, and seals may all be closely related to the grid of basement blocks. Thickness and lithology changes are commonly found along the block boundaries (Figure 4) as a result of the paleotectonic movements. In addition, the boundary zones are areas where folds and faults (Figure 4) are concentrated between the basement blocks. These structures result from post-depositional tectonism and are important in the development of hydrocarbon traps.

The initial formation of the basement blocks and the intervening boundary zones was controlled by Precambrian plate tectonics. The processes that assembled the North American Plate during the Precambrian also produced the zones of weakness that eventually outlined basement blocks. Recurrent block movement has generated corridors of stratigraphic, structural, and geophysical anomalies along the block margins. The linear features mapped on satellite images are only the surface manifestation of stacked anomalies that extend throughout the Phanerozoic rocks and down into the Precambrian basement.

LANDSAT IMAGES

Linear features mapped on satellite images are the primary data set used to interpret lineament zones in this regional investigation. After images have been acquired, linear features are mapped on each individual image and the overlays from the separate images are combined into a mosaic of the study area. This compilation includes long linear features that generally bound corridors where short linear features are concentrated. Regional lineament zones are interpreted from this compilation.

Image Description

Eighteen images from thematic mapper (TM) sensors on board the Landsat 7 satellite are used in this work. Each of nine separate scenes has an image in TM spectral Bands 3 and 5 that sample different portions of the electromagnetic spectrum. Band 3 measures surface reflectance in the range of wavelengths 0.63 - 0.69 micrometers (red colors) and is used to map vegetation and slopes. Band 5 covers wavelengths of 1.55 – 1.75 micrometers (short-wave infrared) that penetrate thin clouds to discriminate soil moisture and vegetation patterns.

The footprint of the nine Landsat scenes included in the study area is shown in Figure 5 using the north-south path and east-west row numbering convention for Landsat 7. The nine scenes were selected online using the New Earth Explorer available from the US Geological Survey's EROS Data Center. Input search parameters included the amount of cloud cover, TM spectral bands, dates of satellite measurements, and general geographic location. Specific entity identification numbers for each selected scene shown in Figure 5, are listed in the Appendix.

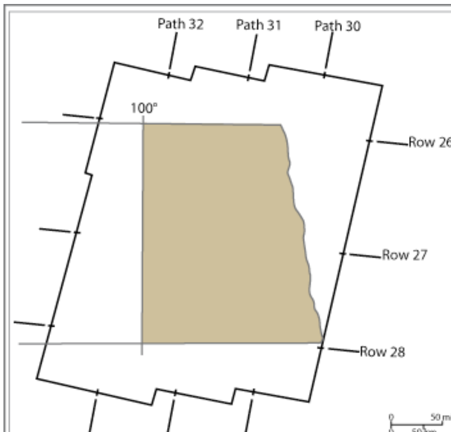

Figure 5. Location of the study area east of longitude 100° W relative to the footprint of nine Landsat scenes employed in the investigation.

The reflectance measurements made by the Landsat 7 sensors were processed at the EROS Data Center using a standard enhancement package. Digital files that are subsequently available as free downloads were used by GeoMart in Ft Collins, CO, to prepare the final photographic quality images. All eighteen images are at a scale of 1:1,000,000 (1 in = 16 mi) and are black and white renditions.

Data Collection

The most fundamental observations made on the eighteen Landsat images are the traces of linear features. These observed linear features are the basis for interpretations of lineament zones that bound structural blocks in the Precambrian basement. There is a difference in terminology when compared with the way "lineament" is sometimes used in the literature. Some workers (e.g., Anderson, 2008a; Penner & Cosford, 2006) use it as the observed surface feature, while others (e.g., Brown, 1978; Thomas, 1974) use it as an interpreted geologic structure. The investigation in eastern North Dakota described in this report, limits "linear feature" to those entities directly observed on the image and "lineament zone" to an interpretation based on those observed linear features. The term "lineament" is not employed in this work.

Linear features are an expression of a variety of landscape elements: elongate or aligned hills, straight stream segments, and elongate or aligned lakes. Subtle tone and texture patterns resulting from moisture and vegetation variations are also used to map linear features. Land use patterns may influence the recognition of linear features as well. The north-south and east-west grid of roads following section lines may introduce an anthropogenic bias. Clear regional land use patterns such as the Canadian border are not mapped.

Linear features are drawn on clear plastic overlays for each of the eighteen images. Each image has several hundred individual linear features ranging in length from more than 50 mi down to less than 5 mi. The dominant qualitative trends of the linear features are to the northwest and northeast which is a trend commonly observed throughout the Northern Great Plains. North-south and east-west linear features are probably under-represented because of attempts to avoid distinctive anthropogenic features, such as the land grid reflected in graveled country roads.

ANALYSIS

Not all of the hundreds of linear features observed on the eighteen Landsat images are of equal significance. Those observed on both Bands 3 and 5 are more important than those mapped on only one image. In addition, long linear features are believed to be more important than short linear features. This is based upon analogy with faults: long faults have larger displacements than short faults (see Chapter 5 for extended discussion). Together these two attributes, viz. multiple observations and length, provide a way to "sort" through all of the hundreds of mapped linear features and extract only the most important ones.

Linear features mapped on overlays for BOTH Bands 3 and 5 are traced onto a single overlay for each of the nine Landsat scenes. The nine scenes with mapped linear features are then combined into an uncorrected mosaic (Figure 6). A generalized grid of latitude and longitude is established by comparing drainage and culture features visible on each image with a base map published at a scale of 1:1,000,000 (1 in = 16 mi). At this point, any linear features that correspond with cultural features are removed. Approximately one dozen linear features with an average length of 22 mi matched segments of railroads and were removed. The final mosaic of important linear features is shown on Plate 1. Selected long linear features are measured on the mosaic to assist in ranking their significance. They are shown as colored lines on Plate 1.

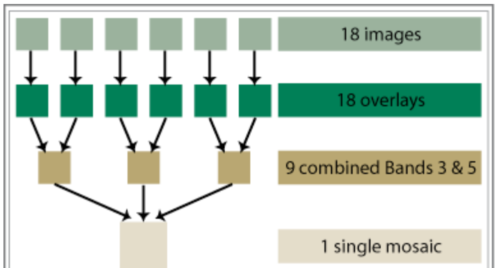

Figure 6. Simplified sequence of steps that lead to the final mosaic of linear features shown in Plate 1.

In some investigations, Landsat mapping is done on a single image that is digitally prepared from adjacent individual scenes (e.g., Anderson, 2008a; Shurr et al., 1990). However, for regional studies that cover wide areas, the digital image mosaic can become prohibitively large. Also, the digital mosaic usually combines multiple spectral bands into a single image; this reduces the "reproducibility" introduced by mapping on the eighteen individual images. It is important to map linear features on the individual images because this also helps to identify the most significant ones: long linear features that extend from one scene into one or more adjacent scenes are very significant, through-going features.

LINEAMENT ZONE INTERPRETATION

The preliminary interpretation of regional lineament zones in North Dakota east of longitude 100° is shown on Plate 2 and in Figure 7. Linear features are mapped well beyond the study area to the southwest and to the northeast because of the distribution of the images. However, lineament zones in those areas, especially western Minnesota and southern Manitoba, are more speculative. Long linear features are combined with corridors or clusters of the short linear features to identify lineament zones.

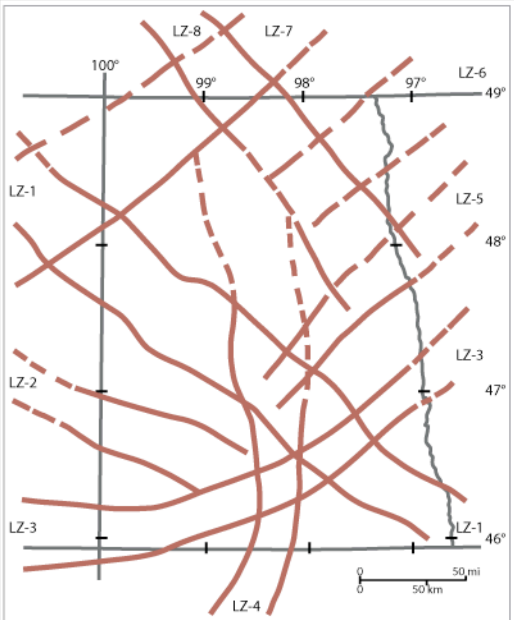

Figure 7. Preliminary interpretation of regional lineament zones in eastern North Dakota. See Plate 2 for a rendition at a scale of 1:1,000,000 (1 in = 16 mi).

There are eight separate lineament zones recognized in eastern North Dakota (Figure 7). Three trend northwest: LZ-1, LZ-2, and LZ-8. Three trend northeast: LZ-5, LZ-6, and LZ-7. LZ-4 has a distinctive north-south trend, in spite of trying to avoide the land survey grid. And, LZ-3 has an east-west trend that changes to the northeast into Minnesota. Three lineament zones are through-going, although they may terminate outside the study area: LZ-1, LZ-3, and LZ-7. Three appear to terminate in the southern part of the study area: LZ-2, LZ-4, and LZ-5. And, two lineament zones terminate in the northern part of the area: LZ-6 and LZ-8.

In general, the lineament zones in the northern one-third of the study area are less well defined than those in the south. Corridors with clusters of short linear features are less distinctive in the north and there are fewer long linear features to mark the boundaries for lineament zones. All of the linear features greater than 60 mi long are found in the southern two-thirds of the study area (Plate 1). In addition to these general differences between the northern one-third and southern two-thirds of the area, it is possible to rank the individual lineament zones.

The most significant lineament zones are long, through-going and have well defined borders; LZ-1, and LZ-3 fit this description. The north-south LZ-4 may extend into the northern one-third of the area and is ranked third. Fourth place goes to LZ-2, and then in succession LZ-5, LZ-7, and LZ-8. The least significant lineament zone is LZ-6 because it has poorly defined borders and is short. So the initial ranking of lineament zones can be summarized as: LZ-1, LZ-3, LZ-4, LZ-2, LZ-5, LZ-7, LZ-8, and LZ-6. This ranked significance can be improved by considering additional data bases.

CHAPTER 3

LINEAMENT ZONE SIGNIFICANCE

Not all of the eight lineament zones identified in eastern North Dakota are of equal significance. The qualitative ranking presented at the end of Chapter 2 is based upon the general map expression of the lineament zones. Chapter 3 starts with a review of how multiple data layers can be used to further evaluate the lineament zones. Maps of geophysical data, stratigraphy, glacial and surface features, and geologic structure are then used to refine the ranking.

MULTIPLE DATA LAYERS

The concept that lineament zones bound tectonic blocks rooted in the Precambrian basement (see Figure 4) is the basis for comparing the Landsat lineament zones and other sets of data (Figure 8). The primary data sets are geophysical maps that have expression of the crystalline basement rocks. Patterns on maps of subsurface stratigraphic attributes and geologic structure may also provide useful insights. Landsat linear features and lineament zones are mapped on the earth's surface, but there are also other data sets such as topography and glacial geology that provide perspective.

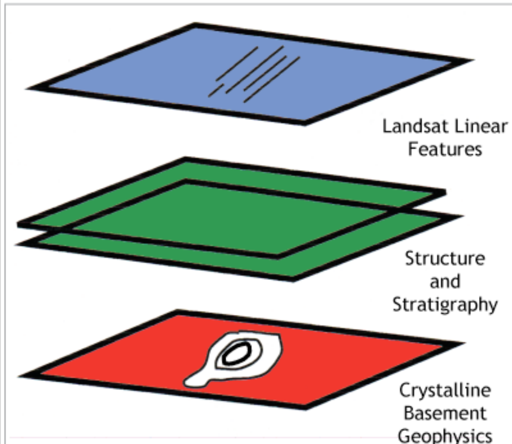

Figure 8. Data sets, including the summary of linear features shown in Plate 1, used to establish the significance of lineament zones.

By looking at multiple data layers, the relative geologic significance of the eight lineament zones is established. This is an important tool that will be used to identify shallow gas "sweetspots" in eastern North Dakota. The ranked lineament zones will subsequently be combined in Chapter 4 with the results of the field screening program recently completed by the North Dakota Geological Survey.

GEOPHYSICAL DATA

Geophysical data is the fundamental basis for our understanding of the Precambrian crystalline basement in the Northern Great Plains. Initial interpretations based on plate tectonics, extended major geophysical trends southward from Canada to identify terranes in North Dakota (e.g., Klassner & King, 1986). More recent refinements (Figure 9) add details in South Dakota and Nebraska, but retain the basic plate tectonic subdivisions in North Dakota.

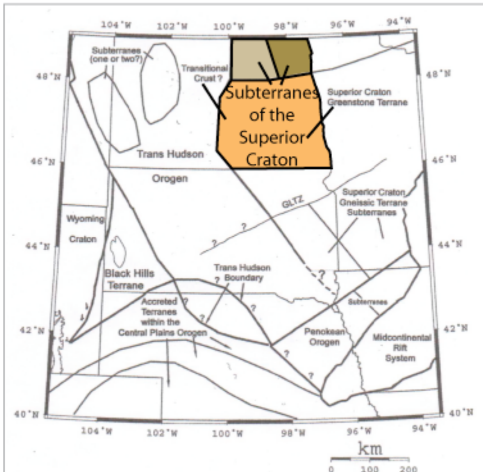

Figure 9. Interpretation of tectonic features in the Precambrian basement in North and South Dakota and in surrounding states. The interpretation is based on geophysical data sets, specifically gravity and magnetic data. Modified slightly from Mickus, 2007.

The Williston Basin in western North Dakota is underlain by the Proterozoic Trans-Hudsonian Orogen (Figure 9). Eastern North Dakota is part of the Superior Craton that is made up of older (Archean) basement rocks. The north-south boundary between the western orogen and eastern craton runs generally along longitude 100° W. Transitional crust may mark the western part of the craton, but the main subdivisions in eastern North Dakota are subterranes in the northern one-third of the study area (Figure 9).

Compilations of magnetic and gravity data in eastern North Dakota and surrounding areas (Plates 3 through 6) have been provided by Dr. Kevin Mickus of Missouri State University. These maps were originally part of his 2007 publication, but are modified and presented at scales of 1:1,000,000 (1 in = 16 mi) for purposes of this investigation. Details of the processing and analysis of the potential field data are available in Mickus (2007). The grid of eight Landsat lineament zones is superimposed on four geophysical maps: 1) magnetic intensity, 2) enhanced magnetic gradient, 3) Bouguer gravity anomaly, and 4) polynomial residual gravity anomaly.

Magnetic Intensity Anomaly Map

Plate 3 shows the reduced-to-pole aeromagnetic intensity anomaly map. The data are from US Geological Survey compilations and the dipolar effect of the total earth magnetic field has been removed. Although terrane interpretations by Mickus (2007) tend to emphasize gravity over magnetic data, work with specific Landsat lineament zones in other areas (e.g. Shurr, Larson & Watkins, 1989;) demonstrates that maps of magnetic anomalies are often closely correlated with the lineament zone grid.

In a general way, the regional magnetic anomalies have lower values (viz., blues and purple) north of latitude 48° N and have higher values (red, orange, yellow) to the south. This is at least in part the basis for recognizing subterranes in the Superior Craton (see Figure 9). In addition, there is generally more character and local variation in the southern two-thirds of the North Dakota study area.

Magnetic highs are located where LZ-1 intersects LZ-3, LZ-4, LZ-5, and LZ-7 (Plate 3). There are two large highs along the LZ-2 trend. LZ-3 has four small highs in North Dakota and one large one in Minnesota. LZ-4 is marked by a north-south trend of three small highs and it is flanked by three large positive anomalies. There are two small highs toward the southwestern end of LZ-5, but no expression to the northeast in Minnesota. LZ-6 has essentially no expression. Three small magnetic highs are distributed along LZ-7 and with LZ-1, it bounds a large positive anomaly that corresponds with the location of the Turtle Mountains in the northwestern corner of the study area. LZ-8 has only fair expression with broad contour patterns that follow the trend and intersections of the lineament zone. All of these observations are summarized in Table 1.

TABLE 1. SUMMARY OF GEOPHYSICAL EXPRESSION OF LINEAMENT ZONES

Lineament Zone	Magnetic Intensity Anomaly Map	Enhanced Magnetic Gradient Map	Bonguer Gravity Anomaly Map	Polynomial Residual Gravity Map
	Plate 3	**Plate 4**	**Plate 5**	**Plate 6**
LZ-1	Excellent	Good	Excellent	Excellent
LZ-2	Good	Excellent	Fair	Good
LZ-3	Good	Excellent	Good	Good
LZ-4	Excellent	Good	Excellent	Excellent
LZ-5	Fair	Fair	Poor	Fair
LZ-6	Poor	Poor	Fair	Fair
LZ-7	Fair	Fair	Fair	Fair
LZ-8	Fair	Good	Good	Fair

Enhanced Magnetic Gradient Map

Plate 4 is a map of the reduced-to-pole magnetic anomalies that are enhanced to emphasize more localized boundaries of rocks with contrasting magnetic susceptibility. This edge enhancement shows the boundaries as positive anomalies to give an overall "wormy" appearance to the map. In general, the northern one-third of the map has less distinctive and fewer edge anomalies. The southern two-thirds has much more character and variation, similar to the magnetic intensity map.

There is a good expression of LZ-1 where it intersects LZ-3, LZ-4, LZ-5, and LZ-7. LZ-2 and LZ-3 have "wormy" anomalies oriented along and perpendicular to their trends. High value anomalies are distributed along the trend of LZ-4, but the "worms" are only locally elongate along the trend. LZ-5 and LZ-6 have only fair to poor expression in the anomaly patterns, but LZ-7 and LZ-8 have fair to good expression. Again, Table 1 provides a summary.

Bouguer Gravity Anomaly Map

Plate 5 shows Bouguer gravity anomalies are based on data from the US Geological Survey, the National Geophysical Data Center, and National Geospatial and Imaging Agency. The merged data were reduced with free-air and Bouguer gravity corrections and the calculated anomalies are displayed with the Landsat lineament zones superimposed. Regional distinctions between the northern one-third and southern two-thirds of the study area are visible on this map. The north has generally higher value anomalies in colors of red, orange, and yellow, while the south has lower values in green, blue, and violet.

A series of more than ten small positive anomalies (red, orange, and yellow) are distributed along the trend of LZ-1. LZ-2 has three or four less distinctive small anomalies along trend. There are three large positive anomalies within LZ-3; the one at the intersection with LZ-4 is particularly conspicuous. LZ-4 has excellent expression in the map with five small anomalies along trend. LZ-5 has only fair expression, but the block between LZ-3 and LZ-5 is clearly defined. LZ-6 and LZ-7 have large, nebulous highs, though LZ-7 broadly bounds, with LZ-8, the large positive anomaly in the area of the Turtle Mountains. LZ-8 has fair to good expression with three small highs along trend. Observations are summarized in Table 1.

Polynomial Residual Gravity Anomaly Map

Plate 6 shows a polynomial residual gravity anomaly map that approximates an isostatic anomaly map. It is generated by subtracting long wave length anomalies summarized by a third-order polynomial from a map of deep-seated gravity anomalies. The deep-seated anomalies are the result of removing the effect of sedimentary rocks from the Bouguer gravity anomalies. These complicated calculations generate an anomaly map that may express differences in isostatic compensation. No matter how the final map is interpreted, it shows the same regional distinction of the northern one-third and southern two-thirds parts of the study area. And, there is expression for individual lineament zones.

A series of small positive anomalies are again distributed along LZ-1. LZ-2 contains both specific limited highs and lows. LZ-3 has a number of small highs, including a prominent anomaly at the intersection with LZ-4. There are a series of four distinctive anomalies along the LZ-4 trend. LZ-5 and LZ-6 have fair expression in the anomalies and LZ-7 and LZ-8 have fair to good expression. Again, the high anomaly near the Turtle Mountains is generally bounded by LZ-7 and LZ-1. And again, these observations are summarized in Table 1.

Summary Ranking

A summary ranking of lineament zones based on geophysical data can be done by assigning numbers of 1 through 4 to the excellent, good, fair, and poor designations in Table 1. This produces the ranking based on geophysical data: LZ-1 and LZ-4, LZ-3, LZ-2, LZ-8, LZ-7, LZ-5, and LZ-6. In general, this ranking compares favorably with that based on attributes of the lineament zone. LZ-1 is best and LZ-6 is worst in both rankings; LZ-2, LZ-3, and LZ-4 are rearranged, but are clustered separately from LZ-5, LZ-7, and LZ-8 which are in reverse order.

North-south differences are of particular importance. The northern one-third of the study area has lineament zones (LZ-5, LZ-6, LZ-7, and LZ-8) that are not as clearly expressed as the lineament zones (LZ-1, LZ-2, LZ-3, and LZ-4) in the southern two-thirds.

This generalization conforms with the interpretation of subterranes in the Superior Craton north of latitude 48°N (see Figure 9). Similar north-south contrasts and specific lineament zone expressions are seen in maps of subsurface stratigraphic data.

SUBSURFACE STRATIGRAPHIC DATA

The grid of lineament zones has been superimposed on a large number of published maps. Representative examples described in this portion of the report focus on subsurface stratigraphic data. The first set of four maps is from regional compilations for the Northern Great Plains (Anna, 1986). The second set of maps is from publications that describe North Dakota stratigraphic variations in specific formations. Observations are summarized in tables similar to those for geophysical data.

Regional Compilations

During the 1980's, the US Geological Survey conducted an analysis of regional aquifer systems in the United States. One component of that program was a review of the ground water systems in Jurassic and Cretaceous rocks in the Northern Great Plains, including Wyoming, Montana, and the Dakotas (Anna, 1986). The stratigraphic column is subdivided into six chronostratigraphic intervals in this regional study; rock stratigraphic formations in four of these regional intervals are shown in Figure 10. Four maps from the folio of more than two dozen regional maps, are illustrated below with the superimposed grid of Landsat lineament zones (Figures 11 – 14).

Time Stratigraphic Series	Rock Stratigraphic Formations	Illustrations
Upper Cretaceous	Pierre Shale (part) Niobrara Formation Carlile Shale Greenhorn Formation Belle Fourche Shale	Figure 16 Figure 14 Figure 13
Lower Cretaceous	Mowry Shale Newcastle Sandstone Skull Creek Shale (upper) Skull Creek Shale (basal) Inyan Kara Group	Figure 11 & Plate 7 Figure 15 Figure 12

Figure 10. Simplified stratigraphic column for Cretaceous rocks in the Northern Great Plains that shows the relative positions of maps used to compare with the lineament zone grid.

Lower Cretaceous rocks between the Inyan Kara Group and Mowry Shale (see

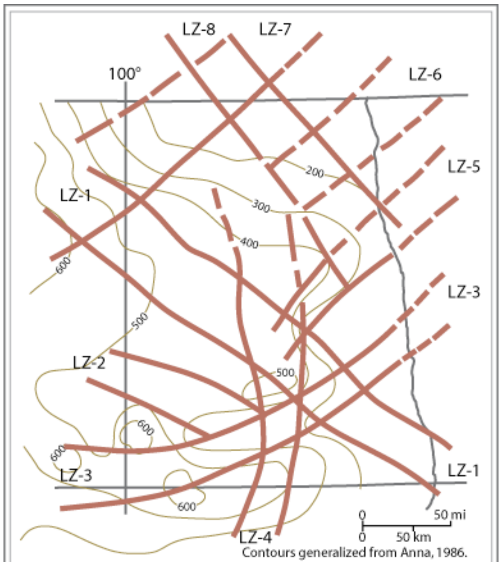

Figure 11. Thickness variations in Lower Cretaceous rocks relative to Landsat lineament zones in eastern North Dakota.

Figure 10) are included in the isopach map shown in Figure 11. There is an overall thinning from west to east across eastern North Dakota, but most of this clastic mass is located in the southern two-thirds of the study area. The northern side of the large thick area generally parallels LZ-1 and the southern side parallels LZ-3. Contours of 300 ft and 400 ft that mark the eastern side of the thick area generally parallel LZ-4, with perturbations at LZ-3 and LZ-5. Areas of local thickening characterize the southwestern part of LZ-3. See Table 2 for a summary.

TABLE 2. SUMMARY OF REGIONAL STRATIGRAPHIC EXPRESSION OF LINEAMENT ZONES

Lineament Zone	Lower Cretaceous	InyanKara/ Skull Creek	Belle Fourche/ Greenhorn	Carlile/ Niobrara/ Lower Pierre
	Figure 11	Figure 12	Figure 13	Figure 14
LZ-1	Yes	Yes	Yes	Yes?
LZ-2	No	Yes	No?	No
LZ-3	Yes	Yes	Yes	Yes
LZ-4	Yes	Yes	Yes	Yes
LZ-5	Yes	Yes	No?	No
LZ-6	No	No?	No	Yes?
LZ-7	No	Yes	Yes	Yes
LZ-8	No?	Yes?	No	No?

Inyan Kara Group and Skull Creek Shale thickness variations are extracted from the total Lower Cretaceous package (see Figure 10) and displayed in Figure 12. In this stratigraphic interval, the northern one-third of the study area is characterized by thin isopach values and the southern two-thirds has more thick sediments. The main part of the regional thickness pod is again bounded by LZ-1, LZ-3, and LZ-4. Local thickening occurs

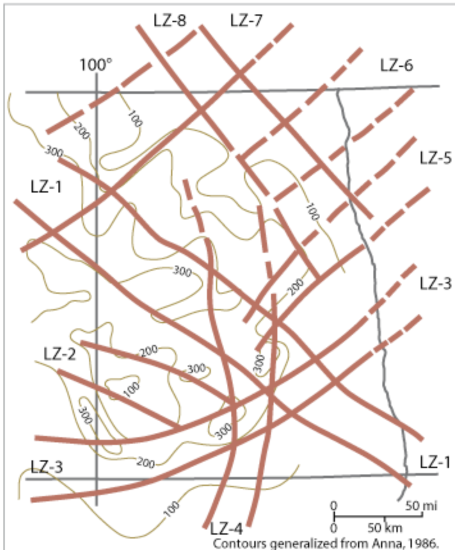

Figure 12. Thickness variations in the Inyan Kara Group and Skull Creek Sandstone relative to Landsat lineament zones in eastern North Dakota.

at the intersections of LZ-4 with LZ-1, LZ-2, and LZ-3. There is a distinctive expression of LZ-2: an area of thinning is located on the lineament zone and it is bounded by two small areas of thickening. Table 2 summarizes characteristics for all lineament zones.

Belle Fourche Shale and Greenhorn Formation (see Figure 10) isopach patterns are shown in Figure 13. The thickness differences between the northern one-third and southern two-thirds of the study area are not as distinctive as on the Lower Cretaceous maps, but in general this interval is thickest in the south. The 250 ft and 300 ft contours that outline the thick area in the south, parallel LZ-1, LZ-3, and LZ-4. There are perturbations in the contours at LZ-2 and LZ-5. In the north, LZ-7 has an area of thickening that extends along trend. A summary of all lineament zones is in Table 2.

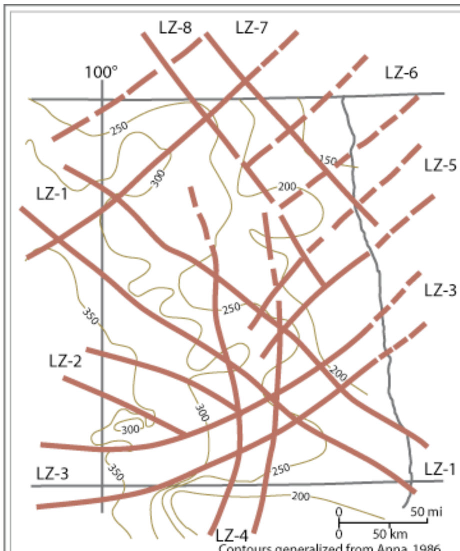

Figure 13. Thickness variations in the Belle Fourche Shale and Greenhorn Formation relative to Landsat lineament zones in eastern North Dakota.

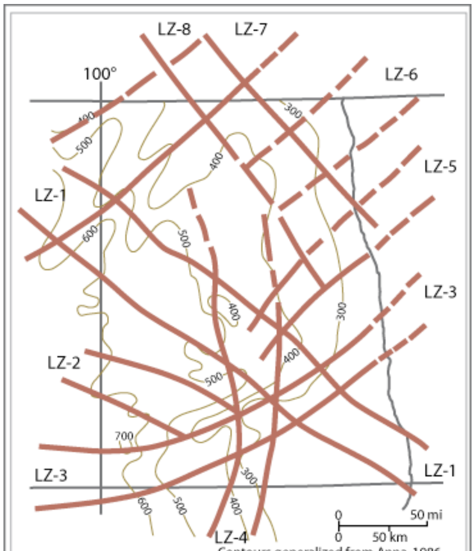

Figure 14. Thickness variations in the Carlile Shale, Niobrara Formation, and Pierre Shale relative to Landsat lineament zones in eastern North Dakota.

Carlile Shale, Niobrara Formation, and Pierre Shale (lower part) (see Figure 10) thickness patterns are displayed in Figure 14. North-south differences are not clearly displayed compared with the previous maps. The area of regional thickening is situated through the central part of the study area. It is bounded by LZ-3, LZ-4, and LZ-7. In addition, LZ-7 has some local variations that parallel the trend. Local perturbations in the thickness patterns are also associated with LZ-1 and LZ-6. Table 2 continues the summary.

North Dakota Formations

Compilations of subsurface stratigraphic data that center on North Dakota, naturally have more detail than the regional compilations. Publications by the North Dakota Geological Survey are particularly useful, although the eastern part of the state has significantly fewer oil and gas tests than the western part of the state.

Mowry-Inyan Kara isopachs are mapped in a recent ND Geological Survey publication (Anderson & Juenker, 2007a). That map has lineament zones superimposed on the thickness patterns on Plate 7. This stratigraphic interval approximately corresponds with a Lower Cretaceous map from the regional publication (see Figure 10). The new ND Geological Survey map shows more detail and may include more control points, but the congruence of thickness patterns and the lineament zone grid is similar to that observed for the regional compilation.

Plate 7 again shows that the northern one-third of the study, viz. north of latitude 48° N, has thin sediments. The central third between latitudes 47° N and 48° N is an area of local thickness anomalies. The southern one-third south of latitude 47° N has the main clastic mass and contours generally trend north-south in this area. Those north-south contour trends parallel LZ-4. Similarly, the 200 ft contour extends along LZ-1. Where these two lineament zones intersect, there is a lot of local thickness variation in the vicinity of Griggs County. Local anomalies also characterize LZ-5 in the same area. The block defined by LZ-2 on the north and LZ-3 on the south is an area of thickening. The expression of Landsat lineament zones in eastern North Dakota is summarized in Table 3.

Another recent publication (Anderson & Juenker, 2007b) presents isopachs for the Greenhorn-Mowry stratigraphic interval. This corresponds with Belle Fourche/Greenhorn interval of the regional compilations (see Figure 13). The associations of lineament zones and isopach patterns on the ND geological Survey map are essentially the same as those described for the regional compilation (see Table 2).

TABLE 3. SUMMARY OF NORTH DAKOTA FORMATIONS AND LINEAMENT ZONES			
Lineament Zone	**Mowry-Inyan Kara**	**Inyan Kara Formation**	**Niobrara Formation**
	Plate 7	**Figure 15**	**Figure 16**
LZ-1	Yes	Yes	Yes
LZ-2	No	Yes	No?
LZ-3	Yes	Yes	Yes
LZ-4	Yes	Yes	Yes
LZ-5	Yes	Yes	No?
LZ-6	No	No?	No
LZ-7	No	Yes	Yes
LZ-8	No?	Yes?	No

Inyan Kara Formation (see Figure 10) isopachs are shown in Figure 15. This ND Geological Survey publication (Moore, Fischer, & Anderson, 1987) makes no distinction between sandstone and shale, but simply maps the total interval. Sandstones referred to as the "Dakota" or "Fall River-Lakota" are part of the mapped interval. Historic gas shows and production for local consumption in southeastern North Dakota are associated with these sandstones (Anderson and Eastwood, 1968). The formation is part of the larger regional stratigraphic interval illustrated in Figure 12.

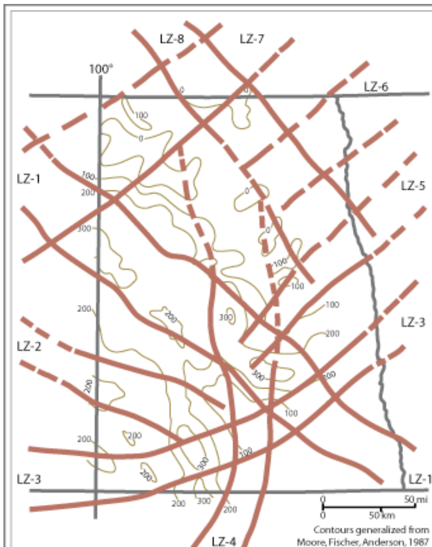

Figure 15. Thickness variations in the Inyan Kara Formation relative to Landsat lineament zones in eastern North Dakota.

The northern one-third of the study area again has thinner sedimentary rock than the southern two-thirds. Contours for 100 ft and 200 ft parallel LZ-1 and local thick anomalies are distributed along trend, especially at the intersection with LZ-4. Local areas of thin and thick anomalies are found along LZ-2 and LZ-3. LZ-5 is marked by a perturbation in contours. Local thickness variations are also associated with LZ-7 and LZ-8. These observations are summarized in Table 3.

Niobrara Formation (see Figure 10) thickness patterns and the grid of lineament zones are shown in Figure 16. The formation is part of the larger regional stratigraphic interval mapped in Figure 14. As in the larger unit, north-south distinctions are not clear. The Niobrara Formation hosts shallow biogenic gas on the eastern margin of the Williston Basin in South Dakota and North Dakota (Shurr, 2008).

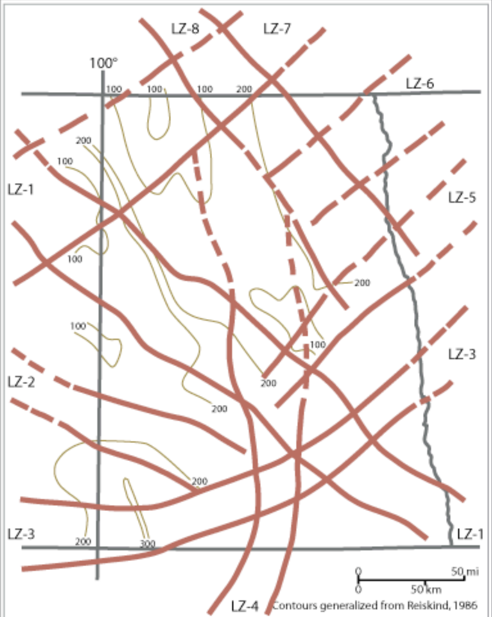

Figure 16. Thickness variations in the Niobrara Formation relative to Landsat lineament zones in eastern North Dakota.

A long and narrow area of greater than 200 ft trends generally along LZ-1. This has been interpreted to be a submarine channel cut into the underlying Carlile Shale and subsequently filled with Niobrara sediments (Shurr & Reiskind, 1984). The block between LZ-2 and LZ-3 also has thicker Niobrara. Blocks between LZ-1 and LZ-2 and between LZ-1 and LZ-8 are characterized by thin Niobrara. These have been interpreted to be erosional channels at the top of the Niobrara (Shurr & Reiskind, 1984). LZ-7 has a number of local thickness variations along trend. All of these expressions of the lineament zone grid are listed in Table 3.

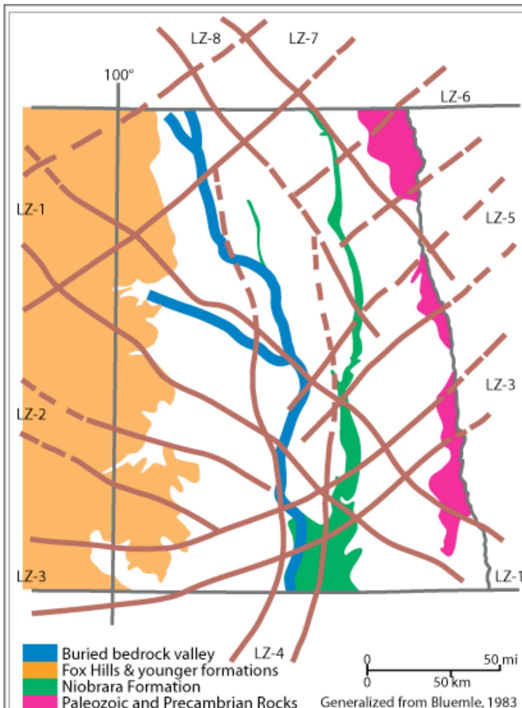

Figure 17. Buried bedrock geology relative to Landsat lineament zones in eastern North Dakota.

Near Surface and Surface Data

Buried Bedrock

The surface of the bedrock buried beneath glacial, lake, and stream sediments has been mapped by the ND Geological Survey (Bluemle, 1983). Four of the features from this compilation are generalized and the grid of lineament zones superimposed in Figure 17.

The subcrop of Paleozoic and Precambrian rocks along the eastern border has fairly good agreement with LZ-5 and LZ-6, and possibly LZ-3. The subcrop pattern of the Niobrara Formation generally runs parallel to LZ-4 and widens at LZ-3. Along the western side of the study area, the subcrop of Fox Hills and younger formations has some similarity to LZ-2 and LZ-3, but does not seem closely related to lineament zones in the north. Finally, the fourth feature from the bedrock map is a major buried stream valley. It trends north-south along LZ-4 and has a tributary that runs along LZ-1. This buried bedrock valley is significant because outwash in the valley has natural gas (Anderson, 2009b). Lineament zone expressions are summarized in Table 4.

TABLE 4. SUMMARY OF NEAR SURFACE AND SURFACE EXPRESSION OF LINEAMENT ZONES

Lineament Zone	Buried Bedrock Patterns	Glacial Features	Digital Elevation Model
	Figure 17	**Figure 18**	**Plate 8**
LZ-1	Yes	Yes	Yes
LZ-2	Yes?	Yes?	Yes?
LZ-3	Yes	Yes	Yes
LZ-4	Yes	Yes	Yes
LZ-5	Yes	Yes	No
LZ-6	Yes	No	No
LZ-7	No	No?	No?
LZ-8	No	No	No?

Glacial Features

Glacial features mapped by the ND Geological Survey (Bluemle, 1988) have patterns related to some Landsat lineament zones (Figure 18). In the eastern part of the study area, sediments deposited on the deltas, beaches, and shores of Lake Agassiz reflect LZ-1, LZ-3, and LZ-5. Through the central part, end moraine and dead-ice moraine complexes follow portions of LZ-1 and LZ-4. In the western part of the study area, moraine complexes occupy the block between LZ-2 and LZ-3. These features are summarized in Table 4.

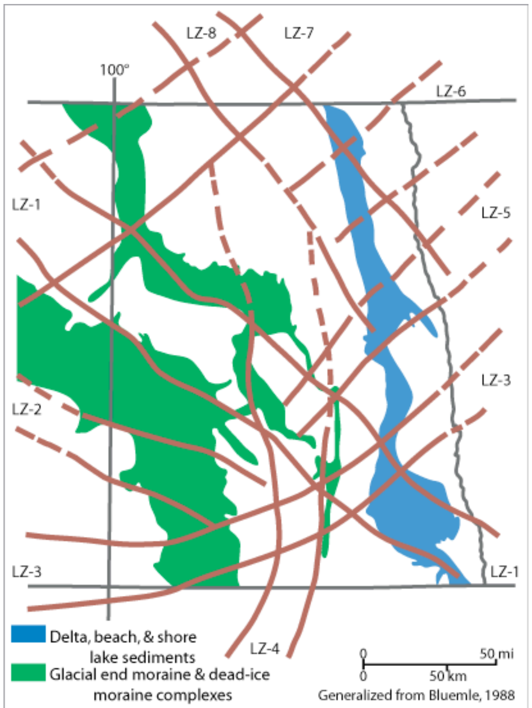

Figure 18. Glacial features relative to Landsat lineament zones in eastern North Dakota.

Digital Elevation Model

The digital elevation model (DEM) displayed in Plate 8 was prepared for this investigation by Dr. Kevin Mickus. It covers the same area as the geophysical maps, specifically eastern North Dakota and adjacent areas in Manitoba, Minnesota, and South Dakota. In a general way, the Turtle Mountains in the northwestern portion of the map are bounded by LZ-1 and LZ-8 and the Prairie Coteau in the southeast is on the block outlined by LZ-1 and LZ-4. But, there are also specific landscape features that correspond with lineament zones.

The northern margin of the Missouri Coteau constitutes the southern side of LZ-1. LZ-1 also marks the southern limit of the 300 m contour that broadly shows the Lake Agassiz plain. Within the high relief area in the southwestern part of the map, higher elevations are distributed along LZ-3 and to a certain extent along LZ-2. LZ-3 also corresponds with a perturbation in the 300 m contour. Stretches of the James and Sheyenne Rivers follow LZ-4 through the central part of the study area. Table 4 summarizes the lineament zones' expression in landscape features visible on the DEM plate.

GEOLOGIC STRUCTURE

Experience has shown in other parts of the Northern Great Plains that geophysical and stratigraphic data sets have more clear expression of regional lineament zones than data on geologic structure at scales of 1:1,000,000 (1 in = 16 mi). Instead, the structural significance of individual lineament zones must be evaluated at more detailed scales. One particularly significant conclusion from the detailed work is that strike-slip displacements are important components of movement along lineament zones. This has been demonstrated in western North Dakota (Shurr, 1995), eastern Montana (Shurr, Larson, & Watkins, 1989;

Shurr, 2000), and central South Dakota (Shurr, Hammond, & Bretz, 1994).

No detailed structural analysis is attempted in this regional investigation of lineament zones and shallow gas systems in eastern North Dakota. However, the sweetspots for shallow gas associated with the lineament zones are obvious candidates for follow-up work. Interpretations of strike-slip displacements are anticipated to be an important aspect of those more detailed studies. In the meantime, published compilations of geologic structure can be used to evaluate the significance of lineament zones in a preliminary way.

Top of Inyan Kara

Geologic structure mapped on the top of the Inyan Kara Formation (Anderson & Juenker, 2006a) is shown with superimposed lineament zones in Plate 9. In general, the northern one-third of the study area has little local structural variation and the middle one-third has a lot of local variability as shown by the configuration of the 0 to 400 ft contours. The southern one-third has some variation, but the picture is less clear as shown by the dashed contours.

TABLE 5. SUMMARY OF GEOLOGIC STRUCTURE AND LINEAMENT ZONES

Lineament Zone	Inyan Kara Top	Mowry Top	Greenhorn Top
	Plate 9	**GI-37**	**GI-31**
LZ-1	Yes	No?	Yes
LZ-2	No?	No?	No
LZ-3	Yes	No?	Yes?
LZ-4	Yes	Yes	Yes
LZ-5	Yes	No	Yes?
LZ-6	No	No	No
LZ-7	No	No?	No
LZ-8	No?	No	Yes?

Local structural anomalies, viz. local highs, are associated with individual lineament zones. LZ-1 has a local high in Cass, Barnes, and Ransom Counties at the intersection with

LZ-3. Also, where LZ-1 intersects LZ-4 there is a local high in Griggs County. LZ-3 has local features in Emmons and McIntosh Counties and LZ-5 has one in Grand Forks County. LZ-2 and LZ-8 have some expression in the shape of structural contours. LZ-6 and LZ-7 have no apparent expression. These observations are all summarized in Table 5.

Other Published Maps

Geologic structure on the top of the Mowry Formation (Anderson & Juenker, 2006b) has been published by the ND Geological Survey (Geologic Investigations Number 37). There are virtually no local structural highs on this map and only subtle expressions of individual lineament zones. Regional north-south contours parallel LZ-4 and some more local contour configurations are associated with LZ-1, LZ-2, LZ-3, and LZ-7. See Table 5 for a summary.

A map of geologic structure on the top of the Greenhorn Formation (Anderson & Juenker, 2006c) has also been published by the ND Geological Survey (Geologic Investigations Number 31). There is a local high in Griggs County at the intersection of LZ-1, LZ-4, and LZ-5. Regional contours parallel LZ-4 and LZ-8. The block outlined by LZ-1, LZ-3, and LZ-4 has a series of local highs that would approximately correspond with the northern extension of the Prairie Coteau. See Table 5 for a summary.

The Prairie Coteau feature raises the issue of structural high versus bedrock high. The area of Greenhorn subcrop is generally east of longitude 98° W (Bluemle, 1983). Consequently, the features in Sargent and Richland Counties may be features on the bedrock surface rather than true geologic structures. In a similar way, elevations on the top of a higher structural datum at the top of the Pierre Shale (Carlson, 1982) may represent erosional features in the buried bedrock topography and not geologic structure.

Compilation of Local Features

Four local structural features have been interpreted from investigations of structural and stratigraphic relationships in Paleozoic formations (Ballard, 1963). The locations of the Cavalier, Foster, Stutsman, and Burleigh Highs are shown relative to the grid of lineament zones in Figure 19. The Cavalier High is at the intersection of LZ-7 and LZ-8 and the Foster High is within LZ-1. Eight local structural features compiled from the Cretaceous structural datums are also shown in Figure 19. Features in Barnes, Sargent, and Richland Counties (1-3, Figure 19) have expression the top of the Greenhorn and the remaining six features are from the top of the Inyan Kara.

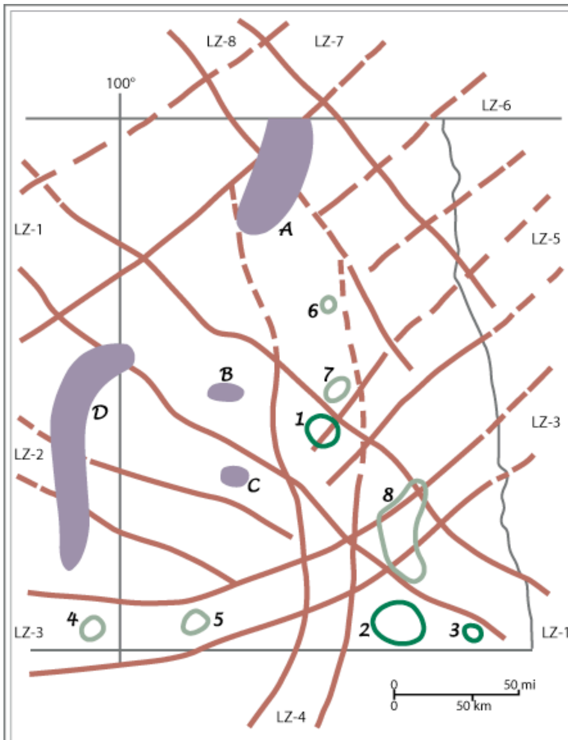

Figure 19. Compilation of local geologic structural features relative to Landsat lineament zones in eastern North Dakota. A through D are from Ballard, 1963; 1 to 3 are visible on maps on the Greenhorn and Mowry; 4 through 8 are visible on the map of Inyan Kara structure.

SUMMARY RANKING

Multiple data layers integrated with the grid of Landsat lineament zones reinforce the generalization about north-south differences in the study area and provide an independent ranking of the significance of individual lineament zones. The data layers have included geophysical maps that are an expression of the Precambrian basement, stratigraphic and structural maps from the overlying envelope of sedimentary rocks, and landscape elements of the surface and shallow subsurface.

Landsat lineament zones in the southern two-thirds of the study area are better defined and more distinctive than in the northern one-third. This conforms with differences in Precambrian terranes interpreted for basement rocks: north of approximately latitude 48° N, two minor subterranes are distinguished from the main Superior Craton to the south. This north-south difference is also seen in maps of stratigraphic data and in addition in the ranking of the significance of individual linear features.

A summary of the relative significance of linear features is shown in Table 6. The Landsat rank and geophysics rank are from Chapter 2 and Table 1, respectively. The geologic rank is produced by assigning numbers to the observations summarized in Tables 2

Table 6. Ranked Significance of Lineament Zones			
Lineament Zone	**Landsat Rank**	**Geophysics Rank**	**Geologic Rank**
LZ-1	1	1-2	1-2
LZ-2	4	4	5
LZ-3	2	3	3
LZ-4	3	1-2	1-2
LZ-5	5	7	4
LZ-6	8	8	8
LZ-7	6	6	6
LZ-8	7	5	7

through 5. "Yes" observations are assigned the number 1, "Yes?" is 2, "No?" is 3, and "No" is 4. The summation of these numbered observations provides a preliminary ranking for the geologic significance of the eight lineament zones. LZ-1 and LZ-4 are ranked as most significant and LZ-6, LZ-7, and LZ-8 are least significant. Furthermore, lineament zones in the southern two-thirds of the study area, viz. LZ-1 through LZ-4, are more important than those in the northern one-third, LZ-5 through LZ-8. This ranking is significant because mapping the lineament zones is a fundamental first step in shallow gas exploration. A very basic second step is based upon documented occurrences of methane.

CHAPTER 4

METHANE FIELD SCREENING

Published studies are at the center of this investigation of shallow gas systems in eastern North Dakota. Lineament zones interpreted from Landsat images have been evaluated and ranked using published maps. However, by far the most important body of published work is the field screening for methane done by the ND Geological Survey. Integration of the lineament zone grid with the results of the field screening program provides another step toward identifying shallow gas sweetspots east of longitude 100° W.

PROGRAM DESCRIPTION

In 2005, the ND Geological Survey initiated an ambitious program to monitor methane levels in shallow ground water observation wells throughout the state. The first field screening was done in 2006 and the program was completed when the last counties were surveyed in 2010. Reports for more than 50 counties have all been published as Geological Investigations along with numerous other reports and presentations at professional meetings. All of the publications can be accessed through the "Publications" link in the "Shallow Gas" portion of the ND Geological Survey website.

A progress report issued in 2009 provides a description of the field screening program (Anderson, 2009a). The majority of the monitored wells were part of the state-wide network developed and maintained by the North Dakota State Water commission. Some of the original wells in the network have been abandoned or destroyed, so one of the fringe benefits of the methane field screening has been to provide verification on the location and condition of existing observation wells.

Methane measurements were made using a portable analytical instrument called a flame-ionization detector (FID). The unit provides real-time readings on methane concentrations in the air column within the casing of the observation wells. When calibrated with a predetermined standard concentration, the FID has a range of 0.5 parts per million (ppm) to 50,000 ppm . The instrument is small, light weight, and reasonably robust under a variety of field conditions.

At each well location, the FID was used to measure methane at the top of the casing and just above the water surface within the well. Methane levels are always higher at the water level than at the top of the casing. Additional data collected at each well location included the depth to water, air temperature, and atmospheric pressure. Published maps show the locations of all observation wells within each individual county. Wells with no FID response are included, as well as wells with measured methane values posted.

County Clusters

Thousands of individual observation wells across the state were visited and monitored for methane in the course of the field screening program. The mean methane measurement and the percent of wells showing a positive FID response in each county are extracted from this large data set. Sioux County is not included in the field screening program. Counties with only one or two measurements (specifically, Adams, Billings, and Trail) are also excluded from this analysis.

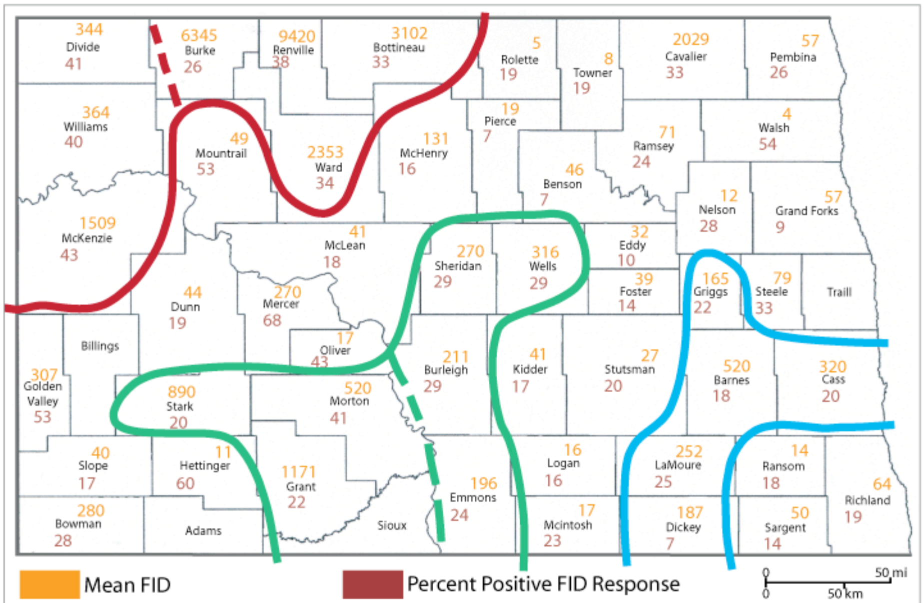

Figure 20. County summary of FID field screening throughout North Dakota. Three distinct clusters of counties are believed to be associated with three separate types of natural gas systems: thermogenic outlined in red in the northwestern part of the state, early generation biogenic outlined in green through the center of the state, and late generation biogenic outlined in blue in the southeastern part of the state.

Three clusters of counties with similar mean and percent positive values are apparent (Figure 20). Seven counties clustered in northwestern North Dakota have high mean and high percent positive values. Seven counties in the central part of the state have lower means and percent positive numbers. Five counties in southeastern North Dakota have values similar to the cluster in the central part of the state, but higher than the adjacent counties.

These three county clusters are more readily apparent on cross plots of mean FID values and percent of wells with positive FID response in each county (Figure 21). Four counties with mean FID values greater than 2000 ppm (Renville, Burke, Bottineau, and Ward) form a distinct cluster on the cross plot (upper red cluster, Figure 21). Three adjacent counties (lower red cluster, Figure 21) have lower means and slightly higher percent positive values (McKenzie, Williams, and Divide). Morton County in the south-central part of the state is included in this lower red cluster, but adjacent Grant and Stark Counties have lower percent positive values (green, Figure 21). Cavalier and Walsh Counties (1 & 2, Figure 21) in northeastern North Dakota are the only eastern counties included on this portion of the cross plot. Cavalier's high mean value is based on only three locations and Walsh has a low mean, but a relatively high percent positive value compared with adjacent counties (Figures 20 & 21). All the other counties with low means and high percent positive values clustered around Walsh on the cross plot are located in the western part of the state.

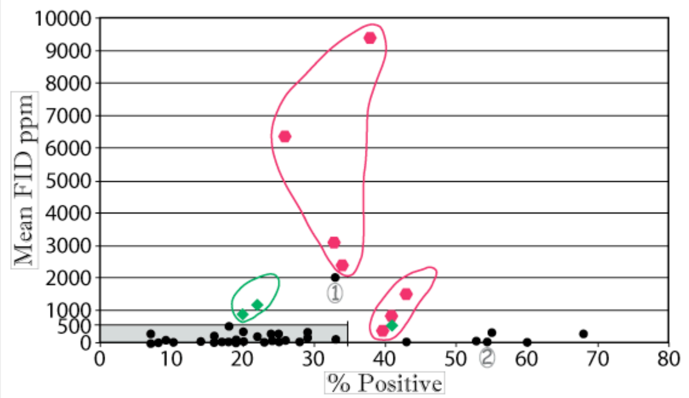

Figure 21. Cross plot of mean FID values and percent positive FID wells in each county. Red and green lines and data points correspond with counties outlined in red and green on the map in Figure 20. The shaded area is shown in more detail in Figure 22.

The cross plot is shown with more detail for means less than about 500 ppm and percent positive values less than 40% in Figure 22. Four counties (Wells, Sheridan, Burleigh, and Emmons) in the central part of the state have means greater than 200 ppm and percent positive values greater than about 25% (green, Figure 22). Bowman County in extreme southwestern North Dakota has about the same numbers as Sheridan County. However, the central county cluster is adjacent to the three western counties that formed a

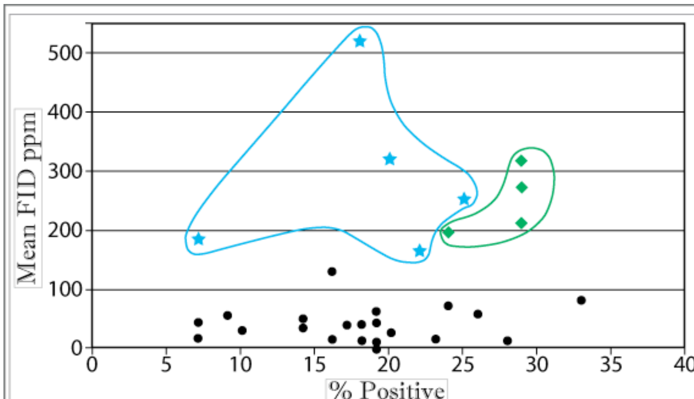

Figure 22. More detailed cross plot of mean FID values and percent positive FID wells in each county. Green and blue lines and data points correspond with counties outlined in green and blue (specifically, southeastern North Dakota) on the map in Figure 20.

cluster on the previous cross plot. Therefore, all seven are included in the cluster in the center of the state (see Figure 20).

The more detailed cross plot also shows a distinctive cluster of counties in southeastern North Dakota (blue, Figure 22). These five counties (Dickey, LaMoure, Barnes, Griggs, and Cass) have larger means than the surrounding counties, although the percent positive values are all in the same range. All remaining counties with mean values generally less than about 130 ppm are counties located between the three distinctive clusters.

NATURAL GAS SYSTEMS

The three county clusters are color coded in the illustrations to emphasize the three natural gas systems described in Chapter 1. The red outline in northwestern North Dakota shows counties that have thermogenic gas. The counties outlined in green in the central part of the state are speculated to have early generation biogenic gas. And, the blue outlined counties in southeastern North Dakota probably have late generation biogenic gas.

Observation wells in the cluster of seven counties in northwestern North Dakota (see Figure 20) are completed in surficial, buried channel, and shallow bedrock aquifers. Available gas analyses have been used to calculate wet gas and biogenic gas indices; both thermogenic and biogenic gas are present in McKenzie County (Anderson, 2008b). There is significant oil and gas production from deep reservoirs in northwestern North Dakota. Gases in shallow aquifers include hydrocarbons heavier than methane that have migrated vertically from deep, thermogenic systems.

There is also a biogenic component in these counties. Ground water compositions in Bottineau County show low sulfate (less than 500 ppm) and high bicarbonate concentrations (greater than 400 ppm) (Anderson, Shurr, & Fischer, 2006). These concentrations are characteristic of late generation biogenic gas (Shurr, 2008). Isotopic analyses are required to distinguish early generation and late generation biogenic gas. However, the seven county cluster in northwestern North Dakota definitely has thermogenic gas.

The seven counties outlined in green (see Figure 20) in the central part of the state also have FID measurements from wells in shallow aquifers in both bedrock and glacial sediments. Although analyses of shallow gas are not readily available and compilations of ground water compositions in the area of gas occurrences have not been made, it is speculated that early generation biogenic gas is the dominant system in this area. This suggestion is based in part upon proximity to commercial production of shallow gas in Bowman County which is generally accepted to be part of an early generation biogenic gas system.

Finally, the five-county cluster outlined in blue (Figure 20) in southeastern North Dakota is believed to have late generation gas systems present. Although there is little direct evidence to support this interpretation, the area does have elements of the exploration model successfully used to explore for late generation gas in other areas (Shurr, 2008). It is this five-county cluster in southeast North Dakota that is the best candidate for being a sweetspot within the study area east of longitude 100° W.

SOUTHEASTERN NORTH DAKOTA

The cluster of five counties in southeastern North Dakota is distinguished from adjacent counties on the basis of mean methane measurements and the percent of observation wells with a positive FID response (see Figures 20 & 21). In effect, the counties are used as sampling cells to characterize shallow gas systems in the study area. The sweetspot cluster has the same general attributes that characterize adjacent counties. But in addition, the cluster has distinctive geology and the location is clearly related to the grid of Landsat lineament zones.

General Attributes

Since the counties are being used as sampling cells, it is possible that differences between the cluster and the adjacent counties are related to differences in size. Although some counties are large, e.g. Stutsman and Cass, and some counties are small, e.g. Foster and Eddy, the average areas for cluster counties (1249 sq mi) and adjacent counties (1030 sq mi) are about the same (Table 7). In a similar way, counties with large populations, such as Cass, might have a larger number of observation wells available for field screening. However, that does not appear to be a problem. If Cass County is excluded, the population densities are about the same: 4.9 persons per sq mi within the cluster and 5.3 persons per sq mi in adjacent counties (Table 7). In addition, the average number of wells visited during the screening program are approximately the same within the cluster (135) as in adjacent counties (104) (Table 7).

TABLE 7. SOUTHEAST NORTH DAKOTA COUNTY SUMMARY

County	Geologic Investigation Number	Year	Area (sq mi)	Population Density* (people/sq mi)	Number of Wells	Maximum FID (ppm)
Dickey	126	2010	1131	4.8	257	3051
LaMoure	56	2007	1147	3.7	198	3712
Barnes	54	2007	1492	7.4	28	2897
Griggs	82	2009	709	3.5	90	2063
Cass	110	2010	1765	75.1	101	5620
Average			**1249**	**18.9/4.9****	**135**	**3469**
Richland	98	2010	1437	11.8	147	1066
Sargent	107	2010	859	4.9	291	933
Ransom	91	2010	863	6.6	191	187
McIntosh	109	2010	975	3.0	48	80
Logan	67	2008	993	2.0	75	43
Stutsman	34	2006	2221	9.3	106	182
Foster	118	2010	635	5.6	69	186
Eddy	117	2010	630	4.0	70	211
Nelson	119	2010	982	3.3	32	60
Steele	30	2006	712	2.7	9	146
Average			**1030**	**5.3**	**104**	**309**

* Data Source: ND Association of Counties

** Average without Cass County.

Although the counties all have approximately the same size, have similar population densities, and approximately the same number of screened wells, there is another possible bias in the county-scale sampling program. Field screening was conducted over a four-year period. There are qualitative indications that during wet years, FID values tend to be lower (Fred Anderson, NDGS, personal communication, 2010). 2010 was a wet year. It is true that most of the adjacent counties were screened in 2010 (Table 7). But, two of the cluster counties were also done in 2010. The influence of variable rainfall has not been fully evaluated.

Mean methane measurements are used to distinguish the sweetspot cluster (see Figures 20 & 22), but maximum values can also be used. Maximum FID values for counties within the cluster are an order of magnitude greater than adjacent counties (3469 ppm versus 309 ppm, Table 7). Cross plots using maximum county values and percent positive response show the same geographic clusters as cross plots that use mean values (specifically, Figures 20 & 22). An apparently aberrant maximum value of 28,123 ppm in Richland County is not included in the analysis. That is one of the highest methane concentrations measured in the state and that well is probably a good candidate for follow-up screening to verify a continuing elevated methane concentration.

Geologic Characteristics

The sweetspot cluster of counties in southeastern North Dakota is clearly related to the grid of Landsat lineament zones (Figure 23). The cluster is elongate along LZ-4, which is one of the most significant lineament zones in the grid (see Table 6). In addition, the cluster corresponds with the location of lineament zone intersections; LZ-1, LZ-3, and LZ-5 all intersect with LZ-4 within the cluster. Furthermore, LZ-2 and LZ-5 terminate within the sweetspot county cluster.

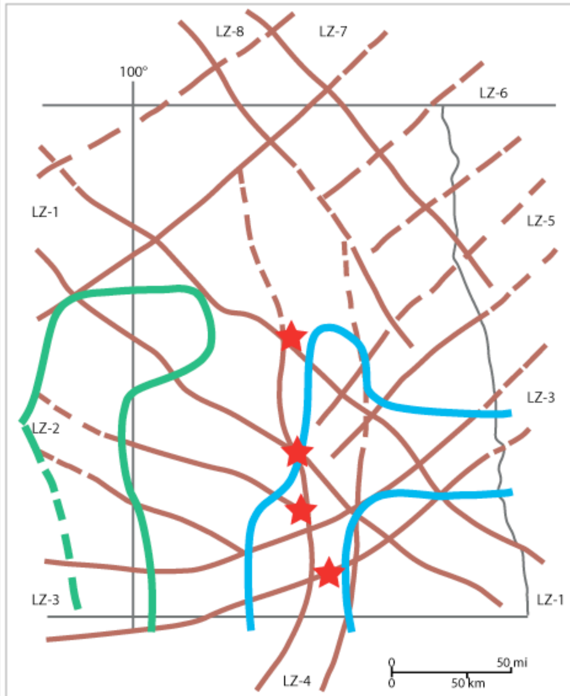

Figure 23. Cluster of sweetspot counties in southeastern North Dakota relative to the grid of Landsat lineament zones. Red stars show areas in the Spiritwood Aquifer with high FID values (Anderson, 2009b).

One of the main conclusions that emerged from the review of published data (see Chapter 3) is a distinct difference in the geology in the northern one-third of the study area compared with the southern two-thirds. These north-south differences also have expression on the map in Figure 23. Both the county cluster in southeastern North Dakota and the one in the central part of the state are limited to the southern two-thirds of the study area.

There are several other useful relationships between the sweetspot cluster and compilations of published data. For example, there are a number of local geologic structures within the cluster (see Figure 19) and it is also the general location of the margins of glacial lobes (see Figure 18). But, the most important relationships are illustrated on the map of bedrock geology (see Figure 17). The north-south trend of sweetspot counties corresponds with the north-south subcrop of the Niobrara Formation and with the north-south trend of a major buried bedrock channel. This buried channel is filled with outwash that is designated as the Spiritwood Aquifer in the hydrogeologic literature of North Dakota.

The majority of the high value wells encountered in the field screening program are located in the Spiritwood Aquifer. In fact, four distinct areas of high value wells are recognized within the aquifer (Anderson, 2009b). Three of the four areas are located within the sweetspot cluster and all are located along the edges of the Landsat lineament zones, (red stars, Figure 23). Methane in the Spirtwood Aquifer appears to be concentrated in areas where there is also substantial fracturing of the bedrock.

Differences between counties within the cluster and adjacent counties are well illustrated in Griggs and Steele Counties where potential shallow gas gravels and sands have been mapped (Anderson, 2009c). The Spiritwood Aquifer in Griggs County is within the sweetspot cluster and has wells with larger methane concentrations than the more discontinuous smaller outwash aquifers distributed throughout Steele County. The Niobrara subcrop belt in central Steele County is positioned to the east of the buried Spiritwood Aquifer channel. This is the classic set up for a late generation biogenic gas system that has been described in both the Antrim Shale in Michigan (McIntosh & Martini, 2008) and in the the Niobrara Formation in eastern South Dakota (Shurr, 2008).

Before discussing the late generation biogenic gas system in eastern North Dakota, however, we will focus on one particularly important aspect of the system. Fractures as mapped on Landsat images are a fundamental component of an exploration program.

CHAPTER 5

POPULATIONS OF LANDSAT LINEAR FEATURES

The cluster of sweetspot counties in southeastern North Dakota appears to be related to the grid of regional lineament zones interpreted from linear features visible on Landsat images. Regional Landsat lineament zones are visualized as corridors of increased fracturing that are an important component of late generation biogenic gas systems. In fact, the highest levels of methane measured in the Spiritwood Aquifer are along lineament zone margins where fracturing is probably most significant.

The population of individual linear features used to interpret lineament zones can also be used to characterize the county cluster in more detail. Recall that linear features were sorted on length and that the long linear features are the basic components of the regional lineament zones (Plates 1 & 2, Chapter 2). The lengths of linear features provide basic information on fracturing in late generation biogenic gas systems in southeastern North Dakota.

THE IDEA

As a general rule, long faults have larger displacements than short faults and fractures. This understanding comes from observations of length and displacement for large numbers of faults and fractures. During the 1990's, it became clear that these measurements in populations of faults and fractures follow power-law distributions (Pickering et al., 1995 & 1999). As a consequence, fault populations can be described as fractals using log-log plots of cumulative frequency and length. The descriptive mathematical relationships are reviewed in an early application aimed at identifying fault populations (Ackermann & Schlische, 1997) and in a more recent paper that looks at changes in fault length related to linkage (Xu et al., 2010).

Log-log plots of cumulative frequency and fault length are linear. The power-law distribution is expressed as:

$$N = aL^C \qquad (1)$$

where N is the cumulative number of faults equal to or greater than length (L) and "a" and "C" are attributes of the line on the log-log plot. Taking the logarithm of both sides of Equation 1, demonstrates how the plot can be used to describe a population.

$$\text{Log } N = \log a + C \log L \qquad (2)$$

The first term on the right side of the equation is the intercept on the log-log plot and the value C is the slope. Published values of C range from -.67 to -2.07 for a variety of compilations of fault length.

Linear features and "lineaments" in western North Dakota have been shown to follow power-law distributions (Anderson, 2008a). Not only does this support the notion that linear features are closely related to faults and fractures, it also provides a way to describe populations of linear features. Conventional statistics based on random normal distributions are of limited utility. But, the attributes of log-log plots showing cumulative frequency and length can be used to compare and contrast linear features in lineament zones with those found in the blocks between lineament zones.

LINEAMENT ZONES AND BLOCKS

The lengths of 130 linear features were measured in an area that extends approximately 100 mi to the east of longitude 101° W and extends approximately 150 mi in a north-south direction. Only linear features observed on both Bands 3 and 5 (see Plate 1) are used; a larger population could be sampled if all linear features mapped on Landsat images were employed.

There are three lineament zones within the area of sampling (LZ-1, LZ-2, and LZ-3, Plate 2) and these three lineament zones bound two blocks. The log-log plots of cumulative frequency and length for linear features within the lineament zones and in the lineament bound blocks are shown in Figure 24 and the attributes of the graphs are summarized in Table 8.

The plot for linear features in the lineament zones is more linear than for those in the blocks (R^2 values .80 versus .61) and the slope for the lineament zone is larger (-1.12 versus -.89). Although the distributions of lengths appear to be different in the lineament zones and the blocks, the slopes both fall within the range commonly observed for faults (viz., -.67 to -2.07). Mean lengths in the lineament zones are greater (23.0 mi versus 17.8 mi) and so are the maximum lengths (48.8 mi versus 37.6 mi). However, calculations of means assume that a population follows a normal distribution and these distributions are power-law distributions.

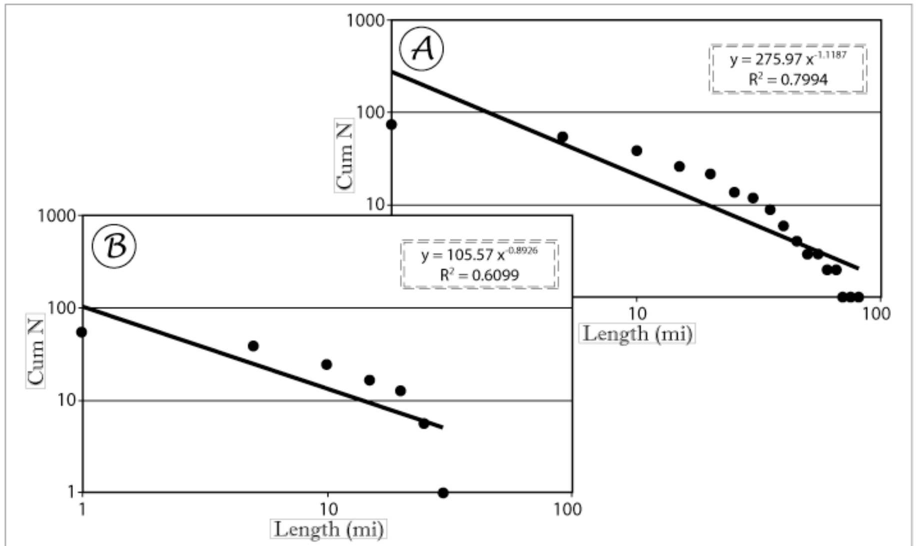

Figure 24. Log-log plots showing cumulative number of linear features (N) equal to or greater than a given length (L). Landsat linear features have attributes similar to fault populations.
(A) Landsat linear features measured within lineament zones.
(B) Landsat linear features measured in blocks bounded by lineament zones.

TABLE 8. CONTRASTS BETWEEN POPULATIONS OF LINEAR FEATURES IN LINEAMENT ZONES AND IN LINEAMENT BOUND BLOCKS

	Lineament Zones	Lineament Bound Blocks
Slope/exponent	-1.12	-.89
Intercept	276	106
R^2	.80	.61
Number	74	56
Mean length (mi)	23.0	17.8
Maximum length	48.8	37.6

SWEETSPOT CLUSTER AND SURROUNDING COUNTIES

Power-law distributions can also be used to contrast the populations of Landsat linear features in the cluster of sweetspot counties with those in the surrounding counties. More than 150 linear features (see Plate 1) were measured in counties in southeastern North Dakota. Lineament zones are located both in the sweetspot cluster and in the surrounding counties (see Plate 2 & Figure 23). The log-log plots that characterize the two populations are shown in Figure 25 and Table 9 summarizes the attributes.

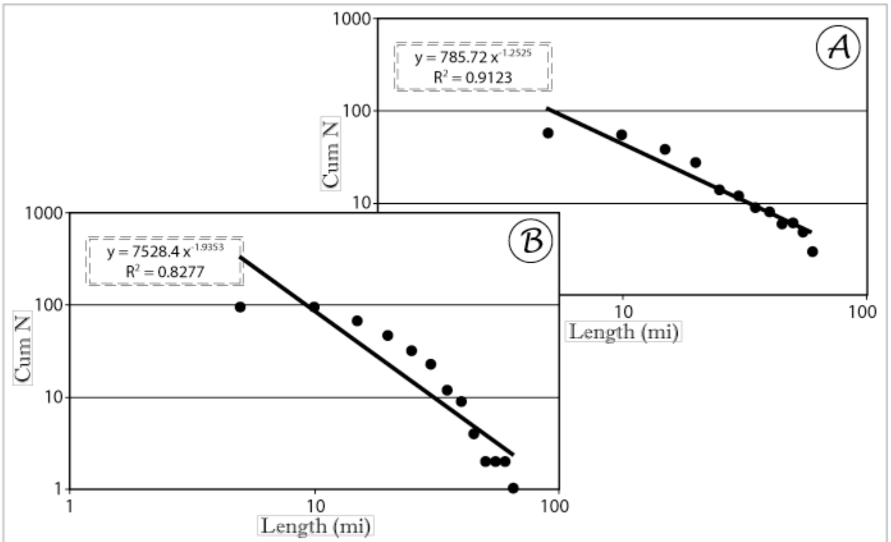

Figure 25. Log-log plots showing cumulative number of linear features (N) equal to or greater than a given length (L) in southeastern North Dakota.
(A) Landsat linear features measured in sweetspot counties (see Figure 20).
(B) Landsat linear features measured in counties surrounding the sweetspot counties.

TABLE 9. CONTRASTS BETWEEN POPULATIONS OF LINEAR FEATURES IN THE SWEETSPOT CLUSTER OF COUNTIES AND IN THE SURROUNDING COUNTIES

	Sweetspot Cluster	Surrounding Counties
Slope/exponent	-1.25	-1.94
Intercept	786	7528
R^2	.91	.83
Number	58	95
Mean length (mi)	23.4	22.8
Maximum length	62.0	67.2

The plot for the sweetspot cluster is very linear and the surrounding counties are comparable to the lineament zones (R^2 values of .91 and .83). Both slopes (-1.25 and -1.94) fall within the range for faults (-.67 to -2.07) and the intercept for the sweetspot cluster is an order of magnitude smaller than for the surrounding counties (786 versus 7528). The maximum length is smaller in the sweetspot counties (62.0 mi versus 67.2 mi) and the mean length is slightly larger (23.4 mi versus 22.8 mi). However, the mean length calculations carry the caveat of the normal distribution assumption.

This analyses clearly demonstrates that the population of linear features in the sweetspot counties is distinct from the population in the surrounding counties. The exercise is also significant because it points the way to more detailed studies that could be initiated in southeastern North Dakota.

FOLLOW-UP STUDIES

Landsat linear features follow power-law distributions that are compatible with those observed in populations of faults. It would be interesting to do an analysis of the log-log plots for cumulative frequency and length on the Landsat "lineaments" mapped in western North Dakota (Anderson, 2008a). This might provide an approach to comparing the features mapped on satellite images and other data sets.

In southeastern North Dakota, an obvious follow-up study would be to map linear features on more detailed images. High altitude photographs have been used to map linear features over the Little Missouri Field in Bowman County, North Dakota (Shurr, 1998). Fractures are important in the production of gas in the early generation biogenic gas system. Similar work has been done in Harding County, South Dakota where early generation gas is produced from the West Short Pine Hills Field and in Spink County, South Dakota where the Niobrara Formation hosts a late generation biogenic gas system (Shurr, proprietary studies).

Fractures are a critical component of late generation biogenic gas systems. But, there are other additional elements of the system that need to be investigated.

CHAPTER 6

LATE GENERATION BIOGENIC GAS SYSTEMS

IN EASTERN NORTH DAKOTA

It is proposed (Chapter 4), that shallow biogenic gas systems in North Dakota east of longitude 100° W are mainly late generation systems. Because there is little or no public domain data on gas composition or isotopic studies in the area, that interpretation relies heavily on analogy with other areas where late generation methane has been documented. Exploration models developed in the Antrim shale on the northern margin of the Michigan Basin and applied to the Niobrara Formation on the eastern margin of the Williston Basin in South Dakota (Chapter 1) provide specific guidance for this analogy.

There are four fundamental components of late generation biogenic gas systems (Shurr, 2008): 1) host rocks must have substantial organic matter; 2) fractured bedrock provides a "plumbing system"; 3) water chemistry must be within certain optimal limits; and 4) robust microbial communities that include methanogens must be present. This Phase I study supported by the North Dakota Industrial Commission has emphasized regional fracture systems mapped as lineament zones from Landsat images. Those regional fracture systems have been integrated with the results from the methane field screening program conducted by the North Dakota Geological Survey. The positive FID methane measurements can be considered to be a proxy for direct observation of methanogenic microbes. As a consequence, two fundamental components of the late generation biogenic gas system have been specifically addressed in this study: fractured bedrock and methane generated by microbes.

FRACTURES AND METHANE

As yet, there are no documented investigations of methanogenic microbes in shallow subsurface geologic environments in eastern North Dakota. The methane measured in ultra-shallow groundwater observation wells could have feasibly leaked upward from deeper sources of early generation biogenic gas or thermogenic gas. However, the geological similarities between eastern North Dakota, eastern South Dakota, and northern Michigan are compelling. Methanogens have been described in Michigan and South Dakota and Landsat linear features and lineament zones are found in all three areas.

Anecdotal information on shallow gas occurrences is available in all three areas, including North Dakota (Anderson, 2008c). However, it is the FID field screening that provides a geographically pervasive data set. FID attributes from individual counties have been used to identify localized clusters (Chapter 4), but the state-wide compilation also shows some important relationships to the grid of Landsat lineament zones (Plate 10). The compilation was originally published by the ND Geological Survey at a scale of 1:500,000 (1 in = 8 mi), but the version shown in Plate 10 is reduced to a scale of 1:1,000,000 (1 in = 16 mi) because that is the scale of the Landsat images and interpreted lineament zones.

Approximately 20% of the more than 4300 wells tested for methane content had measurable concentration levels (Anderson et al., 2010). Although maps of individual counties provide posted methane levels at each well location, the statewide compilation shows just the presence or absence of methane. But, even simplified, the statewide compilation (Plate 10) displays some significant general patterns and some important observations in specific areas.

In a general way, methane occurrences are sparse and widely distributed in the western part of the state. In contrast, the study area east of longitude 100° W, shows more numerous occurrences that tend to be concentrated in distinctive long, linear clusters. This characteristic geometry reflects the map pattern of buried outwash channels that host biogenic gas systems. As described earlier (Chapter 3), some outwash channels parallel the trend of lineament zones. This is well illustrated along LZ-1 and LZ-4 (Plate 10). The genesis of linear bedrock channels may be controlled by fracture zones that are less resistant to erosion. A similar scenario for the development of linear drainages has been described in the southwestern part of the Williston Basin (Shurr, Larson, & Watkins, 1989).

Outwash aquifers filling the bedrock channels are important hosts for methane. In particular, the Spiritwood Aquifer that trends along LZ-4 has four specific zones of high methane concentration (Anderson, 2009b & see Figure 23). The locations of these high methane FID measurements are shown more clearly on Plate 10 where there are clusters of positive wells. The southern most zone of high methane wells in southeastern LaMoure County is at the intersection of LZ-3 and LZ-4. The zone in north central LaMoure County and southwestern Stutsman County is at the intersection of LZ-2 and LZ-4. Just to the north, the zone along the Stutsman-Barnes County line east of Jamestown is in the intersection of LZ-1 and LZ-4 and on trend with LZ-5. The northern most zone in northwestern Griggs County is within LZ-4 and close to the margin of LZ-1. Farther north the Upper Spiritwood Aquifer has fewer positive FID wells and no high value wells. This distinction in methane measurements between the Upper Spiritwood Aquifer and the Lower Spiritwood Aquifer (Anderson, 2009b) generally conforms with the north-south differences within the study area that are described in Chapters 2 and 3.

The statewide compilation (Plate 10) also provides some useful perspectives on the five county sweetspot cluster in southeastern North Dakota. In particular, Barnes County does not have very many methane occurrences, but the total number of wells is small (Table 7) and the maximum and mean FID values are large (Table 7 & Figure 20). Stutsman County did not meet the criteria for the sweetspot, but note that most of the occurrences are distributed along the eastern county line. In contrast, there are many methane occurrences and a large number of wells distributed throughout Ransom, Richland, and Sargent Counties (Plate 10). However, the mean FID values and percent positive wells are smaller than within the sweetspot (Table 7 & Figure 20). The statewide compilation thus points out both the strengths and the weaknesses of the approach used in Chapter 4 that treats each county as an individual sampling cell.

Specific counties have some distinctive relationships between Landsat lineament zones and methane occurrences. In LaMoure County, methane occurrences in the Lower Spiritwood Aquifer that locally trend northwest, are on strike with LZ-2 within the intersection of LZ-3 and LZ-4. In Kidder County, the hosting outwash aquifer has a broad outline, but the methane occurrences are more numerous within LZ-2 than in the block to the north. Similarly, the elongate and linear outwash aquifer in Grand Forks County has fewer methane occurrences than in Walsh County where it is in LZ-6. In Pembina County, the cluster of occurrences at the corner between LZ-6 and LZ-7 may represent an extensional corner in a block caught up in strike-slip displacements. That type of structural setting has both methane occurrences and methanogens in eastern South Dakota. Similar situations in the sweetspot counties of southeastern North Dakota may be more difficult to identify on the statewide compilation because methane occurrences are much more numerous.

FRACTURES AND WATER

Methanogens are anaerobic microbes which require aqueous environments that are oxygen depleted, but the microbial communities are also robust under specific optimal water chemistry. This includes limited ranges of temperature, pH, and salinity (Gilcrease & Shurr, 2007) as well as relatively high bicarbonate and relatively low sulfate concentrations (Shurr, 2008). It is the fracture corridors associated with lineament zones that provide the "plumbing system" for the water which can subsequently host and support methanogens.

A recent statewide compilation of high bicarbonate/low sulfate water wells has been published by the ND Geological Survey (Anderson, 2010). More than 7500 wells were extracted from data bases maintained by the ND State Water Commission. More than 80% of the compiled wells were less than 300 ft deep, so these analyses are from ultra-shallow aquifers. A wide variety of wells make up the data set including domestic, stock, municipal, industrial, irrigation, and observation wells. This is in contrast with the wells involved in the FID field screening for methane (Plate 10); the FID measurements were made almost exclusively in observations wells.

The statewide compilation of favorable water chemistry is shown with the lineament zone grid superimposed in Plate 11. Although originally published at a scale of 1:500,000 (1 in = 8 mi), the map is displayed in Plate 11 at a scale of 1:1,000,000 (1 in = 16 mi) to facilitate the transfer of the lineament zones. Locations of wells with bicarbonate greater than 400 mg/L and sulfate less than 500 mg/L are posted. The fact that only about 900 wells had positive FID responses, but more than 7500 wells had optimal water chemistry suggests that the bicarbonate and sulfate concentrations may be necessary, but not sufficient conditions for methanogenesis. For example, even if the aqueous environment is favorable the aquifer may not contain methanogenic microbes.

Two distinct patterns are obvious in an even cursory examination of Plate 11. The wells are distributed in a fairly uniform way throughout the western part of the state. However, in the central and eastern areas, the wells are concentrated in the same linear buried aquifers that are obvious on the statewide compilation of methane field screening (Plate 10). It also appears that there are many more wells in these linear concentrations than in the area of widely dispersed wells in western North Dakota.

In the study area east of longitude 100° W, the general geologic differences from south to north and the specific influences of the lineament zone grid have expression in the distribution of wells with favorable water (Plate 11). In the northern one-third of the study area, the pattern is similar to the western part of the state. Wells are not clustered in the linear patterns that characterize the southern two-thirds of the study area. In the south, linear concentrations of favorable wells follow the same buried outwash channels that had positive FID responses (Plate 10). And, those buried aquifers conform with the grid of Landsat lineament zones. This is particularly striking in the area of the sweetspot county cluster in southeastern North Dakota.

In eastern Dickey County and northward into LaMoure County, the Lower Spiritwood Aquifer trends along LZ-4 (Plate 11). Continuing north along LZ-4, favorable water is found in the same areas as higher methane concentrations along the Stutsman-Barnes County line and into Griggs County. Wells with favorable water appear to be more numerous in the four zones of the Lower Spiritwood Aquifer that have high methane concentration (see Figure 23). In contrast, there are many wells with favorable water in Ransom, Sargent, and Richland Counties southeast of the sweetspot and in Logan and McIntosh Counties to the southwest, but not many wells with a positive FID response (Plate 10).

Patterns are similar on the statewide compilations of FID field screening (Plate 10) and of favorable water wells (Plate 11). However, the specific association of high methane in individual wells with favorable water has not yet been documented in eastern North Dakota. That is an obvious next step in the investigation of ultra-shallow late generation biogenic gas systems in the study area. Ground water chemistry can be used to "high grade" locations within the cluster of sweetspot counties for more detailed sampling or even test drilling. This exploration approach has been employed in eastern South Dakota (Shurr, Haggar, &

Chadima, 2006).

Total Organic Carbon

A critical component of late generation biogenic gas systems is a host rock with organic matter that can sustain the modern methanogenic microbial communities. There is only very limited information available on the total organic carbon (TOC) in Cretaceous rocks in eastern North Dakota. Although the current investigation does not directly address this issue, there are relatively close specific data in eastern South Dakota (Shurr, 2008) that can provide a useful perspective on TOC in Cretaceous rocks in the sweetspot cluster of counties in southeastern North Dakota.

TOC measurements have been published for nine individual samples from outcrops of the Pierre Shale and Niobrara Formation (see Figure 10) along the Missouri River in southeastern South Dakota. Values range from 3.1% to 10.3%. Core from Cretaceous rocks in Beadle County, South Dakota has a larger data set. The average of 37 samples from the Niobrara is 3.1% with a range of 1.3% - 6.0%. A total of 14 samples from the Pierre, Carlile, and Greenhorn showed a range of .2% to 1.1%. This well is approximately 100 mi south of Dickey County, but there are closer data farther north.

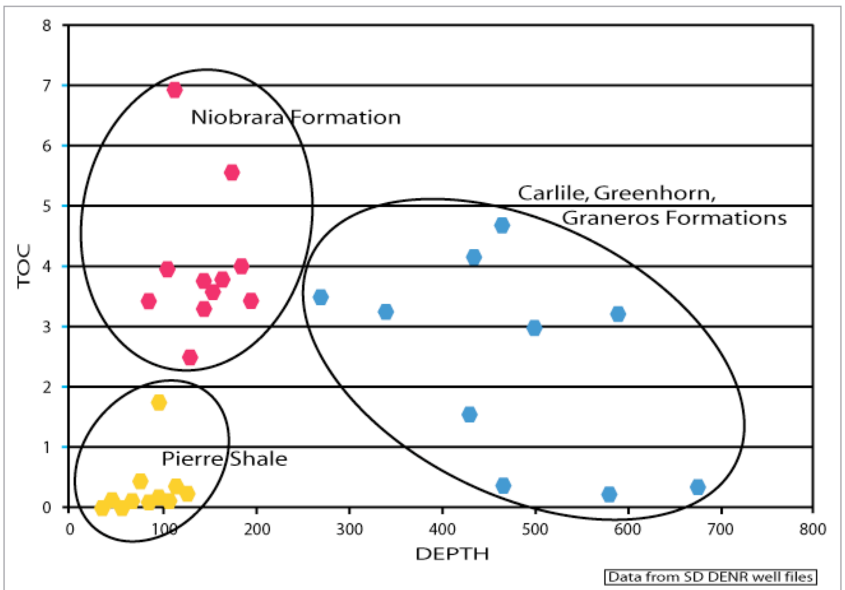

Figure 26. Measurements of total organic carbon (TOC) plotted against depth for cuttings from test wells in Spink County, South Dakota, 60 mi south of the sweetspot in southeastern North Dakota. Taken from Shurr et al., 2009.

Core from a well in Roberts County, South Dakota has 5 samples from the Niobrara that averaged 2.1% and a total of 11 samples from the Pierre, Carlile, and Greenhorn that ranged from 3.0% to 8.0%. This well is about 20 mi from Richland County, North Dakota.

Another important data set is available from a group of six test wells in Spink County, South Dakota, which is located 60 miles south of the state line. Measurements from cuttings show that the Niobrara Formation has the highest TOC values (Figure 26). The majority of the values are above 1%; smaller values are found in the upper and lower parts of the sampled interval. Essentially all of the South Dakota TOC measurements in Cretaceous rocks are well above the 0.5% commonly accepted as the minimum needed for methanogenesis in modern sediments (Claypool & Kaplan, 1974).

EASTERN SOUTH DAKOTA ANALOGS

The geology of eastern North Dakota and South Dakota is very similar. As a result, areas of detailed data collection in South Dakota provide important perspectives on the cluster of sweetspot counties in southeastern North Dakota. Projects in McCook and Spink Counties of South Dakota are particularly useful analogs.

In McCook County, the Dolton Aquifer is a glacial outwash channel cut into bedrock that includes Cretaceous source rocks (Shurr & Scheier, 2007; Shurr, 2008). The bedrock has relatively high TOC values and is fractured at the regional scale of Landsat linear features down to the size of individual fractures in cores. The water in the aquifer has the optimal composition and methane concentrations are high in observation wells above the water level. Thus, all of the fundamental aspects of a late generation biogenic gas system are in place, just as they are in southeastern North Dakota. There is, however, one important difference: viable methanogenic consortia are documented in water samples from the Dolton Aquifer. Microcosm experiments carried out in a laboratory setting show that the "bugs" are present in the aquifer. In effect, these experiments monitor methane production as the microbes grow in a controlled lab environment. McCook County is about 150 mi from the border between North and South Dakota. Microbes that make methane are also demonstrated to be present in the Niobrara Formation in Spink County which is only 60 mi from the border.

The six well testing program in Spink County has verified not only adequate TOC (see Figure 26), but has also demonstrated that there is a late generation biogenic gas system currently at work in the Niobrara. All of the main elements of the system are present:

regional Landsat linear features, optimal water composition, and elevated methane concentrations in observation wells. In addition to the TOC data set, total hydrocarbon concentrations were measured in the headspace gas above cuttings in sealed containers (Figure 27). The results are essentially the same as the pattern in TOC values. The highest hydrocarbon gases are in the Niobrara while the Pierre, Carlile, Greenhorn, and Graneros all have lower concentrations. Eight of the gas samples were large enough to provide isotopic analyses. These samples plot in a stability field that suggests that microbial methane is present (Figure 28). In addition, there is more direct evidence for a contemporary methanogenic microbial community living in the fractured Niobrara Formation. Microcosm experiments on water samples from two observation wells completed in the Niobrara, both showed that methanogens are present (Figure 29). However, methane production was much higher in water from Well A which also had higher methane concentrations in the well bore; note that the scale is much smaller on the axis showing methane production in water from Well B. The "bugs"

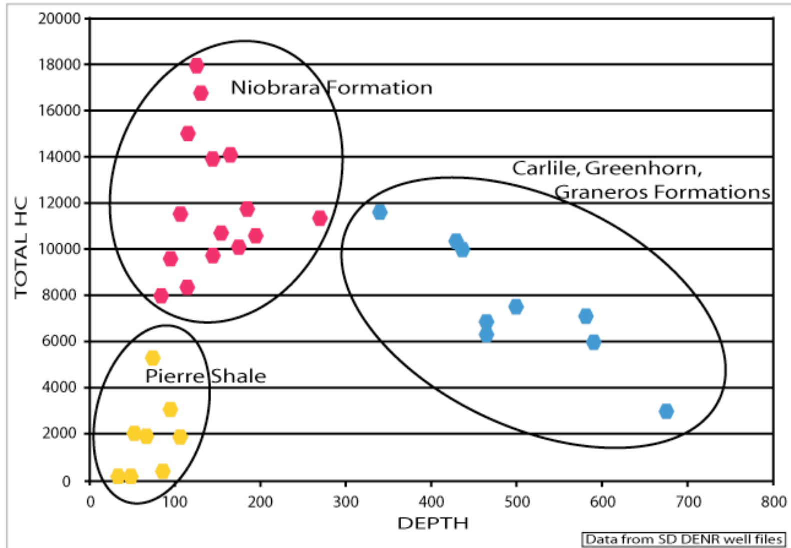

Figure 27. Measurements of total hydrocarbon headspace gas over cuttings from test wells in Spink County, South Dakota. Measurements are plotted against depth. Taken from Shurr et al., 2009.

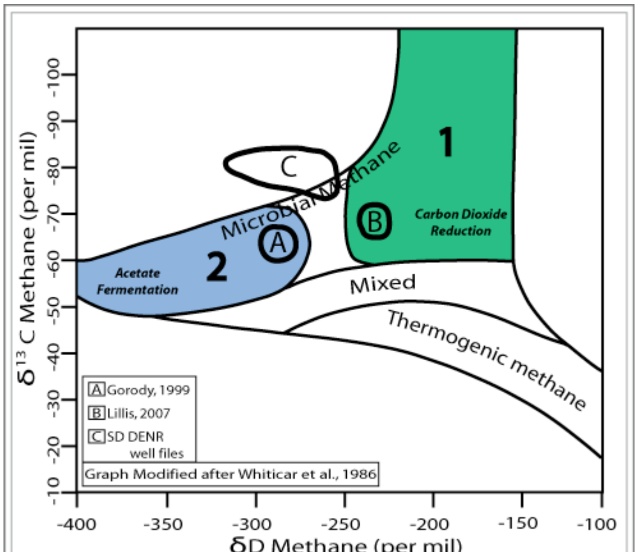

Figure 28. Cross plot of carbon-isotope ratio (δ13C) and deuterium-isotope ratio (δD) for methane from the three main natural gas systems. Early generation biogenic gas is usually based on carbon dioxide reduction (green) and late generation gas is based on acetate fermentation (blue). Ranges of measurements are shown from gas samples in the Powder River Basin (A), Northern Great Plains (B), and test wells in Spink County, South Dakota (C). Taken from Shurr et al., 2009.

are present in both wells, but are more robust in Well A.

A cartoon (Figure 30) summarizing conditions in Spink County, South Dakota, can also be applied to the area of sweetspot counties in southeastern North Dakota. Fractured, organic-rich Niobrara Formation (located at the top of the Colorado Group) has methane and microbes in a favorable aqueous environment. Linear meltwater channels cut into bedrock and filled with outwash provide easy access for the water to get into the fracture plumbing as shown by the blue arrows in Figure 30. The reconstructed glacier is included because initial inoculation of microbes into the fractured bedrock was probably carried out by meltwater. That speculation is borrowed from interpretations of the late generation biogenic gas systems currently identified in the Antrim Shale of the northern Michigan Basin. Possible thermogenic gas (red arrows) could migrate laterally and upward into the Dakota Sandstone. This would be analogous to the shallow gas produced from Lower Cretaceous sands in LaMoure County, North Dakota (Anderson & Eastwood, 1968). The similarities between southeastern North Dakota and eastern South Dakota point the direction that future investigations might progress in the study area east of longitude 100° W.

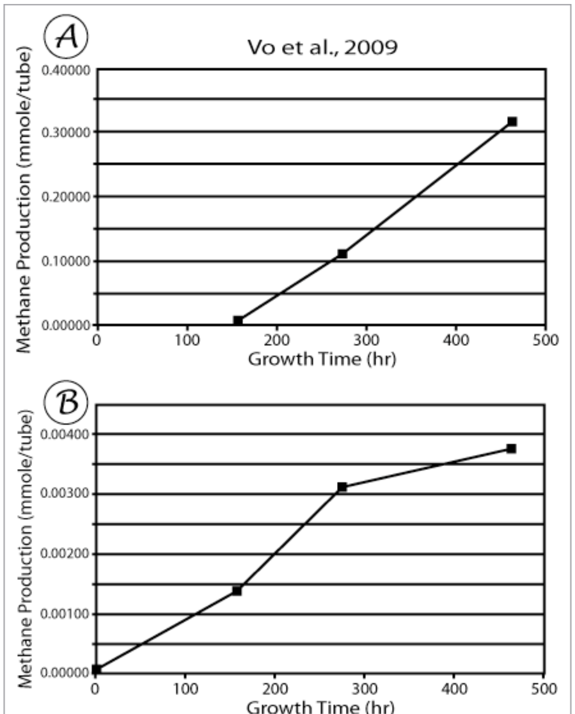

Figure 29. Graphs describing microcosm experiments on water samples taken from Niobrara observation wells in Spink County, South Dakota. Taken from Shurr et al, 2009.

NEXT STEPS

There are some fairly obvious next steps to establish that a late generation biogenic gas system is present in eastern North Dakota. The easiest first step would be to sample water from observation wells in the sweetspot cluster that have elevated FID methane measurements and favorable water chemistry. That is essentially the thrust of Phase II of the current investigation as it was originally proposed. However, rather than collecting detailed geochemical data from the water samples, it is recommended that microcosm experiments be performed. The initial objective would be to see if the methanogens are present in the ground water, but subsequent experiments could be designed to test which sources of organic carbon are preferred by the methanogens. Are they using fractured bedrock, especially the Niobrara Formation, or are they using organic fragments included in the outwash aquifers?

A very important second step is to focus on the geology of the cluster of sweetspot counties. More detailed fracture mapping could be done using high altitude aerial photos, but a basic understanding of the geologic relationships is even more critical. This work should include the stratigraphy and structure of the shallow Cretaceous bedrock and also the fundamental aspects of the glacial and surficial geology. Hydrologic investigations would ultimately be helpful because the microbes of a late generation biogenic gas system are hosted in an aquifer. But, the basic geologic framework of the sweetspot counties needs to be established.

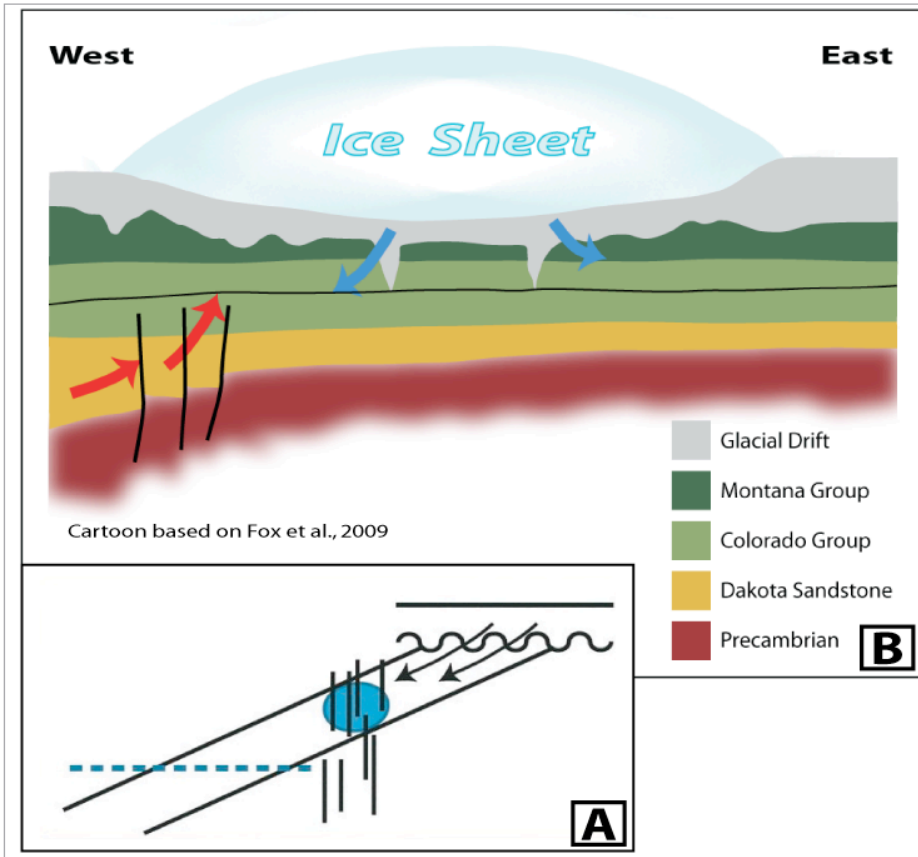

Figure 30. Interpretative summary of geologic conditions leading to creation and maintenance of a late generation biogenic gas system in the eastern Dakotas. Although it is based largely on data in Spink County, South Dakota, it also has application within the cluster of sweetspot counties in southeastern North Dakota. Taken from Shurr et al., 2009.

A third step would be to pick locations and drill test wells aimed at providing specific hard data. This drilling and sampling program would provide the same basic information that was collected in Spink County, South Dakota: total organic carbon, headspace gas for bulk composition and isotopic analyses, and site-specific geology and hydrology. Ultimately, the results of this initial test drilling could guide the location of preliminary production wells needed to research completion procedures.

It is clear that a lot of work remains to be done before late generation biogenic gas can be produced in eastern North Dakota. It is also true that abundant natural gas is currently being produced in the western part of the state. However, the long learning curve provides time to redirect resources and modify attitudes about gas production in southeastern North Dakota. There is good resource potential in this corner of the state. Sometime in the future, local production and consumption of shallow gas could be as significant as it once was one hundred years ago.

CHAPTER 7

CONCLUSION

This investigation of shallow late generation biogenic gas systems in North Dakota east of longitude 100° W has resulted in three main conclusions. Starting with the total study area, each conclusion focuses attention on progressively smaller areas ending with identification of a multi-county sweetspot in southeastern North Dakota.

The first main conclusion is that there are fundamental geologic differences between the areas south and north of latitude 48° N. The southern two-thirds of the study area has more distinctive and better defined Landsat lineament zones. In addition, there are contrasting geophysical signatures and different stratigraphic patterns when compared with the northern one-third of the study area. These differences in geologic framework are accompanied by differences in the distribution of observation wells monitored for methane: wells with a positive FID response are more numerous and are organized in distinctively linear outwash bodies in the south. Contrasts between the southern and northern parts of eastern North Dakota were not a primary investigative target, but instead emerged during the mapping and ranking of lineament zones and the integration with the ND Geological Survey's field screening program.

The second main conclusion of this study relates to the Landsat lineament zones. Eastern North Dakota has a distinctive grid of lineament zones interpreted from observations of linear features on satellite images. These lineament zones are believed to be corridors of increased fracturing associated with the boundaries of discrete tectonic blocks rooted in the Precambrian basement. The geometry of eight lineament zones and the intervening crustal blocks has a clear relationship to patterns on geophysical, stratigraphic, geologic, and structural maps. It is apparent that successive reactivation of the lineament-bound blocks has influenced erosion, deposition, deformation, and fluid movement throughout geologic history. Zones of structural weakness that resulted from Precambrian plate tectonics have ultimately had expression in linear features on the present-day earth's surface. The linear features may not all be faults, but the populations of length measurements have attributes similar to faults. Whatever structural nuances may exist, the conclusion that is ultimately important is that the lineament zones provide insights on a regional fracture system.

The third main conclusion of this Phase I investigation is that there is a sweetspot cluster of five counties in southeastern North Dakota. Published data sets played a significant role in this study, but by far the most critical information came from the FID measurements of methane that were assembled during the field screening program conducted by the ND Geological Survey. Using information extracted from this data set, three clusters of counties with similar FID attributes are identified. The five-county cluster in southeastern North Dakota has a clear relationship to the grid of Landsat lineament zones. Local "hot spots" with high methane values are concentrated along the sides and intersections of the lineament zones. Thus, two of the fundamental components of late generation biogenic gas systems are documented in southeastern North Dakota: fractures and methane produced by microbes. Two additional components, specifically optimal water chemistry and high organic carbon, are indicated to be present on the basis of less direct evidence.

A possible fourth conclusion might be that further studies are clearly warranted. In particular, the geologic framework of the five-county sweetspot needs to be characterized in some detail. Beyond that basic work, water samples should be collected and microcosm laboratory experiments carried out. This is a critical next step because it would demonstrate that methanogenic microbes are in fact currently present in the sweetspot. The existence of the methanogens and their supporting microbial consortia is essential for a viable late generation biogenic gas system to eventually become commercial.

It may seem that deep thermogenic gas produced from shale reservoirs will meet all of the US energy needs in the near future. However, that scenario depends upon sustained production levels and continuing favorable economics for horizontal drilling. Changing conditions may well revive interest in shallow biogenic gas. Research recently reported from the US Midwest (Strapoc et al., 1010) and from China (Li & Lin, 2010) indicates that work on understanding shallow biogenic gas systems continues. On a more practical level, a description of commercial accumulations in the US Gulf Coast has recently been published (Clifford & Goodman, 2010). Pools in relatively unconsolidated Plio-Pleistocene sands less than 4000 ft deep average more than 500 MMcf and are as large as 3 Bcf.

Ultimately, shallow late generation biogenic gas will become an important economic asset for southeastern North Dakota. There may currently be a glut of deep thermogenic gas resulting in depressed prices. But, market conditions will change as natural gas is used more extensively for low-polluting electrical generation. When prices do recover, shallow gas exploration in southeastern North Dakota is clearly warranted. Even if accumulations are too small to support pipeline exportation, local consumption of the local shallow gas resource might be a significant alternative.

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APPENDIX

TABLE A.1. IMAGE INVENTORY			
North – South Path	**East – West Row**	**EROS Entity ID**	**Date Remote Sensing Accomplished**
030	026	P030R026_7X20010928	2001/09/28
030	027	P030R027_7X20010827	2001/08/27
030	028	P030R028_7X20010827	2001/08/27
031	026	P031R026_7X20000815	2000/08/15
031	027	P031R027_7X20000730	2000/07/30
031	028	P031R028_7X20000714	2000/07/14
032	026	P032R026_7X20010825	2001/08/25
032	027	P032R027_7X20000518	2000/05/18
032	028	P032R028_7X20000518	2000/05/18

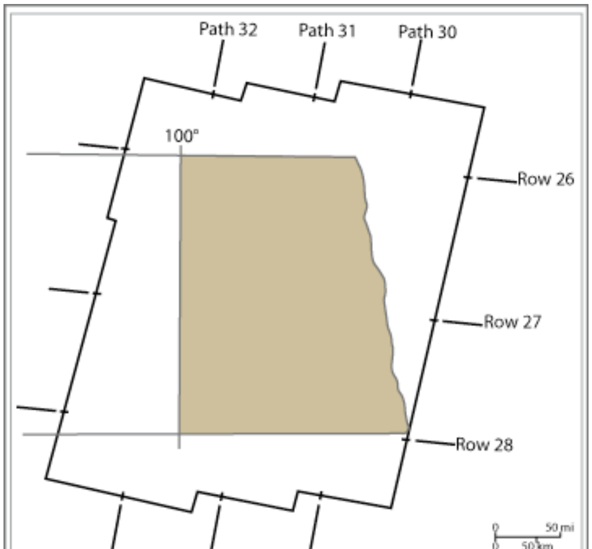


Figure A.1. Location of the study area east of longitude 100° W relative to the footprint of nine Landsat scenes employed in the investigation.

PLATE 1

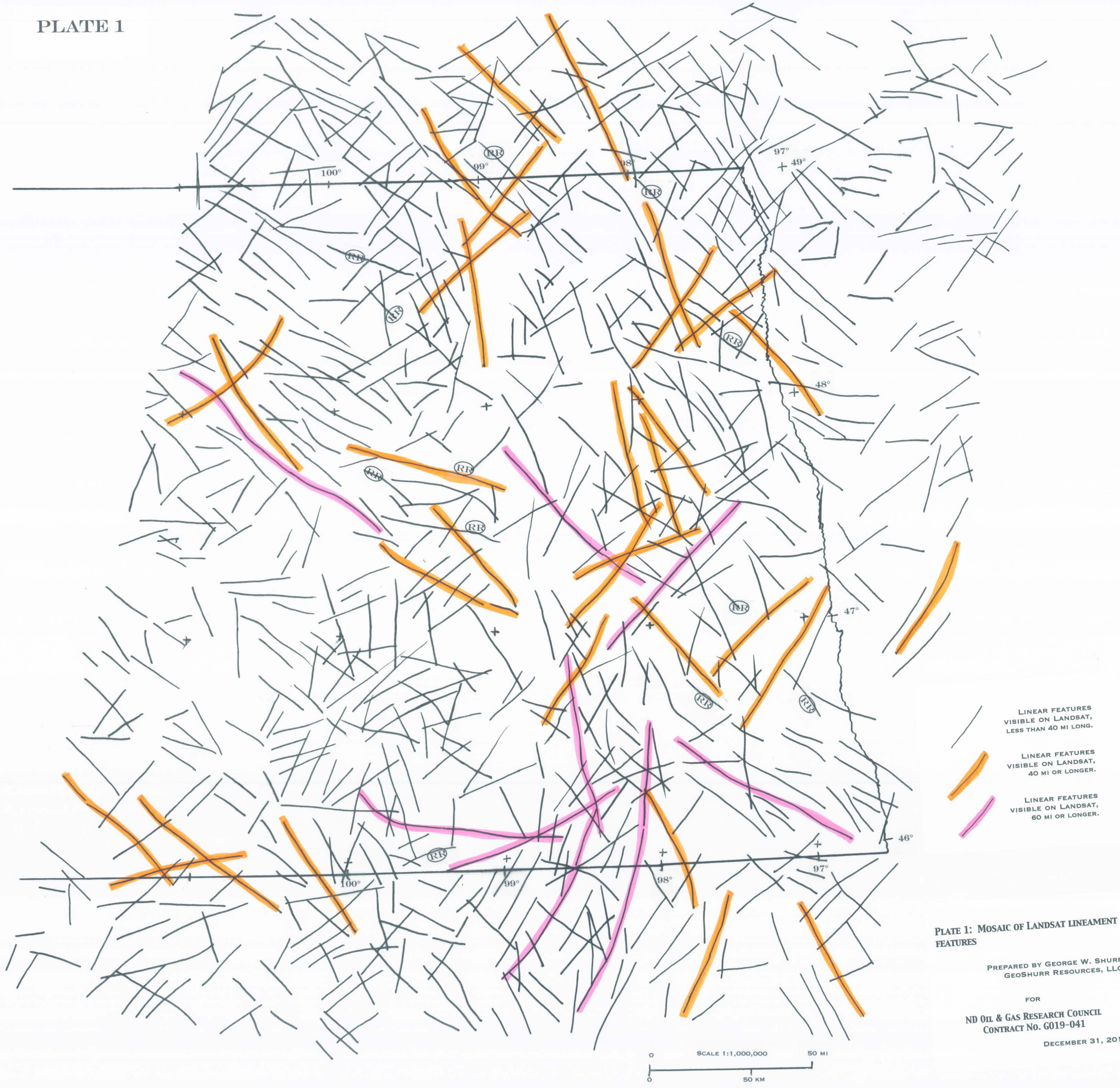


Plate 1: Mosaic of Landsat lineament features

Prepared by George W. Shurr
GeoShurr Resources, LLC

for

ND Oil & Gas Research Council
Contract No. G019-041

December 31, 2010

PLATE 2

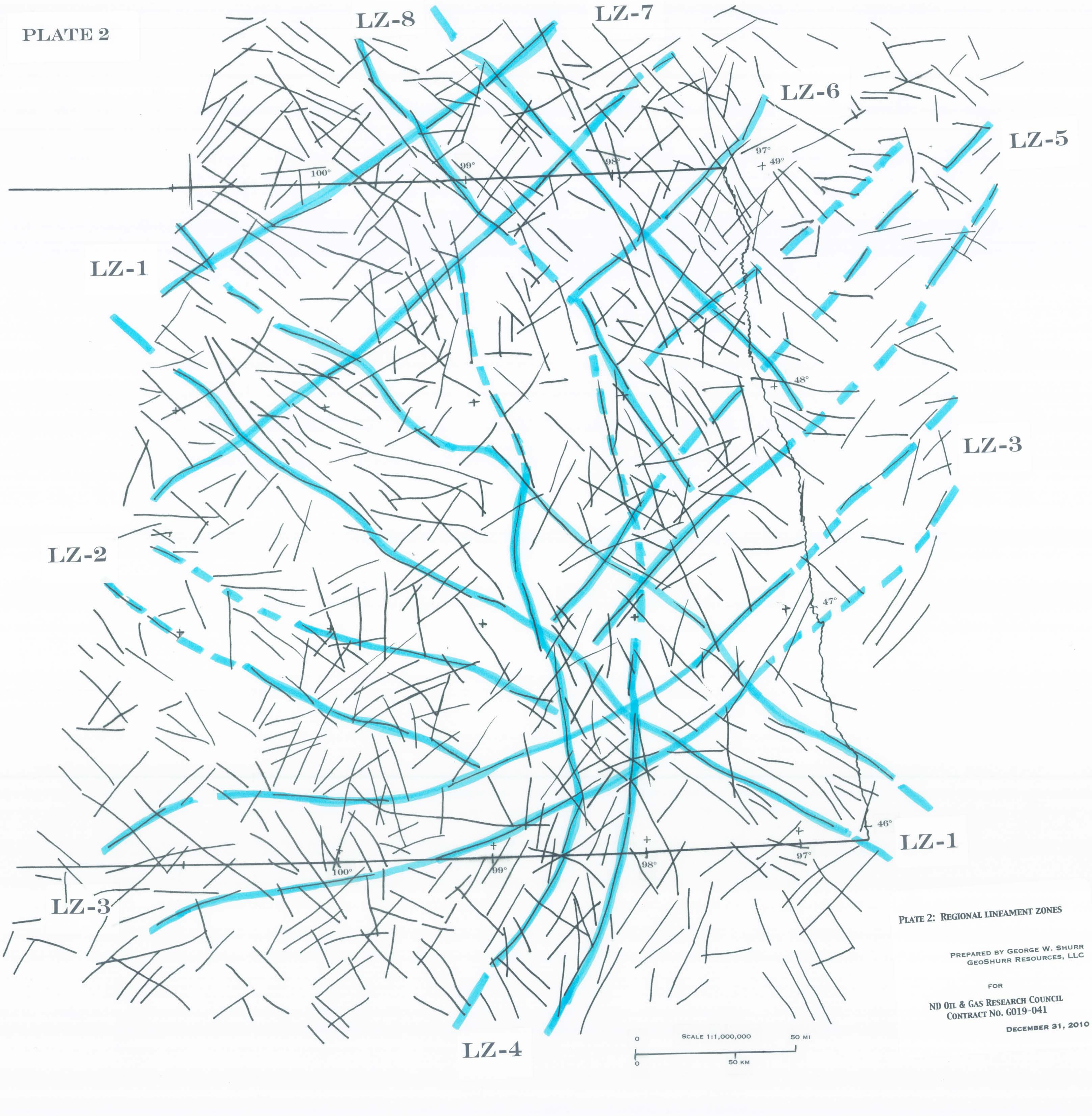


PLATE 2: REGIONAL LINEAMENT ZONES

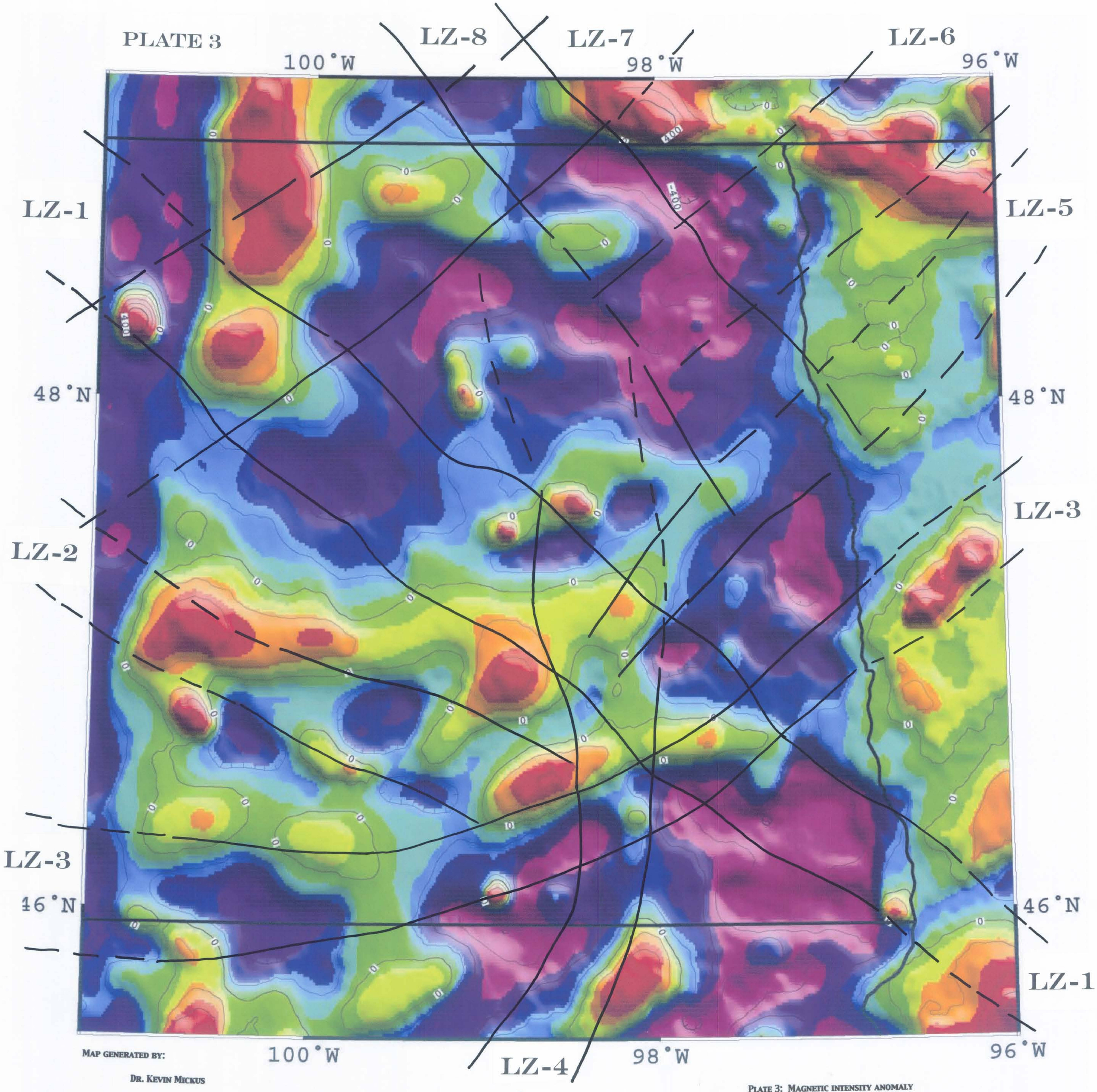
PREPARED BY GEORGE W. SHURR
GEOSHURR RESOURCES, LLC

FOR

ND OIL & GAS RESEARCH COUNCIL
CONTRACT NO. G019-041

DECEMBER 31, 2010

PLATE 3



MAP GENERATED BY:

DR. KEVIN MICKUS

MISSOURI STATE UNIVERSITY

SCALE 1:1,000,000

PLATE 3: MAGNETIC INTENSITY ANOMALY MAP WITH LINEAMENT ZONES

PREPARED BY GEORGE W. SHURR

GEOSHURR RESOURCES, LLC

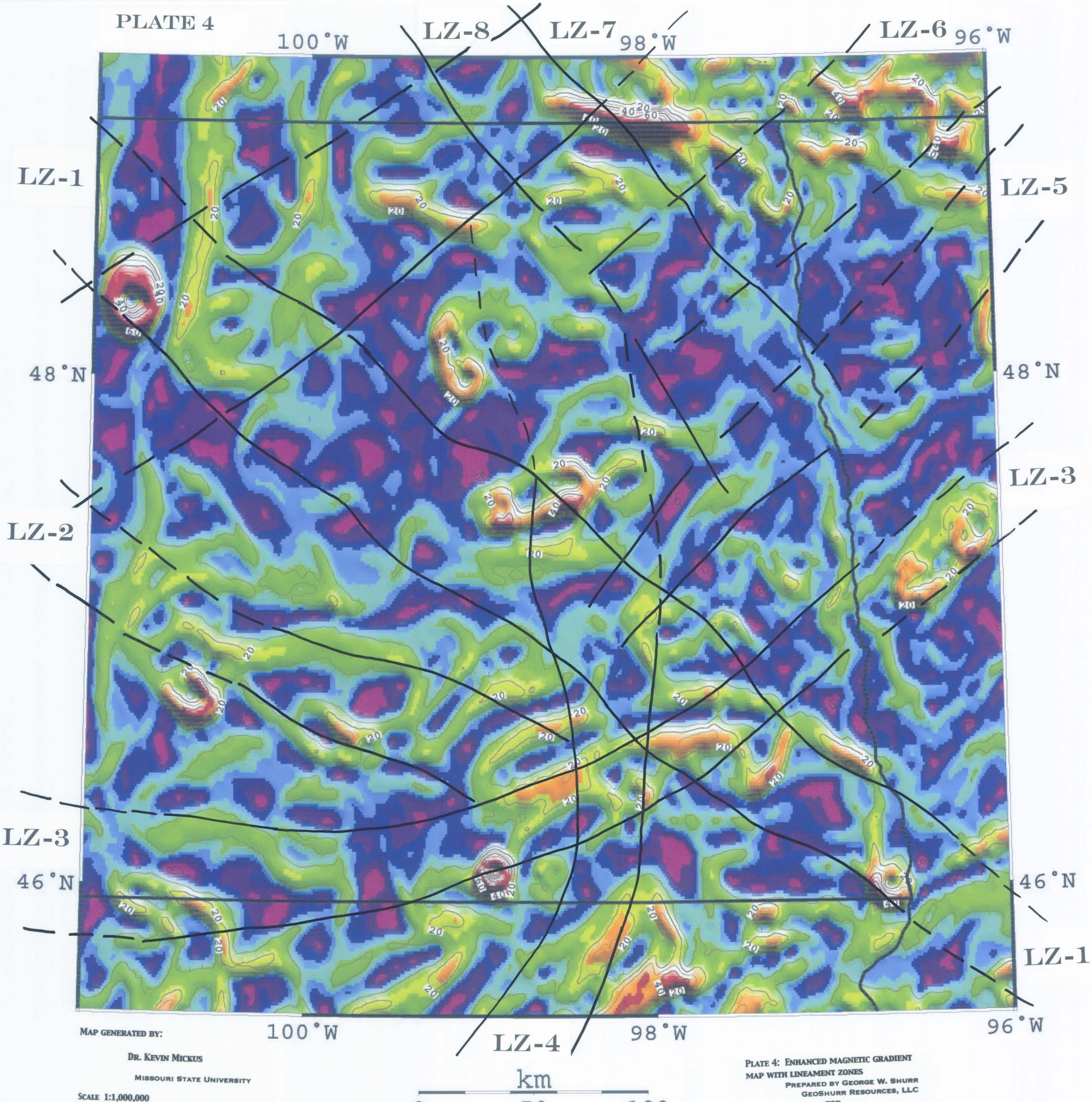
FOR

ND OIL & GAS RESEARCH COUNCIL

CONTRACT NO. G019-041

DECEMBER 31, 2010

PLATE 4



MAP GENERATED BY:

DR. KEVIN MICKUS

MISSOURI STATE UNIVERSITY

SCALE 1:1,000,000

PLATE 4: ENHANCED MAGNETIC GRADIENT MAP WITH LINEAMENT ZONES

PREPARED BY GEORGE W. SHURR

GEOSHURR RESOURCES, LLC

FOR

ND OIL & GAS RESEARCH COUNCIL

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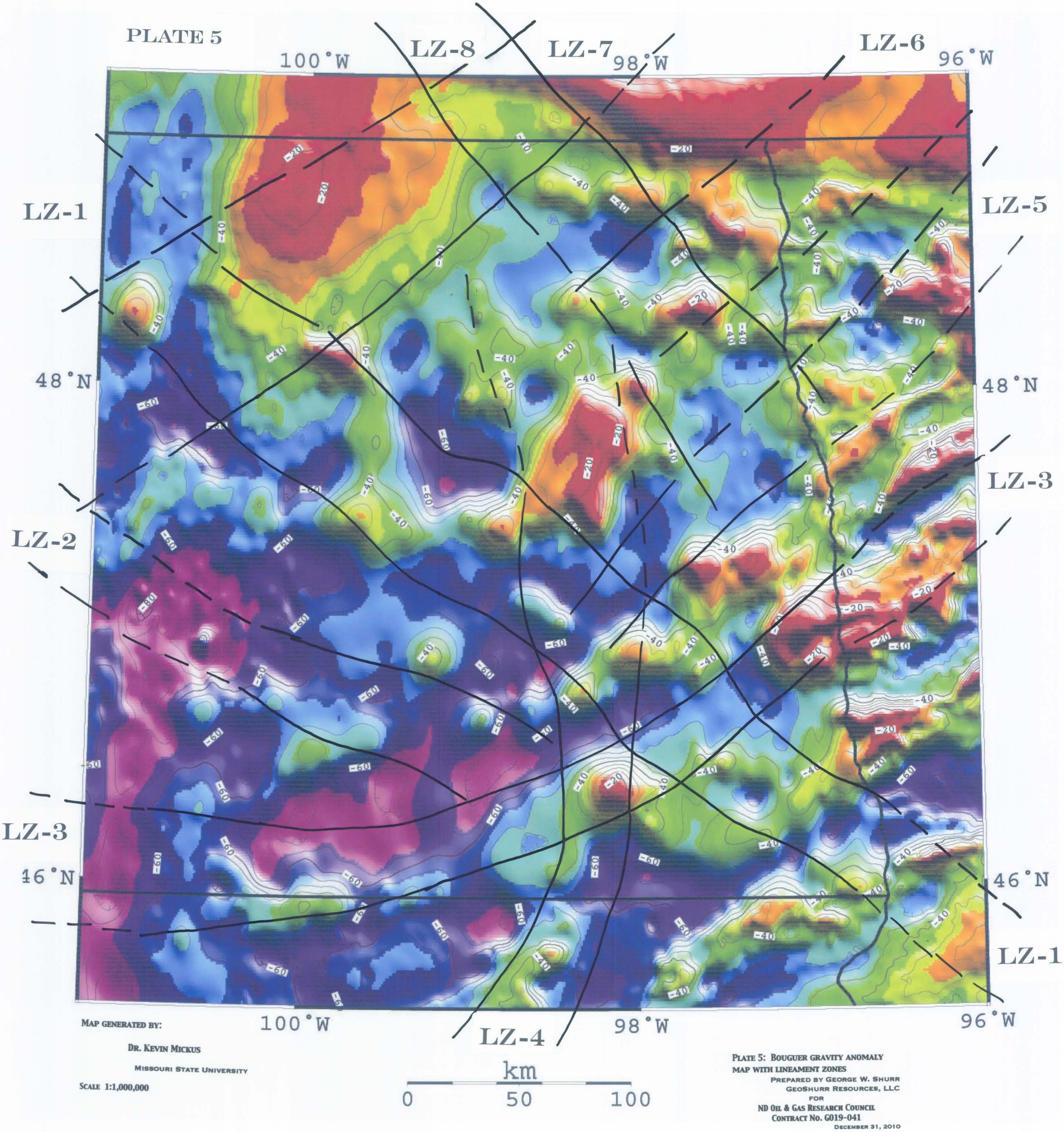
DECEMBER 31, 2010

PLATE 5



MAP GENERATED BY:

DR. KEVIN MICKUS

MISSOURI STATE UNIVERSITY

SCALE 1:1,000,000

PLATE 5: BOUGUER GRAVITY ANOMALY MAP WITH LINEAMENT ZONES

PREPARED BY GEORGE W. SHURR

GEOSHURR RESOURCES, LLC

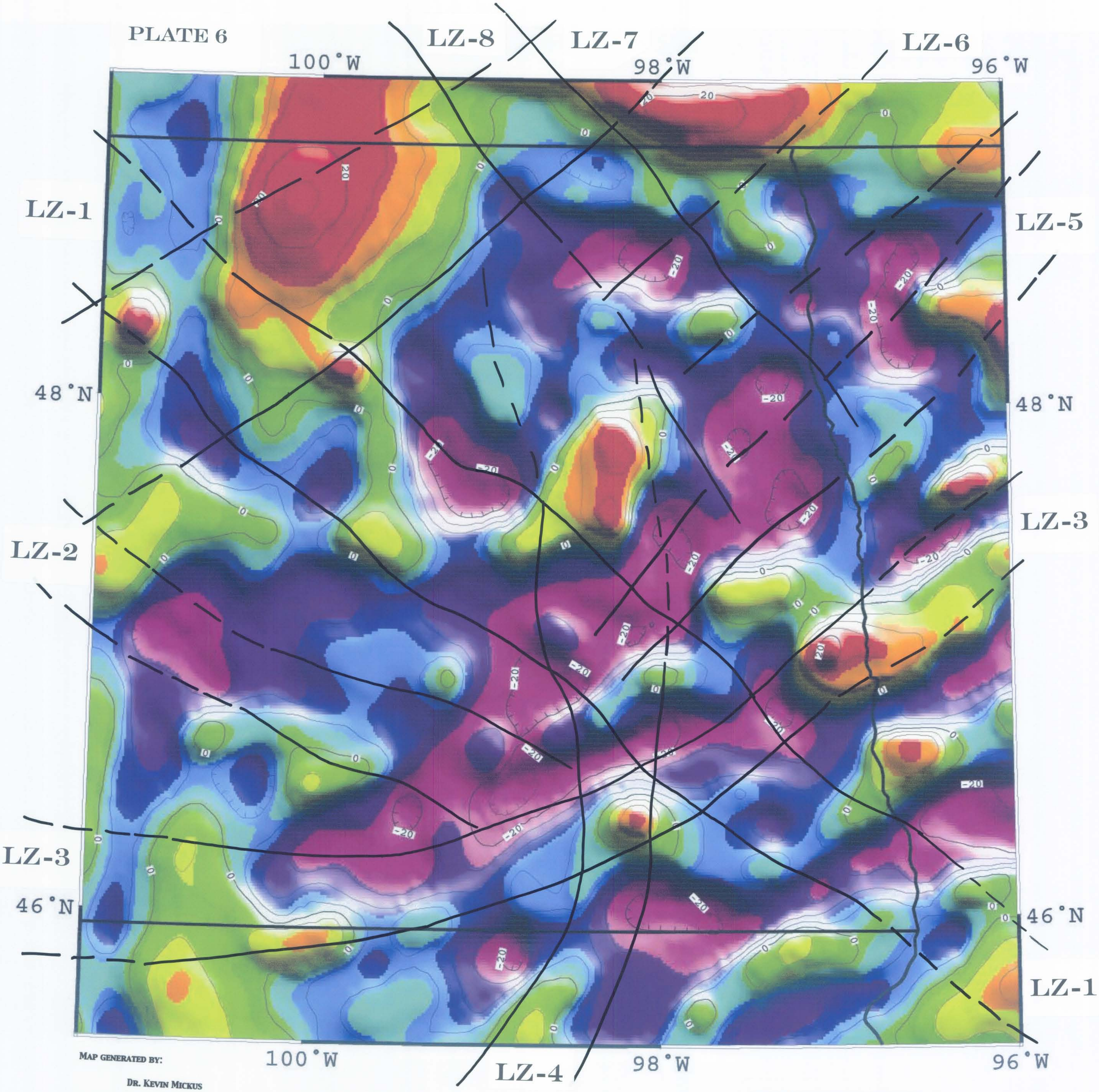
FOR

ND OIL & GAS RESEARCH COUNCIL

CONTRACT NO. G019-041

DECEMBER 31, 2010

PLATE 6



MAP GENERATED BY:

DR. KEVIN MICKUS

MISSOURI STATE UNIVERSITY

SCALE 1:1,000,000

km

0 50 100

PLATE 6: POLYNOMIAL RESIDUAL GRAVITY ANOMALY MAP WITH LINEAMENT ZONES

PREPARED BY GEORGE W. SHURR

GEOSHURR RESOURCES, LLC

FOR

ND OIL & GAS RESEARCH COUNCIL

CONTRACT NO. G019-041

DECEMBER 31, 2010

North Dakota Geological Survey
Geologic Investigations No. 47

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

Preliminary Isopach Map Of The Cretaceous Mowry-Inyan Kara Formation Interval in North Dakota

Fred J. Anderson and Bruce J. Juenker

2007

PLATE 7

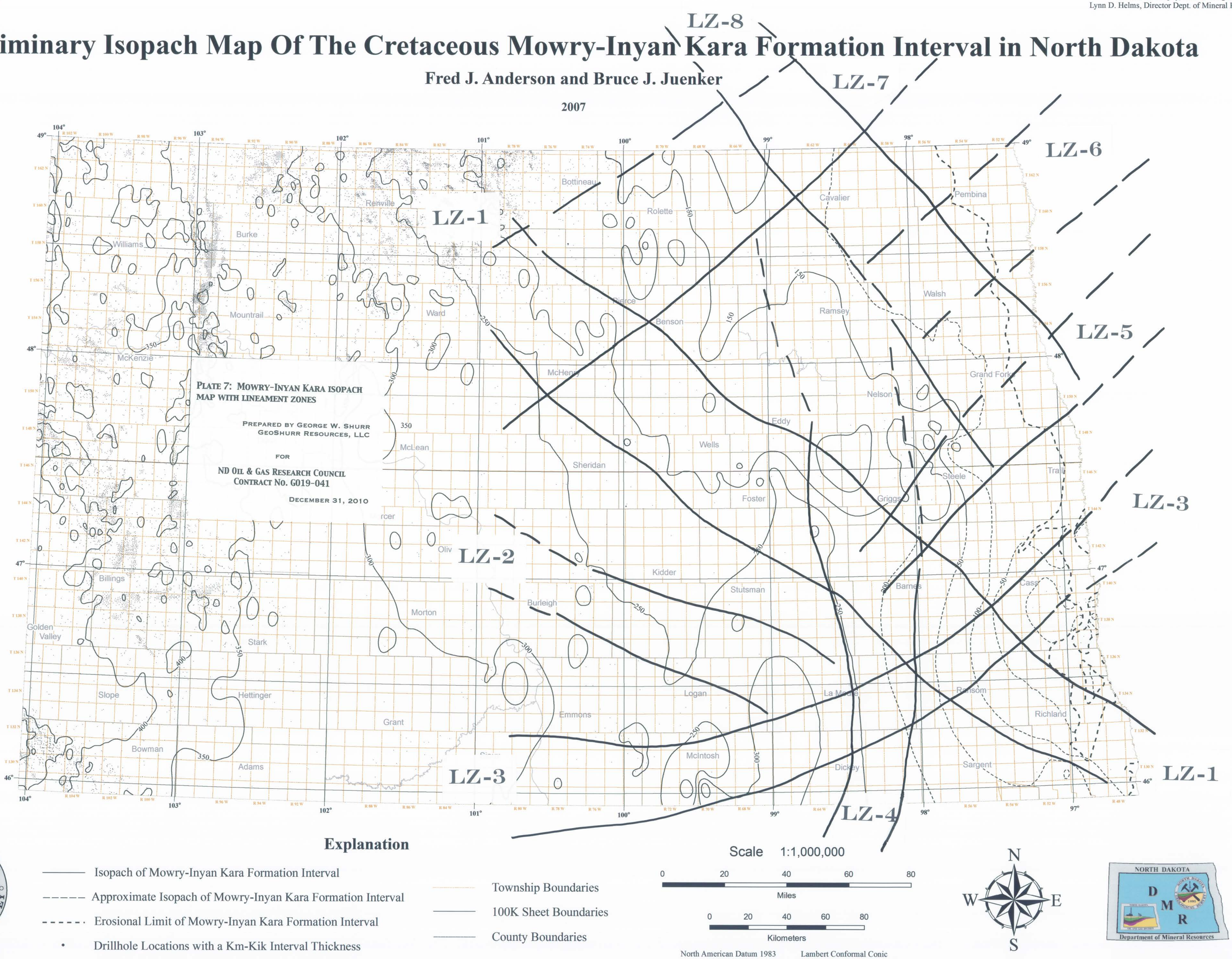
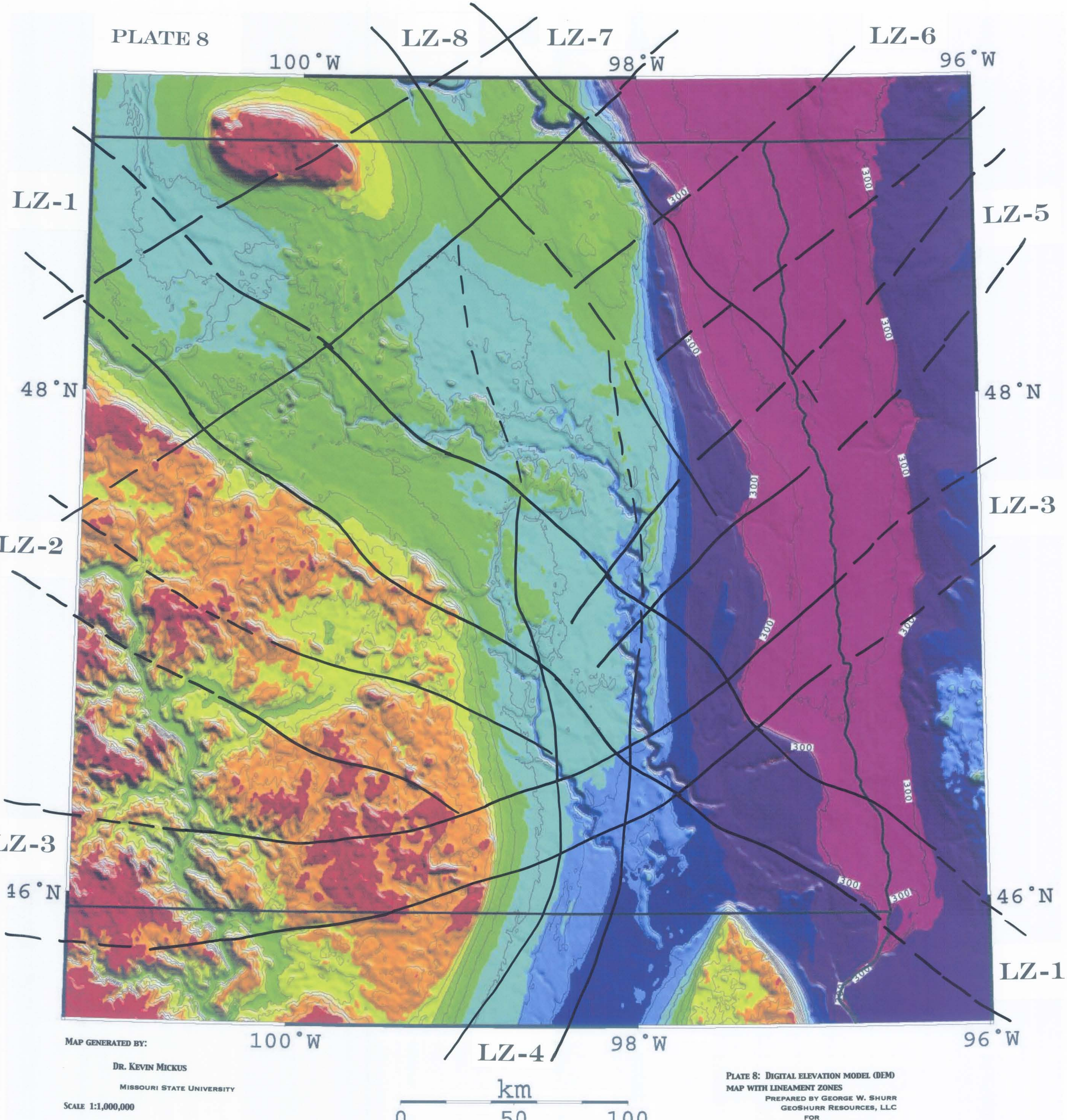


PLATE 8



MAP GENERATED BY:

DR. KEVIN MICKUS

MISSOURI STATE UNIVERSITY

SCALE 1:1,000,000

PLATE 8: DIGITAL ELEVATION MODEL (DEM) MAP WITH LINEAMENT ZONES

PREPARED BY GEORGE W. SHURR

GEOSHURR RESOURCES, LLC

FOR

ND OIL & GAS RESEARCH COUNCIL

CONTRACT NO. G019-041

DECEMBER 31, 2010

North Dakota Geological Survey
Geologic Investigations No. 38

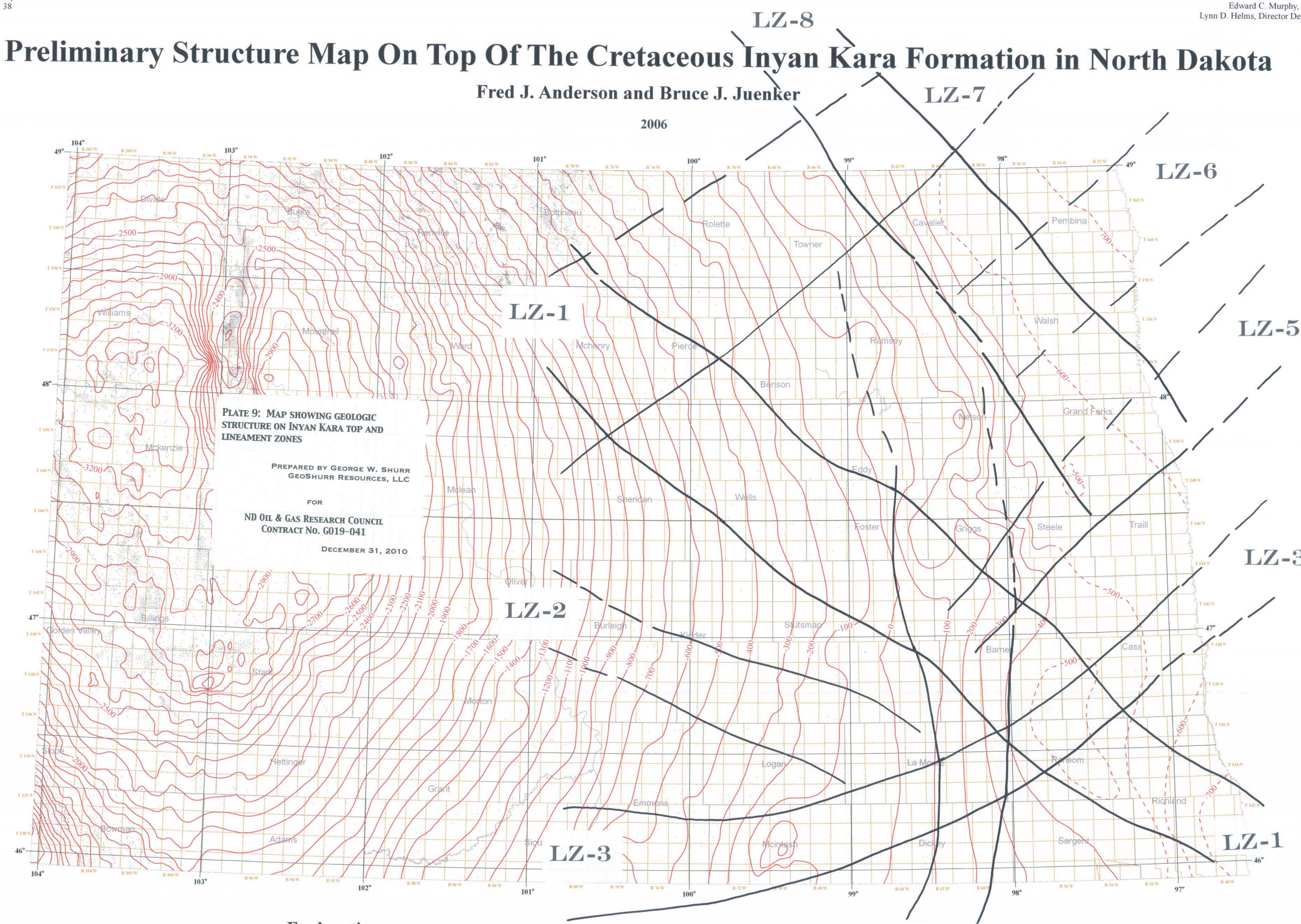
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Reources

Preliminary Structure Map On Top Of The Cretaceous Inyan Kara Formation in North Dakota

Fred J. Anderson and Bruce J. Juenker

2006

PLATE 9



Explanation

Structure Top of Inyan Kara Formation

Control Points for Structure

Township Boundaries

100K Sheet Boundaries

County Boundaries

Scale 1:1,000,000

0 20 40 60 80
Miles

0 20 40 60 80
Kilometers

North American Datum 1983 Lambert Conformal Conic

NORTH DAKOTA
DMR
Department of Mineral Resources

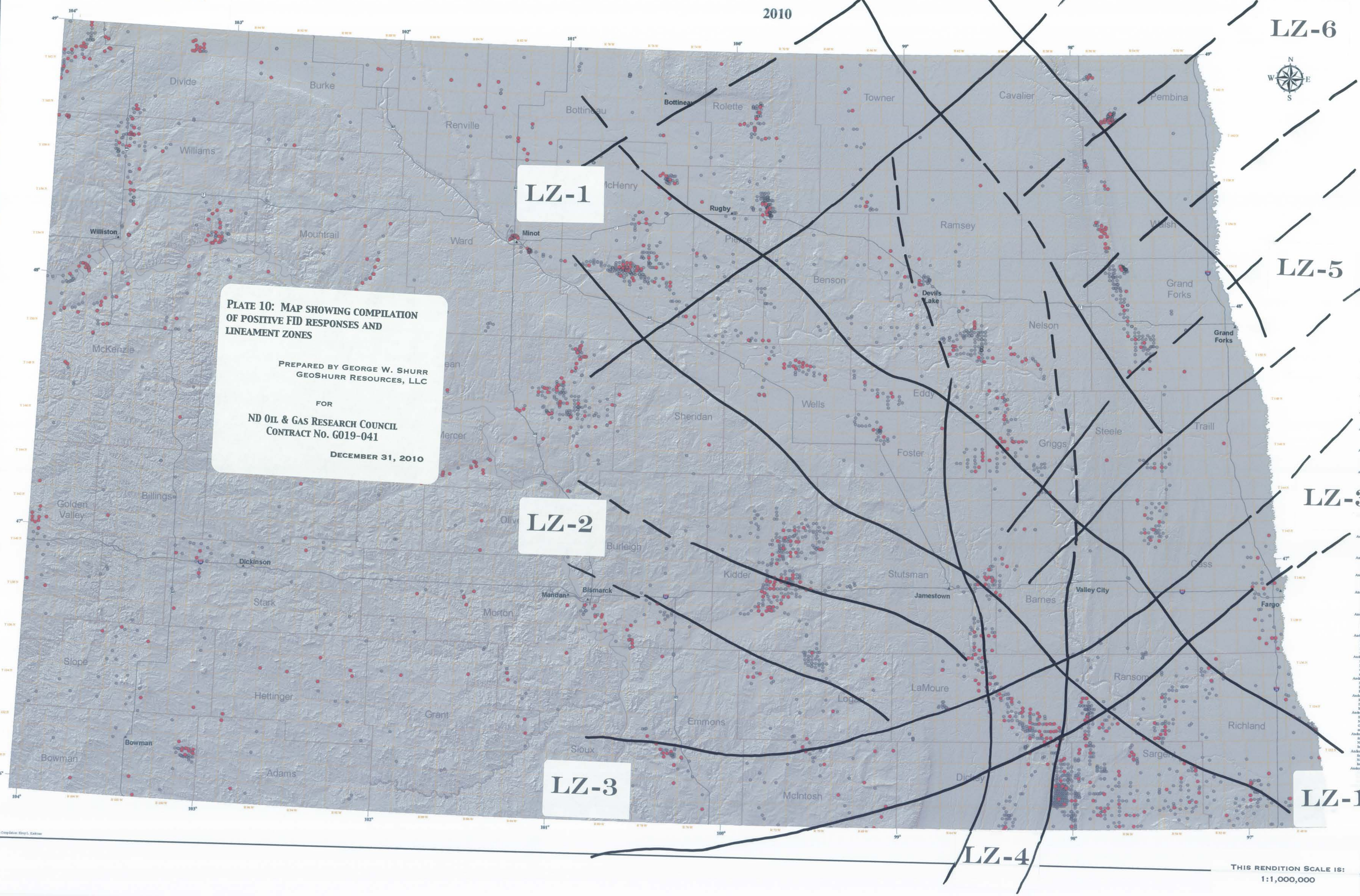
North Dakota Geological Survey
Geologic Investigations No. 128

Locations of FID Shallow Gas Occurrences in North Dakota

Fred J. Anderson, Cassie B. Gudmunsen, Brian H. Hall, Adam J. Ries, Allison R. Christensen, and Bailey J. Bubach

PLATE 10

2010



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

Explanation

The investigation of shallow natural gas occurrences within existing ground-water observation and stock wells was conducted in a reconnaissance fashion during the 2006 - 2010 field seasons in 52 selected counties in North Dakota. A total of 9,390 monitoring well sites were considered for field investigation and testing. Of these, 4,325 were found to exist in the field and were tested for the presence of methane using a portable flame-ionization detector (FID). A total of 905 wells (21%) returned positive FID instrument readings consistent with a methane shallow gas occurrence and are presented on this map at a scale of 1:500,000. 3,420 wells showed no response (0.0 ppm as methane in air). The intent of this map is as an exploration tool, to help identify potential candidate areas for future oil and gas exploration and focused field investigation.

- FID Shallow Gas Occurrence
- Other Wells Tested, No FID Response
- County Boundaries
- Township Boundaries
- Highways
- Cities

References

Scale 1:500,000

THIS RENDITION SCALE IS: 1:1,000,000

Cartographic Compilation: Kimyl L. Ezekiel

North Dakota Geological Survey
Geologic Investigations No. 92

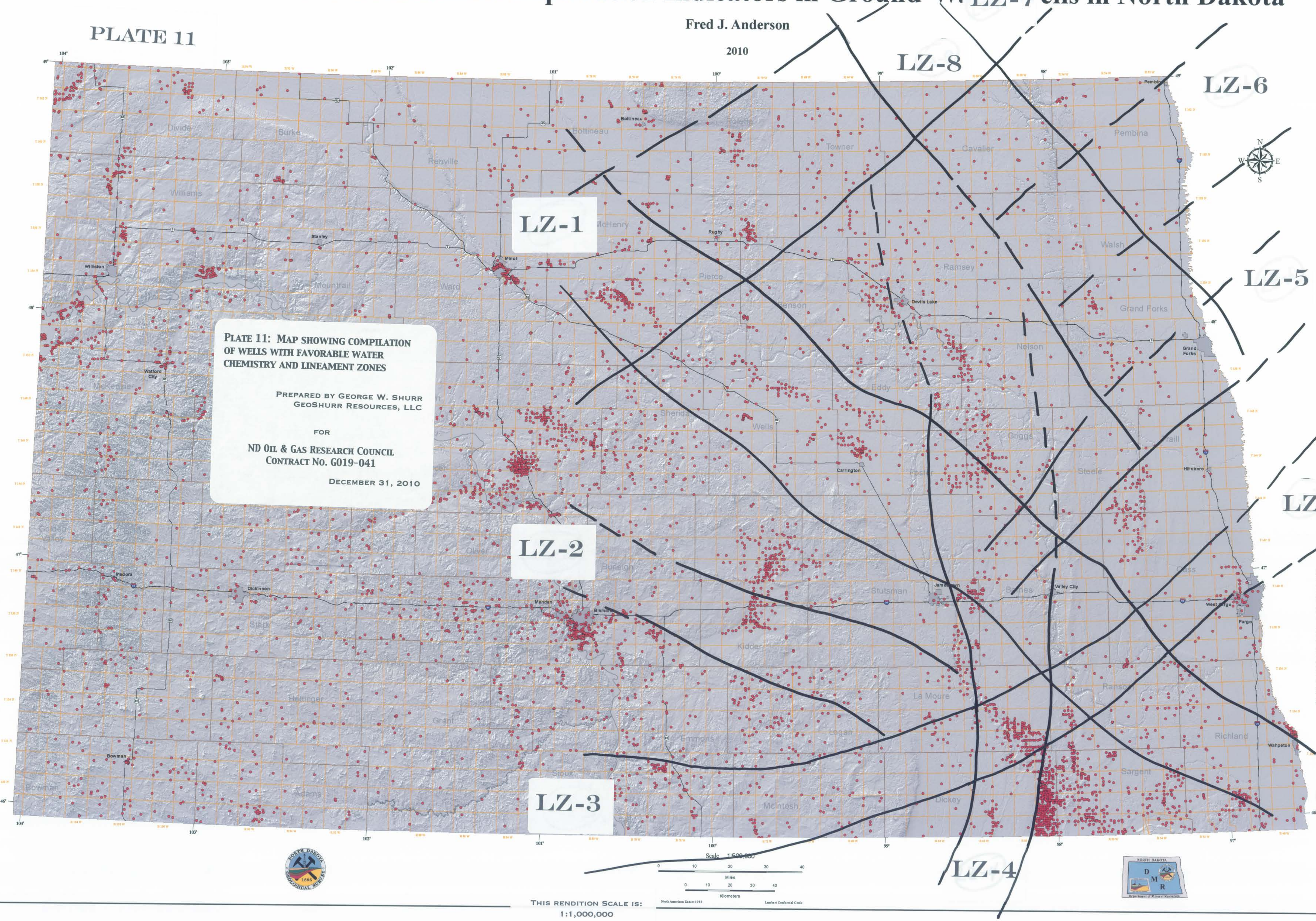
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Reources

Shallow Gas Geochemical Exploration Indicators in Ground-W LZ-7 ells in North Dakota

PLATE 11

Fred J. Anderson

2010



DISCUSSION

Well locations with ground-water constituent chemistries favorable for the occurrence of methane are plotted on this map with a background of surficial topographic shaded relief. The locations of the 7,503 wells shown on this map, date historically over 77 years to 1932, and were extracted and reported here *as is* from the databases of the North Dakota State Water Commission in Bismarck, North Dakota (NDSWC, 2010). Data are reported from all types of wells found across the state and include: domestic, stock, production, municipal, industrial, observation, and irrigation wells. Wells described as "unknowns" were also included here for completeness. Well depths range from as shallow as three feet to as deep as 3,277 feet with the majority of wells (>80%) completed to depths less than 300 feet. Clustering of wells occurs typically where shallow surficial or buried-valley aquifers are known to occur as most of the wells depicted on this map were installed to either monitor or extract shallow ground-water for water supply purposes. In the absence of direct detection of methane (CH_4) through instrumental or analytical means, Sulfate [SO_4^{2-}] and Bicarbonate [HCO_3^-] ion concentrations can be used as proxy indicators for potential occurrences of methane in the shallow subsurface. Previous workers (Anderson, et al., 2006, Martini, et al., 2003, McIntosh and Martini, 2008, Shurr, et al., 2006, Shurr, 2008, VanVoast, 2003) have demonstrated that sulfate ion concentrations less than 500 mg/L coupled with bicarbonate ion concentrations greater than 400 mg/L correlate with groundwater containing detectable concentrations of methane. Well locations are plotted on this map, using this relationship of ground-water constituent geochemistry, for the purpose of shallow gas exploration. The data depicted on this map are from several different individual sampling events and include data from as far back as 1932. Any well sampled with sulfate and bicarbonate ion chemistry meeting the exploration criteria described here is included on this map. Within the selected ion concentration ranges for sulfate of 0 to 500 mg/L and bicarbonate of 400 mg/L to 2800 mg/L, statistical means of 203 mg/L and 639 mg/L were determined, respectively, from a data set of 20,662 values (Table 1). Sample data was included from 1932 to 2009.

Table 1. Descriptive statistical summary of sulfate [SO_4^{2-}] and bicarbonate [HCO_3^-] ion concentrations, from wells shown on this map, within the shallow gas exploration indicator ranges of <400 mg/L sulfate and >500 mg/L bicarbonate.

Constituent	n	Selected Ion Concentration in Groundwater (mg/L)					Sampling Dates
		Range	Minimum	Maximum	Mean	Std. Dev.	
Sulfate [SO_4^{2-}]	20,662	499.9	0.1	500	203	131.8	1932-2009
Bicarbonate [HCO_3^-]		2,400	400	2800	639	265.6	

EXPLANATION

Ground-Water well with CH_4 exploration indicators:

Well location where sulfate ion [SO_4^{2-}] concentration is <500 mg/L coupled with biocarbonate ion [HCO_3^-] concentration >400 mg/L in sampled groundwater.

County Boundaries

ip Boundaries

ys

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Cartographic Compilation: Elroy L. Kadrmas