PHASE ONE FINAL REPORT

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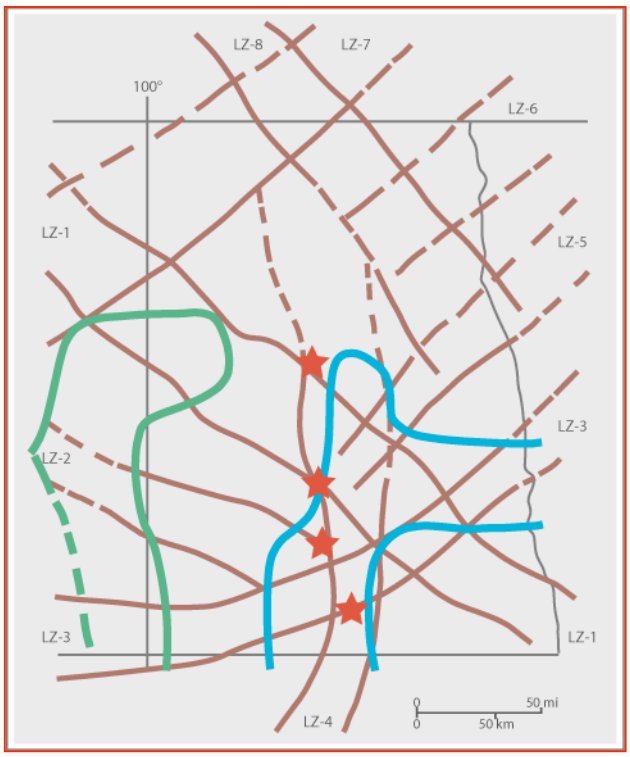
IDENTIFICATION OF

SHALLOW BIOGENIC GAS SYSTEMS

IN EASTERN NORTH DAKOTA



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by

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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.

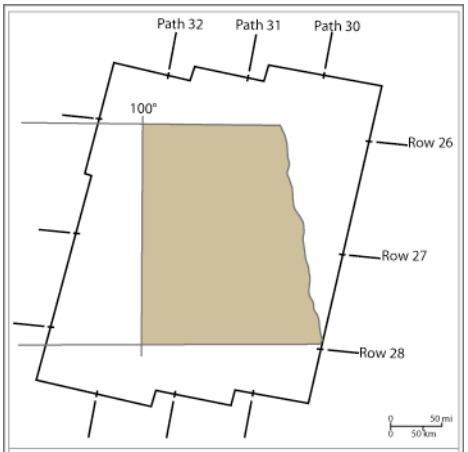

Figure ES.1. Location of the study area east of longitude 100° W relative to the footprint of nine Landsat scenes employed in the investigation.

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.

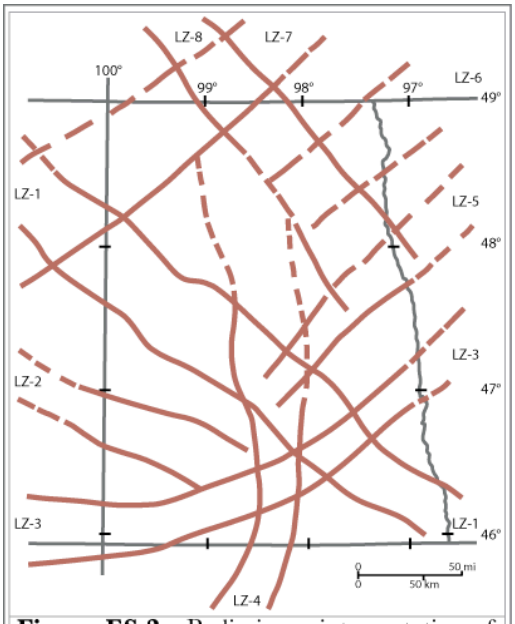

Figure ES.2. Preliminary interpretation of regional lineament zones in eastern North Dakota. See Plate 2 for a rendition at a scale of 1:1,000,000 (1 in = 16 mi).

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 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.

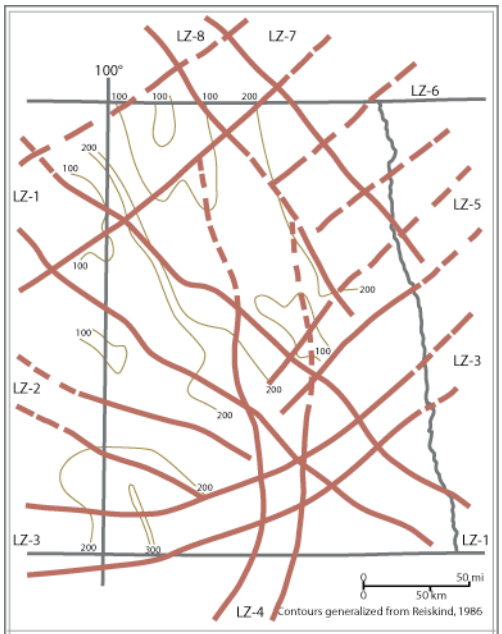

Figure ES.3. Thickness variations in the Niobrara Formation relative to Landsat lineament zones in eastern North Dakota.

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.

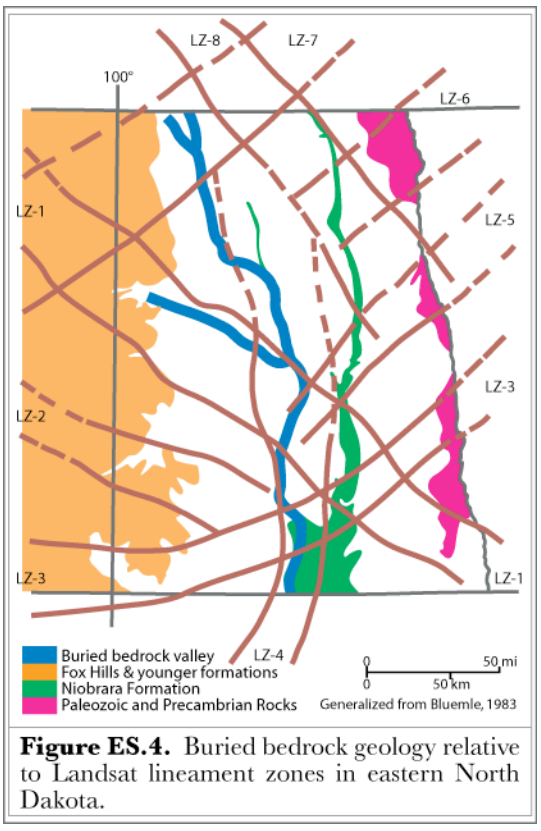

Figure ES.4. Buried bedrock geology relative to Landsat lineament zones in eastern North Dakota.

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.

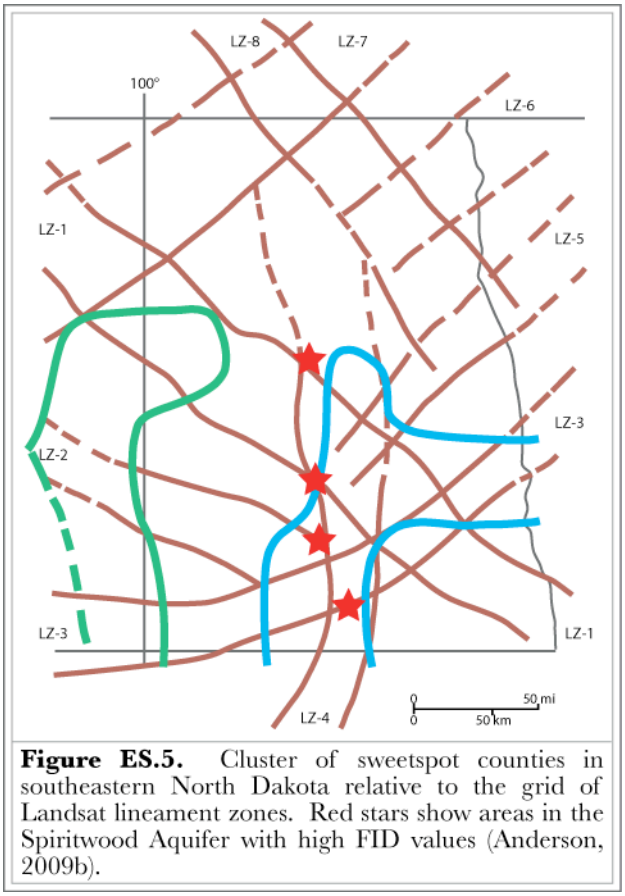

Figure ES.5. Cluster of sweetspot counties in southeastern North Dakota relative to the grid of Landsat lineament zones. Red stars show areas in the Spiritwood Aquifer with high FID values (Anderson, 2009b).

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.