SURFACE LINEAMENTS AND LITHOFACIES DISTRIBUTION OF THE TYLER FORMATION IN SOUTHWESTERN NORTH DAKOTA

BY

NICOLAS BELTRAN GUERRERO

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN GEOLOGY

THE UNIVERSITY OF TEXAS AT ARLINGTON
May 2012

ACKNOWLEDGEMENTS

There are many people to whom I owe a great deal of gratitude: to my parents for their never-ending support, encouragement, fostering an endless curiosity, and for making education a priority in my life. To my thesis committee, Dr. John Wickham for being a great source of knowledge and agreeing to be my advisor, Dr. John Holbrook for his steadfast encouragement, to Dr. Standee for his constructive review, and to Mr. Dale Hostenske, for his empathetic motivation. Also I wish to thank Petro-Hunt and its geology department for providing the data, equipment and topic; especially to Mr. Kevin Allison, who is an enormous resource and an excellent critic, and “Professor” Doug Middleton, who tutored me and accompanied me to the core library. Thanks, to the North Dakota Geological Society and the erudite staff at Wilson M. Laird Core and Sample Library. Thank you, to Mr. Stephen Strum and Mr. Timothy Nesheim for their valuable opinions, insights, and data they so willingly shared. I owe a great thanks to the many scientists whose work I used and learned from.

My hope is that this work inspires others, especially my siblings, to accomplish greater works and proves that “si se puede.”

April 19, 2012

ABSTRACT

SURFACE LINEAMENTS AND LITHOFACIES DISTRIBUTION OF THE TYLER FORMATION IN SOUTHWESTERN NORTH DAKOTA

Nicolas Beltran Guerrero, M. S.

The University of Texas at Arlington, 2012

Supervising Professor: John Wickham

The purpose of this study is to investigate whether a correlation exists between surface lineaments and lithofacies distribution of the Pennsylvanian Tyler Formation in the southwest portion of North Dakota of the Williston Basin. If a cost-effective technique to locate preserved fluvial sandstone bodies can be developed, the Tyler Formation has the potential to be a productive hydrocarbon exploration target.

Many intercratonic sedimentary basins, such as the Williston Basin, exhibit nearly orthogonal surface lineaments. In the case of the Cooper Basin in Australia, lineament analysis helped locate areas where Proterozoic rocks are fractured and filled with quartz veins containing precious metals. In the Michigan Basin, the lineament analysis helped locate deep faults that allow for greater heat flow among anticlinal structures and for thermogenic dolomite to develop. The dolomites are more likely to preserve secondary porosity and be reservoirs for oil.

To locate areas with a greater probability of sandstone preservation, this North Dakota Tyler study attempts to establish the use of surface lineaments as a predictive indicator. The Tyler sandstones are presumably preferentially deposited along lineament orientations. The

surface lineaments are the result of subtle topographic changes due to preferential erosion, minor structures, movement, and/or faults along weak zones in the basement rock. The basement weakness zones are reactivated throughout geologic history and should have resulted in lineaments during Pennsylvanian time. Fluvial morphology is highly susceptible to small topographic changes: consequently, Pennsylvanian surface lineaments should have bounded drainage pattern into the same orientation as present day surface lineaments. Unfortunately, surface lineament analysis alone did not find a correlation with known lithofacies distribution in the study area.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

LIST OF PLATES

See Supplemental File

CHAPTER 1

INTRODUCTION

The purpose of this study is to investigate whether a correlation exists between surface lineaments and lithofacies distribution of the Tyler Formation in the Williston Basin. If cost effective techniques to locate preserved fluvial sandstone bodies can be developed, the Tyler Formation has the potential of being a productive oil and gas exploration target. If lineaments at the surface are related to fractures at depth, they could prove to be expressions of zonal arrangements of small buried fracture traces that cause differential erosion (Shurr 1982). Channel morphology is highly susceptible to subtle structural influences at the time of deposition (Holbrook and Schumm 1999); thus lineaments could prove a useful to locate areas with preserved fluvial reservoirs.

Historically the Tyler Formation of North Dakota has proven to be a difficult target for petroleum exploration because of its heterogeneous nature. The Tyler Formation is Early Pennsylvanian in age and contains multiple reservoir quality sandstones that can be preserved in various stratigraphic layers within the formation (Ziebarth 1964, Murphy et al 2009). It is an important reservoir of oil; over 200 million barrels of oil have been produced to date in North Dakota, with several wells individually producing over a million barrels of oil (Ogden 2010). The thin and erratic distribution of reservoir sandstone bodies in the middle and lower part of the Tyler Formation is a problem for explorers. Conventional, low frequency seismic is not able to resolve sandstone lenses less than 50 feet thick (Hastings 1990).

Oil fields that do produce from the Tyler Formation have strong linear geometries and abrupt terminations. Rocky Ridge Field produced from middle Tyler fluvial sandstone deposits and trends approximately 45º northwest and has very abrupt terminations (Hastings 1990). To date, Rocky Ridge Field has produced 5,414,535 barrels of oil from the Tyler (North Dakota Oil and Gas Commission, 2010). Other Tyler oil fields in the vicinity also exhibit similar patterns. Isopach maps of the upper part of the Tyler productive sandstone lenses in the Medora and Fryburg Fields trend in perpendicular sets from southwest-northeast and northwest-southeast respectively (Barwis 1990, see figure 1.1) Sturm and Peterson (1994) advocated that this preservation pattern implies deposition along faults or joint sets creating the accommodation space.

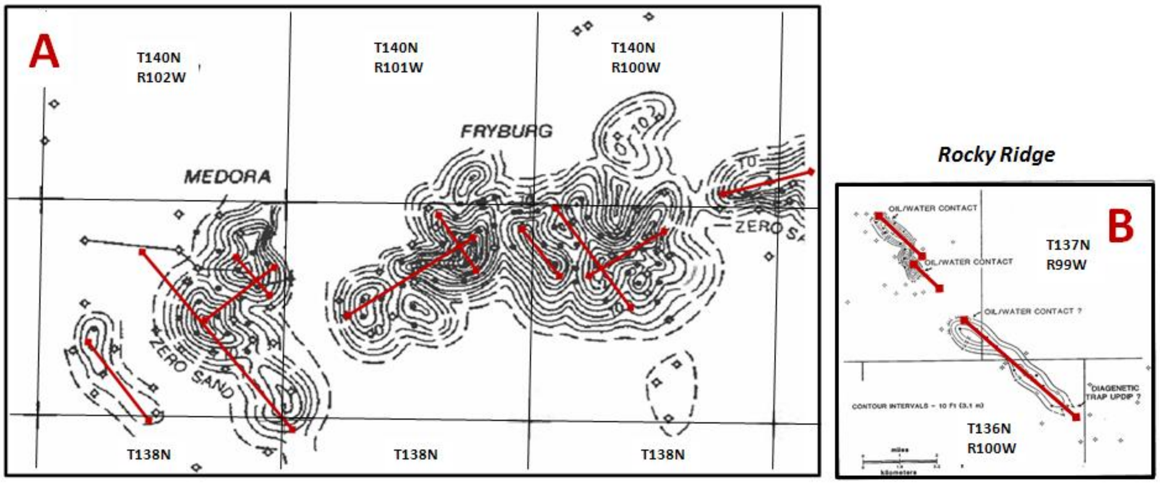


Figure 1.1 A) Medora and Fryburg Fields with Axis of Isopach Thickness of Productive Tyler Sandstone Lenses (modified from Barwis 1990). (B) Rocky Ridge Field with Axis of Isopach Thickness of Productive Tyler Sandstone Lenses (modified from Hastings 1990).The axis of thickest deposition parallels Thomas' block framework (see figure 1.2).

The orientations of the productive Tyler sandstone lenses parallel the block framework proposed by Thomas (1974, see figure 1.2). Thomas (1974), and Brown and Brown (1987) have advocated a wrench-style deformation for the Williston Basin, where basement blocks adjust to tectonic forces along shear zones parallel to lineaments. Change in topographic relief is an important control on deposition and erosion (Brown and Brown 1987). If the fluvial morphology of the Tyler Formation is structurally controlled, then surface lineaments may help locate areas of probable sandstone preservation such as fault-controlled valleys.

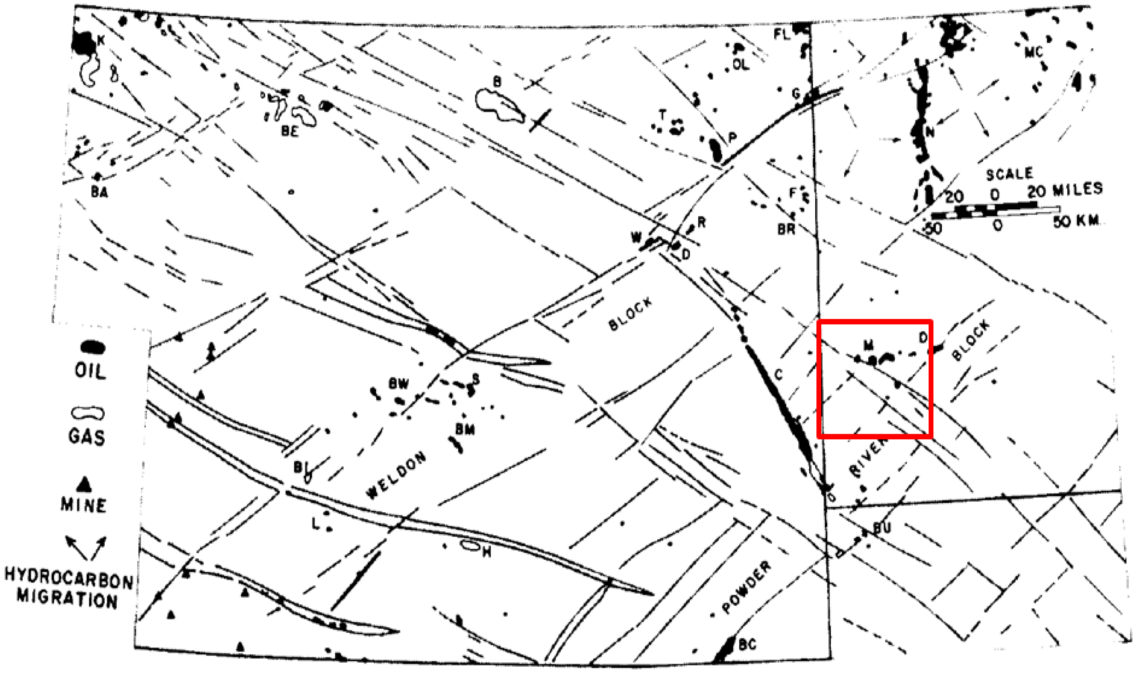


Figure 1.2: Structural Block (Thomas 1974). The figure shows proposed structural block framework with oil and gas fields. Red box is the area of this study. The “M” inside red box is for the Medora field and “D“ is for Dickinson field; both produce from the Tyler Formation.

Surface lineaments have been recognized by many geologists as important expressions of concealed geologic features. Lineaments have been used by O’Driscoll (1985) to locate copper, gold, and uranium ore deposits in Australia, by Trexler et al (1978) in exploration for geothermal energy in Nevada and by Thomas (1974) to decipher tectonic movements in the Williston Basin. Shurr (1982) advocated that Landsat lineaments and constituent linear features are surficial expressions of basement fault zones in the Williston Basin (figure 1.3). If these zones were active and affected topography during Pennsylvanian time, they could help control deposition of the Tyler.

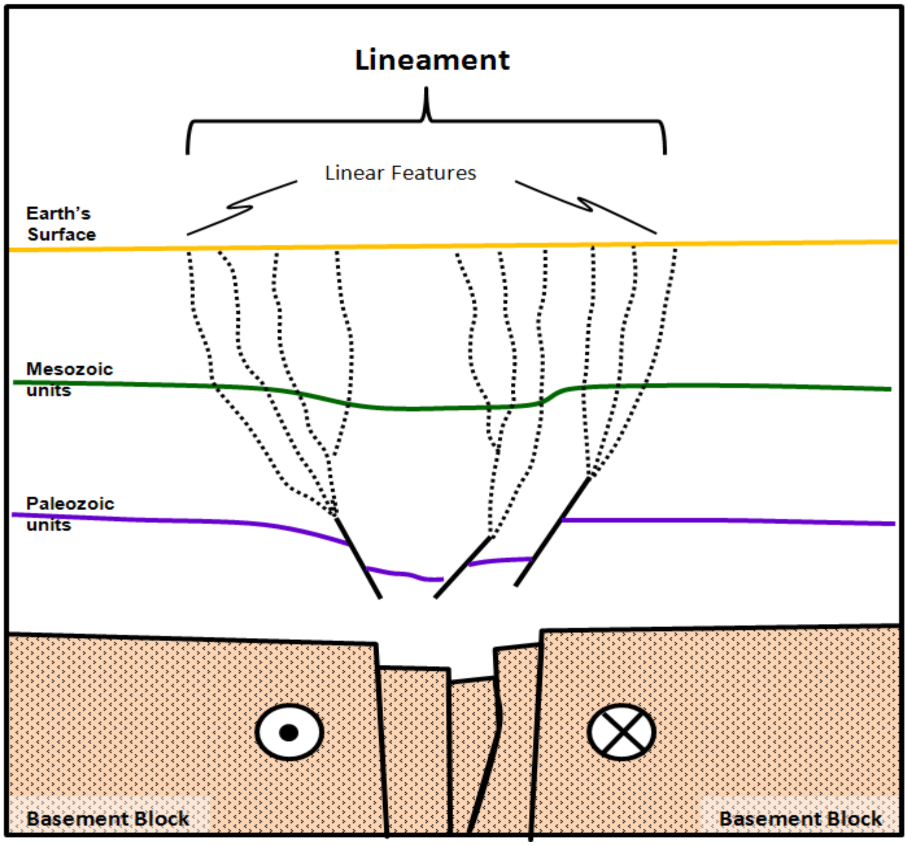


Figure 1.3: Surface Lineament and Constituent Linear Features (modified after Shurr 1982). The figure demonstrates left lateral adjustment on northwest trending basement weakness zones proposed by Thomas (1974). The figure shows surface lineament and constituent linear features as the surface expression of a basement shear zone, its component faults and associated structures. No horizontal or vertical scale is implied.

The study area was deliberately chosen to include known productive Tyler oil fields in an effort to define an area with a high probability of sandstone preservation. Rocky Ridge, Tracy Mountain, Medora, and Fryburg Fields all produce oil from the Tyler sandstones. The study area has a high well density targeting the Tyler Formation, and also has many well logs available from North Dakota Industrial Commission Department of Mineral Resources. The study area is parallel to Sturm's (1987) paleo-shoreline and partially lies within Maughn's (1984) Tyler sandstone fairway (figure 1.4). The study area has a great potential to contain more preserved Tyler sandstones because it meets these geologic conditions.

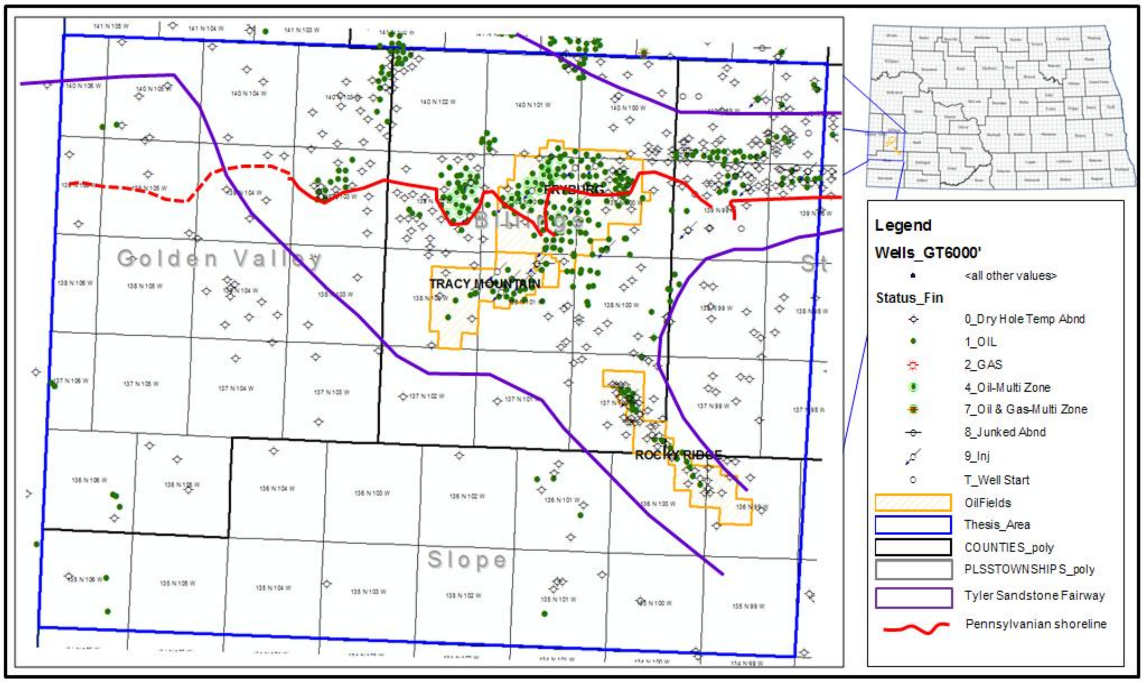


Figure 1.4: Area of Study. Southwestern North Dakota with Maughn's (1984) Tyler Sandstone fairway in purple and Pennsylvanian shoreline in red (Strum 1987). The Tyler oilfield outlines are in orange and wells with total depth greater than 6000 feet.

CHAPTER 2

HISTORICAL REVIEW

2.1 Lineaments and Their Presence in the Williston Basin

The term ‘lineament’ has been in science vernacular since the founding of geology in the 15th century (Hodgson 1974). Despite the antiquity of the word, there was little consensus on the meaning. Hobbs (1904) defined lineament as “nothing more than a generally rectilinear earth feature.” He later (1912) augmented the term as, “significant lines of landscape, which reveal the hidden architecture of the rock basement.” The proliferation of aerial photography in the 1940’s and 1950’s lead to numerous articles extending the term to include curvilinear features and narrow linear zones (Thomas 1974). In the 1970’s and 1980’s the definition of lineament was again expanded to include linear anomalies in geophysical data interpreted to be of geological significance (Argialas et al 1988). The term “surface lineament” is used to differentiate between features observable on the earth surface and features interpreted from geophysical data.

Based on O’Leary’s (1976) definition for lineament, a surface lineament can be defined as a mappable, simple, or composite natural linear feature on the Earth’s surface whose parts have a rectilinear or slightly curvilinear relationship and that differs distinctly from adjacent features or patterns and presumably reflects a subsurface phenomenon. Surface lineaments are identifiable at many scales. At the largest scale, surface lineaments may be expressed as a single trace, *i.e.* a simple lineament, although the same lineament, at smaller scales, consists of a composite of multiple linear features (Shurr 1982; see figure 1.3). Manmade linear features such as highways, dams, power lines, and fences may disguise and destroy “natural” linear features such as collinear streams and moraines. Many features on earth’s curved surface appear straight on map projections; however the true geometry of the lineaments can be curvilinear (Boucher 1997).

Thomas (1974), Shurr (1982), Maughan and Perry, (1986) and Brown and Brown (1987) recognized an association between surface lineaments and weakness zones in the Williston Basin. They proposed that the two primary orientations of surface lineaments define a block framework in the basement, so structure related surface lineaments are concentrated along the edges of the basement blocks (Brown and Brown 1987 figure 2.1). Consequently surface lineaments in the Williston Basin should be expressions of zonal arrangements of small buried fracture traces that cause differential erosion at the surface (Shurr 1982). Mapping of the lineaments helped decipher the tectonic history of the Williston Basin (Thomas1974).

2.2 Williston Basin Structural History

The Williston Basin is North America's largest intracratonic basin (Chimney et al 1992). It lies on the western edge of the North American Platform. The present-day basin occupies more than 300,000 mi^2 (Chimney et al 1992) and encompasses areas of Montana, North Dakota, South Dakota, Manitoba and Saskatchewan (figure 2.1). The basin region has low topographic relief (Peterson 2005) and average dips of about 1° (Chimney et al 1992). The geologic history of the Williston Basin, from Cambrian to Tertiary, is chronicled in the stratigraphic section measuring up to 16,000 feet in west-central North Dakota with unknown amounts of sedimentary rocks removed by several regional unconformities (Carlson and Anderson 1965).

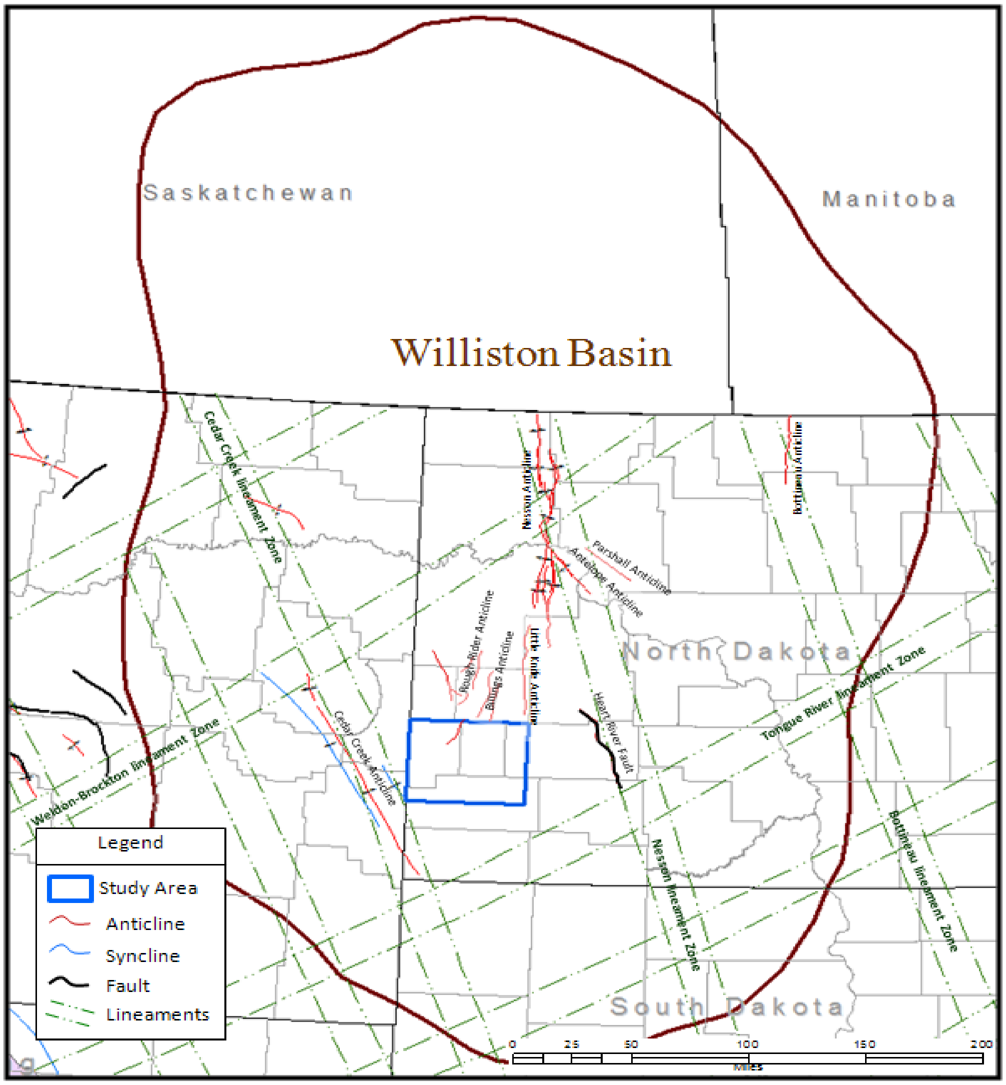


Figure 2.1: Williston Basin with Major Structural Features and Lineament Zones and lineament zones (Nesheim 2011 personal communication and Brown and Brown 1987 respectively). Notice that several structures have nearly parallel orientations. Cedar Creek Anticline and Heart River Fault both lie along lineament zones.

Thomas (1974), Brown (1978), Brown and Brown (1987), and Gerhard et al (1982) have all advocated that the Williston Basin is part of a transpressional tectonic system. According to this model, a system of basement blocks has been intermittently realigned by tectonic forces creating structures along zones of weakness and at the intersections of basement shear zones (Brown and Brown 1982). The shear zones are oriented northeast-southwest and northwest-southeast (Thomas 1974). The Cedar Creek Anticline, Nesson Anticline and Bottineau Anticline are all examples major of structures located along shear zones near the edges of basement blocks (Brown and Brown 1982). Thomas (1974) and Gerhard (1982) suggested that regional transpressional tectonics forces are responsible for creating drag folds (Nesson, Cedar Creek, and Little Knife Anticlines), and vertical displacement of basement blocks.

The Williston Basin has been affected by a series of tectonic events occurring to the west though most of its history. Scotese's (2010) plate reconstruction maps and models suggest these events began as early as the Cambrian with pulses of intense deformation during the Antler (340-300Ma), Ancestral Rockies (320-300Ma), Sonoma (270-240Ma), Sevier (140-50Ma), and Laramide (80-55Ma) Orogenies. These forces reactivated old faults and zones of weakness influencing the Williston Basin's structural features and deposition (Gerhard et al 1982).

The Carboniferous was one of the most tectonically active periods in North America with several orogenies occurring simultaneously (figure 2.2). The Alleghenian Orogeny was forming the Appalachians to the east, the Ouachita Orogeny was occurring in the south from Texas though Oklahoma and Arkansas to Alabama, and the Ancestral Rockies were rising to the west of the Williston Basin. All of these collision-related features transformed the topography and affected the stratigraphy of all major sedimentary basins on the North American Craton: the Williston Basin, Illinois Basin and Michigan Basin all have an erosional unconformity at the end of the Mississippian.

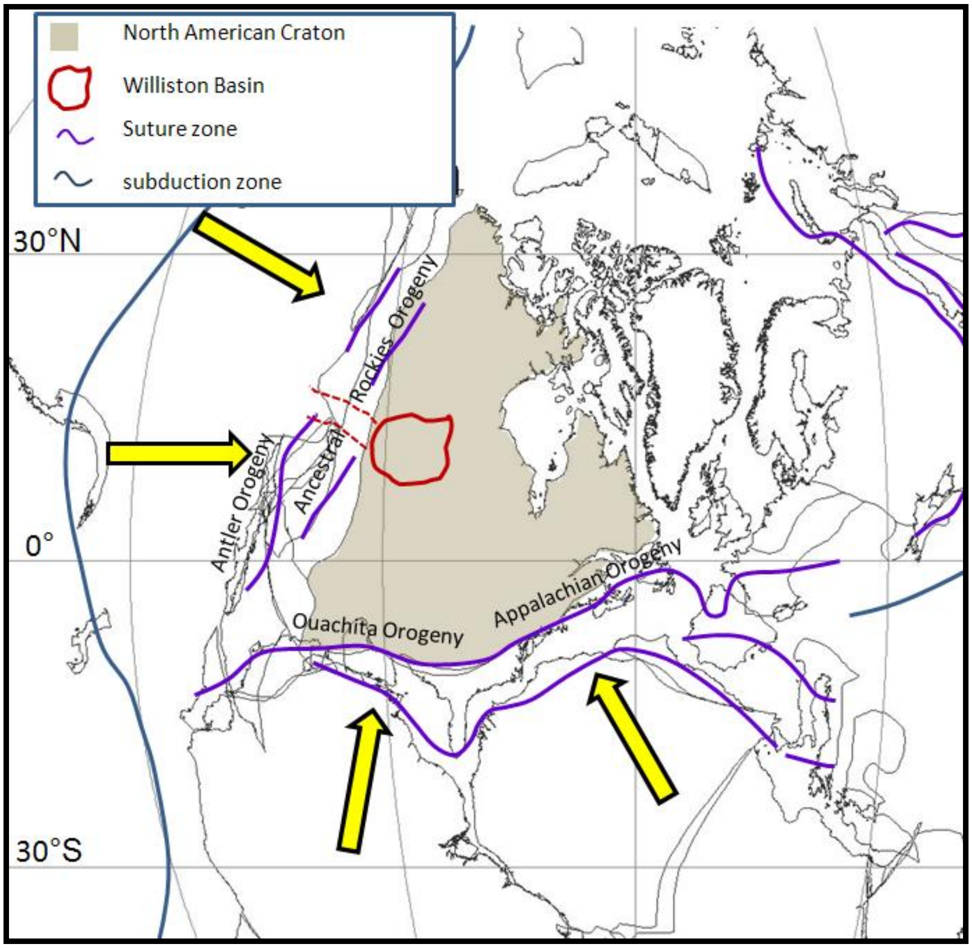


Figure 2.2: Tectonic Plate Movement during Pennsylvanian (≈ 300Ma after Scotese 2010). Yellow arrows indicate general direction of tectonic movement.

The uplift of the North American Craton, between late Mississippian and Early Pennsylvanian, exposed the Wyoming shelf and Alberta shelf (Maughan 1984, Scotese 2010), providing terrigenous material during the deposition of the Tyler Formation (Maughan 1984, Ziebarth 1964). The Williston Basin was temporarily connected to the Sonoma forearc though the Big Snowy Trough (Maughan 1984). Subsurface mapping of the Kibby, Otter, and Tyler sub-crops (see figure 2.5 for stratigraphy) show that each progressively younger formation covered less area (figure 2.3).

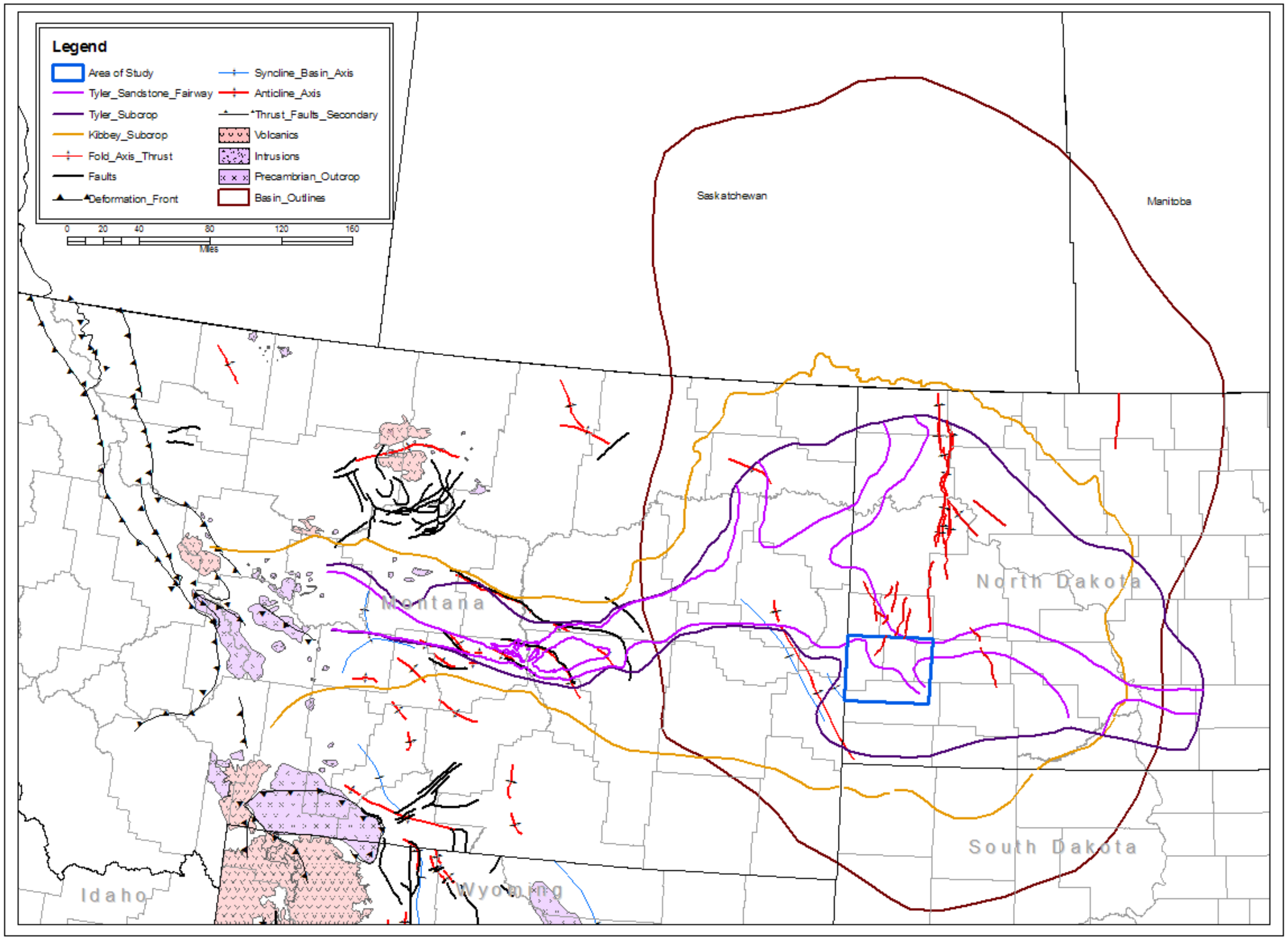


Figure 2.3: Williston Basin Sub-crop Map of Selected Carboniferous Formations (modified from GeoEdges Inc. 2011). Notice that the younger formation sub-crops have less areal extent, with the least area being Maughan's (1984) "Tyler Sandstone Fairway" (see Plate 16 for larger map).

The Williston Basin's stratigraphic history is closely related to other areas of the North American Craton. Most references to the sedimentary record cite Sloss' Cratonic Sequences (Carlson and Anderson 1965, Sloss 1963), shown in figure 2.4. The North American Craton experienced a dramatic sea level fall between the Kaskaskian and Absaroka sequences. In the Williston Basin this relative drop in sea level is marked by the unconformity between the Mississippian Otter Formation and Pennsylvanian Tyler Formation (figure 2.5).

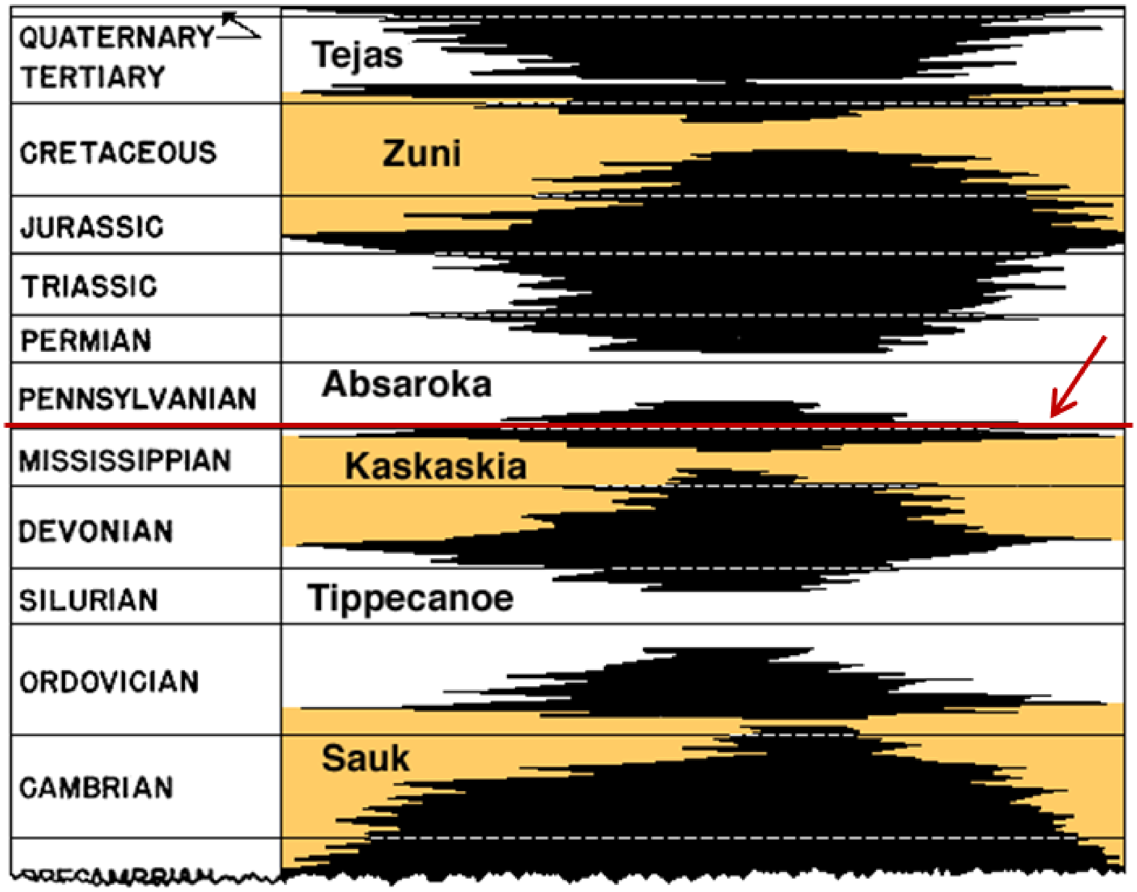


Figure 2.4: Time Stratigraphic Relationships of Sequences in North American Craton (Sloss 1964). White and tan areas represent time of deposition or high relative sea level and the black areas represent non-depositional hiatuses or low relative sea level and erosion. Please note that the Pennsylvanian, part of the Absaroka sequence, lies on a major unconformity and is capped by a time of regional deposition.

Sea level changes have since been described with greater resolution by Haq and Al-Qahtani (2005) and Haq and Shutter (2008). Snedden and Liu (2010) created a Carboniferous sea level chart (figure 2.5). Using the updated sea level curves, it is clear that sea level fluctuations are much more complicated than previously suggested and have both a long-term trend and short-term fluctuations (Snedden and Liu 2010). Near the end of the Mississippian the long-term sea level begins to fall, reaching the relative minimum in both the short-term and long-term trend at about 315 Ma in the Lower Pennsylvanian. From that point forward, the long-term sea level trend rises and plateaus between the Middle and Upper Pennsylvanian.

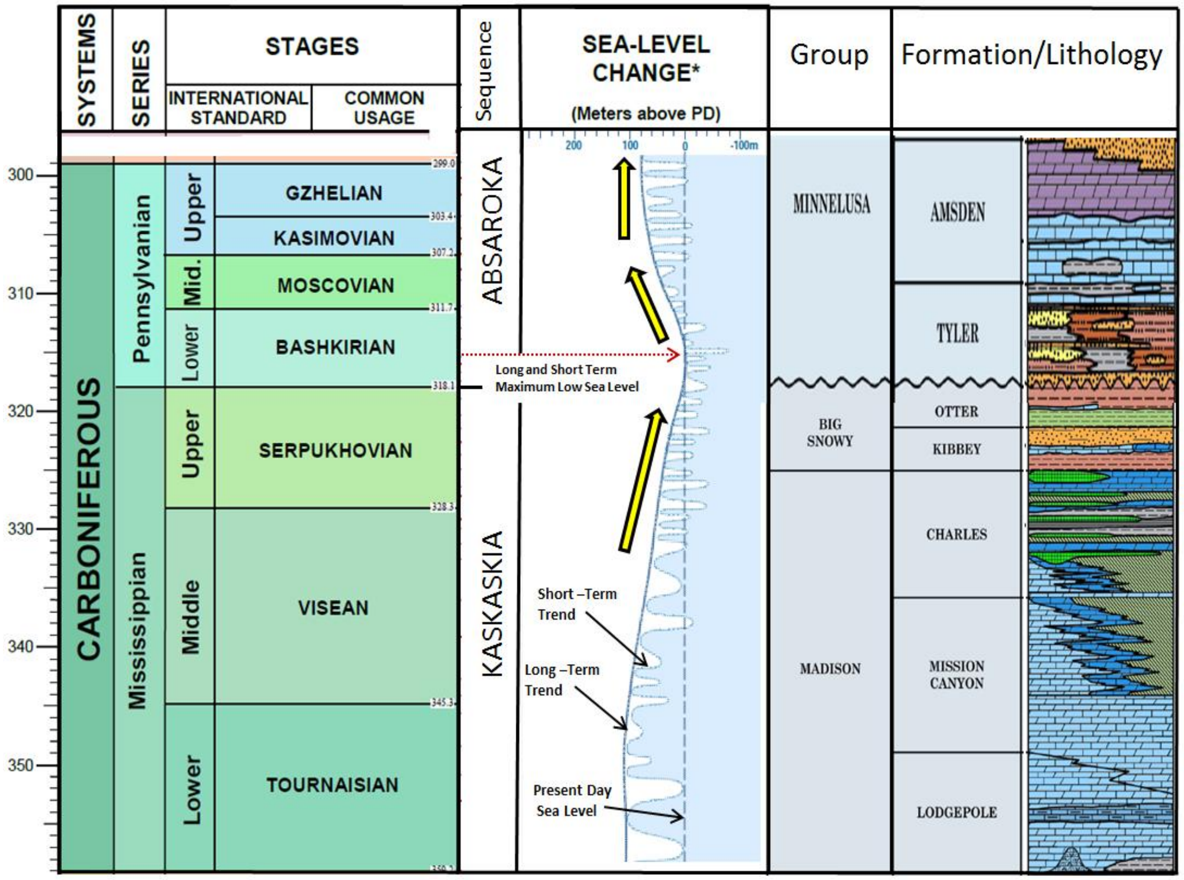


Figure 2.5: Carboniferous Sea Level Changes with North Dakota Stratigraphic Column (modified from Snedden and Liu 2010 and Murphy et al 2009 respectively). Note sea level (red arrow) and the relative fall, rise and plateau of sea level (yellow arrows); for lithology legend please see Murphy et al (2009).

2.3 Williston Basin Carboniferous Stratigraphy

The best exposed Carboniferous stratigraphic sections of the Williston Basin are in central and southern Montana. The first person to describe the Carboniferous rocks and name them was Peale (1893). He named the Madison limestone from exposures near Three Forks, Montana. Weed (1896) described the Quadrant Formation from exposures on Quadrant Mountain in Yellowstone National Park. Weed (1899) later expanded the Quadrant Formation to include the “Kibby Sandstone” and “Otter Creek Shales.”

Darton (1904) termed the Amsden Formation from outcrops in the northern part of the Big Horn Mountains, Wyoming. Reeves (1931) expanded the Amsden terminology into central Montana, advocating that the limestone beds at the top of the Quadrant Formation correlated to the Amsden Formation of Wyoming.

Freeman (1922) was the first to describe and attempt to separate the Tyler sandstones from the Quadrant Formation. He described 300 feet of white to red sandstones interbedded with multicolored shale “beautifully exposed” west of the post office of Tyler, Montana. However Scott (1935) suggested that Freeman’s Tyler sandstone was not a “lithologic, paleontologic, or mappable unit over broad areas,” and that it should be included in the newly defined Heath Formation. Mundt (1956) recognized that the Tyler Sandstone is separated from the lower non-sandy portion of Scott’s Heath Formation by an unconformity, so he gave priority to Freeman’s nomenclature and described the Tyler Formation in the south half of sec. 5, T.12N, R.21E of Fergus County, Montana, with a total measured thickness of 260 feet.

The North Dakota part of the Williston Basin is very similar to that of Montana. The basin as a whole was moderately stable with only minor structural features and shallow dips. The North Dakota Geological Survey has assembled the state stratigraphic column complete with lithologic descriptions. In the study area (figure 2.6 and Murphy et al 2009), the Early Pennsylvanian Tyler Formation sits unconformably on the Mississippian Otter Formation and lies below the Late Pennsylvanian Amsden Formation.

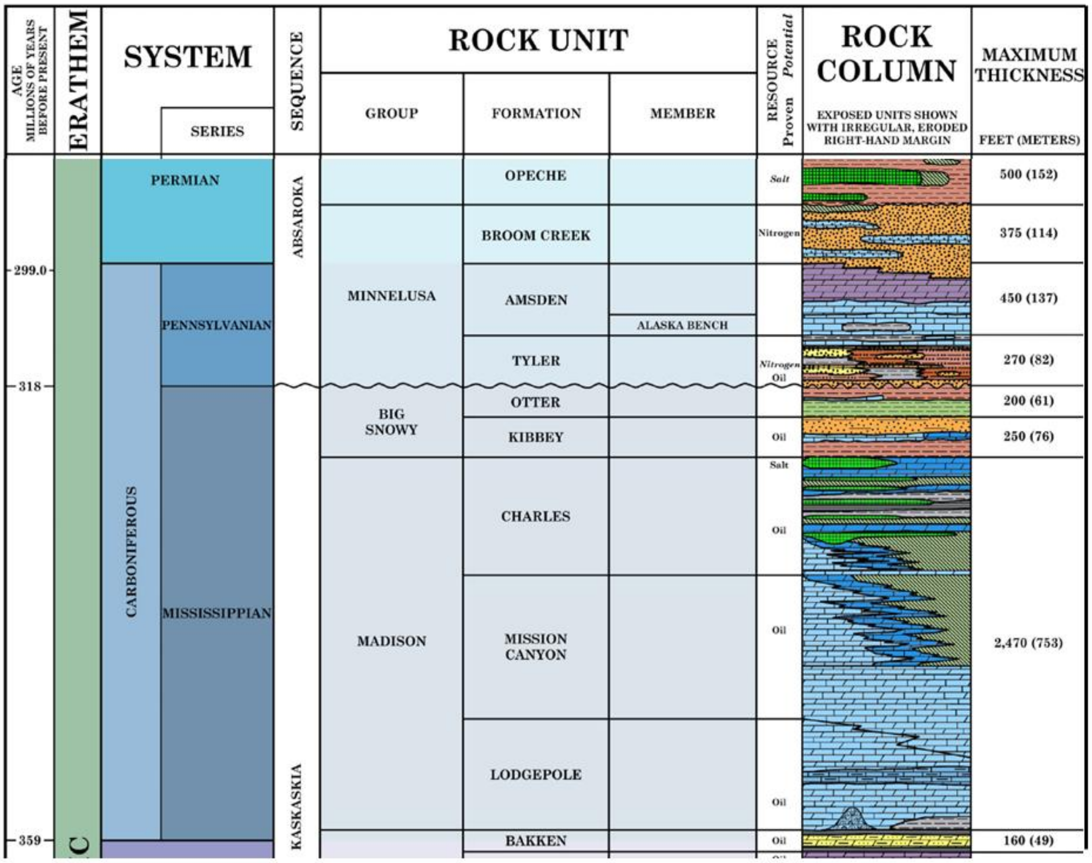


Figure 2.6: North Dakota Carboniferous Stratigraphy (Murphy et al 2009). Notice that the Tyler Formation lies on the unconformity between the Kaskaskia and Absaroka sequences. Also, of importance, the “Kibby Limestone” lies in the middle of the Kibby Formation, and is an excellent regional marker on well logs.

The Tyler Formation is very complicated in the subsurface of North Dakota. I have followed Sturm’s (1982 and 1987) stratigraphic analysis and divided the Tyler Formation into three units: an upper, middle, and lower (figure 2.7). The upper Tyler unit is by far the most consistent across the basin. It is composed of limestone and gray to black calcareous to non-calcareous mudstone to shale, interbedded with trace lignites and rare sporadic thin sandstone lenses at the base. Near the central part of the upper Tyler, there are a pair of limestone beds that are mappable across townships; this pair of limestone beds has very high resistivity and produces distinct forked geometry on the resistivity logs (figure 2.7).

The middle part of the Tyler is usually separated from the upper part of the Tyler by black highly radioactive shale, usually detected by a gamma ray logging tool. The middle pert of the Tyler consists of varicolored, sometimes mottled mudstones and black, calcareous to non-calcareous argillaceous mudstones. It is also interbedded with thin discontinuous lignite beds and occasional thin limestones and rare white to gray and sometimes brown to tan, fine to medium-grained, quartz-rich sandstone lenses. In general the sandstone lenses in the middle part of the Tyler are thicker than the sandstone in the upper part of the Tyler. Occasionally the fluvial channels in the middle part of the Tyler erode into the lower part of the Tyler and result in a preserved amalgamated sandstone lens. The depositional environment of the middle part of the Tyler changes laterally from terrestrial-influenced (*i.e.* back swamps and overbank deposits) to more marine-influenced deposits (i.e. neritic shales and shallow sea carbonate buildups) toward the basin. This is observed by the decrease of sandstone lenses and terrigenous sediment and increase in black calcareous shale and marine fossils.

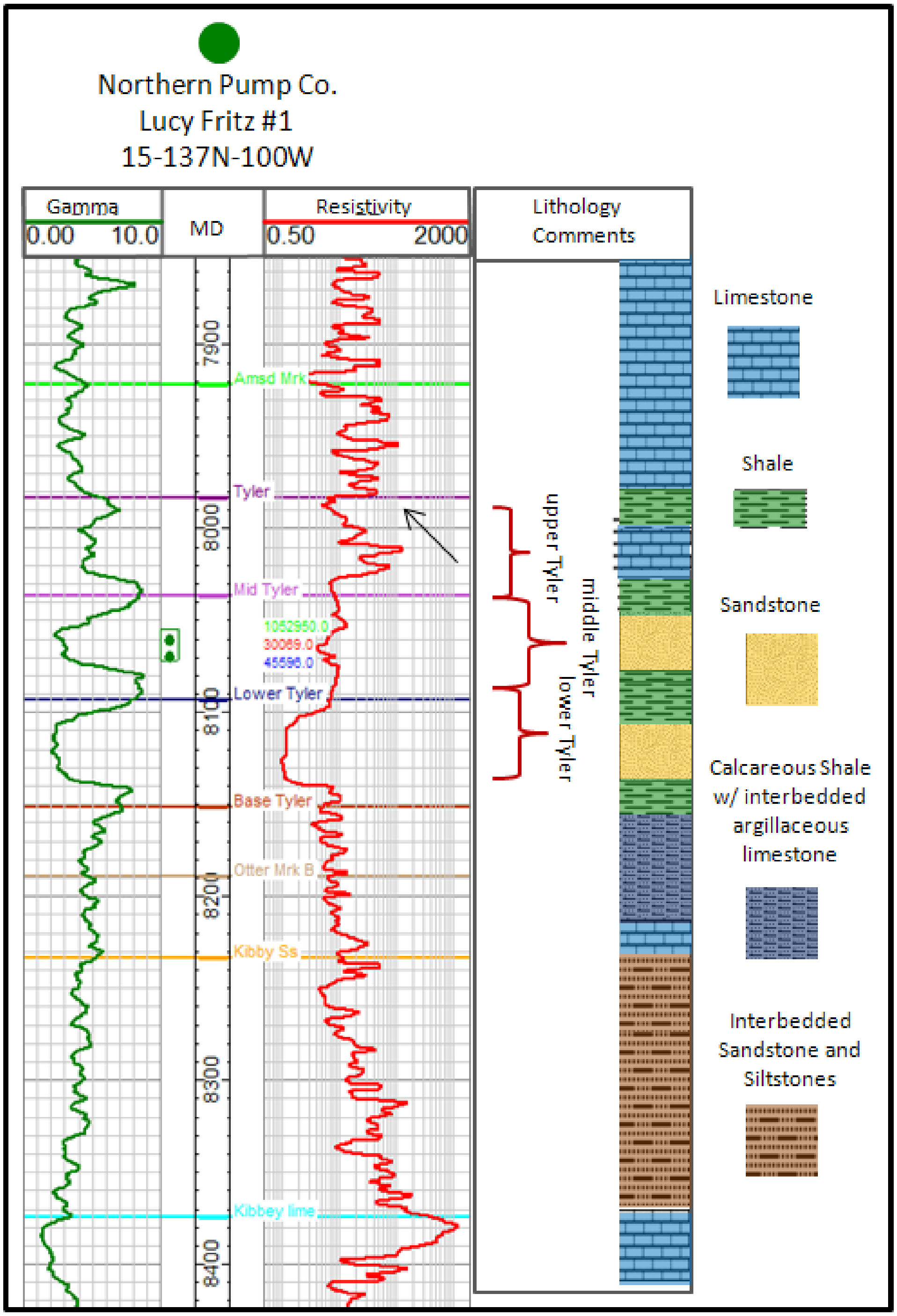


Figure 2.7: Type Log with Tyler Picks and Dominant Lithology. The lower part of the Tyler sandstone has very low resistivity presumably indicating it is water-bearing. The middle part of the Tyler has produced over a million barrels of oil. Notice the upper part of the Tyler fines upward and the resistivity curve has a “forked” geometry just above the contact with the middle part of the Tyler. Gamma units are in micrograms of radium-equivalent per ton instead of API units, due to the age of the log (conversion factor ≈16.5).

The transition between the lower part of the Tyler and middle part of the Tyler is much more difficult to identify on well logs because of the erosional unconformity between the two units. It is normally marked by a gray to black radioactive shale but it was commonly eroded by the middle part of the Tyler channels. Along the flanks of the basin the black shale was not deposited at all; instead a limey argillaceous mudstone replaces it as the transition into the lower part of the Tyler. However, the mudstone can also be eroded by middle part of the Tyler channels. The lower part of the Tyler consists of gray to black mudstone to shale interbedded with thin erratic limestone stringers and tan, brown or gray angular to sub rounded, fine-to medium-grained, quartz-rich sandstone. Overall, I interpret the lower part of the Tyler as less marine influenced than the middle part of the Tyler, because it contains fewer limestone stringers, thicker sandstone lenses and is not deposited uniformly across the entire basin. The lower part of the Tyler was apparently not deposited on the flanks of the basin (figure 2.8).

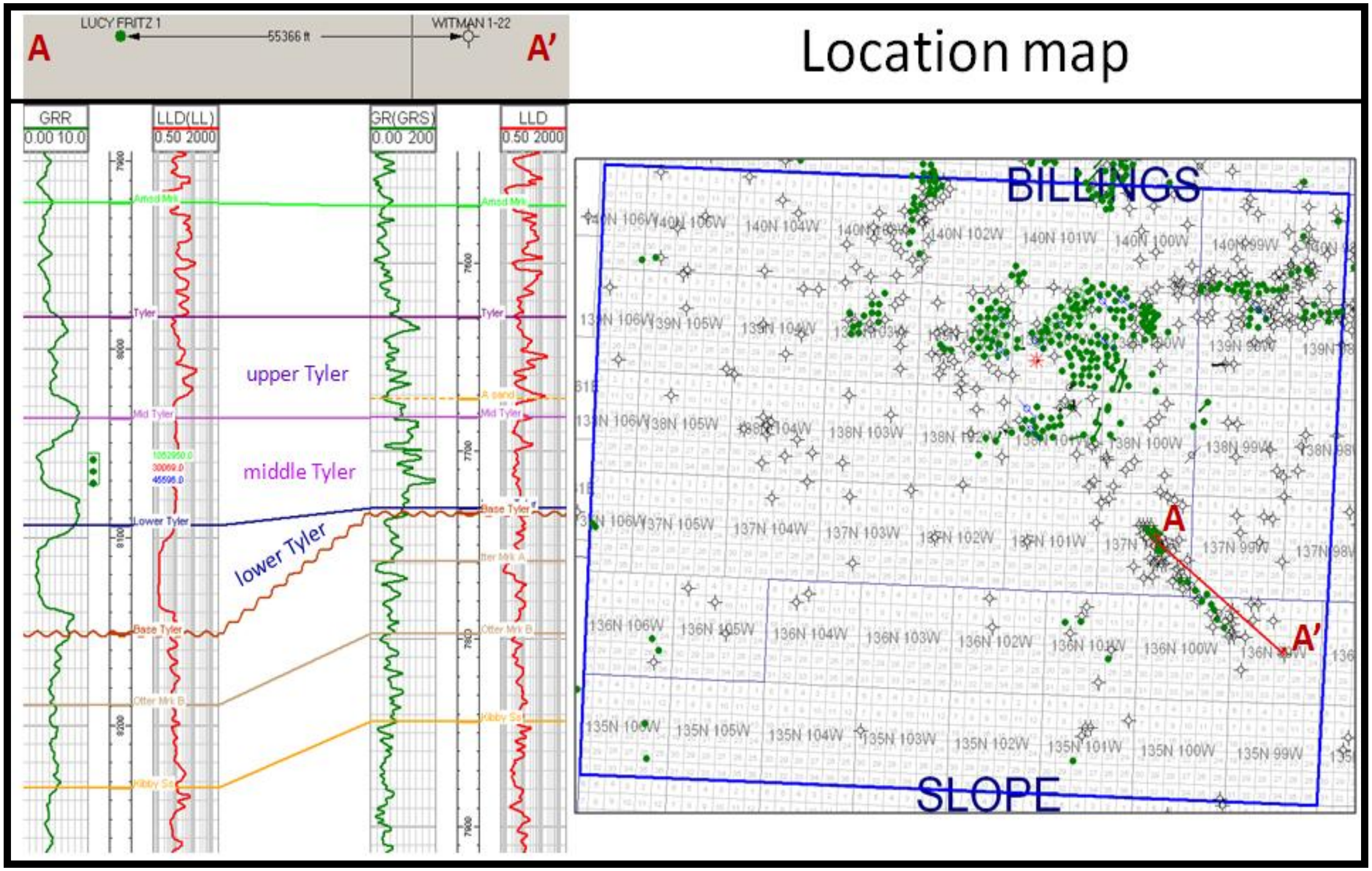


Figure 2.8 Example of Tyler Pinchout.

2.4 Oil from Tyler Sandstones

Major oil production from the Tyler fluvial sandstone in North Dakota started with Rocky Ridge Field. The field is located in southeast Billings County and the north part of Slope County. Rocky Ridge Field was fortuitously discovered in 1957 when the Lucy Fritz No. 1 well encountered an oil column in fluvial sandstones of the middle part of the Tyler Formation (Hastings 1990). The well initially was a test of the deeper Fryburg (upper part of the Madison Group), but the objective proved water productive (Hastinigs 1990). The prospect was identified using 2D seismic that indicated a structure at the Fryburg horizon. Northern Pump Company then came up the hole and tested the oil show they encountered while drilling though the Tyler. The Tyler sandstone tested with an initial potential of 1,224 barrels of oil per day (Hastings 1990). A second pool 2 miles to the southwest was discovered in 1960 by the Shell State #41-36. Rocky Ridge Field (both pools) has 20 productive wells and 46 dry holes and a total cumulative production of 5,419,757 barrels of oil and 283,470 MCF of gas to date (North Dakota Department of Mineral Resources Oct 2011).

Medora Field was discovered by Amerada Petroleum Company in 1964; the Russell Logan #1 well was drilled on a simple dome in an attempt to expand Fryburg Field (Barwis 1990). The well encountered 16 feet of sandstone at the base of the upper part of the Tyler. In 12 of 23 additional wells drilled, this sandstone was either absent, tight and thin, or tested water (Barwis 1990). Most Tyler fields have had similar results, illustrating the complicated nature of the reservoir.

CHAPTER 3

METHODS

3.1 Location of Study

The North Dakota Tyler study area (figure 3.1) was specifically designed to contain a relatively high density of wells and preserved Tyler sandstones, in order to insure that a detailed well log mapping program targeting the Tyler Formation could be completed. The study location has been included in various continental to regional scale surface lineament mapping studies (Thomas 1974, Brown and Brown 1987, Cooley 1983, Maughn and Perry 1986), providing a plethora of data. A recent and larger-scale surface lineament mapping study has been completed by Anderson (2011).

The study area (figure 3.1) is also the primary location of oil production from the Tyler Formation in North Dakota, making it one of the most economically important areas. Many of the older fields have comprehensive field studies (Barwis 1990, Hastings 1990, and Sturm and Peterson, 1994). These articles provide critical data, from discovery though development, on the relationships and heterogeneity of the reservoir sandstones. According to Sturm (1982 and 1987), the study area should lie on the transition between terrestrial and marine depositional environments. This is important because the depositional systems can be evaluated and compared.

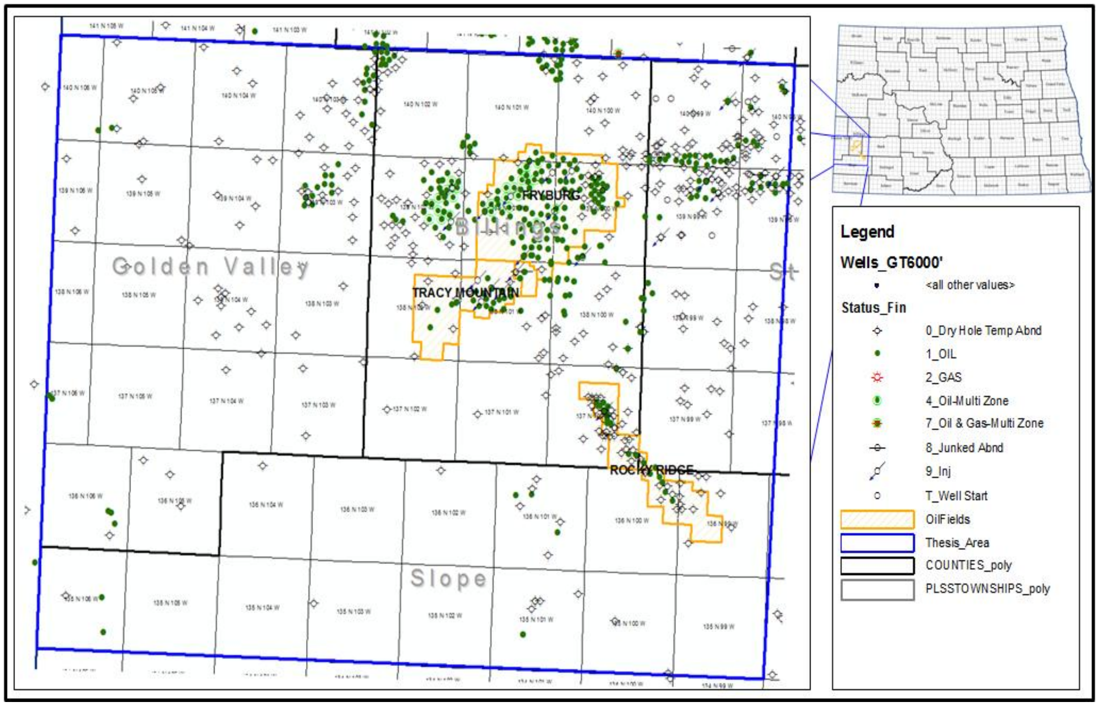


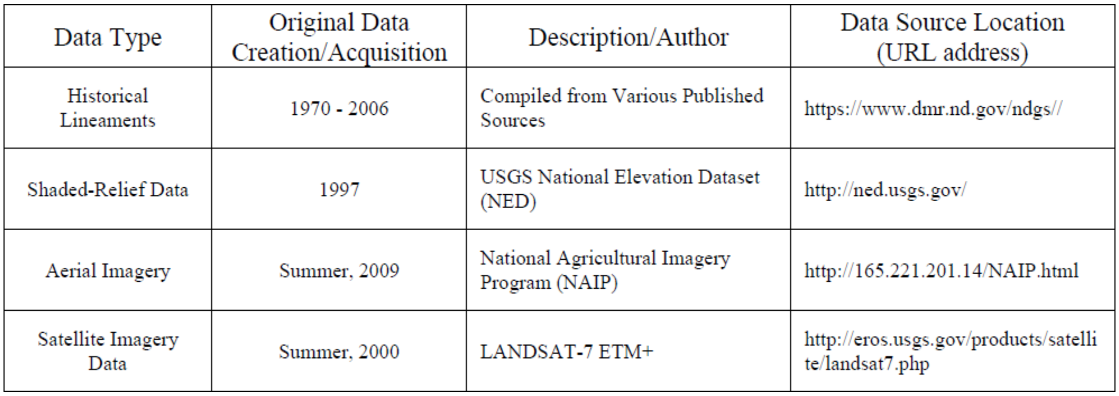
Figure 3.1: Area of Study. Southwestern North Dakota.

3.2 Lineament Analysis

Many interpretations are plagued with erroneous lineaments (Boucher 1997). The human eye is acutely proficient at distinguishing alignments in a random data set; consequently humans may see lineaments that don't exist (Boucher 1997). Mapping of the Tyler Formation has predisposed me to recognize fluvial patterns and geometries related to them. To insure nonbiased results, I relied on an independent lineament analysis study conducted by Fred J. Anderson (2011) of the North Dakota Geological Survey. Anderson is experienced in lineament analysis, having previously completed a similar study over the northeastern part of the Williston Basin in North Dakota in 2008.

Anderson (2011) derived surface lineaments from four primary sources (Table 3.1): previous studies (historical lineaments), digital elevated data (National Elevation Dataset), air photos, and satellite imagery (LANDSAT-7 ETM+). Historical lineaments published in previous studies were compiled and digitized into a single map (Anderson 2011). Digital shaded relief maps were constructed from 1997 USGS National Elevation Dataset (Anderson 2011), and vertically exaggerated maps were created to accentuate topographic features. Surface lineaments were then digitally traced on screen. Surface lineaments were also digitally mapped on a mosaic of air photos from the National Agriculture Imagery Program, and on a mosaic of photos from LANDSAT-7 Enhanced Thematic Mapper Plus imagery program (Anderson 2011).

Table 3.1: Summary of Data and Imagery Used for Lineament Mapping (Anderson 2011)



Data Type	Original Data Creation/Acquisition	Description/Author	Data Source Location (URL address)
Historical Lineaments	1970 - 2006	Compiled from Various Published Sources	https://www.dmr.nd.gov/ndgs//
Shaded-Relief Data	1997	USGS National Elevation Dataset (NED)	http://ned.usgs.gov/
Aerial Imagery	Summer, 2009	National Agricultural Imagery Program (NAIP)	http://165.221.201.14/NAIP.html
Satellite Imagery Data	Summer, 2000	LANDSAT-7 ETM+	http://eros.usgs.gov/products/satellite/landsat7.php

Lineament identification and mapping was conducted by successive visual inspection of each data set at various scales from 1:24,000 to 1:1,000,000 (Anderson 2011). It is crucial to assess all the datasets at varying scales, because differing lineaments are distinguishable at different scales (Boucher 1997). Lineaments were manually traced on screen from each of the four different datasets. The lineaments were then exported into an ESRI shapefile format. Lineament orientations were analyzed for directional trends and rose diagrams were created using Rockworks (http://www.rockware.com/product/overview.php?id=165).

Anderson (2011) created a lineament density map using 1 mile by 1 mile grids that correspond to the actual public land survey system sections, and calculated lineament density from each lineament length contained in the one mile box (Anderson 2011). He then contoured the density grid and created shapefiles of the lineament density contours.

3.3 Well Log Analysis and Surface Identification

I used Seismic Micro-Technology's Kingdom 8.6 geo-scientific interpretation software to assist in the construction of the isopach maps, grids, contours and log interpretation. The projection system I used for the mapping was U.S. State Plane NAD 1927 North Dakota South 3302.

I loaded the available logs for each vertical well that penetrated the Tyler Formation within the area of interest into SMT Kingdom, and saved the sequence surfaces as "Tops." I used the "Zones" in SMT to define the upper, middle, lower and gross Tyler zones. I used the software to run calculations on the wells with data, such as true vertical thickness and subsea depth of the tops. In the vertical view window I was able to construct cross sections though wells to correlate the logs on screen. SMT has a variety of advantages such as instant scaling of 1", 2", and 5" logs as the user sets the vertical scale for viewing on screen. Also SMT provides many time-saving tools such as flattening on surfaces and calculating subsea depth using Kelly Bushing elevations.

For this study, I evaluated over 640 wells that penetrated the Tyler Formation in the study area. I used the available log suites to locate sandstones in the Tyler Formation. Wilson and Nanz (1959) have assembled one of the best papers on identification and evaluation of sandstone bodies using the self-potential log. They subdivide sandstone bodies according to the log characteristics and assign a probable depositional environment. I incorporated their paper with sequence stratigraphy to interpret sandstone depositional environments. I also followed the instructions of Asquith et al (1982) in interpreting the well logs. When porosity logs were available and a lithofacies was in question, I cross-plotted the neutron porosity and density porosity curves using Schlumberger's chart book. When mud logs were available I relied on the lithologic descriptions to identify sandstone and cross-referenced the well logs to build a baseline for manual interpretation from resistivity logs alone.

To identify and map the Tyler valley fills and associated surfaces, I followed the methods of Porter and Sonnenberg (1994). First, I identified the lowstand surface of erosion (base of Tyler). Then, I traced and mapped the transgressive surface of erosion (top of the lower part of the Tyler). I constructed isopach maps between each sequence surface to locate paleovalleys. I then proceeded to map individual channels within the valley and evaluated the influence of paleostructure.

To identify the lowstand surface of erosion, I compared each well log suite to adjacent well logs and looked for a change in the log character near the top of the Otter Formation. Usually this is marked by erosion of the Otter Formation and results in missing some of the upper part of the Otter limestone and shale. Occasionally, the change is not very obvious because a limey mudstone can be preserved at the base of the lower part of the Tyler that can have log characteristics similar to the Otter Formation.

I then used the same technique to identify and trace the transgressive surface of erosion. This is much more difficult because the lower part of the Tyler section is very heterogeneous and what might be perceived as missing section can simply be a lateral change in lithofacies. Also, this surface has a feathered edge and often interfingers, making it challenging to identify. I also constructed numerous cross sections starting from the deeper part of the basin and radiating out toward the margins. On the cross sections, I searched for downlapping surfaces that help identify the transgressive surface of erosion.

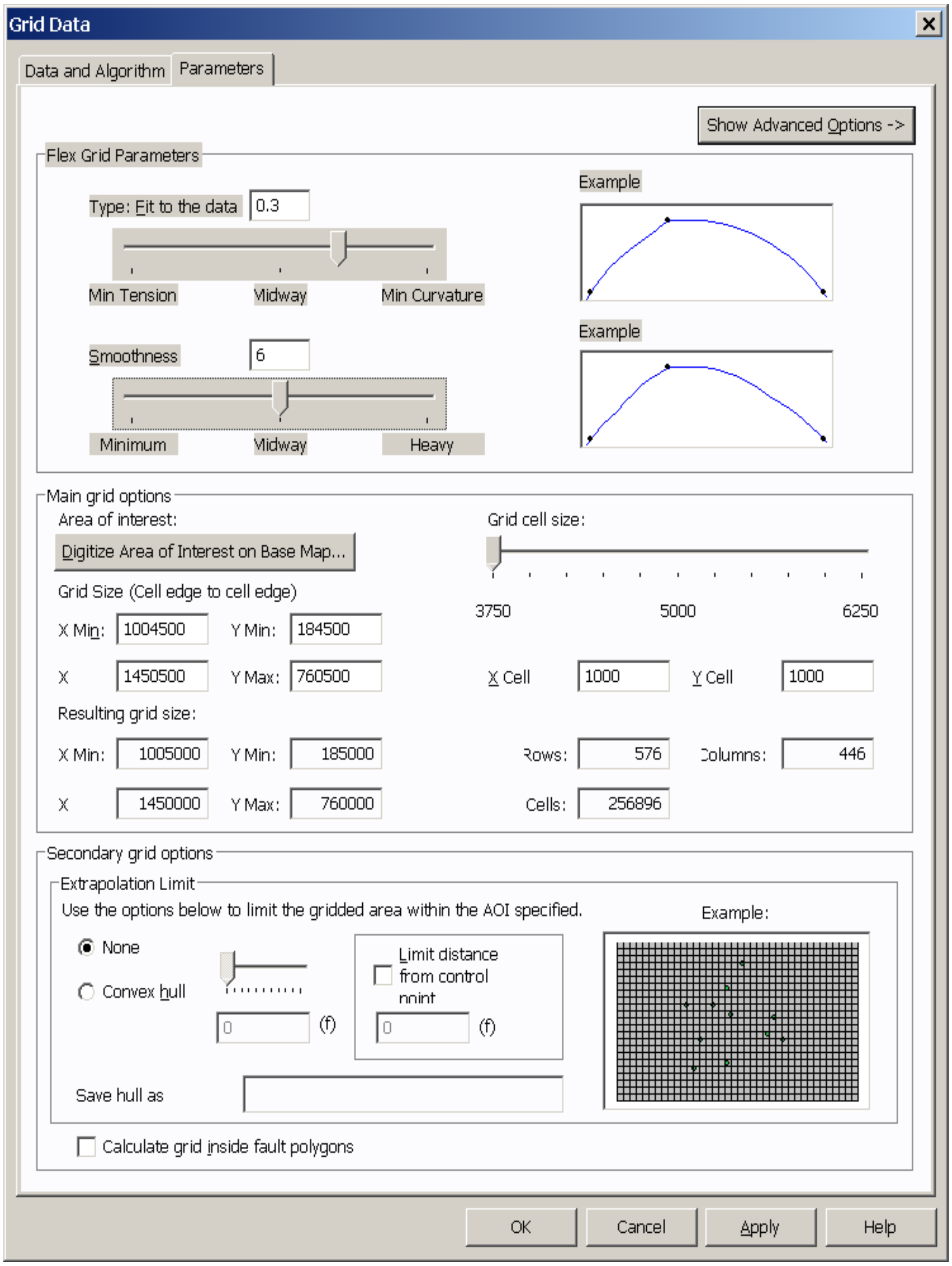
The upper part of the Tyler displays characteristics typical of a highstand systems tract. I documented a maximum flooding surface at the top of the middle part of the Tyler. The maximum flooding surface is recognizable across the area of study and is marked by dark, black, highly radioactive shale. The upper part of the Tyler displays aggradation of a carbonate system, which reinforces a highstand systems tract model.

I mapped paleovalleys by constructing isopach maps between major sequence surfaces. I generated isopach maps for the lower part of the Tyler, which is bounded by the lowstand unconformity (base of Tyler) and the transgressive surface of erosion (top of lower Tyler). I also constructed an isopach map for the middle part of the Tyler, between the maximum flooding surface (top of middle Tyler) and the transgressive surface of erosion (top of lower Tyler). I also generated isopach maps upper Tyler and a combined middle and lower part of the Tyler.

By separating the Tyler into three units, I was able to evaluate the structural evolution and structural influence on sediment deposition. At some locations, paleovalleys incised both the lower and middle part of the Tyler; however at other locations valley scours only occurred in one of the units. The thickness of the units can help decipher evolution of the basin.

3.4 Isopach Maps Construction

Construction of isopach maps can be described as a three step process. First, SMT zone attribute calculator is used to calculate gross thickness between the top and base of the zone; for example the middle part of the Tyler zone is defined from the top of the middle part of the Tyler to the top of the lower part of the Tyler. Next, utilizing SMT's Flex Gridding (an advanced analysis that combines minimum curvature and minimum tensions algorithm to create grids based on cells size designated by the user), a grid is constructed (figure 3.2). Third, a contour map is calculated based on the grid.



Grid Data

Flex Grid Parameters

Type: Fit to the data 0.3

Smoothness 6

Main grid options

Area of interest:

Grid cell size:

Grid Size (Cell edge to cell edge)

X Min: 1004500 Y Min: 184500

X 1450500 Y Max: 760500

X Cell 1000 Y Cell 1000

Resulting grid size:

X Min: 1005000 Y Min: 185000

X 1450000 Y Max: 760000

Rows: 576 Columns: 446

Cells: 256896

Secondary grid options

Extrapolation Limit

Use the options below to limit the gridded area within the AOI specified.

● None

○ Convex hull

0 (f)

☐ Limit distance from control point

0 (f)

Save hull as

☐ Calculate grid inside fault polygons

Figure 3.2: Flex Gridding Parameters in SMT Kingdom Suite. “Type: fit to the data” is where the user decides which balance between minimum tension and minimum curvature fits the data best. In this case it is 0.3. “Smoothness” controls how smooth the gridding is; midway is about 6. The other major control is the cell size; in this case 100’x1000’ was chosen.

To construct the upper Tyler zone (top of Tyler to top of middle Tyler), the gridding parameters in SMT were 1000’x1000’ cell size, with a 0.3 balance factor between minimum tension and minimum curvature and 6 smoothness from minimum to heavily smoothed (results in Plate 1). Then, I used SMT to compute the 5 foot contour interval. To construct the isopach map of the upper Tyler sandstone (also known as Fryburg sandstone), my parameters in SMT for gridding were 500’x500’ cell size, with a 0.3 balance factor between minimum tension and minimum curvature, and 6 smoothness from minimum to heavily smoothed (results in Plate 2). Next, I used SMT to compute 2 foot contours from the grid. To construct the middle part of the Tyler Zone (top of middle part of the Tyler to Top of lower part of the Tyler), the gridding parameters in SMT were 1000’x1000’ cell size, .04 balance factor between minimum tension and minimum curvature and 6 smoothness from minimum to heavily smoothed (results in Plate 3). Then, I computed 5 foot contour intervals using SMT. To construct the lower Tyler zone (top of lower Tyler to base Tyler), my gridding parameters in SMT were 1000’x1000’ cell size, with a .04 balance factor between minimum tension and minimum curvature and 6 smoothness from minimum to heavily smoothed (results in Plate 4). Then, I used SMT to compute the 5 foot contour intervals. To construct the gross Tyler Isopach (top of Tyler to base Tyler), the gridding parameters in SMT were 1000’x1000’ cell size, .04 balance factor between minimum tension and minimum curvature and 6 smoothness from minimum to heavily smoothed (results in plate 5).

Using the isopach maps of each Tyler zone as a base, I began to map the Pennsylvanian valleys. I also incorporated many cross sections looking for the erosion of the Otter Formation and searching for sand-filled channels. This is when I first noticed that not all channel scours are filled with sandstones. Many scoured channels had dark black shale and some lignite and other fine-grained deposits. This led to many challenges such as channels that did not show significant isopach thickness because the fine-grained deposits such as peat and mud are highly compressible and did not preserve much of the original thickness.

3.5 Sandstone Thickness Bubble Map and Surface Lineament Map Construction

I used ESRI ArcView 9.3 (desktop geographic information system mapping software) to assemble the bubble maps, lineament maps, and surface maps. The projection system I used was U.S. State Plane NAD 1927 North Dakota South 3302.

Using ESRI ARC GIS 9.3, I converted the header data for each well into an attribute table; then, I displayed the surface latitude and longitude and exported it as a new point shapefile. I added the gross sandstone thickness for each of the Tyler zones (i.e. upper part of the Tyler, middle part of the Tyler and lower part of the Tyler) as a new attribute in order to manipulate the symbology of the shapefile by sandstone thickness. However, there are not enough wells to map specific channel sands, so I summed all sandstone lenses in each Tyler zone. This created a gross sandstone thickness for each zone. For example in the Hendry-Nieman #1 (API 33033000660000) well, there are two distinct sandstones in the lower part of the Tyler, the first between 7828’-7842’ MD (10’ thick) and the second between 7845’-7855’ (14’ thick) totaling 24’ of lower Tyler sandstone thickness (figure 3.3).

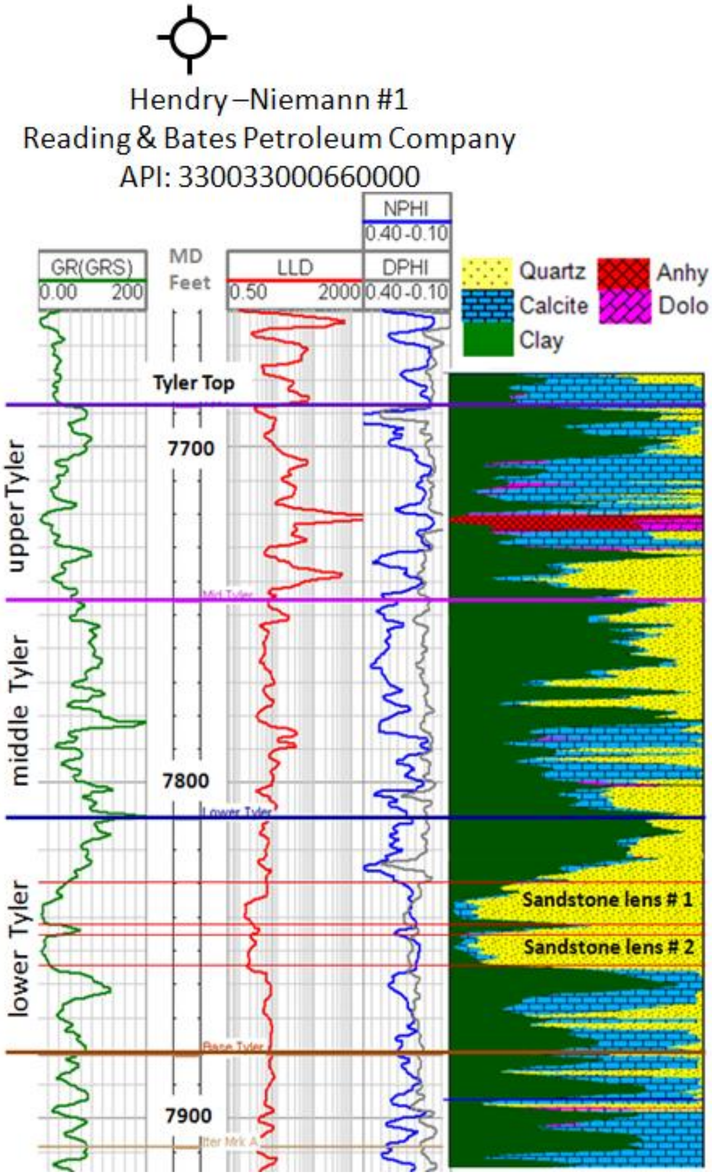


Figure 3.3: Hendry – Niemann #1 Example of How Individual Sandstone Lenses are Added for the Cumulative Gross Sandstone Thickness per Zone. Sandstone lens #1 in lower part of the Tyler section is 14' thick and sandstone lens #2 is 10 feet thick so for the lower part of the Tyler Zone a gross sandstone thickness of 24' was calculated and used for mapping purposes.

I constructed bubble maps based on gross sandstone thickness of each zone. For the upper Tyler zone I divided the range in thickness into 5 distinct classes; 0-2 feet thick are a red size 4 diamond symbol, 3-5 feet thick are orange with a size 8 diamond symbol, 6-10 feet thick are yellow with a size 13 diamond symbol, 11-15 feet thick are green with a size 20 diamond symbol, and 16-25 feet thick are blue with a size 30 diamond symbol (Plate 6). I also labeled the gross sandstone thickness of the upper Tyler zone next to the well. For the middle Tyler zone I divided the range in thickness into 5 distinct classes 0-5 feet thick are a red size 4 triangle symbol, 6-10 feet thick are orange with a size 8 diamond symbol, 11-20 foot thick are yellow with a size 13 triangle symbol, 21-30 feet thick are green with a size 20 triangle symbol, and 31-60 feet thick are blue with a size 30 triangle symbol (Plate 7). I also labeled the gross sandstone thickness for the middle Tyler zone next to the well. For the lower Tyler zone, I divided the range in thickness into 5 distinct classes 0-5 foot thick are a red size 4 circle symbol, 6-10 feet thick are orange with a size 8 circle symbol, 11-20 feet thick are yellow with a size 13 circle symbol, 21-30 feet thick are green with a size 20 circle symbol, and 31-60 feet thick are blue with size a 30 circle symbol (Plate 8). I also labeled the gross sandstone thickness for the lower Tyler zone next to the well.

To construct the surface lineament maps, I used Anderson's 2011 NED lineaments from the North Dakota Geological Survey. I combined them with an elevation map using the 2010 10-meter National Elevation Datasets (NED) from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) geospatial gateway located online at http://datagateway.nrcs.usda.gov/GDGOrder.aspx. I used ArcView GIS spatial analysis to construct a uniformly calibrated merged mosaic from the individual NEDs. I then constructed a hill shade with a sun azimuth at 315° and at a 45° angle from the horizon, to accentuate elevation differences and give the map visual depth (Plate 9). I also placed the historical lineaments on the hillshade map and compared how these lined up with the topography (Plate 10).

For the final comparison, I created a polygon shapefile of the Pennsylvanian valley outline in ArcView. I constructed a map using the Anderson's surface lineament with the valley outlines and visually inspected it to see if a relationship could be deciphered, for example if the surface lineaments outline the Pennsylvanian valleys (Plate 11). To quantify the spatial relationship surface lineaments have to Pennsylvanian valleys, I constructed a map by overlaying the lineament density contours and surface lineaments (Plate 12). I colored in lineament density contours that were greater than 30,000 feet per square mile to distinguish from the background lineament density (Plate 17). The colored-in contours represent the lineament predicated areas where there should be a greater probability of sandstone preservation.

CHAPTER 4

RESULTS AND DISSCUSSION

4.1 Established Relationships of Surface Lineament

Many intracratonic sedimentary basins exhibit nearly orthogonal surface lineament geometry (Broucher 1997). One of the best examples is the Cooper Basin in Australia where Tim O'Driscoll used lineament analysis to successfully locate one of the world's largest copper-uranium-gold-silver deposits at Olympic Dam (Broucher 1997). Another example is the Michigan Basin that lies on the North American Craton. Many oil fields have an obvious preferred orientation along strike to many of the lineaments. The Williston Basin is similar in that many fields are oriented along strike to major lineaments.

Lineament analysis helped locate areas where the Proterozoic rocks are fractured and filled with precious metals in the Cooper Basin of Australia (Broucher 1997). The fractured basement rocks created zones of weakness in the sedimentary layers above that caused these zones to be preferentially eroded so lineaments formed at the surface. In the Michigan Basin, lineament analysis was used to help locate areas where deep faults exist that produced for greater heat flow along the anticline structures, which in turn generate thermogenic dolomite. The dolomite has a greater chance of preserving secondary porosity and being an oil reservoir. In both cases the lineaments had structural ties and a direct influence on the distribution of the target resource.

The North Dakota Tyler study attempts to use surface lineaments to map fluvial sandstones that presumably are preferentially deposited along lineament orientations. The surface lineaments are theorized to be the result of basement weakness zones that have been constantly reactivated though geologic history by tectonic forces and have caused subtle topographic change due to preferential erosion, minor structures or small faults. These subtle topographic changes would also have had to exist during Pennsylvanian time, since the basement weakness zones existed before the Pennsylvanian. The small topographic changes are expected to have, through geologic time, produced the drainage pattern parallel to the surface lineaments.

The hypothetical relationship between surface lineament and preserved Tyler sandstone is much more complicated and less direct then the Cooper Basin or Michigan Basin examples. There are many more controls on river patterns, and preservation of fluvial sandstone is considerably more complicated. Fluvial patterns are controlled by both autocyclic and allocyclic processes. Autocyclic changes do not require a change of total energy or material input into the system, and are usually smaller scale changes that occur over short time periods (Beerbower 1964). In an attempt to suppress the autocyclic response in preservation, I was concerned with more-general trends and grouped the sandstone bodies into the three Tyler zones instead of mapping each sandstone lens, which would have given a high-frequency response. Not every fining-up or coarsening-up log signature is related to an allocyclic control (*i.e.* relative sea level rise and fall).

4.2 Tyler Sandstone Deposition and Preservation

During the deposition of the Tyler Formation, the Williston Basin goes through an overall transition from clastic-dominated to more carbonate-dominated. This change in sedimentation reflects the transition through a depositional sequence from lowstand systems tract to transgressive system tract and finally a highstand systems tract.

The erosional surface (*i.e.* sequence boundary) at the base of the Tyler was created by falling sea level. The lowstand systems tract took over and deposited fluvial sands in the incised valleys; however, sediment supply was low because of low structural relief. The exposed Kibbey Sandstone on the edges of the basin supplied some sand sediment, as did the exposed basement over 500 miles to the north and east. The terrestrial sediment supply could not fill the accommodation space, and so the lower part of the Tyler has a mix of terrigenous and marine-influenced sediment deposited during short episodic sea level rises during a time of overall lowstand sea level.

As the lowstand systems tract gave way to the transgressive systems tract, the sedimentation became slightly more marine-influenced. The rise in sea level is discernable by the presence of more dark calcareous shale and an increase in carbonate sedimentation. However due to the shallow nature of the basin, terrigenous sedimentation is still active, even into the center of the basin, because any small changes in sea level moved the shoreline inland and out by several miles. Short episodic regressions of sea level are marked by thin lignite stringers, paleosols, and multicolored oxidized muds. The terrestrial indicators lessen in frequency toward the top of the middle part of the Tyler.

The upper part of the Tyler is fairly consistent across the entire basin because it is a highstand systems tract. The upper part of the Tyler lies on a black, highly radioactive marine shale that denotes a maximum flooding surface. The limestones located in the upper part of Tyler Formation exhibit aggrading stacking patterns and thin upward. The sandstone located at the base of the upper part of the Tyler zone, just above the maximum flooding surface, are not related to the sandstones in the middle and lower part of the Tyler. This is seen on the gross sandstone bubble map (Plate 13). The sandstones, in the middle and lower parts of Tyler Formation, amalgamate and often create channel scours; they are often oriented in the same orientation and are often found near each other. However the sandstones in the upper part of the Tyler do not amalgamate with the sandstones located in the middle and lower parts of the Tyler. The sandstones in the upper part of the Tyler have independent orientations to the other sandstones. Unlike the sandstones located in the lower and middle part of the Tyler, the sandstones in the upper part of the Tyler are not associated with the areas of thickest gross Tyler.

4.3 Identification of Incised Valleys

The identification of Tyler fluvial valleys requires summing the isopach maps and examining them with cross sections. The isopach maps led me to areas that might have greater Tyler depositions, and I then used the cross section to evaluate whether the Otter Formation is anomalously eroded for that locality. Unfortunately much of the area has widely scattered well distribution. In some areas such as the far west, well density drops to just two or three well per township.

It is possible that I missed some smaller Tyler valleys because the identification of incised valleys is not easily accomplished by isopach maps when the valleys are obscured by differential compaction. The original thickness of deposition in the valley is concealed by the type of rock preserved in the valley. Many mudstones and coals are found in the valley fills because the basin is underfilled and sediment-starved. Mudstones and especially coal have a much higher compressibility than sandstones so mud-filled valleys do not stand out using isopach maps.

I realized that the well density was inadequate for the level of detail needed to precisely map fluvial channels and valleys. There is too much space between wells. Even in the Fryburg Field area, wells that penetrated the Tyler Formation average about ½ mile apart. Out of the field area, the space between wells is several miles. The southwest half of the study area has fewer than 20% of the wells.

4.4 Lineaments

To evaluate the validity of Anderson’s (2011) NED derived lineaments I placed them on a topography map (Plate 9) made from NEDs. To my surprise I did not notice a relationship between topography and many small surface lineaments. I changed the sun azmith, the sun angle from the horizon and adjusted the vertical exaggeration in an attempt to justify some of the small surface lineaments. I could not get some of the lineaments to correlate to anything topographic that I would consider a lineament. However, I did use a different vintage NEDs from a different source. To settle my concern I incorporated part of a separate surface lineament study conducted by Earthfield Technology (http://www.earthfieldtechnology.com/Company-Profile.html) in 2008. I placed Earthfield's surface lineaments (blue) and Anderson's surface lineaments (orange) on my topography map and again visually inspected it (Plate 14). I could see a relationship between Earthfield's surface lineaments and the topography map. The lineaments were surprising completely different. The study area is greater than 1,700 sq. miles, and not a single lineament recognized by Anderson was recognized by Earthfield. Just like the experiment Boucher (1997) conducted, everyone saw a different way and reason to draw the lineaments. Lineament interpretation is sensitive to the interpreter, and is too qualitative to get accurate results.

CHAPTER 5

CONCLUSIONS

Surface lineaments alone cannot distinguish areas of greater fluvial sandstone preservation in the Tyler Formation. The Tyler Formation has a complex depositional system, a highly active tectonic history and surface lineament interpretation is too qualitative to produce quantitative results.

5.1 Tyler Formation and Its Complex Depositional System

Some of the complexity in Tyler Formation is due to the nature of the fluvial deposition. Rivers are controlled by many different factors that affect deposition at different scales. When rivers respond autocyclicly, they mask some of the allocyclic responses due to sea level and topographic changes. Surface lineaments are assumed to have subtle topographic signatures. The subtle change in topography was supposed to be the allocyclic control on the river pattern, helping to designate the areas of deposition and preservation of thicker sandstones. This relationship was not revealed in my study. The best example of a Tyler fluvial valley is Rocky Ridge Field. The field is not bounded by any significant surface lineaments (Plate 11) and the field is not in an area of greater lineament density (plate 15).

Of the roughly 200 sq. miles of Tyler valleys only about 29 sq. miles coincide with lineament density greater than 30,000 feet per mile, with the most contiguous portion of coincidence (13 sq. miles) being in the north center part of the study in Knutson field (Plate 17). The 13 sq. mile area in Knutson field is the only location that the orientation of Tyler valleys and lineament density coincide, in the study area of the more than 1700 sq mile..

5.2 Tectonically Active Basin

The Pennsylvanian was one of the most tectonically active periods in North America. The forming of the Ancestral Rockies, Alleghenian Orogeny, and Ouachita Orogeny all influenced the deposition in the Williston Basin. The shape, orientation, and tilt of the Williston Basin were changed during the Pennsylvanian. The collision-related features complicated and overwhelmed the subtle topographic influence surface lineaments have.

The Williston Basin has undergone many changes since the Pennsylvanian. The older structures are concealed by more recent geologic events such as the Laramide Orogeny and Quaternary Ice Age. These events all produced surface lineaments with different orientations. Glacial advance and retreat generates many scours and moraines that can all be interpreted as lineaments. The orientation of the surface lineaments produced by glaciers would not be related to any basement weakness zone.

5.3 Qualitative Nature of Surface Lineament Interpretation

Lineament studies are too subjective to produce quantitative result. Lineament identification is conducted differently by nearly every scientist (Boucher 1997). In the more than 1,700 sq. miles contained in the study area and thousands of surface lineaments identified by Anderson, none were identified by Earthfield. Many geologic process generate lineaments; without some sort of subsurface data such as seismic, gravity, or magnetic, I cannot filter the surface lineaments for those related to basement weakness zones.

5.4 Further Study

It would be exciting to use a combination of 3D seismic and surface lineament analysis. There have been significant advances in 3D seismic technologies in the past couple of years, allowing for better resolution of individual horizon slices. Applying surface lineament mapping techniques on horizons could prove a powerful technique. The combination would ensure truer ties to basement weakness zones. The technique would reveal the geometry of lineaments as they propagate vertically; as well as possible migration paths for hydrocarbons.

Unfortunately I did not find a conclusive relationship between surface lineaments and lithofacies distribution of the Tyler Formation in North Dakota. The heterogeneity of the fluvial deposition is very complicated. The Williston Basin has been subject to many lineament-producing events; without more data I cannot decipher which surface lineaments are related to subsurface weakness zones.

REFERENCES

Anderson, F., 2009, Lineament Mapping and Analysis in the Northeastern Williston Basin: Exploration and Production Trends in the Parshall Area North Dakota, North Dakota Geological Survey Geologic Investigations, No. 80.

Argialas, D. P., Stearns, R. G., and Shahrokhi, F., 1988, Mapping of Landsat Satellite and Gravity Lineaments in West Tennessee, Journal of Aerospace Engineering 1:74-87.

Asquith, G., and Gibson, C., 1982, Basic Well Log Analysis for Geologist, American Association of Petroleum Geologist.

Barwis, J. H., 1990, Flood-Tide Delta Reservoirs, Medora-Dickerson Trend, North Dakota, Sandstone Petroleum Reservoirs, Springer-Verlag, P. 389-412.

Beerbower, J. R., 1969, Interpretation of cyclic Permo-Carboniferous Deposition in Alluvial Plain Sediments in West Virginia: Geological Society of America Bulletin, v. 80, p. 1843-1847.

Boucher, R. K., 1997, Lineament Tectonic Data, South Australia with a Focus on the Cooper Basin, Mines and Energy Resources South Australia, Report Book 97/39.

Brown, D. L., and Brown, D. L., 1987, Wrench-Style Deformation and Paleostructural Influence on Sedimentation in and Around a Cratonic Basin, Rocky Mountain Association of Geologist, Williston Basin Anatomy of a Cratonic Oil Province, P. 57-70.

Caran, S. C, Woodruff, C. M., and Thompson, E. J., 1981, Lineament Analysis and Inference of Geologic Structure Examples From the Balcones Ouachita Trend Texas, Gulf Coast Association of Geological Societies Transactions, V. 31, P. 59-69.

Carlson, C. G., and Anderson, S. B., 1965, Sedimentary and Tectonic History of North Dakota Part of the Williston Basin, Bulletin of the American Association of Petroleum Geologist, Vol 49, No. 11, P. 1833-1846.

Chimney, P. J., Treska, C.E., Wolosin, C. A., 1992, Richardton/Taylor Fields-U.S.A. Williston Basin North Dakota, American Association of Petroleum Geologist Treatise of Petroleum Geology, Stratigraphic Traps III, P. 421-445.

Cooley, M. E., 1983, Linear Features Determined from Landsat Imagery in North Dakota, Department of the Interior United States Geological Survey Open File report, Plate 1.

Darton, N. H., 1904, Comparison of the Stratigraphy of the black hills, Big Horn Mountains, and Rocky Mountains, Front Range, Geological Society of America Bulletin, Vol. 15, P. 379-448.

Freeman, O. W., 1922, Oil in the Quadrant Formation in Montana, Engineering and Mining Journal, V. 113, No. 19, P. 825-827.

Gerhard, L. C., Anderson, S. B., Fischer, D., 1989, Petroleum Geology of the Williston Basin, American Association of Petroleum Geologist, Interior Cratonic Basins: Chapter 29, P. 507-559.

Gay, S. P., 1973, Pervasive Orthogonal Fracturing in Earth Continental Crust, American Stereo Map Co., Technical Publication No. 2.

Haq, B. U., and Al-Qahtani, A. M., 2005, Phanerozoic Cycles of Sea- Level Changes on the Arabian Platform, Geo Arabian, Vol 10, P. 127-160.

Haq, B. U., and Shutter, S. R., 2008, A chronology of Paleozoic Sea-Level Changes, Science, Vol. 322, P. 64-68.

Hastings, J. O., 1990, Coarse-Grained Meander-Belt Reservoirs, Rocky Ridge Field, North Dakota, Sandstone Petroleum Reservoirs, Springer-Verlag, P. 57-84.

Hobbs, W. H., 1904, Lineaments of the Atlantic Border Region, Geological Society of America Bulletin, Vol. 15, P. 483-506.

Hobbs, W. H., 1912, Earth Features and Their Meaning, an Introduction to Geology for the Student and General Reader, New York, P. 506.

Holbrook, J., and Schumm, S. A., 1999, Geomorphic and Sedimentary Response of Rivers to Tectonic Deformation: A Brief Review and Critique of a Tool for Recognizing Subtle Epeirogenic Deformation in Modern and Ancient Settings, Elservier Science, Tectonophysics, Vol 305, P287-306.

Hodgson, R. A., 1974, Review of Significant Early Studies in Lineament Tectonics, Proceedings of the First International Conference on the New Basement Tectonics, Utah Geological Association Publication, Vol. 5, P. 1-10.

Maughan, E. K., 1984, Paleogeographic setting of the Pennsylvanian Tyler Formation and Relation to Underlying Mississippian Rocks in Montana and North Dakota, The American Association of Petroleum Geologist Bulletin, Volume 68 No. 2, P. 178-195.

Maughan, E. K., and Perry, W. J., 1986, Lineaments and Their Tectonic Implications in the Rocky Mountains and Adjacent Plains Region, J.A. Peterson ed., Paleotectonics and Sedimentation in the Rocky Mountain Region, United States: AAPG Memoir 41, P. 41-53.

Murphy, E. C., Nordeng, S. H., Juenker, B. J., and Hoganson, J. W., 2009, North Dakota Stratigraphic Column, North Dakota Geological Survey.

Mundt, P. A., 1956, The Tyler and Alaska Bench Formations in Judith Mountains: Central Montana, Billings Geological Society: 7th Annual Field Conference Guidebook

North Dakota Oil and Gas Commission, https://www.dmr.nd.gov/oilgas/, accessed May 2010.

O'Driscoll, E. S. T., 1985. The Application of Lineament Tectonics in the Discovery of Olympic Dam Cu-Au-U Deposit at Roxby Downs, South Australia, Global Tectonics and Metallogeny, 3(1):43-57.

Ogden, E., 2010, Formation Creating Interest: Tyler Formation is Similar to the Bakken, Minot Daily News, the Associated Press.

O'Leary, D. W., Friedman, J. D., and Pohn, H. A., 1976 Lineament, Linear, and Lineation: Some Proposed New Standards for Old Terms, Geological Society of America Bulletin, Vol. 87, P. 1463-1469.

Peale, A. C., 1893, The Paleozoic Section in the Vicinity of Three Forks, Montana, United States Geological Survey Bulletin, 110, P. 9-56.

Porter, K. W., and Sonnenberg, S. A., 1994, Overview of Criteria for Recognition and Mapping of Valley Fills and Associated Surfaces: Lower Cretaceous Muddy Sandstone, Rocky Mountain Region, Rocky Mountain Association of Geologist, Unconformity Controls 1994 Symposium, P.157-166.

Reeves, F., 1931, Geology of the Big Snowy Mountains, Montana: U.S. Geological Survey Professional Paper 165-D, P.135-149.

Scotese, C. R., 2010, Paleomap Project, http//www.scotese.com.

Scott, H. W., 1935, Some Carboniferous Stratigraphy in Montana and Northwestern Wyoming, Journal of Geology, Vol 43, P 9-56.

Shurr, G. W., 1982, Geological Significance of Lineaments interpreted From Landsat Images Near the Northern Black Hills, North Dakota Geological Society and Saskatchewan Geological Society, Fourth International Williston Basin Symposium, P. 313-320.

Sloss, L. L., 1964, Symposium on Cyclic Sedimentation: Tectonic Cycles of the North American Craton, Kansas Geological Survey Bulletin 169, P. 449-459.

Snedden J. W., Liu, C., 2010, A Compilation of Phanerozoic Sea-Level Change, Coastal Onlaps and Recommended Sequence Designations, American Association of Petroleum Geologist, Search and Discovery Article #40594.

Sturm, S. D., 1982, Depositional Environments and Sandstone Diagenesis in the Pennsylvanian Tyler Formation of Southwestern North Dakota, Fourth International Williston Basin Symposium, P. 251-262.

Sturm, S. D., 1987, Depositional History and Cyclicity in the Tyler Formation (Pennsylvanian), Southwestern North Dakota, Williston Basin: Anatomy of a Cratonic Oil Province Symposium, P. 209-221.

Sturm, S. D., and Peterson, J. C., 1994, Tectonic Influence on Facies Architecture and Permeability Variation: Pennsylvanian Tyler Formation, Fryburg Field, North Dakota, American Association of Petroleum Geologist, Search and Discovery Article #90986.

Thomas, G. E., 1974, Lineament-Block Tectonics: Williston-Blood Creek Basin, American Association of Petroleum Geologist Bulletin, V. 58, No. 7, July P. 1305-1322.

Trexler, D. T., Bell, E. J., and Roquemore, G. R., 1978, Evaluation of Lineament Analysis as an Exploration Technique for Geothermal Energy, Western and Central Nevada, G. R.

Freeman, O. W., 1922, Oil in the Quadrant Formation in Montana, Engineering and Mining Journal, V. 113, No. 19, P. 825-827.

Wilson, B. W. and Nanz, R. H., 1959, Sand Conditions as Indicated by the Self-Potential Log, EPR Memorandum Report 51, Shell Development Company.

Ziebarth, H. C., 1964, The Tyler Formation of Southwestern North Dakota, The Third International Williston Basin Symposium, North Dakota Geological Society and Saskatchewan Geological Society, P. 119–126.

BIOGRAPHICAL INFORMATION

Nicolas Beltran Guerrero is the second of five children of Mr. Nicolas M. Guerrero and Mrs. Enedina B. Guerrero. He graduated with his Bachelors of Science in Geology from The University of Texas at Arlington (UTA) in 2007 and Masters of Science in Geology from UTA in 2012. As a graduate student he was on UTA's 2010 Imperial Barrel Team that won AAPG's Southwest Section Regional Imperial Barrel Competition and participated for in the International Imperial Barrel Competition. He currently works for Petro-Hunt L.L.C., where he is a member of the "Unconventional Resource Team" and "International Exploration Team".