RELATING STRATIGRAPHY, LITHOLOGIC FACIES, AND 3D SEISMIC ATTRIBUTES TO OIL PRODUCTION IN BAKKEN FORMATION WELLS, RED SKY AREA, WILLISTON BASIN, NORTH DAKOTA

A Thesis Presented to the

Faculty of the Department of Earth and

Atmospheric Sciences University of

Houston

In Partial Fulfillment of the Requirements
for the Degree Master of Science

By

Corbin William Crews II

August 2015

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ABSTRACT

The Bakken Formation is considered the most important hydrocarbon-bearing rock unit in the Williston Basin of North Dakota and is currently one of the most prolific unconventional resource plays in North America with a 2015, basin-wide production of approximately 1.1 million barrels of oil per day. Most production from the Bakken Formation is from wells drilled horizontally and completed using hydraulic fracturing in the relatively thin Bakken formation that varies in thickness from 0 to 160 feet (0 to 49 meters). Studies by previous workers in the Williston basin have identified six, field-scale “sweet spots” characterized by higher production relative to other areas of the Williston Basin. Previous workers have also recognized that significant variation in hydrocarbon production exists even at scales of 1000’s of feet to a few miles between individual wells within these known sweet spots. The objective of this thesis is to understand the causes of these localized, field-scale, production variations and how to best optimize future wells and completions. Unlike previous studies that focused on regional-scale sweet spots, the work presented here focuses on the field level, which is scale for drilling and completion decisions.

I present an integrated interpretation of the geology, geophysics, and drilling and completion designs of wells targeting the Bakken Formation in the Red Sky area, Mountrail County, North Dakota, in order to explain localized variations in well productivity using my compilation of historical production statistics. Using a high-quality, time-migrated, 3D seismic survey combined with well logs, core data, well files, seismic attributes, and production statistics, I have identified the productive reservoir unit and its natural fracture patterns over an area of approximately 730 square miles. Using ArcGIS spatial analysis and TIBCO Spotfire analytical software, I present a simple method to quantify variations in historical production statistics and how these variations reflect geologic controls including facies and fracture patterns. Geologically, the most significant control on the “sweet spot” are thick sand bodies of the Middle Bakken Formation deposited in a tidal dominated barrier bar system. Structurally, the most significant control on sweet spots are areas of the least number of natural fractures as mapped using seismic attributes.

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Chapter 1: Introduction

1.1 Project rational

This project began with the observation that closely spaced, horizontal wells in the Bakken Formation displayed significant variations in production even when drilled with similar orientations and completion designs (Wiley et al., 2004). This observation led to the main objective of this thesis: to understand what geologic processes or characteristics control well quality between adjacent wells on the scale of a typical oilfield development.

The answer to this question is not straightforward as shown by previously published research on the Williston basin and other unconventional shale plays in North America. Reservoir analysis techniques developed for conventional reservoirs are often insufficient to address the scale of geologic variation within unconventional resource plays like the Bakken Formation (Cipolla et al., 2011). Localized sedimentary facies variations -especially in thin (less than 150 feet thick) formations like the Bakken Formation - are commonly below the resolution of both 3D seismic data and well logs (Simenson, 2011). Lenses of calcite cement, which were observed from cores in this study to act as strong vertical barriers on hydrocarbon saturation at the inch to foot scale also exist well below the resolution of both 3D seismic data and well logs (Chapter 2, Figure 20).

Good vertical well-log coverage often is not available in unconventional plays like the Bakken because most wells are drilled horizontally. Well logs run in horizontal wellbores give important information of the reservoir characteristics adjacent to the wellbore, but because the drilling and logging orientation is parallel to bedding variation, horizontal well logs lack the vertical reference frame for accurate mapping of spatial facies changes. Finally, drilling and completion operations induce mechanical effects on the reservoir, which can act to mask the effects of geologic controls including natural fractures (Cipolla et al., 2011).

This thesis uses an extensive data compilation to propose a new technique for evaluating productivity at high spatial resolutions and over large areas in a short time and at reasonable cost. For most operating companies exploring unconventional resources, the use of 3D seismic data is critical in developing drilling plans and identifying drilling hazards. The 3D seismic data are used to assess the fracturing and structure above and below the reservoir and to improve drilling designs.

Unconventional plays are usually restricted to a thin vertical section at depth (less than 160 feet in the case of the Bakken Formation). Because such thin beds may be below the seismic-tuning thickness, seismic resolution is unable to detect thin lithologic changes. Computing seismic attributes based on the 3D seismic data set is an approach for characterizing potential drilling targets that has proven very successful in evaluating deep-water units where thicknesses can be over a thousand feet (Chopra and Marfurt, 2007). Seismic attributes implementation have been less successful in thin unconventional formations, like the Bakken, which is approximately 160 feet at its thickest point with some of the highest quality reservoir facies between 5 and 20 feet thick.

Because the Upper and Lower Bakken shale have high organic content and are characterized by significantly slower seismic velocities than the surrounding carbonate lithologies the Bakken reflector is easily recognized and mappable over most of the Williston Basin (Anna et al., 2010)(Chapter 2, Figure 24). The generation of structural attributes can be used to reveal subtle variation in the reservoir structure that may have an impact upon stress states and the presence of natural fractures that may exist below the resolution of the 3D seismic data (Jones and Roden, 2012). Attribute values can then be compared with normalized production volumes over the lifetime of Bakken wells to establish relationships between the particular attribute characteristic and well quality (Cipolla et al., 2011).

Large-scale hydraulic fracture operations, carried out on reservoirs like the Bakken Formation that have high reservoir pressures - close to ambient critical stress - can significantly, alter in situ stresses during drilling and completion (Zhou et al., 2008). These human-induced engineering effects on the reservoir must also be taken into account to recognize the underlying and complex geologic variations that control production variations at local scales.

1.2 Conventional versus unconventional resources

A brief discussion is required to address nomenclature and fundamental differences and issues between the two primary types of hydrocarbon accumulations being exploited around the world today. Conventional resources, with a much longer period of development extending back to the 19th century, are characterized by three essential elements: a source, a reservoir, and a seal. Conventional petroleum systems also require a process of hydrocarbon generation, migration, trapping, and preservation over geologic time to produce exploitable hydrocarbons. Any conventional petroleum system lacking a crucial component element or having mistimed process will be uneconomic or could lack hydrocarbon accumulations all together.

Conventional petroleum accumulations are characterized by buoyancy effects of hydrocarbons that require pathways for fluid migration away from a source rock and into a sealed trap. Within a trap there are usually multiple fluid phases and contacts between gas, oil, and water segregated vertically according to their buoyancy. These accumulations usually occur over relatively large areas and require gravity drainage and a water-drive mechanism to move hydrocarbons from the reservoir to the surface. Because these mechanisms are quite efficient, very few wells are required to drain large volumes of hydrocarbons from conventional traps and large recovery factors are to be expected (Sonnenberg, 2001).

Conversely, unconventional, or continuous, petroleum accumulations do not require these same petroleum systems elements. Often unconventional resources are associated with shale formations that would be considered the source rock for a conventional system. Thus, unconventional petroleum systems are often characterized by a single formation acting as a source, reservoir, and seal.

Unconventional accumulations are usually associated with tight rock, or formations with very low porosity and permeabilites, and high reservoir pressures, which act as the driving mechanism for hydrocarbon production. As hydrocarbons are produced, the driving high reservoir pressures that drive production is inherently diminished over time, and future production potential is lowered. Unlike conventional reservoirs, which generally produce hydrocarbons at more constant rates throughout their production lifetime, production from unconventional systems decline at a rapid, exponential pace over time (Sonnenberg, 2001). Tight geological formations are defined as reservoirs that have less than 0.1 millidarcy (mD) of matrix permeability and less than ten percent matrix porosity, which generally require large hydraulic fracture completions to be economically produced (Law and Spencer, 1993).

Because of these characteristics, unconventional resource plays require both a large number of wells drilled horizontally over long distances and complex completion designs that use multiple perforation stages and high-pressure hydraulic fracture stimulations to access the hydrocarbon stored within the tight rocks (Cipolla et al., 2011). Because of the high reservoir pressures and extremely low porosities and permeabilites, fractures induced by hydraulic fracturing must be propped open by ceramics or sand-like particles called proppants to reduce the closure of the fracture network after fracture operations cease. The presence of naturally occurring fractures will have major effects on the production within these tight reservoirs. Most of these natural fractures exist at scales well below the resolvable limit of seismic data. The use of a seismic attribute on 3D data, such as edge detection, gives an indication of stress state and possible natural fracture swarms that are irresolvable by seismic offset analysis.

Owing their success to new technological innovations and large areal extents, formations like the Bakken that were known to be hydrocarbon-rich, but uneconomic to develop, now produce huge output volumes and highly favorable return on investment capital, especially in sweet spot areas of basins like the Williston (Theloy, 2014). While these unconventional plays have been considered highly successful, the fact remains that recovery factors -even for the most productive North American unconventional plays, are still dismally low, and often in the single digits, with an average of around 5-8% of oil in place (EIA, 2011). When this small recovery is compared with primary recover factors of conventional reservoirs in the range of 30-40%, the large disparity in production efficiency of conventional vs. unconventional resources is clearly illustrated.

“Tight oil plays,” as these new unconventional resources are called, present a number of additional challenges that are not completely shared with tight gas plays (Aguilera, 2014). First, oil is a liquid that is incompressible and its molecular structure is much larger and more complex than that of natural gas, or methane. Oil is also a generic term and in most case the in-situ fluids are found in a variety of phases at in different areas of a particular basin. Second, this phase complexity impacts reservoir-drive mechanisms and presents additional issues related to processing and deliverability at the surface

The recent boom of unconventional resource success in North America has not come without continuing challenges. One of the biggest issues currently facing exploration and production companies is the application of conventional geological and engineering techniques that have been developed and refined for over a century to unconventional resources that have emerged only within the past decade (Wiley et al., 2004). Though conventional techniques can be used on large, basin- to field-size scales, better methods and techniques must be developed to assess variations in reservoir quality and stress heterogeneity over more useful scales, like the field- to the well-scales. Improvements in these areas will help us increase the efficiency of extraction and improve the recovery factor with which these unconventional resources are developed and support their viability for the futures.

1.3 Project background

This thesis project is the outgrowth of several personal experiences during my academic work and during my applied experiences with the oil and gas industry. I personally witnessed the boom of Barnett Shale production near my hometown of

Dallas, Texas, and became interested in unconventional resource plays and becoming involved in exploring for new shale resources here in North America.

For the two summers following high school, and after my first year as an undergraduate geology major at the University of Texas at Austin, I worked for a small company in Dallas, Brazos Oil & Gas, exploring the Hayneville-Bossier Shale play in east Texas and Western Louisiana. The Haynesville remains a very prolific gas play although production has slackened during the large drop in natural gas prices in 2008 related to overproduction using newly developed, unconventional drilling and production methods.

During the summer after my second year at the University of Texas, I worked for a small, unconventional exploration company, Eldorado Resources, exploring the shallow, immature, but highly organic-rich Bakken shale in eastern North Dakota and southern Manitoba. Being involved in this truly unconventional shale-oil extraction, I was introduced to innovative hydrocarbon extraction method involving dual horizontal well and advanced electrode heating elements that were designed to coerced oil and gas out of immature, but highly organic rich source rocks.

For the last two summers of my undergraduate studies at the University of Texas, I worked for Three Rivers Operating Company, which was an independent operator, working in the west Texas and eastern New Mexico Permian Basin. With the Three Rivers Operating Company I had the opportunity to work on a number of conventional and unconventional play types in the Permian Basin. Around the time of my graduation from the University of Texas in May of 2012, Three Rivers was very interested in the Lower Wolfcamp Shale (also referred to as the Cline Shale) which was an emerging unconventional oil play with large areal extents and very high upside, which is still underexplored.

In a final summer internship with ConocoPhillips as a graduate student at the University of Houston, I had the opportunity to work on exploration of the Eagle Ford shale play in southeast Texas, which was another of North America's most prolific unconventional resource plays. The Eagle Ford Formation has many characteristics similar to the Bakken Formation and my work during this internship has significantly influenced the development of this thesis project.

Because well data and production statistics remain proprietary and restricted for researchers in the state of Texas, I decided to focus my study on the Bakken Shale located in the Williston Basin, North Dakota. All data pertaining to the exploration and production of hydrocarbons in the state of North Dakota is open access and available for a small annual fee. A large volume of data can be accessed by a simple web query, which makes it very attractive for graduate students and others in academia seeking access to high-quality data. I also benefitted from gaining access to the Red Sky 3D seismic and well dataset kindly provided by the Hess Corporation to Dr. Robert Stewart and the AGL Project at the University of Houston.

Chapter 2: INTEGRATION OF STRATIGRAPHY, FACIES, SEISMIC ATTRIBUTES, AND PRODUCTION STATISTICS TO PREDICT BAKKEN WELL PERFORMANCE, RED SKY, WILLISTON BASIN, NORTH DAKOTA

2.1 Introduction

2.1.1 Significance and history of production from the Williston Basin

The Late Devonian-Early Mississippian age Bakken Formation is the most important lithological unit in relation to oil and gas production in the Phanerozoic

Williston Bain according to Sarg (2012). As of June 2015, the Bakken Formation produces approximately 1.2 million barrels of oil a day and is one of the largest unconventional hydrocarbon resources in the United States and the world (EIA, 2015).

The Bakken is a relatively thin (160 foot maximum thickness), heterogeneous formation divided into three main members: The Upper Bakken, the Middle Bakken, and the Lower Bakken. The Upper and Lower Bakken members are black shales; the Middle Bakken member is a dolomitized siltstone with mixed sandstones in some areas. The upper and lower shale members have unusually high organic content (up to 20% total organic carbon (TOC) by weight) that produces significant formation over-pressure where these upper and lower shale members are thermally mature, in the center of the basin (Nordeng et al,. 2010). The Upper and Lower Bakken Shale are the primary source rock for the majority of hydrocarbon production throughout the Williston Basin and are classified as world-class source rocks based on their productivity (Schmoker and Hester, 1983).

Hydrocarbon production in the Bakken Formation began in 1953 with conventional wells that targeted highly fractured and localized oil and gas pools. Success was limited because of the discontinuous nature of the distribution of high-quality reservoir facies in the Middle Bakken member (Price and LeFever, 1991). During this early exploration period in the 1950's, 60's, and 70's, porosity and permeability within in the Bakken Formation itself was considered to be too low for economic exploitation at the time, except for a few isolated, producing fields characterized by extensive natural fractures and exceptional reservoir quality in the Middle Bakken member (Gerhard et al., 1982). Most production in the 1950's through the 1980 in the Williston Basin was from porous, carbonate formations above and below the Bakken

Formation that include the Mississippian Madison Group and the Silurian Red River Formation (Gerhard et al. 1982). This conventional production trend, characterized by vertically-drilled wellbores targeting high-porosity reservoirs, continued through the 1980s but remained largely insignificant; in terms of production volumes compared to other productive US basins at the time such as the Permian Basin of west Texas.

In the late 1980's horizontal drilling technology gained widespread acceptance in the oil and gas industry and led to increased production from thin units including the Bakken Formation (Wiley et al., 2004). However, the reservoir quality and total production, which were approximately 4,500 barrels of oil per day (BOPD) within the Bakken Formation, remained relatively poor in comparison to other resource plays around the United States such as the Permian Basin, which was producing over one million BOPD at the time (UTPB website, 2015) In the early 1990's, hydraulic fracture completions developed in the Cretaceous Barnett Shale of north-central Texas were applied to the thin and tight Middle Bakken reservoir and successfully enhanced porosity and permeability that allowed remarkable increases in production of both liquids and natural gas. Various major and mid-sized companies experimented with combinations of horizontal drilling and hydraulic fracturing over the next decade. By the mid to late 2000's, world oil prices skyrocketed and the 'Bakken Revolution' of tight oil production sparked a bonanza in light- and tight-oil production from the Bakken Formation in the Williston Basin and other unconventional reservoirs in North America like the Barnett and Eagle Ford shale of Texas and the Marcellus shale of Pennsylvania (EIA, 2010).

Estimates of the total recoverable reserves from the Bakken Formation have varied over time by a number of authors, but it is widely accepted that the Bakken petroleum system in the Williston Basin is one of the most significant continuous hydrocarbon accumulations in North America (Sorenson et al., 2010). Various studies estimate the total reserves, recoverable and non-recoverable with today's technology, at up to 24 billion barrels (Sarg, 2012). Another estimate places the figure at 18 billion barrels (LeFever and Helms, 2006). In April 2013, the US Geological Survey released a figure for the expected ultimate recovery of 7.4 billion barrels of oil (Androff and Wade, 2013). Additionally, the existence of highly developed midstream infrastructure and the basin's proximity to major consumer markets in Canada and the United States makes the Bakken one of the most readily exploitable hydrocarbon resources in the world. Operators are able to quickly move hydrocarbons from the ground to the well site to market which added fuel to the Bakken Revolution since late 2014. The Bakken Formation has arguably become a victim of its own success as recent production capacity of the Bakken and other tight oil resources in North America have helped to oversaturated a world oil market in an environment of flat consumer demand, which is exerting downward pressure on the high oil prices that spurred development of in drilling and production methods and technology.

2.1.2 Project goals and methodology

Previous studies have proposed optimal, "sweet spot" areas of Bakken production based upon critical petroleum systems elements recognized at sub-basin scale of tens of miles (Theloy, 2014). These sweet spots have been the primary focus of drilling and production from the major operating companies in the Williston Basin. Significant variation in production also occurs from well to well, even within these regional sweet spot areas (Cipolla, et al., 2011). This project will provide an integrated interpretation of the geology, geophysics, and hydrocarbon-production statistics in the

Bakken Formation to explain variations in well quality in at both the regional scale and well-to-well scale in the eastern region of the Williston Basin in North Dakota.

2.1.3 Project data

The primary subsurface data used in this analysis is the Red Sky 3D seismic and well data provided by Hess Petroleum Company to the University of Houston (UH) Allied Geophysical Laboratory (AGL) in 2014 and an open-access online database from the North Dakota Industrial Commission (NDIC), Department of Mineral Resources (DMR), Oil and Gas Division (<https://www.dmr.nd.gov/oilgas> accessed in 2014 and 2015).

The Hess Red Sky 3D dataset contains both post-stack seismic data and seismic horizon interpretations picked by staff geologists (personal communication with Hess geologist John Hohman, March, 2014). The Hess Red Sky dataset also includes seismic vertical seismic profile (VSP), microseismic, diagnostic fracture injection test (DFIT), core, and well attribute data. The open-access, NDIC online database included scout tickets, well files, well log, and core data for the majority of wells drilled across the North Dakota part of the Williston Basin.

2.1.4 Data integration and workflow

All study data was evaluated using specialized geological and geophysical platforms including IES Petra and Petrel then integrated geospatially in GIS using ArcMap 10.1. ArcMap was chosen for its flexibility in handling many different data types including geology, geophysics, and geospatially referenced surface and subsurface attributes, like historical hydrocarbon-production statistics for specific Bakken oil wells. Additionally, the NDIC has an open-access GIS Map server, compatible with ArcMap, that contains a large, downloadable dataset of North Dakota oil & gas spatial layers, from which I imported data for my study in the Red Sky area. The NDIC shape files illustrate state planes boundaries, unit boundaries, oil fields, well surface locations, directional and horizontal well paths et cetera. I also downloaded, digitized, and imported several open-access geologic studies by the North Dakota Geological Survey with general Bakken and Formation information including regional stratigraphy, structure, thermal maturity, et cetera through the North Dakota Geological Survey's webpage (https://www.dmr.nd.gov/ndgs/bakken/bakkenthree.asp).

Post-stack seismic data provided to UH AGL by the Hess Corporation was evaluated and interpreted in the Petrel software. Seismic attributes generated in Petrel were imported as the spatial values (x, y) and as the attribute value (z). Each attribute horizon contained over two million unique x, y, and z coordinates which were converted using ArcMap, to raster layers in order to optimize their rendering and comparison speed.

Historical fluid production statistics, as well as drilling and completion data, were obtained from the NDIC online database and normalized using Microsoft Excel. The normalized statistics became additional "production statistic attributes" associated individual Bakken Formation oil wells in the study. These production attributes could then be used for further analysis and comparison between the geologic and seismic attributes that were computed in Petra and Petrel.

All of the attribute data were imported into ArcMap for spatial analysis. The geology and geophysics attributes were gridded using empirical Bayesian kriging method and converted to raster layers. Well-paths of Red Sky study wells were linked with their associated production statistics to create individual, ArcGIS feature classes for each study well. Using results from microseismic monitoring studies of hydraulic fracture completion geometries in the Middle Bakken buffer zones were created that measured 500 feet transverse, in all directions, to the wellbores of the study wells (Dohmen, et al., 2014). The wellbore buffer zones account for the average effective area of stimulated rock induced by hydraulic fracture completions, and allows me to compare geologic and geophysical spatial attributes to production statistics for individual wells. Using the spatial analysis toolset in ArcMap, geological and geophysical attributes statistics within each well's wellbore buffer were computed as linked with the associated well.

All of the geological, geophysical statistics computed within the study well's wellbore buffers were imported into TIBCO Spotfire analytics software to be compared with the normalized production statics for each well. Linear-regression analysis was run to analyze relationships between the geology and ultimate well production. These results will be discussed in depth in Section 2.5.2.

2.2 Regional-scale geology

2.2.1 Paleogeography of the Williston Basin

The Bakken Formation is a Late Devonian to Early Mississippian Formation deposited in the intracratonic, Williston Basin which was a partially, enclosed, easterly embayment of the Western Canada sedimentary basin (Figure 1). At the time of deposition, the Williston Basin was situated nearly 600 miles from a convergent plate boundary to the west and formed a shallow epicontinental sea near the Paleozoic equator (LeFever, 1991).

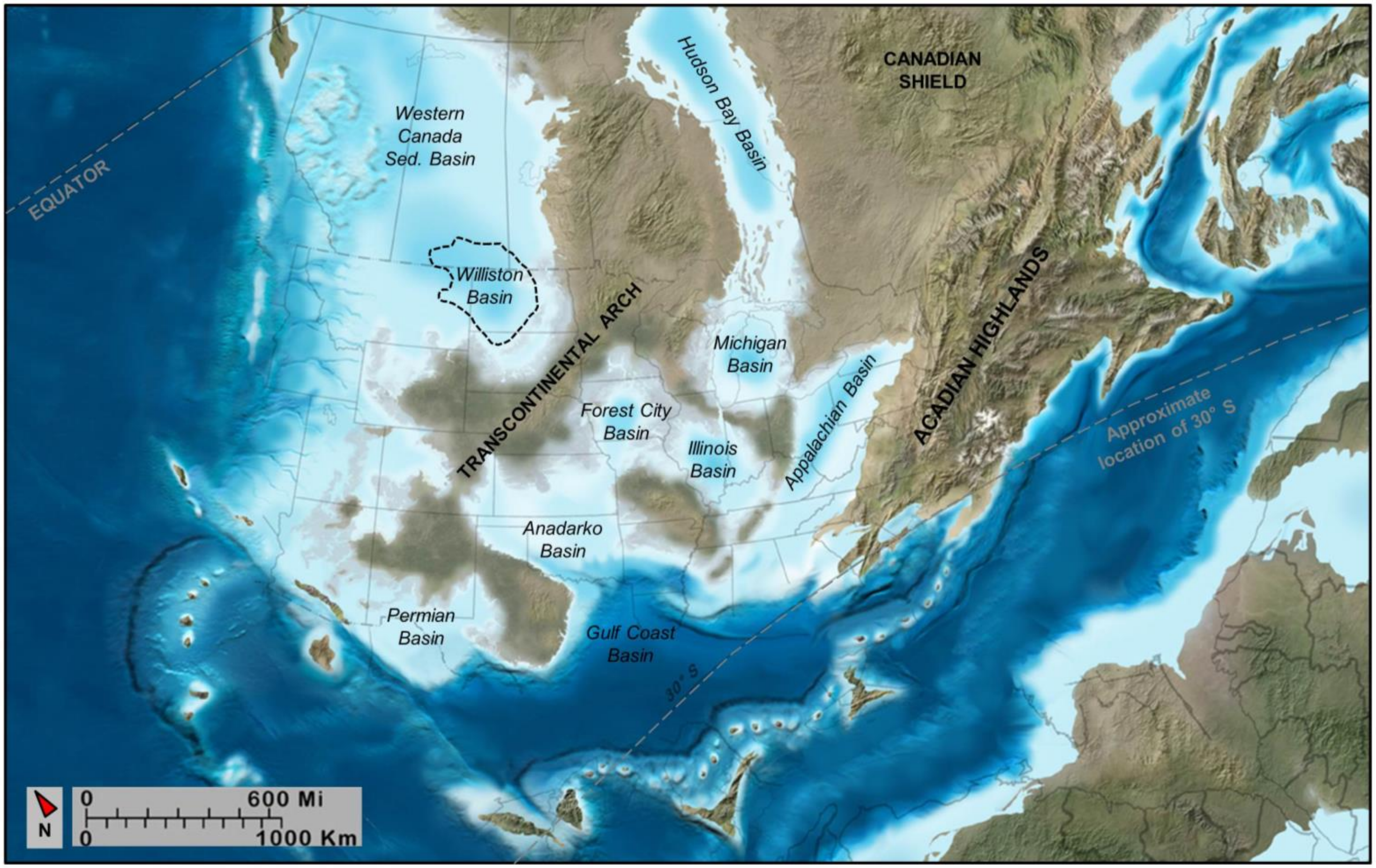


Figure 1: Late Devonian (~375 Ma) paleogeographic reconstruction showing the equatorial, shallow marine, and intracratonic setting of the Williston Basin and other time equivalent sedimentary basins of North America (map modified from Blakey, 2013).

Clastic sedimentary rocks of the Williston Basin were sourced from the southeast and northeast from uplift and erosion of the North American Transcontinental arch. The Lower and Upper Bakken shales were deposited in transgressive systems tracts with max flooding surfaces near their tops. The Middle Bakken member is marked by a complete transgressive-regressive system (Meissner, 1991). These depositional systems generally follow the Paleozoic, eustatic sea level curve as shown by Cobb and Sonnenberg (2013). Bakken lithofacies are also controlled by circulation patterns within the intracratonic Williston basin that promoted cyclical periods of anoxic and oxidized sedimentation (Angulo et al., 2008).

2.2.2 Basement types and structure underlying the Williston Basin

Aeromagnetic surveys by the U.S. Geological Survey (2000) over the Williston Basin show strong, north-south magnetic lineations that correlate with major structures within the overlying Williston Basin of Paleozoic age that include the Nesson and Cedar Creek Anticlines (Figure 2A). The Phanerozoic sedimentary rocks of the Williston basin were deposited above a suture zone separating two Archean age cratons: the Wyoming Craton to the west and the Superior Craton to the east (Green, et al. 1985). It is generally accepted that Phanerozoic sediment was draped upon basement structure and that these and other planes of weakness evolved and were reactivated at numerous time periods in the history of the Williston basin, including the Laramide orogeny during the late Cretaceous to Eocene time (Gerhard et al., 1987). This basement reactivation has produced most of the major structural deformation and natural fractures developed in the Bakken interval (Gerhard et al., 1987; Herrera, 2013). These episodes of basement reactivation propagated upward to control natural fractures within the Bakken Formation interval (Brown and Brown, 1987). My thesis study area (red polygon shown in Figures 2A, 2B) is situated near the center of the Williston Basin, in the northwestern corner of North Dakota. The Red Sky 3D seismic survey, which will be discussed later in the thesis, is shown for reference (blue rectangle, Figures 2A, 2B). The largest structural feature in the Williston Basin and adjacent to my study area is the Nesson Anticline (Figure 2).

2.2.3 Regional structural elements

All of the major anticlines in the Williston basin including the Nesson, Billings, Little Knife, and the Cedar Creek are associated with greater conventional hydrocarbon production related to enhanced porosity and permeability development (Sonnenberg and Pramudito, 2009). Overprinting the major north-south-trending fold axis of the Williston Basin are surface lineaments associated with the Brockton-Froid and the Great Falls Fault Zones, which were formed as a result of the far-field effect of first the Paleozoic Ancestral Rocky Mountains and later during the Cretaceous-Eocene as a result of the Laramide Orogeny (Gerhard et al., 1987: Herrera, 2013). Associated trends can be mapped via surface lineaments and subsurface seismic data (Figure 3). These surface lineaments have been correlated with swarms of subsurface fractures controlled by the modern northeast-southwest direction of maximum stress. Fractures in this orientation have also been observed in cores and from borehole breakout studies by Zoback (1980) and Sonnenberg et al. (2011). More recently this northwest to southeast fracture trend has also been observed from induced fractures and microseismic monitoring of hydraulic fracture stimulations in the Bakken formation (Abbot et al., 2009).

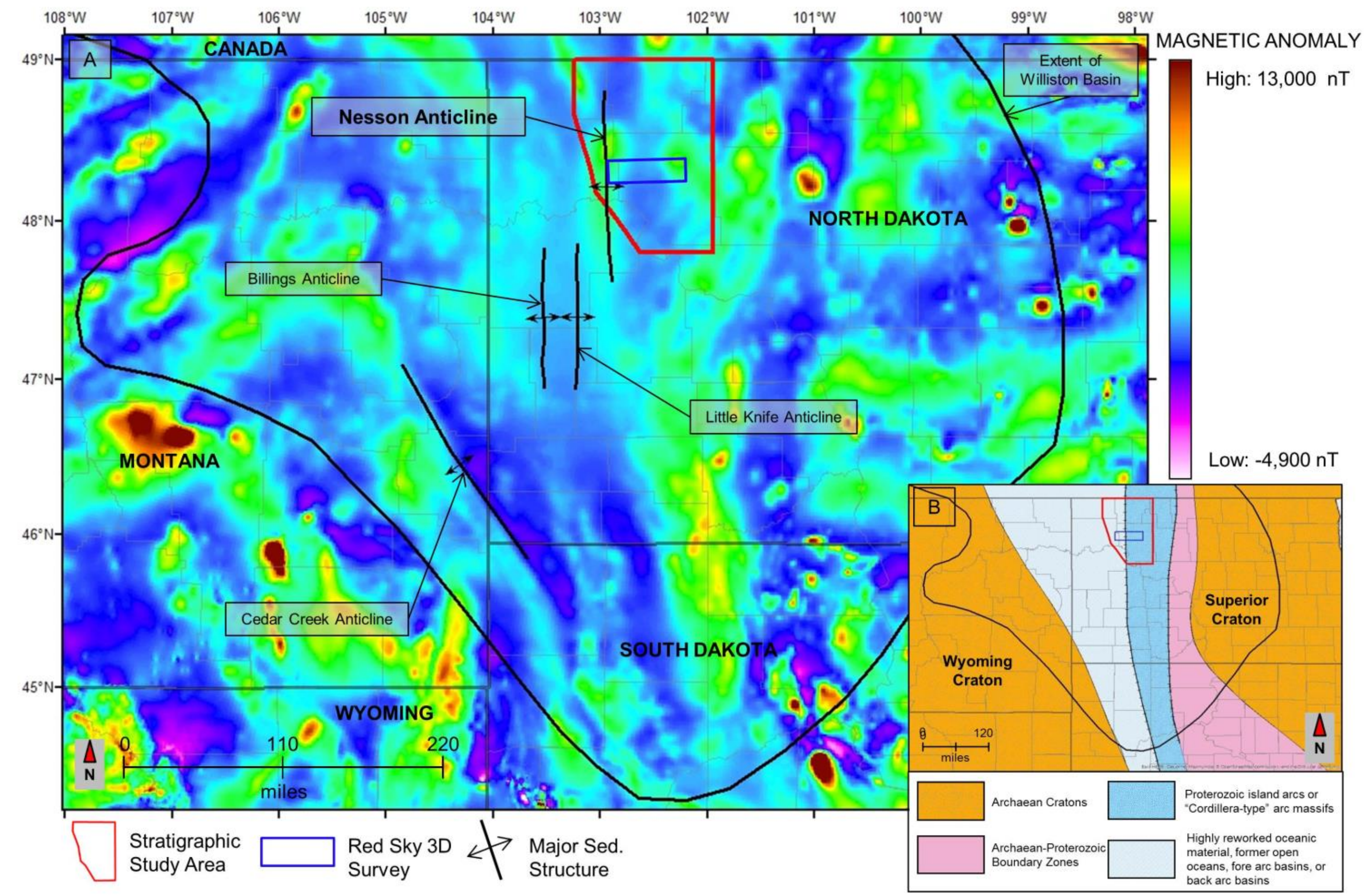


Figure 2: (A) Aeromagnetic map of the United States (from USGS, 2014), for the Williston Basin showing the signature of basement terranes underlying the Phanerozoic sediment fill. The Nesson Anticline is the major structural element in the central Williston Basin. **(B)** The Williston Basin overlies a suture zone between the Wyoming and Superior Archean age cratons (map modified from Fischer, et al. 2005). Faulting and deformation of the suture between the two basement block propagates upward into the overlying, Paleozoic Williston Basin and is expressed by subsidence, faulting, and fracturing in the Williston Basin.

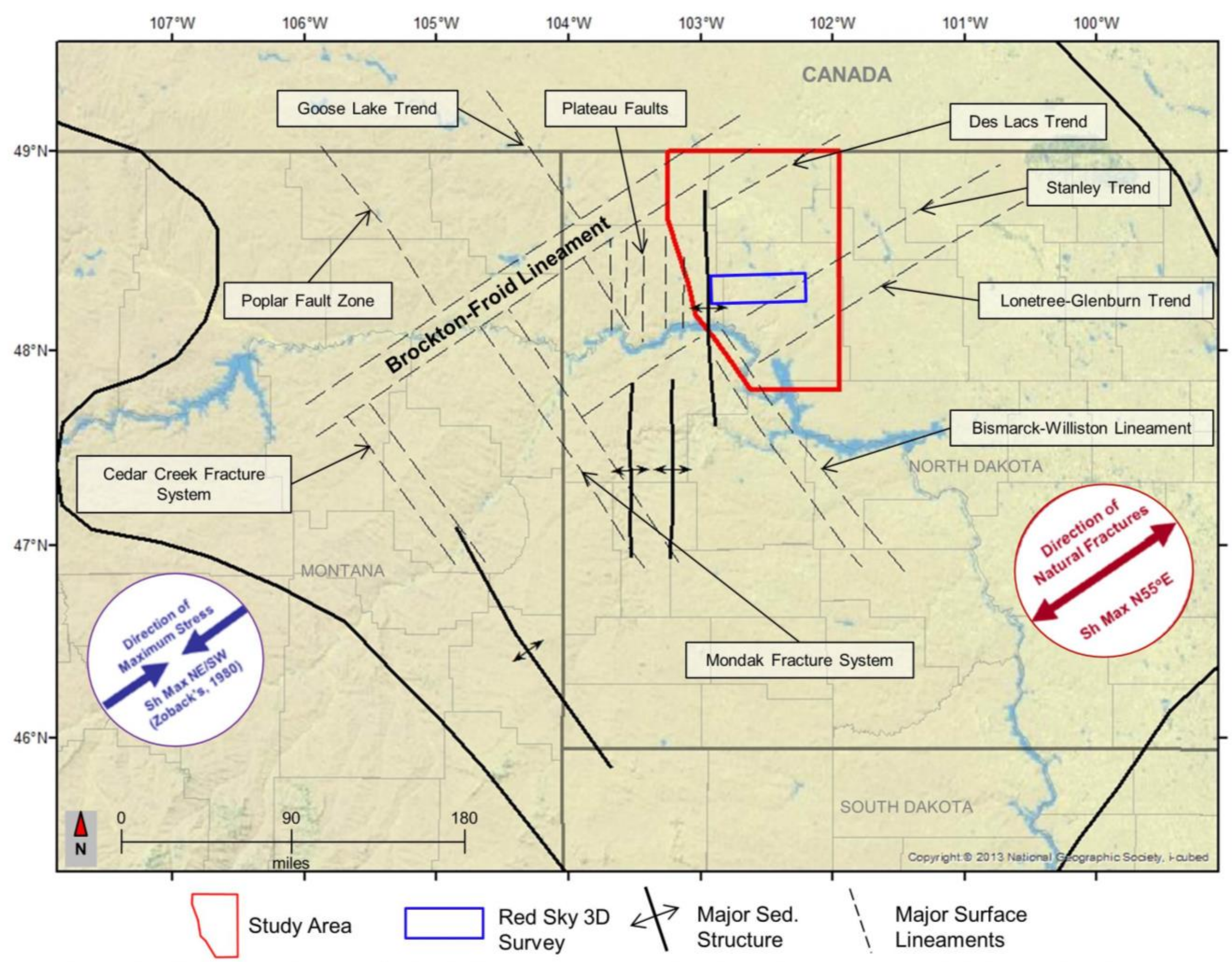


Figure 3: Structural elements in the Williston Basin (modified from Gerhard et al., 1987). The Brockton-Froid Lineament is a major regional fault connecting the Williston basin with the Ancestral Rocky Mountains to the west. Direction of maximum stress modified from Zoback (1980) and Sonnenberg (2011) is consistent with the orientation of observed surface lineaments.

2.2.4 Physical profile and general stratigraphy of the Bakken Formation

While major north-south folds are present in the Williston basin, dips defining these folds are generally less than one degree (Meissner, 1991). The cross section in Figure 4 summarizes the main elements of the Devonian-Mississippian Bakken Petroleum System: the Devonian Three Forks Formation, the Devonian to Mississippian Bakken Formation, and the Mississippian Lodgepole formation (Figure 5).

The Lodgepole Formation is primarily composed of marine limestone and historically has contained the most prolific, Bakken-sourced, conventional reservoirs with more developed conventional porosity and permeability pathways (Stroud and Sonnenberg, 2011). In contrast, the Three Forks Formation is an emerging tight-oil play similar to unconventional Bakken development, sourced from the Upper and Lower Bakken shale (Sonnenberg, et al., 2010). While each of these members have, and continue to, produce significant volumes of hydrocarbons, the Bakken Formation is by far the most significant hydrocarbon sourcing and bearing member in the Williston Basin (Sarg, 2012). The Upper and Lower Bakken shale are classified as world-class source rocks that contain an average TOC content of 11% and source the majority of the hydrocarbon accumulation in the Williston Basin (Jarvie, 2001: Jin and Sonnenberg, 2013).

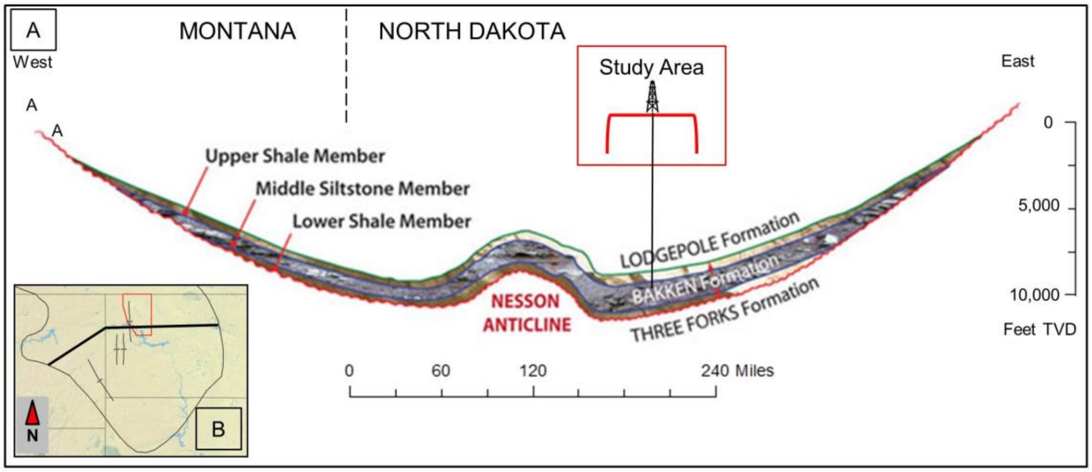


Figure 4: **(A)** Regional west-east cross section modified from Sonnenberg and Pramudito (2009) through the Williston Basin showing major elements the Bakken petroleum system. Mississippian-Devonian, shallow marine deposition was centered in a sub-circular, intracratonic basin with gentle depositional dips towards the basin center. The Nesson Anticline is the major structural element in the basin and lies on the eastern flank of the study area. **(B)** Approximate location of west-to-east cross section through the Williston Basin with the outline of the study area and basin structural elements.

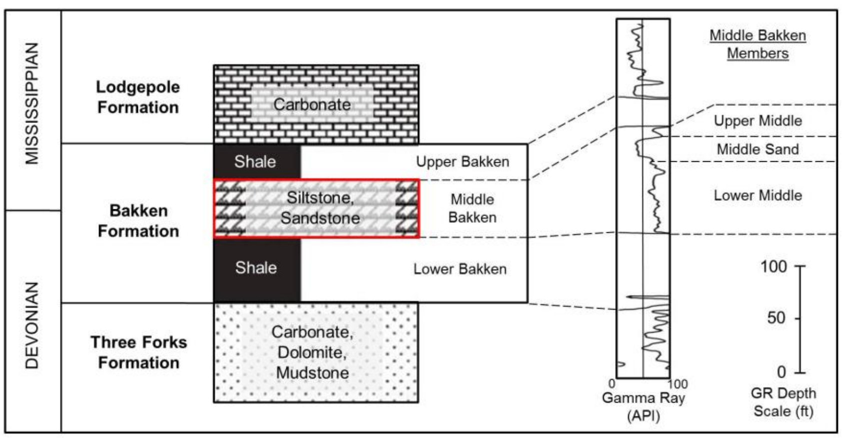


Figure 5: Generalized stratigraphy of the Bakken petroleum system modified from Egenhoff (2011). Deposition of the Bakken Formation lasted from the Late Devonian to the Early Mississippian time. The Bakken Formation is divided into three members: the Upper, Middle, and Lower Bakken Members. The Middle Bakken, which contains silt and sands and is the primary drilling target for operators in the study area is itself divided into three members: the Upper Middle, the Middle Sand, and the Lower Middle. The Middle Sand contains relatively high porosity and permeability and considered the highest quality reservoir facies of the Bakken Formation.

Because the Bakken shales contain such high amounts of TOC, which makes them mechanically ductile, drilling through these ductile shales presents a challenge to maintain borehole stability (Wiley et al., 2004). In contrast, the Middle Bakken member, though relatively thin (<100 feet in most areas), is considered the primary reservoir interval and is the drilling target for the majority of wells drilled in the Bakken Formation (Angulo and Buatois, 2012). The Middle Bakken provides an increased level brittleness favorable for drilling when compared with the Upper and Lower Bakken shales (Grau and Sterling, 2011). In addition to increased brittleness, the Middle Bakken member provides, in some cases, an increase in porosity and permeability similar to a conventional reservoir, but this is largely localized and controlled by the presence of certain Middle Bakken lithologies (Sonnenberg, et al., 2010).

2.2.5 Petroleum system elements of the Bakken in North Dakota

Structure. In the study area dips are subtle, averaging less than 2° over the majority of the study area to the east of the East Nesson Deep and increase slightly, to approximately 5° on the flank of the Nesson anticline (Figure 6). The Williston Basin as a whole is generally symmetrical and typical of intracratonic basin (Meissner, 1991). My study area deepens to the southwest and contains the deepest part of the basin on the eastern flank of the Nesson Anticline. The low dips and lack of major structure allows the Middle Bakken reservoir to be well sealed and overpressured as hydrocarbons are generated (Sorensen et al., 2010).

Stratigraphic thickness. The thickness of the Bakken Formation inside the study area is controlled by the structure of the Nesson Anticline (Figure 7).

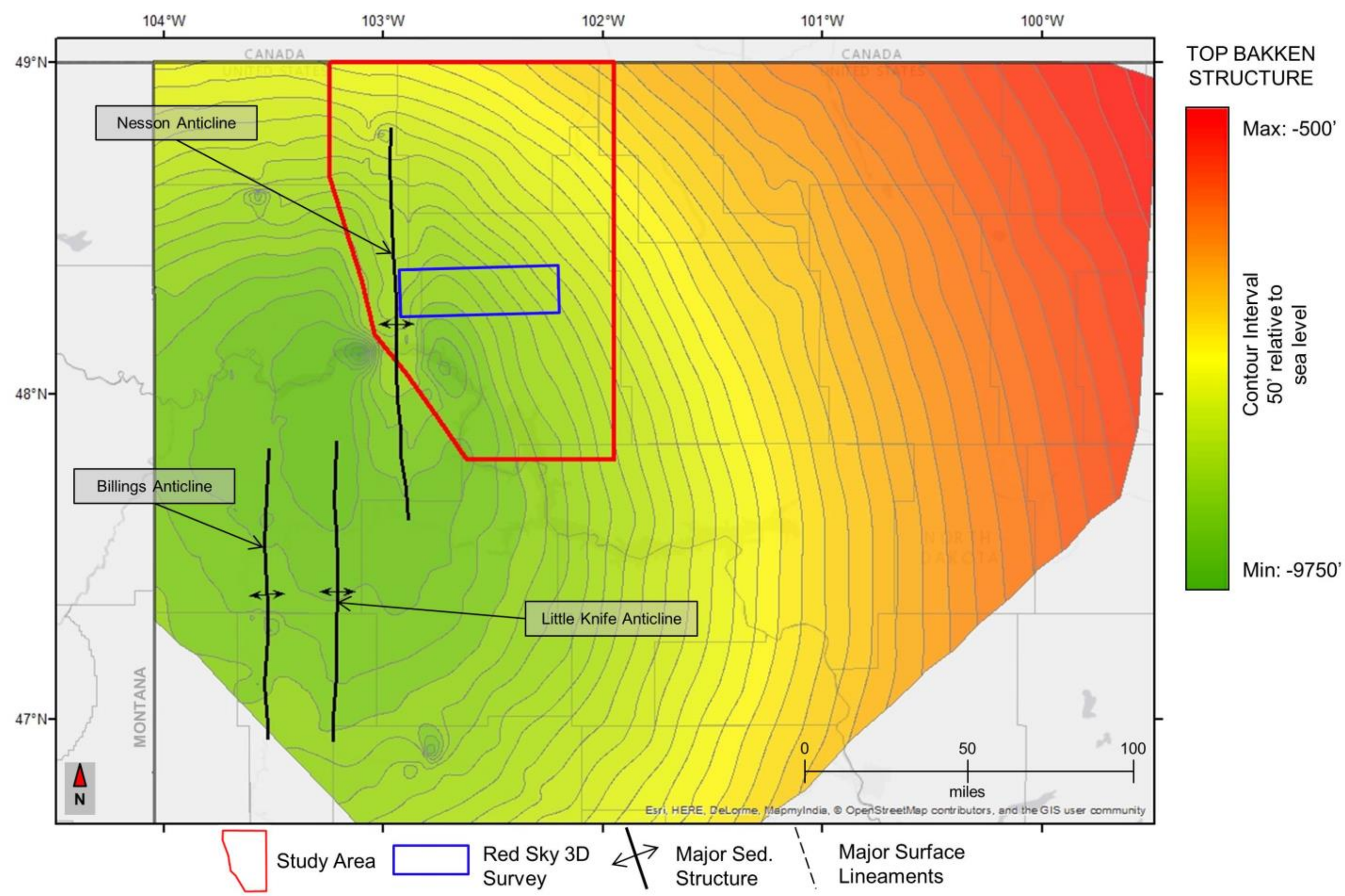


Figure 6: Top of Bakken Formation modified from LeFever (2008) showing subsurface depth of the formation. The North Dakota part of the Williston basin is characterized by its concentric shape and defined by shallow, basinal dips. Major faults and folds in the Phanerozoic sedimentary section are controlled by the upward propagation of faults in the crystalline basement

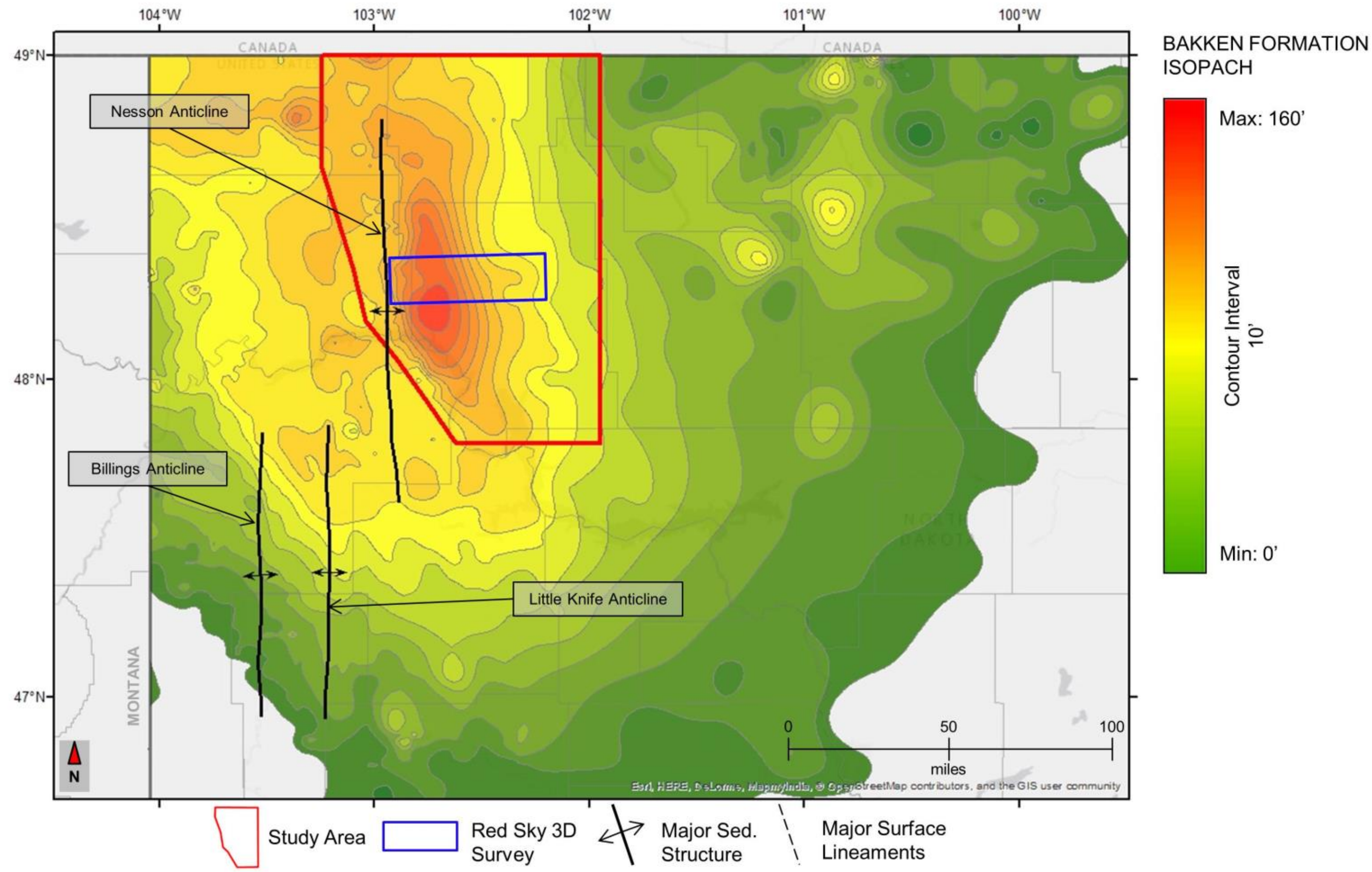


Figure 7: Bakken Formation isopach map modified from LeFever (2008) showing thickness changes within the Bakken. The Nesson Anticline controls the western edge of the thickest isopach, and probably acted as a barrier to sediment transport at the time of deposition of the Middle Bakken sandy facies. The study area contains the thickest section of Bakken Formation within the Williston Basin.

It is asserted that, at the time of deposition, the Nesson Anticline had formed and acted as a barrier to clastic sediment transport in the shallow marine environment (Gerhard, et al. 1987). The thickest occurrence of the Bakken Formation (160 feet) is found within the study area and the Red Sky 3D seismic survey, which, in turn, corresponds to the thickest occurrence of the Middle Bakken clastic rocks (Figure 7).

Maturity. Thermal maturity of the upper and lower Bakken shale corresponds with the greater burial depth of the Bakken Formation in the study area and is a major factor for the productivity of this area (Figure 8). Anomalously high thermal maturity is found outside of the study area to the south and is locally associated a zone of anomalously higher heat flow (Nordeng, 2010).

Overpressure. Thermal maturity of the upper and lower Bakken shale also correlates with overpressure within the Bakken and is a major driver of production in the Bakken tight oil system (Sorensen et al. 2010). This overpressure has contributed to the generation of hydrocarbons by the conversion of solid, compressible kerogen to incompressible liquid hydrocarbons (Duhailan and Sonnenberg, 2014).

Production limits. It is well established that hydrocarbon generation begins at a Time Temperature Index (TTI) value of 15 (Jarvie, 2001). However, historical Bakken production on the eastern side of the Nesson Anticline has established an informal “line of death” where hydrocarbon generation has not been sufficient to create the overpressure necessary to extract meaningful volumes of hydrocarbons from a TTI value of 25. This production boundary is apparent on Figure 8 as the sharp eastern limit of producing Bakken wells within the study area. This thermal maturity boundary aligns with the eastern extent of the Red Sky 3D seismic survey (Figure 8).

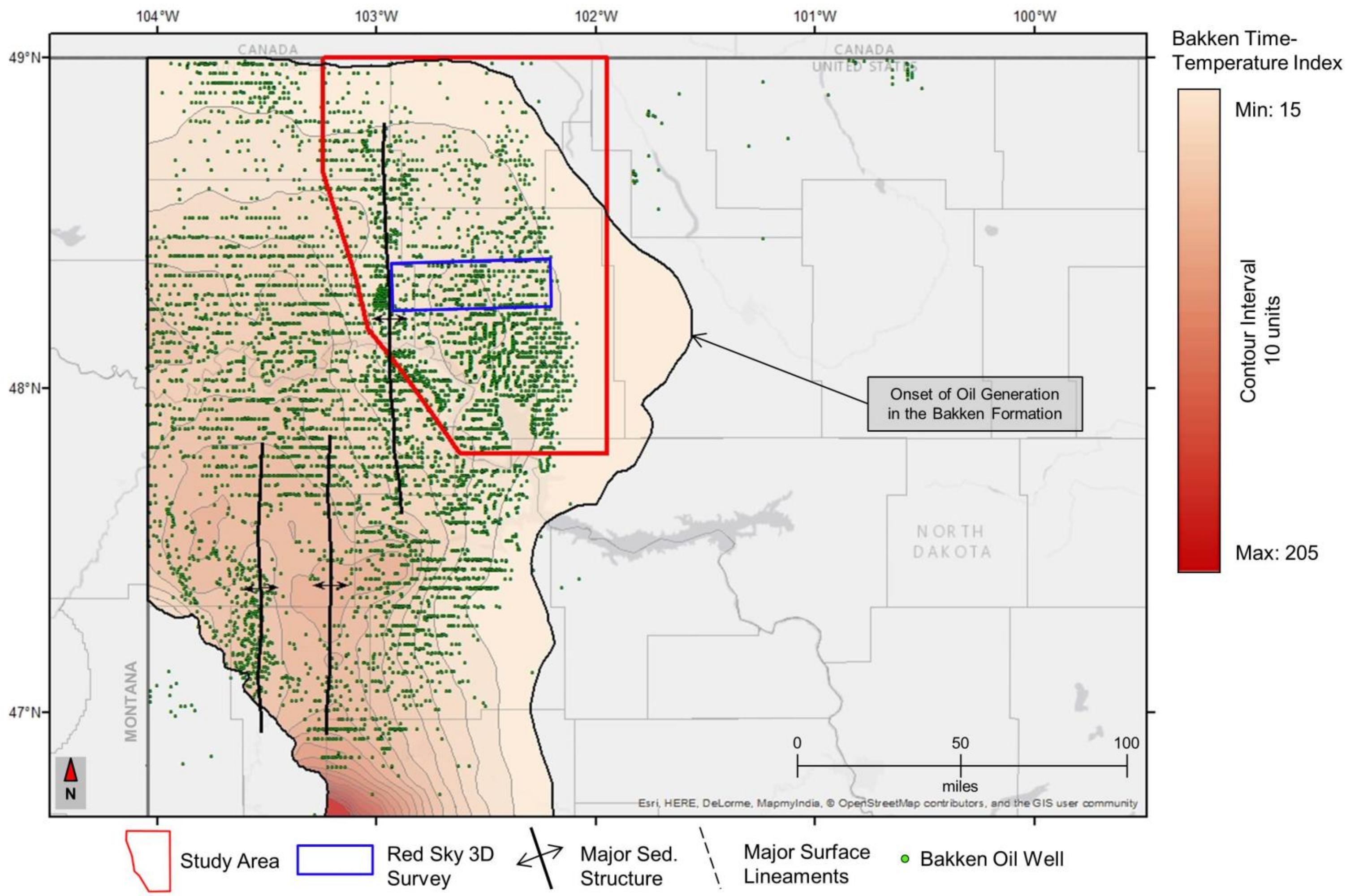


Figure 8: Time-Temperature Index (TTI) of the Bakken Formation in North Dakota (modified from Nordeng et al., 2010). Generation of oil begins at a TTI value of 15, while dry gas is generated at a TTI value of 200. The majority of my study area falls within the Bakken Formation oil generation window.

Sweet spots in the basin. Previous studies in the Williston Basin have proposed sweet spots of the Williston Basin based on their geologic elements and historical well performance (Sorensen et al., 2010). Important elements in these studies include shale thickness, thermal maturity, and overpressure, which is generally concentrated in the central area of the basin (Gerhard et al. 1982). More-recent studies have identified more locally specific sweet spots and characterized the specific attributes that make them unique (Figure 9). The study area for this project encompasses several of these proposed sweet spots, but I will focus primarily on the Sanish-Parshall fields that have been North Dakota’s most prolific oil fields since 2005 (Simenson, 2011).

High reservoir pressure, up-dip migration, and diagenetic trapping all characterize the Sanish-Parshall sweet spot (Theloy, 2014). These characteristics require the presence of a mature source rock, a permeability conduit for hydrocarbon migration, and a high-quality reservoir facies. Even within these proposed sweet spots, significant production variation exists between closely spaced wells within these sweet spots (Sorensen et al., 2010). This study will address the question of what controls this production variation within individual sweet spots and how we can use this knowledge to guide future drilling.

The study will begin with establishing a geologic framework within the study area by mapping changes in the reservoir lithology of the Middle Bakken in the eastern region of the Williston Basin (Figure 9). Upon establishing the geologic framework, I will provide a more detailed evaluation of the geologic heterogeneity within the blue rectangle covered by the Red Sky 3D survey using core data. This detailed geologic interpretation will then be compared with the productivity of wells in the area by analyzing historical

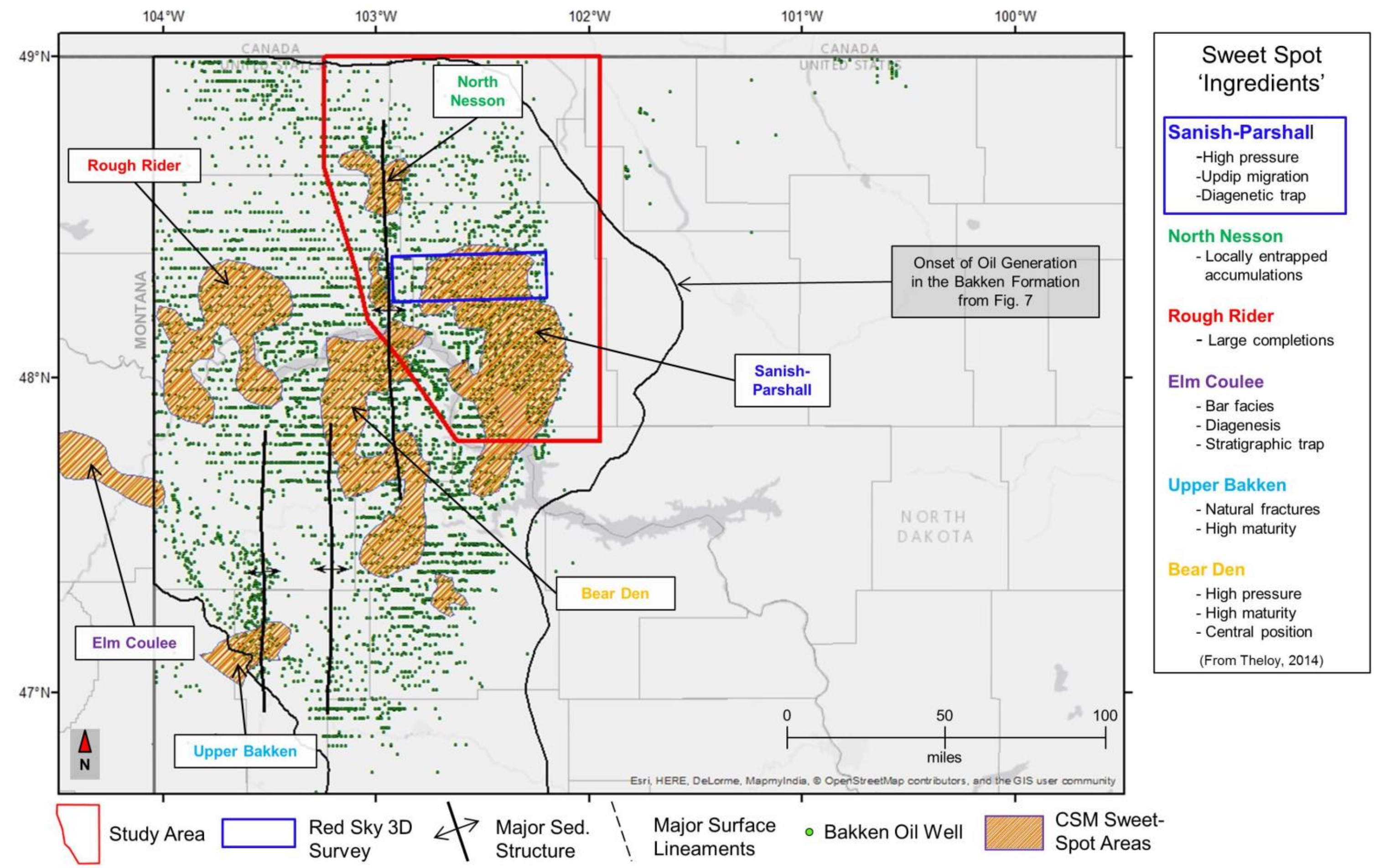


Figure 9: Production "sweet-spots" in the Bakken Formation identified from petroleum systems analysis by Theloy (2014) based on her identification of petroleum system 'ingredients'. The study area encompasses the Nesson, North Nesson, and the Sanish-Parshall sweet-spots of localized production. To date, the Sanish-Parshall is one of the most productive areas in the entire North Dakota part of the Williston Basin.

production statistics to identify important geologic elements that correlate with production variation between closely spaced wells.

2.2.6 Bakken Formation facies distribution

Operators drilling wells in the Bakken Formation in the Williston Basin, east of the Nesson Anticline, generally target a low-gamma-ray sandstone unit in the upper part of the middle Bakken (Sorensen et al. 2010) (Figure 10A, B). This unit is relatively thin (usually less than 15 feet thick) but fairly easy to recognize in the vertical section and using MWD (measurement while drilling) tools. Core analysis of the Bakken Formation in my study area consistently identifies the middle Bakken Sand as the highest quality target due to its high hydrocarbon saturations, good porosity, and good permeability observed by measurements from the Middle Bakken (Simenson, 2011) (Figure 10C). However, the sandstone thickness is quite discontinuous over the study area.

Using 182 wells that have vertical well log suites, including gamma ray, with complete Bakken Formation sections, I correlated the three Bakken members, as well as the Lower Middle, the Upper Middle, and Middle Sand within the Middle Bakken (Figure 10B). Isopach maps were contoured over the study area for the Lower Bakken Shale (Figure 11A), the Lower Middle Bakken Silt (Figure 11B), The Middle Bakken Sand (11C), the Upper Middle Bakken Silt (Figure 11D), and the Upper Bakken Shale (Figure 11E). For reference, an isopach of the summation of the Upper and Lower Bakken Shale thickness with the Middle Bakken Sand thickness (Figure 11F) was made to indicate areas where one would expect high volumes of hydrocarbon in place.

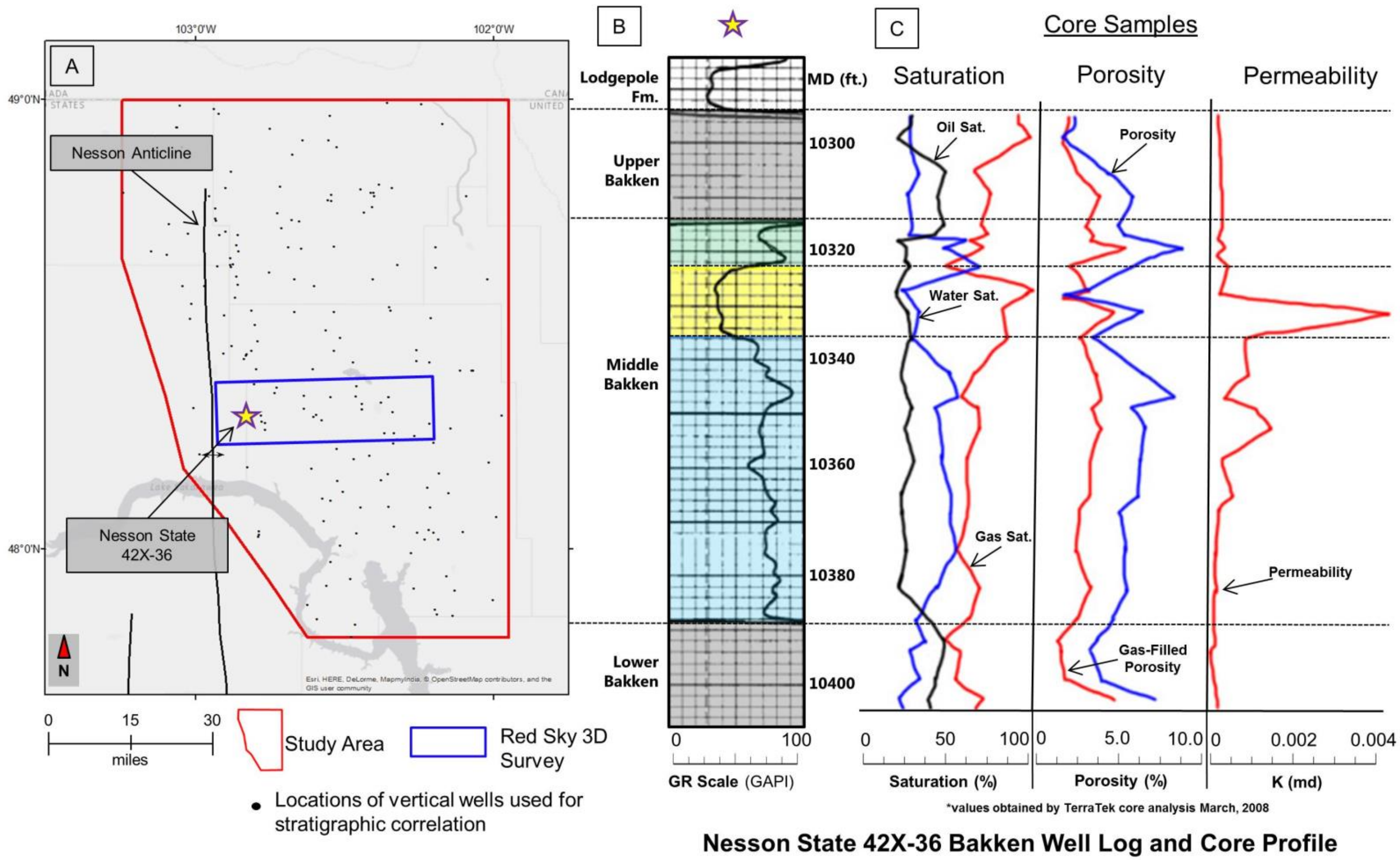


Figure 10: (A) My study area in North Dakota showing the location of 182 vertical well logs used for stratigraphic analysis of the Bakken Formation. **(B)** Well log profile of the Bakken Formation from the Nesson State 42X-36 well, which contains a well-developed sand in the Middle Bakken member (yellow highlight). **(C)** Core plug analysis from the same well with depths matched to gamma ray log. There is higher porosity and permeability development in the Middle Bakken member, particularly in the sandier intervals.

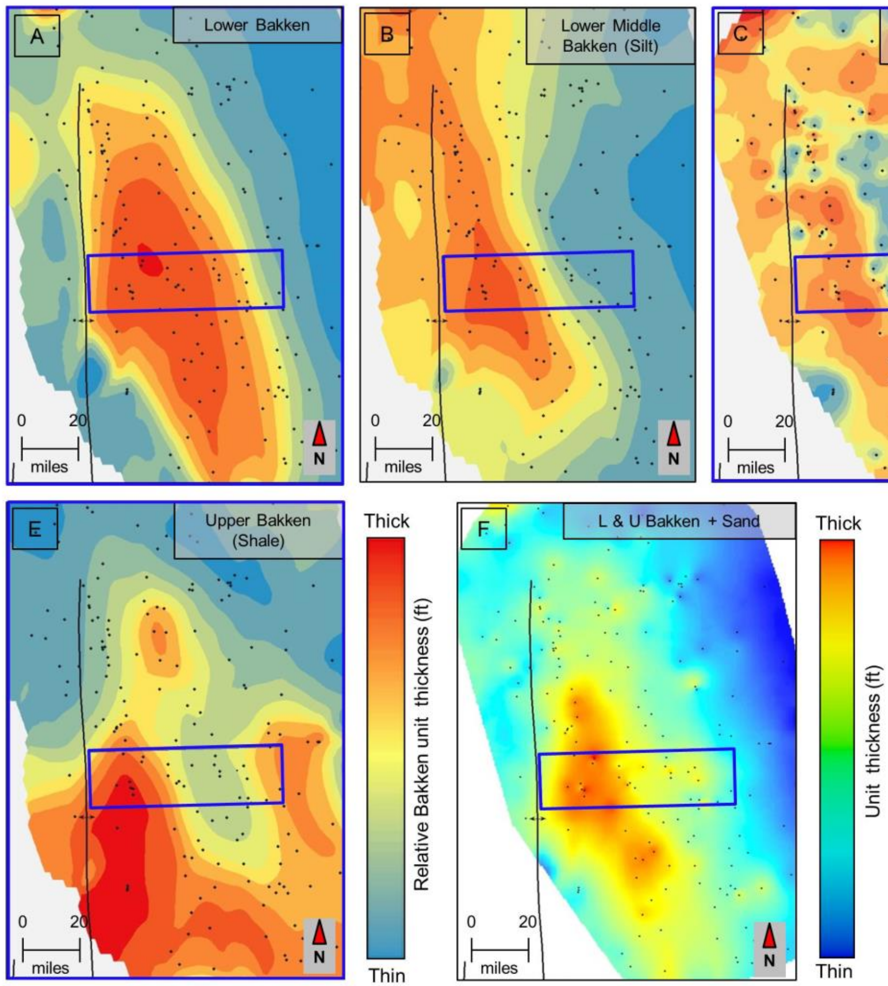


Figure 11: Isopach maps of Bakken Formation facies mapped from 182 wells in the study area. **(A)** Lower Bakken Shale **(B)** Lower Middle Bakken Silt **(C)** Middle Bakken Sand **(D)** Upper Middle Bakken Silt **(E)** Upper Bakken Shale. **(F)** Map showing the total thickness of the Upper Bakken Shale, Middle Bakken Sand, and Lower Bakken Shale in the study area. This thicker area of the Bakken Formation provides the area of highest hydrocarbon storage capacity in the Williston Basin.

I assume that the Upper Middle and Lower Middle Bakken silt facies have matrix porosities too low to provide significant storage of hydrocarbons in place. The Middle Bakken Sand (Figure 11C) has been identified as the highest-quality reservoir facies present in the Middle Bakken member within the study area and where sufficiently charged, would have the inherent porosity and permeably to flow hydrocarbon to a wellbore. Where no sand is present, I assume wells must connect to natural, or induced permeability pathways into the Upper or Lower Bakken Shales. These connections are assumed but supported by observations from core descriptions (Figure, 19).

The Middle Bakken Sand has thicknesses that range from 0-25 feet and is deposited fairly uniformly across the Nesson Anticline structure (Figure 12). The Middle Bakken Sand is more continuous in an elongated northwest-southeast orientation with discontinuous deposits on the eastern side of the study area (Figure 12). From its overall geometry and orientation the depositional environment of the Middle Bakken sand is interpreted to be a barrier bar complex with tidal influences (Angulo and Buatois, 2012). Four cross-sections A – A', B – B', C – C', and D – D', oriented north to south, west to east, south to north, and west to east respectively were constructed to show how facies vary within the Middle Bakken interval (Figure 12).

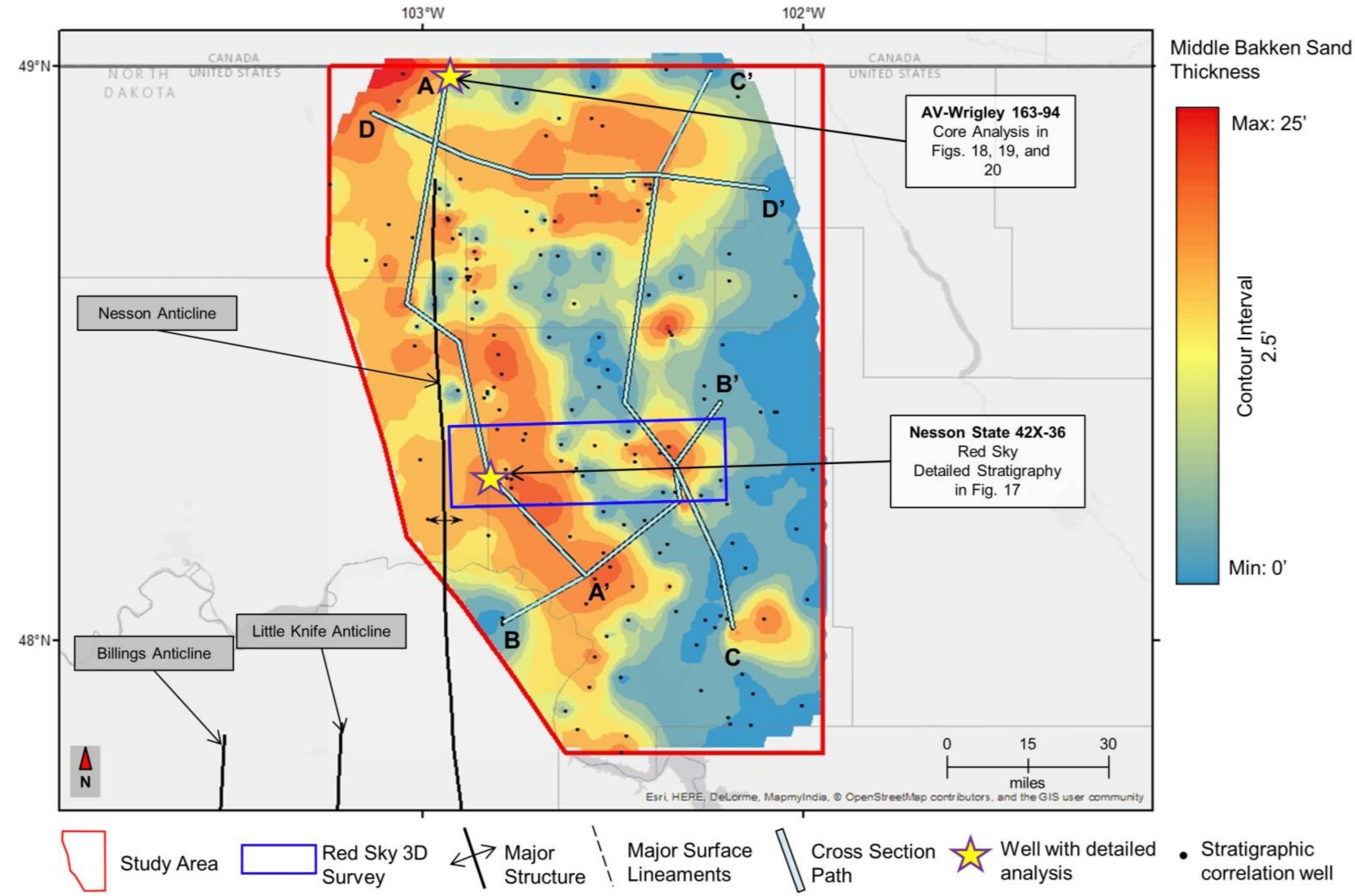
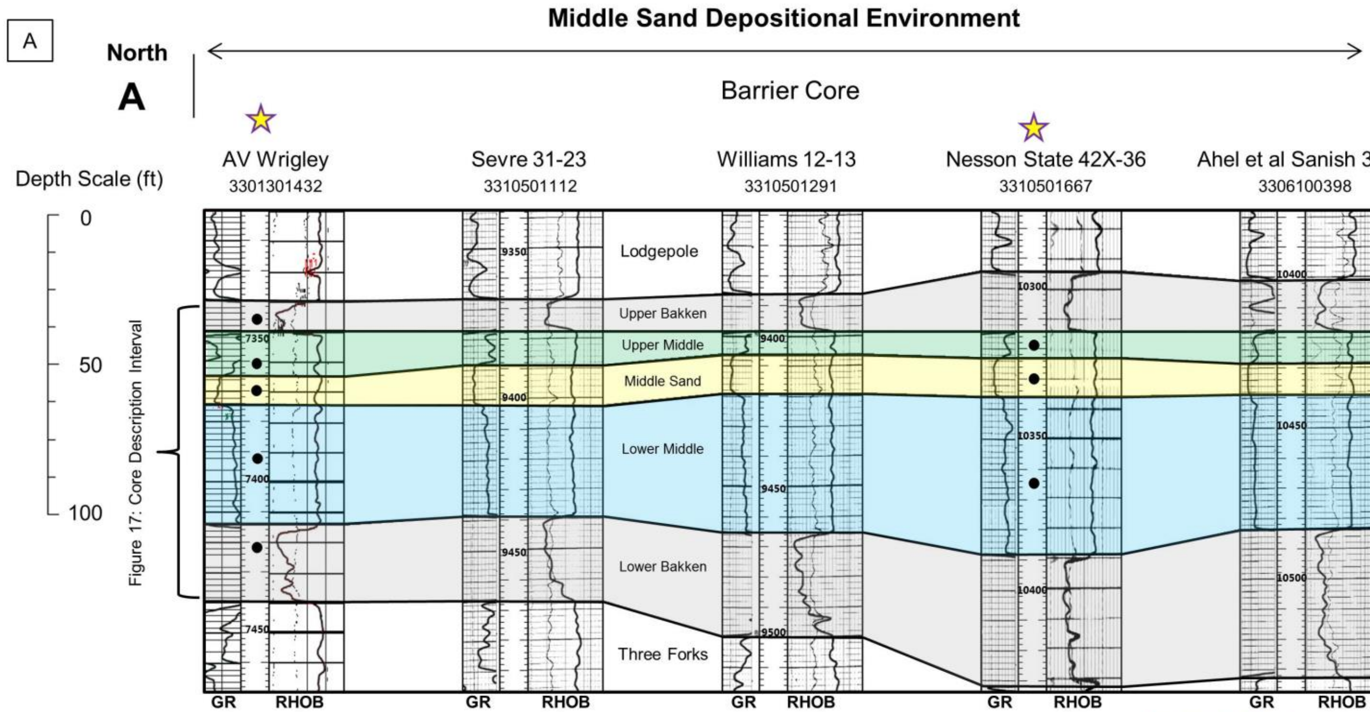


Figure 12: Middle Bakken sand thickness map for the study area. Locations of well log cross sections are indicated: A-A' (Fig. 1-11), B-B' (Fig. 1-12), C-C' (Fig. 1-13), and D-D' (Fig. 1-14). Core descriptions from the Nesson State 42X-36 well drilled by XTO in 2008 and the AV-Wrigley 163-94 well drilled by Hess in 2008 are shown in Figures 1.15 and 1.16, respectively.

Cross-section A – A' runs north to south along the western edge of the study area and includes five vertical well log suites flattened on the base of the Upper Bakken Shale for a better understanding of the stratigraphic variation within the unit (Figure 13). Each well contains a gamma-ray log in the left track and a bulk density log in the right track (Figures 14 – 16). Cross-section A – A' details the most-continuous section of Middle Bakken, with the Middle Bakken Sand unit (shown with yellow overlay across the logs) exhibiting a distinctive blocky, low gamma-ray profile on each well profile. This section runs through what I have interpreted as the barrier core of the Middle Bakken Sand barrier bar complex. This cross-section also contains two important wells that will be discussed in more detail in the Middle Bakken Facies and core analysis sections: the AV Wrigley 163-94, with its associated cored interval, and the Nesson State 42X-36 with its detailed Middle Bakken stratigraphy (Figure 13A, B). Black circles mark important reference points in each respective well's depth track, which will be discussed in detail later.

Cross-section B – B' traverses from west to east in the southern part of the study area, crossing the barrier core, a tidal flood delta inside of the Red Sky 3D area, and finally into a back-barrier lagoonal setting (Figure 14A, B). The tidal-flood delta has a thick Middle Bakken Sand sequence and a thin Lower Middle Bakken unit, but is discontinuous laterally. The sandstone thickness in the Middle Bakken member varies over a distance of 5 to 10 miles.



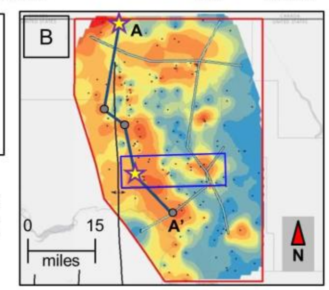


Figure 13: (A) Well log cross section A - A' provides an along-strike cross section through the inferred barrier bar system of the Middle Bakken formation which ranges from 13 to 10 feet thick along the trend of the bar. **(B)** Inset map showing well locations and major structures.

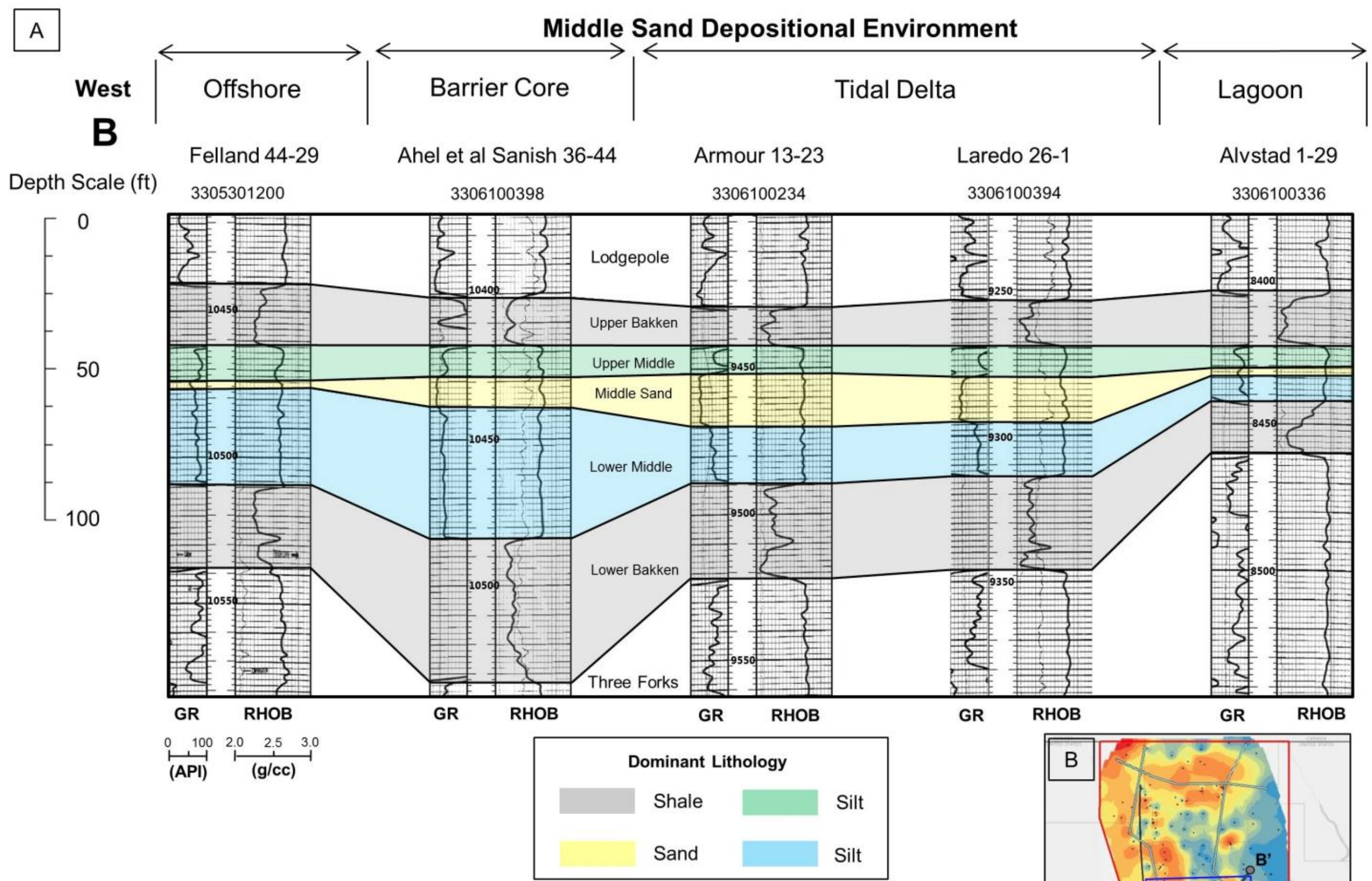


Figure 14: (A) West to east cross section B – B' up-dip from barrier core and extending into a tidal flood delta at the Armour 13-23 and Laredo 26-1 wells. Sand remains thick from barrier core into tidal delta, but thins abruptly into silt-dominated facies on either side of system. **(B)** Inset map showing well locations and major structures.

Cross-section C – C’ runs from south to north, in the eastern part of the study area, and crosses the back-barrier environmental setting (Figure 15A, B). The interpreted tidal flood delta sands occur locally and are separated in wells by predominantly silty Middle Bakken intervals (Figure 15A). The back-barrier setting is characterized by wells with relatively thin total Middle Bakken intervals compared with wells in the barrier core, which is probably due to their position on the flank of the Williston Basin, rather than near the deeper middle portion where the barrier core lies (Figure 15A).

Cross-section D – D’ travels west to east, in the northern part of the study area, through the barrier bar core and across a relatively thin Middle Bakken Sand section interpreted as a wash-over fan deposit (Figure 16A, B). The Middle Bakken Sand unit landward of the barrier bar (east) is relatively thin compared to the core and to the tidal flood delta deposits to the south. This may be due to depositional method (wash-over deposit).

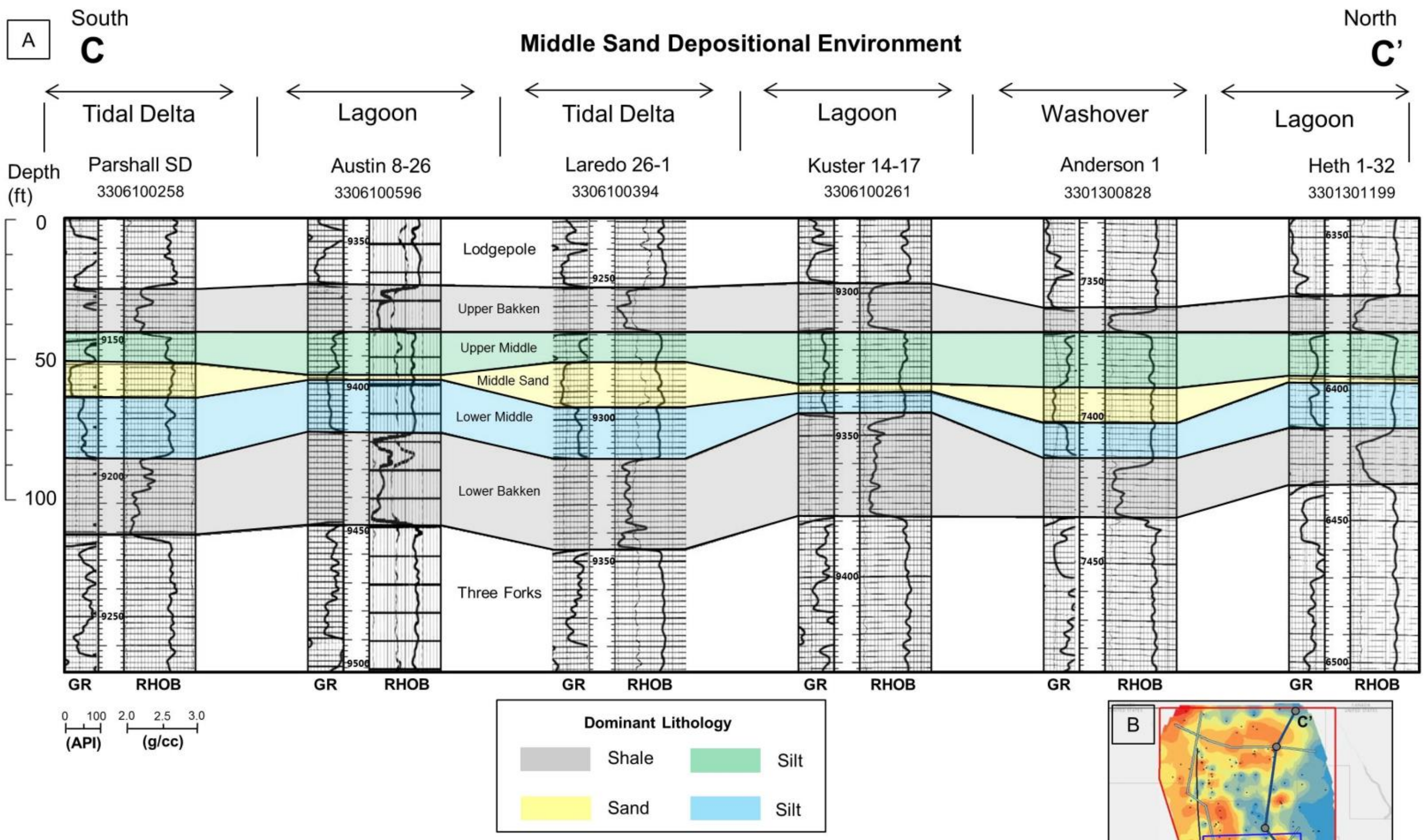


Figure 15: (A) South to north cross section C – C’ through flood delta sands and wash-over sand deposits. In contrast to a relatively constant sand thickness within barrier core, the tidal delta/wash-over complex shows a more variable sand thickness along strike and varies in thickness from 0 to 11 feet thick. Sand deposits thin quickly into silt dominated facies. **(B)** Inset map showing well locations and major structures.

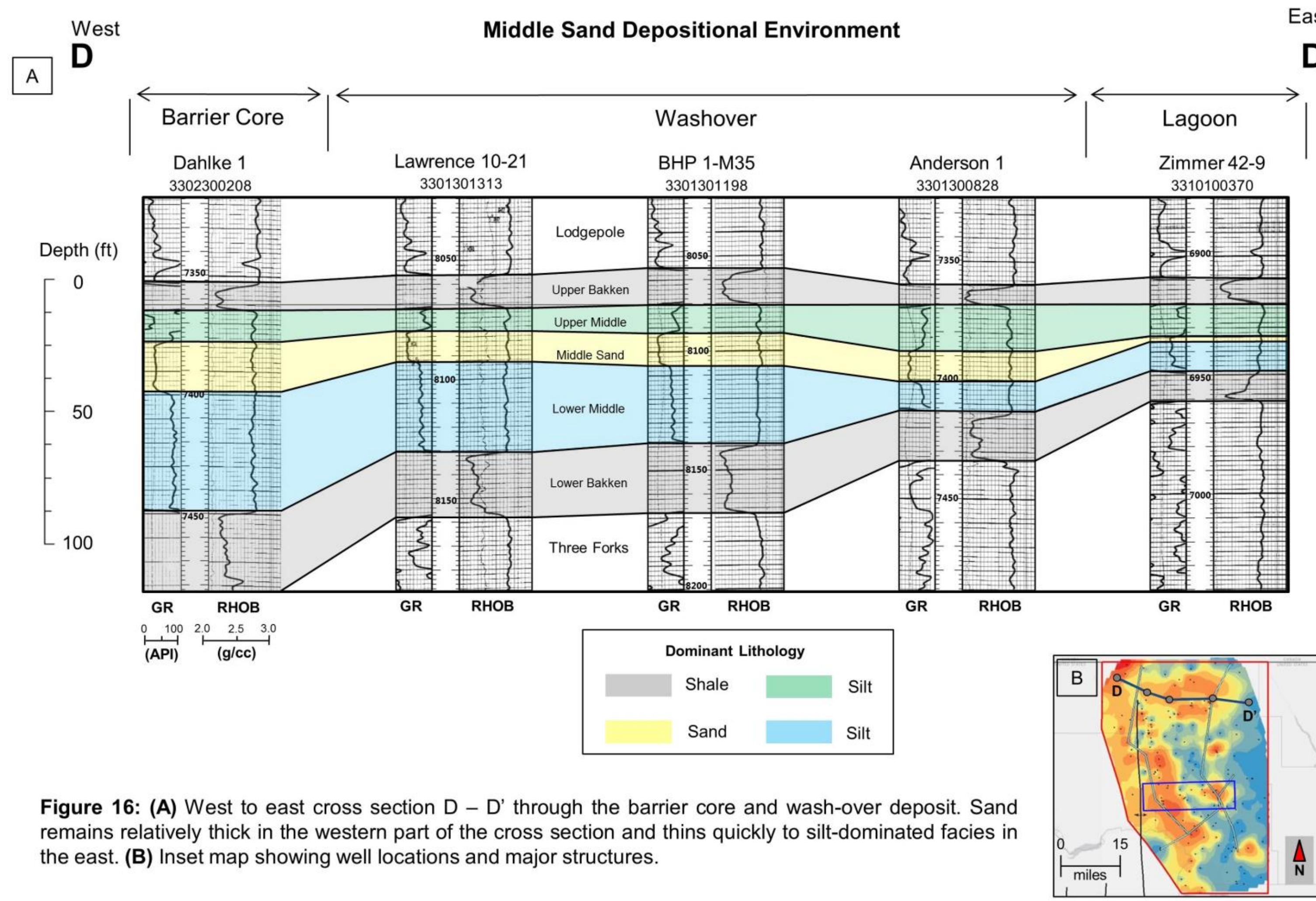


Figure 16: (A) West to east cross section D – D' through the barrier core and wash-over deposit. Sand remains relatively thick in the western part of the cross section and thins quickly to silt-dominated facies in the east. **(B)** Inset map showing well locations and major structures.

2.2.7 Bakken lithofacies analysis of core from the Nesson State 42X-36 well

The Nesson State 42X-36 well is a horizontal well with a deep, vertical pilot hole drilled into the core of the sandy Middle Bakken barrier bar inside of the Red Sky 3D survey area (inset map Figure 17). The Nesson State 42X-36 (henceforth "Nesson State well") was spudded in February, 2008, by Headington Oil Company, now operated by XTO Energy. According to the NDIC well file for this well, the vertical pilot hole penetrated to the top of the Three Forks Formation underlying the Bakken Formation for a total depth of 10,430 feet. The Bakken Formation is approximately 143 feet thick in the Nesson State well, which is near the maximum thickness of 160 feet shown on LeFever's (2008) Williston Basin Bakken isopach map (in Figure 7). The Middle Bakken thickness in the Nesson State is 74 feet total, with a Middle Bakken Sand thickness of 12 feet, an Upper Middle Bakken silt thickness of 8 feet, and a Lower Middle Bakken Silt thickness of 54 feet (Figure 17A). The Upper Middle Bakken is a relatively thin, silty unit with mottled bedding and relatively intense bioturbation (Figure 17B). The Middle Bakken Sand is marked by a blocky low gamma-ray-log signature and low-angle dip to cross bedding (Figure 17A). The Lower Middle Bakken is the thickest well log unit marked by mostly massive bed with variable bioturbation throughout the unit (Figure 17C). I did not have access to core samples for the Nesson State well, thus no detailed core analysis was undertaken on this well. However the Middle Bakken facies present in the Nesson State well closely resemble the well log profile and those facies observed in core analysis of the AV Wrigley 163-94 well.

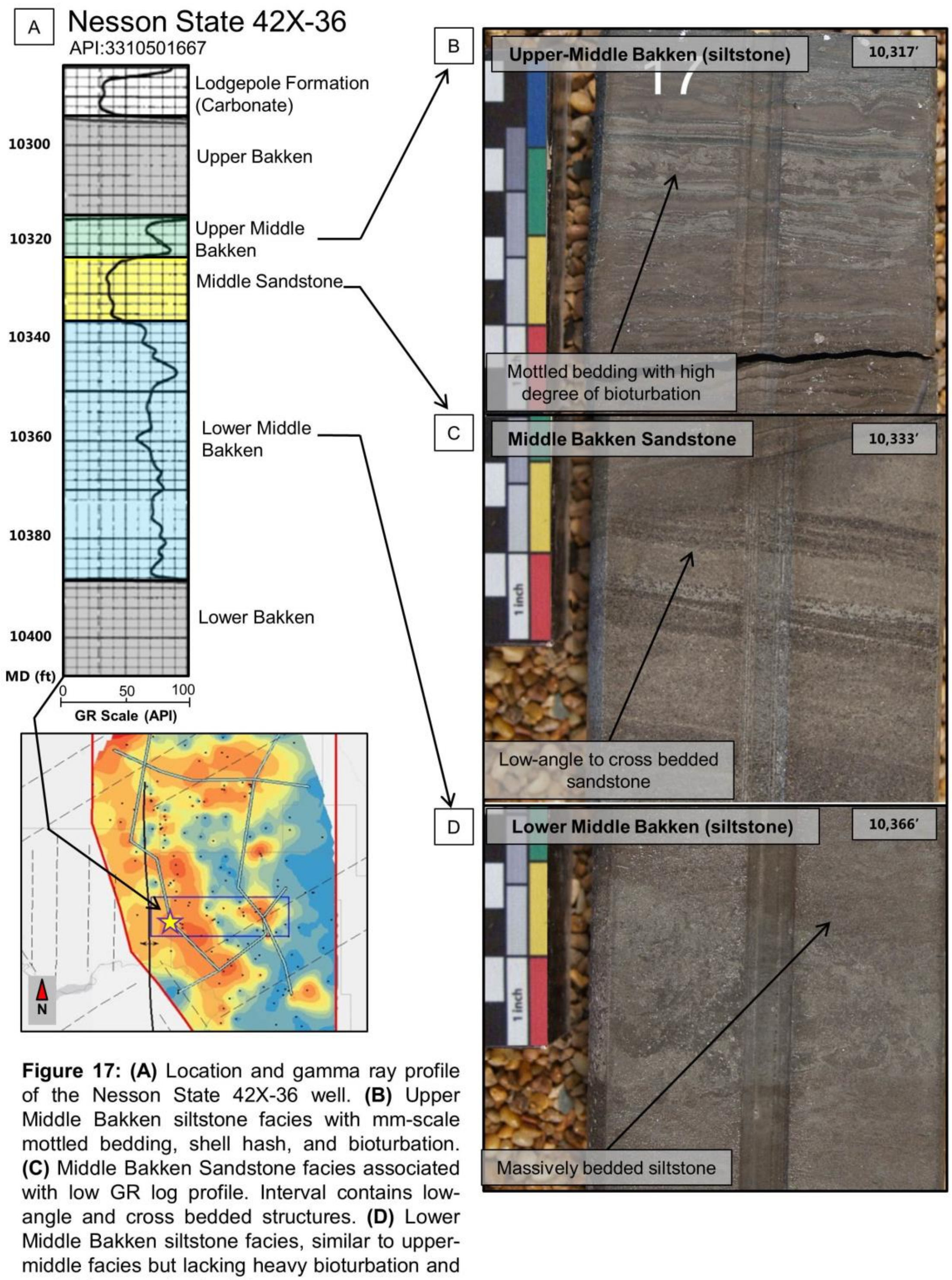


Figure 17: (A) Location and gamma ray profile of the Nesson State 42X-36 well. **(B)** Upper Middle Bakken siltstone facies with mm-scale mottled bedding, shell hash, and bioturbation. **(C)** Middle Bakken Sandstone facies associated with low GR log profile. Interval contains low-angle and cross bedded structures. **(D)** Lower Middle Bakken siltstone facies, similar to upper-middle facies but lacking heavy bioturbation and containing massive bedding.

2.2.8 Bakken lithofacies analysis of cores from the AV Wrigley 163-94 well

I was given access to the slabbed core of the AV Wrigley 163-94 (henceforth "AV Wrigley well"), which was drilled along the barrier bar core in the northern part of the study area (inset map, Figure 18). The AV Wrigley well was drilled in August 2008, by the Hess Corporation with a vertical pilot hole approximately 7,800 feet TD. The AV Wrigley well has a similar Middle Bakken gamma ray profile, though is only 100 feet thick from the Top Bakken to the Three Forks Formation (Figure 18A).

The upper shale is 10 feet thick, the upper middle silt is 16 feet thick, the middle sand is 9 feet thick, the lower middle silt is 39 feet thick, and the lower shale is 26 feet thick. Photos of the Bakken lithofacies are provided to document the unit's sedimentary structures. The Upper and Lower Bakken Shale are nearly identical black, fissile shale facies (Figure 18b and 18f). The Upper Middle Bakken Siltstone is similar to the Nesson State well with mottled bedding with visible bioturbation (Figure 18C). The Middle Bakken Sandstone unit is thinner (12 feet) than the Nesson State well (16 feet), but shows similar low angled bedding and coarser grains than the siltstone above and below (Figure 18D). The Lower Middle Bakken is characterized by a massive siltstone with variable bioturbation over the interval (Figure 18E). The Bakken facies present in the AV Wrigley well are very similar to those in the Nesson State well, and as such, are a good equivalent for detailed core analysis.

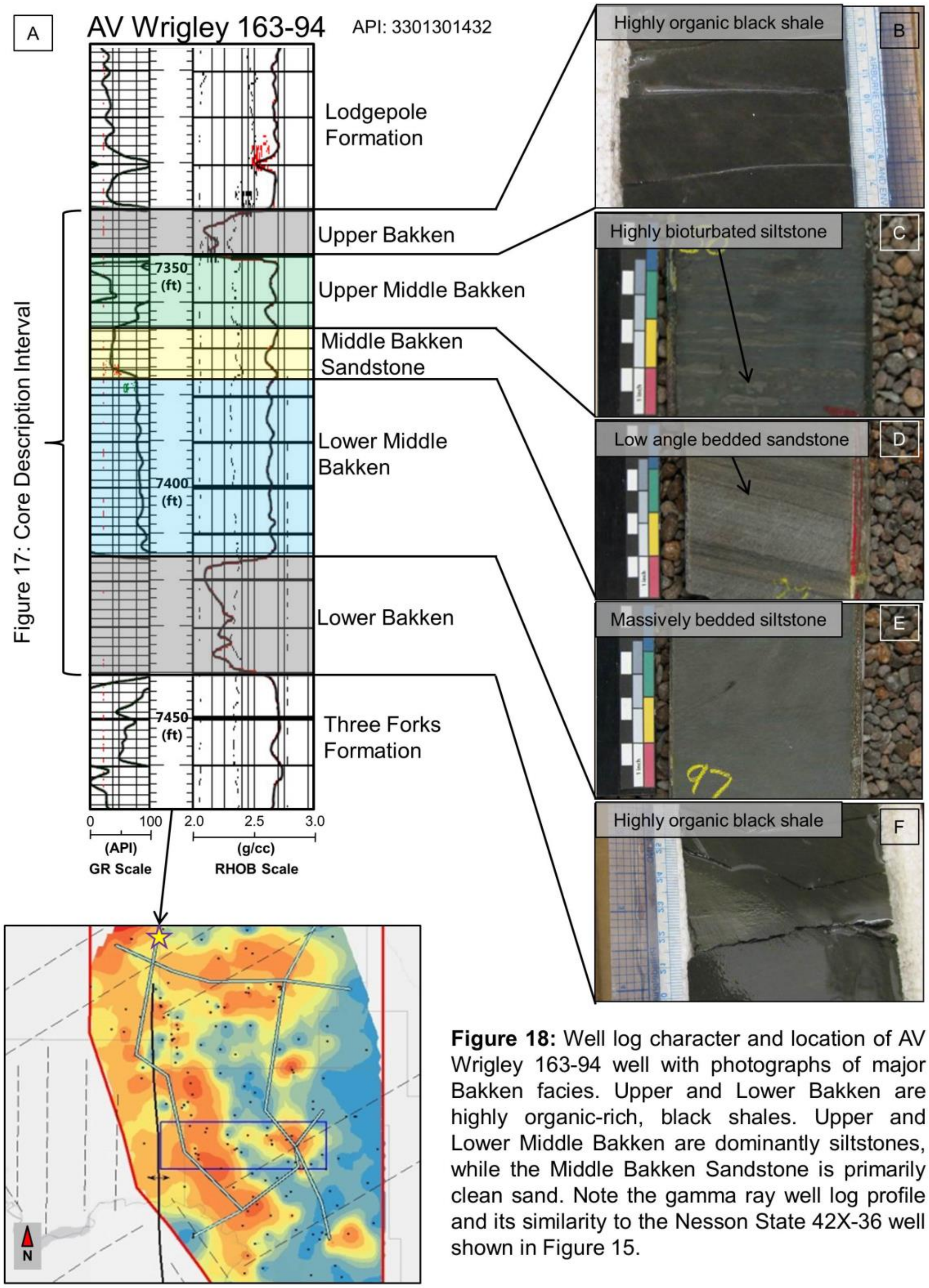


Figure 18: Well log character and location of AV Wrigley 163-94 well with photographs of major Bakken facies. Upper and Lower Bakken are highly organic-rich, black shales. Upper and Lower Middle Bakken are dominantly siltstones, while the Middle Bakken Sandstone is primarily clean sand. Note the gamma ray well log profile and its similarity to the Nesson State 42X-36 well shown in Figure 15.

I described 119 feet of core for the AV Wrigley well from the top of the Three Forks Formation, through the entire Bakken Formation, into the lower Lodgepole Formation. Since I was primarily interested in the Middle Bakken reservoir interval, and the Upper and Lower Bakken shale are effectively homogenous to the naked eye, the core description figures will document a section approximately 90 feet thick that includes the Middle Bakken interval in the AV Wrigley well (Figure 19). The core analysis began from the bottom of the section to the top, following the order of deposition from oldest to youngest strata.

The Lower Bakken Shale is 26 feet thick and is dark black in color, with centimeter-scale, fissile bedding, ubiquitous pyrite, and sparse silty layers near its top contact (Figure 19). The upper contact with the Lower Middle Bakken is sharp and is marked by approximately 3.5 inch lens of skeletal rip-up clasts (Figure 19).

The Lower Middle Bakken is a silt-dominated dolostone and the thickest unit in the Bakken Formation measuring 39 feet in the AV Wrigley well (Figure 19). This unit has moderate bioturbation at its base and intense bioturbation near its top (Figure 19). Where the Lower Middle Bakken lacks bioturbation it is generally massively bedded with sparse pyrite nodules. Skeletal hash contains primarily brachiopod and bivalve shells, with some crinoid columnals (Figure 19). In bioturbated areas ichnology is complex, but primarily *Cruziana* ichofacies (Angulo and Buatois, 2012). Bioturbation ceases and grain sizes coarsen sharply at the Lower Middle Bakken’s top contact with the Middle Bakken Sand.

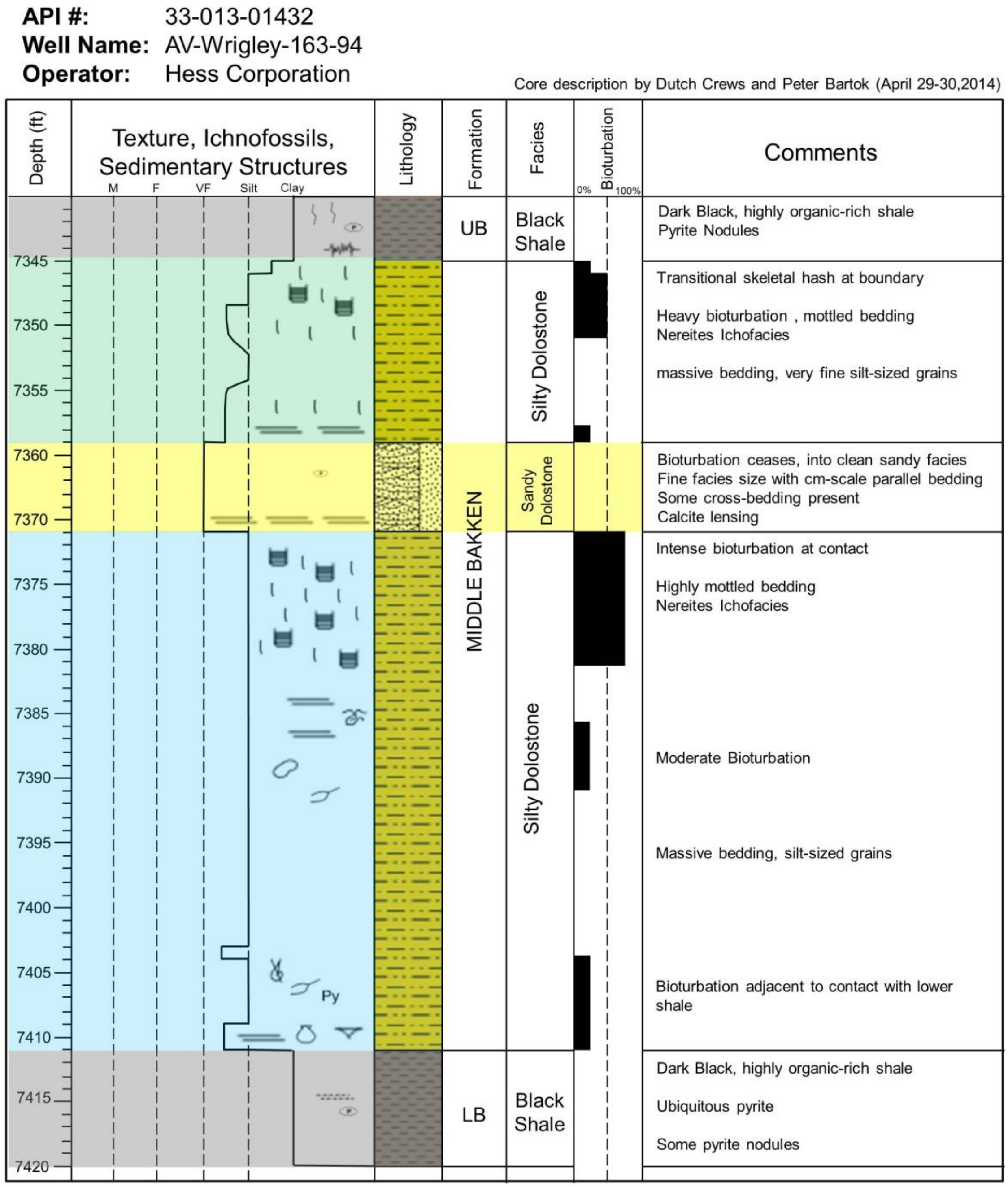


Figure 19: Sedimentary interpretations from the AV Wrigley 163-94 core for the Bakken Formation. Upper and Lower Bakken shales (grey) are highly organic-rich, black shales. Upper and Lower Middle Bakken (green and blue units, respectively) are dominantly silt. The lower Middle Bakken is massively bedded but contains low-angle cross bedding and sparse to intense bioturbation. The Middle Bakken Sand (yellow) is characterized by a clean, relatively coarse-grained, sand containing low-angle to cross beds. Sandy Middle Bakken facies contains zones of high UV fluorescence indicative of hydrocarbon saturation.

The Middle Bakken Sandstone measures approximately 9.5 feet and is a light grey to white, clean (little to no mud), well-sorted sand with centimeter-scale parallel to cross bedded beds and alternating calcite-dolomite banding (Figure 20a). Intergranular porosity is visibly higher in the sand unit relative to all other Bakken units, but varies depending on cementation. The Middle Bakken Sandstone has bright blue fluorescence under ultra violet (UV) light indicative of hydrocarbon saturation, which is compartmentalized by lenses of calcite cement (Figure 20b). Although the unit is relatively thin, the Middle Bakken Sandstone is the highest quality reservoir facies in the Bakken Formation based upon hydrocarbon storage and potential permeability pathways. The sand's upper contact with the Upper Middle Bakken unit is sharp and marked by an increase in bioturbation and a decrease in grain size, as well as a darkening of color.

The Upper Middle Bakken in the AV Wrigley is 16 feet thick, dark grey in color, and silt dominated. The Upper Middle Bakken is similar to the Lower Little Bakken facies but is bioturbated through the entire interval. Grain size is very fine and bedding is highly mottled. The unit has some UV fluorescence near its basal contact with the Middle Bakken Sandstone, but is weaker in intensity and orange-yellow in color which is considered less saturated and ultimately lower quality (Chuparova, Hohman, and Lean 2014). The top contact with the Upper Bakken is sharp into the dark black shale.

The Upper Bakken Shale is visually identical to the Lower Bakken Shale. In the AV Wrigley, the Upper Bakken is 10 feet in thickness, dark black in color and highly organic. Ubiquitous pyrite and fissile bedding characterize the upper shale as well (Figure 19).

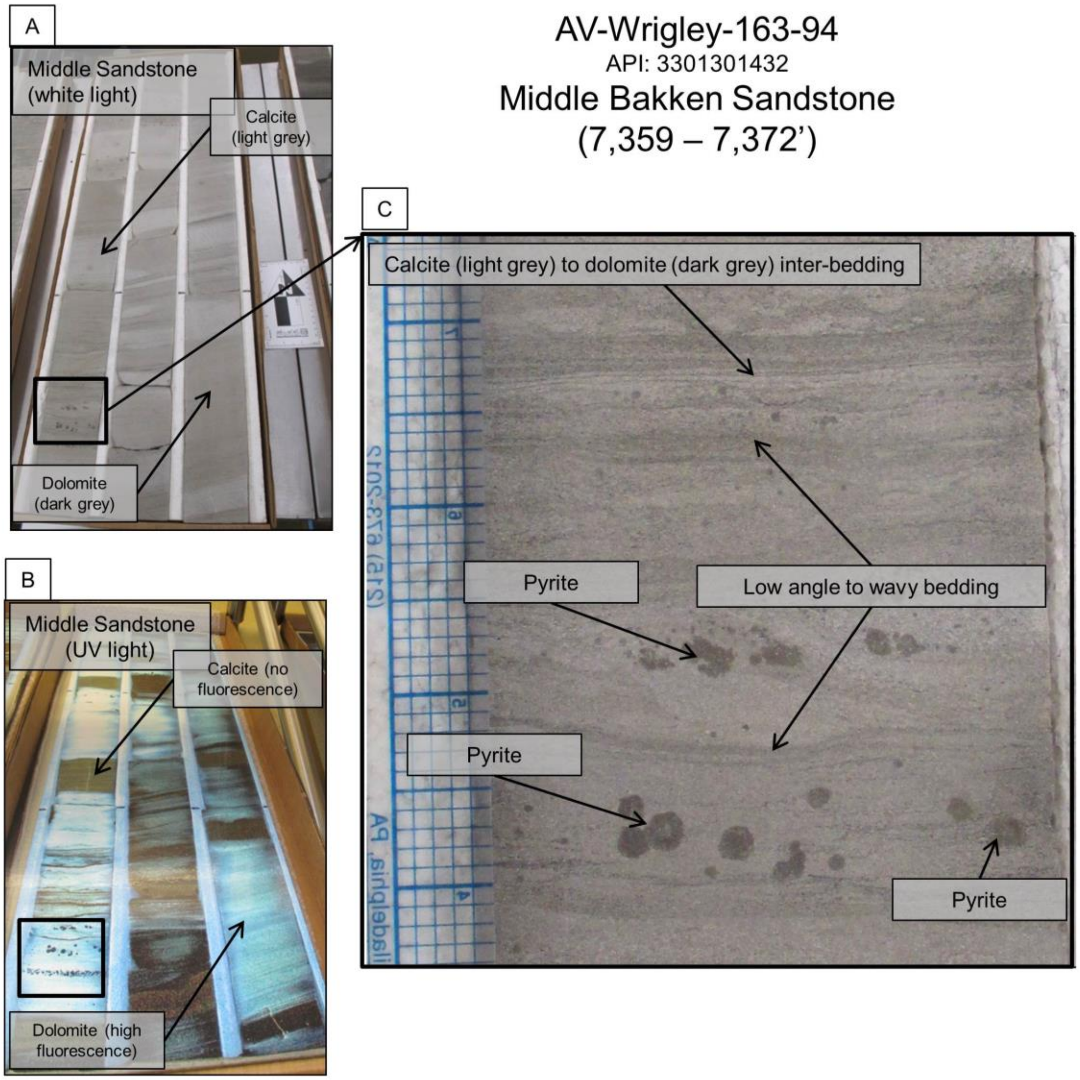


Figure 20: Detailed photographs from the Middle Bakken Sandstone from the core of the AV Wrigley 163-94 well. **(A)** Photograph with white light showing calcite-dolomite lensing on the centimeter to meter scale; and **(B)** Photograph with ultraviolet (UV) light showing zones of hydrocarbon saturation, generally associated with dolomitized lenses. **(C)** The Middle Bakken Sandstone facies contains low angle, wavy, and cross bedded layers with scattered pyrite nodules. Calcite-dolomite lensing appears to also work on a smaller, cm to mm, scale within particular zones of the core.

2.2.9 Interpretation of the Middle Bakken depositional environment

The environment of deposition of the Middle Bakken sand is interpreted to be a barrier bar system with a strong tidal influence similar to the same, coeval unit previously described in southeastern Saskatchewan (Wood et al., 2013). Reinson's (1992) depositional model for an idealized shallow marine barrier bar complex (Figure 21A), closely resembles the two-dimensional sand thickness map mapped via well logs in map view from my study area (Figure 21B). Sand thickness and orientation is controlled in large part by eustatic sea level changes promoting a higher energy environment than observed in the upper and lower middle siltstones.

The most striking feature of the Middle Bakken Sand geometry is the elongated barrier core, which is oriented northwest to southeast, and the tidal flood deltas deposited on the landward (eastward) side of the barrier core (Figure 21B). The tidal flood deltas, though small in area, appear to contain very high reservoir quality with the thickest sands separate from the barrier core. A large wash-over deposit is interpreted in the northern portion of the study area, which covers a relatively large area (Figure 21B).

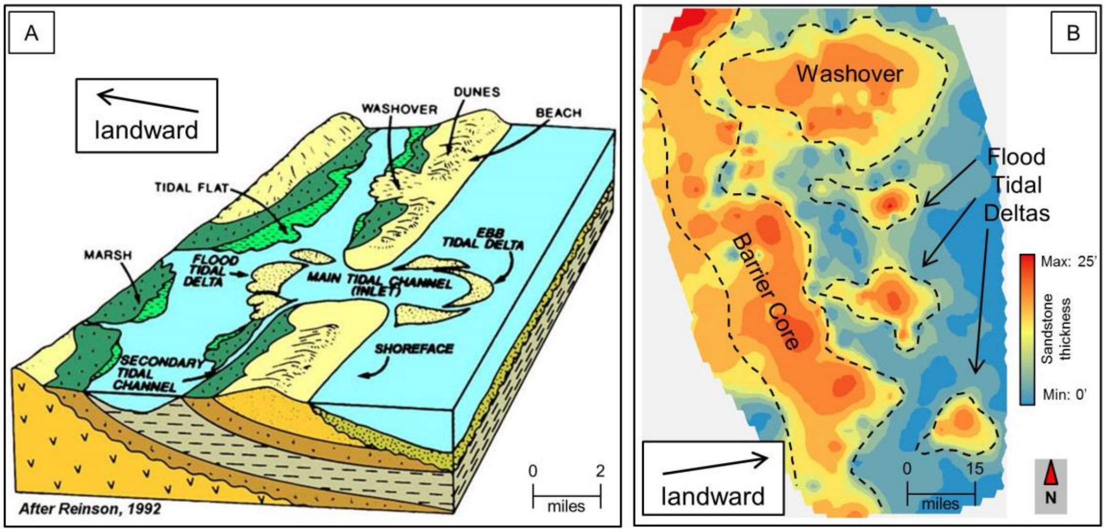
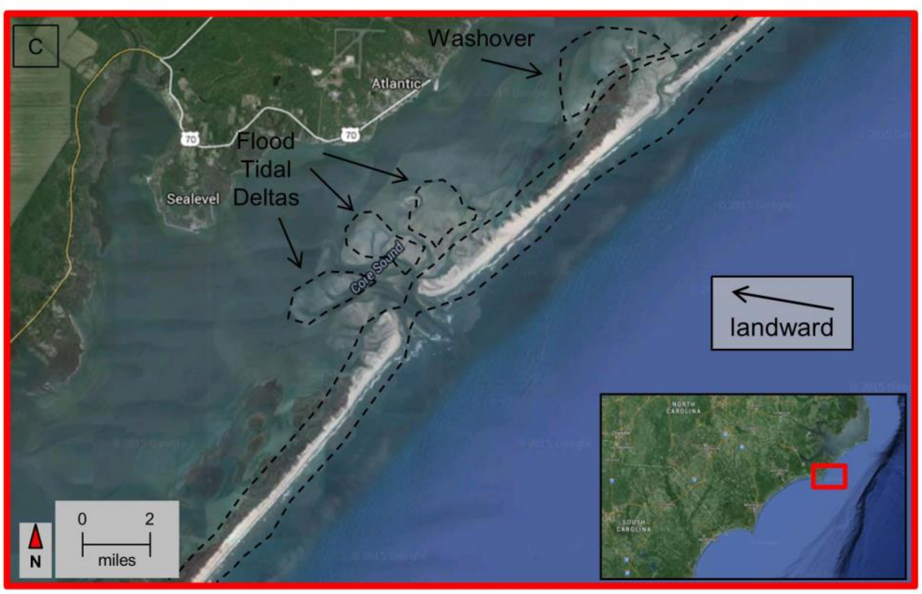


Figure 21: (A) Three-dimensional block diagram showing idealized tide-dominated barrier bar system from Reinson (1992) used as an analog to explain the geometry and thickness variations of the Middle Bakken Sand facies in the thesis study area. **(B)** Interpreted Middle Bakken sand distribution system in the study area.



(C) Modern-day depositional environment analog for the Middle Bakken Sand facies based on a Google Earth satellite image from the Atlantic coast of North Carolina.

However, the wash-over deposit is relatively thin and appears to contain lower-quality reservoir sands than that found in barrier core and flood tidal delta. Coastal North Carolina has been identified as a modern-day analog to the deposition of the Middle Bakken Sand (Figure 21C) though size and scale are not exact. No exact modern analog to the Bakken Formation deposition in an intracratonic basin in an epicontintal seaway (Kasper, 1995).

2.3 Field to well-scale seismic structure

2.3.1 Red Sky 3D seismic survey

The Bakken Formation is a tight-oil reservoir that requires large hydraulic fracture completions to produce at economic volumes (Angster and Sarg, 2013). Therefore, while a thick section of Middle Bakken Sandstone greatly improves the well quality of a Bakken unconventional well, the sand alone is insufficient to produce a high quality well. Permeability pathways from the wellbore to the hydrocarbons generated in the Upper and Lower Shale must be naturally present, or induced through hydraulic fracture treatments. To analyze the field-level structure in the study area, the Red Sky 3D Seismic survey was evaluated for seismic discontinuity that would indicate structural deformation associated with natural fractures.

My study area survey lies on the eastern flank of the Nesson Anticline and includes a portion of the deep Williston basin, shallowing eastward towards the basin margin. Structural dip is relatively shallow, measuring less that one degree in most cases in the Bakken interval (Figure 22A). Eighty-four horizontal Bakken wells drilled from 2005 to 2014 were chosen for production analysis in statistical analysis section, however there location is displayed here for reference. The Red Sky 3D survey is situated in the central portion of the stratigraphic study area discussed in the previous section (Figure 22B). The Red Sky survey covers the central portion of the Middle Bakken barrier bar mapped via well logs on its west side, and includes a major tidal flood delta to the east (Figure 23). The Middle Bakken Sand thins toward the center of the survey, but overall the Middle Bakken is relatively thick in the study area and appears to be of high reservoir quality.

The low dips of the Bakken formation are apparent on the 2D seismic lines (Figure 24). This lack of significant structure is consistent with the intracratonic setting of the Williston Basin (Meissner, 1991). Prominent seismic horizons were tied to study well logs (Kingsley, 2015) and were picked over the study area following the regional 2D seismic work of Anna et al. (2010). The Bakken Formation, though relatively thin, is characterized by strong seismic impedance from the contrast of upper and lower shale with surrounding rock and is continuous and easy to pick across the Red Sky survey (Figure 24). No obvious seismic discontinuities are present within the survey area that would indicate major faults. However, subtle dip changes are evident in the Bakken Formation and above and below that would suggest sub-seismic faulting.

A sample synthetic seismogram from Kingsley (2015) and a zoomed in view of the Bakken and Three Forks reflector reveals that the Bakken formation consists of a trough-trough-peak in the seismic data (Figure 25A, B). Though the formation appears largely flat at the survey scale, subtle structural variation is apparent at smaller scales (Figure 25B). This subtle structural variation at very small scales likely impacts the local stress regimes and may impact drilling and completion effectiveness on a well to well basis (Cipolla, 2011). Quantifying this structural variation will be the aim of the next section of the project.

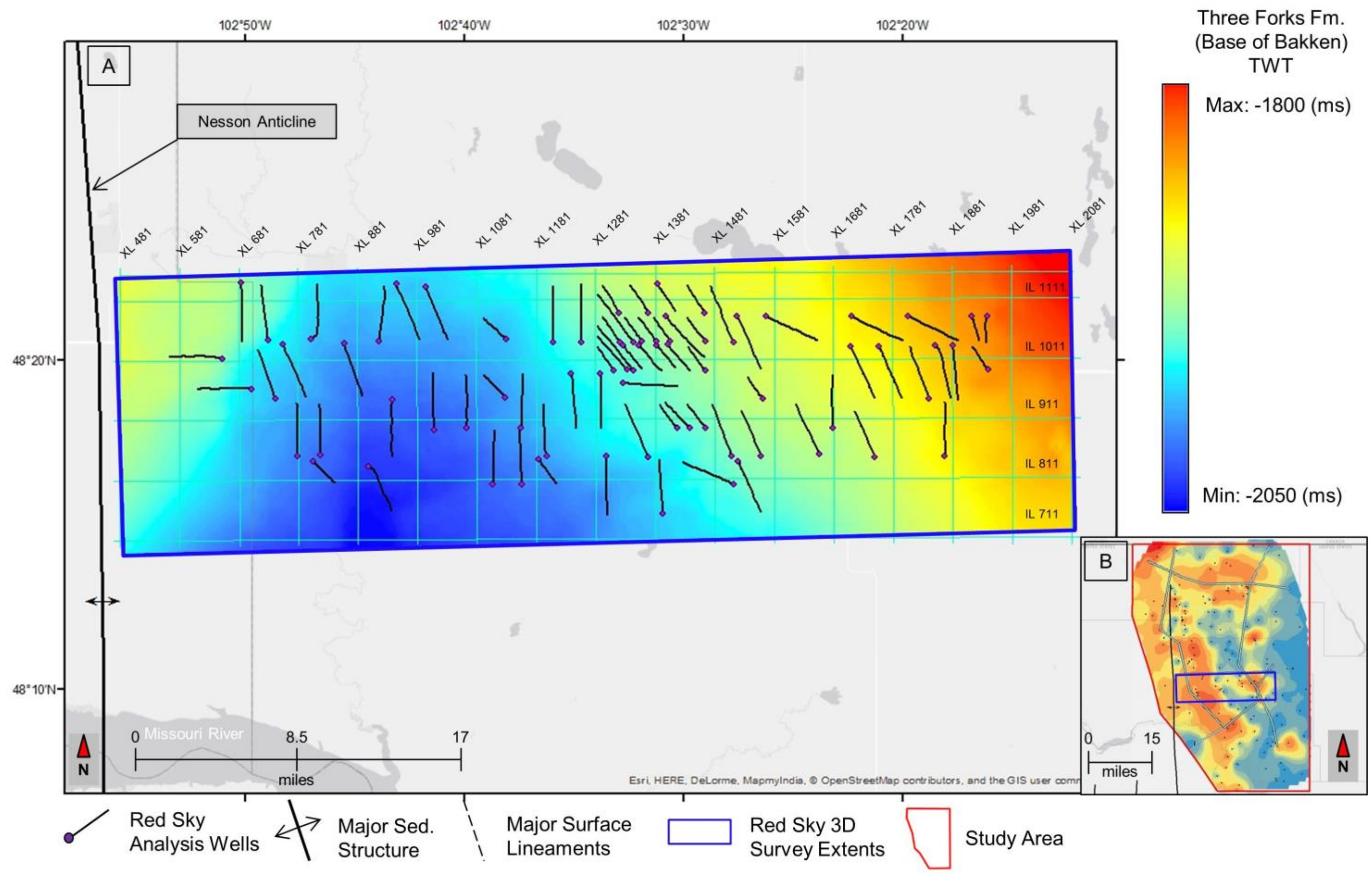


Figure 22: **(A)** Location of Red Sky 3D seismic survey. Top Three Forks two-way time structure map is displayed inside the survey area. The Three Forks surface gently dips westward from the east to its to greatest depth between crosslines 881 and 981. The surface steepens abruptly on the western edge of survey, which is interpreted as the eastern flank of the Nesson Anticline. Locations of wells used for production analysis are included within the survey. **(B)** Map showing extent of the Red Sky 3D seismic shown relative to Middle Bakken Sand facies.

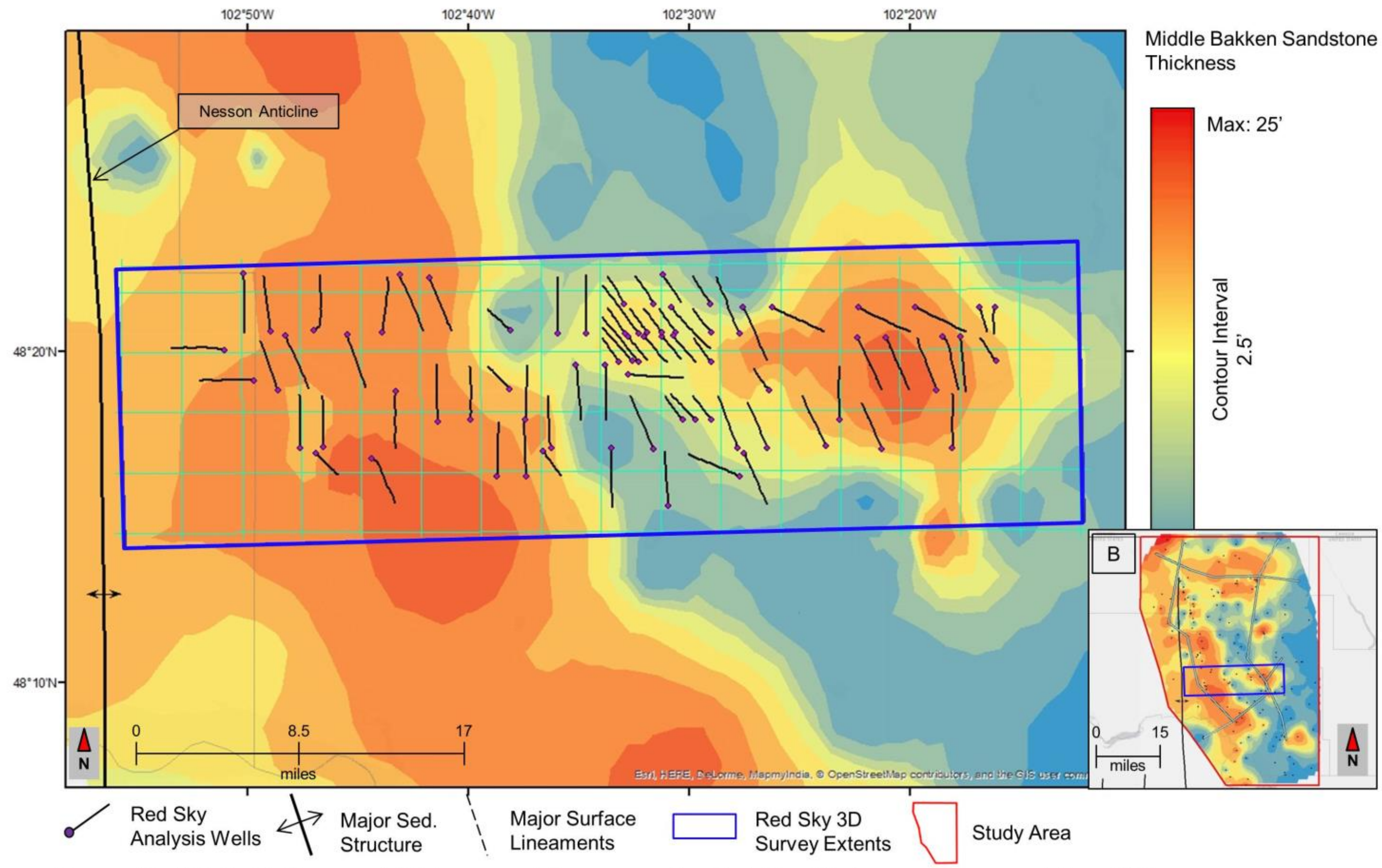


Figure 23: Middle Bakken sand thickness variation across the Red Sky Study area as mapped from 187 vertical well logs shown in section 1. Thicker sands are located along the western and eastern margins of the Red Sky Survey. Location of wells used for production analysis are included within the survey.

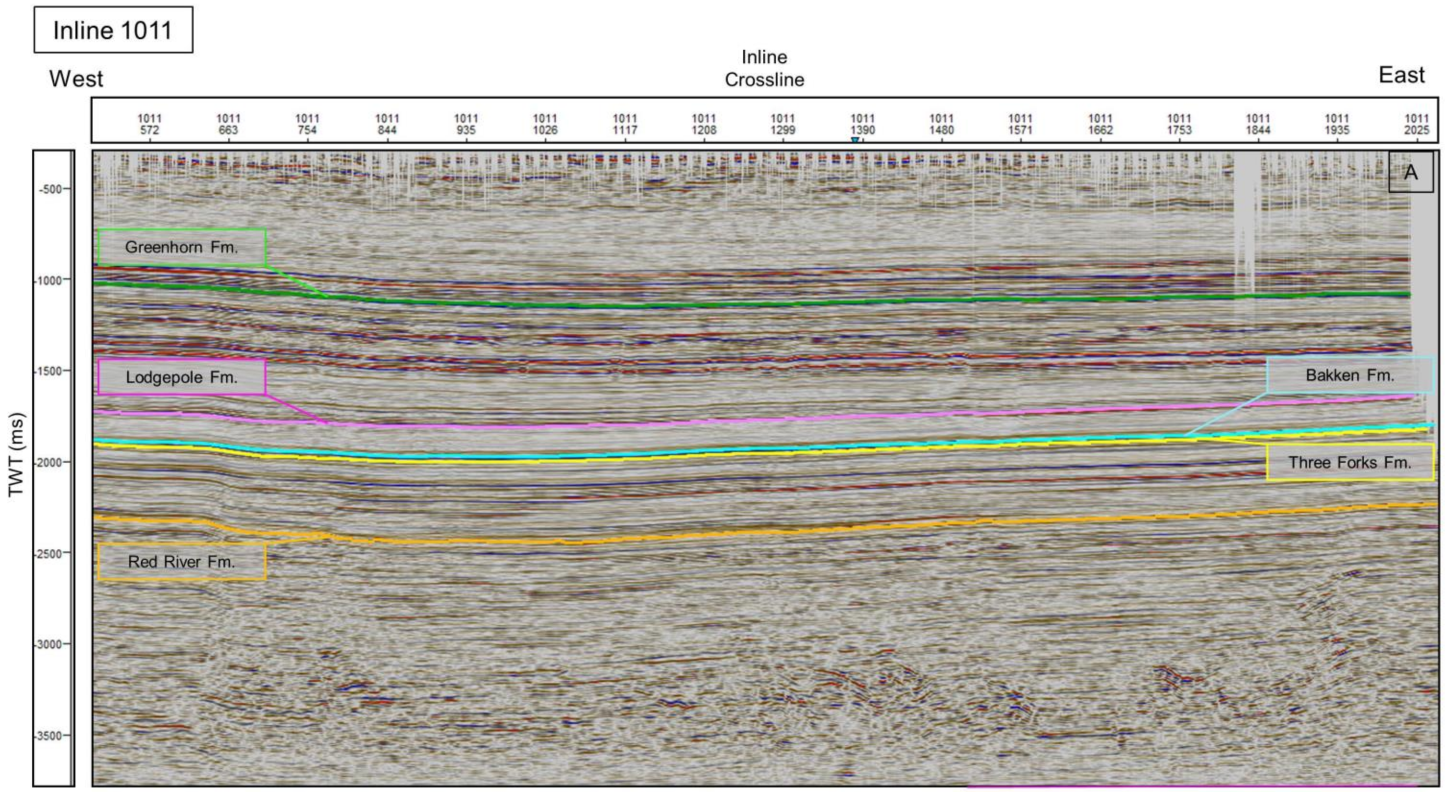
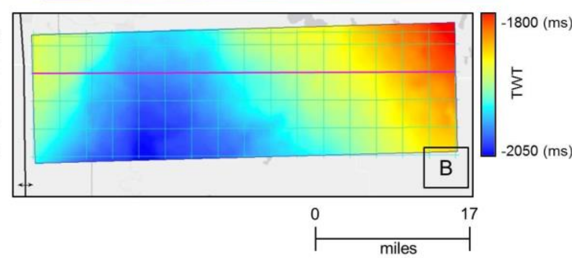


Figure 24: (A) Inline 1011 through the Red Sky 3D viewed from south to north at 20 times vertical exaggeration. Seismic horizons dip gently to west to a maximum depth near crossline 844. This depth maximum is adjacent to the Nesson anticline as shown by increased structural dips and shallowing horizons westward to the limit of seismic coverage. **(B)** Map-view of the top Three Forks Formation time structure and location of inline 1011.



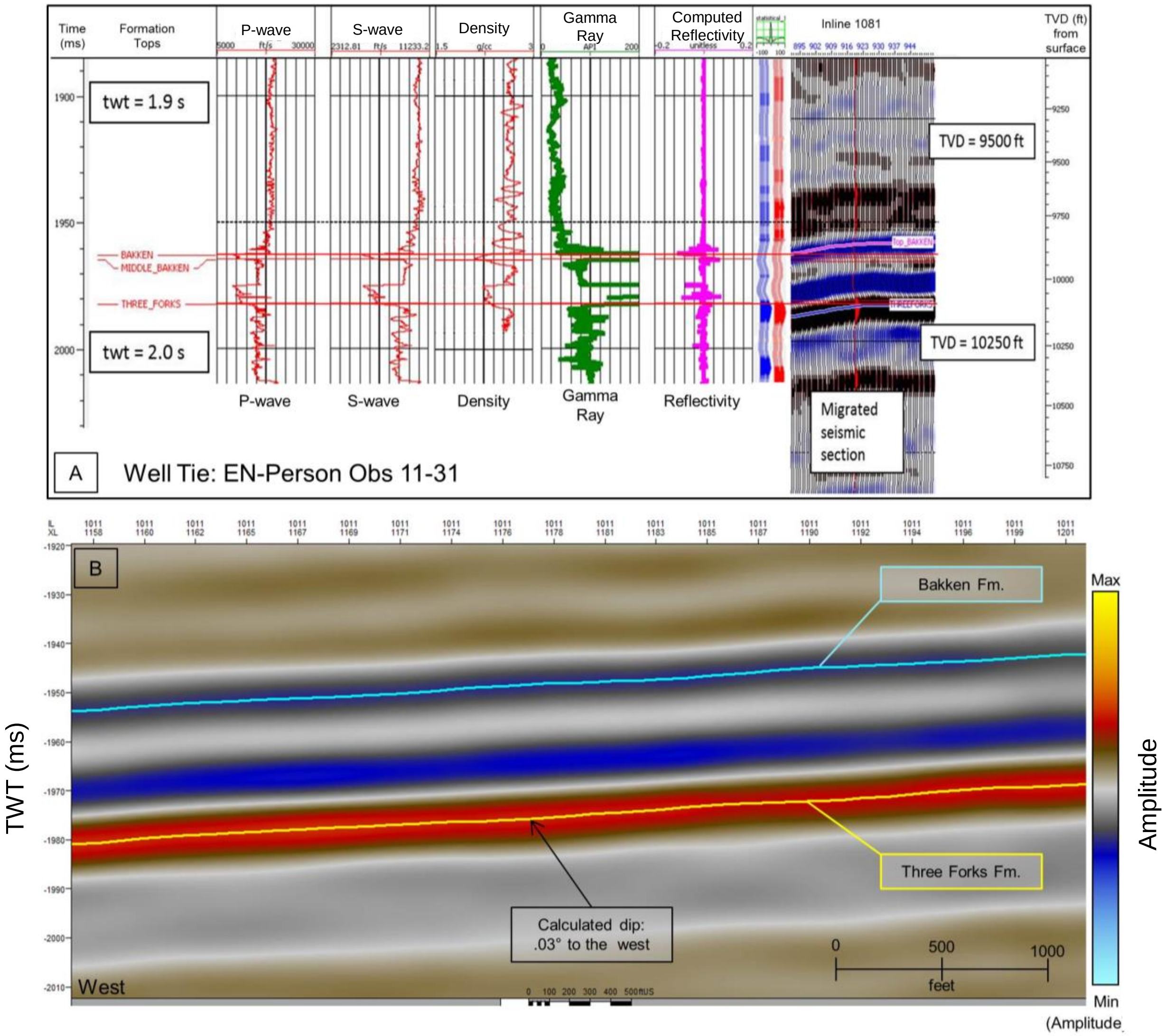


Figure 25: (A) Bakken and Three Forks Formation well and its seismic tie (Kingsley, 2015). **(B)** Zoomed section showing seismic amplitude of the Bakken and Three Forks horizons. Note strong seismic reflection associated with the Upper and Lower Bakken Shale. Seismic attributes in Figures 26, 27, and 28 were generated on the Three Forks Formation horizon.

2.3.2 Seismic attributes for analysis of subtle structural features

Natural fractures present in the Red Sky study area will significantly impact modern, ambient stress regimes with northeast-southwest compression (Sonnenberg et al., 2010) that may preferentially promote the development of fractures along these preexisting planes of weakness during hydraulic fracturing (Gale, 2014). Because the fracturing in the Red Sky 3D seismic volume contains little to no offset on larger faults detectable on the seismic data, or abrupt changes in dips of bedding related to fault offsets (Figure 24), structural attributes were generated on the base of the Bakken Formation to highlight changes in continuity between seismic traces (Figures 26A, B, C). Being the base of the Bakken reservoir, this horizon should be the best representation of the structure of the Bakken as a whole (Figure 26A). These discontinuities likely correspond with structural deformation that is very subtle and interpreted as a system of fractures that parallels the modern direction of maximum compressive stress (Figure 27).

The use of seismic attributes in thin rock formations is a developing field that shows great potential (Marfurt and Alves, 2015). The problem with many tight oil plays, like the Bakken, is that the thickness of the target formation lies near or below the physical limit of seismic resolution, or the tuning thickness. Advanced thin-bed attributes have been developed which use external data sources, such as sonic well logs, to add high frequency bandwidths to the band-limited seismic data. However, these attributes have in inherent non-uniqueness that adds high uncertainty to their interpretation (Taner, 2003). Therefore, I have chosen to utilize well-developed attributes to characterize variation in the strong lower seismic reflector of the Bakken Formation. Any subtle changes in the continuity of the Bakken formation may be indicative of sub-seismic natural fractures or areas of increased stress regimes that may preferentially fracture during hydraulic stimulation (Jones and Roden, 2012).

First, the edge detection attribute was used to identify fractures on the top of the Three Forks Formation that underlies the Bakken Formation (Figure 26B). The edge detection attribute calculated in Petrel is closely related to the semblance algorithm that is also sensitive to changes in both amplitude and waveform along the seismic reflector (Chopra and Marfurt, 2007). Edge detection values were extracted along the top of the Three Forks horizon and plotted in map view with the higher values associated with higher seismic continuity, while lower values are associated with edges associated with fractures. Next, a dip-angle attribute was generated on the Three Forks (base of the Bakken) Formation (Figure 26C). The dip-angle attribute is essentially a first derivative of the seismic structure, which highlights second-order structural changes independent of first-order structural dip (Chopra and Marfurt, 2007). The dip-angle attribute appears to highlight major structural discontinuities, similar to edge detection. Both the edge detection and dip-angle attributes extracted on the Three Forks horizon were compared with attributes extracted on the Lodgepole Formation horizon, approximately 200 ms above, to insure that no shallow-horizon artifacts were present in the Bakken interval of interest. Although the orientations of major structural anomalies appear to correlate, attributes generated on the Three Forks horizon were deemed unique.

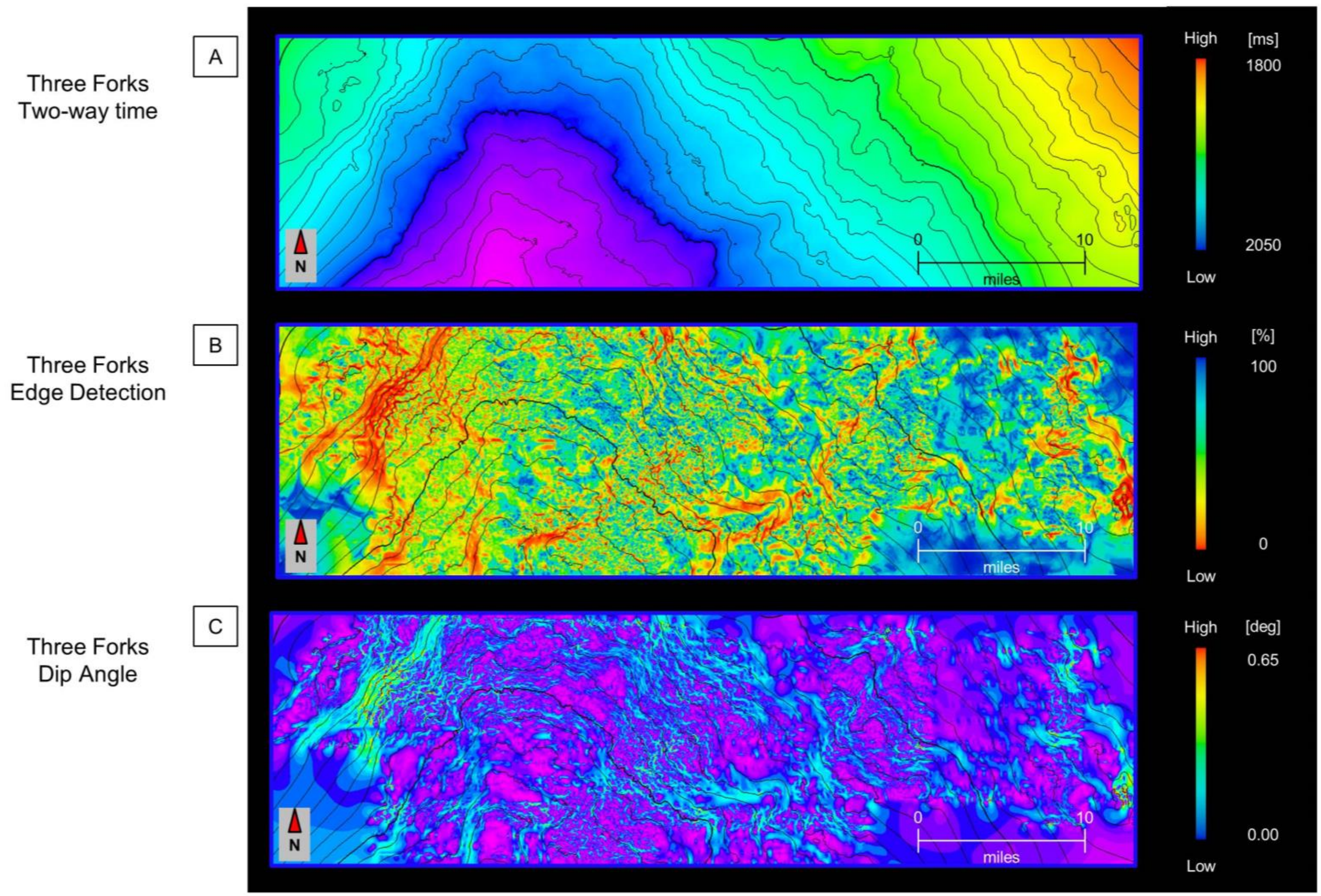


Figure 26: Seismic attributes computed on the top of the Three Forks Formation. **(A)** Two-way time structure, **(B)** edge detection attribute, and **(C)** dip angle. Edge detection and highlight areas of seismic discontinuity and are interpreted to identify local areas of high stress and/or natural fracturing.

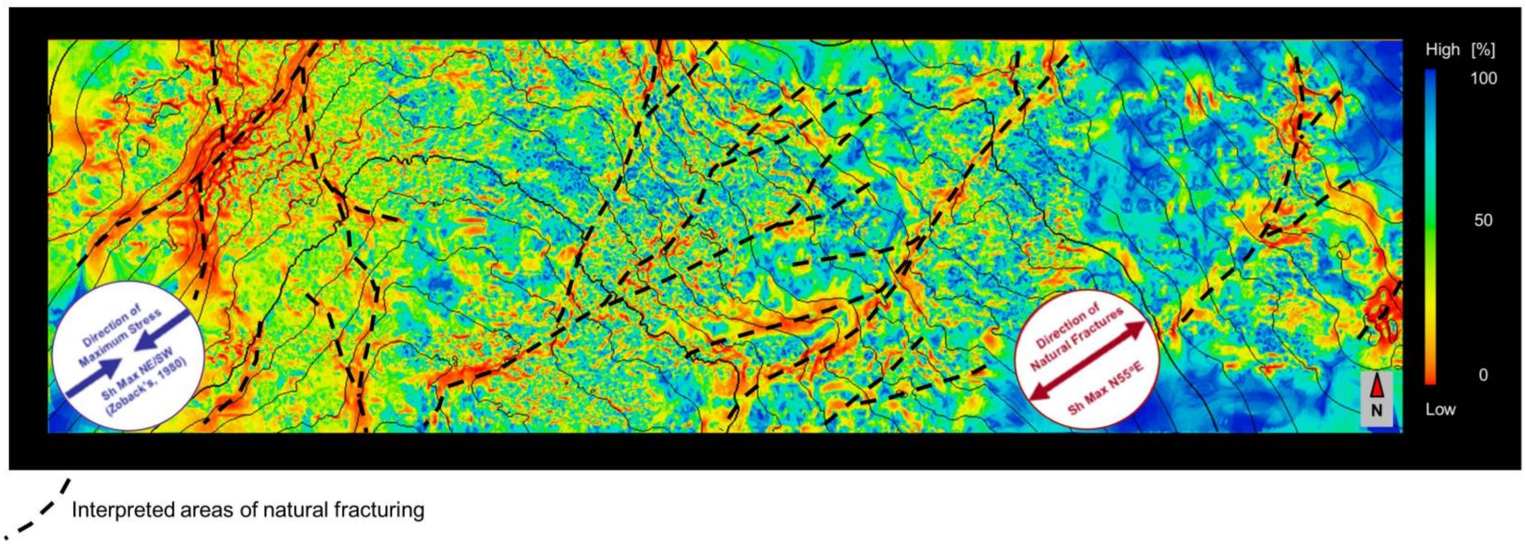


Figure 27: Edge detection on top Three Forks Formation and interpreted areas of natural fracturing within the Bakken interval. Orientation of attribute anomalies correlates well with regional maximum stress direction and direction of fracture propagation shown in Figure 3.

Because it is easiest to visualize structural discontinuities that appear to be geological using edge detection, this attribute is used to illustrate fracturing of the Bakken Formation. Using the edge detection attribute and the regional maximum stress direction from Zoback (1980), I interpreted areas with a high probability of natural fracturing associated with the most extreme edge detection values (Figure 28). The interpreted fracture trends are consistent with the direction of natural propagation seen in other studies in the area (Sonnenberg and Pramudito, 2009). These natural fractures may provide areas of increased permeability development in the low permeability rock and are also likely to influence the local stress and/or pressure state of the Bakken reservoir. Because the Bakken Formation has a solution-gas reservoir drive mechanism, any fractures may be impacting pressure development, especially if the Upper or Lower Bakken Shale has been breached (Theloy, 2014).

2.3.3 Quantifying structural variation in individual wells

Identifying and interpreting areas of possible natural fracture development is a basic observation for characterizing structural variation at the field scale. In order for this fracture analysis to be applied to specific wells, I quantified the attribute values associated with 84 individual, horizontal wells to compare well quality.

I imported seismic attributes generated in Petrel into ArcMap 10.1 for spatial analysis. Using ArcMap I was able to generate statistics for each of the 84 chosen wellbores in comparison to the attribute values for the part of the 3D volume that these individual wells penetrate (Fig. 28A). Because of large, hydraulic fracture completions associated with Bakken Formation horizontal wells, the attribute value intersecting the wellbore may not be an accurate representation of the structural conditions under wich the induced fracture lengthens after initiation. Previous microseismic surveys in the Bakken Formation of the Williston basin encountered fracture growth varying from a few hundred feet laterally, to more than 1000 feet horizontal from the wellbore (Abbott et al., 2009).

Using an approximate average from the observed extreme values, I choose to implement a buffer overlay of 500 feet perpendicular around each wellbore to calculate statistical values of seismic attributes likely to be encountered by induced fractures in each well (Figure 28B). Using ArcMap, I generated statistics within each wellbore buffer and stored them in an Excel table. Statistical values for attribute values within the buffers include minimum, maximum, range, mean, sum, and standard deviation. The same process was used for the dip angle attribute. These statistics will be compared with well quality and quantified using normalized, historical production statistics discussed in the next section.

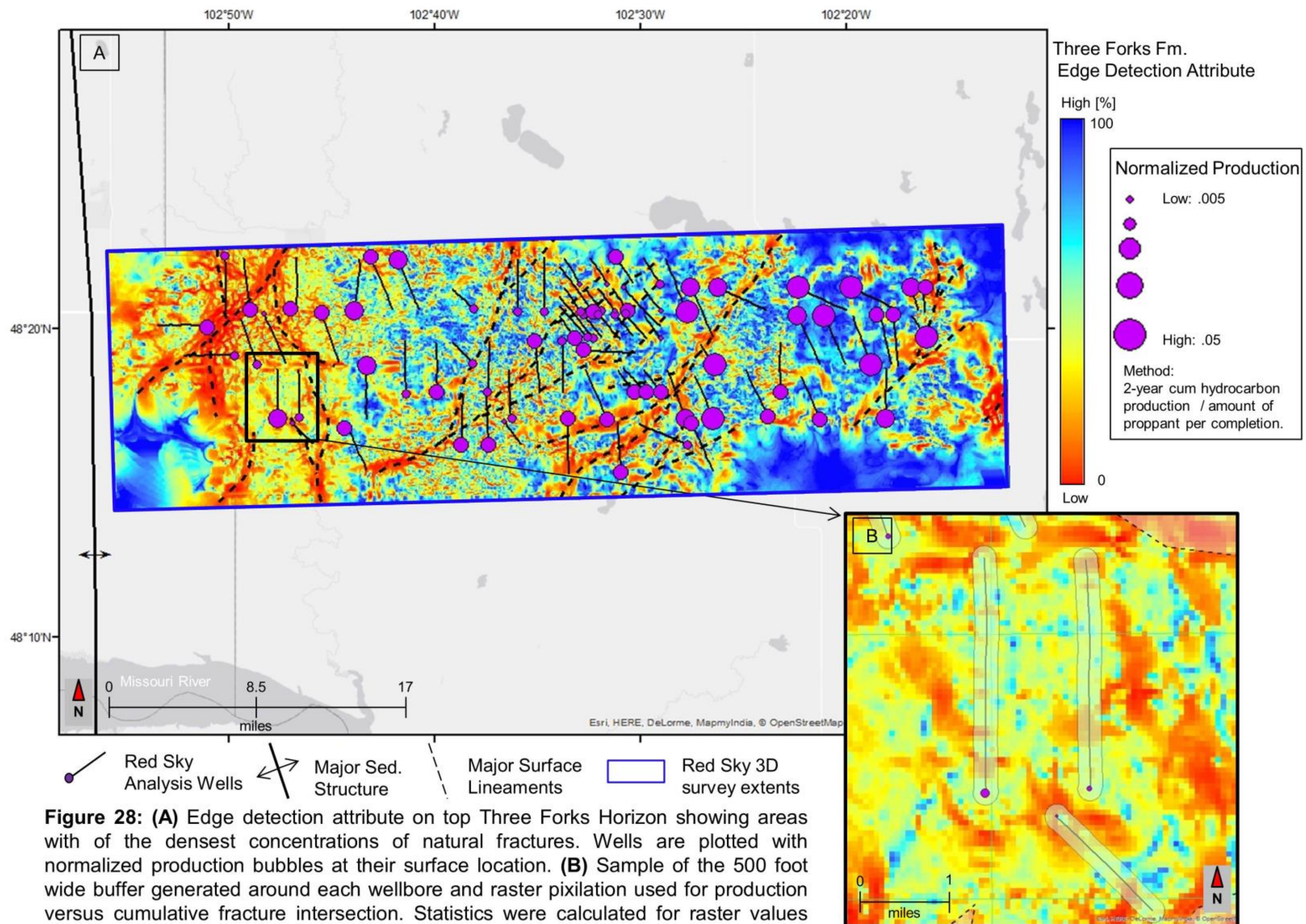


Figure 28: (A) Edge detection attribute on top Three Forks Horizon showing areas with of the densest concentrations of natural fractures. Wells are plotted with normalized production bubbles at their surface location. **(B)** Sample of the 500 foot wide buffer generated around each wellbore and raster pixilation used for production versus cumulative fracture intersection. Statistics were calculated for raster values falling within each wellbore buffer.

2.4 Normalizing historical production to evaluate well quality

2.4.1 Bakken production statistics

To evaluate the relationship between well quality and the seismic-attribute statistics calculated within the wellbore buffers, a quantitative measurement of well quality must be determined. The most obvious quantity associated with the quality of an oil well is cumulative production reported over a certain period of time. However, cumulative production contains numerous inherent variables that must be normalized to make valid comparisons. The majority of the normalization analysis was undertaken in Microsoft Excel.

The Red Sky 3D seismic survey includes more than 300 wells of varying lengths, orientations, target formations, and completion designs that define approximately five separate oilfields (NDIC). Many field regulations dictate well spacing and orientation, but no consistent regulations apply across the entire Williston Basin. I selected 84 wells from within the seismic survey for use in production normalization analysis in this thesis. All chosen wells had at least two years on production records, which accounts for - on the average - approximately 80% of a typical Bakken well's production decline which is typical for most unconventional wells regardless of basin (Cipolla et al., 2011).

To normalize well quality for wells drilled in different areas at different times, I queried production statistics for selected wells from the North Dakota Department of Mineral Resource's online database, which reports statistics both by month and by the number of days per month that each well actually produced (some wells are shut in for various operational reasons). For this study, a 24-month period of cumulative production of oil, gas, and water were extracted, summed for each well, and divided by total number of days on production within that 24-month time period.

One thousand cubic feet (MCF) gas was converted to barrels oil equivalent (BOE) by the industry standard of 1 BOE = 6 MCF gas before summation. Final cumulative production was reported in BOE. Cumulative water production was included in the calculated production volume as water is a minor contributor to produced fluids. Water may represent additional produced fluids, but for most wells in the analysis, water volumes produced were approximately equivalent in volume to fluids pumped during hydraulic fracturing operations. Twenty-four month cumulative production was calculated using this method for all 84 wells in the project in terms of BOE.

This time-normalization analysis was conducted for a variety of time periods including, one-year and five-year cumulative production. Short-term normalization (one-year) sometimes did not include significant production variation. On the other hand, a long-term (five-year) normalization window yielded few data points for comparison because many wells within the Red Sky Survey area had not been online for that period of time at the time of this work. Additionally, normalized production numbers from wells older than 5 years were plotted against their own 24-month normalized cumulative and a strong linear relationship exists. Therefore, it is reasonable to assume that records for a 24-month cumulative production is a good sampling of well performance for a typical Bakken well over its production lifetime.

In addition to time-normalization, the advance of technology and the steep learning curve of drilling and completion optimization cause changes in production values over the cycle of development within a particular basin (Cipolla, 2011). The Bakken, like other unconventional resource plays in North America has seen steadily increasing lateral lengths and proppant volumes used during hydraulic fracture completions. These “operational variables” must be normalized as along with time on production, because a newer well - drilled into a lower quality reservoir - may produce more because of its larger completion design with a more complexly-induced fracture network (Cipolla, 2011).

To simplify this normalization as much as possible I divided the time-normalized production statistics calculated above by the size of the respective well's completion, which was reported in the well files as pounds of proppant. Proppant volume is the simplest approximation of the well's stimulated rock volume - or, in other words - the induced, effective permeability of the unconventional system. With lower proppant volumes a complex fracture system may be induced by hydraulic fracturing, but will not contribute to sustained hydrocarbon production due to fracture closure that occurs at high pressure in unconventional reservoirs like the Bakken Formation (Gale, 2014).

I define "normalized production" as the time-normalization procedure described above divided by the amount of proppant, or completion size. Although this method may oversimplify a complexly variable system, I will demonstrate in the next section that statistical relationships can be observed between production and seismic attribute statistics calculated for the buffer areas surrounding these wells.

2.5 Well-scale analysis of relationship between multi-source attributes

2.5.1 Analyzing attribute relationships

In Figure 28A, production statistics from 84 wells within the Red Sky 3D survey - including cumulative and initial oil, gas, and water volumes - were reviewed and normalized following the procedure described in Section 2.4. Normalized production for each well was then added to ArcMap for visualization and comparison with fractures in the Bakken Formation imaged using the edge detection attribute derived from the 3D seismic volume. While some trends begin to emerge from visual analysis alone, it is difficult to draw any conclusion from the attribute image alone. Adding to the difficulty is the necessity to consider all attribute values along the wellbore and more realistically within a set buffer around the wellbore that is likely to control induced fractures and stimulated rock volume orientation. Therefore, statistical analysis is necessary to show conclusive relationships between normalized production and fractures in the reservoir.

2.5.2 Statistical analysis of attribute relationships

All generated and calculated attributes were compiled on a spreadsheet in Microsoft Excel for each well and then imported into TIBCO Spotfire analytical software for statistical analysis of attribute relationships using linear regression. A positive linear relationship with high statistical significance was discovered between the summation of edge detection values within the 500 foot wellbore buffer and normalized production values for the 84 wells inside the Red Sky 3D survey area (Fig. 29). The higher, edge-detection values correspond with areas of continuous seismic reflectors and cooler colors in the attribute map in Figure 28 showing that wells drilled in fractured areas correlate with lower normalized production volumes over the well's lifetime.

Another strong linear relationship with high statistical significance, although negatively trending, was determined between mean dip angle inside the 500-foot wellbore buffer and normalized production for the wells inside the Red Sky 3D Survey area (Fig. 30). This relationship, like the one previously discussed associated with edge detection, indicates that higher quality wells are associated with drilling in areas not affected by natural fracturing.

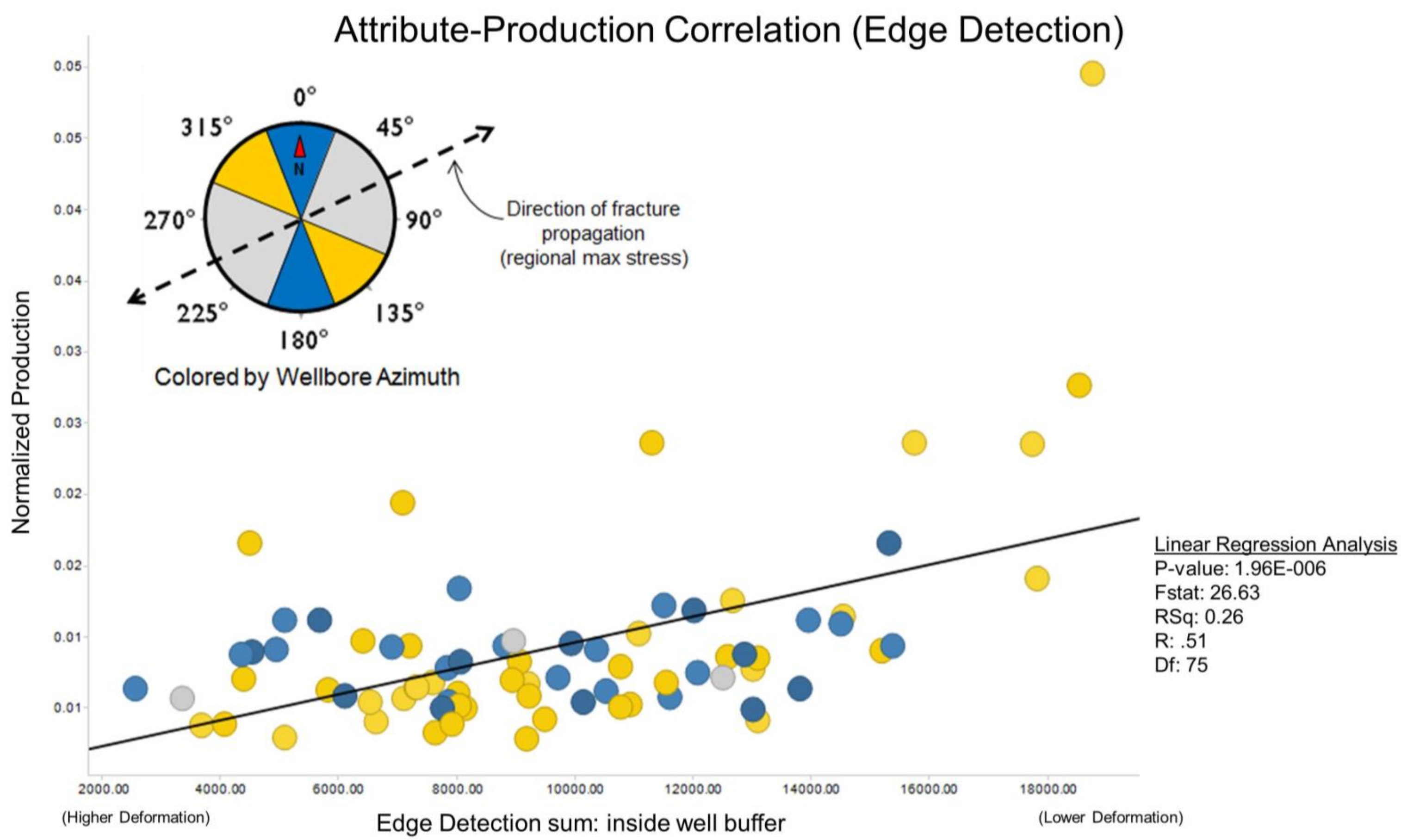


Figure 29: Cross plot of edge detection sum inside 500 foot wide, well buffers (Figure 28A) versus normalized hydrocarbon production. A strong statistical correlation exists between normalized production and sum of the edge detection attribute. Wells in less naturally fractured areas tend to produce better relative to the other wells in more naturally fractured areas. Relationship intersections are colored by azimuth of their wellbore, which is generally considered an important property for optimal well design. No overall trend is evident in the direction of the wellbore azimuth. Higher production tends to be associated with wellbores drilled perpendicular to the regional maximum stress direction.

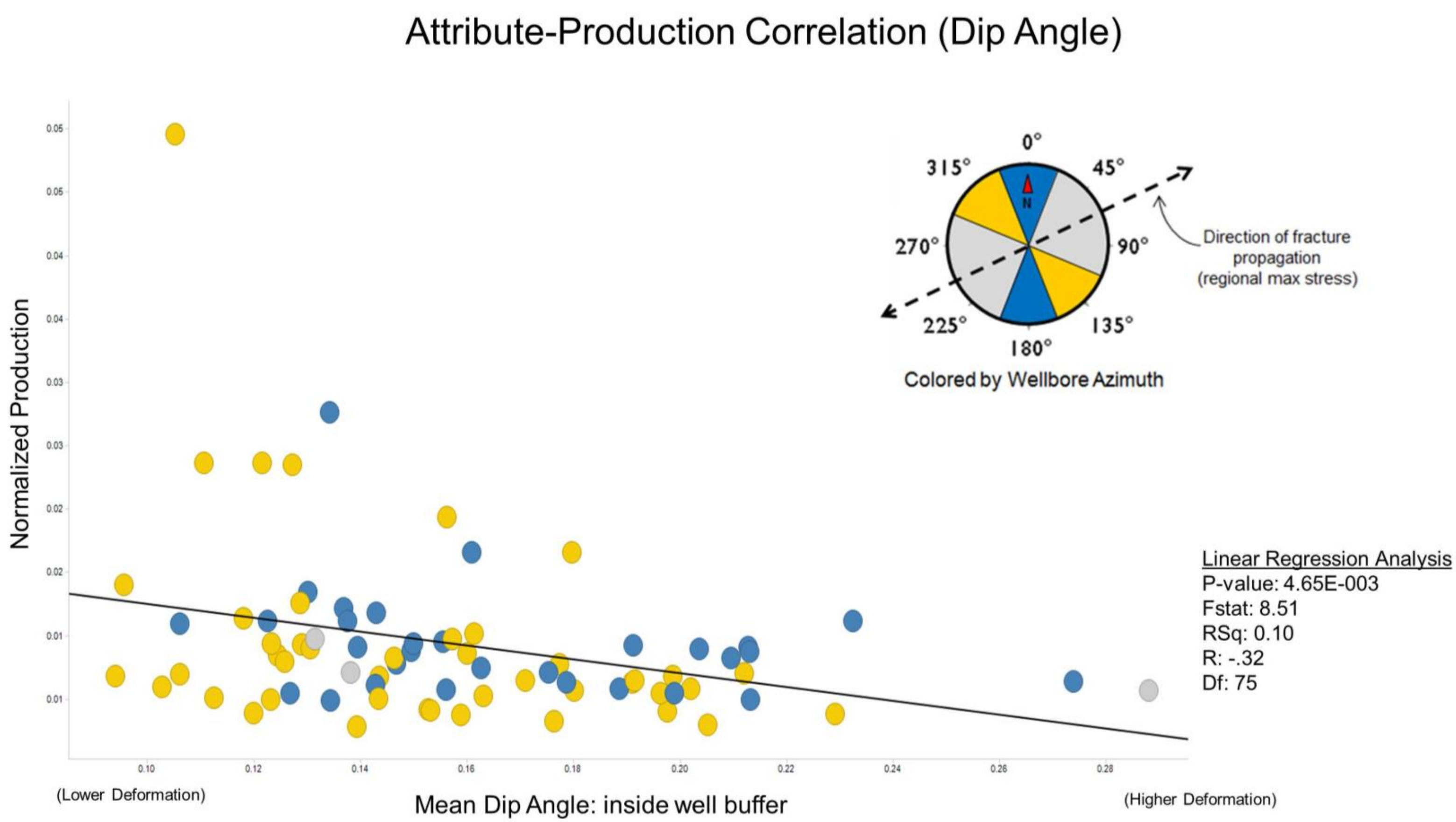


Figure 30: Cross plot of mean dip angle inside well buffers (Figure 28B) versus normalized hydrocarbon production. A strong statistical correlation exists between normalized production and dip angle variation.

2.6 Discussion and conclusions

2.6.1 Discussion of results

Through a combination of regional stratigraphic and local structural analysis I have interpreted an integrated system that explains variations in production observed between closely spaced wells (1,000-5,000 feet separations) in the Red Sky area. Thick sections of the Middle Bakken Sandstone facies (10-25 feet) in areas with the least number of natural fractures - mapped with attributes from 3D seismic volumes - correspond with the most productive Bakken Formation wells when analyzed using normalized hydrocarbon production volumes over their first two years of production (Fig. 31). Conversely, wells that are drilled in areas characterized by thin Middle Bakken reservoir facies with large numbers of fractures - mapped from attributes of 3D seismic volumes - tend to show poorer production over their lifetime.

An early Mississippian age, sandy barrier bar complex in the Middle Bakken Formation controls the presence of high-quality, sandy reservoir facies over the study area. Thick sections (10-25 feet) of the Middle Bakken Sand reservoir deposited in barrier bar settings correspond with more productive wells when normalized for time on production and changes in completion method. Statistical analysis of the relationships between normalized production and structural attributes of the Bakken Formation reveal an unexpected result contrary to the widespread assumption in the Bakken basin that natural fractures enhance the effective permeability of an inherently tight hydrocarbon system and thus should contribute to higher production wells in most cases.

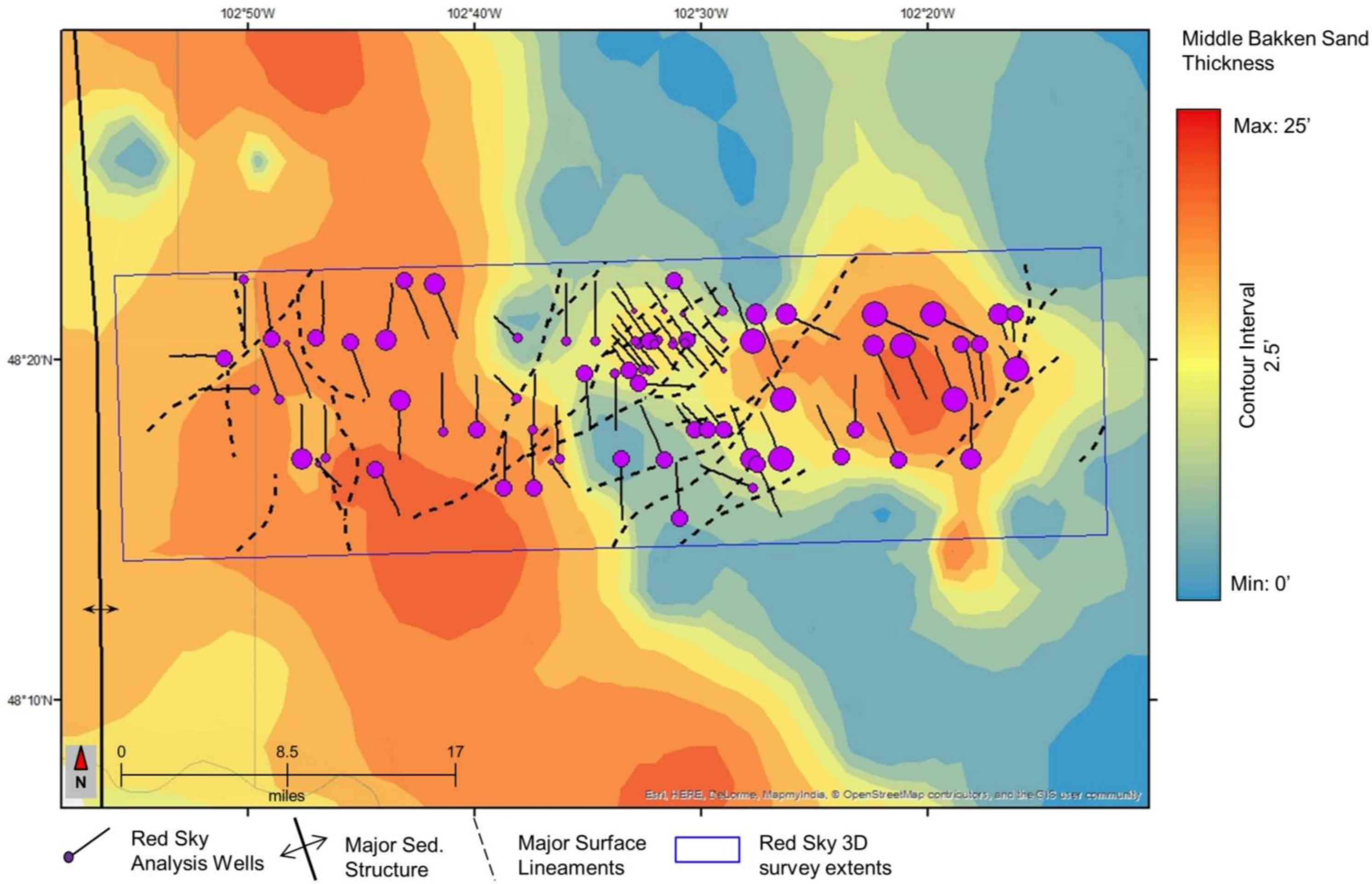


Figure 31: Middle Bakken sand thickness with fracture interpretation based on overlay of seismic attributes. Sand thickness of the high quality Middle Bakken sand is considered a first-order control on normalized hydrocarbon production within the study area. Geologic horizon continuity, interpreted from the edge detection and dip angle attributes, is considered a second-order control on production. Wells intersecting areas with higher densities of natural fractures tend to produce less over their lifetime relative to wells sited in less fractured areas.

The factor that eludes direct observation in core analysis and conventionally exploited resource plays is the pressure dependence observed in many unconventional reservoir plays (Cipolla, 2011). The Bakken Formation is an over-pressured reservoir and is at or near its critical stress in its normal, un-fractured state (Meissner, 1991). This means that any natural fracture that breaks the upper or lower sealing shales of the Bakken Formation may allow local overpressure to dissipate. This fracture-related, dissipation of overpressure will negatively impact the primary driving mechanism for hydrocarbon production in the unconventional resource and lead to lower production. Because accurate estimates of reservoir pressure are often impossible or impractical to obtain, the presence or absence of overpressure is difficult to detect prior to bringing a Bakken well on production.

In addition to pressure degradation by natural fractures in the Bakken Formation, another phenomenon may control lower quality well production linked to local fracturing may be the local stress state (Fig. 27). Areas of the Williston Basin with a preferred natural fracture orientation in a northeast-southwest orientation related to the ambient high stress state may control relatively simple, linear completions instead of the ideal amorphous fracture ‘clouds’ which are typical of more intensively, stimulated rock volumes. This phenomenon is regularly observed in microseismic surveys of more highly fractured reservoirs like the Eagle Ford Formation in Texas (EIA, 2011), but should also be considered as an important factor on local well productivity when drilling and completing wells in the Bakken Formation.

2.6.2 Conclusions and recommendations

Through integration of observations from subsurface geology, facies interpretation, 3-D seismic data and their attributes, and production analysis from wells, I present an explanation for the production variation observed between closely-spaced wells at separation distances of 1,000 to 5,000 feet, in the Bakken Formation in the North Dakota part of the Williston Basin. Unlike previous studies which focused on regional scale sweet spots, this work presented focuses on the field level which is the scale for drilling and completion decisions. My main explanations and recommendations for improving local production include:

1.) As recognized by previous workers in the area (Theloy, 2014: Grau et al., 2013, Simenson, 2011:) The highest-quality reservoir facies in the Bakken Formation, within The Red Sky area, is the Middle Bakken Sandstone, which can be mapped using well logs from the NDIC. Following Simenson (2011) I have interpreted the Middle Bakken Sandstone as an Early-Mississippian, northwest-trending barrier bar depositional system with a strong tidal influence. Areas of greatest production in the Red Sky area tend to cluster above the core barrier ridge and the tidal flood deltas.

2.) Northeast-trending fracturing in the Bakken Formation can be mapped using 3D seismic attributes at the field-level scale of 1 to 5 miles and correspond to regional maximum stress direction and observed induced fracture orientations. These natural fractures are shown to have significant negative impact on production results from wells that have wellbores that intersect them.

3.) Areas characterized by fracturing the Bakken Formation tend to correspond with poorer well quality. This is likely due to a breach in the sealing capacity of the Upper and/or Lower Bakken shale which allows the naturally high reservoir pressure, which is the main driving mechanism for the tight oil reservoir, to bleed off from the Middle Bakken Reservoir prematurely. In addition to diminished reservoir pressure, highly fractured areas are characterized by a preferred plane of weakness oriented parallel to the natural fracture trend. This preferred-weakness plane will promote linear fracture growth during hydraulic fracture completions, which will decrease the complexity of the simulated rock volume, and hurt the overall cumulative production for the lifetime of the well.

4.) Using the method I described in Section 2.5, complex relationships, such as those between seismic discontinuity and normalized production statistics can be evaluated on a well-to-well basis by using a wellbore buffer zone and spatial analysis software like ArcMap to link multi-source attributes calculated in specialized geologic or geophysical software to their associated oil well. These relationships may be observable by the visual correlation between simple production bubble charts and geologic attributes maps. It is likely necessary, as was the case in this project, to use more advanced analytical software like TIBCO Spotfire to unravel more complex relationships between multisource attributes which may be blurred by evolving technology and operational variables.

5.) To optimize the quality of unconventional wells targeting the Bakken Formation in the eastern region of the Williston Basin in North Dakota, an operator should target thick sections of Middle Bakken Sandstone with planned well paths through areas least affected by natural fracturing. The best sandstones in the study area are the least fractured.

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2.8 Appendix Tables

Table 1: Well information for production normalization

Well API Number	ND File	Longitude	Latitude	Operator	Spud Year	Lateral Length	Well Azimuth
14-digit #	*5-digit #*	*degrees*	*degrees*	*name*	*year*	*feet*	*degrees*
33061004890000	15845	-102.440163	48.313559	EOG	2005	4407	325
33061004910000	15916	-102.782023	48.282000	Missori River Royalty	2006	4923	135
33061004940000	16011	-102.635174	48.343822	Amerada Hess	2006	5266	313
33061005300000	16586	-102.545948	48.340543	EOG	2008	4572	142
33061005310000	16587	-102.520857	48.340815	EOG	2010	4395	141
33061005440000	16674	-102.794296	48.284609	Hess	2007	9067	0
33061005620000	16771	-102.776438	48.285089	Hess	2007	8885	0
33061005720000	16800	-102.441222	48.284590	Hess	2007	9707	337
33061005770000	16824	-102.351351	48.339908	Hess	2007	10536	156
33061005980000	16898	-102.610543	48.282913	Brigham	2007	4898	144
33061006250000	16984	-102.462319	48.342350	Hess	2008	10476	338
33061006700000	17076	-102.268657	48.328421	Slawson	2008	4738	314
33061006790000	17093	-102.372859	48.339833	Hess	2008	9728	155
33061006840000	17105	-102.313553	48.313504	Hess	2008	9666	339
33061006880000	17117	-102.731914	48.342643	Hess	2008	9726	6
33061007100000	17167	-102.354752	48.284314	Hess	2008	8525	337
33061007160000	17184	-102.483946	48.357049	EOG	2008	5323	327
33061007190000	17190	-102.464032	48.284734	Hess	2008	9567	340
33061007390000	17258	-102.816512	48.343244	Hess	2008	9066	353
33061007860000	17408	-102.437841	48.355399	Hess	2008	9750	115
33061008070000	17477	-102.635556	48.314260	Oasis	2008	4980	315
33061008110000	17484	-102.459431	48.355559	Hess	2008	10070	156
33061008300000	17526	-102.527329	48.356996	EOG	2009	5222	327
33061008320000	17531	-102.532184	48.342599	EOG	2009	4305	324
33061008510000	17572	-102.458772	48.282238	Hess	2008	9637	156
33061008810000	17664	-102.527344	48.284312	Hess	2008	10064	336
33061008960000	17720	-102.329389	48.355269	Hess	2008	9531	116
33061009170000	17792	-102.461956	48.270376	Hess	2009	9882	294
33061009200000	17795	-102.520251	48.371760	EOG	2008	4631	147
33061009330000	17835	-102.758334	48.341476	Hess	2009	9566	161
33061009410000	17852	-102.718453	48.371601	Hess	2009	10145	157
33061009510000	17887	-102.805157	48.341023	Hess	2009	9720	156
33061009750000	17950	-102.510154	48.342592	EOG	2009	4296	323
33061009770000	17954	-102.810851	48.313789	Hess	2009	8949	340
33061009780000	17956	-102.696644	48.370230	Hess	2009	9948	160
33061009910000	18001	-102.372736	48.355239	Hess	2009	9912	115
33061009980000	18024	-102.553171	48.327961	EOG	2009	4916	324
33061010110000	18059	-102.397145	48.285749	Hess	2009	9434	334
33061010130000	18062	-102.483636	48.299040	EOG	2010	4932	322
33061010340000	18118	-102.549246	48.357061	EOG	2010	5384	329
33061010440000	18146	-102.281069	48.355588	Hunt Oil	2009	3665	163
33061010980000	18262	-102.739856	48.279082	Hess	2009	8710	152
33061011410000	18371	-102.665163	48.299128	Brigham	2009	9130	359
33061011660000	18444	-102.520867	48.342610	EOG	2009	4514	323
33061011740000	18466	-102.603966	48.284768	Oasis	2010	9280	355
33061012380000	18609	-102.308723	48.340511	EOG	2010	9119	165
33061012780000	18744	-102.645184	48.270213	Brigham	2010	9510	0
33061012850000	18763	-102.504989	48.298835	EOG	2010	4898	322
33061012930000	18784	-102.559040	48.284390	Brigham	2010	9880	179
33061013000000	18819	-102.483801	48.327842	EOG	2010	4850	323
33061013070000	18843	-102.483575	48.342939	EOG	2010	4978	321
33061013110000	18855	-102.563475	48.326160	Oasis	2011	9352	179
33061013510000	18981	-102.515839	48.255435	Brigham	2011	9393	359
33061013650000	19036	-102.623768	48.298903	Oasis	2010	9562	0
33061013890000	19097	-102.585593	48.326479	Oasis	2010	9576	175
33061014390000	19358	-102.548947	48.342282	EOG	2010	4875	324
33061014940000	19560	-102.495676	48.298753	EOG	2010	5438	317
33061015200000	19679	-102.538267	48.342393	EOG	2010	10101	322
33061015310000	19722	-102.534125	48.340817	EOG	2010	5805	140
33061015410000	19764	-102.623572	48.270107	Brigham	2011	9413	359
33061015420000	19767	-102.537945	48.327794	EOG	2011	9799	320
33061016380000	20202	-102.546042	48.321446	Oasis	2011	9368	90
33061016590000	20295	-102.512424	48.341017	EOG	2011	5051	141
33061016600000	20296	-102.513680	48.355519	EOG	2011	8860	138
33061017020000	20542	-102.295573	48.340842	EOG	2012	9019	174
33061017160000	20634	-102.269452	48.355445	Hunt Oil	2011	3814	180
33061017400000	20790	-102.689793	48.297842	Brigham	2011	9841	358
33061017890000	21048	-102.599570	48.342335	Oasis	2011	9850	360
33061017980000	21110	-102.578252	48.342209	Oasis	2011	10287	360
33061018380000	21304	-102.386372	48.299103	Samson	2011	9228	0
33061019040000	21676	-102.301384	48.284502	Slawson	2012	9492	356
33105024700000	22031	-102.836760	48.372018	Continental	2012	10225	163
33061020170000	22354	-102.543300	48.328199	EOG	2012	7468	320
33105025520000	22513	-102.850737	48.333741	Hess	2012	9317	297
33061021920000	23374	-102.721992	48.312957	Hess	2012	9478	192
33061022540000	23773	-102.783711	48.343596	Hess	2012	10014	57
33105028850000	24352	-102.828769	48.318469	Continental	2013	9593	275

Table 2: Completion Attributes

ND File	Proppant Amount	2-year cum HC	Daily HC	Daily Water	Oil/Water	HC/Length	HC/Proppant
5-digit #	*lbs*	*boe*	*boe*	*bbls*	*ratio*	*bbls/ft*	*bbls/lb*
15845	453,000	116,309	75.21	14.44	5.21	0.017066704	0.0166
15916	647,800	33,091	24.31	12.49	1.95	0.004938409	0.0038
16011	514,275	17,848	30.90	14.65	2.11	0.005867323	0.0060
16586	1,897,720	127,651	108.00	68.00	1.59	0.023621662	0.0057
16587	1,804,400	113,232	121.40	55.69	2.18	0.027621495	0.0067
16674	289,359	42,010	38.92	20.88	1.86	0.004292813	0.0135
16771	1,700,986	116,922	92.79	29.58	3.14	0.010443971	0.0055
16800	303,003	89,952	71.63	15.85	4.52	0.007378739	0.0236
16824	289,039	208,733	143.35	28.99	4.94	0.013605802	0.0496
16898	1,977,198	76,455	58.27	33.85	1.72	0.011897518	0.0029
16984	279,844	172,483	77.41	22.09	3.50	0.007389265	0.0277
17076	1,057,819	264,458	205.24	50.98	4.03	0.043317031	0.0194
17093	981,700	82,427	138.03	11.92	11.58	0.014189452	0.0141
17105	1,028,940	276,000	170.73	10.15	16.82	0.017663423	0.0166
17117	1,027,300	117,372	125.01	26.74	4.68	0.012852712	0.0122
17167	1,257,460	126,763	108.21	20.02	5.40	0.012693074	0.0086
17184	2,221,078	64,927	110.36	72.67	1.52	0.020732681	0.0050
17190	1,174,400	175,570	131.47	18.11	7.26	0.013741916	0.0112
17258	1,342,470	58,948	120.11	30.18	3.98	0.013248118	0.0089
17408	1,343,480	200,647	153.46	26.03	5.89	0.015739844	0.0114
17477	1,283,780	91,145	65.97	30.79	2.14	0.013247434	0.0051
17484	978,680	164,762	123.09	24.83	4.96	0.012222965	0.0126
17526	5,093,080	100,617	164.76	123.87	1.33	0.031550755	0.0032
17531	2,546,971	171,271	160.66	84.79	1.89	0.037320277	0.0063
17572	2,194,100	207,181	170.68	26.78	6.37	0.017710583	0.0078
17664	1,726,640	156,858	146.62	23.74	6.18	0.014568961	0.0085
17720	977,620	376,238	230.14	35.81	6.43	0.024146285	0.0235
17792	1,742,757	107,877	91.64	24.05	3.81	0.009273775	0.0053
17795	2,038,132	74,573	138.57	91.16	1.52	0.029922792	0.0068
17835	1,632,200	144,064	127.37	23.03	5.53	0.013314655	0.0078
17852	1,705,800	91,193	159.62	24.48	6.52	0.015733378	0.0094
17887	1,720,800	78,866	69.24	30.07	2.30	0.00712362	0.0040
17950	1,774,220	127,663	124.75	80.66	1.55	0.029039051	0.0070
17954	1,716,170	109,482	100.31	42.86	2.34	0.011209596	0.0058
17956	1,723,070	71,712	192.87	47.46	4.06	0.019387868	0.0112
18001	980,340	304,743	231.96	22.59	10.27	0.023402068	0.0237
18024	1,645,942	104,698	154.23	62.50	2.47	0.031372285	0.0094
18059	1,583,574	162,167	143.36	22.28	6.43	0.015195975	0.0091
18062	1,543,113	125,900	127.20	47.51	2.68	0.025789834	0.0082
18118	2,868,625	50,135	81.45	63.00	1.29	0.015128503	0.0028
18146	1,645,071	177,417	184.05	114.44	1.61	0.050217183	0.0112
18262	2,285,533	271,599	233.11	42.11	5.54	0.026763896	0.0102
18371	3,642,780	147,008	320.92	152.33	2.11	0.035150411	0.0088
18444	2,739,167	108,910	105.53	77.92	1.35	0.023378274	0.0039
18466	3,150,012	187,901	157.86	108.04	1.46	0.017010942	0.0050
18609	3,714,253	348,103	349.34	147.19	2.37	0.038308939	0.0094
18744	3,948,140	287,165	281.50	158.55	1.78	0.029600254	0.0071
18763	3,077,391	198,905	215.10	84.17	2.56	0.043916216	0.0070
18784	4,014,100	417,635	365.88	150.66	2.43	0.037032093	0.0091
18819	3,086,207	124,036	130.49	75.63	1.73	0.026904598	0.0042
18843	3,090,283	111,372	120.94	101.85	1.19	0.024294414	0.0039
18855	4,496,210	255,359	276.51	145.97	1.89	0.029567071	0.0061
18981	3,843,760	245,710	317.22	165.41	1.92	0.033771968	0.0083
19036	4,426,410	264,415	253.99	127.71	1.99	0.026562019	0.0057
19097	4,431,416	356,003	403.01	96.79	4.16	0.042084968	0.0091
19358	2,149,591	122,855	139.33	72.61	1.92	0.028580168	0.0065
19560	2,565,070	191,156	203.76	49.02	4.16	0.037470022	0.0079
19679	3,310,648	199,588	225.40	119.99	1.88	0.022314405	0.0068
19722	2,368,012	135,822	153.64	88.07	1.74	0.026467227	0.0065
19764	3,854,880	264,744	366.41	199.72	1.83	0.038926308	0.0095
19767	3,064,563	160,511	178.94	96.79	1.85	0.01826136	0.0058
20202	4,480,294	182,538	320.40	172.09	1.86	0.034201338	0.0072
20295	2,268,845	102,093	123.80	57.80	2.14	0.02450953	0.0055
20296	4,247,407	141,459	174.74	131.13	1.33	0.019722077	0.0041
20542	5,799,564	291,160	435.08	181.37	2.40	0.048240016	0.0075
20634	1,872,400	123,267	163.44	119.27	1.37	0.042852053	0.0087
20790	3,937,040	170,712	192.87	167.79	1.15	0.01959867	0.0049
21048	4,494,832	148,219	286.12	203.42	1.41	0.029047611	0.0064
21110	4,541,467	135,881	247.70	162.28	1.53	0.024078929	0.0055
21304	2,382,494	151,411	220.62	93.12	2.37	0.023907833	0.0093
21676	1,306,261	127,662	154.54	125.74	1.23	0.016281314	0.0118
22031	3,708,888	124,098	236.71	108.64	2.18	0.023149965	0.0064
22354	4,875,827	204,453	247.46	106.10	2.33	0.033135694	0.0051
22513	1,942,508	102,156	189.27	82.58	2.29	0.020313967	0.0097
23374	1,969,366	127,873	215.87	67.53	3.20	0.022776097	0.0110
23773	1,513,075	79,675	147.51	80.38	1.84	0.014730537	0.0097
24352	3,022,560	71,712	172.42	133.38	1.29	0.017973431	0.0057

Table 3: Geologic and geophysical attributes

ND File	Edge Detection Attribute					Dip Angle Attribute					Middle Bakken Sand Thickness				
5-digit #	*min*	*max*	*range*	*mean*	*sum*	*min*	*max*	*range*	*mean*	*sum*	*min*	*max*	*range*	*mean*	*sum*
15845	4.90	88.29	83.39	36.97	4510.06	0.09	0.27	0.18	0.18	21.92	3.92	11.87	7.95	7.84	23.52
15916	4.58	76.05	71.47	28.64	3694.09	0.06	0.32	0.25	0.16	20.49	7.30	11.29	3.98	9.91	29.73
16011	29.49	93.98	64.49	58.24	8036.62	0.04	0.18	0.13	0.10	14.16	0.16	2.97	2.81	1.25	3.75
16586	3.40	97.34	93.93	53.42	7104.99	0.07	0.33	0.26	0.18	23.95	5.21	6.61	1.40	5.94	17.83
16587	34.41	98.13	63.72	70.81	9205.41	0.08	0.20	0.12	0.14	18.65	4.69	4.84	0.16	4.76	19.03
16674	5.41	84.78	79.37	35.34	8057.03	0.03	0.37	0.34	0.13	29.67	6.03	8.05	2.02	7.16	42.94
16771	6.72	73.55	66.83	34.33	7861.17	0.03	0.27	0.24	0.13	29.03	8.18	8.18	0.00	8.18	8.18
16800	9.77	95.13	85.36	52.63	11314.90	0.01	0.27	0.26	0.11	23.76	4.60	4.90	0.31	4.80	23.98
16824	45.35	99.53	54.18	80.87	18761.10	0.07	0.14	0.07	0.11	24.41	12.75	14.45	1.71	13.23	79.38
16898	0.15	85.36	85.21	37.75	5096.26	0.06	0.61	0.54	0.21	27.69	6.11	7.08	0.97	6.53	19.59
16984	20.86	95.73	74.86	72.96	18532.60	0.05	0.22	0.17	0.13	34.10	1.52	6.82	5.30	3.67	18.34
17076	5.32	96.02	90.71	56.77	7096.84	0.06	0.29	0.23	0.16	19.52	7.34	7.61	0.27	7.47	22.40
17093	50.91	98.77	47.86	76.15	17819.80	0.05	0.19	0.14	0.10	22.38	11.61	13.43	1.82	12.39	74.33
17105	16.62	98.77	82.15	65.43	15311.60	0.11	0.22	0.11	0.16	37.64	11.62	11.83	0.21	11.73	58.65
17117	0.85	92.11	91.27	49.15	11502.10	0.03	0.46	0.43	0.14	32.01	8.86	15.59	6.74	11.05	44.19
17167	9.61	97.40	87.79	60.78	12581.90	0.10	0.27	0.17	0.16	33.11	6.50	10.55	4.05	9.05	45.25
17184	4.13	97.77	93.64	54.66	8144.24	0.05	0.23	0.18	0.12	18.34	2.93	3.17	0.24	3.02	9.07
17190	0.45	95.54	95.09	24.44	5694.50	0.11	0.41	0.30	0.23	54.14	4.44	5.30	0.86	4.68	23.42
17258	0.15	55.79	55.65	19.56	4538.94	0.01	0.63	0.62	0.20	47.21	8.77	9.02	0.25	8.89	44.45
17408	4.56	99.60	95.04	61.39	14550.10	0.04	0.24	0.20	0.12	27.98	5.45	8.90	3.45	7.39	44.35
17477	14.85	97.14	82.29	60.00	8039.50	0.02	0.24	0.23	0.11	15.07	6.51	6.70	0.19	6.62	19.87
17484	1.48	93.84	92.35	52.82	12675.80	0.01	0.31	0.31	0.13	30.88	3.38	14.68	11.30	9.10	54.63
17526	3.25	95.83	92.58	51.99	7642.52	0.05	0.35	0.29	0.18	25.91	4.00	4.84	0.84	4.45	13.34
17531	5.92	97.03	91.11	44.20	5833.78	0.05	0.31	0.26	0.19	25.21	5.77	6.13	0.37	5.97	17.92
17572	5.67	96.90	91.24	54.94	13021.70	0.09	0.32	0.23	0.18	42.02	2.86	4.02	1.15	3.42	17.12
17664	9.13	92.28	83.16	54.57	13096.00	0.01	0.27	0.25	0.12	29.86	2.29	2.77	0.49	2.55	15.31
17720	13.32	98.18	84.86	76.77	17734.30	0.07	0.24	0.17	0.13	29.39	7.92	10.57	2.65	9.10	54.58
17792	2.15	95.31	93.16	45.77	10938.80	0.02	0.41	0.39	0.16	38.97	3.01	3.58	0.58	3.33	19.96
17795	28.37	87.65	59.28	53.59	7609.28	0.03	0.17	0.14	0.09	13.34	3.50	3.86	0.36	3.69	11.07
17835	0.81	87.96	87.16	33.79	7839.00	0.02	0.34	0.32	0.15	34.05	9.95	10.20	0.25	10.07	50.33
17852	2.76	90.72	87.96	35.18	8831.03	0.01	0.35	0.34	0.13	32.36	10.40	16.35	5.95	13.40	80.42
17887	0.05	86.65	86.60	27.69	6645.10	0.03	0.91	0.88	0.20	47.43	8.34	8.96	0.62	8.73	52.39
17950	4.40	84.88	80.48	34.20	4411.24	0.13	0.31	0.17	0.21	27.35	4.38	4.96	0.58	4.65	18.61
17954	0.00	78.79	78.79	28.30	6113.56	0.03	0.75	0.72	0.19	40.72	8.58	8.77	0.20	8.65	51.93
17956	12.45	95.86	83.41	58.84	13945.70	0.02	0.29	0.26	0.14	32.60	8.09	11.85	3.76	9.83	58.99
18001	27.92	96.33	68.41	66.70	15742.10	0.06	0.20	0.15	0.12	28.68	10.80	12.14	1.34	11.76	58.80
18024	14.97	93.02	78.06	55.92	7214.02	0.02	0.25	0.23	0.12	15.91	5.38	5.78	0.40	5.63	16.90
18059	11.49	97.18	85.69	64.37	15190.60	0.04	0.27	0.23	0.13	30.82	5.50	7.02	1.53	6.54	32.71
18062	17.92	96.09	78.17	65.63	9057.33	0.04	0.25	0.21	0.15	20.18	3.96	4.30	0.34	4.10	12.30
18118	30.10	96.09	65.99	63.40	9193.71	0.06	0.22	0.16	0.14	20.20	3.87	5.22	1.35	4.56	13.68
18146	3.13	94.08	90.94	44.75	5101.78	0.02	0.27	0.25	0.12	13.97	5.75	6.52	0.77	6.07	18.20
18262	1.38	94.20	92.82	52.54	11085.70	0.07	0.34	0.27	0.16	34.04	12.45	12.86	0.40	12.64	50.55
18371	0.88	91.85	90.97	56.75	12882.60	0.06	0.39	0.33	0.15	33.93	7.40	9.31	1.91	8.37	50.21
18444	1.43	95.74	94.31	30.24	4082.23	0.12	0.36	0.25	0.23	30.92	4.84	5.50	0.66	5.26	21.02
18466	0.07	94.36	94.29	34.79	7758.94	0.05	0.64	0.59	0.21	47.53	5.22	10.08	4.85	7.55	37.76
18609	23.68	97.20	73.52	67.74	15376.70	0.06	0.23	0.16	0.15	34.02	9.45	10.05	0.59	9.83	59.00
18744	1.32	93.27	91.95	41.03	9724.01	0.02	0.42	0.40	0.18	41.55	8.48	10.92	2.44	9.70	19.40
18763	14.57	95.30	80.73	65.72	8938.36	0.02	0.21	0.19	0.11	14.43	3.13	3.44	0.31	3.30	13.19
18784	1.35	83.99	82.64	20.50	4961.70	0.06	0.39	0.33	0.21	51.49	1.19	4.42	3.23	2.71	18.95
18819	23.03	98.62	75.59	70.82	9489.43	0.09	0.23	0.14	0.15	20.46	4.93	6.16	1.23	5.55	16.66
18843	25.43	92.55	67.11	57.91	7933.86	0.03	0.18	0.15	0.12	16.42	3.93	4.92	1.00	4.40	13.20
18855	4.93	96.48	91.55	50.18	10537.40	0.03	0.31	0.28	0.14	29.97	1.42	4.18	2.76	2.74	16.44
18981	0.02	94.17	94.15	34.97	8078.45	0.05	0.64	0.60	0.21	48.40	2.13	2.59	0.45	2.44	9.75
19036	2.77	98.02	95.24	48.23	11622.80	0.03	0.34	0.32	0.16	37.59	5.29	8.40	3.11	6.60	39.62
19097	4.14	98.04	93.89	45.12	10377.60	0.04	0.31	0.28	0.14	32.09	1.97	3.45	1.48	2.68	16.05
19358	5.96	94.14	88.19	52.26	7316.02	0.07	0.34	0.27	0.17	23.92	5.35	6.67	1.32	6.04	18.13
19560	24.88	96.25	71.37	66.59	10787.20	0.03	0.21	0.18	0.13	20.38	3.32	3.65	0.33	3.53	10.58
19679	1.75	96.82	95.07	45.48	11552.00	0.08	0.35	0.27	0.20	50.45	4.23	6.40	2.17	5.45	32.69
19722	6.75	99.14	92.39	48.88	7331.69	0.05	0.31	0.26	0.19	28.71	4.65	5.97	1.32	5.29	21.17
19764	1.30	94.15	92.86	42.31	9941.95	0.04	0.41	0.37	0.16	36.55	8.25	8.83	0.59	8.52	42.59
19767	2.39	93.40	91.02	37.97	9226.55	0.06	0.38	0.32	0.20	49.09	5.39	6.49	1.10	5.95	29.74
20202	9.47	98.65	89.18	57.37	12506.00	0.04	0.29	0.25	0.14	30.10	3.92	4.64	0.71	4.20	29.42
20295	16.83	80.88	64.04	44.55	6549.09	0.16	0.24	0.08	0.20	28.85	4.53	5.33	0.80	4.89	14.68
20296	16.34	99.00	82.67	57.96	13100.00	0.05	0.23	0.18	0.15	34.61	4.27	5.94	1.68	4.82	24.09
20542	7.90	95.27	87.38	52.79	12088.50	0.07	0.26	0.19	0.16	37.25	8.91	9.36	0.45	9.08	45.38
20634	0.56	91.61	91.04	35.47	4362.73	0.02	0.42	0.40	0.21	26.21	5.01	6.37	1.36	5.67	17.00
20790	3.88	98.49	94.61	57.14	13028.10	0.02	0.35	0.33	0.13	30.63	9.38	10.46	1.08	9.74	58.47
21048	2.95	97.77	94.82	54.79	13807.70	0.08	0.34	0.26	0.18	45.03	2.87	3.61	0.75	3.23	19.41
21110	1.87	95.98	94.11	45.66	10137.00	0.07	0.36	0.29	0.20	44.17	3.52	4.61	1.09	4.07	24.42
21304	0.25	80.44	80.19	32.29	6910.47	0.06	0.81	0.75	0.19	40.90	7.74	9.98	2.25	9.01	54.04
21676	10.14	92.57	82.43	51.63	12029.90	0.01	0.31	0.30	0.14	33.30	7.09	9.84	2.75	8.57	51.43
22031	0.00	53.17	53.17	10.89	2570.44	0.09	0.78	0.69	0.27	64.63	8.34	8.41	0.06	8.37	50.24
22354	6.19	97.59	91.40	54.16	10777.20	0.01	0.30	0.29	0.14	28.54	5.50	6.22	0.72	5.91	23.65
22513	1.03	94.43	93.41	26.87	6421.41	0.01	0.47	0.46	0.16	37.57	7.57	8.03	0.46	7.77	69.94
23374	20.65	96.64	75.99	67.79	14506.10	0.02	0.18	0.16	0.11	22.70	10.65	12.19	1.54	11.45	68.70
23773	4.97	66.13	61.15	36.75	8966.83	0.03	0.29	0.26	0.13	32.05	9.70	10.04	0.34	9.89	59.33
24352	0.06	83.63	83.57	14.83	3366.77	0.05	0.72	0.67	0.29	65.37	8.47	8.85	0.38	8.72	69.76