The depositional environment and diagenetic effects on sand bodies within the unconventional resource play of the Spearfish Formation (triassic) in north central North Dakota

Matthew J. Sebade

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THE DEPOSITIONAL ENVIRONMENT AND DIAGENETIC EFFECTS ON SAND BODIES WITHIN THE UNCONVENTIONAL RESOURCE PLAY OF THE SPEARFISH FORMATION (TRIASSIC) IN NORTH CENTRAL NORTH DAKOTA

by

Matthew J. Sebade
Bachelor of Science, University of Wyoming, 2012

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements

for the degree of
Master of Science

Grand Forks, North Dakota
August 2014
This thesis, submitted by Matthew J. Sebade in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Title The Depositional Environment and Diagenetic Effects on Sand Bodies Within the Unconventional Resource Play of the Spearfish Formation (Triassic) in North Central North Dakota

Department Geology

Degree Master of Science

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Matthew J. Sebade

May 30, 2014
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ABSTRACT

The Triassic Spearfish Formation in North Dakota is comprised of three members, the Belfield, Pine, and Saude Members, in ascending order. This study focuses on the Saude Member in north-central North Dakota on the eastern margin of the Williston basin. Both the upper and lower contacts of the Spearfish in the study area are unconformable. In this region, the lateral distribution of red sandstone and argillaceous siltstone lithofacies were mapped using well log data. Four sandstone bodies were identified then mapped across the region using gamma ray logs. Sandstone bodies in descending order are the A sand, B sand, water sand, and basal sand.

The six lithofacies identified are: A) Friable immature paleosol, B) Mottled to massive, quartz wacke siltstone, C) Laminated to massive, siltstone to fine grained sandstone that is a lithic wacke or quartz wacke, D) Laminated to mottled, very fine to medium grained quartz wacke, E) Mottled to massive, quartz wacke siltstone with sandstone lenses, and F) Massive to laminated, poorly sorted sandstone which is a quartz wacke, quartz arenite, lithic arenite, or wacke sandstone. From mapping and core descriptions sandstone deposition is dominant in the lower two thirds of the formation. Sandstones pinch out against the basal unconformity and stratigraphically higher sandstones onlap further east indicating a transgressive nature for the system.

Sandstones and siltstones of the Spearfish Formation were deposited across the low dipping broad plain of the eastern margin of the Williston basin. The basal sand is a
transgressive sand unit that is deposited in paleographic lows formed on the Mississippian unconformity. These paleogeographic lows were formed through small river incision and irregular erosional surfaces from exposure. Following this transgression the Triassic seas reached a stillstand and siltstones and sandstones of the Spearfish prograded across the basin margin. The fluctuations between argillaceous and sandstone rich units are generated from stillstands during the overall transgression of the Triassic sea. Within the sand bodies a stacking pattern of fining-upward sequences is observed. Sedimentary structures within these stacked patterns includes climbing ripples, varying cross-beds, bi-directional ripples with mud drapes, in-phase ripples, paleosols, laminar bedding, ripples, and rip-up clasts. The interpretation of these structures and their stacking pattern indicates a subtidal to supratidal environment for the formation and more specifically for the sand units. The Spearfish Formation is a transgressive system tract that onlaps to the northeast with prograding sandstone units throughout the basin, during times of relative sea level still stands.

Petrographical analysis noted eogenesis and mesogenesis diagenetic alterations. Eogenesis alterations included nodular anhydrite formation from displacive growth of gypsum crystals in argillaceous sections. Minor quartz overgrowths were observed along with dolomitization of the upper half of the formation. Finally, areas of high mottled texture resulted from heavy bioturbation or more likely from early mechanical compaction. Mesogenesis resulted in further mechanical compaction of bedding and grains. Precipitation of anhydrite preferentially occurred in coarser grained sands before authigenic clay developed. Primary porosity preservation is poor because of high amounts of anhydrite cement and clay matrix. However, secondary porosity is abundant
in some lithofacies as both fracture and dissolution porosity. Dissolution of anhydrite cement by acetic acids generated from hydrocarbon migration generates up to 25% porosity within the sandstone lithofacies in localized areas.
CHAPTER I
INTRODUCTION

Study Area

This study area is located in north central North Dakota, and is centered in Bottineau County. It also covers western Rolette, northern McHenry, northern Ward, Renville, and the very northwestern corner of Pierce Counties (Figure 1). To the north the study area is bounded by Manitoba and Saskatchewan. In Canada the equivalent formations to the Spearfish have undergone recent expansions in drilling. Drilling rates in Bottineau County are on the rise which has resulted in an increase in oil production and interest in the Spearfish formation (Table 1). This study area will cover the entire oil producing region of the Spearfish Formation. Dow (1967) described three individual members in the Spearfish Formation, the Saude, Pine, and Belfield Members, respectively. This study is limited to the Saude Member of the Spearfish Formation and does not continue into the Belfield or Pine Members to the East. The study area is limited to the Saude Member because of the transgressive nature and erosional contacts of the formation.

Regional Geologic Setting

The Williston basin is a large intracratonic basin that is situated in the geographic center of North America. The basin covers approximately 200,000 square miles and extends across Saskatchewan, Manitoba, North Dakota, eastern Montana and
northwestern South Dakota. Nearly 16,000 ft (5000 m) of sediments ranging in age from the Cambrian to the Holocene are deposited on top of the Precambrian unconformity near the center of the basin in McKenzie County North Dakota (Gerhard et al., 1982). The earliest known Paleozoic rocks in the basin were deposited during the late Cambrian (approximately 520 Ma). However, initial subsidence and formation of the Williston basin began no later than deposition of the Deadwood Formation in the Ordovician (490 Ma) (LeFever et al., 1987). Carbonate deposition was dominant in the Williston basin from the Cambrian until the unconformity between the Big Snowy Group and
Minnelusa Formation at the Mississippian and Pennsylvanian boundary. The basin was then taken over by the deposition of siltstones, shales, and sandstones. However, both siliciclastic and carbonate deposits can be found in all Eras deposited in the basin. Thick evaporite beds are also common, with the majority of these beds between the Pine Salt of the Triassic Spearfish Formation and the Devonian Prairie Salt.

Since the initial generation of the basin there have been five major subsidence events in the Williston basin. LeFever and LeFever (1991) discussed these subsidence events as being rapid at the start and waning to little or no subsidence. This cyclic nature of subsidence, combined with major eustatic sea level drops established the major unconformities in the basin. One of these large unconformities divides the Madison Group from the Spearfish Formation and creates a subcrop of the Madison Group in the study area. This erosional surface displays a northwest trend (LeFever & LeFever, 1991). A variation in relief across the study area was generated from differential erosion. The variation in lithology of the Madison Group allows for these differential erosion rates. Also, rock units to the northeast were exposed longer than those in the center of the basin allowing for more incision and erosion. This sequence allowed for the generation of relief in the form of cuestas and small incising valleys across the landscape (Musial, 1995). These differences greatly influenced the deposition of the lower sandy units of the Spearfish as it transgressed over the unconformity.

During Triassic time, the supercontinent Pangaea had reached its greatest extent as a single land mass, reaching nearly from pole to pole (Ziegler et al., 1983). North Dakota resided approximately 15 degrees north of the equator during the Triassic
(Blakey, 2011). The complete Triassic sequence lasted from 252.2 ± 0.5 Ma to 201.3 ± 0.2 Ma (Hillebrandt et al., 2008). During the Triassic much of the southwestern United States was an arid to semi-arid climate. As Pangaea moved North during the Triassic, seasonality would have become stronger and continental interior regions would have become drier (Dubiel, 1994). These conditions continued northeast into the Williston basin and are evident from abundant evaporite deposition and common oxidizing conditions.

The Williston basin is bounded on the south by the Sioux arch, on the southwest by the Black Hills uplift and the Miles City arch, and on the west by the Bowdoin dome. Several hypotheses have been presented to describe the origin of the basin. Gerhard et al. (1982) put forward three separate hypotheses: 1) the favored model is basin generation by a depressed block produced from left lateral shear along the Brockton-Froid-Fromberg zone and the Colorado-Wyoming lineament; 2) the basin has an aulacogen origin and is coupled with the Central Montana Embayment and the Belt Super Group; 3) basin generation started from shear stress that created a horst and graben fault system that allowed for accommodation of sediment and subsequent subsidence. Other research suggests a thermal model for generation of the Williston basin. (Ahern & Mrkvicka, 1984; Crowley et al., 1985). This model suggests a point load forming from an initial hot region which eventually cools resulting in basin subsidence.

Another model based on a mafic subcrustal body undergoing a phase change into eclogite was described by Fowler and Nisbet (1985). The phase change would result in a point load and eventual subsidence for the generation of the basin. The final and most
plausible model for structures in the Williston basin, especially those in Bottineau County was described by Green et al. (1985). Who generated a tectonic map of the Precambrian basement in the Williston basin. They were able to reconstruct this with the use of mapping on the Canadian Shield, a complete regional aeromagnetic anomaly map, and a regional gravity anomaly map. From these maps the authors were able to distinguish varying terrains and cratons below the Phanerozoic of the Williston basin. This allowed for detailed mapping of the suture zone which displayed the Wyoming craton to the west, the Churchill craton to the east, and a series of Proterozoic volcanic island arcs and their associated fore-arc and back-arc basins between the cratons (Figure 3). This final map when compared to structures in the Williston basin today, such as the Nesson anticline, Little Knife anticline, Newburg syncline, and Billings anticline, parallels the trends of the Proterozoic terrains (Figure 2). These structures are normal faults that trend north-south and certainly formed along Proterozoic zones of weakness. As the basin grew and sediment load became greater throughout time these structures should be reactivated, which is seen in many structures like the Nesson anticline.

The dominant structural features in north-central North Dakota are dissolution features and faults that trend north-south along the eastern flank of the Williston basin (Figure 2). Synclinal features often form and are attributed to dissolution of the underlying Prairie Formation. In areas, complete dissolution of the Prairie Salt has occurred forming extensive regions of subsidence from collapse in the Devonian system. Baillie (1953) described collapse features like breccias zones that overlie the Winnipegosis Formation. This observation was made in a well southwest of the Newburg
Figure 2. Major structural features across the Williston Basin (modified from Gerhard et al., 1982).

Figure 3. Basement rocks underlying the Williston Basin (modified from Fischer et al., 2005, after Green et al., 1985).
and South Westhope oil field area in the California Oil Company #1 Blanche Thompson well (SW SE Sec. 31, T160N, R81W). Salt dissolution in the Prairie Formation was later recognized by Anderson and Hunt in 1964 is noted by (LeFever and LeFever, 1991). Anderson and Hunt hypothesized that natural fractures formed from uplift and fluid movement in these faults result in the dissolution features in north-central North Dakota. These fault systems follow the north-south trend of the Proterozoic suture zone and undoubtedly form along weak lineaments in the basement (Figure 3). Anderson and Hunt contributed anomalous thicknesses in the Madison Group to dissolution of the salts which was later described by Marafi in 1972. The largest of these structures in the study area is the syncline generated at Newburg and South Westhope fields in Bottineau County. Marafi (1972) thought this synclinal feature formed slowly over time and in two separate stages. The first stage was dissolution of the underlying Prairie Formation prior to the deposition of the Ratcliffe (Madison Group). The second stage allowed for the deposition of the Ratcliffe and overlying transgressive Spearfish sediments through ensuing subsidence. This sequence of events formed a stratigraphic trap that is enhanced by the synclinal structure to create the oil fields of Newburg and South Westhope fields (LeFever & LeFever, 1991).

Nicolas (2007) also described structural features paralleling the north-south trend of the Superior and Wyoming craton suture zone. This study described activate faulting during the Devonian along the Superior Boundary Zone which contributed to Three Forks oil production in Manitoba (Figure 4). In the southern section of the Superior Boundary Zone lies the Birdtail-Waskada Axis which is similar in structure to the Newburg
Syncline. It is a region of active salt dissolution during the Devonian and Mississippian which altered the Madison Group deposition. The study area presented by Nicolas is adjacent to north-central North Dakota to the North and displays the continuation of structural features into Manitoba. It is evident when comparing Figures 2, 3, and 4 that fracture systems in this study are generally oriented north-south. Local structures will have formed during the Devonian and Mississippian which will affect accommodation for Triassic sediments. This varying relief on the Madison unconformity will generate varying environments for the lower sandy units in the Spearfish Formation.

Figure 4. A simplified tectonic map for Manitoba that displays the Superior Boundary Zone and the Birdtail-Wakada Axis (Modified from Nicolas, 2007).
Purpose

The purpose of this study is to describe the depositional environment and diagenesis of the Spearfish Formation in north central North Dakota. The study will focus solely on the Saude Member of the Spearfish Formation to specifically correlate wire line log signatures of sandstone bodies within the formation. The wireline logs will then be correlated to core and thin sections in order to better predict lithofacies heterogeneities throughout the study area. Thin sections examinations will describe the occurrence and type of porosity in varying lithofacies throughout the formation. Correlation and mapping of these log signatures will enhance the depositional and diagenetic models of the Saude Member in this region. These descriptions will generate a model to better understand and predict the controls on sand bodies in the region. This will allow for a more accurate prediction of reservoir characteristics in the Spearfish Formation. Accurate mapping, correlations, and description are extremely important as exploration in the Spearfish Formation is currently in a boom. Spearfish equivalent production in Canada has yielded very economical results and is currently being tested in north-central Bottineau County. As of December 2012, the region produced 55,771,975 barrels from the Spearfish, Spearfish/Charles, and Spearfish/Madison (NDIC). Drilling and completion in the Spearfish has increased dramatically over the past 3 years (Table 1).
Table 1. List of formations and their cumulative oil production in the study area.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Spearfish</th>
<th>Spearfish/Charles</th>
<th>Spearfish/Madison</th>
</tr>
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<tbody>
<tr>
<td>2012 Cumulative Oil</td>
<td>1,107,961 (bbls)/59</td>
<td>49,997,591 (bbls)/210</td>
<td>4,666,423 (bbls)/103</td>
</tr>
<tr>
<td>Production/Wells</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011 Cumulative Oil</td>
<td>758,094 (bbls)/39</td>
<td>49,733,943 (bbls)/210</td>
<td>4,601,174 (bbls)/98</td>
</tr>
<tr>
<td>Production/Wells</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010 Cumulative Oil</td>
<td>675,876 (bbls)/32</td>
<td>49,485,950 (bbls)/210</td>
<td>4,542,713 (bbls)/98</td>
</tr>
<tr>
<td>Production/Wells</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Methods**

Three types of data were used in this study; core, thin section, and well log. Approximately 2,800 wire line logs were used within the study area and surrounding areas to determine the tops of the significant formations and sandstone units (Figure 1). Four different sandstone members were identified and picked wherever present in the study area (Figure 5). Picks were based on gamma ray signatures with the aid of other log signatures to determine formation and sandstone depths. These picks were made in PETRA (2013) and were picked by their somewhat uniform signature across the study area. Sandstone picks were then incorporated into cross sections, isopach maps, and contour maps. Isopach maps were generated in SURFER (2013) for each sandstone unit to aid in the understanding of the depositional environment of these sandstone units. A detailed structural contour map was constructed for the Mississippian and Triassic unconformity in an attempt to discover channels and other depositional structures generated on the Mississippian strata.
Figure 5. A typical Spearfish log showing the picks made in the study area. Notice the four separate sand bodies, A, B, water sand, and basal sand.

The study area contained a significant quantity of core data and therefore cores were categorized by thickness and sandstone units drilled. A distribution map of these cores was then generated and 28 cores were selected and examined to maximize geographic and lithologic distribution. Each township and range that contained core had at least one core examined based on its geographic and stratigraphic location. Cores portraying unique features, such as a paleosol horizon, had proximal wells examined to clarify features and the lateral extent of these sedimentological features. A total of 1,500
feet (460 meters) of core in the 28 selected wells was described. Cores were described using a hand lens and reflected light microscope to efficiently describe grain size, type, and sedimentary structures. Core descriptions were based closely on the AAPG Sample Examination Manual. The classification scheme used for this study was Williams, Turner, and Gilbert from (1982). This model classifies the rocks based on percent matrix and percent grains of quarts, lithics, and feldspatic grains. This model often concludes descriptions with massive or mottled because it comingles with the oil staining type. The heavy mineral occurrence and abundance is also placed at the end of the description for this study. All but two cores in this study were slabbed cores and were cleaned to examine for sedimentary structures which are often obscure in the massive appearance of the Spearfish. Quantitative descriptions were not listed in percentages but rather a qualitative scale of rare, trace, occasional, common, and abundant, respectively.

Thin section descriptions closely mimic those of the core descriptions. The major diagenetic feature studied in thin sections is the development of secondary porosity. A total of four wells with thin sections were used for their location and stratigraphic location. The four wells produced the description of 123 thin sections. The descriptions are very similar to those used in core and used the same classification scheme. Thin section descriptions often allow for a more detailed study of matrix and porosity quantity which aids in core sample descriptions. Secondary porosity was delineated from the primary porosity by dissolution features common in the anhydrite cement zones. The more argillaceous sections were labeled with secondary porosity when fractures were present.
These three tools: log correlations, core description, and thin section descriptions, were then synthesized to generate a model for the depositional environment. The combination of the isopach and core descriptions developed a method to predict facies across the study region. Diagenetic developments within these facies were then predicted across the area using the facies predictions from correlation and core work.

**Previous Work**

The Spearfish Formation was first named for the reddish brown outcrops that surround the town of Spearfish, South Dakota (Darton, 1899). Spearfish studies in the state of North Dakota have been very limited over the past century. This is in part due to the fact that the Spearfish Formation is one of the least hydrocarbon productive units in the state. A detailed study regarding the Spearfish was done by Dow (1964b). Dow’s paper examined previous work related to the Spearfish and set a framework for future researchers to examine the formation. Dow (1964b) described three distinct members in the formation and creates a type section for each. In descending order they are the Saude, Pine, and Belfield members (Dow 1967). The members are conformable and represent an overall transgressive system with each member deposited further onto the basin margins. The study was a basin wide model that hypothesized the possible depositional environments and structural settings. Dow (1967) discussed two previous works, Goldsmith (1959) and Cummings (1956). Goldsmith (1959) suggests a large alluvial plain persisted over much of North Dakota during Saude deposition. The research concluded that the Saude is continental in origin and the sediment source is in northwestern North Dakota and southeastern Saskatchewan. This conclusion is drawn
from the previous works he examined, lack of strand line deposits, and the irregularity of bedding throughout the Saude. However, other research has suggested a slightly different model for the depositional environment of the Saude (Cummings, 1956). Cumming (1956) sampled the lower sand unit to test a cumulative frequency curve and compare it with the typical sand dune curve. When the curves were compared it was suggested to distinguished the lower sand unit from the typical sand dune curve. Heavy minerals present in the lower unit of the Saude were also examined. Observed sediments included red garnet, angular pink garnet, zircon and tourmaline. Conclusions pointed toward sediment sourcing from the Precambrian shield to the east and northeast. Interpretation of the summation of these studies indicates a depositional environment with periods of shallow water deposition that were often punctuated by exposure and evaporation.

Other research concerning the Newburg and South Westhope oil fields has failed to draw any conclusions on the depositional environment of the Spearfish Formation in Bottineau County (Marafi, 1967). However, Marafi (1967), concluded that specific lithofacies were correlative across the study area by dividing the Spearfish into different units based on specific log signatures and core descriptions with the main signature being the “water sand.” Unfortunately, correlations used by Marafi (1967) were based primarily on spontaneous potential logs making it difficult to correlate smaller signatures to the gamma ray signatures.

More recently LeFever and LeFever (1991) described the Newburg and South Westhope fields in a comprehensive and extensive study covering the geologic factors in Bottineau County. A brief discussion for the depositional environment is introduced by
LeFever and LeFever (1991). They described a clastic environment that transgressed over an unconformable and irregular Madison Group. Rather than choose a specific environment of deposition they discussed the possibility that both marine and continental environments existed during the Triassic. The continental setting is plausible from the common occurrence of desiccation cracks and oxidation of sediments. The anhydrite present in both cements and nodular form suggests common exposure and evaporation of deposited sediments. A marine environment is also suggested due to the nature of thin laterally continuous beds across the region. There are obvious fluctuations in the energy during deposition which is indicated by the interbedding of fine to coarse grained clastic units. These clastic deposits also express heterogeneity in the energy during deposition through varying sedimentary structures. The features include cyclical fining-upward sequences, large scale cross-beds, climbing ripples, planar bedding, small scale cross-beds, and rip up clasts. LeFever and LeFever (1991) interpreted the Saude as a complex depositional model that contains both continental and marine sediments.

The final research related to the Spearfish Formation in North Dakota is that of Oglesby and Fischer (1991). This study is focused on South Starbuck field in Bottineau County. It resides just to the southwest of the Newburg and South Westhope fields. The paper hypothesized that production at South Starbuck field is related to channel deposition on the unconformable Madison surface. The facies progression observed was as follows: coarse-grained lag deposits of thalweg; medium to fine grained, festoon cross-stratified sandstone; fine-grained, planar-bedded sandstones; fine to very fine-grained, current ripple-laminated sandstone; and abandonment fill (sparsely burrowed siltstones
with occasional climbing ripples). The high permeability of the coarser grained sediments allowed for early anhydrite cementation leaving the lower energy and finer grained sediments to be the reservoir rock. Although this study was limited in extent, it is critical to the understanding of depositional environments in the basal section of the Saude.

Multiple studies were completed in Canada on correlative units to the Spearfish Formation and common study localities are shown in Figure 6. The first to describe a depositional environment in Canada was McCabe in 1956. McCabe (1956) suggested an arid climate in a terrestrial setting with oxidizing conditions instead of a marine setting like more recent work. He observed common frosted and pitted quartz grains that were often well rounded, which he interpreted as derived from a terrestrial source. McCabe also describes well rounded and well sorted grains with occasional unaltered feldspar grains which he believes to be indicative of arid eolian transport. Anhydrite within the Lower Amaranth was believed to be clastic and sourced from somewhere on the land mass.

Barchyn completed publications in 1984 and 1982 that are similar in content and described the environment of deposition for the Lower Amaranth which is the Spearfish equivalent in Manitoba. The research described the environment as being very transitional from marine and continental. The common interbedded siltstone and sandstone beds represent an environment with highly variable depositional energies. The common red coloring and desiccation cracks in the more argillaceous sections suggest common exposure. This is supported by the occurrence of well rounded frosted grains as “float” in a finer matrix. This type of sorting suggests an eolian depositional model and
Figure 6. Oilfields with discovery dates for the Spearfish Formation and equivalent formations in Canada. The oilfields are underlain by a structural contour map of the Madison unconformity (modified from LeFever, 2011)
again supports exposure. Also, the abundance of anhydrite in the unit suggests common wetting and later exposure with evaporation. The lower sandy unit is indicative of variable environments while the upper more shaly section suggests more constant depositional environments.

Barchyn (1982) also discussed the overall consistency of well-log correlations across the Lower Amaranth in Manitoba which suggests a marine environment. The study describes the primary sedimentary structures in the Lower Amaranth as representing cyclical variation of depositional environments common in channel systems. Yet, there are no significant channels actually observed in Canada, so Barchyn (1984) suggested these features are high energy systems possibly related to emergence with flash floods. A possible model for the depositional environment is an extensive mud flat with playa lakes, eolian deflation and deposition. The thin sheet sandstone bodies represent a poorly developed fluvial system during storms or simply a winnowing of sediments in shallow water by wave action during storms. In either case widespread reworking of these sand bodies continued throughout the transgressive system tract which resulted in the sheet like sand bodies (Barchyn, 1982).

Hansen (1987) completed a thesis on the depositional environment of the Lower Amaranth in Manitoba. She interpreted the depositional environment to be similar to that of the Colorado Delta along the northeast Gulf of California. Her thesis described seven facies and their corresponding depositional setting. Hansen (1987) noted nodular anhydrite as being displacive growth in sediments and describes the Upper Amaranth as a termination to the upper shaly unit by extensive anhydrite deposition. Sediments in this
model were deposits in a tidal environment that contained wave action, tidal channels, progradation, aeolian processes, supratidal mudflats, recessions, and common intertidal to subtidal zones.

One of the more recent studies was completed by Musial (1995) in southeastern Saskatchewan. This study concluded that oil production from the Triassic on the eastern flank of the basin originates from a 12 foot or smaller zone in the basal sand section. This is true for all four major producing fields; North Dakota Spearfish production from Newburg, Manitoba production from the Lower Amaranth at Waskada and Pierson, and Lower Watrous production in Saskatchewan at Manor (Musial, 1995). Musial (1995) interpreted the Triassic section as a marginal marine setting with a transgressive system. This transgressive system is the major contributor to sediment deposition. The three major Triassic fields overlie significant topographic lows in the Mississippian unconformity. Musial described the Manor “microbasin” and its depositional model (Figure 7). The initial transgression deposits a thin argillaceous siltstone that contains rip up clasts. Next, is an interbedded siltstone and mudstone which is followed by a four foot sandstone bed generated in a shoal or bar in a subtidal environment. The rest of the basin is filled with siltstone and muddy siltstones of intertidal origin. The “microbasin” is then capped by the final transgressive unit which is a muddy sandstone unit that is highly bioturbated (Figure 7).

Husain (1991) divides the Lower Amaranth Formation into an upper shaly unit and lower sandy unit. The lower unit described up to four cyclical sand facies that fine upwards. Sediments in these sand bodies are usually subrounded to rounded and range in
size from very fine to coarse grained. Sandstone bodies are often lens shaped and frequently contain cross-bedding. The fining up sequences observed in the lower section is common during the progradation of tidal flats. Husain notes that fining up cycles can often be terminated when an erosive tidal channel cuts into the fining up sequence (Husain, 1991). This lower sequence is labeled as a subtidal environment. A transitional facies of siltstone is observed between the upper and lower unit. The lower section of the siltstone contains lenses of very fine to coarse grained sands while the upper section contains interbeds of argillaceous lenses. These deposits range anywhere from upper subtidal to intertidal deposits and can still contain channelized sediments. The upper unit described by Husain is labeled with a supratidal environment (Figure 8). The upper section is dominated by mud and shales and only contains localized area of siltstone and
sandstone. It is homogeneous over a large area and massive. Deposition took place in a low energy environment and in very shallow water conditions.

Figure 8. A log from the Coulter Pierson area that shows cyclical fining up sequences along with interpreted depositional environments. (Modified from Hussain, 1991; Klein, 1977)
CHAPTER II

STRATIGRAPHY OF THE SPEARFISH FORMATION

Nomenclature

The Spearfish Formation is named for the reddish brown outcrops surrounding the town of Spearfish, South Dakota. The formation was named by Darton in 1899 and later described by Darton in 1901. A grayish maroon shale and gypsum bed at the top of the formation was originally included with the Spearfish Formation but was later assigned as the Gypsum Springs Formation of Middle Jurassic age (Imlay, 1947). The continuation of these formations into the Williston basin in Canada and the United States was unknown until oil exploration expanded into the Williston basin. When drilling explorations expanded across the basin the stratigraphic position and red color of the Spearfish seemed to continue across the basin. Later work by Dow (1964b and 1967) and Ziegler (1955 and 1956) would confirm these early hypotheses.

Three distinct members make up the Spearfish Formation in North Dakota. In descending order the members are the Saude, Pine, and Belfield Members. Ziegler (1956) described the informal terms Spearfish Formation (restricted), Pine, and Saude Members, respectively. Ziegler (1956) also includes the Dunham Salt in the Spearfish Formation which later work by Dow (1967) suggested to be invalid. Ziegler (1956) initially placed the Spearfish Formation of North Dakota in the Jurassic, which would also later be refuted by Dow (1967). These members were again used by Dow in his 1964a thesis on
the Newburg and South Westhope oil fields in Bottineau County. However, in 1964b Dow published a paper on the Spearfish Formation that presented the Pine and Saude to Member status. Dow (1967) labeled the lowermost unit below the Pine Member as the Lower Shale Member which was Ziegler’s restricted Spearfish unit. This unit was not given member status until Dow’s 1967 paper which completed the entire section of the Spearfish Formation by adding the Belfield Member (Dow, 1967). Today the three members used in descending order are the Saude, Pine, and Belfield Members.

**Correlative Units**

After the initial discovery of the post-Minnekahta pre-Piper red beds in the Williston Basin many varying age correlations were generated. The Spearfish Formation in North Dakota was initially correlated to the Triassic/Permian Spearfish Formation in the Black Hills of South Dakota (Figure 8). Ages for the Spearfish in South Dakota came from correlations made with Wyoming strata where Wyoming geologists interpreted the Pine Member equivalent to the Goose Egg Formation (Permian) (Dow, 1967). Fossil specimens discovered in the Black Hills also aided in the age description for the Spearfish in South Dakota. Due to its stratigraphic position between the Permian Minnekahta Formation and Jurassic Piper Formation the literature places the Spearfish from Permian to Jurassic in age.

As stated earlier Ziegler (1956) first named possible members for the Spearfish Formation in North Dakota. He assigned them all a Jurassic age. His opinion was based on his belief of a large unconformity occurring at the base of the Pine Member. He correlated this unconformity to the regional unconformity placed at the base of the
Jurassic system in surrounding states. He concluded that Triassic sediments from the Spearfish Formation in the Black Hills beveled to the north and east. Zieglar’s research resulted in a Jurassic age for his Pine, Saude, and Dunham Members of the Spearfish (Zieglar, 1956). This research argues that the Spearfish Formation was Triassic except for Zieglar’s lower most restricted shale unit (Belfield). The research also suggests that the formation is conformable with rock units overlying and underlying the formation. The only unconformity noted by the authors was the large unconformity found on the margin of the basins, which are the Mississippian strata underlying the Spearfish Formation on the margin of the Williston basin.

Goldsmith (1959) believed that a major unconformity lasting from the Middle Triassic to the Early Jurassic existed between the Saude Member and the Poe Member of the Piper Formation. Goldsmith (1959) correlated the lowermost unit or Zieglar’s restricted unit to a series of red and green mudstone outcrops in the Black Hills. These units in the Black Hills had already been interpreted as Permian.

Dow (1967) agreed with Goldsmith (1959) but made a few modifications which have been widely accepted throughout the literature. The lower most shale unit (Belfield) is Permian because it is conformable with the underlying Minnekahta Formation. Also its depositional region is similar to that of the Minnekahta suggesting a similar basin model for the Belfield and Minnekahta. Finally, Dow (1967) discussed how the grey marine shales interpreted to be Permian in the Black Hills correlated to the Belfield. The Goose Egg Formation of Wyoming is Permian and is correlated to the Pine Member in North Dakota marking the end of the Permian in North Dakota. A correlation between the Pine
Figure 9. Correlation of the Spearfish Formation in western North Dakota with equivalent strata in Wyoming, Canada, and South Dakota (Modified from Dow 1967).

Member and the Ervay Tongue of the Phosphoria Formation (Permian) of Wyoming is also plausible (Figure 9) (Dow, 1967).

The contact between the Saude Member and the Pine Member is conformable (Dow, 1967). A sequence of red siltstones directly overlies the Pine Member and stayed constant until an apparent basin restriction and deposition of the anhydritic “G Marker.” In Wyoming the Triassic System is placed slightly below the top of the Goose Egg and is separated from the G Marker by a thin siltstone unit, the top of the Pine is approximately at the same stratigraphic position (Dow, 1967). From this Dow (1967) concluded that the top of Permian System in North Dakota is marked at the top of the Pine Member. Dow
(1967) also noted the similarity of marine type bedding sequences in the Red Peak Member of the Chugwater Formation (Triassic) and the Saude Member of Spearfish Formation in North Dakota. Dow (1967) stated the upper contact between the Poe Formation and Spearfish has an angular relationship over his study area.

The correlation between the Spearfish Formation and its equivalents in Canada are more involved. Dow’s Saude Member is correlated by Ziegler (1956) to the Watrous Formation of Saskatchewan. The Watrous is subdivided into three lithologic units, the upper unit is an evaporate unit, the middle unit is comprised of shale and silt, and the lower unit is a sandstone. The sandstone unit is rich in frosted grains and correlates well with the basal sand member in the Saude. Similarly the middle unit of the Watrous is correlative to the upper silt and shale prone unit of the Saude. The evaporite unit of the Watrous is correlative to the Poe Member of the Piper Formation in North Dakota (Dow, 1967). This correlation was then used to correlate the Gypsum Springs Formation in the Black Hills to the Gypsum Springs in the Wind River Basin of Wyoming which was given a Middle Jurassic age (Love et al., 1945). The Triassic Chugwater Formation below the Gypsum Springs Formation in central Wyoming is correlative with the Triassic Spearfish in South Dakota (Dow, 1967). In the Black Hills an unconformity separates the Spearfish Formation from the Gypsum Springs Formation but the exact age of this unconformity during the Jurassic is unclear. Even further complicating the age restraint is this correlation is carried across the Williston basin onto the eastern flank, the Watrous Formation (Saude equivalent) in Saskatchewan is considered conformable by Cummings (1956) further complicating the age restriction. This discrepancy in the age of the
unconformity, age between the Spearfish (Triassic) and Watrous (Jurassic), and unfossiliferous nature of the Spearfish in North Dakota restricted Dow (1967) to a simple hypothesis.

As the Spearfish was being onlapped onto the eastern margin of the basin progressively younger sediments were being deposited to the northeast. This gives rise to the possibility that the transgressive sequence tract of the Spearfish may have resulted in Jurassic sediments to the northeast. Without an exact age at the top of the unconformity an exact age for the upper most Spearfish sediments to the northeast can only be speculated as Triassic and Jurassic (Figure 9).

More recent work was completed by Butcher et al. (2012) to determine the exact age of the Lower Watrous Formation and equivalent units in the U.S.A. (Saude Member of the Spearfish Formation) and Manitoba (Lower Amaranth Formation). Butcher et al. (2012) discussed the overabundance of previous works on the age and recognized there is a 150 million year time gap between the proposed ages. Their publication used these previous works along with new geochemical analysis to assign an age range for the Lower Watrous.

Butcher et al. (2012) examined all sources of previous studies on the Watrous age to draw conclusions. Butcher et al. (2012) began their work by discussing the commonly cited work completed by Dow (1967). They agreed with Dow’s correlations and continue these correlations further into Saskatchewan (Figure 10). Dow (1967) originally correlated the Spearfish Members to surrounding states to attain the conclusion of a Triassic age for the Saude Member of the Spearfish. He hypothesized that there is an
Figure 10. Cross-section of the Spearfish Formation with younger and older strata (modified from Dow, 1967). Butcher added a well in Saskatchewan to show well-log correlations from the center of the Williston Basin to the northeast of the Williston basin. The locations are given in section, township and range, along with the latitude and longitude. Log signatures are described as follows G.R. = Gamma Ray, L.L. = Lateralog, and S. = Sonic logs (modified from Butcher et al., 2012).
unconformity between the Saude and overlying Piper Formation which Butcher et al. (2012) discussed as plausible but lacked the sufficient correlation data in Canada to prove this. Butcher et al. (2012) were able to conclude through the use of seven thin bed correlations that the Lower Watrous overlies definitely dated Permian strata below.

Other previous works examine palynology, impact structures, isotope geochemistry, and palaeomagnetism. Palynomorphs were initially recognized by Pocock (1972) in the Upper and Lower Watrous Members but were too scarce to form a definitive age range. White et al (2002) also confirmed this data but were able to identify Classopollis classoides in the Upper Watrous. A species which did not appear until the middle Triassic, resulting in a Middle Triassic or older age for the Upper Watrous. Butchers et al. (2012) described the work completed by McCabe (1971), Sawatsky (1972), and McCabe and Bannatyne (1970) on three separate impact structures. From the conclusions reached by these three authors Butcher and others are able to conclude that the Watrous and equivalents are no older than Late Permian in age. Palaeomagnetism data is also examined for the Watrous and its equivalent units. Measurements were made on natural remnant magnetization in the Lower Watrous by Enkin et al. (2001) and Cioppa (2003). Szabó et al. (2009) conducted a similar study on the Lower Amaranth Formation which is the Manitoba equivalent to the Lower Watrous. An age range from Mississippian to Triassic was established from the studies previously listed. Magnetic data in this time interval is highly variable because it overlaps a major reverse in polarity. Enkin et al. (2001) noted a reverse in polarity in a single well (1-31-1-20W2) and concluded that the Lower Watrous was deposited sometime between Mississippian and
Pennsylvanian time, while the upper Lower Watrous was deposited during Latest Permian to Triassic time. Cioppa (2003) examined both the green and red beds of the Lower Amaranth which resulted in a Pennsylvanian age in the red beds and a Cretaceous to Cenozoic age in the green beds. This result is most likely due to later migration of hydrocarbons and the reduction of previously oxidized beds. The final previous works discussed in this paper were Isotope geochemistry ages by Denison et al. (2001) and Qing et al. (2005). Dension et al. (2001) collected data for $^{87}$Sr/$^{86}$Sr ratios and $\delta^{34}$S and $\delta^{18}$O isotopic analyses for the Upper Watrous and Upper Amaranth Formations. The data was pulled from 16 separate wells in Saskatchewan, Manitoba and North Dakota from bedded anhydrite. Denison et al. (2001) interpreted their data to be Upper Pennsylvanian in age. Qing et al. (2005) studied sulfur and oxygen isotope values from the Weyburn Field area for anhydrites found in the Lower Watrous. The difficulty with the isotope studies is that results must be compared with previous isotope results which are often highly variable. This has created a great discrepancy in age values which can been seen in Quing et al. (2005). A time age of early Pennsylvanian or Triassic is initially suggested but later when compared with an age based on the oxygen isotope curve a Pennsylvanian to Middle Permian or Triassic through Middle Jurassic age was observed by Qing et al. (2005).

Age conclusions established by Butcher et al. (2012) were derived from several dating methods. The first of these was strontium isotope data values from sulfates in the Lower Watrous. Butcher et al. (2012) have very similar results to Denison et al. (2001) but discuss the terrigenous nature of this strontium which would have altered values compared to the marine strontium values which they compare results with. If the
strontium isotope values measured are not terrigenous and represent marine strontium then an Early or Late Triassic age is interpreted by Butcher et al. (2012).

These results also correlate well with a Pennsylvanian age for strontium within Lower Watrous anhydrite nodules (Denison et al., 2001). Results were based on the 95% confidence limits of statistical LOWESS fits for the marine strontium isotope record of McArthur et al. (2001) and data more recently collected by Korte et al. (2003). Sulfates in this study were very consistent with Qing et al. (2005) and are consistent with a Triassic or Middle Jurassic seawater source (Butcher et al., 2012). Conversely, oxygen isotope values for the Lower Watrous sulfates in this study were inconsistent with the results of Qing et al. (2005). A result which Butcher and others (2012) related to a sensitivity of oxygen isotopes to local variation in temperature, evaporation, and meteoric water input (Holt & Kumar, 1991). The increasing enrichment of both sulfur and oxygen isotopes in the Watrous sulfates through time indicate they probably fit best on a rising trend of the isotopic seawater curves. When these curves are examined with the strontium isotope data (Figure 11), either an Early or Late Triassic age is considered most likely for the Lower Watrous sulfates. Combined with the Strontium, Sulfur, Oxygen isotope analysis, palynological data, crater impacts, and log correlations results allow for the accurate dating of the Lower Watrous and equivalent units as either Early or Late Triassic (Butcher et al., 2012).
Figure 11. LOWESS statistical fit for $^{87}\text{Sr}/^{86}\text{Sr}$, from Mississippian to Middle Jurassic time, with 95% confidence bounds (adapted from McArthur et al. 2001). Brachiopod and conodont samples are overlain from the Late Permian and Triassic time (adapted from Korte et al., 2003). The average $^{87}\text{Sr}/^{86}\text{Sr}$ value for Lower Watrous samples in this study were (0.708482) and are displayed as the solid green line with the range represented as the green dashed lines (0.708246 to 0.708639). The $^{87}\text{Sr}/^{86}\text{Sr}$ value for Upper Watrous sample from this study (0.708268) is shown as the solid purple line (modified from Butcher et al., 2001).
Type Section

Type sections for the Spearfish Formation in North Dakota are limited to log interpretations. Due to the high lithologic variability of the Spearfish Formation across North Dakota, a type section for each Spearfish member could not be made in a single well. A typical log section for the Spearfish can be viewed in Figure 12. The Saude Member type section is the interval between 6,290 and 6,610 feet in the Amerada Petroleum Corporation Pederson Cater No. 1 Well, NE/4 SW/4 sec. 21, T. 158 N., R. 95 W., Williams Co., ND (Dow, 1967). The Saude Member of the Spearfish is 320 feet thick in the type section well and is capped by the Poe Member of the Piper Formation.

The type section for the Pine Member is between the interval of 5,237 and 5,432 feet in the Carter Oil Co., L.L. Johnson No. 1 well, NW, Sec. 9 T. 129 N., R. 106W., Bowman County North Dakota. From the base of the Pine Member to the upper contact with the Saude Member is approximately 215 feet in the type section well. However, in 1967 Dow discusses that the Pine is highly variable across North Dakota and reaches a maximum thickness of 300 feet about 35 miles north of the Black Hills.

The type section for the Belfield is the interval between 7,228 and 7,431 feet in the Amerada Petroleum corporation, R.E. Newton No. 1 well, NW, SW, Sec. 31, T. 140 N., R. 99 W., Stark County, North Dakota. In North Dakota the Spearfish Formation reaches a maximum thickness of 715 feet (Dow, 1967). The Belfield Member in the type section measures a total of 230 feet from the basal contact with the Minnekahta Formation and the upper contact with the Pine Member of the Spearfish.
The lithology of the Spearfish Formation in its type locality is similar to the lithology in north central North Dakota. The bottom Belfield Member is mainly comprised of reddish orange siltstones and shales. Within the lowermost unit there are sections of bedded anhydrite and blebs of anhydrite (Dow, 1967). The Pine Member is also referred to as the Pine Salt and is mainly comprised of salt with lenticular beds of orange and dark grey shale. Also within this unit are thinly bedded layers of fine grained sandstone and siltstone.

The Saude Member of the Spearfish contains the highest concentrations of finely grained sandstones and siltstones (Ziegler, 1955). The sandstones and shales of this member are dominantly reddish brown in color with a few samples containing dark grey shale. The Saude contains a high concentration of anhydrite blebs and is slightly calcareous in the lower sections (Dow, 1967). The sandstone layers of the Saude are dominantly fine grained and sub angular. However, there are frequent appearances of frosted quartz grains that are medium to coarse grained having a sub rounded to rounded texture.
Figure 12. The typical radiation and electric logs of the members of the Spearfish Formation and the Poe Member of the Piper Formation (modified from Dow, 1967).
CHAPTER III

RESULTS

Well Log Correlations

Four log signatures were identified and picked when present in any of the 2,800 well logs across the study area. From these wells seven cross sections were generated across the region to best represent well-log heterogeneities. Logs in these cross-sections were used based on their position across the study area, type of log (gamma ray), and amount of core where available. Each cross-section has a tie log so that it can be correlated with a proximal cross-section. The cross-sections are structural cross-sections and each well has been hung on the top of the Spearfish Formation to best show the basal sand pinchouts. Cross sections were built in sections of six to preserve enough size to observe log signatures on the paper provided.

The first correlation completed in the study area was the unconformity between the Spearfish Formation and Madison Group. A structure contour map was generated and can be viewed in Figure 13. However, the Madison and Spearfish are only unconformable in the northwest section of the map starting in the southwest corner of Renville County and moving east. This is because the Big Snowy Group, another siliciclastic unit becomes present above the Mississippian units here. On the map this contact occurs where the contour lines are more concentric to the west which closely follows the 3,200 foot contour line on the Figure 13. Further east on the map the contours
become more irregular and in areas of great well control (north-central Bottineau County) small irregularities are observed. Overall the surface dips to the southwest towards the center of the Williston basin.

After identifying the Madison Unconformity the Spearfish Formation top was then picked. Combining these picks with the lower Madison picks an isopach map of the Spearfish Formation is generated (Figure 14). Figure 14 displays a thickening trend to the southwest for the Spearfish. The 200 foot contour interval trends in two directions, east-west in the north and north-south in center of Bottineau County. Contours representing true Spearfish thickness mimic this depositional trend. Minor changes in thickness across the study are present with local variations occurring across the study area. The larger depositional trend is north-south. This is especially true for those areas proximal to the Newburg syncline region. Comparing Figure 13 to Figure 14 it is noted that the largest trends on the contour map correlate well with thicker zones on the isopach map. The cross-sections in Figure 15 and 16 display the same thickening trend for the Spearfish in the study area. The termination of sand bodies against the underlying unconformity shows the onlapping nature of the Spearfish sediments (Figure 15). Also within this cross-section are zones of local thickening and thinning which do not match the overall trend. These anomalous zones of thickness coincide with thickening and thinning of the basal sand.

The basal sand is highly variable across the study area in both log signature and thickness. The general trend is a thickening to the southwest with a zero edge occurring in eastern and north-western Bottineau County. Bottineau County experiences the
Figure 13. A structure contour map of the Madison Group in north-central North Dakota.

Figure 14. An isopach map from the Spearfish Formation top to the Madison Group top.
Figure 15. A cross-section of the Spearfish Formation across the lower section of Bottineau County with A'' occurring to the far West. Note the overall thickening towards the basin center.
Figure 16. A continuation of the cross-section in Figure 15 of the Spearfish Formation across the lower portion of Bottineau County with A' occurring to the far West. Again note the overall thickening towards the basin center.
Figure 17. A map of the cross-sections in Figure 16 and 15 A’ is the tie well for the two cross-sections.
greatest heterogeneity in the basal sand with two thick trends. The first trend is a north-south trend that is proximal to the Newburg structural trend. The second trend is an east-west trend that follows the same trend as the Spearfish isopach map (Figure 18). Figures 15 and 16 display the overall thickening trend towards the basin center on the southern margin of the study area. Conversely, the cross-sections in Figure 19 and 20 show the highly variable trends in the basal sand across the northern margin of the study area. Along with the larger trends in the basal sand, pockets of isolated thickness occur across the study area and are present within these larger trends.

Figure 18. An isopach map of the basal sand unit to the Madison top across the study area. The thicker regions greater than 75 feet in the southwest include the Big Snowy Group.
The next sand above the basal sand is the water sand which is a regionally extensive sand unit that spans the majority of the study area. The water sand displays many of the same trends as the basal sand unit but is less pronounced. The north-south trend observed in both the Spearfish isopach and basal sand isopach map is observed in the water sand unit. However, in the case of the water sand it is shifted east and the thickest region occurs proximal to the Canadian border, north of the Newburg structure. The zero edge observed in north-western Bottineau County for the basal sand thickness in Figure 18 correlates to a thin area in the water sand in Figure 22. The water sand doesn’t thicken toward the basin center; rather it is thickest along the trends observed in Figure 18. Figures 19, 20, and 21 show the easily recognized signature of the water sand and the thickening trend across the Newburg syncline and central region of Bottineau County.

The B sand overlies the water sand but doesn’t show the same trends that the water sand had (Figure 27). The main trend for the B sand is northwest to southeast. An anomalous thick trend is not observed in this section rather a general thickening across the study area towards the southwest is the most prevalent feature. Pockets of thicker B sand occur sporadically across the region with a cluster of these pockets trending north-south near the Newburg syncline. Figure 29 shows the consistency in log signature in the western part of the study area. When comparing this to Figure 25 a wide variance in log signature is observed, with the water sand becoming more proximal to the unconformity further to the northeast. Figure 23 shows a very similar trend to Figure 29 with only minor variations in log signature and thickness. The B sand is widespread across the study area with log signatures having more heterogeneity further to the basin margin.
Figure 19. A cross-section of the Spearfish Formation in the upper part of Bottineau County with $A''$ occurring to the far West.
Figure 20. A continuation of the cross-section in Figure 19 of the Spearfish Formation in the upper section of Bottineau County with A’ occurring to the far west. Note the variations in thickness with a slight thickening trend to the west.
Figure 21. A map of the cross-sections in Figure 19 and 20 with A' the tie well for the two cross-sections.
Figure 22. An isopach map of the water sand in north-central North Dakota.

The final sand body mapped is the A sand which is the thinnest and most difficult to map and correlate. Log signatures for this unit are highly variable and are often open to interpretation. The A sand averaged ten to twenty feet in thickness and is seen across the entire study area. Gamma ray signatures for this unit are not as high as the previous sand units but usually have a prominent clean signature compared to stratigraphically proximal rocks. The A sand shows pockets of thicker section across the region with no consistent pattern to these pockets. However the sand is very sheet like in deposition with one lobe of thickness trending from west to east across the study region (Figure 28). The north-south and east-west trend previously observed in Bottineau County is not present even in clusters. The Stead 33-14 #3 well in Figures 29 and 30 displays the signature picked which generates the lobe trend across the region. The gamma ray signature in that well is typical for the A sand especially in the thicker regions of A sand deposition.
Figure 23. A cross-section of the Spearfish Formation across the Newburg structure in Bottineau County with A’ occurring to the far South. Note the variations in thickness of the basal sand unit.
Figure 24. A map of the cross-sections in Figure 23.
Figure 25. Cross-section in north-central north Bottineau County of cored wells in the Spearfish Formation with A’ to the west. Note the variations in thickness in the sand units.
Figure 26. A map of the cross-sections in Figure 25.
Figure 27. An isopach map of the B sand in north-central North Dakota.

Figure 28. An isopach map of the A sand in north-central North Dakota.
Figure 29. A cross-section of the Spearfish Formation running north-south across the western part of Bottineau County with A’ to the south.
Figure 30. A map of the cross-sections in Figure 29.
The four sand bodies mapped in this study are generally continuous across the study region. Sand bodies which are stratigraphically higher display less variation in thickness and have little change in depositional trends. The basal sand displays the greatest difference in thickness with multiple thickening trends and zero edges. Cross-sections in this study area show that sand bodies in the Spearfish Formation are correlative across north-central North Dakota. However, signatures do have some heterogeneity especially for the A sand. Signatures closer to the basin margin become less thick and more obscure. An overall thickening of the formation occurs to the southwest with two major depositional trends occurring. The first trend is a north-south linear trend which is in close proximity to the Newburg syncline. A second trend occurs east-west which parallels the Canadian border on the upper region of the study area.

**Core Description**

In this study a total of 28 cores were used to evaluate heterogeneities in lithofacies across the study area. Cores were selected on their location and total footage cut in the Spearfish Formation (Table 2). The cores selected showed a highly variable sequence of siliciclastic lithofacies. Lithofacies in core descriptions were based on the grain size and the abundance of the grains. The core descriptions provided in the Appendix are for the most part subdivided on these lithofacies. The highly variable sedimentary structures, accessories minerals, color, oil staining, and cement in this formation contribute to the accurate depiction of lithofacies. For example diagenetic reduction of the red beds commonly indicated a change in lithofacies so is given a separate lithofacies. Six separate lithofacies were identified in the core study.
The first lithofacies observed in core was a very argillaceous brown to tan unconsolidated paleosol. It was given the label of lithofacies A. Examples of this were observed in wells 21504 and 21482 (Figure 31). Well 21482 had two paleosols developed at depths of 3135 and 3155 feet. These beds were often a foot or less in thickness and were consolidated enough to pick up but could easily be broken. They had an overall mottled look that was highly bioturbated. The paleosols did not display the development of multiple soil horizons but rather resemble a single soil profile. This lithofacies occurred in the upper half of the Spearfish Formation and were confined to proximal wells. They correlated well with higher gamma ray log signatures.

The most abundant lithofacies observed in this study is a quartz wacke siltstone unit with varying levels of argillaceous matrix which is labeled B. It varied in color on the amount of oxidation in each section and most commonly displayed a mottled or massive look. Anhydrite is also a common feature in this siltstone section. Nodular anhydrite is the most common type and varied greatly in quantity and size. Figure 32 displays small anhydrite blebs but it is not uncommon to see nodular anhydrite up to an inch or more in diameter. This lithofacies also contains trace to common amounts very fine grained quartzs that are subangular to subround. Medium sized quartz grains rarely occur in this section but when present they are isolated as float in the siltstone and matrix. Slight dolomitization of this facies was observed in several cores solely in the upper most section of the Spearfish. Where dolomitization is present the core becomes more brittle.
Table 2. List of 28 cores examined in this thesis with their state well number, API number, County, Township, original well name, original operator name, and cored interval in the Spearfish Formation.

<table>
<thead>
<tr>
<th>Well</th>
<th>API</th>
<th>County</th>
<th>Township</th>
<th>Original Operator</th>
<th>Original Well Name</th>
<th>Cored Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>(33-009-00004-0000)</td>
<td>Bottineau Co.</td>
<td>NWNW 23-163-75</td>
<td>Lion Oil Company</td>
<td>Huss #1</td>
<td>3398-3418 ft.</td>
</tr>
<tr>
<td>1967</td>
<td>(33-009-00320-0000)</td>
<td>Bottineau Co.</td>
<td>SESW 4-161-79</td>
<td>Amerada Petroleum Corp.</td>
<td>L. Rothe #3-A</td>
<td>3338-3367 ft.</td>
</tr>
<tr>
<td>3860</td>
<td>(33-009-00881-0000)</td>
<td>Bottineau Co.</td>
<td>NWSE 9-160-78</td>
<td>Superior Oil Co.</td>
<td>Mona Doman #1</td>
<td>3245-3254 ft.</td>
</tr>
<tr>
<td>9287</td>
<td>(33-009-01545-0000)</td>
<td>Bottineau Co.</td>
<td>SWSE 15-162-81</td>
<td>Clarion Resources Inc.</td>
<td>Stead #1-15</td>
<td>3575-3622 ft.</td>
</tr>
<tr>
<td>10251</td>
<td>(33-009-01609-0000)</td>
<td>Bottineau Co.</td>
<td>SENE 34-164-78</td>
<td>Norcen Energy Inc.</td>
<td>Norsegard #1</td>
<td>2960-3025 ft.</td>
</tr>
<tr>
<td>10452</td>
<td>(33-009-01629-0000)</td>
<td>Bottineau Co.</td>
<td>NENW 29-163-77</td>
<td>Dorechester Exploration Inc.</td>
<td>McDonald #21-29</td>
<td>2945-3017 ft.</td>
</tr>
<tr>
<td>10454</td>
<td>(33-009-01631-0000)</td>
<td>Bottineau Co.</td>
<td>SESE 5-160-79</td>
<td>Dorechester Exploration Inc.</td>
<td>Strom #44-5</td>
<td>3380-3430 ft.</td>
</tr>
<tr>
<td>11347</td>
<td>(33-009-01717-0000)</td>
<td>Bottineau Co.</td>
<td>NWNE 8-160-78</td>
<td>Turtle Mountain Gas &amp; Oil Inc.</td>
<td>Goodman #1-8</td>
<td>3247-3273 ft.</td>
</tr>
<tr>
<td>11397</td>
<td>(33-007-00049-0000)</td>
<td>Rolete Co.</td>
<td>NESE 17-160-73</td>
<td>Anasco Production CO.</td>
<td>Daniel Anderson #1</td>
<td>2648-2695 ft.</td>
</tr>
<tr>
<td>11804</td>
<td>(33-009-01766-00-00)</td>
<td>Bottineau Co.</td>
<td>NWSE 24-163-79</td>
<td>Georesources Inc.</td>
<td>Anderson et Al #1-24</td>
<td>3075-3122 ft.</td>
</tr>
<tr>
<td>12053</td>
<td>(33-009-01786-0000)</td>
<td>Bottineau Co.</td>
<td>SWSE 10-162-76</td>
<td>Turtle Mountain Gas &amp; Oil Inc.</td>
<td>Craig #1-10</td>
<td>2929-3017 ft.</td>
</tr>
<tr>
<td>13556</td>
<td>(33-009-01943-0000)</td>
<td>Bottineau Co.</td>
<td>SENW 32-164-83</td>
<td>Continental Resources Inc.</td>
<td>South Antler Creek Unit #5-32</td>
<td>3747-3766 ft.</td>
</tr>
<tr>
<td>14153</td>
<td>(33-009-01985-0000)</td>
<td>Bottineau Co.</td>
<td>NENW 20-163-80</td>
<td>Bluesky Oil &amp; Gas Inc.</td>
<td>Bluesky Ledoux #1</td>
<td>3353-3378 ft.</td>
</tr>
<tr>
<td>21482</td>
<td>(33-009-02245-0000)</td>
<td>Bottineau Co.</td>
<td>SWSW 16-163-76</td>
<td>Legacy Oil &amp; Gas ND Inc.</td>
<td>Legacy Etal Seter 13-16H</td>
<td>3111-3168 ft.</td>
</tr>
<tr>
<td>21504</td>
<td>(33-009-02246-0000)</td>
<td>Bottineau Co.</td>
<td>SWNW 31-164-76</td>
<td>Legacy Oil &amp; Gas ND Inc.</td>
<td>Legacy Et Al Berge 5-31H</td>
<td>3030-3148 ft.</td>
</tr>
</tbody>
</table>
Figure 31. An unconsolidated paleosol showing a high amount of bioturbation. (Well # 21482, API (33-009-02245-0000), Township SWSW 16-163-76, and depth of 3155 ft.).
and effervesces with acid. Sedimentary structures are limited in this section but some
cross-bedding, soft sedimentary deformation, and ripple structures are present. Accessory
minerals are limited in this lithofacies with the exception of heavy minerals.

The third lithofacies is labeled C which is a siltstone to fine grained sandstone that
is normally classified as a quartz wacke or lithic wacke and is dominantly green, brown,
and black in color. It is the best reservoir section in the Spearfish which is shown by the
asphaltenes and abundant oil staining observed. The lithofacies is well sorted with very
fine grains to fine grains being the dominate grain size. Heavy minerals are the second
most common grains after quartz grains. The green color originates from hydrocarbon
migration and reduction which gives a massive look in the center of the reservoir and a
mottled appearance on the edges of the reservoir (Figure 33). This lithofacies is usually
void of nodular anhydrite and anhydrite cement causing a large decrease in the weight of
core. Throughout the 28 core samples the lithofacies rarely reached more than ten feet
thick and is normally approximately three feet thick.

Lithofacies D is the fourth lithofacies and is most commonly a quartz wacke unit
comprised of very fine to medium grains with fair sorting. Grains are subangular to well
rounded with the more mature sediments being the larger grains, which are also
commonly frosted. Rip up clasts commonly occur in this section and become more
prevelant the closer this lithofacies is to the Mississippian unconformity. This unit
contains trace to abundant amounts of nodular anhydrite and cement. Lithofacies four is
normally found near the center of the Spearfish and is ussually mottled to massive. When
this lithofacies is not heavily cemented by anhdrite it makes a good reservoir rock and is
Figure 32. A siltstone section displaying a mottled to massive look with small blebs of anhydrite. This is very typical in the Spearfish Formation (Well # 10706, API (33-009-01644-0000), Township SENEW 34-164-79, and depth of 3090 ft.).
Figure 33. A sandstone section showing reduction from hydrocarbon migration. This is typical for lithofacies C (Well # 3840, API (33-009-00873-0000), Township SWSE 1-163-80, and depth of 3198 ft.).
commonly oil stained. Laminar and cross-bedding are the most common sedimentary structures in this unit. These structures are usually deformed and give a mottled look that masks structures (Figure 34). The contact between this lithofacies and other lithofacies is both gradational and sharp throughout the study area. Argillaceous material in this unit is confined to thin beds and some massive zones where it constitutes as trace amounts of matrix.

The fifth lithofacies E is a siltstone and sandstone quartz wacke having a wide range in colors. It is described as being poorly to fairly sorted depending on the grain size in the sandstone lenses. Trace larger grains appearing in this lithofacies were well rounded as both clear and frosted quartz grains up to coarse size. Siltstone is usually the dominant texture with common lenses of sandstone less than two inches in thickness. Sandstone and siltstone beds frequently display a mottled appearance (Figure 35). Dominant sedimentary structures in this unit include soft sediment deformation, small scale cross-bedding, and ripples. Soft sediment deformations in this lithofacies contain large scale injectite loading features that are vertical and up to several inches in diameter. The loading features are coarse grained sandstones that are well cemented by anhydrite making them easily distinguishable from the surrounding siltstones.

The final lithofacies F is commonly located in the lower section of the cores. It is commonly a quartz wacke, quartz arenite, and lithic arenite or wacke sandstone unit that is commonly well indurated by anhydrite cement. Depending on the quantity of lithic fragments and feldspar grains it is also feldspathic arenite or lithic arenite. Rip up clasts from the Madison Group range from sand size to several inches in diameter and are a
Figure 34. Sandstone lithofacies displaying a mottled to massive appearance that is obscuring laminar, low angle cross bedding, and ripple structures. (Well # 21504, API (33-009-02246-0000), Township SWNW 31-164-76, and depth of 3090 ft.).
Figure 35. The siltstone and sandstone lithofacies with small nodular anhydrite. Notice the lens shape of the sandstone bodies. (Well # 18997, API (33-009-02185-0000), Township NENE 27-163-78, and depth of 3062 ft.).
frequent component in this lithofacies. The grain size in this section ranges from silt to coarse grained resulting in poor sorting (Figure 36). Quartz grains are regularly frosted with a subrounded to well rounded nature. Oil staining in this section is limited to zones of anhydrite dissolution. In this lithofacies cross-bedding is the dominant sedimentary structure. The color is highly variable in this section, resulting from the amount of anhydrite cement or argillaceous matrix. Heavy minerals are often present in this unit with zircons observed in both core and thin section samples.

Sedimentary structures in these six lithofacies are often difficult to see because of the mottled and massive nature of the Spearfish. Soft sediment deformation is the most common feature present but cross-bedding of varying kinds is also prevalent. The ability to see structures is dependent on a variation in the grain size, grain type, cementation, and color. Changes in color are attributed to the amount of argillaceous matrix available for oxidation. Changes in porosity create a bimodal reservoir which limits oil staining and reduction to the higher permeable reservoir zones.

**Thin-Section Description**

In this study a total of four wells with thin sections were used to validate core descriptions, describe grain maturity, and define porosity variations. The wells selected for thin section examinations were based off their geographic location and stratigraphic location in the Spearfish Formation (Table 3). Thin sections used for the study showed a wide range in lithofacies and validated much of the core work. Lithofacies in core descriptions were based on the grain size and the abundance of the grains which fit well with thin section descriptions (Appendix).
Figure 36. Coarse grained sandstone with abundant rip up clasts from the underlying Madison unit. (Well # 3860, API (33-009-00881-0000), Township NWSE 9-160-78, and depth of 3245 ft.).
The first lithofacies recognized, the argillaceous immature paleosol, had no thin sections available for description. However the B lithofacies is more abundant in this study and is a quartz wacke siltstone unit with varying amounts of argillaceous matrix. Nodular anhydrite is abundant in this section and most commonly occurs as singular nodules separated from other anhydrite by several inches to feet (Figure 41). Dolomite rhombs are observed in several thin-sections but are rare and difficult to differentiate from the fine grained subangular quartz. Compaction of the argillaceous matrix is enhanced around the nodular anhydrite. These highly compacted zones often result in fractures in the most compacted and argillaceous sections (Figure 39). Measurable porosity other than the fracture porosity is rare in thin-sections for the B lithofacies.

The C lithofacies is a siltstone to fine grained sandstone often classified as a lithic wacke or quartz wacke and is dominantly green and black in color. Compared to the B lithofacies it is a much better reservoir rock and is the best reservoir rock observed in thin-sections. The C lithofacies is commonly labeled as a lithic wacke because it contains greater than ten percent lithic fragments. Heavy minerals are difficult to differentiate between magnetite and pyrite in this lithofacies because of their fine grained nature and comparable petrographic properties. Heavy minerals present in this unit often have a cubic shape leading to a pyrite label of the mineral but this is not always the case and varies greatly between wells. Asphaltenes and residual oil are also observed in thin-sections for this lithofacies. The remainders of grains in this lithofacies are quartz which is fairly sorted and usually subangular to subrounded with rare rounded medium grains (Figure 38). Porosity in this section is dominantly secondary from the dissolution of cement between grains. This dissolution generates high percentages of porosity where
anhydrite cement was abundant. Small scale sedimentary structures are observed as planar and low angle cross-beds. These structures in some wells have sorted the bimodal grains into bedding planes generating alternating beds of grain size. In several wells rip up clasts of argillaceous material were observed as the base of this facies which correlate well with a sharp contact with underlying facies.

Lithofacies D is either a quartz wacke or lithic wacke comprised of very fine to medium grains with fair sorting. In this fourth lithofacies grains are subangular to well rounded. The larger sediments are more mature displaying a rounded to well rounded texture. Rip up clasts commonly occur in this section which are sourced from the Spearfish and Madison. Heavy minerals are present in this section but occur in rare to trace amounts. Small scale cross-bedding is observed in this facies with the basal section containing heavy minerals (Figure 37). These small scale beds are very discontinuous and form a wisp looking structure in most thin-sections. The D lithofacies represents the second best reservoir rock with trace to common amounts of primary and secondary porosity. Anhydrite in this lithofacies occurred as both nodular form and cement with trace to common amounts of both (Figure 41). Where secondary porosity is generated it is in the form of fractures and dissolution of anhydrite cement. This dissolution is far less complete than dissolution in lithofacies C.

The fifth lithofacies labeled E is a siltstone and sandstone quartz wacke. Figure 40 is a good representative section of the sandstone lenses contained within in this facies. Soft sedimentary structures are observed frequently in this section as sand injectite type features. Compaction and small dewatering structures are also present in the more argillaceous sections. Porosity in this facies is limited to trace amounts of primary
porosity with trace to occasional fracture porosity. Oil staining is less abundant in this section than in the previous two lithofacies. Feldspar grains are rare in this lithofacies with the few examples occurring as very fine grained subangular grains. Lithic fragments are most commonly comprised of consolidated argillaceous siltstones clasts. Nodular anhydrite is common throughout this lithofacies with the average diameter being less than an inch. Anhydrite cement in this unit is focused in zones of coarser sediments. Injectite features will be up to several inches across with silt to medium sized grains squeezed between argillaceous siltstones and even shale sections (Figure 43). In the more sand rich sections of this lithofacies the argillaceous material is deformed and concentrated amongst the sandstones bodies (Figure 42).

The final facies noted as F is commonly the basal sand section in the wells studied. This facies most commonly displayed a poorly sorted quartz arenite that is well cemented by anhydrite (Figure 44). Very rarely does this section display more than 10 percent lithic or feldspathic minerals in thin-sections. The majority of the wells contain over 90 percent quartz that range from very fine grained to coarse grained with the larger grains becoming more rounded. However, both potassium feldspars (microcline) and plagioclase feldspars are observed in the majority of the wells containing the F facies. These feldspar grains are often subangular to subrounded with minimal erosional features. Along with these feldspars, rip up clasts up to 3 inch in diameter from the Madison are observed. Heavy minerals are also noted in this lithofacies but are less common as in other facies. Among these heavies zircons and tourmaline were observed. Sedimentary structures were nonexistent in this lithofacies because of the large grained nature and abundant anhydrite cement (Figure 44). Minor development of quartz
Figure 37. Picture from well 110 at a depth of 3018 feet showing bedding with heavy minerals, larger grains, and a zircon at the base of the cross-bedding. The photo was taken at 10x.

Figure 38. Picture from well 110 taken at 4x zoom at a depth of 3405 feet.
Figure 39. Photo taken at 10x zoom from well 10097 at a depth of 2999.5 feet.

Figure 40. A photo taken at 4x zoom at a depth of 2973 feet from well 10097.
Figure 41. Nodular anhydrite photographed at 4x from well 10097 at a depth of 2976 feet.

Figure 42. Photo taken at 4x zoom in well 1682 at a depth of 3375.25 feet. Soft sedimentary deformation and loading features are common in lithofacies E. Minor amounts of dolomite rhombs are observed.
Figure 43. Photo taken at 4x zoom from well 10097 at a 3020.75 feet. This shale section is extremely rare for the Spearfish Formation and more commonly is an argillaceous siltstone.

Figure 44. Photo taken at 10x zoom from well 1682 at a depth of 3359 feet.
overgrowth was noted in varying wells in this lithofacies. Very little argillaceous matrix occurred in this section but when it is present the argillaceous matrix is in the form of hematite. Porosity in this section is rare for both primary and secondary porosity.
CHAPTER IV

INTERPRETATIONS

Depositional Model

Results from core examination, petrographic analysis, and well log mapping have resulted in an accurate model for the depositional environment of the Spearfish Formation across north-central North Dakota. Well log analysis shows four sand bodies that are continuous across the study region. However, signatures within the sand bodies vary depending on the well’s location. These signatures represent multiple fining upward sequences, with the exception of the basal sand. The basal sand when present is a single fining upward sequence that does not repeat. The Madison unconformity was exposed across much of the region which resulted in syneresis cracks (i.e. well 13536). This exposure caused irregular weathering of the unconformity which generated accommodation for the basal sand to accumulate during the initial transgression. Basal sand deposition is confined to channels and paleographic lows developed on the unconformity by erosion and salt dissolution. Major channel incision is not observed due to the arid temperatures at that time. The large quantity of frosted quartz grains is a result of the transgression reworking small dune complexes that had developed during this exposure. Paleogeographic high areas across the unconformity have argillaceous siltstones and shales deposited on top of them (Figure 46). The paleogeographic high areas farthest to the west are thicker and more argillaceous. Sheet sands or overbank
sands in the basal sand section are poorly developed in Bottineau County. This lack of lateral sand is indicative of a fast transgression or bypass of sediment to the deeper basin in strong channels. Where the basal sand becomes laterally continuous to the west, the study area is void of cores so a specific depositional environment is hard to depict. Figure 45 displays a visual representation for the Spearfish depositional model. The basal transgression doesn’t fit well into any one specific progression of environments from Figure 45. Tidal channels were proximal to mud flats on paleographic highs, while in some areas local sand flats connected tidal channels during this initial transgression. Following the basal sand deposition the Spearfish Formation underwent a somewhat predictable series of sandstone rich and argillaceous siltstone dominated depositional sequences.

Sheet sands are well developed in the Spearfish across the entire study area. They form as stacked fining upward sequences. At the base of these sands a one foot thick thalweg commonly develops. These thalwegs contain the coarsest material and usually have a sharp erosional contact at the base (Figure 47). These channel sands, where muddy fluid is present, produce a very indicative bimodal grain size (Dalrymple et al., 2003). Figure 48 shows reduced and oxidized beds with preferential hydrocarbon migration (reduction) in these bimodal reservoirs. Ephemeral and perennial streams occur at the base of the sequence while ebb and flood channels develop higher in the sequence (Figure 47 and Figure 49).

After thalweg deposition the fining upward sequence has variable sedimentary structures. High energy environments are observed in numerous cores. These structures include but are not limited to; climbing ripples, in-phase ripples, plane beds,
Figure 45. A diagram showing tidal environments described in the Spearfish Formation in north-central North Dakota. Note the fining upward sequences generated by this model (Modified from James and Dalrymple, 2010).

bi-directional ripples, and various cross-beds (Figure 49). Sedimentary structures formed in lower energy environments cap these fining upward sequences. In several wells immature paleosols form at the top of these sequences. Fining up sequences are often sharply truncated. A new fining upward sequence is then initiated which is indicative of heavy channel avulsion in the tidal system (Figure 51). The progradational fining upward sequences result in a regressive nature to the sandstone units (Dalrymple, 1992). This regression results in exposure and deposition of windblown sands (Figure 50). Well preserved feldspar grains along with frosted quartz grains indicate an arid environment.
with sediment derived from the Canadian Shield. Oxidation throughout the formation also indicates frequent exposure of sediments.

However, when comparing the isopach map results with the tidal depositional model for the Spearfish Formation more depositional processes must be recognized. Once sediments were deposited on the broad plain of the eastern margin they became very susceptible to redistribution. This reworking came in the form of storm events, minor transgressions, and small wave action. These processes deposited sands into the paleogeographic lows of the Newburg syncline and east-west trend in northern Bottineau County. This east-west trend is presumably from erosion similar to what forms cuestas today. These processes are confirmed through core work which shows more massive sandstone units developing in these paleo lows. These massive sands are the remnants of tidal bars and sand ridges formed in the tidal system.

Above the sandstone units is an argillaceous section that contains minor lenses of sandstones up to 30 feet thick. This sequence is deposited mainly as a mud flat or mixed flat with occasional sand flats appearing (Figure 45). Large and small nodular anhydrite occurs more abundantly in this section from the inundation and generation of hypersaline brines. This inundation although minor is a transgression across the often exposed regressive deposits in the upper section of the sandstone units. Also, gamma ray signatures and core in this section suggest minor channel incision matching well with Figure 45. This argillaceous section represents a further transgression of the sea over the basal sand unit. The water sand unit overlies this first argillaceous section and contains stacked fining upward sequences. This series of sequences is repeated until after the A sand, when the formation becomes argillaceous throughout.
Interpretations for the depositional environment of the fining upward sequences prove sandstone units are progradational tidal systems (Weimer et al., 1982; Terwindt, 1988; Dalrymple, 1992). Sandstone units represent a still-stand in sea level when sand bodies could prograded across the basin. Argillaceous very fine grained sandstones and siltstones represent a reactivation of the transgressive sea over the basin. The Spearfish Formation remained a transgressive system throughout deposition due to the northeast onlapping nature of progressively younger sediments in the formation.

Figure 46. Photo of the unconformity between the Spearfish and Madison with argillaceous covering the unconformity. Photo is from well 11347 at a depth of 3273 feet.
Figure 47. Photo of channel lag from water sand with cross-bedding at the base in well 11347 at a depth of 3264 feet.
Figure 48. A bimodal reservoir is shown in this picture through the reduction of preferentially laminated planar bedding. This type of sorting is caused by a switch in the amount of energy during deposition. Photo is from well 10706 at a depth of 3108 feet.
Figure 49. Sandstone section with climbing ripples at the base, in-phase ripples in the middle, and bi-directional ripples at the top with mud drapes. Photo from well 18997 at a depth of 3060 feet.
Figure 50. Photo of the uppermost argillaceous section in the fining upward sequences from well 10706 at a depth of 3139 feet. Notice the laminar to low angle cross-beds.
Figure 51. A photograph of a sharp contact above a channel sand in well 11347 at a depth of 3263 feet Intertidal.
Diagenesis

Porosity in the Spearfish Formation forms as both primary and secondary intergranular porosity. Primary porosity is commonly low for the formation with higher porosity zones being around 10 percent. However, secondary porosity is often very abundant in sand bodies resulting in 10 to 25 percent porosity in some samples. The secondary porosity is a result of hydrocarbon migration through the rock and later dissolution of the anhydrite cement (Surdam et al., 1990). The chemical equation for this reads

$$C_9H_{20} (HC) + 0.25 Fe_2O_3 \text{(hematite)} + CaSO_4 \text{(anhydrite)} + 1.125 H_2O + 3.125 CO_2 \rightarrow 4.0625 CH_3COOH \text{(acetic acid)} + 0.5 FeS_2 + Ca^{++} + 2 CH_3COO^-.$$  

The Spearfish has all the reactants from this equation within its stratigraphic bounds. However, secondary porosity is limited to the water sand and B sand because the proper amount of anhydrite cement and hematite matrix is present. The basal sand contains sufficient anhydrite but lacks hematite matrix, while the A sand is deficient in anhydrite. For obvious reasons the very argillaceous sections between the sands don’t display secondary porosity because of low levels of anhydrite cement. Secondary porosity in the argillaceous zones is limited to fracture porosity. Nodular anhydrite in the Spearfish formed from displacive growth of gypsum crystals in the more argillaceous sections. Gypsum crystals continued to grow with the addition of $Ca^{2+}$ and $SO_4^{2-}$. Pseudomorphs of anhydrite formed and eventually dehydrated into anhydrite nodules (Boggs, 2006). This decrease in size generates a zone of compaction around the nodular anhydrite in argillaceous sections. This shale compaction zone is the most common area for fracture development. Fractures also develop in bedding planes of argillaceous sections that are often compacted between two coarse grained sandstones. These fractures form in more argillaceous sections because
compaction aligns the clay minerals generating lineaments for preferential fracture formation.

Dolomitization in the Spearfish is limited to the upper half of the formation with the only notable sections occurring in the north-central region of Bottineau County. Dolomitization could be more widespread across the study region but the lack of cores cut in the upper half limits this conclusion. Boggs (1995) describes three models for dolomitization: the hypersaline model, the mixing-zone model, and the seawater (shallow subtidal) model. The most plausible model for dolomitization in this formation is the hypersaline model. The tidal/sabkha environment of Spearfish generates evaporitic conditions which generate hypersaline pools. The gypsum and anhydrite forming in the sediments below these pools removes the Ca\(^{2+}\) from the water which generates a higher Mg/Ca ratio. Evaporitic pumping from lower groundwater zones or seepage refluxing from concentrated brine pools on the surface then drives the development of dolomitization. The overall low volume of dolomite examined in the formation is in agreement with the amount of dolomite produced from the hypersaline model.

Anhydrite is an abundant constituent in the Spearfish Formation as cement and nodular anhydrite. The cement is preferentially associated with the coarser grained sediments. This cement is formed from the precipitation of gypsum or anhydrite in the sulphate rich formation waters. These waters then preferentially flowed through the more porous and permeable coarser grained sediments precipitating out the anhydrite cement (Figure 52). Waters similar to this are to be expected in a tidal/sabkha type environment of the Spearfish. The nodular anhydrite is associated more with the argillaceous siltstone sections.
Both potassium feldspar and plagioclase are observed in the Spearfish Formation. The majority of these grains are subangular to subround with very small variations in the level of weathering and alteration. Feldspars within the formation are well preserved showing little to no diagenetic changes to feldspars. This is supported by the lack of authigenic minerals observed in the formation. The small amount of weathering observed on these feldspars occurred during the short transportation over arid conditions from the proximal Canadian Shield. Dissolution of these grains after burial is rare to nonexistent in the Spearfish Formation.

Figure 52. Photo from well 10706 at a depth of 3111 feet showing a sand injectite feature. This coarser grained sand is preferentially filled with anhydrite cement compared to the surrounding argillaceous siltstone.
The diagenetic history of the Spearfish Formation is divided into two stages of development. The first is eogenesis which encompasses the early burial alterations (Choquette & Pray, 1970). This stage includes the reworking or mottling of sediments through bioturbation or soft sediment deformation. Hematization also occurred during this phase of diagenesis and occurred throughout the entire section of the Spearfish Formation. Clay rims on quartz grains are seldom observed in petrographic work showing precipitation of anhydrite cementation simultaneously or prior to any feldspar dissolution or authigenic clay formation. It is probable that some argillaceous materials are authigenic; however the vast majority of clays are matrix. Formation of nodular anhydrite occurred during the early stages of burial as shown from the inclusion of sand grains in the nodular anhydrite.

The second stage of diagenesis, mesogenesis, resulted in a few areas with minor amounts of quartz overgrowths, especially in the basal sand which contains coarse grained quartz. Mesogenesis also resulted in further mechanical compaction of sediments. Precipitation of anhydrite occurred preferentially in coarser grained sands before significant authigenic clay could develop. Authigenic clays were sourced from minor dissolution features observed on feldspar grains and from the clay matrix. Primary porosity is poorly preserved because the clay matrix and anhydrite cement effectively fills pore space. However, secondary porosity is abundant in some lithofacies as both fracture and dissolution porosity. Where dissolution of anhydrite cement is present up to 25% porosity is observed.
CHAPTER V
CONCLUSIONS

1. The Saude Member of the Spearfish Formation is deposited over an extensive angular unconformity. Oil migration from the underlying Madison Group into the red bed sandstones has resulted in economic accumulations of hydrocarbons.

2. Age dating for the Saude has been very controversial throughout history but is now confidently labeled Triassic. A Triassic age is assigned through the use of accurate correlations, palynology, impact structures, isotope geochemistry, and palaeomagnetism.

3. Gamma ray log signatures are divided into four sandstone units: A sand, B sand, water sand, and basal sand, in descending order. Signatures are traceable across the study region for the upper three sandstone units while the basal sand locally pinches out further. Isopach maps show the B, water, and basal sands trending north-south over the Newburg syncline and east-west in northern Bottineau County.

4. Six lithofacies are recognized in the Saude based on grain size and sorting. The six lithofacies identified are labeled:
   A. Friable immature paleosol;
   B. Mottled to massive, quartz wacke siltstone;
   C. Laminated to massive, siltstone to fine grained sandstone that is a lithic wacke
or quartz wacke;

D. Laminated to mottled, very fine to medium grained quartz wacke;

E. Mottled to massive, quartz wacke siltstone with sandstone lenses;

F. Massive to laminated, poorly sorted sandstone which is a quartz wacke, quartz arenite, lithic arenite, or wacke sandstone.

Sandstone deposition is dominant in the lower two thirds of the formation while argillaceous siltstones are prominent in the upper third. Sandstone units are comprised of stacked fining upward sequences. At the base of these sequences is a thalweg deposit with argillaceous rip up clasts from underlying siltstone units. Fining up sequences contain varying sedimentary structures and lithofacies but are noted in the majority of cores described. All six lithofacies recognized in the Spearfish are in at least one of these stacking patterns. Most commonly lithofacies F, D, or E initiate the sequence with varying sequences of finer lithofacies overlying them. Contacts within the sandstone units are sharp and often truncate other fining up sequences initiating a new fining upward sequence. On average the fining up sequence is from three to five feet thick. Overall sandstone thickness ranges greatly depending on location and sandstone unit.

5. The Saude Member was deposited on a broad low dipping plain on the eastern margin of the Williston basin. A tidal environment with hypersaline water conditions and arid climate persisted throughout deposition. Basal sandstones deposited on the irregular Mississippian unconformity are confined to paleogeographic lows from salt dissolution and channel incision. Paleographic highs were covered in argillaceous siltstones and shales. This same transgressive
nature is observed throughout the entire formation with progressively younger sediments onlapped to the northeast. Sandstone deposition was associated with still-stands in sea level during this transgression. Progradation of sands across the basin margin were supplied from the Canadian shield by channels which formed during the still-stands. These sediments were then distributed into sand ridges, tidal channels, and tidal bars forming sheet sands through light wave action and storm action.

6. The diagenetic history of the Spearfish Formation is separated into eogenesis and mesogenesis processes. The shallow burial eogenesis resulted in mechanical compaction forming vertical sand injectites and mottled textures. Minor quartz overgrowths formed in the quartz rich sandstone facies. Minor dolomitization formed in the upper section of some wells from the hypersaline model. Mesogenesis resulted in further mechanical compaction of bedding planes. Precipitation of anhydrite cement preferentially occurred in coarser grained sands during this time as well. The absence of significant authigenic clay development suggests early anhydrite cement precipitation. Primary porosity is limited due to the high amounts of anhydrite cement and clay matrix. Secondary porosity developed in the D and E lithofacies as dissolution porosity from hydrocarbon migration. Hydrocarbon migration generates up to 25% porosity but is limited to the D and E lithofacies. Finally, fracture porosity is well developed in compacted argillaceous sections around nodular anhydrite and bedding planes.
Appendix
Core Descriptions

The following core descriptions are from cores and thin sections at the Wilson M. Laird Core and Sample Library, Grand Forks, North Dakota. Descriptions are listed according to footage depth in descending order. Thin section descriptions are indented and are preceded by TS. The title to the explanations describes the NDIC file no, API no, County, township and range, original oil company, original well name, and Kelly Bushing. Depths given are the footages marked on cores and the correlative wire-line log depths. Sample descriptions are formatted to match the sample examination manual by R.G. Swanson in the American Association of Petroleum Geologists in 1981.

Well 1682 (33-009-00230-0000)
Bottineau Co., SENE 9-161-79
Amerada Petroleum Corp., A. Kvalheim "A" #1
KB = 1483 ft.

3343-3355 Siltstone: Quartz wacke, red, brown, fair to well sorted, subangular to subrounded, with trace to occasional very fine grained sandstone, mottled, argillaceous stringers, nodular anhydrite, anhydrite cement, tight with no oil shows

TS 3344.5- Sandstone. Quartz wacke, brown, white, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), majority argillaceous matrix, trace anhydrite cement, larger grains usually occur in clusters, trace primary porosity, trace secondary porosity, heavy minerals present, rare feldspar grains, rare to trace dolomite, mottled textures with argillaceous solutions or concentrations

TS 3346- Sandstone. Quartz wacke, brown, white, fair sorting, very fine grained to fine grained, sub angular to rounded (larger grains are usually rounded to well rounded), majority argillaceous matrix, trace anhydrite cement, larger grains usually occur in clusters, trace primary porosity, trace secondary porosity, heavy minerals present, mottled textures with argillaceous solutions or concentrations

TS 3347- Sandstone. Quartz wacke, brown, white, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), majority argillaceous matrix, trace anhydrite cement, larger grains usually occur in clusters, rare primary porosity, trace secondary porosity increasing with depth, rare to trace dolomite, heavy minerals present often in clusters, mottled textures with argillaceous solution or concentrations
TS 3349- Sandstone, Quartz wacke, brown, white, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), majority argillaceous matrix, trace anhydrite cement, larger grains usually occur in clusters, rare primary porosity, rare secondary porosity increasing with depth, trace fracture porosity, heavy minerals present often in clusters, rare to trace mica, mottled texture

TS 3353- Sandstone, Quartz wacke, brown, white, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), majority argillaceous matrix, trace anhydrite cement, larger grains usually occur in clusters, rare primary porosity, rare secondary porosity increasing with depth, trace fracture porosity, heavy minerals present often in clusters, rare to trace mica, mottled texture

TS 3354- Sandstone, Quartz wacke, green, tan, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), majority argillaceous matrix, rare anhydrite cement, larger grains usually occur in clusters, rare primary porosity, rare dolomite, rare secondary porosity, heavy minerals present often in clusters or bedding planes, mottled texture

TS 3354.5- Sandstone, Quartz wacke, tan, green, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), majority argillaceous matrix, rare anhydrite cement, larger grains usually occur in clusters, rare primary porosity, rare to trace dolomite, rare secondary, heavy minerals present often in clusters or bedding planes, mottled texture

3355-3373 Sandstone: Lithic wacke, red, brown, tan, green, white, poor sorting, very fine grained to coarse grained, subangular to well rounded, common to abundant anhydrite cement, rare argillaceous matrix, common nodular anhydrite, trace to common rip up clasts from Madison Group

TS 3355.5- Sandstone, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, rare to trace medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), argillaceous matrix, anhydrite cement, larger grains usually occur in clusters, trace primary porosity, rare secondary porosity, heavy minerals present often in clusters or bedding planes, mottled texture

TS 3357- Sandstone, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, rare to trace medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), argillaceous matrix, common anhydrite cement, larger grains usually occur in clusters, trace to occasional primary porosity, rare secondary porosity, rare fracture porosity, rare heavy
minerals present often in clusters or bedding planes, rare feldspars, mottled texture

TS 3359- Sandstone, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, rare to trace medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), argillaceous matrix, common anhydrite cement, larger grains usually occur in clusters, trace to occasional primary porosity, rare secondary porosity, rare fracture porosity, rare to trace dolomite, rare heavy minerals present often in clusters or bedding planes, rare feldspars, mottled texture

TS 3360- Sandstone, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, trace to occasional medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), argillaceous matrix, common anhydrite cement especially in areas of larger grains, larger grains usually occur in clusters or beds, trace to rare primary porosity, rare secondary porosity, trace fracture porosity, rare heavy minerals present often in clusters or bedding planes, small nodular anhydrite, rare feldspars, mottled texture

TS 3362- Sandstone, Quartz wacke, tan, light brown, white, fair sorting, very fine grained to fine grained, trace to occasional medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), argillaceous matrix, common anhydrite cement especially in areas of larger grains, larger grains usually occur in clusters or beds, trace to rare primary porosity, rare secondary porosity, rare fracture porosity, rare heavy minerals present often in clusters or bedding planes, small nodular anhydrite, rare feldspars, mottled texture

TS 3363.75- Sandstone, Quartz wacke, tan, light brown, white, fair sorting, very fine grained to fine grained, trace to occasional medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), common argillaceous matrix, common anhydrite cement, larger grains usually occur in clusters or beds, trace to rare primary porosity, rare secondary porosity, rare fracture porosity, rare heavy minerals present often in clusters or bedding planes, rare small nodular anhydrite, rare feldspars, mottled texture

TS 3364- Sandstone, Quartz wacke, tan, light green, white, poor sorting, very fine grained to medium, trace coarse grains, sub angular to rounded (larger grains are usually rounded to well rounded), trace argillaceous matrix, common to abundant anhydrite cement, larger grains usually occur in clusters along beds, trace to common primary porosity, trace secondary porosity (majority of this porosity is pin point), rare fracture porosity, rare heavy minerals present often in clusters or bedding planes, rare feldspars, mottled texture

TS 3365- Sandstone, Quartz wacke, dark grey to black, light green, white, fair sorting, very fine grained to medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), trace argillaceous matrix, common to
abundant anhydrite cement, larger grains usually occur in clusters along beds, 
trace to common primary porosity, trace secondary porosity (majority of this 
porosity is pin point), rare fracture porosity, rare heavy minerals present often in 
clusters or bedding planes, rare feldspars, mottled texture, residual oil throughout 
section

TS 3366- Sandstone, Quartz wacke, dark grey to black, light green, white, brown, 
fair sorting, very fine grained to fine grained, rare medium grains, sub angular to 
rounded, trace angular, (larger grains are usually rounded to well rounded), 
common argillaceous matrix, trace anhydrite cement, larger grains are scattered, 
trace primary porosity, trace secondary porosity, rare fracture porosity, rare 
heavy minerals present often in clusters or bedding planes, rare feldspars, mottled 
texture, residual oil throughout section

TS 3367.5- Sandstone, Quartz wacke, dark grey to black, light green, white, 
brown, fair sorting, very fine grained to fine grained, rare medium grains, sub 
angular to rounded, (larger grains are usually rounded to well rounded), common 
argillaceous matrix, trace anhydrite cement, rare primary porosity, trace 
secondary porosity, rare fracture porosity, rare heavy minerals, rare feldspars, 
mottled texture

TS 3368- Sandstone, Quartz wacke, light green, white, brown, fair sorting, very 
fine grained to fine grained, rare medium grains, sub angular to rounded, (larger 
grains are usually rounded to well rounded), common argillaceous matrix, trace 
anhydrite cement becoming more common, larger grains scattered, rare primary 
porosity, trace secondary porosity, rare fracture porosity, rare heavy minerals, 
rare feldspars, mottled texture

TS 3369- Sandstone, Quartz wacke, light green, white, brown, fair-well sorted, 
very fine grained to fine grained, sub angular to rounded, common argillaceous 
matrix, common anhydrite cement becoming more common, larger grains 
scattered, rare primary porosity, trace secondary porosity, trace-common fracture 
porosity (focused around nodular anhydrite), common nodular anhydrite, rare 
heavy minerals, rare feldspars, mottled texture

TS 3370- Sandstone, Quartz wacke, light green, white, brown, fair-well sorted, 
very fine grained to fine grained, sub angular to rounded, common argillaceous 
matrix, trace-common anhydrite cement, trace primary porosity, trace-common 
secondary porosity, rare nodular anhydrite, trace fracture porosity, rare heavy 
minerals, rare feldspars, mottled texture

TS 3371- Sandstone, Quartz wacke white, fair sorting, very fine grained to 
medium grained, common medium grains, sub angular to well rounded, rare 
argillaceous matrix, abundant anhydrite cement, larger grains scattered, rare 
primary porosity, rare secondary porosity, trace nodular anhydrite, rare fracture 
porosity, rare heavy minerals, rare feldspars, mottled texture
TS 3372- **Sandstone**, Quartz wacke, white, dark green, fair sorting, very fine grained to medium grained, trace medium grains, sub angular to rounded, trace to common argillaceous matrix, common anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, trace nodular anhydrite, common fracture porosity, rare to trace heavy minerals, rare feldspars, mottled texture

TS 3373- **Sandstone**, Quartz wacke, white, green, red-brown, fair sorting, very fine grained to medium grained, rare medium grains, sub angular to rounded, trace argillaceous matrix, common anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, trace nodular anhydrite, rare heavy minerals, mottled texture with argillaceous stringers

3373-3375 **Siltstone**: Quartz wacke, red, brown, fair to well sorted, subangular to subrounded, with trace to occasional very fine grained sandstone, mottled, argillaceous stringers, nodular anhydrite, anhydrite cement, tight with no oil shows

3375-3385 **Sandstone**: Quartz wacke, red, pink, tan, green, white, poor sorting, subangular to well rounded, bedded anhydrite cement, beds void of anhydrite cement, mottled green and black beds are less dense and commonly oil saturated, rare nodular anhydrite confined to red and brown beds

TS 3375.25- **Sandstone**, Quartz wacke, white, red-brown, fair sorting, very fine grained to medium grained, rare medium grains, sub angular to rounded, trace argillaceous matrix, common anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, common fracture porosity, trace nodular anhydrite, rare heavy minerals, mottled texture with stringers of clay, large clay dewatering structure.

TS 3376- **Sandstone, Mudstone**, Lithic wacke, white, green, fair sorting, very fine grained to medium grained, rare medium grains, sub angular to rounded, abundant argillaceous matrix, trace anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, trace fracture porosity, abundant nodular anhydrite, rare heavy minerals, mottled texture with beds of clay, large siltstone rip up clasts

TS 3377- **Sandstone**, Lithic wacke, white, red-brown, fair sorting, very fine grained to medium grained, rare medium grains, sub angular to rounded, half argillaceous matrix, half anhydrite cement, larger grains abundant in anhydrite cement section, rare primary porosity, rare secondary porosity, abundant nodular anhydrite, rare heavy minerals, trace siltstone rip up clasts

TS 3377.5- **Sandstone**, Quartz wacke, white, red-brown, green, fair sorting, very fine grained to medium grained, rare medium grains, sub angular to rounded, trace argillaceous matrix, common anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, trace nodular anhydrite, rare heavy
minerals (found in bedding planes or clusters), mottled texture with stringers of clay

TS 3376- Sandstone, Quartz wacke, red-brown, green, fair sorting, very fine grained to medium grained, rare medium grains, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, rare heavy minerals, massive

TS 3378.5- Sandstone, Quartz wacke, red-brown, green, fair sorting, very fine grained to medium grained, rare medium grains, abundant very fine grained Quartz, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, rare heavy minerals, rare feldspars, massive to mottled

TS 3380- Sandstone, Quartz wacke, red-brown, green, fair sorting, very fine grained to medium grained, rare medium grains, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, rare heavy minerals, rare feldspars, massive to mottled

TS 3380.75- Sandstone, Quartz wacke, red-brown, green, fair sorting, very fine grained to medium grained, rare medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), common argillaceous matrix, trace anhydrite cement, larger grains scattered, rare primary porosity, rare secondary porosity, common fracture porosity with residual oil, rare heavy minerals, rare feldspars, massive to mottled with argillaceous stringers

TS 3381- Sandstone, Quartz wacke, white, clear, fair to poor sorting, very fine grained to coarse grained, abundant medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare heavy minerals, rare feldspars, massive

TS 3381.75- Sandstone, Quartz wacke, white, clear, dark green, fair to poor sorting, very fine grained to coarse grained, abundant medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), anhydrite cement, rare heavy minerals, rare feldspars, rare rip up clasts, rare nodular anhydrite, massive to partially mottled

TS 3382- Sandstone, Anhydrite, Quartz wacke, white, clear, dark green, fair to poor sorting, very fine grained to medium grained, common medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare heavy minerals, rare feldspars, rare to trace rip up clasts, abundant nodular anhydrite, massive
TS 3383- Sandstone, Anhydrite, Quartz wacke, white, clear, red-brown, fair to poor sorting, very fine grained to coarse grained, common medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), anhydrite cement, rare argillaceous matrix, rare heavy minerals, rare to trace feldspars, rare to trace rip up clasts, abundant nodular anhydrite, massive

TS 3384- Sandstone, Anhydrite, Lithic arenite, white, clear, red-brown, fair to poor sorting, very fine grained to coarse grained, common medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), anhydrite cement, rare argillaceous matrix, rare heavy minerals, rare chert, rare to trace feldspars, trace rip up clasts, abundant nodular anhydrite, massive

TS 3385.5- Sandstone, Anhydrite, Lithic arenite, white, clear, fair to poor sorting, very fine grained to coarse grained, trace to common medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), anhydrite cement, rare heavy minerals, rare feldspars, trace rip up clasts, abundant nodular anhydrite, massive

Well 110 (33-009-00004-0000)
Bottineau Co., NWNW 23-163-75
Lion Oil Company, Huss #1
KB = 2205 ft.

3398-3402 Sandstone, Siltstone: Quartz wacke, red-brown, tan, well sorted, siltstone to very fine grained, subangular to subrounded, possible staining, rare heavy minerals, massive to mottled

3402-3418 Sandstone: Quartz wacke, red, pink, tan, green, white, poor sorting, very fine grained to medium grained, subangular to well rounded, larger grains are commonly frosted and well rounded, smaller grains are clear and subangular to subrounded, trace nodular anhydrite, staining, rare heavy minerals, massive to mottled

TS 3402.5- Sandstone, Quartz wacke, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), rare argillaceous matrix, abundant anhydrite cement, trace to common primary porosity, common secondary porosity, trace fracture porosity, common nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

TS 3403- Sandstone, Quartz wacke, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), trace to common argillaceous matrix, trace anhydrite cement, trace to common primary porosity, trace to common secondary porosity, rare nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled
TS 3403.5- **Sandstone**, Quartz wacke, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), trace to common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare to no secondary porosity, trace fracture porosity rare nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

TS 3404.5- **Sandstone**, Quartz wacke, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), trace argillaceous matrix, trace anhydrite cement, trace to common primary porosity, abundant secondary porosity, rare nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

TS 3405- **Sandstone**, Quartz wacke, tan, red-brown, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded (larger grains are rounded to well rounded), abundant argillaceous matrix, rare anhydrite cement, rare primary porosity, rare secondary porosity, trace nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

TS 3406- **Sandstone**, Quartz wacke, clear, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), trace argillaceous matrix, common anhydrite cement, rare primary porosity, trace secondary porosity, trace nodular anhydrite, rare feldspars, heavy minerals present, massive

TS 3408.5- **Sandstone**, Quartz wacke, clear, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), trace argillaceous matrix, abundant anhydrite cement, rare primary porosity, common nodular anhydrite, rare feldspars, heavy minerals present, massive

TS 3409- **Sandstone**, Quartz wacke, clear, tan, red-brown, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare secondary porosity, trace nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

TS 3410.5- **Sandstone**, Quartz wacke, clear, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare secondary porosity, trace nodular anhydrite, rare feldspars, heavy minerals present, massive

TS 3412- **Sandstone**, Quartz wacke, clear, white, tan, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), abundant argillaceous matrix, trace anhydrite cement, rare primary
porosity, trace fracture porosity, trace nodular anhydrite, heavy minerals present, massive

TS 3413- Sandstone, Quartz arenite, clear, white, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), anhydrite cement, common nodular anhydrite, heavy minerals present, massive

TS 3415- Anhydrite, Shale, Trace Sandstone, Quartz wacke, clear, white, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, rare anhydrite cement, rare primary porosity, rare secondary porosity, abundant nodular anhydrite, heavy minerals present, massive

TS 3416-5 Sandstone, Quartz wacke, clear, white, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare secondary porosity, common nodular anhydrite, heavy minerals present, massive

TS 3417- Anhydrite, Nodular Anhydrite

Well 10097 (33-009-01599-0000)
Bottineau Co., NWNE 34-164-78
Norcen Energy Inc., Lindstrom #34-1
KB = 1543 ft.

2966-3016 Sandstone, Siltstone: Quartz wacke, red-brown, tan, well sorted, siltstone to very fine grained, subangular to subrounded, possible staining, trace anhydrite cement, trace nodular anhydrite, rare heavy minerals, massive to mottled

TS 2968- Sandstone, Quartz, brown, red-brown, dark green, fairly sorted, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), trace to common argillaceous matrix, common to abundant anhydrite cement, rare primary porosity, rare secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

TS 2969- Sandstone, Quartz, brown, red-brown, dark green, poorly sorted, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), common to abundant argillaceous matrix, common anhydrite cement, trace primary porosity, trace secondary porosity, common fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled with burrowed appearance
TS 2969.5- **Sandstone**, Quartz, brown, red-brown, dark green, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

TS 2970.5- **Sandstone**, Quartz wacke, tan, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

TS 2971- **Sandstone**, Quartz wacke, tan, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common to abundant argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled

TS 2972- **Sandstone**, Quartz wacke, brown, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, trace primary porosity, trace secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled

TS 2973- **Sandstone**, Quartz wacke, brown, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, trace primary porosity, trace to common secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

TS 2976- **Anhydrite**, clear, nodular, massive, **Trace Sandstone**, Quartz wacke, red-brown, brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace argillaceous matrix, trace anhydrite cement, no to rare porosity, rare feldspars, heavy minerals present, massive

TS 2978.5- **Sandstone**, Quartz wacke, brown, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, trace primary porosity, trace to common secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

TS 2980- **Sandstone**, Quartz wacke, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, rare
primary porosity, trace secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled

TS 2981- Sandstone, Quartz wacke, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded, common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled

TS 2984.5- Sandstone, Quartz arenite, Shale, clear, fair to poor sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), anhydrite cement, abundant nodular anhydrite, rare feldspars, heavy minerals present, massive

TS 2985- Sandstone, Quartz wacke, tan, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace to common anhydrite cement, trace to common primary porosity, common secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled

TS 2985.5- Sandstone, Quartz wacke, tan, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace to common anhydrite cement, trace primary porosity, trace secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled

TS 2987.5- Sandstone, Quartz wacke, tan, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common to abundant argillaceous matrix, trace anhydrite cement, trace primary porosity, trace secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled

TS 2990- Sandstone, Quartz wacke, tan, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common to abundant argillaceous matrix, trace anhydrite cement, trace primary porosity, trace secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled to massive

TS 2991- Sandstone, Quartz wacke, tan, green, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common to abundant argillaceous matrix, trace anhydrite cement, trace primary porosity, trace to common secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, rare nodular anhydrite, mottled to massive

TS 2992- Sandstone, Lithic wacke, tan, green, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common to abundant argillaceous matrix, trace anhydrite cement,
trace primary porosity, trace to common secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, trace rock fragments, rare nodular anhydrite, mottled to massive

**TS 2993.5-** Sandstone, Quartz wacke, red-brown, brown, green, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present (concentrated in bedding planes), trace nodular anhydrite, mottled to massive

**TS 2994-** Sandstone, Quartz wacke, red-brown, brown, green, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

**TS 2995.5-** Sandstone, Quartz wacke, red-brown, brown, green, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare to trace secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

**TS 2998-** Sandstone, Quartz wacke, red-brown, brown, green, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, rare primary porosity, trace secondary porosity (concentrated in areas of more abundant sand/more anhydrite cement), common fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

**TS 2999.5-** Sandstone, Quartz wacke, red-brown, brown, rare dark green, fair sorting, very fine grained to fine grained with rare medium grains, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, common fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled

**TS 3001-** Sandstone, Quartz wacke, red-brown, brown, trace dark green, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, trace to common nodular anhydrite, mottled

**TS 3002.5-** Sandstone, Quartz wacke, red-brown, brown, trace dark green, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare to trace
secondary porosity, trace fracture porosity, rare feldspars, heavy minerals present, common nodular anhydrite, mottled

**TS 3004.5- Sandstone**, Quartz wacke, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, common nodular anhydrite, mottled

**TS 3005.5- Sandstone**, Quartz wacke, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, common nodular anhydrite, mottled

**TS 3007- Sandstone**, Quartz wacke, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, rare feldspars, common nodular anhydrite, mottled

**TS 3007.5- Sandstone**, Quartz wacke, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare secondary porosity, rare feldspars, heavy minerals present (often in beds or clusters), trace to common nodular anhydrite, mottled to massive with rare shale stringers

**TS 3008.5- Sandstone**, Quartz wacke, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded, common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, trace to common nodular anhydrite, mottled to massive with rare shale stringers

**TS 3010.5- Sandstone**, Quartz wacke, tan, clear, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common to abundant argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, trace nodular anhydrite, mottled to massive

**TS 3011.5- Sandstone**, Quartz wacke, tan, clear, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common to abundant argillaceous matrix, trace anhydrite cement, trace primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, trace to common nodular anhydrite, mottled to massive

**TS 3012- Sandstone**, Quartz wacke, tan, clear, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded (larger grains are rounded to well rounded), common to abundant argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, common nodular anhydrite, mottled to massive
TS 3014- Sandstone, Quartz wacke, tan, clear, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, trace to common nodular anhydrite, mottled to massive

TS 3015- Sandstone, Quartz wacke, tan, clear, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, trace to common nodular anhydrite, mottled to massive

TS 3015.5- Sandstone, Quartz wacke, tan, clear, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, trace to common nodular anhydrite, mottled to massive

3016-3026 Sandstone: Lithic wacke, red, tan, green, white, poor sorting, very fine grained to coarse grained, subangular to well rounded, larger grains are commonly frosted and well rounded, smaller grains are clear and subangular to subrounded, common nodular anhydrite, anhydrite cement in coarser grained sandstones, staining, rare heavy minerals, common rip up clasts, mud drapes, herringbone cross bedding, alternating reduced and oxidized beds

TS 3017- Sandstone, Quartz wacke, tan, clear, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare fracture porosity, rare feldspars, heavy minerals present, horizontal beds to massive

TS 3018- Sandstone, Quartz wacke, tan, clear, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, trace primary porosity, rare secondary porosity, common fracture porosity, rare feldspars, heavy minerals present, horizontal beds

TS 3018.5- Sandstone, Quartz wacke, tan, clear, light green, red-brown, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, trace primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, massive to layered

TS 3019.5- Sandstone, Quartz wacke, tan, clear, light green, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement,
trace primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, massive to mottled

TS 3019.75- **Sandstone**, Quartz wacke, tan, clear, light green, fair sorting, very fine grained to medium grained (abundant), sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, trace primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, massive to mottled

TS 3020- **Sandstone**, Quartz wacke, tan, clear, fair to well sorted, very fine grained to fine grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, rare primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, horizontal bedding

TS 3020.25- **Sandstone**, **Siltstone**, Quartz wacke, tan, red-brown, fair to well sorted, very fine grained to fine grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace anhydrite cement, trace primary porosity, rare to trace secondary porosity, rare fracture porosity, common nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

TS 3020.5- **Sandstone**, Quartz wacke, tan, clear, fair sorting, very fine grained to medium grained (abundant), sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, trace to common primary porosity, rare secondary porosity, rare feldspars, heavy minerals present, massive to mottled

TS 3020.75- **Sandstone**, Quartz arenite, Shale, Quartz wacke, red-brown, clear, brown, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), trace to common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, abundant fracture porosity, rare nodular anhydrite, rare feldspars, heavy minerals present, massive to layered

TS 3021.5- **Sandstone**, Quartz wacke, tan, clear, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are rounded to well rounded), common argillaceous matrix, trace to common anhydrite cement, rare primary porosity, rare secondary porosity, common nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

TS 3023- **Sandstone**, Quartz wacke, tan, clear, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), trace to common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, common nodular anhydrite, rare feldspars, heavy minerals present, rare siltstone rip up clasts, massive to mottled
TS 3024- Sandstone, Quartz wacke, tan, clear, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), trace to common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, common nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

TS 3025- Sandstone, Quartz wacke, tan, red-brown, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), trace to common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, common nodular anhydrite, rare feldspars, heavy minerals present (often in bedding planes), massive to mottled

TS 3025.5- Sandstone, Quartz wacke, tan, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are rounded to well rounded), trace to common argillaceous matrix, common anhydrite cement, rare primary porosity, rare secondary porosity, common nodular anhydrite, rare feldspars, heavy minerals present, massive to mottled

Well 3122 (33-009-00682-0000)
Bottineau Co., NESW 19-163-78
Tiddens Petroleum Corp., Nelson "C" #1
KB = 1522 ft.

3067-3069 Shale: dark brown, trace green, rare nodular anhydrite, massive to mottled

TS 3068- Anhydrite, Shale, brown, white, nodular anhydrite, argillaceous stingers, soft sediment deformation

3069-3088 Sandstone: Quartz wacke, green, black, trace red-brown, fair sorting, very fine grained to medium grained, subangular to well rounded, larger grains are commonly frosted and well rounded, trace anhydrite cement, trace nodular anhydrite, staining, rare heavy minerals, massive to mottled

TS 3069.5- Sandstone, Quartz wacke, tan, green, poorly sorted, very fine grained to coarse grained, subangular to well rounded (larger grains are usually well rounded), rare anhydrite cement, argillaceous matrix, abundant secondary porosity (filled with residual oil), trace fracture porosity, heavy minerals

TS 3070.5- Sandstone, Quartz, tan, green, fair sorting, very fine grained to medium grained, subangular to well rounded (larger grains are usually well rounded), rare anhydrite cement, argillaceous matrix, occasional secondary porosity, trace fracture porosity, heavy minerals

TS 3071.5-Sandstone, Quartz, tan, green, occasional brown, poorly sorted, very fine grained to medium grained, sub angular to rounded (larger grains are usually
rounded to well rounded), alternating beds of anhydrite cement and argillaceous matrix, larger grains usually occur in clusters, possible secondary porosity, heavy minerals present, rare feldspar grains

TS 3072.5- Sandstone, Quartz, tan, green, occasional brown, poorly sorted, very fine grained to medium grained, sub angular to rounded (larger grains are usually rounded to well rounded), alternating beds of anhydrite cement and argillaceous matrix, larger grains usually occur in clusters, possible secondary porosity, heavy minerals present, rare feldspar grains

TS 3073.5 A- Sandstone, Quartz wacke, brown, white, poorly-fairly sorted, very fine grained to fine grained, trace medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), heavy anhydrite cement, larger grains usually occur in clusters, small fracture porosity, argillaceous in part, heavy minerals occur in clumps

TS 3073.5 B- Sandstone, Quartz wacke, tan, green, white, brown, fair sorting, very fine grained to fine grained, trace medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), argillaceous matrix, rare-trace anhydrite cement, larger grains usually occur in clusters, occasional secondary porosity, heavy minerals present

TS 3073.5 C- Sandstone, Quartz wacke, tan, green, white, poorly sorted, very fine grained to mg, common medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), larger grains contain anhydrite cement and argillaceous matrix in other regions, larger grains usually occur in clusters, possible secondary porosity, trace to rare heavy minerals

TS 3073.5- Sandstone, Lithic wacke, tan, green, white, poorly-fair sorted, very fine grained to fine grained, trace medium grains, sub angular to rounded (larger grains are usually rounded to well rounded), alternating beds of anhydrite cement and argillaceous matrix, larger grains usually occur in clusters, possible secondary porosity, trace lithics heavy minerals occur in clumps

TS 3074- Sandstone, Quartz wacke, tan, green, white, fair-poor sorting, very fine grained to medium grained, sub angular to rounded, medium grains are rounded, argillaceous matrix and anhydrite cement, rare secondary porosity, occasional fracture porosity, possible oil fill in porosity, heavy minerals present in clumps, mottled

TS 3075- Sandstone, Quartz wacke, tan, green, white, brown, fair sorting, very fine grained to medium grained, sub angular to rounded, argillaceous matrix and anhydrite cement, common nodular anhydrite in brown beds, possible trace primary porosity, common to abundant secondary porosity in green, trace secondary porosity in brown, trace fracture porosity, heavy minerals present in clumps, mottled
TS 3075.5- **Sandstone**, Quartz wacke, tan, green, white, fair to poor sorting, very fine grained to medium grained, sub angular to rounded, medium grains are rounded, argillaceous matrix and abundant anhydrite cement especially around larger grain clusters, rare secondary porosity, occasional fracture porosity, heavy minerals present linear beds, soft sediment deformation, mottled

TS 3077.5- **Sandstone**, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, sub angular to rounded, argillaceous matrix and anhydrite cement, rare nodular anhydrite, common secondary porosity, trace fracture porosity, heavy minerals present in clusters, mottled

TS 3078.5- **Sandstone**, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, sub angular to rounded, argillaceous matrix and anhydrite cement, possible trace primary porosity, common secondary porosity, trace fracture porosity, residual oil fill in porosity, heavy minerals present, mottled

TS 3080- **Sandstone**, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, sub angular to rounded, argillaceous matrix and anhydrite cement, rare nodular anhydrite, abundant secondary porosity, trace fracture porosity, zircons present, mottled

TS 3081.5- **Sandstone**, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, sub angular to rounded, argillaceous matrix and anhydrite cement, nodular anhydrite, trace secondary porosity, common fracture porosity, heavy minerals present, mottled

TS 3082.5- **Sandstone**, Quartz wacke, tan, green, white, brown, fair sorting, very fine grained to fine grained, sub angular to rounded, argillaceous matrix and anhydrite cement, large common nodular anhydrite, common secondary porosity, argillaceous stringers, heavy minerals present

TS 3083- **Sandstone**, Quartz wacke, tan, green, white, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded, argillaceous matrix and anhydrite cement, nodular anhydrite, common secondary porosity, heavy minerals present in clusters, mottled

TS 3084.5- **Sandstone**, Quartz wacke, brown, white, fair sorting, very fine grained to fine grained, rare medium grains, sub angular to rounded, argillaceous matrix and common anhydrite cement, rare to trace nodular anhydrite, argillaceous stringers, horizontal bedding planes, heavy minerals present in clusters, mottled

TS 3085.5- **Sandstone, Anhydrite**, Quartz wacke, brown, white, fair sorting, very fine grained to fine grained, sub angular to well rounded, abundant argillaceous matrix and trace anhydrite cement, massive nodular anhydrite, large fracture porosity surrounding nodular anhydrite, heavy minerals present, mottled to massive
3088-3095 Missing core

3095-3097 Sandstone: Quartz wacke, red-brown, fair sorting, very fine grained to medium grained, subangular to well rounded, larger grains are commonly frosted and well rounded, smaller grains are clear and subangular to subrounded, occasional to common nodular anhydrite, anhydrite cement in coarser grained sandstones, argillaceous stringers, trace to occasional nodular anhydrite, rare heavy minerals

TS 3096.5- Sandstone, Quartz wacke, brown, white, fair sorting, very fine grained to medium grained, sub angular to rounded (larger grains are usually rounded to well rounded), occasional anhydrite cement, common argillaceous matrix, argillaceous stringers, rare secondary porosity, heavy minerals present

TS 3097- Sandstone, Quartz wacke, brown, white, poor sorting, very fine grained to coarse grained, sub angular to rounded (larger grains are usually rounded to well rounded), occasional anhydrite cement, common argillaceous matrix, argillaceous stringers, rare secondary porosity, heavy minerals present, rare feldspars

Well 3840 (33-009-00873-0000)
Bottineau Co., SWSE 1-163-80
Chandler & Associates, Inc., Federal Wildlife #1
KB = 1476 ft.

3185-3188 Sandstone: Quartz wacke, tan, brown, fair sorting, very fine grained to medium grained, subangular to well rounded, larger grains are commonly frosted and well rounded, trace nodular anhydrite, oil staining, rare heavy minerals, massive to mottled

3188-3198 Siltstone: Quartz wacke, tan, brown, red, well sorted, subangular to subrounded, trace nodular anhydrite, rare heavy minerals, massive to mottled

3198-3199 Sandstone: Quartz wacke, tan, green, fair to well sorted, very fine grained to fine grained, subangular to well rounded, reduced zones, rare heavy minerals, massive to mottled

3199-3213 Siltstone: Lithic wacke, tan, brown, red, well sorted, subangular to subrounded, trace nodular anhydrite, rare heavy minerals, Madison rip up clasts in bottom foot up to 3 cm in diameter, massive to mottled
3090-3096 Siltstone: Quartz wacke, brown, red, well sorted, subangular to subrounded, trace very fine grains, common nodular anhydrite, common heavy minerals, very argillaceous, massive to mottled

3096-3098 Sandstone: Quartz wacke, tan, white, green, fair sorting, very fine grained to medium grained, subangular to well rounded, larger grains are commonly frosted and well rounded, common nodular anhydrite, argillaceous beds at base, laminar and cross-bedding present, oil staining, heavy minerals, massive to mottled

3098-3105 Siltstone: Quartz wacke, brown, red, well sorted, subangular to subrounded, trace very fine grains, common nodular anhydrite, common heavy minerals, very argillaceous, massive to mottled

3105-3113 Sandstone: Quartz wacke, dark green, black, trace red, fair to well sorted, very fine grained to fine grained, rare medium grains, subangular to well rounded, frosted quartz grains, clear quartz grains, trace nodular anhydrite, oil staining, rare heavy minerals, mottled

3113-3120 Siltstone: Quartz wacke, brown, red, well sorted, subangular to subrounded, trace very fine grains, common nodular anhydrite, common heavy minerals, very argillaceous, massive to mottled

3120-3121 Sandstone: Quartz wacke, dark green, black, fair to well sorted, very fine grained to fine grained, subangular to well rounded, frosted quartz grains, trace nodular anhydrite, oil staining, rare heavy minerals, massive to mottled

3121-3131 Siltstone: Quartz wacke, brown, red, well sorted, subangular to subrounded, trace very fine grains, common nodular anhydrite, common heavy minerals, very argillaceous, massive to mottled

3131-3143 Sandstone: Quartz wacke, tan, white, green, fair sorting, very fine grained to medium grained, subangular to well rounded, larger grains are commonly frosted and well rounded, trace nodular anhydrite cement, argillaceous beds at base, laminar and cross-bedding present, oil staining, heavy minerals
Well 21482 (33-009-02245-0000)
Bottineau Co., SWSW 16-163-76
Legacy Oil & Gas ND, Inc., Legacy Etal Seter 13-16H
KB = 1835 ft.

3111-3125 **Siltstone:** Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace very fine grains (occur in zones of cleaner gamma), common nodular anhydrite, heavy minerals, argillaceous, common oil staining, massive

3125-3127.5 **Sandstone:** Quartz wacke, tan, fair sorting, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, Well cemented by anhydrite, trace nodular anhydrite, oil staining, heavy minerals, massive

3127.5-3135 **Siltstone:** Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace very fine grains (occur in zones of cleaner gamma), common nodular anhydrite, heavy minerals, argillaceous, common oil staining, massive

3135-3136 **Shale:** Soil horizon, unconsolidated, very argillaceous, bioturbation, mottled

3136-3155 **Siltstone:** Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace very fine grains to fine grains (occur in zones of cleaner gamma), larger grains often form in failed cross-bedding “whisps”, common nodular anhydrite, heavy minerals, argillaceous, common oil staining, massive

3155-3156 **Shale:** Soil horizon, unconsolidated, very argillaceous, bioturbation, mottled

3156-3162 **Sandstone:** Quartz wacke, tan, fair sorting, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, beds well cemented by anhydrite, common nodular anhydrite, oil staining, heavy minerals, massive

3162-3168 **Siltstone:** Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace very fine grains to fine grains (occur in zones of cleaner gamma), larger grains often form in failed cross-bedding “whisps”, common nodular anhydrite, heavy minerals, argillaceous, common oil staining, massive
Well 12053 (33-009-01786-0000)
Bottineau Co., SWSE 10-162-76
Turtle Mountain Gas & Oil, Inc., Craig #1-10
KB = 1680ft.

2929-2935 **Shale**: green, tan, red, bedded anhydrite, common nodular anhydrite, some consolidated, massive (Poe Member of the Piper gradational with Spearfish Formation)

2935-2955 **Siltstone**: Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace to rare very fine grains to medium grains (larger grains commonly well rounded), frosted and clear quartz grains, larger grains often form in failed cross-bedding “whisps”, common nodular anhydrite, heavy minerals at base of whisps, massive

2955-2967 Missing Core

2967-3017 **Siltstone**: Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace to rare very fine grains to medium grains (larger grains commonly well rounded), frosted and clear quartz grains, larger grains often form in failed cross-bedding “whisps”, common nodular anhydrite, heavy minerals at base of whisps, massive

Well 21504 (33-009-02246-0000)
Bottineau Co., SWNW 31-164-76
Legacy Oil & Gas ND, Inc., Legacy Et Al Berge 5-31H
KB = 1794ft.

3030-3055 **Siltstone**: Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace to rare very fine grains to medium grains (larger grains commonly well rounded), frosted and clear quartz grains, common nodular anhydrite, oil staining, heavy minerals present, massive

3055-3058 **Sandstone**: Quartz wacke, tan, fair sorting, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, common nodular anhydrite, oil staining, heavy minerals, massive

3055-3073 **Siltstone**: Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace to rare very fine grains to medium grains (larger grains commonly well rounded), frosted and clear quartz grains, common nodular anhydrite, oil staining, heavy minerals present, massive

3073-3076 **Sandstone**: Quartz wacke, tan, fair sorting, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, common nodular anhydrite, oil staining, heavy minerals, massive
3076-3083 Siltstone: Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace to rare very fine grains to medium grains (larger grains commonly well rounded), frosted and clear quartz grains, common nodular anhydrite, oil staining, heavy minerals present, massive

3083-3084 Shale: Soil horizon, unconsolidated, very argillaceous, bioturbation, mottled

3083-3088 Siltstone: Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace to rare very fine grains to medium grains (larger grains commonly well rounded), frosted and clear quartz grains, common nodular anhydrite, oil staining, possible cross-bedding, heavy minerals present, massive

3088-3091 Quartz wacke, tan, fair sorting, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, common nodular anhydrite, oil staining, heavy minerals, massive

3091-3134 Siltstone: Quartz wacke, brown, red, tan, fair to well sorted, subangular to subrounded, trace to rare very fine grains to medium grains (larger grains commonly well rounded), frosted and clear quartz grains, common nodular anhydrite, possible cross-bedding, oil staining, heavy minerals present, massive

3134-3148 Sandstone: Lithic wacke, tan, white, fair sorting, fine grained to coarse grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, common rip up clasts, heavy minerals

Well 11658 (33-009-01753-0000)
Bottineau Co., SENW 18-162-80
Mesa Petroleum Co., Kleinert 18 #1
KB = 1506ft.

3458-3470 Siltstone: Quartz wacke, brown-red, fair to well sorted, subangular to subrounded, trace to rare very fine grains to fine grains, frosted and clear quartz grains, common nodular anhydrite, possible cross-bedding (3470), argillaceous in part, sharp contact in color and oil saturation, mottled

3470-3482 Sandstone: Quartz wacke, tan, white, green, fair to well sorted, very fine grained to fine grained, trace medium grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, great oil saturation, mottled to massive
Well 15243 (33-009-02065-0000)
Bottineau Co., SWNE 9-161-78
Eagle Operating, Inc., E-M Aol #9-7
KB = 1491 ft.

3196-3208 Siltstone: Quartz wacke, red-brown, red, well sorted, subangular to subrounded, rare very fine grains, common nodular anhydrite, heavy minerals, very argillaceous, soft sediment deformation, laminar to mottled

3470-3482 Sandstone: Quartz arenite, white, pink, fair sorting, very fine grained to coarse grained, abundant medium and coarse grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, well cemented by anhydrite, feldspars and heavy minerals present, massive

Well 10454 (33-009-01631-0000)
Bottineau Co., SESE 5-160-79
Dorchester Exploration, Inc., Strom #44-5
KB = 1467 ft.

3380-3406 Siltstone: Quartz wacke, red-brown, brown, well sorted, subangular to subrounded, rare very fine grains and fine grains, trace to common nodular anhydrite, trace nodular cement, heavy minerals, very argillaceous, soft sediment deformation, oil staining, cross-bedding, mottled

3406-3424 Sandstone: Quartz wacke, tan, brown-red, fair to well sorted, very fine grained to fine grained, trace medium grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, trace nodular anhydrite and cement, oil staining, mottled to massive

3424-3430 Sandstone: Quartz arenite, white, pink, poor sorting, very fine grained to coarse grained, abundant medium and coarse grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, common anhydrite cement, zircons present, feldspars and heavy minerals present, massive
3003--3008 Siltstone: Quartz wacke, red, tan, well sorted, subangular to subrounded, rare very fine grains to medium grains, frosted and clear quartz grains, trace to occasional nodular anhydrite, rare heavy minerals, soft sediment deformation, mottled

3008-3018 Sandstone: Quartz wacke, tan, pink, red-brown, fair to poorly sorted, very fine grained to fine grained, occasional medium to coarse grains (occurring more at base), thin siltstone beds, subrounded to well rounded, larger grains are commonly frosted and well rounded, trace nodular anhydrite, occasional anhydrite cement, trace oil staining, trace heavy minerals, mottled to massive

3018--3022 Siltstone: Quartz wacke, red-brown, brown, well sorted, subangular to subrounded, rare very fine grains to medium grains, frosted and clear quartz grains, trace nodular anhydrite, rare heavy minerals, soft sediment deformation, mottled

3022-3028 Sandstone: Quartz wacke, tan, pink, red-brown, fair to poorly sorted, very fine grained to fine grained, occasional medium to coarse grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, sand bodies seem to form from soft sediment deformation, trace nodular anhydrite, occasional anhydrite cement, trace oil staining, trace heavy minerals, mottled to massive

3028--3032 Siltstone: Quartz wacke, red-brown, brown, pink, well sorted, subangular to subrounded, rare very fine grains to medium grains, frosted and clear quartz grains, trace to occasional nodular anhydrite, rare heavy minerals, soft sediment deformation, mottled

3032-3041 Sandstone: Quartz wacke, tan, pink, red-brown, fair to poorly sorted, very fine grained to fine grained, occasional medium to coarse grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, trace nodular anhydrite, occasional anhydrite cement, trace oil staining, trace heavy minerals, mottled to massive

3041-3064 Siltstone, Sandstone: Quartz wacke, tan, pink, red-brown, fair to well sorted, subangular to subrounded, trace to rare very fine grains to coarse grains (larger grains commonly well rounded), frosted and clear quartz grains, occasional nodular anhydrite, anhydrite cement in coarse grains (injection features), bidirectional cross-bedding, mud drapes, oil staining, heavy minerals present, massive
Well 9287 (33-009-01545-0000)
Bottineau Co., SWSE 15-162-81
Clarion Resources, Inc, Stead #1-15
KB = 1511 ft.

3575-3587 Siltstone, Sandstone: Quartz wacke, tan, pink, red-brown, fair to poorly sorted, subangular to subrounded, trace to occasional very fine grains to coarse grains (larger grains commonly well rounded), frosted and clear quartz grains, occasional nodular anhydrite, heavy minerals present, mottled

3587--3607 Siltstone: Quartz wacke, dark brown, well sorted, subangular to subrounded, rare very fine grains to fine grains, frosted and clear quartz grains, rare nodular anhydrite, rare heavy minerals, soft sediment deformation, mottled

3607-3616 Sandstone: Quartz arenite, white, tan, poor sorting, very fine grained to coarse grained, abundant medium and coarse grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, trough cross-beds, staining where cement is missing, feldspars and heavy minerals present, massive

3616--3622 Siltstone: Quartz wacke, red-brown, tan, white, well sorted, subangular to subrounded, thin beds of very fine grains to medium grains, frosted and clear quartz grains, trace nodular anhydrite, oil staining in sandstone beds rare heavy minerals, soft sediment deformation, mottled

Well 1967 (33-009-00320-0000)
Bottineau Co., SESW 4-161-79
Amerada Petroleum Corp., L. Rothe #3-A
KB = 1479 ft.

3338--3348 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, trough cross-beds, occasional to common nodular anhydrite, oil staining, mottled

3348-3353 Sandstone: Quartz arenite, white, tan, fair to poor sorting, very fine grained to coarse grained, abundant medium and coarse grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, staining where cement is missing, feldspars and heavy minerals present, massive

3363--3367 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, occasional to common nodular anhydrite, oil staining, mottled
Well 11347 (33-009-01717-0000)
Bottineau Co., NWNE 8-160-78
Turtle Mountain Gas & Oil, Inc., Goodman #1-8
KB = 1460 ft.

3247--3261 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, occasional nodular anhydrite, large soft sediment deformation, oil staining, mottled

3261-3265 Sandstone: Quartz arenite, white, tan, brown, pink, fair to poor sorting, very fine grained to coarse grained, abundant medium and coarse grains, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement at base, trough cross-bedding, fining up, argillaceous rip up clasts, staining where cement is missing, rare feldspars and heavy minerals present, massive

3265-3271 Sandstone: Feldspathic arenite, white, tan, brown, pink, fair to poor sorting, very fine grained to coarse grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement at base, trough cross-bedding, fining up, argillaceous rip up clasts, staining where cement is missing, trace feldspars and heavy minerals present, massive

3271-3273 Siltstone: Quartz wacke, red-brown, red, brown, fair sorting, subangular to subrounded, trace to rare very fine grains to medium grains, frosted and clear quartz grains, trace nodular anhydrite, rare nodular anhydrite cement, oil staining, mottled

Well 10251 (33-009-01609-0000)
Bottineau Co., SENE 34-164-78
Norcen Energy, Inc., Norsgaard # 1
KB = 1540 ft.

2966-2974 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, occasional nodular anhydrite, large soft sediment deformation, oil staining, mottled

2995-2996 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, occasional nodular anhydrite, large soft sediment deformation, oil staining, mottled

2997-3015 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz
grains, occasional nodular anhydrite, large soft sediment deformation, oil staining, mottled

3016-3019 **Sandstone**: Quartz arenite, white, tan, red-brown, fair to poor sorting, very fine grained to medium grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, trough cross-bedding, fining up, argillaceous rip up clasts, staining where cement is missing, rare feldspars and heavy minerals present, massive

3019-3025 **Siltstone, Sandstone**: Quartz wacke, tan, red-brown, fair to poorly sorted, subangular to subrounded, trace very fine grains to coarse grains (larger grains commonly well rounded), frosted and clear quartz grains, occasional nodular anhydrite, heavy minerals present, mottled

Well 3860 (33-009-00881-0000)
Bottineau Co., NWSE 9-160-78
Superior Oil Co., Mona Doman #1
KB = 1465 ft.

3245-3247 **Sandstone**: Quartz arenite, white, tan, red-brown, fair to poor sorting, very fine grained to medium grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, trough cross-bedding, fining up, argillaceous rip up clasts, staining where cement is missing, chert, feldspars and heavy minerals present, massive

3247-3251 **Sandstone**: Quartz arenite, white, tan, red-brown, fair to poor sorting, very fine grained to medium grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, trough cross-bedding, fining up, argillaceous rip up clasts, staining where cement is missing, feldspars and heavy minerals present, massive

3251-3254 **Sandstone**: Lithic arenite, white, tan, red-brown, fair to poor sorting, very fine grained to medium grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, trough cross-bedding, fining up, Madison rip up clasts (2 inch in diameters), staining where cement is missing, feldspars and heavy minerals present, massive
Well 1996 (33-009-00336-0000)
Bottineau Co., NWNW 23-161-79
Amerada Petroleum Corp., Rollin Stair TR 2 #2
KB = 1465 ft.

3319-3325 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, trace nodular anhydrite, small cross-bedding, soft sediment deformation, oil staining, mottled

3325-3339 Sandstone: Quartz wacke, tan, green, fair to well sorted, very fine grained to fine grained, subangular to well rounded, reduced zones, rare anhydrite nodules and cement, thin argillaceous layers, great oil staining, rare feldspars and heavy minerals, massive to mottled

3339-3350 Siltstone, Sandstone: Lithic wacke, tan, red-brown, fair to poorly sorted, subangular to subrounded, trace very fine grains to coarse grains (larger grains commonly well rounded), frosted and clear quartz grains, occasional to common nodular anhydrite, rip up clasts in basal section (up to 1 inch in diameter), heavy minerals present, mottled

Well 14153 (33-009-01985-0000)
Bottineau Co., NENW 20-163-80
Bluesky Oil & Gas Inc., Bluesky Ledoux #1
KB = 1513 ft.

3353-3355 Siltstone: Quartz wacke, red-brown, tan, green, well sorted, subangular to subrounded, trace nodular anhydrite, soft sediment deformation, mottled to massive

3355-3358 Sandstone: Quartz arenite, white, tan, fair to poor sorting, very fine grained to coarse grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, common anhydrite cement, staining where cement is missing, feldspars and heavy minerals present, massive

3358-3378 Siltstone: Quartz wacke, red-brown, tan, green, well sorted, subangular to subrounded, occasional to common nodular anhydrite, smooth contact with unconformity, soft sediment deformation, mottled
Well 14733 (33-009-02019-0000)  
Bottineau Co., SESE 24-163-82  
Samedan Oil Corporation, Tennyson #44-24  
KB = 1531 ft.

3545-3551 Siltstone, Sandstone: Lithic wacke, tan, red-brown, green, fair to poorly sorted, subangular to subrounded, trace very fine grains to coarse grains (larger grains commonly well rounded), frosted and clear quartz grains, occasional to common nodular anhydrite, rip up clasts in basal section (up to 1 inch in diameter), heavy minerals present, mottled

Well 10552 (33-009-01636-0000)  
Bottineau Co., SESW 33-164-78  
Georesources, Inc., Harold Lindstrom #1-R  
KB = 1536 ft.

2997-3013 Siltstone: Quartz wacke, red-brown, tan, green, fair to well sorted, subangular to subrounded, trace very fine grains, thin sandstone bed at 2999, frosted and clear quartz grains, trace nodular anhydrite, soft sediment deformation, mottled

3013-3018 Sandstone: Quartz arenite, white, tan, pink, fair sorting, very fine grained to fine grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, cross-bedding, feldspars and heavy minerals present, massive to mottled

3018-3035 Siltstone: Quartz wacke, red-brown, tan, green, fair to well sorted, subangular to subrounded, trace very fine grains, frosted and clear quartz grains, trace nodular anhydrite, soft sediment deformation, mottled

3035-3039 Sandstone: Quartz arenite, white, tan, pink, fair to poor sorting, very fine grained to medium grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, cross-bedding, feldspars and heavy minerals present, massive

3039-3053 Siltstone: Quartz wacke, red-brown, tan, green, fair to well sorted, subangular to subrounded, trace very fine grains, frosted and clear quartz grains, trace to occasional nodular anhydrite, soft sediment deformation, mottled

3053-3058 Sandstone: Quartz arenite, white, tan, pink, fair to poor sorting, very fine grained to medium grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, rip up clasts (less than .5 inches in diameter), feldspars and heavy minerals present, massive
Well 17606 (33-009-02142-0000)  
Bottineau Co., SENE 22-163-82  
Ward-Williston Company, Artz 22-42  
KB = 1546 ft.

3575-3578 Sandstone: Quartz arenite, white, tan, trace red, fair to poor sorting, very fine grained to medium grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, argillaceous in part, heavy minerals present, massive

3578-3580 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, trace nodular anhydrite, soft sediment deformation, mottled

3580-3583 Sandstone: Quartz arenite, white, tan, trace red, fair to poor sorting, very fine grained to coarse grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, heavy minerals present, massive

3583-3589 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, trace to rare nodular anhydrite, small cross-bedding, soft sediment deformation, mottled

3589-3591 Sandstone: Quartz arenite, brown, tan, red, fair to poor sorting, very fine grained to medium grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, trace anhydrite cement, argillaceous, common soft sediment deformation, heavy minerals present, massive

3591-3596 Siltstone: Quartz wacke, red-brown, tan, green, fair sorting, subangular to subrounded, trace very fine grains to medium grains, frosted and clear quartz grains, trace nodular anhydrite, soft sediment deformation, mottled

Well 4651 (33-009-01009-0000)  
Bottineau Co., NESW 30-162-79  
Amerada Petroleum Corp., Durnin Unit "A" #2  
KB = 1496 ft.

3375-3384 Siltstone: Quartz wacke, red-brown, tan, fair to well sorted, subangular to subrounded, trace very fine grains, frosted and clear quartz grains, trace to occasional nodular anhydrite, cross-bedding at base, argillaceous in part, soft sediment deformation, mottled

3384-3390 Siltstone, Sandstone: Quartz wacke, tan, red-brown, fair to poorly sorted, subangular to subrounded, trace very fine grains to fine grains (larger grains
commonly well rounded), frosted and clear quartz grains, occasional nodular anhydrite, trace anhydrite cement, heavy minerals present, mottled

3390-3395 Siltstone, Sandstone: Quartz wacke, green, tan, red-brown, fair to poorly sorted, subangular to subrounded, trace very fine grains to medium grains (larger grains commonly well rounded), frosted and clear quartz grains, occasional nodular anhydrite, occasional to common anhydrite cement, laminar bedding, feldspars and heavy minerals present, mottled

3395-3405 Sandstone: Quartz arenite, white, tan, pink, poor sorting, very fine grained to coarse grained, subrounded to well rounded, larger grains are commonly well rounded, abundant anhydrite cement, rare rip up clasts, feldspars and heavy minerals present, massive to mottled

Well 13536 (33-009-01943-0000)
Bottineau Co., SENE 32-164-83
Continental Resources, Inc., South Antler Creek Unit #5-32
KB = 1609 ft.

3747-3749 Sandstone: Quartz arenite, red, brown, tan, poor sorting, very fine grained to coarse grained, subrounded to well rounded, larger grains are commonly well rounded, abundant anhydrite cement, common nodular anhydrite, rare to trace chert, feldspars and heavy minerals present, massive to mottled

3749-3766 Siltstone, Sandstone: Lithic wacke, green, tan, red-brown, fair sorting, subangular to subrounded, trace very fine grains to fine grains frosted and clear quartz grains, trace nodular anhydrite, very argillaceous laminar bedding, common angular rip up clasts, trace rock fragments, feldspars and heavy minerals present, mottled

Well 11804 (33-009-01766-00-00)
Bottineau Co., NWSE 24-163-79
Georesources, Inc., Anderson Et Al #1-24
KB = 1517 ft.

3075-3080 Siltstone, Sandstone: Quartz wacke, tan, red, fair to well sorted, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, occasional anhydrite nodules and cement, thin argillaceous layers, rare feldspars and heavy minerals, massive to mottled

3080-3085 Siltstone, Sandstone: Quartz wacke, tan, green, fair to well sorted, very fine grained, subangular to well rounded, reduced zones, argillaceous, great oil staining, rare feldspars and heavy minerals, massive to mottled
3085-3090 **Siltstone, Sandstone**: Quartz wacke, tan, red, fair to well sorted, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, trace to occasional anhydrite nodules and cement, thin argillaceous layers, rare feldspars and heavy minerals, massive to mottled

3090-3093 **Siltstone, Sandstone**: Quartz wacke, black, green, fair to well sorted, very fine grained, subangular to well rounded, reduced zones, argillaceous, great oil staining, trace feldspars and heavy minerals, massive to mottled

3093-3100 **Siltstone, Sandstone**: Quartz wacke, tan, red, fair to well sorted, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, trace to occasional anhydrite nodules and cement, thin argillaceous layers, rare feldspars and heavy minerals, massive to mottled

3100-3119 **Siltstone, Sandstone**: Quartz wacke, tan, red, fair to well sorted, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, occasional anhydrite nodules and cement, thin argillaceous layers, rare feldspars and heavy minerals, massive to mottled

3119-3122 **Siltstone, Sandstone**: Quartz wacke, black, green, fair to well sorted, very fine grained to fine grained, subangular to subrounded, trace very fine grains, frosted and clear quartz grains, occasional to common nodular anhydrite, soft sediment deformation, argillaceous in part, great oil staining, rare feldspars and heavy minerals, massive to mottled

Well 10452 (33-009-01629-0000)
Bottineau Co., NENW 29-163-77
Dorchester Exploration, Inc., Mcdonald #21-29
KB = 1527 ft.

2945-2963 **Siltstone, Sandstone**: Quartz wacke, tan, red-brown, fair to well sorted, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, trace to occasional anhydrite nodules and cement, siltstone beds that are very argillaceous, heavy minerals, mottled

2963-2980 **Siltstone**: Quartz wacke, brown, tan, well sorted, subangular to subrounded, trace very fine grains, frosted and clear quartz grains, occasional to common nodular anhydrite, soft sediment deformation, argillaceous in part, heavy minerals present, mottled

2980-2990 **Siltstone, Sandstone**: Quartz wacke, tan, red-brown, fair to well sorted, very fine grained to medium grained, subangular to well rounded, frosted and clear quartz grains, trace to occasional anhydrite nodules and cement, siltstone beds that are very argillaceous, heavy minerals, mottled
2990-3005 **Siltstone**: Quartz wacke, red-brown, tan, well sorted, subangular to subrounded, trace very fine grains, frosted and clear quartz grains, occasional to common nodular anhydrite, soft sediment deformation, argillaceous in part, heavy minerals present, mottled

3005-3017 **Sandstone**: Lithic arenite, white, tan, poor sorting, very fine grained to coarse grained, subrounded to well rounded, larger grains are commonly frosted and well rounded, abundant anhydrite cement, nodular anhydrite towards top, rip up clasts (less than .5 inches in diameter), feldspars and heavy minerals present, massive

Well 11397 (33-079-00049-0000)
Rolette Co., NESE 17-160-73
Amoco Production CO., Daniel Anderson #1
KB = 1555 ft.

2648-2660 **Shale**: brown, tan, white, red, thick bedded anhydrite, common nodular anhydrite, massive

2660-2668 **Siltstone**: Quartz wacke, red-brown, green, well sorted, subangular to subrounded, trace very fine grains to fine grains, frosted and clear quartz grains, occasional nodular anhydrite, soft sediment deformation, argillaceous in part, heavy minerals present, massive

2668-2695 **Siltstone, Sandstone**: Quartz wacke, tan, red-brown, fair to poorly sorted, very fine grained to coarse grained, sandstones occur in cluster with no apparent bedding, subangular to well rounded, frosted and clear quartz grains, larger grains are rounded to well rounded, trace to occasional anhydrite nodules and cement, siltstone beds that are very argillaceous, argillaceous layer overly the unconformity, feldspars and heavy minerals present, mottled
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