



2015

Lithostratigraphic investigation and components of a complete petroleum system within an Upper Devonian carbonate-evaporite sequence : the Birdbear Formation, Williston Basin, North Dakota

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LITHOSTRATIGRAPHIC INVESTIGATION AND COMPONENTS OF A
COMPLETE PETROLEUM SYSTEM WITHIN AN UPPER DEVONIAN
CARBONATE-EVAPORITE SEQUENCE; THE BIRDBEAR
FORMATION, WILLISTON BASIN, NORTH DAKOTA

by

Benjamin L. Engleman
Bachelor of Science in Geology, Brigham Young University-Idaho, 2013

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

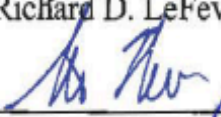
Grand Forks, North Dakota

May

2015


This thesis, submitted by Benjamin L. Engleman 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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Dean of the School of Graduate Studies

May 1, 2015
Date

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Department Geology

Degree Master of Science

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ACKNOWLEDGMENTS

I am grateful to the University of North Dakota for providing the facilities and funding necessary to complete this study. I wish to thank the members of my committee; Drs. Richard D. LeFever, Stephan Nordeng and Dongmei Wang for their guidance throughout this study and providing their insights and support in review of the manuscript.

Dr. Julie LeFever (NDGS) of the Wilson M. Laird core library provided the cores and thin sections used in this study. She was also an invaluable resource of information regarding technical aspects of data collection and interpretation.

The opportunity to pursue my degree was made possible by the unfailing love, support and sacrifice of my wife, Amy Engleman, to whom I am always indebted, thank you. Additional credit must be given to my children: Alexis, April, Ariel, Ryan and Spencer without whose love and support of my education, devotion to God and their tireless patience this degree would not have been earned. Finally I would like to thank Samila Nickell for her support, edits and comments made regarding this work.

ABSTRACT

The Birdbear Formation of the Williston Basin of southwestern North Dakota represents one carbonate-evaporite sequence of the Late Devonian. The formation was deposited during regression on a broad, shallow epeiric shelf and is composed principally of dolomite, limestone and anhydrite. The Birdbear Formation is conformable with the Duperow Formation below and the Three Forks Formation above. The designations of 17 lithofacies form the context for describing hydrocarbon generation, migration and accumulation. Rock-Eval 6 and total organic carbon of 42 samples were used to identify the quality of source rocks present in the formation. Good and excellent source rocks were identified in both the upper and lower members, at varying intervals, as organic rich limestones, microbialites and stromatolites. The vertical terminus of each interval is anhydrite, forming excellent seals to the present source rocks and providing conduits to three stratigraphic traps. The Birdbear Formation of the Williston Basin in southwestern North Dakota encapsulates the vital components for a complete petroleum system.

FORWARD

Recent discovery of the North American shale gas reserves and initiatives seeking to reduce America's dependency on foreign oil, coupled with advances in horizontal drilling technologies has opened the door for a variety of opportunities in the Williston Basin. North Dakota has reaped the benefits as investors, engineers and exploration geologists have flocked to the basin, reducing unemployment to less than 2.5% in April 2014 (U.S. Bureau of Labor Statistics, *retrieved* 2015). This renewal of interest in the basin began with Mike Johnson's discovery at the Parshall Oil Field in 2006. Since that time focus has branched out to other formations in the Basin.

One of these formations, the Birdbear, has been a successful target for hydrocarbon resources in the Williston Basin since the 1960s. Since being formally defined as the 90' interval occurring between 10,310'-10,400' from the Mobil Oil Producing Co. 1 Birdbear Well (C SENW Sec 22, T149N, R91W, Dunn County, North Dakota) by Sandberg and Hammond (1958), the formation has produced 823,527 m³ (Martiniuk, et al, 1995). The Birdbear Formation in southwestern North Dakota represents one of the final cycles of the Kaskaskia Sequence. Famennian in age, the Birdbear Formation conformably overlies the brown to light-grey carbonates of the Duperow Formation and is conformable with the red and green shales of the Three Forks above.

The Birdbear Formation is well documented in north-central North Dakota and Canada. Those studies cover a variety of topics such as depositional environment (Halabura, 1982), lithofacies (Martiniuk et al., 1995), diagenesis (Kent, 1998; Whittaker and Mountjoy, 1996), oil types (Osadetz et al., 1992) and more. A paucity of recent research has been done in the southwestern parts of the basin. This study focuses on the Birdbear Formation of southwestern North Dakota.

CHAPTER I
INTRODUCTION

Geologic Setting

The Williston Basin is an elliptical cratonic basin of North America, elongated in a northwest-southeast direction (Figure 1). It covers portions of Saskatchewan, Manitoba, North Dakota, South Dakota and Montana. It lies above the granites and amphibolite facies of the Trans-Hudson Orogenic Belt. The basin resides between the

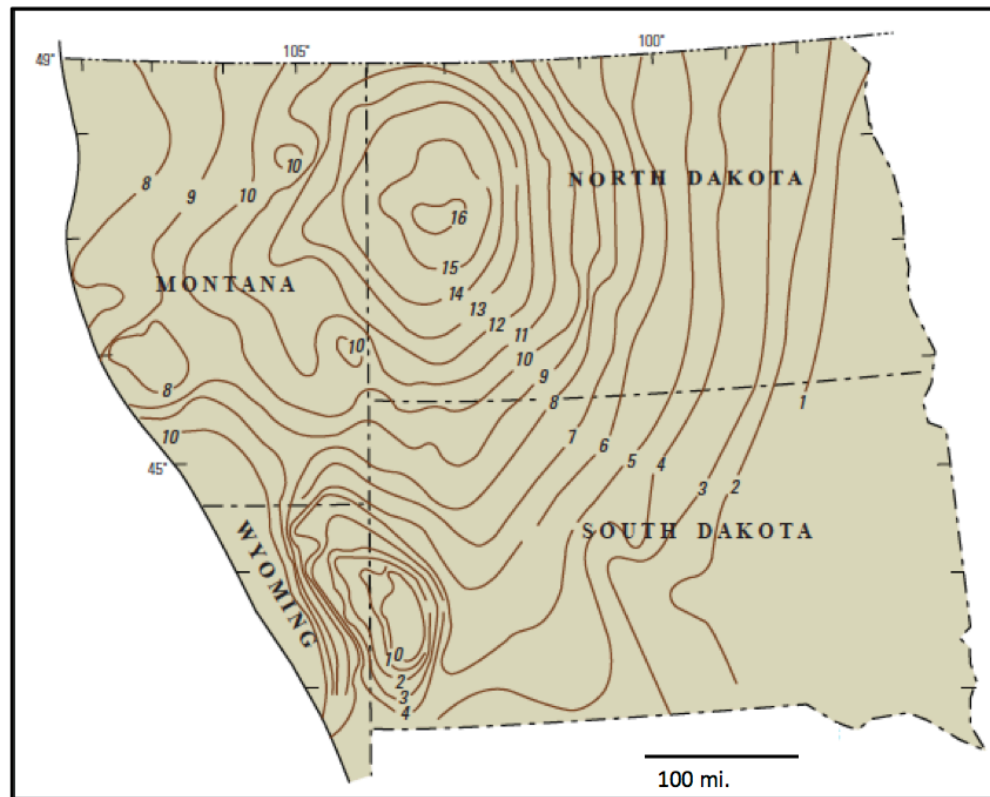


Figure 1. Thickness map of the Williston Basin showing one major closure in west-central North Dakota, and a second minor closure in southwest South Dakota. Contour interval is 1,000 ft. After Anna et al., 2013.

Superior Craton on the east and the Wyoming Craton to the west. The lithologic record of the Williston Basin is composed of over 16,000 ft. of marine, non-marine, and fluvial deposits spanning six major stratigraphic sequences from the Sauk to the Tejas, (Murphy et al., 2009). Carbonate sedimentation began atop the Precambrian unconformity with the shallow marine deposits of the Deadwood Formation and continued throughout most of the Paleozoic Era. Clastic deposition began in the Late Permian with the Spearfish Formation and continued throughout the Mesozoic and Cenozoic Eras. During the Kaskaskia Sequence the overall circular shape of the basin began to change.

The Kaskaskia sequence (Devonian-Mississippian) marked the beginning of a second order transgressive cycle that terminated in the Early Mississippian (Figure 2).

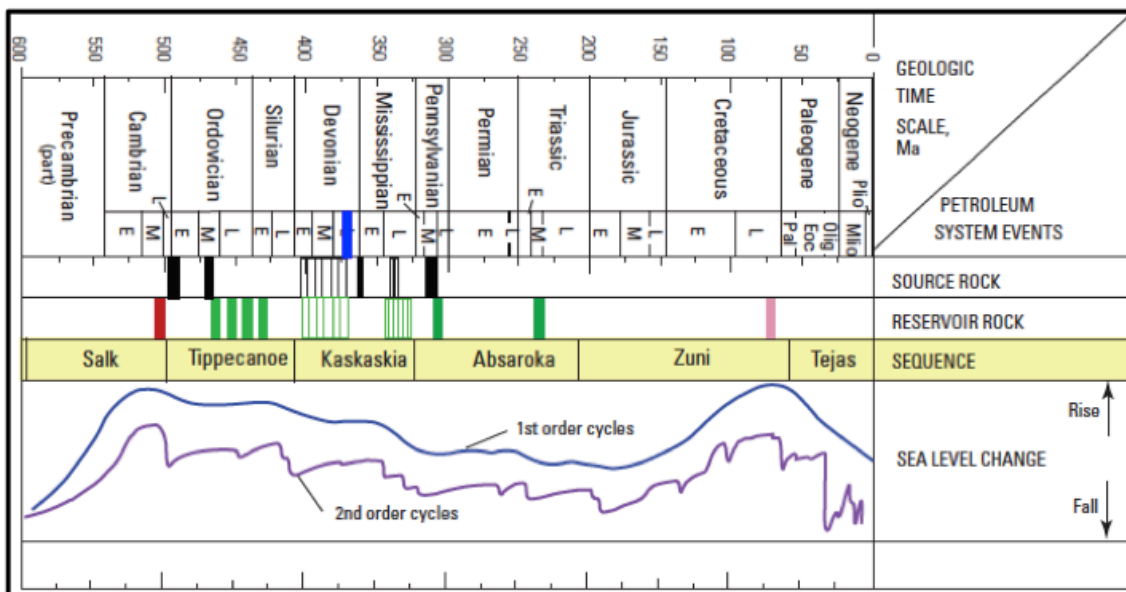


Figure 2. Showing geologic time, source rock, reservoir rock, sequences of Sloss (1984), first and second-order sea level curves (Vail et al., 1977). In the source rock column, black bands represent significant shale deposits, thin lines are carbonate cycles. In the reservoir rock column green signifies oil and red represents gas. The thin green lines show stratigraphic position of reservoirs that may possess other entities besides oil. The blue band represents the stratigraphic position of the Birdbear Formation (modified from Anna et al., 2013).

During this time, uplift of the transcontinental arch changed the basin configuration from a circular basin centered in northwestern North Dakota with a southwestern connection to the Cordilleran sea, to a northwest-southeast trending elongated shelf basin that extended to the Arctic Ocean. This new configuration is called the Elk Point Basin, and it maintained marine connections to the northwest and southeast until the Early Mississippian. At that time, both first order and second order cycles reflected sea level decline. At the end of the Early Mississippian there was a shift back to the circular shape of the Williston Basin, once again centered in North Dakota (Anna et al., 2013).

In the Elk Point Basin, the numerous cycles of restricted marine conditions were followed by episodes of normal circulation coupled with sea level change, giving rise to a variety of lithologic successions of limestone, dolomite and evaporites. For example, there are three, second order cycles in the Kaskaskia. The first is an initial transgression that deposited the Ashern and Winnipegosis Formations followed by the Praire Formation, which represents a regression resulting from a major restriction at the margin of the Elk Point Basin. The second transgression re-established normal marine circulation in the basin and resulted in the deposition of the Dawson Bay Formation. As overall sea level regressed, the Souris River, Duperow, Birdbear, and Three Forks Formations were deposited. The third major transgression occurred during the Late Devonian and resulted in the deposition of the Bakken Formation (Anna et al., 2013). Despite the radical shift in basin geometry, the Williston Basin has remained mostly tectonically undisturbed.

As has been noted, some of the structural elements in the Williston Basin are north and northwest trending, such as the Cedar Creek, Antelope, Poplar, Nesson, Billings and Little Knife anticlines (Figure 3). Seismic data support their association with

the Rocky Mountain Province and indicate that the initiation of the Williston Basin was due to vertical movement that resulted from shear between the Brockton-Froid-Fromberg zone and the Colorado-Wyoming lineament (Gerhard, 1982; LeFever, R. and LeFever, J., 1991). Kent (1987) describes the Williston Basin as having been floored by a collage of Archean paleocontinents, Proterozoic suture zones, a major transform fault, and a province of anorogenic granites. In a relatively quiescent basin with such a dynamic Proterozoic history substantiates evidence suggesting sedimentation and structure of the basin are initiated by overburden. This overburden caused subsidence by reactivating Precambrian basement blocks.

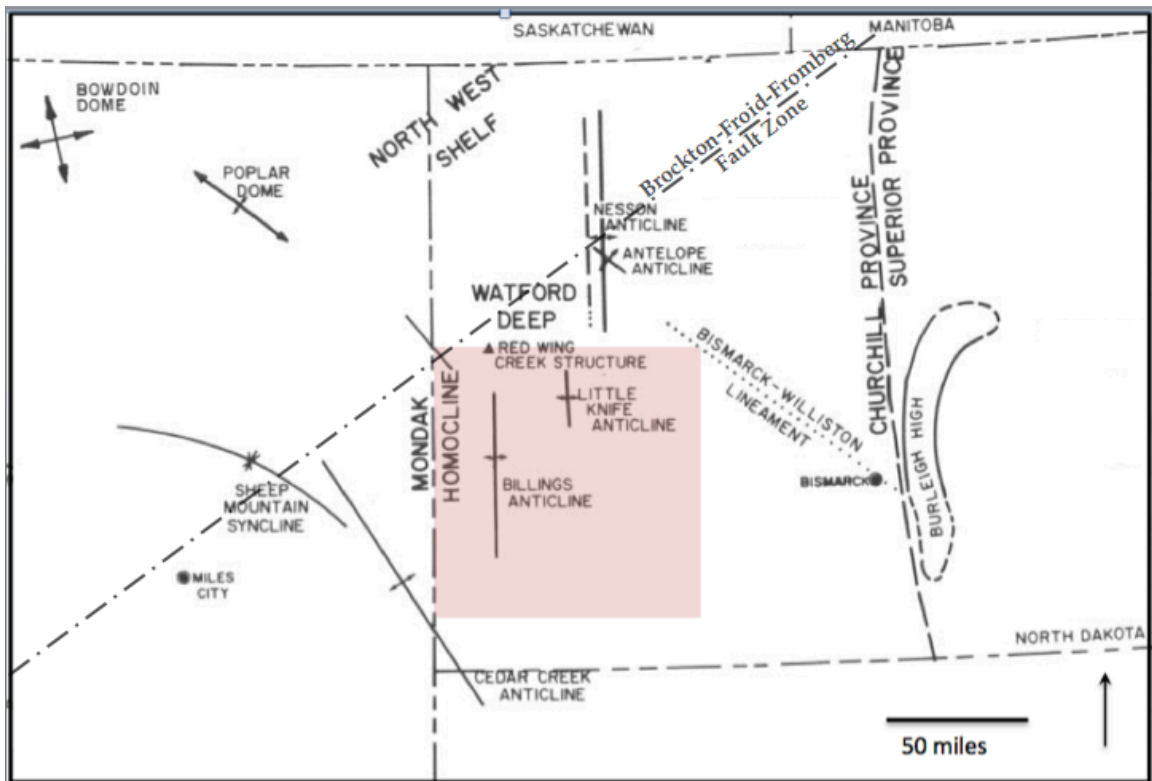


Figure 3. Map showing major structural components within and surrounding the study area (modified from Gerhard et al., 1982).

The basin has experienced five periods of rapid subsidence since the Late Cambrian, each quickly shifting to slower subsidence rates (LeFever, R. and LeFever, J., 1991). These episodes of subsidence, coupled with fluctuations of sea level control the stratigraphy of the Williston Basin. LeFever (1991) records the beginning of the second period of subsidence as being the precursor of the predominant mode of deposition of shallow marine carbonates. This period of subsidence began sometime during the Interlake Formation and continued until the Lodgepole Formation. The Birdbear Formation is one of the carbonates produced during this period of subsidence and occurred after subsidence had begun slowing down.

Sedimentation of the Birdbear Formation occurred during the Famennian Age at low latitudes. Euramerica was formed by the Early Devonian with the suturing of Baltica, Avalonia and Laurentia. The Famennian Age interval lies between two extinction events, the Kelwasser and Hangenberg. The Kelwasser is one of earth's five major extinction events that lost 19% of all families and 50% of genera (Baez, 2006). This event mostly affected marine organisms. The Hangenberg event impacted both marine and terrestrial worlds at the close of the Devonian (Kaiser et al., 2008).

Previous Work

Interest in the Birdbear Formation began in 1960 with oil discoveries along the Wolf Creek Nose in Montana. Steep-sided structural traps formed as a result of multi-stage salt dissolution of the underlying Prairie Formation, and were the primary target for early explorers. Since that time there has been copious amounts of work done in Saskatchewan, Manitoba and north-central North Dakota, with much fewer studies completed in western North Dakota. Subsequent studies following the initial discoveries

in Montana highlight the importance of paleostructural and facies controls on reservoir development (Ehrets and Kissling, 1983; Kissling and Ehrets, 1985). In 1995 Martiniuk, Young and LeFever delineate lithofacies of the formation in southwestern Manitoba and north-central North Dakota, and explored petroleum potential across that region. In their paper they discussed the stratigraphy of the Birdbear Formation, described the lithofacies, interpreted the depositional environments, listed the locations of favorable reservoir facies and identified structural and stratigraphic traps.

The Birdbear Formation is composed of two informal members (lower and upper). The lower member is a dolomitic limestone, while the upper member is composed of interbedded anhydrites, shales and dolomites. The members are divided by the first occurrence of anhydrite beds of the upper member. The formation is conformable with the Duperow and Three Forks Formations. The authors divide 15 lithofacies, eight to the lower member and seven to the upper member. They also identify three reservoir facies belonging to the lower member; they are the stromatoporoid bank deposits, *Amphipora* banks, and the microsucrosic dolomites. Porosity and permeability of these reservoir facies are controlled by lithology and secondary diagenesis.

Lithofacies of the lower member are grossly segregated according to environments of deposition, specifically into platform facies, inter-bank and intra-bank facies and biohermal or bank facies. The seven lithofacies of the upper member are both vertically and laterally discontinuous and represent supratidal and sabkha facies. The authors (Martiniuk et al., 1995) interpret the depositional environments of the upper and lower members as occurring within an epicontinental sea. Deposition included three main

environments: subtidal, inter-tidal and finally, supratidal. They go on to describe significant features important to production.

Salt dissolution features exist in the Birdbear Formation near a zone of structural weakness between the Churchill and Superior provinces known as the Newburg syncline. The authors indicate that fluid movement along this zone is responsible for salt dissolution of the Prairie Formation and is the cause for this structure. Near the Newburg syncline, in southwestern Manitoba, salt removal and collapse is most evident in the areas along, or near the Birdtail-Waskada axis and its extension into north-central North Dakota. The eastern limit of the present Prairie Formation salt dissolution edge is coincident with this axis. These features are important traps for petroleum production. In addition to these features, the authors identify other traps that exist in a variety of stratigraphic settings. For example, the stromatoporoid and *Amphipora* bank deposits are listed as primary lithostratigraphic traps wherever they are pinched out against the impermeable lime mudstones to packstones of the interbank facies. There is also a possibility that secondary porosity has developed significant diagenetic-stratigraphic traps. These zones of higher porosity become reservoirs wherever pinched out against tighter dolomite or anhydrite zones in the upper facies of the lower member.

Basement controlled traps have been well documented as significant contributors to overall Birdbear Formation reserves. Basement controlled structural traps are located in areas of fault block reactivation such as the Cedar Creek and Nesson anticlines in the Williston Basin. Fault block reactivation along zones of structural weaknesses near the Birdtail-Waskada axis and its southern extension have produced the most from

Mississippian and Triassic-Jurassic rocks. Martiniuk et al. (1995) concluded their paper with a section discussing source rock and migration paths.

Family D oil is produced from the Birdbear Formation in southeastern Saskatchewan. Family D oils have terpane compositional characteristics similar to kukersite derived oils, but they are distinguished by a greater relative acyclic isoprenoid and higher carbon number n-alkane abundance (Osadetz, et al., 1992). Family D oil source system is derived from the Winnipegosis Formation, with most Family D oil being found near the thermally mature source rock. These findings at the Kisbey and Walpole fields suggest considerable lateral (>100 mi.) and vertical migration of Family D oil. The authors end by suggesting that the Winnipegosis Formation is the source of the oils found in southwestern Manitoba and north-central North Dakota.

Purpose

The purpose of this study is to identify the components of a complete petroleum system found in the Birdbear Formation in southwestern North Dakota. This study will use core and thin section descriptions to establish lithofacies and to interpret depositional environment. Wireline logs are used to generate subsurface maps and are used in conjunction with core descriptions, cross sections and chemical analysis to identify the lithostratigraphic position of source rocks. The study area includes the southern half of McKenzie County beginning just north of Watford City, most of Dunn, Stark and Hettinger counties and all of Slope, Golden Valley and Billings counties (Figure 4). It is bounded on the west by Montana and the south by the northern borders of Bowman and Adams counties.

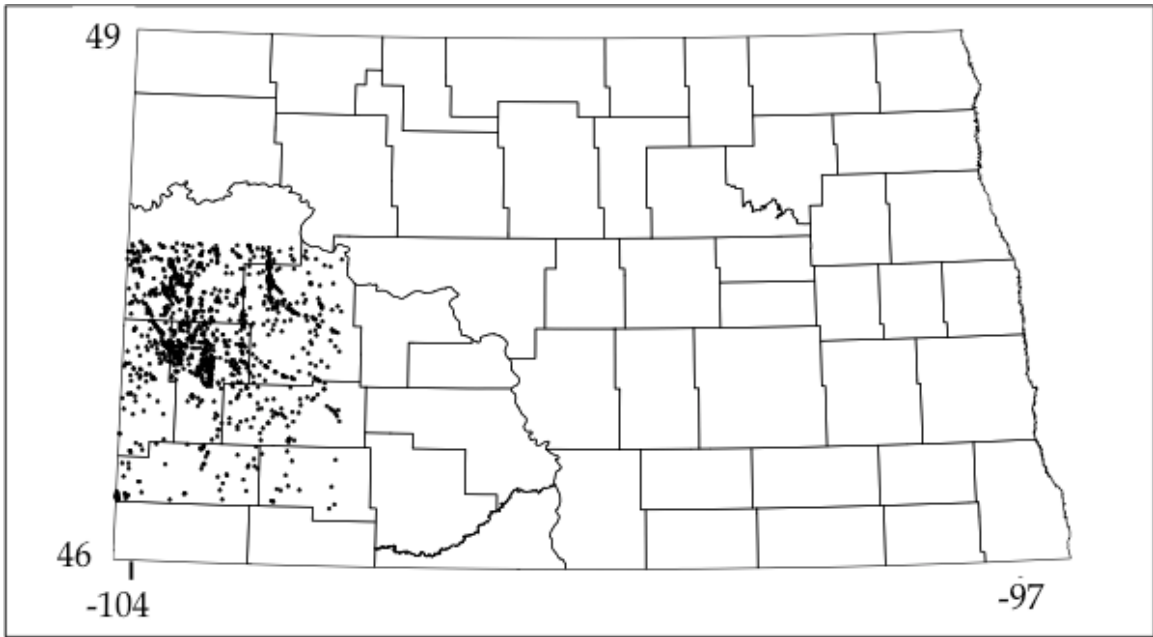


Figure 4. Location map showing all of the wells that penetrate the study area in 2014.

Methods

Data that form the basis of this study include core, thin section, well log, drill stem test (DST), core analysis (from well files) and Rock-Eval 6. Within the study area, nine-cored intervals of the Birdbear Formation are examined to determine lithofacies, depositional environment and stratigraphy (Figure 5).

Cores were selected based on availability, quality, extent, and association with well logs. Descriptive schemes are based on Dunham's (1962) classification method with modifications by Folk (1959), Embry and Klovan (1971). Dunham's method describes lithology based on texture emphasizing deposition, which is problematic when considering the complexity of fabrics after diagenesis, thus Folk (1959) modifiers are employed to describe cementation. Expansion of Dunham's method by Embry and Klovan help to subdivide the boundstone category. Cores are examined using 10X and 20X hand lenses in addition to a binocular light microscope. Abundance of content is

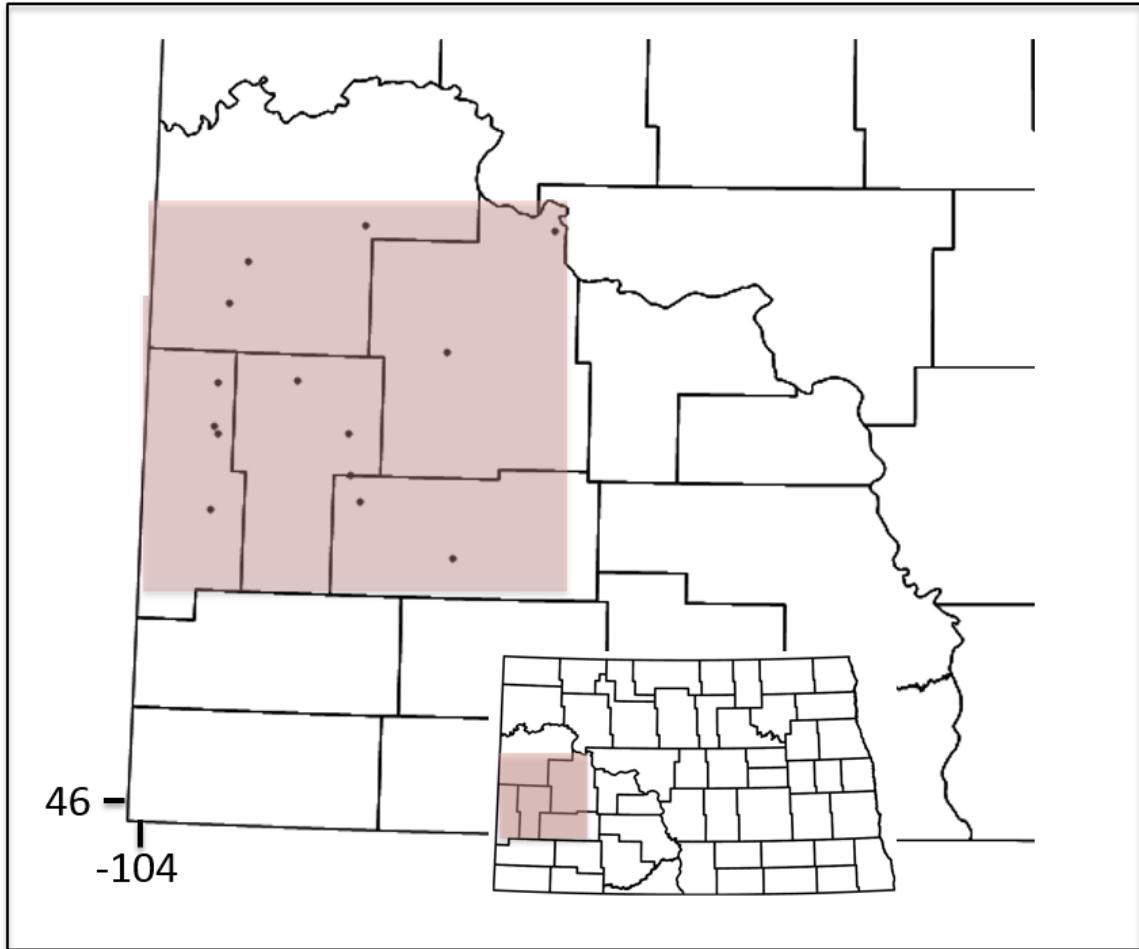


Figure 5. Map showing location of cored intervals.

indicated through the use of singular and plural terms or the qualifier, “abundant” to indicate one, few, or many, respectively. A similar method is employed to describe 114 thin sections from eight cored intervals. Thin sections are examined using a Leica DM EP polarizing microscope system. Porosity quantities and types are identified for slides that have been impregnated with blue epoxy and when reasonable estimates can be made. Caption explanations for thin sections are as follows: PPL, plane polarized light; XPL, cross-polarized light; HA, length of horizontal axis; BSE, blue filled epoxy; AR, alizarin red S; WU=U, L, R or D, way up as designated (up, left, right or down). Lithofacies are

divided based on lithology and extent by incorporating data from hand specimen, well log analysis and thin section.

Well logs from over 1,200 locations are used to determine formation thickness, log porosity and stratigraphy. A significant drop in gamma ray distinguishes the Birdbear Formation from the younger Three Forks and older Duperow Formations. Picks are made in PETRA (2014) based on these signatures and provide the basis for contour mapping and cross sections. Neutron and sonic logs are digitized to model total and matrix porosities, respectively. Core analysis provide porosity, permeability and oil/water saturations and are displayed graphically using SURFER (2013). Bottom hole pressures (BHP) from successful drill stem tests (DST) were calculated for a potentiometric surface and are also modeled in SURFER (2013). Only successful BHP's that meet the criteria outlined by LeFever (1998) and Horner (1951) were used. Potentiometric surface was calculated using the following equation:

$$h_w = (KB - RD) + P/Dg \quad \text{Eq. 1}$$

where KB is the height of the Kelly Bushing (ft.), RD is the depth at which the pressure is measured (ft.), P is the pressure (psi), and Dg is the pressure gradient for the fluid (psi/ft.). Data is recorded in Appendix B.

Probable source rocks are sampled from cored intervals. Microbialites, shale partings, dolomitic mudstones to wackestones, limy wackestones to grainstones or boundstones, shale, stromatoporoids and stromatolites were all sampled for quantity and quality of organic content. A minimum total organic carbon (TOC) of 1.5 wt. % was the economical baseline of additional chemical analysis (Rock-Eval). Weatherford performed both TOC and Rock-Eval 6. A general description of Rock Eval is as follows: Samples

were heated at 25°C/min between 300°C and 600°C to yield the quantity of volatile hydrocarbons (S_1), the amount of thermogenic hydrocarbons (S_2), and the quantity of CO_2 released during pyrolysis to 390°C (S_3). From these the hydrogen index (HI) and oxygen index (OI) are calculated using equations 2 and 3, respectively.

$$HI = 100 \times S_2 / TOC \quad \text{Eq. 2}$$

$$OI = 100 \times S_3 / TOC \quad \text{Eq. 3}$$

Organic matter thermal maturity is obtained by measurement of maximum hydrocarbon release during pyrolysis (T_{max}) as introduced by Espitalie et al. (1977). The compilation of these data constitutes the basis for interpretations of this work.

CHAPTER II

STRATIGRAPHY OF THE BIRDBEAR FORMATION

Core Descriptions

The last major regression of the Late Devonian either began at the close of Duperow time or during the deposition of the Birdbear Formation. The Birdbear Formation is considered conformable with the Duperow Formation below and the Three Forks Formation above. However, the Birdbear is observed in three cores to have local unconformities with the Three Forks Formation. These unconformities occur in the form of truncated anhydrites and are probably due to deflation as the anhydrites are periodically sub-aerially exposed due to evaporite processes. The Birdbear Formation of southwestern North Dakota is stratigraphically equivalent to the Nisku and the Zeta Formations in the central plains of Alberta. The Birdbear Formation is also equivalent to the Nisku Formation in Montana, and the Birdbear Formation in western Manitoba. In the northeast plains of Alberta the lower member of the Birdbear Formation is known as the Woodbend Group. The rocks of the upper member in this area compose the lower Winterburn Formation (Figure 6).

Throughout the study area nine cores were selected and their lithologies were described using Dunham's (1962) classification scheme with Folk (1959) modifiers. None of the cores available made contact with the Duperow Formation; however, there

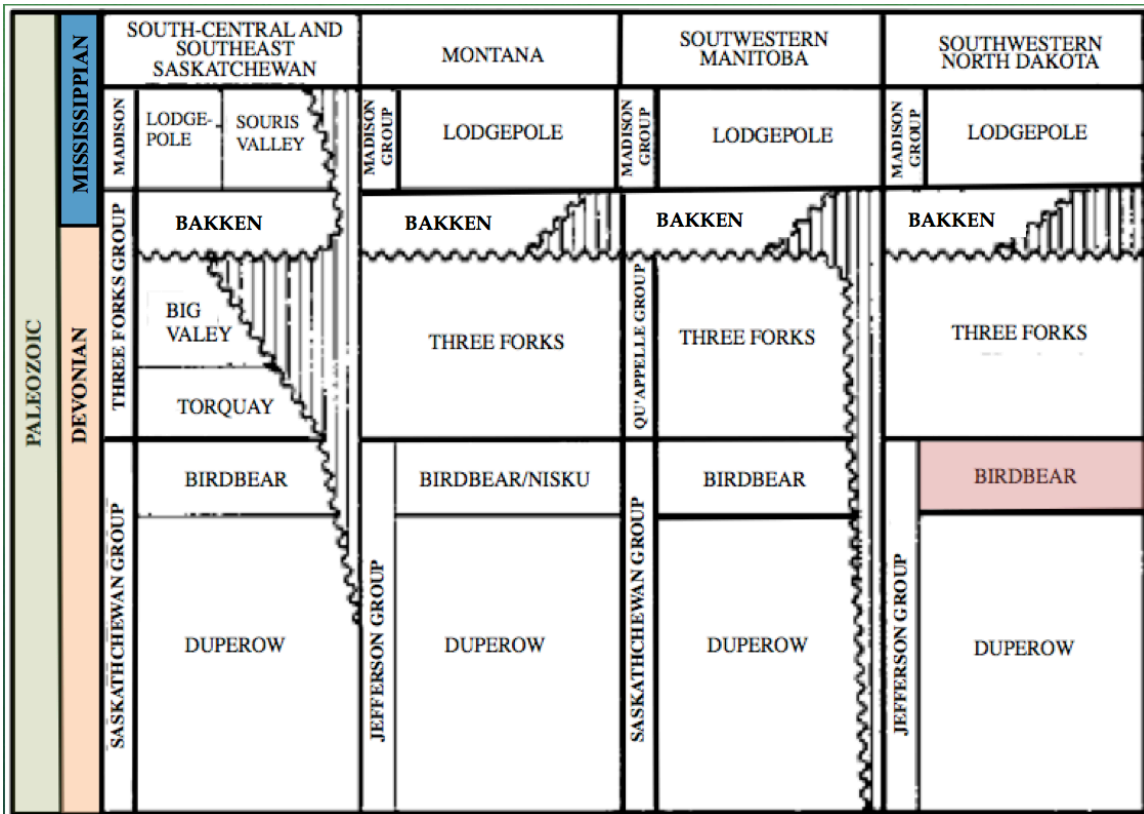


Figure 6. Stratigraphic correlation chart. (After Saskatchewan Department of Mineral Resources Petroleum and Natural Gas Branch, Drawing Number G-193, 1963, Blumle et al., and Canadian Society of Petroleum Geologists, 1990; *in* Martiniuk et al., 1995).

were five cores that showed the contact between the Birdbear and Three Forks Formations. The general lithology of the Birdbear Formation can be described as the dolomitic mudstones to wackestones belonging to the lower member and the interbedded anhydrites and dolomites of the upper member. The division of the upper and lower members is placed at the bottom of the lowest occurring anhydrite bed, as this indicates a significant shift in sedimentation and has implications regarding environment. Lithofacies identified across the study area are vertically and laterally discontinuous as in north-central North Dakota, southwestern Manitoba and southeastern Saskatchewan.

Lithofacies Descriptions

Lithofacies are hereby designated for the Birdbear Formation in southwestern North Dakota. Lithofacies are divided into two groups (upper and lower) and designated Lithofacies (L), and Upper Lithofacies (UL), according to their stratigraphic position within the lower and upper members.

The lower member averages 83 ft. thick across the study area. The general components of the Lithofacies comprising the lower member are dolomite, limestone and to a lesser degree, anhydrite. These rocks vary from light-brown to grey. Heavy burrowing is common throughout and has destroyed evidence of primary structures. The upper portions of the lower member are composed of *Amphipora* and bryozoan wackestones and packstones. The lower member is often capped by thick, coalesced anhydrites or interbedded dolomites and anhydrites.

Lithofacies 1 is composed of light-brown heavily bioturbated limy mudstone. Fossils are rare but include small gastropods, uniserial benthic foraminifera, impunctate bryozoans and stromatoporoid fragments (Figure 7).

Lithofacies 2 consists of light-brown or grey, wispy laminated limy mudstones to wackestone. Fossils include gastropods and fragments of brachiopod valves and spicules, stromatoporoids and rugose corals. This unit is often moderately to heavily bioturbated and has nodular anhydrite (Figure 8).

Lithofacies 3 is a dark-brown and grey massive and wavy laminated limy wackestone to packstone. Fossils of *Amphipora*, fistuliporoid bryozoans, stromatoporoids and ostracods are found in this partly bioturbated interbank facies (Figure 9). This

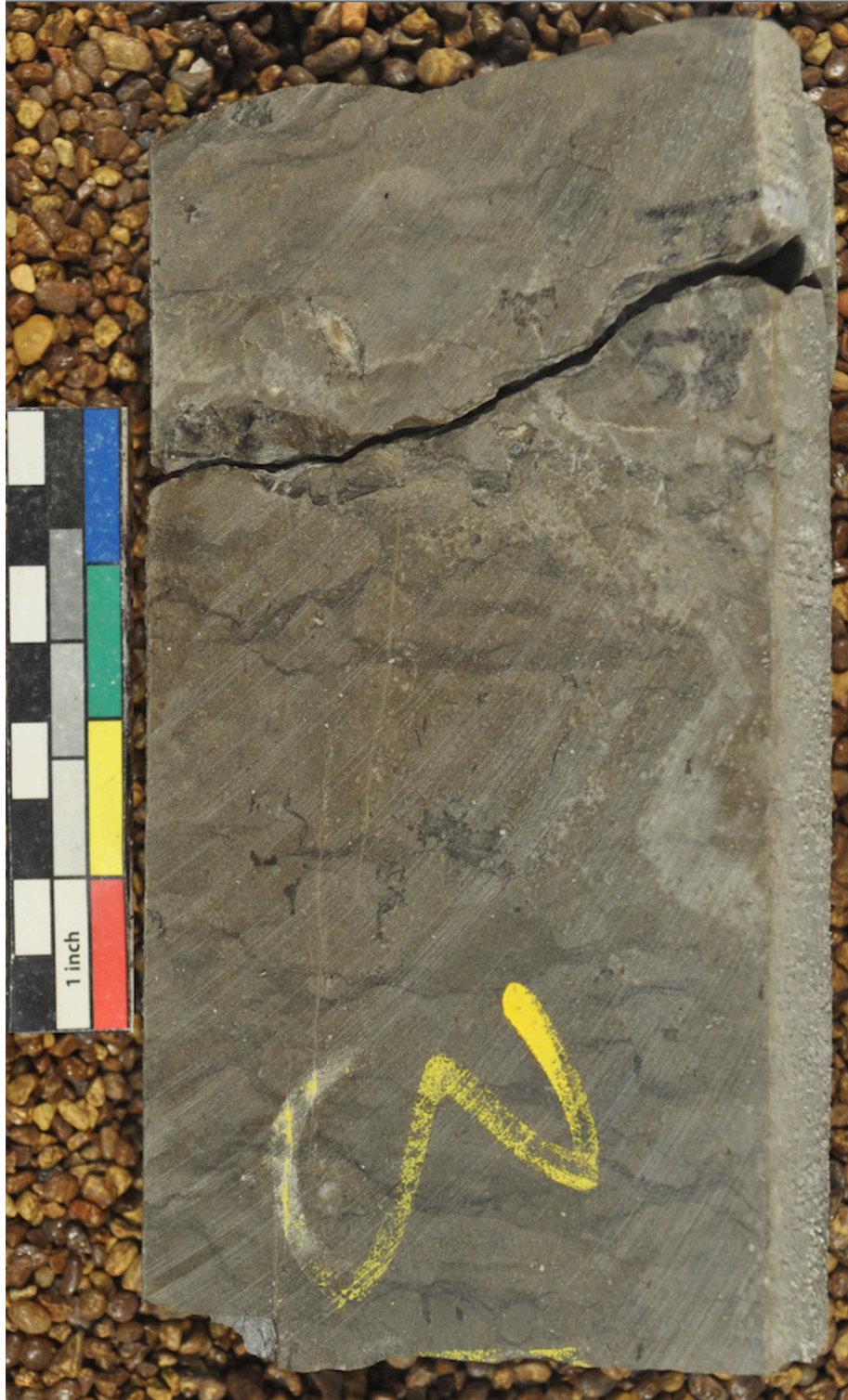


Figure 7. Birdbear Lithofacies L1. Heavy burrowing has destroyed the primary structures of this limestone. (Core depth of 10,058', NDIC Well #21139, API #33-089-00646, NENE 30-138-95).



Figure 8. Birdbear Lithofacies L2. (Core depth 11,009', NDIC #12249, API # 33-053-02208, NENW 17-146-102).

limestone has occasional secondary anhydrite and poor inter-granular porosity. Vugs are either calcite or anhydrite filled. In thin section replacement dolomite occurs along stylolites.



Figure 9. Birdbear Lithofacies L3. (Core depth 10,997', NDIC #12249, API # 33-053-02208, NENW 17-146-102)

Lithofacies 4 is composed of light to medium-brown, massive and microbial laminated dolomudstones of the bank facies. This unit is often heavily bioturbated. Anhydrite is found as nodules and void-fill.

Rocks of Lithofacies 5 also represent bank deposits. Lithofacies 5 is a grey to light-brown peloidal limestone to wackestone. Planar, muddy laminations characterize the limestone with skeletal wackestone beds that are comprised of *Amphipora* and bryozoans. Blocky, sub-angular anhydrite grains are supported by a micrite matrix as seen in Figure 10. In hand specimen, large, irregular anhydrites appear angular, and are observed to contain light-brown host sediment within their lattice.

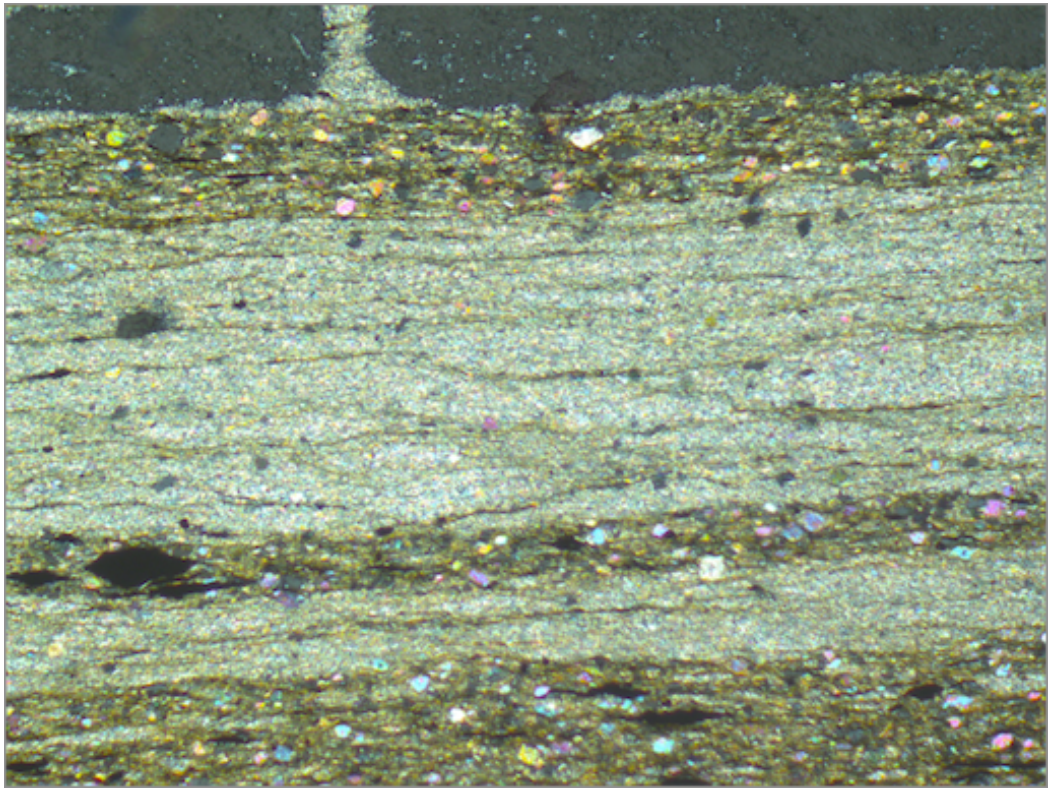


Figure 10. Birdbear Lithofacies L5. Thin section showing dark laminations. (Thin section depth 10,339', magnification 10X, XPL, WU=U, HA=2.25 mm, NDIC #793, API # 33-025-00005, SENW 22-149-91).

The carbonates of Lithofacies 6 are chiefly light to dark grey planar laminated dolomudstones to dolosiltstones with abundant anhydrite rip up clasts.

Rocks of Lithofacies 7 are interbedded, microbial, limy mudstones to packstones and anhydrites (Figure 11). Peloidal packstones support *Amphipora* and benthic, uniserial foraminifera in a calcite matrix and have excellent inter-particle porosity (30%).

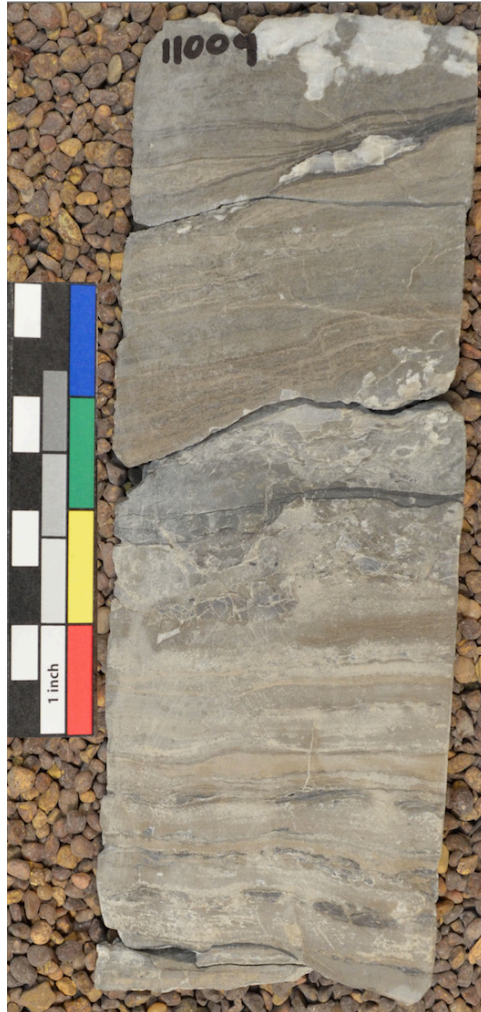


Figure 11. Birdbear Lithofacies L7. Microbial laminated and interbedded limy mudstones and packstones. (Core depth 11,009', NDIC #20034, API # 33-089-00620, LOT 3 3-140-99).

Rocks of Lithofacies 8 occur locally and are light-brown dolostones. Where present they exhibit good inter-crystalline porosity.

The upper member of the Birdbear Formation averages 14.75 ft. thick in southwestern North Dakota. The lithology is described as an interbedded carbonate/evaporite, with major constituents of anhydrite, dolomite and limestone. The three fourth-order sequences identified by Burke (2005) within the upper member are laterally discontinuous across the study area.

Lithofacies UL1 is composed of brown and grey nodular and coalesced anhydrites and they mark the transition from the lower and upper member. There are crinkly microbial laminates with anhydrite cement. Structures include partial interbedding and soft sediment deformation with occasional burrowing.

Lithofacies UL2 are dark-brown limestones and dolomudstones. The structures of this facies vary from parallel, wavy to occasionally contorted laminates. Microbial laminates persist near the base with peletal limestones. Authigenic pyrite is common with less abundant green, nodular anhydrite.

The dark-brown peloidal limy mudstone to wackestones of Lithofacies UL3 are planar parallel and wavy laminated, similar to structures of UL2. Microbial laminations occur in the dolomitic portions. This unit has abundant *Amphipora* and bryozoan fragments. Portions of massive, crystalline limestone contain displacive anhydrite. Fractures are commonly anhydrite-filled and inter-granular and intra-skeletal porosity ranges between 5 and 8% (Figure 12).

Lithofacies UL4 is composed of grey-green and sometimes light-brown nodular mosaic to wispy laminated anhydrite. Partings are parallel to inclined where anhydrite is more prominent (Figure 13). Anhydrite is pseudomorph after gypsum and is truncated in some wells indicating sub-aerial exposure.

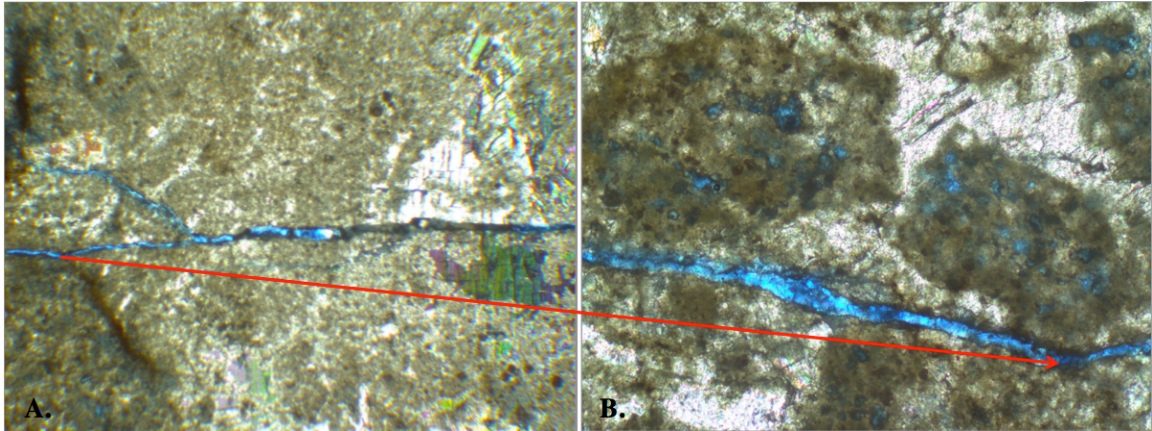


Figure 12. Birdbear Lithofacies UL3. Thin sections showing pelatal limestone with good intra-granular porosity. (Thin sections depth 11,109.3', A. magnification 4X; B. magnification 10X, XPL, WU=U, HA=2.25 mm, NDIC #21424, API # 33-025-01453, NESE 27-145-95).

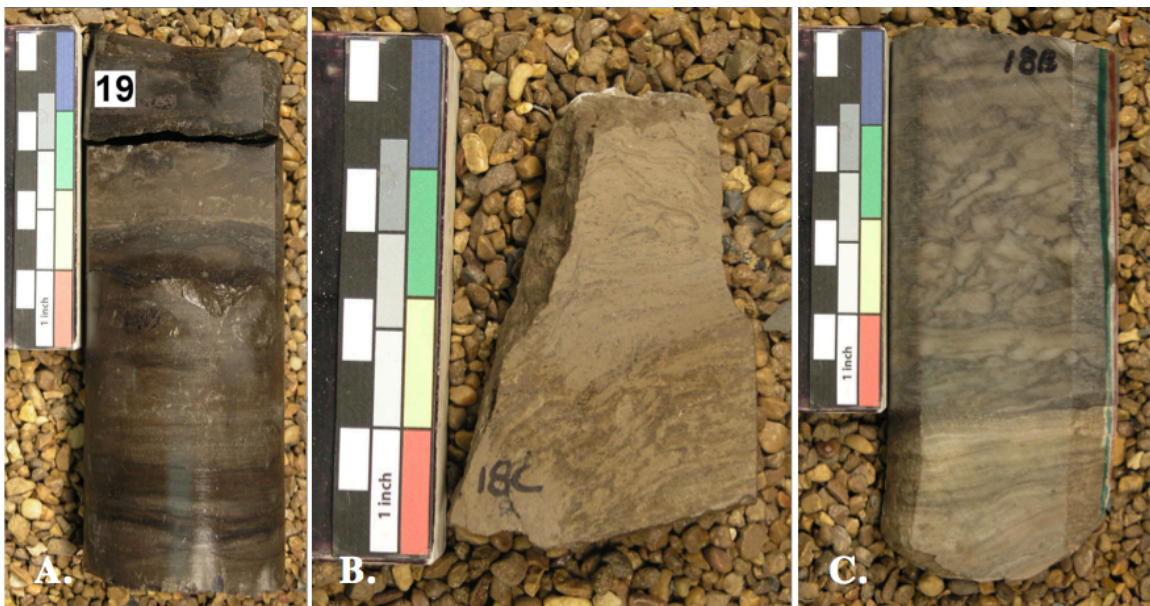


Figure 13. Birdbear Lithofacies UL3 (A. and B.) and UL4 (C.). The arrangement of organic rich limestone (A.), microbial dolomite (B.) and partially inclined nodular anhydrite (C.) constitute a possible self-sourcing system within the second sequence of the Upper Birdbear. (Core depth 10,318'-10,319', NDIC #793, API # 33-025-00005, SENW 22-149-91).

The peloidal light-brown dolomudstones and dark-brown limy mudstones characterize Lithofacies UL5. These rocks are predominately interlaminated, but do occur as microbial dolomudstones at the basin margins. Where stromatolitic, carbonates have soft sediment deformation and contain anhydrite nodules near the top unit, where preserved.

Lithofacies UL6 has been observed as nodular and chickenwire anhydrite. The texture of anhydrite indicates subaqueous gypsum formation in soft sediment.

Lithofacies UL7 is composed of interbedded anhydrites and dolomudstones. These deposits are planar parallel and represent deposits in more quiet water settings. The presence of bedded anhydrite suggests elevated salinities as gypsum forms on the lagoon floor.

The rocks of Lithofacies UL8 are dolomudstones and limestones and occur in the northern portions of the study area. Wavy laminations are common, cross-laminations are rarer. Fractures are often anhydrite healed. These structures represent higher energy environments.

Lithofacies UL9 is a white nodular anhydrite capping an interlaminated grey-green mudstone (Figure 14). In some places the anhydrite may be interlaminated with mudstones or dolomudstones. Truncation of anhydrites is evident in three locations, evidence of local unconformities between the Three Forks and Birdbear Formations.

Thin Section Descriptions

Thin sections were examined from eight of the nine cores previously described. A total of 114 thin section descriptions were made and were used as an aid in delineating

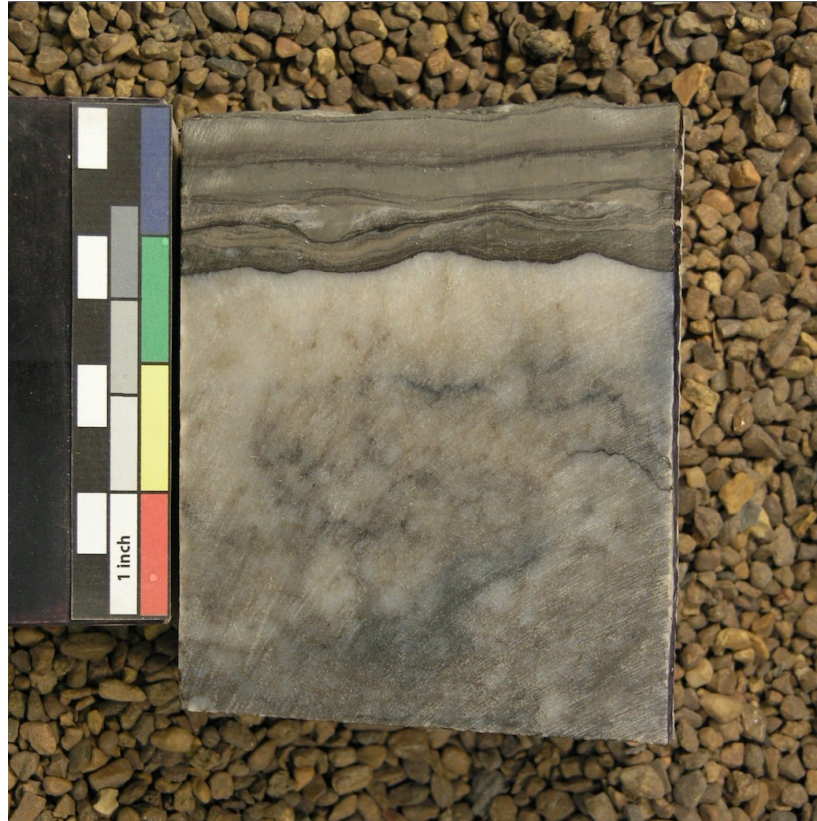


Figure 14. Birdbear Lithofacies UL9. Contact between the Birdbear and Three Forks Formations. Coalesced anhydrite has been truncated possibly due to sub-aerial exposure. (Core depth 10,712', NDIC #15679, API #33-033-00251, SENE 28-142-103).

lithofacies. Thin Sections Descriptions (Appendix A) include porosity estimates, wherever possible. The following shows thin sections representative of selected lithofacies of the upper and lower members. Several porosity types found in the Birdbear Formation of southwestern North Dakota are identified. Porosities are generally described as inter-crystalline, inter-granular and fracture porosity. The occasional description of intra-crystalline is only assigned wherever blue epoxy resonates through the interior bounds of crystal habits. This probably represents enhanced porosity due to incorporation of calcite into the crystal lattice of dolomite.

Figure 15 is an image of Lithofacies 3. This image shows a wackestone to packstone with dual matrices, both micrite and microspar. It has poor porosity; inter-crystalline porosity is present within the micrite, and inter-granular porosity between the grains. A relatively whole foram is seen center screen indicating low energy deposits due to its non-abraded appearance. The presence of micrite and microspar suggest diminution of larger crystal as a result of post-depositional processes. This mixed micrite matrix is commonly observed throughout the limestones of the lower member of the Birdbear Formation.

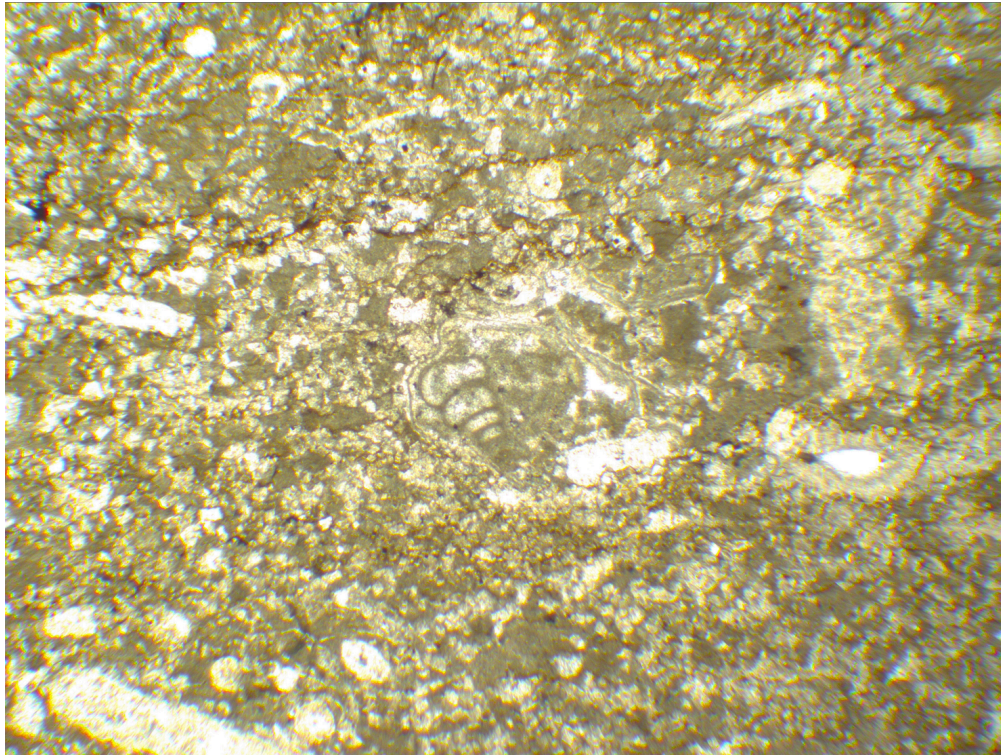


Figure 15. Thin section photograph of the Birdbear Lithofacies 3 showing the depositional fabric. Note the uniserial benthic foraminifer center photo. (Core depth 10,356', NDIC #793, API #33-025-00005, SENW 22-149-91, 4X, HA=2.25 mm, PPL, WU=U).

Lithofacies 4 (Figure 16) is a crystalline dolomite that exhibits excellent porosity. Much of the dolomite is replaced as evidenced by the darker centers and clear rims of the euhedral to subhedral crystals. Fenestral and inter-crystalline porosity are the chief contributors in this thin section totaling ~28%. Lithofacies 4 also contains moldic and vuggy porosity in other areas. These types of porosity suggest a marine environment and are supported by the amount of mud present.

The peloidal packstones of Lithofacies 7 are shown in Figure 17 A. Peloids fine upward and are bound by microbialites above. Anhydrite has permeated the shrinkage structure and spaces between the peloids. Aggrading neomorphism from micrite to

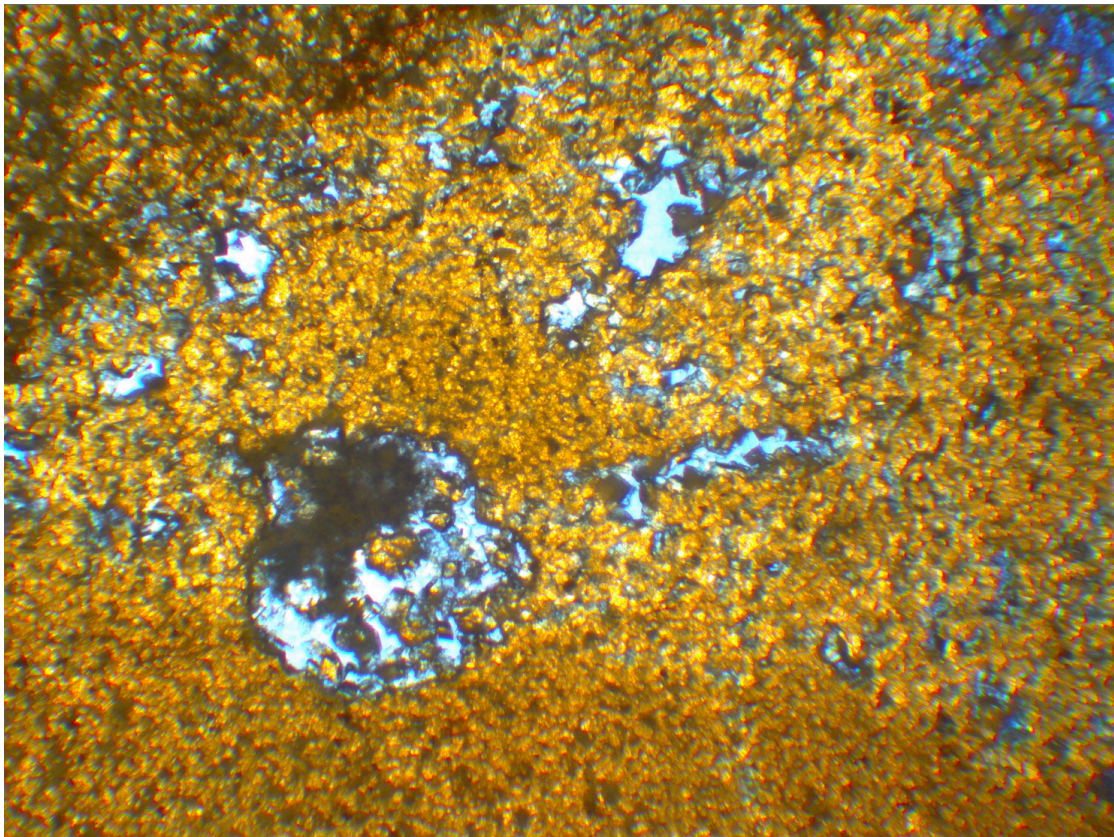


Figure 16. Image showing good fenestral porosity common in the rocks found in the lower member. Intra-crystalline porosity is well developed among the microbial laminated dolomudstone of this Birdbear Lithofacies 4. (Core depth 10,521', NDIC #21734, API #33-033-00308, SWSW 12-139-104, 4X, HA=2.25 mm, PP, WU=U).

microspar is evidenced in Figure 17 B. Here an abraded *Amphipora* is seen in cross section supported by microspar and organic matter. The combination of the degree of sorting and abrasion of skeletal remains supports Lithofacies 7 as bank deposits.

Microbial deposits probably developed following shallow burial, or on the tops of wet surfaces. Typically the porosity of this facies is poor. In places where neomorphism has advanced intra-crystalline porosity has likewise developed.

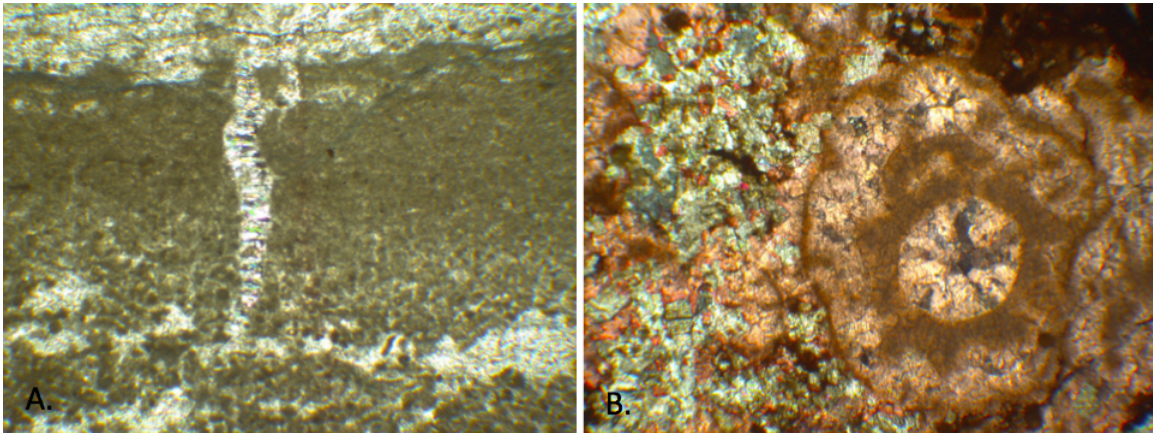


Figure 17. Photographs showing the peloidal packstones of Birdbear Lithofacies 7. The image on the left has peloidal beds deposited below microbial laminates with a possible desiccation crack that has been anhydrite filled. The image on the right shows an abraded *Amphipora* fragment in a microspar matrix. Note well-developed transaxial canal. (A. Core depth 10,511', NDIC #21734, API #33-033-00308, SWSW 12-139-104, 4X, HA=2.25 mm, XPL, WU=U; B. Core depth 11,006', NDIC #20034, API # 33-089-00620, LOT 3 3-140-99, 10X, HA=2.25 mm, XPL, WU=L).

Rocks of Upper Lithofacies 2 have been identified as microbial dolomudstones and limestones. These planar to wavy and often microbial laminated muds have been observed with pellets and often bear anhydrite nodules with authigenic pyrite (Figure 18). Porosity is poor in this facies but improves upsection in Upper Lithofacies 8. The peloidal limy mudstones and wackestones of UL 3 (Figure 19) have a good inter-skeletal and inter-crystalline porosity (8%). These two lithofacies are nested between the nodular

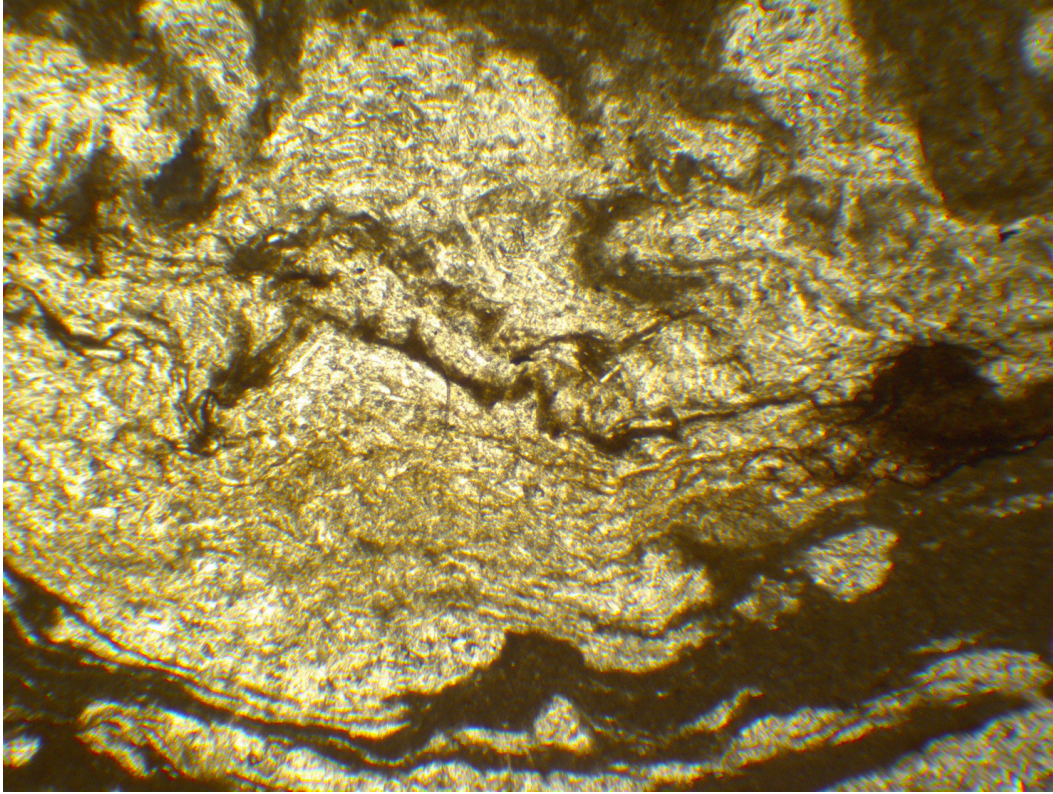


Figure 18. Image showing the microbialites of the Birdbear Upper Lithofacies 2. (Core depth 10,509', NDIC #21734, API #33-033-00308, SWSW 12-139-104, 4X, HA=2.25 mm, PPL, WU=U).

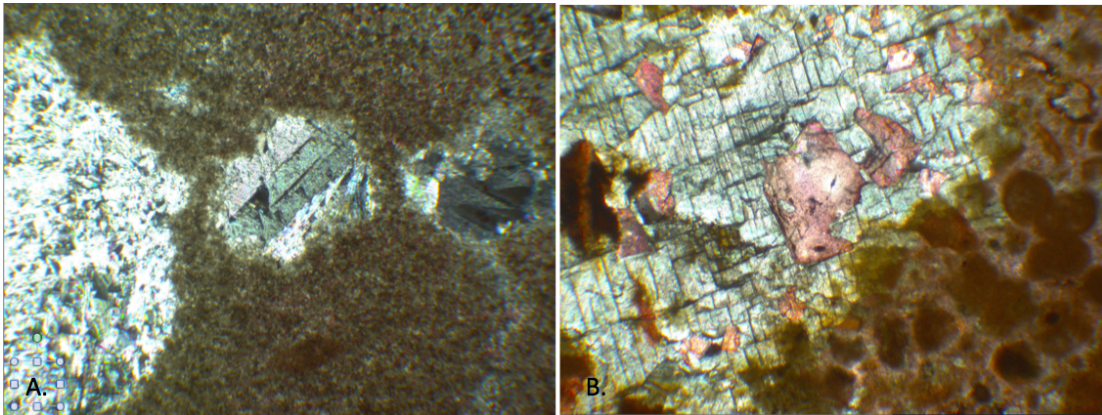


Figure 19. Photographs of the Birdbear Upper Lithofacies 3. Pelloidal limy wackestones with anhydrite (A.) and anhydrite replacing peloids (B.). (A. Core Depth 10,969', NDIC #12962, API #33-053-02336, SWSE 35-148-102, 4X, HA=2.25 mm, XPL, WU=U, AR-R; B. Core depth 10,723', NDIC #15679, API # 33-053-02336, SWSE 35-148-102, 4X, HA=2.25 mm, XPL, WU=U, AR-BSE).

and coalesced anhydrites of UL 1 and the nodular, wispy laminated anhydrites of UL 4. This coincides with Burkes (2005) Cycle 1.

The limestones and dolomites of the Upper Lithofacies 8 are occasionally cross-laminated. These cut and fill structures occur commonly in higher energy environments. Questions regarding the duration these conditions prevailed seem to indicate that they were short lived due to the combined thickness of these laminates ranging from 0-3” across the study area. Figure 20 is impregnated with blue epoxy and contrasts the enhanced porosity between the replacement dolomite (upper frame) and the limestone (lower frame). Post depositional dolomitization probably occurred shortly after burial as meteoric waters mixed with brine solutions.

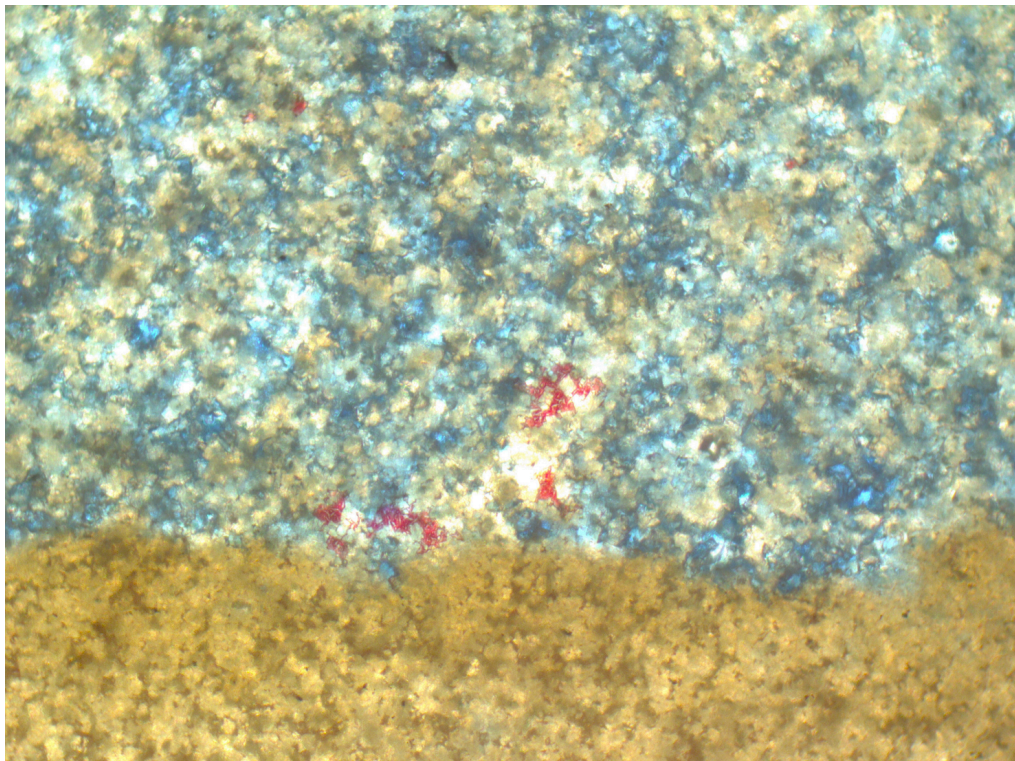


Figure 20. Image of the Birdbear Upper Lithofacies 8. Secondary dolomitization greatly enhances porosity as dolomite replaces limestone. (Core depth 11,105.6', NDIC #21424, API #33-025-01453, NESE 27-145-95, 10X, HA=2.25 mm, PPL, WU=U, BSE).

Associated Depositional Environments

The preceding information obtained by observation from core descriptions, and thin sections are used to combine the designated lithofacies into their respective depositional environments. Previous work regarding the depositional environments of the Birdbear Formation is discussed and differences between lithofacies are compared. These comparisons highlight the difference in depositional settings between the shelf deposits of southwestern North Dakota and the deeper water deposits of the Alberta Basin.

Lower Member

The lithofacies of the lower member are found throughout the study area and are interpreted to represent shallow-marine deposits occurring between the storm-wave base and the top of the high-energy inter-tidal zone. The basal lithofacies represent platform facies and have a striking similarity as to those described by Martiniuk et al. (1995) in north-central North Dakota and southwestern Manitoba. In southwestern North Dakota evidence of muddy matrices and partings are as abundant as those observed to the northeast where postulates of a western source of terrestrial sediments have been made (Halabura, 1982). This suggests the positive topography supplying sediments to the basin may have had a northwesterly source. The platform facies to the south lack colonial coral and possess blocky anhydrites and anhydrite-healed fractures. Lithofacies 1 grades from a limy mudstone to a limy wackestone (Lithofacies 2). Bioclastic debris is fragmental in both of these facies with nothing observed in the growth position. This suggests post-mortem transportation and destruction of life assemblages, likely due to storm action.

Other post-mortem assemblages occur within Lithofacies 3, 4 and 5. The shelf margin deposits of these lithofacies show faunal assemblages that suggest elevated

salinities. The presence of mud and wavy to planar laminations along with microbial laminated dolomudstones indicate deposition below diurnal effects of the tide, but above fairweather wave-base. These ramp deposits resemble Lithofacies B of Halabura (1982) and Lithofacies B, and C of Martiniuk et al. (1995). A basal occurrence of whole ostracods may be the cause of burrow mottling that occurs in this facies.

Lithofacies 6–8 represents the relatively higher-energy intertidal zone. These rocks are bioclastic limy mudstones and dolomudstones. Rare cross laminations are preserved as much of the fabric has been obliterated, whether by dolomitization or bioturbation. Locally, interbedded, peloidal limy-mudstones and packstones indicate deposition in a protected back bank or lagoon environment. Influence of storm tides are evidenced by anhydrite rip up clasts in Lithofacies 6, and muddy rip up clasts of Lithofacies 7. Martiniuk identifies these Lithofacies (6 & 7) as the *Amphipora* and stromatoporoid bank facies. *Amphipora* and *Idiostroma* are present in every core in southwestern North Dakota except the ZENT 30-138-95 A 1H and OLSON 12-139-104 A 1H wells near the southern margins of the basin. Lithofacies 7 experienced periods of increased energy, followed by periods of prolonged quiescence. This is evidenced by the presence of abraded skeletal remains, microbialites, sorted pellets and peloids.

Upper Member

The interpreted depositional environments of the nine lithofacies composing the upper member range from quite water intertidal to supratidal deposits. Regression had an amplified impact on the shelf and led to vast expanses of shallow waters well above the influence of high-energy tides. This means that supratidal deposits were still subaqueous and harbored carbonate and evaporite sedimentation. Lateral discontinuity of the

lithofacies is pervasive throughout the upper member and across the study area. A variety of factors contributed to the abbreviated local occurrence of these facies, and sedimentation overall. Namely: variable topography due to antecedent sediment accumulation, sea level fluctuations, position of the water table and spring tides. Another important consideration regarding sediment accumulation in a shallow water carbonate factory is accommodation space. A healthy shallow water platform is capable of accumulating up to 3.3 ft./k.y. of carbonate sediment which is able to outpace normal subsidence rates (Kendall, 1992). The upper member of the Birdbear Formation does not show evidence of a robust ecosystem. Fossil assemblages are suggestive of hypersaline conditions, indicative of stressed environments. Sediment accumulation via the carbonate factory would have been hampered, however still possible due to relative tectonic inactivity at that time. Each of these factors contributes to these rocks that show a repeating pattern of nodular anhydrites, peloidal limestones and dolostones.

The Upper Lithofacies were shallow water deposits and are composed of varying forms of anhydrite, limestone and dolomite. These configurations in the upper member are commonly seen across the study area and have been reported in southeast Saskatchewan (Halabura, 82), and in southwestern Manitoba (Martiniuk et al., 1995). The regularity of shallow deposits across such vast distances implies deposition on an epeiric sea as supposed by Shaw (1964) and Irwin (1965). Wave action is considered to be very low in this setting as waves are hampered due to the shallowness of the water. Normal diurnal effects of the tide are not evident in the study area, making it difficult to precisely identify depositional environments. However, bioclastic debris from the bank deposits are present in UL 2 and 3. The regular occurrence of these lithostratigraphic patterns

indicates depositional environments near to one another. The following describes the depositional environments and some of the processes of the Upper Lithofacies.

Nodular to coalesced and interlaminated anhydrites are the common forms of evaporites observed in the upper member. Nodular and coalesced anhydrites of Upper Lithofacies 1, 4 and 9 have two probable modes of deposition: primary gypsum or anhydrite. Subaqueous gypsum deposits either precipitate near the surface of shallow waters, or are bottom grown among soft sediment. These gypsum crystals eventually accumulate on the floor and become gypsum slush. Growth and accumulation among soft sediment leads to organic and dolomite partings; sometimes these partings develop to be several inches thick. This displacement of soft sediment destroys evidence of primary structures. The presence of nodular and coalesced anhydrites may also indicate primary anhydrite formation. Conditions amicable to anhydrite development are stringent. The nucleation of anhydrite requires seasonal temperatures greater than about 95°F and is preserved when temperatures average 68°F (Kendall, 1992). Preservation of primary anhydrite seldom occurs without multiple transitions to gypsum due to spring tides, fluctuations in the water table, response to sea level change, a drop in base level, or the effects of dewatering from burial and compaction. Displacement of anhydrite and gypsum can subaerially expose the sediments. This leads to deflation, which results in the presence of truncated anhydrites and were commonly found throughout the selected cores. These local unconformities may not represent significant hiatuses as they were dependent on the severity of seasonal winds, the duration of exposure and the rate of compaction of subaqueous sediments.

The interlaminated anhydrites and dolomudstones of UL 7 formed in shallow ponds. Kendall (1992) describes the process responsible for the development of interlaminated evaporites with observations from shallow perennial lakes. These lakes are similar to the environment of the upper member in that wave action is restricted, and periodic refreshing of the super saturated ponds would occur in the form of storm events or minor sea level rise. During saturated conditions gypsum crystals would be continuously abraded as they grow, unless they are just below the surface. Periods of freshening initiate, or mark a return to carbonate sedimentation.

Upper Lithofacies 2 and 3 represent lagoon deposits with microbial limy wackestones to dolomudstones. Microbial laminates and bottom muds suggest quiet waters, in a protected environment. Discontinuous storm deposits with abraded *Amphipora*, coral and anhydrite fragments are observed and were washed over from adjacent bank deposits. The low faunal diversity and regular presence of microbialites may indicate increased levels of salinity.

Hypersalinity progressed as deposition continued. The following Upper Lithofacies show radically decreased faunal assemblages. The microbial laminated dolomudstone and limestone of UL 5 and UL 8 are comparatively similar and were deposited in sporadic ponds or pools on a shallow elevated shelf. Plan view of a domical stromatolite was observed in the FEDERAL 32-4 well in Golden Valley County. This dolomitic stromatolite was seen in UL 5. The wavy and sometimes cross-laminated dolomudstones of UL 8 are capped by the grey-green mudstones and nodular anhydrite of UL 9.

CHAPTER III

PETROLEUM SYSTEM CHARACTERISTICS

Hydrocarbon Generation, Migration, and Accumulation

Magoon (1998) listed the essential elements of the petroleum system concept, they are: source, reservoir, seal and overburden. Two general processes of the system are trap formation and the generation, migration and accumulation of hydrocarbons. Dow (1974) adapted the petroleum system concept to identify the distribution of three oil types found by Williams (1974) in the Williston Basin. Aptly named Type I, Winnipegosis, Type II, Bakken and Type III, Tyler for their source formations; Dow presented three oil systems: 1) Winnipeg-Red River, 2) Bakken and 3) Tyler. He then defined these oil systems with their areal and stratigraphic extent, probable migration paths, seals and estimated their volume of oil generated. These oil systems became the basis of several studies in the Williston Basin.

The Birdbear Formation has complete petroleum system characteristics. From a lithostratigraphic perspective, the formation has several intervals with significant reservoirs and cap rocks. Reservoirs include dolomites and peloidal limestones of the upper member and the dolostones of the lower member. Cap rocks are the nodular anhydrites that form the boundary between the lower and upper members and at various intervals of the upper member. An unsolved factor surrounding the Birdbear petroleum system is whether it has the capability to generate the hydrocarbons it produces. A recent

publication of petroleum systems and oil families of the Williston Basin was done by Paul Lillis (2013). Lillis focused on the characteristics, distribution and origin of the oil families in the basin. Nine oil families within the Williston Basin are discussed (Figure 21) and parameters for consideration as apparent oil systems are outlined. For instance, petroleum systems must have documented oil source correlations, otherwise they will be considered hypothetical. Petroleum systems with a known source correlation include the Red River, Winnipegosis, Bakken, Madison and Tyler Formations. Although Lillis discounts the Birdbear petroleum system as hypothetical because it lacks an oil source correlation, evidence suggest the Birdbear Formation is self-sourcing and the evidence is growing.

Lillis recognizes several studies that suggest the Birdbear Formation contains a distinct oil family. Although Obermajer (1998) supposed oils from the Birdbear Formation were a mixture of several oils from the Middle-Upper Devonian he later found in southeast Saskatchewan nine oil samples within the Birdbear Formation that showed a uniform gasoline range and biomarker composition consistent with a single source (Obermajer et al., 1998; Obermajer et al., 1999). In 1998 Stasiuk et al. identified three oil types within the Birdbear Formation using fluorescence microspectrometry of hydrocarbon fluid inclusions. In 2001 Fowler et al. evaluated kerogens and showed the Birdbear Formation in Saskatchewan has Type I and Type II source rocks in significant quantities. The focus of this section is to show that the essential elements for a petroleum system exist within the Birdbear Formation of southwestern North Dakota, and to identify the potential source for these systems.

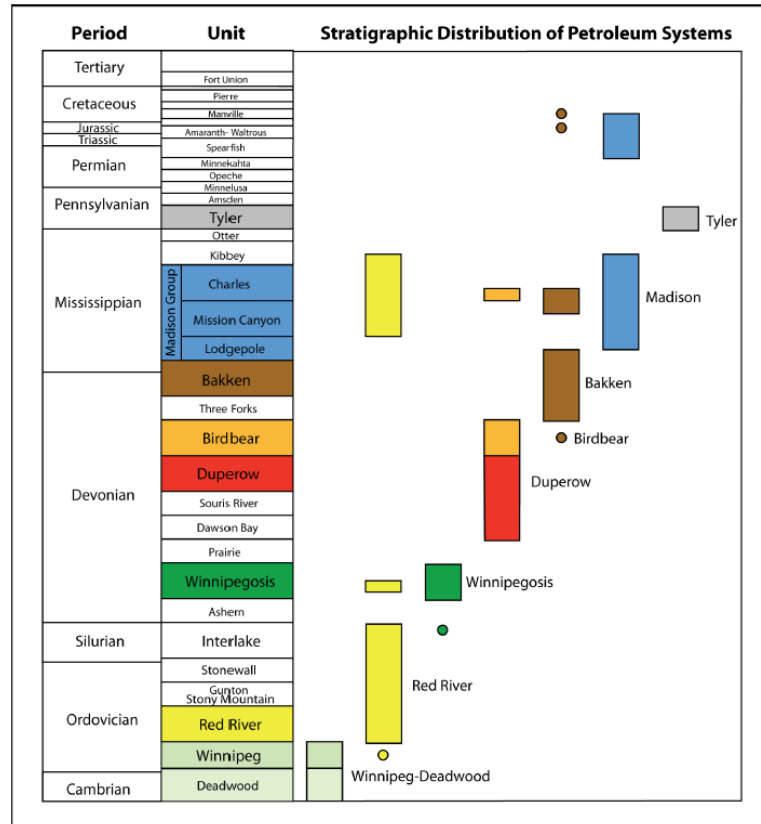


Figure 21. Stratigraphic column of the Williston Basin showing the petroleum systems in color (excluding gas systems) and the stratigraphic distribution of the petroleum system fluids. Circles represent minor occurrences or a single oil analysis. Systems without a documented oil source correlation are considered hypothetical and include the Winnipeg, Duperow, and Birdbear. The Deadwood petroleum system is speculative because a good oil-prone source rock has not been identified. After Lillis (2013).

Generation

Significant accumulations of oil found in southwestern North Dakota raise questions regarding their source rocks. Pay zones historically were the top of the lower member and recently, a thin interval in the upper member. Sampling available cores for TOC and Rock-Eval pyrolysis have identified source rocks within the Birdbear Formation. A total of 39 samples were made from the upper and lower members of the Birdbear Formation. Of these, 11 had TOC's greater than 1.5 wt. % and were further tested with Rock-Eval 6 pyrolysis and the results are found in Table 1. Rock-Eval 6

pyrolysis is an inexpensive way to test for TOC quality, type and maturity. A formation tops map populated with sampled well locations shows the line of section selected to display sampled depths in context of the well logs and lithostratigraphy (Figure 22). Eleven source rocks were identified with TOC's greater than 1.5 %.

The source rocks that occur within the study area are organic limestones, stromatolites and microbial mats. Microbial mats are by far more abundant in the core, however the organic limestones have much greater TOC and S₂ values, making for better source rocks. Figure 23 shows the stratigraphy of the lithofacies previously designated in relation to cores that were tested for Rock-Eval 6. This stratigraphic cross-section transects a path from near the basins depocenter to the southern basin margin. The depocenter is assumed to reside in central McKenzie County as shown in the isopach map of Figure 24. A common misconception made in the evaluation of source rocks is the reliability on TOC to determine the source rocks ability to produce. Many of the microbial mats sampled in the deeper portions of the basins had TOC values less than 1.5 % and were not further tested. Daly and Edman (1987) note that after generation and migration of hydrocarbons the amount of organic matter remaining in the source rock is diminished. This means that care must be taken not to overlook source rocks that have already produced (Dembicki, 2009). It is likely that many of the microbial mats that commonly occur deeper in the basin are source rocks that have passed through the oil window because they are genetically related to sampled rocks with positive results along the margin. This is important because the microbial mats occur more frequently in the upper member and the upper member is more prevalent in the distal regions of the basin, due to thinning along the margin (Figure 23).

Table 1. Table of TOC and Rock-Eval 6 results. TOC- total organic carbon wt. %. S1-volatile hydrocarbon (HC) content, mg HC/g rock. S2- remaining HC generative potential, Mg HC/g rock. S3-carbon dioxide content, mg CO2/g rock. HI-Hydrogen index=S2x100/TOC, mg HC/g TOC. OI-Oxygen index=S3x100/TOC, mg CO2/g TOC. PI- Production index=S1/(S1+S2). The asterisk represents an omission of lithofacies assignment due to lack of a suitable core for description.

API #	NDIC #	WELL NAME	DEPTH (ft)	TOC	S1	S2	S3	Tmax (°C)	HI	OI	S2/S3	S1/TOC X 100	PI	LITHOFACIES
3308900646	21139	ZENT 30-138-95 A 1H	10004.50	2.88	2.43	9.65	0.22	439.00	334.84	7.63	43.86	84.32	0.20	L 6
3308900646	21139	ZENT 30-138-95 A 1H	10006.80	5.37	2.12	20.90	0.31	440.00	389.34	5.77	67.42	39.49	0.09	L 6
3303300308	21734	OLSON 12-139-104 A 1H	10511.50	2.71	1.51	7.03	0.36	439.00	259.03	13.26	19.53	55.64	0.18	L 8
3303300251	15679	BROWN 42-28	10716.00	1.57	0.97	6.26	0.29	438.00	397.97	18.44	21.59	61.67	0.13	L 7
3303300251	15679	BROWN 42-28	10726.00	1.67	3.85	5.19	0.30	443.00	310.04	17.92	17.30	229.99	0.43	L 2
3305302336	12962	NORTH BRANCH #35X-34 BN	10987.00	1.58	0.97	2.50	0.32	453.00	158.73	20.32	7.81	61.59	0.28	L 2
3305302336	12962	NORTH BRANCH #35X-34 BN	10965.10	3.49	1.21	7.58	0.29	450.00	217.19	8.31	26.14	34.67	0.14	UL 2
3305302336	12962	NORTH BRANCH #35X-34 BN	10991.20	2.45	0.85	4.30	0.32	450.00	175.51	13.06	13.44	34.69	0.17	L 2
3305302336	12962	NORTH BRANCH #35X-34 BN	11000.10	2.27	1.27	4.32	0.26	449.00	190.31	11.45	16.62	55.95	0.23	L 2
3300700016	859	GOV'T-M.S. PACE #1	11199.00	1.52	0.47	0.82	0.39	445.00	54.02	25.69	2.10	30.96	0.36	*
3305302208	12249	PIERRE CREEK 21-17	10992.00	6.87	1.93	14.29	0.31	452.00	208.01	4.51	46.10	28.09	0.12	L 5

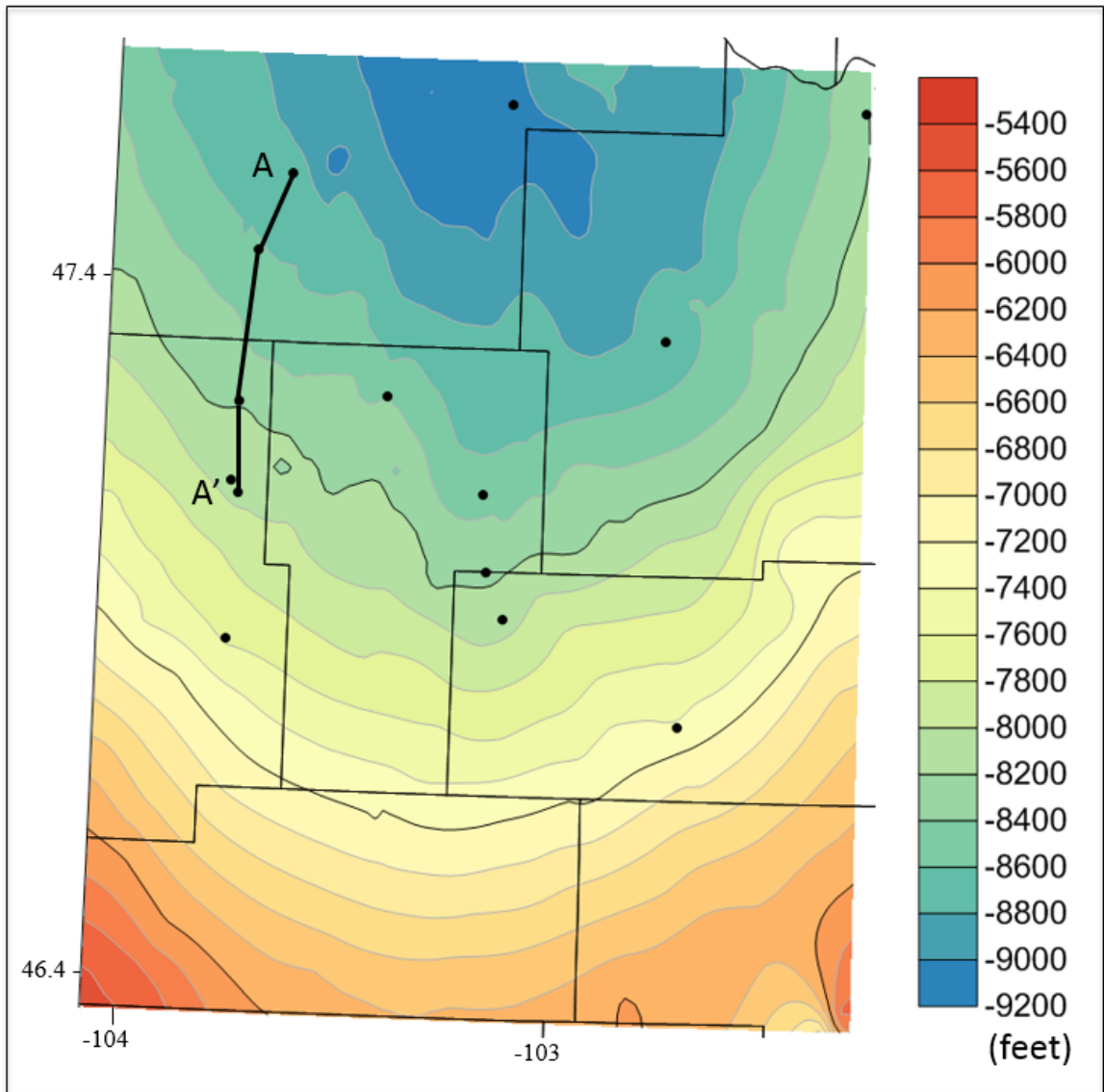


Figure 22. The depth to top of the Birdbear Formation was constructed from acoustic gamma ray logs and is shown here. Location of sampled wells imposed with cross-section shown.

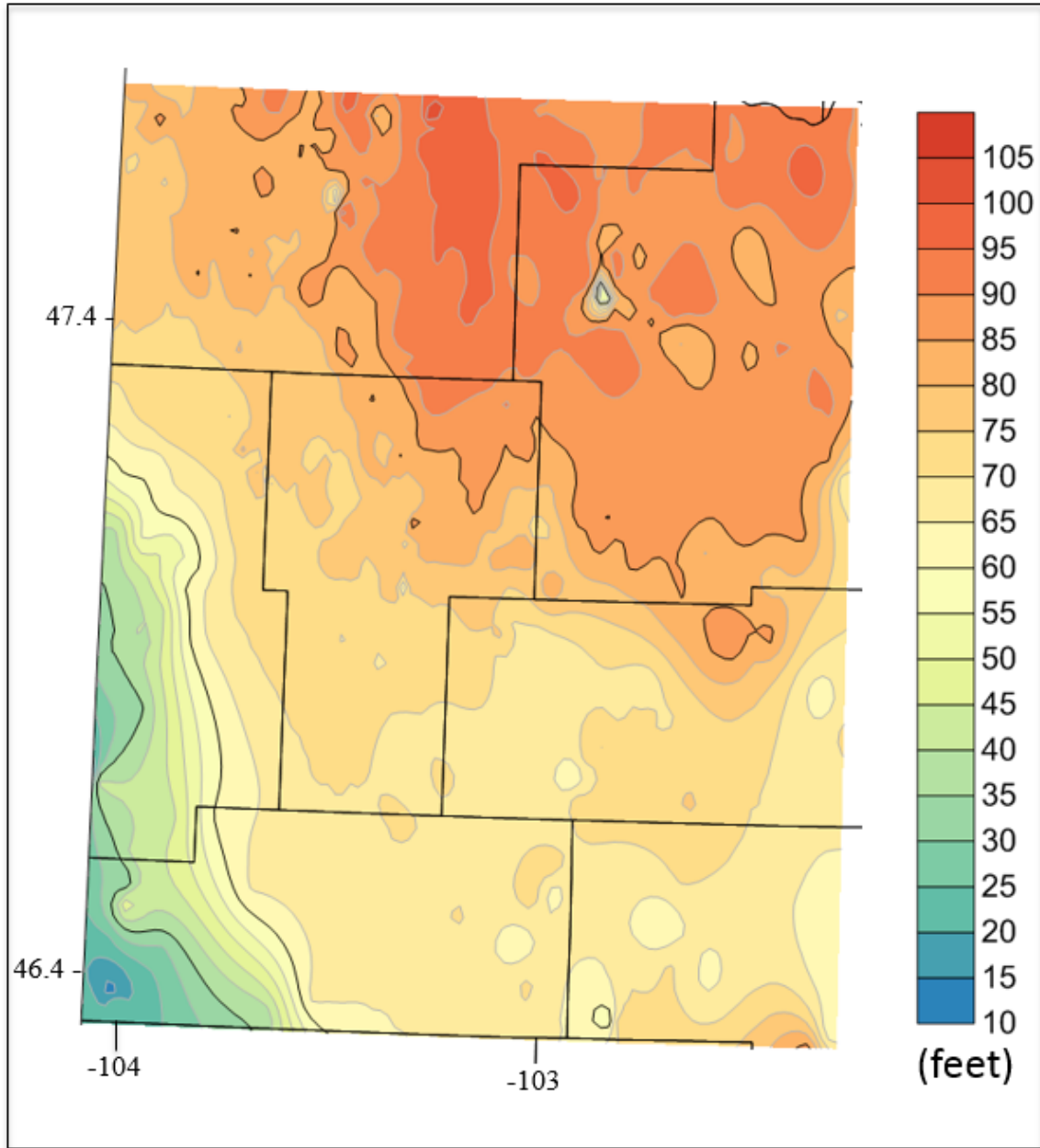


Figure 24. Isopach map of the Birdbear Formation of southwestern North Dakota shows the thickest portion of the basin to be centered in southeastern McKenzie County.

Not all organic carbon is created equal. Some produce oil, some produce gas, and some produce nothing at all (Tissot et al., 1974). The amount of hydrogen present in a rock is directly proportional to the quantity of hydrocarbons it can produce. With this in mind, the sampled results of the Birdbear Formation are shown using a Dembicki (2009)

plot in Figure 25. A Dembicki plot shows the proportionality between TOC and hydrogen by using the S2 value from the Rock-Eval. The S2 value estimates the hydrogen present in the organic sediments. Results shown in Figure 25 indicate two wells with excellent TOC and S2, three wells with excellent TOC and good S2, and one well with two samples plotting with excellent TOC and fair S2. Other samples falling within the good, fair to poor range of TOC and S2 are also shown. The PIERRE CREEK 21-17 and ZENT 30-138-95 A 1H wells have excellent source rocks with S2 values reflecting large hydrogen concentrations in the organic sediments. They have the potential to produce more than samples with lower S2 values.

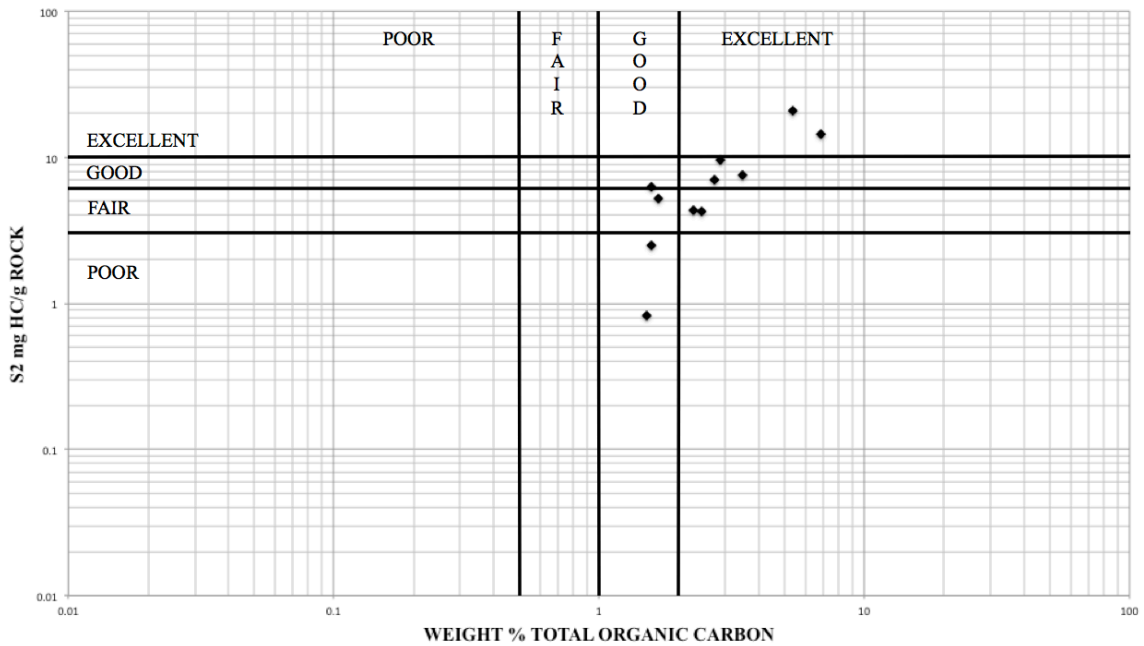


Figure 25. Dembicki plot showing the results of eleven source rock samples.

Burke (2005) reopens the source rock problem due to an increase in production rates coming from several wells near the Montana border. In his paper he uses core descriptions and wire line logs to establish three fourth order cycles within the upper member. Cycles one and two contain the components necessary for a complete petroleum

system: source, reservoir and seal. Pay is derived from a 2' interval at the base of cycle two. This target interval lies beneath the nodular anhydrites of UL 4, within the microbial laminates of UL 3, or in the case of its absence UL 2. Burke (2005) calls for source rock analysis to resolve the source rock issue. In this study all samples within cycle one were below the 1.5 % threshold for further testing, but this does not exclude them as containing source rocks. Results of samples taken from cycles two and three had TOC's greater than 1.5 % and were further tested using Rock Eval. Those results (along with others) are shown using Dembicki's (2009) plot in Figure 25. Results show that the laminated muds of cycle two have 7.58 mg. HC/g Rock (good S2) and 3.49 wt. % TOC (excellent) at a depth of 10,976 ft. from the NORTH BRANCH #35X-34BN well. The wispy-laminated dolomudstones of UL 7 were sampled from the BROWN 42-28 well. They plotted with fair S2 values and good TOC. These rocks could potentially be the source for the oils produced within the intervals of cycle one and two. Further pyrolysis-gas chromatograph (PGC) testing can further substantiate Burke's hypothesis by allowing comparisons of kerogen type(s) between the source rock and reservoir oil.

To further substantiate the hypothesis that the Birdbear is self-sourcing, PGC testing should be done. Oil source correlations can be made by comparing the source rocks with the oil produced. This could eliminate the possibility that the source rocks are not the source of oil produced from the Birdbear Formation.

Migration

The discontinuity of the Birdbear Formation would suggest that the hydrocarbons it generates would not be prone to significant lateral migration. In fact, other authors believe lateral migrations of hydrocarbons are often restricted in the North Dakota

portions of the Williston Basin. Lateral migrations have been hampered due to geometry of reservoir rocks in the Tyler Formation and loss of porosity of limestone in the Spearfish (LeFever, R. and LeFever, J., 1991). There are significant factors present within the Birdbear Formation that would improve the likelihood of significant lateral migration.

The Birdbear Formation has several intervals of extensive cap rock. The lower member is separated from the upper member by nodular or interbedded anhydrite in every well observed. The lower anhydrite typically ranges from 2-9 ft. thick, where present. Two other intervals of nodular or chickenwire anhydrite exist. The upper member is divided from the Three Forks Formation by an average of 3.4 ft. of anhydrite which also occurs in every well present selected for this study. The presence of these cap rocks would facilitate lateral migration and impede cross-stratal migration.

Another factor that would facilitate lateral migration of hydrocarbons is the presence of porous zones of limestone and dolomite found within these intervals. The mixed-fossil limestone of L 7 has an average porosity of 17% while L 8 has about 9% porosity. Lithofacies 7 is more extensive than L 8 however; both are directly below the coalesced anhydrites of UL 1. The peloidal limy mudstones-wackestones of UL 3 have an average porosity of 14% and are underneath the nodular anhydrites of UL 4. In like fashion, the interbedded dolomudstones and limestones of UL 8 lie directly beneath the nodular anhydrites of UL 9 and have the highest average porosity of 23%. Each of these porous intervals could be considered good to excellent highways for up-dip lateral migration.

The oil saturation and water saturation maps gathered from DST data show a first-order correlation indicating water accumulation occurs at greater depth (basin center) and oil accumulates at the basin margins (Figure 26). These results are normal and the interfacial tension between oil and water would drive hydrocarbons to places of accumulation.

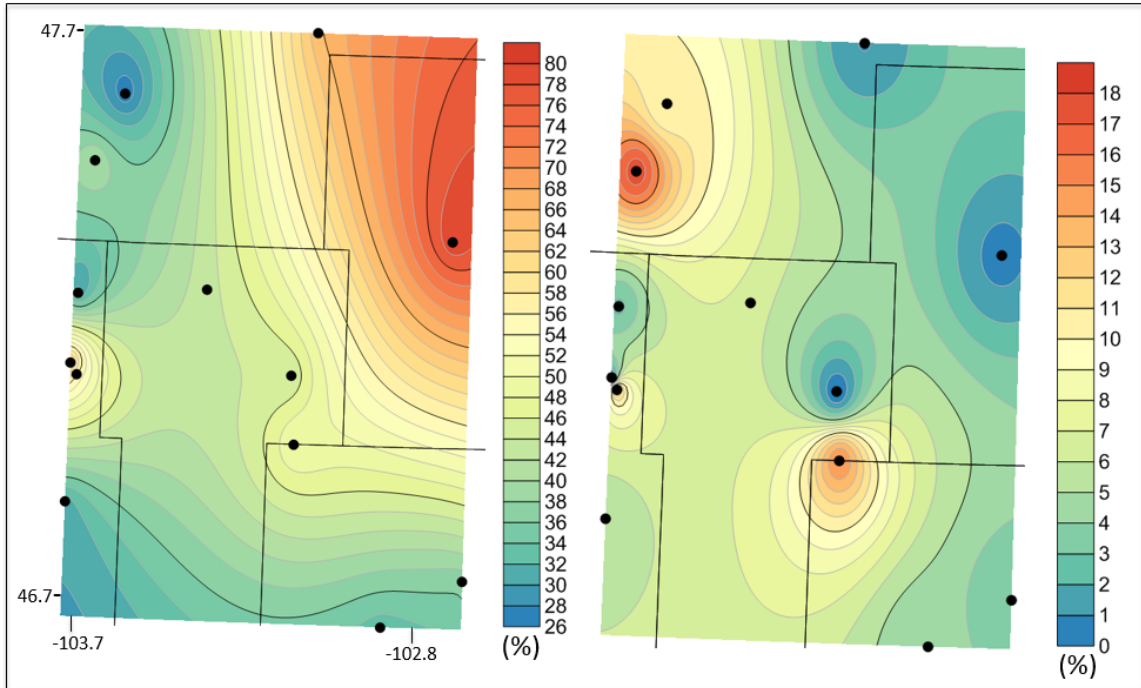


Figure 26. Water saturation (L), and oil saturation (R) maps are shown with contributing wells. Water saturation was computed using Krigging method of interpolation while the oil saturation was interpolated using the inverse distance method.

A common practice during the drilling process is to perform formation tests down hole. These are called drill stem tests (DST). Information regarding conditions present during drilling are valuable, indicating a close approximation to actual formation conditions. Bottom hole pressure (BHP) recorded from eight successful DST's give an indication of the height water would flow if left unhindered. The potentiometric surface in Appendix B (Figure 27) shows a northeasterly flow across Billings County and a

southerly flow from McKenzie County. These results are highly dependent upon the availability of data, and may not reflect actual hydrodynamics in the Birdbear Formation. With the variation shown between the southern and central margin from the potentiometric surface it is assumed that hydrodynamic conditions do exist in the Birdbear Formation, suggesting the reservoirs are not in hydraulic continuity.

Accumulation

Halabura (1982) reasons that because the Birdbear Formation is a shallow-shelf carbonate-evaporite it would have developed excellent stratigraphic reservoirs, suggesting all the elements necessary exist. These conditions were later recognized by Martiniuk et al. (1991) as the lateral and vertical variation of lithofacies and impermeable cap rock. In north-central North Dakota and southwestern Manitoba primary and secondary lithostratigraphic traps are identified within the Birdbear Formation. Primary stratigraphic traps are thought to exist where the *Amphipora* and stromatoporoid bank facies pinch out against the limy mudstones to packstones. In addition, two diagenetic-stratigraphic traps are identified. First, at the subcrop of the Birdbear Formation edge dolomitization and anhydritization has reduced porosity and created an up-dip seal. Second, locally enhanced porous zones of the limy wackestones to grainstones of the lower member pinch out against the dolostones to dolomudstone to wackestone. (Martiniuk et al., 1995).

Three stratigraphic traps of southwestern North Dakota are identified. The first stratigraphic trap is considered to exist where the bioturbated dolomudstones of Lithofacies 8 pinch out against the nodular anhydrites of Upper Lithofacies 1. The second trap is where the planar parallel to wavy bedded peloidal limy mudstones to wackestones

of UL 3 pinch out against the nodular and wispy laminated anhydrites of UL 4. Third, where the stromatolitic dolomudstones and limestones pinch out against the chickenwire anhydrite of UL 6 wherever present, or the nodular anhydrites of UL 7 in case of absence of UL 6. The second stratigraphic trap between UL 3 and UL 4 had an initial 5-8% porosity that was locally enhanced as secondary dolomite developed inter-crystalline porosity (see Figures 13 and 19).

CHAPTER IV

CONCLUSIONS

The odds of successfully locating and recovering hydrocarbons are greatly improved with accurate interpretations of depositional environments. The 17 lithofacies of the Birdbear Formation of southwestern North Dakota were designated. These Lithofacies were divided into two groups, the upper and lower, based on a shift from shallow marine deposits to upper-intertidal and supratidal-evaporite deposits. The formation both shoals and brines upward as regression of the Late Devonian seas progressed. The lithofacies of the lower member occur throughout the study area and represent shallow-marine shelf deposits occurring between the storm-wave base and the top of the high-energy inter-tidal zone. The informal lower member was interpreted as being deposited on a broad shallow shelf.

The interpreted depositional environments of the nine lithofacies composing the upper member range from quiet water intertidal to supratidal deposits. These carbonate-evaporite intervals were deposited on a vast, greatly restricted shelf under very shallow waters. Several local unconformities were observed throughout the study area, recording a variable topography due to antecedent sediment deposition, sea level fluctuations and evaporite processes. Shallow pools served as carbonate factories producing organic-rich limestone while serving as host to various stromatolites and microbialites. These

environments favored organic sediment deposition and are the source rocks in the upper member of the formation.

The petroleum system concept is an approach to exploration that minimizes risk in the development of viable plays. The petroleum system concept requires an understanding of the generation, migration and accumulation of hydrocarbons for a given source. This knowledge allows explorers to acquire and reach targets with greatly improved efficiencies. The Birdbear Formation has all of the components of a complete petroleum system. Source rocks have been found within eight lithofacies with TOC and S₂ values ranging from poor to excellent. Following generation, hydrocarbons likely migrated up dip along the porous intervals of L 7, L 8, UL 3 and UL 8. Accumulation of hydrocarbons likely occurs in stratigraphic traps. Three stratigraphic traps are identified. The first stratigraphic trap is considered to exist where the bioturbated dolomudstones of Lithofacies 8 pinch out against the nodular anhydrites of Upper Lithofacies 1. The second trap is where the planar parallel to wavy bedded peloidal limy mudstones to wackestones of UL 3 pinch out against the nodular and wispy laminated anhydrites of UL 4. Third, where the stromatolitic dolomudstones and limestones pinch out against the chickenwire anhydrite of UL 6 wherever present, or the nodular anhydrites of UL 7 in case of absence of UL 6.

Ultimately this documents the lithofacies, depositional environment, and the types of source rocks present in the Birdbear Formation. Further studies focusing on mapping the geographic extent of the lithofacies can locate resources and provide estimates of original oil in place. This, combined with oil source correlation between source rocks and

oil produced serves as an excellent risk management tool for exploration geologists and investors seeking to develop the Birdbear Formation in southwestern North Dakota.

APPENDICES

Appendix A
Core and Thin Section Descriptions

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Well #793

API (3302500005)

Mobil Producing Co. 1 Pegasus Div Solomon Bird Bear #F-22-22-1

SENW 22-149-91

Dunn County

Core -7.75"

10,310'-10,314' Anhydrite, dolomudstone, white, green, brown, interbedded dolomudstones and microbial laminates, wavy laminated, rare, ripple beds, rare, poorly sorted sub angular skeletal wackestone beds (< 0.18"), rare anhydrite-healed hairline fractures, oil stained. Sharp and conformable with the red, green muddy shales of the Three Forks Formation.

10,314'-10,316' 5" Dolomudstone, anhydrite, light-brown, planar-wavy interbedded, microbial laminates, stromatolites, moderately abundant stylolites, intra-crystalline porosity.

10,316' 5"-10,317' 4.5" Limestone, dark-brown, dark-grey, wavy, planar bedded, abundant dark laminae, inter-granular porosity, oil stained. Sharp contact above.

TS: 10,317' Crystalline dololimestone, brown, buff, translucent, opaque, very fine-grained (upper), microspar and pseudospar matrix, euhedral to subhedral dolomite, euhedral calcite, irregular dolomite, blocky and irregular anhydrite, inter-granular (4%) and intra-crystalline porosity (2%), anhydrite-filled porosity in part. Composite description of four slides.

10,317' 4.5"-10,318' 6" Anhydrite, light-brown, nodular, wispy laminated. Sharp contact above.

TS: 10,318' 6" Anhydrite, grey, green, fine-grained (lower) to coarse-grained (lower), subhedral, bladed to acicular.

10,318' 6"-10,319' Dolomudstone, light-brown, microbial laminated, muddy nodules, stylolite, hairline fractures, intra-crystalline porosity. Sharp contact above.

10,319'-10,321' 3" Limestone, dark-brown, grey, muddy, contorted bedding, wavy bedding, vertical healed hairline fractures, inter-granular porosity, oil stained.

TS: 10,320' Anhydrite, grey, green, fine-grained (lower), wispy organic partings, irregular habit.

10,321' 3"-10,329' Dolomudstone-packstone, anhydrite, brown, grey, light-grey, light-brown, wavy, contorted interbeds, coarse-grained, sub-rounded-sub-angular anhydrite-filled vugs, dark-green anhydrite nodules with authigenic pyrite, intra-crystalline porosity. Gradational contact above.

TS: 10,323' Crystalline dolomudstone, translucent, brown, green, very fine-grained (lower), calcite matrix in part, anhydrite cement, microbial laminates, euhedral calcite and dolomite, replacement dolomite, solution seams with anhydrite fill, euhedral to blocky and simple twinned anhydrite-filled vugs, intra-crystalline porosity.

TS: 10,323' 6" Crystalline dolomite, buff, brown, very fine-grained (lower), calcite cement, sub-hedral, inter-crystalline porosity.

TS: 10,325' 6" Crystalline dolomite, buff, brown, very fine-grained (lower), calcite cement, sub-hedral, low amplitude high frequency stylolite swarm, inter-crystalline porosity.

TS: 10,326' 6" Interlaminated limy mudstone and nodular anhydrite, transparent, brown, grey, very fine-grained (lower) with fine-grained (upper) calcareous sediment laminae, calcite cement, microspar matrix, organic laminae, microbial laminates, euhedral calcite and dolomite, blocky anhydrite, inter-crystalline porosity.

TS: 10,327' 6" Anhydrite, grey, green, fine-grained (lower) to coarse-grained (lower), wispy muddy laminae, subhedral, bladed to acicular.

TS: 10,327' 10" Limy dolomudstone, brown, translucent, opaque, very fine-grained (lower), calcite cement, blocky to bladed anhydrite with simple twins, euhedral anhydrite-filled vugs, euhedral to sub-hedral dolomite, inter-crystalline porosity, intra-crystalline porosity, vuggy porosity (10%).

10,329'-10,329' 8" Limy mudstone, dark-brown, wavy bedding, authigenic pyrite, inter-granular porosity, oil stained. Sharp contact above.

TS: 10,329' Peloidal dololimestone, buff, brown, translucent, very fine-grained (upper), microspar matrix, microbial laminates, peloidal laminae, stylolites, inter-crystalline porosity.

10,329' 8"-10,334' Anhydrite, grey, light-brown, coalesced, rare dolomudstone beds, interbedded microbial laminates.

TS: 10,330'-10,331' 3" Limy mudstone, buff, transparent, opaque, calcite cement, micrite matrix, blocky to irregular to bladed anhydrite nodules, Fe-Mg crust, rare microbial wisps, common interlaminated microbialites, skeletal fragments, euhedral to sub-hedral dolomite, abundant low amplitude, low frequency stylolites, euhedral twinned, dolomite filled vugs, inter-granular porosity. Composite description of five thin sections.

10,334'-10,335' Dolomudstone, light-grey, dark-grey, stromatoporoids, microbial laminates, oil stained. Sharp contact above.

10,335'-10,342' Limy mudstone-wackestone, grey, dark-brown, muddy, planar laminated, wavy bedded, common skeletal wackestone beds (sub-angular) bryozoan,

Amphipora, dolomite nodules, abundant low amplitude stylolites, healed hairline fractures, inter-granular porosity, oil stained.

TS: 10,337' 10" Limy mudstone, brown, buff translucent, very fine-grained (lower), calcite cement, abundant sub-rounded mud fragments, abundant sub-rounded anhydrite clasts, possible sub-rounded potassium feldspar, microbial calcite dissolution seam, inter-granular porosity.

TS: 10,338' 6"-10,339' Anhydritic limy mudstone, buff, transparent, opaque, medium-grained (upper), calcite cement, planar laminated, blocky anhydrite (< 2.5mm), euhedral to sub-hedral anhydrite grains, sub-rounded to sub-angular anhydrite grains, nodular limy mudstone, muddy partings ("wispy laminations"), stylolite swarms, inter-granular porosity. Composite description of two thin sections.

TS: 10,339' 9"-10,339' 10" Peloidal limestone to limy mudstone, brown, buff, transparent, very fine-grained (upper), calcite cement, micrite clast, muddy laminated, abraded peloids, coral fragments, sub-rounded anhydrite clasts and nodular anhydrite, stylolites, hairline fracture with organic halo, inter-granular porosity, fracture porosity. Composite description of three thin sections.

10,342'-10,357' Limy wackestone-packstone, light-brown, dark-brown, stromatolites, stromatoporoids, rugose coral, *Amphipora* fragments, brachiopods, anhydrite-filled vugs, dolomite nodules, bioturbated, stylolites, hairline fractures often confined to stromatolites, inter-granular porosity, oil stained.

TS: 10,345' 6"-10,346' Limy mudstone, light brown, buff, transparent, very fine-grained (lower), calcite cement, microbialite, inter-granular porosity. Composite of six thin sections.

TS: 10,347' - 10,347' 6" Limy mudstone, light brown, brown, very fine-grained (lower), micrite matrix, calcite cement, stromatolite (microbially laminated), euhedral dolomite and calcite, inter-crystalline porosity. Composite description of two thin sections.

TS: 10,351' 6"-10,354' Limy packstone to wackestone, brown, grey, cream, green, micrite matrix, abundant brachiopod spines, abundant articulated ostracods, and ostracod fragments, peloidal interbeds, abraded and deformed *Amphipora* (rare), blocky anhydrite, euhedral dolomite, anhydrite healed vertical fracture, inter-skeletal, inter-granular and intra-crystalline porosity, intra-granular porosity oil stained. Composite descriptions of six thin sections.

TS: 10,354' 6" Peloidal packstone, buff, brown, cream, translucent, fine-grained (lower), calcite cement, abundant spherical and semi-conical pellets and peloids, brachiopods, euhedral to sub-hedral dolomite, inter-crystalline, inter-granular porosity.

TS: 10,356'-10,356' 6" Limy packstone, brown, buff, cream, translucent, medium-grained (lower), sparry matrix in part, micrite matrix, abundant peloids,

uniserial benthic foraminifer, euhedral and sub-hedral dolomite, stylolite, vertical fracture, inter-granular porosity, inter-skeletal porosity. Composite descriptions of two thin sections.

10,357'-10,368' 6" Limy mudstone, light-brown, dark-brown, heavily bioturbated, dolomite nodules, anhydrite-filled vugs, skeletal fragments, stylolites, anhydrite-healed hairline fractures, inter-granular porosity.

TS: 10,358' Limy wackestone to packstone, brown, grey, buff, translucent, fine-grained (lower), micrite matrix with microspar matrix zones, peloidal, uniserial benthic foraminifera, burrows, brachiopod spicules, disarticulated brachiopod valves, bryozoa, euhedral dolomite and calcite pore-filling of vugs, rounded anhydrite inclusions, anhydrite-filled fractures in part, intra-skeletal porosity, inter-crystalline porosity, fracture porosity (20%). Composite descriptions of six thin sections.

TS: 10,363'-10,367' Boundstone, cream, brown, opaque, coarse-grained (lower), micrite matrix, fenestrate and trepostome bryozoan, brachiopod, euhedral dolomite, partially anhydrite filled fracture, vuggy, intra-skeletal porosity, inter-crystalline porosity (15%). Composite description of five thin sections.

10,368' 6"-10,369' 10" Limy wackestone, dark-brown, brown, wispy laminated, bioturbated, dolomite nodules, skeletal fragments, *Amphipora*, stromatoporoids, peloids, brachiopod spicules, sparry cement, stylolites, healed hairline fractures, inter-granular porosity. Sharp contact above.

10,369' 10"-10,392' Limy mudstone-wackestone, light brown, dark brown, heavily bioturbated, skeletal fragments, brachiopod spicules, anhydrite-filled vugs, anhydrite-healed fractures, inter-granular porosity, oil stained.

TS: 10,370' Bioturbated limy mudstone-wackestone, green, brown, translucent, very fine-grained (lower), organic mud matrix in part, micrite matrix in part, skeletal fragments, heavily burrowed and bioturbated, blocky anhydrite, possible authigenic plagioclase feldspar, euhedral calcite, euhedral dolomite (micrite) stylolite, anhydrite healed fracture, intra-skeletal porosity, inter-crystalline porosity, fracture porosity.

TS: 10,372' 6" Bioturbated limy mudstone-wackestone, green, brown, translucent, very fine-grained (lower), organic mud matrix in part, microspar matrix in part, stromatoporoid and brachiopod skeletal fragments, heavily burrowed and bioturbated, blocky anhydrite, possible authigenic plagioclase feldspar, euhedral calcite, sub-hedral to euhedral dolomite (micrite), epigenetic dolomite, stylolite, calcite filled vugs, vuggy, inter-crystalline porosity, fracture porosity. Composite description of three thin sections.

TS: 10,373' 6"-10,374' 6" Limy mudstone-wackestone, brown, translucent, very fine-grained (lower), recrystallized microspar cement in part, micrite matrix in part, coral and brachiopod skeletal fragments, uniserial benthic foraminifera, bioturbated, sub-hedral to euhedral dolomite (micrite), stylolite, calcite filled

vugs, vuggy, inter-crystalline porosity, fracture porosity. Composite description of two thin sections.

TS: 10,374' 6"-10,376' 6" Skeletal limy wackestone-packstone, brown, cream, very fine-grained (upper), microspar matrix in part, micrite matrix in part, pellets, uniserial benthic foraminifera, brachiopod spine and valve fragments, euhedral dolomite (micrite matrix), blocky calcite, high amplitude, low frequency stylolites, inter-crystalline porosity, intra-skeletal porosity, intra-crystalline porosity, fracture porosity. Composite description of three thin sections.

TS: 10,377'-10,377' 3" Peletal limy packstone, brown, cream, buff, very fine-grained (upper), micrite matrix in part, microspar and pseudospar matrix in part, coral, replaced uniserial benthic foraminifera, fenestrate impunctate bryozoan fragments, sub-hedral to euhedral dolomite (micrite matrix), inter-crystalline porosity, intra-crystalline porosity. Composite description of two thin sections.

TS: 10,379' 6"-10,381" Skeletal limy wackestone, brown, cream, very fine-grained (lower), organic mud matrix in part, micrite matrix, coral and fenestrate impunctate bryozoan fragments, benthic uniserial foraminifera, possible fish tooth mold, sub-hedral to euhedral dolomite, blocky anhydrite and calcite mold fill, stylolite swarms, inter-granular porosity, inter-crystalline porosity, intra-skeletal porosity, intra-crystalline porosity. Composite of three thin sections.

TS: 10,384'-10,386' Skeletal limy wackestone-packstone, brown, cream, translucent, very fine-grained (lower), organic mud matrix in part, micrite matrix in part, pellets, fenestrate impunctate bryozoan fragment, deformed coral fragments, uniserial benthic foraminifera, microspar void fill, anhydrite filled burrows and vugs, stylolites, inter-granular porosity, inter-crystalline porosity, intra-crystalline porosity, intra-skeletal porosity. Composite description of two thin sections.

TS: 10,388'-10,389' 6" Limy mudstone-wackestone, brown, translucent, very fine-grained (lower), micrite matrix in part, organic mud matrix, coral, bryozoan and abraded benthic foraminifera fragments, articulated brachiopod, microspar and anhydrite filled vugs, inter-crystalline porosity, inter-granular porosity, intra-skeletal porosity. Composite description of two thin sections.

TS: 10,389' 9" Limy mudstone, brown, translucent, very fine-grained (lower), micrite matrix, anhydrite nodules, organic muds are highly fractured and are displaced by anhydrites, anhydrite fracture fill, inter-granular porosity. Composite description of four thin sections.

TS: 10,391' Limy wackestone, grey, translucent, very fine-grained (lower), organic mud matrix in part, micrite in part, impunctate bryozoan fragments, skeletal fragments, sub-hedral to euhedral dolomite, rounded microspar and anhydrite vug fill, calcite lined fractures, stylolites, inter-granular porosity, inter-crystalline porosity. Composite description of two thin sections.

TS: 10,395'-10,397' Skeletal limy wackestone-packstone, brown, transparent, medium-grained (upper) with a very fine-grained groundmass, organic mud matrix in part, micrite in part, impunctate bryozoans, coral fragments, benthic foraminifera, possible brachiopod spines, anhydrite nodule, sub-hedral to euhedral dolomite, healed hairline fracture, anhydrite filled fractures, stylolites, inter-granular porosity.

Well #12249

API 3305302208

Meridian Oil Inc., MOI #21-17

NENW 17-146N-102W

McKenzie County

10,964'-10,966' Limy mudstone, brown, dark-brown, black, crystalline, cross-bedded, wavy laminations, micro-stylolites, hairline fractures, inter-granular pinpoint porosity.

10,966'-10,967' Dolomudstone, tan, grey-light grey, white, brown, dark grey, wavy laminations, intra-crystalline porosity. Sharp contact above.

10,967'-10,968' Anhydrite interbedded with dolomudstone, light brown to brown and dark grey, coalesced and nodular anhydrite, soft-sediment deformation, intra-crystalline porosity.

10,968-10,970' 2.5" Anhydrite, limestone, dark brown to black, brown, nodular, interbedded, vertical calcite-healed hairline-fractures increasing with depth, inter-granular porosity. White basal nodular (angular to sub-angular) anhydrite with horizontal and vertical fractures.

10,970' 2.5"-10,972' 7" Dolomudstone, light-tan to grey speckled (brown effervesces weakly without pulverization while the grey effervesces with pulverization), light grey parallel and sub-parallel thin muddy laminations, rare skeletal fragments, nodular anhydrite, good pinpoint porosity, intra-crystalline porosity. DST

TS: 10,970' 10" Dolomudstone, brown, buff, cream, very fine-grained (lower), micrite matrix, calcite cement, muddy laminated, sub-hedral to euhedral dolomite, intra-crystalline porosity (40%), oil stained.

TS: 10,971' 1.5" Dolomudstone, brown, buff cream, very fine-grained (lower), micrite matrix, calcite cement, muddy laminae, sub-hedral to euhedral dolomite, sub-vertical partially healed hairline fracture, intra-crystalline porosity, fracture porosity (40%).

10,972' 7"-10,974' Anhydrite, light-grey-green, thin calcareous muddy laminations (4") capping a dark-gray, brown to white chicken-wire anhydrite with horizontal hairline fractures. Sharp contact above.

TS: 10,974' Cross-laminated microbial dolomudstone, brown, translucent, very fine-grained (lower), possibly calcite cement, anhedral dolomite, inter-crystalline porosity.

10,974'-10,975' 6" Dolomudstone, light-brown, brown, silty, microbial laminations, stromatoporoids, rare nodular anhydrite with growth halos, visible porosity, crystalline anhydrite-filled vugs in part, intra-crystalline porosity.

TS: 10,974' 5" Cross-laminated microbial dolomudstone, brown, translucent, very fine-grained (lower), possibly calcite cement, micrite matrix, anhedral dolomite, inter-crystalline porosity.

10,975' 6"-10,978' 2" Limy mudstone, dark-brown, black, planar laminated, rare skeletal fragments, inter-granular porosity.

TS: 10,975' 11"-10,976' 11" Peletal limy packstone, brown, buff, cream, opaque, very fine-grained (upper), calcite cement, microbial laminated, skeletal fragments, blocky anhydrite, stylolites, fracture porosity (<1%). Composite description of two thin sections.

TS: 10,977' 5" Peletal limy grainstone, brown, opaque, translucent, very fine-grained (upper), calcite cement, pellets, coral fragments, blocky anhydrite, abundant stylolites, fracture porosity (1%).

10,978' 2"-10,979' 6" Mudstone, grey, green, light-brown, wavy to microbial laminated, bioturbated, coalesced anhydrite.

10,979' 6"-10,987' 9" Anhydrite, mudstone, grey, white, brown, interbedded, wavy to planar laminated, massive in part, soft-sediment deformation. Sharp contact above, local unconformity.

10,987' 9"-10,989' 11" Dolomudstone, anhydrite, dark-grey, tan, brown, mud and silt interbeds, abundant vertical and horizontal hairline fractures, healed, rarely confined by bedding planes, intra-crystalline porosity. Sharp contact above, possible unconformity.

10,989' 11"-10,992' Dolomudstone-wackestone, light-brown, brown, skeletal fragments abundant anhydrite nodules, anhydrite-healed hairline fractures, anhydrite filled vugs, intra-crystalline porosity. Gradational contact above.

10,992'-10,994' 2" Anhydrite, limy mudstone-wackestone, dark-brown, brown, white, wavy interbeds, minor soft-sediment deformation, *Amphipora* skeletal fragments, anhydrite-healed hairline fractures. Limy mudstone occurs as cap and base to anhydrite. Sharp contact above.

10,994' 2"- 10,998' Limy wackestone-packstone, light-brown, black *Amphipora*, bryozoans, stromatoporoids, rugose coral fragments, anhydrite-filled vugs, bioturbated, muddy laminations, inter-particle porosity.

10,998'- 11,001' Limy muddy-siltstone, brown, black, muddy-wispy laminations, bioturbated (*Planolites*), *Amphipora*, brachiopod spicules, anhydrite nodule, inter-granular porosity, pinpoint porosity. Gradational contact above. DST

11,001'-11,011' Dolomitic mudstone-wackestone, brown, black, sucrosic, wispy laminations, bioturbated, skeletal fragments, intra-crystalline porosity, pinpoint porosity, vugs. Sharp contact above. DST

11,011'-11,011' 9" Limy silty-wackestone, brown, skeletal fragments, stylolites, inter-granular porosity, pinpoint porosity.

11,011' 9"-11,015' 4" Limy silty-mudstone, brown, light brown, mottled, bioturbated, rare coral skeletal fragments, stylolites, inter-granular porosity.

11,015' 6"-11,017' Limy mudstone, dark-brown-grey, mottled, heavily bioturbated, skeletal brachiopod fragments, stylolite swarms, vertical fracture, inter-granular porosity.

11,017'-11,024' Limy mudstone, light-brown, wavy laminated, mottled, heavily bioturbated, stylolites, basal circuitous fractures, inter-granular porosity.

Well #12962

API 3305302336

Penzoil Exploration & Production Co. North Branch 35X-34 BN

SWSE 35-148N-102W

McKenzie County

C – 10'

10,962'-10,963' Anhydrite, dark-grey, white, brown, nodular, minor pyrite.

10,963'-10,966' 6" Limestone, grey, black, white, wavy, parallel laminations, micro stylolites, angular-anhydrite after gypsum interclasts, calcite healed hairline fractures, rare inter-granular porosity, oil-stained.

10,966' 6"-10,969' 11" Anhydrite, limy mudstone, grey, brown, white, nodular, coalesced anhydrite, parallel, non-parallel laminations, algal base with dolomitic clasts, interbedded, vertical hairline fractures increasing with depth, intra-crystalline porosity, inter-granular porosity. Interbedded dolomudstone occurs as cap to anhydrite, oil-stained.

TS: 10,969' 10" Limy mudstone, brown, light-brown, black, translucent, very fine-grained (lower), microspar matrix and organic muds in part, anhedral to sub-hedral dolomite and anhydrite nodules (≤ 0.5 mm), stylolites, inter-granular porosity (3%).

10,969' 11"-10,973 Dolomitic silty-mudstone, limy mudstone, brown, grey, black, dissolution seems, wavy laminated, parallel laminated, soft-sediment deformation, peloidal, rare fossil fragments, anhydrite pseudomorphs after gypsum interclasts (within the top 9"), stylolites, pinpoint intra-crystalline porosity, oil stained. Interbedded limestone above, basal shale partings.

10,973-10,974' 4.5" Anhydrite, dark grey, green, white, parallel laminations, wispy laminations, chicken-wire anhydrite.

10,974' 4.5"-10,977' 6" Limy mudstone, dolomitic mudstone, planar, non-parallel laminations, massive, crystalline limestone, black angular anhydrite pseudomorphs after gypsum interclasts, rare stylolite, horizontal and vertical calcite-healed fractures, inter-granular pinpoint porosity.

TS: 10,975' Limy mudstone, grey, black, translucent, fine-grained (lower), fine grained (upper), coarsens upward, microspar (top) pseudospar (bottom) matrix, anhedral, inter-granular porosity (8%).

10,977' 6"-10,988' 9" Anhydrite, dolomudstone, grey, brown, white, nodular and coalesced anhydrite, parallel laminations, non-parallel laminations in part, dissolution seems, crinkly microbial laminae, in part, minor soft-sediment deformation, interbedded in part, rare calcareous muddy laminae, bioturbated, hairline fractures, intra-crystalline porosity. Dolomudstone occurs as cap and base to anhydrite.

10,988' 9"-10,993' 7" Limy mudstone-wackestone, black, grey, *Amphipora*, black sub-angular anhydrite pseudomorphs after gypsum, white angular anhydrite, rare hairline fractures, intra-crystalline pinpoint porosity, inter-granular pinpoint porosity, faint oil stain.

TS: 10,991' *Amphipora* (mixed fossil) limy wackestone-grainstone, brown, grey, translucent, coarse-grained (lower), calcite matrix, fossiliferous, *Amphipora*, peloids, benthic uniserial foraminifera, inter-particle porosity, fracture porosity (30%).

10,993' 7"-11,002' Limy mudstone, black, grey, brown, wispy laminated, parallel laminated, brachiopod, *Amphipora*, bryozoans, bioturbated, mottled, inter-granular pinpoint porosity, intra-skeletal pinpoint porosity.

11,002'-11,004' 2" Limy silty-wackestone, brown, light brown, wispy laminated, stromatoporoids, brachiopod, coral fragments, bryozoans, bioturbated, *Planolites*, rare authigenic pyrite, stylolites, healed fractures, intra-skeletal porosity, pinpoint inter-granular porosity, oil stained.

11,004' 2"-11,008' 7" Limy wackestone, brown, grey, light brown, solution seems, stromatoporoids, bryozoans, anhydrite-filled vugs, rare small amplitude stylolites, anhydrite-healed hairline fractures, inter-granular pinpoint porosity, intra-skeletal porosity, oil stained.

11,008' 7"-11,022' Limy mudstone, grey, light brown, coral fragments, mottled, bioturbated, brachiopods, white anhydrite-filled vugs, rare low-amplitude stylolites, rare horizontal fractures, inter-granular pinpoint porosity, oil stained.

TS: 11,009' Limy mudstone, brown, light-brown, translucent, very fine-grained (lower), calcite matrix, *Amphipora* fragment, burrowed, sub-hedral-anhedral dolomite rhombs, intra-crystalline, intra particle porosity, fracture porosity (3%).

Well #15412
API 3303300239
Equity Oil Company Federal 32-4
SWNE 4-143-103
Golden Valley County

10,679'-10,680' 2" Anhydrite, white, grey, nodular.

10,680' 2"-10,680' 11" Anhydrite, limy mudstone, brown, grey, wavy interbeds.

10,680' 11"-10,681' 10" Dolomitic silty-mudstone, light-brown, grey, wavy-bedded, microbial laminated, intra-crystalline porosity.

10,681' 10"-10,683' 5" Dolomitic silty-boundstone, light-brown, dark-grey, domal stromatolites, intra-crystalline, pinpoint porosity, anhydrite-filled vugs, in part, oil-stained.

TS: 10,682' Crystalline dolomite, grey, black, fine-grained, fine carbonate mud matrix and anhydrite, subhedral-euhedral dolomitic rhombs and anhydrite-filled solution seams, intra-crystalline porosity (25%).

10,683' 5"- 10,686' 2" Anhydrite, light-brown, dark grey, grey, white, nodular in part, wavy laminated, planar laminated.

10,686' 2"- 10,688' 4" Dolomitic silty-mudstone, light-brown, grey, non-parallel, rare cross bedding, sub-angular dolomite rhombs, anhydrite-filled vugs and seems, inter-crystalline porosity.

10,688' 4"-10,689' 10" Limy mudstone, black, massive, wavy laminated in part, microbial laminated, angular-crystalline clasts, vertical fracture, stylolites, inter-granular porosity, faintly oil stained.

10,689' 10"- 10,691' 8" Anhydrite, dolomudstone, grey, brown, white, nodular, massive, parallel, non-parallel in part, interbedded in part, rare calcareous muddy laminae, hairline fractures. Dolomudstone occurs as cap to anhydrite.

TS: 10,689' 3" Crystalline dolomite, white, brown, grey, fine-grained, calcite matrix, euhedral-subhedral dolomite rhombs, anhydrite-filled intra-crystalline porosity.

10,691' 8"-10,696' 9.5" Anhydrite, dolomudstone, buff, cream, coalesced and nodular anhydrite with dolomudstone partings, intra-crystalline porosity. Locally unconformable with the Three Forks Formation above.

10,696' 9.5"-10,698' 7" Dolomudstone, light-brown, buff, microbial laminated, cross-bedded, nodular anhydrite in part, healed horizontal hairline fractures, intra-crystalline porosity.

10,698' 7"-10,706' 9.5" Limy wackestone, brown, light brown, dark grey, skeletal, *Amphipora*, coral, stromatoporoids, pyrite, nodular anhydrite, stylolites, calcite-healed fractures, vuggy in part, intra-granular pinpoint porosity and inter-granular porosity. Calcite base with nodular intra-clasts. Unconformable above.

TS: 10,702' 6" Mixed-fossil lime packstone, white, brown, grey, medium-grained, carbonate mud matrix, vuggy, intra-particle porosity (10%).

10,706' 9.5"-10,729' Limy silty-mudstone, brown, wavy laminations, euhedral calcite-filled vugs, abundant transparent, milky-white anhydrite, stylolites, excellent inter-granular porosity, oil stained.

TS: 10,725' 8" Lime mudstone, anhydrite, crystalline dolomite, yellow, dark-grey, fine-grained, sub-hedral, hairline fractures, intra-granular, inter-granular porosity and fracture porosity (12%).

10,729'-10,738' 3.5" Limy mudstone, grey, light brown, mottled, heavily bioturbated, brachiopods, white anhydrite-filled vugs, rare, horizontal fractures, inter-granular pinpoint porosity, oil stained.

Well #15679

API 3303300251

FH Petroleum Corp. Brown 42-28

SENE 28-142-103

Golden Valley County

10,700'-10,702' 8.5" Anhydrite, white, dark grey, medium-brown, nodular, rare stylolites, rare healed vertical hairline fractures.

10,702' 8.5"- 10,703' 10.5" Limestone, dolomudstone, anhydrite, dark-grey, brown, white, wavy laminations, anhydrite nodules, abundant vertical calcite and anhydrite-healed hairline fractures refract from anhydrite to dolomite or lime, inter-granular porosity, intra-crystalline porosity, oil stained.

10,703' 10.5"-10,707' 1" Dolomudstone, light-brown, black, massive, wavy laminations, angular, sub-angular anhydrite and dolomite clasts, anhydrite nodules, vertical-healed hairline fractures, minor, planar laminated shale with authigenic pyrite and dolomudstone rip up clasts, intra-crystalline porosity, oil stained.

TS: 10,704' 3"-10,705' 5" Dolomudstone, light-brown, translucent, cream, very fine-grained (lower), microspar matrix, microbial laminated in part, irregular anhydrite nodules, euhedral anhydrite filled fractures, sub-hedral to euhedral dolomite, intra-crystalline porosity (4%), fracture porosity (1%). Composite description of two thin sections.

10,707' 1"-10,708' 6" Anhydrite, dolomudstone, white, light-brown, dark-brown, nodular anhydrite, wavy laminated dolomudstone, intra-crystalline porosity.

10,708' 6"-10,710' 3.5" Dolomudstone, light-brown, dark-grey, wavy laminations, in part, parallel laminated, abundant light-brown rip up clasts, horizontal fractures, intra-crystalline porosity, oil stained.

TS: 10,708' 10" Peloidal dolomudstone, brown, light-brown, translucent, very fine-grained (upper), microspar matrix, peloids, pellets, nodular anhydrite, anhydrite porosity fill, intra-crystalline porosity (<1%).

TS:10,709' 3" Microbial dolomudstone, brown, light-brown, gold, micrite matrix in part, microspar matrix in part, microbial laminates, rare skeletal fragments, sub-hedral to euhedral dolomite, horizontal hairline fracture porosity (<1%), intra-crystalline porosity (1%), oil stained.

TS: 10,709' 6"-10,709' 10" Dolomudstone, brown, translucent, light brown, very fine-grained (lower), micrite matrix, microbial laminated in part, anhydrite nodules, sub-hedral to euhedral dolomite, intra-crystalline porosity (4%).
Composite description of two thin sections.

10,710' 3.5"-10,712' 3" Mudstone, light-grey, grey, wavy laminations, anhydrite intra-clasts, inter-granular porosity, weakly oil stained.

10,712' 3"-10,720' Anhydrite, mudstone, white, grey, nodular anhydrite, interbedded mudstone, planar laminations, in part, minor-wavy laminations, stylolites, intra-crystalline porosity. Local unconformity with Three Forks Formation above.

10,720'-10,722' 9.5" Dolomudstone, brown, wavy laminations, contorted bedding, in part, anhydrite nodules, rare horizontal fractures, pinpoint intra-crystalline porosity, oil stained.

10,722' 9.5"-10,724' 1" Limy mudstone-wackestone, dark-brown-brown, wavy laminations, bryozoans, stylolites, inter-granular pinpoint porosity, oil stained.

TS: 10,723' Peloidal limy wackestone, brown, buff, translucent, very fine-grained (upper), micrite matrix, peloids, pellets, *Amphipora* skeletal fragments, sub-hedral to euhedral dolomite, anhydrite and calcite filled dissolution seam, sub-vertical fracture, healed sub-vertical fractures, stylolite, inter-granular porosity, intra-crystalline porosity, intra-skeletal porosity (5%), oil stained.
Composite description of two slides.

10,724' 1"-10,726' 8.5" Dolomudstone-wackestone, dark-brown-brown, sucrosic, wavy laminations, stylolites, anhydrite-filled vugs, excellent intra-crystalline pinpoint and fenestral porosity, oil stained.

10,726' 8.5"-10,728' Dolomudstone-wackestone, dark-brown-brown, sucrosic, wavy laminations, mud drapes, bryozoans, rare stylolites, muddy laminations, anhydrite-filled vugs, excellent intra-crystalline pinpoint and fenestral porosity, oil stained.

10,728'-10,741' 10" Dolomudstone-wackestone, dark-brown, brown, sucrosic, wispy laminations, in part, skeletal fragments, bioturbated, stylolites, anhydrite-filled vugs, excellent intra-crystalline pinpoint and fenestral porosity, oil stained.

10,741' 10"-10,749' 7.25" Dolomudstone, brown, grey, sucrosic, wispy laminations, mud drapes, rare skeletal fragments, heavily bioturbated, stylolites, nodular anhydrite, vuggy, good intra-crystalline pinpoint porosity, oil stained.

10,749' 7.25"-10,752" Limy dolo-mudstone, grey, light-grey, sucrosic, wispy laminated, heavily bioturbated, skeletal fragments, in part, brachiopod spicules, inter-granular porosity, oil stained.

10,752'-10,754' 6" Dolomudstone, brown, light-brown, sucrosic, wispy laminations, mud drapes, rare skeletal fragments, heavily bioturbated, stylolites, nodular anhydrite, vuggy, good intra-crystalline pinpoint porosity, oil stained.

10,754' 6"-10,758' 2" Limy mudstone, brown, light-brown, wispy laminations, horizontal fractures along laminae, inter-granular porosity, oil stained.

Well #20034

API 3308900620

Continental Resources, Inc. Debrecen 1-3H

3-140N-99W LOT 3

Stark County

10,987' 6"-10,988' Limy mudstone, dolomudstone, dark brown, light green, grey, interbedded limestone lag deposits, wavy parallel laminations, medium to coarse grained, angular skeletal clasts, calcite cement, nodular anhydrite, inter-granular porosity, intra-crystalline porosity. Gradational contact with the Three Forks Formation above.

10,988'-10,991' Anhydrite, light grey, dark grey, wavy bedded, wispy laminated, recumbent fold with muddy partings, nodular anhydrite, minor authigenic pyrite within stratified sections, rare horizontal fractures.

TS: 10,988' 5" Dolomudstone, light-brown, brown, very fine-grained (lower), calcite matrix in part, microspar matrix in part, sub-hedral, dolomite nodules, intra-crystalline porosity (2%), fracture porosity (1%).

10,991'-10,992' 2" Limy wackestone-packstone, opaque, dark brown, grey, wavy laminated, skeletal, numerous healed vertical hairline fractures confined by bedding planes, inter-granular porosity, oil stained.

10,992' 2"-10,995' 8.5" Dolomudstone, light-brown, dark-brown, parallel bedded, stylolite swarm, rare hairline horizontal fractures, intra-crystalline porosity, oil stained. Sharp contact above.

TS: 10,993' 7" Microbial dolomudstone, light-brown, brown, opaque, fine-grained (lower), pseudospar matrix, authigenic pyrite, anhedral, stylolites, intra-granular porosity (45%).

10,995' 8.5"-10,997' 1.5" Anhydrite, mudstone, grey, brown, nodular, wispy laminations, healed hairline fractures.

10,997' 1.5"-11,002' 3" Dolomudstone, anhydrite, limy mudstone, dark-grey, grey, interlaminated dolomudstone and anhydrite, bioturbated, rip up clasts, abundant anhydrite-filled hairline fractures, intra-crystalline porosity.

11,002' 3"-11,003' Anhydrite, white, medium-brown, nodular, wispy laminated.

11,003'-11,005' 7" Mudstone, anhydrite, medium-brown, grey, green, wispy laminated, interbedded, muddy rip up clasts, anhydrite clasts, rare horizontal fractures.

11,005' 7"-11,006' 1" Dolosiltstone, light brown, dark brown, parallel laminated, rip up clasts, anhydrite clasts, healed vertical-hairline fractures, horizontal fractures (<1 mm) intra-crystalline porosity.

11,006' 1"-11,007' 1" Limy wackestone, dark-grey, dark-brown, minor wavy laminations, *Amphipora*, bioturbated, soft sediment fill, rip up clasts, healed vertical calcite-filled hairline fractures (<= 1 mm), inter-granular, intra-skeletal porosity, oil stained.

TS: 11,006' 5" *Amphipora* limy packstone, brown, light-brown, buff, translucent, very coarse (upper), carbonate mud matrix in part, calcite cement in part, peloidal, organic mud wisps, abraded skeletal fragments, dolomite-filled inter-granular and intra-granular porosity (20%).

11,007' 1"-11,009' 4" Dolosiltstone, light-brown, medium-brown, white, massive, microbial laminated, nodular anhydrite in part, intra-crystalline porosity, oil stained.

TS: 11,007' 6" Dolomudstone, brown, cream, translucent, dark-brown, very fine-grained (lower), microspar matrix, heavily burrowed, anhedral, anhydrite-filled porosity, intra-crystalline porosity (4%), fracture porosity (1%).

11,009' 4"-11,021' 5" Limy wackestone-packstone, dark-grey, medium brown, wispy laminations, *Amphipora*, bryozoans, stromatoporoids, brachiopod, bioturbated in part, authigenic anhydrite, stylolite swarms, vugs, inter-granular pinpoint porosity, intra-skeletal pinpoint porosity.

TS: 11,020' Bryozoan limy wackestone, dark-brown, brown, cream, coarse-grained (upper), microspar matrix, fistuliporoid bryozoan, *Amphipora*, replacement dolomite along stylolites, anhydrite and calcite-filled vugs, fracture porosity, intra-crystalline porosity, inter-granular porosity (3%).

11,021' 5"-11,026' 4" Limy mudstone-wackestone, dark-brown, medium-brown, massive, wavy-laminated, stromatoporoids, authigenic anhydrite, stylolites, shale partings, healed hairline fractures (<1 mm), inter-granular pinpoint porosity.

11,026' 4"-11,059' 11" Limy mudstone-wackestone, light-brown, grey, wispy laminated, brachiopod, stromatoporoid fragments, coral, moderately bioturbated, authigenic anhydrite, healed hairline fractures (<1 mm), inter-granular porosity, pinpoint porosity, in part.

Well #21139

API 3308900646

Chesapeake Operating, Inc. Zent 30-138-95 A 1H

NENE 30-138-95

Stark County

9,989'-9,991' Anhydrite, brown, white, nodular, interbedded green mudstone and limy mudstone (brown), sub-parallel to wavy laminated, intra-crystalline porosity. Sharp, conformable contact with the red, argillaceous dolomudstone of the Three Forks Formation.

9,991'-9,992' Dolomudstone, limy wackestone, coalesced anhydrite, light-green, brown, parallel interbeds, peloids, authigenic pyrite, intra-crystalline porosity. Sharp contact above.

9,992'-9,993' Mudstone, anhydrite, dark-grey, white, nodular, anhydrite clasts, authigenic pyrite, anhydrite-healed hairline fractures, rare anhydrite-filled vugs. Sharp contact above.

9,993'-9,997' 9.5" Dolomudstone, light-brown, disturbed parallel bedding, anhydrite nodules, rare, pyrite-filled vugs, intra-crystalline porosity. Sharp contact above. Contains truncated anhydrite.

9,997' 9.5"-10,000' Anhydrite, white, chicken wire, planar laminated dolomudstone, grey, rare, healed hairline fractures.

10,000'-10,004' 1" Dolomudstone, limestone, dark-grey, grey, white, parallel laminated, interbedded calcareous muds and dolomudstones, nodular and coalesced anhydrite, soft sediment deformation, intra-crystalline porosity, inter-granular porosity, oil stained. Sharp contact above.

10,004' 1"-10,007' 9" Dolomudstone-siltstone, light-brown, brown, microbial laminations, bioturbated, rare skeletal fragments, stylolites, mud drapes, healed hairline fractures, continuous fracture, rare mud nodules, intra-crystalline porosity. Sharp contact above. DST

10,007'9"-10,015" Limy mudstone, dolomudstone, brown, dark-grey, massive, wispy-bedded, wavy bedded, rare skeletal fragments (near base), bioturbated, stylolites, healed hairline fractures confined by bedding, intra-crystalline porosity. Sharp contact above.

10,015'-10,018' Limy mudstone-siltstone, dark-brown, wispy laminated, dolomitic rhombs, *Amphipora*, bryozoan, coral fragments, healed hairline fractures, inter-granular porosity. Sharp contact above.

10,018'-10,048' 5" Limy mudstone, dark-brown, brown, wispy laminations, heavily bioturbated, brachiopod valve fragments and spicules, rugose coral and coral fragments,

gastropod, stylolites, healed hairline fractures, inter-granular porosity. Gradational contact above. DST

10,048'5"-10,059' Limy mudstone, light-brown, bioturbated, rare skeletal fragments, stylolites, horizontal and vertical healed hairline fractures, rarely continuous, inter-granular pinpoint porosity. Gradational contact above.

Well #21424

API 3302501453

Denbury Onshore, LLC Johnson 43-27WNH

NESE 27-145N-95W

Dunn County

C+5'

11,100' 5"-11,104' 9.75" Anhydrite, dark-grey, grey, coalesced, relict stylolite, authigenic pyrite, abundant horizontal fractures. Sharp contact with the interbedded grey grainstone and green shale of the lower Three Forks Formation.

TS: 11,099' 9" Laminated dolomudstone, opaque, translucent, yellow, microspar matrix, mottled, anhydrite nodules (near base), poor inter-granular porosity, fracture porosity (<1%).

11,104' 9.75"-11,106' 7" Limy mudstone, dolomudstone, grey, brown, interbedded, skeletal fragments, abundant isolated networks of healed hairline fractures, inter-granular porosity. Sharp contact above.

TS: 11,105' 7" Limy dolomudstone, brown, light-brown, cream, grey, fine-grained (lower), microspar matrix, subhedral, vuggy, inter-granular and intra-crystalline porosity (50%).

11,106' 7"-11,107' 6" Dolomudstone, brown, dark-brown, wavy to planar-bedded, skeletal fragments, peloids, desiccation cracks, basal stylolite, rare horizontal hairline fractures, intra-crystalline porosity, readily absorbs water, oil stained. Sharp contact above. DST

11,107' 6" 11,109' 3" Anhydrite, dark-grey, coalesced, 1/2" dark shale bed near the top, stylolites, anhydrite rip up clasts near the top, multiple wavy healed and reactivated fractures. Sharp, unconformable contact above. DST

11,109' 3" 11,110' Dolomudstone, brown, wavy bedded where preserved, stromatolites, algal matt, skeletal fragments, brachiopod valve fragments, good intra-crystalline porosity, readily absorbs water, oil stained. Sharp contact above.

TS: 11,109' 5" Dolomudstone, brown opaque, translucent, peloidal dolowackestone, very fine-grained (lower) to medium-grained (upper), microspar

matrix, peloids, *Amphipora* fragments, microbial crusting, wisps of organic material, blocky anhydrite with twin lamellae, blocky dolomite with simple twinning, hairline fractures and organically-filled hairline fractures, intra-skeletal porosity (3%), inter-crystalline porosity (5%), fracture porosity (1%).

11,110'-11,112' 5" Limy mudstone, dark-brown, planar bedded, horizontal and vertical fractures, and hairline fractures occasionally confined by bedding surfaces, inter-granular porosity. Sharp contact above. DST

11,112' 5"-11,113' 7" Dolomudstone, brown, planar bedded (<1") stylolites, intra-crystalline porosity, oil stained. DST

11,113' 7"-11,122' 2" Dolomudstone, mudstone, anhydrite, green, dark-brown, light-brown. Mudstones are planar, ripple bedded with bryozoans and skeletal fragments, authigenic pyrite (near anhydrite), good inter-granular and intra-crystalline porosity. Coalesced anhydrite interbedded with the mudstones. Gradational contact above. DST

11,122' 2"-11,124' 3" Limy mudstone, dark-grey, wavy bedded, (<1/2"), vertical and horizontal fractures, inter-granular porosity. Gradational contact above.

TS: 11,122' 3" Limy mudstone, crystalline dolomite, brown, grey, opaque, fine-grained (upper), dolomite matrix, coral fragments, replacement dolomite, stylolite swarm, hairline fracture, fracture porosity (<1%).

11,124' 3"-11,128' Dolomudstone, light-brown, brown, wavy to planar parallel bedded (<1mm-1/2"), soft-sediment deformation, stylolites, fractured anhydrite-after gypsum nodules (near top), intra-crystalline porosity. Sharp contact above.

TS: 11,126' 9" Limy mudstone, brown, grey, cream, fine-grained (lower), microspar matrix, euhedral to sub-hedral dolomite crystals, planar bedded, inter-granular porosity (7%).

11,128'-11,131' 1" Limy mudstone, dark-grey, dark-brown, planar parallel bedded, stylolites, healed vertical hairline-fractures confined to bedding planes, horizontal and arcuate fractures, inter-granular porosity. Sharp contact above.

11,131' 1"-11,132' Limy mudstone-wackestone, dark-grey, dark-brown, planar bedded (where preserved) *Amphipora*, bryozoans skeletal fragments, healed hairline fractures, inter-granular porosity. Gradational contact above. DST

TS: 11,131' 1" Dolomudstone, buff, brown, opaque, very fine-grained (lower), dolomite matrix, microbial laminae, sub-hedral, low amplitude, low frequency stylolite.

11,132'-11,136' 6" Limy mudstone-wackestone, light-brown, brown, dark-grey, skeletal fragments, stylolite swarms, vertical fractures, inter-granular porosity. Sharp contact above. DST

11,136' 6"-11,137' Limy wackestone-packstone, light-brown, grey, heavily bioturbated, bryozoans, *Amphipora*, brachiopod valve fragments, inter-granular porosity. Gradational contact above.

11,137'-11,155' Limy mudstone, light-brown, grey, dark-grey, bioturbated in part, *Amphipora*, brachiopod valve, coral skeletal fragments, anhydrite-filled vugs, soft sediment deformation, abundant healed fractures, in part confined by burrows, mud drapes or stylolites, inter-granular porosity. Gradational contact above.

Well #21734

API 33033003308

Chesapeake Operating Inc. OLSON 12-139-104 A 1H

SWSW 12-139-104

Golden Valley County

10,493' 6"-10,497' 3.5" Anhydrite, white, brown, grey, green, nodular, coalesced, in part, chicken wire fabric, concave down healed hairline-fractures. Gradational contact between the red siltstones of the Three Forks Formation.

TS: Dolomitic limy wackestone to mudstone, grey, brown, yellow, opaque (grains), microspar matrix, rounded lithic fragments, vertical organic-filled hairline fractures confined to organic intervals, subhedral, inter-granular porosity (2%), fracture porosity (<1%). Carbonaceous mudstone is suprajacent the wackestone with a gradational contact.

10,497' 3.5"-10,497' 8.5" Limy mudstone, dark-brown, grey, wavy laminations, authigenic pyrite, concave down, calcite healed hairline fractures, inter-granular porosity.

10,497' 8.5"-10,501' 10" Dolomudstone, light-brown, brown, planar bedding, anhydrite rip-up clasts, rare shale partings, anhydrite couplets (1-2 cm), intra-crystalline porosity.

TS: 10,498' 4" Crystalline dolomite, cream, very fine-grained-lower, dolomite matrix, sub-hedral, organic-filled hairline fractures, intra-crystalline porosity (28%), fracture porosity (<1%).

10,501' 10"-10,502' 2" Anhydrite, white, grey, nodular, healed hairline fractures.

10,502' 2"-10,504' 7" Mudstone, grey, green, red, wavy laminations, abundant nodular anhydrite, inter-granular porosity.

10,504' 7"-10,509' 5" Anhydrite, dolomudstone, white, grey, dark-brown, nodular chicken-wire, interbedded, in part wavy laminations, in part wispy laminations, microbial laminates, horizontal hairline fractures along bedding planes, intra-granular porosity.

TS: 10,509' 3" Microbial dolomudstone, cream, brown, opaque, very fine-grained (lower), dolomite matrix, anhedral, rare skeletal dissolution molds, poor inter-granular porosity.

10,509' 5"-10,513' 10" Dolomudstone-siltstone, brown, light-brown, green, wavy laminations, abundant nodular anhydrite near the top and middle, skeletal fragments near

base, healed vertical hairline fractures confined to anhydrite near the top, medium grained calcareous sediment near the middle containing microbial laminates (2"), inter-granular porosity, excellent intra-crystalline porosity.

TS: 10,511' 7" Peloidal dolomudstone, brown, opaque (grains), translucent, very fine-grained (lower), dolomite matrix, anhedral, microbial wisps, pellets, anhydrite-filled shrinkage fractures, horizontal and vertical hairline fracture porosity (1%).

10,513' 10"-10,517' Dolomudstone-wackestone, black, dark-brown, bryozoans, skeletal fragments, concave up shell fragments, stylolites, in part, anhydrite nodules, rare wavy laminations, inter-granular porosity.

10,517'-10,521' 2.5" Dolomudstone, brown, dark-brown, skeletal fragments, bioturbated, stylolites, visible pinpoint and fenestral porosity.

TS: 10,521' Crystalline dolomite, yellow, brown, opaque, very fine-grained (upper), organic mud matrix in part, rare authigenic pyrite, sub-hedral to euhedral (where vuggy), organic mud-filled hairline fractures, inter-granular (23%), intra-crystalline porosity (5%), moldic, and vuggy porosity in part.

Appendix B Potentiometric Surface

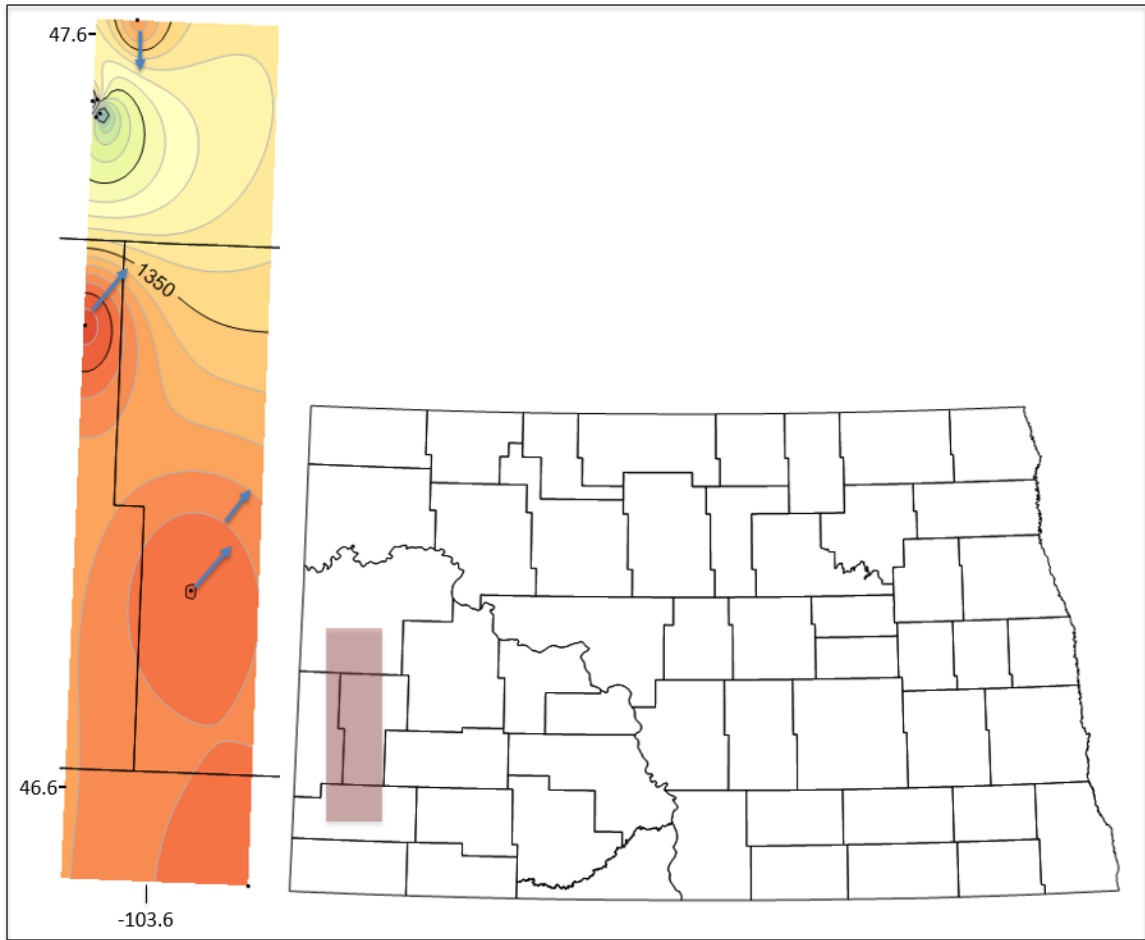


Figure 27. Potentiometric surface showing flow direction based on contributing wells. Surface is constructed with successful results from DST's. All surfaces have been blanked at data limits. (Wells with contributing DST shown)

Table 2. Data composing potentiometric surface constructed in SURFER (2013). Values calculated from Equation 1.

API #	NDIC #	KB (ft.)	RD (ft.)	Lat	Long	hw (ft.)	BHP (psi)	Dg (psi)
3300701042	11335	2495	10229	46.870067	-103.511816	1600.615385	4854	0.52
3303300163	11422	2363	10582	47.216251	-103.736171	1667.538462	5141	0.52
3305302097	11729	2378	10990	47.491481	-103.731907	1111.076923	5056	0.52
3305302482	13796	2420	11052	47.497296	-103.725385	400.6923077	4697	0.52
3308700071	5499	2863	9798	46.484277	-103.381177	1590	4433	0.52
3305301085	7680	2380	10902	47.512192	-103.739394	1639.538462	5284	0.52
3305301664	10105	2288	11013	47.621212	-103.658244	1471.153846	5302	0.52
3305302259	12560	2307	10900	47.514773	-103.730931	1216.615385	5101	0.52

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