Lithological and sequence stratigraphic examination of the Madison Group marker beds, eastern Williston Basin margin, North Dakota

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University of North Dakota

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LITHOLOGICAL AND SEQUENCE STRATIGRAPHIC EXAMINATION OF THE MADISON GROUP MARKER BEDS, EASTERN WILLISTON BASIN MARGIN, NORTH DAKOTA

by

Troy JD Skitt

Bachelor of Science, Colorado State University, 2011

A Thesis
Submitted to the Graduate Faculty
of the
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for the degree of

Master of Science

Grand Forks, North Dakota
December
2013
This thesis, submitted by Troy JD Skitt 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.

Dr. Richard LeFever, Chairperson

Dr. Nels Forsman,

Dr. Joseph Hartman,

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Dr. Wayne Swisher
Dean, School of Graduate Studies

Date

December 10, 2013
**PERMISSION**

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ABSTRACT

The Frobisher-Alida interval consists of eight log-defined subintervals or “beds” within the Mississippian upper Mission Canyon and lower Charles Formations of the Madison Group in the Williston Basin. The subintervals are composed of predominantly evaporite and carbonate lithologies, and include in descending order: 1) Midale, 2) Rival, 3) Bluell, 4) Sherwood, 5) Mohall, 6) Glenburn, 7) Wayne, and 8) Landa. The top of the lower six subintervals are separated by thin but areal extensive log-defined markers of contrasting lithologies and include in descending order: 1) State A, 2) Sherwood Argillaceous Marker (S.A.M.), 3) K-1, 4) K-2, 5) K-3, and 6) Landa Marker. An additional localized marker, State A2, is identified defining the lower boundary of an Upper Bluell subinterval. This study focuses on the lithologic and sequence stratigraphic significance of markers with the exception of the Landa Marker.

The area studied covers Burke, Mountrail, Renville, Ward, western Bottineau and northwestern McHenry Counties in North Dakota. Geologically, the region is situated on the eastern flank of the Williston Basin; characterized by a shallow dipping (between 0.25 and 0.5 degrees) carbonate platform of an epicontinental sea on the western flank of the North American craton.

Seventy-three marker descriptions were completed on the six markers from fifty-eight different cores throughout the study area. Six lithotypes reflecting unique depositional conditions were identified within the markers and include: 1) anhydrite, 2) dolomudstone, 3) dolomitic sandstone, 4) calc-mud/wackestone, 5) grain-supported, and 6) skeletal wackestone. Of these, the dolomudstone and dolomitic sandstone lithotypes are considered characteristic.
marker bed lithotypes, while the remaining are present as interbeds. The lithotypes reflect deposition in a variety of environments from a supralittoral, salina-like embayment to the east, through shallow sublittoral settings and into an open marine environment to the west.

The section studied lies within the first-order Kaskaskian megasequence and second-order Madison sequence which includes part of the upper Bakken shale and extends to the basinwide Madison unconformity. The Frobisher-Alida interval represents a single third-order sequence spanning 2-3 million years and the compositional subintervals are considered fourth-order sequences.

The subintervals are progradational and become increasingly restrictive up section and therefore represent individual fourth-order regressive systems tracts. Markers dominated by the dolomudstone lithotype (State A, State A2, S.A.M.) reflect deposition during a highstand systems tract where the basal contact represents a fourth-order maximum flooding surface. Dolomitic sandstone markers reflect initial deposition during a lowstand systems tract with unconsolidated sediments reworked and further cemented with the subsequent transgressive tract. Contrasting sediment input and consolidating mechanisms obscure definitive sequence surfaces; therefore, a sequence stratigraphic model is defined that places the maximum regressive surface at the lower contact and maximum flooding surface at the upper contact of the sandstone dominated markers.
CHAPTER I

INTRODUCTION

Geographic and Stratigraphic Setting

This study area is located in eastern North Dakota and includes all of Burke, Mountrail, Renville Ward, western Bottineau, and northwestern McHenry Counties (Figure 1). The interval studied is known as the Frobisher-Alida in the North Dakota part of the basin. The Frobisher-Alida is one of five, informal, log-defined intervals within the Mission Canyon and Charles formations (Smith, 1960). The Frobisher-Alida interval is within the upper Mission Canyon and lower Charles Formations of the Madison Group. Biostratigraphic and coral zonation studies date these sediments from the Osagian to Meramecian Epoch (Sando, 1978; Sando and Mamet, 1981).

The Frobisher-Alida interval is further divided into eight log-defined subintervals, frequently termed “beds”. The subintervals, in descending order, are: 1) Midale, 2) Rival, 3) Bluell, 4) Sherwood, 5) Mohall, 6) Glenburn, 7) Wayne, and 8) Landa. The lower 6 subintervals or “beds” were defined by Harris et al. (1969) where thin but regionally extensive marker beds, or “markers”, separate the beds. The marker beds define the top of each subinterval and named, in descending order: 1) State A, 2) Sherwood argillaceous marker (S.A.M.), 3) K-1, 4) K-2, 5) K-3, and 6) Landa marker. The Landa subinterval, and corresponding Landa marker, however, was excluded from this study due to relatively limited areal extent and difficult marker identification (Figure 2). An additional marker is recognized in this study as the State A2. Hendricks et al. (1987) identified this marker as pervasive in and around Burke County;
Figure 1: Study area with location of cores used in this study and marker present in core at each location. Overlaid on county boundaries (black lines) and townships (blue lines) with position of Nesson Anticline (Heavy black arrows). Inset: Location of study area with outline of the Williston Basin.
Figure 2: Gamma ray type curve of Frobisher-Alida interval markers and subintervals examined in the study. NDGS # 11646, North Haas field, NWNW 17-163-82.
stratigraphically positioned between the State A and S.A.M. and is used here to separate the Bluell subinterval into the overlying Upper Bluell and underlying Bluell beds.

In core, the markers are identified by a variation in lithology from the surrounding rocks. Gamma ray logs record elevated levels of radioactivity due to K\textsuperscript{40} bearing clay minerals in marker bed lithologies (Quinn, 1986). The marker beds are known to cut across evaporite and carbonate lithologies, as well as formation boundaries (Lindsay, 1988). The focus of this study is on the lithologic characteristics and sequence stratigraphic significance of these marker beds.

**Geological Setting**

The Williston Basin of North Dakota, South Dakota, Montana, as well as the Canadian provinces of Manitoba and Saskatchewan, is an intracratonic sedimentary basin located on the western flank of the North American craton. The evolution of the basin began in the Ordovician and since was intermittently downwarped throughout the remainder of the Paleozoic and Mesozoic eras (Gerhard et al., 1982; Sandberg, 1964). Nearly 16,000 ft of sedimentary rocks are preserved in the deepest part of the basin (northwest Dunn County, North Dakota) representing every geologic period from present to the Precambrian (Figure 3) (Gerhard et al., 1982).

The study area is situated on the eastern flank of the basin from the emergence of the Frobisher-Alida interval, beneath the basinwide Madison unconformity (around R77W), to the Nesson Anticline (R95W): the most prominent intrabasinal structure which formed from reactivated movement of Precambrian blocks (LeFever et al., 1987).

Early Madison deposition was characterized by normal marine conditions beneath an epicontinental sea that expanded across areas of the craton, and connected to the open ocean to the west via the Montana Trough (Gerhard et al., 1982). The predominantly normal marine conditions which persisted through deposition of the Lodgepole Formation gave way to an
Figure 3: Paleozoic and Mesozoic stratigraphic column of the Williston Basin. From Gerhard et al. (1982). Expanded Mississippian stratigraphic with formation, interval and age correlations of the Madison Group. Modified from Lindsay (1988).
increasingly more restrictive carbonate and evaporite shelf setting of the Mission Canyon and Charles Formations respectively. The end of Madison deposition was characterized by widespread evaporite precipitation extending basinward from the northeast margin of the Williston Basin (Carlson and Anderson, 1966).

**Previous Works**

Porter (1955) first recognized very thin clastic beds within the overall limestone and evaporite sequence of the Madison Group. He suggested these beds represent “time-lines,” which resulted from epeirogenic fluctuations during sedimentation. Proximal anhydrites, persistence of individual beds, and internal structures revealed deposition occurred in very shallow, transient bodies of water that were episodically scattered across the eastern shelf (Fuller, 1956).

Acknowledging the beds as reliable time markers, Harris et al. (1966) characterized deposition during an abrupt and short-lived influx of terrigenous sediments during an eastward transgression of the sea. Additional, interpretations suggest the markers represent “kick-backs” from a more restricted and saline environment to a less restrictive and less saline one (Irwin, 1965).

Other authors have suggested these beds mark the culmination of basinwide regressive phases, where accumulations of arenaceous sediments were reworked into thin, aerially extensive beds by aeolian processes (exception to the State-A marker) (Potter, 1995; Kent, 2004). However, alternate concepts were proposed for the expanded “Kisbey” sands in southwestern Manitoba and parts of eastern Bottineau and Renville counties. Kent (2004) described thick accumulations as remnants of aeolian dunes, while Potter (1995) characterized deposition in channels incised across the shelf.
Historically, Madison group marker beds have been subject to blanket descriptions with little regard towards differentiating between individual markers. Argillaceous, sandy, dolomitic mudstone beds and some sandstone are common descriptors used in the literature. Only recently has attention been given to the intricacies of individual markers, primarily those rich in quartz sands (Potter, 1995; Kent, 2004; Kent, 2007; Petty 2010).

**Purpose**

The purpose of this study is to: 1) identify the areal extent of each marker bed within the Mississippian Madison Group from characteristic log signatures across the eastern flank of the Williston Basin in North Dakota; 2) describe and interpret the changes in depositional settings of each marker bed within the study area; and 3) identify the sequence stratigraphic significance of the marker bed within the overall regressive sequence of the Madison Group.
CHAPTER II

METHODS

Seventy-three marker bed descriptions were done on fifty-eight different cores throughout the study area (Appendix A). Descriptions completed on each marker are as follows: State A (18), State A2 (8), S.A.M. (19), K-1 (12), K-2 (11), and K-3 (5). Cores used in this study were selected based on geographic position to incorporate the largest sample area for each marker (Figure 1). Preference was given to cores that penetrated the entire thickness of the marker when multiple cores were accessible in close proximity.

Cores were examined using a hand lens and binocular microscope. Hydrochloric acid diluted to 10% was used to aid in identification of principal rock type. A long and short wave ultraviolet light was used to confirm oil staining. Core chips were sent to Weatherford Laboratories for evaluation of total organic carbon content. Carbonates were described in accordance to the classification scheme developed in Dunham (1962), and evaporite forms follow that of Maiklem (1969).

Cross section and areal maps were constructed in Petra from a preloaded data set of 3,824 well logs by Dr. Richard LeFever. Additional wireline log investigations including confirmation of cored intervals were completed with the aid of the Petra software. When necessary, supplemental logs and well information were retrieved from the North Dakota Industrial Commission website.

Measurements in this study were taken and recorded both in English and metric units. Conventional units commonly used for specific applications were employed accordingly. For
example, core and log depths were recorded using feet, and grain sizes reported in millimeters or centimeters. Units of measure (English or metric) are included with corresponding values for reference.
CHAPTER III
LITHOTYPE DESCRIPTIONS

Anhydrite Lithotype

The anhydrite lithotype consists of white to light grey anhydrite in various forms including bedded, chicken wire, enterolithic, and nodular. Grey dolomitic and argillaceous mudstone and tan to light brown micrite, of the dolomudstone and calc-mud/wackestone lithotypes respectively are common as interbeds and as an interstitial matrix (Figure 4). Thin wisps and planar lamina 1 to 2 mm thick of black, organic-rich shale dissect thick sections of predominantly bedded anhydrite. Infrequent thin (<1 in, <25 mm) beds of broken coated grainstones are present and interpreted as storm generated deposits.

The anhydrite lithotype is considered a non-marker lithotype despite localized interbeds within individual marker beds. This lithotype dominates the eastern portion of the study area and the lowermost anhydrite is found continuously shallower (stratigraphically) from east to west.

Dolomudstone Lithotype

The dolomudstone lithotype consists of dark grey, argillaceous, intensely dolomitized and bioturbated mudstones (Figure 5) that commonly exhibit a dark to light yellow color when dolomitization is most extensive. This lithotype is present in the State A marker throughout the study area, and is common in the S.A.M to the east of the paleoshoreline. Dolomudstone is less...
Figure 4: Anhydrite lithotype. a) Bedded form with anhydrite cemented enterolithic dolomudstone, NDGS # 38, 4235.3 ft, Wildcat, SWSE 31-160-81. b) Condensed nodular to chickenwire form with argillaceous dolomudstone infilled water escape conduits, NDGS # 38, 4231 ft, wildcat, SWSE 31-160-81. c) Chickenwire form, NDGS # 5809, 5861.2 ft, Wildcat, SENE 3-157-86.
common in the K1 and K2 markers where the lithotype is typically sandier and grades rapidly into the fine dolomitic sandstone lithotype.

Allochems, where present, constitute less than 10% of the rock and include skeletal and, less commonly, non-skeletal grains. Skeletal grains include echinoderms and brachiopods, and are usually found near the base of the lithotype throughout much of the study area. Skeletal grains are typically replaced by saddle dolomite or white anhydrite, and corals often display greater sparry calcite content. Non-skeletal grains are rare, and include pellets and micritized, algal oncoids.

Mineralogically, this lithotype is dominated by dolomite. Lesser amounts of calcite, anhydrite, and silica are present predominantly as replacement and crystalline, pore-occluding cements. Disseminated frambooidal pyrite is responsible for intense patterning frequently seen in this lithotype. Anhydrite nodules are not uncommon, especially where the adjacent anhydrite lithotype persists. The argillaceous content, lending the characteristic grey color, is illite; identified in a previous study through powder x-ray diffraction analysis (Stephens, 1986).

Dolomite in this lithotype is most common as fabric retentive and microcrystalline replacement form. Stephens (1986) identified three forms of dolomite in a similarly reported lithotype through detailed micropetrographic analysis: 1) fine-grained replacement (≤20 μm), 2) coarsely crystalline replacement (15-120 μm), and 3) saddle dolomite replacement and cement (≤4 mm). Texturally all of these forms appear to be present; however, without an extensive micropetrographic analysis in this study, these forms cannot be confirmed. The first type comprises >90% of the dolomite present. The second form is likely present in the light tan to yellow dolomudstone as a coarser, sucrosic texture always accompanies the color. The third type predominantly occludes moldic and fenestral pores.
Figure 5: Dolomudstone lithotype. a) Argillaceous dolomudstone with cryptalgal laminations and framboidal pyrite patterning, NDGS # 14815, 7887 ft, Banner field, SWSE 23-151-89. b) Sucrosic dolomudstone with framboidal pyrite patterning, NDGS # 14815, 7860 ft, Banner field, SWSE 23-151-89.
The dolomudstone lithotype is commonly homogenized and massive in texture probably in part from bioturbation. Faint planar laminations 0.2 to 0.5 mm are common between argillaceous silt and carbonate mudstones, though more often dissected by small <1 cm vertical burrows. Low-amplitude suture-seam stylolites are uncommon and often resemble organic-rich, slack-water laminations. Cryptalgal laminations are common near the top of the lithotype and appear stromatolitic; rarely concentrations may approach boundstone conditions.

Porosity in this lithotype is predominantly microintercrystalline and may exceed 20 to 30%. However, due to low pore-throat diameter, permeability is negligible; typically making this lithotype an impermeable barrier for hydrocarbon migration. Additional porosity may be present as fenestrae (<5 mm and ≤10%) or moldic, but typically occluded.

Dolomitic Sandstone Lithotype

The dolomitic sandstone lithotype consists of a very fine to medium grained quartz sandstone with interstitial argillaceous dolomudstone (Figure 6). The lithotype is typically light to medium grey but can appear light tan to brown depending on degree of hydrocarbon staining. Locally in the northeast portion of the study area, periodic exposure led to oxidization of interstitial mudstones, turning the rock shades of deep red and purple. This lithotype is preferentially found to the northeast and east though may be present as stringers (Kent, 2004) towards the southwest. The dolomitic sandstone is the principal rock type of the K1, K2, and K3 marker beds and is often referred to as the “Kisbey sands.”

Colorless to milky white quartz grains constitute >50% of the rock and are very well sorted. Grains vary from subangular to subrounded with a higher concentration of angular grains lower in the stratigraphic section and typically further to the east. Fragmental brachiopod shells are rare and typically concordant with bedding. Poikiloblastic and nodular
Figure 6: Dolomitic sandstone lithotype. a) Fine sandstone, dolomite cemented with crossbedded aeolian foreset NDGS # 16631, 6021 ft, Greenbush field, NESW 11-159-87. b) Poorly cemented oil stained sandstone, NDGS # 15347, 3941 ft, North Haas field, SWSE 24-163-83. c) Oxidized very fine sandstone with massive texture and faint ripple marks, NDGS # 1431, 3722.6 ft, Wayne field, NENE 31-162-81.
pyrite and anhydrite occur. The pyrite precipitation is dependent on the presence of organic matter and typically concentrated to select bedding planes. Anhydrite nodules are infrequent, often condensed, and located mainly where anhydrite cement persists.

Mineralogically, quartz dominates the dolomitic sandstone lithotype, but dolomite, anhydrite and silica (non-quartz) cements comprise much of the interparticle mineralogy; dolomite cementation is the most prevalent. This lithotype can include up to 10% of potassium-aluminum silica clay (Quinn, 1986). Anhydrite cement occurs most frequently where an adjacent anhydrite lithotype persists; and cementation can extend as much as 5 ft into the dolomitic sandstone lithotype. Silica cements have been reported in the form of chalcedony and celestite by various authors (Stephens, 1986; Hendricks, 1987; Lindsay, 1988).

The dolomitic sandstone lithotype is very homogenized and typically displays planar and tabular crossbedding where thin, clay-rich laminae and condensed anhydrite nodules preserve depositional fabric. Crossbedded foreset angles range between 5° and 25°, with the majority at 15°. Small (≤2 cm), mud-draped, current and bi-direction ripples are common in select cores.

Porosity in this lithotype is predominantly interparticle and averages 5 to 10% but may exceed 15% where cementation is poor. A strong dependence on porosity and cementation type is observed. Where anhydrite cements persist porosity may only reach 1 to 2%; conversely, solution enhancement of pores is common in dolomitic cements and porosity may exceed 15%. Solution enhancement is common along select bedding planes adjacent to argillaceous laminations which effectively channel formation fluids. Hydrocarbon production from the dolomitic sandstone lithotype has been reported for the Haas and North Haas fields of Bottineau County, among others.
**Calc-mud/wackestone Lithotype**

The calc-mud/wackestone lithotype consists of two types of rocks, light tan to brown calcareous and dolomitic mudstone and peloidal, algal, pisolithic and intraclastic calcareous and dolomitic wackestone (Figure 7). This lithotype commonly exhibits thin (typically <1 cm, rarely exceeding 2 cm) black, organic-rich shale laminae in both rock types. These rocks are in part argillaceous and dolomitic, often resembling the dolomudstone lithotype, though patterning and intensive dolomitization (>90%) is extremely rare. This lithotype is common in the S.A.M. to the west of the paleoshoreline and is found regularly throughout the intermarker bed intervals basinward of the anhydrite lithotype. Rocks of this lithotype not in the markers grade laterally to the west into rocks of the grain-supported lithotype.

Pellets, algal oncoids, and intraclasts with pisolithic coating comprise the majority of allochems present in both rock types. The calcareous mudstone lithology contains <10% allochems and the wackstone is matrix support with >10% allochems (Dunham, 1962). Grains range in size from 2 mm to >5 cm: averaging from 0.5 cm to 1 cm. Intraclasts are often condensed with a pisolithic coating, commonly containing ooids and broken pisoids from the adjacent grain-supported lithotype. Skeletal fragments comprise <10% of allochems. Skeletal grains include brachiopods and echinoderms, and rugose coral to the west. Non-skeletal allochems are typically micritized.

Mineralogically, the calc-mud/wackestone lithotype is composed of calcite, dolomite, and lesser amounts of anhydrite, silica, and non-carbonate muds. Calcite occurs as micrite and secondary spar. Dolomite, less pervasive than calcite, occurs mainly as fabric preserving microcrystalline replacement.

Anhydrite comprises >10% and occurs primarily as replacement and pore occluding crystallotopic forms. Anhydrite poikiloblasts and nodules (≤2 cm) are rare; confined to margins
Figure 7: Calc-mud/wackestone lithotype. a) Lightly bioturbated mudstone with wavy slack-water lamination, NDGS # 5809, 5877.5 ft, Wildcat, SENE 3-157-86. b) Peloidal wackestone with sparite-plugged fenestral pores, NDGS # 5809, 5888 ft, Wildcat, SENE 3-157-86. c) Peloidal and intraclastic mudstone to wackestone with organic-rich, black shale laminae NDGS # 3819, 4851 ft, Sevenmile Coulee field, SWNW 11-162-86.
adjacent to the anhydrite lithotype. Brown poikiloblasts referred to as “metasomatic anhydrite” (Fuller, 1956) occur along bedding planes and less commonly disseminated throughout beds typically <1ft thick.

Silica exists in two forms: 1) quartz sand and 2) non-quartz, cryptocrystalline. Quartz sand is fine, non-pervasive, and concentrated into thin beds <1 cm thick where it may be the dominant mineralogy. Non-quartz silica is rare, existing as chert nodules, isolated lenses and replacement of allochems. Stephens (1986) reported chert nodules up to 15 cm in an analogous lithotype.

Non-carbonate muds exist in two forms: 1) organic-rich shale and 2) potassium- and aluminum-silica clays (illite and smectite, respectively).

The calc-mudstone/wackestone lithotype typically displays laminations, sutured-seam stylolites and microstylomites. Laminations are most common in the mudstone and may be cryptalgal or slack water in origin: typically <1 mm thick, wavy to planar, and horizontal to sub-horizontal. Frequently laminations are condensed around allochems or may be disrupted by small (<5 cm) vertical burrows and dehydration structures. In many cases, extreme bioturbation led to complete destruction of previous structures. Hummocky cross stratification is often observed where quartz sand is present. Stylolites commonly contain large accumulations (can exceed 1 cm thick) of insoluble, non-carbonate muds.

Porosity in this lithotype is dominated by fenestral pores from organic decomposition. Dissolution and moldic pores typically make up <10% of total pore volume. Though porosity may exceed 20%, pores are normally occluded, leading to a net porosity of <5% in most cases. Hydrocarbon staining is common where pores are not occluded. Where dolomitization is prevalent, microinter- and intracrystalline porosity exists, though pore diameter prevents pores from being effective for hydrocarbon storage.
**Grain-supported Lithotype**

The grain-supported lithotype consists of light to dark tan and brown, grainstone to packstone (Figure 8). Allochems, in decreasing abundance, include ooids, pisoids, intraclasts, peloids, and bioclasts. Rocks of this lithotype are generally found with gradational contacts to adjacent rocks of the calc-mudstone/wackestone lithotype. These rocks are the most prominent lithology in the study area comprising a majority of the intermarker beds to the west of the shoreline. The grain-supported lithotype is a non-marker lithotype but interbeds are commonly found within the markers.

Ooids are <2 mm in diameter, occurring as spherical grains (occasionally broken) with radial fibrous and micritized centers. Pisoids are generally >2 mm in diameter, rarely spherical, more commonly micritized centers and often display 3 or more stages of growth banding.

Intraclasts are highly variable; ≤6 cm in the longest dimension but usually 0.5 cm to 1 cm, and commonly contain ooid with lesser pisoids and bioclasts. Intraclasts are often elliptical from compaction.

Peloids include fecal pellets, or aggregates thereof, and other unidentifiable allochems similar to those described by Stephens (1986). Non-fecal peloids are structureless micritized grains above the upper range of for fecal designation (0.15 mm) defined by Folk (1962, p. 64). Peloids <0.15 mm, when identified in aggregates, were assumed to be of fecal origin.

Bioclasts include skeletal grains and oncoids. Skeletal grains include: brachiopods, ostracodes, gastropods, echinoderms, and foraminifera. Bioclasts are rarely unbroken and commonly micritized. Occasional replacement by anhydrite and sparite is observed in skeletal grains.

Mineralogically, the grain-supported lithotype is dominated by calcite, with lesser amounts of dolomite and anhydrite. Calcite persists as cement; micrite and sparite, as well as
Figure 8: Grain-supported lithotype. a) Pisolitic and pseudo-oolitic intraclastic packstone to grainstone with fenestral and vugular porosity, NDGS # 9823, 4429 ft, Mohall field, SWNW 6-161-83. b) oolitic and intraclastic grainstone with underlying peloidal packstone, NDGS # 15784, 7653 ft, Wildcat, NESW 25-152-89. c) Oolitic and pisolitic packstone and grainstone with dissolution seams and collapse breccia from periodic exposure, NDGS # 15784, 7676.1 ft, Wildcat, NESW 25-152-89.
the compositional mineral of all allochems. Large transparent to translucent sparite (and less commonly saddle dolomite) rhombs ≤1 cm, more commonly 3 to 5 mm, line large solution enhanced pores and span voids where collapse breccia persists. Occasionally euhedral, milky anhydrite of similar size will form, where stratigraphically proximal to the anhydrite lithotype.

A vadose solution enhanced fabric is common in the grain-supported lithotype, notably aiding porosity development. Collapse breccia is observed in select cores. High amplitude (> 5 cm), sutured-seam stylolites are common. Desiccation features (including: micritic envelopes, teepee structures, and sheet cracks) are abundant in select intervals.

Porosity in this lithotype ranges between 10 to 15%, and can exceed 20%. Fenestral to vuggy porosity persists throughout the lithotype. Fenestrae are common in the packstone rock type where partial solution of the interstitial micrite has occurred. Fenestral pores are usually 2 to 6 mm and typically occluded. Vugular pores are common as interparticle and moldic in both rock types. Solution enhanced vugs typically range in size from 0.5 cm to 1 cm, but can be >3 cm. Oil saturation is common and hydrocarbon production can be lucrative.

**Skeletal wackestone Lithotype**

The skeletal wackestone lithotype consists of dark brown to black, laminated skeletal mudstones and wackestones (Figure 9). Skeletal allochems in decreasing order include: crinoids, brachiopods, rugose coral and bryozoans. The skeletal wackestone lithotype is considered a non-marker bed lithotype and is found primarily in the westernmost extent of the study area. This lithotype was infrequently observed in core during this study due to its spatial relationship with the disappearance of the marker beds. Rocks of this lithotype grade laterally to the east with rocks of the grainstone lithotype.
Compositionally this lithotype is dominated by calcareous mudstone with argillaceous and organic-rich shale laminae. Argillaceous sediments likely consist of potassium-aluminum silica clays (probably as illite) since gamma ray logs typically read higher overall in these rocks than previous lithotypes. Silica is also present as chert in disseminated nodules and occasionally as a bedded precipitant. Dolomite is locally pervasive where significant amounts of matrix have been replaced. Anhydrite occurs mainly as a replacement of skeletal grains. A spatial relationship between dolomitization and anhydrite replacement of allochems may be present in this lithotype (Petty, 2010). Sparry calcite also acts to occlude moldic pores where dissolution of allochems has occurred.

Laminations are black, argillaceous and typically organic-rich, and wavy or highly condensed around skeletal grains. Bioturbation is frequent in localized beds, leading to mottling in occasionally massive bedding.

Skeletal allochems are usually unbroken, with the exception of infrequent lag deposits, and crinoid stems more commonly occur segmented. Crinoid stems are 1 to 3 mm in diameter, and may be intact, up to 2 cm long. Brachiopods are typically concordant with bedding unless in higher energy lag deposits. White rugose coral ranges in size from 1 to 3 cm, and can exceed 5 cm in some cases. Corals are infrequent but easily recognized due to size and contrasting color.

Porosity is limited in the dense micritic matrix and occurs mainly as biomolds. Pore occlusion is typical in this lithotype. Significant intercrystalline porosity may be present locally where dolomitization has occurred, but permeability is low.
Figure 9: Skeletal wackestone lithotype. a) Echinoderm (crinoid) and coral wackestone with irregular reduced shale laminations, NDGS # 6982, 4064 ft, Haas field, NENE 26-163-83. b) Rugose coral and echinoderm wackstone interbedded with reduced mudstones, NDGS # 21762, 5522 ft, South Greene field, Lot2 30-160-85.
CHAPTER IV
DEPOSITIONAL INTERPRETATIONS

Dolomudstone lithotype

The dolomudstone lithotype was the product of an evolving, protected sub to supralittoral, sabkha-like lagoonal environment. Initial deposition likely occurred in a partially restricted, sublittoral marine environment under similar conditions as the calc-mudstone/wackestone lithotype. By the end of deposition of the dolomudstone, conditions were completely restricted, reducing and hypersaline. Allochems and internal structures are rare; therefore, the interpreted environment conceptually favors observed lithotype relationships, and satisfies criteria used to identify the regional setting of study area at the time of deposition.

Dolomitization of this lithotype has been characterized as syndepositional on the basis of dolomite crystal size and morphology (Stephens, 1986; Quinn, 1986). Tabular dolomitized bodies and adjacent anhydrite beds suggest dolomitization occurred under a reflux system (Jones and Xiao, 2005). Reflux dolomitization is common in a restricted marine environment where evaporation leads to over saturation of seawater with respect to sulfate (SO$_4^{-}$). Calcium (Ca$^{2+}$) is then removed from calcareous sediments and replaced with free magnesium (Mg$^{2+}$) dissolved in the seawater (Adams and Rhodes, 1960). Jones and Xiao (2005) modeled reflux dolomitization under variable conditions, and found the dolomitization followed by anhydrite precipitation was greatest (1.1%/k.y.) in carbonate muds (due to high reactive surface area) at temperatures near 50°C.
The low abundance of benthic fauna observed at the base of the lithotype is typically considered evidence for a stressed environment. Factors that may induce stress on local fauna include depleted nutrients, temperature extremes, and oxygen deficiencies. While a depleted food source can neither be confirmed nor dismissed in the scope of this study, speculation can be made with regard to temperature and dissolved oxygen levels.

A complete absence of epifauna and higher concentration of cryptalgal laminations up section is a characteristic of oxygen deficiency (Byers, 1977, p. 8). Byers (1977) noted that oxygen levels decrease due to reduced solubility when salinity levels are increased. Salinities, at the time of deposition, were near gypsum saturation, as indicated by nodular anhydrite commonly observed in this lithotype. The typical relationship between the dolomudstone and anhydrite lithotypes in core (anhydrite overlies dolomudstone) suggest salinities continued to increase; eventually surpassing gypsum saturation.

Continually increasing salinities and depleted oxygen levels are effects of a restricted, stagnant body of water and subsequent evaporation. Stagnation can be achieved by density stratification, or by a topographically positive barrier; physically restricting interaction with circulating ocean currents, although no study to date has identified the presence of a built up barrier.

Stephens (1986) suggested that reduced circulation due to frictional forces across the shallow shelf accompanied by slight topographic depressions may have had a restricting effect on the environment. Since it is unlikely the shelf was a completely flat plain, slight depressions are presumably present. Depression may have created a network of lows effectively reducing the mean elevation of the upper shelf. Similar conditions with mudstone deposition and high salinity brines have been observed in the Persian Gulf (Kassler, 1973). Because of the shallowness of the shelf at the time of deposition, stratification over a large area is unlikely since
shallow water depths would be susceptible to mild storm activity (LeFever, 2013, oral communication). Interaction with atmospheric condition would result in homogenization and oxygen replenishment. Therefore, it is likely elevated salinity levels had more of an effect on faunal restriction than dissolved oxygen levels.

Reduction of the dolomudstone is evident from the frambooidal pyrite causing the patterning in this lithotype. Framboids are a product of sulfide consuming anaerobic bacteria attacking newly formed pyrite crystals (Dixon, 1976). Patterning is observed disseminated, dissecting, and parallel to bedding surfaces throughout the mudstone. Therefore, formation of the pyrite is interpreted to be syndepositional, and anaerobic conditions must have persisted within the sediments.

Temperature effects can greatly influence biotic habitation, although the lack of conclusive temperature indicators only allows for speculation on this variable. Surface temperatures of 40°C (Perthuisot, 1977) are common and sometimes exceed 50°C (Butler, 1969) in the Trucial Coast (UAE). Trucial Coast is considered to be the nearest modern analog to the regional environment during deposition (Hendericks, 1987; Lindsay, 1988; Potter, 1995; Kent, 2004; etc.). Currently the Trucial Coast is approximately 24.5°N, while the study area was at 4°N (Habicht, 1979) during deposition. Assuming a latitude temperature gradient similar - 0.66°C/degree of latitude from the equator (calculated from average pole to equator temperatures reported in Borron and Washington (1982), surface temperatures exceeding 50°C are reasonable. This temperature is likely inhospitable to organisms other than blue-green algae (LeFever, 2013, oral communication).

It is not known if hypersalinity or elevated surface temperatures played a greater role in faunal restrictions during deposition of the dolomudstone lithotype. Both extremes are considered by the author to be present at this time. The dolomudstone is interpreted to have
been deposited in a very shallow restricted marine environment where hypersaline brines persisted and temperatures sometimes exceeded 50°C. This is further supported by simulated models (as previously stated) where precipitation of anhydrite following reflux dolomitization was most favorable with mesohaline brines at 50°C (Jones and Xiao, 2005). However, the absence of a modern analog causes ample uncertainty when discerning specifics of the environment.

**Grain-supported lithotype**

The grain-supported lithotype was deposited in a shallow sublittoral marine environment where slightly agitated conditions persisted. Normal wind and storm induced wave activity was likely present over much of the study area during deposition. Allochems were subject to transport evidenced by fossil fragmentation, broken grains, and abundant intraclasts.

Development of the grainstones observed in this lithotype is believed to have been in part a result of subaerial exposure and vadose leaching of unconsolidated mud. Evidence for exposure is common in the grainstones and includes micritic crusts, teepee structures, sheet cracks, and occasional pisolite pendants (Dunham, 1969). Isopachous and pore occluding cementation suggests these islands eventually returned to subaqueous conditions (Harris, 1979). Furthermore, collapse brecciation could indicate select areas underwent multiple episodes of exposure.

Packstone lithologies with similar allochem content represent subtle energy reduction and lack of subaerial exposure. Fibrous ooids and pisoid are indicative of low-energy environments and subaqueous precipitation (Land et al., 1979). Areas with quiet water and a predominantly subaqueous setting include intershoal deposits and protected shoal foreslopes.
Theoretically, these areas would be mud-rich, with respect to adjacent shoal-island rocks, due to their topographically low setting.

Micritic crusts and sheet cracks rarely observed in the packstone lithology signify widespread exposure of the entire shelf. However, given preferential solution of mud from grain-supported rocks (Wilson, 1975, p. 11), the significant mud content still present suggests exposure was brief.

A grain supported lithology was developed due to slight continual agitation in a sublittoral marine setting. Shoaling effects from wave generated currents developed a large scale hummocked topography on the sea floor. Periodic eustatic drops in sea level exposed a mosaic of low-relief shoal-island and intershoal deposits. Vadose flushing of meteoric water in shoal-islands led to localized development of a grainstone lithology and ample desiccation features. Mud-rich packstone lithologies suggest the environment remained predominantly in a low-energy subaqueous state.

**Calc-mud/wackestone lithotype**

The calc-mud/wackestone lithotype was deposited in a protected, mostly open, sublittoral platform environment. This lithotype reflects multiple depositional settings present over this area. Settings including: open lagoons, localized sinks (or cut-off ponds), and strandline build-ups. Calm conditions persisted over much of the area with occasional influence from storm activity. Periodic restriction of the platform is evident; however, restriction may not have been widespread, and is believed to be short-lived since syndepositional evaporites are rare. This environment is believed to be the temporal and spatial precursor to the completely restricted environment responsible for depositing sediments of the dolomudstone lithotype.
The mudstone was deposited primarily in quiet water. The high volume of micrite, lack of coated grains, and laminated argillaceous shale indicate nearly complete absence of water agitation (Dunham, 1962; Land et al., 1979). Quinn (1986) identified an abundance of tubiform algae as additional evidence for slack-water conditions, although their presence could not be confirmed in this study. Heavily bioturbated, homogenized muds with frequent pellets indicate normal marine conditions with salinities between 37-45ppm (Wilson, 1975, p. 27). Dolomitization is weak to absent during deposition; however, post depositional dolomitization may be present from advancing tabular bodies from up dip reflux processes (Jones and Xiao, 2005).

Cryptalgal, and non-bioturbated argillaceous, laminations and partial syndepositional dolomitization characterize an environment where oxygenation and salinity levels limited local fauna and salinity was >45ppm (Wilson, 1975, p. 26-27). What anhydrite does occur in this lithotype tends to be associated with these internal structures.

The spatial relationship of mudstones deposited in a clearly oxygenated setting and those deposited in a restricted one across the platform is not fully understood. Discontinuity of similar conditional indicators between adjacent cores, at the same stratigraphic level, suggests oxygen levels and salinity varied significantly across the platform. Wilson (1975, p. 26) indicates fresh, salt and hypersaline waters can occur where cut-off ponds and lagoons are present across the platform. What remains in question is the duration of these localized conditions. Interbedded open and restricted deposits may develop from prograding localized subenvironments or from slight regional regression or transgression; which in effect would restrict or circulate, respectively, greater areas of the platform at any given time.

Wackestones, commonly containing algal oncoids and pellets or peloids, as well as intraclasts of those allochems, represent local build-ups or bioherms in this setting (Hendricks,
Exposure of these build-ups was uncommon, but limited desiccation features are present in some areas. Wackestones containing ooid-bearing intraclasts and skeletal fragments are presumed to be storm generated deposits that were transported from the shoaling environment (of the grain-supported lithotype) to the west.

Constant water agitation was minimal, so ooids are likely allogetic to this environment, deposited during infrequent storm activity. Quartz sand in the lithotype was transported by aeolian processes evident from sorting, grain-size and association with hummocky cross-stratified laminations. Windblown terrigenous sediments are common across a shallow platform (Wilson, 1975, p. 26) and may be responsible for the argillaceous content occasionally observed.

The calc-mud/wackestone was deposited on a low-energy, protect, sublittoral platform. The environment was likely composed of variable subenvironments in the form of build-ups, cut-off ponds, and lagoons. Restricted and oxygenated conditions varied between subenvironments leading to a discontinuity of paleoenvironmental indicators. Complete circulations and restriction of the platform may have occurred intermittently, but the persistent dynamic conditions make interpretation difficult.

Dolomitic sandstone lithotype

The dolomitic sandstone lithotype was deposited by aeolian processes in a restricted, sub- to supralittoral, sabkha-like, lagoonal environment. The environment of deposition was essentially identical to that of the dolomudstone lithotype with a prominent terrigenous input of clastic material. The limited proximity of the lithotype to the craton and the well sorted fine to medium-fine sand grains suggest normal winds offered means for transport. Interstitial
mudstones were developed as the sand was initially deposited in a subaqueous setting, and dolomitization followed the same reflux processes responsible in the dolomudstone lithotype.

Accumulations of the dolomitic sandstone lithotype vary considerably in thickness. The accumulations can reach in excess of 50 m (Howard, 2000) where adjacent wells may display the lithotype thickness of 2-3 m at the same stratigraphic interval. Anhydrite and dolomite cemented coastal dune cores were suggest by Kent (2004) to describe the thick deposits. Other authors (Howard, 2000; Perras, 1990) have credited tidal channels and sand shoals for the expanded section. It is interpreted in this study to be the result of both accumulating processes.

Grain size, rounding and homogeneity of the sands observed in the lithotype reflect wind as the primary means of transport. Although pinpointing the source of the sand would require a comprehensive investigation of the hinterland at the time. Deposition and large accumulations of windblown sand occurs where depositional sinks offer drastically lower energy conditions (Ritter et al., 2002, p. 282). High-angle crossbedding (10° - 34°) is a measured characteristic of most dunes today (Ritter et al., 2002, p. 283), and an asymptotic or tangential base may explain bedding <10°.

These dunes likely migrated with an easterly paleowind (oriented northeast to southwest today) across the coastal plain and into the restricted lagoon. Red and purple stained sand bodies were observed by Kent (2004) in southeastern Saskatchewan, as well in this study to the northeast. This oxidation represents a primarily subaerial counterpart to the subaqueous setting towards the southwest. It is not known if initial deposition aggraded the shallow up-dip lagoonal setting then prograded to the southwest, or if a complete supralittoral standing dune field was also present throughout deposition.

Massively bedded sandstone lithologies are not common in aeolian dunes. Quinn (1986) suggests saltation of grains and individual capillary entrapment in low-lying areas as an
explanation to the lack of bedding commonly seen in this lithotype. However, anomalously thick accumulations are not believed to develop in this manner. Localized sinks and/or fluvial channels that formed during supralittoral conditions likely provided the accommodation space necessary for these thick accumulations (Potter, 1995). The exact cause of the structureless bedding is still a bit of a mystery. Massive bedding forms from physical disruption due to liquefaction, or reworking of sediment while still in a waterlogged state (Collinson and Thompson, 1982, p. 101). Both processes require a subaqueous setting during deposition and bi-directional ripples indicate some form of agitation was present. Extreme bioturbation will destroy internal structures, though the action is dismissed due to lack of fauna.

The dolomitic sandstone lithotype was deposited by aeolian processes as dunes and in an aggradational subaqueous setting. The majority of deposition took place in an environment similar to the restricted lagoonal setting of the dolomudstone lithotype; however a significant supralittoral counterpart may have been present as well.

**Anhydrite lithotype**

The anhydrite lithotype was deposited in a completely restricted, supralittoral, salina-lagoonal or playa environment. This lithotype began precipitating subaqueously in the highly restricted lagoon of the dolomudstone lithotype as gypsum nodules. Continued regression completely restricted the environment and deposition of anhydrite in the bedded form persisted in a salina-like embayment.

Nodular and chicken-wire structures are produced by displacive growth of anhydrite within the sediment. Nucleation of nodules will occur when supersaturation is reached, typically when normal marine water is concentrated to slightly more than 1/3 its original volume (Blatt et al., 1980). Nodules can precipitate anywhere in the water column; eventually they will
fall to the floor of the basin where the majority of growth will occur (Collinson and Thompson, 1982, p. 127). Contorted and wavy bedding develops by coalescing of individual nodules into chicken-wire and bedded form occurring so long as other ions do not interfere (Shearman, 1978, p. 22), or by differential compaction. The grading commonly seen in contact with underlying dolomudstones suggest salinity increased with time and open circulation was not intermittent.

Organic-rich shale, sand and other allogenic grains were transported by storm activity from adjacent sublittoral settings.

This lithotype has historically been labeled as a sabkha deposit due to analogous anhydrite bedforms observed in modern sabkas (Butler, 1969). However, sabkhas typically form 1 to 2 m above sea level (Shahid et al., 2007); leading to significant accommodation concerns since accumulations of bedded anhydrite commonly exceed 40 ft thick throughout the study area. Stephens (1986) and Kendall (1984, p. 275) suggested deposition occurred in shallow ponds and lagoons superimposed on a sabkha surface. However, the uppermost layers of sabkhas are characterized by wind-blown surfaces of red ferruginous dust (Shahib et al., 2007) which was not observed in this study.

Potter (1995) characterized deposition of the anhydrite in a large continental embayment (playa) landward of a continuous intertidal barrier. This would satisfy the criteria for complete restriction and remain subaqueous. Episodic transgressions likely flooded this embayment and created a lagoonal-type environment depositing mudstone beds until the next regression and subsequent restriction.

**Skeletal wackestone lithotype**

The skeletal wackestone lithotype was deposited in an open, sublittoral shelf environment. The environment was characterized by open marine conditions with deposition
occurring between the lower most storm wave base, and oxygenation level. The environment was subjected to calm conditions influenced by subtle circulating ocean currents and infrequent storm generated disturbances.

Bioclastic and whole fossiliferous wackestones are the principal rock types of the shelf setting, and are commonly interbedded with bioturbated and wavy laminated shale-rich marls (Wilson, 1975, p. 26). Unabraded and unbroken skeletal allochems indicate little to no transportation. Disarticulation of crinoids may reflect degradation of soft organic tissue and movement by burrowing organisms (Beckel, 1972, p. 235), whereas beds of disconcordant and broken brachiopod shell fragments reflect intermittent storm induced lag deposits.

Laminated black and organic-rich shales may reflect the development of stressed conditions (Petty, 2010). Prolonged episodes devoid of storm induced currents are hypothesized to result in ascension of the oxygenation level. This in turn, would limit fauna habitation, preventing bioturbation and homogenization of sediments.

Dolomitization in this lithotype may reflect the down dip extent of reflux derived tabular bodies because of the association with replacement anhydrite (Petty, 2010; Jones and Xiao, 2005). Chert beds and nodules likely formed from silica introduced to the environment from sponge spicules or silica based pelagic microorganisms (e.g. radiolarians).

The skeletal wackestone, therefore, represents deposition on an open shelf setting, where normal marine conditions were dissected by infrequent storm derived deposits, and stagnant, hypoaerobic influences.
CHAPTER V

MARKER CHARACTERISTICS

State A

The State A marker bed divides the overlying Rival subinterval from the underlying Bluell subinterval within the Frobisher-Alida beds. The Bluell is identified as a single subinterval through the much of the study area but is subdivided into two subintervals by the development of a second State A marker in Burke and northern Mountrail counties (Hendricks, 1987). The second State A in this study will be referred to as State A2 for its analogous lithology and juxtaposition with the Bluell beds. Additionally, the Bluell will represent the entire interval to the east of, and the beds beneath, State A2. Upper Bluell will be the nomenclature used for those beds between the State A and State A2.

The State A is the most widespread and recognizable marker in the Madison Group. To the east, the State A first emerges beneath the eroded top of the Madison Group east of Newburg field in central Bottineau County, and is persistent to the west throughout the study area. The State A is the only marker in this study that can be recognized with complete confidence by log signature on the Nesson Anticline.

Like the other markers in this study, the State A is housed between two thick accumulations of the anhydrite lithotype in the eastern most extent. Overlying the State A, the Rival subinterval remains principally anhydrite further east than all Frobisher-Alida subintervals (Figure 10). The Rival grades into porous wackestone of the calc-mud/wackestone lithotype.
Figure 10: Approximate paleoshoreline of the Rival subinterval mirroring a prominent facies change (adapted from Lindsay, 1988). Anhydrite dominates the lithology to the east and transitions about the paleoshoreline into carbonates to the west. Overlaid on county boundaries (black lines) and townships (blue lines).
The Bluell subinterval (and Upper Bluell where present) underlying the State A grades from anhydrite into variable mudstones and locally porous peloidal and intraclastic wackestones of the calc-mud/wackestone lithotype. Facies transition occurs along a variable boundary through central Renville and Ward Counties (Figure 11).

Thickness of the State A remains relatively constant, ranging 6 to 10 ft thick. With first appearance in the east, bed thickness is usually 4 to 6 ft. However, (unlike the subinterval beds) thickness of the State A does not reflect increasing accommodation space basinward, suggesting the eastern margin had an apparent dip at time of deposition less than the ¼ to ½ of a degree average for the Mission Canyon-Charles sequences.

Compositionally the State A is the most homogenous of all marker beds throughout the study area. The dolomudstone lithotype dominates the lithology with interbeds of the calc-mudstone/wackestone lithotype. These interbeds are commonly dolomitized as with the dolomudstone lithotype but are recognized in core by strong bioturbation and frequent allochems. The eastern most State A core in the study area (Burns #1-21, Clarion Resources, Inc., NENE 21-163-85) displays a thin 2 ft zone of extensive bioturbation. This zone is inferred to represent the maximum transgressive event of the Rival subinterval.

The upper contact of the State A in this area of the Burns well is typically sharp, and overlying anhydrite is present in bedded form from the contact. To the west, the upper contact is commonly represented by the development of nodular anhydrite grading up section into chicken-wire, then bedded form (e.g. St. Croix #1, BHP Petroleum Company, Inc., NENW 8-163-88). This gradational influence reflects a gradual increase in salinity within the environment of deposition. In western Burke County where precipitating anhydrite no longer overlies the State A, the upper contact is gradational characterized by decreasing argillaceous content and a
transition from dolomite cemented to anhydrite cemented carbonate mudstones (e.g. O’Neil #34-34, First Energy Corp., SWSE 34-161-94).

Where anhydrite is persistent in the Bluell beds the lower contact is sharp and erosional in nature. This contact is undoubtedly a transgressive surface since it indicates the reintroduction of seawater and marine sediments to the environment. To the west where carbonates underlie the marker, the lower contact becomes more abstract. An increase in argillaceous content and dolomitization from the underlying calcareous rich lithologies usually denotes this contact.

The State A marker is recognized in well logs by a sharp gamma ray peak that typically reads between 30 and 40 GRapi units and seldomly greater than 50 GRapi units. A second softer peak often overlies the characteristic spike reading between 15 to 20 GRapi units. Precise recognition is aided by porosity logs; since anhydrite lithotype or anhydrite cemented mudstones overlie the State A in the study area, the marker is easily identified by a drastic increase in porosity. Resistivity is low due to capillary restriction of hydrocarbons, typically ranging between 0.8 and 2 ohms.

**Sherwood Argillaceous Marker**

The Sherwood Argillaceous Marker (S.A.M.) divides the overlying Bluell subinterval from the underlying Sherwood subinterval within the Frobisher-Alida beds. The S.A.M. is the second most extensive marker in the Madison Group. To the east, the S.A.M. is very ambiguous and is difficult to recognize. Theoretically the marker should be present beneath the unconformity to east of the first emergence of the State A due to the S.A.M.’s chronostratigraphic relationship (Figure 11); however, condensed Sherwood and Bluell beds make positive identification difficult
Figure 11: Approximate extent of each marker (dashed) with paleoshoreline (solid) identified at facies change from evaporites to the east to carbonates to the west. Overlaid on county boundaries (black lines) and townships (blue lines).
without core control. Therefore, the confirmed eastward extent for the State A is the same for the S.A.M. To the west the S.A.M. can be observed on the Nesson Anticline although standard log signatures no longer apply, making positive identification tricky.

The S.A.M is contained between accumulations of the anhydrite lithotype in the eastern portion of the study area. A localized salt deposit within the study area is also present beneath the marker in southwestern Bottineau County. Overlying the S.A.M., the Bluell subinterval grades into the peloidal and intraclastic wackestone as previously stated with the State A. Underlying the marker, the Sherwood subinterval grades basinward into a peloidal, intraclastic, and algal wackestone, of the calc-mud/wackestone lithotype. Pervasive desiccation features along this facies transition likely indicate a continuous positive feature was present at time of deposition. Algal assisted aggradation may have played a role in the build-up. It is also believed that the build-up may have been responsible for the increased restriction that led to salt precipitation.

Thickness of the S.A.M. typically ranges from 8 to 12 ft. To the east, thicknesses are usually 4 ft or less, and maximum thickness is achieved in central Burke County at about 16 ft. Unlike the State A, the S.A.M. does reflect a gradual thickening as accommodation space increases basinward.

Compositionally the S.A.M. can be broken into two regionally pervasive lithotypes about the late Sherwood shoreline (Figure 11). The dolomudstone lithotype characterizes the S.A.M. to the east, where the marker separates evaporite dominated subintervals. West of the paleoshoreline the S.A.M. is composed predominantly of the calc-mud/wackestone with interbeds of the grain-supported lithotype.

In the region to the west of the paleoshoreline a unique, 3 fold, cyclic pattern is present in the S.A.M. This pattern is readily observed in gamma ray logs and core (Figure 12); and the
characteristic pattern may aid in the identification of the marker where radioactivity is otherwise low. Inherent lithological features observed in core are a dark grey, densely argillaceous and weakly dolomitized wackestone with basal packstone that may be as much as a foot thick, though typically ≤6 in. Up section, the argillaceous content fades and the muddy matrix transitions into tan to light tan calcareous mudstone. Once argillaceous content is no longer detectable in the core an oolitic, pisolitic and intraclastic packstone to grainstone of the grain-supported lithotype predominates. This lithological trend repeats three times cyclically over the extent of the marker. Individual cycles vary in thickness due to large stylolites commonly associated with argillaceous and allochem transition but most commonly observed from 2 to 5 ft thick.

The upper contact of the S.A.M. east of the paleoshoreline is typically sharp where anhydrite becomes prevalent. Similar to the State A, anhydrite is present at the contact in bedded form in the eastern extent of the study area, but often grades from nodular to chicken wire form to the west. The upper contact west of the paleoshoreline is often difficult to identify due to the up-section gradational nature of the cycles. Gradational contacts described in the study were typically placed where argillaceous content faded out. However, these “contacts” are believed to be premature given the nature of the underlying cycles, but truncation of the upper cycle is necessary to prevent extrapolation of the marker into the overlying Bluell beds. Sharp contacts identified in this study were often chosen at conveniently located stylolites that overlay the last cycle.

Where anhydrite is persistent in the Sherwood beds the lower contact is sharp, and reflects erosional processes. This contact, similar to the State A lower contact, reflects a trangressional surface in which seawater was reintroduced to the restricted hypersaline embayment. To the west where carbonates underlie the marker, the lower contact is often
Figure 12: Cross section of gamma ray/compensated neutron density logs showing S.A.M. facies change from the dolomudstone lithotype to the cyclic, argillaceous and allochem-rich rocks of the calc-mud/wackestone and grain-supported lithotypes. Note the characteristic three-peak gamma ray signature in NDGS # 12229 resulting from the cyclic nature of argillaceous sedimentation.
sharp though non erosional. The contact is represented by a noticeable increase in dark grey argillaceous content and the basal packstone of the first cycle of S.A.M. deposition.

The S.A.M. is recognized in well logs to the east of the paleoshoreline by a gamma ray peak that typically reads between 20 and 40 GRapi but can read up to 60 GRapi units (e.g. E.P. Stoner #1, Arex Corp., NENW 26-160-84). This marker is often observed as the third gamma ray spike beneath the State A; however, this is not a reliable method for tracking the S.A.M. given the limited expanse of the argillaceous lenses between the S.A.M. and State A marker. Porosity readings are variable but always very high in this region due to the microintercrystalline pores of the dolomite. Resistivity is low due to capillary restriction of hydrocarbons, typically ranging between 0.8 and 2 ohms. To the west of the paleoshoreline, the S.A.M. appears as three consecutive softer peaks within an 8 to 12 ft zone. The peaks are derived from the cyclic nature of argillaceous muds in the mark as previously stated. These subtle peaks typically read between 10 and 20 GRapi units. In this area porosity logs read very low, typically <5%. On CND logs, the neutron density and density porosity reading will often track on top of one another indicating very low permeability. The low porosity and permeability results in very high resistivity, often exceeding 100 ohms.

A transitional zone is present within the marker between the dolomudstone lithotype and the well-developed cyclic carbonates. This zone appears on porosity logs where one or more cycle at the top of the marker is usually represented by the characteristic dolomudstone porosity spike underlain by low porosity and low permeability readings. The inherent resistivity of each porosity value also relates to this zone. However, this zone is not observed by the gamma ray, and in core no unique macroscopic properties were observed.
The K-1 marker divides the overlying Sherwood subinterval from the underlying Mohall subinterval within the Frobisher-Alida beds. The K-1 marker is the third most extensive marker in the Madison Group. To the east, the K-1 emerges beneath the Madison Unconformity to east of and proximal to the first appearance of the State-A and S.A.M. To the west, the K-1 can be traced with confidence into eastern Mountrail County but becomes abstract by the Nesson Anticline (Figure 11).

The K-1 is housed between two accumulations of the anhydrite lithotype in the eastern portion of the study area. Overlying the K-1, the Sherwood beds grade basinward into the dolomudstone lithotype or algal and peloidal-rich mudstone of the calc-mud/wackestone lithotype depending on minor variability in shoreline orientation. This facies change occurs roughly north-south in R85W and R84W lithotype (Figure 11). Underlying the K-1, the Mohall beds grade basinward directly into an ooid-rich packstone and grainstone of the grain-supported lithotype.

Thickness of the K-1 is highly variable throughout the study area. K-1 typically ranged between 10 and 20 ft in core described for this study; however, thicknesses exceeding 70 ft have been reported (Potter, 1995). In Canada, the K-1 is observed as discontinuous bodies commonly exceeding 33 ft thick (Kent, 2004). The thickest accumulations in the study area are observed west of the anhydrite-carbonate facies transition but localized to 0.6 mi wide elongated bodies roughly parallel to regional dip (Potter, 1995). In general, the K-1 thickens toward the west indicating increased accommodation space during deposition.

Compositionally, the K-1 is one of three quartz rich sand bodies in the Frobisher-Alida interval. The dolomitic sandstone lithotype in this study was defined using the K-1 and is thus the dominant lithotype throughout the extent of the marker. The marker often contains
frequent interbeds of dolomudstone lithotype broken coated grains and intraclasts from the grain-supported lithotype. The dolomudstone is more pervasive to the east and becomes thinner and less prevalent basinward. Extensive iron-oxide staining and frequent interbeds of coated grain wackestones are observed characteristics of the K-1 marker in Canada (Kent, 2004): these were rarely observed in this study. Anhydrite cementation is common in the upper 1 to 3 ft of the marker where overlying bedded anhydrite lithotype characterizes the Sherwood subinterval; otherwise dolomite cement dominates.

The upper contact of the K-1 marker is typically sharp where the anhydrite lithotype is prevalent in the overlying Sherwood beds. Anhydrite above the upper contact is typically present in chickenwire form grading up-section into bedded form. Nodules are common in the marker leading up to the contact; however, the nodules are typically suspended in a sandy or dolomudstone matrix and therefore are considered part of the marker. Where carbonates overlie the K-1 the upper contact is remarkably ambiguous. The marker often displays a lack of argillaceous content beneath the contact and siliciclastics fade into the overlying carbonates across the upper contact.

The lower contact of the K-1 marker is characteristically sharp irrespective of underlying lithology. Where anhydrite persists beneath the contact the sharp, often irregular boundary reflects erosional processes. Directly above this contact the K-1 is compositionally a fine, sand to siltstone with destroyed internal structures (e.g. Stordahl #26-31, Marathon Oil Company, NWNE 26-157-84). To the west where carbonates underlie the marker, the lower contact is often sharp though non-erosional. The contact is represented by a noticeable increase in dark grey clays and/or dolomitization, and a disappearance of allochems from the underlying units. This contact, unlike the State A and S.A.M., is inferred to represent a maximum regressive surface within the Mohall sequence. A basinward progradation of environments is evident
where carbonates underlie the marker when the grain-supported lithotype grades up-section to dolomudstones. In addition, aeolian sands were likely deposited across the subaerially exposed evaporite plane to the east.

The K-1 marker is recognized on logs by a steadily increasing gamma ray from the lower contact up section, and a sharp decline in radiation at the upper contact. Radiation at the base of the marker ranges 10 to 20 GRapi units depending on underlying lithology, and maximum radiation (at upper contact) typically ranges between 45 and 55 GRapi units. It is not uncommon for the gamma ray signature to reflect a linear increase in radiation from the lower to upper contact where expanded sections are absent. Typical gamma ray log response for an expanded K-1 marker is a consistent 40 to 50 GRapi unit average framed on either side by low radiation (around 10 GRapi) carbonates. Porosity readings are often highly variable depending on cementation, interbedded lithologies and thickness of the marker; therefore, no specific porosity trend is identified in this marker. Where expanded sections persist, porosity can exceed 15% and are locally productive (e.g. Fargo #31-15, Ritter, Laber & Associates, Inc., NWNE 15-159-87). Resistivity varies with porosity and fluid saturation: no characteristic trend is evident.

K-2

The K-2 marker divides the overlying Mohall subinterval from the underlying Glenburn subinterval. Deemed the “Regional Kisbey” the marker also serves as the division between the Frobisher and Alida beds within the overall Frobisher-Alida interval. The K-2 marker is fourth most extensive marker in the Madison Group. To the east, the K-2 emerges beneath the Madison Unconformity along the eastern boundary of Roth and South Starbuck fields (R78W),
and along the western edge of production in Northeast Landa Field. To the west, the K-2 can be traced into central Burke and eastern Mountrail Counties (Figure 11).

The K-2 is stratigraphically positioned between two accumulations of the anhydrite lithotype in the eastern portion of the study area. The lower Mohall beds, overlying the K-2, grade basinward into an ooid and pisoid-rich, grain-supported lithotype. The K-2 may also be dissected by a dolomitic sandstone lithotype of an expanded section of the K-1 marker. Underlying the K-2, the Glenburn beds grade basinward into an ooid rich wackestone to packstone of the calc-mud/wackestone lithotype.

Thickness of the K-2 in the study area ranges from 5 ft to the northeast to about 16 ft to the south and west. Kent (2004) reports the K-2 being about 5.5 ft (1.7m) in southwestern Saskatchewan. This indicates accumulation of marker sediments was partly controlled by increasing accommodation space basinward. Expanded sections of this marker are less common than the K-1 marker, but a thickened deposit exceeding 60 ft is present in the Sherwood and Elmore field area.

Compositionally, the K-2 is very similar to the K-1 and is identified as the second of three quartz rich sand bodies in the Frobisher-Alida interval. The dolomitic sandstone lithotype dominates the marker, with frequent interbeds of the dolomudstone and anhydrite lithotype. Occasional carbonate allochems including broken ooids and pisoids are present along select bedding planes. Nodular anhydrite and anhydrite cement is more pervasive in the K-2 than the K-1. Disseminated pokioblastic pyrite is a common sight in the marker. Iron-oxide staining is observed to the northeast along the international border (e.g. Artz “A” #1, Chandler & Associates, Inc., SESE 16-163-82), and extremely common in Canada (Kent, 2004).

The upper contact of the K-2 marker is mostly observed as rapidly gradational (within a 6 in window) to sharp where anhydrite is prevalent in the overlying Mohall beds. Anhydrite
about the contact is typically present as a nodular supported fabric and chickenwire form. Floating nodules are common beneath the upper contact. Where carbonates overlie the marker the same gradual trend observed in the K-1 applies here too—continual deposition where carbonate sedimentation became favored over siliciclastic and argillaceous deposition.

The lower contact of the K-2 marker in the study area is rapidly gradational to sharp where the anhydrite lithotype underlies the marker. Unlike the K-1 this contact is typically non-erosional and anhydrite may persist as lenses and condensed nodules into the lowermost siliciclastic sediments. This suggests a shallow brine actively precipitating sulfates may have been present over much of the depositional area during the initiation of K-2 sedimentation. However, Kent (2004) observed the lower contact as erosional above bedded anhydrite suggesting an up dip exposed counterpart to this environment. To the west and south, the lower contact is analogous to the K-1 marker in that allochems become absent and dolomitization and siliciclastics progress up-section. It is believed that analogous events led to the deposition of both the K-1 and K-2 marker beds. However, the overlying brine lens across the embayment inhibited aeolian erosion in the study area.

The K-2 marker is readily recognized on logs as the next gamma ray spike underlying the K-1 marker. The structure of the K-2 gamma ray response typically resembles that of the K-1 though is not as consistent. A pronounced spike to about 30 GRapi units contrasts the standard <20 GRapi unit curve of the overlying carbonate-evaporite lithologies. A subsequent decline of radiation down-section typically follows en suite. Commonly, the K-2 will display three prominent gamma ray spikes from 20 to 30 GRapi units separated by low radiation intervals of <15 GRapi units. This is reflected in core as zones of anhydrite-rich interbeds in the otherwise argillaceous, silty sandstone. Porosity and resistivity readings are highly variable due to varying dolomite and anhydrite cementation and therefore are not reliable indicators of the marker.
The K-3 marker divides the overlying Glenburn subinterval from the underlying Wayne subinterval within the Frobisher-Alida interval. The K-3 is fifth most extensive marker in the Madison Group, and subsequently the most localized marker in this study. To the east, the K-3 emerges beneath the basinwide unconformity proximal to the eastern extent of the K-2 marker. The condensed Glenburn beds to the east cause up dip erosion of the K-2 and K-3 to occur couple sections of one another—a trivial variance within the overall study area. To the west, the K3 becomes obscure and difficult to follow in western Ward and Renville Counties (Figure 11).

The K-3 is stratigraphically positioned between two accumulations of the anhydrite lithotype to the east which grade basinward into marine carbonates. The lower Glenburn beds, overlying the K-3, grade basinward into an oolitic and pisolithic packstone of the grain-supported lithotype. The observed absence of muddy lithotypes between anhydrite dominated facies and oolitic bearing grain-supported lithotype may be an artifact of low sample population in this study. The Wayne beds, underlying the K-3, grade basinward of the anhydrite dominated facies into a thin belt of peloidal and intraclastic mudstone and wackestone with interbedded peloidal packstones of the cal-mud/wackestone lithotype. An ooid-rich grain-supported lithology is present immediately west of the mud-rich belt indicating rapid facies changes of the Wayne beds.

Thickness of the K-3 ranges from 10 ft thick to the east to a about 17 ft thick in the western extent of the marker. North of the international border thickness of the K-3 averages about 5.5 ft, with localized deposits up to 33 ft (Kent, 2004). The subtle thickening trend indicates gradual increase of accommodation space during deposition. Expanded sections were not readily observed in the study area but are expected given the unlikelihood of a perfectly flat depositional setting.
Compositionally, the K-3 is similar to the K-1 and K-2 markers and is identified as the third of three quartz rich sand bodies in the Frobisher-Alida interval. The dolomitic sandstone lithotype is characteristic of this marker, but the dolomudstone lithotype is readily observed as interbeds and may be the dominant lithology in select wells. A persistent bed of nodular anhydrite with interstitial mudstone occurs throughout the study area and splits the marker into two sandy units. This feature is also present in the K-3 through southwestern Saskatchewan (Kent, 2004). Anhydrite cementation is also especially common from the basal contact where adjacent anhydrite persists. Iron-oxide staining is observed throughout the study area, but is absent along the west extent of the marker. In some cases, the entire section may be stained red (e.g. Oscar Fossum 1-R, HRC Operating, LLC, NENE 31-162-81).

The upper contact of the K-3 marker is sharp and conformable where anhydrite persists in the lower Glenburn beds. Chickenwire anhydrite is the typical overlying bed form and basal nodules have frequently sagged across the upper contact (e.g. Anderson 2, Enduro Operating, LLC, SENW 20-163-82). Where carbonates overlie the marker, the contact is rapidly gradational, similar to the upper boundary of the K-1 and K-2 markers.

The lower contact of the K-3 marker resembles the lower contact of the K-1 marker in that, an erosional surface is present above the anhydrite lithotype to the east, and rapid, non-erosional contact is present on underlying carbonates. Aeolian sands were likely deposited across the subaerially exposed evaporite plane to the east, analogous to, but less extensive than the depositional surface of the K-1 marker. Anhydrite cementation in the marker adjacent to the lower contact may have resulted from seepage of super saturated brines where loading of siliciclastics caused mechanically induced dehydration. Irregular wavy bedding in the anhydrite resulting from differential compaction further supports this hypothesis.
The K-3 marker is often difficult to locate on logs but is made easier when K-1, K-2, and K-3 are present in descending order. The gamma ray signature of the K-3 resembles that of the K-1 and K-2 where anhydrite surrounds the marker; an up-section increase of radiation from between 10 and 15 GRapi units to between 30 and 35 GRapi units, followed by a sharp drop in radioactivity at the top of the marker. Where the marker is proximal to carbonates in the underlying Wayne beds the K-3 marker is characterized by two large gamma ray spikes separated by ≤5 ft zone of low radiation. This signature is a result of the persistent anhydrite rich bed separating two sandstone bodies as mentioned above. Radiation can be variable, but usually ranges between 20 and 30 GRapi units for the two peaks, with the overlying spike typically displaying relatively higher radioactivity, and 10 to 20 GRapi for the separating anhydrite rich zone. Porosity in the dolomite cemented sandstone can exceed 20%, though permeability of the microintercrystalline pores makes them ineffective for hydrocarbon retention. Locally cementation may be poor, larger interclastic porosity can exceed 10% and is often oil saturated. The K-3 marker is the principal reservoir for North Haas field oil production.
CHAPTER VI
SEQUENCE STRATIGRAPHY

Overview

In this study, an emphasis is placed on the significance of each marker bed in the overall sequence stratigraphic framework of the Madison Group. At the first-order scale, prominent subaerial unconformities represent sequence boundaries (Petty, 2010). The Devonian to Mississippian Kaskaskian Sequence defined by Sloss (1963) is considered to be the first-order sequence. Regional bounding unconformities are traced throughout the basin and recognized by intensive subaerial erosion (Carlson and Anderson, 1965).

The second-order sequence in which the Madison Group belongs to is the “Madison sequence” of Petty (2006) or “Madison supersequence” of Sonnenfeld (1996, p. 179). A discrepancy between the second-order sequence boundaries exists between the two authors. Petty (2006) placed the lower boundary at the base of the Bakken Formation and the upper boundary on the Kibbey limestone at the basin center; whereas Sonnenfeld (1996, p. 176) used the upper and lower boundaries of the Madison Group as the sequence boundaries. It is suggested in this study that the boundaries for this sequence incorporate elements from both authors with the lower boundary placed at the base of the newly designated pronghorn member of the Bakken Formation; and the upper boundary is marked by the top of the Madison Group. Extensive evaporite deposition at the upper boundary marks the farthest basinward extent of the Madison epeiric sea. The maximum flooding surface that separates the second-order transgressive and regressive tracts was placed on a second maximum flooding surface in
the lower to middle Bottineau interval by Petty (2010). This too is corrected in this study to the middle of the upper Bakken shale since maximum transgression of the sea is reflected by the extreme anoxic conditions present in this member.

A single third-order sequence encompasses all the marker beds in this study. The Frobisher-Alida interval represents a 2-3 million-year old cycle (Petty, 2003). The cycle is considered to be single third-order sequence in which prominent maximum flooding surfaces are used as sequence boundaries since wide-spread subaerial unconformities are not present (Galloway, 1989; Petty, 2010). This suggests that the MC-2 marker (not included in this study) which denotes the top of the Tilston interval is the product of marine regression.

The subintervals separated by the marker beds within the Frobisher-Alida interval, therefore are defined as fourth-order sequences (Witter and Shanely, 1992; Lindsay, 1993; Petty, 2010). A breakdown of ordered sequences can be seen in figure 13. The fourth-order sequences are suggested to result from glacially derived sea-level fluctuations (Lindsay, 1988). Alternatively, Potter (1995) suggests these sequences are bounded by passive type 2 sequence boundaries, where basinal subsidence rates exceed eustatic sea-level fall resulting in an offlapping relationship of overlying strata (Van Wagoner et al., 1988). Within these sequences the marker beds have been described as representing a short-lived transgression (Harris et al., 1966; Voldseth, 1987) while other authors credit deposition during regression and an exposed platform (Potter, 1995; Kent, 2004). It remains unclear what was the controlling mechanism of these fourth-order sequences, and a clear inconsistency exists within the literature on the relative timing of the marker beds with respect to the subintervals. The scope of the sequence stratigraphy in this study does not attempt to reconcile the uncertainty in sea-level controls, rather when the deposition of each marker bed occurred relative to fourth-order systems tracts.
Figure 13: Second, third, and fourth-order sequence orders found within the Madison Group and late Devonian and Mississippian strata.
Two empirical categories exist among the marker beds in this study: Dolomudstone dominated and Dolomitic Sandstone dominated. These categories represent two contrasting systems tracts within the fourth-order sequences. The dolomudstone dominated markers which include the State A, State A2, and S.A.M. are spatially dependent on overlying anhydrite lithotypes. The dolomitic sandstone dominated markers which include K-1, K-2, and K-3 display evidence of subaerial transport and proximity to the craton is a controlling factor.

Dolomudstone dominated markers

Along the eastern margin of the study area the lower contact of all the dolomudstone dominated markers show sharp transition from the underlying anhydrite lithotype into the markers. Predominantly this contact is erosional but may appear locally conformable due to minor topographic inconsistencies along the depositional surface.

The State A, State A2, and S.A.M. reflect an introduction of marine sediments into a supralittoral setting atop an erosional surface. The sharp lower contact of these markers therefore, represents a marine flooding surface. It is likely, from the erosional basal contact, that transgression of these fourth-order sequences was rapid and short-lived. Since reflux dolomitization processes are considered the main cause of the characteristic dolomite, evaporites will immediately follow deposition of a more calcareous mudstone. The upper contacts with overlying anhydrite are sharp to rapidly gradational (but non-erosional) indicating continually regressive and restricting conditions following initial deposition. Since continual regressive systems overlie the State A, State A2, and S.A.M. it is inferred that the sediments deposited in these markers represent a highstand systems tract of individual fourth-order sequences.
A sequence stratigraphic relationship can now be defined for the subintervals with respect to the dolomustone dominated markers. The transgressive systems tract for the fourth-order sequences is observed only as a marine flooding surface along the lower contact of each marker. Deposition of the dolomitic mudstone occurred during highstands within the sequences. Therefore the State A, State A2, and S.A.M. all represent highstand systems tract within a transgressive-regressive cycle. The regressive counterpart within an individual cycle is the overlying carbonate and evaporite lithologies to each marker respectively (Figure 14).

**Dolomitic sandstone dominated markers**

The lower contact of these markers, similar to the dolomudstone dominated markers, are sharp and often erosional. The K-1 and K-3 display a well-developed erosional surface above the anhydrite lithotype; while the erosional lower contact of the K-2 above the anhydrite is only apparent proximal to the craton. Where anhydrite is replaced by carbonates in the underlying subintervals the lower contact is characteristically sharp and siliciclastic deposition limited the carbonate factory.

The K-1, K-2, and K-3 reflect an introduction of the terrigenous sediments by aeolian processes across a broad mostly exposed evaporative embayment. Therefore, deposition of these markers occurred during regressive phases of the epiarc sea. Maximum regression of the fourth-order sequences likely occurred syndepositionally with aeolian sediments in the study area. This is supported by the preservation of high-angle foresets of coastal dunes, with the chronostratigraphically equivalent, fluvial channels to the west/southwest.

Subsequent transgression of these sequences also began amidst siliciclastic deposition. The landward migration of the shoreline is reflected in bi-directional ripples, (intertidal regime) carbonate cementation, and interbedded carbonate lithologies. This transgression is likely
Figure 14: Fourth-order sequence stratigraphy with prominent surfaces and relative sea-level curve for dolomudstone dominated markers (State A, State A2, and S.A.M.).
responsible for the regional continuity of these markers by reworking unconsolidated sands, which accumulated in localized depressions and dune complexes, into “shoestring-shaped bodies” (Kent, 2004). The upper contact, similar to the dolomudstone dominated markers, reflect increasingly regressive and restrictive conditions. This suggests maximum transgression of these fourth-order sequences is also housed within the dolomitic sandstone markers; although a definitive maximum flooding surface is not observed because of continued input of siliciclastics and low-energy reworking of unconsolidated grains.

The dolomitic sandstone dominated markers reflect siliciclastic sedimentation predominantly during late regressive, and lowstand system tracts of the fourth-order sequences. Diagenetic features of these markers, including massive bedding, bi-directional ripples, cementation, and nodular anhydrite, are effects associated with a succeeding transgression of the sea. Since early deposition was likely coeval with regression, the presence of a maximum regressive surface can only be inferred. In this study the maximum regressive surface is placed at the lower contact of the markers. The lower contact was chosen as it is believed to be an easily recognizable, time-equivalent surface proximal to the inferred maximum regression of the fourth-order sequences (Figure 15). The same adjustments are made for the maximum flooding surface of these sequences. Continual siliciclastic input and low-energy reworking of mostly unconsolidated sediments likely obscured the development of an easily recognizable surface. Therefore, the maximum flooding surface associated with the transgressive events in these sequences is placed at the upper contact of the dolomitic sandstone markers. From this surface, the overlying subintervals then reflect prolonged regression of the fourth-order sequences.
Figure 15: Fourth-order sequence stratigraphy with prominent surfaces and relative sea-level curve for dolomitic sandstone dominated markers (K-1, K-2, and K-3).
CHAPTER VII

ORGANIC-RICH SHALES

During the core investigation phase of this research numerous black shale laminae were observed proximal to heavily oil stained areas. These laminates were typically <1 cm thick (rarely up to 2 cm thick) and had a strong petroliferous odor (eg. Figure 7c). They are commonly associated with the calc-mud/wackestone lithotype but are also observed in the dolomudstone lithotype. Occasionally, these deposits were concentrated as insoluble matter along stylolitic seams. In conjunction with the North Dakota Geological Survey, samples were taken and tested for organic carbon content by Weatherford Laboratories. The results of these samples are reported in appendix C.

TOC ranged from <1% to 23.64%, well above the 2% needed to generate hydrocarbons. Samples with <1% total organic carbon (TOC) are representative of insoluble concentrations along stylolites. Deposition of organic-rich laminations reflects localized anoxic conditions within a generally aerobic setting. A possible mechanism for the development of such conditions is mechanical stratification of the water column in localized sinks on the platform. This feature is analogous to the conditions currently in the Black Sea where the basin floor is restricted from circulating currents by an elevated passageway connecting it to the Aegean Sea through the Marmara Sea.

Identification of organic-rich units in the Mission Canyon is a significant discovery since the Madison Group is not believed to be self-sourced. Preliminary testing done in this study was intended to confirm the hypothesis that these units were indeed rich in organic carbon. While it
cannot be determined here if these laminations have generated a significant amount of hydrocarbons (or any for that matter), it is noted that organic carbon concentrations are certainly high enough to suggest the presence of *in situ* oil. Further testing of these samples will be required to determine if maturation of the units prompted hydrocarbon generation.
CHAPTER VIII
CONCLUSION

1) Lithologies can be grouped into six primary lithotypes. These lithotypes are present throughout the study area and are extant within, and/or adjacent to, the markers. These lithotypes include: a) anhydrite, b) dolomudstone, c) dolomitic sandstone, d) calc-mud/wackestone, e) grain-supported, f) skeletal wackestone.

2) Five of the lithotypes are representative of distinct depositional environments located along the depositional platform. From east (shallowest) to west (deepest) these environments are: a) anhydrite lithotype – highly restricted, lagoonal to salina-like embayment, b) dolomudstone lithotype – evolving sub to supralittoral, restricted lagoonal, c) calc-mud/wackestone – protected, mostly open, sublittoral platform, d) grain-supported – shallow sublittoral environment, with slightly agitated conditional and periodic exposure of shoal build-ups, e) skeletal wackestone – open marine, lower shelf environment.

3) The dolomitic sandstone lithotype resulted from terrigenous input of siliciclastic sediments by aeolian process into environments characterized by the anhydrite, dolomudstone, calc-mud/wackestone and grain-supported lithotypes. Primary deposition occurred in the restricted lagoonal and salina-like embayment environments.

4) Extensive dolomitization of the dolomudstone lithotype occurred through evaporative reflux processes where $Ca^{2+}$ was remove from calcareous mudstones in favor of gypsum (CaSO$_4$) precipitiation and replaced with free $Mg^{2+}$ in a subaqueous setting around 50°C.
5) The six markers identified in this study can be categorized into two categories reflecting contrasting lithologies and depositional mechanisms. These categories include, dolomudstone dominated markers (State A, State A2, S.A.M.) and dolomitic sandstone dominated markers (K-1, K-2, K-3).

6) The S.A.M. is comprised of three depositional cycles beyond the paleoshoreline. Each cycle includes a basal, poorly-sorted lag deposit, accompanied by a drastic increase in argillaceous content which fade up section until the next cycle begins. This deposition feature is readily recognized in core and on gamma ray log signatures.

7) Dolomudstone dominated markers were deposited following a rapid and short-lived transgression of the sea in an otherwise regressive sequence. The lower contact of individual dolomudstone dominated markers denotes a maximum flooding surface, and the sediments represent highstand systems tract in a fourth-order depositional sequence.

8) Dolomitic sandstone dominated markers reflect more dynamic conditions than their dolomudstone dominated counterparts. Siliciclastic sedimentation occurred primarily during the late regressive, and lowstand systems tracts of individual fourth-order sequences. Reworking of unconsolidated sediments and dolomitic cementation occurred during the subsequent transgressive systems tract.

9) The lower contact of the dolomitic sandstone dominated markers is considered a maximum regressive surface for its proximity to the inferred maximum regression of the fourth-order sequences. Maximum regression likely occurred syndepositional to siliciclastic sedimentation and therefore the development of an easily recognizable surface is ambiguous. The upper contact of these markers is considered the maximum flooding surface to these sequences under the same premise.
10) Select organic-rich shale laminae sampled in this study were found to contain >20% organic carbon. These laminae may suggest Madison oil is in part self-sourced; future study with rock evaluation data should confirm this.
### Appendix A

#### Cores Examined in Study

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Appendix B
Core Descriptions

Well #: 38 Marker: K-3

Wayne
Light tan, pisolithic wackstone to mudstone. Faintly laminated to massive. Dark tan, faintly laminated and rippled, fine to very fine sandstone with dolomite cement and oil staining from 4259’-4261’.

4251.5’-4248’
Tan to pinkish tan, calcareous siltstone to mudstone. Mudstone dominates lower zone grading upward into siltstone, separated by black, slack-water laminae and mud drapes. Disseminated “metasomatic” anhydrite and colorless replacement anhydrite (5%). Top of zone may be very fine sandstone. Faint oil staining throughout zone. Lower contact is sharp at black shale laminae.

4248’-4245.5’
White to grey, chickenwire and condensed nodular anhydrite with interstitial light tan dolomudstone. Mudstone mostly cemented by anhydrite. Mudstone filled water escape features common.

4245.5’-4244.5’
Tan, calcareous siltstone. Frequent dark brown mud drapes and hummocked beds. Possible bioturbation and/or ripple marks. Spotty oxidation and oil staining. Common replacement anhydrite in flame structures and select irregular bedding planes.

4244.5’-4242.2’
Light tan, pseudo-oolitic packstone to wackstone. Ooids (≤3mm) are micritized. Original bedding poorly preserved. Extensive fenestral and vuggy/interparticle porosity. Vertical hairline fractures healed by anhydrite. Anhydrite is light brown from oil staining in pores. Patchy oxidization. Upper contact is sharp were anhydrite becomes bedded.
Glenburn

White and light tan to light grey, bedded anhydrite. Becomes more chickenwire with interstitial dolomudstones upsection.

Well # 1087 Marker: State A

Bluell

White, nodular anhydrite in light grey to green matrix. Grades downsection into more bedded/chickenwire anhydrite. Nodules are large (≤4cm) and compacted.

4610.2’-4607.7’

Dark grey, highly argillaceous dolomudstone. Zones of light grey to light tan (less argillaceous) with extensive “metasomatic” anhydrite (large crystals, >1cm) at 4609.2’, 4610’ and 4607.8’. Mudstone laminated with infrequent ripples, dense, blocky cleavage.

4607.7’-4606.7’

Dark grey, highly argillaceous silty dolomudstone. Mostly massive with blocky texture (moderately to poorly cemented). Upper 4in of zone is heavily laminated, hummocked and rippled (1cm wide, 4mm high). Upper contact is sharp where anhydrite begins.

Rival

White and grey, bedded and chickenwire anhydrite with minor component of light tan dolomudstone.

Well # 1087 Marker: S.A.M.

Sherwood

Tan, oolitic and pisolitic, packstone to grainstone. High vuggy porosity (comprising as much as 50% in localized areas, ≤8mm), open and oil stained. Lower contact is missing between core pieces.

4650’-4646.1’

Light tan to white, oolitic grainstone to wackestone (in select beds). Well cemented, well sorted, dense. Extensively fractured. Fractures are vertical to subvertical, mostly hairline, oil stained and healed by colorless anhydrite. Low interparticle porosity (5%), completely plugged at base of zone.

4646.1’-4643.2’

Light tan, partly dolomitic, oolitic wackstone to
mudstone. Faint planar laminations and blocky texture (core is in pieces). Fractures from overlying zone continue into zone. Upper contact is sharp where anhydrite first appears.

**Bluell**

White to light grey, bedded to chickenwire anhydrite with lower (2ft) dominated by white nodular anhydrite (>50%, ≤3cm) in light tan partly dolomitic mudstone matrix.

Well # 1685 Marker: S.A.M.

**Sherwood**

Light tan to tan, intraclastic and oolitic grainstone to packstone interbedded with wackstones to mudstone. Highly variable. Interparticle porosity (20% in grainstone) and minor fenestrae (5%) in muddier areas, plugged by colorless anhydrite or dolomite. Oil staining on pore margins.

4948.5’-4947.8’

Light grey, nodular anhydrite (70%) in argillaceous dolomudstone matrix (30%). Lower contact is sharp and irregular, possibly erosional or due to compaction.

4947.8’-4946’

Light tan, dolomudstone. Dense, lightly patterned. Dolomitization decreases upsection and disseminated replacement anhydrite begins. Thin bed (1cm) of planar bedded anhydrite at 4946.9’. Thin bed (2in) of tan intraclastic and oolitic grainstone at 4946.5’. Intraclasts are angular to subangular (≤5mm) moderately sorted and ooids are mostly broke (likely a lag deposit).

4946’-4942’ (top of core)

Grey to light grey, argillaceous dolomudstone with extensive nodular anhydrite. Nodules are light grey to white and 10-70% depending on bed. Infrequent, contorted lamination in mudstone. Microporosity is prevalent, indicated by rapid water absorption. Upper contact not present in core.

Well # 3092 Marker: K-3

**Wayne**

Light grey and tan, calcareous and dolomitic mudstone. Variable zones of reduced and oil

4039.7′-4030′
Tan to light tan, arenitic and calcareous mudstone. Laminated with wavy, subhorizontal, black (argillaceous) laminations. Oil staining. Spotty reduction halos. A 6in zone of reduced dolomite cemented sandstone persists at 4034′. Lower contact is rapid where fenestral porosity stops and sands begin.

4030′-4026.6′
Light to dark grey, argillaceous dolosiltstone to dolomudstone. Mostly anhydrite cemented with infrequent dolomite cements. Faintly laminated with highly contorted laminations from compactions. Nodular anhydrite with interstitial dolomudstone at top and bottom of zone. Nodules are condensed and wispy, likely syndepositional.

4026.6′-4024′
Dark grey to grey, quartz arenite. Dolomite cemented. Mottled with light grey patterning. Infrequent, condensed anhydrite nodules at 4025.5′.

4024′-4021′
Grey, white and black, anhydrite cemented, argillaceous dolosiltstone to mudstone. Variable bedding with wavy horizontal to subhorizontal beds. Very dense. Infrequent poikiloblastic pyrite blebs.

Glenburn
Light grey to white, bedded anhydrite with interbedded anhydrited cemented argillaceous dolomudstone.

Well # 3424 Marker: State A

Upper Bluell
Brown, intralastic-oolitic-pisolitic packstone. Grainy texture. Interparticle and fenestral porosity (5-10%), plugged by anhydrite.

7496′-7494′
Light brown, calcareous mudstone. Poorly cemented, organic-rich with dull appearance. Organic content may be of terrestrial origin(?). Petroliferous staining and UV florescence is
prominent.

7494’-7491’ Light tan-beige, dolomudstone, poorly cemented with blocky texture and frequent (15%) white/grey, sucrosic anhydrite nodules. Upper contact is sharp where anhydrite cement begins.

Rival Dark grey, anhydrite cemented mudstone above lower contact quickly transitioning into bedded anhydrite.

Well # 3424 Marker: State A2

Bluell Dark grey, pisolitic, oolitic, intraclastic, and peloidal packstone to grainstone. Extensive fenestral and interparticle porositsy (20%), plugged by dolomite.

7512’-7507.5’ Light brown, peloidal and pisolitic packstone with thin beds of wackestone. Frequent black stylolites separate alternating lithologies. Lower contact is rapid where zone becomes muddier.

7507.5’-7506.5’ Chocolate brown, intraclastic wackestone. Intraclasts are micritic with darkened margins, compacted (ellipsoidal, ≤2cm). Very dense zone.

7506.5’-7505’ Dark grey to dark tan, dolomudstone. Very dense, patterned. Thin (<5mm) organic-rich shale laminae at top of zone. Upper contact is sharp where allochems start.

Bluell Chocolate brown, oolitic packstone. Bituminous with bitumen coating on pore margins. Extensive interparticle and fenestral porosity (20-30%), plugged by crystalline dolomite and sparite.

Well # 3426 Marker: K-1

Mohall Tan, oolitic grainstone with frequent rip-upclasts (oolid bearing) and skeletal fragments (mostly brachiopods). Ooids are very fine (≤0.5mm)
and very well sorted. Vuggy and dissolution porosity is high just beneath marker contact with interparticle porosity down section. Pores and fractures are bitumen coated and completely plugged by sparite and/or dolomite. Black, argillaceous, organic-rich laminae beneath marker contact.

4554′-4552.5′ Light grey, argillaceous dolomudstone with thin interbeds of tan, pisolitic grainstone (poorly sorted, discordant). Upper 6in of zone characterized by stylolites and black, organic-rich shale laminae. Extensive replacement of select pisoids and plugged interparticle pores by anhydrite and dolomite. Lower contact is sharp where ooids stop.

4552.5′-4549.5′ Light grey to light tan, quartz arenite with interstitial dolomite and dolomitic cement. Sand is fine to medium-fine, well sorted. Faint planar to subplanar bedding. Poikiloblastic anhydrite infrequent. Spotty oxidation and oil staining along select beds.

4549.5′-4545.2′ Tan, dolomitic siltstone with interbeds of fine sandstone and dolomudstone. Black, argillaceous shale laminae common, possibly bioturbated. Spotty oils staining where sands dominate. Infrequent fenestrae (1cm) plugged by colorless dolomite.

4545.2′-4544.8′ Grey and tan, oolitic and peloidal dolopackstone. Ooids are micritized and many are missing. Dense, moderately sorted (≤2mm). Upper contact is sharp where anhydrite begins.

Sherwood Grey, nodular to chickenwire anhydrite with interstitial dolomudstone to dolosiltstone. Siltstone predominantly adjacent to top of marker.

Well # 3454 Marker: K-2

Glenburn Tan to light grey, oolitic packstone to wackestone. Extensive vuggy and fenestral porosity, mostly pugged by colorless anhydrite with zones of open oil stained pores.
4168.2’-4163.2’  Grey to light grey, argillaceous dolosiltstone. Very fine, subrounded quartz sand grains in siltstone. Weakly patterned, distinctly laminated in select areas with planar subhorizontal laminations (5-10°), and contorted laminae. Fenestral porosity with spotty oil staining where sands are limited.

4163.2’-4163'(top of core)  Light grey, quartz arenite. Fine sands, well sorted, well rounded. Possible white anhydrite nodules (cannot confirm due to limited thickness in core).

Well # 3454 Marker: K-3

Wayne  Tan to light tan and grey, oolitic and pisolitic grainstone to packstone, interbedded with wackstone. Vuggy and moldic porosity (20%) plugged by sparite. Highly stylolitic. Becomes more argillaceous down section.

4209’-4204.1’  Light tan, calcareous and fragmental quartz arenite. Fragments (10%) include skeletal grains (brachiopods) and broken ooids. Sand is very fine, well rounded, very well sorted. Calcite cemented, mostly massive. Zone of dark, planar, argillaceous laminations with 5° dip at 4206. 4207’-4206’ zone becomes siltier with faint reduction patterning. Dark, possibly oil stained or argillaceous above 4206’. Reduction halos and mud drapes common upsection. Lower contact is sharp at slack-water laminae.

4204.1’-4201’  Tan to grey, quartz arenite. Very fine, very well sorted, rounded to subrounded, faintly and discontinuously laminated to mottled. Partly dolomitized. Cementation is weaker than in adjacent zones. Oil stained with petroliferous odor. Small (1mm) intergranular pores. Zone becomes slightly argillaceous above 4202’.

4201’-4198’  Tan, quartz arenite. Very fine, very well sorted, rounded to subrounded. Mostly calcite cemented. Laminated with planar, nearly horizontal, silty and argillaceous laminae. Localized wavy to hummocked laminae. Select laminations are partly dolomitized.
4198’-4196.5’ Tan to light tan, quartz and fragmental arenite. Fragments include broken ooids and brachiopod shells (10%, 2-4mm). Quartz sand is very fine, very well sorted, subrounded. Discontinuous, wavy laminations with frequent mud drapes. Mostly calcareous cementation with localized dolomite cements.

4196.5’-4195’ Dark tan, sandy and oolitic dolomudstone to dolowackestone. Most ooids are micritized with frequent dissolution leading to small vuggs. Infrequent patterning. Oil staining and strong petroliferous odor.

4195’-4902’ Light tan, dolomudstone with few quartz sand grains. Light to distinct patterning, dense. Fenestral porosity (5%, 2mm) increasing upsection to 10%. Most pores have dark grey reduction halos. Upper contact is sharp where porosity becomes vuggy (20%) and allochems start.

Glenburn Light grey to grey, argillaceous oolitic packstone to wackestone. Extensive vuggy and fenestral porosity mostly open with oil stained pores.

Well # 3465 Marker: K-2

Glenburn Tan to light tan, oolitic packstone to wackestone with interbeds of grainstone and mudstone. Highly stylolitic. Extensive fenestral porosity (≤20%) and fracture porosity (adjacent to marker), both plugged by anhydrite. Bituminous staining on select bedding planes and pore margins.

4153’-4149’ Light grey, argillaceous dolomudstone. Lightly patterned, poorly cemented. Sparatic anhydrite nodules (<5%) above 4152’, increasing concentration upsection. Thin (<1cm) calcareous sandstone laminae present at 4150.5’. Fenestral porosity (<10%), plugged by anhydrite. Lower contact is sharp where allochems stop and dolomitization begins.

4149’-4145.7’ Grey, quartz arenite with interstitial argillaceous
dolomudstone. Fine grained, dolomite cemented, very well sorted, subrounded grains. Mostly massive to very faint subhorizontal bedding. Burnt oil (asphalt) specks common. Zone possibly coarsens upward.

4145.7’-4145.2’(top of core) White, nodular to bedded anhydrite interbedded with anhydrite cemented mudstone. Lower 1in is black, shale (possibly organic-rich) laminae, anhydrite cemented around large anhydrite nodules. This zone may be lower Mohall beds, but cannot confirm without more core.

Well # 3572 Marker: S.A.M.

Sherwood Ivory white, bedded and chickenwire to nodular anhydrite with interstitial than to grey dolomudstone. Anhydrite forms are interbedded. Occasional thin (<1cm) beds of black organic-rich shale.

4706’-4703.8’ Brown to dark brown, partially dolomitized mudstone. Spotty oil staining and petroliferous odor at bottom of zone where block texture and poor cementation persists. Replacement anhydrite present in dewatering structures. Lower contact is sharp, possibly erosional.

4703.8’-4703’ Light grey, argillaceous dolomudstone. Dense, lightly patterned.

4703’-4700.8’ Brown to dark brown, faintly dolomitized mudstone. Frequent black, slack-water laminae and mud drapes. Blocky to fissile texture (especially where argillics are concentrated). Spotty oil staining and petroliferous odor. Organic rich laminae at base of zone and at 4701.2’.

4700.8’-4699’ Dark tan to grey, dolomudstone. Partly argillaceous, lightly patterned, dense. Upper 4in of zone is oil stained where zone is less dense with blocky texture. Colorless crystalline anhydrite (or dolomite?) has filled and expanded small vertical fractures. Upper contact is sharp where nodular anhydrite begins.
Bluell

White, nodular (≤1cm) anhydrite with grey to tan interstitial dolomudstone.

Well # 3673 Marker: State A

Bluell

Tan, oolitic and pisolitic packstone. Significant intraparticle and fenestral porosity mostly occluded by translucent, euhedral anhydrite. Faintly oil stained where pores are open.

6792′-6790.5′

Dark grey to brown, calcareous mudstone. Lightly patterned, massive. Spotty oil staining. Lower contact is marked by 5 in zone of dark grey, argillaceous, anhydrite cemented mudstone. Stylolitic seams above and below this zone.

6790.5′-6789′

White to grey, chickenwire anhydrite.

6789′-6782.5′

Dark grey to Dark Tan, anhydrite cemented, argillaceous mudstone. Heavily patterned.

6782.5′-6781′

Dark grey, dolomudstone. Organic rich, blocky, laminated - parts easily along laminations (almost fissile). Disseminated white anhydrite nodules (4cm diameter).

6781′-6780′

Tan to grey, dolomudstone with dark grey to black argillaceous laminae interbedded with anhydrite cemented, patterned mudstone. Infrequent white anhydrite nodules (3cm) where anhydrite cement persist. Upper contact is sharp into overlying anhydrite.

Rival

White, chickenwire anhydrite interbedded with dense, grey to dark grey, anhydrite cemented mudstone.

Well # 3802 Marker: K-2

Glenburn

Tan to light tan, oolitic and oncolitic to pseudo-oolitic grainstone to packstone. Poorly sorted, heavily fractured. Extensive vuggy and dissolution porosity, plugged by colorless anhydrite.

4799.5′-4796.5′

Light grey, quartz arenite with interstitial
argillaceous dolomudstone. Fine to medium fine, very well sorted, subrounded, partly laminated and mostly contorted. Mud drapes common upsection (reverse grading). Lower contact is sharp where sandstone begins.

4796.5’-4795.5’ Grey to light grey, chickenwire to condensed nodular anhydrite with interstitial dolosiltstone. Highly dissected by water escape conduits and flame structures.

4795.5’-4792.9’ Grey to dark grey, dolosiltstone to very fine sandstone with interstitial dolomudstone. Mostly anhydrite cemented. Faint, wavy laminations and planar dark grey dolomudstone beds (1in). Zone becomes mottled and sandier upsection. Upper contact is sharp where anhydrite begins.

Mohall Light grey and white, bedded to chickenwire anhydrite. Highly condensed.

Well # 3817 Marker: K-2

4111’(bottom of core)-4107’ Light grey, quartz arenite. Dolomite cemented. Fine sands, very well sorted, subrounded. Mostly massive with infrequent horizontal laminations, possible high-angle (20-25°) foresets at 4109’. Zone becomes muddier upsection. Lower contact not reached in core.

4107’-4105.5’ Grey, argillaceous dolosiltstone with extensive (30%) grey and white nodular anhydrite. Nodules are condensed and “stringy” from syndepositional compaction. Siltstone displays contorted bedding from compaction and dewatering.

4105.5’-4101.5’ White and grey, chickenwire anhydrite with infrequent bedded and nodular form and interstitial grey, argillaceous dolosiltstone. Anhydrite is highly condensed. Matrix becomes sandier upsection.

4101.5’-4100’ Light grey, quartz arenite slightly argillaceous. Fine to medium-fine, well cemented (siliceous), well sorted, well rounded. Massive fabric. Anhydrite filled vertical fractures and water
escape conduits. Nodular anhydrite starts at 4100.5’ and increases upsection. Upper contact is rapid and conformable where mudstone begins.

Mohall

Light tan to dark tan, pisolitic and oncolitic packstone. Poorly sorted. Laminated, sandy mudstone to wackestone adjacent to contact and persist up to 4082’.

Well # 4017 Marker: State A

Bluell

White to grey, bedded and chickenwire anhydrite.

4691’-4689’

Dark grey, argillaceous dolomudstone. Very fissile to blocky (some core is bagged). Zone becomes more micritic upsection (not reflected in appearance). Thin (3mm), black, organic-rich, shales at 4691’ and 4690’. Lower contact is sharp where illite and dolomitization begins.

4690’-4688.5’

Brown, dolomitic mudstone-siltstone with wavy to planar, slack-water laminations. Possible burrows or roots (difficult to confirm with whole core). Prevalent dark brown, crystalline “metasomatic anhydrite,” preferential along bedding. Organic rich, fissile shale bed at top of interval.

4688.5’-4687.5’

White, bedded anhydrite. Sharp upper and lower contacts of zone.

4687.5’-4683’

Dark grey, argillaceous dolomudstone. Uniformly patterned. Frequent large (≤6cm) anhydrite nodules up to 4685’. Upper contact is sharp and wavy where anhydrite begins.

Rival

White to grey anhydrite in chickenwire form at lowermost 1ft. Bedded form dominates upsection.

Well # 4017 Marker: State A2

Bluell

Light tan, pisolitic wackestone-packstone.

4710’-4707’

Light grey, pisolitic wackestone to partially
dolomitized, patterned mudstone (base of marker). Pattern quickly fades upsection. Frequent vertical fractures lined with bitumen. Stromatolitic at 4707.5’. Lower contact is gradual where argillic muds increase.

4707’-4701’ Greenish grey, highly argillaceous, dolomudstone with frequent (≤50%) white anhydrite nodules (<3cm). Mudstone is blocky and fissile where anhydrite is absent. Sharp where anhydrite becomes bedded and mudstone becomes absent.

Bluell White, primarily bedded anhydrite, 10ft thick.

Well # 4092 Marker: K-3

3873.2’(bottom of core)-3870’ Red to reddish brown and light grey, argillaceous siltstone to mudstone. Completely cemented by anhydrite. Heavily oxidized with splotches of reduction (mottled appearance). Relict laminations are very faint and contorted. Lower contact not reached in core.

3870’-3869’ White to light grey, bedded anhydrite. Wavy, subhorizontal, enterolithic laminations of anhydrite cemented mudstone. Upper 2in of core present in zone appears heavily oxidized (deep maroon).

3869’-3869.2’ Missing core.

3869.2’-3867.6’ White, light grey, light brown and red, enterolithic anhydrite with interlaminated anhydrite cemented mudstone and siltstone. Laminations are wavy, condensed and vary frequently in color. Lower most zone is nodular anhydrite in a white and red, patterned mudstone matrix. Mud drapes common above 3868.6’. Infrequent poikiloblastic pyrite blebs.

3867.6’-3865.7’ Light grey and red, argillaceous quartz arenite. Sands are very fine, very well sorted and subrounded. Dolomite cemented. Zone irregularly oxidized on contorted bedding. Relict bedding may have been angled foresets,
but nearly destroyed. Poikiloblastic anhydrite common.

3865.7’-3861.9’ Dark brown, light grey and red, argillaceous quartz arenite. Very fine (slightly coarsens upsection), very well sorted, subrounded to subangular, dolomite cemented. Angled foresets (5-15°) common and contorted bedding upsection. Lowermost zone is dark brown, poorly cemented, with heavy oil staining and petroliferous odor (fades upsection). Upsection lithology becomes grey, and then red (oxidized) near upper contact. Anhydrite cementation in upper 6in of zone. Upper contact is sharp where bedded anhydrite and anhydrite cemented mudstone starts.

Glenburn White to light grey and light tan, bedded anhydrite interbedded with anhydrite cemented mudstone. Interbeds are highly irregular and condensed.

Well # 4186 Marker: K-2

3754.5’(bottom of core)-3751.3’ Grey to red, siltstone. Very fine, faint subhorizontal bedding (accentuated by oxidization), and highly irregular laminations dissected by dewater structures. Zone becomes sandier and more oxidized upsection. Small (<1cm) reduction halos with poikiloblastic pyrite. Lowermost 1in of zone is red anhydrite (may represent lower contact).

3751.3’-3750’ Maroon, pink, and yellow, siltstone to claystone with interlaminated mudstone. Large nodular (possibly thinly bedded) anhydrite at top and bottom of zone, and replacement anhydrite filling dewatering structures. Zone fines and becomes more yellow upsection.

3750’-3748.9’ Red to grey, siltstone. Mud draped, mostly oxidized. Mud drapes are highly irregular, continuous and subhorizontal. Subvertical hairline fractures with reduced margins. Infrequent aggregate pyrite precipitation.

3748.9’-3746’ Grey to light brown, quartz arenite. Sands are fine
to medium-fine coarsening upsection, very well sorted, rounded to subrounded. Lowermost 1ft is siltier, oxidized with crossing fluid-flow paths at 15° (likely mimics bedding). Spotty oil staining in sands along relict crossbeds at 15°.

3746’-3744.5’ Brown, quartz arenite. Medium-fine, poorly cemented, homogeneous, very well sorted, subrounded. Heavily oil stained.

3744.5’-3743’ Light grey and red, quartz arenite. Fine to medium-fine, very well sorted, subrounded, mostly well cemented. Very faint and infrequent mud drapes present upsection. Oxidization increases upsection. Reduced margins along hairline fractures.

3743’-3741.9’ Red to pink, tan and grey, very fine siltstone to mudstone. Wavy discontinuous and subhorizontal laminations, numerous desiccation cracks and dewatering features. Oxidation increases upsection and frequent reduced zones become present. Zone is anhydrite cemented beneath upper contact. Upper contact is sharp where bedded anhydrite begins.

Mohall White to light grey, bedded anhydrite with interbedded anhydrite cemented mudstone (light grey).

Well # 4363 Marker: K-2

Glenburn White to grey, bedded anhydrite. Grey, anhydrite cemented mudstone beneath 4337’.

4332.5’-4330.6’ Green-grey, argillaceous dolomudstone to claystone. Very dense, massive. Partly cemented by anhydrite.

4330.6’-4328.5’ Light grey and light tan, mudstone interbedded with white bedded anhydrite. Contorted bedding from dissection of water escape features. Black, shale laminae/mud draping around anhydrite nodules at 4329.5’. Some mudstone beds with nearly complete pyrite precipitation throughout.
4328.5’-4327.5’

4327.5’-4325’
Grey, quartz arenite to dolosiltstone. Sands are very fine, well sorted, well rounded, mostly to completely massive, coarsens upward. Upper contact is sharp where anhydrite starts.

Mohall
White to grey and tan, bedded anhydrite interbedded with anhydrite cemented mudstone and interstitial sand lenses. Black mud drapes or shale laminae at 4324.1’ (possibly organic-rich).

Well # 4657 Marker: K-1

Mohall
White to grey, nodular to chickenwire anhydrite with interstitial and interbedded very fine sandstone and siltstone.

4653’-4651.7’
Tan to green-grey, quartz arenite. Sand is fine to very fine, faintly planar and cross-bedded (20°). Frequent poikiloblastic and nodular anhydrite (15%, ≤1.5cm), nodules are condensed along bedding planes. Zone becomes argillaceous upsection with black shale laminae at top. Lower contact is sharp where sandstone begins to dominate lithology.

4651.7’-4649.9’
Grey to white, nodular (≤2cm) to chickenwire, and bedded anhydrite with interstitial tan, grey, and black mudstone to siltstone. Texture of anhydrite varies throughout zone. Nodule size decreases upsection. Mudstone alternates in planar fashion.

4649.9’-4648.3’
Tan, quartz arenite. Fine to very fine. Frequent milky white poikiloblastic anhydrite (40%, <2.5mm). Roll front reduction areas with disseminated pyrite and bituminous resin. Anhydrite precipitation favors reduction.

4648.3’-4647.2’
Red to tan, oxidized siltstone to very fine sandstone. Reverse grading, dense.
Oxidization decreases where sand is present. Anhydrite cemented. Planar and discontinuous bedding with frequent dewatering structures.

4647.2’-4644.5’ Red to reddish brown, oxidized siltstone. Dense, faint wavy and subhorizontal laminations, frequent dewatering structures. Becomes sandier upsection.

4644.5’-4643.5’ Tan with green and red, quartz arenite. Radial, acicular anhydrite crystals (likely diagenetic “gypsum roses”) and small (≤3mm) anhydrite nodules upsection. Red wisps from preferential oxidation in silty areas.

4643.5’-4639.6’ Greenish tan and red, siltstone to mudstone. Anhydrite cemented. Dense, laminated. Laminations are weak and faint, and prominent where oxidation is not present. Subvertical to vertical fractures with reduced mineralization at 4642.5’ and 4640’. Red beds dominate 4642’-4640.5’, surrounded by reduced lithologies. Base of zone laminated with black, argillaceous, slack-water laminae.

4639.6’-4637.5’ Light greenish grey, sandstone to siltstone. Very fine, mostly massive with subhorizontal bedding. Reduced zone with pokioblastic pyrite (≤1cm) and milky white anhydrite at 4638’. Diagenetic mineralization more prevalent upsection. Top of section is anhydrite cemented. Upper contact is sharp where bedded anhydrite begins.

Sherwood White to grey bedded anhydrite.

Well # 4768 Marker: S.A.M.

Sherwood Tan to light brown, oolitic and intraclastic wackestone. Fenestral and vuggy porosity (10-29%, ≤5mm). Partially plugged by colorless anhydrite. Oil staining in open pores.

6622’-6617.8’ Light grey to light tan, partially dolomitized and argillaceous mudstone. Dense, faintly and irregularly laminated, varying degrees of patterning. Lower contact is rapid to sharp
where allochems stop and argillic muds begin.

6617.8'–6616.5'
Yellow-tan, dolomudstone. Extensively dolomitized. Sucrosic texture, dense (<5% fenestral porosity, plugged), lightly patterned.

6616.5'–6615'
Grey to light grey, lightly dolomitized argillaceous mudstone grading upsection into dark tan oolitic and intraclastic wackestone. Dense, patterned. Intraclasts are micritic.

6615'–6613'
Light grey, argillaceous dolomudstone. Becomes increasingly more calcareous upsection. Dense, patterned. Zone capped by heavy, low-amplitude stylolite, or slack-water laminae, concentration.

6613'–6611'
Pinkish tan, partly dolomitized mudstone. Weakly laminated and weakly patterned. Lower 1ft of zone has thin beds of oolitic packstone and extensive “metasomatic” anhydrite.

6611'–6609.2'
Light pinkish tan to light grey, slightly argillaceous dolomudstone. Very dense, extensively dolomitized, and heavily patterned which decreases up section. Upper contact is sharp where anhydrite nodules begin.

Bluell
White to grey, nodular anhydrite with interstitial grey to tan dolomudstone. Nodules comprise 80% (<2cm) and are condensed.

Well # 5063 Marker: State A

Bluell
White-grey, bedded and chickenwire anhydrite

5918'–5917'
Light grey, dolomudstone. Small colorless and brown (possibly “metasomatic”) anhydrite nodules (≤5mm) frequent and decrease upsection. Lower contact absent between core chips.

5916'–5914'
Grey, dolomudstone, dense and lightly patterned.

5913'–5912'
Light grey to tan, dolomudstone. Small (≤2mm) mudstone intraclasts (tan to brown). Fenestral pores (≤2mm) and hairline fractures filled with
crystalline dolomite. Bituminous staining. Color due to decrease in argillaceous content from underlying zone.

5911’-5908’ Grey to dark grey, argillaceous dolomudstone, increasingly more patterned upsection. Black, mud drapes on preferential bedding planes at 5909’ along with first emergence of white, nodular (≤2cm) anhydrite. Anhydrite at nearly 50% bulk composition in 5908’ chip. Upper contact likely gradual but not confirmed.

Rival White and grey, bedded anhydrite.

Well # 5063 Marker: State A2

Bluell Greyish tan, pisolitic-oolitic wackestone

5931’-5929’ Grey to dark grey, pisolitic and intraclastic wackestone, patterned and lightly dolomitized. Darkens upsection due to increasing illite. Heavily stylolitic at 5931’. Lower contact is gradual where dark muds become prominent.

5929’-5927’ Light grey to tan, micrite, extensive fenestral porosity (30%) plugged by colorless anhydrite, residual bitumen on pore margins.

5927’-5925’ Grey to tan pisolitic and oolitic packstone alternating with beds of dark grey to light tan patterned dolomudstone. Bedding is highly variable in this zone. Vertical hairline fractures and infrequent fenestral pores, both filled by crystalline dolomite(?)

5925’-5924’ Light tan, dolomudstone (completely dolomitized), very dense.

5924’-5921’ Dark tan to grey, dolomitic micrite-siltstone, wavy to irregular bedding and possibly lenticular. Algal/stromatolitic texture around 5922.5’. Dark grey color dominates above 5922’ with first appearance of anhydrite nodules (white, ≤5cm) in argillaceous dolomudstone matrix. Upper contact is sharp at 5921’ where anhydrite becomes bedded.
Upper Bluell  White and grey, bedded anhydrite.

Well # 5186 Marker: K-1

Mohall  Brown, oolitic and intraclastic packstone to grainstone.  Intraclasts (≤2cm) are micrite and compacted.  Heavily oilstained.

4412’-4411’  Light grey, argillaceous dolomudstone.  Dense, lightly patterned.  Shrink/swell fractures at top of zone, healed by bladed anhydrite.  Lower contact is sharp where lithology becomes dense and oil staining stops.

4411’-4410.2’  Dark to light tan, oolitic packstone to wackestone.  Faint, highly irregular bedding.  Vuggy porosity at bottom and top of zone (≤30%, ≤3mm).  Middle of zone is muddier and lighter in color.  Concentration of microstylolites at top of zone.

4410.2’-4408.5’  Light grey, argillaceous dolomudstone.  Dense, lightly patterned (increases upsection) to mottled.  Fenestral porosity (5-15%) mostly plugged by anhydrite.  Small pores (≤1mm) are open.

4408.5’-4406’  Tan, intraclastic and pisolitic wackestone to dolomudstone.  Wackestone is more calcareous.  Irregularly laminated with black argillaceous laminae.  Replacement anhydrite is frequent throughout zone (“metasomatic” form).  Vuggy porosity prevalent above 4423.4’ (10-15%).  Oil staining throughout zone, heavy above 4407’.  Likely high sand content above 4407’ with intergranular porosity.

4406’-4402.2’  Light tan and light grey, dolomudstone grading upsection through fine siltstone and into fine quartz arenite with dolomite cement.  Faintly laminated and patterned where muddier.  Very dense.  White to colorless, large nodular anhydrite (4cm) present in lower 1ft of zone.

4402.2’-4399.5’  Light greyish tan, silty quartz arenite.  Silt particles likely from dolomitic muds.  Fine grained, well sorted, mostly massive.  Whispy inclined beds of condensed nodular white and grey anhydrite.
(≤4cm) above 4400.5’.

4399.5’-4397’ Dark grey to light grey, argillaceous dolomudstone. Dense, blocky, contorted bedding. Grades upsection into dolomitic and quartzose siltstone to fine sandstone at 4414.4’. Nodular anhydrite (condensed, ≤4cm) (>50%) zone. Upper contact is sharp and highly irregular from compaction.

Sherwood White and grey, bedded to chickenwire anhydrite. Grades upsection into anhydrite cemented mudstone.

Well # 5198 Marker: K-2

6580.5’(bottom of core)-6578.9’ Grey, argillaceous dolosiltstone and quartz arenite. Sands are very fine, mostly massive. Disseminated reduction halos around organics. Infrequent poikiloblastic anhydrite (≤3mm). High interclastic porosity (indicated by quick water absorption). Lower contact not reached in core.

6578.9’-6576.9’ Tan to light tan, pisolitic and quartzose wackestone. Patterned and partially dolomitized at base of zone. Sand increases and allochems decrease upsection. Faintly laminated, highly stylolitic.

6576.9’-6575’ Tan to light grey, pisolitic and oolitic wackestone to mudstone with basal 2in packstone. Partially dolomitized, lightly patterned, highly stylolitic. Dark brown argillaceous laminations up section (possibly algal). Fenestral porosity (<10%, ≤2mm), mostly plugged by anhydrite.

6575’-6573’ Grey to light grey, argillaceous and dolosiltstone and dolomudstone. Mostly massive with faint wavy lamintations (possibly algal) at 6574’. Disseminated reduction halos around organics. Fenestral porosity up section (<10%, 2mm), mostly open.

6573’-6568’ Tan to light tan and grey, slightly argillaceous mudstone to calcareous siltstone. Horizontal to subhorizontal wavy laminations (possibly algal), faintly patterned. Zone becomes more
argillaceous and dolomitized above 6571’. Fenestral porosity is high (20%) along select bedding, more commonly 5%. Pores open below 6571’, mostly filled by anhydrite above. Upper 1ft is bears mudstone clasts (angular with pisolitic coating). Upper contact is very gradual where allochems increase.

Mohall

Light tan, pisolitic packstone to wackestone with interbedded oolitic grainstone. Laminations persist up to 6563’. Porosity (15%) mostly open, increases upsection.

Well # 5531 Marker: K-2

Glenburn

Grey to white, chickenwire anhydrite with interstitial grey to light tan dolosiltstone and dolomudstone. Infrequent interbeds (6in thick) of tan, very fine sandstone. Black, organic-rich shale laminae at 4839.8’. Light tan, pisolitic packstone to wackstone persists beneath 4852’.

4832’-4829.2’

Light grey, quartz arenite with interstitial argillaceous dolomudstone. Very fine sands, mottled, faintly bedded, possible ripple foresets. Infrequent anhydrite lenses (condensed nodules) concordant to select bedding planes. Lower contact is sharp where anhydrite becomes the secondary lithology.

4829.2’-4828.2’

White and light grey to light tan, bedded anhydrite. Dissected by subhorizontal (<5°), anhydrite cemented, mudstone laminae. Disseminated pyrite poikiloblasts common (<5mm).

4828.2’-4826’

Light tan to light grey, dolosiltstone. Heavily mottled with anhydrite cemented mudstone and thin interbeds of bedded anhydrite. Anhydrite cementation decreases upsection. High angle bedding (20-25%) and ripple foresets faintly preserved in siltstone. Infrequent reduction halos around organics. Upper contact is sharp where anhydrite begins.

Mohall

White and light tan to light grey bedded anhydrite. Wavy, horizontal laminations of enterolithic
mudstone.

Well # 5809 Marker: State A

Bluell

Tan to light brown, pisolitic and pelodial wackestone to packstone. Weakly and irregularly laminated. Fenestral porosity low (<10%, ≤4mm), mostly plugged by white anhydrite and colorless dolomite.

5885.1’-5880.2’

Light grey to tan, dolomudstone interbedded with calcareous mudstone. Patterned to mottled, mostly massive and weakly laminated with localized algal laminations at 5880’. Heavily fractured at 5883.2’ (hairline, vertical to subvertical). Fenestral porosity low (<5%), plugged by dolomite. Lower contact is rapid where lithology becomes more argillaceous.

5880.2’-5876’

Tan to brown, dolowackestone interbedded with brown to dark brown, dolomitic and argillaceous siltstone. Locally sandy. Laminated with light bioturbation and infrequent hummocked beds, becomes massive upsection. Poikiloblastic “metasomatic” anhydrite at 5877’. Heavily oil stained with strong petroliferous odor. Upper contact is sharp and compacted where anhydrite begins.

Rival

White to grey, nodular to chickenwire anhydrite with interstitial dark grey, argillaceous dolomudstone.

Well # 5809 Marker: S.A.M.

Sherwood

Tan to light tan, oolitic, pisolitic, intraclastic packstone to grainstone. Intralasts (<3cm) are condensed and ooid bearing. Vuggy and moldic porosity (≤10%, ≤4mm), mostly plugged by dolomite.

5949’-5946.3’

Grey to tan, argillaceous, intraclastic and pisolitic wackestone with basal (3in) oolitic and pisolitic packstone. Allochems and agrillics decrease upsection and zone becomes tan. Fenesteral porosity (15%, 3mm), plugged by anhydrite. Stylolitic. Lower contact is sharp where
argillaceous muds being.

5946.3’-5938.1’

Dark grey, argillaceous, argillaceous dolomudstone. Infrequent micritic intraclasts. Stylolitic, infrequent horizontal to subhorizontal bedding. Extensive fenestral porosity (30%, 2mm), plugged by colorless anhyrite. Argillaceous content fade upsection, zone becomes lighter grey. Upper 3in of zone displays a sharp fabric change to tan, oolitic grainstone.

5938.1’-5937.1’

Light brown to light tan, pisolithic wackstone. Faintly laminated. Large (1cm), grey, angular rip-up clasts of underlying lithology along base of zone. A 4in thick bed of light tan, poorly-sorted intralastic and pisolithic packstone to grainstone present at 6800.5’. Fenestral (≤3mm) porosity with minor vugs (<1cm) (<5% increasing upsection to 10%), plugged by colorless anhydrite. Oil staining on margins of vugs.

6798.1’-6797.5’

Dark to light grey, argillaceous dolomudstone with interbedded oolitic packstone and brecciated intraclasts. Degree of dolomitization varies throughout zone. Dense, with frequent stylolites and dissolution seams. Low fenestral porosity (<5%) and filled with “metasomatic” anhydrite. Upper contact is missing in core, sharp color change between two pieces of core.

Bluell

Tan, peloidal packstone to wackestone. Faintly bedded to massive. Low (<3%) vuggy porosity, mostly filled with rimming sparite.

Well # 6157 Marker: State A

Upper Bluell

White and grey, bedded anhydrite

5581’-5580’

Tan, dolomudstone, well laminated with black argillaceous shale. Laminations frequently offset by small (<3cm) soft sedimentary thrusts. Likely microporous as intercrystalline between dolomite crystals. Grey anhydrite nodules (=5cm) separate laminated mudstone from overlying light grey-tan dolomudstone with blocky texture. Lower contact is very sharp where mudstone begins. Top of core at 5580’.
Well # 6157 Marker: State A2

Bluell White, chickenwire to bedded anhydrite.

5591’-5590.3’ Light to dark grey, argillaceous dolomudstone, patterned, irregularly laminated with black argillaceous slack water lamina. Vertical hairline fractures and frequent dewatering structures are present. Lower contact is sharp and has a concentration of black laminae.

5590.3’-5589.8’ White, chickenwire anhydrite with interstitial, light grey, dolomudstone.

5589.8’-5587’ Light grey, dolomudstone (60%) with white, nodular anhydrite (40%, ≤4cm). Upper contact is sharp where mudstone becomes completely absent.

Upper Bluell White to light grey, bedded anhydrite.

Well # 6402 Marker: State A

Upper Bluell Dark tan to grey, oolitic and intraclastic packstone with intraparticle porosity (10%). Ooids are mostly broken, intraclasts have pisolitic coating.

8179.1’-8178’ Yellow-tan, dolomudstone. Very dense, sucrosic texture, with dolomite plugged fenestral porosity (10%). Zone capped by thin (1in) bed of black slack-water laminae.

8178’-8175’ Light to dark tan, pisolitic wackestone, quickly fades upsection into dark tan, mudstone, laminated, dense. Bituminous stained, fenestral pores (5%, 2-3mm, some ≤8mm) at 8176.2’ plugged by colorless sparite.

8175’-8172’ Dark tan, brown, and grey, oolitic wackestone. Dense, partly argillaceous (increasing upsection) coinciding with increase laminations. Microstylolitic. Top of zone marked by black, organic-rich shale laminae.

8172’-8171’ Light grey to tan, dolomudstone. Very dense, faintly mottled, lacks internal structure. Upper
contact is sharp where anhydrite cementation begins.

Rival

- Light grey to tan, anhydrite cemented mudstone.
  - Mottled and faintly laminated.

**Well # 7134 Marker: K-1**

Mohall

- Whit to grey, bedded anhydrite and anhydrite cemented argillaceous dolomudstone. Grey to dark grey, argillaceous dolomudstone interlaminted with bedded anhydrite.

4521.8’-4519.8’ (top of core)

- Light grey, quartz arenite with interstitial dolomudstone. Fine to very fine sands, dolomite cemented, mostly massive with localized ripple foresets (20°) at 4521.2’. Anhydrite cement persists up to 4521.3’ where zone is less sandy.

**Well # 7134 Marker: K-2**

Glenburn

- Tan to light grey, dolomudstone with frequent dark grey to black shale laminae. Mottled to patterned in select areas, contorted laminations (possibly bioturbated). Vuggy and fenestral porosity, mostly open, oil stained. Large vertical fractures (2mm wide), healed by anhydrite.

4575’-4572’

- Light grey to light tan, dolomudstone with interbeded dark grey shale laminae and thin (0.5in) very fine sandy beds. Dense, faintly patterned, subplanar and wavy laminations (possibly algal). Fenestral porosity developed adjacent to sandy beds. Sands are oil stained.

4572’-4570’

- Light grey, dolomudstone to very fine siltstone. Dense, patterned, infrequent planar beds. Frequent reduction haloes.

4570’-4568’

- Grey, chickenwire anhydrite with interstitial light grey dolomudstone. Mudstone becomes more argillaceous upsection.

4568’-4566.8’

- Grey to dark grey, anhydrite cemented, argillaceous
mudstone. Mottled with frequent reduction haloes. Original bedding poorly preserved.

4566.8’-4565’
Light tan and light grey, anhydrite cemented mudstone and very fine sandstone. Highly irregular and dissected by small flame structures. Thin black mud drapes around large (6cm), condensed, anhydrite nodules. Thin bed of pseudo-oolitic packstone with superficial coating. Vertical fractures in packstone. Euhedral pyrite (≤1mm) precipitation in the uppermost zone.

4565’-4564’

4564’-4559.6’
Grey to dark grey, argillaceous dolomudstone to siltstone. Mostly anhydritic cemented. Zone becomes sandier and lighter grey upsection. 4560’-4562’ is missing. Fine sandstone beneath contact. Upper contact is sharp where anhydrite begins.

Sherwood
Light grey to white bedded anhydrite.

Well # 7261 Marker: K-2

Glenburn
Tan to brown, sandy and oolitic wackstone to packstone with beds of grainstone. All ooids are micritized and infrequently replaced by sparite except above 4119.5’. Vuggy and interparticle porosity increasing downsection (zone becomes coarse [≥2mm] oolitic grainstone). Heavily oil stained.

4112’-4110.5’
Tan to brown, quartz sandstone to siltstone. Fine sands, well sorted, subrounded, calcite cemented. Massive texture. Interstitial micrite increases upsection. Interparticle (0.5mm) and infrequent vuggy porosity (10%). Pore occluding calcite in larger vugs. Heavily oil stained.

4110.5’-4109.5’
Tan to light tan, quartz-rich calcareous mudstone. Grades upsection ion quartzic and oolitic packstone. Highly stylolitic. Lightly oil stained.
and bituminous with replacement sparite of select allochems.

4109.5’-4108.5’ Light grey, quartzic and arillaceous dolosiltstone with basal dark grey, argillaceous, oolitic dolopackstone. Fenestral porosity (10-15%, 2-3mm) in siltstone, occluded by anhydrite. Patchy oil staining in siltstone where anhydrite is absent.

4108.5’-4108’(top of core) Dark tan to brown, quartzic and micritic siltstone. Original fabric mostly destroyed, with faint and weak laminations. Fenestral porosity (20%) plugged by anhydrite. Heavy oil staining and petroliferous odor. Bituminous pore margins.

Well # 7368 Marker: State A

Bluell Tan, oolitic and intraclastic (pisolitic coating) packstone with extensive fenestral porosity (30%) completely plugged by colorless sparite.

7465.8’-7464.8’ Yellowish tan, deeply patterned, sucrosic dolomudstone with basal tan, partially dolomitized mudstone with bioturbated, black argillaceous laminations.

7464.8’-7463’(top of core) Dark tan to dark grey, wavy laminated and microstylolitic mudstone. Possibly rippled lamination. White, disseminated nodular and poikiloblastic andydrite (<10%, ≤2mm) and anhydrite replaced laminae.

Well # 7368 Marker: S.A.M.

Sherwood Pinkish tan, oolitic and intraclastic (pisolitic coating on intraclasts) packstone to gainstone. Extensive fenestral porosity (30%, ≤3mm) and fracture porosity, both plugged by colorless sparite. 2ft zone of open vuggy porosity adjacent to the marker.

7553.8’-7553.3’ Dark grey to dark tan, oolitic and intraclast, argillaceous packstone with decreasing argillaceous content upsection. Lower contact is sharp where argillaceous content starts.
7553.3’-7553’ Dark tan, cemented oolitic grainstone, well sorted with sparite plugged intraparticle porosity. Most ooids are broken, full ooids are 1.5mm.

7553’-7550’ Dark tan to grey, oolitic and intraclastic wackestone. Stylolitic, extensive fenestral porosity (30%, ≤3mm). Mud decreases at 7546’ and lithology becomes packstone to grainstone.

7549’-7546.8’ Grey, oolitic wackstone to mudstone with basal (6in) oolitic and intraclastic (oid bearing, ≤3.5cm, compacted) packstone to grainstone. Superficial ooids. Extensive fenestral porosity (20%, ≤4mm) plugged by colorless sparite. Microstylolitic.

7546.8’-7544.2’ Dark tan, oolitic, intraclastic and bioclastic packstone to grainstone. Ooids (90%, ≤1mm), intraclasts are ooid bearing (8%, 1-2cm), bioclasts (2%) include brachiopod shells, gastropods, and formanifera. Intraclastic and shelter porosity (20%), sparite filled. Minor sparite replacement of select allochems.

7544.2’-7543’ Dark grey, intraclastic wackstone to dense dolomudstone. Heavy concentration of black slackwater laminae at base of zone. Steady decrease in agillics upsection. Highly stylolitic. Fenestral porosity (20%, 3-10mm) partially plugged by white anhydrite. Upper contact is gradual where allochems reappear.

Bluell Tan, oolitic and pisolitic, wackestone to packstone with large (≤5mm) vugular pores (30%), open.

Well # 7471 Marker: S.A.M.

Sherwood Light tan, intraclastic (≤3cm) and oolitic grainstone. Coarse, poorly sorted, partially cemented. Extensive moldic, vuggy, and intraparticle porosity (30%), partly open (10%), mostly plugged by sparite.

7592.2’-7591.6’ Dark tan, oolitic packstone to wackestone. Sparite plugged fenestral porosity (15%, ≤5mm) and vertical fracture porosity, also plugged. Ooids
are well sorted (<2mm). Irregular erosion surface at top of zone.

7591.6’-7589.8’ Dark tan to light grey, oolitic (<1mm) and intraclastic (3-10mm packstone. Intraclasts are angular and increase in size and roundness upsection. Sparite plugged fenestral porosity (10%, ≤5mm). Highly stylolitic.

7589.8’-7586.6’ Grey, argillaceous skeletal and pisolithic wackestone with basal (6in) poorly sorted intraclastic (≤3cm, ooid bearing and compacted) and oolitic grainstone to packstone. Fenestral porosity (30%, <3mm) plugged by sparite.

7586.6’-7584.3’ Tan, oolitic and intraclastic packstone. Intraclasts are large (4.5cm), compacted, rounded, ooid bearing and have pisolithic coating. Fenestral porosity (30%, ≤6mm) plugged by sparite. Stylolitic.

7584.3’-7582.5’ Grey, argillaceous, pisolithic and intraclastic wackestone with basal (5in) poorly sorted, intraclastic (≤4cm, subrounded), oolitic, and pisolithic grainstone. Faintly laminated. Sparite plugged fenestral (≤4mm) porosity which increases upsection from 10% to 30%.

7582.5’-7579.5’ Tan, oolitic, intraclastic, and bioclastic packstone to grainstone with section (1ft thick) of wackestone at 7588’. Bioclasts include gastropods and brachiopods. Intraparticle and moldic porosity (20% in grainstone, 10% in wackestone. Wavy laminated bedding at 7580.5’.

7579.5’-7577.5’ Grey, argillaceous, oolitic wackestone with basal (4in) intraclastic, oolitic and pisolithic grainstone. Extensive fenestral porosity (30%, ≤5mm) with minor amounts of moldic porosity upsection, plugged by sparite. Upper contact is gradual where argillaceous muds fade.

Bluell Tan, oolitic, intraclastic, and bioclastic packstone to grainstone. Bioclasts include brachiopods and gastropods. Vuggy and moldic porosity (20%), plugged by sparite.
Well # 7612 Marker: State A

Bluell

White, nodular and chickenwire anhydrite with interstitial tan dolomudstone overlying light tan, oolitic and pisolitic wackestone to packstone.

6866.5’-6862.5’

White and dark grey, nodular anhydrite with interstitial dark grey, argillaceous dolomudstone. Argillaceous content fade upsection and mudstone becomes dark tan in color. Anhydrite nodules decrease in size to (<1cm) and concentration (>80%).

6862.5’-6859’

Tan to brown, dense, partially dolomitic mudstone with faint, irregular wavy laminations. "Metasomatic" anhydrite present in fenestral pores (20%, 2mm) with burnt oil stained margins. A (4in thick) lag deposit of bioclastic and intraclastic organic-rich shale (<2cm) gives bed a conglomeritic texture at 6861’.

6859’-6852’

Dark grey to grey, faintly and irregularly laminated, dense, argillaceous mudstone, anhydrite cemented. Grey, chickenwire anhydrite characterizes lower- and upper-most 1ft of zone. Upper contact is sharp where illite fades in anhydrite cemented mudstone.

Rival

Tan, anhydrite cemented mudstone.

Well # 7910 Marker: K-1

Mohall

Tan to grey and white, bedded anhydrite and localized areas of anhydrite cemented mudstone. Frequent black, organic-rich shale laminae without anhydrite cement.

5405.5’-5405’

Greenish grey, quartzose siltstone to very fine sandstone with interstitial dolomudstone. Infrequent light grey to white discontinuously bedded anhydrite. Lower contact is rapid where siltstone begins.

5405’-5404’

Grey to light grey, anhydrite cemented mudstone, grading upsection into extensive replacement anhydrite and chickenwire form. Highly
condensed with large water escape (mud volcanoes?) throughout chickenwire. Interstitial mud fades from grey to tan upsection.

5404’-5403’
Light tan, dolomudstone with interlamination of green-grey argillic claystone and irregular anhydrite nodules. Zone partially cemented by anhydrite and dolomite. Faintly pattern, contorted bedding.

5403’-5400.2’
Grey and white, bedded and replacement anhydrite. Thin mud drapes between beds of anhydrite.

5400.2’-5398.7’
Grey to dark grey, siltstone to very fine quartz sandstone with interstitial argillaceous dolomudstone. Dolomite cemented. Infrequent wavy horizontal mud draps (may indicate relict bedding planes). Anhydrite cementation persists above 5399’ where lithology becomes darker.

5398.7’-5397.3’
Light grey to white bedded anhydrite with very fine laminations (<1mm) of dolomudstone. Laminations are wavy and horizontal to subhorizontal.

5397.3’-5393.7’
Grey to light grey, argillaceous siltstone grading upsection into fine to very fine sandstone with interstitial argillaceous dolomudstone. Faint bedding and lamination (more prevalent in siltstone), crossbed foresets (10-15°) in sandstone. Lower 6in of zone is anhydrite cemented. Thin beds (1in) of condensed nodular anhydrite (2cm) in upper 4in of zone.

5393.7’-5393.1’
Grey to light grey and white, bedded anhydrite and anhydrite cemented dolomudstone. Heavily condensed and mottle at top of zone when argillic content begins to increase.

5393.1’-5390.2’
Grey to light grey, argillaceous siltstone grading upsection into fine to very fine sandstone with interstitial argillaceous dolomudstone. Faint bedding and lamination (more prevalent in siltstone), crossbed foresets (10-15°) in sandstone. Sandstone is mottled to irregularly
bedded with frequent mud drapes. Lower of zone is partially anhydrite cemented. Thin beds (1in) of nodular anhydrite (2cm) in upper part of zone.

5390.2’-5388’
Dark grey, anhydrite cemented dolomudstone. Upper contact is sharp where bedded anhydrite begins.

Sherwood
White and tan, bedded anhydrite. Frequent horizontal laminations (<1mm) of anhydrite cement mudstone.

Well # 8009 Marker: S.A.M.

Sherwood
Tan to light tan, oolitic (≤3mm), pisolitic (5-15mm) packstone with interbeds of grainstone. Extensive interparticle porosity (30%) with minor fenestrae, plugged by anhydrite.

7130’-7127.3’
Grey to dark grey, argillaceous, intraclastic and oolitic wackestone. Intraclasts of brown mudstone are angular and concentrated to lower 6in of zone. Extensive black, slack-water laminae also present at base of zone. Argillic fade at 7128.5’ coinciding with development of tan, packstone. Fenestral porosity (10-20%, ≤5mm), plugged by anhydrite. Lower contact is sharp, possibly erosional or due to slumping.

7127.3’-7124.8’
Dark tan to tan, intraclastic and pisolitic packstone to wackestone. Intraclasts consist of pisoids and have pisolitic coating. Poorly sorted. Extensive vuggy and moldic porosity in packstone and fenestral in wackestone (20-30%) plugged by colorless anhydrite. Spotty oil staining in select pores.

7124.8’-7123.7’
Light brown, oolitic grainstone. Well sorted, uniform, isopachous cementation. Interparticle anhydrite, possibly poikiloblastic.

7123.7’-7122’
Light grey, dolomudstone with basal, intraclastic dolowackestone. Intraclasts are white mudstone and/or ooid bearing. Anhydrite has replaced all ooids and select intraclasts in wackestone. Fenestral porosity low (<5%) in
mudstone, and plugged.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7122′-7121.3′</td>
<td>Light grey to dark tan, dolomudstone and interlaminated calcareous mudstone. Laminations are wavy and bioturbated. Dense.</td>
</tr>
<tr>
<td>7121.3′-7119.3′</td>
<td>Light grey, dolomudstone with basal, intraclastic dolowackestone. Intraclasts are white mudstone and/or ooid bearing. Anhydrite has replaced all ooids and select intraclasts in wackestone. Fenestral porosity low (&lt;5%) in mudstone, and plugged. Repeat section of 7123.7′-7122′. Upper contact is sharp where anhydrite begins.</td>
</tr>
<tr>
<td>Bluell</td>
<td>Grey and white, chickenwire anhydrite with interstitial argillaceous dolomudstone. Anhydrite becomes bedded upsection.</td>
</tr>
</tbody>
</table>

**Well # 8636 Marker: State A**

<table>
<thead>
<tr>
<th>Interval</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluell</td>
<td>Bluish grey, bedded to chickenwire anhydrite with interstitial argillaceous dolomudstone.</td>
</tr>
<tr>
<td>4373′-4372′</td>
<td>Light to dark grey, argillaceous dolomudstone. Mostly massive in lower zone with few black, organic-rich laminations (horizontal) upsection, faint patterning. Faint oil staining along bedding.</td>
</tr>
<tr>
<td>4372′-4368′</td>
<td>Tan to light brown, weakly dolomitized mudstone. Heavily distorted subhorizontal bedding with frequent intraclasts (&lt;5mm) along bed. Possibly bioturbated.</td>
</tr>
<tr>
<td>4368′-4366′</td>
<td>Light to dark brown and grey, argillaceous dolomudstone. Extensively bioturbated along wavy, discontinuous laminations. Laminations become thinner and more frequent upsection with small (1in) hummocked beds in uppermost zone. Infrequent dissolution seams. Extensive “metasomatic” anhydrite concentrated in 8in zone. Upper contact is sharp to erosional where anhydrite begins.</td>
</tr>
<tr>
<td>Rival</td>
<td>Reddish grey, bedded to chickenwire anhydrite with thin (1mm) enterolitic black shale laminae,</td>
</tr>
</tbody>
</table>
anhydrite cemented.

Well # 8636 Marker: S.A.M.

Sherwood
Tan, intraclastic and pisolitic wackestone. Heavy concentration of black stylolites and low-amplitude dissolution seams at contact. Frequent “metasomatic” anhydrite.

4418’-4422’
Grey, argillaceous dolomudstone. Entire marker is homogeneous and patterned. Upper 1 ft of zone becomes laminated with wavy, horizontal laminations and small (1mm) reduction halos around organics. Lower contact is sharp at dissolution seams. Upper contact is sharp and irregular where anhydrite begins.

Bluell
White to light grey, bedded to chickenwire anhydrite with interstitial dark grey, argillaceous dolomudstone.

Well # 8819 Marker: State A

Bluell
Grey to tan, oolitic and pisolitic packstone.

5965’-5964.5’
Grey to dark grey, argillaceous micrite, faintly dolomitize and lightly patterned. Frequent fenestral pores (2mm, 20%), plugged by colorless anhydrite. Lower contact is sharp where allochems disappear.

5964.5’-5961’
Tan to light grey, dolomudstone, very dense, irregularly bedded and patterned. Dolomitization decreases upsection and color becomes more grey. Very fine fenestral (or dissolution) porosity (<0.5mm) develops where dolomitization is weakens. Pores plugged by colorless anhydrite. Stylolite concentration increases up section. Faintly oil stained.

5961’-5959’
Dark grey, argillaceous, intraclastic and pisolitic wackestone, patterned (weakly dolomitized). Intraclasts (≤3mm) are dark grey, dense, micrite.

5959’-5954’
Tan to light grey, oolitic and pisolitic (≤2mm)
wackestone with extensive anhydrite-plugged fenestrae (15%, ≤3mm). 5956’-5955’ is packstone with similar allochems. Petroliferous staining along margins of select ooid aggregates and larger grains. Black, organic-rich, slack water lamina characterize top and bottom of zone, absent in center.

5954’-5950’  
Grey to tan, argillaceous micrite (middle) and dolomudstone (top and bottom), dense, patterned. Extensively stylolitic at 5953’. 5952’-5951’ displays highly extensive (40%) dissolution and fenestral porosity, completely plugged by crystalline anhydrite and stained brown from organic content. 3-4in zone of black, slack-water lamina in mudstone with small (≤5mm) white anhydrite nodules and hummocked bedding.  
Top of core at 5950’, upper contact not present.

**Well # 8991 Marker: State A2**

Bluell  
Tan, oolitic and intraclastic grainstone. Intraclasts (≤3cm) are ooid bearing and condensed. Interparticle porosity (10-20%), mostly plugged by anhydrite.

7951’-7949’  
Brown and grey to dark grey, argillaceous dolomudstone with infrequent tan micritic intraclasts (5mm). Wavy laminated (possibly algal) with laminations increasing upsection. Poikiloblastic “metasomatic” anhydrite preferential to bedding adjacent to lower contact. Lower contact is rapid where laminations and argillaceous muds begin.

7949’-7947’  
White, nodular anhydrite in tan to grey dolomudstone matrix. Nodules are large (some >5cm) and grade upsection in to 10cm bed of white, bedded anhydrite.

7947’-7941’  
Light grey to tan, argillaceous dolomudstone. Very dense, lightly patterned, laminated to stromatolitic at 7945’ and 7943’. Infrequent dolomudstone intraclasts (<3mm). Faint oil staining in algal laminations. Fenestral porosity (<5mm) develops above 7942’. Upper contact
Upper Bluell

White and grey, nodular (>3cm) anhydrite with interstitial argillaceous dolomudstone matrix.

Well # 8991 Marker: S.A.M.

Sherwood

Tan to light tan, oolitic and intraclastic (pisolitic coating on intraclasts) packstone to gainstone. Extensive interparticle porosity (30%, ≤4mm) and fracture porosity, both plugged by colorless sparite.

7997.7’-7994’

Dark tan, cemented oolitic grainstone with basal (6in) Dark grey argillaceous packstone. Illite decrease upsection. Well sorted with sparite plugged intraparticle porosity. Most ooid are broken, full ooids are 1.5mm. Lower contact is sharp where argillaceous content starts.

7994’-7991.2’

Dark tan to grey, oolitic and intraclastic packstone. Stylolitic, extensive fenestral porosity (30%, ≤3mm). Mud decreases at 7992’ and lithology becomes grainstone.

7991.2’-7988.8’

Grey, oolitic wackstone to mudstone with basal (6in) oolitic and intraclastic (oid bearing, ≤3.5cm, compacted) packstone to grainstone. Extensive fenestral porosity (20%, ≤4mm) plugged by colorless sparite. Stylolitic.

7988.8’-7986.8’

Dark tan, oolitic and intraclastic packstone to grainstone. Intraclasts are ooid bearing (8%, 1-2cm). Intraclastic and shelter porosity (20%), sparite filled. Minor sparite replacement of select allochems.

7986.8’-7983’

Dark grey, intraclastic wackstone to dense dolomudstone. Steady decrease in agillics upsection. Highly stylolitic. Fenestral porosity (20%, 3-10mm) partially plugged by white to colorless dolomite. Upper contact is gradual where allochems reappear.

Bluell

Tan, oolitic and pisolitic, wackestone to packstone with large (≤5mm) vugular pores (10%), mostly open.
Well # 9036 Marker: K-1

Mohall
Dark grey to tan, argillaceous mudstone to oolitic grainstone. Highly variable lithology and bedding structures. Compacted. Extensive fenestral and interparticle porosity (25-30%), completely plugged by anhydrite. Frequent vertical fractures. Pores and fractures are oil stained.

6811.5’-6808.9’
Light tan to light grey, dolomudstone. Lightly patterned, frequent reduction haloes (disseminated and preferential to bedding). Intercrystalline microporosity high (logs). Lower contact is sharp where allochems stop and dolomitization starts.

6808.9’-6807.2’
Dark grey, chickenwire anhydrite with interstitial light tan to light grey dolomudstone.

6807.2’-6806’
White to grey, anhydrite cemented, argillaceous mudstone. Relict irregular and subplanar bedding preserved throughout zone.

6806’-6803.5’
Dark grey to green-grey, quartz arenite and interstitial, argillaceous dolosiltstone. Bedding is poorly preserved from dehydration, remaining beds subplanar and irregular with possible ripple forsets. Infrequent nodular and replacement anhydrite near upper contact. Upper contact is sharp where anhydrite begins.

Sherwood
White to grey and tan, bedded anhydrite.

Well # 9424 Marker: State A

Bluell
Light tan, oolitic and pisolithic wackestone to micrite, dense.

5164’-5163’
Dark grey, argillaceous micrite, lightly patterned, with bituminous staining, likely organic rich. Bed (2in) of black, organic-rich, slack-water lamina at top and bottom of zone. Lower contact is sharp where marked by black, lamina.

5163’-5160’
White and grey, nodular anhydrite with tan,
interstitial dolomudstone matrix. Anhydrite nodules (≤1cm, 80%).

5160’-5159’
Grey, replacement anhydrite after argillaceous dolomudstone, densely patterned (remaining from original mudstone lithology). White, bedded anhydrite (1in thick) at top of zone.

5159’-5157’
Dark tan, dolomudstone with frequent (40%), large (≤6cm), white/grey, nodular anhydrite. Anhydrite becomes more abundant up section. Upper contact is sharp where anhydrite becomes bedded.

Rival
White to tan-grey, bedded anhydrite.

Well # 9823 Marker: K-1

Mohall
Light brown to tan, oolitic packstone to grainstone. Heavily oil stained. Interparticle porosity (≤20%), mostly open. Concentrations of black microstylolites common.

4428.5’-4427.5’
Light grey, argillaceous dolomudstone. Dense. Fenestral porosity common (≤2mm), likely not effective due to no staining. Lower contact is sharp where lithology becomes dense and oil staining stops.

4427.5’-4426.1’
Dark to light tan, oolitic packstone to wackestone. Faint, highly irregular bedding. Vuggy porosity at bottom and top of zone (≤30%, ≤3mm). Middle of zone is muddier and lighter in color. Thin bed of argillaceous black laminae at 4426.5’.

4426.1’-4425’
Light grey, argillaceous dolomudstone. Dense, lightly patterned to mottled. Fenestral porosity (5-15%) mostly plugged by anhydrite. Small pores (≤1mm) are open.

4425’-4424.2’
Brown to dark brown, sandy (quartzose), pisolitic wackestone with basal oolitic packstone. Heavily oil stained with strong petroliferous odor. Bitumen coated allochem. Vuggy porosity (10%), mostly open, and likely high intergranular porosity.
4424.2′-4422.2′ Tan, intraclastic and pisolitic wackestone to dolomudstone. Wackestone is more calcareous. Irregularly laminated with black argillaceous laminae. Lowermost 4in of zone is white bedded anhydrite. Replacement anhydrite is frequent throughout zone. Vuggy porosity prevalent above 4423.4′ (10-15%). Oil staining in porous areas.

4422.2′-4418.5′ Light tan and light grey, dolomudstone grading upsection through fine siltstone and into fine quartz arenite with dolomite cement. Faintly laminated and patterned where muddier. Very dense. White to colorless, nodular anhydrite (<3cm) present in lower 1ft of zone.

4418.5′-4416′ Light greyish tan, silty quartz arenite. Silt particles likely from dolomitic muds. Fine grained, well sorted, mostly massive. Wispy inclined beds of nodular white and grey anhydrite (≤5mm) frequent below 4417.5′.

4416′-4413.5′ Light grey to grey, argillaceous dolomudstone. Dense, contorted bedding. Grades upsection into dolomitic and quartzose siltstone to fine sandstone at 4414.4′. Nodular anhydrite (condensed, ≤4cm) frequent throughout zone. Upper contact is sharp and highly irregular from compaction.

Sherwood White and grey, bedded to chickenwire anhydrite. Grades upsection into anhydrite cemented mudstone.

Well # 9968 Marker: State A

Bluell Chocolate brown, micrite, very dense with massive texture.

7618′-7615′ Dark grey, argillaceous micrite, dense, wavy black laminations frequent (likely organic rich).

7615′-7614′ Light tan, dolomudstone with highly irregular bedding planes (compaction), patterned. Blocky text through lowermost 6in. Zone grades up section into cherty lithology with
same internal structures.

7614’-7612’ Dark grey-black, micrite with planar and wavy argillaceous laminations. Hummocked bedding (3cm wide) common. Infrequent ripples and vertical burrowing. Lower 1ft of zone characterized by highly condensed nodular anhydrite (≤60%) with sucrosic texture, grading up section into euhedral “metasomatic anhydrite.” All anhydrite is absent by 7613’

7612’-7611.5’ Light grey to light tan, micrite, dense and patterned with extensive white, replacement anhydrite (≤50%, increasing upsection). Mudstone highly dissected due to evaporite precipitation, dewatering and desiccation. Upper contact is gradational where anhydrite cementation persists.

Rival Grey to tan, anhydrite cemented mudstone. Zones of black organic-rich, lamina between 7605.5’-7607’.

Well # 9968 Marker: S.A.M.

Sherwood Dull brown, micrite, dense with grainy texture and largely bioturbated.

7667’-7662’ Dark brown, micrite with argillaceous mud drapes and infrequent laminations grading upsection into skeletal wackestone and higher concentrations of irregular/wavy laminations. Most shells replaced by colorless sparite and anhydrite. Bioturbation is extensive throughout interval. Lower contact is sharp at high-amplitude stylolite.

7662’-7656’ Dark grey to black, skeletal (brachiopods and echinoderms) wackestone with heavy argillaceous black lamina. Laminations are wavy/irregular, highly condensed, and bioturbated. Bioclasts are commonly replaced by white anhydrite with sucrosic texture. Similar anhydrite nodules (1cm), condensed and infrequent. Brachiopod shell beds are concordant, disseminated shells are discordant to sub-concordant. Select laminations are organic rich.
7656’-7651’ Brown to black, micrite interbedded with skeletal (brachiopod and echinoderm) wackestone. Heavily mottled, bioturbated with very faint laminations. Infrequent anhydrite nodules (≤1.5cm). Sparite replacement of select bioclasts. Upper contact is subtle, gradational decrease of argillic sediments.

Bluell Brown, micrite and skeletal (brachiopod and algal) wackestone. Fenestral porosity (<5%), occluded. Hydrocarbon staining is weak.

Well # 10266 Marker: State A2

Bluell Dark tan, argillaceous and bituminous mudstone. Very dense. Infrequent rugose coral (≤2.5cm) replaced by sparite. Concentrated beds of black slack water lamina at 5415’, 5411’, and 5408.5’.

5400’-5401’ Dark grey, argillaceous micrite. Occasional vertical and subhorizontal hairline fractures, many are oil stained. Lower contact is subtle where color changes.

5401’-5396’ Grey to dark tan, argillaceous dolomudstone. Patterned, very dense. Homogeneous zone. Lower contact is rapid where dolomitization and argillaceous content decreases.

Upper Bluell Dark tan to grey and brown, partially dolomitized micrite. Very dense, heavily stylolitic. “Metasomatic” anhydrite common (30%). Transitions upsection into nodular, followed by chickenwire and bedded anhydrite.

Well # 10615 Marker: K-1

Mohall Tan to light tan, oolitic, pisolitic, and intraclastic grainstone to packstone. Intraclasts are micritized. Extensive fenestral and vuggy porosity (30%), plugged by colorless dolomite. Oil staining on select pore margins.

6411.7’-6409’ Very light grey to yellowish tan, dolomudstone. Heavily patterned, sucrosic texture. Thin interbed (3in) of grey to dark tan laminated
mudstone with “metasomatic” anhydrite. Laminations are black, argillaceous, and planar. Infrequent fenestrae, plugged by crystalline dolomite. Lower contact is sharp and erosional with a coarse, poorly sorted, broken oolitic and intraclastic lag deposit.

6409’-6408.1’ Grey to light grey, argillaceous dolosiltstone to very fine quartz arenite. Dense, patterned to mottled. Less porous than adjacent zones.

6408.1’-6407.5’ Tan to yellow-tan, dolomudstone. Sucrosic texture, lightly patterned, preferential to planar bedding. Intercrystalline microporosity high.

6407.5’-6403.5’ Dark grey, argillaceous quartz-rich siltstone with interstitial dolomudstone. Extensive replacement anhydrite (30-40%). Anhydrite appears bladed and preferential to dewatering structures. Bedding and laminations are highly contorted where anhydrite is present and horizontal planar where anhydrite is absent. Anhydrite absent above 6405’. Zone becomes sandier upsection.

6403.5’-6402.2’ Light grey to light tan, dolomudstone with extensive nodular (≤5cm) and replacement anhydrite (50%). Mudstone is laminated, patterned, and anhydrite cemented. Upper contact is very sharp, possible erosional where bedded anhydrite begins.

Sherwood White to grey bedded and chickenwire anhydrite with interstitial dark tan, mudstone.

Well # 11095 Marker: S.A.M.

5707’(bottom of core)-5704.5’ Light tan to tan, partially dolomitized micrite. Dolomitization decreases upsection and grades into pisolitic wackestone. Weakly patterned, faintly laminated. “metasomatic” anhydrite throughout zone increasing to >50% in uppermost zone. Fenestral porosity (10%, ≤3mm), plugged by dolomite.

5704.5’-5704’ Dark tan to grey, pisolitic and oolitic wackstone to packstone. Frequent black mud drapes. Thin
beds (1cm) of black, slack-water laminae at top and bottom of zone. Fenestral porosity (10-15%, <4mm), plugged by dolomite.

5704'-5699.5'

Light grey to grey, argillaceous dolomudstone. Very uniform zone. Faintly laminated with infrequent reduction halos around select laminae. Grey and white anhydrite nodules (<5cm) concentrated in upper 4in of zone. Upper contact is sharp where chickenwire anhydrite forms.

Bluell

Grey to white, chickenwire anhydrite with interstitial argillaceous dolomudstone.

Well # 11555 Marker: S.A.M.

Sherwood

Greyish tan to light brown, oolitic grainstone to packstone alternating with skeletal and oolitic wackestone. Rugose coral (≤2cm) abundant in wackestone with some brachiopod shells. Dense, well cemented with healed vertical and subvertical fractures. Argillaceous content and mud drapes increase upsection.

6055.8'-6053'

Tan to grey, dolomudstone with basal (4in) skeletal and oolitic grainstone. Heavily patterned (fades upsection), faintly laminated, infrequent anhydrite nodules near top of zone, and intraclastic lag deposit at 6054.2'.

6053'-6052.6'

Dark brown, argillaceous mudstone. Very dense, abundant mud drapes and compacted burrows, small scale flame structures at base of zone. Highly compacted.

6052.6'-6050'

Light grey, argillaceous, oolitic packstone and wackstones interbedded. Lithologies alternate every 1-3cm, mostly planar to subplanar. Low moldic porosity and plugged by anhydrite.

6050’-6047.3’

Greyish tan, slightly argillaceous dolomudstone with basal oolitic and arenitic dolowackstone. Infrequent white anhydrite nodules (≤1cm) at base of zone, with some replacement anhydrite in larger allochems (3mm). Current ripples and/or hummocked beds at 6048.5'.
Microintercrystalline porosity high (as indicated on logs). Thin (1in) mud draped bed of calcareous mudstone with compacted anhydrite nodules at top of zone.

6047.3’-6046.5’

Dark grey, argillaceous, oolitic packstone. Coarse grained (2-3mm), moderately sorted. About half of the ooids are broken.

6046.5’-6043.5’

Brown to greyish brown, oolitic and skeletal grainstone to packstone. Skeletal allochems (<2%) include brachiopods, gastropods, and rugose coral. Two zones of dark brown, highly argillaceous mudstone and fragmental wackestone with extensive mud draping below 6046 and above 6044. Concentrations of black, slack-water laminae in a 1in bed at 6402.4’. Upper contact is rapid to sharp where mud content becomes infrequent.

Bluell

Greyish tan, oolitic and pisolitic grainstone to packstone. Frequent rugose coral allochems. Large-scale tabular crossbeds present (likely indicates shoaling complex).

Well # 11671 Marker: State A

Upper Bluell

Dark grey to brown-black, micrite. Mottled colors, very dense.

6010’-6305.5’

Light tan to yellow, dolomudstone. Patterned.

6305.5’-6303’

Tan, dolomudstone. Faintly laminated, extensive pokioblastic “metasomatic” anhydrite.

6303’-6302’

Light tan, dolomudstone. Densely patterned, organic rich slack water lamina at upper contact. Upper contact is sharp where anhydrite starts.

Rival

White, nodular to chickenwire anhydrite and tan interstitial dolomudstone.

Well # 11671 Marker: State A2

Bluell

Dark brown, micrite, organic rich, mottled.
6330’-6329’  
Chocolate brown, micrite. Very dense, bioturbated (small, 2cm, horizontal burrows) with few black slack water laminations still present. Frequent vertical hairline fractures (partly open). Lower contact is sharp.

6329’-6322.5’  
Light to dark grey, argillaceous dolomudstone. Very dense, faint patterning, mostly massive. Darkens and becomes more argillic upsection. Larger 2 ft vertical dissolution seam. Sharp upper contact marked by sutured-seam stylolite.

Upper Bluell  
Dark Brown to grey, skeletal wackestone. Partly dolomitized. Rugose coral, crinoidal.

Well # 11849 Marker: K-1

5799’(Bottom of core)-5798.5’  
Dark tan to grey, oolitic wackestone with uppermost (2in) oolitic grainstone. Fenestral porosity in wackestone (10%, ≤3mm) plugged by anhydrite. Heavy concentrations of stylolites mark top of zone. Lower contact not present in core.

5798.5’-5796.4’  
Dark grey, argillaceous dolomudstone. Patterned, fairly dense. Dewatering brecciation at top of zone. Fenestral porosity low (5%, ≤3mm), anhydrite filled.

5796.4’-5795’  
Dark tan to dark grey, argillaceous, pisolitic and oolitic wackestone to mudstone with infrequent laminations of oolitic grainstone. Ooids are mostly micritized. Faintly and irregularly laminated, dense, and nodular at base of zone. Heavily stylolitic.

5795’-5793.8’  
Dark tan to grey, pisolitic (possibly oncolitic) wackestone to mudstone. Irregularly laminated with frequent dissolution seams between laminae. Pisoids (≤8mm) are light tan in color with a micritic envelopes. Fenestral pores (<3%) are completely plugged by anhydrite.

5793.8’-5791.5’  
Grey to light tan, argillaceous dolomudstone. Illite fades upsection and color becomes tan. Patterned, dense. Microintercrystalline porosity
high (as indicated on logs). Anhyrite replaced allochens observed at base of zone.

5791.5’-5789.5’ Light tan, oolitic dolograinstone to dolopackstone. Patterned, moderately sorted. Anhydrite replacement of allochens and interparticle anhydrite (≤10%). Similar zone to 5793.8’-5791.5’ only with allochens. Upper contact is gradual where allochens disappear.

Sherwood Light to dark tan, oolitic, pisolitic, oncolitic, and intraclastic grainstone. Extensive vuggy porosity (30%, ≤2cm), mostly open (some with drusy calcite along pore margins). Oil staining frequent in pores.

Well # 12229 Marker: S.A.M.

Sherwood Tan to light tan, oolitic, pisolitic, intraclastic packstone to grainstone. Intraclasts are large (some >8cm), condensed and ooid bearing. Extensive vuggy and moldic porosity (≤30%, ≤8mm), mostly open below 6812’.

6806.9’-6805.9’ Grey, argillaceous, intraclastic and pisolitic wackestone with basal (3in) oolitic and pisolitic packstone. Allochens and agrillics decrease upsection. Top of zone marked by 1cm thick concentration of black, slack-water laminae. Lower contact is sharp and possibly erosional.

6805.9’-6802.9’ Light grey to white, oolitic and pisolitic grainstone. Coarse (some pisoids >5mm), moderately sorted. Some larger allochens appear to be ooid aggregates with pisolitic coating. High interparticle porosity (20-25%) completely plugged by colorless anhydrite. A very coarse and poorly sorted oolitic and intraclastic grainstone marks top of zone. Intralasts (≤1cm) are subangular and pisoid and ooid bearing.

6802.9’-6801.9’ Dark tan to light brown, oolitic and pisolitic packstone to grainstone. Many ooids are broken and bear ooid aggregate cores. Low moldic and interparticle porosity (10%), plugged by anhydrite. Top of zone marked by
concentration of microsylolites.

**6801.9’-6801.1’**
Grey, argillaceous, oolitic wackestone with basal (2in) pisolitic wackstone to packstone. Ooids are very small (<1mm). Plugged fenestral porosity (20%, 2mm). Upper 3in of zone displays a sharp fabric change to oolitic grainstone. Top of zone marked by thin, slack-water laminae.

**6801.1’-6798.1’**
Light brown to light tan, pisolitic wackstone. Faintly laminated. Large (1cm), grey, angular rip-up clasts of underlying lithology along base of zone. A 4in thick bed of light tan, poorly-sorted intrclastic and pisolitic packstone to grainstone present at 6800.5’. Fenestral (≤3mm) porosity with minor vugs (<1cm) (<5% increasing upsection to 10%), plugged by colorless anhydrite. Oil staining on margins of vugs.

**6798.1’-6797.5’**
Grey to light grey, oolitic (≤3mm) and pisolitic (≤8mm) grainstone to packstone. Moderately sorted. Extensive interparticle and replacement anhydrite.

**6797.5’-6796’**
Dark to light grey, argillaceous dolomudstone. Degree of dolomitization varies throughout zone. Dense, patterned. Patterning varies with dolomitization. 1in bed of black, slack-water laminae at 6796.3’ may indicate upper contact or upper contact not reached in core.

**Well # 12301 Marker: K-1**

Mohall
Light tan, oolitic and intraclastic dolowackstone to dolomudstone. Faintly and irregularly laminated in select areas, grainy texture. Allochems are micritized. Infrequent, healed horizontal and subvertical fractures.

**4890.5’-4888.8’**
Light grey to light tan, dolomudstone to siltstone. Dense, faintly patterned. 6in bed of bidirectional ripples at 4890’ with light mud drapes on foresets. Infrequent oil staining. Lower contact is rapid where allochems disappear.

**4888.8’-4887.8’**
Grey, argillaceous dolosiltstone to quartz arenite.
Slightly mottled and patterned, poorly laminated, dark grey muds. Sands are very fine. Infrequent, disseminated and small (5mm) anhydrite nodules. Top of zone characterized by dark grey to black, argillaceous planar laminations (1in) and hummocky cross-stratification.

4887.8’-4886.9’

Light tan to cream, dolomudstone. Irregularly laminated with black argillaceous mudstone and algal laminations. Frequent contorted (dehydrated and broken) anhydrite nodules (≤3cm).

4886.9’-4877.3’

Medium grey, argillaceous dolosiltstone to quartz sandstone. Very fine sand. Dominantly massive and mottled, with discontinuously laminated dark grey argillaceous muds and mud drapes. Argillaceous banding between 4885’-4882’. Ripple foresets at 4883.7’. Anhydrite occurs as disseminated blebs below 4882’ and as thin beds (2in) of bedded form at 4880’. Anhydrite cementation characterizes upper 1ft of zone. Upper contact is sharp where bedded anhydrite begins.

Sherwood

Grey to white, bedded anhydrite. Horizontally bedded.

Well # 12758 Marker: State A

Bluell

Tan, pisolitic and oolitic grainstone to packstone. Fenestral pores completely plugged by euhedral white and colorless anhydrite.

5509’-5508’

Tan to grey, pisolitic wackestone (possibly peloidal) to mudstone, dense and patterned. Lower contact at rapid color transition and emerging mud (1ft).

5509’-5506’

Tan and grey, micrite to dolomudstone, patterned and very dense. Porosity indeterminable in core. White, nodular anhydrite (≤4cm) at 5507.5’.

5506’-5496’

Dark grey, dolomudstone with black argillaceous slack-water laminae. Wavy laminated.
Frequent interbeds of white and grey anhydrite common as bedded (5505’), chickenwire (5503.5’), and nodular (above 5503’) forms. Upper contact is sharp where dolomudstone stops.

**Rival**

White and grey, bedded anhydrite.

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**Well # 12758 Marker: S.A.M.**

**Sherwood**

Dark tan to light brown, pisolithic wacke-packstone with open, large fenestral to vuggy pores (≤14mm)

5551’-5546’

Grey to tan, mudstone and locally pisolithic wackestone. Fenestral porosity (30%), pores (≤3mm) completely plugged by anhydrite. Highly stylolitic. Lower contact is gradual where argillaceous muds increase.

5546’-5544.5’

Light tan, oolitic (90%, 1-2mm) and pisolithic (10%, ≤5mm) grainstone. Section becomes more micritic and grades from grainstone to packstone to a patterned mudstone upsection.

5544.5’-5543’

Light tan, very dense and completely dolomitized mudstone with sucrosic texture.

5543’-5539’

Dark grey to tan, dolomitic mudstone to intraclastic/pisolithic dolowackestone and locally packstone. Mottled and patterned. Possibly stromatolitic at 5541’. Lower contact is gradational where argillaceous muds decrease.

**Bluell**

Light tan, intraclastic and pisolithic packstone. Colorless anhydrite plugged fenestral porosity (<4mm).

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**Well # 12930 Marker: State A**

**Bluell**

Dark tan, oolitic and pisolithic packstone, very coarse grained (≤5mm).

5277’-5273’

Dark tan to grey, oolitic, intraclastic and peloidal packstone (≤3mm). Fenestral porosity (20%, ≤2mm), and hairline fractures completely
plugged/healed by colorless anhydrite. Anhydrite has trapped some bitumen along pore margins. Replacement anhydrite along select grain margins. Zone of effective, open, vuggy porosity at 5275.8’. Lithology becomes more peloidal and argillaceous upsection to a zone of black slack water lamina.

5273′-5267.5′
Light tan to light grey, peloidal wacke-mudstone, dense and faintly laminated. Frequent vertical hairline fractures. Extensive “metasomatic anhydrite” replacing mudstone from fractures and disseminated nuclei. Anhydrite filled fenestral porosity increases from 5-15% upsection. Concentration of organ-rich shale lamina at top of marker. Upper contact not preserved in core, but is likely sharp indicated by logs and overlying lithology.

Rival
White to tan-grey, bedded anhydrite.

Well # 12951 Marker: State A

5146.5′-5144′
Dark grey and tan, argillaceous, dolomudstone, dense and heavily patterned heavily patterned. Tan color coincides with areas of more extensive dolomitization. Lower contact not observed in core

5144′-5142′
Light grey, partially dolomitized micrite with disseminated white, replacement anhydrite (<1cm). Alternating zones of dark grey to black, argillaceous micrite, weakly laminated with argillaceous slack water lamina. Likely organic rich with heavy petroliferous staining at 5143.5’ where texture becomes less dense. Upper contact is sharp but non-planar from compaction where anhydrite begins.

Rival
Grey to white, bedded anhydrite.

Well # 12951 Marker: State A2

Bluell
Tan, oolitic to pisolitic packstone. Extensive fenestral to vuggy porosity. Colorless anhydrite plug fenestrae, vuggs are open.
5516.5’-5515.5’  Light to dark grey, argillaceous dolomudstone, interlaminated with black argillaceous lamina. Lower contact is sharp at microstylolitic concentration.

5515.5’-5154’  Light grey to tan, oolitic, pisolitic and peloidal packstone. Extensive fenestrae (or small vuggs) (30%, ≤3mm), completely plugged colorless anhydrite. Zone displays noticeable decrease in argillaceous content from adjacent intervals.

5154’-5150’  Dark grey, argillaceous, intraclastic wackestone. Dense, microstylolitic. Intraclasts composed of micrite and display superficial pisolitic coating. Wackestone grades upsection into grey to tan, patterned dolomudstone. Dolomudstone likely includes increased intercrystalline porosity (indicated by log response). Upper contact appears gradual where argillics fade and dolomitization decreases.

Upper Bluell  Tan, oolitic and pisolitic dolowackestone to dolopackstone, interbedded with tan, non-argillaceous and patterned, dolomudstone.

Well # 13193 Marker: S.A.M.

Sherwood  Tan to light tan, oolitic, pisolitic, intraclastic, and bioclastic packstone. Moldic and fenestral porosity (10%, ≤5mm), plugged by sparite. Open vuggular porosity also present (5%, ≤1cm). Highly stylolitic.

7345.5’-7343’  Grey, argillaceous, oolitic and pisolitic packstone with basal (6in) of very poorly sorted, intraclastic (≤2cm, ooid bearing) packstone. Porosity exists as intra- and interparticle, and fenestral form (10-15%), plugged by sparite. Argillaceous muds fade upsection, and lithology transitions into oolitic and pisolitic grainstone.

7343’-7340.8’  Grey, argillaceous, pisolitic wackestone to mudstone with basal (4in) oolitic, pisolitic, intraclastic packstone. Slightly patterned. Sparite plugged fenestral porosity (15%, ≤3mm). Thin zone of black, irregular slack-
water laminae at 7342’. Uppermost 6in is a poorly sorted oncolitic and oolitic packstone.

7340.8’-7340’ Light tan to white, oolitic, intraclastic, and pisolithic grainstone. Poorly sorted at base and well sorted upsection, lightly patterned.

7340’-7339’ Yellowish tan, dolomudstone. Heavily patterned, very dense.

7339’-7337’ Tan to light grey, weakly dolomitized mudstone.

7337’-7336’ Very light grey, dolomudstone. Very dense, heavily patterned. Highly stylolitic at top of zone.

7336’-7334.8’ Tan to Brown, pisolithic and oolitic wackestone with interbedded packstone. Infrequent brachiopod shells replaced by sparite.

7334.8’-7333.5’ White, intraclastic and skeletal wackestone.

Bluell Light to dark tan, skeletal and pisolithic wackestone to packstone. Extensive (<30%) vuggy and moldic porosity, mostly open/partially plugged by anhydrite. Spotty oil staining.

Sherwood Light to dark tan, oolitic and pisolithic grainstone to wackestone. Extensive (30%) vuggy porosity in coarser fabrics and fenestral porosity in muddier lithologies. Pores mostly open with select zones plugged by colorless anhydrite. Oil stained vuggs.

5907.5’-5906’ Grey, argillaceous dolomudstone. Dense, patterned and faintly laminated. Infrequent white and grey anhydrite nodules. Prominent

Well # 13370 Marker: S.A.M.
stylolites at base of zone.

5906’-5905’

Dark tan to brown, oolitic, peloidal, and pisolitic grainstone. Well cemented, parallel laminated, lightly patterned at top of zone. Minor moldic (<5%), plugged. Lower 2in is very argillaceous and extremely mud draped.

5905’-5903.5’

Grey, argillaceous dolomudstone. Dense, patterned. Nodular anhydrite. Repeat of zone 5907.5’-5906’.

5903.5’-5902.5’

Tan to dark tan, mudstone to oolitic wackestone. Faintly laminated (planar). Fenestral porosity increases upsection (from 5 to 15%) and pore size decreases (from 1-2mm to <1mm). Larger pores plugged by anhydrite, smaller pores open. Upper contact is very rapid to sharp into allochem-rich lithologies.

Bluell

Light to dark tan, oolitic (≤2mm) and pisolitic (≤2cm) (possibly oncolitic) grainstone. Extensive vuggy and moldic (≤3mm) porosity, mostly open. Select zones are completely plugged by colorless anhydrite. Infrequent beds of rip-up clasts and lag deposits.

Well # 13610 Marker: K-1

Mohall

White and grey, nodular to chickenwire anhydrite with interstitial tan, fine quartz arenite, cemented by anhydrite. Anhydrite becomes bedded below 6232’.

6219.6’-6218.9’

Light tan, dolomudstone to dolosiltstone. Highly irregular and compacted bedding with thin laminae of black, organic-rich shale. Disseminated reduction halos around organics. Low fenestral porosity (<5%), plugged by anhydrite. Lower contact is rapid where anhydrite nodules stop.

6218.9’-6214.7’

Light grey, dolosiltstone to dolomudstone. Mostly massive with infrequent faint laminations. Thin bed (0.5in) of black, argillaceous (possibly organic-rich) shale laminae at 6216.9’ with overlying bed of compacted and concordant
intraclastic lad deposit. Anhydrite filled fenestral pores and selective replacement anhydrite.

6214.7'-6210.4' Grey to green-grey, dolosiltstone interbedded with nodular anhydrite. Nodules are large (≤8cm). Partial anhydrite cementation of siltstone. Faintly laminated with possible ripple foresets (20°) at 6211.4’. Dewatering and flame structures present where anhydrite dominates. Zone becomes sandier upsection and less anhydritic.

6210.4'-6208.5' Grey to dark grey, anhydrite cemented, argillaceous mudstone and siltstone. Thin irregular laminae (1-2mm) of fine sandstone near upper contact of zone.

6208.5'-6207.3' Green-grey, argillaceous sandstone with interstitial dolosiltstone. Very faint, highly irregular bedding with possible (poorly defined) ripple marks.

6207.3'-6206' White to grey and tan, bedded anhydrite grading upsection into dark grey, anhydrite cemented, argillaceous mudstone.

6206'-6203.4' Grey to green-grey, quartz arenite with interstitial argillaceous dolomudstone. Dense, mostly massive to mottled. Upper contact is sharp where anhydrite begins.

Sherwood White to grey, bedded anhydrite with minor tan sands and mudstone laminae.

Well # 14734 Marker: K-1

Mohall Tan to light tan, oolitic wackstone to packstone with thin (≤3in) interbeds of grainstone. Stylolitic, collapse brecciation. Extensive fenestral porosity (20%, ≤3mm) mostly plugged by anhydrite (or dolomite). Zones of open vuggy porosity, lightly oil stained.

4274'-4272.5' Grey, argillaceous siltstone to dolomudstone. Dense, faintly patterned, and faintly laminated. Interbeds of tan, fine calcareous sandstone
present, mostly massive and subhorizontal planar bedding. Lower contact is sharp where allochems stop and lithology becomes grey.

4272.5’-4270.7’ Tan, calcareous sandstone, mottled with light grey mudstone. Sands are very fine and planar laminated. Mudstone appears as compacted aggregates. Fenestral porosity low (<10%), plugged by sparite. Heavy concentration of stylolites at 4270’.

4270.7’-4270’ Light grey to light tan, oolitic and pisolitic packstone. Moderately to poorly sorted, coarse grained (3-10mm). Stylolitic upsection. Subvertical healed fractures.

4270’-4269.1’ Tan, oolitic grainstone. Very well sorted (1-2mm). High interparticle porosity (20-25%), open with heavy bitumen staining and asphalt. Zone becomes slightly sandier up section and bitumen decreases.

4269.1’-4267.5’ Greyish tan, quartz arenite to argillaceous dolosiltstone. Very fine sands with bi-directional ripples. Light patterning in siltstone. Intergranular porosity with spotty oil staining.

4267.5’-4264.3’ Light grey to light tan, dolomudstone to dolosiltstone. Heavily patterned, sucrosic. Intercrystalline microporosity high (logs). Thin zone (6in) of 30% vuggy porosity at 4266’.

4264.3’-4262.5’ Light tan, calcareous sandstone to siltstone. Very fine sands, massive bedding, stylolitic, faintly patterned to mottled upsection. Infrequent reduction haloes around organic matter.

4262.5’-4258’ Light tan, calcareous sandstone. Fine to very fine, wavy horizontal laminations interbedded with zones of highly contorted and mottle mudstone to siltstone. Extensive dissolution and vuggy porosity along dewatering conduits, mostly plugged by crystalling and sucrosic calcite. Infrequent apple-green chloritic laminae near upper contact. Upper contact is very gradual where allochems begin to appear.
Sherwood

Light tan, oolitic wackestone to packstone. Extensive vuggy porosity (>30% in localized areas), mostly open. Stylolitic.

Well # 14815 Marker: S.A.M.

Sherwood

Tan to light tan, oolitic, intraclastic, and pisolitic packstone to grainstone. Faintly laminated with alternating beds of packstone and grainston. Vuggy and fenestral porosity (15-20%, ≤5mm), mostly open.

7890’-7888.5’

Tan, pisolitic wackestone with thin beds of packstone. Faintly laminated in wackestone. Thin zone (6in) of lightly patterned, weakly dolomitized mudstone at 7889’

7888.5’-7886.8’

Dark grey to tan, intraclastic (possibly micritized pisoids) wackestone to mudstone, partly dolomitized. Dense, Heavily patterned. Intraclasts are brown and subrounded (≤1cm).

7886.8’-7885’

Light tan to white, dolomudstone with grey to dark grey patterning, to intraclastic calc-rich wackestone up section. Heavily patterned. Intraclasts in wackstone are brown and subangular to subrounded. High amplitude stylolite concentrating organic-rich insolubles.

7885’-7881’

Missing section.

7881’-7880’

Tan to grey, dolomudstone. Patterned, dense, highly contorted bedding and dewatering/loading structures.

7880’7879’

Tan, oolitic and pisolitic, wackstone, partially dolomitized. Faintly laminated. Heavy oil staining where dolomitization is more extensive. Rare intercrystalline porosity enhancement with dolomitization. Upper contact is sharp at a heavy black stylolite.

Bluell

Tan to light tan, pisolitic, intraclastic, oolitic packstone to grainstone. Ooids are fragmental, intraclasts are elongate, angular to subangular, and discordant. Extensive vuggy porosity (30%), mostly open with spotty asphalt on
select pore margins. Infrequent replacement sparite and anhydrite.

Well # 14930 Marker: K-2

Glenburn Light tan to tan, pisolithic and pseudo-oolitic packstone to wackestone. Frequent dark brown to black, slack-water laminae. Extensive vuggy and fenestral porosity (30%, ≤6mm), mostly open with localized areas of anhydrite plugged pores. Oil stained where vugs dominate.

4707′-4706′ Light tan, bedded anhydrite grading upsection into bedded anhydrite mottled by dark grey argillaceous dolosiltstone. Massive texture down section. Disseminated poikiloblastic pyrite (5mm). Lower contact is sharp where anhydrite starts.

4706′-4705.5′ Dark grey, argillaceous dolosiltstone. Partially cemented by anhydrite. Planar, subhorizontally bedded (<5) with continuous mud drapes (or reduction halos) along bedding surfaces. Cross-stratification possible upsection (poorly preserved).

4705.5′-4704′ Light tan to light grey, bedded anhydrite. Interlaminted by anhydrite cemented mudstone. Laminations and beds are planar with localized contortion from dewatering muds. Lower 6in is grey, anhydrited cemented, argillaceous mudstone. Compacted mudstone lenses (3-25mm) replaced by pyrite near top of zone.

4704′-4701.6′ Grey to dark grey, argillaceous dolosiltstone. Partially to completely cemented by anhydrite. Planar to subplanar, mostly horizontal bedding with thin mud-draped laminae. Mud drapes (1-2mm) are replaced by pyrite at 4703.1′. Ripple foresets (10°) faint and infrequent. Reduction halos and condensed mud lenses common upsection.

4701.6′-4699′ Grey, quartz arenite with interstitial argillaceous dolomudstone. Fine to very fine sands, mostly
massive, slightly mottled. Infrequent disseminated reduction halos and small (<1cm) dark grey mud lenses. Zone becomes less sandy in uppermost 4in of zone. Upper contact is sharp where anhydrite begins.

**Mohall**
Grey to light grey, bedded anhydrite with interbedded anhydrite cemented mudstone and siltstone. Bedding is subplanar to wavy, mostly horizontal.

**Well # 15347 Marker: K-3**

**Wayne**
Light grey to white, bedded anhydrite with uppermost anhydrite cemented dolosiltstone. Small (<1cm) condensed nodular anhydrite with interstitial anhydrite cemented siltstone just below contact.

3943.4′-3942.6′
Light grey, quartz arenite. Very fine, very well sorted, subrounded to subangular. Well cemented with dolomite cement. Frequent reduction halos. Lower contact is sharp where anhydrite stops.

3942.6′-3939.4′
Brown with grey, quartz arenite. Spotty cementation leading to reduced areas. Heavily oil stained, strong petroliferous odor. Bedding not determinable although preferential cementation may be an artifact of bedding. Thin (2in) bed of black, bitumen rich bed at top of zone. Interparticle porosity (10-20%) is effective, evident from staining.

3939.4′-3937.3′
Light grey to white, argillaceous and dolomitic quartz arenite to siltstone. Very fine sands with dolomite cement, dense. Zone becomes finer and anhydrite cemented upsection. Mostly massive with weak and wavy laminations at base of zone. Upper contact is sharp where anhydrite becomes bedded.

**Glenburn**
White to light grey, bedded anhydrite. Mottled with condensed relict laminations.
Well # 15784 Marker: S.A.M.

**Sherwood**

Light tan, oolitic, pisolithic and skeletal packstone to grainstone. Vuggy porosity (10%) mostly plugged by anhydrite, larger pores (>1cm) open. Desiccation features prevalent. Highly stylolitic.

7669.5’-7666.2’

Light grey to dark tan, argillaceous, oolitic and pisolithic packstone and isopachous cemented grainstone. Poorly sorted. Highly stylolitic. Large dissolution pores completely plugged by anhydrite. Fenestral and intergranular porosity in packstones (10-15%, ≤3mm), plugged.

7666.2’-7664.3’

Grey to tan, argillaceous, oolitic and pisolithic wackestone with thin beds of packstone and basal (6in) of poorly sorted packstone. Highly stylolitic. Fenestral porosity (20-25%, ≤5mm), anhydrite plugged. Illite fades upsection by 7665’. Black shale laminae at 7665.7’.

7664.3’-7661.8’

Grey to grey-tan, argillaceous, intraclastic and pisolithic wackestone with interbeds and basal (6in) oolitic, pisolithic, and intraclastic (6-8mm, ooid bearing) packstone. Argillaceous content fade upsection. Fenestral porosity (10%, ≤3mm), plugged.

7661.8’-7660.2’

Tan, oolitic, intraclastic, pisolithic, and bioclastic (brachiopods) packstone to grainstone. Extensive porosity (mostly around 30%), fenestral, moldic, interparticle types, plugged by colorless anhydrite.

7660.2’-7658.9’

Grey to dark tan, argillaceous, pisolithic and superficial oolitic packstone. Coarse grained (2-15mm) and poorly sorted at base of zone. Argillaceous content fade upsection into partially dolomitized mudstone just below upper contact. Top of zone marked by black, slack-water laminae. Upper contact is sharp at laminae.

**Bluell**

Tan to light tan, oolitic, intraclastic, and bioclastic packstone to wackestone. Fenestral (≤3mm) and dissolution porosity (≤30%). Fenestrae are open, biomolds and vugs are plugged by
colorless anhydrite. Spotty oil staining along pore margins.
### Appendix C
Total Organic-Carbon Measurements

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<th>Operator</th>
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<th>Subinterval/Marker</th>
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