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Christopher F. Quinn
University of North Dakota

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DEPOSITIONAL HISTORY AND DIAGENESIS
OF THE SHERWOOD AND BLUELL BEDS (MISSISSIPPIAN)
SOUTHWESTERN RENVILLE COUNTY, NORTH DAKOTA

by
Christopher F. Quinn
Bachelor of Science, Montana State University, 1979

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Arts

Grand Forks, North Dakota
December, 1986
Depositional History and Diagenesis
of the Sherwood and Bluell Beds (Mississippian)
Southwestern Renville County, North Dakota

Christopher F. Quinn
University of North Dakota, 1986
Faculty Advisor: Professor Howard Fischer

The Sherwood "bed" and the overlying Bluell "bed" are two log-defined zones at the top of the Frobisher-Alida interval. The Frobisher-Alida interval, within either the Mission Canyon carbonates or the overlying Charles evaporites, is composed of a number (up to six) of log-defined zones. On the northeast flank of the Williston Basin the zones are separated by even, lithologically homogeneous, argillaceous marker beds. Basinward, these marker beds terminate into less argillaceous carbonates.

The area studied covered four townships in southwestern Renville County, North Dakota. The section studied included the K-1 marker, the Sherwood bed (with the Sherwood argillaceous marker), and the Bluell bed (with the State "A" marker). About 290 m 940 ft of core and 225 thin sections from 19 boreholes were examined. Depths varied from 1540 m (5000 ft) to 1840 m (6000 ft). Rocks were categorized into six lithotypes: 1) pisoid-ooid-intraclast wackestone to packstone; 2) mudstone to stromatolite boundstone; 3) massive anhydrite; 4) argillaceous silty dolomudstone; 5) ooid grainstone; and 6) sandy carbonates.

Lithofacies within individual zones form bands
parallel to regional strike. Deposition occurred on an arid, peritidal carbonate buildup bordered by a warm, restricted, shallow-basin sea to the southwest and a shallow, evaporite-precipitating lagoon to the northeast. The argillaceous markers were probably deposited during a slight, basin-wide sea-level drop, that drained most of the hyper-saline lagoon and exposed a wide, flat, sabkha plain. Deposition or erosion of marker beds was controlled by groundwater capillary-fringe entrapment and deflation of higher areas. Marker-bed deposition terminated at the sea edge in intertidal or subtidal ooid shoals. Some evidence remains of drowned quartz and detrital-anhydrite sand bodies. Because progradation of the "continental"-type eolian sabkha was very rapid, the marker beds in the study area are considered quasi-lithochronozones.

Eogenetic diagenesis included cementation (calcite, anhydrite, and celestite), dissolution, micritization, and compaction. Matrix-selective pores were opened by early dissolution and are the predominant pore type in the study area. Mesogenetic diagenesis included cementation (calcite, dolomite, and anhydrite), minor amounts of silicification, high amplitude stylolitization, fracturing, and oil migration.

The development of most local structures in the study area was subsequent to the Mississippian-Triassic unconformity. Precipitation of diagenetic anhydrite was a major cause of pore occlusion in much of the study area and is related, in part, to structural features.
This thesis submitted by Christopher F. Quinn in partial fulfillment of the requirements for the degree of Master of Arts 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.

Chairperson

This thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

(Dean of the Graduate School) date
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Title: Depositional History and Diagenesis of the Sherwood and Bluell Beds (Mississippian), Southwestern Renville County, North Dakota

Department: Geology

Degree: Master of Arts

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And last, but certainly not least, I would like to thank my fellow graduate students, especially those in the carbonate program, for learning with me.
ABSTRACT

The Sherwood "bed" and the overlying Bluell "bed" are two log-defined zones at the top of the Frobisher-Alida interval. The Frobisher-Alida interval, within either the Mission Canyon carbonates or the overlying Charles evaporites, is composed of a number (up to six) of log-defined zones. On the northeast flank of the Williston Basin the zones are separated by even, lithologically homogeneous argillaceous marker beds. Basinward, these marker beds terminate into less argillaceous carbonates.

The area studied covered four townships in southwest-Renville County, North Dakota. The section studied included the K-1 marker, the Sherwood bed (with the Sherwood argillaceous marker), and the Bluell bed (with the State "A" marker). About 290 m (940 ft) of core and 225 thin sections from 19 boreholes were examined. Depths varied from 1540 m (5000 ft) to 1840 m (6000 ft). Rocks were categorized into six lithotypes: 1) pisoid-ooid-intraclast wackestone to packstone; 2) mudstone to stromatolite boundstone; 3) massive anhydrite; 4) argillaceous silty dolomudstone; 5) ooid grainstone; and 6) sandy carbonates.

Lithofacies within individual zones form bands parallel to regional strike. Deposition occurred on an arid, peritidal carbonate buildup bordered by a warm, restricted, shallow-basin sea to the southwest and a shallow, evaporite-precipitating lagoon to the northeast. The argillaceous markers were probably deposited during a slight,
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Eogenetic diagenesis included cementation (calcite, anhydrite, and celestite), dissolution, micritization, and compaction. Matrix-selective pores were opened by early dissolution and are the predominant pore type in the study area. Mesogenetic diagenesis included cementation (calcite, dolomite, and anhydrite), minor amounts of silicification, high amplitude stylolitization, fracturing, and oil migra­tion.

The development of most local structures in the study area was subsequent to the Mississippian-Triassic uncon­formity. Precipitation of diagenetic anhydrite was a major cause of pore occlusion in much of the study area and is related, in part, to structural features
INTRODUCTION

The study area is located in southwest Renville County, North Dakota, and includes four townships from T158W to T159N and from R85W to R86W (Fig.1). The interval studied is within the upper Mission Canyon Formation and lower Charles Formation of the Madison Group. Sando's (1978) and Sando and Mamet's (1981) biostratigraphical studies of coral zonation in the Williston Basin date the upper Mission Canyon Formation as Osagian to Meramecian.

Numerous writers in the past 30 years have divided and subdivided the Madison Group into different units based on correlatable characteristics of borehole logs and given these divisions informal names. These units were termed "Intervals" by Smith (1960). The five intervals of the Madison Group, in ascending order, are: 1) Bottineau, 2) Tilston, 3) Frobisher-Alida, 4) Ratcliffe and 5) Poplar. The Frobisher-Alida interval is the informal, log-defined unit discussed in this thesis.

Characteristic argillaceous markers define the base and top of an interval, as well as the beds within the interval. The six beds within the Frobisher-Alida interval, in ascending order, are: 1) Wayne, 2) Glenburn, 3) Mohall, 4) Sherwood, 5) Bluell and 6) Rival.
Figure 1: Study area map.
Figure 2 shows a diagram of the history of the Madison Group nomenclature (adapted from Shanley, 1983, and Obelenus, 1985). In ascending order, the marker beds in the Frobisher-Alida interval are; Landa, K-3, K-2, K-1, Sherwood Argillaceous Marker (S.A.M.), and State "A". The marker beds cross-cut evaporite and other carbonate lithologies (Fig.3).

Four producing oil fields are located within the study area; Lake Darling, MacKobee Coulee, Donnybrook, and White Ash. Production is from the Sherwood and Bluell beds of the Frobisher-Alida interval.

The Sherwood and Bluell beds, along with the defining K-1, S.A.M. and State "A" Marker are included in this study. Most well core comes from within these beds.

The argillaceous marker beds give characteristic responses on the gamma ray, porosity and resistivity well bore logs (Fig.4). Microprobe analysis showed up to 10% K, Al siliciclastic clay content in the marker bed lithologies, and no significant percentages (<1%) in most underlying and overlying lithologies. Radioactive K\(^{40}\), found in the clays, causes the higher gamma ray log responses. The fine sizes of the dolomite and clay crystals in the marker beds have high relative porosity unless cemented with anhydrite. The fine crystal sizes with extremely fine pore throat diameters cause pore fluids to have high water saturations and low oil saturations. Therefore, the marker beds usually have high porosity log responses and low
Figure 2: History of the Madison Group, stratigraphic nomenclature from the northeast Williston Basin. Adapted from Shanley (1983) and Obelenus 1985).
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Figure 3: Southwest-northeast schematic section demonstrating the argillaceous markers cross-cutting the evaporite and carbonate lithologies in north-central North Dakota. Adapted from Harris and others (1966).
MISSION CANYON FACIES RELATIONSHIPS IN NORTH CENTRAL NORTH DAKOTA
Figure 4: Characteristic log responses of the upper Frobisher-Alida Interval in the study area.
N.D.G.S.#4965, Lake Darling Field.
DEPCO; ELBERG #1, NE/NW, S27, T159N, R85W, RENVILLE CO.
resistivity log responses

**Purpose**

The purpose of this thesis is sixfold: 1) to describe lithologies and define lithofacies in the study area; 2) to suggest probable depositional environments and determine relative order of deposition of the various lithofacies; 3) to determine the sequences of diagenetic processes including compaction, cementation, dissolution, and mineral replacement; 4) to map and discuss local structure; 5) to relate the above characteristics to the development of hydrocarbon reservoirs in the study area; and 6) to compare the conclusions derived from the study of a small field area to the conclusions derived from regional studies of the northeast Williston Basin by Fuller (1956), Harris and others (1966), Shanley (1983) and Obelenus (1985).

**Methods**

Two hundred and eighty-seven metres of core from 19 boreholes were examined from the study area (Fig.5). The whole rock core was slabbed and examined with a hand lens and binocular microscope. Two hundred and twenty-five thin sections were prepared from this core. Alizarin red was used to stain calcite on half of the slide. The thin sections were examined using a microfiche reader, an optical microscope and in some cases, a scanning electron microscope.

Dunham's (1962) classification system with modifiers
Figure 5: Map of core locations described in the study.

Dashed lines are oil field boundaries.
was used in describing the carbonates. Maiklem, and others' (1969) terminology was used in describing evaporites.

Structure and isopach maps were constructed using borehole log depths. Cross-sections were made using log characteristics and core and thin-section descriptions. Two cross-sections were made along regional strike and one was made along regional dip. Four criteria were used in correlating core: 1) primary lithology, 2) fossil content, 3) diagenesis and 4) log responses.

All measurable units are metric in this study with the exception of depths taken off core or log intervals, which are in feet. The original footage of existing cores and logs was used to make correlation easier.

**Structure**

Regional structure dominates the attitude of beds in the study area, which dip southwest at approximately one degree. A series of small southwest-plunging anticlines run subparallel to regional dip (Fig.6).

Lake Darling and MacKobee Coulee Fields are located on two of the subtle noses in the northeast and southeast quadrants, respectively, of the study area. Donnybrook and White Ash Fields are located on the more prominent nose in the southwest quadrant of the study area. The sharp closure to the south side of Donnybrook is suspect, as data was obtained from only one well on the south side of the structure.

A structure map of the State "A" is nearly identical
Figure 6: Study area structure map of the top of the State "A" argillaceous marker. Regional dip to the southwest is about one degree. Circles are dry holes, small dots are wells with initial production of less than 100 barrels of oil per day; and large dots are wells with initial production greater than 100 B.O.P.D.
STRUCTURE MAP—TOP OF STATE 'A' ARGILLACEOUS MARKER
50' CONTOUR INTERVAL
to a structure map of the underlying Sherwood Argillaceous Marker (S.A.M.) or the overlying Midale Interval. This almost identical structural relief indicates no major lithostratigraphic thickening or thinning in the upper Frobisher-Alida Interval within the study area. This was evident in isopachous maps drawn on the Bluell bed (Fig.7) and the Sherwood bed. Two minor structural features within the beds are: 1) a general thickening through ooid-rich lithologies and 2) a general thinning in the evaporite sequences and mudstones. These lithologies are described in the lithotype section. Locations are given in the depositional history section. The slight interval thickness variations within the study area may be due to compaction differences in the carbonates and some dissolution in the evaporites.

The Madison Group is conformably overlain by the Upper Mississippian Big Snowy Group in the southwestern portion of the study area and unconformably overlain by the Spearfish Formation (Permian-Triassic) in the rest of the study area. A structure map of the top of the Madison Group (Fig.8) shows at least two of the same subtle anticlines found on the State "A" structure map. The similarity in symmetry of these two anticlines found in beds sixty metres apart suggests that these structures developed later than deposition of the Spearfish Formation, as pre-existing structures would be erased during the hiatus.

The origin of the series of southwest-plunging noses
Figure 7: Isopachous map of the Bluell Bed. The Sherwood argillaceous marker in the extreme southwest portion of the study area is absent, so the interval can not be isopached (diagonal shading).
ISOPACH MAP OF BLUELL BED

(FROM TOP OF STATE % TO TOP OF SHERWOOD ARGILLACEOUS MARKER)

TEN FOOT CONTOUR INTERVAL
Figure 8: Study area structure map of the top of the Madison Group. The Madison is conformably overlain by the upper Mississippian Kibbey Formation (Big Snowy Group) in the southeast portion of the study area and unconformably overlain by the Permian-Triassic Spearfish Formation in the rest of the study area.
STRUCTURE MAP- TOP OF MADISON GROUP

UNCONFORMABLY OVERLAIN BY THE PERMIAN SPEARFISH FM.
NORTHEAST OF —- LINE

CONFORMABLY OVERLAIN BY KIBBEY FM (U.Miss.) S.E. OF LINE
30' CONTOUR INTERVAL
is unclear. Gerhard and others (1982) proposed that structural features in the Williston Basin were due to movement along lineaments in Precambrian basement rocks.

The subtle structural differences are important influences on oil reservoir qualities. The producing wells are located on the noses or just off-structure and immediately down-dip from permeable/porous stratigraphic pinch-outs. In wells that are off-structure the pores are usually plugged with anhydrite cement.
DESCRIPTIVE PETROGRAPHY

Allochems and Orthochems

Carbonate allochems and orthochems are the primary components of rocks in the study area. Depositional environment interpretations are based on the types, quantities, fabrics and associations of these components.

Allochems are aggregates formed by chemical or biological precipitation within the basin of deposition (Folk, 1980). Four types are found in the study area: 1) fossils 2) peloids, 3) intraclasts and 4) coated grains. Orthochems include the microcrystalline ooze and sparry calcite forming the matrix and cement of the carbonate rocks. Cement is discussed in the diagenesis chapter.

Fossils

Types of fossils in the study area from most to least abundant include: algae, calcispheres, ostracodes, forams, gastropods. The fossils, though limited in diversity, show large numbers of individuals within each taxon in some horizons of the study area. Horizons can be correlated within many of the described cores, both as lithofacies (i.e., boundstones) and biofacies (fauna and flora).

Algae- Algae in the study area include Cyanophyta (blue-green) and possibly calcareous Chlorophyta (green). Representatives of the Cyanophyta group are stromatolite and oncoid forms), and branching tubiform types.

Stromatolite boundstones are prominent in the study area and often correlate laterally among adjacent wells.
stromatolites show different structures and textures. The most predominant stromatolite structures are a smooth, horizontally-laminated fabric, with or without fenestrae (Fig. 9) and spherical oncoids (Fig. 10). Occasionally, spaced, laterally-linked hemispheroid (LLH-S) structures (Fig. 11) and pustular or blister type textures are found.

Modern stromatolites are formed from blue-green algal mats. Cyanophyta do not precipitate CaCO₃ in their cell walls but trap and bind carbonate sediment with algal fibers (Gebelein and Hoffman, 1974).

Oncoids found in the study area were either concentrically stacked spheroids (SS-C) or randomly-stacked hemispheres (SS-R). Many of the oncoids appear to have inorganically precipitated radially fibrous laminae as well as algal laminae.

Identifying the blue-green algal types in dolomitized stromatolites is usually impossible. The intertwining-tubular algal mat is usually poorly preserved when found. Many Paleozoic oncoids, or cyanoids (Riding, 1983), were constructed by the genus Girvanella. No intertwining tubular structures were found in the oncoids described. Several calcareous blue-green algae-tubiform microfossils are associated with carbonate mudstones and wackestones. Many of these delicate branching types, some over 1 cm in diameter, are well preserved and consist of two identifiable taxa, the genus Ortonella (Fig. 12) and the genus Garwoodia. All of the branching forms of microfossils
Figure 9: Horizontally laminated stromatolite.

NDGS.#5827, 5326.0'

Figure 10: Spherical oncoid, partially dolomitized.

NDGS.#5063, 5827.0' Plane polarized (P.P.).

Figure 11: Spaced, laterally linked hemispheroid (LLH-S).

NDGS.#5159, 5806.0'
observed in thin section grew upward.

An individual microfossil found in several horizons has the same geometry as the green algae, Dasycladaceae (Fig.13). The size of this microfossil averages 4 mm in length and 0.7 mm in width. The walls of these fossils have been micritized, making further identification impossible.

**Calcispheres**—Calcispheres were abundant in many of the cores. The small (50-200 um), spherical fossils are single- or double-walled with a smooth or spiny outer wall. The fossils are hollow and are poorly to moderately preserved (Fig.14). The walls are commonly micritized and center filled with either cement or micrite. Calcispheres are found in all of the study area lithofacies, except the massive anhydrites, and accumulations sometimes form wackestones and rare, thin packstones.

**Ostracodes**—Ostracodes are abundant in many horizons. Shell size is from 0.3 mm to 1 mm and often the carapace is found to be articulated. Shell shapes are often well preserved, but internal microstructures usually have been recrystallized. Two types of ostracode carapaces were observed in thin section. A thin-walled variety (Fig.15) is most abundant; much rarer is a thick-walled variety (Fig.16). Abundant carbonate mud is associated with the ostracodes.

**Foraminifera**—Foraminifera are only sparsely present in the study area; only one thin section had more than two specimens. Preservation is fair to poor, with
Figure 12: Ortonella. NDGS.6344, 5126.0' P.P.

Figure 13: Dasycladaceae? NDGS.5037, 5422.0' P.P.

Figure 14: Smooth double-walled calcisphere.

NDGS.5159, 5826.0' Crossed Nicols (X.N.
Figure 15: Thin-walled ostracode. Swimming variety, common. NDGS.#6344, 5126.0' P.P.

Figure 16: Thick-walled ostracode. Burrowing variety, very rare. NDGS.#5037, 5422.0' P.P.
recrystallization of the microstructure, but the test shape is still clear (Fig.17). Test size averages 0.5 mm in diameter. There are three to four chambers on one side of an axial cross-section (Fig.18). All identifiable types are of the families Endothyridae or Tournayellidae.

*Others*- Traces of four other fossil groups were found. One gastropod shell, which may have been in situ, was found. Other groups represented include brachiopods, molluscs and echinoderms. All of these fossils were broken, recrystallized and usually are nuclei of coated grains. All have been transported and are probably not indigenous.

**Non-Fossiliferous Allochems**

Non-fossiliferous allochems, along with carbonate mud matrix, were the primary sedimentary components found in the study area. The allochems originated in many different environments, were transported and deposited by many sedimentary processes, and upon burial, were further affected by differing eogenetic and mesogenetic processes.

**Peloids**- Peloids are the smallest allochems represented, averaging between 30 and 200 μm in diameter. These are rounded micritic grains that lack internal structure. In some horizons, peloids and micrite form the matrix between larger allochems. There are occasional thin zones of peloid packstones and rare zones of peloid grainstones.

**Intraclasts**- Intraclasts are allochems derived from contemporaneous, partially cemented carbonate sediment that
Figure 17: Sagittal section through a foraminifera of the 
Family Tournayellidae. NDGS.5159, 5826.0' P.P.

Figure 18: Axial section through a Tournayellidae. 
NDGS.5159, 5826.0' P.P.
has been reworked and transported locally (Folk, 1980). It is difficult to distinguish between smaller intraclasts and larger peloids from the study area, especially if the clasts have been abraded. For descriptive purposes, a diameter of mm was used to separate peloids from intraclasts (after Folk, 1959). Average sizes for intraclasts in the study area range between 0.5 and 3 mm; sorting was usually poor.

Intraclasts often have one radially-fibrous coat due to CaCO₃ precipitation. These are superficial-coated grains, as the cortex thickness is less than 1/2 of the grain radius (Simone, 1981).

Two types of allochems are included in the intraclast group by default: 1) possible coated grains which have lost internal structure, and 2) intraformational breccia clasts formed by in situ desiccation, which are sometimes impossible to distinguish from transported clasts.

Coated Grains—Inorganic coated grains are the most complex and problematical allochems. Descriptive characteristics for coated grains within the study area include: size, shape, number of laminae, laminae microtexture, nucleus composition and laminae chemical composition.

Several coated grain types are defined according to size. Ooids are less than 2 mm; pisoids are greater than 2 mm and less than 10 mm; and macroids are greater than 10 mm (Peryt, 1983). Genetic implications are used to separate coated grains formed in the marine environment (ooids), from coated grains formed in the vadose environment.
Most coated grains are of ooid size, although some zones contained abundant pisoids (>50% by volume). The larger grains were often broken, with additional laminae later enveloping the fractured grain. Cleavage occurred parallel to crystal surfaces and normal to laminae. The larger coated grains are often associated with intraclasts and occasionally with fossils of restricted faunal and floral types. The smaller coated grains most often form homogeneous, thin-bedded grainstones and packstones.

The number of laminae in a coated grain vary from one thick, radially-fibrous coat (>1/2 grain radius), to over 60 thin, mostly micritic, laminae on a complex pisoid-oncoid (Fig.19). Laminae numbers often vary widely in coated grains within one lithotype population.

Coated grains found in this study often show a well-preserved microstructure that is easily seen in thin section. Laminae morphologies, in decreasing order of abundance are: 1) combination types with radially-fibrous and micritic laminae; 2) radially-fibrous types with crystal habit radiating from the grain center or normal to underlying laminae surface (Fig.20); 3) asymmetric, thickly-laminated, micritic types with individual coatings of varying thickness, often causing the grains to have ellipsoidal cross-sections (Fig.21); and 4) symmetrical, thinly-laminated, micritic types with no crystal structure pattern within laminae (Fig.22). Radially-fibrous laminae occur

(vadoids) (Peryt, 1983).
Figure 19: Complex oncoid-pisoid, showing crenulated algal laminations (A) and even inorganic precipitated laminations (B). NDGS.#5211, 5802.2' P.P.
Figure 20: Radially fibrous coated grain.
NDGS.#4238, 5901.6' P.P.

Figure 21: Asymmetric, thickly laminated micritic coated grain or oncoid. Some of these grains are formed by vadose processes and some are formed by algal processes. NDGS.#4965, 5368.8' P.P.

Figure 22: Symmetrical thinly laminated micritic coated grain. NDGS.#5063, 5950.1' P.P.
most often in the larger coated grains (> 1 mm). The symmetrical, thinly-laminated, micritic laminae were found in the smaller grains (0.2-1 mm).

Nucleus composition in the coated grains varies greatly. The smaller ooids often have peloid and rarely have fossil fragment nuclei. Larger pisoids often have intraclasts, broken fibrous crusts, ooid grapestone, or broken, coated-grain fragments for nuclei. Microprobe analysis of the coated grains from the study area shows a chemistry of low-Mg calcite for all types.

Orthochems: Microcrystalline Matrix

All of the cores described in the study contain horizons which are largely micrite. Individual crystal size and geometry can not be identified under the petrographic microscope, as all crystal sizes are less than 10 μm in diameter. This is the "micron sized" fraction described by Friedman 1965).

Micrite in the study section is composed of low-Mg calcite or dolomite, as determined by microprobe analysis and alizarin red staining. Calcitic micrite is usually associated with carbonate allochems, and dolomitic micrite is usually associated with precipitated evaporites or as matrix to clastic quartz and anhydrite grains. The micrite may either be "clean" (having a relative low clay percentage), or argillaceous (having a relative high clay percentage) in calcite or dolomite chemistries. Usually the calcite form is "clean" and the dolomite form is argillaceous.
Primary and Syndepositional Lithotypes

This section identifies specific constituents textures of the major lithologies. When applicable, descriptive modifiers precede the name of the dominant lithotype.

Six lithotypes comprise the lithologies in the study area: 1) pisoid, ooid, intraclast wackestone-packstone; 2) mudstone-stromatolite boundstone; 3) argillaceous, silty dolomudstone; 4) bedded anhydrite; 5) ooid grainstone; and 6) sandy carbonate (Fig.23). The percentages of these rock types vary considerably, both vertically (within a core), and laterally (within a bed). Usually, there are many thin beds of other lithologies intercalated with the major component of a lithotype.

Pisoid, Ooid, Intraclast Wackestone-Packstone Lithotype

Approximately sixty percent of the core examined consists of this lithotype. Constituents include pisoid, ooid, intraclast, and fossil allochems, and a micrite-peloid matrix. Fossils include ostracodes, calcispheres, oncoids, blue-green calcareous branching algae and some stromatolite mats.

The allochems are usually poorly sorted, and many are broken or abraded and appear to have been transported. Some allochems which show evidence of a lack of transport articulated ostracodes and unbroken radially-fibrous grains. Percentages of allochem types and packing often change every few centimetres. The rock is thin- to medium-
Figure 23: Chart of lithotype features. If the feature is present in many of the specific lithotype core or thin-section descriptions, the feature is common. If the feature is present in three or more specific lithotypes, but it is not common, the feature is occasional. If the feature is present in only one or two cases, it is rare.
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bedded. Micrite laminae, which drape over the allochems, frequently separate the wackestone-packstone beds into approximately 10 cm intervals (Fig. 24). When sorted, beds occasionally have a reverse-graded texture (Fig. 25).

Common syndepositional features include fenestral fabric, tepee structures and desiccation cracks. Fenestrae usually are horizontal (Fig. 26). The fenestrae are lined with fibrous or bladed calcite and/or are occluded equant calcite or anhydrite cement. Where open, the fenestrae are often enlarged by solution. Complete small tepee structures (less than core width) occasionally to rarely occur in the wackestone-packstone lithotype. Often gently- to medium- dipping erratic beds with no signs of internal cross-bedding are bounded by horizontal beds. These erratic beds could be one flank of a larger tepee structure. Isolated deposits of sorted, transported ooids or ostracodes sometimes underly the dipping bed. Desiccation cracks (Fig. 27) are related to the tepee structures and common to the wackestone-packstone lithotype. The fractures are up to 0.5 m deep and up to 1 cm wide. Filling the desiccation cracks are allochems and anhydrite cement.

Features less common to the wackestone-packstone lithotype than fenestrae or desiccation cracks are micritized-peloidized sediment (Harrison, 1977), caliche crusts, breccias, meniscus and pendant cements, and matrix-selective vugular porosity. Micritization-peloidization has recrystallized parts of allochems (Figs. 28 and 29), or an entire zone
Figure 24: Micrite lamination draping over allochems in a wackestone-packstone lithotype. There is later dissolution of the matrix below the laminae. NDGS.#4965, 5396.5' P.P.

Figure 25: Reverse grading in a packstone. Matrix has been leached out in part. NDGS.#4238, 5927.8' P.P.
Figure 26: Cemented horizontal fenestrae in a wackestone-packstone lithology. NDGS.$5244, 5415.0'$

Figure 27: Large desiccation fracture in a wackestone caused by wetting and drying of the sediment prior to lithification. Crack was later filled with allochems and cemented with anhydrite. NDGS.$5211, 5790.0'$
Figure 28: Micritized portion of a coated grain into microspar and peloids. This was probably a subaerial weathering process. NDGS.#6553, 6109.0' P.P.

Figure 29: Micritization and peloidization of two coated grains. NDGS.#5159, 5829.0' P.P.
Some beds of wackestone-packstone are capped by thin caliche profiles. The caliche profiles are only a few centimetres thick and incorporate buried allochems, unlike micrite laminae which drape over allochems. The color is cream to light brown. Possible root casts were found in one caliche crust (Fig.30).

Brecciation is occasional to common in the wackestone-packstone lithotype. Brecciated profiles range from a few centimetres to 0.5 m thick.

Matrix-selective vugular porosity is common in the wackestone-packstone lithotype. Solution of the matrix apparently caused overpacking of the allochems. Some vugs contain geopetal sediment, and in one case, ostracode shells. This is the major porosity type forming the reservoir in the area.

Mudstone Stromatolite-Boundstone

A carbonate mudstone, stromatolite-boundstone lithotype is prevalent in a large portion of the core described. This lithotype includes all carbonates containing over 90% micrite and a low siliciclastic clay and silt percentage. The micrite may be calcite or dolomite, although calcite is the most common mineralogy. Bedding thickness is disregarded in this category, and laminated stromatolites and thick-bedded mudstones are lumped together.

The mudstone, stromatolite-boundstone lithotype is commonly intercalated with, or overlies, the wackestone-packstone lithotype. This relation is sometimes only due to
Figure 30: Possible root casts in a caliche crust.

NDGS.#6553, 6101.2' P.P.
differences in the percentages of identical allochems between the two lithotypes, but in many cases the mudstone has different allochem types than the underlying or intercalated wackestone-packstone.

The mudstone, stromatolite-boundstone beds are thick-bedded to laminated. Laminations may be due to stromatolites or may have a non-algal, "varve-like" pattern (Fig.31). The lamination patterns were described in the algal section. Massive and smooth, horizontally-laminated beds are the most common bedding types.

Burrowed mudstones are rare; (Fig.32) burrows are limited in width, averaging 0.15 cm in diameter.

Selenitic gypsum crystals (Fig.33), now converted to anhydrite, are uncommon to occasional in the mudstone lithotype. These crystals often disrupt bedding.

Allochems common to the mudstone, stromatolite-boundstone lithotype include calcareous, blue-green algae; calcispheres; ostracodes and intraclasts. The algae are predominantly undisturbed with the delicate branching tubes in an upright position. The ostracodes are often articulated and in place. Intraclasts are commonly micrite chips or small (<1 cm) cemented, coated-grain clusters.

Allochems rarely found in the mudstone-stromatolite lithotype are the benthonic foraminifera. When found, other fossil types are present.

The mudstone, stromatolite-boundstone lithotype is sometimes dolomitized and forms a dolomudstone which
Figure 31: Thinly laminated mudstone. NDGS.$\#4943, 5341.0'$

Figure 32: Burrowed mudstone. NDGS.$\#6386, 5994.5'$

Figure 33: Euhedral selenitic porphyrotopes in mudstone matrix. NDGS.$\#5827, 5318.0'$
retains primary textures and allochems. The dolomite crystal size is less than 10 µm in diameter. This dolomudstone is classified separately from the argillaceous silty-dolomudstone lithotype due to differences in siliciclastic clay and silt percentages, and the presence of carbonate allochems.

**Argillaceous Silty Dolomudstone**

Approximately 15% of the core described is of the argillaceous, silty dolomudstone lithotype. The lithotype has a sheet-like morphology and can be correlated across the study area. The maximum thickness of the lithotype in the study area is three metres, but it averages less than two metres. The argillaceous silty dolomudstone lithotype is the predominant lithology of the argillaceous marker beds (Fig.34).

The dolomudstone lithotype always contains dolomicrite, clay, and quartz silt. Other constituents include calcite-micrite matrix, anhydrite cement or nodules, dolomite silt, and pyrite.

Dolomicrite crystals are subhedral to anhedral and are less than 10 µm in diameter. Clay (K,Al) is disseminated within the dolomicrite. Percentages of clay are up to 50% in isolated areas, but average less than 10%. Angular quartz silt grains (20 to 60 µm in diameter) are dispersed in the dolomicrite matrix, and rarely make up more than 10 percent of this lithotype.

Associated minerals are often a significant component...
Figure 34: Argillaceous silty dolomudstone with black pyrite frambooids. NDGS/#5827, 5321.0'
of the dolomudstone in this lithotype, but are ubiquitous. Disseminated calcite micrite is common in portions of the dolomudstone lithotype where the carbonate is not completely dolomitized. Anhydrite cement is common in some portions of this lithotype. Small anhydrite nodules (less than 2 cm in diameter and dolomite silt (10 to 40 um in diameter) occur occasionally. Rarely, the dolomite silt is bedded in medium to low-angle cross-laminae 0.2-0.5 mm thick (Fig.35). Celestite occurs in thin zones as displacive cement crystals (Fig.36). Pyrite occasionally occurs in patterned areas (Dixon, 1976), or as small framboinds in the dolomudstone lithotype.

Rare "patterned" textures occur at the base of this lithotype. Carbonate ghost fabrics (micritized packstone and wackestone), occur at the base of some marker beds.

Bedded Anhydrite

Ten percent of the core described in the study area is bedded anhydrite. The relative volume of the anhydrite sampled is considerably less than the volume of anhydrite actually present in these beds, since petroleum companies which collected the data were searching for reservoir rock, and were not interested in obtaining cores of evaporite lithologies. A very thick section (up to 70 m) of bedded anhydrite is present in the eastern portion of the study area.

Anhydrite types found in the section studied are thick- to thin-bedded with massive, enterolithic, mosaic
Figure 35: Low-to medium-angle, finely laminated, cross-sets containing dolomite silt grains in a dolomudstone matrix. NDGS.*5130, 5385.0' P.P.

Figure 36: Celestite rosette in a dolomudstone.

NDGS.*5130, 5413.5' X.N.
nodular textures (Figs. 37, 38). Rarely, selenitic (swallowtail features occur (after Schreiber, 1978).

anhydrite is relatively pure with the exception of dispersed clay and, in the mosaic and nodular textures, exhibits a matrix of microdolomite, clays and quartz silt.

**Ooid Grainstone**

Approximately seven percent of the core described consists of the ooid-grainstone lithotype. This lithotype is concentrated in the southwest portion of the study area. Allochems are predominantly ooids. Other allochems found in rare to trace amounts are intraclasts, peloids, forams, and broken micritized fossil fragments.

Ooids in the grainstones are of three types. From most abundant to least abundant these are: 1) combination; 2) symmetrically, thinly-laminated micritic; and 3) radially fibrous types. Many of the ooids are broken. This lithotype is usually medium- to well-sorted. Bedding, where present, is usually thin and sometimes cross-bedded. The grainstone lithotype is often interbedded with the wackestone-packstone lithotype. The only other syndepositional feature is rare, horizontal sheet-cracking.

Most interparticle pores in this lithotype are occluded with calcite cement. Cement crystal morphologies include fibrous and bladed isopachous types lining pores and equant crystals occluding the pore center.
Figure 37: Massive anhydrite. NDGS.#6344, 5120.0'

Figure 38: Massive bedded anhydrite overlying mosaic, non-bedded anhydrite. NDGS.#5827, 5306.0'
**Sandy Carbonate**

Five sandy carbonate beds occur in four separate wells. Sand grains from four of these beds were anhydrite and sand grains from two of these beds were quartz.

Three anhydrite sandstones are thin units (<30 cm) containing between 50 and 60% well-sorted, fine, angular detrital anhydrite grains in an argillaceous-dolomudstone matrix (Figs. 39 and 40). The grains average between 0.1 and 0.2 mm in diameter. No structures were observed. All three beds are located within the K-1 Marker.

Two cores contained a high percentages of siliciclastic sand. These sandy lithologies have complex mineralogies and are within the K-1 Marker. One of these lithologies is a sandy limestone (Fig. 41 with well-sorted and well-mixed peloid and angular quartz grains. Rare orthoclase grains (<2%) are silt-sized and sometimes occur with the sand-sized anhydrite grains. Clay is a minor matrix material. The sandstone is thick-bedded (>3 m) with uniform, low- to medium-angled cross-laminae. Primary porosity was high; over 30% of the rock is cemented with equant calcite.

The second sandy lithology contrasts texturally with the sandy limestone described above. The quartz grains are moderately to poorly sorted and float in argillaceous dolomicrite with celestite cement (Fig. 42). The sandy dolostone lithology is thin- to medium-bedded with some disrupted bedding and is greater than 2 m thick. The sand grains are similar to grains in the sandy limestone described above.
Figure 39: Anhydrite sandstone. Angular, well-sorted, clastic anhydrite grains in a dolomericite matrix. NDGS.#4965, 5400.2' P.P.

Figure 40: Borings (root casts?) in a caliche crust covered by anhydrite sandstone. Located at the base of the K-1 marker. NDGS.#4965, 5400.3' X.N.
Figure 41: Well-sorted, fine-grained, subangular, quartz-peloid and anhydrite sandstone with calcite cement. NDGS.#4943, 5353.2' P.P.

Figure 42: Sandy, celestite-rich dolomudstone. Quartz sand grains (A) are angular and poorly sorted, partially due to dissolution. Celestite (B) is diagenetic. Dolomicrite (C) forms the matrix. NDGS.#5803, 5471.8' S.E.M. photo X100
INTERPRETIVE PETROGRAPHY

Interpretations of the allochems, orthochems lithotypes can be made by comparing descriptive characteristics of the study area rocks with characteristics of sediments in modern environments. Many of the ancient features can be found in the modern sediments of the coastal sabkhas of the Persian Gulf and of Baffin. These modern environments are warm, arid to semi-arid, have low-to medium energy, and are in carbonate-precipitating areas.

Paleogeography and Paleoclimate

Paleogeographic reconstructions place the Williston Basin between 5 and 15 degrees North latitude during the Mississippian (Visean Series) (Habicht, 1979; Scotese and others, 1979 (Fig. 43). If the continents were rotated to Mississippian global geographic orientation, trade wind belts could be superimposed on the model. Clockwise trade-wind motion caused warm, dry, wind coming off of the landmass of Laurussia, to blow westwardly over the Williston Basin. Habicht (1979) proposed similar continental wind directions using interpretations from cross-sets in Mississippian sandstones in the southwestern United States. This paleoclimatic interpretation is supported in the study area by generally evaporitic conditions and by transport of terrigenous material by eolian processes. It has been suggested that the source for the siliciclastic material was possibly
Figure 43: Paleogeographic map showing location of the Williston Basin during Visean time. Continental reconstructions are after Scotese and others (1979). Wind directions are inferred from Habicht (1979) and from modern trade wind directions at 15 degrees North latitude.
exposure of the Bakken Formation or the Qu'Appelle Group (Three Forks Formation), which were located 320 km north-east of the study area (Fuller, 1956). Arid paleoenvironmental characteristics of the study area are cited in regional studies by Edie (1958) in southeastern Saskatchewan, and by Shanley (1983) and Obelenus (1985) in north-central North Dakota.

**Allochems and Orthochems**

**Fossils**

Within the study area, most fossil flora and fauna represent organisms that lived in greater than normal marine salinity environments (>35 parts per thousand).

**Algae**—The algae and tubiform microfossils, forming stromatolite mats, are the group that have the greatest effect on sedimentation and left the largest imprint on the rock record in the study area. Additionally, the algal types and structures are environmental indicators.

Modern algal stromatolites can survive on sabkha flats with salinities up to 272 ppt (Bathurst, 1975). Although stromatolites can exist in the subtidal, intertidal and supratidal zones, certain textures are environmentally specific. Areas where pustular stromatolite textures are found (Fig. 44) indicate an upper intertidal depositional environment with moderate to high sedimentation rates (Hoffman, 1976). Concentrically stacked spheroidal (SS-C) or randomly stacked spheroidal (SS-R) oncoids require a subtidal to lower intertidal environment with frequent to

The presence of occasional tubiform microfossils is an indication that the depositional environment was quiet as the delicate calcareous branches could not survive either desiccation in the supratidal zone or turbulent open marine waters (Jamieson, 1971). There are no indications of adjacent reefs having sheltered the delicate porostramata forms. In Tsien and Dricott's (1977) study of Devonian calcareous algae from Belgium, G. Ortonella, similar to forms found in this study, was found to be one of the main rock-forming organisms of the lagoonal facies.

Calcispheres—Rupp (1967) has noted the similarity of ancient, smooth-walled calcispheres to the cysts of the modern Dasycladacian Acetabularia. Smooth, double-walled calcispheres in the study area often occur in association with the Porostromatan Ortonella (Fig. 45).

The high number of calcispheres occurring in thin zones may have been localized by sedimentary processes, such as wave action, which concentrated the floating, unattached cysts.

Ostracodes—Thin-walled exoskeletons are attributed to swimming ostracodes, and thick-walled exoskeletons are attributed to burrowing ostracodes (Benson, 1961). Some modern ostracodes are found in salinities of up to 55 parts per thousand (Benson, 1961). Other environmental factors associated with modern ostracode assemblages include 1 an
Figure 44: Pustular texture in fossilized algal mat.

NDGS.#6344, 5142.6' P.P.

Figure 45: Calcispheres associated with the algae Ortonella. NDGS.#6344, 5126.0' P.P.
affinity to salt-tolerant sea plants such as algae and salt-marsh grasses (Benson, 1961), and 2) low energy water levels; ostracodes are nearly to completely absent from oolite rich sediment.

Ostracodes found in the cores could have tolerated higher than normal marine salinities, but not as high as the salinity needed for evaporite precipitation.

*Foraminifera*- Some modern foraminifera can tolerate slight fluctuations in marine water salinity (brackish and hypersaline waters), but abnormal salinities tend to retard a given species' reproductive cycle (Loeblich and Tappan, 1964). Benthonic foraminifera are less tolerant of highly saline water than the other biota represented (i.e., algae and ostracodes). Where found in the study area, these benthonic types may indicate a less hypersaline paleoenvironment than found elsewhere in the core study area.

**Non-Fossiliferous Allochems and Orthochems**

*Peloids*- Peloids can originate as fecal pellets, from abrasion of larger allochems, or from algal or vadose weathering processes causing micritization of bioclasts or inorganic clasts (Taylor and Illing, 1971; Bathurst, 1975). The rarity of bioturbation and of the traces of burrowing fauna in the study area suggests that fecal pellets form a minor percentage of the peloids. Many peloids may have been formed by diagenetic recrystallization.

*Intraclasts*- Intraclast roundness, sphericity, internal textures, sorting and grading are indicators of deposi-
tional environments that were present. The intraclasts in the core studied are usually rip-up clasts of ooid and pisoid wackestones-packstones, or rarely, flat pebble conglomerates of mud chips (Fig. 46).

The abundance of poorly sorted, intraclast-rich carbonates in some beds of the study area may indicate the lack of a continuous current during deposition. These intraclast-rich beds were probably deposited during storms.

**Coated Grains**—Interpreting the genesis of ancient coated grains is difficult, at best, given the plethora of different interpretations in the literature concerning the genesis of modern coated grains. The microstructure of laminae in coated grains (radially fibrous, tangential and micritic crystal-morphologies) and the grain chemistry (low-Mg calcite, high-Mg calcite, and aragonite) have been attributed to specific environmental conditions. Environmental characteristics cited to produce specific types of coated grains include water salinity, water Ca/Mg ratio, algal activity, CaCO$_3$ saturation, water agitation and vadose precipitation. However, many of these genetic factors have been disregarded to some degree. Coated grains with multiple types of microstructures and chemistries have been found in specific types of environments, and an unique grain type or chemistry has been found in multiple types of environments (Land and others, 1979; Milliman and others, 1975; and Marshall and Davies, 1975).

Water agitation in modern, CaCO$_3$ environments does
Figure 46: Carbonate rip-up clasts forming two beds of flat-pebble conglomerate. NDGS.4943, 5342.0'
have a direct correlation with the type of coated grain that is produced. Low-energy environments, especially those associated with above average concentrations of humic acid, produce radially-fibrous morphologies (Given and Wilkinson, 1985; Davies and others, 1978; Land and others, 1979).

Humic acids, in marine water, act as catalysts for radially fibrous CaCO₃ precipitation (Kitano and Kanamori, 1966; Davies and others, 1978). The humic acids may come from abundant algal activity (Land and others, 1979; Friedman and others, 1973). More agitated environments tend to inhibit radially fibrous growth, and are more likely to produce tangential crystal morphologies in coated-grain laminae (Loreau and Purser, 1973; Kahle, 1974)

Micritic-type laminae in Quaternary coated grains are due to endolithic boring algae causing micritization (Bathurst, 1975), or subaerial diagenesis (Siesser, 1973; Read, 1974). Asymmetric, thickly-laminated, micritic-coated grains in the study area were probably a product of subaerial diagenesis. This may be inferred by comparing this texture with that of similar, modern, subaerial-coated grains. The in situ genesis gave the grains an ellipsoid geometry and an overpacked rock fabric. Coated grains of this type can be fractured but are not transported clastic fragments.

The symmetrical, thinly-laminated, micrite-coated grains found in the study area can not be attributed to widespread micritization, as these coated grains often have isolated, unaltered, radially-fibrous laminae. There may
have been some original chemical difference between the present micritic and radially-fibrous laminae that caused localized, diagenetic changes. Thinly-laminated micritic-crystal morphologies seem to be similar to tangential, aragonite crystal morphologies on microscopic examination under the scanning electron microscope (Land and others, 1979). Thinly-laminated, micritic-coated grains in the study area may be micritized, tangential-coated grains. Tangential coated grains indicate possible formation environments of higher energy (Land and others, 1979) than would be found in the slightly agitated environments required for the radially-fibrous, coated grains. The primary mineralogy of the micritic ooids is unknown. Present coated-grain chemistry found in the study area is low-Mg calcite.

The larger pisoids and the poorly-sorted coated grains of many wackestones and packstones in the section studied do not have many modern equivalents. Some writers suggest ancient pisoids were formed in situ by submarine genesis (Esteban and Pray, 1983), or precipitated in slightly agitated, hypersaline ponds (Obelenus, 1985). Other writers suggest a vadose genesis of the pisoids (Dunham, 1965; Thomas, 1965; Gerhard and others, 1978). The multiply broken and often recoated aspect of many pisoids in the study area, indicates that some transport of the pisoids occurred prior to deposition. Some large, complex pisoids-oncoids have continuous, crenulated-algal
laminations in addition to the inorganically precipitated laminations. Continuous algal laminations in modern oncoids indicate some movement of the allochems, since the lack of light due to shadowing will cause discontinuous laminations (Logan and others, 1964).

Orthochems: Microcrystalline matrix

Modern micrite consists of carbonate crystals from one to four microns in diameter (Folk, 1959). Three general sources for the microcrystalline carbonate are possible: 1) mechanical or biological abrasion of larger carbonate particles, 2) direct inorganic precipitation of aragonite, calcite or dolomite and 3) production of micrite due to algal activity (Blatt and others, 1980).

The volume of silt and fine sand-sized, abraded-allochem fragments is relatively small in the study area, indicating that the amount of micrite derived from mechanical abrasion is probably also limited. Algal and bacterial boring of allochems may have contributed some micrite to the sediment, although most micritized allochems seem to have retained their geometry and did not disaggregate. Mechanical or biological abrasion of larger carbonate particles probably contributed minor amounts of micrite to the section studied.

The modern Dead Sea precipitates aragonitic micrite when maximum temperatures are reached (Blatt and others, 1980). Precipitation is caused by increased carbonate saturation due to evaporation. Because there is evidence
high evaporation during deposition of the section studied, direct inorganic precipitation of micrite from hypersaline brines cannot be ruled out.

Algae cause precipitation of most of the modern microcrystalline carbonate in hypersaline waters (Friedman others, 1973). Biochemical processes, most importantly removal of CO\textsubscript{2} for photosynthesis in CaCO\textsubscript{3}-saturated water, cause large amounts of micrite precipitation. Mississippian algae probably contributed most of the micrite to the study area, especially where abundant algal activity is recorded (as in stromatolite boundstones).

**Primary and Syndepositional Lithotypes**

Interpretations of lithotype depositional environments are made by studying mineralogies, textures, allochem associations, matrix and other sedimentary characteristics

**Wackestone-Packstone Lithotype**

Three characteristics are used to interpret the depositional environments of the wackestone-packstone litho-

The presence of allochem types, radially-fibrous coated grains and delicate skeletons of only highly saline tolerant type fossils, which suggests the occurrence of periods of slightly agitated, highly saline water conditions during deposition. The presence of many thin, poorly sorted beds containing broken grains with an overlying micrite lamination, is indicative of storm scouring and flooding (Folk, 1980). The presence of multiple, subaerial-
exposure features including desiccation cracks, micritization-peloidization, caliche crusts and brecciation, indicating periodic to extended subaerial exposure which interrupted shallow-water deposition

Micritization-peloidization replacement was described by Harrison and Steinen (1978) in Holocene rocks in Barbados, and Mississippian rocks in Kentucky. Micritization textures from Holocene wackestones from St. Croix, Virgin Islands are similar to textures found in some wackestones of the section studied (see diagenesis section)

Caliche is an indurated soil horizon in which CaCO\textsubscript{3} has been transported and precipitated either by upward, ground-moisture (capillary) movement due to evaporation, or downward, meteoric-water movement (Reeves, 1976). Caliche forms in arid to semi-arid climates (Reeves, 1976). Modern field evidence suggests that soil brecciation is due to direct exposure of the caliche after overlying soil zones have been stripped away (Reeves, 1976).

The depositional environment of the wackestone-packstone lithotype probably was a protected, subaqueous area, that was periodically scoured by storms and occasionally subaerially exposed. This interpretation agrees with Obelenus's (1985) environmental interpretation for parts of the upper Frobisher-Alida interval of north-central North Dakota. His "pisolite ooid wackestone-grainstone" lithofacies is interpreted to have been deposited in the shallow, hypersaline ponds and subaerially exposed areas of a tidal flat.
Two generalized conditions of the depositional environment can be inferred from mudstone and stromatolite-boundstone samples: 1) The mudstone was deposited primarily in quiet water. This may be inferred from the abundance of delicate tubiform algae, the high volume of micrite deposited, and the absence of coated grains which require some water agitation (Land and others, 1979). 2) The aqueous environment was generally highly saline and occasionally became less saline. Evidence for high salinity is the syndepositional precipitation of selenitic gypsum crystals and syndepositional dolomite within portions of the mudstone, as well as the occurrence of highly saline-tolerant fossils. The presence of rare burrows and foraminifera indicates that there were periods when salinity dropped low enough for an infauna and foraminifera to survive.

Two other depositional features modify the paleoenvironmental interpretation of the mudstone, stromatolite-boundstone lithotype: 1) The presence of intraclasts in parts of the mudstone despite the otherwise quiet-water features suggests that periodic storms could possibly have ripped up and deposited the intraclasts, 2) The rare "varve" type laminae found in some areas of the mudstone lithotype may be due to salinity changes causing stratification of the water body (Bradley, 1970; Byers, 1977).

The mudstone, stromatolite-boundstone lithotype was probably deposited in a protected body of water which
usually lacked agitation and was hypersaline. Infrequently, storm agitation and influxes of more normal marine water occurred.

**Argillaceous Silty Dolomudstone**

Since allochems are lacking in the argillaceous, silty, dolomudstone lithotype, the depositional environment must be determined by interpreting the dolomite crystal characteristics as well as the associated mineralogy and sedimentary features.

The generally fine dolomite crystal size and subhedral-anhedral shape indicates rapid crystallization (Folk and Land, 1975). Some dolomite crystals show evidence of transport, as indicated by the presence of rare bedding planes and cross-lamination of dolomite silt grains. Dolomitization was therefore syndepositional rather than meso-genetic.

Quartz silt and clay are disseminated throughout this lithotype and indicate a fairly continuous influx of terrigenous material. Associations of primary anhydrite and celestite cement indicate high depositional salinities. Authigenic celestite cement can be precipitated in modern environments when the salinity is over 210 ppt (Bathurst 1975). More primary sulfates may have been precipitated than the amount found in the core, as occasional "patterned" textures of pyrite crystals may represent areas of sulfate reduction (Dixon, 1976).

The general absence of bedding structures or burrow-
ing trails, a lack of allochems, and the associated minerals of the dolomudstone lithotype are features almost identical to those found on portions of the modern carbonate sabkha located in the Persian Gulf (Kinsman, 1964). Sedimentation in the modern sabkha is controlled by capillary water which traps eolian carbonate and siliciclastic material. Wind desiccates and deflates the sediment not held in place by ground water (Kendall, 1979). Dolomitization and sulfate precipitation are caused by hypersaline ground water moving beneath and through the subaerially exposed sediment while evaporation provides the head for the brine movement (Kinsman, 1964).

The argillaceous, silty dolomudstone lithotype in the study area was probably deposited in an environment similar to that of the present day Persian Gulf Coast. Exposed micritized carbonate was probably the source for much of the eolian sediment. As only a thin horizon seems to have undergone this syndepositional dolomitization, it seems likely that the hypersaline water table was perched on a cemented horizon or a buried calcrete

**Bedded Anhydrite**

Evaporitic conditions in the study area during Visean time can be interpreted from three representative characteristics: 1) primary evaporite deposits, both precipitated and clastic; 2) restricted marine biota remains which are limited to highly saline tolerant organisms and 3) a paucity of terrestrial plants—there are only rare
root casts and no coals.

Gypsum is the predominant evaporite precipitated in both subaqueous and subaerial modern environments (Kendall, 1979). It precipitates when normal marine water has been concentrated to slightly more than 1/3 of its original volume (Blatt and others, 1980).

Nodular and enterolithic textures occur on modern coastal sabkhas and imply supratidal precipitation (Kendall, 1979). Concentration of sulfates and salts in the carbonate sediments of the supratidal surface occurs by capillary evaporation through the sediment above the water table. A maximum thickness of one metre of evaporites is recorded on Persian Gulf sabkhas (Kendall, 1979). Associated with the coastal sabkha evaporites are algal mats and dolomitized carbonates (Kendall, 1979).

The nodular and enterolithic anhydrite in the section studied was probably precipitated in an ancient coastal-sabkha environment, particularly when interbedded with algal mat structures and dolomitized carbonate.

For any significant accumulations of evaporites to have been deposited in the section, marine water must have been replenished, and continued relative subsidence of the evaporite facies must have occurred. An equilibrium between rate of evaporation and rate of subsidence was needed to preserve the large volume of Frobisher-Alida evaporites.

Massive sulfate, along with sections of selenitic (swallowtail or laminated gypsum and sometimes mosaic
gypsum indicate subaqueous evaporitic conditions in modern environments (Kendall, 1979; Schreiber, 1978). Most of anhydrite beds in the study area have subaqueous evaporite features. The thick sections of the relatively pure sulfates probably accumulated in a hypersaline lagoon, since the evaporites are laterally continuous throughout the study area. Water depth is unknown, but is surmised to be relatively shallow because: 1) the even rhythmic lamination of deep evaporite basins are absent; and 2) isopach cross-sections show relatively even thicknesses between the evaporites and laterally equivalent supratidal carbonates. Red beds, indicative of extremely shallow-water evaporites (Schreiber, 1978), are not present in the study area, but exist to the east in laterally equivalent evaporites (Shanley, 1983). Oxidized red beds in the study area could possibly have been reduced after deposition.

Ooid Grainstone

Five characteristics help interpret the depositional environment of the ooid grainstone lithotype: 1) the medium to well-sorted texture, 2) breakage of many ooids, 3) the lack of micrite matrix between the grains, 4) the presence of radially-fibrous coated grain microstructures and 5) absence of fossils. Three characteristics, sorting, grain breakage and absence of mud, imply some water agitation at the deposition site. The presence of radially fibrous ooids implies that this agitation was primarily gentle (see interpretive section on coated grains). A lack of fossils
is probably due to hypersaline waters, and/or some moderately agitated water conditions.

Other characteristics help define the syndepositional environment: 1) sheet cracking; and 2) isopachous cementation. Horizontal sheet cracking indicates the occurrence of periods of subaerial exposure (Shinn, 1983), while isopachous cementation in grainstones is due to subaqueous precipitation (Harris, 1979). Thus, the ooid grainstone lithotype was probably deposited in a shallow, slightly agitated, hypersaline ooid shoal, which was periodically exposed.

**Sandy Carbonates**

The sandy carbonate lithotype contributes an insignificant amount to the total sediment package described, but, where it occurs, the lithotype is an important environmental indicator. The sand grains (anhydrite, quartz and rare carbonate peloids) come from three different provenances; an evaporitic, a siliciclastic, and a marine source.

The source of the detrital-anhydrite grains was probably the desiccation of gypsum or anhydrite surfaces located on a sabkha or an evaporated saline pond. Similar gypsum sands are found in modern environments within the sabkha complex of the Persian Gulf (Kinsman, 1966; Fryberger and others, 1983).

The angularity and good sorting of the anhydrite grains found in the section studied implies eolian transport; as aqueous transport would tend to partially
dissolve, and therefore quickly round, grains. Additionally, the preservation of the anhydrite sand bodies required hypersaline ground waters throughout the burial history.

source of the mineralogically mature >98% of the siliciclastic grains are quartz), texturally immature (angular grains) siliciclastic sand is unclear. Similar mineralogies are reported in the sandstones of the Frobisher-Alida K-2 and K-3 marker beds (Fuller, 1956; LeFever and others, 1984) to the east and northeast of the area studied lack of bedding structures in all but one of the sandy carbonates may be due to eolian-sabkha deposition. In this type of deposition, saltating grains are individually entrapped and captured by capillary moisture in low-lying areas causing adhesion-produced strata (Fryberger and others, 1983).

The thick body of cross-bedded sandy limestone may represent a standing dune. It is unknown if the sandy carbonate was deposited subaerially or subaqueously. The cross-bedded, sand-rich body seems isolated; none of the four other cores penetrating this zone contained bedding structures
DEPOSITIONAL HISTORY

Argillaceous Markers vs Time Markers

The K-1, S.A.M. and State "A" marker beds define the Sherwood and Bluell Beds. It is therefore necessary to describe the spatial and temporal relations of the argillaceous marker beds in the study area before interpreting the depositional history of the Sherwood and Bluell Beds.

Spatial:

The marker beds in the section studied average two metres in thickness, and are no thicker than three metres (Fig. 47). The Sherwood bed (section between the top of the K-1 and S.A.M.) averages 13 m. The Bluell bed (section between the S.A.M. and the State "A"), averages 14 m. The marker beds are approximately parallel planes from which subsurface beds can be recognized and mapped.

Temporal:

There is no conclusive evidence that the argillaceous markers (K-1, S.A.M. and State "A") can be considered time lines in the study area. The markers are devoid of fossils, so that first-hand biostratigraphic evidence is absent. However some general time-rock relations can be inferred from the morphological and lithological nature of the marker beds.

1.) The markers are thin, even beds of mostly uniform lithology, primarily consisting of argillaceous, silty dolomudstone. The dolomudstone markers cross-cut other lithologies, including the evaporite, mudstone, and
Figure 47: Southwest-northeast stratigraphic cross-section along regional dip through the study area showing the marker beds cross-cutting the evaporite and carbonate lithologies. Datum is the State "A" Marker.
wackestone-packstone lithotypes. The same lithotype can both underlie and overlie the marker bed. Shanley (1983) made similar observations in his regional study of the Frobisher-Alida Interval in the northeast Williston Basin.

The dolomudstone markers grade into argillaceous coated grain lithologies basinward and into an argillaceous evaporite lithology "landward". The argillaceous character diminishes rapidly basinward in the limestone lithologies. The marker beds do extend beyond the normal, gradual, basinward progradation of the evaporite lithofacies (Fig.47).

The rocks of the Sherwood and Bluell beds within the section studied display the characteristics of shallow-sublittoral to perilittoral deposits. There is evidence of subaerial exposure in every lithotype, and no evidence of deep-water, open-marine sediments, such as fossil crinoids. This implies an extremely flat topography in which a slight drop in sea level of even a few metres would expose a large area.

4.) The Persian Gulf slopes about 0.5 m per km. The vertical aggregation of modern detrital-dominant sabkhas in the Persian Gulf is usually about 2.5 to 5 cm per year depending on water table elevation and sediment supply (Fryberger and others, 1983). An estimation for the maximum Williston Basin slope during deposition of the Frobisher-Alida interval is 0.2 m per km. This slope is calculated from a vertical maximum photic zone depth (30 m) in the center of the Williston Basin and a horizontal distance
(150 km) to the basin margin located in the study area. It is assumed that parts of the center of the basin were in the photic zone during Frobisher-Alida deposition time from algal evidence found there (Waters, 1984 and Stephens, 1986).

Thus, it would take as short as 100 years to deposit a three-metre-thick marker bed at the same rate as modern detrital-dominated sabkhas, provided water table elevations and sediment supply were ideal. Since the paleoslope was almost negligible, progradation rates would be very rapid.

Of the above points are a bit circumstantial, considering the limited extent of the study area, but the markers seem to represent relatively short periods of geologic time compared to the entire Frobisher-Alida interval. The markers in the study area can therefore be considered quasi-chronozones. More about the depositional history of the marker beds is discussed in the following Sherwood Argillaceous Marker section.

Harris and others (1966, p.2272) proposed that the argillaceous markers in north-central North Dakota were, "reliable time-stratigraphic markers in the upper Mission Canyon sequence", and that the markers were "deposited during an abrupt, short-lived influx of terrigenous clastic material..."

Shanley (1983, p.99 interpreted the Frobisher-Alida argillaceous markers of north-central North Dakota as wind-laid deposits and that this "...allows the marker-horizons to be considered time-stratigraphic markers separating time
stratigraphic units which reflect a cyclic relationship between eustatic sea level fluctuation and sedimentation".

Assuming that each marker-bound bed represents a relatively isochronous unit, the depositional history chapter is subdivided into three sections discussing the Sherwood, S.A.M. and Bluell. The K-1 marker bed's lithology relations are described, but the depositional environment is not interpreted due to limited core data.

Facies Relations Within Beds

**K-1 Marker**

northeastern and eastern portions of the study area are the only area with cores that penetrate the K-1. Electric logs from wells drilled in the two western townships of the study area do not display K-1 Marker characteristics.

The rocks of the K-1 Marker, where sampled, are diverse and lithotypes seem discontinuous between adjacent wells. Four separate sediment types occur in the K-1 Marker: 1) argillaceous dolomicrite, 2) non-dolomitized stromatolite-laminated micrite, 3) anhydrite sand, and 4) quartz-peloid sand.

The major lithologies of the K-1 Marker are argillaceous, laminated to patterned dolomudstones, and interbedded anhydrite sandstones. Dolomitization is not uniform; some portions are undolomitized (NDGS# 5308). A lithofacies map (Fig.48) shows estimated facies boundaries.

northeast to southwest lithofacies trend of the
Figure 48: Lithofacies map of the K-1 Marker. Siliciclastic sandstone may represent a channel between Basin waters to the West and an evaporitic lagoon East of the study area. Triangles indicate core data control.

The MacKobee Coulee Field boundary, on this map and the following lithofacies maps, is drawn in for location reference only.
K-1 DOES NOT DEVELOP

DOLOMUDSTONE

& ANHYDRITE SANDSTONE

SILICICLASTIC SANDSTONE

MACKOBEE COULEE FIELD

DOLOMUDSTONE

0 5km
sands differs from the northwest-southeast lithofacies orientation of overlying beds. A channel connecting the basin waters with an inland-evaporitic lagoon may have contributed to the isolated sand-body morphology. There are enough data points to construct a depositional model the K-1.

Sherwood Bed

The best core and thin-section control in the study area is in the Sherwood bed. Lake Darling Field produces from this interval. Sherwood bed lithofacies trend north-northwest to south-southeast, parallel to the regional strike of the area. This orientation is perpendicular to the orientation of the sand body in the underlying K-1 Marker.

The Sherwood bed can be segregated into four lithofacies: 1 ooid grainstone, 2) intraclast-pisoid wackestone, 3) stromatolite mudstone, and 4) anhydrite-dolomudstone (Fig.49)

Ooid Grainstone: The Sherwood Bed in the southwest portion of the study area is composed predominantly of ooid grainstones. A peloid-intraclast packstone is often interbedded with the grainstones. Pisoids are abundant toward the eastern edge of the grainstone lithofacies.

Intraclast-pisoid Wackestone: Immediately east of the grainstone lithofacies in the Sherwood bed is an intraclast-pisoid wackestone lithofacies. This lithofacies forms a belt running north-northwest to south-southeast through the study area.
Figure 49: Lithofacies map of the Sherwood bed. Triangles indicate core data control. A-A' is the location of the cross-section in Figure 50.
In association with the pisoids and intraclasts are ooids, peloids and a restricted fossil fauna and flora. Occasionally the ooids form thin (less than one metre) grainstones within the wackestone lithofacies. Fenestral textures, desiccation fractures and thin caliche profiles are common in the pisoid-intraclast lithofacies.

Biota are limited in the pisoid-intraclast wackestone lithofacies. Restricted faunal and floral types include algae (oncoids and branching forms), calcispheres, ostracodes and rare benthonic foraminifera. Vertical continuity of biofacies is extremely limited. The biofacies can rarely be correlated between adjacent cores, except for stromatolites.

**Mudstone Stromatolite-boundstone**: A mudstone-stromatolite-boundstone lithofacies lies east-northeast of the intraclast-pisoid lithofacies in the Sherwood bed. The lithofacies contains features of quiet water deposition.

The most common lithologies are laminated mudstones, formed of planar stromatolites and thick bedded mudstones, which are often partially dolomitized and contain euhedral gypsum crystals. Thin beds of intraclastic wackestones occur at the base of this lithofacies, but the rocks become increasingly intraclast-poor up-section.

Restricted fossil floras and faunas are common and include laminated and pustular algal textures, calcispheres, ostracodes and tubiform algae. In some zones, calcispheres are abundant enough to form thin packstones.
stromatolite-mudstone lithofacies does contain some caliche profiles, small tepee structures and rare, small, breccia zones. Fenestral textures are rare to common; porosity is usually occluded by anhydrite.

**Anhydrite-dolomudstone**: An evaporite lithofacies is located in the extreme east of the study area (NDGS# 4943 & 6344). Rock types that are represented in this lithofacies include massive to bedded anhydrites, argillaceous dolomudstones interbedded with mudstones, intraclastic wackestones and a thin anhydrite sandstone.

Thin zones of abundant, restricted-type fauna and flora are found in this lithofacies. Fossils include calcispheres, ostracodes and, rarely, tubiform algae. Occasionally there are horizontally laminated stromatolite structures.

The anhydrite and the mudstone-stromatolite lithofacies are very closely related. Such features as inter-tonguing, anhydrite onlapping, high clay content and roughly correlative storm deposits between the two adjacent lithofacies point out the similarity between the two lithofacies.

Figure 50 depicts a composite cross-section of the lithofacies found along regional strike in the Sherwood bed. Note the uniform thickness of the Sherwood Argillaceous Marker.

**Sherwood Argillaceous Marker**

Sherwood argillaceous Marker (S.A.M. is an extensive, thin, marker bed (between 2 and 3 m thick).
Figure 50: Cross-section of the Sherwood bed along regional strike (see map in Figure 49 for location of A-A'). Lithofacies have limited horizontal extent in this figure because the cross-section straddles two lithofacies (Intraclast-pisoloid wackestone and the stromatolite-mudstone lithotypes of the Sherwood bed.)
S.A.M. is found throughout the study area except in the southwest corner (NDGS# 6553). Lithofacies within the S.A.M. include ooid grainstone, ooid wackestone, dolomudstone and argillaceous mudstone (Fig. 51).

In the extreme southwest of the study area (NDGS#'s 6553 and 4238), the S.A.M. or S.A.M. lateral-stratigraphic equivalent is an ooid grainstone or packstone. The characteristically sharp, high gamma-ray peak of the S.A.M. is absent or only occurs as a very broad, subtle increase in this region. There is no evidence of a discontinuity between the Sherwood bed and the S.A.M. in vertical section in this area.

North and northeast of the ooid grainstone lithofacies is an ooid wackestone lithofacies. Interbedded with ooid wackestones are mudstones and silty argillaceous dolomudstones. The wackestone becomes less oolitic but more pisolitic and intraclastic towards the north edge of the lithofacies.

Immediately northeast of the ooid wackestone lithofacies, and extending across most of the study area, is a silty argillaceous dolomudstone lithofacies. The lithology is remarkably uniform. The dolomudstone is usually massive to distorted and thinly bedded. Only rarely is non-distorted bedding found. Rare, low-angle cross-laminae occur in NDGS# 5130 and stromatolites in NDGS# 5827.

Northeast of the dolomudstone lithofacies is the argillaceous mudstone lithofacies. This is best typified by
Figure 51: Lithofacies map of the Sherwood Argillaceous Marker. Triangles indicate core data control.
NDGS core # 6344. This lithology is predominantly argil-laceous mudstone, interbedded with thin fossiliferous and intraclastic wackestones.

The mudstones have been partially dolomitized and often contain syndepositional gypsum laths. Thin beds of abundant, restricted-type fossils (tubiform algae and ostracodes) are found in this interval, and are often numerous enough to create bafflestones and packstones. Other allochems include peloids and algal covered intraclasts. The beds alternate frequently in allochem type, allochem quantity, and mineralogy (dolomite, calcite, anhydrite, clay and quartz silt percentage).

**Bluell Bed**

The lithofacies of the Bluell Bed form four narrow northwest-southeast trending bands (Fig. 52). The lithofacies include ooid-pisoid packstones, ooid grainstones, pisoid-ooid packstone-wackestones, and evaporites. These lithofacies are not homogeneous and each band has thin beds of lithologies from adjacent lithofacies. The Bluell bed thickens from 7.5 m in the evaporite and argillaceous lithologies in the northeastern portion of the study area to 16.5 m in the coated grain lithologies in the southwestern portion (Fig. 53).

The Bluell Bed in the southwestern half of the study area contains coated grains, predominantly ooids, in varying percentages. A poorly defined, three-kilometre-wide band of grainstone bisects the more micrite-rich ooid,
Figure 52: Lithofacies map of the Bluell bed. Triangles indicate core data control. B-B' is the cross-section location in Figure 53.
Figure 53: Cross-section of the Upper Frobisher-Alida Interval along regional dip (see Figure 52 for location of B-B'). The ooid grainstone shoals in the southwest portion of the study area probably caused the restriction leading to evaporite precipitation in the northeast.

Solid lines delineate where the marker beds can be differentiated in core and on well logs. Dashed lines delineate where the marker beds can be differentiated on the logs only; i.e., the lithology of the marker beds are similar to underlying and overlying strata in core.
pisoid and intraclast wackestone-packstone lithologies.

To the northeast of the coated grain lithofacies is an evaporite lithofacies consisting of anhydrite and dolomudstone. Minor accessory lithologies include mudstone, intraclast wackestone, shale, and one basal ooid grainstone.

The anhydrite is thinly bedded to massive. The most common textures found are mosaic and poikilitic (anhydrite after large bladed selenite crystals). The anhydrite is often argillaceous. It becomes more homogeneous to the northeast and the associated lithologies become rarer.

Dolomudstone is interbedded with, and sometimes incorporated into the matrix of, the anhydrite. The dolomudstone is usually argillaceous and often silty. Stromatolite textures are common. Other lithologies (intraclast wackestones, shales and ooid grainstones) are uncommon and non-continuous, and are found only in one Bluell bed core.

**Depositional Model**

The Sherwood and Bluell beds in the study area have many similarities. Three of these are of considerable interest: 1) the common allochem types; 2) the same semi-parallel lithofacies bands that are arranged in a series. This series, in order away from the basin center, is formed by ooid grainstone-wackestone-mudstone (dolomudstone)-anhydrite lithotypes; and 3) each bed is capped with a silty argillaceous dolomudstone marker.
Elevated salinities during deposition of the Sherwood and Bluell beds were localized in the Williston Basin. Normal-marine faunal remains such as crinoid, brachiopod, coral, and trilobite fossils are found within the Bluell in the Flaxton Field area, 70 km northwest of the study area (Dirk Schwartz, 1985, personal communication).

An island-complex depositional environment, trending northwest to southeast, is represented within the Sherwood and Bluell beds of the Stanley Field area located 40 km to the southwest of the study area (Beach and Schumacher, 1982). Open marine rocks occur west of the island complex, and shallow-water lagoon rocks are found to the east of the island complex. The northern and southern limits in the Stanley Field area, upper Frobisher-Alida, island complex are unknown, but if the islands were extensive enough, they could have formed a barrier between the more normal marine-water environments of the central Williston Basin and the restricted highly saline environments found throughout the study area.

Since the characteristics of the Sherwood and Bluell beds are similar, both beds will be included in the same depositional models. Two models are proposed: 1) the deposition of the main limestone body; and 2) the deposition of overlying marker bed. It is understood that the lithofacies of the Bluell bed are slightly basinward with respect to similar lithofacies of the underlying Sherwood.

The diagrams reflect data collected from the Sherwood
bed and the S.A.M., as better core control was obtained from these sections than in the Bluell bed and the State marker.

**Main Carbonate Body**

Three main depositional areas (Fig. 54) are interpreted in the main carbonate body of the Sherwood and Bluell beds. These are 1) an ooid shoal area, 2) a ponded mud flat area and 3) an evaporitic lagoon area.

In the ooid shoal area, gentle water agitation produced ooids and deposited primarily ooid grainstones. The shoal was periodically subaerially exposed long enough to develop desiccation cracks.

In the ponded mud flat area, the main deposit was wackestones and packstones. This area contained quiet, supersaline ponds which were periodically scoured by storms. Much of the area was subaerially exposed, and in some places, developed caliche profiles.

In the evaporitic lagoon area, the mudstone and stromatolitic-boundstone lithotype was deposited in the less hypersaline portions (in the west) and the evaporites were deposited in the more hypersaline portions (to the east). The evaporitic lagoon was isolated from the basin waters by ooid shoal and the built up, ponded mud-flats. Due to evaporation, the water elevation of the lagoon was equal to, or slightly less than, the elevation of the larger adjacent Williston Basin water body.

Deposition of the main carbonate body within the bed
Figure 54: Diagrammatic model of the study area during deposition of the Sherwood bed. Evaporitic lagoon surface elevation is equal to or slightly less than the Williston Basin's water level due to evaporation of the more restricted smaller water body. Adapted in part from Shanley (1983) and Obelenus (1985).
extended over a considerable time; the rate of deposition
was probably controlled by the rate of basin subsidence.

**Marker Beds**

Deposition of the marker beds occurred primarily in
an eolian sabkha environment. The ooid shoal in the western
portion of the study area separated the sabkha from basin
waters. Remnants of the hypersaline lagoon existed to the
east (Fig. 55).

The elevation of the inland sea was lowered relative
to the hypersaline lagoon water elevation. It is unknown if
this was a regional or eustatic event. Deposition of
sabkha sequence occurred during the regression.

As sea level dropped, drainage of the high-Mg\(^{++}\)
lagoon waters moved through the subaerially exposed carbo­
nate sediment that was deposited during the previous cycle
(peri-littoral sediments). The high-Mg\(^{++}\) groundwater caused
dolomitization of the upper sediment layer. The groundwater
probably only affected the upper sediment because it
perched on an impermeable calcrete or cemented horizon

As the evaporitic lagoon drained, the non-cemented
lagoon sediment (micrite, siliciclastic silt and clay, and
selenitic gypsum) was exposed. This uncedmented sediment
(not in the groundwater capillary zone), along with fine
sediment eroded from the transcontinental arch to the
east, was transported into the area by the easterly winds.

Wind direction was an important factor during deposi­
tion of the marker beds, as it is today in the Persian
Figure 55: Diagrammatic model of the study area during deposition of the Sherwood Argillaceous Marker. Adapted in part from Shanley, (1983), and Luther (1986, personal communication).
Gulf. Fryberger and others (1983, p.284 state "... overall conditions of sedimentation along the Arabian Gulf, the nature of the shoreline, whether siliciclastic or carbonate dominant, is dependent on wind direction."

The eolian sediment accreted in mostly structure-less, homogeneous, fine-grained, clastic-carbonate, quartz silt, siliciclastic clay and clastic-evaporite deposits. This eolian detrital and evaporitic dominant sabkha deposit is the silty, argillaceous dolomudstone lithofacies found in core.

Gypsum or anhydrite sand dunes could have been abundant on the exposed evaporite flats. Remaining deposits are rare, however, due to reworking and dissolution as the sea transgressed over the western flank of the sabkha to begin deposition of a new bed.
DIAGENESIS

Much of the original fabric and mineral composition of the primary sediment in the study area is masked by cementation, dissolution, micritization, compaction, mineral replacement and neomorphism. A descriptive section will list the characteristic features of diagenesis found with associated lithofacies. A second section will interpret the diagenetic processes and the paragenesis within the study area.

Cement

Four minerals form cement in the study area. In decreasing order of abundance these are: 1) calcite, 2) anhydrite, 3) dolomite and 4) celestite.

Calcite

Calcite cement (spar) was found in all lithofacies in the study area. It is rare in the evaporite and dolomudstone lithofacies. Qualitative chemistry by microprobe analysis indicates low-Mg calcite to be the mineral phase in all crystal forms. Types of spar crystal fabrics found include fibrous (>6/1:Length/Width), bladed (6/1 to 2/1:L/W), blocky (equant, 2/1 to 1/1:L/W), and micritic. Radialaxial (Bathurst, 1975) and syntaxial crystal morphologies were not found in the study area. Among crystal fabric morphologies present are random, isopachous, meniscus and pendant.

Fibrous Cement: Fibrous cement is common in the study area. It has an isopachous morphology and primarily lines
fenestral pores in the wackestone-packstone lithofacies, interparticle pores in grainstones, desiccation cracks within allochems, and intraparticle pores in most fossils. Fibrous crystals, where not partially dissolved, average between 48-158 um long and between 5-10 um wide. Individual crystals may be smaller when cementing fine-grained allochems (i.e., peloids). This cement fabric rarely occludes entire pore except for interparticle pores in fine-grained grainstones

Bladed Cement: Bladed calcite cement is uncommon. Where present, crystals with a bladed habit line walls of primary pores or of secondary vugs. Blades usually have euhedral pyramid points. Individual bladed calcite crystals are often intergrown at their outer margins with blocky calcite crystals. Individual crystal sizes are from 0.1 to mm wide and 0.2 to 0.6 mm long. Width to length ratios are between 1:2 and 1:3.

Bladed crystal fabrics are primarily associated with the carbonate mud-rich lithologies where there was originally high fenestral porosity and high matrix selective vugular porosity. Bladed crystal habits are sometimes associated with grainstones having interparticle pores remaining after fibrous isopachous cementation. The bladed fabric rarely occludes the center of a pore.

Equent Cement: Equant calcite cement is the most abundant spar form. Crystals with a blocky habit occur in all lithofacies and often occlude pores. The blocky fabric
morphology usually forms a random pattern. Equant cement grew over radially fibrous cement and geopetal cement, and is intermixed with bladed crystals, lining pore walls, or sharing pore space with saddle dolomite or anhydrite cement. Crystal size varies widely from fine (<15 um) blocky crystals lining fenestrae to large (>1 mm) crystals occluding an entire vug. Crystal form also varies widely, from anhedral interlocking crystals to euhedral pyramid crystals. Most crystals retain the enfacial junction required of cement rather than the random triple junctions described for neomorphic spar (Bathurst, 1975), (Fig.56).

The micritic cement in evidence (blocky cement with crystal diameters <10 um) is difficult to differentiate from the primary micritic matrix or secondary micritized sediment that is present. The micritic cement morphologies present are meniscus (pore rounding) (Fig.57), and pendant (gravitational (Fig.58) forms. Both of these cements are uncommon to rare.

**Anhydrite**

Anhydrite cement is common in the study area. It often occludes pores in association with large blocky calcite crystals and/or large saddle dolomite crystals. Replacement of a portion of the pore wall by anhydrite is common when anhydrite fills the pore. Usually the anhydrite crystals are clear. Uncommonly brown-colored crystallotopic anhydrite occurs. This brown-colored replacement anhydrite is usually associated with matrix-rich rocks and dolostones.
Figure 56: Equant (blocky) calcite spar (A), and saddle dolomite (B) occluding sheet crack in an ooid grainstone. Ooids are micritized. Fibrous and bladed calcite crystals are eogenetic cement. Equant calcite crystals and dolomite are mesogenetic cements. The pore was possibly cemented and later reopened before equant cementation.

Equant cement shows enfacial junctions of Bathurst's cement criteria. NDGS.#4238, 5937.2' P.P.
Figure 57: Meniscus (pore rounding) micritic cement and some draping micritic sediment in an ooid grainstone. NDGS.#4238, 5901.6' P.P.

Figure 58: Pendant (gravity) (A) and Meniscus (B) micrite cements in a grainstone. NDGS.#4965, 5396.5' X.N.
The anhydrite crystal size (from less than 10 \( \mu \)m to over 5 mm in diameter) varies widely depending on pore size and crystal habit. Blocky crystal fabric is the most common anhydrite cement habit, while felted crystal fabric is rare in cement.

**Dolomite**

Dolomite cement occurs in minor amounts in the study. Approximately 15 percent of the thin sections examined had at least traces of dolomite cement. The dolomite cement has the saddle dolomite crystal habit (Radke & Mathis, 1980), (Fig.59). The average crystal size is between 0.15 and 1 mm, depending on pore size. Crystals are euhedral to subhedral.

Dolomite is never the major cement in any lithology. It occurs primarily in wackestones, packstones or grainstones containing vugs. Rarely does dolomite occlude the entire pore unless it is associated with blocky calcite. Dolomite cement and replacement crystals are associated with stylolites.

**Celestite**

Celestite is a rare cement, and occurs in argillaceous dolomudstones and anhydrite sandstones (Fig.60). Celestite cement very rarely occludes vugs. Average crystal size is between 0.1 and 0.5 mm. Crystals are subhedral to euhedral.

**Internal Sediment**

Internal sediment is common in desiccation cracks. It
Figure 59: Saddle dolomite cement. NDGS.#4238, 5915.0' X.N.

Figure 60: Celestite cement (A) occluding a vug. Anhydrite cement (B) occludes an adjacent vug. NDGS.#5063 5937.5' X.N.
occasionally drapes allochems in grain-supported lithologies as well as in matrix selective vugs (Fig. 61). Internal sediment is rare in fenestrae. The internal sediment is often reverse-graded and is medium- to well-sorted. Sizes range from <4 μm for micrite to >0.5 mm for ooids. Geopetal sediment may underlie or overlie primary cement.

**Caliche Crusts**

Caliche is a pedogenic horizon (the "K" horizon in soil classification). Multiple caliche zones reflect arid conditions instead of the karst zones that are indicative of humid regions. Caliche is formed as a weathering product in arid to semi-arid climates, with precipitation usually less than 45 cm/yr (Reeves, 1976). It is formed by leaching overlying and sometimes underlying soil horizons. Leaching is due to high $\text{CO}_2$ levels in meteoric water and high soil $\text{CO}_2$ caused by organic activities. Precipitation of micritic $\text{CaCO}_3$ in the caliche profile is due to $\text{CO}_2$ degassing from evaporation and a decrease in pore water pressure (Reeves, 1976).

Caliche profiles (calcretes) are primarily found in the wackestone-packstone lithofacies. Each horizon is thin (usually only a few centimetres), and often separates different lithologies. The caliche profiles in the study area are associated with two notable matrices: 1) under-lying and overlying beds which commonly display leaching, (mostly matrix selective vugular), and 2) vadose characteristics that are commonly to occasionally represented and
Figure 61: Geopetal sediment in a vug. NDGS.#5115, 5405.5'
P.P.

Figure 62: A series of caliche profiles overlying wackestone and packstone lithologies.
NDGS.#6386, 6009.0'
which include in situ brecciation, pendant and meniscus cements, geopetal textures, and tepee structures. Caliche profiles in the study area are numerous and often repetitious in the vertical succession (Fig. 62).

Dissolution

Evidence for dissolution of carbonate, evaporite, and, in rare cases, quartz exists throughout the study area. Dissolution has radically altered the texture and mineralogies of the lithofacies. Three dissolution types are present: 1) matrix selective vugular, represented by enlarged fenestrae, cement dissolution (Fig. 63), and micrite dissolution (Fig. 64); 2) non-matrix selective vugular enlarged fenestrae; and 3) moldic forms.

Dissolution features vary widely in intensity from the etching of cement crystal surfaces to wholesale brecciation (Fig. 65). Dissolution types and intensity vary widely within a short distance, often within laterally adjacent pores or between opposite sides of a stylolite.

Replacement

Mineral replacement has altered the lithology to some degree throughout the study area. Several types of replacement have occurred, including anhydrite, dolomite, calcite and silica.

Anhydrite

Anhydrite commonly replaces carbonate minerals in allochems, in matrix and in cement. The extent of anhydrite replacement varies widely. The most common sites of
Figure 63: Anhydrite cement dissolution in a vug. Spheres are bubbles in epoxy. NDGS.#4965, 5362.0' P.P.

Figure 64: Matrix-selective vugular dissolution causing overpacked allochems. NDGS.#5159, 5864.5' P.P.
Figure 65: In situ brecciation and micritization of carbonate. NDGS.#5244, 5412'
replacement are the walls of anhydrite-filled vugs or in a carbonate bed underlying an evaporite bed. Between the contact of the primary limestone and replacive anhydrite there is a replacement front which often has a microdolomite fringe. The secondary anhydrite is often optically continuous adjacent to this microdolomite fringe (Fig.66). Sometimes primary textures are preserved, such as ooid ghosts floating in anhydrite (Fig.67). The anhydrite can also be associated with fractures, (Fig.68), but, more commonly, the replacive anhydrite has grown from isolated sulfate cements in vugs. A late stage crystallotopic anhydrite is stained brown due to oil or bitumen inclusions and is identical to "metasomatic-type" anhydrite described by Kendall and Walters (1978).

The degree of replacement may vary from isolated scattered brown crystallotopic anhydrite crystals, to quite complete, as when an entire carbonate lithology has been converted to anhydrite. Interpretations of primary lithologies made from borehole logs are often incorrect because of secondary anhydrite replacement.

**Dolomite**

Dolomite has replaced calcite allochems and calcite matrix to varying degrees throughout the study area. Replacement consists of minor amounts of dolomite by volume and can be very localized. Alternate laminations have been converted to dolomite in some coated grains (Fig.69), and in some stromatolites. Replacive dolomite is associated
Figure 66: Optically continuous anhydrite (A) replacing carbonates (B). There is a replacement front with a microdolomite fringe (C). NDGS.5037, 5414.0' X.N.

Figure 67: Anhydrite (A) replacing ooids and matrix. NDGS.5063, 5927.0' X.N.

Figure 68: Anhydrite filling fracture (A), and replacing fracture walls (B). NDGS.5130, 5380.3' X.N.
with Type I stylolites to a small degree. Dolomite replacement was occasionally more pervasive, as a response to pressure solution in a carbonate mud-rich, siliciclastic clay-poor rock similar to processes described by Wanless (1979).

Dolomite has also replaced quartz silt in some silty, argillaceous-dolomudstone markers (Fig.70). The quartz grains are completely replaced in some instances.

Silica

Cryptocrystalline quartz which has replaced carbonate occurs in several zones only a few centimetres thick. The quartz can replace either allochems (Fig.71), or matrix, or both (Fig.72). These thin silica zones can be correlated between cores taken several kilometres apart.

Calcite

Within the study area, evidence for the replacement of calcite crystal forms by other crystal morphologies is rare, except where micritization has occurred. Micritization of allochems is common in many zones, leaving a peloid-micrite texture. Micritization is most common in the wackestone-packstone lithologies.

Some calcite crystals may have been recrystallized since initial deposition; however, most spar shows Bathurst's (1975) fabric criteria for cement. Indicators that the spar is cement are: 1) no relict structures are found in the spar; 2) The micrite matrix has sharp contacts with the large spar crystals; and 3) there are no floating
Figure 69: Dolomite (A) replacing alternate laminations in a coated grain. NDGS.#5211, 5802.5' P.P.

Figure 70: Quartz silt grain (A) in dolomudstone matrix. Quartz is partially replaced by dolomite, giving the grain edges a pitted texture. NDGS.#5211, 5768.0' P.P
Figure 71: Cryptocrystalline quartz replacing calcispheres in a stromatolite boundstone. NDGS.#5115, 5374.7' P.P.

Figure 72: Cryptocrystalline quartz (A) replacing matrix and allochems. Calcite cement (B), occluding fenestra is unaltered. NDGS.#6344, 5146.3' P.P.
micrite patches. Minor amounts of neomorphic microspar and pseudospar, however, are found in recrystallized fossils.

Compaction

Compaction features are common throughout the rock studied. Some of these features are; in situ broken and overpacked allochems, Type I large amplitude stylolites in allochem-rich or cemented sediment, Type II seam or swarm stylolites in matrix supported sediment with some insoluble matrix material (Fig.73), and Type III pervasive dolomitization in cleaner mudstones or wackestones (Fig.74). The Type I,II, and III features are described by Wanless (1979).

In some rocks of the study area, compaction of sediment prior to competent cementation led to in situ broken allochems (crushed fossils (Fig.75) and collapsed fenestrae (Fig.76). Soft sediment compaction is most common in mudstone and wackestone lithologies.

Some stylolites represent large volumes of dissolved carbonate. Evidence for this is the offset distances between allochem pieces and the large accumulations of insoluble residues remaining in stylolites that have cut relatively clean host rock. The insoluble residues incorporate clay, organic matter, pyrite, dolomite (including large saddle type cement crystals), and blocky calcite cement (Fig.77). Stylolites often separate lithologies, cementation types, pore types and porosity percentages.
Figure 73: Microstylolite seam (A), and microstylolite swarm (B), type II non-sutured stylolites in a mudstone overlying a packstone. Later type I sutured stylolites cross-cut the type II stylolites. NDGS.5244, 5410.0' P.P.

Figure 74: Pervasive dolomitization of micrite matrix in a wackestone. NDGS.5115, 5370.0' P.P.
Figure 75: Crushed allochems in a micrite rich wackestone due to soft sediment compaction. NDGS.#6344, 5138.3' P.P.

Figure 76: Collapsed fenestrae due to soft sediment compaction. NDGS.#5159, 5826.0'
Figure 77: Saddle dolomite (A) and equant spar (B) cement concentrated in a stylolite seam. This shows late stage stylolitization subsequent to mesogenetic saddle dolomite. NDGS.5037, 5450.5' P.P.
PARAGENESIS

The order of diagenetic events, or paragenesis, is difficult to determine in many cases because certain diagenetic features are lithotype-specific. Since there are no cross-cutting relations in these cases, diagenetic features are correlated with diagenetic features found in other studies. The diagenetic features will be classified as eogenetic or mesogenetic (Choquette and Pray, 1978). In the eogenetic zone diagenetic events occurred due to surface processes undergone prior to deep burial. In the mesogenetic zone, diagenetic events occurred due to burial processes and are not affected by processes from the surface.

Eogenetic Zone

Cementation, dissolution, micritization and compaction were the diagenetic processes active after final deposition in the eogenetic zone

Cementation: Primary fibrous calcite cement occurs in grain-supported rocks (all coated allochem grainstones and most packstones). Isopachous fibrous crystals line interparticle pores. Fibrous cement is also common in fenestrae associated with allochem-rich rocks.

Fibrous crystal habit is attributed to high carbonate saturation (Given and Wilkinson, 1985). Precipitation of carbonate can be due to CO₂ degassing, water movement, or temperature rise (Hanor, 1978). All lithofacies deposited in environments where there was free marine water movement (shoals or storm washed sediment) display signs of fibrous
cementation. Fibrous crystal habit is not common in mudstones or argillaceous dolomudstones due to initial lower permeabilities.

Other eogenetic cements are gypsum, anhydrite and celestite. Early evaporite cementation is most obvious in mudstones and dolomudstones, where cement crystallization has caused some soft sediment deformation. The extent of early evaporite cementation in the study area is unclear to later dissolution.

**Micritization:** Some micritization and micrite cementation (pendant, meniscus) occurred in the eogenetic regime. The allochems that have gone through these processes are adjacent and intermixed with non-altered allochems. Some coated grains went through several diagenetic processes before final deposition.

Occasionally, micritic meniscus cements and, rarely, micritic pendant cements are found in grain-supported rocks within the study area. Meniscus and pendant cements are formed in the meteoric vadose zones in modern environments (Dunham, 1971). In the study area, these cements are in horizons of limited thickness (less than one metre), indicating there was little sediment thickness above the water table. The rarity of these cements may be due to the relative dryness of the subaerial environment, and limitation on vadose meteoric processes.

Conversions of primary allochems, cement and matrix by micritization was sufficiently intense, within some zones
of the study area, to erase primary textures. Micritization is commonly associated with caliche zones, only occasionally associated with in situ breccias, and rarely associated with pendant cements.

Micritization can occur both subaerially and subaqueously (James, 1972; Bathurst, 1975). Subaqueous micritization is attributed to boring by algae and the growth of fungi that has left micritic rims on allochems (Bathurst, 1975).

In the study area, micritization has altered allochems to micrite and peloids. The conversion started on one side of the allochem and proceeded towards the other side. The association of caliche zones, breccias, pendant cements and perched inclusions, combined with the absence of subaqueously bored micritic rims on allochems, indicates subaerial micritization in the study area. Blocky, vug-filling calcite spar postdates micritization in these rocks.

Only minor amounts of soil moisture are needed to subaerially convert allochems and calcite cement into micrite (James, 1972). Calcite cement can convert to microspar to degrading neomorphism (Folk, 1965). The primary micritization process involves dissolution of cement and allochems and reprecipitation of micrite as expressed by the cycle of dissolution-precipitation-sparmicritization or D.P.S. (Kahle, 1977). D.P.S. is due to acids from decaying organic matter. Some allochems are converted by subaerial boring endolithic fungi and algae (Kahle, 1977).
Figure 78: Micritization of packstone in the study area. Micritization is probably due to subaerial weathering. NDGS.#5211, 5792.0' X.N

Figure 79: Micritization of packstone in the vadose zone. Collected from Quaternary rocks on Hamm's Bluff St. Croix Island, by R.Burke (NDGS) and T.Obelenus (1979). P.P.
Micritized floating allochem ghosts and micrite-peloid matrix textures within the study area (Fig. 78) appear similar to the subaerial textures in Holocene and Pleistocene carbonates (Fig. 79) (as described by James (1972) and by Harrison and Steinen (1978)).

Compaction: Eogenetic compaction affects mudstones and wackestones to a minor degree within the study area. Evidence of this includes collapsed fenestrae, and horizontally oriented ostracodes with some compaction breakage of the carapaces.

Dissolution: The amount of eogenetic zone dissolution that occurred is often difficult to determine. Primary evaporite cement (gypsum, anhydrite and celestite) can be completely dissolved (resurrected porosity) (Feazel and Schatzinger, 1985) and this secondary dissolution porosity can not be distinguished from the primary porosity. Early dissolution processes did remove some carbonate matrix, causing realignment of carbonate allochems.

Reasons for eogenetic carbonate dissolution can only be surmised. One cause for dissolution and brecciation may have been the presence of small amounts of meteoric water over an extended period of subaerial exposure. Similar brecciation is found in Barbados and described by Harrison and Steinen (1978). Another cause of dissolution could have been infiltration by Ca++ depleted groundwater which percolated from gypsum-precipitating lagoons.
Mesogenetic Zone

Mesogenetic diagenetic processes include cementation, (by equant spar, blocky anhydrite, and saddle dolomite), further dissolution, pressure solution, recrystallization, fracturing, and oil migration.

Cement

Equant Calcite: Some pores have equant cements growing on fibrous crystals. The contact between equant and fibrous cement forms is gradational in some pores, while adjacent pores can show dissolved fibrous cement overlain by pore-occluding equant cement. Whether cementation continuous or discontinuous, some precipitation factor changed the cement from a fibrous to an equant crystal habit.

Equant calcite crystals form when carbonate saturation and/or rates of fluid flow are low (Given and Wilkinson, 1985). Early cementation caused pore throats to tighten and fluid flow to diminish. Carbonate saturation of pore fluid was lowered after a volume of calcite had been precipitated as cement.

There are at least two stages of equant calcite cementation visible in the rocks studied: 1) an early, small crystal; and 2) a later, large crystal. The early, small-sized, crystals cover fibrous crystals or geopetal textures. This cement rarely occludes the pore and is often partially dissolved and/or is replaced with anhydrite. The later, large-sized crystals often occlude the entire
Figure 80: Large, equant-calcite cement crystals occluding a vug. NDGS.#4238, 5921.0' P.P.

Figure 81: Large equant calcite crystal (A) predating anhydrite cement (B) in a vug. NDGS.#5037, 5426.0' P.P.
(usually a vug) with a few crystals (Fig.80). The larger equant spar is often associated with simultaneous saddle dolomite and anhydrite cement (Fig.81). The large crystal form rarely shows dissolution features.

**Dolomite:** Saddle dolomite, found in vugs, is another mesogenetic cement. The saddle morphology is a good mesogenetic thermometer, as it crystallizes between 60 and 150 degrees C (Radke and Mathis, 1988). Sulfate reduction is often associated with the formation of saddle dolomite cement (Radke and Mathis, 1980). Anhydrite dissolution features are common adjacent to saddle dolomite in the study.

**Silica Replacement**

timing of cryptocrystalline quartz replacement within the study area is uncertain. The carbonates in silica zones are usually pervasively replaced with cryptocrystalline quartz, often in association with some microdolomite and anhydrite. The only paragenetic relations are: 1) silica replacement postdated early microdolomite replacement of stromatolites and some matrix; and 2) silica replacement was prior to late stage anhydrite replacement. Evidence for earlier silica emplacement is the presence of silicified allochems in an anhydrite replaced matrix.

Source of the silica could have been the dissolved quartz silt of the argillaceous markers. Often the quartz silt grains in portions of the silty, argillaceous, dolomudstone markers are partially dissolved, giving the grain edges a pitted texture. There is usually an
argillaceous marker within a metre of the thin silicified zone. The cause of silica dissolution/precipitation may have been the presence of high-pH waters (Reeves, 1976).

**Pressure Solution**

Pressure solution features were formed by many events over an extended period of time in the study area. Type II stylolite seams and swarms were later cross-cut by large Type I stylolites. As early Type II pressure solution caused adjacent cementation, the beds became competent enough to support later, high amplitude Type I stylolitization. Large Type I stylolites post-date the precipitation of large equant calcite spar and saddle dolomite, as shown by the fact that both these cements are concentrated in some large high-amplitude stylolites.

Stylolites may also act as permeability barriers. This is shown by the presence of large-scale vugular dissolution on one side of a stylolite and minor vugular dissolution on the other side of the stylolite.

**Late Stage Fractures**

Late stage fractures cross-cut all lithologies to some extent, but displacement is negligible. Fracturing postdates most diagenetic features, including large, Type I stylolites. Most fractures are filled with late-stage, blocky anhydrite, which often replaces part of the fracture wall. Rare calcite-filled fractures are located in the lower portions of beds and/or in core taken from wells down-dip (basinward) from the Donnybrook Field.
Fractured zones are not laterally correlatable between wells and are not lithotype-specific. Fracturing may have been a regional response to differential compaction-dissolution, or may have been a regional response to basin flexure.

**Late Stage Anhydrite Cementation**

Late stage clear anhydrite cementation is the leading cause of porosity occlusion in most wells. Matrix-selective vugular pores, non-matrix-selective vugular pores and enlarged fenestral pores, along with fractures, are often closed entirely with optically continuous anhydrite cement. Often, portions of the carbonate adjacent to the cemented pore/fracture are replaced with anhydrite. Late stage anhydrite cementation/replacement cross-cuts and postdates all other diagenetic features including silica-replaced horizons.

Clear anhydrite cementation and replacement usually occurred proximally to, and had an affinity with, primary evaporite deposits. Anhydrite-plugged pores are usually located in the updip sections of the Bluell or Sherwood Beds immediately below massive anhydrite. The lower pores are more likely to be open unless they are occluded with equant calcite. This implies down dip or basinward flow of anhydrite-precipitating pore fluids. Downward movement was probably due to the high density of the sulfate saturated brines. This downward fluid movement happened before the Larimide Orogeny (Late Cretaceous), as ground water has been flowing updip in the eastern flank of the Williston
Basin since the Larimide Orogeny (Downey, 1984).

Oil Migration

Hydrocarbon migration has an influence on diagenesis for two reasons: 1) Hydrothermal waters associated with oil and gas are often corrosive brines and cause secondary porosity by dissolving cements (Feazel and Schatzinger, 1985), (sulfates are particularly susceptible to this leaching). 2) Once displacement of pore water by oil or gas migration has taken place, precipitation of cement is significantly retarded, as most minerals are inactive in hydrocarbon fluids (Feazel and Schatzinger, 1985).

Hydrocarbon migration into the northeast portion of the Williston Basin has probably occurred since Late Cretaceous time. The Laramide Orogeny caused uplift on the western and southwestern flanks of the basin and groundwater movement to the northeast (Downey, 1984). Deep groundwater flow transported hydrocarbons from the central portion of basin into the study area. The hydrocarbon source rock have been the Bakken Shale of Late Devonian-Early Mississippian age (Webster, 1982; Dow, 1974).

Brown crystallotopic anhydrite containing oil or bitumen staining (Fig. 82) was precipitated simultaneously with, or subsequent to oil migration. Kendall and Walters (1978) date the late anhydrite replacement and cementation in the Mississippian carbonates of southeast Saskatchewan as Late Cretaceous.

Figure 83 shows a relative time scale of the various diagenetic features discussed.
Figure 82: Late stage brown crystallotopic anhydrite crystals replacing carbonate. NDGS.5308, 5360.0'
Figure 83: Chart showing relative time scale of the various diagenetic features discussed.
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**CEMENT**
- Calcite
  - Fibrous
  - Micritic (meniscus, pendant)
  - Bladed
  - Equant
- Evaporite
  - Gypsum
  - Anhydrite
  - Celestite
- Dolomite
  - Saddle dolomite

**Dissolution**
- Micritization
- Cement, matrix selective
- Non-matrix selective

**Compaction**
- Soft sediment
- Type II stylolitization
- Type I stylolitization
- Pervasive dolomitization

**Replacement**
- Dolomite
- Anhydrite
- Silica

**FRACTURING**
- Brecciation
- Desiccation
- Late fracturing

**OIL MIGRATION**
CONCLUSIONS

Though limited in area and vertical extent, the study area shows many characteristics similar to those found in regional and field studies done on the Frobisher Alida Interval. However, some characteristics in the study area are unique and differ from previous reports. Upon collective consideration of these characteristics, the following conclusions can be made of the Sherwood and Bluell beds in the study area:

1. The paleotopography was extremely low-relief, water depths were quite shallow. A small drop in basin sea-level elevation would have caused a large area to be subaerially exposed.

2. The depositional environment was arid. Mostly super-saline water conditions existed. The near lack of fresh or normal marine water caused: a) a precipitation of primary evaporites; b) only a high salt-tolerant biota to exist. Desiccation features developed on briefly subaerially exposed sediment and weathering features developed on sediment exposed for a prolonged period.

3. Six lithotypes are represented in the section studied. From most to least abundant these lithotypes are a) pisoid-oid, intraclast wackestone to packstone, b) mudstone, stromatolite-boundstone, c) silty, argillaceous dolomudstone, d) bedded anhydrite, e) ooid grainstone f) sandy carbonates

4. The six lithotypes can often be correlated between
study area cores. Correlatable lithologies form lithofacies that trend northwest-southeast, parallel to regional strike in any one marker-defined bed. The lithofacies represents specific depositional environments varying with salinity, water depth, water energy and wind erosion.

5) Water agitation in most of the study area was nearly non-existent except during periodic storms. An ooid shoal in the southwestern portion of the study area was probably the cause of the lack of agitation in the rest of area studied. The shoal separated the open sea from a restricted, super-saline lagoon located to the east.

6) The argillaceous marker beds (predominantly silty argillaceous dolomudstones) within the study area are relative chronostratigraphic beds that cross-cut slowly basinward prograding lithofacies. The marker beds were deposited as a rapidly prograding eolian-sabkha, possibly during an eustatic sea level drop of a few metres. A planar horizontal surface was maintained by a capillary groundwater fringe. Dolomitization was probably due to hypersaline high-groundwater draining from the evaporitic lagoon.

7) Eogenetic diagenesis in some horizons caused dissolution of mostly matrix sediment. Dissolution opened matrix-selective, vugular pores. Dissolution may have been due to small amounts of meteoric water or Ca$^{++}$ depleted ground water. Matrix-selective, vugular porosity (mostly in the wackestone-packstone lithotype) is the predominant pore found. These early pores may have been preserved with subsequent evaporite cementation followed by
later evaporite dissolution.

8) Late mesogenetic anhydrite cementation and replacement of carbonates was the major diagenetic factor in pore occlusion in much of the study area. Most of the anhydrite cement is located along the sides of subtle structural noses.

9) Other late diagenetic events that affected reservoir properties include: a) varying degrees of calcite dissolution causing pore reopening, non-matrix selective vuggy porosity, and pore enlargement; b) minor amounts of silicification; c) some equant spar and saddle dolomite cementation; d) high amplitude stylolitization; and e) oil migration.

10) The Lake Darling, MacKobee Coulee, Donnybrook and White Ash Fields are a combination of structural and stratigraphical traps. Porosity/permeability pinchouts, of porous carbonates into nonporous evaporites and argillaceous dolomudstones with low permeability, created stratigraphic traps up-dip. The reservoirs are closed by subtle anticline limbs running parallel to regional dip. Structure does not seem to have been much affected by differential compaction of lithotypes.
APPENDIX A

Well Locations and Formation Tops

NDGS# is North Dakota Geological Survey number
KB is Kelly Bushing Elevation above Sea Level
MAD. is Mississippian-Triassic Unconformity Elevation
Mme is Mission Canyon Formation Elevation
  (Base of Midale Beds)
StA is State "A" Marker Bed Elevation
SAM is Sherwood Argillaceous Marker Elevation
K-1 is K-1 Marker Elevation

All elevation values are subsea numbers
@ - Depth not covered in logged interval
* - Does not develop on logs

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### APPENDIX B

**Cored Intervals Studied**

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<tr>
<th>NDGS#</th>
<th>Operator; Well Name: Interval Cored; Upper and Lower Beds Cored</th>
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<tr>
<td>#4238</td>
<td>Anschultz Corp.; Sandberg #1: 5874-5957'; Rival-Sherwood</td>
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<td>#4943</td>
<td>Depco; Anderson #1: 5297-5357'; Bluell-Kl Marker</td>
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<td>#4965</td>
<td>Depco; Elberg #1: 5341-5401'; Sherwood Argillaceous Marker-Mohall</td>
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<td>Depco; L. Hedberg #1: 5400-5451'; Bluell-Sherwood</td>
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<td>Great Western; Erickson #1: 5918-5964'; Bluell-Sherwood</td>
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<td>Depco; Bryans #1: 5364-5411'; Sherwood Argillaceous Marker-Sherwood</td>
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<td>Depco; Satterlund #1: 5380-5424'; Bluell-Kl Marker</td>
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<td>Kissinger; Lee #12-23: 5466-5520'; Bluell-Sherwood</td>
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<td>#6553</td>
<td>Polumbus; Finke #31-9</td>
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APPENDIX C

Core and Thin Section Descriptions

The following core and thin section descriptions are from cores housed in the Wilson Laird Core Library, Grand Forks, North Dakota. Carbonate lithologic nomenclature is from Dunham, 1961. Core depths, (in feet), are corrected to electric log depths where possible.

NDGS # 4238

In Rival Beds

5874.0-5876.8 Dolomudstone- Light gray, clean, stylolitic.

5875.0 Dolomudstone- 90% microdolomite, 5% micrite, 5% siliciclastic clay, trace pyrite.

5876.8-5878.0 Mudstone- Tan, small scattered anhydrite inclusions.

5877.3 Mudstone- 98% micrite, 1% anhedral calcite vug fill, <1% anhedral anhydrite crystals 0.2-1mm.

5878.0-5882.0 Dolomudstone- Tan-light gray-brown, mottled, clean, rare large anhydrite crystals, oil saturated in part.

TS3 5879.2 Dolomudstone- 60% dolomite <10u, 25% micrite, 5% anhedral anhydrite crystals 0.2-0.5mm, 5% intercrystalline porosity.

State A Marker

5882.0-5885.0 Mudstone- Tan, dense.

5885.0-5887.0 Dolomudstone- Light gray-tan-brown, mottled in part, soft.

5887.0-5891.2 Solution Breccia- Medium gray-tan, oolitic, pisolithic, partially dolomitized, anhydrite cemented fractures and primary interparticle and secondary moldic porosity.

TS4 5888.0 Solution Breccia- 30% intraclasts 0.2-2mm, 30% peloids, 15% micrite coated clasts,
10% micrite, 9% blocky calcite cement, <1% interparticle porosity, trace pyrite. Dissolution of micrite matrix caused collapse and repacking of allochems.

Bluell Beds

5891.2-5895.0 Grainstone-Packstone- Light gray-tan, oolitic, intraclastic, anhydrite and calcite cement, slight-fair vugular and interparticle porosity with oil stain.

5894.0 Grainstone-Packstone- 30% ooids-micritized, 20% intraclasts 0.2-6mm-grapestone, 5% peloids, 30% calcite cement 1) fibrous filling pseudofenestrae 2) bladed lining vugs 3) blocky filling vugs, 2% micrite-often forming meniscus cement, 6% vugular porosity, 3% intercrystalline porosity, 2% moldic porosity. Poorly sorted allochems.

5895.0-5902.0 Grainstone-Mudstone- Medium gray-tan, oolitic, pisolitic, intraclastic, anhydrite and calcite vug cement, large type I stylolites.

5899.0 Packstone-Grainstone- 40% intraclasts 0.2-3mm, 25% ooids tangential, 5% peloids, trace algae-micritized, 10% micrite, 15% calcite cement 1) fibrous between grains 2) blocky filling vugs, Well-very poorly sorted allochems.

TS7 5901.6 Grainstone- 65% ooids-many broken-tangential- radially fibrous and micritic, 5% pisoids <2.0mm with some compaction, 30% calcite cement 1) fibrous isopachous, 2) blocky interparticle and vug fill.

5902.0-5902.5 Grainstone- Medium gray, oolitic, peloidal, calcite cement, fair vugular porosity, trace of oil stain.

TS8 5902.2 Grainstone- 65% ooids tangential, 20% peloids, <1% pisoids 2.0-3.0mm, 25% calcite cement 1) fibrous isopachous 2) bladed-blocky fenestrae and vug fill, 6% vugular porosity, 3% interparticle porosity, Well-sorted allochems except for occasional floating pisoid.
5902.5-5903.5 Packstone—Dark-medium gray, oolitic, pis­
olitic, intraclastic, peloidal, poorly
sorted allochems, anhydrite vug cement.
Large type I stylolite.

5903.0 Packstone—60% ooids radially fibrous-
slightly compacted, 5% intraclasts 0.2-
2mm with peloid grapestone nuclei-
many are coated, 4% peloids, 15% micrite,
15% calcite cement 1) fibrous-bladed lin-
ing vugs 2) blocky vug fill, 1% dolomite
replacing parts of some ooids and in sty-
lolite zones, 1% intercrystalline poros-
ity. Allochems poorly sorted and slight-
ly reverse-graded in 10mm thick beds
partly due to matrix solution collapse.

5903.5-5906.0 Wackestone—Tan, peloidal, occasional pis-
oids and ooids, anhydrite cemented vugs.

TS10 5904.5 Packstone—55% peloids, 1% calcispheres-
forams, blue-green algae and ostracodes,
30% micrite, 15% calcite cement 1) fib-
rous lining some vugs 2) blocky filling
vugs, <1% anhydrite filling some vugs.

5906.0-5908.5 Wackestone-Packstone—Medium-light gray,
oolitic, peloidal, poorly sorted, slight-
-fair vugular porosity, trace oil stain.

TS11 5908.0 Mudstone overlying Wackestone—30% ooids,
10% peloids, 2% intraclasts 0.2-2mm
most coated, 50% micrite, 3% blocky cal-
cite cement filling some vugs, <1% anhy-
drite filling vugs, 5% matrix selective
vugular porosity. Large type I stylolite
with mudstone above and wackestone below.

5908.5-5914.0 Grainstone—Medium-light gray, oolitic,
graded 5-10cm bedding, anhydrite on
some disconformities.

5910.0 Grainstone—70% ooids radially fibrous
and micritic coats, <1% pisoids 2-5mm,
24% calcite cement 1) fibrous isopach-
ous 2) blocky interparticle fill, 1%
interparticle porosity, Well-sorted al-
lochems.

5914.0-5916.0 Packstone—Medium gray-tan, oolitic, moder-
ately sorted, slight-fair vugular por-
osity.
TS13 5915.0  Grainstone- 70% ooids—mostly micritized and tangential, <1% intraclasts 1-2mm, 20% calcite cement 1) fibrous isopachous 2) bladed interparticle fill 3) blocky vug fill, 9% vugular porosity. Well-moderately sorted allochems.

5916.0-5920.8  Packstone- Tan, oolitic, peloidal, anhydritic.

TS14 5919.0  Packstone- 40% ooids, 10% peloids, 2% intraclasts 1-3mm, 10% micrite, 35% calcite cement 1) fibrous interparticle and lining fenestrae 2) bladed lining fibrous 3) blocky filling fenestrae. Poorly sorted allochems.

5920.8-5924.7  Packstone-Wackestone- Tan, oolitic, peloidal, reverse grading in 0.2-2mm size, poor vugular porosity and trace of good interparticle porosity.

TS15 5921.0  Wackestone- 25% ooids radially fibrous-micritized, 2% peloids, 40% micrite, 20% blocky calcite cement filling fenestrae, 8% enlarged fenestral and matrix selective vugular porosity. Moderately sorted allochems. Collapse of most fenestrae.

5924.7-5928.4  Wackestone interbedded with Grainstone-Tan oolitic, peloidal, calcite cement and anhydrite vug fill.

TS16 5927.8  Packstone interbedded with Grainstone- 35% ooids radially fibrous, 15% peloids, 2% intraclasts 1-2mm, trace ostracodes, 20% micrite, 25% calcite cement 1) bladed isopachous in grainstone 2) blocky filling matrix selective vugs and fenestrae, 5% anhydrite filling vugs. Reverse graded.

5928.4-5934.6  Packstone-Grainstone- Medium gray-tan, oolitic, intraclastic, poorly sorted, calcite cement, argillaceous, clay seams, large type I stylolite.

TS17 5930.6  Packstone- 45% ooids micritized in part, 15% intraclasts 0.2-6mm, 15% peloids, 15% micrite, 5% blocky calcite cement filling vugs, 10% anhydrite filling vugs. Allochems poorly sorted and overpacked due to some solution of matrix.
TS18 5933.0  Packstone- 55% ooids radially fibrous and micritic, 5% pisoids 2-4mm radially fibrous, 5% intraclasts 0.2-4mm, 10% micrite. 15% blocky calcite cement filling vugs, 5% dolomite replacing part of matrix, 5% anhydrite filling vugs. Allochems poorly sorted and overpacked due to solution of matrix.

Sherwood Argillaceous Marker

5934.6-5947.0  Packstone-Wackestone- Light gray-tan, oolitic, anhydritic in part, fair-good oomoldic and vugular porosity in part.

5937.2  Grainstone overlying Packstone- 40% ooids tangential-many micritized, 15% peloids, 3% intraclasts, 15% micrite, 25% calcite cement: 1) bladed isopachous in grainstone 2) blocky filling interparticle and vug porosity, 2% intercrystalline porosity in vugs. Moderately sorted, reverse graded, overpacking in packstone due to solution of matrix. Large type I stylolite separating two lithologies.

TS20 5942.8  Packstone- 60% ooids radially fibrous-micritic, 20% micrite forming meniscus cement at top of slide, 6% bladed calcite cement lining vugs, 10% moldic-matrix selective vugular-intercrystalline porosity. Well-moderately sorted, reverse graded allochems.

Sherwood Beds

5947.0-5957.0  Packstone- Light gray-tan, oolitic, intraclastic, peloidal, poorly sorted, slight vugular-moldic and interparticle porosity.

5950.2  Packstone-Wackestone- 30% peloids, 10% ooids micritized, 10% intraclasts 0.2-3mm rare gastrapod, 30% micrite, 15% calcite cement 1) fibrous filling interparticle-intraparticle and lining vug porosity 2) blocky filling vugs, 3% anhydrite filling vugs, 2% vugular and interparticle porosity. Allochems are unsorted and overpacked due to solution of matrix and some collapse.
Wackestone-Solution Breccia- 40% intraclasts 0.2->10mm many with fibrous outer laminae, 10% peloids, 25% micrite, 10% calcite cement 1) micritic meniscus 2) fibrous lining fenestrae and some vugs 3) blocky filling vugs, 5% anhydrite in vugs, 5% vugular porosity-predominately matrix selective. Poorly sorted, slightly reversed graded allochems. 2cm beds. Caliche zone overlying solution breccia.

In Bluell Beds

5297.0-5304.0 Anhydrite- Medium gray, mosaic-bedded nodular texture, argillaceous, silty, dolomite matrix.

Sherwood Argillaceous Marker

5304.0-5306.5 Dolomudstone- Tan-brown-patterned, medium thin bedded, very anhydritic in part, argillaceous.

5306.5-5313.0 Mudstone-Packstone- Tan-brown, medium bedded, poorly sorted, pisolitic, intraclastic, partially dolomitized, very anhydritic with brown anhydrite replacing matrix, interbedded with anhydritic patterned Dolomudstone as above.

Sherwood Beds

5313.0-5323.5 Anhydrite- Medium gray, distorted bedded nodular, with tan microdolomite matrix grading into Dolomudstone- Tan-mottled, laminated grading into patterned texture.

5323.5-5324.5 Mudstone-Tan, thick bedded, calcispheres, brown crystallotopic anhydrite, microstylolite swarm at base.

TS1 5324.5 Wackestone- 25% intraclasts 0.2-4mm, 3% peloids, <1% calcispheres and ostracods, 45% micrite, 25% anhydrite cementing pseudofenestrae and replacing micrite, trace calcite cement filling some vugs, <1% dolomite along stylolite, 2% vugular porosity. Type I stylolite in mudstone. Most allochems micritized.
5324.5-5326.1 Stromatolite Boundstone- Tan, horizontal laminae, calcispheres, dolomitic.

TS2 5325.2 Dolomudstone- 70% microdolomite and larger euhedral rhombs, 25% micrite including flattened peloids, 4% anhydrite in euhedral crystals, 1% calcite cement filling vugs, trace ostracods. 2-10mm thick laminae lacking stromatolite features such as fenestrae. Dolomite in two stages 1) syndepositional 2) formation of larger rhombs.

5326.1-5328.5 Dolomudstone- Light gray, thick bedded, floating pisoid ghosts.

5328.5-5332.0 Packstone-Wackestone- Medium gray brown, thin bedded, poorly sorted, intraclastic, pisolithic, anhydrite filling fenestrae and vugs, several thin caliche crusts, some pisoids are vadose.

TS3 5330.0 Wackestone-Solution Breccia- 25% intraclasts and breccia clasts 0.2-3mm, 5% peloids, <1% calcispheres, 35% micrite matrix and geopetal fill, 1% blocky calcite cement filling shelter porosity, 30% anhydrite filling vugs and replacing carbonate, 3% microspar, <1% vugular porosity. Brecciation due to solution of matrix and collapse.

5332.0-5336.0 Grainstone-Packstone- Tan, thick bedded well sorted, fossiliferous, fair-good intraparticle and moldic porosity, many open vertical fractures, partially dolomitized, oil stained throughout.

TS4 5333.0 Mudstone- 1% ostracods-horizontally oriented-some compacted, 90% micrite, 2% dolomite replacing micrite, 1% anhydrite replacing carbonate, 7% microvugular porosity.

5336.0-5338.0 Intraformational Breccia- Gray brown, disrupted bedded, intraclastic, anhydrite filling fractures and vugs and replacing carbonate.

5338.0-5341.5 Dolomudstone- Medium gray-mottled in part, disrupted bedded, silty, sandy, anhydritic.
5340.0  Anhydrite Sandstone- 60% anhydrite sand grains 100-200µ-angular with rare anhydrite nodule, 10% quartz sand-angular-well sorted. 30% microdolomite matrix. No evident bedding.

5341.5-5342.0  Mudstone- Dark gray brown, very thinly and evenly laminated.

TS6 5341.5  Mudstone- 20% unidentifiable fossils-re-crystallized-concentrated in laminae, 60% micrite, 15% microdolomite replacing micrite, 5% anhydrite euhedral crystals replacing micrite. 0.5-2mm thick laminae. Small fossils are probably algal.

5342.0-5343.0  Packstone-Flat Pebble Conglomerate- Medium gray, intraclastic, anhydritic.

5343.0-5349.7  Grainstone-Packstone- Brown gray, thick-medium bedded, coarse-grained, well sorted, oolitic, pisolitic, intraclastic, calcite cement, several caliche crusts, many microstylolites.

5345.0  Grainstone- 65% intraclasts 0.2-4mm, 4% peloids, one bivalve 1mm, 30% calcite cement 1) rare fine bladed 2) blocky filling interparticle and fracture porosity, 1% microdolomite replacing occasional allochem. Poorly sorted. Overpacking of grains and sutured grain-grain contacts.

K-1 Marker

5349.7-5357.0  Sandstone- Light gray, thin bedded with low angle sets, well sorted, fine grained, quartzose and anhydritic grains, microdolomite matrix, argillaceous, tight, many microstylolites.

TS8 5353.2  Sandy Dolopackstone- 36% quartz sand grains-well sorted-angular, 25% peloids-well sorted, 3% anhydrite sand grains-angular, 2% K-feldspar sand grains, 30% calcite cement-blocky, 2% illite clay, 2% dolomite cement. Peloids and sand (both anhydrite and quartz grains) are the same size 0.1-0.2mm. Anhydrite and quartz sand is evenly distributed, peloids are more concentrated in low angle sets.
In Sherwood Argillaceous Marker

5341.0-5345.0
Dolomudstone- Medium gray, argillaceous, silty, massive.

5342.3
Dolomudstone- 75% microdolomite, 10% microspar, 10% subangular quartz silt, 4% siliciclastic clay, <1% pyrite concentrated in blebs.

Sherwood Beds

5345.0-5347.8
Packstone-Wackestone- Tan-light-medium gray, oolitic, peloidal, intraclastic, very anhydritic, soft sediment deformation, faint stromatolite texture overlying peloid packstones.

TS2 5346.7
Packstone- 55% ooids- tangential with micrite envelopes, 10% intraclasts .2-4.0mm many with radially fibrous outer laminae, 10% peloids, <1% calispheres, <1% pisoids 2-3mm radially fibrous, 3% micrite 10% anhydrite replacing matrix and some allochems, 10% dolomite replacing micrite in layers, 1% matrix selective vugular porosity. Over packed allochems due to solution of matrix. Anhydrite cementing most pores and starting to replace adjacent allochems.

5347.8-5351.0
Packstone- Tan-light-medium gray, peloidal, intraclastic, oolitic, medium-thin bedded, anhydrite cement, Rare oil stain in slightly dolomitized zone.

5347.8
Packstone-Solution Breccia- 35% ooids-micritic and radially fibrous-many are broken, 25% peloids, 3% pisoids 2-3mm, 15% micrite, 20% anhydrite cementing vugs and replacing matrix and allochems, 2% dolomite in matrix, trace pyrite. Overpacked allochems due to some solution of matrix. Grains have gravity cement oriented in different directions due to repacking.

5349.0
Packstone-Solution Breccia- 25% peloids, 10% intraclasts 0.2-1mm, <1% calcispheres, 30% micrite, 20% microdolomite replacing micrite, 8% calcite cement filling vugs, 6% anhydrite filling vugs and
replacing some matrix, 1% chert replacing some allochems. Calcite cementation of vugs was prior to anhydrite cementation. Overpacking due to solution of matrix.

5351.0-5355.4 Wackestone-Packstone- Light gray-tan, intraclastic, thin-thick bedded, poorly sorted, anhydrite replacement and vug fill, stromatolite, scattered oil staining.

5351.4 Mudstone- 6% calcispheres and ostracodes, 3% peloids, 85% micrite, 4% calcite cement filling calcispheres and vugs, 2% dolomite forming along bedding planes, <1% anhydrite filling vugs, 2% moldic and intercrystalline porosity, <1% anhydrite filling vugs. Thin bedded-laminated.

5351.8 Wackestone- 35% intraclasts 0.2-4mm, 3% ooids micritic, 2% peloids, 32% micrite, 25% anhydrite replacing matrix and allochems, 3% blocky calcite cement filling vugs, <1% chert replacing some ooids. Poorly sorted and overpacked allochems due to solution of matrix.

5354.5 Packstone- 55% intraclasts 0.2-4mm, 1% calcispheres, 20% micrite, 13% calcite cement 1) fine bladed isopachous-recrystallized in part 2) blocky filling vugs, 5% dolomite replacing micrite, 3% interparticle and vugular porosity. Poorly sorted and overpacked allochems due to solution of matrix.

5355.4-5356.4 Dolopackstone-Wackestone- Brown-light gray, anhydrite matrix, poorly sorted, thick bedded, trace of oil stain.

TS8 5355.8 Anhydrite- 60% anhydrite 0.1-0.5mm after gypsum laths, 35% microdolomite, 5% intercrystalline vugular and moldic porosity.

5356.4-5357.7 Packstone-Wackestone- Tan, intraclastic, peloidal, poorly sorted, medium-thick bedded, oil stained at base.

5357.7-5363.0 Packstone- Brown, intraclastic, peloidal, poorly sorted, thin-thick bedded, intra-
formational breccia at base, good vuggy, moldic, and solution interparticle porosity, vugs often filled with anhydrite, oil saturated.

**TS9 5359.0**
Packstone- 40% intraclasts 0.2-1.5mm, 15% peloids, 15% fine bladed isopachous calcite cement, 15% anhydrite filling vugs and replacing matrix, <1% dolomite, 10% matrix selective vugular porosity. Poorly sorted and overpacked allochems due to solution of matrix. Some vugs are enlarged fenestrae.

**TS10 5362.0**
Anhydritic Packstone- 15% intraclasts 0.2-1mm, 10% peloids, 40% anhydrite replacing carbonate, 15% micrite, 10% calcite cement 1) fine bladed lining allochems and vugs 2) rare blocky filling vugs, 10% matrix selective vugular porosity.

**5363.0-5366.0**
Mudstone- Tan-light gray, partially dolomitic, thick-thin distorted bedding with nodular texture. Possible algal structures causing bedding.

**TS11 5364.7**
Dolowackestone- 20% peloids, 78% anhedral microdolomite, <1% anhydrite filling vugs, 1% fine vugular porosity.

**5366.0-5386.0**
Packstone-Collapse Breccia- Light-medium gray-tan-brown, medium-very thin bedded moderately sorted, pisolitic, large type I stylolites, anhydrite filling many vugs, fair-good-poor fenestral-matrix selective vugular porosity, oil saturated in most zones, many thin caliche type profiles-especially in high porosity zones, occasional large rip-up clasts making a flat pebble conglomerate. Occasional stromatolite.

**TS12 5368.0**
Wackestone-Collapse Breccia- 37% pisoids micritic-partially dolomitized, 20% intraclasts 0.2-0.7mm, 5% peloids, 25% micrite, 15% calcite cement 1) fine bladed lining vugs 2) blocky filling vugs, 3% anhydrite replacing matrix, 3% fracture-vugular-and intercrystalline porosity. Poorly sorted and overpacked allochems due to matrix solution and collapse. Gravity cements on many coated grains.
Thin caliche cements and geopetal mud covering collapse breccia.

**TS13 5371.9**  
Packstone- 39% intraclasts 0.2-6mm, 10% peloids, 5% fossils: stromatolites- cal­cispheres- rare ostracods and molluscs, 18% micrite, 20% calcite cement 1) fib­rous filling fenestrae 2) blocky filling vugs, 1% dolomite replacing parts of some intraclasts, 7% vugular-intercrys­talline and fenestral porosity.

**TS14 5377.8**  
Wackestone- 15% pisoids 2-10mm radially fibrous outer laminae-micritic, 10% in­traclasts 0.2-5mm, 5% peloids, <1% for­ams and calcispheres, <1% ooids-tangent­al and radially fibrous, 50% micrite, 3% calcite cement filling vugs, 5% anhy­drite filling vugs and replacing carbon­ate, 12% moldic-fenestral-vugular and intercrystalline porosity. Thin caliche crust and gravity micritic cement coating many pisoids.

**K-1 Marker**

**5386.0-5387.0**  
Mudstone- Light-medium gray-mottled, thick bedded-burrowed, dolomitic.

**TS15 5386.5**  
DolomitizedWackestone- 45%micrite, 40% dolomite 10-100u-replacing allochems, 5% anhydrite- nodular to subfelted texture.

**5387.0-5390.0**  
Dolomudstone- Medium-dark gray, thin-thick bedded, very argillaceous. Bedding and texture may be due to algal laminations.

**TS16 5389.8**  
Dolomudstone- 3% quartz silt-20-80u, 30% micrite, 60% microdolomite replacing micrite, trace pyrite, 7% vugular and intercrystalline porosity. Desiccation fracture, dolomitization of burrows, late calcite filling of some desiccation fractures.

**5390.0-5401.0**  
Packstone-Wackestone- Medium-light gray, thin-medium bedded, moderately sorted, oolitic, oncotic, paeloidal, fenestrae filled with anhydrite, many microstyro­lite swarms and clay seams.

**TS17 5392.7**  
Wackestone- 15% pisoids 2-15mm with radially fibrous outer coat, 10% ooids;
radially fibrous with micrite envelopes, 3% intraclasts 0.2-2mm, rare unbroken ostracode, 55% micrite, 15% blocky calcite filling vugs, trace intercrystal-line porosity in vugs.

**TS18 5396.5**

Wackestone-Packstone- 50% ooids tangential and micritic, 12% peloids, 2% pisoids 2-4mm, 1% intraclasts 0.2-0.5mm, 10% micrite, 20% calcite cement 1) fibrous filling fenstral-interparticle porosity and lining vugs 2) blocky filling vugs, <1% dolomite scattered, <1% intercrystalline porosity. Well sorted allochems. Some realignment due to solution of matrix.

**Mohall Beds**

**TS19 5400.2**

Anhydrite Sandstone overlying Packstone- 45% anhydrite after well sorted angular gypsum sand, 35% microdolomite matrix, 5% intraclasts 0.3-1.5mm, 4% siliciclastic clay, 6% microspar, 1% quartz silt. Algal borings in micrite crust overlying packstone.
In Bluell Beds

5400.0-5404.0  Anhydrite- Light-dark gray, bedded nodular mosaic, interbedded with Dolomudstone-Medium gray, thin distorted bedding.

Sherwood Argillaceous Marker

5404.0-5405.0  Dolomudstone- Medium-dark gray-circular and wavy mottled, very argillaceous, many distorted anhydrite nodules.

TS1 5404.7   Anhydritic Dolomudstone- 50% microdolomite, 45% anhydrite- distorted nodules with subfelted texture and scattered euhedral crystals after gypsum, 3% quartz silt, 2% siliciclastic clay. Horizontal and vertical desiccation fractures.

TS2 5405.0  Dolomitic Anhydrite- 50% anhydrite-distorted nodular bedded and subhedral crystals after gypsum, 49% microdolomite with some larger crystals along bedding planes, 1% micrite.

TS3 5405.5  Dolomudstone- 70% microdolomite, 15% micrite-disseminated, 10% anhydrite-evenly scattered anhedral-subhedral crystals, 5% quartz silt-evenly scattered.

5405.0-5413.0  Dolomudstone- Medium-dark-light gray-mottled, patterned in part, very argillaceous-clean, silty, thick-very thin bedded, bioturbated in part?, many microstylolite zones.

TS4 5407.7  Dolomudstone- 75% microdolomite, 10% anhydrite, 8% micrite in thin beds, 6% quartz silt, 5% siliciclastic clay, 1% pyrite concentrated in microstylolites.

Sherwood Beds

5413.0-5420.5  Wackestone-Packstone- Medium gray, poorly sorted, thin-medium bedded, oncolitic, oolitic, intraclastic, many caliche type horizons with underlying intraformational breccias cemented with anhydrite, slightly dolomitized, rare scattered oil staining.
5414.0  Packstone-Solution Breccia- 25% pisoids 2-9mm spherical, 15% ooids radially fibrous, 5% peloids, 5% intraclasts 0.2-3mm, trace ostracodes and calcispheres, 35% micrite, 8% calcite cement 1) some fibrous isopachous 2) blocky filling vugs, 7% anhydrite filling vugs and replacing carbonate. Many microstylolites forming around and through slightly overpacked allochems. Overpacking due to solution of matrix. Pisoids have multiple radially fibrous coatings covering gravity micritic cements.

TS6 5418.0  Wackestone-Solution Breccia- 25% intraclasts 0.2-3mm, 5% peloids, rare ostracode, 50% micrite, 5% calcite cement 1) micritic gravity 2) rare bladed lining some vugs 3) large blocky filling vugs and cementing geopetal peloids, 10% anhydrite filling vugs- fractures and replacing carbonate, 2% dolomite in microstylolite swarms, 3% matrix selective vugular porosity. Thin bedded. Geopetal peloids and micrite filling many vugs indicate early solution. Overpacking in some zones due to solution of matrix.


5422.0  Wackestone- 15% fossils-(99% calcispheres-trace ostracodes-trace algae-trace pelecypod), 55% micrite, 10% blocky calcite cement filling vugs, 5% anhydrite filling vugs and replacing carbonates, 15% moldic-vugular-intraparticle porosity.

5423.0-5435.0  Packstone- Light gray, poorly sorted, intraclastic, peloidal, oolitic, oncolitic Thin bedded. Fenestral texture with anhydrite fill. Abundant thin caliche profiles.

TS8 5426.0  Wackestone- 23% pisoids 1-10mm with multiple fibrous and micritic coatings, 5% ooids-micrite layers alternating with radially fibrous ones, 2% peloids, trace fossils (ostracodes, calcispheres, algae),
50% micrite, 18% anhydrite filling vugs and shelter porosity and replacing carbonate, 1% calcite cement filling vugs, 2-3% vugular and moldic porosity. Allochems poorly sorted and overpacked due to solution of matrix. Many vertical desiccation fractures.

5435.0-5446.0 Packstone- Tan-light gray, very thin-medium bedded, poorly sorted, intraclastic, many thin caliche zones, slight-fair matrix selective vugular-moldic and interparticle porosity with anhydrite filling some vugs, several large type I stylolites.

5436.4 Solution Breccia- 35% intraclasts 0.2-2mm many with micritic coats, 3% peloids, trace ostracodes, 45% micrite, 15% anhydrite filling vugs and replacing carbonate, 1% blocky calcite cement filling vugs, 1% vugular porosity. Overpacking due to solution of matrix.

5441.3 Wackestone- 20% intraclasts 0.2-1mm, 5% peloids, 1% siliciclastic clay, trace ostracodes, 65% micrite, 5% microdolomite, 5% anhydrite filling vugs, 2% blocky calcite cement filling vugs, trace pyrite, 2% vugular porosity-fine. Clay, pyrite and dolomite concentrated in large type I stylolites.

5446.0-5451.0 Packstone- Light gray-tan, thin bedded, poorly sorted, pisolithic, pores becoming increasingly filled with anhydrite towards base, scattered anhydrite nodules at base.

TS11 5450.5 Mudstone- 2% intraclasts 0.2-1mm, 85% micrite, 7% microspar, 5% microdolomite disseminated in matrix, 1% anhydrite in nodules and filling vugs and fractures. Thin bedded, many vertical desiccation fractures.

NDGS # 5063

In Bluell Beds

5918.0-5920.4 Anhydrite- Medium gray, fine mosaic-massive texture, tan dolostone matrix.

5920.4-5926.2 Dolomudstone- Olive-tan-mottled in part,
thinly laminated-massive, argillaceous, microstylolites and clay seams, anhydrite nodules in upper interval.

5924.0 Dolomudstone- 94% microdolomite, 3% siliciclastic clay, 1% anhydrite-small isolated nodules, 2% small vugular porosity, trace of pyrite.

5926.2-5929.3 Wackestone-Mudstone- Light gray-tan, thin bedded, partially recrystallized, oolitic, anhydritic in part.

5927.0 Wackestone-Solution Breccia- 20% intraclasts 0.2-1mm, 20% ooids, 10% peloids, 1% pisoids 2-4mm fibrous-tangential-some dolomitized, 30% micrite, 10% calcite cement 1) bladed-fibrous lining vugs and filling fenestrae 2) blocky filling vugs and interparticle porosity, 5% anhydrite replacing carbonate, 4% dolomite replacing allochems and scattered matrix. Overpacking due to solution of matrix.

5929.3-5930.4 Dolomudstone- Tan-mottled, massive, argillaceous.

5930.1 Dolomudstone- 99% microdolomite, <1% siliciclastic clay. Mottled-caused by sulfide displacement or burrowing.

5930.4-5938.5 Wackestone-Packstone- Light gray, thin bedded, poorly sorted, intraclastic, peloidal, interbedded with calcisphere packstones, anhydrite filling vugs.

5932.2 Packstone- 27% peloids, 25% intraclasts 0.2-3mm, 10% fossils(99% calcispheres, 1% ostracodes), 20% micrite, 3% calcite cement filling intra and interparticle porosity, 10% microdolomite replacing matrix, 5% moldic-small matrix selective vugular porosity, trace of interparticle porosity.

TS5 5937.5 Packstone- 30% peloids, 8% intraclasts 0.2-3mm, 5% ooids radially fibrous, 7% pisoids radially fibrous 2-3mm, 20% micrite, 25% anhydrite filling vugs and replacing carbonate, 2% calcite cement 1) lining vugs and filling interparticle porosity 2) rare blocky late vug fill, trace microdolomite, trace celestite
cement. Poorly sorted. Repacked allochems due to solution of matrix.

5938.0-5945.0 Packstone-Grainstone-Wackestone- Light gray thin-medium bedded, well sorted, often reverse graded, intraclastic, pisolithic, oolitic, some anhydrite vug and fracture fill, fair-good vugular porosity, many type I stylolites.

TS6 5938.9 Solution Breccia- 65% ooids radially fibrous-overpacked, 10% peloids, trace of calcispheres, 10% micrite-geopetal in part, 7% anhydrite filling vugs, 5% micrdolomite, 2% matrix selective vugular porosity. Overlain by- 30% peloids, 25% intraclasts 0.2-2mm, 2% ostracodes, 22% micrite, 1% blocky calcite cement filling primary porosity, 5% anhydrite filling primary and secondary porosity, trace dolomite, 15% vugular enlarged fenestral porosity and trace of interparticle porosity. Overpacked allochems due to solution of matrix. Micritic gravity cements alternating with fibrous laminae.

TS7 5940.9 Grainstone-Packstone- 45% ooids-smaller ooids are tangential-larger ooids are radially fibrous, 20% peloids, 2% pisoids 1-2mm radially fibrous outer laminae, 3% micrite, 20% calcite cement 1) fibrous-bladed filling interparticle porosity and lining vugs 2) blocky filling some vugs, trace dolomite, 10% vugular porosity-possibly enlarged fenestral porosity. Moderately-well sorted bimodal allochems. Primary porosity is filled with calcite or geopetal mud. Some solution of matrix. At least two stages of solution.

TS8 5944.5 Packstone-Grainstone- 25% pisoids 2-4mm broken-radially fibrous and micritic-partially dolomitized-partially silicified, 15% ooids-same as pisoids except smaller ones are tangential, 10% intraclasts, 8% peloids, 15% micrite, 12% calcite cement 1) bladed filling interparticle-fenestral porosity and fractures in ooids 2) blocky filling vugs, 3% microdolomite, 12% matrix selective vugular-fenestral and interparticle

5945.0-5952.0  Wackestone-Packstone-Grainstone- Light gray, thin-medium bedded, poorly sorted, intraclastic, fossiliferous(calcisphere), slight intraparticle and vuggy porosity. Becoming more anhydritic.

5946.3  Packstone- 25% intraclasts 0.2-2mm, 20% fossils(95% calcispheres-4% ostracodes-1% calcareous algae[dyasyclads]), 12% peloids, 1% ooids, 20% micrite, 7% blocky calcite cement filling interparticle-vuggy porosity, trace anhydrite filling vugs, 15% moldic-intraparticle-interparticle and vuggy porosity.

TSlO 5950.1  Grainstone- 75% ooids-combination radially fibrous and micritic, 2% intraclasts 10mm, 18% calcite cement 1) bladed isopachous filling interparticle porosity 2) blocky filling vugs, <1% micritic geopetal pore filling, 1% late anhydrite porosity fill, trace dolomite replacing some micrite, 4% interparticle porosity. Very well sorted.

Sherwood Argillaceous Marker

5952.0-5958.0  Dolomudstone- Olive tan, argillaceous, occasional anhydrite nodules, interbedded with Wackestone-Packstone- Medium brown gray, oolitic, intraclastic, caliche zones and desiccation fractures.

TSl 5953.5  Dolomudstone- 90% microdolomite, 10% quartz silt, <1% anhydrite in small blebs, trace pyrite. Some large(50-100u) dolomite rhombs floating in matrix.

Sherwood Beds

5954.0  Grainstone-50% peloids, 25% ooids with radially fibrous-tangential and micrite coatings, 6% intraclasts 0.2-4mm, 2% micrite in thin laminae, 13% calcite cement 1) bladed isopachous lining allochems 2) blocky filling interparticle
porosity, 4% anhydrite filling vugular and fracture porosity, <1% dolomite associated with stylolite. Very thin bedded, moderately-well sorted, poor normal grading.

5958.0-5964.0 Packstone-Wackestone-Grainstone- Light gray brown, thick-medium bedded, poorly sorted oolitic, intraclastic, many large type I stylolites, slight-good large vugular porosity.

TS13 5961.0 Grainstone-Packstone-55% ooids-tangential, 5% peloids, 2% intraclasts 0.2-6mm, 20% micrite, 15% calcite cement 1) bladed-fibrous lining allochems and vugs 2) blocky filling shelter and interparticle porosity. Poorly-moderately sorted-poorly washed grainstone.

5963.0 Packstone- 65% ooids-radially fibrous, 3% peloids, 13% micrite, 9% calcite cement 1) fibrous lining vugs 2) bladed lining fenestrae 3) blocky filling vugs-fenestrae and shelter porosity, 10% matrix selective vugular porosity. Poorly sorted, matrix (peloid-micrite) starved packstone.

NDGS # 5115

In Sherwood Argillaceous Marker

5364.0-5368.5 Dolomudstone- Dark-medium gray, thin-distorted bedded, very argillaceous, silty anhydritic, clay seam at base.

5368.0 Dolomudstone- 75% microdolomite, 15% quartz silt, 10% siliciclastic clay, <1% small isolated vugular porosity.

Sherwood Beds

5368.5-5372.4 Mudstone-Wackestone- Tan-light gray, mottled in part, burrowed in part, peloidal, crystallotopic anhydrite, occasional calcispheres, dolomitic in part.

TS2 5370.0 Wackestone- 35% intraclasts 0.2-0.5mm, 2% ooids-tangential and radially fibrous, trace fossils (90% calcispheres-10% ostroacodes), <1% pisoids 6mm, 55% microdolomite replacing matrix, 8% anhydrite
replacing matrix and some allochems, 5% microspar, <1% vugular-intraparticle and moldic porosity.

TS3 5371.3  Packstone- 25% fossils (95% calcispheres, 4% algae, 1% ostracodes), 15% intraclasts 0.2-1mm, 10% peloids, 25% micrite, 5% calcite cement filling intraparticle porosity, 10% anhydrite from gypsum laths 4-10mm, 5% microspar from micrite, 5% moldic and intraparticle porosity.

5372.4-5374.8  Doloboundstone- Tan-light gray, laminated stromatolitic, slight-fair intercrystalline porosity.

5374.0  Dolostromatolitic Packstone-Mudstone- 8% peloids, 7% ooids micritized, 5% intraclasts 0.2-1mm, 1% calcispheres, 5% micrite, 55% microdolomite replacing matrix and some allochems, 5% microspar, 2% anhydrite filling interparticle porosity, 2% blocky calcite cement filling intraparticle porosity, trace pyrite, <1% moldic porosity.

5374.7  Silicified-Dolomitized-Stromatolite-Packstone-Wackestone- 15% silicified peloids, 10% silicified intraclasts 0.2-0.5mm, 4% calcispheres mostly silicified, 2% micrite, 55% microdolomite, 35% chert replacing allochems and some matrix, 2% organic matter, 2% silica clay. Thin laminae are alternately mineralized between chert and dolomite.

5374.8-5380.7  Wackestone-Mudstone- Tan-light gray, thick bedded, very argillaceous, intraclastic, dolomitized in part, anhydritic in part.

5376.5  Packstone-Wackestone- 30% intraclasts 0.2-1mm, 20% ooids-radially fibrous, 1% peloids, 40% micrite, 7% anhydrite filling vugs and replacing matrix, 1% blocky calcite cement filling vugs, 1% matrix selective vugular porosity. Poorly sorted, overpacked allochem. Calcite cement is both prior and subsequent to anhydrite filling.

5378.5  Wackestone- 25% intraclasts 0.2-2mm, 4% pseudo ooids radially fibrous and
micritic, 2% peloids, 50% micrite, 10% microspar from matrix, 7% microdolomite
2% small vugular and intercrystalline porosity. Compacted allochems.

5380.7-5387.7 Packstone- Light gray-brown, medium-thin bedded, oolitic, pisolitic, anhydrite filling fenestral and sheltered porosity. Fair to good matrix selective vugular porosity, abundant microstylolites, oil saturated.

TS8 5382.3 Collapse Breccia-Wackestone- 45% intraclasts 0.2-3mm, 5% peloids, 10% micrite, 30% calcite cement 1) fibrous lining vugs and shelter porosity 2) trace blocky filling center of vugs, 5% anhydrite vugs and replacing carbonate, 5% vugular with slight intercrystalline porosity. Very poorly sorted overpacked allochems due to solution of matrix.

5387.7-5390.5 Packstone-Wackestone- Light clastic, slightly argillaceous, abundant type I stylolites.

5390.5-5394.7 Packstone- Tan-brown, thin-medium bedded, poorly sorted oolitic, oncolitic, pisolithic, allochems partially dolomitized, some anhydrite pore filling, good-fair matrix selective vugular and fair intercrystalline porosity, oil stained, occasional caliche zones.

TS9 5391.0 Solution Breccia- 40% intraclasts 0.2-8mm, 8% peloids, 1% ooids, trace calcispheres, 5% micrite, 35% calcite cement 1) micritic gravity 2) fibrous lining vugs 3) bladed filling vugs, 1% dolomite, 10% vugular-intercrystalline and moldic porosity. Poorly sorted overpacked allochems due to solution of matrix.

5394.7-5397.0 Intraformational Breccia-Wackestone- Tan-light-medium gray, oolitic, intraclastic, slightly argillaceous, large type I stylolites, slight small vugular porosity-mostly anhydrite filled.

TS10 5395.7 Solution Breccia- 55% intraclasts 0.2-6mm, 2% peloids, 10% micrite, 30% calcite cement 1) fibrous lining vugs 2) blocky filling vugs, 4% microdolomite, 3%
anhydrite filling vugs and replacing carbonate, 1% vugular and trace intercrystalline porosity. Collapse due to solution of matrix.

5397.0-5399.5 Intraformational Breccia-Wackestone- Tanbrown, intraclastic, fenestral texture, slight-good vugular porosity enlarging fenestrae, oil stained. Caliche zones developing every 5-20cm.

TS11 5399.3 Mudstone-Algal Boundstone- 15% micritized algal structures, 30% micrite, 45% calcite cement 1) fibrous lining interparticle and vug porosity 2) blocky filling vugs, 10% vugular and secondary intercrystalline porosity. Some vugular porosity may be enlarged fenestrae.

5399.5-5411.0 Packstone- Tan-light-medium gray, thin bedded, poorly sorted, oncoidal, peloidal, pisoidal, oolitic, intraclastic, anhydrite fenestrae fill, slightly argillaceous, slightly dolomitized, scattered oil staining.

TS12 5402.8 Packstone-Solution Breccia- 35% intraclasts 0.2-20mm, 5% peloids, 2% pseudo pisoids 2-3mm radially fibrous and micritic, <1% ooids radially fibrous, 15% micrite, 25% calcite cement; 1) micritic gravity 2) fibrous lining vugs 3) blocky filling vugs, 4% microdolomite, 9% vugular-moldic and intercrystalline porosity. Overpacking due to solution of matrix.

TS13 5405.5 Solution Breccia- 15% solution clasts 0.2-8mm, 5% peloids, <1% ooids, 60% micrite, 25% calcite cement 1) micritic gravity 2) fibrous filling fenestrae and lining vugs 3) blocky filling vugs and fractures, 1% anhydrite filling vugs, <1% microdolomite replacing matrix, 5% vugular-moldic and fracture porosity. Poorly sorted allochems, non-laminated algal features, desiccation fractures, collapse due to solution of matrix. Geo-petal micrite and peloid fill. Many microstylololites and sutured grains.
In Bluell Beds

5380.0-5380.5  Wackestone- Light-medium gray, thick bedded with laminated base, recrystallized allochems.

5380.3  Packstone- 30% ooids radially fibrous-par­tially dolomitized, 20% intraclasts 0.2-4mm, 5% peloids, 30% micrite, <1% cal­cite cement filling vugs and interparti­cle porosity, 10% anhydrite filling fracture and vugs and replacing carbon­ate, 2% microdolomite replacing parts of some allochems, 1% microspar, 1% pseudo­spar. Thin bedded, well sorted overpack­ed allochems.

Sherwood Argillaceous Marker

5380.5-5387.2  Dolomudstone- Medium-light-dark gray-tan, mottled in part, very argillaceous in part, very anhydritic in part with nod­ular-distorted nodular mosaic anhydrite zones, rare fine crosslaminations, several wispy stylolite zones.

5381.5  Dolomudstone- 55% microdolomite, 40% anhy­drite nodular (subfelted) and floating eu­hedral crystals, 5% siliciclastic clay, 1% quartz silt, <1% fracture porosity. Desiccation fractures.

5385.0  Silty Dolomudstone, 75% dolomite-4-10μ in matrix and 50-100μm diagenetic subhedral crystals, 15% quartz silt-well sorted, angular, 5% siliciclastic clay, 5% intercrystalline porosity. Cross-bedded silt with very fine (0.5-1mm) cross sets

5386.8  Dolomudstone- 85% microdolomite, 4% quartz silt, 4% siliciclastic clay, 2% micro­spar in thin zones close to microstylo­lites, 5% vugular and slight intercrys­talline porosity.

Sherwood Beds

5387.2-5392.0  Mudstone- Tan-medium gray, thinly laminated to thin-medium bedded, tepee structures.

5387.9  Stromatolitic Boundstone- 5% peloids, 1%
intraclasts 0.2-3mm, trace calcispheres, 40% micrite, 7% calcite cement filling fenestrae, 25% dolomite replacing some laminae, 20% microspar, 1% organic matter concentrated in laminae, 1% fracture and intercrystalline porosity. Dolomitization predominantly in matrix of allochem rich zones.

5389.9 Algal Boundstone-Dolomudstone- 15% fossils (99% algae Girvanella, 1% ostracodes <1% calcispheres), 25% micrite, 8% calcite cement 1) fibrous filling interparticle porosity 2) rare blocky filling vugs, 55% microdolomite, 1% anhydrite filling sheltered-moldic and vugular porosity, 1% intercrystalline-moldic and vugular porosity.

5392.0-5398.0 Packstone-Mudstone- Tan-medium gray, thick-thin bedded, fossiliferous-calcispheres, good moldic and interparticle porosity, brown crystallotopic anhydrite. Type I stylolite and stylolite swarm at base.

5394.5 Wackestone-Packstone- 20% fossils-mostly micritized (80% calcispheres-20% algal clumps-trace ostracodes), 20% intraclasts 0.2-3mm-some micritized ooids included, <1% peloids, 50% micrite, 1% calcite cement filling vug and interparticle porosity, 1% microspar, 8% moldic and intraparticle porosity.

5398.0-5402.0 Packstone-Mudstone- Medium gray, thin-medium bedded, poorly sorted, oolitic, intraclastic, calcite and anhydrite vug filling.

TS8 5401.0 Wackestone-Collapse Breccia- 20% intraclasts 0.2-5mm, 6% peloids, 2% ooids-combination radially fibrous and tangential, 47% micrite, 5% calcite cement 1) micritic gravity 2) fibrous fenestrae fill 3) blocky vug fill, 15% anhydrite filling vugs, <1% dolomite adjacent to stylolites and replacing parts of some allochems. Poorly sorted and overpacked in some zones due to solution of matrix.

5402.0-5408.0 Mudstone- Tan, thick-thin bedded, recrystallized, zones of scattered nodular and crystallotopic anhydrite, slight-good intercrystalline porosity.
Mudstone- 10% intraclasts 0.2-2mm, 50% micrite, 30% dolomite-sub-anhedral, 7% anhydrite-euhedral crystals after gypsum, 2% siliciclastic clay, 1% intercrystalline and small vugular porosity. Faint stromatolite 'ghost' texture.

Mudstone-Intraformational Breccia- Tancream, thick-disrupted bedded, recrystallized, many microstylolite swarms, slight-fair intercrystalline porosity.

Dolomitized Intraformational Breccia- 2% peloids, trace calcispheres, 30% micrite in isolated breccia clasts, 60% microdolomite, 7% anhydrite filling fractures and replacing carbonates, 1% microspar. Dolomitized along all fractures, late anhydrite fills remaining fractures.

Anhydritic Dolowackestone- 1% peloids in undolomitized portion, 1% calcispheres in undolomitized portion, 8% micrite, 60% microdolomite, 30% anhydrite after euhedral gypsum crystals, trace chert. Anhydrite only found in dolomitized zone.

Mudstone- Light gray, thick-bedded, partially recrystallized, subvertical fractures filled with euhedral anhydrite, some bedding is tilted >30 degrees, occasional slight intercrystalline porosity.

Wackestone- 25% intraclasts 0.2-15mm, 25% micrite, 25% microdolomite replacing micrite, 25% anhydrite filling vugs and replacing carbonate. Appears brecciated in part due to solution of matrix.

Dolomudstone- Medium gray, thick-thin distorted bedding, argillaceous, thin patterned zone, occasional distorted anhydrite nodules.

Anhydrite Sandstone- 55% anhydrite-bimodal angular grains, 25% microdolomite matrix, 10% micrite scattered through dolomite, 10% siliciclastic clay scattered through matrix. Anhydrite after well sorted gypsum sand and silt grains. Grains later recrystallizing and replacing some carbonate.
In Bluell Beds

5805.0-5805.5 Grainstone interbedded with Mudstone- Light gray, thin bedded, well-moderately sorted, reverse-nongraded, oolitic, intraclastic, calcite cement, anhydrite fenestrae fill, some desiccation cracks.

5805.2 Grainstone-Packstone- 45% intraclasts 0.5-1mm, 15% peloids, <1% ooids tangential, 15% micrite, 20% calcite cement 1) fibrous filling interparticle and lining fenestrae and sheet cracks 2) blocky filling fenestrae, 5% anhydrite filling vugs-fractures and replacing carbonate. Thin bedded-laminated. Moderately sorted-bimodal.

5805.5-5806.0 Stromatolite Boundstone- Dark gray, laterally linked hemisphere-horizontally laminated, very anhydritic, argillaceous.

5806.0-5815.0 Wackestone-Packstone interbedded with Mudstones- Brown gray, thin-medium bedded, moderately-poorly sorted, oolitic, intraclastic, pisolithic, anhydrite filled fenestrae and fractures, several thin hardgrounds or caliche zones. Several type I stylolites.

5813.5 Packstone- 35% ooids combination: micrite-radially fibrous and tangential—many are broken, 10% peloids in matrix, 10% pisoloids 2-5mm most radially fibrous, 5% intraclasts with fibrous outer laminae, 10% micrite, 15% calcite cement 1) fibrous lining allochems 2) blocky filling matrix selective vugs, 5% anhydrite in vugs and replacing carbonate, <1% vugular porosity. Poorly sorted. Up to 23 laminations on pisoloids.

5815.0-5824.5 Packstone-Wackestone interbedded with Grainstone- Gray brown, thin bedded, moderately sorted, oolitic, pisolithic, intraclastic, anhydrite cementing grainstones and desiccation fractures, fair-good vug and enlarged fenestral porosity-especially in wackestones, trace oil stain. Microstylololites following bedding planes.
5821.8 Grainstone-Packstone- 45% ooids-tangential, 5% intraclasts 0.2-2mm, 5% peloids, 10% micrite, 30% calcite cement 1) fibrous grain cement and fenestral lining 2) long bladed filling fenestrae and lining vugs 3) blocky vug fill, 4% moldic and vugular porosity. Poor-well sorted, poorly washed grainstone.

5824.0 Packstone- 30% ooids combinations of radially fibrous-micritic and tangential, 25% intraclasts 0.3-3mm, 4% peloids, 15% micrite, 25% calcite cement 1) fibrous cement and fenestrae lining 2) blocky filling fenestrae and early vugs, 1% fenestral and early vugular porosity.

5824.5-5831.0 Grainstone-Packstone- Tan, thin-medium bedded, well-moderately sorted, bimodal in part, oolitic, peloidal, intraclastic, intraformational breccia at base, collapsed fenestrae, several hardgrounds, calcite cemented, anhydrite filling rare desiccation cracks and fenestrae, dense-slight-fair matrix selective vugular porosity.

TS5 5826.0 Wackestone- 25% intraclasts 0.2-0.5mm, 10% peloids, 10% fossils (95% calcispheres, 4% ostracodes <1% forams, <1% recrystallized blue-green algae), 35% micrite, 20% calcite cement blocky spar filling collapsed fenestrae, 1% anhydrite filling center of vugs, <1% intercrystalline porosity. Abundant partially collapsed fenestrae many early vugs, collapse after formation of very thin fibrous cement.

5829.0 Grainstone- 45% ooids radially fibrous, 25% pisoids 2-5mm radially fibrous many broken internally, 13% calcite cement 1) radially fibrous isopachous 2) blocky late interparticle and vug cement, 17% interparticle and orthochem-selective vugular porosity. Well sorted.

Sherwood Argillaceous Marker

5831.0-5843.0 Wackestone-Mudstone- Medium gray, thick-thin bedded, poorly sorted, intraclastic oolitic, abundant anhydrite filled fenestrae, several thin hardgrounds with packstone-grainstone lags.
Sherwood Beds

5843.0-5865.0 Wackestone-Packstone-Grainstone- Tan-brown gray, thin-medium bedded, poorly sorted except in thin grainstone, some low-medium angle crossbedding, oolitic, pisolithic, intraclastic, peloidal, calcite filling some fenestrae, anhydrite filling some vugs, slight-fair-good vugular porosity, many thin caliche crusts and small desiccation fractures, trace of oil stain in upper part of zone.

5844.5 Wackestone-Packstone- 19% intraclasts 0.2-40mm, 15% peloids, 3% ooids micritized, 10% micrite, 10% calcite cement 1) fibrous lining fenestrae 2) bladed lining vug 3) blocky filling vugs, 30% microspar, 1% anhydrite filling latest vugular and fracture porosity, 12% matrix selective vugular porosity.

TS8 5857.0 Wackestone- 25% intraclasts 0.2-2mm, 10% peloids, 35% micrite, 20% calcite cement 1) fibrous lining fenestrae 2) blocky vug fill, 10% vugular and some fenestral porosity. Poorly sorted. At least two stages of solution and vug development.

5860.4 Packstone-Grainstone- 30% ooids combination radially fibrous-micritic and tangential, 10% peloids, 5% oncoids 4-5mm, 30% micrite, 15% calcite cement 1) fibrous interparticle and lining vugs 2) blocky filling vugs, 10% large vugular porosity. Well sorted. Large vugs with little cement fill.

TS10 5864.5 Packstone- 50% pisoids 2-4mm radially fibrous-most broken, 20% micrite with small peloids included, 20% calcite cement 1) fibrous filling shelter-fenestral and fracture porosity 2) blocky filling matrix selective vugs, 10% predominantly matrix selective vugular porosity. Moderately sorted, very high primary fenestral porosity filled with fibrous cement, some pseudo-fenestrae caused by transport of previously cemented clumps not meshing. Overpacked in some areas with microstylolites beginning to develop.
In Bluell Beds

5756.0-5758.5 Wackestone- Light gray-tan, thin bedded, intraclastic, moderately sorted, many thin caliche zones, rounded partially micritized allochems, slight matrix selective pinpoint vugular porosity.

5756.5-5761.0 Packstone-Grainstone- Tan-light gray, thin-medium bedded well sorted, oolitic, anhydrite filled fenestrae and vertical fractures.

TSL 5760.8 Grainstone- 20% ooids many micritized or partially dolomitized, 15% intraclasts 0.2-2mm, 5% peloids, 3% micrite, 40% fine isopachous calcite cement, 2% microspar, 10% anhydrite filling vugs-fractures and replacing carbonate, 1% microdolomite replacing parts of some allochems, 5% vugular porosity.

5761.0-5762.0 Packstone- Light gray, poorly sorted, pisoidal, anhydrite filling most vugs and replacing some carbonate, slight matrix selective vugular porosity.

5762.0-5767.5 Wackestone-Packstone- Light gray-tan, thin-thick bedded, oolitic, intraclastic, well-poorly sorted, anhydrite filling vugs, calcite filling rare fenestrae, partially recrystallized, fair to good matrix-selective vugular porosity.

5763.5 Wackestone- 25% intraclasts 0.2-9mm, 10% peloids, 1% fossils (99% calcispheres, 1% ostracodes), 35% micrite, 5% blocky calcite filling vugs, 12% anhydrite filling vugs and replacing carbonate, 12% vugular porosity. Poorly sorted.

5765.9 Packstone- 30% pisoids radially fibrous- many broken and recoated, 10% ooids- radially fibrous, 5% peloids, 4% intraclasts 0.2-3mm, 35% micrite, 1% blocky calcite cement filling some vugs, 5% anhydrite filling vugs, <1% dolomite replacing some allochems, 10% matrix selective vugular porosity. Moderately sorted allochems. All allochems have at least one radially fibrous outer coat.
Anhydrite and calcite vug cementation is simultaneous.

Sherwood Argillaceous Marker

5767.5-5769.0 Dolopackstone-Dolomudstone—Light gray, thick bedded, intraclastic?, recrystallized, slightly argillaceous.

5768.0 Dolomudstone—90% microdolomite (matrix & replacing silt grains), 6% quartz silt, 3% siliciclastic clay, trace pyrite, 1% intercrystalline porosity.

5769.0-5770.5 Wackestone—Light brown, thin bedded, oolitic, pisolithic, anhydrite filled fenestrae, thin horizontal micrite laminations, several microstylolites.

5770.5-5771.7 Dolomudstone—Light gray-salt and pepper, intraclastic, very silty, scattered argillaceous zones.

5771.5 Dolomudstone—93% dolomite (matrix and replacing silt), 3% quartz silt, 2% siliciclastic clay, trace pyrite blebs, 2% intercrystalline porosity. Mottled texture with many flattened allochem ghosts.

Sherwood Beds

5771.7-5776.0 Wackestone-Mudstone—Medium gray, thin bedded, intraclastic, argillaceous, anhydrite filling small vugs, recrystallized in part, large clay seam.

TS6 5772.5 Packstone—50% intraclasts 0.2-3mm, 9% peloids, 2% ooids radially fibrous and tangential, 20% micrite, 4% dolomite replacing parts of some allochems, 15% calcite cement 1) trace fine bladed lining vugs 2) blocky filling vugs. Poor to well sorted, reverse graded allochems, which are overpacked and micritized.

5776.0-5801.5 Wackestone-Packstone—Tan-light brown, thin to medium bedded, poorly sorted, intraclastic, oolitic, pisolithic, Many thin caliche zones, calcite lining vugs anhydrite filling desiccation cracks, slight-good vugular and fenestral porosity.

5783.8 Grainstone-Packstone—25% ooids tangential
and radially fibrous, 15% peloids, 2% intraclasts 0.2-0.4mm, 2% pisoids 2-10mm tangential— with micrite envelopes, <1% micrite, 50% calcite cement 1) fibrous isopachous 2) bladed filling some vugs, 5% moldic and vugular porosity. Poorly—moderately sorted-bimodal.

**TS8 5792.0**

Packstone—Solution Breccia— 35% intraclasts—solution clasts 0.2-4mm, 15% peloids, 15% micrite, 23% calcite cement 1) fibrous lining fenestrae and vugs 2) blocky filling vugs, 12% enlarged fenestral and vugular porosity.

**5801.5-5804.7**

Wackestone— Tan—light gray, thin—medium bedded, intraclastic, pisolitic, anhydrite filling some vugs.

**5802.2**

Wackestone—Solution Breccia— 25% intraclasts 0.2-25mm some are coated, 20% oncoids 2-8mm, 5% ooids radially fibrous—most are broken, 5% peloids, 15% micrite, 18% calcite cement 1) fibrous filling shelter and lining vugular porosity 2) blocky lining and filling vugs, 1% anhydrite filling vugs, 1% dolomite replacing some allochem laminae, 6% vugular—moldic and intercrystalline porosity. Some matrix is geopetal. Poorly sorted allochms in part due to solution of matrix. Two thin caliche crusts.

**5804.7-5811.0**

Wackestone interbedded with Anhydrite— Light—medium gray—tan, medium—thin bedded, intraclastic, pisolitic, many desiccation fractures filled with anhydrite, slight isolated vugular porosity. Thin bedded massive texture anhydrite zones.

**NDGS # 5244**

In Sherwood Argillaceous Marker

**5378.0—5387.0**

Dolomudstone— Dark gray, thick—medium—distorted bedded, very silty, very argillaceous, nodular anhydrite at top.

**5385.5**

Dolomudstone— 85% microdolomite, 10% siliciclastic clay, 5% quartz silt scattered throughout, trace micrite in clay concentrations.
Sherwood Beds

5387.0-5397.0  Dolomudstone- Tan-light gray-patterned, laminated-thick bedded, clean, very anhydritic in part, interbedded with Mudstone-Packstone- Tan-medium gray, moderately-poorly sorted, oolitic, pisolithic, intraclastic, very anhydritic with anhydrite vug and fracture fill, allochems micritized. One large clay seam, many microstylolites, one thin stromatolite boundstone.

5392.4  Solution Breccia- 33% ooids radially fibrous-compacted, 30% intraclasts 0.4-4mm-alternating radially fibrous and micritic gravity cements coating larger clasts, 2% peloids, 5% micrite, trace blocky calcite cement filling late small vugs, 30% anhydrite filling matrix selective vugs and replacing matrix. Moderately sorted although anhydrite may have replaced smaller allochems. Overpacked due to solution of matrix and to pressure solution with sutured grain-grain contacts.

5396.0  Recrystallized dolomitic, anhydritic, siliceous Carbonate- 20% micrite and allochem ghosts, 15% microdolomite replacing micrite, 35% anhydrite replacing carbonate in upper portion of slide, 30% silica replacing allochem ghosts and anhydrite nodules in lower portion of slide. A few siliceous ooids floating in anhydrite in upper part of slide. Order of diagenesis: 1) dolomitization and compaction, 2) anhydrite replacement, 3) silica replacement.

5397.0-5404.5  Wackestone-Packstone-Intraformational Breccia- Brown gray-tan, thin-medium bedded, poorly sorted, pisolithic, oolitic, intraclastic, very anhydritic in part with anhydrite filling desiccation fractures and vugs. Many thin hardgrounds and calciche crusts. Slight-good vugular porosity, several open diagonal and vertical fractures. Oil stain in vugs and fractures.

TS4 5399.0  Wackestone-Solution Breccia- 10% intraclasts 0.2-2mm, 5% oncoids 2-4mm, 50% micrite, 15% calcite cement 1) fibrous
filling fenestrae and lining some vugs
2) blocky vug fill-just prior to anhydrite, 15% anhydrite filling vugs and replacing carbonate, 1% microdolomite replacing allochems, 4% enlarged fenestrae and vugular porosity. Very high original fenestral porosity. Overpacking at base of slide due to solution of matrix.

5404.5-5411.5 Mudstone-Packstone-Grainstone- Tan-light gray, medium-thin low angle-horizontal bedded, poorly sorted, pisolithic, oolitic, intraclastic, very anhydritic in part with large nodules and anhydrite cementing desiccation fractures-fenestral and vug porosity, partially recrystallized, several type I stylolites and many microstylololites, slight vugular porosity, open vertical and diagonal fractures with oil stain.

TS5 5407.0 Grainstone-Packstone- 26% ooids tangential, 20% intraclasts 0.2-2mm, 10% peloids, 10% micrite matrix in some beds, 20% calcite cement 1) fine blocky filling interparticle porosity, 2) coarse blocky filling vugs, 8% anhydrite filling vugs, 2% microdolomite replacing some allochems, 4% vugular and some interparticle porosity. Well-moderately sorted.

TS6 5409.0 Dolomudstone- Trace ostracodes and calcispheres, 40% microdolomite replacing micrite, 15% micrite, 30% anhydrite small rhombs after gypsum, 10% pseudospar recrystallizing micrite, trace pyrite, 5% intercrystalline and moldic porosity.

5411.5-5425.0 Packstone-Wackestone-Intraformational Brecchia- Tan-light gray, thin-medium bedded-laminated, poorly sorted, intraclastic, pisolithic, oolitic, anhydrite cementing vugs and desiccation factures, calcite cementing fenestrae, dense-slight matrix selective vugular porosity, scattered oil stain. One thin laminated stromatolite.

TS7 5414.0 Packstone- 47% ooids tangential, 15% intraclasts 0.2-1mm, 2% peloids, <1% calcispheres, 20% micrite, 15% calcite
cement 1) micritic gravity on larger intraclasts 2) fibrous cement and fenestrae fill, 3) late blocky cement filling fenestrae and vugs, trace dolomite replacing parts of some allochems, 1% moldic and vugular porosity. Moderately sorted, overpacked in part due to solution of matrix.

TS8 5418.0  
Wackestone- 30% intraclasts 0.2-3mm, 5% peloids, <1% calcispheres, 50% micrite, 9% calcite cement 1) early micritic gravity cement 2) late blocky cement filling vugs and fractures, <1% dolomite forming along microstylolites, 5% anhydrite latest vug and fracture fill, 1% small vugular porosity.

NDGS # 5308

In Sherwood Argillaceous Marker

5354.0-5357.5  
Dolomudstone- Medium-light gray-mottled in part, argillaceous, silty, slightly anhydritic with brown crystalotopic texture, large type I stylolite.

5355.2  
Dolomudstone- 93% microdolomite with 40-60µ floating subhedral rhombs, 5% quartz silt angular, 2% siliciclastic clay, trace pyrite. Evenly disseminated silt and dolomite rhombs.

Sherwood Beds

5357.5-5362.0  
Mudstone interbedded Wackestone- Tan-light gray-mottled in part, medium-thin bedded, oolitic, crystalotopic anhydrite.

5361.0  
Solution Breccia-Wackestone- 25% ooids-sub sphero id with alternating radially fibrous and micritic gravity cements, 9% peloids, 2% intraclasts 0.2-0.4mm-most have radially fibrous outer coat, 35% micrite, 1% blocky calcite cement filling small vugs, 25% anhydrite filling vugs and replacing adjacent carbonate, 2% dolomite 50-100µ replacing matrix, 1% intercrystalline and small vugular porosity. Poorly sorted and overpacked due to solution of matrix.
5362.0-5365.3 Mudstone-Stromatolite Boundstone- Light gray-light brown gray, thick bedded-thinly laminated, intraclastic, partially dolomitized.

5365.3-5368.0 Packstone-Wackestone- Gray brown, thin-medium bedded, moderately sorted, oolitic, intraclastic, anhydrite fenestrae and vug fill, slight small vugular porosity, scattered oil stain.

5366.7 Wackestone-Solution Breccia- 20% intraclasts 0.2-1mm, 5% peloids, 5% pisoids with alternating radially fibrous and micritic gravity cements, 50% micrite, 1% blocky calcite cement filling vugs, 4% matrix selective vugular porosity. Reorientation of many allochems due to solution of matrix.

5368.0-5374.0 Mudstone-Wackestone- Light gray-tan, thin to thick-distorted bedded, intraclastic, dolomitic in part, large type I stylolites.

5374.0-5378.0 Dolomudstone interbedded Dolomitic Wackestone- Tan-light gray-mottled, thin bedded, poorly sorted. Possible algal depositional control. Patterned texture in dolostone caused by diagenesis.

5378.0-5386.5 Packstone-Mudstone- Tan-brown-light gray, thin-medium bedded, poorly sorted, intraclastic, pisolitic, fair matrix selective vugular porosity filled in part by anhydrite, scattered oil stain.

5380.2 Wackestone- 30% intraclasts 0.2-2mm some with micritic gravity cements, 10% peloids, trace calcispheres, 40% micrite, 1% blocky calcite cement filling vugs, 5% microspar, 5% anhydrite filling vugs and fenestrae, <1% microdolomite replacing some intraclasts, 9% mostly matrix selective vugular porosity.

5386.5-5396.5 Packstone-Wackestone-Intraformational Breccia- Light gray, pisolitic, anhydrite filled fenestrae, calcite and anhydrite filled vugs, calcite filled fractures, slight vugular porosity, slight oil staining, many microstylolites.
TS5 5392.0  Intraformational Breccia- 15% intraclasts 0.2-6mm, 10% peloids, 10% pisoids 1.5-6mm, 40% micrite, 15% calcite cement 1) micritic gravity cements on some grains 2) bladed lining fenestrae 3) blocky filling vugs and fractures, 5% microspar, 5% mostly matrix-selective vugular porosity. Realignment and overpacking of some zones due to solution of matrix. Separated by overlying mudstone by disconformity.

K-1 Marker

5396.5-5398.0  Mudstone-Stromatolitic Boundstone- Light gray, thin-medium bedded, silty in part

TS6 5397.0  Stromatolite Boundstone- 65% peloids, trace calcispheres and ostracodes, 15% micrite, 15% calcite cement filling fenestral-interparticle and moldic porosity, 3% matrix selective vugular porosity. Thinly laminated. Pustular texture in part.

In Bluell Beds

5483.6-5485.5  Anhydrite- Light-dark gray, massive-uneven bedded with distorted dolomitic clay laminae. Disseminated pyrite in part.

5485.5-5486.0  Dolomudstone- Tan-medium gray-mottled, argillaceous, nodular anhydrite.

5486.0  Dolomudstone- 80% microdolomite, 15% siliclastic clay, 3% anhydrite in subfelted nodules, 1% quartz silt, <1% pyrite. Overlain by subfelted massive anhydrite. Concentration of clay at disconformity. Clay laminae do not bend around anhydrite nodules.

5486.0-5490.0  Shale- Dark gray, blocky-platy, firm dolomitic in part, many anhydrite nodules.

5486.5  Shale- 35% siliciclastic clay, 40% anhydrite-nodular mosaic-felted texture, 25% microdolomite-scattered in clay, 1% quartz silt, <1% pyrite. Clay distorted by anhydrite.
5490.0-5498.0  Anhydrite- Light-dark gray-mottled, small ‘chicken wire' texture with many distorted argillaceous dolomite laminae.

5496.5  Distorted nodular mosaic Anhydrite with argillaceous Dolostone matrix- 75% anhydrite-felted-subfelted, 20% microdolomite and euhedral dolomite rhombs, 3% siliciclastic clay, 1% quartz silt, <1% pyrite.

5498.0-5505.4  Dolomudstone- Tan with patterned texture in part, abundant anhydrite nodules, 10cm laminated stromatolite.

5498.0  Dolomudstone- 90% microdolomite with larger rhombs associated with microstylolites, 5% anhydrite disseminated in matrix, 3% micrite-scattered, 2% quartz silt scattered through mudstone. Thinly laminated-possible algal origin.

5505.4-5507.5  Dolomudstone- Dark brown, laminated, rare anhydritic nodules. Oil saturated except in anhydritic areas. Slight intercrystalline porosity.

5507.0  Dolomudstone- 1% ooids-silicified and floating in anhydrite, <1% peloids, 74% microdolomite, 10% anhydrite from gypsum laths, 10% pseudospar, 5% microspar, trace pyrite, 1% intercrystalline porosity.

5507.5-5509.0  Dolomudstone interbedded with Wackestone- Light gray-tan, thin-medium bedded, well sorted allochems, Large type I stylolite at base.

5508.3  Wackestone- 25% intraclasts 0.2-2mm, 20% pseudo ooids radially fibrous, 15% peloids, 10% micrite, 30% microdolomite replacing matrix. Many allochems are broken. Overpacking in some zone due to solution of matrix.

5509.0-5511.0  Dolomudstone- Light gray-tan, thick bedded, abundant floating anhydrite laths after gypsum.

0-5513.0  Grainstone- Light gray-tan, medium bedded, well sorted, oolitic, slight interparticle porosity, slight oil staining in
porosity and along closed vertical fracture.

**TS7 5512.1**  
Grainstone- 30% ooids radially fibrous and tangential with micrite envelopes, 15% peloids, 15% intraclasts 0.2-8mm, 3% micaceous envelopes, 32% calcite cement 1) isopachous fibrous pore lining 2) blocky pore filling, 2% anhydrite replacing carbonates, 3% interparticle porosity—possibly solution of primary cement.

**Sherwood Argillaceous Marker**

5513.0-5516.8  
Dolomudstone- Medium gray-tan-mottled in part, thin-medium-distorted bedded, very argillaceous.

**TS8 5516.0**  
Dolomudstone- 90% microdolomite, 4% siliciclastic clay, 3% pseudospar, 2% quartz silt, trace pyrite, 1% small vugular porosity.

**Sherwood Beds**

5516.8-5518.0  
Wackestone- Tan, thick bedded, oolitic, peloidal, small type I stylolites.

**TS9 5517.0**  
Wackestone- 25% ooids radially fibrous-tangential and with micrite envelopes, 10% peloids, 5% intraclasts 0.2-8mm, 5% oncoids 2-3mm, 1% pisoids 2-4mm micritic and radially fibrous, 35% micrite, 15% calcite cement; 1) fibrous lining vugs 2) blocky filling vugs, 2% microdolomite replacing grains and matrix, 1% anhydrite replacing carbonate, <1% intercrystalline porosity. Poorly sorted and overpacked in part due to solution of matrix.

**NDGS # 5771**

**In Bluell Beds**

5466.0-5468.7  
Anhydrite- Medium-light gray, nodular-mosaic texture, argillaceous dolomite matrix.

5468.7-5475.5  
Dolomudstone- Tan-light gray-mottled, very argillaceous, very anhydritic in part with large nodules.
<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5472.0</td>
<td>Dolomudstone- 65% microdolomite, 30% siliciclastic clay, 2% quartz silt, 2% microspar, &lt;1% pseudospar, &lt;1% anhydrite, trace pyrite. Upper part of thin section has microstylolite swarm. Laminated.</td>
</tr>
<tr>
<td>5475.5-5483.4</td>
<td>Anhydrite- Medium-light gray, thick-thin bedded-mosaic texture, much soft sediment deformation. Interbedded with Dolomudstone- Tan, laminated, very anhydritic with crystalloclastic texture.</td>
</tr>
<tr>
<td>5482.6</td>
<td>Anhydrite- 85% euhedral anhydrite after gypsum crystals, 13% siliciclastic clay, 2% microdolomite. Some compaction with clay laminae bending around anhydrite crystals.</td>
</tr>
</tbody>
</table>

**Sherwood Argillaceous Marker**

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>5483.4-5488.5</td>
<td>Dolomudstone- Light-dark gray-tan-mottled, Very-moderately argillaceous, two microstylolite swarms.</td>
</tr>
<tr>
<td>5484.6</td>
<td>Dolomudstone- 80% microdolomite, 10% quartz silt, 4% siliciclastic clay, 3% pseudospar, 3% intercrystalline porosity, trace pyrite.</td>
</tr>
</tbody>
</table>

**Sherwood Beds**

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>5488.5-5490.1</td>
<td>Wackestone-Mudstone- Light gray-tan, thin bedded, oolitic, pisolitic, poorly to moderately sorted, slight interparticle porosity.</td>
</tr>
<tr>
<td>TS4 5489.2</td>
<td>Packstone-Solution Breccia- 30% peloids, 25% ooids radially fibrous with micritic envelopes, 15% intraclasts Ø.2-2mm with radially fibrous and micritic gravity cements, &lt;1% calcispheres, &lt;1% pisoids radially fibrous, 2% micrite-envelopes and geopetal, 15% dolomite replacing matrix, 7% anhydrite replacing dolomite and after gypsum laths, &lt;1% quartz silt, &lt;1% pseudospar, 5% interparticle-vugular and moldic porosity. Realignment and overpacking of grains due to matrix solution. Later compaction of grains with sutured grain-grain contacts after partial lithification. Dolomitization of micrite followed by anhydrite replacement. Solution-enhanced porosity.</td>
</tr>
</tbody>
</table>
5490.1-5490.8 Dolomudstone- Tan-slightly mottled, slightly argillaceous.

5490.8-5497.5 Wackestone-Packstone- Tan-light gray, thin-medium bedded, moderately sorted, intraclastic, oolitic, anhydritic in part, dense-slight oomoldic porosity.

5491.0 Packstone- 35% peloids, 20% ooids micritized-radially fibrous and tangential, 10% intraclasts 0.2-2mm, 1% calcspheres and blue-green algae, 6% micrite, 20% microdolomite replacing matrix, 5% pseudospar, 1% anhydrite filling vugs, 1% vugular and interparticle porosity. Poorly sorted. Realignment and overpacking of allochems due to matrix solution. Dolomitization of matrix. Later partial anhydrite vug filling.

5494.0 Wackestone- 15% peloids, 2% calcspheres, trace ostracodes, 68% micrite, 1% calcite cement filling vugs and moldic porosity, 8% microdolomite replacing matrix, 2% anhydrite filling vugs, 1% pseudospar, 3% vugular-moldic and interparticle porosity. 1) lithification, 2) dolomitization and development of small vugular porosity, 3) infill of some vugs with anhydrite, 4) infill of other vugs with calcite.

5496.6 Solution Breccia-Wackestone- 25% peloids, 20% ooids micritized, 10% intraclasts 0.2-1mm rounded with radially fibrous or micritic coat, trace calcspheres, 30% micrite, 2% blocky calcite cement filling vugs, 5% microdolomite euhedral rhombs in beds, 3% anhydrite filling vugs trace pyrite, 5% vugular-intercrystal-line and moldic porosity. Moderately-well sorted. Thin beds of realigned allochems with matrix dissolved separated by thin beds of dolomitized wackestone.

5497.5-5501.0 Packstone-Wackestone- Tan-medium brown, thin bedded, poorly-moderately sorted, oolitic, pisolithic, anhydritic.

TS8 5498.0 Solution Breccia- 40% pisoids 1-8mm spherical with intraclast nuclei and alternating radially fibrous and micritic
laminae, 15% intraclasts 0.2-3mm, 10% peloids, 10% micrite, 5% calcite cement filling vugs, 15% anhydrite replacing micrite and filling vugs, 5% dolomite replacing laminae in allochems, <1% vug-ular and moldic porosity. 1) solution of matrix causing overpacking and realignment of grains, 2) lithification, 3) partial dolomitization, 4) solution of more matrix, 5) anhydrite cementing vugs, 6) replacement of some matrix with anhydrite, 7) cementation of remaining vugs with calcite. Poor-well sorted.

5501.0-5508.5 Packstone-Wackestone- Tan-cream-light gray, thin-medium bedded, well-moderately sorted, oolitic, peloidal, fossiliferous, crystallotopic anhydrite increasing towards base, slight-fair interparticle and oomoldic porosity, traces of oil stain.

5503.0 Wackestone- 15% intraclasts 0.2-3mm, 10% peloids, <1% calcispheres, 60% micrite, 10% anhydrite filling vugs and replacing adjacent carbonate, 7% microspar 3% microdolomite replacing matrix, 5% vugular and moldic porosity. Higher percentage of anhydrite replacement of matrix than previous slides.

TS10 5505.0 Mudstone- 75% micrite, 20% microdolomite in scattered euhedral rhombs, 3% quartz silt, 2% microspar, trace pyrite, <1% vugular porosity.

TS11 5507.5 Wackestone- 20% peloids, 3% intraclasts 0.2-1mm, 45% micrite, 12% anhydrite after gypsum, 2% dolomite replacing some matrix, 8% vugular porosity. Large floating gypsum laths in matrix.

5508.5-5516.0 Mudstone-Wackestone- Medium-light gray-tan, brecciated-distorted and compacted, intraclastic, very anhydritic in part, oolitic in part, dense-slight moldic and small vugular porosity.

5510.0 Dolowackestone- 10% intraclasts 0.2-2mm, 7% peloids, 5% micrite, 60% microdolomite replacing allochems and matrix, 15% anhydrite-crystallotopic and late pore filling, 3% matrix selective vugular and moldic porosity.
TS13 5512.7  Solution Breccia- 45% intraclasts 0.2-4mm with radially fibrous outer coat, 15% peloids, 5% ooids radially fibrous, <1% calcispheres, 15% micrite, 3% blocky calcite cement filling vugs, 5% microdolomite, 7% anhydrite filling vugs and replacing carbonate, 5% vugular porosity. Poorly sorted and overpacked allochems due to solution of matrix.

TS14 5515.7  Anhydritic Dolomudstone- 45% microdolomite, 50% crystallotopic anhydrite and replacing matrix, 4% micrite scattered through matrix, 1% siliciclastic clay, 1% intercrystalline porosity.

5516.0-5519.2  Anhydrite- Light-medium gray, medium-thick bedded massive texture interbedded with Stromatolite boundstone- Tan-brown, crystallotopic anhydrite.

TS15 5517.4  Stromatolite Boundstone- 70% micrite in 1-4mm laminations, 27% anhydrite replacing some carbonate, 3% microdolomite replacing micrite. Pustular texture in part.

NDGS # 5803

In Sherwood Argillaceous Marker

5425.0-5430.0  Dolomudstone- Medium gray, massive-distorted thin beds, very argillaceous, silty, sandy.

TS1 5427.5  Dolomudstone- 75% microdolomite, 10% anhydrite after gypsum laths, 10% quartz silt, 5% siliciclastic clay, trace pyrite.

Sherwood Beds

5430.0-5439.5  Mudstones interbedded with Packstones and Grainstones- Gray brown-tan, very thin-medium bedded, horizontal-low angle cross bedding, reverse-nongraded, oolitic, pisolitic, poor-well sorted, anhydrite replacing carbonate in upper zone, partial dolomitization of some mudstone.

TS2 5434.7  Packstone- 45% ooids radially fibrous-many are broken, 15% peloids, 25% micrite, 5% blocky calcite cement filling
1) sheltered and interparticle porosity  
2) vugular porosity, 15% anhydrite filling vugs. Ooids are well sorted. 
Trace of micritic meniscus cement.

5436.6 Grainstone-Packstone overlain by Mudstone-  
60% ooids radially fibrous-overpacked, <1% peloids, 20% micrite-mostly forming meniscus cement, 20% anhydrite cementing ooid grainstone and filling vugs, <1% calcite cement filling vugs. Micrite has partially filled grainstone interparticle porosity and increases % towards mudstone-grainstone contact, indicating mudstone was deposited before grainstone was cemented. Well sorted allochems. Anhydrite is secondary and is filling orthochem-selective vugular porosity.

5439.5-5442.0 Dolomudstone- Cream-tan-mottled in part, some allochem ghosts, anhydritic, interbedded with Wackestone- Tan, recrystallized oolitic, intraclastic, partially dolomitized.

TS4 5440.5 Wackestone- 15% intraclasts 0.2-2mm, trace ostracodes and calcispheres, 65% micrite, 1% calcite cement filling vugs, 10% dolomite replacing micrite, 5% anhydrite, 4% small vugular porosity.

5441.8 Packstone overlain by Dolomudstone- 20% intraclasts 0.2-1mm- many are dolomitized, 10% peloids, 15% micrite, 35% microdolomite replacing micrite above stylolite-allochems below stylolite, 2% calcite spar filling vugs, 13% microspar, 5% vugular and intercrystalline porosity. Moderately sorted allochems.

5442.0-5446.5 Wackestone-Packstone- Medium-light brown, thin bedded, poorly sorted, oolitic, pisolithic, some thin distorted algal laminations, fenestrae filled with anhydrite, fair vugular porosity-mostly matrix selective, scattered oil stain.

5443.7 Wackestone- 15% oncoids 2-4mm micritized, 10% intraclasts 0.2-2mm, 5% ooids micritized-partially dolomitized, 35% micrite, 15% fine bladed calcite lining fenestrae, 5% anhydrite filling vugs and replacing carbonate, 3% dolomite
replacing some oncoid laminae and matrix, 12% enlarged fenestral and matrix-selective vugular porosity.

5446.0 Solution Breccia- 60% intraclasts 0.2-2mm-many with thin radially fibrous outer laminae, 4% calcispheres and trace of algae, 16% micrite, 3% calcite cement lining vugs, 17% matrix-selective vug porosity. Realignment and overpacking of grains due to matrix solution.

5446.5-5451.0 Dolomudstone- Medium-light gray-tan-mottled in part, thin-distorted bedded, anhydrite disrupting bedding, large stromatolite separating anhydrite rich muds from less anhydritic underlying muds, some floating allochems.

5449.2 Dolomudstone- 3% calcispheres, 45% microdolomite, 40% micrite, 7% anhydrite nodules, 5% intercrystalline-moldic and small vugular porosity.

0-5455.2 Wackestone-Packstone- Light brown-tan, thin bedded, poorly sorted, pisolithic (some may be vadose), many thin caliche crusts with one microtepee structure, high fenestral porosity filled with anhydrite

5453.5 Algal Boundstone- 30% intraclasts 0.2-3mm, 15% peloids, 8% fossils (70% algal structures, 30% calcispheres), 10% micrite, 10% calcite cement in two stages: 1) fibrous lining fenestrae 2) blocky in some large vugs, 15% microspar recrystallizing matrix, 12% fenestral and vugular porosity. Moderately sorted.

5455.2-5461.0 Mudstone interbedded with Wackestones and Packstone- Light gray-brown gray, medium-thin bedded, pisolithic, oolitic, mud-cracks and fenestrae filled with anhydrite, slight scattered vugular porosity. Sequences are cyclic and sometimes interrupted with stromatolite mat. Several type I stylolites and many type II stylolites. Base is ripped up intraclasts above mudstone.

TSL0 5457.0 Recrystallized Mudstone- 9% pseudo ooids-radially fibrous and tangential-mostly micritized, 30% micrite, 2% blocky
| TS11 5460.8 | Recrystallized Mudstone- 60% micrite, 3% calcite cement filling vugs, 25% psuedospar replacing micrite, 10% blocky anhydrite filling vugs and replacing carbonate, 2% microvugular porosity. Syntaxial pseudospar often connected by fracture systems. |
| 5461.0-5468.0 | Stromatolite Boundstone interbedded with Wackestone- Brown gray-tan, thin bedded vadose pisoids, large fenestrae filled with anhydrite, poor scattered vugular porosity. Abundant type II stylolites, rare type I stylolites. |
| TS12 5465.1 | Stromatolite Boundstone- 30% peloids, 15% intraclasts 0.2-5mm-most have fibrous rim, 5% oncoes 1-4mm-spherical, 10% micrite, 8% calcite cement-two generations 1) fine fibrous rim cement 2) blocky fenestral fill, 20% microspar, 12% bladed anhydrite filling vugs. Thin distorted beds- spaced laterally linked hemispherestromatolites. |
| 5468.0-5470.5 | Mudstone- Light gray, thick bedded, large floating intraclasts-possibly algal colonies, dolomitized in part. |
| TS13 5469.8 | Partially Dolomitized Algal Boundstone- 10% peloids, 15% micrite, 20% microspar, 50% microdolomite replacing micrite, 5% anhydrite filling vugs. |
| K-1 Marker | Dolomudstone- Medium gray, thin-medium bedded, some disrupted bedding, some laminations may be recrystallized stromatolite, argillaceous, very anhydritic in part, several clay seams, sandy. |
| TS14 5471.8 | Sandy Dolomudstone- 31% quartz sand, 1% K feldspar sand, 37% dolomicroite matrix, 21% celestite cement, 7% siliciclastic clay, 2% calcite cement, |
1% anhydrite cement. Grains are angular and moderately well-sorted.

**NDGS # 5827**

**In Bluell Beds**

5305.0-5319.2  Anhydrite- Medium gray, fine mosaic with nonbedded nodular texture, interbedded with Dolomudstone- Tan, thin distorted beds, anhydritic becoming very argillaceous at base.

**Sherwood Argillaceous Marker**

5319.2-5322.5  Dolomudstone- Medium gray-mottled at base, massive-medium bedded, very argillaceous very silty, dark gray blebs scattered throughout.

TS1 5320.8  Dolomudstone- 55% dolomite 1) microdolomite 2) floating subhedral rhombs, 35% anhydrite euhedral laths floating in matrix, 5% siliciclastic clay, 2% quartz silt, trace pyrite, 3% intercrystalline porosity.

**Sherwood Beds**

5322.5-5325.8  Stromatolite Boundstone- Light brown gray, thinly laminated, peloidal, anhydrite crystals along several bedding planes and vertical fractures, slightly argillaceous, interbedded with Dolomudstone-Tan-light gray-mottled, very argillaceous.

TS2 5325.0  Packstone- 60% ooids mostly micritized and compacted, 10% intraclasts 0.3-2mm, 1% calcispheres concentrated in thin laminae, rare ostracode, 20% micrite, 2% calcite cement filling interparticle-vugular and moldic porosity, 5% microdolomite replacing matrix and parts of some allochems along bedding planes, trace pyrite concentrated along microstylolites, 2% moldic-intercrystalline and small vugular porosity. Moderately sorted, overpacked due to some solution of matrix.

5325.8-5331.0  Dolomudstone- Tan-olive gray-mottled,
thin-medium distorted bedded, floating ooids and intraclasts, interbedded with Mudstone-Wackestone-Packstone- Tan, thin bedded, moderately sorted, oolitic, intraclastic, partially dolomitized, trace of oil stain.

5331.0-5344.5 Dolomudstone- Tan-brown-olive gray, very thin-thick bedded, very anhydritic in part with crystallotopic texture and filling vertical fractures, argillaceous in part, dense-good fine intercrystalline porosity, interbedded with Wackestone-Stromatolite Boundstone- Wavy laminae, intraclastic in part, very dolomitic in part, very anhydritic in part, dense-fair intercrystalline porosity, oil saturated in both types of rock.

TS3 5339.5 Dolomudstone- 30% micrite, 65% dolomite replacing micrite in two sizes 1) micro-dolomite <4μm and sub-euhedral rhombs 50-100μm, 1% anhedral anhydrite replacing carbonate, 4% intercrystalline porosity.

TS4 5341.8 Stromatolite Boundstone- 30% intraclasts 0.2-1.5mm, 20% peloids, 15% micrite, 10% calcite cement-3 stages 1) primary fibrous fenestrae fill- 2) fibrous vug lining- 3) blocky vug fill, 25% blocky anhydrite filling solution enlarged fenestrae. Micrite arranged in wispy laminae and around allochems, no compaction, pustular texture.

5344.5-5355.4 Wackestone-Packstone-Stromatolite Boundstone- Thin-medium bedded, poorly-well sorted, oolitic, pisolitic, several caliche profiles, desiccation cracks, spaced laterally linked hemisphere stromatolites, several type I stylolites, many microstylolites, fair-good vugular porosity in part, oil stained in part.

TS5 5350.2 Stromatolite Boundstone- 30% peloids, trace calcispheres and ostracodes, 45% micrite, 20% calcite cement; 1) fibrous lining fenestrae 2) fibrous lining vugs 3) blocky filling vugs, 5% vugular porosity-may be due to solution of cement. Pustular-distorted blister stromatolite texture, originally with very high primary fenestral porosity.
Stromatolite Boundstone interbedded with Wackestone- 35% peloids, 7% fossils (75% calcispheres- 25% ostracodes), 5% intraclasts 0.2-1mm, 25% micrite, 25% calcite cement 1) fibrous filling fenestrae 2) fibrous-bladed lining vugs 3) blocky filling vugs, <1% anhydrite replacing carbonate, 3% moldic and vugular porosity. Pustular texture in boundstone.

Packstone- 23% peloids, 20% intraclasts 0.2-2mm, trace of fossils (calcispheres-ostracodes and blue-green algae), 25% micrite, 20% calcite cement 1)fibrous lining fenestrae 2)blocky vug fill, 12% enlarged fenestral porosity. Many fenestrae later enlarged and then filled with blocky cement.

NDGS # 6157

In State A Marker

Dolomudstone- Light-dark gray, thick-finely laminated at base, many microstylololites and clay seams, very argillaceous, pyritic at base.

Dolomudstone grading into Anhydrite- 80% microdolomite, 14% anhydrite at base of slide, 5% quartz silt, 1% siliciclastic clay. Horizontally oriented gypsum crystals indicate early compaction.

Bluell Beds

Anhydrite- Light gray, massive with occasional distorted dolomite laminae.

Anhydrite- Light gray nodular with dark gray very argillaceous dolomicrite matrix. Matrix contains many small disseminated euhedral anhydrite crystals.

Anhydrite- 80% anhydrite 1)after euhedral gypsum crystals- 2)subfelted textured nodules, 18% microdolomite, <1% siliciclastic clay, <1% quartz silt.

Anhydrite- Light-dark gray bedded distorted nodular texture, interbedded with Dolomudstone-Tan, distorted bedded, slight intercrystalline porosity.
TS3 5592.0

Anhydrite- 95% bedded massive anhydrite with subfected texture, 3% microdolomite, 2% siliciclastic clay.

5597.6-5600.0

Mudstone-Wackestone-Algal Boundstone-Tan, thin-medium bedded, gypsum crystals growing up through carbonate mud, dolomitic, some intraformational brecciation due to gypsum growth, stromatolitic in part.

TS4 5598.0

Packstone-Wackestone- 30% calcispheres, 20% peloids, trace broken ooids, 25% micrite, 7% blocky calcite cement filling moldic and intraparticle porosity, 15% anhydrite replacing micrite, 3% microdolomite replacing micrite. Thin bedded, moderately sorted Some calcispheres are slightly compacted, others micritized.

5600.0-5605.0

Dolomudstone- Tan-light-medium gray-mottled, laminated in part, isolated anhydrite nodules to thin beds of anhydrite, many stylololite swarms, becoming more stromatolitic at base, slight intercrystalline porosity.

TS5 5601.0

Wackestone- 25% intraclasts 0.2-1.5mm-angular- compacted- some with broken outer fibrous coat, 2% peloids, 1% ooids-flattened, 27% micrite, 25% microdolomite replacing matrix and some allochems, 10% anhydrite replacing matrix-allochems and some dolomite and filling fractures. Compaction features- 1) flattened allochems 2) microstylolite swarms 3) massive dolomitization.

5605.0-5607.0

Dolomudstone- Dark brown, thin bedded, anhydritic, slight intercrystalline porosity, oil saturated.

5605.0

Dolomudstone- 70% microdolomite, 28% anhydrite- distorted nodules and filling desiccation fractures, 2% siliciclastic clay concentrated in microstylolite swarms.

5606.5

Dolomudstone- 90% microdolomite, 10% anhydrite scattered through matrix.

5607.0-5608.0

Dolomudstone- Light gray, thick bedded, anhydritic, dense-slight intercrystalline
porosity.

TS8 5607.5  
Dolomudstone- Trace floating allochem ghosts, 70% microdolomite, 10% micrite, 20% anhydrite filling intercrystalline porosity and replacing rare allochem. Anhydrite crystallization is prior to oil migration.

NDGS # 6344

In Bluell Beds

5117.0-5121.2  
Anhydrite- Blue gray, massive, argillaceous in part, traces of distorted dolomitic laminae.

5120.0  
Anhydrite- 98% felted anhydrite, 1% subhedral dolomite-disseminated, <1% siliciclastic clay, <1% pyrite.

5121.2-5125.3  
Anhydrite- Light gray, thin bedded to nodular with clay seams, interbedded with Shale- Light green, platy, subwaxy, firm to soft, pyritic, very dolomitic, and with Dolomudstone- Light gray, thin-medium bedded-distorted in part, some thin microstylolites and clay partings.

5124.3  
Dolomudstone- 96% microdolomite, 2% quartz silt, 1% siliciclastic clay, 1% pyrite. Microstylolite seams at base of slide with increased concentrations of quartz silt, silica clay, organic matter, and pyrite.

Sherwood Argillaceous Marker

5125.3-5128.0  
Dolomudstone- Medium gray-tan, patterned in lower interval, massive-distorted bedded, very argillaceous in part becoming cleaner at base, grading into limestone.

5126.0  
Algal Boundstone- 40% fossils (50% algae Garwoodia, 15% Ortonella, 5% unidentified calcareous algae, 20% calcispheres, 5% ostracodes), 10% peloids, 5% intraclasts 0.2-0.6mm, 4% micrite, 8% calcite cement filling pores, 2% microporous, 25% anhydrite filling vugs-fractures-intraparticle and moldic porosity and replacing micrite, 6% moldic vugular-intraparticle and interparticle porosity.
5127.5 Packstone- 50% peloids, 13% fossils (60% algae-mostly micritized, 20% calcispheres and 20% ostracodes), 10% intraclasts 1-25mm often algal coated, 2% micrite, 15% calcite cement 1) blocky filling intraparticle and sheltered porosity 2) blocky filling vugs, 10% anhydrite replacing micrite and filling some intra-particle porosity, 1% interparticle-vugular and intraparticle porosity.

5128.0-5131.0 Mudstone- Tan-medium gray-brown, thick-thin-distorted bedded, trace of algal structures growing over contorted massive micrite containing gypsum laths, very argillaceous in part, very dolomitic and grading into dolomudstone in part.

5129.3 Dolomudstone- 75% microdolomite, 20% micrite, 4% quartz silt, <1% pyrite. Dolomite and calcite thoroughly disseminated (protodolomite?). Pyrite and organic matter form patterned texture.

Sherwood Beds

5131.0-5139.0 Wackestone- Tan, thick-thin bedded, fossiliferous, anhydritic in part, fair intraparticle-moldic and small vugular porosity, oil saturated.

5131.2 Dolomudstone- 50% microdolomite, 25% micrite, 15% anhydrite, 4% pyrite in laminae, 2% quartz silt-scattered, 2% pyrolusite in dendritic patterns. Laminated.

5135.0 Wackestone- 43% intraclasts 0.2-8mm most coated with micritic gravity cements, 1% algae-micritized, 31% micrite, 5% calcite cement 1) fibrous filling fenestrae and lining vugs 2) blocky filling vugs, 20% anhydrite replacing micrite. Many microstylolites bend around allochems. Anhydrite is secondary (even subsequent to stylolitization) and distorts some thin bedding in micrite.

5138.3 Algal Boundstone- 40% fossils (90% Ortonella, 10% ostracodes, <1% inarticulate brachiopod), 45% micrite, 22% blocky calcite cement filling intraparticle porosity and vugs, 1% anhydrite replacing micrite, 3% intraparticle-vugular
and interparticle porosity. Algal encrustations over mudstones. Slight compaction causing broken ostracode shells.

5139.0-5147.5 Mudstone Breccia- Tan-light gray, thin-medium-distorted bedded, numerous caliche crusts, some pendant cement, many cemented desiccation fractures up to 50cm deep ending in caliche zones, rare anhydrite inclusions.

TS9 5142.6 Wackestone- Algal Boundstone- 44% fossils (70% micritized blue-green algae, 24% micritized green algae, <1% bivalves, <1% ostracodes), 10% peloids, 5% oncoids 2-6mm, 15% micrite, 25% calcite cement 1) fibrous filling fenestrae 2) fine bladed lining vugs 3) blocky filling vugs, 1% vugular and interparticle porosity. Pustular texture in part.

TS10 5146.3 Silicified Grainstone- 45% intraclasts Ø.2-3mm, 20% ooids tangential-mostly micritized, 2% oncoids 1-2mm, 1% peloids, 2% micrite envelopes, 30% calcite cement two generations 1)fibrous primary 2)blocky secondary, 40%crypto-crystalline quartz replacing ooids-intraclasts and some cement, 1% vugular-interparticle-fracture and moldic porosity. Moderately sorted allochems.

5146.3-5149.0 Mudstone interbedded with Grainstone- Medium gray- brown, thick bedded with distorted bed boundaries, fossiliferous, dense-fair intraparticle and interparticle porosity, oil saturated in grainstone.

TS11 5148.3 Packstone-Wackestone- 30% peloids, 20% intraclasts Ø.2-1.5mm, 4% fossils (60% algae, 20% calcispheres, 20% ostracodes, 1% brachiopod), 25% micrite, 1% blocky calcite cement filling vugs, 4% anhydrite filling vugs, 15% matrix selective vugular with trace of intraparticle porosity

5149.0-5150.4 Dolomudstone- Medium gray, thin bedded with beds dipping slightly.

5150.4-5153.1 Mudstone- Medium-light gray, interbedded many thin to thick beds of peloid and intraclast packstones and grainstones, abundant calcite filled fenestrae.
TS12 5151.6  Packstone-Wackestone- 30% peloids, 5% intraclasts 0.2-2mm, 1% ostracodes and calcispheres, 34% micrite, 30% calcite cement 1) fibrous filling fenestrae and shelter porosity 2) blocky filling vugs, <1% intercrystalline porosity. Distorted laminae may be stromatolites. Solution of high percentage of matrix.

5153.1-5160.2  Dolomudstone- Light gray, very thin bedded with clay seams to thick bedded with patterned texture, very argillaceous.

TS13 5158.6  Dolomudstone- 60% microdolomite, 39% disseminated micrite, <1% quartz silt, <1% siliciclastic clay, trace pyrite in blebs.

5160.2-5165.5  Mudstone-Wackestone- Tan-mottled, thick distorted bedded, intraclastic, partially dolomitized, anhydritic with large nodules to small euhedral inclusions, rare oil staining in dolomitized zones.

TS14 5160.3  Solution Breccia- 40% intraclasts 0.2-4mm many have alternating fibrous and micritic gravity cement laminae, 8% ooids-mostly micritized, 4% peloids, <1% calcispheres and ostracodes, 30% micrite, 15% anhydrite replacing carbonate, 2% dolomite in stylolite zone, trace pyrite, 1% intercrystalline and moldic porosity. Overpacked allochems due to solution of matrix. Many longitudinal, concavo-convex and sutured contacts.

TS15 5163.7  Dolowackestone- 15% peloids, trace ostracodes, 25% micrite, 30% microdolomite replacing micrite, 30% anhydrite disseminated in 0.1-0.2mm anhedral crystals, 5% vugular and intercrystalline porosity.

5165.5-5174.3  Anhydrite- Blue gray-light gray, massive-mosaic nodular texture, occasional distorted clay seams and dolomite laminae.

K-1 Marker

5174.3-5174.6  Mudstone- Dark-light gray, distorted bedded with clay seam dipping 45 degrees, very argillaceous, anhydritic, scattered pyrite.
In Bluell Beds

5990.0-5990.5 Mudstone- Light gray, thick bedded, recrystallized with occasional faint floating allochem ghosts, anhydrite filling small fractures and replacing carbonate.

TS1 5990.2 Wackestone- 35% intraclasts 0.2-4mm mostly micritized, 10% peloids, 40% micrite, 13% calcite cement blocky filling matrix and non-matrix vugular porosity, 2% anhydrite filling remaining vugs, <1% dolomite replacing micrite.

5990.5-5993.2 Dolomudstone- Light gray-slightly mottled, very argillaceous, silty, anhydritic in part, one large clay seam, slight-fair intercrystalline porosity with low permeability.

5992.8 Dolomudstone- 85% microdolomite matrix with floating 30-80um subhedral rhombs 4% siliciclastic clay, 4% quartz silt-angular, <1% pyrite scattered, 6% intercrystalline porosity.

5993.2-5994.3 Mudstone-Packstone- Light gray, thick bedded, poorly sorted, pisolithic, oolitic, recrystallized in part, partially collapsed fenestrae, sheltered-fenestral and pseudofenestral porosity filled with anhydrite.

5993.5 Grainstone- 33% peloids, 25% ooids micritic-tangential and radially fibrous, 7% oncoids 2-4mm, 5% intraclasts 0.3-1.5mm, 30% blocky calcite cement. No fibrous rim cement. Poorly sorted-bimodal with peloid matrix.

5994.3-5995.8 Mudstone- Mottled tan-medium gray, thin-medium bedded where present, heavily burrowed, very anhydritic.

TS4 5995.5 Mudstone- 3% peloids, trace calcispheres,
75% micrite, 20% microdolomite-especially in burrowed areas, 2% quartz silt.

**5995.8-5998.2** Wackestone-Packstone- Tan, thin bedded, poorly sorted, partially recrystallized oolitic, intraclastic, fossiliferous, anhydrite filled fenestrae-pseudofenestrae and small vugs, slight vugular porosity. Many microstylolites.

**TS5 5997.8** Packstone-Wackestone- 25% intraclasts 0.2-2mm, 15% peloids, 1% fossils (99% calcispheres, <1% calcareous algae, trace ostracodes), 67% micrite, 12% calcite cement in three generations l)fibrous primary 2)fibrous vug rim 3)blocky vug fill, 5% anhydrite filling vugs, 5% vugular porosity. Some zones originally had very high primary porosity of the 'pustular' type stromatolite. Anhydrite and blocky cement may be simultaneous.

**5998.2-6000.0** Mudstone- Tan-mottled, heavily burrowed, many calcispheres, anhydritic.

**TS6 5998.8** Wackestone- 25% peloids, 10% fossils (90% blue-green algae, 9% calcispheres, 1% ostracodes), 65% micrite, 7% microdolomite replacing micrite, 3% moldic porosity. No sorting or bedding.

**6000.0-6004.5** Packstone-Wackestone- Brown gray, thin-disrupted bedded, oolitic, pisolitic, intraclastic, anhydrite filled desiccation fractures some up to 3cm wide, walls of fractures lined with coated grains, fractures and stylolites disrupting bedding and fractures acting as pressure solution boundaries.

**6004.5-6008.0** Packstone-Wackestone-Grainstone- Medium gray, thin-thick bedded, poorly-well sorted, oolitic, intraclastic, anhydrite filled fractures-vugs and fenestrae, several large type I stylolites.

**6008.0-6010.5** Packstone-Grainstone interbedded with Wackestone- Tan, thin bedded, well to moderately sorted, oolitic, intraclastic, anhydrite cementing fenestrae and fractures.
In Rival Beds

6100.0-6100.8

Anhydrite- White, nodular interbedded with Dolomudstone- Medium gray, thin distorted bedded, very argillaceous.

TS1 6100.2

Anhydrite- 82% anhydrite subfelted, 10% micro dolomite in deformed laminae, 1% pyrite, <1% quartz silt, <1% siliciclastic clay, trace organic matter.

6100.8-6103.2

Wackestone- Tan-medium gray, intraclastic, anhydritic, argillaceous, recrystallized algal laminations, vertical fractures with oil stain.

TS2 6101.2

Wackestone- 30% peloids, 10% intraclasts 0.2-20mm, 5% fossils (50% ostracodes, 49% calcareous algae, <1% calcispheres), 5% micrite, 37% calcite cement-mostly fibrous-some blocky, <1% euhedral dolomite rhombs. Horizontally oriented allochems, and unbroken ostracodes. Calcareous hardground in center of slide with numerous vertical borings.

TS3 6102.2

Laminated Algal Boundstone- 40% peloids, 3% intraclasts 0.2-1mm, 1% fossils (50% ostracodes, 50% micritized algae), 55% micrite, <1% dolomite-subhedral rhombs in microstylolites, <1% anhydrite 1-3mm laths after gypsum, <1% quartz silt concentrated in stylolite seams, trace pyrite, 1% intercrystalline porosity. Horizontally oriented allochems. Microstylolite swarm. Many borings.

State "A" Marker

6103.2-6105.7

Packstone-Wackestone- Light-medium gray, intraclastic, oolitic, anhydrite filled fenestrae, dense-slight vugular porosity open vertical fractures with oil stain.

TS4 6103.4

Packstone- 40% intraclasts 0.2-2mm, 8% peloids, 17% micrite, 35% calcite cement filling vugs in two stages 1) trace fine bladed isopachous 2) large blocky fill, <1% intercrystalline porosity in vugs. Overpacking due to solution of much of matrix.
6105.5-6106.8 Wackestone-Mudstone- Tan, oolitic, peloidal, abundant calcite vug fill, several argillaceous zones with thin (<5cm) caliche crusts, dense-slight vugular porosity with oil stain.

6106.4 Packstone-Wackestone- 25% intraclasts 0.2-1.5mm micrite envelopes, 15% peloids, 35% micrite, 25% calcite cement filling fenestrae in two stages 1) fibrous isopachous 2) blocky, 2% microspar, <1% anhydrite replacing carbonate, 1% intercrystalline porosity. Unsorted allochems. Overpacking due to some matrix solution.

6106.8-6109.1 Packstone-Wackestone- Light gray-tan, medium bedded, moderately sorted, pisolitic, peloidal, oolitic, calcite vug fill dense-fair interparticle and vugular porosity in thin horizontal zones after fenestrae, scattered oil stain.

6109.0 Solution Breccia- 55% intraclasts 0.2-4mm with micritic gravity cements and fibrous coatings, 13% peloids, 2% micrite, 30% calcite cement in two stages 1) fibrous filling vugs 2) bladed filling vugs, 2% intercrystalline porosity in vugs. Many algal boring in intraclasts. Overpacked due to solution of matrix.

Blueell Beds

6109.0-6112.6 Packstone-Grainstone- Tan, medium-thick bedded, well-moderately bimodally sorted, occasional scattered large intraclasts, calcite cement.

TS7 6112.4 Wackestone-Packstone- 40% peloids, 1% intraclasts 0.2-20mm, 40% micrite, 18% blocky calcite cement filling vugs, <1% intercrystalline porosity within matrix selective vugular porosity.

6112.8-6117.0 Packstone-Wackestone- Medium gray-tan, thick bedded, moderately-well sorted, recrystallized, oolitic, pisolitic, calcite filled vugs.

TS8 6114.0 Wackestone-Packstone- 30% intraclasts 0.2-2mm, 20% peloids, <1% ostracodes, 30% micrite, 8% blocky calcite cement filling vugs, 13% enlarged vugular porosity
Many algal borings in intraclasts and caliche zone in center of slide. Numerous microstylolites.

6117.0-6117.9 Packstone-Grainstone- Tan, Very thin-medium bedded, well-poorly sorted, oolitic, calcite cement, peloid and micrite matrix in part, one very thin (5mm) 25 degree dipping well sorted grainstone, ooids filling intraformational breccias.

TS9 6117.7 Packstone- 55% peloids, 1% intraclasts 0.2 to 2mm -micrite envelopes, 1% micritized ooids, 3% micrite, 40% calcite cement in two stages 1) fibrous filling fenestrae 2) blocky vug fill, <1% quartz silt. Well-moderately sorted, reversed graded, thin bedded. Some cements recrystallized.

6117.9-6124.7 Mudstone-Packstone- Medium gray, massive, peloidal, argillaceous, occasional allochem ghosts, calcite filling fenestral porosity, slightly pyritic, microstylolite swarms and clay seams.

TS10 6118.0 Packstone- 70% peloids, 20% micrite, 5% microdolomite concentrated in stylolite, 2% quartz silt, 2% siliciclastic clay, 1% pyrite. Well sorted.

6124.7-6129.5 Wackestone-Mudstone interbedded with stringers of well sorted oolitic Grainstone-Medium gray-brown, thick bedded pisolithic, ooid grainstone also filling large desiccation fractures, slight-fair matrix selective vugular porosity-mostly calcite filled, large later vertical fractures are filled with anhydrite in center and ooids on sides.

TS11 6129.4 Packstone- 35% ooids tangential, 25% peloids, 2% oncoids 0.8-7mm, 3% micrite, 30% calcite cement 1) fibrous filling collapsed fenestrae 2) blocky filling vugs and fractures, 5% bladed anhydrite filling fractures and rare vug and replacing adjacent carbonate, 1% oomoldic porosity.

6129.5-6135.0 Mudstone-Packstone- Medium gray, poorly sorted, peloidal, intraclastic, oolitic, pisolithic, numerous caliche surfaces, most vugs filled with calcite cement.
**TS12 6131.0**  
Wackestone-Packstone- 20% ooids radially fibrous and tangential-mostly micritized, 5% peloids, 1% intraclasts 10mm-could be from collapse breccia, 35% micrite, 2% calcite cement 1) fibrous lining fenestral-shelter and vugular porosity 2) blocky filling vugs and part of vertical fracture, 1% anhydrite filling larger burrows and single vertical fracture. Burrowed peloidal mudstone overlying reverse graded peloidal-oolitic packstone.

**TS13 6133.0**  
Packstone- 55% ooids radially fibrous-most broken, 8% pisoids 2-6mm radially fibrous-all broken in place, 8% peloids, 10% micrite, 14% calcite cement 1) fibrous lining shelter porosity and some vugs 2) blocky filling vugs and fractures, 2% matrix selective vugular porosity. Moderately sorted, reverse graded thin bedded.

**TS14 6133.2**  
Mudstone- 5% peloids, 95% micrite. Thin bedded.

**TS15 6133.3**  
Packstone- 55% ooids radially fibrous-most broken in place by desiccation and cement growth, 1% pisoids 2-4mm broken radial fibrous, <1% peloids, 1% micrite 42% calcite cement 1) fibrous isopachous cement lining allochems and shelter porosity 2)blocky filling shelter porosity, 1% matrix selective vugular porosity.

**6135.0-6140.6**  
Mudstone-Packstone- Medium brown gray, medium bedded, poorly-moderately sorted, peloidal, oolitic, occasional very large coated solution breccia clasts and pisoids, calcite filling fenestrae and vugs, anhydrite filling large diagonal fractures.

**6140.6-6148.3**  
Wackestone-Packstone- Medium brown gray, medium-thin bedded reverse graded, well-poorly sorted, oolitic, pisolitic, dense-rare large vugular and moldic porosity.

**TS16 6147.4**  
Packstone-Grainstone- 40% peloids, 15% ooids tangential-partially micritized, 1% intraclasts 2-4mm radially fibrous outer coating-may be isopachous cement, 1% pisoids 2-4mm, 20% micrite, 32% calcite cement 1) fibrous filling interparticle-fenestral and early vugular
porosity 2) blocky filling early and late vugs, 2% matrix selective vugular porosity. Micrite caliche zone in center of slide. Peloids have reverse grading.

6148.3-6151.5 Wackestone-Grainstone- Tan, well-moderately sorted, oolitic, calcite cement, slight-fair-good interparticle and vugular porosity.

TS17 6151.3 Packstone- 40% intraclasts 0.2-2mm, 25% peloids, 15% micrite, 5% blocky calcite cement filling vugs, 15% matrix selective vugular porosity.

6151.5-6154.3 Packstone- Medium brown gray, thick-medium bedded, poorly sorted, slightly normally graded in part, pisolitic, calcite cement, several small type I stylolites.

TS18 6152.0 Packstone-Solution Breccia- 35% ooids fractured radially fibrous, 35% pisoids 2-4mm radially fibrous with pendant gravity cement and isopachous cements, 2% peloids in matrix, 15% micrite and caliche crusts, 11% calcite cement 1) micritic gravity cement 2) fibrous filling sheltered and vugular porosity 3) blocky filling vugs, <1% intercrystalline vugular and sheltered porosity. Some overpacking of grains due to solution of matrix.
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