UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

RESERVOIR-SCALE STRATIGRAPHY, SEDIMENTOLOGY, AND POROSITY CHARACTERISTICS OF MISSISSIPPIAN RESERVOIRS, NORTHEASTERN ANADARKO SHELF, OKLAHOMA

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By

COLTON BENNION BIRCH
Norman, Oklahoma
2015

RESERVOIR-SCALE STRATIGRAPHY, SEDIMENTOLOGY, AND POROSITY CHARACTERISTICS OF MISSISSIPPIAN RESERVOIRS, NORTHEASTERN ANADARKO SHELF, OKLAHOMA

A THESIS APPROVED FOR THE
CONOCOPHILLIPS SCHOOL OF GEOLOGY AND GEOPHYSICS

BY

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This is dedicated to my late father, V.Lane Birch, without whom I would not have been able to complete, what was in my eyes, a herculean task. If I can be said to have an ounce of drive, skill, work ethic, or integrity, it is because of him. To my greatest example, love you Dad.

Acknowledgements

This research was funded through the sponsors of the Reservoir Characterization and Modeling Laboratory and the Mississippi Lime Consortium: Chesapeake Energy, Devon Energy, QEP Resources, and Sinopec (Tiptop Oil and Gas). I would like to acknowledge Devon Energy for providing the data for my thesis studies. The sizeable data set allowed me to explore more detail of the Mississippian Lime than I could have hoped for. I thank Schlumberger for the use of Petrel, IHS for the use of Petra, and Spectrum Petrographics, Inc. for making the thin sections used in my research. I also acknowledge Dr. Matthew Pranter for his commitment, patience, and help with such a large endeavor. Likewise I thank the others who have helped me throughout the research process: Alyssa Karis, Anna Turnini, Fnu Suriamin, Katherine Lindzey, Alyssa Wickard, Dr. R. Douglas Elmore, Dr. Roger Slatt, Bryan Turner, Dr. Mike Grammer, Matt Herrin, and David Tilghman. Lastly, I would like to thank my family: Joy, Jordan, Justin, Ellie, and Ariana Birch, for their extraordinary patience, love, and support during these trying two years. They keep me going.

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Abstract

The "Mississippi Lime" has been a productive carbonate play for several decades. However, geologic controls on production and reservoir quality have frequently been ambiguous to geologists. The Mississippian limestone varies significantly in reservoir quality, with some zones characterized by higher porosity tripolite, other parts characterized by lower porosity chert, and some characterized by unaltered limestone.

Lithologically, the Mississippian limestone consists of tripolite, chert, cherty limestone and limestone. The dominant lithofacies include tripolitic chert-breccia (tripolite), skeletal grainstone, skeletal-peloidal packstone, bioturbated wackestone-packstone, and bioturbated mudstone-wackestone. Tripolitic intervals and brecciation occur most often near the top of the Mississippian interval, and commonly represent the best reservoir in terms of porosity and permeability. The peloidal packstone facies has on average the second highest porosity of any facies, but is significantly lower than tripolite. This variability (both vertical and lateral) is established through cores and thin sections. Mississippian-aged limestones demonstrate a variety of alteration types, such as silicification, dolomitization, brecciation, and fracturing. Porosity is highly variable and most often a function of alteration (mostly the amount of dissolution). Pore type is also variable, but is predominantly vuggy, while other types, like moldic and fracture porosity depend on facies type and degree of alteration.

In northern Oklahoma, the Mississippian limestone formed on the east-west trending margin of the Anadarko shelf/ramp. This carbonate system is characterized by a shallowing-upward character as well as high-order transgressive-regressive cyclicity.

Five shallowing-upward fourth-order cycles are observed in the Mississippian in the study area, based on cores and thin sections. Well-log response also shows a degree of cyclicity, as well as the progradational nature of the carbonate ramp. Unconformities in the area are caused by relative falls in sea level in addition to regional tectonics. Pre-Pennsylvanian tectonics created the Nemaha uplift, the cause of subaerial exposure in the area, which then led to alteration and brecciation of the rocks.

Three-dimensional reservoir models constrained to well-log data from the show five fourth-order cycles that thicken as they prograde to the south down the carbonate ramp. Porosity, resistivity, and bulk density petrophysical models show favorable reservoir zones. These zones are irregularly distributed, but are highly concentrated in the regressive phase of the Mississippian third-order sequence. Peloidal packstone intervals, which have slightly better reservoir quality than the other facies, could be predicted based on the stratigraphy and cyclicity, but are less porous and permeable than tripolitic-chert intervals. Tripolitic reservoirs are controlled predominantly by the amount and distribution of alteration. Stratigraphically lower cycles show less alteration, and therefore lower reservoir quality. The degree and areas of diagenetic alteration as well as the sequence-stratigraphic framework provide the main controls on reservoir quality and its distribution.

Introduction

Mississippian chert and carbonate reservoirs of northern Oklahoma and southern Kansas have produced oil and gas for much of the past century. Traditionally drilled with vertical wells since the early 1900's, horizontal wells have become increasingly more common, as 1700 horizontal wells have been drilled in addition to 12,000 vertical wells (from IHS). Many of the cherty reservoirs of the "Mississippian limestone" are compartmentalized, thus leading to the use of horizontal drilling to more effectively deplete them. Drilling in the Mississippian interval is aided by relatively shallow drilling depths (3,000-6,000 ft, 914-1828 m). However, given the reservoir complexities, coupled with high oil-water ratios means that an improved understanding of the geological controls on reservoir distribution are essential.

Most studies in regard to Mississippian stratigraphy and sedimentology have concentrated on the higher porosity Mississippian chert reservoirs at the top of the Mississippian interval (Parham et al. 1993; Montgomery et al. 1998; Northcutt et al. 2001; Rogers, 2001; Watney et. al., 2001; Mazzullo et al., 2009). These studies have focused on areas in Kansas, eastern Oklahoma, and northwestern Arkansas. Lithologies of the best-producing chert reservoirs include in-situ spiculitic chert (composing the top of the Osagean and base of the Meramecian intervals), in-situ brecciated and partly weathered spiculitic chert (directly below the unconformity, near the very top of the Osagean), and highly weathered, transported chert conglomerate above the Osagean (Montgomery et al., 1998; Turnini, 2015). Seven lithofacies were established in the Mississippian limestone through analysis of core from the Spivey-Grabs field (Watney et al., 2001). These seven lithofacies vary in chert type, mud content, and skeletal-grain abundance, yet in their entirety represent a shallowing-upward, high-order succession.

An additional study by Mazzullo et al. (2009) characterizes both the Mississippian Cowley and Reeds Spring formations as having a high degree of bedded spiculite in several forms deposited on a low-gradient ramp. Rogers (1995) defined the "chat" as Osagean chert and proposed that sponge bioherms dictate its distribution, at least in the study area in Glick field, Kansas. In a later study, Rogers (2001) analyzed 6,600 wells in Osage and Kay County, Oklahoma that proposes an in-situ model of chert weathering and subsequent weathering of detrital Mississippian chert. In the study area of Grant County, Oklahoma, tripolitic chert intervals do not exhibit as many spicules as observed in Kansas samples (Figure 1).

Because the Mississippian limestone covers such a large aerial extent, a wide range of carbonate environments are reflected in the rock record. Studies by Farzaneh (2012) and Haynes (2013) examined the lithology of cores located in Garfield, Noble, and Logan counties, Oklahoma. Two relevant limestone units were recognized: the Burlington-Keokuk Limestone and the Reeds Springs Formation. Bedded-chert breccia, chert breccia, peloidal packstone, oomoldic grainstone, and mudstone comprise the Reeds Springs Formation (Farzaneh, 2012). The Burlington-Keokuk unit comprises three facies: crinoidal grainstone, fossiliferous limestone, and a shaly mudstone (Haynes, 2013). The facies types found in these two units featured significantly less sponge spicules compared to southern Kansas and eastern Oklahoma studies (those by Mazzullo, 2009; Rogers, 2001; Watney, 2001). Reservoir quality in these two limestone units is directly tied to diagenetic processes such as dissolution and fracturing. Besides the brecciated tripolitic chert facies, the only other facies to have favorable reservoir quality are oomoldic grainstones, in which the oomolds exhibit high porosity.

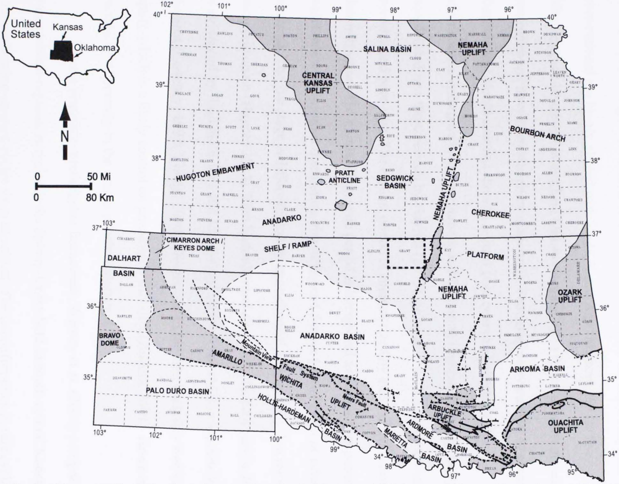


Figure 1. Regional base map illustrating the major tectonic and basinal features of Oklahoma and Kansas. The study area of Grant County is marked. It lies on the southern edge of the Anadarko Ramp. The carbonate ramp in the area progrades to the south. The Nemaha Uplift directly to the east is the tectonic feature with the largest imprint on the geology in my study area. It is a likely contributor to the subaerial exposure seen in Mississippian aged units in the vicinity. (Modified from Johsnon and Luza, 2008, Northcutt and Campbell, 1995, and Campbell, et al., 1988).

The reservoirs of the Mississippian limestone have also been divided into three distinct groups based on their mineralogical and porosity alteration, as well as the range of porosity values they exhibit (Matson, 2013). Unconventional reservoirs are unaltered with 2-6 % porosity, semi-conventional are altered with 15-20 % porosity, and conventional are highly altered with 35-48 % porosity (Matson, 2013). The Mississippian limestone in northern Oklahoma most often forms unconventional reservoirs and have been altered by diagenesis. Petrographic evaluation of cores from Garfield and Noble counties showed several pore types and alteration due to silicification, dolomitization, brecciation, and fracturing (Farzaneh, 2012). Diagenesis was divided into three periods by Haynes (2013), helping to delineate the variability of porosity and pore type. The earliest period is characterized by early silicification and dolomitization. The middle diagenetic period is interpreted as subaerial exposure in which brecciation, silica dissolution, fracturing and further precipitation of silica occurred. The last stage is differentiated by hydrothermal alteration by dolomitization and pyritization (Haynes 2013). That hydrothermal alteration played a part in diagenesis is evidenced by fluid inclusions and Mississippi Valley Type (MVT) deposits found in the area (Coveney, 1992; Young, 2010). Diagenesis in the area is closely tied to tectonic uplift, which is a likely control on pore-type variability (Rogers, 2001). However, variability of porosity in the area is poorly understood.

From a sequence-stratigraphic framework, Watney et al. (2001) recognized transgression-regression cycles in the Spivey-Grabs field in south-central Kansas, where four shallowing-upward cycles were identified. The unconformities in this cyclic model caused by relative drops in sea level are minor compared to major post-Mississippian erosion and exposure. The Cowley Formation, for example, is interpreted as a deepening-upward transgressive systems tract overlain by a shallowing-upward highstand systems tract. Unconformities caused by subaerial exposure from falling sea level are also observed in the rock record (Mazzullo et al., 2009). In studies by both Leblanc (2014) and Price (2014), five facies types were established that repeatedly stack into a shoaling-upward succession. These repeated stacks exhibit third and fourth-order hierarchies, as well as some fifth-order cycles. Understanding the Mississippian through a sequence-stratigraphic framework has aided in understanding reservoir quality distribution.

Well-log response of Mississippian limestone intervals is distinct. Transitioning from the bottom of the Pennsylvanian to the top of the Mississippian, spontaneous potential (SP) and gamma-ray logs commonly show a sharp decrease in values. Tripolitic chert reservoirs appear as low-resistivity zones with low density and high porosity; the reservoir would be viewed as wet and nonproductive in most fields. Saltwater in the formation leads to a low resistivity reading, even with the presence of resistive hydrocarbons. Rogers (2001) suggested that in order to have a productive tripolitic reservoir, porosity from logs should be greater than 25 %, exhibit less than 80 % water saturation calculated by the Archie equation, and low resistivity with micro-log signifying permeability in the interval.

The study is located within Grant County, Oklahoma (Figure 2). The dataset includes 14 wells and their corresponding log data (Figure 3: gamma-ray (GR), neutron-porosity (NPHI), bulk-density (RHOB), density-porosity (DPHI), spontaneous potential (SP), photoelectric index (PE), and deep resistivity (ILD/RT90)). Also included in this dataset are two cores (total 1127 ft, 343.5 m) that were described in detail, with 107 core plugs acquired at an increment of nearly every 10 ft (3.05 m). These core plugs were used to make a total of 107 thin sections for both cores that were analyzed petrographically. These data have been used to better understand the complicated study area in terms of the lithology/lithofacies in the area, the variability of porosity in the Mississippian interval, the spatial distribution of lithology and reservoir quality and the potential sequence-stratigraphic relationships in the region.

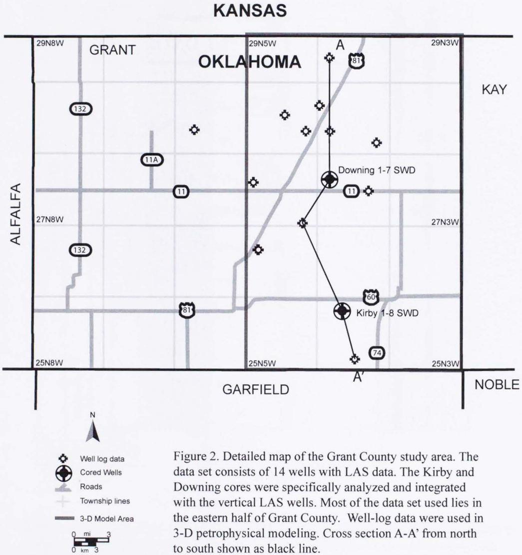


Figure 2. Detailed map of the Grant County study area. The data set consists of 14 wells with LAS data. The Kirby and Downing cores were specifically analyzed and integrated with the vertical LAS wells. Most of the data set used lies in the eastern half of Grant County. Well-log data were used in 3-D petrophysical modeling. Cross section A-A' from north to south shown as black line.

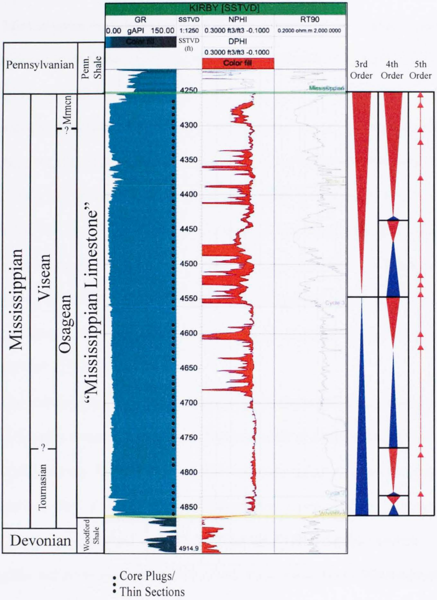


Figure 3. Type log of the area (Kirby 1-8 SWD). The complete Mississippian section is shown, with Woodford Shale at the base and Pennsylvanian-Cherokee Group (Penn. Shale) on top. Core plugs were acquired at approximately every 10 ft (3.05 m) in both this well and the Downing 1-7 SWD. Porosity and permeability measurements were acquired from both by Weatherford. Thin sections were made from the sampled core plugs, and thus thin sections exist for nearly every 10 ft (3.05 m) of the core, and are shown as black dots on the figure. Also shown are the third, fourth, and fifth-order cycles to the right of the wireline logs.

Geologic Setting

Mississippian deposition occurred in four different stages (Ages) (Appendix C.1): Kinderhookian, Osagean, Meramecian, and Chesterian (Northcutt et al., 2001). The Mississippian interval that has been most productive in Grant County is mostly Osagean in age, as younger Meramecian and Chesterian strata were not deposited on many structures with positive relief (Parham, 1993). Uplift along the Nemaha ridge eroded parts of the Osagean interval, and subsequently this uplift did not allow for much deposition of younger Mississippian units, as the Chesterian is absent and the Meramecian is present, but is limited in its thickness (Appendix C.2). Erosion also removed most of the Kinderhookian interval in north-central Oklahoma, and it is unclear whether the Osagean is deposited directly on top of the Woodford Shale (Northcutt et al., 2001; Figure 3).

The Mississippian limestone in north-central Oklahoma is associated with the east-west trending ramp margin of the Burlington shelf of a starved basin environment (Lane and De Keyser, 1980; Figure 4). This margin is indicative of a ramp environment as opposed to a shelf. During the early Mississippian, warm oxygenated waters covered much of the ramp in the study area. Fauna abounded with abundant crinoids, brachiopods, and bryozoans in the rock record. Regionally, lower Mississippian intervals comprise three depositional settings: mid-ramp, outer ramp, and distal outer ramp (Handford, 1986). In Osagean deposits in Kansas, the quiet water depositional environment of the main shelf was most common (Parham, 1993). Deposition during the Osagean was largely controlled by eustatic sea-level rise/fall as tectonic activity was quiescent. The units in the Osagean stage are identified as the Burlington-Keokuk

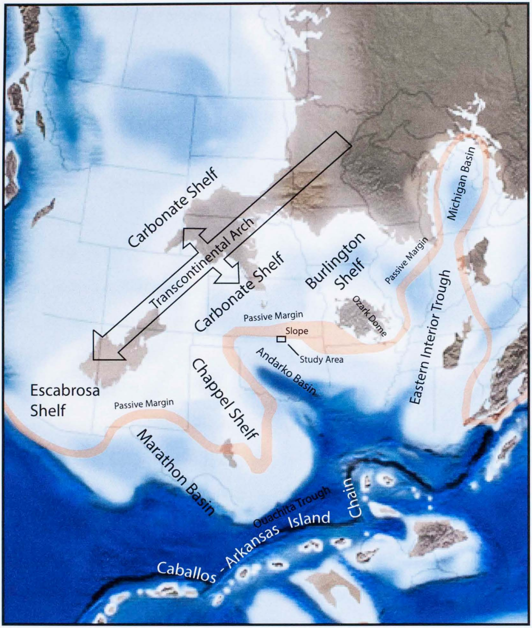


Figure 4. Paleogeographic map of the Early Mississippian. The study area is in the Anadarko basin, in the medial to distal ramp portion of the Anadarko ramp. A warm shallow sea was present with a starved basin to the south and the Caballos-Arkansas island chain also to the south. (Modified from Blakey, 2011 and Gutschick, 1983).

limestone, Reeds Spring Formation, Pierson Formation, and Elsey Formation (Watney et al., 2001). Limestone was the dominant lithology in Oklahoma during the Osagean (Northcutt et al., 2001). Chert replacement is widespread in the area, with the silica provenance possibly being volcanic emissions to the south (Watney et al., 2001), though hydrothermal discharges, weathering of quartz rich rocks due to uplift, and dissolution of in-situ sponge spicules have been proposed as well (Parham, 1993; Rogers, 2001).

Regional uplift occurred during the Pennsylvanian, creating the Pennsylvanian unconformity that overlies most of the Mississippian in the midcontinent (Parham, 1993). However, the Nemaha uplift just east of Grant County (Figure 1) is the major tectonic feature of the area. This uplift, coupled with erosion, was the principal cause of the unconformity at the top of the Mississippian interval in the study area, separating it from the overlying Desmoinesian deposits (Rogers, 2001). The Ouachita Orogeny created the Ouachita Mountains to the south, and east-west compression during the late Mississippian to early Pennsylvanian formed the Pratt anticline, which borders the study area to the west (Montgomery et al., 1998). The study area is bordered in the north by the Kanoka ridge, caused by the Ouachita collision (Mazzullo, 2011). The high degree of uplift and erosion play key roles in the diagenesis that occurred in the area.

The Pennsylvanian uplift not only removed large amounts of rock, but also reworked and altered much of the top of the Mississippian interval through subaerial exposure, wave action and erosion (Rogers, 2001). Subaerial exposure, wave action, erosion, and later diagenesis from external hydrothermal flow combined with chert replacement have created three distinct chert types in the area: 1) autochtonous, glassy chert; 2) highly weathered, highly porous, tripolitic chert; and 3) highly porous, reworked detrital chert. The autochtonous, glassy chert was formed in-situ, via silica replacement by invading fluids, possibly hydrothermal or meteoric. Residual tripolitic chert was formed by concentrated weathering of the autochtonous chert described above in which residual limestone/calcite is dissolved to create porosity. This is marked by collapse breccias. The detrital reworked tripolitic chert has been exposed to wave action and appears in part to have been transported, but brecciated fragments appear similar to the in-situ tripolitic chert (Parham, 1993).

The Mississippian interval represents a third-order sequence and the upper portion of the Kaskaskia sequence defined by Sloss (1963). This sequence is capped by the large Pennsylvanian unconformity at the top of the Mississippian. Higher-order (fourth- and fifth-order) cyclicity is observed as well, as this shallow carbonate environment is highly affected by water depth (Leblanc, 2014). Higher-order cyclicity have both allogenic and autogenic controls including sedimentation rates, climate, tectonics, and variable glacial volumes due to Milankovitch cycles. Milankovitch cyclicity has the largest impact, but it is at times difficult to distinguish the largest control on any given cycle due to the number of variables that influence it (examples: subsidence, sedimentation rate, accommodation rate, and tectonics) (Leblanc, 2014). Regardless of controls, shoaling-upward transgressive-regressive cycles are commonly observed throughout the Mississippian interval (Watney, 2001; Mazzullo, 2009; LeBlanc, 2014; Price, 2014).

Mississippian Lithofacies and Pore Types

In order to understand the study area in terms similar to the studies already conducted by Watney (2001), Mazzullo (2009), LeBlanc (2014), and Price (2014), two cores in eastern Grant County, Oklahoma (the Kirby 1-8 SWD and Downing 1-7 SWD cores, total footage: 1127 ft, 343.5 m, Figure 2) were described in detail. This was done to determine key lithofacies, lithologies, pore-types, rock fabrics, fractures, brecciation, sedimentary structures, fossils, lithofacies successions, and other reservoir heterogeneities. Thin-section analysis was used in conjunction with core analysis to determine these features. Sixty-one thin sections were made using core plugs from the Kirby 1-8 SWD core, and forty-six from the Downing 1-7 SWD core. Other core data used includes porosity and permeability measurements on the core plugs. All 107 thin sections were polished and vacuum-impregnated with blue epoxy to highlight porosity. The descriptions are based on Dunham (1962) and Choquette and Pray (1970) classifications for facies textures and pore types.

As the carbonate ramp prograded to the south, it also thickened in the same direction. This is observed not only from well logs, but in the core, as the Kirby core is approximately 100 ft (30.5 m) thicker than the Downing core. As mentioned before, no Kinderhookian units are observed in the study area. Both cores lie directly on top of the Woodford Shale (the Mississippian-age portion of the Woodford Shale was not included in this analysis) and are overlain by the Pennsylvanian-age Cherokee Group, a much shalier unit than the limestone and chert-rich Mississippian interval.

With the exception of a tripolitic chert interval near the top of both cores, both are lithologically and petrographically heterogeneous, and due to variable degrees of alteration, difficult to correlate between wells. The lithofacies identified in this study exist in both cores. Five different facies types are observed in the Mississippian limestone: 1) bioturbated mudstone/wackestone, 2) bioturbated wackestone/packstone, 3) peloidal packstone, 4) skeletal grainstone, and 5) tripolitic chert (Figure 5). A sixth facies type, glauconitic sandstone, occurred infrequently in both. Tripolite primarily occurs as collapse breccia, however, flow breccias are also observed. Within the Mississippian limestone, tripolitie is often sporadic and patchy, as other carbonate fabrics persist around these zones. It is also important to note that facies types may have different characteristics in the Mississippian interval due to the amount of bioturbation and alteration that affects them (Figure 6).

Diagenesis has a dramatic imprint on the Mississippian limestone. Silica replacement is one of the most prominent of these diagenetic features. It most regularly occurs as cemented zones. These zones are interpreted as diagenetic fronts, in which fluid moves through the rock replacing calcite with silica in the specific areas it moved through. Sedimentary features like laminations persist throughout these zones, but the mineralogy has changed to silica. Chert nodules are present, especially in highly reworked and bioturbated zones. Nodules of calcite and pyrite are common in hand sample, while other oxides like magnetite can be observed in thin section. Fractures are often filled with silica or calcite (Figure 7). Pressure-solution features, most notably seams and styolites, are frequent. Pressure solution is so extensive that at points it appears laminated, with seams stacked on each other like laminations. Many times in hand sample, the rock color has been bleached, which is interpreted to be a result of fluid flow. Dolomite is often fine-grained and coupled with chert in diagenetic fronts as

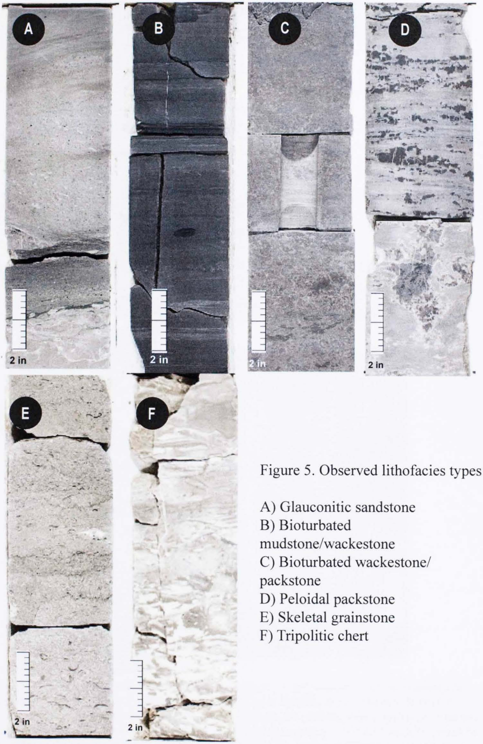


Figure 5. Observed lithofacies types:

A) Glauconitic sandstone
B) Bioturbated mudstone/wackestone
C) Bioturbated wackestone/packstone
D) Peloidal packstone
E) Skeletal grainstone
F) Tripolitic chert

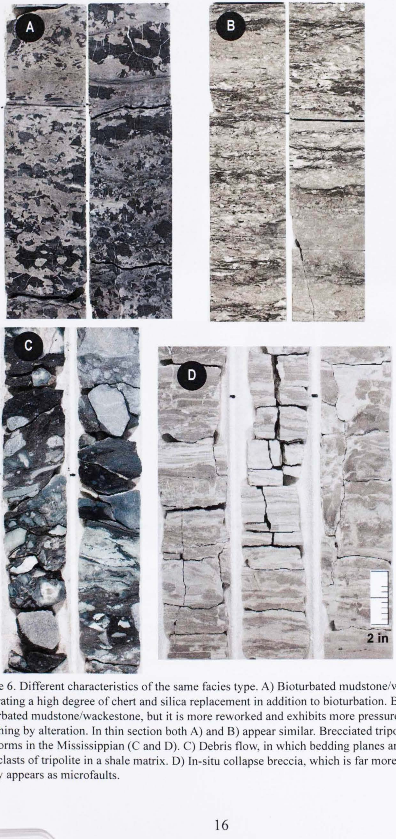


Figure 6. Different characteristics of the same facies type. A) Bioturbated mudstone/wackestone, illustrating a high degree of chert and silica replacement in addition to bioturbation. B) Also a bioturbated mudstone/wackestone, but it is more reworked and exhibits more pressure solution and bleaching by alteration. In thin section both A) and B) appear similar. Brecciated tripolite is seen in two forms in the Mississippian (C and D). C) Debris flow, in which bedding planes are preserved with clasts of tripolite in a shale matrix. D) In-situ collapse breccia, which is far more common, nearly appears as microfaults.

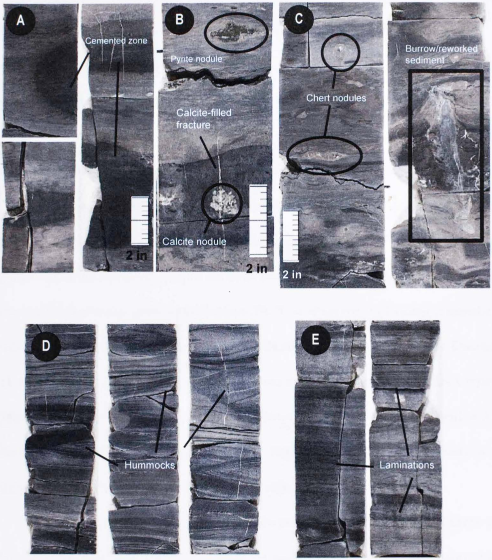


Figure 7. Diagenetic and sedimentary features in core. A) Cemented silica/dolomitized zones, interpreted as fluid-flow alteration. B) Pyrite and calcite features, such as nodules and fracture-fill. C) Silica features, such as nodules and silica replacement of burrows/reworked sediment. D) Hummocky cross stratification, indicative that storm events at some point affected the depositional features of the Mississippian limestone. E) Examples of the laminations that exist throughout both cores. It is possible that these laminations are in fact pressure solution features and are darker due to insoluble clays that styolites leave behind.

described earlier. Other times, larger crystals with their distinct rhombic shape are pervasive. In a few of the samples, saddle dolomite with its curved edges and undulatory extinction was observed. This is significant because it implies formation at elevated temperatures, most likely from hydrothermal or hydrocarbon associated burial fluids. Hydrothermal fluids thus had some effect on the alteration of the Mississippian limestone, though the extent of this effect is unknown (Figure 8).

Because diagenesis has such a strong imprint on the expression of limestone in the Mississippian, often sedimentary structures are destroyed. When such structures are preserved, laminations are one of the most common sedimentary features. In a few intervals, hummocky cross-stratification (HCS) is observed, indicating a storm event was coincident with deposition (Figure 7). Bioturbation (most commonly Cruziana or Skolithos) is ubiquitous throughout both cores and all the established facies types of the Mississippian limestone. Crinoids and brachiopods are the most widespread and indeed the only fossils easily distinguished in core. Bryozoans, spicules, and peloids occur frequently as well, and are differentiated in thin section (Figure 9).

Pore type classification could only be performed in thin section (Figure 10). Vugs, molds, fractures, and channels are the most frequent pore types observed in the study area. Throughout the samples, vuggy porosity is easily the most prominent pore type. Dissolution is widespread throughout both core and thin section, so it follows that vugs pervade. Often this pore type is associated with tripolite, but exists in all of the established facies types. Often times the pores undergo subsequent silica replacement, stripping the vugs of their porosity. The volume of these pores could be aided by the persistent dolomitization that exists throughout the samples. Moldic porosity is also

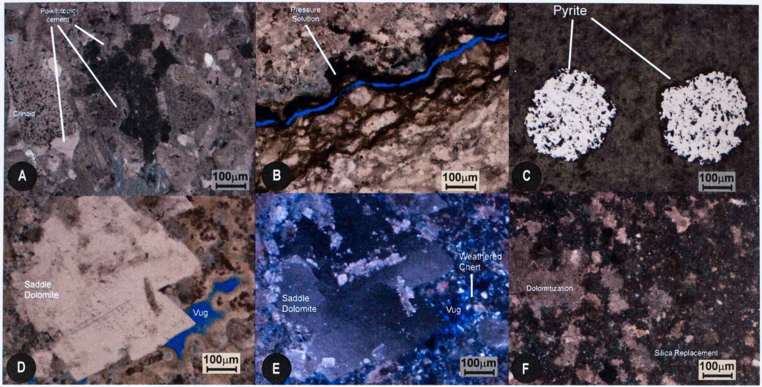


Figure 8. Diagenetic features in thin section. A) Poikilotopic cement, consisiting of coarser crystals of cement enclosing smaller grains, indicative that it formed during the burial stage of deposition. B) Pressure solution features, including styolites. Always accompanied with insoluble clays/organic material that remains after the pressure solution occurs. C) Pyrite nodules, which are scattered throughout, as are other oxides. They tend to be found most often in reworked zones. D) Saddle dolomite. Significant because it implies the formation at elevated temperatures from hydrothermal or hydrocarbon associated burial fluids. Note the curved edges and rhombic shape of the dolomite grain. E) Weathered chert, commonly accompanied by vuggy porosity. Also note the saddle dolomite in cross polarized view(exhibits undulatory extinction). F) Dolomitization. It is often paired with silica replacement to form dolomitized cherty zones, in which porosity and permeability is all but destroyed. These zones possibly coincide with the diagenetic fronts seen in core.

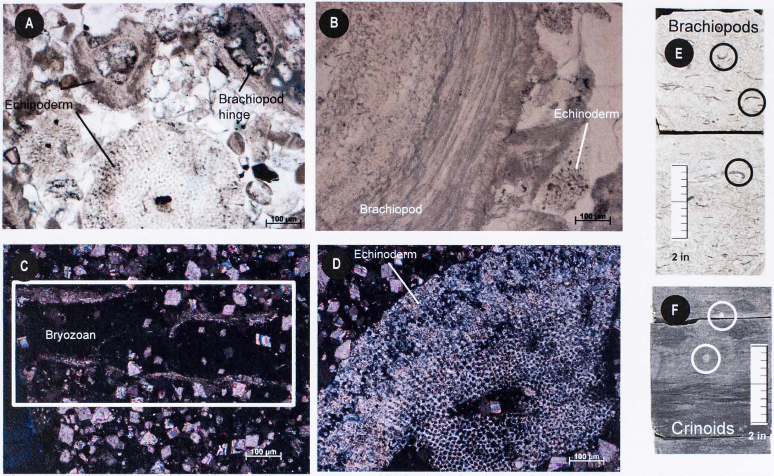


Figure 9. Fossils in core and thin section. Fossils are best preserved in the skeletal grainstone facies of the Mississippian interval, but are present in the other lithofacies. A) Echinoderm segments and brachiopods hinge observed in a skeletal grainstone. B) Brachiopod and echinoderm grains in another skeletal grainstone sample. C) Bryozoan fossil segment in a the same bioturbated mudstone. D) Large echinoderm grain in the same bioturbated mudstone sample as C). E) Brachiopods observed in hand sample, F) Crinoids observed in hand sample.

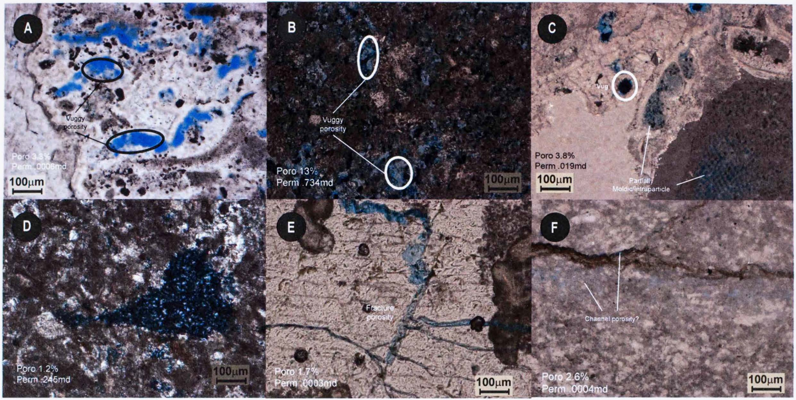


Figure 10. A: Vuggy porosity- by far the most frequent porosity type in thin section. Dissolution is widespread throughout the core and thin section. B: This figure exhibits the best porosity of any sample from the two cores. Dissolutive vugs are abundant, while there is a noticeable absence of chert/silica grains. There appears to be significant dolomitization, which might have helped create pore space. C: Partially moldic porosity. Skeletal grains are being preferentially dissolved out, probably due to its calcite composition. Vugs can also occur in a skeletal grainstone such as this. D: Example of chert/silica replacement filling in a pore and destroying porosity. E: Fracture porosity. Fractures occur along planes of weakness in which case porosity is sometimes introduced. F: Possible example of channel porosity along a pressure solution seam. This seam might have created a barrier to fluid flow where the fluid preferentially traveled along the seam instead of through it.

common, especially in packstone and grainstone facies that exhibit more skeletal grains. In these molds, skeletal grains are preferentially dissolved, leaving partial molds of the remaining grains. Fracture and channel porosity are both observed as well, but less frequently. Fractures are generally silicified or calcified, and porosity is not well preserved within. Channels follow along styolites and seams when they infrequently occur. These seams and styolites possibly created a barrier for fluid flow in which the fluid preferentially traveled along the seam instead of through it, thereby dissolving and creating a channel. With the exception of moldic porosity in packstone and grainstone facies, the other pore types are observed in every facies type.

Lithofacies

Lithofacies observed in core and thin section commonly stack to form shoaling-upward successions. An idealized facies succession consists of (from deep to shallow) glauconitic sandstone, bioturbated mudstone/wackestone, bioturbated wackestone/packstone, peloidal packstone, skeletal grainstone, and tripolitic chert. Rarely are more than three of these facies preserved in succession due to erosion or non-deposition. However, these shoaling-upward cycles persist throughout the Mississippian (Figure 11).

FACIES 1: GLAUCONITIC SANDSTONE:

The deepest facies type in the lithofacies succession, glauconitic sandstone, occurs intermittently and is characterized by an abundance of very fine to fine-grained glauconite. The glauconite grains are rounded to subrounded, and are moderately sorted. Its characteristic green color is obvious in core. Also this facies is characterized by much finer, silt-sized quartz grains. Fossils such as crinoids and brachiopods are

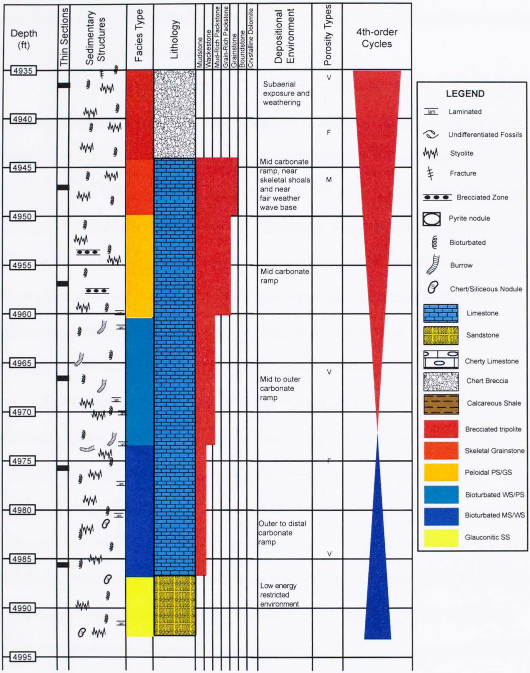


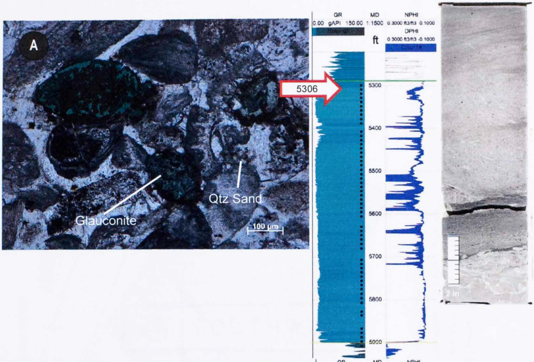
Figure 11. Idealized facies succession for the Mississippian. The deepest facies type is glauconite sandstone. Shoaling upward from there is the bioturbated mudstone/wackestone, the bioturbated wackestone/packstone, peloidal packstone, skeletal grainstone, and tripolitic chert facies. Rarely are more than three of these facies preserved in succession due to erosion or non deposition, yet these shoaling upward cycles persist throughout the Mississippian.

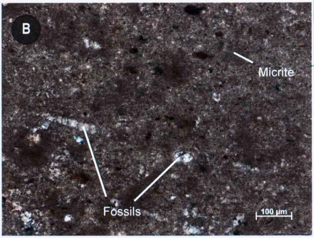
occasionally present, but most commonly glauconite and quartz are the sole constituents. Often this facies is bioturbated and reworked. Syntaxial cement of skeletal fragments reduce porosity and permeability (Figure 12).

Glauconite is authigenically formed from potassium-rich smectite clay. It can form in a variety of environments, but commonly is characteristic of low-energy, low-oxygen submarine environments in which sedimentation rate is low or negligible (Middleton et al. 2003). Small skeletal grains with thin shells are observed, also lending to the idea that it formed in a low energy environment. From this, the glauconitic sandstone facies is interpreted to represent a low-energy, restricted environment, in which circulation was poor. That it occurs most often near the bottom of the cores indicates coincidence with early cyclic flooding on a regional scale.

FACIES 2: BIOTURBATED MUDSTONE/WACKESTONE

The bioturbated mudstone/wackestone is a calcareous mudstone with millimeter-scale burrows and some laminations (Figure 12). This facies type is the muddiest by far, and micrite is its principle constituent. It exhibits a mottled texture, interpreted as extensive bioturbation and reworking. Spicules are among the most abundant fossil of this facies type, though trace brachiopod and crinoid fragments are observed as well. Most of its features are too fine grained to observe with the naked eye. Pressure-solution features are distributed throughout this facies type. The mudstone facies also consistently correlates to poor reservoir quality (2 % average porosity, 0.04 md average permeability, Appendix B). This is a function of both its mud content and diagenetic features. Silicified zones occur frequently and exhibit poor porosity.





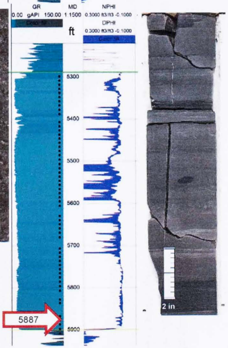


Figure 12. A) Example of glauconite in thin section, with corresponding log and core photo. No thin sections were made of a glauconitic sandstone interval, but grains are seen in other facies types, like this skeletal grainstone. This sample exhibits 1.4 % porosity and 0.0004 md of permeability.
B) Bioturbated mudstone/wackestone in thin section, log, and core. Very reworked and bioturbated, spicules are the most common fossil in this facies type. Micrite is abundant. Sometimes this facies is unaltered, but often is cherty. (Average porosity: 2 %; average permeability: 0.04 md).

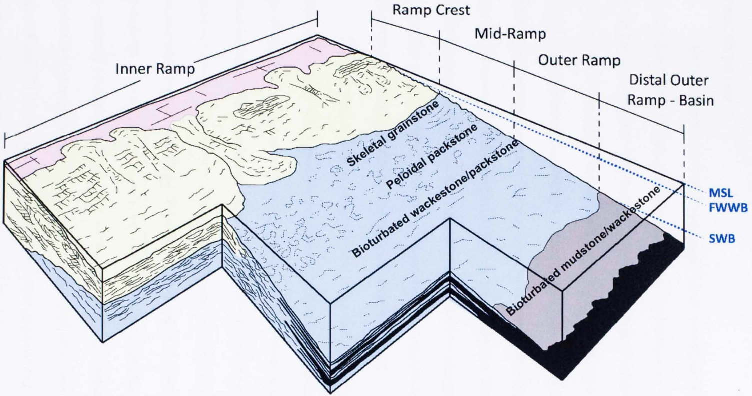


Figure 13. Schematic diagram of a carbonate ramp environment. A variety of depositional environments are represented, from deeper distal out ramp environments in which the bioturbated mudstone/wackestone facies is deposited, to the higher-energy, shallower upper mid-ramp, in which skeletal grainstone facies are deposited. Labeled are the approximate locations of the different lithofacies types. Brecciated tripolite requires subaerial exposure to modify one of the other facies types. MSL: maximum sea level; FWWB: fair weather wave base; SWB: storm wave base. (Modified from Handford, 1986).

Dolomitization occurs in concert with the silicified zones, and seems to have no positive impact on porosity.

The bioturbated mudstone/wackestone facies is interpreted as being part of the outer to distal ramp (Figure 13), deposited below fair weather wave base in a restricted, low-energy environment. This facies type exhibits a limited variety of fossil types: mainly isolated thin-shelled brachiopods, spicules, and some trace crinoid grains. The lack of fossils indicates that conditions for a diverse marine fauna were not met. Burrows are frequent, as are millimeter-scale laminations signifying the alternation of restricted anaerobic marine conditions with aerobic conditions. The abundance of micrite throughout this facies also suggests a restricted low-energy environment; lower energy than the bioturbated wackestone/packstone that generally lies above it.

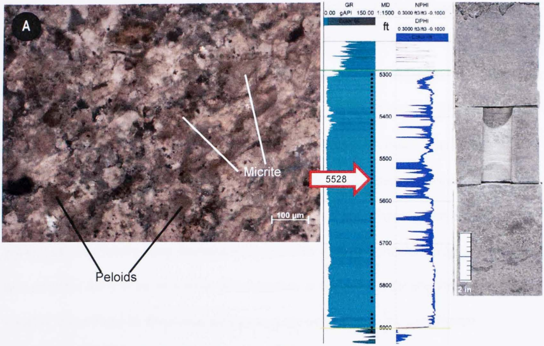
FACIES 3: BIOTURBATED WACKESTONE/PACKSTONE

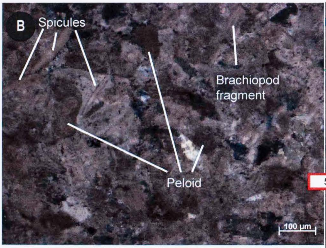
The bioturbated wackestone/packstone facies is a highly bioturbated and burrowed facies in which peloids, brachiopods, and crinoids are common. Micrite is less abundant in this facies type, and overall seems to be more of a transitional facies between finer grained mudstone and grainier packstone/grainstone facies. Spicules and bryozoans occur but with less frequency than brachiopods and crinoids. It often exhibits extreme bioturbation, reworking, and silica replacement with chert sections distributed throughout. This facies type is also frequently dolomitized and these dolomitic portions are typically coupled with chert. Fine sand-sized peloids are abundant, but to a lesser degree than the peloidal packstone facies. It is also marked by low porosity and low permeability (2.1 % average porosity, 0.05 md average permeability, Appendix B), similar to the mudstone/wackestone facies. This is most likely due to a high degree of micrite mud, as well as syntaxial overgrowth of skeletal grains destroying porosity and connectivity (Figure 14).

As the facies succession shoals upward, this facies type is interpreted as being farther up the carbonate ramp, in the middle to outer portion (Figure 13). A much more diverse assemblage of fossils are observed in this lithofacies type indicating deposition in a less restricted, well-circulated, normal-marine setting. Vertical burrows are common amongst the highly bioturbated sediments; possibly Skolithos and Cruziana. Micrite is still very common, which suggests that both clean and muddy sand substrates existed during the time of deposition (MacEachern et al., 2009). Thus, this represents an intermediate facies type between finer grained mudstones below and packstones/grainstones that lie above. The presence of HCS in some intervals of this facies type partly indicates that storm events played a role in deposition.

FACIES 4: PELOIDAL PACKSTONE

The peloidal packstone lithofacies is a gray, grain-dominated facies characterized by an abundance of peloids and skeletal debris. Peloids are increasingly dominant compared to shallower facies types. Skeletal grains of crinoids, brachiopods, and some spicules occur regularly as well (Figure 14). Though micrite is present, this facies type is grain-supported. Bioturbation and reworking of sediments are frequent, as are pressure solution features like styolites and seams. Silica replacement frequently occurs and is often chert-rich. Diagenetic fronts abound, in which fluid invasion completely replaces the original fabric, most often with silica, but frequently with dolomite as well. Some zones of tripolite occur, but these zones are localized. Overall, the porosity and permeability in this facies is noticeably better than the previous three





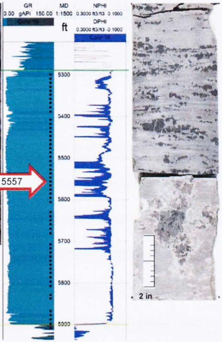


Figure 14. A) Bioturbated wackestone/packstone. Increasingly more micrite as facies deepen. Less skeletal grains than shallower facies types, but peloids, crinoids, brachiopods, and spicules all occur regularly. Very bioturbated and reworked. Often is silica replaced/cherty. (Average porosity: 2.1 %; average permeability: 0.05 md). B) Peloidal packstone. Peloids in abundance; often several skeletal grains as well. Pressure solution features occur with more regularity. Spicules are also seen periodically. Micrite seen but still grain supported. Often bioturbated/reworked. Silica replacement occurs commonly. (Average porosity: 3.8 %; average permeability: 0.03 md).

facies, with porosities ranging from 2 % all the way to 8 % (3.8 % average porosity, 0.03 md average permeability, Appendix B). There are several samples that exhibit porosity values around 6 %. Permeability was as high as 0.245 md in parts, though these did not necessarily correlate to higher porosity (e.g., the sample with 0.245 md had 2 % porosity). Most exhibited permeabilities around 0.005 md or lower. Alteration from fluid invasion and subsequent dissolution is the most likely cause for increased porosity.

The peloidal packstone facies is interpreted as being deposited on the mid-ramp portion of a carbonate ramp environment, proximal to skeletal shoals (Figure 13). It is also possible for it to be on a more distal portion of the ramp crest environment near fair weather wave base. Its fossil assemblage is more diverse than the bioturbated wackestone/packstone below it, suggesting well circulated normal conditions during deposition. Bioturbation is prevalent here as shown by its mottled texture. This facies is strongly suggestive of an inactive portion of a shoal.

FACIES 5: SKELETAL GRAINSTONE

The skeletal grainstone lithofacies is light-gray to white and grain-supported. Skeletal debris is its primary constituent, as skeletal grains dominate throughout this lithofacies type. Echinoderms, brachiopods, bryozoans, and peloids occur frequently, while spicules occur occasionally (Figure 15). Some skeletal grains, especially crinoid grains have syntaxial cement overgrowths occluding porosity. There is virtually no micrite in this facies type, and is completely grain-supported. Silica replacement and dolomitization occurs here, but not to the extent it does in the other facies types. This facies is regularly bleached in color and exhibits silica replacement and localized zones of chert. Often this facies type exhibits partially moldic porosity, where individual skeletal grains have been partly dissolved out. Vugs occasionally occur in the cement between grains, and fracture porosity can be sometimes be discerned along planes of weakness. This facies type is generally marked by unfavorable porosity and permeability measurements. From the core plug data, the highest porosity measurement was 4 % with 0.019 md of permeability. Skeletal grainstone intervals exhibit average porosity values around 2.6 % with average permeability values of 0.004 md (Appendix B).

The diverse assemblage of skeletal grains indicates that this facies type was deposited on or near a skeletal shoal. This shoal was most likely on the mid-ramp portion of the carbonate ramp, near fair weather wave base (Figure 13). It displays some truncated contacts, possibly indicating the shoal was active during deposition. The presence of occasional cross bedding suggests this as well. At times this facies exhibits a mottled texture indicative of bioturbation. Diagenesis has a negative impact on porosity, as syntaxial cement occludes its porosity (e.g., crinoidal overgrowths).

FACIES 6: BRECCIATED TRIPOLITIC CHERT

The brecciated tripolitic chert facies is marked by abundant tripolite. With tripolite, silica replaces limestone, and residual calcite is dissolved out due to subaerial exposure and fluid invasion. Often the original fabric has been completely destroyed. As mentioned previously, this facies type has two expressions: flow breccia and collapse breccia. The in-situ collapse breccia is marked by micro-faults and cemented fractures. The flow breccia exists as float in a muddy shale matrix in which there are bedding planes in the shale. Hand samples have a gritty, sandy feel, and readily absorb water. Rarely skeletal grains are observed. It is apparent in both thin section and hand sample that this facies type exhibits the largest degree of alteration of any of the lithofacies (Figure 15). Vuggy porosity is the most common pore type in tripolite. Dissolution in general is the largest creator of porosity, and has a hand in the creation of most of the pore types (vugs, molds, fracture). It also exhibits the highest porosity and permeability measurements. Most of the core plug samples in tripolitic chert intervals exhibit average porosity values of 9.2 % and average permeability values of 0.36 md (Appendix B). There is one sample (1-45 from the Kirby well) that is clearly tripolitic, but only has 3 % porosity and 0.001 md of permeability. In that specific case, a second stage of silica replacement occurred and began filling available pore space. Tripolite is not always indicative of favorable reservoir quality, though overall it exhibits better reservoir quality than most of the Mississippian section in the study area.

The tripolitic chert facies is unique in that it involves the destruction by diagenesis and weathering of other facies types into a new one. Though the depositional history is not revealed through the presence of tripolite, it is diagnostic of sea level. Most models proposed for the formation of tripolitic chert involve subaerial exposure, and thus, this facies is interpreted as being the shallowest lithofacies type. Karst, fractures, vugs, and other collapse-related features support this hypothesis. Hydrothermal fluid alteration is also argued to play a role in the alteration of the Mississippian interval (Farzanah 2012, Haynes, 2013), and the presence of baroque saddle dolomite in deeper facies suggests as much. Such diagnostic features were not preserved in tripolitic thin sections, and cannot be verified. The conglomeratic flow breccia containing tripolite is interpreted as being weathered from other tripolitic zones and deposited through mass transport in a structural low.

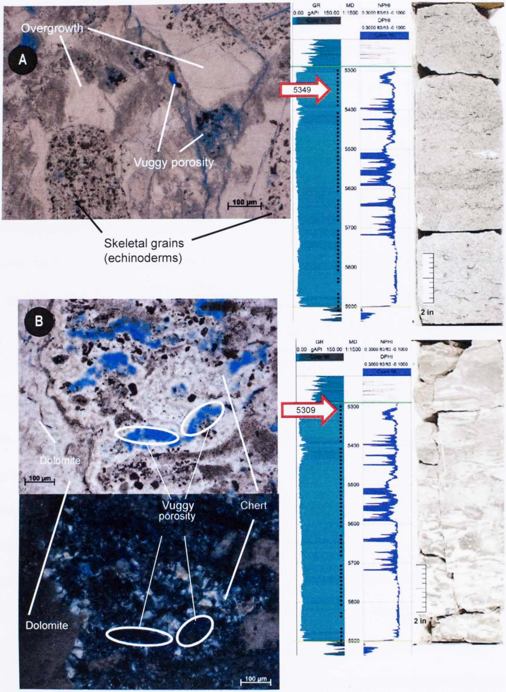


Figure 15. A) Skeletal grainstone. Echinoderm and brachiopod grains are most abundant in this facies type. Bryozoans and peloids are common as well. Crinoids frequently have overgrowths. Often exhibits partially moldic porosity in the shape of skeletal grains. Almost no micrite. Cherty zones occur in this facies. (Average porosity: 2.6 %; average permeability: 0.004 md.)
B) Brecciated tripolite: silica replaced limestone unit with residual calcite dissolved out due to subaerial exposure and fluid invasion. Often the original fabric has been completely destroyed. Most often seen as collapse breccia, but also manifests as flow breccia. (Average porosity: 9.2 %; average permeability, 0.36 md).

Stratigraphic Framework

Establishing a stratigraphic framework is essential for predicting reservoir quality. Favorable tripolitic chert intervals are commonly present at the top of the Mississippian interval (a third-order sequence). The peloidal packstone facies seen in core exhibits 8-10 % porosity, which is similar to the tripolite studied in terms of reservoir quality. It is one of the most common regressive-stage facies, and is typically present in fourth-order cycles common to the Mississippian. From core, cycles 3, 4, and 5 often display peloidal packstones near or at the cycle boundary (Figure 16). Thus sequence stratigraphy can also be helpful in predicting the occurrence of these intervals.

The stratigraphic framework for the Mississippian interval was determined using the idealized facies succession/stacking pattern developed from core and thin-section analysis (Figure 11). The framework was then expanded to non-cored wells using log data. This stacking pattern exists in both of the observed cores, in southeast Logan and Payne counties, Oklahoma, in outcrop from northwest Arkansas, and the Spivey-Grabs field in south Kansas (LeBlanc, 2014, Price, 2014, Watney, 2001). No conodont or biostratigraphy was performed to delimit specific time intervals or duration of specific cycle hierarchies. This analysis would most likely only be helpful in defining third-order sequences but not the numerous fourth and fifth-order cycles observed in the aforementioned cores. The classification of cycles and their hierarchies is meant to illustrate relative changes in frequency throughout different hierarchies and does not reflect quantitative measurements.

The stratigraphic succession reflects a shallowing/shoaling upwards profile. The first two facies in the succession (glauconitic sandstone and bioturbated

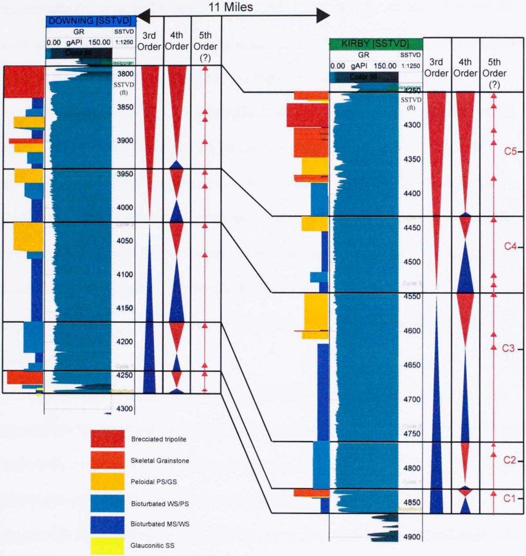


Figure 16. Correlative fourth-order cycles between the Downing 1-7 SWD and Kirby 1-8 SWD cores. Five such cycles are distinguished and shown on the GR of both wells. High-order cycles can be seen in both cores, but were not correlative between cores. Fourth-order cycles in the Kirby are thicker than the Downing, interpreted as being a byproduct of greater accomodation space on the carbonate ramp. Also shown are the lithofacies types that correspond to the cores, in which a shoaling upward character is observed. Red triangles represent the regressive phase of its corresponding cycle, while blue triangles correspond to the transgressive phase. Potential fifth-order cycles are also shown by shallowing upward red arrows, though they were not correlated across wells.

mudstone/wackestone) correspond to a transgressive phase and the next four (bioturbated wackestone/packstone, peloidal packstone, skeletal grainstone, and tripolitic chert) correspond to a regressive phase. Due to autocyclic processes, the full facies succession is not often preserved in its entirety, but establishing such a succession is helpful in understanding variability, heterogeneity, and hierarchy of cycles.

Several levels of sequence-stratigraphic hierarchy are present, with the whole Mississippian interval representing a third-order sequence. This overall third-order sequence consists of the upper portion of the Kaskaskia first-order sequence of Sloss (1963) and is removed by the great Pennsylvanian unconformity. This cycle generally shows a shallowing-upward trend, with a larger degree of deeper facies near the base, while coarser, higher energy shallow-water facies proliferate the top of the section. This correlates well to the general trend of sea-level fall in the Mississippian (Haq and Schutter, 2008).

Higher-order cycles are present, but much more difficult to distinguish. It is proposed that the idealized facies succession detailed above is most likely indicative of fourth-order cyclicity. These cycles are on average 25 ft (7.62 m) thick or more, but can be hundreds of feet thick. Fourth-order cycles typically consist of one or more transgressive facies (Facies 1-2) capped by one or more regressive facies (Facies 3-6). Cycle thickness varies according to their position on the carbonate ramp. The core farther to the south (Kirby) with more accommodation space has cycles that are thicker than the northern core (Downing), which is likely due in part to greater accommodation space, and less erosion farther down the carbonate ramp. Fourth-order cyclicity is the most obvious control on lithofacies distribution.

Fifth-order cycles are difficult to distinguish. The cycles are differentiated on a smaller scale, mostly consisting of two facies types, such as a peloidal packstone and a skeletal grainstone or a mudstone and a wackestone. As such, they tend to be much thinner than fourth-order cycles. They are, however, much more variable, inconsistent, and difficult to correlate. The variations are due to high-frequency sea-level change coupled with varying accommodation rates. Fifth-order sequences are ubiquitous. However, due to their variability and inconsistency between cores, these fifth-order cycles were unable to be correlated. They might, however, control internal facies heterogeneity (Leblanc, 2014).

Five correlative fourth-order cycles have been distinguished in the Mississippian interval (Figure 16) and correlated in all wells of the study area (Figure 17). Such cycles were classified both on the facies successions present in core but also based on their log characteristics (largely their gamma ray (GR) and deep resistivity logs (ILD/RT90), but also neutron porosity (NPHI), density porosity (DPHI), spontaneous potential (SP), and photoelectric index (PE)). Identifying these units is advantageous in identifying reservoirs because it allows for predictability of specific lithofacies and sea level (which is important for subaerial exposure and the creation of tripolite).

Cycle 1 exhibits a near complete succession of all observed lithofacies types in core (Figure 16). In the cored wells and non-cored wells, it exhibits zones with a higher gamma-ray signature (>30 API), but a markedly higher deep resistivity relative to the rest of the resistivity curve. Its sequence boundary is often marked by a spike in resistivity (Figure 18). Cycle 2 does not exhibit the same variety of lithofacies types as cycle 1 in core, and often only has bioturbated mudstones or wackestones present. It

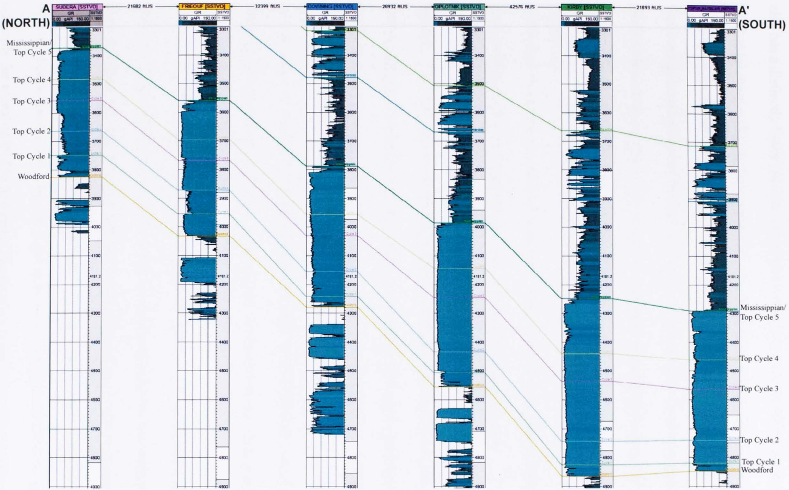


Figure 17. Structural cross section from north (left) to south (right) Grant County, Oklahoma. The cycle and formation tops are shown. The Mississippian limestone and its cycles prograde and thicken to the south (e.g., the Mississippian in the Subera well is 440 ft (134 m) and the Toews is 550 ft (167 m)). Note the higher GR signature near the top of most of the wells; this is interpreted as tripolite occurrence.

also has a distinctly lower gamma ray signature than cycle 1 (<30 API), and is often marked by sharp spikes in deep resistivity at its boundaries (Figure 18). Cycle 3 in both cores has a significant amount of bioturbated mudstone, but is also capped with a shallower peloidal packstone (Figure 16). Cycle 3 does not have many noticeable log characteristics that are diagnostic. In fact, it commonly shows little-to-no variability in the log suites analyzed. However, it often shows a sharp decrease in deep resistivity at its sequence boundary. Cycle 4 is similar to cycle 3 in core, in that it shallows from a bioturbated mudstone to a peloidal packstone. It lacks consistent log characteristics in most cored and non-cored wells (Figure 18). Deep resistivity and neutron porosity/density porosity spike in certain wells, but these curves do not behave regularly. The homogeneity of the log signatures throughout the cycle is its most distinguishing characteristic. Cycle 5 is the most variable of all cycles, and every lithofacies type is seen in core. Though highly variable, it still displays a shallowing-upward character in lithofacies. Cycle 5 consistently shows an increase in gamma-ray near its sequence boundary. It is also marked by erratic PE, NPHI/DPHI, and deep resistivity measurements. Both cycle 4 and cycle 5 are marked by the highest porosity log readings (neutron and density porosity).

Using the interpreted horizons (tops) for the cycles, a 3-D stratigraphic and structural framework (3-D reservoir model grid) was constructed for the Mississippian interval (Figure 19). The 3-D grid contains 210 layers according to the thickness of the five different cycles interpreted from core and well-log response. The 3-D grid has individual cells that are 200 ft by 200 ft (61 m by 61 m) aerially and 2 ft (0.61 m) vertically for a total of 89,536,230 cells. The layering (stratal geometry) within each cycle was created to follow (parallel) the basal surface of each cycle with truncated layers at the top of each cycle to reflect the erosional character of each cycle top. The average thickness of the Mississippian limestone in the study area is approximately 420 ft (128 m) (though thinner in the north and thicker in the south; Figure 19). The cycles are slightly progradational, as the units thicken to the south going down the carbonate ramp and seem to show a clinoformal geometry. The 3-D stratigraphic framework shows cycle 1 thinning (from 70 ft (27 m) to 20 ft (6 m), cycle 2 maintaining thickness of about 100 ft (30 m) and cycle 3 (from 100 ft (30 m) to 200 ft (61 m)), cycle 4 (from 50 ft (15 m) to 70 ft (27 m)), and cycle 5 (from 100 ft (30 m) to 190 ft (58 m)) thickening to various degrees (Figure 19). All five cycles are present in the entire study area, and are not heavily affected by structural features.

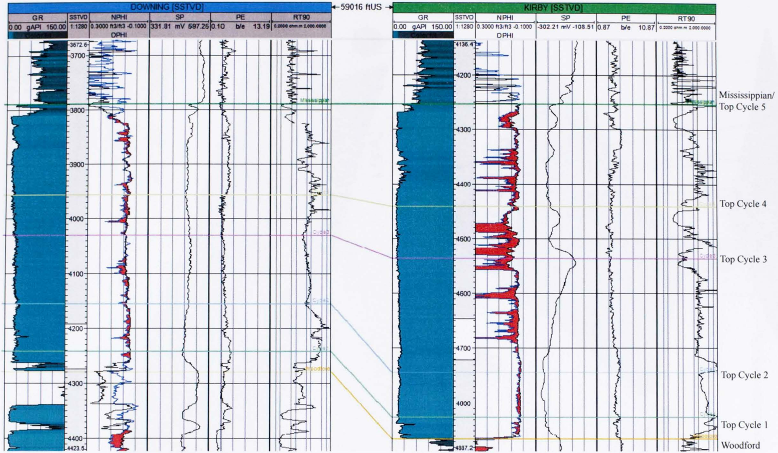


Figure 18. Logs from cored wells illustrating the five different observed cycles. In the north, distinguishing log characteristics are more easily seen. Distinct deep resistivity (RT90) curves were most helpful in correlating cycles from core, but GR and NPHI/DPHI also aided this process. Cycle 5 consistently shows the most variability in its logs, while other cycles tend to be more homogenous. Spikes in porosity and resistivity abound, however, throughout all cycles.

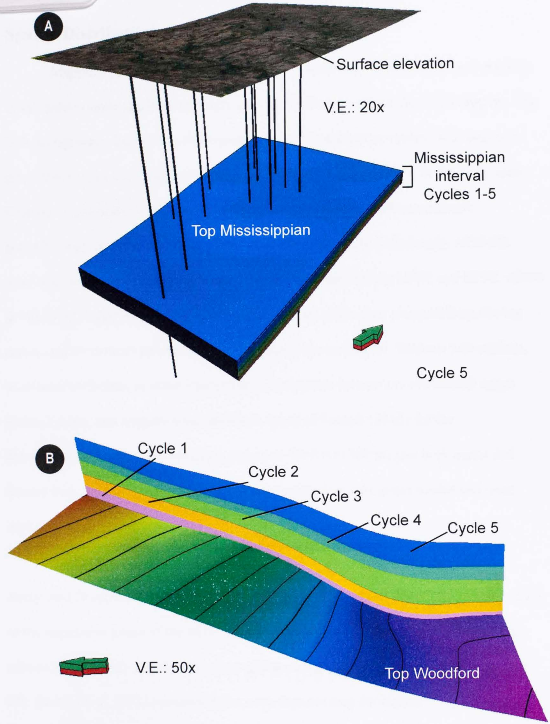


Figure 19. Three-dimensional stratigraphic framework. A) Ground surface with georeferenced image from Google Earth and 3-D model grid. Black lines show well paths. B) 3-D model cross-section showing the stratigraphic zones/cycles of the study area. Cycles 3-5 thicken to the south and appear to be clinoformal. The surface at the bottom represents the base of the Mississippian/Woodford top.

Spatial Distribution of Petrophysical Properties

Mapping petrophysical properties such as resistivity, bulk density, and porosity is valuable to understanding reservoir quality distribution within the Mississippian. The 3-D stratigraphic framework (3-D model grid of Mississippian cycles) was used as a constraint to map the spatial distribution of petrophysical properties in the study area. Sequential-gaussian simulation (SGS) was used to generate well-constrained petrophysical models using 1) upscaled well logs (Figure 2): bulk density (RHOB), deep resistivity logs (ILD/RT90), and cross-plot porosity (using NPHI and DPHI, where $\phi=\sqrt{(NPHI)^2+(DPHI)^2}$), 2) normalized histograms of the data obtained from the log suites, and 3) vertical and horizontal variograms for each cycle. Without 3-D seismic, horizontal well-data, or other nearby cores, variogram parameters (horizontal range, vertical range, and nugget) were similar to those of Turnini (2015) for the Mississippian: horizontal variogram ranges at 5000 ft (1524 m) (for both major and minor) with a vertical range of 50 ft (15 m). A spherical variogram model was used with the nugget set at zero.

Within the Mississippian, highly porous zones (>30 %) are irregularly distributed (Figure 20). However, the most consistently porous zones are cycles 4 and 5, or the regressive phase of the third-order Mississippian sequence. Though the porous zones are irregularly distributed, some appear to have a sub-vertical character (Figure 20). Elebiju et al. (2011) proposed that such features may be vertical fractures/brecciation zones that act as a conduit for fluids. Seismic data would be necessary to confirm this hypothesis.

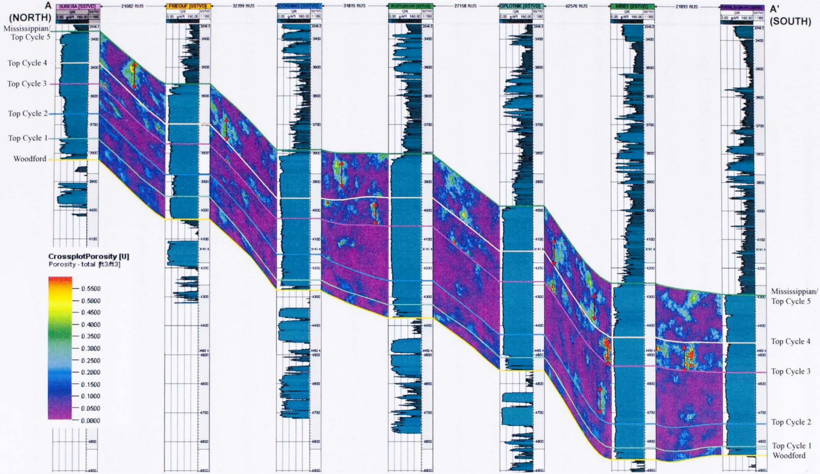


Figure 20. Structural cross section with moedeled porosity between the wells (Figure 2), Grant County, Oklahoma. The cycles and formation tops are shown. Overall, cycles 4 and 5 show the most consistently porous zones, possibly due to more occurence of regressive phase facies like peloidal packstone and tripolitic chert. High porosity zones in other cycles are more difficult to predict, and are likely directly tied to the degree of alteration. Red arrows indicate possible zones in which sub-vertical fractures might exist.

Low-resistivity measurements (Appendix C.3) exist throughout, but the lowest values are most commonly in cycles 4 and 5. There is a similar trend in bulk density, in which cycles 4 and 5 exhibit the lowest measured density. A filter was applied to the 3-D reservoir model of the Mississippian (Figure 21) to show only zones that are greater than 40 % porosity, less than 50 ohm.m, and less than 2.5 g/cm^3. According to Rogers (2001), these criteria will highlight tripolitic intervals. Again, there is significant concentration of these zones in the regressive phase of the third-order cycle (Figure 16), while the lower Mississippian, transgressive phase (cycles 1-3) exhibits only patches of high porosity.

Average porosity maps for the interpreted cycles (Figure 22) show additional evidence of highly variable reservoir quality in the Mississippian established by the other petrophysical models. The cycles pertaining to the regressive phase of the interpreted Mississippian third-order sequence (cycles 4 and 5) again show markedly better porosity than do those pertaining to the transgressive phase (cycles 1-3). Indeed, cycle 4 has better porosity than cycle 5, which appears counterintuitive because of the proximity of cycle 5 to the Mississippian unconformity. This difference is attributed to cycle 5 undergoing subsequent alteration and diagenesis that partly destroyed its porosity. Cycles 1-3 in contrast show poor average porosity values, typically below 10 % (Figure 22).

A possible explanation for the concentration of porosity throughout all cycles is the distribution of lithofacies. Cycles 4 and 5 exhibit a higher degree of reservoir quality lithofacies. Peloidal packstone and tripolitic chert have been identified as potential reservoirs from core, and there are large intervals of both lithofacies that occur in cycles

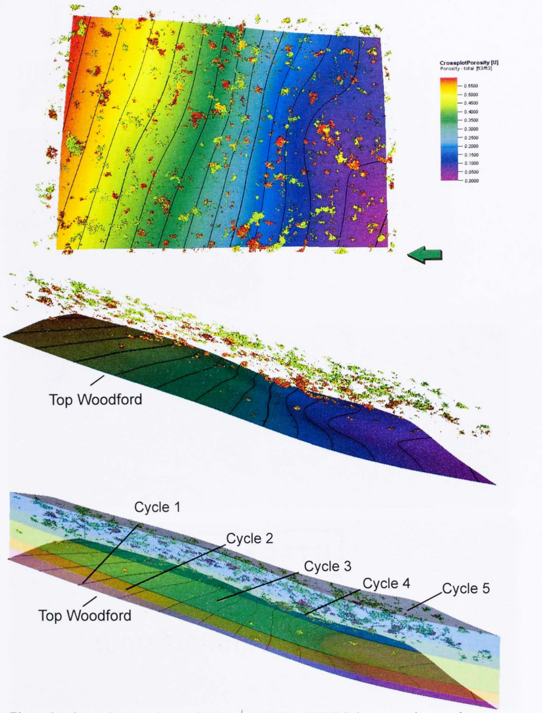


Figure 21. Crossplot porosity model ($\phi = \sqrt{(NPHI)^2 + (DPHI)^2}$) incorporating a value filter proposed by Rogers (2001), in which only porosity greater than 40%, resistivity lower than 50 ohm m, and bulk density lower than 2.5 g/cm^3 are shown to indicate, most likely, tripolitic zones. Note their distribution falls almost entirely in cycles 4 and 5, or the regressive phase of the third-order sequence in the Mississippian.

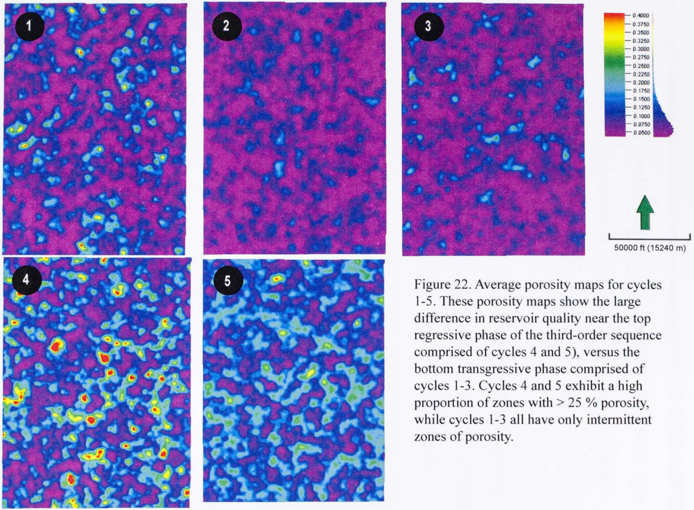


Figure 22. Average porosity maps for cycles 1-5. These porosity maps show the large difference in reservoir quality near the top regressive phase of the third-order sequence comprised of cycles 4 and 5), versus the bottom transgressive phase comprised of cycles 1-3. Cycles 4 and 5 exhibit a high proportion of zones with > 25 % porosity, while cycles 1-3 all have only intermittent zones of porosity.

4 and 5. Conversely, cycles 1-3 exhibit a large amount of bioturbated mudstone/wackestone and bioturbated wackestone/packstone facies which have been shown in core to be disadvantageous for production. It is likely that lithofacies type plays a role in reservoir quality to some degree. However, porous zones are highly irregular and therefore reservoir distribution is unlikely to be principally controlled by lithofacies type.

From logs, core, and petrophysical models, cycles 4 and 5 are interpreted as having significant tripolitic chert development. This is shown by lithofacies distribution in core, highly variable log characteristics common to tripolite, and significant distribution of zones with high porosity, low resisitivity, and low bulk density in the petrophysical models (Rogers 2001). As mentioned previously, these interpreted tripolitic zones were most common in cycles 4 and 5, but within those cycles there was no regular distribution. More high porosity zones were expected to be near the top of each cycle, as reservoir-quality lithofacies (tripolitic chert, peloidal packstone) occur there, but that is not the case. Distribution of these favorable areas is too scattered to draw such a conclusion. An apparent control on reservoir quality is third-order cyclicity, as the regressive phase of the Mississippian third-order sequence correlates well with tripolite occurrence and porosity. There is a major difference in the degree of tripolite as well as porosity in general at the boundary between the regressive and transgressive phase of the third-order cycle. Yet the degree of alteration and the distribution of that alteration is the largest control on reservoir quality. In core samples, any lithofacies type could have favorable reservoir characteristics if introduced to sufficient diagenetic alteration. The presence of tripolite was the foremost indication of alteration in core, well-logs, and models. The distribution of this alteration was irregular in core, in well-log signature, and in the models. Consequently, with the exception of identifying the regressive phase of the Mississippian third-order sequence, it is problematic defining reservoir units in the Mississippian limestone. Fourth and fifth-order cyclicity would be expected controls on reservoir quality (in addition to the established effect third-order cyclicity has on reservoir distribution), but the effect they have is not able to be resolved by this dataset.

Petrophysical modeling of the study area illustrates the significant heterogeneity present in the Mississippian. The only concentrated areas of porosity lie near the top half (regressive phase) of the Mississippian third-order sequence. Other areas of higher porosity seem to be unpredictably scattered according to localized diagenetic alteration. Muddier facies types, such as the bioturbated mudstone/wackestone and bioturbated wackestone/packstone consistently show inferior porosity development. Of the shallower facies, the peloidal packstone actually shows the best porosity, yet in petrophysical models, lithofacies type (excepting tripolitic chert) does not appear to have a major influence on porosity distribution. Accordingly, the degree and areas of diagenetic alteration, as well as sequence stratigraphy (in locating the regressive phase of the third-order cycle in the Mississippian) provide the clearest controls on reservoir quality and distribution.

Conclusions

The Mississippian limestone is a productive carbonate reservoir, yet its geologic controls on production and reservoir quality are frequently unclear due to its heterogeneous nature. Such heterogeneity is expressed in lithology, lithofacies type, alteration type, porosity, and pore type. The predominant lithologies of the Mississippian limestone are tripolite, chert, cherty-limestone, and limestone. The dominant lithofacies include tripolitic chert-breccia (tripolite), skeletal grainstone, skeletal-peloidal packstone, bioturbated wackestone-packstone, and bioturbated mudstone-wackestone. Tripolitic intervals occur most often near the top of the Mississippian interval, and commonly represent the best reservoir quality. The peloidal packstone facies exhibits the second-highest porosity of any facies, but is considerably lower than tripolite. Mississippian-aged limestones demonstrate a variety of alteration types, such as silicification, dolomitization, brecciation, and fracturing. Porosity is highly variable and most often a function of alteration (chiefly, the amount of dissolution). Pore type is also variable, but is predominantly vuggy. Other pore types like molds and fractures depend on lithofacies type and degree of diagenetic alteration.

The Mississippian carbonate system studied lies on the east-west trending margin of the Anadarko shelf/ramp. It is characterized by a shallowing-upward character, as well as high-order transgressive-regressive cyclicity. Five shallowing-upward fourth-order cycles are observed in the Mississippian interval, based on cores, thin sections and well-log response. Three-dimensional reservoir models constrained to well-log data show these cycles thickening as they prograde to the south down the carbonate ramp. Porosity, resistivity, and bulk density petrophysical models show favorable reservoir zones. These zones are irregularly distributed, but are highly concentrated in the regressive phase of the Mississippian third-order sequence. Tripolitic chert and peloidal packstone facies types are both regressive in nature and showed the best reservoir quality of all facies types. Sequence stratigraphy can help predict their occurrence, though alteration remains a large control on reservoir quality. Stratigraphically lower cycles show less alteration, and therefore lower reservoir quality. The degree and diffusion of diagenetic alteration as well as the sequence-stratigraphic framework provide the main controls on reservoir quality and its distribution.

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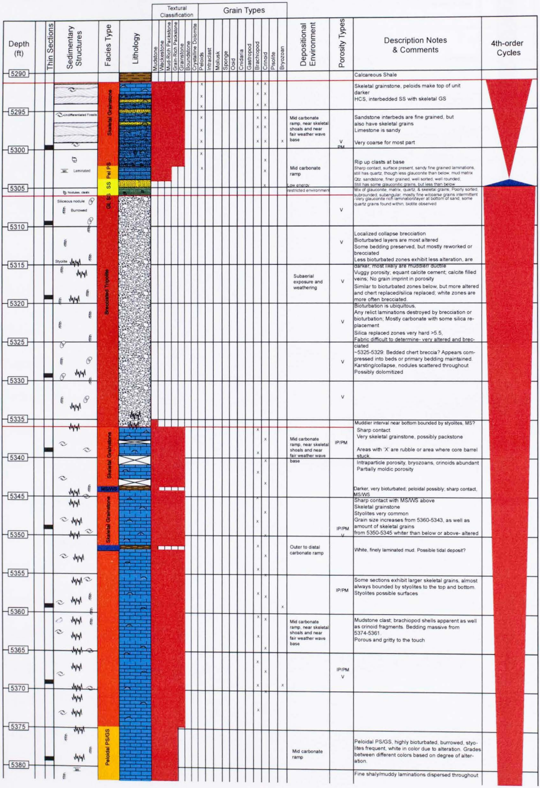
Appendix A: Detailed core description

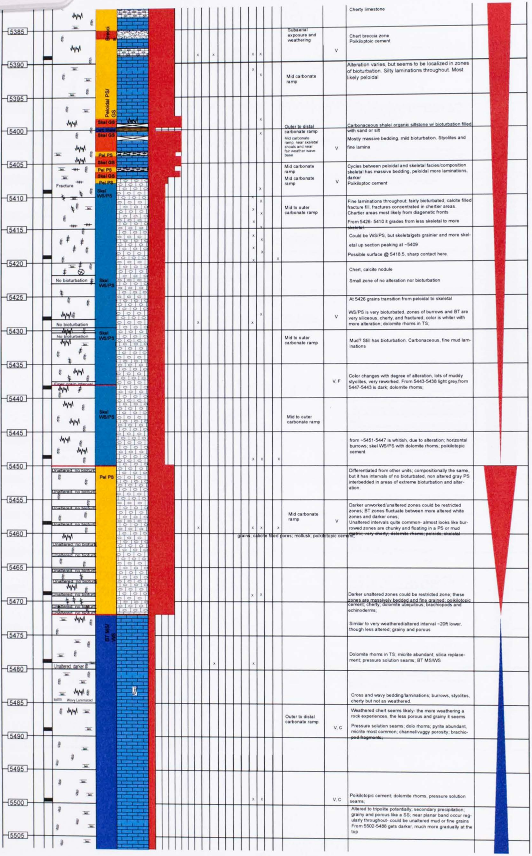
The Kirby 1-8 SWD core found in 9-25N 4W, Grant County, and the Downing 1-7 SWD core found in 18-27N 4W, Grant County, Oklahoma. The Kirby core represents ~600 ft of Mississippian interval, while the Downing core represents ~500 ft. Both contain the entire Mississippian interval, with portions of the Pennsylvanian shale above and Woodford shale below.

Devon: Kirby 1-8 SWD, 3505323102, Grant County, OK

Formation: Mississippi Limestone **Depth Interval: 5290'-5902'**

By: Colton Birch

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Fracture
No bioturbation
No bioturbation
No bioturbation
Finer grain interval
Unaltered, no bioturb
Unaltered, darker
Wavy Laminated
Breccia
Peloidal PS/ GS
Skel GS
Carb Shale
Skel GS
Pel PS
Skel GS
Pel PS
Skel GS
Pel PS
Skel WS/PS
Skel WS/PS
Skel WS/PS
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Pel PS
BT MS/ WS
Subaerial exposure and weathering
Mid carbonate ramp
Outer to distal carbonate ramp
Mid carbonate ramp; near skeletal shoals and near fair weather wave base
Mid carbonate ramp
Mid carbonate ramp
Mid to outer carbonate ramp
Mid to outer carbonate ramp
Mid to outer carbonate ramp
Mid carbonate ramp
Outer to distal carbonate ramp
V
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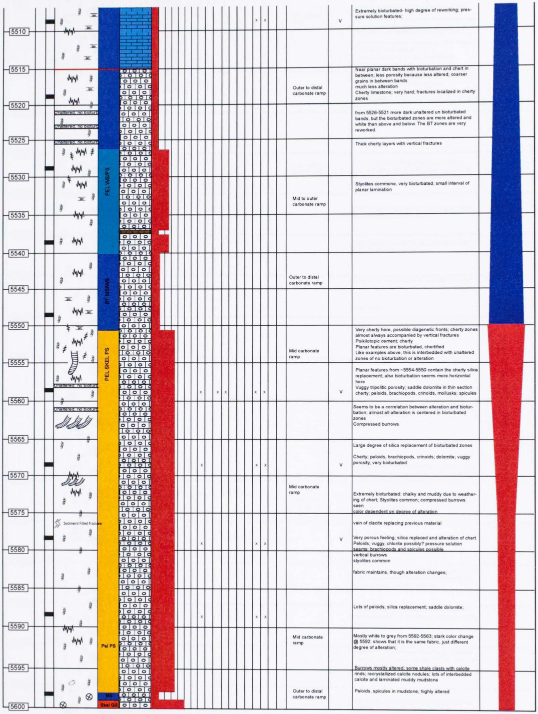
Cherty limestone
Chert breccia zone
Poikiloptoic cement
Alteration varies, but seems to be localized in zones of bioturbation. Silty laminations throughout. Most likely peloidal
Carbonaceous shale/ organic siltstone w/ bioturbation filled with sand or silt
Mostly massive bedding, mild bioturbation. Styolites and fine lamina
Cycles between peloidal and skeletal facies/composition skeletal has massive bedding, peloidal more laminations, darker
Poikiloptoc cement
Fine laminations throughout; fairly bioturbated; calcite filled fracture fill, fractures concentrated in chertier areas. Chertier areas most likely from diagenetic fronts
From 5426- 5410 it grades from less skeletal to more skeletal.
Could be WS/PS, but skeletalgets grainier and more skeletal up section peaking at ~5409
Possible surface @ 5418.5, sharp contact here.
Chert, calcite nodule
Small zone of no alteration nor bioturbation
At 5426 grains transition from peloidal to skeletal
WS/PS is very bioturbated, zones of burrows and BT are very siliceous, cherty, and fractured; color is whiter with more alteration; dolomite rhoms in TS;
Mud? Still has bioturbation. Carbonaceous, fine mud laminations
Color changes with degree of alteration, lots of muddy stylolites, very reworked. From 5443-5438 light grey,from 5447-5443 is dark; dolomite rhoms;
from ~5451-5447 is whitish, due to alteration; horizontal burrows; skel WS/PS with dolomite rhoms; poikilotopic cement
Differentiated from other units; compositionally the same, but it has intervals of no bioturbated, non altered gray PS interbedded in areas of extreme bioturbation and alteration.
Darker unworked/unaltered zones could be restricted zones; BT zones fluctuate between more altered white zones and darker ones;
Unaltered intervals quite common- almost looks like burrowed zones are chunky and floating in a PS or mud matrix; very cherty; dolomite rhoms; peloids, skeletal grains; calcite filled pores; mollusk; poikilotopic cement;
Darker unaltered zones could be restricted zone; these zones are massively bedded and fine grained; poikilotopic cement; cherty; dolomite ubiquitous; brachiopods and echinoderms;
Similar to very weathered/altered interval ~20ft lower, though less altered; grainy and porous
Dolomite rhoms in TS; micrite abundant; silica replacement; pressure solution seams; BT MS/WS
Cross and wavy bedding/laminations; burrows, styolites, cherty but not as weathered.
Weathered chert seems likely- the more weathering a rock experiences, the less porous and grainy it seems
Pressure solution seams; dolo rhoms; pyrite abundant, micrite most common; channel/vuggy porosity; brachiopod fragments;
Poikilotopic cement; dolomite rhoms, pressure solution seams;
Altered to tripolite potentially; secondary precipitation; grainy and porous like a SS; near planar band occur regularly throughout- could be unaltered mud or fine grains From 5502-5488 gets darker, much more gradually at the top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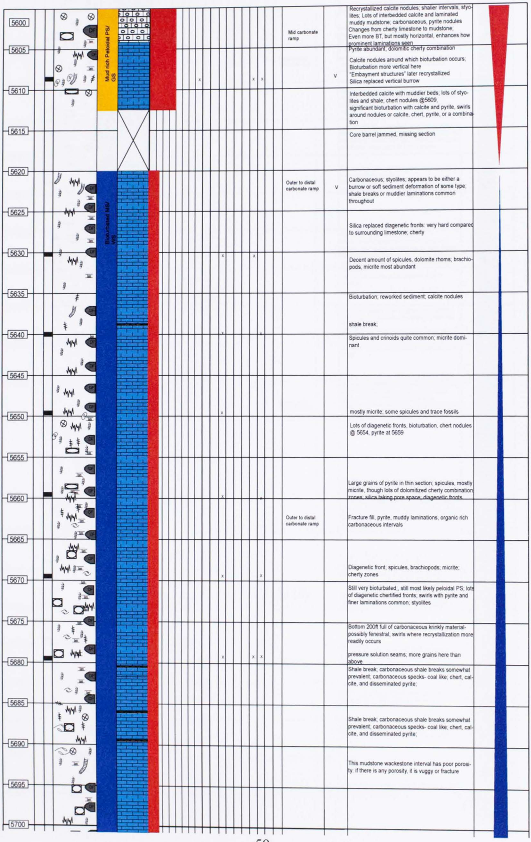
Unaltered, no bioturb
Sediment Filled Fracture
PEL WS/PS
BT MS/WS
PEL SKEL PS
Pel PS
MS
Skel GS
Extremely bioturbated- high degree of reworking; pressure solution features;
Outer to distal carbonate ramp
Near planar dark bands with bioturbation and chert in between; less porosity because less altered; coarser grains in between bands
much less alteration
Cherty limestone; very hard; fractures localized in cherty zones
from 5526-5521 more dark unaltered un bioturbated bands, but the bioturbated zones are more altered and white than above and below. The BT zones are very reworked.
Thick cherty layers with vertical fractures
Mid to outer carbonate ramp
Styolites commone, very bioturbated; small interval of planar lamination
Outer to distal carbonate ramp
Mid carbonate ramp
Very cherty here, possible diagenetic fronts; cherty zones almost always accompanied by vertical fractures
Poikilotopic cement; cherty
Planar features are bioturbated, chertified
Like examples above, this is interbedded with unaltered zones of no bioturbation or alteration
Planar features from ~5554-5550 contain the cherty silica replacement; also bioturbation seems more horizontal here
Vuggy tripolitic porosity; saddle dolomite in thin section
cherty; peloids, brachiopods, crinoids, mollusks; spicules
Seems to be a correlation between alteration and bioturbation: almost all alteration is centered in bioturbated zones
Compressed burrows
Large degree of silica replacement of bioturbated zones
Cherty; peloids, brachiopods, crinoids; dolomite; vuggy porosity, very bioturbated
Mid carbonate ramp
Extremely bioturbated: chalky and muddy due to weathering of chert; Styolites common; compressed burrows seen
color dependent on degree of alteration
vein of clacite replacing previous material
Very porous feeling; silica replaced and alteration of chert
Peloids; vuggy, chlorite possibly? pressure solution seams; brachiopods and spicules possible
vertical burrows
styolites common
fabric maintains, though alteration changes;
Lots of peloids; silica replacement; saddle dolomite;
Mid carbonate ramp
Mostly white to grey from 5592-5563; stark color change @ 5592: shows that it is the same fabric, just different degree of alteration;
Burrows mostly altered; some shale clasts with calcite rinds; recrystallized calcite nodules; lots of interbedded calcite and laminated muddy mudstone
Outer to distal carbonate ramp
Peloids, spicules in mudstone; highly altered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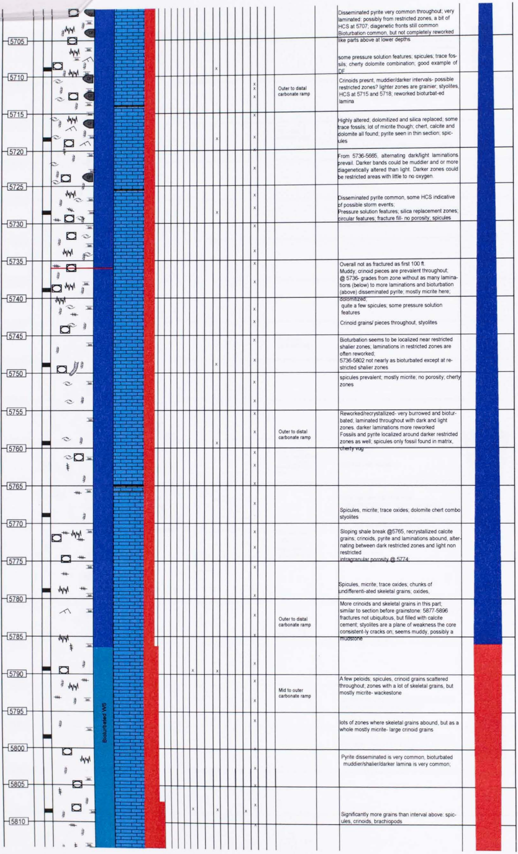
Mud rich Peloidal PS/GS
Bioturbated MS/WS
Mid carbonate ramp
Outer to distal carbonate ramp
Outer to distal carbonate ramp
Recrystallized calcite nodules; shalier intervals, styolites; Lots of interbedded calcite and laminated muddy mudstone; carbonaceous, pyrite nodules Changes from cherty limestone to mudstone; Even more BT, but mostly horizontal, enhances how prominent laminations seen
Pyrite abundant, dolomitic cherty combination
Calcite nodules around which bioturbation occurs; Bioturbation more vertical here "Embayment structures" later recrystallized Silica replaced vertical burrow
Interbedded calcite with muddier beds, lots of styolites and shale; chert nodules @5609, significant bioturbation with calcite and pyrite, swirls around nodules or calcite, chert, pyrite, or a combination
Core barrel jammed, missing section
Carbonaceous; styolites; appears to be either a burrow or soft sediment deformation of some type; shale breaks or muddier laminations common throughout
Silica replaced diagenetic fronts: very hard compared to surrounding limestone; cherty
Decent amount of spicules, dolomite rhoms; brachiopods, micrite most abundant
Bioturbation; reworked sediment; calcite nodules
shale break;
Spicules and crinoids quite common; micrite dominant
mostly micrite; some spicules and trace fossils
Lots of diagenetic fronts, bioturbation, chert nodules @ 5654, pyrite at 5659
Large grains of pyrite in thin section; spicules, mostly micrite, though lots of dolomitized cherty combination zones; silica taking pore space; diagenetic fronts
Fracture fill, pyrite, muddy laminations, organic rich carbonaceous intervals
Diagenetic front; spicules, brachiopods; micrite; cherty zones
Still very bioturbated;, still most likely peloidal PS; lots of diagenetic chertified fronts; swirls with pyrite and finer laminations common; stylolites
Bottom 200ft full of carbonaceous krinkly material- possibly fenestral; swirls where recrystallization more readily occurs
pressure solution seams; more grains here than above
Shale break; carbonaceous shale breaks somewhat prevalent; carbonaceous specks- coal like; chert, calcite, and disseminated pyrite;
Shale break; carbonaceous shale breaks somewhat prevalent; carbonaceous specks- coal like; chert, calcite, and disseminated pyrite;
This mudstone wackestone interval has poor porosity: if there is any porosity, it is vuggy or fracture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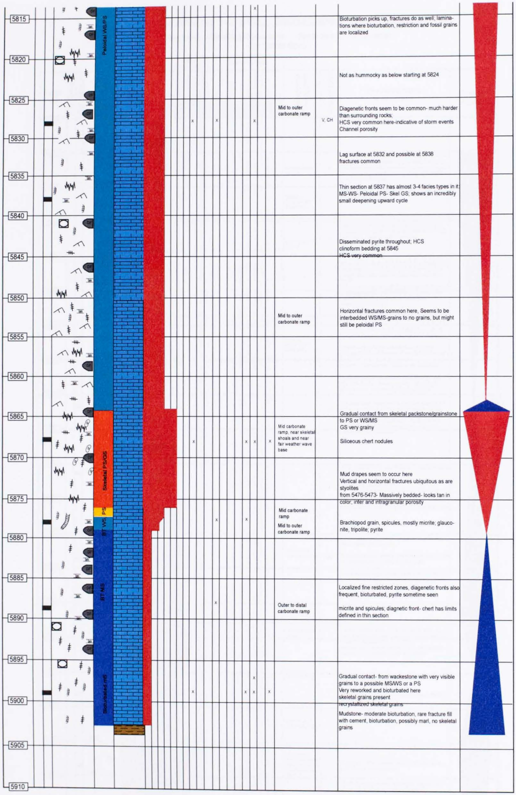
Bioturbated WS
Outer to distal carbonate ramp
Outer to distal carbonate ramp
Outer to distal carbonate ramp
Mid to outer carbonate ramp
Disseminated pyrite very common throughout; very laminated: possibly from restricted zones, a bit of HCS at 5707; diagenetic fronts still common
Bioturbation common, but not completely reworked like parts above at lower depths
some pressure solution features; spicules; trace fossils; cherty dolomite combination; good example of DF
Crinoids presnt, muddier/darker intervals- possible restricted zones? lighter zones are grainier; styolites, HCS at 5715 and 5718; reworked bioturbat-ed lamina
Highly altered; dolomitized and silica replaced; some trace fossils; lot of micrite though; chert, calcite and dolomite all found; pyrite seen in thin section; spicules
From 5736-5665, alternating dark/light laminations prevail. Darker bands could be muddier and or more diagenetically altered than light. Darker zones could be restricted areas with little to no oxygen.
Disseminated pyrite common, some HCS indicative of possible storm events;
Pressure solution features; silica replacement zones; circular features; fracture fill- no porosity; spicules
Overall not as fractured as first 100 ft.
Muddy; crinoid pieces are prevalent throughout;
@ 5736- grades from zone without as many laminations (below) to more laminations and bioturbation (above) disseminated pyrite; mostly micrite here; dolomitized;
quite a few spicules; some pressure solution features
Crinoid grains/ pieces throughout, styolites
Bioturbation seems to be localized near restricted shalier zones; laminations in restricted zones are often reworked;
5736-5802 not nearly as bioturbated except at restricted shalier zones
spicules prevalent; mostly micrite; no porosity; cherty zones
Reworked/recrystallized- very burrowed and bioturbated; laminated throughout with dark and light zones. darker laminations more reworked
Fossils and pyrite localized around darker restricted zones as well; spicules only fossil found in matrix, cherty vug
Spicules, micrite; trace oxides; dolomite chert combo styolites
Sloping shale break @5765, recrystallized calcite grains; crinoids, pyrite and laminations abound, alternating between dark restricted zones and light non restricted
intragranular porosity @ 5774;
Spicules, micrite; trace oxides; chunks of undifferenti-ated skeletal grains; oxides,
More crinoids and skeletal grains in this part; similar to section before grainstone: 5877-5896 fractures not ubiquitous, but filled with calcite cement; styolites are a plane of weakness the core consistent-ly cracks on; seems muddy, possibly a mudstone
A few peloids; spicules, crinoid grains scattered throughout; zones with a lot of skeletal grains, but mostly micrite- wackestone
lots of zones where skeletal grains abound, but as a whole mostly micrite- large crinoid grains
Pyrite disseminated is very common, bioturbated muddier/shalier/darker lamina is very common;
Significantly more grains than interval above: spicules, crinoids, brachiopods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5895
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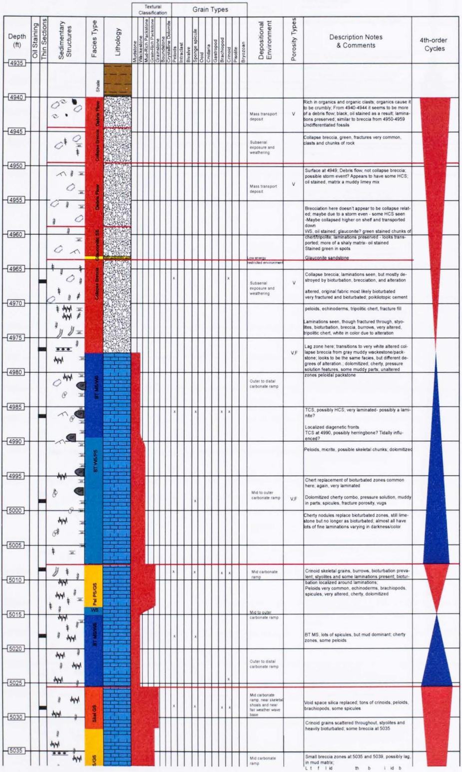
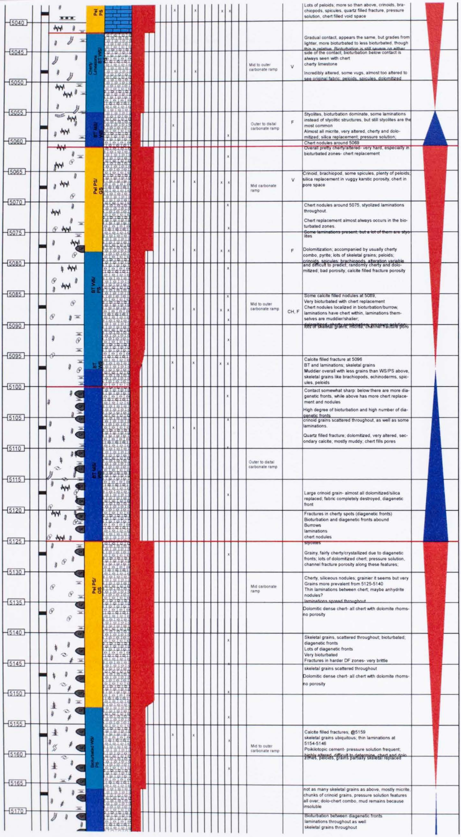
Peloidal WB/PS
Skeletal PS/GS
PS
BT WS
BT MS
Bioturbated md
Mid to outer carbonate ramp
V, CH
Mid to outer carbonate ramp
Mid carbonate ramp, near skeletal shoals and near fair weather wave base
Mid carbonate ramp
Mid to outer carbonate ramp
Outer to distal carbonate ramp
Bioturbation picks up, fractures do as well; laminations where bioturbation, restriction and fossil grains are localized
Not as hummocky as below starting at 5824
Diagenetic fronts seem to be common- much harder than surrounding rocks;
HCS very common here-indicative of storm events
Channel porosity
Lag surface at 5832 and possible at 5838
fractures common
Thin section at 5837 has almost 3-4 facies types in it: MS-WS- Peloidal PS- Skel GS; shows an incredibly small deepening upward cycle
Disseminated pyrite throughout; HCS
clinoform bedding at 5845
HCS very common
Horizontal fractures common here, Seems to be interbedded WS/MS-grains to no grains, but might still be peloidal PS
Gradual contact from skeletal packstone/grainstone to PS or WS/MS
GS very grainy
Siliceous chert nodules
Mud drapes seem to occur here
Vertical and horizontal fractures ubiquitous as are styolites
from 5476-5473- Massively bedded- looks tan in color; inter and intragranular porosity
Brachiopod grain, spicules, mostly micrite; glauconite, tripolite; pyrite
Localized fine restricted zones, diagenetic fronts also frequent, bioturbated, pyrite sometime seen
micrite and spicules; diagnetic front- chert has limits defined in thin section
Gradual contact- from wackestone with very visible grains to a possible MS/WS or a PS
Very reworked and bioturbated here
skeletal grains present
recrystallized skeletal grains
Mudstone- moderate bioturbation, rare fracture fill with cement, bioturbation, possibly marl, no skeletal grains

Devon: Downing 1-7 SWD, 3505323061, Grant County, OK

Formation: Mississippi Limestone   Depth Interval: 4935'-5450'

By: Colton Birch

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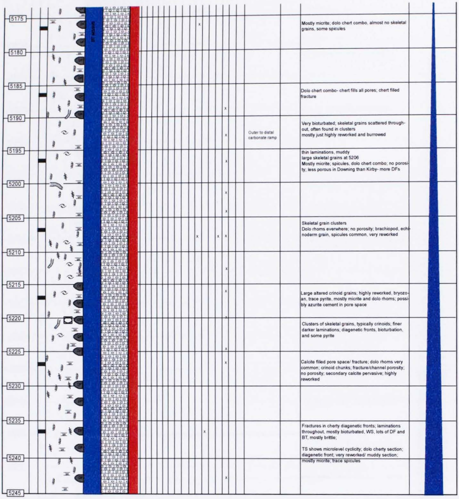
Mid to outer carbonate ramp
Outer to distal carbonate ramp
Mid carbonate ramp
Mid to outer carbonate ramp
Outer to distal carbonate ramp
Mid carbonate ramp
Mid to outer carbonate ramp
Lots of peloids; more so than above, crinoids, brachiopods, spicules, quartz filled fracture, pressure solution, chert filled void space
Gradual contact, appears the same, but grades from lighter, more bioturbated to less bioturbated, though this is relative. Bioturbation is still severe on either side of the contact; bioturbation below contact is always seen with chert
cherty limestone
Incredibly altered, some vugs, almost too altered to see original fabric; peloids, spicules, dolomitized
Styolites, bioturbation dominate, some laminations instead of styolitic structures, but still styolites are the most common
Almost all micrite, very altered, cherty and dolomitized; silica replacement; pressure solution;
Chert nodules around 5069
Overall pretty cherty/altered- very hard, especially in bioturbated zones- chert replacement
Crinoid, brachiopod, some spicules, plenty of peloids; silica replacement in vuggy karstic porosity, chert in pore space
Chert nodules around 5075, styolized laminations throughout.
Chert replacement almost always occurs in the bioturbated zones.
Some laminations present, but a lot of them are styolites
Dolomitization; accompanied by usually cherty combo, pyrite; lots of skeletal grains; peloids; crinoids, spicules; brachiopods, alteration variable and difficult to predict; randomly cherty and dolomitized; bad porosity; calcite filled fracture porosity
Some calcite filled nodules at 5089,
Very bioturbated with chert replacement
Chert nodules localized in bioturbation/burrow, laminations have chert within, laminations themselves are muddier/shalier;
lots of skeletal grains, micrite, channel fracture poro
Calcite filled fracture at 5096
BT and laminations; skeletal grains
Muddier overall with less grains than WS/PS above, skeletal grains like brachiopods, echinoderms, spicules, peloids
Contact somewhat sharp: below there are more diagenetic fronts, while above has more chert replacement and nodules
High degree of bioturbation and high number of diagenetic fronts
crinoid grains scattered throughout, as well as some laminations.
Quartz filled fracture; dolomitized, very altered, secondary calcite; mostly muddy; chert fills pores
Large crinoid grain- almost all dolomitized/silica replaced; fabric completely destroyed, diagenetic front
Fractures in cherty spots (diagenetic fronts)
Bioturbation and diagenetic fronts abound
Burrows
laminations
chert nodules
Grainy, fairly cherty/crystallized due to diagenetic fronts; lots of dolomitized chert; pressure solution, channel fracture porosity along these features;
Cherty, siliceous nodules; grainier it seems but very
Grains more prevalent from 5125-5140
Thin laminations between chert; maybe anhydrite nodules?
laminations spread throughout
Dolomitic dense chert- all chert with dolomite rhoms- no porosity
Skeletal grains, scattered throughout; bioturbated; diagenetic fronts
Lots of diagenetic fronts
Very bioturbated
Fractures in harder DF zones- very brittle
skeletal grains scattered throughout
Dolomitic dense chert- all chert with dolomite rhoms- no porosity
Calcite filled fractures; @5159
skeletal grains ubiquitous; thin laminations at 5154-5146
Poikilotopic cement- pressure solution frequent;
zones, peloids, grains partially skeletal replaced
not as many skeletal grains as above, mostly micrite, chunks of crinoid grains, pressure solution features all over; dolo-chert combo, mud remains because insoluble
Bioturbation between diagenetic fronts
laminations throughout as well
skeletal grains throughout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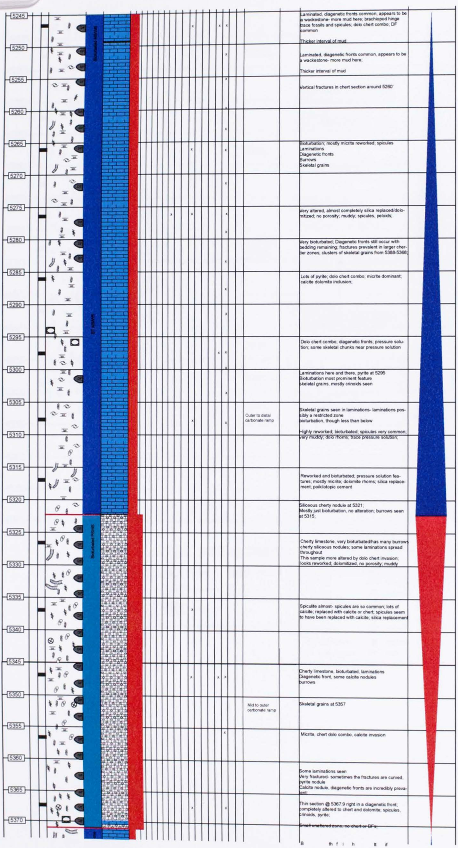
Mostly micrite; dolo chert combo, almost no skeletal grains, some spicules
Dolo chert combo- chert fills all pores; chert filled fracture
Outer to distal carbonate ramp
Very bioturbated; skeletal grains scattered throughout, often found in clusters
mostly just highly reworked and burrowed
thin laminations, muddy
large skeletal grains at 5206
Mostly micrite; spicules, dolo chert combo; no porosity; less porous in Downing than Kirby- more DFs
Skeletal grain clusters
Dolo rhoms everwhere; no porosity; brachiopod, echinoderm grain, spicules common, very reworked
Large altered crinoid grains; highly reworked, bryozoan, trace pyrite, mostly micrite and dolo rhoms; possibly azurite cement in pore space
Clusters of skeletal grains, typically crinoids; finer darker laminations; diagenetic fronts, bioturbation, and some pyrite
Calcite filled pore space/ fracture; dolo rhoms very common; crinoid chunks; fracture/channel porosity; no porosity; secondary calcite pervasive; highly reworked
Fractures in cherty diagenetic fronts; laminations throughout, mostly bioturbated, WS, lots of DF and BT, mostly brittle;
TS shows microlevel cyclicity; dolo cherty section; diagenetic front; very reworked/ muddy section; mostly micrite; trace spicules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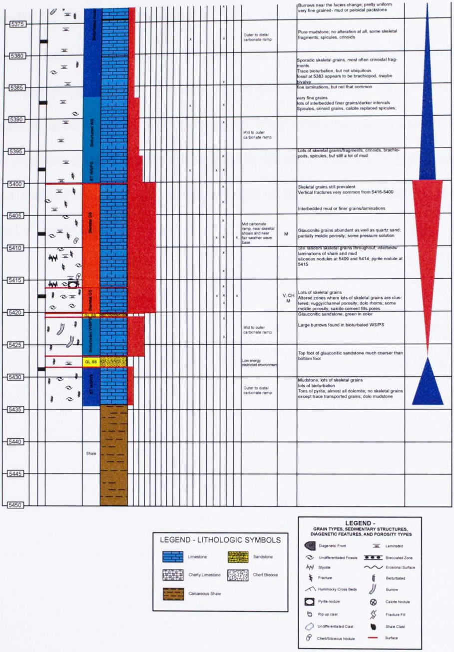
Outer to distal carbonate ramp
Mid to outer carbonate ramp
Laminated, diagenetic fronts common, appears to be a wackestone- more mud here; brachiopod hinge trace fossils and spicules; dolo chert combo; DF common
Thicker interval of mud
Laminated, diagenetic fronts common, appears to be a wackestone- more mud here;
Thicker interval of mud
Vertical fractures in chert section around 5260'
Bioturbation; mostly micrite reworked; spicules
Laminations
Diagenetic fronts
Burrows
Skeletal grains
Very altered, almost completely silica replaced/dolomitized; no porosity; muddy; spicules, peloids;
Very bioturbated; Diagenetic fronts still occur with bedding remaining; fractures prevalent in larger chertier zones; clusters of skeletal grains from 5388-5368;
Lots of pyrite; dolo chert combo; micrite dominant; calcite dolomite inclusion;
Dolo chert combo; diagenetic fronts; pressure solution; some skeletal chunks near pressure solution
Laminations here and there, pyrite at 5295
Bioturbation most prominent feature
skeletal grains, mostly crinoids seen
Skeletal grains seen in laminations- laminations possibly a restricted zone
bioturbation, though less than below
Highly reworked; bioturbated; spicules very common; very muddy; dolo rhoms; trace pressure solution;
Reworked and bioturbated; pressure solution features; mostly micrite; dolomite rhoms; silica replacement; poikilotopic cement
Siliceous cherty nodule at 5321;
Mostly just bioturbation, no alteration; burrows seen at 5315;
Cherty limestone, very bioturbated/has many burrows cherty siliceous nodules; some laminations spread throughout
This sample more altered by dolo chert invasion; looks reworked; dolomitized, no porosity; muddy
Spiculite almost- spicules are so common; lots of calcite; replaced with calcite or chert; spicules seem to have been replaced with calcite; silica replacement
Cherty limestone, bioturbated, laminations
Diagenetic front, some calcite nodules
burrows
Skeletal grains at 5357
Micrite, chert dolo combo, calcite invasion
Some laminations seen
Very fractured- sometimes the fractures are curved, pyrite nodule
Calcite nodule, diagenetic fronts are incredibly prevalent;
Thin section @ 5367.9 right in a diagenetic front; completely altered to chert and dolomite; spicules, crinoids, pyrite;
Small unaltered zone; no chert or DFs;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Outer to distal carbonate ramp
Mid to outer carbonate ramp
Mid carbonate ramp, near skeletal shoals and near fair weather wave base
Mid to outer carbonate ramp
Low energy restricted environment
Outer to distal carbonate ramp
M
V, CH M
Bioturbated WS
BT WS/PS
Skeletal GS
GL SS
Shale
Burrows near the facies change; pretty uniform very fine grained- mud or peloidal packstone
Pure mudstone; no alteration at all, some skeletal fragments; spicules, crinoids
Sporadic skeletal grains, most often crinoidal fragments
Trace bioturbation, but not ubiquitous
fossil at 5383 appears to be brachiopod, maybe bivalve
fine laminations, but not that common
very fine grains
lots of interbedded finer grains/darker intervals
Spicules, crinoid grains, calcite replaced spicules;
Lots of skeletal grains/fragments, crinoids, brachiopods, spicules, but still a lot of mud
Skeletal grains still prevalent
Vertical fractures very common from 5416-5400
Interbedded mud or finer grains/laminations
Glauconite grains abundant as well as quartz sand; partially moldic porosity; some pressure solution
Still random skeletal grains throughout; interbeds/laminations of shale and mud
siliceous nodules at 5409 and 5414; pyrite nodule at 5415
Lots of skeletal grains
Altered zones where lots of skeletal grains are clustered; vuggy/channel porosity; dolo rhoms; some moldic porosity; calcite cement fills pores
Glauconitic sandstone, green in color
Large burrows found in bioturbated WS/PS
Top foot of glauconitic sandstone much coarser than bottom foot
Mudstone, lots of skeletal grains
lots of bioturbation
Tons of pyrite, almost all dolomite; no skeletal grains except trace transported grains; dolo mudstone
LEGEND - LITHOLOGIC SYMBOLS
Limestone
Sandstone
Cherty Limestone
Chert Breccia
Calcareous Shale
LEGEND -
GRAIN TYPES, SEDIMENTARY STRUCTURES, DIAGENETIC FEATURES, AND POROSITY TYPES
Diagenetic Front
Laminated
Undifferentiated Fossils
Brecciated Zone
Stylolite
Erosional Surface
Fracture
Bioturbated
Hummocky Cross Beds
Burrow
Pyrite nodule
Calcite Nodule
Rip up clast
Fracture Fill
Undifferentiated Clast
Shale Clast
Chert/Siliceous Nodule
Surface

Appendix B: Thin section data

Thin section data/analysis from the 107 thin sections made. 61 were made from Kirby 1-8 SWD core plugs (5 specific depths have two thin sections each). 46 thin sections were made from Downing 1-7 SWD core plugs. With some exceptions, these thin sections represent about every 10 feet of depth in the cores. Porosity and permeability is provided in addition to the descriptions. Averages of these data by facies type is shown at the end of the appendix.

APPENDIX B: THIN SECTIONS

Sample #	Core Plug #	Depth	Thin Section Description	Permeability, md to Air	Permeability, md Klinkenberg	Porosity, % Ambient	Porosity, % NCS
002	1-35	5299.4	**Skel GS:** lots of skeletal grains, fossiliferous grainstone;	0.0024	0.0005	2.8671115	2.7300249
003	1-45	5309.3	**Tripolitic Chert;** Classic example of weathered tripolitic chert; bioturbated; vugs and dissolution porosity abound; equant calcite cement, no grain imprint on porosity; calcite filled vein, chunks of calcite remain; 5% porosity	0.0006	0.0001	3.3447521	3.1783074
004	1-55	5319.1	**Tripolitic Chert;** Vuggy porosity- 15-20%; maybe more calcite; mostly carbonate/dolomite remains, and thus porosity and permeability are better: more connectivity; dark spots most likely artifact of thin section process	0.142	0.087	10.669442	10.539276
005	1-65	5329.1	**Tripolitic Chert:** Almost exact same as 1-55; 15-20% porosity; vuggy in nature; all carbonate (calcite/dolomite), no skeletal grains.	0.734	0.528	13.009288	12.86794
006	1-75	5339.1	**Skeletal GS**: Intraparticle/ moldic porosity; 1-5% bryozoans, crinoids abundant- porosity in bryozoan chambers; brachiopod fragments; some interparticle porosity; maybe gastropod as well; overgrowths on crinoids abound; some trace fracture porosity	0.019	0.008	3.843612	3.7081589
007	2-6	5349.1	**Skeletal GS:** Very poor porosity; brachiopods, echinoderms; bryozoans; very similar to 1-75; some silica replacement/cherty zones; mostly calcite; moldic/intraparticle porosity; vugs also abound; overgrowths	0.0025	0.0006	2.7685419	2.6223866
008	2-16	5359.1	**Skeletal GS**: Very similar to 2-6 & 1-75; brachiopod chunks very prevalent; echinoderm (crinoids); possibly some mollusks; bryozoans, mostly calcite; some scattered/trace silica; moldic porosity 1-5%; overgrowths	0.0016	0.0003	2.6031619	2.466686
009	2-26	5369.1	**Skeletal GS:** same as above (2-16) brachiopods; echinoderms; some bryozoans; intraparticle porosity (1-5%) vugs where particles have been dissolved out- mostly calcite; some trace fracture porosity; some scattered quartz grains; dissolution as well; overgrowths	0.0051	0.0015	2.6297511	2.4908627
010	2-36	5379.45	**Peloidal PS:** pressure solution seams; micrite in seams; calcite grains; hardly any skeletal grains; probably some fluid came through where crystalline calcite is present, otherwise micritic; some sparry calcite present; nil porosity; peloids abound	0.0004	0.0001	2.5937082	2.45959
011	2-46	5389.1	**Peloidal PS:** Peloids, skeletal grains, very muddled/bioturbated; brachiopods; crinoids, possibly some spicules; some bryozoans, some micrite; some localized porosity; mollusk fragment- calcite	0.0003	<0.0001	3.1651361	3.0330986

012	3-9	5409.1	**Skeletal WS/PS**: Nil porosity; pressure solution features (seams); appears laminated as a result- lots of qtz grains scattered throughout "laminations", bioturbated/muddled; small skeletal fragments have been weathered/broken; poikilotopic cement- very prevalent; brachiopods; organic material/clays in styolites.	0.075	0.042	1.7490809	1.6015916
013	3-19	5419.6	**BT WS/PS:** Poikilotopic cement; micrite common; brachiopod and echinoderm fragments prevalent; qtz. Grains, looks very similar to 3-9; looks muddled- BT; micrite mud prevalent, but not fully mud supported; bryozoans and possibly mollusks	0.0001	<0.0001	0.8305918	0.6787402
014	3-28	5428.7	**BT WS/PS:** Poikilotopic cement; micrite common; brachiopod and echinoderm fragments prevalent; qtz. Grains, looks very similar to 3-9; looks muddled- BT; micrite mud prevalent, but not fully mud supported; bryozoans and possibly mollusks		<0.0001	1.3894329	1.2491409
015	3-38	5438.4	**BT WS/PS:** micrite abundant, organic material throughout; dolomite rhoms in silica matrix; very prevalent (similar to 3-9 and 3-28) some fracture porosity; calcite mineralization along fractures; cherty dolomite nodules throughout (diagenetic fronts?)	0.0001	<0.0001	5.0735534	4.9296472
016	3-48	5448.7	**BT WS/PS:** Micrite abundant, echinoderms and crinoids; though fossils broken and fragmented; poikilotopic cement, mostly calcite; just like 3-28 and 3-38; cherty dolomite throughout; styolites with porosity following along them (channel?); porosity throughout, mollusk fragment	0.002	0.0004	5.04631	4.8765607
017	3-58	5458.85	**Peloidal-Skeletal PS**: Very cherty; similar to 3-38 and 3-48; bioturbated; predominantly silica/qtz with rhoms of dolomite; peloids, skeletal fragments-very broken; brachiopod and crinoid grains; calcite filled pores; mollusks with overgrowths; porosity localized in cherty zones; peloids; dolomite inclusions; poikilotopic cement	0.02	0.0084	2.8607551	2.7180053
018	3-68	5468.6	**Peloids skeletal PS**- Fracture, organic material/clays; poikilotopic cement in places; calcite, but in chert; dolomite ubiquitous; secondary dolomite: replacive texture; mostly dolomite; floating rhoms; brachiopods and echinoderms	0.0011	0.0002	2.8932339	2.7598934
019	3-78	5478.6	**BT MS/WS:** dolomite rhoms- near perfect, micrite most abundant; silica replacement still occurs very often in dark patches around micrite; seams from pressure solution; not as altered in terms of dissolution	0.0009	0.0002	5.8946988	5.756337
020	3-88	5488.6	**BT MS/WS**: pressure solution, organic material/clay accumulated there; dolomite rhoms, pyrite and other oxides common; micrite also very common; porosity 5-10%; vugs, channels of porosity; dolomite very common, brachiopods; pyrite as well; calcite grains, skeletal fragments; very broken- hard to distinguish- spicules possibly; organic material/clays; high bioturbation; very altered.	0.008	0.0027	7.8974584	7.7662517
021	4-9	5499.7	**BT MS/WS:** Decent porosity- 10%; echinoderm fragments, crinoids, brachiopod fragments; altered- more dissolution; dolomite rhoms very common, mostly dolomite; porosity exists within these dolomitic zones; some qtz grains, pressure solution features; weathered skeletal grains; lots of calcite, bleached; almost appears laminated due to pressure solution features; poikilotopic cement; altered	0.05	0.026	10.650379	10.48673

022	4-18	5508.15	**BT MS/WS:** same as above (4-9) very porous from alteration/dissolution; very bioturbated; pressure solution with insoluble organics/clay; dolomite very common, calcite almost equally abundant; brachiopod chunks, echinoderm/crinoid as well, some trace magnetite-pyrite, micrite	0.023	0.01	9.2993144	9.1647145
023	4-28	5518	**BT MS/WS:** brachiopods, micrite very common, same as above (4-9 and 4-18) less porosity because less altered; more skeletal grains than above, less broken and altered pocket of coarser grains, skeletal fragments, qtz grains between 2 pressure solution features; micrite and poikilotopic cement common.	0.0005	0.0001	4.5030638	4.3612773
024	4-38	5528.9	**BT Peloidal WS/PS:** skeletal fragments; peloids; poor porosity, brachiopods, crinoids, poikilotopic cement; some qtz grains, still some micrite, channel porosity along pressure solution; dolomite rhoms in qtz matrix in some part; trace qtz grains; overgrowths, poikilotopic cement; cherty	0.0004	<0.0001	2.0197263	1.8823859
025	4-47	5537.8	**BT peloidal MS/WS**: peloids; brachiopods and crinoids. Very dolomitized; cherty; pressure solution seams, micrite, perhaps dolomitized; very altered and bioturbated; poikilotopic chert matrix in some places- silica dissolution; mixture of calcite, chert, dolomite; vugs but not porous	0.0003	<0.0001	2.5137544	2.3580475
026	4-57	5547.75	**BT MS/WS:** Peloids, brachiopods, and crinoids; very dolomitized; cherty; pressure solution seams, micrite; very altered and bioturbated; poikilotopic cement, chert matrix in some places; mixture of calcite, chert and dolomite; vugs, but poor porosity		<0.0001	0.9814425	0.8288817
027	4-67	5557.7	**Peloidal PS:** Tripolitic porosity; crinoids prevalent, brachiopods as well; large grain of dolomite; saddle dolomite here indicating influence from hydrothermal fluids; maybe some mollusks; lots of peloids, lots of dolomite, maybe some framework porosity; spicules	0.012	0.0043	4.3119743	4.1767188
028	4-77	5567.6	**Peloidal PS:** Peloids, brachiopods, some crinoids, but a decent amount of mud and dolomite; pressure solution features abound; silica replacement very common; cherty dolomite combination; dolomicrite; pretty altered and bioturbated	0.02	0.0087	7.5581797	7.3816617
029	4-87	5577.6	**Peloidal PS**: lots of peloids, dolomitization; silica replacement common; vuggy karstic porosity; possibly magnetite or pyrite; green grain looks bright pink blue in RF; pressure solution; possible saddle dolomite; spicules/brachiopods	0.0031	0.0008	6.0819814	5.9331815
030	4-98	5588.6	**Peloidal PS**: lots of peloids, silica replacement, saddle dolomite, crinoid, brachiopods; very similar to 4-87	0.058	0.03	6.8189491	6.6809988
031	5-4	5597.7	**Bioturbated MS/WS:** dolomite rhoms abundant, spicules, brachiopods, small crinoids; highly altered; possibly too altered to tell original fabric; peloids very common, maybe a peloidal PS at one point	0.0069	0.0022	0.9344361	0.7684013
032	5-15	5608.55	**Peloidal PS**: lots of peloids, lots of bioturbation preserved in thin section; very altered; oxides like pyrite abundant; zone with dolomitic chert combination; brachiopods, crinoids, some calcite spar	0.0013	0.0002	1.0549828	0.9126425

033	7-8	5630.1	**BT MS/WS**: decent amount of spicules here; dolomite rhoms prevalent; brachiopods and lots of micrite;	0.0002	<0.0001	0.7556455	0.5974176
034	7-18	5640.25	**BT MS/WS**: crinoids, spicules quite common; mostly micrite; trace fossils.	0.0002	<0.0001	0.7300405	0.5834867
035	7-27	5649.05	**BT MS/WS**: mostly micrite with some spicules and trace fossils randomly placed.	0.0002	<0.0001	1.0503539	0.896697
036	7-37	5659	**BT MS/WS**: Large grains of magnetite/pyrite, some spicules, mostly micrite; in part silica replaced, dolomitized cherty zones (probably in diagenetic zones); silica robs pore space; lots of spicules;	0.0002	<0.0001	0.6206333	0.4755031
037	7-47	5669.05	**BT MS/WS:** still the same as 7-37; still very altered in diagenetic fronts; spicules brachiopods, dolomite; cherty, silica replaced at spots;	0.0003	<0.0001	0.562923	0.4354825
038	7-57	5679.05	**BT MS/WS:** pressure solution features/styolites; brachiopods, spicules, crinoids- probably closer to a wackestone- has more grains than 5 thin sections above	0.118	0.07	2.0723108	1.9524426
039	8-14	5709.05	**BT MS/WS:** some pressure solution; dolomite rhoms throughout; spicules, trace fossils, good example of diagenetic front; cherty pockets with dolomite as well	0.0001	<0.0001	2.1570948	1.9886911
040	9-5	5718.75	**BT MS/WS:** highly altered; dolomitized; silica replaced; still a lot of mud left; mostly altered; some fossils; chert, calcite and dolomite all seem to be in equal abundance in altered zones; mostly mud otherwise; pyrite; spicules	0.0001	<0.0001	1.5025287	1.3666318
041	9-15	5728.7	**BT MS/WS**: pressure solution features, silica replacement zones; circular features scattered throughout- calcite or quartz filled veins with porosity along the fracture	0.688	0.485	2.0603779	1.8972173
042	9-25	5738.55	**BT MS/WS**: mostly micrite; some pressure solution features, dolomitized- lots of rhoms; some potential spar; silica replacement; quite a few spicules; fills in pore space; pyrite	0.289	0.195	2.2719791	2.1244146
043	9-35	5748.2	**BT MS/WS**: spicules and micrite; hardly any pores in any of the mudstone samples; cherty zones; maybe 1 crinoid grain	0.0001	<0.0001	0.7012942	0.5678115

044	9-45	5758.5	**BT MS/WS**: spicules only fossil found; porosity non existent; micrite overwhelmingly dominant; good example of a vug filled with chert		<0.0001	0.6437267	0.5116108
045	9-55	5768.25	**BT MS/WS**: spicules and micrite; trace oxides; styolites?; dolomite rhoms and trace chert; some calcite spar-maybe chunks of skeletal grains		<0.0001	0.991833	0.8256244
046	9-65	5778.25	**BT MS/WS**: spicules, micrite, chunks of undifferentiated skeletal grains; crinoid grains; weird circular features, oxide half replaced a calcite grain		<0.0001	0.7623412	0.6295362
047	10-8	5787.7	**BT MS/WS**: a few peloids; spicules, micrite, spar or dolomite rhoms; crinoid grains scattered throughout- zones where skeletal grains abound- bioturbation; large crinoid grains	0.0003	<0.0001	0.8715804	0.723365
048	10-19	5798.2	**BT MS/WS**: lots of zones where skeletal grains abound, but not as a whole; mostly micrite, crinoid grains- very large in size	0.0002	<0.0001	0.8155091	0.6851132
049	10-28	5807.8	**BT WS/PS**: more grains than 10-19; spicules mostly, but crinoids as well; calcite spar/dolomite; pressure solution situations; brachiopods? Mollusks, zones of MS but overall a WS/PS	0.0005	0.0001	0.9790696	0.8504758
050	10-49	5828	**BT WS/PS**: lots of micrite, but mostly WS-PS, peloids, spicules, crinoid chunks, fracture/channel porosity; almost a PS in some places.	0.475	0.319	1.3616584	1.1998816
051	10-58	5837.75	Strange sample; Displays 3-4 facies types in it; mudstone to wackestone to packstone to skeletal grainstone. Very high order cycle, possibly a deepening/fining upward cycle according to orientation of core; crinoids, spicules, brachiopods, mollusks, peloids, micrite, dolomite, not much chert	0.0007	0.0001	0.9598712	0.8322183
052	10-88	5867.55	**Skeletal GS:** brachiopods, crinoids abundant; dolomite chert combo; bryozoans, possibly some forams, but not certain; strange bluish mineral- possibly glauconite; no porosity	0.0011	0.0002	2.0650505	1.8856942
053	11-8	5877.35	**BT MS/WS:** brachiopod grains, spicules, mostly micrite, weird zones in pressure solution with weird porosity; or glauconite; some cherty chunks filling void spaces	0.0002	<0.0001	0.9670797	0.8415295
054	11-18	5887.35	**BT MS:** micrite and spicules; diagenetic front; chert has limits defined in thin section	0.0003	<0.0001	0.777609	0.6520981

055	11-29	5898.45	**Dolo-Skeletal MS/WS**: Highly altered, dolomitized, lots of quartz sand, huge skeletal grains, both crinoid and brachiopod; fracture porosity- partially filled with calcite; lots of dolomite- mollusk, almost completely quartz; dolomitized; qtz grains sandy it seems; cherty dolomite combo; bryozoan	0.059	0.031	2.6078099	2.4690034
056	11-39	5908.85	**Shale-** sandy, some fossils and pyrite		+	5.9114297	
062	0.067361111	4967.5	**Start of Downing: Tripolitic chert:** poikilotopic cement; lots of peloids; karstic vuggy porosity; highly dolomitized; peloids in abundance; (probably a Peloidal PS before alteration) highly altered; lots of fossils, must be echinoderms mostly; overgrowths; fracture porosity as well, but fracture filled and dissolved	0.047	0.024	9.45503	9.3157365
063	1-47	4977.55	**Tripolitic Chert:** very dolomitized; cherty; altered; fracture porosity with vugs/karsts; non altered peloids; pressure solution where fractures localize- some party very muddy; peloidal packstone where unaltered, but overall tripolitic	0.859	0.616	9.3682427	9.2311909
064	1-57	4987.35	**BT MS/WS**: Peloids; possibly skeletal chunks; spicules; dolomitized some brachiopods and crinoid chunks		<0.0001	2.6656158	2.5177623
065	2-5	4998.55	**BT WS/PS**: dolomitized cherty combo; pressure solution; muddy in parts; muddy overall; spicules, fracture porosity; some mild karstic porosity	0.0017	0.0004	3.2765334	3.1286561
066	2 15	5008	**Skeletal-Peloidal PS**: micrite common, cherty; dolomitized most likely; some peloids; altered skeletal grains; crinoids, spicules; brachiopods; looks like whole skeletal grains are silica replaced;		+	1.0221133	
067	2-24	5017.8	**BT MS/WS:** lots of spicules, but mud/micrite dominant; cherty zones where silica replacement occurred; some peloids, very altered	0.0003	<0.0001	1.0192425	0.8728761
068	2-34	5027.4	**Skeletal GS:** peloidal, brachiopods, crinoids, some spicules; void space silica replaced; tons of crinoids; peloids	0.0012	0.0002	3.8832291	3.7401504
069	2-44	5037.45	**Peloidal PS/GS:** lots of peloids; more so than above; but crinoids, brachiopods and spicules also apparent; quartz filled fracture; pressure solution; chert filled void space	0.245	0.162	1.2037062	1.0590804
070	2-54	5047.3	**BT MS/WS**: Incredibly altered; some vuggy porosity; almost too altered to see original fabric; some peloids, some spicules; dolomitized; good deal of micrite in it	0.0087	0.003	6.9988567	6.8719519

071	2-64	5057.15	**BT MS/WS**: almost all micrite/mud; very altered; chertified, dolomitized; silica replacement destroys all porosity; pressure solution features with some chunks of skeletal grains; peloids; fracture porosity;			<0.0001	2.1057519	1.9748588
072	2-74	5067.1	**Skeletal Peloidal PS:** crinoid brachiopods; some spicules; plenty of peloids; silica replacement in vuggy karstic porosity; trace micrite; chert in pore space	0.0029		0.0007	5.8609557	5.7167691
073	2-84	5077.05	**Skel-Peloidal PS**: Dolomitization; consistently accompanied by chert; pyrite; lots of skeletal grains; peloids, crinoids, spicules, brachiopods; alteration variable and difficult to predict; randomly cherty/dolomitic; bad porosity; calcite filled fracture- fracture porosity	0.0003		<0.0001	1.6849648	1.5617236
074	3-3	5087.75	**BT WS/PS**: dolomitization and silica replacement combine; pressure solution; lots of skeletal grains; some large crinoid grains; brachiopods, spicules, micrite; channel and fracture porosity along pressure solution seams	0.0005		0.0001	1.8037607	1.6740066
075	3-13	5097.75	**BT WS**: muddier overall that 3-3, less grains; still significant skeletal grain occurrence: brachiopods, crinoids, spicules, peloids, but more mud as well			<0.0001	0.6831222	0.564874
076	3-23	5107.6	**BT MS/WS**: quartz filled fracture; possibly calcite in fracture; dolomitized; pretty altered; secondary calcite pretty common; spicules possibly; grainier zones with some crinoids and brachiopods; mostly muddy; chert fills pore space; micrite; spicules, crinoid, trace peloids			<0.0001	0.7204367	0.5845829
077	4-3	5117.5	**Fabric destroyed-** dolomitized chert; almost completely altered- no original fabric left; most likely resides in a diagenetic front; dense chert			<0.0001	0.7108345	0.5665527
078	4-13	5127.8	**Peloidal PS**: lots of dolomitized chert; pressure solution- channel fracture porosity along these features; where not overly altered; chunks of crinoid grains	0.0016		0.0003	5.945903	5.8092382
079	4-23	5137.4	**Fabric destroyed-** dolomitized chert; almost completely altered- no original fabric left; most likely resides in a diagenetic front; dense chert; some fracture porosity			<0.0001	1.7752801	1.6527089
080	4-33	5147.1	**Fabric destroyed-** dolomitized dense chert; chert with dolomite rhoms; channel porosity/fracture porosity			<0.0001	0.3288541	0.2138762
081	4-43	5157.05	**Bioturbated Skeletal WS/PS**: poikilotopic cement; pressure solution frequently occurs; highly altered; difficult to determine original fabric; chert and dolomitic zones; of course, spicules; pressure solution; large grains only thing preserved; peloids;	0.0008		0.0001	2.8565817	2.7405258

082	4-53	5167.05	**BT MS/WS**: not as many skeletal grains as 4-43; mostly micrite; chunks of crinoid grains scattered; pressure solution features; dolomitized chert throughout; possible all dissolved out and muddy just because it is insoluble	0.138	0.084	3.6798118	3.5383103
083	4-63	5177	**BT MS:** mostly micrite; dolomitized chert; almost no skeletal grains; some spicules		<0.0001	1.1561861	1.0442787
084	4-72	5186.9	**BT MS:** dolomitized chert throughout; chert typically fills all pores; chert filled fracture	0.0003	<0.0001	0.3318575	0.2283765
085	4-82	5196.8	**BT MS:** mostly micrite; spicules dolomitized chert; right around diagenetic fronts; no porosity; mudstone more altered; less porous in Downing than Kirby; more diagenetic fronts here	0.0004	<0.0001	0.4293679	0.3219241
086	4-92	5206.85	**BT MS/WS**: dolomite rhoms everywhere; no porosity; brachiopod grain, crinoid grain, but skeletal grains trace; spicules common, but overall mostly micrite; dolomitized, no porosity, highly reworked; some fine grain chert filling pore space	0.0001	<0.0001	1.3579578	1.2380924
087	4-102	5216.8	**BT MS/WS**- large altered crinoid grains in matrix; highly reworked; bryozoan; trace pyrite; mostly micrite and dolomite rhoms; possibly azurite cement in pore space?- blue birefringence- maybe weathered calcite;	0.0017	0.0004	2.1054112	1.9692236
088	4-113	5227	**BT MS/WS**: calcite filled pore space/fracture; dolomite rhoms very common; crinoid chunks, some fracture/channel porosity along pressure solution seams; highly dolomitized; no porosity; calcite invasion pervasive; mostly micrite	0.0005	0.0001	2.978786	2.8502287
089	5-2	5236.75	**BT MS/WS**: same as above (4-113) possible micro level cyclicity; dolo-cherty section; diagenetic front; very reworked- muddy section, trace spicules	0.0004	<0.0001	1.136102	0.9954967
090	5-12	5246.75	**BT MS/WS**: same as above (5-2) highly reworked; brachiopod hinge; only trace fossils and spicules; dolo chert combos; diagenetic front		<0.0001	0.8719584	0.7358111
091	6-9	5266.9	**BT MS/WS**: same as 5-12: micrite with diagenetic fronts; mostly micrite, some trace skeletal chunks and spicules	0.0003	<0.0001	0.8103664	0.6878604
092	6-19	5276.65	**BT MS**: Very altered; almost completely dolomitized/silica replaced; no porosity; muddy; fabric altered; spicules, peloids, huge grain of calcite; mud most common	0.0002	<0.0001	0.8316292	0.6936184

093	6-29	5286.6	**BT MS/WS**: Lots of pyrite; same as 5-12; dolomitic/ cherty all over; micrite dominant; calcite and dolomite invasion	0.0001	<0.0001	0.7088578	0.6006837
094	7-6	5298.05	**BT MS/WS:** Same as 5-12; dolomitic chert calcite invasion; diagenetic fronts; pressure solution; some skeletal fragments near pressure solution; crinoid and brachiopod grains	0.0004	<0.0001	1.5373001	1.3970772
095	7-16	5308	**BT MS/WS**: highly reworked; good example of bioturbation common to these samples; spicules prevalent, possibly a spiculite; secondary chert/dolomite/calcite very common; more grains in this but still very muddy; dolomite rhoms, trace pressure solution	0.0002	<0.0001	1.7312914	1.6180246
096	7-25	5317.95	**BT MS/WS:** same as 5-12; spicules; pressure solution features; mostly micrite, dolomite rhoms, chert invasion; calcite grains; poikilotopic cement; crinoid grains; bioturbation	0.0019	0.0004	1.8503314	1.7146981
097	7-35	5327.95	**BT MS/WS** (assumed because fabric is nearly destroyed): This sample very altered by dolomitic chert invasion; looks muddled and reworked; same as before: spicules, no porosity, muddy	0.0001	<0.0001	1.012096	0.8777035
098	7-45	5337.95	**BT MS/WS**: almost a spiculite; lots of spicules; lots of calcite invasion; all pores replaced with calcite or chert; spicules seem to have been replaced with calcite; some silica replacement;	0.238	0.156	0.9599649	0.8161707
099	7-55	5347.9	**BT MS/WS**: Looks exactly like 7-35; dolomitized chert; muddy micrite; lots of spicules; grains of crinoids and brachiopods here and there;		+	0.9841873	
100	8-5	5357.85	**BT MS/WS**: Dolomite rhoms, no porosity; mostly micrite; some grains; calcite invasion along with chert/dolomitic zones	0.0003	<0.0001	0.8803761	0.7477899
101	8-15	5367.9	**BT MS/WS**: (assumed because fabric destroyed by alteration) Right in a diagenetic front; completely altered to chert, dolomite, secondary calcite; calcite filled veins; spicules; crinoid grains; pyrite, very reworked, difficult to establish because fabric destroyed	0.0001	<0.0001	0.710644	0.5792266
102	8-25	5377.9	**BT MS**: Pure mudstone, almost no alteration hardly; decent amount of skeletal fragments- spicules, crinoids, brachiopods		<0.0001	1.0228775	0.8869428
103	9-4	5388.15	**BT MS/WS**: spicules, crinoid grains, calcite replaced spicules; mostly micrite, little to no alteration; more grains than plain mudstone		<0.0001	0.7025561	0.5638786

104	9-13	5397.85	**BT WS/PS:** lots more skeletal grains than 9-4; crinoid, brachiopod, spicules; mud, but more altered than 9-4	0.0003	<0.0001	0.6607301	0.517489
105	10-3	5408.15	**Skeletal GS with GL SS portions**: glauconite grains, qtz grains; lots of skeletal grains: crinoid, brachiopod, bryozoans; chambers of bryozoans; some pressure solution; partially moldic porosity, pyrite	0.0004	0.0001	1.4351725	1.3077973
106	10-13	5418	**Skel GS**: vuggy/channel porosity; lots of crinoids/overgrowth; huge grains of crinoids and bryozoans; dolomite rhoms; brachiopod grains ubiquitous; some small moldic porosity; calcite overgrowth/cement around grains; overgrowth fills pore space; fracture porosity in places as well; calcite exhibits cleavage	0.0046	0.0013	1.7826021	1.6332705
107	10-23	5428.15	**Dolomudstone**: tons of pyrite; almost all dolomite; technically a MS- no skeletal grains except trace transported constituents;	0.18	0.114	5.4854366	5.3459067

Average Porosity/Permeability by Facies Type

Facies Type	Permeability, md		Porosity, %	
	to Air	Klinkenberg	Ambient	NCS
Tripolitic Chert	0.3565	0.251	9.1694	9.0265
Skeletal Grainstone	0.0042	0.0014	2.6531	2.5094
Peloidal Packstone	0.0282	0.0196	3.7898	3.8617
Bioturbated Wackestone/Packstone	0.0506	0.0517	2.1331	1.9918
Bioturbated Mudstone/Wackestone	0.039	0.0666	2.0	1.9

*No core plugs taken from Glauconitic Sandstone facies

Appendix C: Assorted figures

Supplementary figures, such as stratigraphic columns, sub-crop maps, and other petrophysical models.

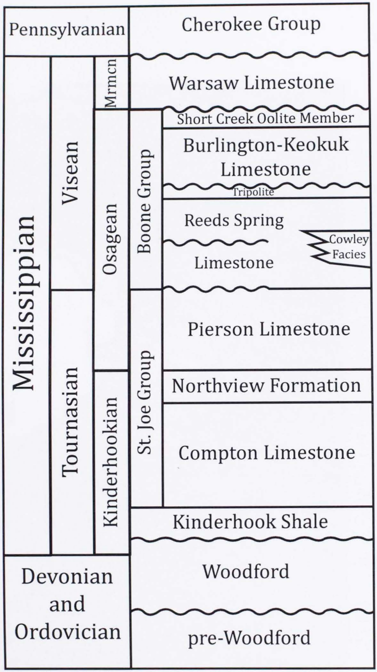

Figure C.1. Stratigraphic column. Shows the units that would be present in an idealized Mississippian section in the study area. Note the large unconformity at the top of the Mississippian (the Mississippian-Pennsylvanian unconformity). As mentioned previously, only some Meramecian is present with the majority of the section in my area being Osagean. The Kinderhookian shale for example is conspicuously absent. (Modified from Mazzullo 2011).

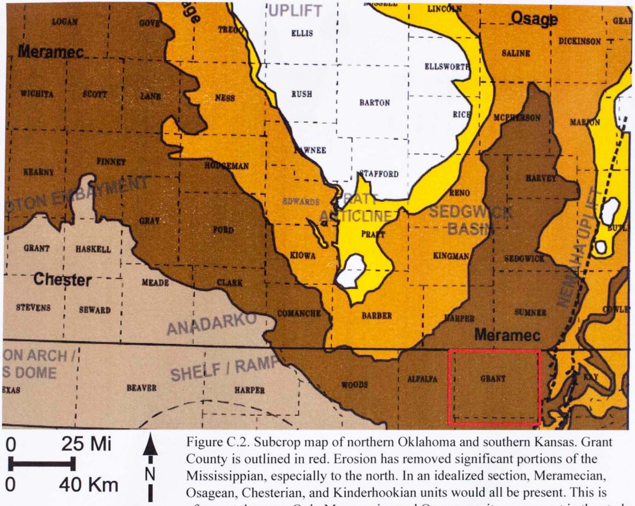

Figure C.2. Subcrop map of northern Oklahoma and southern Kansas. Grant County is outlined in red. Erosion has removed significant portions of the Mississippian, especially to the north. In an idealized section, Meramecian, Osagean, Chesterian, and Kinderhookian units would all be present. This is often not the case. Only Meramecian and Osagean units are present in the study area. (Modified from Nissen et al., 2004).

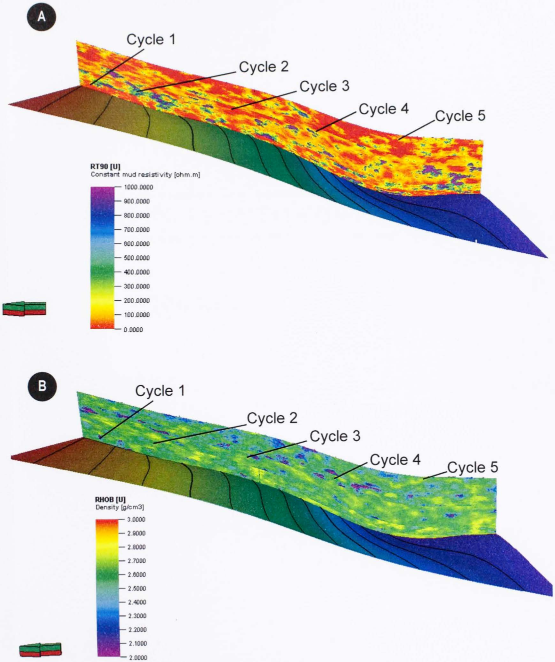

Figure C.3. Petrophysical models. A) Resistivity model highlighting lower resistivity zones in red, most noticeably concentrated near the top and irregularly distributed throughout the rest which is expected due to the high occurrence of tripolite near the top. Other zones are less predictable. B) Bulk density model using RHOB logs. Zones of interest are lower density zones. Calcite has a density of 2.71 g/cm^3, while chert has a density of 2.65 g/cm^3. Thus values lower than 2.6 g/cm^3 are anomalous and could be higher porosity zones. Note that low density zones are more concentrated in cycles 4 and 5 which coincides with the regressive phase of the third-order cycle in the Mississippian (Figure 16).