RESERVOIR QUALITY OF THE UPPER THREE FORKS FORMATION, FORT BERTHOLD INDIAN RESERVATION, WILLISTON BASIN, NORTH DAKOTA, U.S.A

by

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ABSTRACT

This thesis uses a five well database from the Fort Berthold Indian Reservation within the Williston Basin of North Dakota to document the reservoir quality of the Late Devonian upper Three Forks Formation.

There are five facies observed in the upper Three Forks: dolomitic claystone, brecciated, tan dolostone, interbedded claystone and dolostone, and chaotic. Based upon sedimentary structures and depositional interpretations, three facies associations were identified: A) shallow shelf marine, B) supratidal flat, and C) storm dominated mixed flat. Shallow shelf marine deposits demonstrated structure less bedding with rare storm influence. Supratidal flat deposits display abundant syndepositional anhydrites which indicate arid conditions during deposition. Storm dominated mixed flat deposits display abundant episodic erosion surfaces, pinch and swell laminations, ball and pillow features, and hummock cross stratification. There is a depositional shift recognized in the upper Three Forks between facies association B and C. This depositional shift is controlled by intrabasinal allogenic processes in response to the Late Devonian transition of the Williston Basin. This upward stratigraphic allogenic shift is represented by a decrease in aridity in the facies of the upper Three Forks between facies association B and C. Also, high frequency vertical and lateral variability in facies indicates a response to local changes in eustacy and climate.

Ultraviolet light (UV) photographs demonstrate extremely localized and preferential hydrocarbon saturation throughout the facies of the upper Three Forks. The dolomitic claystone facies demonstrates poor UV fluorescence indicating lack of hydrocarbon saturation. The brecciated facies demonstrates highly localized UV fluorescence, with claystone matrix showing no hydrocarbon saturation and dolostone clasts showing moderate hydrocarbon saturation. There are dolostone clasts in the brecciated facies that show no UV fluorescence indicating diagenetic occlusion of pore space preventing hydrocarbon saturation. The tan dolostone facies demonstrates pervasive UV fluorescence with many locations of no UV fluorescence indicating diagenetic occlusion of pore space and no hydrocarbon saturation. The interbedded claystone and dolostone facies displays highly localized UV fluorescence, the claystone beds show no saturation while the dolostone beds display moderate to bright UV fluorescence. The chaotic
facies also displays highly localized UV fluorescence, with claystones demonstrating a lack of saturation and dolostones showing moderate to intense saturation.

Pore types, sizes and shapes are variable throughout the facies of the upper Three Forks. The variability in the size, shape, and connectivity of these pores is a fundamental control on storage capacity and reservoir quality of the facies of the upper Three Forks. Inter-particle, intercrystalline, and slot microporosity are rare to moderate throughout facies of the upper Three Forks. Regional meteoric fluids and local mineralization are responsible for dissolution of both clay-rich and dolomite-rich intervals resulting in dissolution microporosity. This dissolution microporosity is the dominant storage capacity through the upper Three Forks. Microporosity of the upper Three Forks is connected by a common microfracture network found within the claystones of the interbedded claystone and dolostone and chaotic facies.

Diagenesis and cementation are complex throughout the facies of the upper Three Forks based upon mineralogy. The quartz and dolomite-rich brecciated and tan dolostone facies demonstrate coarse sucrosic dolomite framework with abundant rhombic overgrowth and laterally linked partial overgrowth cements. This pervasive cementation occludes pore space and prevents dissolution. The interbedded claystone and dolostone and chaotic facies lack pervasive dolomite cementation due to higher clay content. These facies display common secondary pyrite precipitation, and local dissolution. Facies with lithologic heterogeneity demonstrate a greater dissolution and secondary mineralization. Due to this, facies with higher frequency lithologic heterogeneity have the highest reservoir quality throughout the upper Three Forks.
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Figure 5-7: Plane and ultraviolet light photographs of the chaotic facies from the Henry Bad Gun well at 10,586.0 ft. chaotic facies demonstrating preferential fluorescence and typical hydrocarbon saturation patterns seen in the chaotic facies (Photos courtesy of Enerplus Resources). A) Plane light photo of chaotic facies demonstrating abundant soft sediment deformation (SSD), clay clasts (CLST), and mud cracks (blue triangles) B) Ultraviolet light photo of chaotic facies demonstrating intense fluorescence in areas of soft sediment deformation. Mud cracks filled with dolomitic sediment demonstrate confined fluorescence (blue triangles). Claystone clasts occlude saturation and display a dull to non-existent fluorescence (red arrows).

Figure 5-8: Graphs of major mineralogical constituents vs porosity for all wells in the study area. Each color box represents a different rock type and the associated porosity. The yellow box represents rock type A which is claystone rich and dolomite poor and demonstrates the worst hydrocarbon saturation. The red box represents rock type B which is very rich in dolomite but has diagenetic effects which cause lower porosity values making this rock type moderate in hydrocarbon saturation. The green box represents rock type B which is mixed in lithology but demonstrates no diagenetic effects and shows the best porosity and hydrocarbon saturation.

Figure 5-9: Oil saturation vs porosity from all wells in this study area. Showing that there is a negative correlation between oil saturation and porosity in the upper Three Forks; indicating that there may have been microporosity not recorded by these testing methods. Also; indicating that there are other components to the storage capacity of the upper Three Forks.

Figure 6-1: Schematic showing the distinction between a slot pore and intercrystalline pore in the dolostone lithologies. A slot pore is recognized as an elongate 2 dimensional pore between two crystal edges. Intercrystalline pores are recognized as a 3 dimensional angular pore between multiple crystal faces or an edge.

Figure 6-2: Photomicrographs of the claystone lithology demonstrating commonly observed mineralogy, texture, commonly observed microfractures, and abundant pyrite. A) plane polarized light (PPL) image of the interbedded claystone and dolostone facies from the Danks well at 10,688.05 ft. Pyrite nodules (gold triangles), microfracture (FX) and the associated microporosity, and showing the lower dolomite content observed in the claystones of the interbedded claystone and dolostone facies. B) PPL image of the “RT” marker from the Danks well at 10,721.00 ft. Demonstrating the higher dolomite content commonly associated with this interval, as well as a microfracture (FX) and the associated microporosity. C) Cross polarized light (XPL) image of the interbedded claystone and dolostone facies from the Hognose well at 10,403.15 ft, demonstrating low dolomite content of claystone lithology. Orange arrow represents a microfracture with internal mineralization of dolomite, and preferential dissolution around the boundaries of
the microfracture as this serves as a conduit for fluid flow; allowing both mineralization and dissolution. D) PPL image of the interbedded claystone and dolostone facies from Henry Bad Gun well at 10,592.15 ft, demonstrating low dolomite content, pyrite nodules (gold triangles), and microfractures (FX). These microfractures demonstrate microporosity resulting from preferential fluid flow and dissolution. E) PPL image of the interbedded claystone and dolostone facies from Roberts Trust well at 10,749.2 ft. Pyrite nodules (gold triangles) which are commonly observed in the Claystone lithology, as well as, a microfracture (FX) showing microporosity. F) PPL image of chaotic facies from Roberts Trust well at 10,754.9 ft. abundant pyrite nodules (gold triangles), and microporosity from preferential dissolution (orange arrows). This dissolution most likely occurred to fine grained dolomite within the claystone lithology. The claystone lithology found in the chaotic facies has a higher dolomite content which allows for preferential fluid flow and dissolution in these claystones.

Figure 6-3: Photomicrographs of silty dolostone lithology demonstrating mineralogy, texture, grain size, and commonly observed porosity types. The compaction, dissolution, and porosity are variable based upon the amount of diagenesis experienced. A) PPL image of the interbedded claystone and dolostone facies from Roberts Trust well at 10,752.00 ft. Silty dolostone lithology dominated by sucrosic dolomite; which is recognized by its rhombic texture, as well as, internal structure and anomalous interference colors in XPL. Detrital mica (MUSC) and quartz (QTZ) grains are also shown. Porosity in the silty dolostone lithology is seen in multiple forms. The most prominent is microporosity (MCP) from dissolution of both dolomite and other minerals. This image demonstrates silty dolostone with higher clay content. B) PPL image of chaotic facies from Roberts Trust well at 10,769.8 ft. Silty dolostone lithology by sucrosic dolomite. The most common type of porosity observed in this lithology is microporosity (MCP) resulting from dissolution. Intercrystalline (IXP) and slot (SP) porosity are also present in the silty dolostone lithology. This image demonstrates clean silty dolostone with a lack of clays.

Figure 6-4: Photomicrographs of the sandy dolostone lithology demonstrating mineralogy, texture, grain size, and porosity types found in this lithology. A) PPL image of tan dolostone facies from Hognose well at 10,428.00 ft. Sucrosic dolomite is observed along with a higher quartz (QTZ) content with fine sand sized quartz grains. It is interpreted that the coarser rock fabric allows for the growth of coarser dolomite rhombs and promotes the development of dolomite cement in this lithology. In this photomicrograph porosity is very limited due to the development of dolomite cement, but microporosity (MCP) from dissolution and slot porosity (SP) are seen. B) PPL image of tan dolostone facies from Roberts Trust well at 10,773.2 ft. Both fine-grained silt sized and very fine sand sized dolomite are observed, as well as fine sand quartz (QTZ) grains. This photo demonstrates more microporosity (MCP) from the result of dissolution, as well as, intercrystalline (IXP) and slot porosity (SP).

Figure 6-5: Photomicrographs of all three distinct lithologies demonstrating variability in mineralogy, texture, grain size, dissolution, and porosity. A) PPL image of interbedded claystone and dolostone facies from Danks well at 10,682.00 ft. Boundary from sandy dolostone and silty dolostone lithology, grain size differential is noticeable with the sandy
dolostone lithology being located on the right side of the image and having a very fine sand to fine sand grain size. In this image, there is pervasive dissolution creating microporosity. The microporosity and dissolution are more pervasive in the silty dolostone which is interpreted to be the result of dolomite cement that has developed in the sandy dolostone preventing fluid flow. B) PPL image of the boundary between tan dolostone and interbedded claystone and dolostone facies from Roberts Trust well at 10,773.2 ft. Silty dolostone versus the sandy dolostone demonstrating the contrast in quartz content between the two lithologies, as well as, grain size. Microporosity is seen in both of these lithologies, however the sandy dolostone contains larger intercrystalline and slot porosity. This image shows much less local dissolution than the previous image indicating that fluid flow in the upper Three Forks is preferential based upon depositional and diagenetic pathways. C) PPL image of the chaotic facies from Danks well at 10,686.1 ft. Demonstration of all three lithologies claystone, silty dolostone, and sandy dolostone. This image properly demonstrates the difference in grain size between all three lithology of the upper Three Forks. Variable dissolution is also observed in this image with the silty dolostone showing the most abundant dissolution and accompanied microporosity. In the sandy dolostone, there is visible intercrystalline and slot porosity. D) PPL image of the interbedded claystone and dolostone facies from Henry Bad Gun well at 10,586.00 ft. Another example of all three lithologies in the upper Three Forks, showing the distinct variation in grain size. It is interpreted that this is a syneresis crack infilled with sandy dolostone within the interbedded claystone and dolostone facies. Preferential dissolution is demonstrated in this image with the silty dolostone lithology displaying the most abundant dissolution and microporosity. E) PPL image of interbedded claystone and dolostone facies from Pumpkin well at 10,267.00 ft. Contact between silty dolostone and claystone, showing preferential dissolution at this lithology boundary and the associated microporosity, indicating that lithology boundaries are dominant fluid pathways in the upper Three Forks. The claystone shows no visible porosity and abundant pyrite nodules. The silty dolostone is dominated by sucrosic dolomite and shows microporosity, intercrystalline porosity, and slot porosity. F) PPL image of chaotic facies from Roberts Trust well at 10,767.00 ft. Silty dolostone with limited dissolution and microporosity and silty dolostone with abundant dissolution and microporosity. This image demonstrates the variable amounts of dissolution observed in the upper Three Forks which is interpreted to be controlled by mineralogy, texture, and diagenetic cements. It is also observed that the silty dolostone with abundant dissolution has abundant pyrite nodules which may be a contributing factor to dissolution.

Figure 6-6: Photomicrographs of the dolomitic claystone facies demonstrating common mineralogy, texture, and porosity types. A) PPL image of dolomitic claystone facies from Danks well at 10,682.7 ft. Image showing the dominant mineralogy of the dolomitic claystone facies which is illite and chlorite clays with variation in dolomite content; the dolomite rhombs in this facies are silt to clay sized. This image shows variable dissolution in this facies which is a result of the dolomite content. The two kinds of porosity found in the dolomitic claystone facies are dissolution microporosity (MCP) and microfracture porosity. (FX) B) PPL image of dolomitic claystone facies from Danks well at 10,688.05 ft. abundant pyrite nodules are observed (Gold Triangles) commonly associated with dissolution, this is interpreted to be a result of pyrite precipitation possibly causing dissolution of dolomite in areas of preferential fluid flow. Both
microporosity (MCP) from dissolution and fracture (FX) porosity are seen in this image. In the dolomitic claystone facies dissolution preferentially occurs to the dolomite due to the fact that there is no porosity or fluid pathway throughout the claystone aside from microfractures, causing preferential fluid flow in dolomite rich locations and microfractures.

Figure 6-7: Photomicrographs demonstrating mineralogy, texture, and porosity observed in the brecciated facies. A) PPL image of brecciated facies from Roberts Trust well at 10,779.10 ft. Image showing typical bedding style of brecciated facies with claystone matrix (fill) between two dolostone clasts. The claystone infill is illite and chlorite rich and demonstrates dissolution microporosity (MCP). The dolostone clast to the right of the image has higher quartz content, fine sand grain size, and displays slot (SP) and microporosity (MCP). The dolostone clast to the left of the image shows lower quartz content, silt grain size, and displays slot (SP) and microporosity (MCP). It is also observed that at the lithology boundary between the claystone and dolostone there is prominent microporosity. It is interpreted that this is a result of the contrast in mineralogy, porosity type, and pore throat size at lithology boundaries that there is preferential fluid flow and dissolution. B) XPL image of brecciated facies from Roberts Trust well at 10,779.10 ft. Common sweeping extinction of the illite and chlorite claystone, anomalous birefringence of dolomite, and low first order birefringence of quartz.

Figure 6-8: Additional photomicrographs of the brecciated facies demonstrating mineralogy, texture, porosity, and dissolution. A) PPL image of brecciated facies from Danks well at 10,707.00 ft. This photomicrograph demonstrates the commonly observed bedding nature of the brecciated facies caused by dewatering, dissolution of evaporites, and soft sediment deformation. Fine sand grain size is seen in the brecciated facies, due to the depositional energy of this facies. There is very little dissolution in this image which indicates that dissolution in the UTF is localized and may be attributed to chemical evolution of pore fluids, dissolution through precipitation of pyrite and the associated acids, or organic acids during the migration of hydrocarbons. B) PPL image of brecciated facies from Hognose well at 10,433.35 ft. This image demonstrates a similar relationship between lithologies and bedding nature; however there is pervasive dissolution present. This dissolution seems to have preferentially occurred in the claystone. This is another example of preferential dissolution occurring in the UTF. C) XPL image of brecciated facies from Hognose well at 10,428.00 ft. This image is a further example of the typical contorted bedding nature of the brecciated facies when observed in thin section. Minimal dissolution is present in this image which is five feet above image B in the Hognose well, indicating preferential dissolution. D) PPL image of Brecciated facies from Roberts Trust well at 10,779.1 ft. Another example of contorted bedding nature and upper silt to fine sand grain size of the brecciated facies. There is preferential dissolution at the lithology boundaries and within the microfractures (FX) of the claystone. There is microporosity (MCP) seen in the dolostone clasts.

Figure 6-9: Photomicrographs demonstrating common mineralogy, texture, and porosity seen in the tan dolostone facies. A) PPL image of the tan dolostone facies from Henry Bad Gun well at 10,618.00 ft. High quartz content and very fine to fine sand grain size of the tan dolostone facies. Common poikilotopic anhydrite (ANH) seen in the tan dolostone
facies. Sucrosic dolomite is the dominant dolomite in the tan dolostone facies. There is minimal to no dissolution or porosity, which is interpreted to be the result of dolomite cement in this facies. B) XPL image of tan dolostone facies from Henry Bad Gun well at 10,618.00 ft. Poikilotopic anhydrite (ANH) is recognized by high first order birefringence. C) PPL image of tan dolostone facies from Pumpkin well at 10,294.00 ft. Image demonstrating the similarity in the tan dolostone association across the well in the FBR study area. The very fine to fine sand grain size, as well as, the high quartz content is interpreted to be the result of high energy of the storm tides that supply sediment to the supratidal tan dolostone location. Poikilotopic anhydrite (ANH) is also observed. There is no visible dissolution or porosity, which is interpreted to be the result of pervasive dolomite cement. D) XPL image of tan dolostone facies from Pumpkin well at 10,294.00 ft. poikilotopic anhydrite (ANH) is recognized by high first order birefringence.

Figure 6-10: Additional photomicrographs demonstrating mineralogy, texture, and porosity of the tan dolostone facies. A) PPL image of tan dolostone facies from Henry Bad Gun well at 10,618.00 ft. Demonstration of the typical highly cemented tan dolostone facies, dolomite cement has occluded almost all intercrystalline and slot porosity leaving only slight microporosity in the sand flat facies. The grain size of the tan dolostone facies is very fine to fine sand, which allows for coarser textural development of sucrosic dolomite and dolomite cement. The tan dolostone facies has much higher quartz content than any other facies in the UTF. B) XPL image of tan dolostone facies from Henry Bad Gun well at 10,618.00 ft. Demonstration of anomalous birefringence of dolomite, and low first order interference colors of quartz.

Figure 6-11: Photomicrographs of the interbedded claystone and dolostone facies demonstrating common mineralogy, texture, bedding, and porosity types. A) PPL image of interbedded claystone and dolostone facies from Henry Bad Gun well at 10,600.45 ft. Sharp contacts between lithologies in this facies are observed. It is noted that the dolomite content of the claystones in the interbedded claystone and dolostone facies is lower than in the Dolomitic claystone facies. Variable thickness in laminations is shown, indicating heterogeneity in duration of sedimentation, accommodation space, and sediment supply. Microporosity from dissolution is observed in the silty dolostone sediment of this image. Pyrite nodules (gold triangles) tend to be associated with lithology boundaries, which are interpreted to be a result of these lithology boundaries being pathways for fluid flow and where mineralization and precipitation will preferentially occur. B) PPL image of interbedded claystone and dolostone facies from Henry Bad Gun well at 10,600.45 ft. Demonstration of sharp lithological contacts and variation of lamination thickness indicating heterogeneity in duration of sedimentation, accommodation space, and sediment supply. Microfractures (FX) with porosity are observed in the claystones. Pyrite nodules (gold triangles) are again observed trending along lithology boundaries where fluid pathways exist allowing for dissolution and precipitation. C) PPL image of interbedded claystone and dolostone facies from Hognose well at 10,423.15 ft. This image demonstrates variation in dolomite content of the claystone lithology and the variable dissolution that is a result of this mineralogy. The claystone in the bottom of the image is very illite and chlorite rich and shows little dissolution aside from a microfracture (FX). The claystone at the top of the image has higher dolomite content and is demonstrating abundant dissolution and microporosity. D)
PPL image of interbedded claystone and dolostone facies from Pumpkin well at 10,270.00 ft. This image demonstrates sharp contacts between lithologies, illite and chlorite rich claystones. There is the appearance of hummocky cross stratification (HCS) and parallel laminations in the silty dolostone. The silty dolostone also demonstrates microporosity from dissolution. E) PPL image of interbedded claystone and dolostone facies from Hognose well at 10,420.1 ft. Lithology boundary of claystone and silty dolostone, the claystone demonstrates no visible porosity. The silty dolostone exhibits common microporosity (MCP) from dissolution. There are also the commonly observed clasts that demonstrate microporosity from dissolution, it is interpreted that these are clay clasts (blue triangles) within the dolomitic intervals that experience preferential dissolution. It is not known if this porosity is effective during hydrocarbon generation or production. F) XPL image of interbedded claystone and dolostone facies from Henry Bad Gun well at 10,602.05 ft. This image demonstrates a fining upward (Black triangle) sequence in the interbedded claystone and dolostone facies, from claystone to sandy dolostone to silty dolostone back to claystone. There is microporosity from dissolution in both the sandy and silty dolostone; however the most abundant microporosity is observed in the silty dolostone. Pyrite nodules are also observed (gold triangles). .....................

Figure 6-12: Photomicrographs demonstrating common mineralogy, texture, and porosity observed in the chaotic facies. A) XPL image of chaotic facies from Roberts Trust well at 10,774.00 ft. Image showing two silty dolostone clasts and claystone with a much higher quartz and dolomite content then observed in the interbedded claystone and dolostone facies. This is interpreted to be the result of depositional energy in the chaotic facies being higher and mixing coarser sediment with the claystone. Microporosity is observed more abundantly in this facies at the lithology boundaries of the sandy dolostone clasts and the claystone. It is interpreted that these are locations for preferential fluid pathways based upon the difference in mineralogy and porosity. Dissolution can also occur more strongly in the claystones of the chaotic interval due to higher dolomite content. B) PPL image of chaotic facies from Roberts Trust well at 10,750.6 ft. Demonstration of the higher depositional energy of the chaotic facies, showing a clast of the bedded interbedded claystone and dolostone facies (Orange dotted outline). It is interpreted that storm processes are dominant in the deposition of the chaotic facies which yields the scour surfaces, clasts, and other high energy features observed in the chaotic facies. Common microfracture (FX) porosity and microporosity (MCP) from dissolution are observed. Pyrite nodules (gold triangles) are observed in association with dissolution, which is interpreted to be a result of the acid created during the precipitation of pyrite causing dissolution..............................................................

Figure 6-13: Photomicrographs showing additional examples of mineralogy, texture, porosity, and variable dissolution seen in the chaotic facies. A) XPL image of chaotic facies from Danks well at 10,687.00 ft. Demonstration of the intensity of microporosity from dissolution that can be present in the chaotic facies. Microfracture (FX) porosity is abundant in the claystone. There is a clast from the interbedded claystone and dolostone facies (orange dotted outline) which indicates a higher energy depositional environment of the chaotic facies. Dissolution is seen at high intensity throughout the entire image however, it’s important to note that in the claystones, dissolution is associated with fractures. There are pyrite nodules (gold triangles) at the lithology boundaries and
associated with dissolution within the interbedded claystone and dolostone clast. There is a syneresis crack (blue dotted outline) that penetrates the interbedded claystone and dolostone clast; this is interpreted to be to the rapid sedimentation and dewatering of the chaotic facies. The syneresis crack is filled with the coarse grained sediment transported and put into the water column by the higher energy deposition of the chaotic facies. B) PPL image of chaotic facies from Hognose well at 10,403.15 ft. Demonstration of variability in dissolution seen in the chaotic facies, dissolution is abundant in this image but not of the same intensity as image A. Microporosity is associated with dissolution; this image also demonstrates porosity in microfractures (FX). It is interpreted that the bedding observed in this image is soft sediment deformation at the microscopic scale. 153

Figure 6-14: Sucrosic dolomitization model showing the five stages and their relation to the processes that drive this style of dolomitization: Nucleus, Cortex, Crystal-Cluster Cortex, Lateral Linkage Cement, Pore-Filling Cement (Choquette and Hiatt, 2014). 155

Figure 6-15: Photomicrograph of complete sucrosic dolomitization in the tan dolostone facies. A) PPL image from Hognose well at 10,431.00 ft. This image demonstrates complete sucrosic dolomitization and cementation. In the clean tan dolostone facies there are no clays to obstruct growth of dolomite cement allowing for pervasive dolomitization developing rhombic overgrowth cement, lateral linkage cement, and pore-filling cement. This is a case where dolomitization is detrimental to reservoir quality. In the center of this image there is an example of a rhombic overgrowth on a dolomite cortex (orange arrow). B) XPL image from Hognose well at 10,431.00 ft. Cross polarized view of image. 156

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Figure 6-19: Photomicrograph of dolomiticite in the upper Three Forks from interbedded claystone and dolostone facies. A) XPL image from Pumpkin well at 10,262.50 ft. This dolomiticite may have not had the opportunity to experience textural maturation from early compaction and high quartz content. Sucrosic dolomite is seen occluding porosity in this image.

Figure 6-20: Photomicrograph of limpid dolomites seen filling pores in the tan dolostone facies. A) PPL image from Pumpkin well at 10,296.00 ft. Limpid dolomite crystals (orange arrows) are recognized by near perfect crystal faces and edges, and being inclusion free or relatively inclusion free. Limpid dolomites are indicative of a stressed salinity environment and varying salinity conditions. There is rare microporosity visible and sucrosic dolomitization has created laterally linked overgrowth and pore-filling cements in the tan dolostone facies. B) XPL image from Pumpkin well at 10,296.00 ft. Cross polarized view of image A. Limpid dolomites are highlighted by orange arrows.

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Figure 6-22: Cathodoluminescence microscopy of the tan dolostone facies A) PPL image from Henry Bad Gun well at 10,617.00 ft. Note pervasive sucrosic dolomite network with limited intercrystalline and slot porosity. B) CL image from Henry Bad Gun well at 10,617.00 ft. Detrital quartz grains are easily identified by their blue luminescence in CL. Dolomite core nuclei are irregular and dull to orange in luminescence. Cortical overgrowths have developed subhedral to euhedral crystals. Continued dolomitization during diagenesis created thin to thick zones that indicated a change in pore water redox conditions. Late ferroan dolomite cement is seen filling pore space between dolomite rhombs and is non-luminescent. Green arrows indicate rhombic overgrowth cements surrounding luminescent dolomite cortices; the rhombic overgrowths display different luminescence than the cortices, indicating varying pore water conditions during dolomitization.

Figure 6-23: Cathodoluminescence microscopy of the claystone in the interbedded claystone and dolostone facies A) PPL image from Henry Bad Gun well at 10,600.45 ft. Note the low percentage of dolomite, moderate pyrite nodules, and microfractures. B) CL image from Henry Bad Gun well at 10,600.45 ft. Quartz grains are easily identifiable from their blue luminescence in CL, note the difference in grain size of quartz in the
claystone lithology (less than 10 µm) as compared to the dolostone lithology (up to 50 µm). Dolomite is seen forming irregular to subhedral rhombs. Limited overgrowths are observed due to limited pore space in the claystone lithology preventing fluid-rock interaction and continued dolomitization with burial. Dolomite rhombs are bright yellow in luminescence indicating high Mn²⁺ in the early diagenetic pore water conditions.  

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Figure 6-25: Cathodoluminescence microscopy of the tan dolostone facies A) PPL image from Henry Bad Gun well at 10,617.00 ft. Note pervasive sucrosic dolomite network with minimal intercrystalline to slot porosity. Pyrite nodules are seen replacing dolomite rhombs. B) CL image from Henry Bad Gun well at 10,617.00 ft. Detrital quartz grains are recognized by their blue luminescence in CL. There are two dolomite crystals that display intensely bright yellow luminescence indicating that the pore waters were very rich in Mn²⁺ during their precipitation. Core nuclei are irregular and dull to orange in luminescence. Cortical overgrowths have developed subhedral to euhedral dolomite crystals. Continued dolomitization during burial produced thin to thick overgrowths of varying luminescence indicating change in redox pore water conditions during diagenesis. Late ferroan dolomite cement is seen filling pore space between dolomite rhombs and is non-luminescent. Some dolomite rhombs (blue arrow) display at least four changes in pore water redox conditions during dolomitization. Green arrows indicate rhombic overgrowth cements surrounding luminescent dolomite cortices; the rhombic overgrowths display different luminescence than the cortices, indicating varying pore water conditions during dolomitization.  

Figure 6-26: Cathodoluminescence microscopy of laterally linked partial overgrowth cement in interbedded claystone and dolostone facies A) PPL image from Hognose well at 10,410.00 ft. Note the vug filling laterally linked partial overgrowth dolomite cement with an isopachous rim (orange arrow). There is microporosity from dissolution visible in the upper portion of the vug. Note sucrosic dolomite network with no visible intercrystalline or slot porosity. B) CL image from Hognose well at 10,410.00 ft. Detrital quartz grains are easily identifiable by their blue luminescence in CL. Note the vug filling laterally linked partial overgrowth dolomite cement is non luminescent and inclusion pore. The non- luminescence may indicate the vug filling laterally linked partial
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CHAPTER 1 INTRODUCTION

Over the last 15 years unconventional oil and gas plays have been dominant contributors to U.S. production. This has caused an increase in exploration and drilling throughout the Williston Basin. These increased efforts have targeted both the Late Devonian-Early Mississippian Bakken formation and the Late Devonian Three Forks Formation (Berwick, 2008). This has resulted in a significant increase in available data for research of these formations.

From this increased exploration and available data, it has become clear that there are many local heterogeneities and complexities in the Three Forks Formation. The heterogeneities and complexities of this formation provide motivation for a further geologic understanding. A more in depth geologic understanding of heterogeneities and complexities should lead to more efficient and economic production of the Three Forks. These geologic findings and understandings may also be used as an analogue in future unconventional exploration.

The upper Three Forks strata are close in proximity to the source rocks of the lower Bakken shales. These strata will be the interval of focus for this thesis. There have been multiple previous works with focus on the Three Forks Formation; however this study aims to address questions of dispute.

1.1 Location of Study Area

The Three Forks Formation is located in the Williston Basin, which extends into parts of North Dakota, Montana, and the provenances of Saskatchewan and Manitoba in Canada. The study area for this research project is located within the United States region of the Williston Basin in North Dakota. Fort Berthold Indian Reservation (FRB) is the area of interest for this thesis; this area is located in portions of Mountrail, Ward, Dunn, Mclean, and Mercer counties. The southeastern nose of the Antelope anticline protrudes into the study area (Figure 1-1). Fort Berthold is an Indian reservation in North Dakota (Figure 1-1, see page 7).
1.2 Research Objectives

This study aims to address the differential reservoir quality and localization of hydrocarbons of the upper Three Forks Formation in FBR. Classification of the lithofacies and depositional environment of the upper Three Forks can help to resolve the continued questions surrounding the deposition of the Three Forks. Analysis of reservoir quality in the upper Three Forks may help to understand its localization and variation; which may be applied to future petroleum exploration efforts.

Objectives of this study are:

1) Describe vertical and lateral facies variation in the upper Three Forks in FBR.
2) Describe the depositional environments of the upper Three Forks.
3) Describe variable reservoir quality within the upper Three Forks facies.
4) Document differential reservoir quality and hydrocarbon localization in the upper Three Forks and address the controls on this localization.
5) Describe the process of dolomitization in the upper Three Forks.
6) Describe diagenesis and the paragenetic sequence of the upper Three Forks.
7) Document pore throat size and variation throughout the upper Three Forks.

1.3 Research Contributions

Contributions of this study include:

1) Description of lithofacies and depositional facies of the upper Three Forks.
2) Documentation of the controls on reservoir quality in the upper Three Forks.
3) Description of dolomitization in the upper Three Forks.
4) Recognition of diagenetic processes and relationships in the upper Three Forks.
5) Documentation of the controls on reservoir quality in the upper Three Forks throughout Fort Berthold Reservation.

1.4 Previous Work

The Williston Basin is a highly studied basin and has been for the last 20 years, since the initiation of unconventional reservoir production. There have been many studies
on the Three Forks Formation throughout the Williston Basin from its deposition, lithology, and production mechanisms; however the Fort Berthold area is relatively unstudied when it comes to research of the Three Forks Formation (Bob Larson personal communication, 2014). The background and previous works for this study is classical papers on the Williston Basin and previous thesis studies on the Bakken Total Petroleum System and the Three Forks Formation.

Studies on the Williston Basin have resulted in significant amounts of research conducted on numerous geologic parameters from sequence stratigraphy, sedimentation, structure, diagenesis, depositional systems, eustacy, petroleum systems and many other topics by numerous authors (Anna et al., 2010; Blakely, 2005; Christopher, 1962; Dow, 1974; Gerhard et al., 1987 & 1990; LeFever, 1991 & 1992; Meissner, 1978; Meissner et al., 1984; Peterson and MacCary, 1987; Sloss, 1963; and Webster, 1984). Recently more work has been done specifically on the Three Forks Formation and its potential as a petroleum reservoir. Seven papers on the Three Forks Formation stand out in discussion of depositional environment, lithofacies, facies association, and other characteristics of the Three Forks (Table 1-1).

Table 1-1: List of papers used a background study in this thesis

<table>
<thead>
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<th>Title</th>
<th>Author and Institution</th>
<th>Year</th>
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Dumonceaux (1984) addressed facies variation and depositional environments of the Three Forks Formation. She identified four facies that span supralittoral to sublittoral, which resulted in an initial depositional model of the Three Forks (Figure 1-2). Dumonceaux (1984) recognized the presence of anhydrite in the Three Forks and
interpreted that deposition occurred in arid climate conditions. She also deduced that cyclic transgressions and regressions caused lateral migration of depositional environments, thus creating complex facies stacking.

Berwick (2008) studied the upper Three Forks and the Sanish member which is now termed the Pronghorn (LeFever 2011, Johnson 2013). He identified five facies in the upper Three Forks: Facies A is a moderate red to pale red dolomitic shale with common shale clasts and discontinuous lenses of very-fine to fine-crystalline dolomite. Facies B is calcareous (limey) and silty dolomite that is dark greenish to dark gray with angular rip up clasts. Facies C is a silty dolomite with gray to green shale and abundant soft sediment deformation and brecciation. Facies D is a light green to gray silty dolomitic shale. Facies E is bioturbated and burrowed gray silty dolomite. Berwick developed a depositional model leading to the currently accepted yet debated depositional setting of the upper Three Forks. He also classified the sequence stratigraphy of the upper Three Forks identifying a bounding discontinuity, flooding surfaces, and a transgressive surface in the upper Three Forks and (now recognized as the Pronghorn formations) (Figure 1-3). Finally, Berwick did work on the presence of dolomite in the upper Three Forks identifying the presence of primary, detrital and secondary dolomite.

Gantyno (2010) analyzed lateral and vertical facies distribution and depositional environments of the Three Forks Formation. This included identifying the sequence stratigraphy, lithofacies, and microfacies of the Three Forks and combining these into facies associations. Gantyno identified 11 lithofacies, nine microfacies, and five facies associations. His facies associations were as follows: 1) upper supratidal sabkha, 2) lower supratidal sabkha, 3) upper intertidal mud flat, 4) lower intertidal mud flat, 5) open marine. He stated that the lower and middle Three Forks consisted of facies associations 1 and 2 and the upper Three Forks consisted of facies associations 3 and 4 with occasional facies association 5. The key stratigraphic surfaces that Gantyno identified were a type two sequence boundary at the base of the Three Forks, a type one sequence boundary at the top of the Three Forks, and a transgressive surface in the middle of the Three Forks. He also identified six fourth order parasequence sets and two major systems tracts; a lowstand and transgressive systems tract. Gantyno also conducted initial work on the diagenesis of the Three Forks recognizing dolomitization, anhydrite precipitation and cementation,
compaction, clay authigenesis, dolomite dissolution, and pyritization (Figure 1-4). Finally, Gantyno developed a more in depth depositional model of the Three Forks which is currently accepted in academia and industry (Figure 1-5).

Bottjer et al. (2011) focused on the stratigraphic relationships of the upper Three Forks and the Bakken unconformity, as well as, lithology and reservoir quality of the upper Three Forks. Bottjer subdivided the Three Forks into lower, middle, and upper subunits for his classification. Bottjer agreed with LeFever’s (2011) nomenclature for the stratigraphy of the Williston Basin and classifying the sands atop the Three Forks as the Pronghorn member of the Bakken Formation (Figure 1-6). Bottjer recognized the stratigraphic relationship between the Three Forks and overlying Pronghorn member of the Bakken Formation as an unconformity due to a sharp erosional surface observed in numerous cores throughout basin. He stated there is a change from regression to transgression observed in the stratigraphic architecture and that the boundary between the Three Forks and the Pronghorn member is a sequence boundary. Bottjer (2011) also looked at the reservoir quality and lithology of the upper Three Forks stating that the upper Three Forks consists of interbedded pinkish tan dolostones and green dolomitic mudstones and represents a shallowing upward succession of tide dominated near shore facies ranging from subtidal sand flats to intertidal mudflats.

Mitchell (2013) from ConocoPhillips did a search and discovery article on the Three Forks Formation that slightly differs from previous depositional environment interpretations of the Three Forks. Mitchell subdivides the Three Forks into lower, middle, and upper subdivisions similar to Bottjer (2011). Mitchell claims a wholly continental origin for a majority of the Three Forks Formation. He states the main processes for sedimentation of the Three Forks are: transport of sediment into basin by wind, modification of sediments by soil processes including caliche and intrasediment evaporite sedimentation (paleosoils and sabkha), reworking of loess by subaerial gravity flows during storms (mudflows are common in the middle Three Forks), and reworking of sediment in sand flats and mudflats of the shallow ephemeral lake. He justifies this sedimentation of the Three Forks due to the following reasons: 1) During the Late Devonian and Early Mississippian time the Williston Basin was separated from the open ocean from the Sweetgrass and Transcontinental arches and subsequently, low sea level may have caused
basin restriction. 2) Dolomite and siliciclastic silts of the Three Forks having similar grain sizes and shapes indicating they share a hydrodynamically equivalent depositional energy. He claims the transport mechanism for these silt grains into the basin is wind. Finally, he has an alternate facies association for the Three Forks with six facies from base to top: terrestrial paleosoils, sabkha, subaerial gravity flows, intertidal, peritidal, and subtidal.

Theloy (2013) classified the lithofacies of the Three Forks using the existing stratigraphic framework, and named three subdivisions each containing multiple facies. The subdivisions she named were the lower, middle, and upper Three Forks in concordance with Bottjer (2011). She classified the lower Three Forks as deposited in a low energy, supratidal sabkha setting in dry, evaporative climate conditions, the middle Three Forks as storm-deposit dominated with chaotic mud flat and brecciated facies, and the upper Three Forks as sandy dolostones that range from massive to brecciated and laminated and represent different environments within a tidal flat system. Theloy (2013) divided the Three Forks into nine lithofacies, A through I. She also analyzed the mineralogical composition of each subdivision of the Three Forks. One important factor she discusses is the broad and expansive nature of the Three Forks Formation and that there are surfaces within the Three Forks which can be correlated basin wide, indicating this basin was broad, flat, and shallow system during deposition. Theloy (2013) also concluded four important geologic factors controlling production in the Williston Basin: 1) the Three Forks is slightly more overpressured than the Middle Bakken reservoir. 2) Oil/(Oil+water) is a great tool to map oil rich zones in the basin and this ratio correlates very well to areas of high productivity. 3) She also stated that trapping mechanisms likely play a crucial role in voluminous hydrocarbon accumulations, 4) The Bakken Total Petroleum System is not uniform and consists of a number of different play types which are productive for different reasons.

Franklin (2014) addressed many issues with the Three Forks Formation in the Williston basin from deposition, stratigraphy, provenance, and reservoir characterization. She also has a different classification of facies associations and environments for the Three Forks Formation. Franklin defines the Three Forks as: schizohaline-storm dominated intrashelf deposits, arid shallow shelf deposits, and mudflats which rim both the aforementioned shelf environments (Figure 1-7). Franklin also noted the variability in
hydrocarbon saturation of the dolomitic reservoirs in the Three Forks; and began preliminary work on differential reservoir quality and hydrocarbon localization in the Three Forks.

These previous works serve as the basis for the stratigraphic, depositional, and diagenetic framework of the Three Forks Formation; however this study will focus on identifying local variation in the Three Forks Formation within FBR which contribute highly productive wells and good EUR’s (estimated ultimate recovery).

Figure 1-1: Location of FBR within the Williston Basin in purple. Major structures of the Williston Basin are in black, with the Antelope and Nesson Anticlines running on the north and western boundary of FBR. Parshall Field is the closest highly productive field which is outlined in Blue. Modified from USGS and IHS Energy Group (2009).
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Figure 1-4: Paragenetic sequence of the Three Forks Formation (Gantyno, 2010).
Figure 1-5: A recent depositional environment and lateral facies changes of the Three Forks Formation (Gantyno, 2010).
Figure 1-6: Correlation chart for the Three Forks and Bakken Formations of the Williston Basin, North Dakota, Montana, and Canada from multiple studies. Demonstrating current industry accepted nomenclature of Pronghorn formation which overlies the Three Forks Formation (Bottjer et al. 2011).
Figure 1-7: Updated depositional model for the Three Forks as a schizohaline storm dominated and arid shallow shelf with associated mud flats (Franklin, 2014).
CHAPTER 2 GEOLOGIC BACKGROUND

This chapter discusses the geologic evolution, stratigraphy, and petroleum geology of the Williston Basin. The major structural components of the Williston Basin include the Cedar Creek, Nesson anticlines, and the Poplar Dome. Structures with specific influence on the Fort Berthold Reservation are the Nesson and Antelope anticlines. The Williston Basin contains strata from the Cambrian through Tertiary (LeFever et al., 1991). The stratigraphy of focus for this study is the Bakken Total Petroleum System with a particular focus on the upper Three Forks Formation. The Three Forks has been proven as a productive reservoir in the Williston Basin. All figures for this chapter can be found following the text. They are displayed in numerical order beginning on page 27.

2.1 Regional Geologic Overview

The Williston Basin is an extensive oval shaped, intracratonic sag basin that includes parts of South Dakota, North Dakota, and Montana in the United States, and parts of Saskatchewan and Manitoba regions of Canada (Meissner, 1978; Gerhard et al., 1990). This basin contains over 16,000 ft of sediment with a nearly complete stratigraphic record from Cambrian to Tertiary time (LeFever et al., 1991). The Williston basin has developed from three Precambrian tectonic provinces: the Archean Wyoming craton in the west, the early Proterozoic Trans-Hudson orogenic belt, and the Archean Superior craton to the east (Peterson and MacCary, 1987). The Trans-Hudson orogenic belt is north-south trending and sutured the two Archean provinces (Figure 2-1). Episodic reactivation of major basement faults and regional compression related to plate collision during Late Cretaceous to Eocene times shaped present day regional structural features of the Williston Basin (Gerhard et al., 1987).

Paleozoic landmasses of the North American craton were the Canadian Shield and the Transcontinental Arch which was southwest of the craton (Peterson and MacCary, 1987) (Figure 2-2). The Transcontinental Arch sufficiently separated the eastern and western marine shelf of the continent during the early and middle Paleozoic. The elongated western flank of the North American craton is known as the Cordilleran Shelf. Gerhard et al. (1990) interpreted the evolution of the Williston Basin in the early and middle Paleozoic as a continental shelf or craton-margin basin, where accretion of terranes and crustal
fragments to the active western continental margin produced deformation during Ordovician orogenic events. Early Paleozoic sedimentation was classified by shallow marine cyclical sedimentation of wide spread carbonate deposition. These Paleozoic carbonates were deposited in a stacked and cyclic nature, and vary in thickness based on rates of subsidence and eustatic changes. Some of these carbonate cycles are bounded by unconformities (Anna et al., 2010). Periodic movement of basement faults and structures exerted control on Paleozoic sedimentation atop the Precambrian crystalline basement (Gerhard et al., 1990; Peterson and MacCary, 1987). During Devonian time, movement along the Transcontinental Arch reoriented the Devonian seaway to the Northeast connecting the Williston Basin to the Canadian Elk Point Basin (Figure 2-3). Orogenic activity of the Antler orogenic belt during Late Devonian and Early Mississippian uplifted the Sweetgrass Arch disconnecting the Williston Basin from the Elk Point Basin and Devonian seaway; forming the modern day Williston Basin and Alberta basins (Gerhard et al., 1990; LeFever et al., 1991) (Figure 2-4).

In Late Mississippian time, the Central Montana Trough re-opened to marine conditions in the Antler Foreland Basin (LeFever et al., 1991). In the late Paleozoic and early Mesozoic, the Antler Foreland Basin separated the Cordilleran shelf from the Antler orogenic belt, a narrow north-south trending island arc. Blakey (2005) interpreted the Antler orogenic belt as stretching the entire length of the active western continental margin. The Alberta and Wyoming shelves of the Cordilleran shelf were separated by the east-west trending Central Montana Trough. The Central Montana Trough connected the Williston basin to the Antler Foreland Basin.

Sea level fell during the Pennsylvanian and Triassic times and these late Paleozoic and early Mesozoic sediments are marginal marine, evaporate and terrestrial sediments. A long period of erosion and non-deposition occurred during the lower Triassic; represented by the unconformable contact between Mesozoic and Paleozoic strata. During early Mesozoic time, differential uplift occurred in the Williston Basin, resulting in an uplifted northeastern portion of the basin, yielding more continuous and thick strata in the southern portion of the basin (McCabe 1959). Thick Jurassic and Cretaceous clastic sediments were deposited in the Williston Basin. During the Upper Cretaceous and Tertiary, the Williston
Basin no longer had control on sedimentation as a structural unit, but was part of the larger Western Interior Cretaceous Basin (Gerhard et al., 1990).

Subsidence played a significant role in the development of the Williston Basin and its many cycles and sequences; however, the mechanisms for subsidence are still debated and not completely understood. Multiple mechanisms have been proposed and have a wide range in duration, periodicity and method of subsidence (Haid, 1991). The most deliberated topic is whether the subsidence of the Williston Basin was continuous or episodic. Tectonic subsidence for the Williston Basin has been reported from 50 Ma to 520 Ma (Sleep, 1972; Hamdani et al., 1994). There are multiple models and causes for the subsidence of intracratonic basins such as the Williston Basin. Haid (1991) favored a continuous model of subsidence for the Williston basin for the following reasons: simplicity, strong correlation between subsidence curve and data, depocenter of basin remains virtually stationary, uplift and erosion of features surrounding the basin during depositional breaks, and good correlation between relative sea level falls and unconformities within the Williston Basin. Proof for this theory of subsidence is lacking but it is used as a likely model for basin subsidence. It is clear that controversy on timing of events and subsidence in the Williston Basin exists. Sloss (1963) stated that regional sequences are not good correlations with models of erosion, burial history, or sea level curves for the Williston Basin (Kuhn et al., 2012; Vail and Mitchum, 1979). Timing for the sequences was adapted from Murphy et al., (2009): Sauk~470 Ma, Tippecanoe~416 Ma, Kaskaskia~318 Ma, Absoroka~201 Ma, Zuni~65.5 Ma, and Tejas~40 Ma through Cenozoic. Burial history models match most erosional events of the Williston Basin, as well as, changes in sea level and reduced subsidence rates (Kuhn et al., 2012). To some extent first and second order events to some extent match this model, however with higher order cycles there is confusion and the models do not match as well. This indicates an incomplete understanding of subsidence, eustacy, sediment supply, and sedimentation of the Williston Basin (Haid, 1991).

2.2 Regional Structure

The major structural features of the Williston Basin are the north-northwest trending Nesson Anticline and the northwest trending Cedar Creek Anticline (Figure 2-5).
The Cedar Creek and Nesson anticlines are the most prominent structures in the basin and have associated faulting which has boosted production in fields near each of these structures (LeFever, 1992). The Nesson and Antelope anticlines are present in FBR and are the structures most important to this study (Figure 1-1).

The Cedar Creek and Antelope anticlines have northwest trends, with the Poplar Dome having a similar trend. The Nesson, Little Knife, and Billings anticlines are north trending. There are two left lateral fault zones that dissect the Williston Basin; the Brockton-Froid fault system and the Wyoming-Colorado lineament. These fault systems are an important feature of the regional structural setting as they provide migration pathways for hydrocarbons. The largest structural feature of the basin, the Cedar Creek Anticline, is interpreted to have four periods of evolution: Early and Late Devonian, Late Mississippian, Triassic, and post Pliocene. Episodic structural evolution has caused thinning or absence of Devonian and Silurian strata in the region of the Cedar Creek Anticline (Gerhard et al., 1987; LeFever, 1992).

The Williston Basin experienced several periods of uplift and erosion in its evolution leading to the current structural setting. During the Mississippian to early Jurassic, Paleozoic strata in the north were differentially eroded due to uplift and tilting of the Transcontinental Arch. However, sediments in the southern portion of the basin remained relatively untouched by erosion. In one of these periods of uplift between the Late Devonian and early Mississippian, erosion of Devonian strata occurred along basin margins, while deposition continued in the basin center. Preferential erosion created complex contacts between upper Devonian units. In the basin center contacts are conformable but at the basin margins, erosion created unconformable contacts (Christopher, 1961; Meissner, 1978; and Sonnenberg, 2011). This was the last major uplift event affecting the stratigraphy of the Williston Basin. Continued subtle and episodic uplift caused reactivation to Precambrian and Paleozoic fault blocks, which resulted in the present structural setting of the Williston Basin.

2.3 Regional Stratigraphy

At the center of the Williston Basin is a nearly complete stratigraphic record from the Cambrian to Tertiary (LeFever et al., 1991). These strata can be divided into six Sloss
sequences which were modified by Gerhard et al. (1990) and Murphy (2009). These sequences are unconformity-bound and record within each sequence transgressive and/or regressive events within the Williston basin. Within each of the major sequences there are first and second order cycles, as well as, multiple third and fourth order cycles (Anna et al., 2010). The Bakken Total Petroleum System lies within the Kaskaskia sequence which has been divided into a lower and upper sequence, representing two transgressive cycles. The unconformity between the lower and upper Kaskaskia lies between the Three Forks and Bakken Formations (Gerhard et al., 1990). The Three Forks Formation of the Bakken Total Petroleum System will be the focus of this study and will therefore be investigated in greater depth (Figure 2-6).

The basal Sauk sequence contains the Late Cambrian to Early Ordovician Deadwood Formation, which was deposited during transgression onto the Cordilleran shelf (Gerhard et al., 1990). Transgressive sediments of the Deadwood Formation consist of quartz-rich sandstones and conglomerates, thin shales, and glauconitic limestones. Pre-existing Precambrian surface irregularities and structures caused thinner deposition of the Deadwood over topographical high points. The upper Deadwood glauconitic limestones represent the thickening trend from east to west across North Dakota. The Taconic orogeny ended the Sauk sequence. Erosion of strata occurred coevally with this orogeny. The Taconic orogeny produced a structural depression and began the evolution of the Williston Basin (Gerhard et al., 1991).

The Tippecanoe sequence contains sediments from the Middle Ordovician to Silurian and consists of the Winnipeg, Red River, Stony Mountain, Stonewall, and Interlake formations. The Winnipeg Formation contains transgressive sandstones, siltstones, and organic-rich shales. Carbonate deposition, which characterizes strata of the lower and middle Paleozoic, began during deposition of the Red River formation in the Williston Basin (Gerhard et al., 1990). Upper Red River carbonates are interbedded with organic-rich argillaceous sediments that transition into evaporitic sabkha like sediments toward the top upper Red River Formation. Stony Mountain and Stonewall formations consist of shallow-marine, peritidal carbonates and shales. Silurian Interlake carbonates and shales conformably overlie these formations (Theloy, 2013). At the top of the Interlake carbonate weathering and dissolution from subaerial exposure created local petroleum reservoirs. At
the conclusion of the Tippecanoe, most current day structures of the Williston Basin were in place (Gerhard et al., 1990).

During the Tippecanoe sequence, the Williston Basin was open to marine influence from the south and southwest. Uplift of the transcontinental arch at the conclusion of the Tippecanoe caused northwest tilting of the Williston Basin which connected it with the Canadian Elk Point Basin (Gerhard et al., 1990; LeFever et al., 1991). This resulted in a shift of the basin depocenter in the Williston Basin from western North Dakota to the north in the direction of the Elk Point Basin. Orogenic activity from the Antler orogenic belt at the onset of the Lower Kaskaskia produced uplift of the Sweetgrass arch (Gerhard et al., 1990; LeFever et al., 1991). The Sweetgrass arch possible acted as a barrier that, at times, restricted the Williston Basin from normal or near normal marine influence (Berwick 2008).

In the Late Mississippian, transgression and Antler orogenic activity re-opened the Williston Basin to the Devonian sea and the Antler foreland basin. These Late Devonian sedimentological complexities have been addressed using conodonts (Sandberg, 1988). Sandberg (1988) also addressed the paleogeography of the Williston Basin. The late Devonian has 17 eustatic and epeirogenic events representing 17 M.y depophase (Sandberg, 1988). Antler orogenic activity contributed to epeirogenic events in the Devonian. Multiple depressions in the Transcontinental Arch allowed for the Devonian seaway to reach the Williston Basin during major eustatic rises (Sandberg, 1988). The early Late and Late Devonian strata are within Famennian conodont zone (Sandberg, 1988). The Famennian had four major transgressions with each separated by long regressive events (Sandberg, 1988). These regressive events allowed for exposure and erosion of Devonian rocks (Sandberg, 1988). The first Famennian transgression created sabkha and evaporite settings in the Williston Basin (Sandberg, 1988) (Figure 2-7). The major regression during the Famennian coincides with the Williston Basin being closed to the Devonian sea and Antler foreland basin, having little to no marine influence (Figure 2-8). The fourth and final transgression of the Famennian had a massive areal extent (Sandberg, 1988). The final transgression of the Famennian re-connected the Williston basin to the Devonian sea and Antler foreland basin (Figure 2-9).

The Lower Kaskaskia sequence includes the Devonian Winnipegosis, Prairie Evaporite, Dawson Bay, Souris River, Duperow, Birdbear, and Three Forks formations.
Excluding the Prairie Evaporite and Three Forks, these formations are dominated by limestone and dolomite. The Prairie Evaporite contains halite, sylvite, and anhydrites. Prairie salt dissolution and subsequent collapse in these sediments affected younger Paleozoic and Mesozoic strata (Gerhard et al., 1990). The lower Three Forks consists of silty dolomite, mudstone, and anhydrite. The upper Three Forks has silty dolomite, mudstone, and rare anhydrite.

The Upper Kaskaskia includes the Devonian-Mississippian Bakken Formation and the Mississippian Madison and Big Snowy groups. During the Upper Kaskaskia, the Central Montana Trough reconnected the seaway. This shifted the Williston Basin depocenter to the western portion of North Dakota (Figure 2-10). The Bakken Formation conformably overlies the Three Forks Formation in the basin center but at the basin margin the contact becomes unconformable (Sonnenberg et al., 2011). The Bakken is composed of four members: silty, sandy, dolomitic, shaley, and calcareous Pronghorn, organic-rich Lower Bakken Shale (LBS), silty, sandy, and dolomitic Middle Bakken (MB), and organic-rich Upper Bakken Shale (UBS) (LeFever et al., 2011; Theloy, 2013). The excellent preservation of organic matter in the lower and upper Bakken shales indicates conditions of restricted circulation, a stratified water column, and anoxic bottom water conditions. During Bakken times, there was a rapid rate of both transgression and regression in the Williston Basin. At its base the Mississippian Madison group was deposited in deep water (Lodgepole Formation). The upper Madison (Mission Canyon and Charles Formations) is regressive and has numerous shallowing upward paracies. Upper Madison sediments consist of small scale shoaling upward cycles that are capped by muddy carbonates and prograding evaporites which form up dip permeability seals (Gerhard et al., 1990). The Charles Formation represents the conclusion of shoaling upward cycles and consists of sabkha evaporites and salt. The lowest salt bed in the Charles Formation is used as a marker horizon in industry and is referred to as the base of the last Charles salt (BLS) (Theloy, 2013).

The Absaroka sequence has Pennsylvanian, Permian, and Triassic strata (Tyler, Minnelusa, Opeche, Minnekahta, and Spearfish formations). During the Absaroka, compressive tectonic forces and slowed subsidence caused regional uplift and erosion (Theloy, 2013). Uplifts of the Canadian Shield, Hartville Uplift, and possibly the Sioux
Arch supplied detrital sediment to the Williston Basin. The introduction of clastic detritus marks the transition from carbonate and evaporite deposition to mixed siliciclastic and carbonated sediments dominating the deposition of the Williston Basin (Gerhard et al., 1990). Although there was a transition to siliciclastic deposition, there was still marine influence in the Williston Basin from the Central Montana Trough.

The Tyler formation represents marginal marine, estuarine, and fluvial sediments. The Opeche Formation is composed of thin progradational siliciclastics and salts (evaporites). The Minnekahta Formation contains carbonates and is thin and progradational. The Spearfish Formation is shale and fine-to-medium grained sandstone (Gerhard et al., 1990).

Zuni and Tejas sequences are composed of Jurassic and Cretaceous sediments. Neither of these sequences is strongly represented in the Williston Basin (Gerhard et al., 1990). Basal Zuni units are carbonates, evaporites, and siliciclastics. Late Cretaceous deposits of the Zuni are dominantly shales, siltstones, and sandstones. The last heavily marine influenced unit in the Williston Basin being the Pierre Shale of the Upper Cretaceous (Gerhard et al., 1990).

### 2.4 Bakken Total Petroleum System Stratigraphy

The Bakken Total Petroleum System stratigraphy bridges the Upper and Lower Kaskaskia sequence with sediments ranging in age from Late Devonian to Early Mississippian (Theloy, 2013)(Figure 2-11). The lower most unit of the Bakken Total Petroleum System is the Three Forks Formation, which is the focus of this thesis (Figure 2-12).

The Three Forks Formation conformably overlies the Birdbear formation (upper Devonian), and is part of continued carbonate deposition. This formation has been identified as a common interval of interest in the Bakken Total Petroleum System. The Late Devonian Three Forks thinly interbedded green shale and tan dolostone, with green to reddish shales, brownish siltstones and anhydrite (Berwick, 2008). The Three Forks was deposited in broad subtidal to supratidal mudflats in an arid, evaporative climate (Franklin and Sonnenberg, 2012). The Three Forks is subdivided into lower, middle, and upper
members. These members all contain several facies that are dependent on local sediment supply and diagenetic factors (Theloy, 2013).

The lower Three Forks is recognized as a low energy supratidal sabkha within dry evaporitic climate conditions. Distinctly fine-grained sediments and a large abundance of anhydrite set the lower member apart (Sonnenberg et al., 2012). Anhydrite in the lower member occurs as massive anhydrite or within distinct beds, stringers, and nodules of the mudstone matrix, and is interpreted to have occurred coevally with sedimentation or very early in diagenesis (Gantyno, 2010). The lower member also contains dolomitic claystones that are reddish brown to green and are structureless to faintly laminated (Gantyno, 2010).

The middle Three Forks has a cyclic deposition pattern and demonstrates repeated facies (Franklin, 2014). It is interpreted to be a storm deposit, dominated by chaotic and brecciated facies (Gantyno, 2010). Brecciated fabrics formed from storm deposit reworking and evaporite dissolution in underlying stratigraphy (Gantyno, 2010). Lower supratidal to upper intertidal laminated facies of thin to thickly bedded alternating layers of green mudstones and tan dolostones are capped by massive appearing brown to gray shales are seen cyclically in the Middle Three Forks (Theloy, 2013). The depositional environment of the middle Three Forks is interpreted as lower supratidal to upper intertidal setting (Theloy, 2013). The middle Three Forks shows deepening upward cycles associated with transgression in the Late Devonian (Theloy, 2013).

The upper Three Forks contains basal dolomite with silty to sandy dolostones that are massive, mottled, brecciated, or laminated (Theloy, 2013). There is a range in grain size and clay content seen within the upper member indicating varying depositional energy and environments throughout the deposition of the upper member (Bottjer et al., 2011). The massive subfacies were deposited in shallow marine subtidal and tidal flats within the lower intertidal to supratidal regime. The mottled subfacies were deposited in distal lower energy environments on the seaward edge of tidal flats. The laminated subfacies by tidal channels with upper flow regime laminations, with influence of tidal, wave, and storm energy (Theloy, 2013). This depositional energy change in the upper Three Forks represents an overall progradational stacking pattern within the member (Theloy, 2013).

The Three Forks sediments indicate a gradual deepening of the depositional system from anhydrite-rich sabkha to intertidal and subtidal sediments and are transgressive
sediments within the Lower Kaskaskia sequence (Gantyno, 2010). At the end of Three Forks deposition (Late Devonian), there was a sea-level fall of approximately 300 feet (Haq and Schutter, 2008). This produced erosion at the top Three Forks and a complicated contact between the Three Forks and the overlying Bakken Formation. In the basin center, the contact between these formations is conformable, however, at the basin margins it is erosive and unconformable (Sonnenberg et al., 2011).

The Bakken Formation has four members: Pronghorn, Lower Bakken Shale, Middle Bakken, and the Upper Bakken Shale (LeFever, 2011). The Bakken Formation is both transgressive and regressive. The Pronghorn and two Bakken shales are transgressive while the Middle Bakken is regressive (Bottjer et al., 2011).

The Pronghorn is shallow marine intertidal to subtidal with into four lithofacies. These lithofacies may or may not be present at any given location. The lithofacies are: at the base the first Pronghorn lithofacies: heavily bioturbated, fine grained dolomitic sandstone, burrowed dolomitic siltstone and silty mudstone with storm deposits. The third pronghorn lithofacies is skeletal lime mudstone and wackestone. The top lithofacies is shale with siltstone and rare sandstone laminations (Johnson, 2013; Theloy, 2013). The Pronghorn shows an overall deepening and fining upward trend from basal rip up clasts, pyrite nodules, and abundant bioturbation to capping shale with silt and rare sand laminations (Theloy, 2013).

In the center of the basin, the Lower Bakken Shale (LBS) is conformable with underlying Pronghorn. This shale thins and pinches along the edges of its depositional limits, producing areas along the basin margins with an unconformable contact with underlying formations (Sonnenberg, 2010). The Bakken shales are world class source rocks with high organic matter (Sonnenberg, 2011). The Lower Bakken Shale is dark gray to black and is massive to slightly fissile along planar laminations. Pyrite is abundant and is present as thin lenses, laminations, and is also disseminated throughout the shale. Fossils within the LBS include: Tasmanites (algal fragments) spores, conodonts, fish bones, brachiopods, ostracods, and woody plant fragments (Theloy, 2013). Amorphous, sapropelic, organic matter is ubiquitous in the formation and not confined to laminations (Christopher, 1961). Depositional environment for the LBS is interpreted to be offshore marine to vast swamp settings. Offshore marine is most likely because the kerogen found in the organic
matter of the LBS is Type II and only at the basin margins is Type III kerogen found which is indicative of land plants (Sonnenberg, 2012).

The Middle Bakken (MB) conformably overlies the LBS in the basin center, but where the LBS pinches out along the basin margins, the member can unconformably overlie the Three Forks (Sonnenberg, 2011). The Middle Bakken has been divided into six lithofacies: MB-A- skeletal lime wackestone, MB-B- bioturbated argillaceous shaley siltstone, MB-C- laminated siltstone to sandstone, MB-D- calcareous cross stratified sandstone to oolitic and bioclastic grainstone, MB-E- laminated dolomitic siltstone, and MB-F- Massive fossiliferous mudstone to wackestone (Sonnenberg, 2011). There is an erosive contact between MB-C and MB-D, indicating that MB-D is a lowstand tidal deposit where increasing energy and longshore currents produced shoals rich in ooids and carbonate muds (Gent, 2011). Contemporaneous with deposition of longshore shoals of MB-D, exposure of topographic highs of MB-C cause erosion and scouring creating this erosive contact between MB-C and the overlying units including the discontinuous MB-D (Gent, 2011). MB-E is associated with deepening near the contact with the overlying Upper Bakken Shale (Gent, 2011).

The Upper Bakken Shale (UBS) is nearly identical to the LBS and is a world class source rock which caps the Bakken Formation (Sonnenberg, 2011).

The last unit of the Bakken Total Petroleum System is the Lodgepole Formation of the Madison Group. The Lodgepole Formation has multiple members and is the regional seal for the Bakken Total Petroleum System (Theloy, 2013). The Scallion Member is at the base of the Lodgepole and is gray to tan skeletal mudstone to wackestone. The Scallion member has a high degree of bioturbation with brachiopods, ostracods, mollusk shells, and coral fragments (Stroud, 2010).

These formations and members encompass the Bakken Total Petroleum System. The upper Three Forks formation will be the stratigraphy of focus in this thesis.

2.5 Petroleum Geology of Bakken Total Petroleum System

The petroleum geology of the Bakken Total Petroleum System has all the aspects of a conventional petroleum system: source rocks, reservoir rocks, petroleum migration, top seals and lateral traps. The source rocks for the Bakken Total Petroleum System are
organic-rich UBS and LBS (Theloy, 2013). These shales demonstrate and average TOC over 11 weight percent and as high as 35 weight percent (Jin, 2014; Smith and Bustin, 2000). The reservoir rocks of the Bakken Total Petroleum System are the Middle Bakken and the Three Forks Formation (Sonnenberg, 2010). There has been a line of death identified in these shales within the Williston Basin (Figure 2-13).

The extent of the source rocks were determined by thermal maturity and source rock data where \( T_{\text{max}} \) exceeds the oil generation window and the UBS and LBS become post mature (Figure 2-14) (Theloy, 2013). Maturity of the UBS and LBS have been tied to wireline log resistivity where oil saturated shales attain high resistivities (Theloy, 2013). Oil generation begins in shales with resistivity of 75 to over 100 ohm-m (Meissner, 1978; Hester and Schmoker, 1985).

The reservoir rocks of the Bakken Total Petroleum System are the Middle Bakken member, Pronghorn Member, and the Three Forks formation. These reservoir units all display low porosities and permeabilities (Theloy, 2013). For this study the Three Forks formation is the interval and reservoir of interest.

The primary migration mechanism identified for the Bakken Total Petroleum System is hydrocarbon generation in the extraordinarily highly overpressured Bakken shales (Figure 2-14) (Theloy, 2013). Meissner (1978) stated that there was a relationship between this overpressured system and hydrocarbon generation. Overpressure was created by the generation of hydrocarbons in the UBS and LBS. During generation, solid kerogen is converted to bitumen which is then converted to oil through thermal maturity (Theloy, 2013). This phase change causes fractures in the source rock and creates primary migration pathways for hydrocarbons in the Bakken Total Petroleum System (Theloy, 2013). Source rock data indicates that a vitrinite reflectance \((R_o)\) of at least 0.6 -0.8 \( R_o \) % is the lower limit of maturity necessary to produce overpressure and hydrocarbon generation (Spencer, 1987). Natural fractures are dominant in primary and secondary migration in this petroleum system (Theloy, 2013). There are multiple scales of natural fractures: regionally tectonically induced, reservoir scale fractures, and microfractures (Theloy, 2013).
The seal of the Bakken Total Petroleum System is recognized as the impermeable Mississippian Lodgepole limestones (Sonnenberg, 2012). These are regionally extensive seals.

There are multiple trapping mechanisms for the Bakken Total Petroleum System: stratigraphic pinch outs, diagenetic traps, and shale thermal maturity/resistivity boundary (Figure 2-13, Figure 2-14) (Theloy, 2013).

### 2.5.1 Three Forks Formation Production

The Three Forks Formation is most productive in areas with high Oil/ (Oil+Water) ratios. This Oil/(Oil +Water) ratio was recognized by Theloy (2013) as a proxy for identifying oil-rich areas. Sharp contacts between highly oil bearing and water saturated Three Forks can indicate trapping mechanisms (Figure 2-15)(Theloy, 2013). There is a strong correlation between areas of high Oil/(Oil+Water) and high initial production in the Three Forks (compare Figure 2-13 and Figure 2-15).

The upper Three Forks Formation reservoirs show a strong correlation between the thickness of the formation (Figure 2-16), high initial production, and high (Oil/Oil+Water). These factors control Three Forks production in the Fort Berthold study area. This provides motivation for this study and the understanding of the geologic controls on the productivity of the upper Three Forks formation.
Figure 2-1: Archean superior and Wyoming craton basement blocks are connected by the Trans-Hudson orogenic belt. Blue line is the superimposed location of the Williston Basin (modified by Gent, 2011; from Forster et al., 2005).
Figure 2-2: Regional paleogeography and paleostructural elements of the Williston Basin during the Paleozoic and Mesozoic (modified by Gent, 2011; from Peterson and MacCary, 1987).
Figure 2-3: Paleogeographic reconstruction of North America during the Late Devonian (360 Ma). The Williston Basin is outlined in blue. This map shows the relative location of the Canadian Shield, Transcontinental Arch and Antler Foreland Basin. During the Late Devonian the Williston Basin was open to the Antler Foreland Basin, Devonian sea, and connected to the Elk Point basin (Modified from Blakey, 2005; Sonnenberg, 2011; and Theloy, 2013).
Figure 2-4: Paleogeographic reconstruction of North America during the early Mississippian (345 Ma). Movement along the Transcontinental Arch (TA) to the southeast and uplift of the Sweetgrass Arch (SA). This structural movement caused the Williston Basin (WB) to be separated from the Alberta Basin (AB) and separated from the Devonian seaway (modified from Blakey, 2005; and Berwick, 2008).
Figure 2-5: Structure of the United States region of the Williston Basin, demonstrating the major and minor structures: Brockton-Froid fault system, Nesson, Cedar Creek, Little Knife, Billings, and Antelope anticlines. Study area of Fort Berhold Reservation is located just to the southeast of the Antelope anticline and outlined by the black box (modified from Pollastro et al., USGS 2010).
Figure 2-6: Condensed stratigraphic section demonstrating the stratigraphy of the Bakken Total Petroleum system which contains the Three Forks Formation (Modified from Berwick, 2009; Gantyno, 2010; Johnson, 2013).
Figure 2-7: Map of Late Devonian sedimentation in the Famennian conodont zone. This includes the first Famennian transgression and the sabkha and evaporitic depositional setting in the Williston Basin (Sandberg, 1988).
Figure 2-8: Peak regression of the late Devonian Famennian conodont zone. This coincides with the Williston Basin being partially restricted from the Devonian sea by the Sweetgrass arch. This map shows isolated depocenter and sedimentation of the Williston Basin during the Late Devonian to Early Mississippian time (Sandberg, 1988).
Figure 2-9: This map shows final transgression of the Famennian conodont zone, and subsequent deposition of the early Mississippian Bakken Formation in the Williston and southern Alberta basins (Sandberg, 1988).
Figure 2-10: Illustration of the evolution of sediment infill in the Williston Basin, and direction of marine influence. A) Tippecanoe sequence, B) Lower Kaskaskia sequence, C) Upper Kaskaskia sequence, D) Absaroka sequence (Gerhard et al., 1982).
Figure 2-11: Schematic stratigraphic column of the Bakken Total Petroleum System. The Upper Three Forks Formation which is the focus of this study is highlighted in a red box (modified from Sonnenberg et al., 2011).
Figure 2-12: Cross section of the Bakken Total Petroleum system showing the capping Lodgepole limestone, source rock UBS and LBS, and middle Bakken and Three Forks reservoirs. This cross section is oriented southwest to northeast and crosses the Nesson Anticline which is close in proximity to the Fort Berthold Reservation (Figure 1-1). The upper Three Forks is outlined in red (modified from Continental Resources and Sonnenberg, 2013).
Figure 2-13: Map depicting the “line of death” for the source rocks (UBS and LBS) in the Williston Basin. The line of death for the UBS is blue; the line of death for the LBS is purple. The lines of death are labeled with the lower limit of resistivity when the UBS and LBS are in the proper maturity window as source rocks. Initial production of the Three Forks is represented on this map with a general outline of Fort Berthold Reservation in black (modified from Sonnenberg, 2015).
Figure 2-14: These maps were generated using $T_{\text{max}}$ values in the Upper Bakken Shale and Lower Bakken Shale source rocks (Top). $T_{\text{max}}$ maturity limits are outlined in green and depositional limits of UBS and LBS outlined in brown. The area of intense hydrocarbon generation from Bakken source rocks is shown in the bottom map. The limit of hydrocarbon generation is outlined in green. Fort Berthold Reservation is outlined in red (modified from Theloy, 2013).
Figure 2-15: A structure map on the top of the Bakken Formation and superimposed Oil/(Oil+Water) map showing oil rich zones in the Three Forks Formation. Sharp contacts of bright colors with soft colors indicate trapping mechanisms and limits of productivity in the Three Forks formation. The study area Fort Berthold Reservation is outlined in red (modified from Sonnenberg, 2013).
Figure 2-16: Isopach map of the upper Three Forks formation. Outline of Fort Berthold Reservation is in red (modified from Sonnenberg, 2012).
CHAPTER 3 DATA AND METHODS

This chapter will explain the data provided and the methods of analysis used in this study. The order in which the methods are listed outlines the research framework of this study. The framework of this study was done with the objective of working from the macro to the micro scale in the study of the upper Three Forks formation of in the Fort Berthold Reservation. All figures for this chapter can be found following the text. They are displayed in numerical order beginning on page 50.

3.1 Data

Data for this study were provided by Enerplus Resources Corporation. These data are at multiple scales to allow for multiple depths of investigation. All data for this study are in Fort Berthold Reservation. The data set is as follows:

Five cores located at Triple O Slabbing in Denver Colorado (Table 3-1)(Figure 3-1);

High resolution photographs – with both plane and ultraviolet light for all five cores;

227 Thin sections from each plug taken during core analysis, as well as, routine core analysis data associated with these plugs a summary table of this data can be found at the beginning of appendix C;

Scanning Electron Microscope samples from each of the five cores (Table 3-3);

Mercury Injection Capillary Pressure data from 10 samples were analyzed by Ben Harrell at PoroTechnology in Kingwood, Texas (Table 3-4);
Table 3-1: List of cores made available for this study by Enerplus Resources Corporation. The location of these cores is in Figure 3-1.

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<th>Core</th>
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<td>ND</td>
<td>151</td>
<td>94</td>
<td>17</td>
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Table 3-2: List of Scanning Electron Microscope samples used in this study. These samples were taken directly from core at Triple O Slabbing. The well, depth, and facies association of each sample are listed.

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Table 3-3: Table of plugs used for MICP sampling which includes sample depth, well, and facies.

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### 3.2 Methods and Framework

This section will summarize the methods used in data analysis for this study. For all of the analysis in this study the proportion descriptors: abundant, common, moderate, and rare are used.

Core descriptions were done at Triple O Slabbing located in Denver, Colorado. Standard lithological descriptors of the rock were used including: texture, stratigraphic structures, bed contacts, mineralogy, and color. During description, a Wentworth grain size scale chart, 20X hand lens, and Munsell Geologic Rock Color Chart were used to define lithology and color. Core descriptions were completed to interpret depositional environment, vertical stacking pattern, and facies variation in the upper Three Forks.

Ultraviolet photo analysis was done for each well throughout the entire section of the upper Three Forks. Ultraviolet light photographs demonstrate fluorescence from both
minerals and hydrocarbons. Bright blue and yellow fluorescence is recognized as hydrocarbon saturation. Analysis of these photos was done to document variation and localization of hydrocarbon saturation throughout the upper Three Forks facies.

X-Ray Diffraction, porosity and permeability data were compared to ultraviolet fluorescence. Fluorescence was used as a proxy for hydrocarbon saturation. Mineralogy, porosity, and permeability, were correlated to facies with hydrocarbon fluorescence. Graphs of mineralogy versus porosity were made to determine the mineralogical control on porosity in each facies. Porosity is interpreted to be directly correlated to fluorescence and hydrocarbon saturation.

Petrographic analysis of all 227 thin sections was done using a Leica 2500 DM microscope available in Berthoud Hall 116 at the Colorado School of Mines. These thin sections were impregnated with fuchsia red epifluorescent epoxy and half stained with alizarin red to detect calcite. Petrographic analysis was done to document and interpret variations of mineralogy, porosity, dolomitization, and diagenesis throughout the upper Three Forks facies.

Cathodoluminescence (CL) analysis was done on select thin sections. This analysis was conducted at the University of Colorado Boulder using a Leitz-Ortholux microscope outfitted with a Technosyn-8200-MK-II-cathodoluminescence unit. Operating conditions were 12-kV with a gun current of 450 uA. A cooled Olympus digital camera specifically for low light applications was used for both plane light and CL microphotography. CL was conducted to better document and interpret the variation and process of dolomitization throughout the upper Three Forks facies.

Scanning Electron Microscope (SEM) analysis was done using the JEOL-JSM-7000F Scanning Electron Microscope available in Hill Hall room 176 at the Colorado School of Mines. These SEM samples were made in John Skok’s lab at the Colorado School of Mines from rock chips. This work was done to characterize variation in pore throat shape and size throughout the upper Three Forks facies. Additional objectives of SEM work were to observe and document diagenesis at a high resolution.
Mercury injection capillary pressure testing was done through PoroTechnology in Kingwood, Texas using plugs taken from the cores in this study. This testing used a proven method to define the pore throat size and variation in the upper Three Forks facies.

This summarizes the methods and framework of this research project used to address the hypothesis of this study.

Figure 3-1: Location of wells with cores provided by Enerplus Resource Corporation with the study area. Wells are represented by red stars and Fort Berthold Reservation is outlined in orange (modified from Bob Larson, 2014).
CHAPTER 4 LITHOLOGY, FACIES, AND DEPOSITIONAL ENVIRONMENT

This chapter describes the lithologies, facies, facies associations, and inferred depositional environments of the upper Three Forks in the Fort Berthold Reservation. Detailed core descriptions and summaries of vertical stacking patterns for each core in this study can be found in Appendix A: Core Descriptions. All figures for this chapter can be found following the text. They are displayed in numerical order beginning on page 60.

4.1 Lithologies

The upper Three Forks formation is separated into lithologies based upon mineralogy, grain size, texture, and color observed in the core data. Three lithologies are recognized in the upper Three Forks in Fort Berthold Reservation: green dolomitic claystone, brown silty dolostone, and tan fine-grained sandy dolostone. Each of these lithologies is present in varying proportions throughout the upper Three Forks facies.

4.1.1 Claystone

The claystone lithology is green and composed dominantly of illite and chlorite clays. Dolomite crystals and, trace amounts of detrital quartz and mica are also present. Grain size ranges from clay to very fine silt. This lithology appears massive to structure less with rare pinch and swell laminations, and thin dolomite lenses. Pyrite nodules are common (Figure 4-1).

4.1.2 Silty dolostone

The silty dolostone lithology is dark brown to beige in color and is dominantly dolomite with varying amounts of quartz, feldspar, and clay. Quartz and feldspar grains are very fine to upper silt in size. Sedimentary structures are common and their types are related to depositional energy (Figure 4-2). Pyrite is rare to moderately rare, and nodular anhydrite is rare to absent.
4.1.3 Sandy dolostone

The sandy dolostone lithology is tan to light tan and composed of dolomite and quartz. This lithology has the coarsest grain size, and grains range from very fine to upper fine-grained sandstone. This lithology is massively bedded, but locally has scour and fill structures and ripple laminations (Figure 4-3). Anhydrite nodules are common in this lithology (Figure 4-3).

4.2 Facies

Facies are defined as groups of genetically related lithologies that have been deposited and modified by sedimentary and biological processes active within an environment of deposition (Galloway, 1989). In this study, interpretation of core data yielded five distinctive facies (Table 4-1). For the upper Three Forks from base to top the facies are as follows: dolomitic claystone, brecciated, tan dolostone, interbedded claystone and dolostone, and chaotic.

Table 4-1: Correlation of facies from various studies of the upper Three Forks. A brief facies description is given for each facies.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Facies</td>
<td>Dolomitic claystone-shallow shelf, composed of claystone lithology</td>
<td>Claystone</td>
<td>Dolomitic Claystone and Mudstone</td>
<td>Green Mudstone</td>
<td>Structure less-faintly laminated greenish claystone</td>
<td>Facies A-Dolomitic and slightly silty shale</td>
</tr>
<tr>
<td>Brecciated-upper intertidal to supratidal, composed of all three lithologies</td>
<td>Distorted and Brecciated mudstone</td>
<td>Brecciated Silty Dolomite</td>
<td>Lower Mottled Clean Dolomite</td>
<td>Chaotic greenish silty claystone and dolomite siltstone</td>
<td>Highly deformed and Brecciated silty dolomite</td>
<td></td>
</tr>
<tr>
<td>Tan dolostone - supratidal and tidal flat, composed of sandy dolostone</td>
<td>Sandstone</td>
<td>Dolomite-Light Brown, Silty to Sandy</td>
<td>Clean Dolomite</td>
<td>Structure less to ripple cross laminated dolomitic siltstone</td>
<td>Very slightly silty dolomite</td>
<td></td>
</tr>
</tbody>
</table>
Table 4-1 continued:

<table>
<thead>
<tr>
<th></th>
<th>Interbedded claystone and dolostone-upper mixed tidal flat, composed of all three lithologies</th>
<th>Laminated</th>
<th>Silty dolomite-thinly laminated to thickly bedded</th>
<th>Laminated</th>
<th>Very thinly-bedded greenish claystone and dolomitic siltstone</th>
<th>Silty dolomite and Shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chaotic upper mixed flat, composed of all three lithologies</td>
<td>Dolomudstone</td>
<td>N/A</td>
<td>Laminated</td>
<td>Very thinly-bedded greenish claystone and dolomitic siltstone</td>
<td>Burrowed and slightly silty dolomite</td>
<td></td>
</tr>
</tbody>
</table>

### 4.2.1 Dolomitic Claystone

The dolomitic claystone facies is the basal facies of the upper Three Forks and is recognized in industry as the “RT” marker. This dark to light green and slightly gray facies is composed dominantly of the claystone lithology with sparse laminations of silty dolostone (Figure 4-4). XRD data shows the clays are illite and chlorite. There is no visible porosity at the core scale observed in this facies. Common pyrite nodules are observed. This facies is structureless with rare pinch and swell laminations and lenses of dolomitic sediment. This facies occurs in packages between less than 7 inches up to 14 feet thick. The contact surface with other facies is sharp and distinct to undulose and/or erosive.

**INTERPRETATION**

This facies demonstrates strong laterally continuity across the study area. Industry recognizes this facies by increase in API units in the gamma log tool at the base of the upper Three Forks; it has been correlated across the Williston Basin. Based upon this lateral continuity, very fine grain size, high clay content, and structureless texture, it is interpreted that this facies is a low energy subtidal environment. This is a shallow shelf marine deposit below wave base on the very shallow slope of the shelf during deposition of the Three Forks. Rare lenses and pinch and swell laminations of dolomitic sediment indicate rare storm influence and high energy sedimentation. Low abundance and diversity of trace fossils indicate possibly stressed salinity conditions.
4.2.2 Brecciated

This facies consists of all three lithologies, and is composed of sandy dolomitic clasts with either silty dolostone or claystone matrix (Figure 4-5). This variation in green claystone matrix or dark brown silty dolostone matrix indicates variable amounts of dolomite and clays supplied to the system during deposition. There is no visible porosity at the core scale observed in this facies. There is no bioturbation observed in this facies.

This facies displays a various textures that are intermixed in a vertical succession. Brecciation is both clast and matrix supported. In clast supported breccia, gravel to pebble sized clasts are commonly in contact, moderately to poorly sorted, and angular (Figure 4-6). In matrix supported breccia, the dolomitic clasts are smaller in size, moderately sorted, and sub-rounded to angular (Figure 4-7). The dolomitic clasts display both brittle and ductile deformation (Figure 4-5). Some clasts show partial lithification prior to deformation which creates stratiform breccia. Stratiform breccia is defined by wavy to distorted layers within clasts (Franklin, 2014). Dewatering and tee-pee structures are observed as upward v-ing forms (Figure 4-5, Figure 4-7). Soft sediment deformation is also seen as a syndepositional structure. Another possible syndepositional feature is dendritic pyrite (Figure 4-6), which is created from sulfur associated with the dissolution of evaporites (Carstens, 1985). This facies occurs in packages from 3 to 7 feet thick. The contact with both the underlying dolomitic claystone facies and overlying sand flay facies is erosive and undulose.

INTERPRETATION

This facies formed through a variety of mechanisms: dewatering, soft sediment deformation associated with rapid sedimentation rates, and syndepositional evaporite precipitation and dissolution. Due to multiple mechanisms of formation, a wide variety of textures are present in this facies and end members are difficult to decipher (Franklin, 2014). The angular and fitted nature of dolomitic clasts and internally deformed laminations (Figure 4-5) indicate in-situ processes responsible and clast transport was not responsible for the texture of this facies. Internal clast laminations indicate early lithification before dewatering and soft sediment deformation process began. There are multiple stages of water influx causing dewatering, brecciation, and subsequent flooding.
Syndepositional features observed indicate the occurrence of precipitation and dissolution of evaporites. Gypsum nodules and crystals could break sediments apart during dissolution. Dendritic pyrite requires significant sulfur which is interpreted to come from dissolution of evaporites (Carstens, 1985).

Berwick (2008) presented a model for brecciation by dissolution of evaporites. Saline tidal flats experience frequent subaerial exposure developing mud cracks. This allowed the precipitation of evaporites under hypersaline and evaporitic conditions. Frequent fresh water influx in these tidal flats from meteoric groundwaters and rain, caused dissolution of these evaporites. This evaporite dissolution created brecciated clasts which filled in mud cracks during flooding and drying of the tidal flat. As this process is repeated there was brecciation and deformation.

Precipitation and dissolution of evaporites indicates that salinity levels fluctuated by the introduction of freshwater during deposition of this facies. The variation in amount of dolomitic sediment indicates variation in salinity. With reduced salinities dolomite can form at lower Mg/Ca rations (Folk and Land, 1975) indicating more rapid dolomite precipitation in this facies during times of reduced salinities. Finally lack of bioturbation indicates stressed salinity or oxygen conditions (MacEachern et al., 2009).

This is an upper intratidal flat deposit that experienced freshwater influx from both storms and introduction of meteoric ground waters. There was a reduction in relative sea level from the dolomitic claystone facies, demonstrating a shallowing upward trend in the upper Three Forks.

4.2.3 Tan dolostone

This tan to beige facies is composed of the sandy dolostone lithology with rare claystone and silty dolostone laminations. This is the coarsest grained of the facies observed in the upper Three Forks. In hand sample there is no visible porosity in this facies. Rare pyrite nodules and abundant anhydrite nodules occur (Figure 4-8). This facies is massive to planar laminated with sparse cross stratification. This facies occurs in packages from 1 to 4 feet in thickness. The contact with the overlying facies is undulose to erosive.
INTERPRETATION

This facies was deposited in the upper intertidal to supratidal sand flat environments. The coarser dolomite crystals and quartz grains indicates higher energy transport and depositional currents. The planar laminations and rare cross stratification also indicate high depositional energy. Common anhydrite nodules are interpreted to be syndepositional evaporite precipitation associated with supratidal flat environment (Murray, 1964). The sand flat is a boundary on the supratidal flat between the intratidal and subtidal marine sediments and the landward remainder tidal flats (Shinn and Lloyd, 1964).

This facies shows a continuing shallowing upward trend in the upper Three Forks from the deeper brecciated and dolomitic claystone facies, indicating a decrease in relative sea level in Fort Berthold Reservation.

4.2.4 Interbedded claystone and dolostone

This dark brown dolostone to green claystone facies is interbedded silty dolostone and claystone with lenses of sandy dolostone. There is no visible porosity at the core scale observed in this facies. There is rare to absent bioturbation seen in this facies. Possible Zoophycos traces were observed (Figure 4-9). Claystone beds range from less than ¼ inch up to 2 inches. Dolostone beds range from less than ¼ inch up to 4 inches thick. Rare pyrite nodules are observed.

There are multiple sedimentary structures observed in this facies that can be divided into depositional categories: storms and episodic sedimentation, syndepositional structures, and high energy current structures. Storm and episodic structures observed are: scour surfaces, pinch and swell laminations, and hummocky cross stratifications. High energy current structures include oscillatory ripples, current ripples, climbing ripples, and normal grading of bedding (Figure 4-9). Scour surfaces occur at lithological boundaries or within single beds (Figure 4-9). Pinch and swell laminations occur within thick beds and contain the variable lithologies (Figure 4-10, Figure 4-11). Hummocky cross stratification is associated with scour surfaces and pinch and swell laminations (Figure 4-12).
Syndepositional structures observed are mud cracks, syneresis cracks, soft sediment deformation, and ball and pillow structures. Syneresis cracks are rare and are distinct in morphology. They are wavy in nature and can intersect other syneresis or mud cracks. They can extend both upward and downward in sediments, and are smaller than mud cracks. Mud cracks are common but are larger in size and taper downward (Figure 4-11). Soft sediment deformation and ball and pillow structures occur in the dolomitic sediments or at lithologic boundaries (Figure 4-12).

This facies is in packages from 6 inches to 5 feet thick and is interbedded in vertical stacking with the chaotic facies. The contacts between the interbedded claystone and dolostone and chaotic facies are sharp and display distinct changes in bedding style.

**INTERPRETATION**

This facies is a storm dominated tide influenced mixed tidal flat. Storm deposits alternate with fairweather conditions indicating the episodic nature of deposition (Figure 4-9). Abundant scour surfaces indicate the erosive energy and frequent of storm events. Structures such as pinch and swell laminations, cross stratification, current ripples, and oscillatory ripples represent high energy storm events. These structures also indicate significant wave influence during the deposition of this facies. The syndepositional features of mud and syneresis cracks indicate episodic exposure and salinity fluctuations during deposition of this facies. Soft sediment deformation and ball and pillow structures indicate high rates of deposition.

Bioturbation indicates that there is variation in duration of fairweather conditions. Zoophycos traces indicate sufficient time for fauna to thrive within sediment (Figure 4-9) (Pemberton et al, 2014).

Variables that controlled sedimentation and preservation were storm frequency, duration of time between storms, and storm energy. These all created high levels of variability in this storm dominated facies in structures and bed thickness preserved. This storm dominated mixed tidal flat is a continuation in the shallowing upward trend in the upper Three Forks. This facies demonstrates the changing from a tidally dominated to a storm dominated depositional environment of the upper Three Forks.
4.2.5 Chaotic

This dominantly brown to beige facies consists of all three lithologies in varying proportions. There is no visible porosity at the core scale observed in this facies. There is rare to moderate mottled bedding in this facies. Rare pyrite nodules are observed. This facies demonstrates multiple sedimentary structures and is dominated by syndepositional structures such as soft sediment deformation, ball and pillow structures, and mud cracks (Figure 4-13). Storm and wave features also occur within dolomitic packages of 1 inch or thicker. These features include oscillatory and current ripples, pinch and swell laminations, and scour surfaces (Figure 4-14). Claystone clasts occur as a result of higher energy storms. Rapid sedimentation rates are indicated by soft sediment deformation and mottled bedding. This facies occurs in packages from 6 inches to over 10 feet thick, and is vertically intermixed with the interbedded claystone and dolostone facies. The contact with the interbedded claystone and dolostone facies is undulose and convolute.

INTERPRETATION

This facies is a storm dominated mixed flat. Abundant scour surfaces, pinch and swell laminations, and claystone clasts indicate storm processes controlling the deposition of this facies (Figure 4-13). Convolute and mottled bedding, soft sediment deformation, and ball and pillow structures indicate high depositional rates. Lack of bioturbation indicates stressed environment storm conditions controlling deposition of this facies.

There is significant variability observed in the sedimentation of this facies based upon the storm processes responsible for deposition. This facies continues the shallowing upward trend of the upper Three Forks, and shows less tidal influence than the interbedded claystone and dolostone facies. It is interpreted that this decrease in tidal processes is related to changes in relative sea level and an increase in storm frequency in the basin.

SUMMARY

The five facies of the upper Three Forks (Table 4-2) were deposited in a mixed siliciclastic and carbonate tidal environment. The vertical stacking pattern of the upper Three Forks displays facies complexity. The interbedded claystone and dolostone and chaotic facies are intermixed in intimate vertical association throughout the upper section.
of the upper Three Forks. The depositional controls and environments of the upper Three Forks evolved through time.

Table 4-2: Summary table of facies, associated sedimentary structures, and inferred depositional environment in the upper Three Forks.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sedimentary Structures</th>
<th>Depositional Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomitic claystone</td>
<td>Pyrite nodules, dolomitic lenses</td>
<td>Shallow shelf marine, low energy suspension deposit</td>
</tr>
<tr>
<td>Brecciated</td>
<td>Matrix and clast supported breccia, dewatering, dissolution of evaporites, dendritic pyrite, soft sediment deformation</td>
<td>Upper intertidal flat to tidal flat hardgrounds, syndepositional dissolution of evaporites, dewatering, influx of freshwater, and subaerial exposure, stressed salinity conditions</td>
</tr>
<tr>
<td>Tan dolostone</td>
<td>Parallel laminations, Anhydrite nodules</td>
<td>Sand flat tidal flat deposit, high energy currents, and frequent subaerial exposure, hypersaline</td>
</tr>
<tr>
<td>Interbedded claystone and dolostone</td>
<td>Pinch and swell laminations, scour surfaces, oscillatory ripples, current ripples, climbing ripples, cross stratification, ball and pillow, mud and syneresis cracks</td>
<td>Storm dominated – tide influenced mixed tidal flat, frequent high energy episodic storms, wave influence, fluctuating salinity</td>
</tr>
<tr>
<td>Chaotic</td>
<td>Soft sediment deformation, syneresis cracks, ball and pillow, clasts, current ripples, cross stratification, scour surfaces</td>
<td>Storm dominated mixed tidal marsh, frequent high energy storms, rapid sedimentation, fluctuating salinity conditions</td>
</tr>
</tbody>
</table>

4.2.6 Facies Associations

Facies associations are defined as a group of facies used to define a particular sedimentary environment (Allaby, 2008). There are three facies associations recognized in the upper Three Forks of Fort Berthold Reservation (Table 4-3).

Table 4-3: Table summarizing the facies associations of the upper Three Forks.

<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Depositional setting</th>
<th>Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Shallow shelf marine</td>
<td>Dolomitic claystone</td>
</tr>
<tr>
<td>B</td>
<td>Intertidal and Supratidal flat</td>
<td>Brecciated and Tan dolostone</td>
</tr>
<tr>
<td>C</td>
<td>Storm dominated mixed flat</td>
<td>Interbedded claystone and dolostone and Chaotic</td>
</tr>
</tbody>
</table>

4.3 Depositional environment

A depositional environment is defined as a three dimensional assemblage of multiple process related sedimentary facies assemblages, commonly identified by the geographic elements in which deposition occurs (Walker, 1992).
4.3.1 Depositional model

Although the Three Forks formation is regionally extensive in the Williston Basin, there are high frequency local heterogeneities based upon local topography, eustacy, and shoreline position. The depositional model of the upper Three Forks is not an end member model but one that shows changes in depositional controls through time (Figure 4-15). In the basal portion of the upper Three Forks, the depositional environment is a shallow shelf and intertidal - supratidal flat environment consisting of facies associations A and B. In the upper portion of the upper Three Forks the depositional environment is a storm dominated mixed flat environment consisting of facies association C. Facies associations A and B developed in the deeper water and were dominated by tidal processes. Facies association C was deposited in the shallowest water of the upper Three Forks and was dominated by storm and tide processes.

4.3.2 Discussion

The depositional model for the upper Three Forks shows an intimate relationship between depositional processes of storms and tides. Variation between eustacy and these depositional processes causes lateral migration of depositional environment and creates complex facies stacking. The combination between eustacy and depositional process creates multiple small scale transgressions and regressions in the upper Three Forks, which contribute to the complex facies stacking. This complexity of facies stacking is best observed in facies association C. Within this facies association the interbedded claystone and dolostone and chaotic facies are complexly intermixed based upon eustacy and storm energy. The relationship between eustacy and storm processes is also represented in the vertical stacking pattern where the facies shift from tidal dominated deposits to storm dominated deposits. This shift in depositional environment occurs above the tan dolostone facies before the interbedded claystone and dolostone and chaotic facies. Figure 4-16 demonstrates the change in eustacy and associated depositional controls at this shift in depositional environment.

The shift in depositional environment in the upper Three Forks is evident in sedimentary features of the upper Three Forks as well. In the basal tidal deposits, and arid
conditions are indicated in the anhydrite bearing sandy dolostones. In the upper storm
dominated deposits, limited bioturbation and dewatering features indicate hypersaline
conditions and greater freshwater influx.

It is interpreted that this depositional and climatic shift in the upper Three Forks is
related to autogenic responses to larger intra-basinal processes. These intra-basinal
processes were controlled during the Late Devonian to Early Mississippian by a change in
the connection to the Elk Point Basin. Through structural movement of the transcontinental
arch, this change opened the Williston basin to the Devonian sea and Antler orogenic belt.
This orogenic activity created changes in the eustacy and climate of the Williston Basin
which are responsible for the depositional shift and high frequency facies variation in the
upper Three Forks.
Figure 4-1: Photographs of claystone lithology (Photos courtesy of Enerplus Resources). Figure A) From Henry Bad Gun, 10,610 ft, “A” Marker. Note the structure-less texture of the claystone lithology. Pyrite is common (gold arrows). Figure B) From Danks 17-44H, 10,699.00 ft, “RT” Marker. This is a good example of typical green claystone and the massive appearing fabric. The upper right corner contains a rare dolostone clast (CLST) within the claystone lithology. Figure C) From Pumpkin, 10,288.6 ft. Moderately common pyrite (py) nodules are shown with gold arrows. Rare lenses of dolomite crystals and silt grains are tan.
Figure 4-2: Photographs of the silty dolostone lithology (Photos courtesy of Enerplus Resources). Demonstrating variability in brown to beige color and sedimentary structures observed: Figure A) Danks, 10,691.00 ft, silty dolostone lithology. This lithology is dark brown and has massive appearing (structure-less) bedding and, pyrite (observed at break in core, gold arrows). Figure B) Hognose 10,416.00 ft, silty dolostone lithology. This lithology is brown to dark brown with ball and pillow (B/P) (high depositional rate features), and nodular anhydrite (pink anhydrite). Figure C) Pumpkin 10,272.7 ft, silty dolostone lithology. This image shows dark brown massive bedding with a pinch and swell lamination (P/S).
Figure 4-3: Photographs of sandy dolostone lithology (Photos courtesy of Enerplus Resources). A) Hognose, 10,430.00 ft, tan sandy dolostone lithology, structure less bedding, few lenses of dolomicrite are present (black arrows). B) Danks 10,707.5, tan sandy dolostone lithology, structure less bedding, common anhydrite nodules (pink arrows), and a scour surface that displays on lap (blue dashed lines). C) Pumpkin 10,294.00 ft, tan sandy dolostone lithology, structure less bedding, anhydrite nodules are present (pink arrows). D) Henry Bad Gun 10,619.00 ft, Light tan sandy dolostone lithology, demonstrating soft sediment deformation (SSD) indicating rapid depositional rates and higher depositional energy.
Figure 4-4: Photographs of dolomitic claystone facies (Photos courtesy of Enerplus Resources). Examples of massive bedding and inferred calm water deposition of this facies. A) Henry Bad Gun 10,626 ft, This is the “RT” marker of the Henry Bad Gun B) Pumpkin 10,300 ft, This is “RT” marker of the Pumpkin.
Figure 4-5: Photographs of brecciated facies (Photos courtesy of Enerplus Resources).

Common sedimentary structures and stacking patterns of the brecciated facies are displayed. A) Henry Bad Gun 10,622 ft. This is an example of clast supported brecciated facies. This sample shows a dewatering pipe with upward curving siltstone clasts with primarily ductile response to dewatering (DWP). The large clast in the middle that shows bedding indicating partial lithification prior to deformation from dewatering and/or evaporite dissolution. This is an example of clast supported brecciated facies. B) Roberts Trust 10,779 ft. These clasts demonstrate brittle deformation response to dewatering and evaporite dissolution shown with orange arrows. This is an example of a clast supported brecciated facies. Note both silty dolostone and claystone matrix infilling between the fine sandy dolomitic clasts.
Figure 4-6: Additional photographs of brecciated facies (Photos courtesy of Enerplus Resources). Further examples of sedimentary structures and stacking patterns in the brecciated facies are shown. A) Pumpkin 10,300 ft. This is a clast supported brecciated facies example. This is an example of the contact of the brecciated facies with dolomitic claystone facies. Note the sharp contact and variable clast size created by evaporite dissolution and dewatering. B) Hognose 10,434.00. This is also a clast supported breccia. A dewatering pipe (DWP) and dendritic pyrite (CP) created from evaporite dissolution, possibly syndepositional, are well displayed in the lower half of this sample. Note variation in clast size. C) Henry Bad Gun 10,625 ft. Evaporite dissolution and dewatering possible produced these clasts. This is another example of clast supported brecciated facies.
Figure 4-7: Additional photographs of brecciated facies (Photos courtesy of Enerplus Resources). Further examples of sedimentary structures and stacking patterns of the Brecciated facies are shown. A) Henry Bad Gun 10,296 ft. Upward V-ing clasts, showing ductile response to evaporite dissolution and dewatering in the brecciated facies. A dewatering Pipe (DWP) is present in the middle of the sample. This is an example of matrix supported brecciated facies. B) Roberts Trust 10,780 ft. This is an example of variable clast size created during sediment deformation from evaporite dissolution and sediment dewatering. There is a variation in the types of sediment that infill the matrix; claystone infill seen in A, and dolomicrite infill seen in B.
Figure 4-8: Photographs of typical sedimentary structures of the tan dolostone facies (Photos courtesy of Enerplus Resources). A) Pumpkin 10,294 ft. Tan dolostone facies demonstrating pyrite (PY) (gold arrows), and abundant nodular anhydrite (pink arrows) are shown. B) Henry Bad Gun 10,618 ft Tan dolostone facies demonstrating higher energy and rapid sedimentation rates that can be observed in this facies by soft sediment deformation and distorted bedding.
Figure 4-9: Photographs of interbedded claystone and dolostone facies (Photos courtesy of Enerplus Resources). These images include examples of sedimentary structures and stacking patterns in the interbedded claystone and dolostone facies: A) Danks 10,684 ft. oscillatory ripples (OR), ball and pillow (B/P), current ripples (CR), mud cracks (blue arrows), and soft sediment deformation (SSD). Clear triangles represent fining upwards cycles which are commonly seen in the interbedded claystone and dolostone facies. A1) Danks 10,684 ft Higher magnification shows, examples of oscillatory ripples (OR), as well as, a scour surface (dashed white line). B) Danks 10,685.00 ft. oscillatory ripples (OR), ball and pillow (B/P), planar laminations (PL), scour surfaces (dashed white lines), Zoophycos traces (Zo), and pyrite (PY) (gold arrows) are shown. Clear triangles represent fining upwards cycles which are commonly seen in the interbedded claystone and dolostone facies. The location of the Zo traces demonstrates fairweather conditions where infauna had sufficient time to thrive and then fair weather deposition was interrupted by the storm as shown by the scour surface above.
Figure 4-10: Additional photographs of interbedded claystone and dolostone facies (Photos courtesy of Enerplus Resources). Here are examples of stacking pattern variations (lamina and bed thickness), and sedimentary structures in the interbedded claystone and dolostone facies. A) Roberts Trust 10,758 ft. A scour surface (white dashed line) indicating storm process and erosion is shown. Common mud cracks (blue arrows), and pinch and swell laminations (P/L) are shown. B) Pumpkin 10,271 ft, Variations in thickness of bedding indicating storm influence and accompanying tidal influence in deposition of the interbedded claystone and dolostone facies. Pinch and swell laminations (P/L). Clear triangles represent fining upwards cycles which are commonly seen in the interbedded claystone and dolostone facies. B1) Pumpkin 10,271 ft At higher magnification, blue dashed lines indicate ripple lamination surfaces that on-lap at different angles. Different flow directions are indicated with orange arrows. This indicates bi-directional flow during the deposition of the sandy dolostone.
Figure 4-11: Additional photographs of interbedded claystone and dolostone facies (Photos courtesy of Enerplus Resources). Here are examples of dewatering and desiccation features.

A) Henry Bad Gun 10,595.5 ft. Two large mud cracks indicate dewatering of the interbedded claystone and dolostone facies in a subaqueous setting (blue triangles). Some of this dewatering was strong enough to create clasts of dolostone. B) Pumpkin 10,274 ft. A large mud crack is present (blue triangle). Pinch and swell (P/L) laminations of dolostone are observed near the bottom portion of this image.
Figure 4-12: Additional photographs of interbedded claystone and dolostone facies (Photos courtesy of Enerplus Resources). These are examples of sedimentary structures, stacking patterns, and ichnological elements in the interbedded claystone and dolostone facies. A) Hognose 10,402 ft. Scour surface (white line) indicating storm process and erosion, pyrite (PY) (gold arrow), oscillatory ripples (OR), and ball and pillow structures (B/P) are also present. B) Roberts Trust 10,754 ft. A scour surface (white line) indicating storm process and erosion, and fractures (Fx) (red lines) are shown.
Figure 4-13: Photographs of chaotic facies (Photos courtesy of Enerplus Resources). These are examples of sedimentary structures, stacking patterns, and ichnological elements of chaotic facies. A) Danks 10,703 ft. Multiple scour surfaces are (white dashed lines) indicating storm process and erosion, claystone clasts (green dashed lines), ball and pillow structures (B/P), soft sediment deformation (SSD), oscillatory ripples (OR), and abundant mud cracks (blue arrows) are shown. B) Danks 10,683 ft. At this depth there is abundant soft sediment deformation (SSD), scour surface (dashed white line), mottled bedding (white arrows). C) Hognose 10,418 ft. A scour surfaces (dashed white line), mud cracks (blue arrows), pinch and swell laminations (P/L) and abundant soft sediment deformation (SSD) are shown. These structures indicate high sedimentation rates in the depositional of the chaotic facies.
Figure 4-14: These are additional photographs of the chaotic facies (Photos courtesy of Enerplus Resources). Examples of common sedimentary structures, stacking patterns, and ichnological elements of the chaotic facies are shown.  A) Hognose 10,417 ft. Multiple scour surfaces (dashed white lines), abundant soft sediment deformation (SSD), mottled bedding (MB), and ball and pillow structures (B/P) are shown. B) Pumpkin 10,280 ft. A scour surface (dashed white line), abundant soft sediment deformation (SSD), this is a more claystone rich chaotic interval which may indicate rapid sedimentation in a disturbed water column C) Hognose 10,404 ft. Abundant soft sediment deformation (SSD) and mottled bedding (MB). D) Henry Bad Gun 10,582 ft. A scour surface (dashed white line), clasts (green dashed line), and soft sediment deformation (SSD) are present in this sample.
Figure 4-15: Depositional model for the upper Three Forks representing the position of each facies within the mixed siliciclastic and carbonate tidal setting. This model demonstrates how the depositional environment of the upper Three Forks evolves through time based upon autogenic responses to intrabasinal processes. The depositional environment changes from tide dominated with rare storm influence in the basal upper Three Forks, to storm dominated in the upper portion of the upper Three Forks.
Figure 4-16: Stratigraphic column through the upper Three Forks demonstrating the vertical facies association and shift in depositional environment (red dashed line). Relative storm and tide influence are represented on the left of the column. This illustrates variation in vertical stacking of the Upper Three Forks. Relative sea level is on the right of the image to illustrate eustatic influences the depositional environments and the shallowing upward trend of the upper Three Forks. The combination of eustacy, storm, and tidal influence created a complex facies stacking pattern in the upper Three Forks. The basal upper Three Forks can be identified as a high stand deposit with the most marine influence. The upper portion of the upper Three Forks can be identified as a low stand deposit. There are multiple transgressive and regressive cycles in the upper Three Forks. The Three Forks is capped by an unconformity.
CHAPTER 5 UV FLUORESCENCE AND POROSITY AND PERMEABILITY

This chapter will address hydrocarbon saturation and localization throughout the facies of the upper Three Forks based upon ultraviolet fluorescence. XRD accompanied with porosity and permeability data is also plotted to demonstrate mineralogical and diagenetic controls on porosity and permeability. It is recommended that the reader view Appendix B: UV photos to obtain an understanding of variation and localization of hydrocarbon saturation throughout the facies of the upper Three Forks. All figures for this chapter can be found following the text. They are displayed in numerical order beginning on page 91.

5.1 UV fluorescence and hydrocarbon localization in facies

UV fluorescence from core provides a critical visual representation of oil storage within tight reservoirs and as a means to calibrate characterization efforts (Hohman and Chuparova, 2014). In the Three Forks basic observations are that oil accumulations are represented by blue to locally yellow. The distribution, intensity, and color of fluorescence in core present a direct and detailed, yet qualitative estimation of oil in place (Hohman and Chuparova, 2014). Blue and yellow show oil fluorescence and dull gold shows mineral fluorescence; it is critical to distinguish this in the utilization of UV fluorescence (Hohman and Chuparova, 2014).

UV fluorescence demonstrates variable hydrocarbon saturation throughout the facies of the upper Three Forks. The three lithologies of the upper Three Forks demonstrate variable fluorescence and hydrocarbon saturation as well. The claystone lithology typically displays very dull to no fluorescence. The silty dolostone displays variable fluorescence from slight to intense bright blue fluorescence. The sandy dolostone lithology displays variable fluorescence from non-fluorescent to bright blue fluorescence, and yellow fluorescence. Note that though UV fluorescence is a proxy for hydrocarbon saturation, mineral fluorescence can also affect the color and intensity of UV fluorescence. Fluorescence can also be a useful tool to further document sedimentary structures.

5.1.1 Dolomitic claystone

The dolomitic claystone facies is dominated by the claystone lithology and tends to be non-fluorescent (Figure 5-1). It is interpreted that this represents a lack of hydrocarbon
saturation in the dolomitic claystone facies. Due to this the dolomitic claystone facies is described as having poor reservoir quality in the upper Three Forks.

5.1.2 Brecciated

The brecciated facies demonstrates extremely variable fluorescence based upon sedimentary texture of being clast or matrix supported breccia and lithologic composition of the matrix. The variation and localization of fluorescence is documented in Appendix B. Typically fluorescence is of the brightest intensities within the dolomitic clasts or dolomitic matrix (Figure 5-2). The claystone lithology continues to display a lack of fluorescence when it comprises the matrix of the brecciated facies. Though fluorescence is displayed in the dolomitic clasts and matrix of the brecciated facies, it is still significantly localized between the clast and matrix sediments. Figure 5-3 reflects dolomitic clasts that demonstrate no fluorescence. This indicates that there are possible diagenetic cements which prevent fluorescence and hydrocarbon saturation within the dolomitic clasts of the brecciated facies. Due to this nature of fluorescence and localization, the brecciated facies is moderate in reservoir quality. The possible diagenetic affects cause concern for the reservoir quality of this facies.

5.1.3 Tan dolostone

The tan dolostone facies displays intense fluorescence through a majority of the facies (Figure 5-4). This facies is composed of the sandy dolostone lithology and has the most consistent and highest dolomitic content. Figure 5-5 displays swaths of non-fluorescence in this facies which are interpreted to be the result of diagenetic processes and cements. Localization of fluorescence or hydrocarbon saturation in this facies solely occurs within these diagenetic swaths. Fairly homogeneous fluorescence in the tan dolostone facies indicates moderate reservoir quality. The presence of diagenetic swaths is cause for concern for the reservoir quality in this facies.

5.1.4 Interbedded claystone and dolostone

The interbedded claystone and dolostone facies displays variable and localized fluorescence which seems to be dependent upon lithology. The claystone beds display dull to non-fluorescence. Silty dolostone beds display bright blue and intense fluorescence
The lithology boundaries display significantly intense fluorescence. Fluorescence is significantly localized in this facies occurring even in syndepositional features such as mud cracks and syneresis cracks. When mud cracks are filled with claystone no fluorescence is observed, yet when dolomitic sediment fills these structures bright fluorescence occurs. Even with the localization of saturation, the net hydrocarbon saturation of this facies appears to be of the best quality observed in the upper Three Forks. Note that no diagenetic indicators occur in this facies, or at least cannot be observed in the UV fluorescence photos.

5.1.5 Chaotic

The chaotic facies displays variable and localized fluorescence that seem to be predominately controlled by lithology. The claystone-rich sediment displays dull to no fluorescence. The silty and sandy dolostones display variable fluorescence from low to high intensities of bright blue fluorescence. Fluorescence in this facies is significantly localized along the lithology boundaries and within the sedimentary structures (Figure 5-7). The chaotic facies has a greater proportion of dolomitic sediment due to the storm dominated depositional style. This greater net dolomitic sediment leads to a higher net pay of hydrocarbon saturation in this facies. Due to this, the chaotic facies is interpreted to have good reservoir quality in the upper Three Forks. Note that no diagenetic indicators occur in this facies, or at least cannot be observed in the UV fluorescence photos.

5.1.6 Discussion

UV fluorescence provides an insightful tool for interpreting net hydrocarbon saturation and reservoir quality of the facies in the upper Three Forks. Analysis of the UV photo data is interpreted that the dominant controls on net hydrocarbon saturation are mineralogy and diagenesis. With the claystone lithology showing consistent non-fluorescence, the sandy dolostone shows moderate to bright fluorescence aside from diagenetic swaths, and the silty dolostone showing bright fluorescence with no indications of diagenesis. From this interpretation the facies of the upper Three Forks can be split into three rock types based upon net fluorescence and hydrocarbon localization observed. These rock types can be associated with the facies associations defined in chapter 4.2.6 (Table
The reservoir quality of the rock types can be divided into poor, moderate, and good (Table 5-1). The three reservoir rock types correlate well with the three depositional environments of the upper Three Forks. This indicates that depositional energy, lithology, and sedimentary structures have control on hydrocarbon saturation and localization within the upper Three Forks. Though both rock types B and C display bright blue luminescence there are two factors that set rock type C apart as the best reservoir of the upper Three Forks. Rock type B displays possible diagenetic prevention of hydrocarbon saturation whereas rock type C shows no evidence of diagenesis. Second, the net thickness of rock type B is over 20 feet thicker on average in each well. Note that the net hydrocarbon saturation of the rock type C is roughly half of the total average thickness based upon the frequent lithologic changes. This results in a net hydrocarbon saturation of over 15 feet on average which is double the average thickness of rock type B.

Table 5-1: Reservoir rock types of the upper Three Forks based upon UV fluorescence photos and interpreted hydrocarbon saturation. The facies and facies association that make up each rock type are listed as well as the reservoir quality of each rock type.

<table>
<thead>
<tr>
<th>Rock Type and UV Characteristics</th>
<th>Facies</th>
<th>Facies Association and depositional setting</th>
<th>Reservoir Quality</th>
<th>Average Thickness (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-very dull to non-luminescent, dominantly claystone lithology</td>
<td>Dolomitic claystone</td>
<td>A-shallow shelf marine</td>
<td>Poor</td>
<td>9.6 ft</td>
</tr>
<tr>
<td>B-yellow to bright blue luminescence, luminescence is not present in locations of interpreted diagenetic cements</td>
<td>Brecciated Tan dolostone</td>
<td>B-Intertidal and Supratidal flat</td>
<td>Moderate</td>
<td>7.2 ft</td>
</tr>
</tbody>
</table>
5.2 Porosity and permeability data

Following the UV photo analysis on the upper Three Forks it became evident that there was a mineralogical control on hydrocarbon saturation. To attempt to understand this control the routine core analysis data was used to graphically represent the rock types of the upper Three Forks.

5.2.1 Mineralogical control on porosity

The routine core analysis data provided by Enerplus Resources and collected at the Mineral Lab, Inc. in Golden, CO. Consisting of XRD, oil saturation, and porosity from each well in this study area. Using this data, it is possible to represent mineralogical controls on the reservoir properties of porosity and oil saturation. The dominant mineral constituents of contrasting rock types are dolomite and total clays (Illite + Chlorite). Both dolomite and total clays are plotted against porosity (Figure 5-8). The three rock types are outlined on this plot. The yellow square represents rock type A; very rich in clays and poor in dolomite with limited porosity. The red square represents rock type B with significantly rich dolomite content but limited porosity, due to diagenetic processes. The green square represents rock type C which has high dolomite content but moderate clay content. This indicates that there is a mineralogical balance for the best rock type in the upper Three Forks. If the rock is too dolomite rich there is poor porosity, if the rock is too clay rich there is poor porosity. The mineralogical control that can be seen on porosity from Figure 5-8 is that the correct proportion of dolomite and clays yields the best porosity. This indicates that dolomite rich intervals may be cemented which occludes porosity, and that in
intervals with the proper mineralogical proportions cementation is prevented and porosity is preserved.

5.2.2 Discussion

Combination of UV and routine core analysis data shows that there are three rock types or flow units that can be distinguished in the upper Three Forks. Each rock type displays different mineralogical and diagenetic controls on porosity.

Looking at a graphical representation of porosity against oil saturation (Figure 5-9) it is shown that there is a negative trend between porosity and oil saturation in the upper Three Forks. This indicates that there may be a substantial portion of microporosity in the upper Three Forks not observed by the testing methods Mineral Lab, Inc. This can also be seen as evidence for another fluid pathway and component of storage capacity in the upper Three Forks. This that SEM and MICP work should be done on the upper Three Forks to document the microporosity and other components of storage capacity in the upper Three Forks.

Analysis of UV fluorescence and routine core analysis data demonstrates that there are multiple controls at play in the localization of hydrocarbons in the upper Three Forks. It is not simply mineralogy or diagenesis and fracture network that control the reservoir quality of this formation but a combination of all three. The intermixing of these controls causes the complex hydrocarbon localization in the upper Three Forks.
Figure 5-1: Plane and Ultraviolet light photographs of the dolomitic claystone facies from the Pumpkin well at 10,301.0 ft. (Photos courtesy of Enerplus Resources). The lack of fluorescence and hydrocarbon saturation in this facies indicates poor reservoir quality. A) Plane light of the “RT” marker in the Pumpkin well, this dolomitic claystone facies is a slightly dolomitized claystone. B) Ultraviolet light showing the lack of fluorescence in the dolomitic claystone facies.
Figure 5-2: Plane and Ultraviolet light photographs of the brecciated facies from the Danks well at 10,716.0 ft. Photos of variable fluorescence and hydrocarbon saturation typically observed in the brecciated facies (Photos courtesy of Enerplus Resources). A) Plane light photo of the brecciated facies demonstrating the commonly observed texture interpreted to have resulted from dewatering and dissolution of evaporites. This is an example of matrix supported brecciated facies. B) Ultraviolet light photo of brecciated facies demonstrating preferential fluorescence. The tan dolostone clasts isolate the intense fluorescence. The brown dolostone matrix which is interpreted to be silty grain size has a very dull fluorescence. The claystone laminations occlude fluorescence. This facies illustrates a sharp contrast in fluorescence between lithologies.
Figure 5-3: Plane and Ultraviolet light photographs of the brecciated facies from the Henry Bad Gun well at 10,625.1 ft. Photos of variable fluorescence and hydrocarbon saturation typically observed in the brecciated facies (Photos courtesy of Enerplus Resources). A) Plane light photo of brecciated facies demonstrating commonly observed texture interpreted to have resulted from dewatering and evaporite dissolution. This is an example of clast supported brecciated facies. Black arrows represent clasts that demonstrate brittle deformation. B) Ultraviolet light photo of brecciated facies demonstrating preferential fluorescence. In this image the matrix brown dolostone isolates the fluorescence. The tan dolostone clasts occlude saturation; it is interpreted that the development of dolomite cement in these clasts prevented hydrocarbon saturation. The lithology boundaries exhibit the most intense saturation (white arrows).
Figure 5-4: Plane and ultraviolet light photographs of the tan dolostone facies from the Hognose well at 10,429.0 ft. Photos demonstrating variable fluorescence and typical hydrocarbon saturation observed in the tan dolostone facies (Photos courtesy of Enerplus Resources). Intense fluorescence in this image is interpreted to be a response to the structural location of the Hognose off the nose of the Antelope anticline creating a better fracture network for migration of hydrocarbons. A) Plane light photo of tan dolostone facies demonstrating structureless texture commonly observed in this facies, ball and pillow (B/P), and thin claystone laminations. B) Ultraviolet photo of tan dolostone facies demonstrating intense fluorescence throughout the image. Fluorescence is demonstrated in the claystone laminations as well in this image.
Figure 5-5: Plane and ultraviolet light photographs of the tan dolostone facies from the Pumpkin well at 10,293.0 ft. Photos demonstrating variable fluorescence and typical hydrocarbon saturation observed in the tan dolostone facies (Photos courtesy of Enerplus Resources). A) Plane light photo of the tan dolostone facies demonstrating structureless texture commonly observed, abundant anhydrite nodules (pink triangles). B) Ultraviolet light photo of tan dolostone facies demonstrating intense saturation. Two swaths demonstrating a lack of fluorescence indicate possible diagenesis and cementing in this facies preventing hydrocarbon saturation in these swaths.
Figure 5-6: Plane and ultraviolet light photographs of the interbedded claystone and dolostone facies from the Roberts Trust well at 10,752.0 ft. interbedded claystone and dolostone facies demonstrating preferential fluorescence between lithologies, as well as, typical hydrocarbon saturation of the interbedded claystone and dolostone facies (Photos courtesy of Enerplus Resources). A) Plane light photo of the interbedded claystone and dolostone facies, demonstrating sharp lithology boundaries, and multiple distinct mud and cracks (blue triangles). B) Ultraviolet light photo of interbedded claystone and dolostone facies, demonstrating good intense fluorescence at lithology boundaries (orange arrows), as well as, the dolostone lithofacies. Preferential saturation is also indicated in the mud cracks filled with dolomitic sediment (blue triangles).
Figure 5-7: Plane and ultraviolet light photographs of the chaotic facies from the Henry Bad Gun well at 10,586.0 ft. chaotic facies demonstrating preferential fluorescence and typical hydrocarbon saturation patterns seen in the chaotic facies (Photos courtesy of Enerplus Resources). A) Plane light photo of chaotic facies demonstrating abundant soft sediment deformation (SSD), clay clasts (CLST), and mud cracks (blue triangles). B) Ultraviolet light photo of chaotic facies demonstrating intense fluorescence in areas of soft sediment deformation. Mud cracks filled with dolomitic sediment demonstrate confined fluorescence (blue triangles). Claystone clasts occlude saturation and display a dull to non-existent fluorescence (red arrows).
Figure 5-8: Graphs of major mineralogical constituents vs porosity for all wells in the study area. Each color box represents a different rock type and the associated porosity. The yellow box represents rock type A which is claystone rich and dolomite poor and demonstrates the worst hydrocarbon saturation. The red box represents rock type B which is very rich in dolomite but has diagentic effects which cause lower porosity values making this rock type moderate in hydrocarbon saturation. The green box represents rock type B which is mixed in lithology but demonstrates no diagentic effects and shows the best porosity and hydrocarbon saturation.
Figure 5-9: Oil saturation vs porosity from all wells in this study area. Showing that there is a negative correlation between oil saturation and porosity in the upper Three Forks; indicating that there may have been microporosity not recorded by these testing methods. Also; indicating that there are other components to the storage capacity of the upper Three Forks.
CHAPTER 6 PETROGRAPHIC ANALYSIS AND DIAGENESIS

This chapter will address the petrographic analysis of the facies of the upper Three Forks. The process of dolomitization will be a large focus of this chapter along with the paragenetic sequence of the upper Three Forks. Both traditional thin section and cathodoluminescence microscopy were used to interpret the dolomitization and diagenesis of the upper Three Forks. It is recommended that the reader view both: Appendix C: Thin section images, and Appendix D: Cathodoluminescence images for additional photomicrographs used to document and understand both dolomitization and diagenesis. All figures for this chapter can be found following the text. They are displayed in numerical order beginning on page 132.

6.1 Petrography of Upper Three Forks lithologies

Petrographic reconnaissance of the lithologies of the upper Three Forks was done to document mineralogical and diagenetic heterogeneities. The terms slot pore and intercrystalline pore are used in this section (Figure 6-1).

![Slot Pore and Intercrystalline Pore Schematic](image)

Figure 6-1: Schematic showing the distinction between a slot pore and intercrystalline pore in the dolostone lithologies. A slot pore is recognized as an elongate 2 dimensional pore between two crystal edges. Intercrystalline pores are recognized as a 3 dimensional angular pore between multiple crystal faces or an edge.
6.1.1 Claystone

The claystone lithology is composed dominantly of illite and chlorite and is incredibly fine grained. The amount of dolomite within the claystone lithology is variable and is dependent upon the facies. In the dolomitic claystone facies, (Figure 6-1, Image B) the dolomite content of claystone is much higher compared to the claystone of the interbedded claystone and dolostone and chaotic facies. There is no inter-particle porosity visible in the claystone. Common microfracture porosity is the dominant storage component of this lithology. Rare dissolution microporosity occurs in this lithology. Abundant replacement pyrite is observed in this lithology (Figure 6-2).

6.1.2 Silty dolostone

The silty dolostone lithology is composed dominantly of sucrosic dolomite with up to 20% quartz, and variable clay content, with trace detrital micas and feldspars. The grain size of the detrital components in this lithology is silt. The dolomite rhombs grow to a silt size in this lithology. Common microporosity dissolution is observed in this lithology along with moderate slot porosity (Figure 6-3). Moderate to rare microfracture and intercrystalline porosity are observed in this lithology. Rare pyrite nodules are observed in this lithology and are commonly associated with dissolution.

6.1.3 Sandy dolostone

The sandy dolostone lithology is composed of sucrosic dolomite and quartz content up to 50% which is much higher than the silty dolostone lithology. The detrital sand grains are of very fine to sand grain size. The dolomite rhombs grow to a very fine sand size in this lithology. Rare intercrystalline, slot, and microporosity are observed in this lithology (Figure 6-4). This lithology demonstrates common poikilitopic anhydrite nodules. Abundant dolomite cement occurs in this lithology.

6.1.4 Discussion

These lithologies are distinct from each other in mineralogy, grain size, diagenesis, and dissolution that occur (Figure 6-5). The claystone is the finest grained lithology and has the lowest dolomite content. The dominant porosity of the claystone lithology is found
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in microfractures, there is rare to moderate microporosity from dissolution. The silty
dolostone has high dolomite content and low to moderate quartz content, with variable clay
content. The silty dolostone porosity demonstrates the best porosity with common
microporosity from dissolution and slot porosity. The sandy dolostone is the coarsest
lithology and has the highest quartz content. The sandy dolostone lithology displays the
worst porosity with rare intercrystalline and slot porosity. Microporosity from dissolution is
not observed in the sandy dolostone lithology. Note that dissolution is variable throughout
the lithologies based upon local diagenesis experience.

6.2 Petrography of Upper Three Forks facies

Petrographic reconnaissance of the facies of the upper Three Forks was done to
document mineralogical and diagenetic heterogeneities.

6.2.1 Dolomitic claystone

The dolomitic claystone facies is composed dominantly of illite and chlorite clays
with variable dolomite content, and trace quartz. Microfracture porosity occurs commonly
in this facies with microporosity from dissolution in regions with higher dolomite content
(Figure 6-6). Inter-particle porosity is not observed in this facies. Replacement pyrite
nodules are abundant in this facies. These pyrite nodules occur replacing clays and
occluding pore space in this facies. Variability in this facies is most predominately seen in
the dolomite content and amount of dissolution (Figure 6-6). This facies demonstrates poor
reservoir quality with no visible inter-particle porosity and minimal microporosity from
dissolution. The microfracture network in this facies may act as a fluid network for
diagenetic fluids and hydrocarbons. However fluids flowing through the microfracture
network lack fluid-rock interaction due to very poor inter-particle porosity.

6.2.2 Brecciated

The brecciated facies is composed of all three lithologies, with the sandy dolostone
appearing in clasts. Sandy dolostone clasts have higher quartz content than the matrix
lithologies. Matrix composition is variable between claystone and silty dolostone. This
variability in matrix is interpreted to be related to the combination of processes of
brecciation. Brecciation is interpreted to be caused by dewatering, soft sediment
deformation, and syndepositional precipitation and dissolution of evaporites. Because there are multiple controls on brecciation, multiple textures of preservation are preserved in the rock, and cause variation in matrix composition. Common microporosity from dissolution is observed in this facies (Figure 6-7). There is moderate microporosity and slot porosity observed within matrix silty dolostone. Matrix claystone exhibits moderate microfracture and dissolution microporosity. Sandy dolostone clasts exhibit very rare intercrystalline and slot porosity. The sandy dolostone clasts display pervasive dolomite cement. Dissolution occurs in both the claystone and silty dolostone matrix and is variable based upon local fluid flow and diagenesis (Figure 6-8). Due to complex lithologic relationships and preferential dissolution and diagenesis this facies has moderate reservoir quality. These lithologic relationships create difficult pathways for fluid flow and diagenesis can prevent hydrocarbon saturation.

6.2.3 Tan dolostone

The Tan dolostone facies is composed of coarse sucrosic dolomite and quartz. The Tan dolostone is the coarsest and most lithologically simple facies in the upper Three Forks. The grain size of the tan dolostone is fine-grained sand. There is no dissolution microporosity observed in this facies, very rare intercrystalline and slot porosity are present (Figure 6-9). Dolomite cement has occluded a majority of the porosity and is seen pervasively throughout this facies (Figure 6-10). Common syndepositional poiklitopic anhydrite nodules occur in the Tan dolostone facies. The Tan dolostone facies displays the most homogenous lithology and bedding of the upper Three Forks. This facies displays poor reservoir quality based upon heavy cementation observed which occludes porosity.

6.2.4 Interbedded claystone and dolostone

The interbedded claystone and dolostone facies consists of dominantly silty dolostone and claystone lithologies, with variable sandy dolostone based upon episodic storm events of higher energy. Frequent variation in bed thickness is observed due to variation in storms duration, magnitude and episodic nature (Figure 6-11). Fining upwards sequences are observed in the bedding of this facies from sandy dolostone to silty dolostone to the claystone lithology (Figure 6-11-F). The contacts between lithologies are
sharp and display dissolution microporosity. The dominant porosity observed in this facies is moderate dissolution microporosity. Rare to moderate intercrystalline and slot porosity occurs in the silty dolostone and sandy dolostone beds. The claystone beds demonstrate moderate microfracture porosity. Common pyrite nodules occur in this facies. These pyrite nodules are bimodal in size, the replacement pyrite in the claystone are finer than the replacement nodules that occur in the dolostone lithologies. Pyrite nodules commonly occur at lithology boundaries, indicating that there is preferential fluid flow along the lithology boundaries (Figure 6-11). There are rare to moderate pyrite swaths with association dissolution observed. Vug filling dolomite cement and pore filling anhydrite are observed in this facies and will be addressed in depth later in the chapter. Dissolution and diagenesis are variable in this facies and are typically associated with the silty dolostone lithology. The moderate dissolution microporosity accompanied with rare intercrystalline and slot porosity and microfracture network give this facies good reservoir quality.

### 6.2.5 Chaotic

The chaotic facies consists of all three lithologies in varying proportions based upon storm duration, magnitude, and episodic nature. The claystone lithology of the chaotic facies has a higher dolomite and quartz content due to the high depositional energy. This facies demonstrates complex lithologic relationships from sandy dolostone clasts within claystone matrix that is high in quartz content to rip ups of interbedded claystone and dolostone within chaotic claystone and sandy dolostone matrix (Figure 6-12). There can also be claystone clasts within a silty dolostone matrix in this facies (Figure 6-13) due to the high energy storm deposition. The storm processes that control deposition of the chaotic facies create high frequency variability in lithologic relationships. This high variability in lithologic relationships contributes to the moderate to abundant dissolution microporosity observed in this facies by providing multiple fluid pathways at the frequent lithology contrasts (Figure 6-12, Figure 6-13). Moderate microfracture porosity occurs in the claystone lithology. Rare intercrystalline and slot porosity are observed in the silty dolostone clasts and matrix. Common pyrite nodules and swaths occur. Pyrite nodules display a bimodal nature between lithologies, with nodules in the silty dolostones being coarser in nature. There are rare to moderate pyrite swaths with association dissolution
observed. Vug filling dolomite cement and pore filling anhydrite occur in this facies and will be addressed in greater detail later in this chapter. Due to the high frequency variability in lithology, the chaotic facies also demonstrates high frequency variability in both dissolution and diagenesis. The abundance of dissolution microporosity and fluid pathways from lithologic variations, gives this facies a good storage capacity and reservoir quality.

6.2.6 Discussion

Petrographic analysis of the facies of the upper Three Forks provides insight into inter-facies and intra-facies heterogeneity, lithological complexities, porosity types, and reservoir quality. Each facies displays internal variation and heterogeneity of either textural relationships based upon deposition or diagenetic features based upon localized fluid flow and fluid-rock interaction. Table 6-1 summarizes the petrographic analysis of each facies in the upper Three Forks. It is evident that contrasts in lithology provide preferential fluid flow pathways. This is demonstrated by frequent dissolution microporosity observed at lithology boundaries. The porosity in the claystone is very low and therefore not a viable conduit for fluid flow. The dolostones typically display cementation, creating a difficult path for fluid to migrate through. However, at lithology boundaries, contrasts in lithology, pore sizes, and shapes prevent cementation and allows for preferential fluid flow. The preferential fluid flow locations are more susceptible to diagenetic events and dissolution based upon increased fluid-rock interaction. Therefore, facies with higher frequencies in lithologic contrast provide a greater percentage of fluid pathways for dissolution to create microporosity and storage capacity. However, high frequency variability in lithology creates complex and localized dissolution and diagenesis in the upper Three Forks.

The dolomitic claystone facies displays minimal lithologic variability and dissolution, making the reservoir quality poor and the storage capacity low. The brecciated facies displays high lithologic variability and moderate dissolution. However, diagenetic cementation occludes porosity and some fluid pathways, making the reservoir quality and storage capacity moderate. The tan dolostone facies displays the lowest lithologic variability and pervasive dolomite cementation, which occludes porosity, making the reservoir quality and storage capacity poor. The interbedded claystone and dolostone facies displays high frequency lithologic variation and minimal cementation. There are moderate
fluid pathways in this facies from a combination of dissolution microporosity and microfracture network. The reservoir quality and storage capacity of the interbedded claystone and dolostone facies is good. The chaotic facies displays the greatest lithologic variability of high frequency. There is abundant dissolution due to the high frequency of lithologic changes yielding fluid pathways. The reservoir quality and storage capacity of the chaotic facies is also good.

Table 6-1: Table summarizing petrographic characteristics of each facies. Variabilities, lithologic relationships, porosity types, diagenetic features, and reservoir quality are addressed.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Types of variability</th>
<th>Lithologic relationships</th>
<th>Porosity types</th>
<th>Diagenetic features</th>
<th>Reservoir quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomitic claystone</td>
<td>Dolomite content, abundance of microfractures and pyrite nodules</td>
<td>Dominantly claystone with rare increase in dolomite content</td>
<td>Abundant microfracture porosity, rare dissolution microporosity</td>
<td>Pyrite nodules</td>
<td>Poor-minimal porosity, and dolomite content</td>
</tr>
<tr>
<td>Breciated</td>
<td>Matrix lithology, abundance of dissolution based upon lithologic complexities</td>
<td>Complex due to multiple processes of brecciation and their intermix nature</td>
<td>Rare microfracture porosity, rare intercrystalline and slot porosity, moderate dissolution microporosity</td>
<td>Dolomite cementation, pyrite nodules, dissolution</td>
<td>Moderate-common dissolution, but displays dolomite cement and complex lithologic relationships</td>
</tr>
<tr>
<td>Tan dolostone</td>
<td>Very homogeneous</td>
<td>Composed of sucrosic dolomite and quartz</td>
<td>Very rare intercrystalline and slot porosity</td>
<td>Pervasive dolomite cement, Poiklitopic anhydrite</td>
<td>Poor-pervasive dolomite cement</td>
</tr>
<tr>
<td>Interbedded claystone and dolostone</td>
<td>Thickness of beds Abundance of dissolution, diagenetic features based upon local fluid and rock interaction</td>
<td>Storm energy dictates if fining upward sequence includes sandy dolostone lithology</td>
<td>Common dissolution microporosity, rare to moderate intercrystalline and slot porosity, moderate microfracture porosity</td>
<td>Bimodal pyrite nodules Vug filling dolomite, pore filling anhydrite, pyrite swaths and dissolution</td>
<td>Good-abundant dissolution microporosity combined with microfracture network and preferential fluid flow at lithology boundaries</td>
</tr>
</tbody>
</table>

Table 6-1 continued:
6.3 Dolomitization

Humphrey (1988) stated that coastal zones with mixing freshwater and marine phreatic waters provide a diagenetic environment for dolomite. The shallow mixed marine flat environment with prominent storms and freshwater influx of the upper Three Forks fits these parameters as an environment for the diagenesis of dolomite. Multiple types of dolomite occur in the upper Three Forks in variable proportions throughout each facies. Murray (1960) defined sucrosic dolomitization as all degrees of dolomitization present in intimate vertical and horizontal association. This section will define sucrosic dolomitization and dolomite cements, as well as, document and interpret the variable types of dolomite observed in the upper Three Forks.

6.3.1 Sucrosic Dolomitization and Dolomite Cement

Sucrosic dolomite is observed in 85-90% of the dolomite occurring in the upper Three Forks. In sucrosic dolomitization, all degrees of dolomite occur in intimate vertical and horizontal association (Murray, 1960). Choquette and Hiatt (2008) define sucrosic dolomitization as the textural maturation of lime mud into a crystalline dolomite framework. This textural maturation occurs through three processes during early and late burial and has five stages (Figure 6-14). Compaction and dewatering during early burial diagenesis causes textural coarsening and cementation which creates a sucrosic dolomite network. The five stages of sucrosic dolomitization are the nuclei stage, cortex stage, crystal cluster cortex stage, lateral linkage cement stage, and pore-filling cement stage (Figure 6-14). This textural maturation causes three distinct responses through the stages in the development of the sucrosic dolomite network (Table 6-2). Note that the sucrosic dolomitization model created by Choquette and Hiatt (2008) is for a carbonate system. The
upper Three Forks is a mixed carbonate and siliciclastic system which can cause complexities in the development of sucrosic dolomite.

Sucrosic dolomitization commonly occurs in multiphase systems that will contain both replacive and cementing dolomite (Choquette and Hiatt 2008). The recognition of cement is crucial in petroleum exploration. Cement phases in carbonates play a fundamental role in controlling porosity and permeability relationships (Choquette and Hiatt 2014). Dolomite cement is defined as dolomite chemically or biochemically precipitated from aqueous solution onto faces of dolomite crystals, and will bond grains filling intraparticle pore space and replace pre-existing carbonate phases (Choquette and Hiatt 2008, Choquette and Hiatt 2014). Dolomite cements found in these multiphase sucrosic dolomite systems can be broken down into three types (Table 6-3). There are rhombic overgrowth, laterally linked partial overgrowths, and compound zoned cements. These cements are important to recognize as they occlude porosity and can be damaging to the reservoir quality of a dolomite rich rock. Replacive dolomitization often occurs early these systems (Choquette and Hiatt, 2014).

Table 6-2: Summary of the responses to the textural coarsening and maturation of lime mud creating sucrosic dolomite.

<table>
<thead>
<tr>
<th>Response</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarsening</td>
<td>First there is growth of cortices around Dolomite Nuclei or “cores”, then there is precipitation of syntaxial cement around the cortices</td>
</tr>
<tr>
<td>Induration</td>
<td>Combination of cortex intergrowth, cement overgrowth and possible chemical compaction</td>
</tr>
<tr>
<td>Occlusion of Pore System</td>
<td>Further cement overgrowth and chemical compaction</td>
</tr>
</tbody>
</table>

Table 6-3: Table summarizing types of dolomite cement found in a sucrosic dolomite network and the petrographic characteristics of these cements involved in recognition of these cements.

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhombic overgrowth cements</td>
<td>partially or completely in optical continuity with the crystal they enclose, normally adjoin intercrystalline pores and micropores</td>
</tr>
</tbody>
</table>
Table 6-3 continued:

<table>
<thead>
<tr>
<th>Laterally linked partial overgrowths</th>
<th>In optical continuity with their substrate crystals but enclose multiple dolomite rhombs, common in coarse sucrosic dolomite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compound zoned cements</td>
<td>found in large vugs; characterized by competitive growth of dolomite rhombs</td>
</tr>
</tbody>
</table>

### 6.3.2 Dolomitization pathways

Dolomite has three main pathways of formation, and is precipitated in two mole to mole reactions and one replacement reaction (Choquette and Hiatt, 2014). The pathways for dolomitization are: seawater in conjunction with evaporative conditions, freshwater and seawater mixing zones, and burial diagenetic environments. All three of these settings are present in the upper Three Forks which may contribute to the complex dolomite network as there are multiple dolomitization pathways active in this environment.

**Reaction (1): Mole to Mole**

\[
2\text{CaCO}_3 + \text{Mg}^{2+} \rightarrow \text{CaMg(CO}_3)_2 + \text{Ca}^{2+}
\]

It is interpreted that porosity is created by this reaction as two moles of \( \text{CaCO}_3 \) are replaced by one mole of \( \text{CaMg(CO}_3)_2 \). In this reaction there is replacement of lime mud and intercrystalline microporosity is created often producing a sucrosic dolomite texture (Choquette and Hiatt, 2014).

**Reaction (2): Mole to Mole**

\[
\text{Ca}^{2+} + \text{Mg}^{2+} + 2\text{CO}_3^{2-} \rightarrow \text{CaMg(CO}_3)_2
\]

In a reaction, where dolomite cement is produced, porosity is occluded (Choquette and Hiatt, 2014).

**Reaction (3): Replacement**

\[
(2-X)\text{CaCO}_3 + \text{Mg}^{2+} + X\text{CO}_3^{2-} \rightarrow \text{CaMg(CO}_3)_2 + (1-X)\text{Ca}^{2+}
\]

It is interpreted that when there is a high degree of microstructure (crystalline framework) preservation, that replacement dolomitization is the process in which dolomitization occurs.
This replacement dolomite reaction occurs early in burial and is known as mimetic because it preserves the original texture. Replacive dolomitization is associated with alkaline conditions and evaporative environments as they are commonly alkaline (Choquette and Hiatt, 2014).

### 6.3.3 Variation of Dolomite in the Upper Three Forks

Sucrosic dolomite composes over 90% of the dolomite present in the upper Three Forks, with trace detrital dolomite, vug filling compound zoned dolomite cement, dolomitic lime mud, and limpid pore filling dolomites. There is variation in the grain size and dissolution observed in the sucrosic dolomite network throughout the facies of the upper Three Forks. Some phases of dolomite are only observed in particular facies, whereas sucrosic dolomite is seen throughout the facies of the upper Three Forks.

Sucrosic dolomite varies from a coarse crystalline framework that is pervasively cemented by rhombic and laterally linked partial overgrowth cements (Figure 6-15) to fine crystalline framework with limited cementation and moderate dissolution microporosity (Figure 6-16). The coarse crystalline pervasively cemented sucrosic dolomite occurs in the Brecciated and Tan dolostone facies. The fine crystalline moderately dissolution microporosity sucrosic dolomite occurs in the interbedded claystone and dolostone and chaotic facies.

Detrital dolomite is recognized by abraded edges, abundant relict internal structure, and grain size (Figure 6-17). Detrital dolomite is rare in the upper Three Forks and is found in the interbedded claystone and dolostone and chaotic facies.

Compound zoned dolomite cements are observed filling vugs and commonly surrounded by fine crystalline sucrosic dolomite (Figure 6-16, Figure 6-18). These cements occur in the interbedded claystone and dolostone and chaotic facies of the upper Three Forks.

Dolomitic lime mud is observed in clasts and as matrix (Figure 6-19). Dolomitic lime mud is seen in the dolomitic claystone, interbedded claystone and dolostone, and chaotic facies in varying proportions based upon the depositional and waining energy.
Limpid pore filling dolomites are recognized by nearly perfect crystal faces and lack of inclusions (Figure 6-20). Limpid dolomites are rare in the upper Three Forks and are found in the Tan dolostone facies where the most pervasive sucrosic dolomitization and cementation have occurred. Limpid dolomite cements are coarse analogues of ultra-crystalline dolomite cements (Choquette and Hiatt, 2008).

Inclusion rich dolomite cores are represented in the upper Three Forks (Figure 6-21). These inclusions indicate pervasive dolomitization and change in pore water conditions during the continued dolomitization of the upper Three Forks.

This wide array of dolomite phases fits the sucrosic dolomite definition of Murray (1960) as they are in intimate vertical and horizontal association. It also indicates pervasive dolomitization throughout the burial of the upper Three Forks.

6.3.4 **Cathodoluminescence Reconnaissance**

Petrographic analysis shows multiple phases of dolomite and variable amounts of dolomite cement. Cathodoluminescence (CL) microscopy was used to document and interpret these complex dolomite relationships observed in the upper Three Forks. It is recommended that the reader view Appendix D: Cathodoluminescence Images. This appendix contains CL images from each facies and particular diagenetic features.

CL is an invaluable tool for distinguishing detrital, authigenic, diagenetic phases, and, porosity evolution in carbonate rocks (Hiatt and Pufahl, 2014). CL provides information about the diagenesis of the framework, cement overgrowths, and understanding diagenetic relationships based upon luminescence observed. The color of the wavelength of light produced by CL is a function of the crystal field symmetry and strength, which are controlled by atomic distance between transition metal and surrounding atoms (Hiatt and Pufahl, 2014). There are certain metals that activate or quench luminescence commonly associated with dolomite. Manganese (Mn$^{2+}$) and Iron (Fe$^{3+}$) fit into the crystal structure of trigonal carbonates. Mn$^{2+}$ is preferentially incorporated in the Mg$^{2+}$ site of dolomite. Mn$^{2+}$ is the most common activator of luminescence. Fe is the most common quencher of luminescence (Hiatt and Pufahl, 2014). CL gives an insight into concentrations of metals and redox conditions in the pore waters during precipitation based upon the color
and intensity of luminescence (Table 6-4). \( \text{Mn}^{2+} \) and \( \text{Fe}^{3+} \) concentrations are useful for interpreting the redox conditions of pore waters during diagenesis because they have different redox conditions (Hiatt and Pufahl, 2014).

Table 6-4: Cathodoluminescence characteristics and their correlation to redox conditions and cations present in pore fluids.

<table>
<thead>
<tr>
<th>Oxygen Level</th>
<th>Cations present in pore water</th>
<th>CL characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{O}_2 ) rich porewater</td>
<td>( \text{Mn}^{4+} ) and ( \text{Fe}^{3+} )</td>
<td>Dull to Dark</td>
</tr>
<tr>
<td>( \text{O}_2 ) poor porewater-reduced</td>
<td>( \text{Mn}^{2+} ) and ( \text{Fe}^{3+} )</td>
<td>Bright Yellow to Orange</td>
</tr>
<tr>
<td>Anoxic porewater-highly reduced</td>
<td>( \text{Mn}^{2+} ) and ( \text{Fe}^{2+} )</td>
<td>Dark Red to Black</td>
</tr>
</tbody>
</table>

CL analysis focused on the documentation and interpretation of the variation of sucrosic dolomite throughout the facies of the upper Three Forks. Additional benefits to CL were documentation of phases of dolomitization, dolomite cements, and diagenetic relationships of the upper Three Forks.

Sucrosic dolomite makes up a majority of the dolomite in the upper Three Forks. There is variation in sucrosic dolomitization between the facies of the upper Three Forks. In clean dolomitic sediments that are composed of dolomite and quartz there is a coarse sucrosic dolomite framework with pervasive cementation (Figure 6-22). In sediments with higher clay content there is fine crystalline sucrosic dolomite framework with rare cementation (Figure 6-23). The tan dolostone and dolomitic clasts of the brecciated facies demonstrate coarse sucrosic dolomite and pervasive cementation. The dolomitic claystone, interbedded claystone and dolostone, and chaotic facies have fine crystalline sucrosic dolomite framework with rare to moderate cementation. There is variable cementation in the dolomitic sediment of the interbedded claystone and dolostone and chaotic facies based upon proximity to claystone. The more clay rich the dolostones, the less cementation and porosity occlusion. Figure 6-24 illustrates a lithology boundary in the interbedded claystone and dolostone facies where the sucrosic dolomite framework is fine crystalline with limited cementation. This demonstrates that mineralogy is a control on the process of dolomitization. Clean dolostones will experience complete sucrosic dolomitization and develop both laterally linked partial overgrowths and pore filling dolomite cement. Dirty
dolostone and claystones will experience partial sucrosic dolomitization that stop at stage three of the sucrosic dolomitization model (Figure 6-14) and show limited cementation.

CL microscopy allows for documentation of waves of dolomitization and pore water changes that occur during burial and diagenesis. The tan dolostone facies displays complete sucrosic dolomitization and pervasive dolomite cementation which allows for the best interpretation and documentation of waves of dolomitization and pore water changes. Figure 6-25 demonstrates the following CL characteristic for dolomitization of the upper Three Forks. Dolomite core nuclei are typically irregular in shape and dull to orange in luminescence. Cortical overgrowths create euhedral crystals with dull to orange to slightly yellow luminescence indicating reduced conditions during precipitation. Pervasive dolomitization during burial of the upper Three Forks created rhombic and laterally linked overgrowths. These overgrowths display thin to thick bands of variable dull to orange luminescence indicating changes in pore water redox conditions during diagenesis. A maximum of four bands of contrasting luminescence are seen indicating four generations of dolomitization and pore water change during diagenesis. Non luminescent late ferroan cement is seen filling pore space between overgrowths on dolomite crystals.

In summation, dolomitization is pervasive throughout burial and diagenesis in the upper Three Forks. CL reconnaissance allows for recognition of five waves of dolomitization and late dolomite replacement (Table 6-5).

Table 6-5: Table summarizing the dolomite phases and cements of the upper Three Forks. The CL response of each phase and pore water conditions are represented.

<table>
<thead>
<tr>
<th>Dolomite cement stage</th>
<th>CL response</th>
<th>Pore water redox conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Euhedral Cortical overgrowths</td>
<td>Dull to faint orange</td>
<td>Reduced</td>
</tr>
<tr>
<td>2 Rhombic overgrowth A</td>
<td>Orange to bright orange</td>
<td>Oxygenated</td>
</tr>
<tr>
<td>3 Rhombic overgrowth B</td>
<td>Dull to faint orange</td>
<td>Reduced</td>
</tr>
<tr>
<td>4 Rhombic overgrowth C</td>
<td>Orange to bright orange</td>
<td>Oxygenated</td>
</tr>
<tr>
<td>5 Late Ferroan dolomite cement</td>
<td>Non luminescent</td>
<td>Reduced</td>
</tr>
</tbody>
</table>
CL was used to document common diagenetic anhydrite and pyrite of the upper Three Forks, as well. Anhydrite and pyrite will be addressed in detail in later sections of this chapter. There are common bright yellow luminescent dolomite crystals observed associated with anhydrite and pyrite, as well as, dissolution. It is interpreted as increased Mn$^{2+}$ content in the pore waters during precipitation of anhydrite and pyrite, and the dissolution of surrounding clays and carbonates.

6.3.5 Discussion

Dolomitization in the upper Three Forks is continuous from early burial to the end of diagenesis. Early dolomitization is represented by sucrosic dolomite and euhedral cortical overgrowths. Late dolomitization is represented by ferroan dolomite cement and potential late dolomite replacement. There are multiple phases of dolomite present in the upper Three Forks: sucrosic, detrital, dolomitic lime mud, and limpid pore filling dolomite. Three types of dolomite cement are found in the upper Three Forks: rhombic overgrowths (Figure 6-25), laterally linked partial overgrowths, and compound zoned cements. Rhombic overgrowths display variable dull to bright orange luminescence representing the change in pore water redox conditions during burial and dolomitization. Laterally linked partial overgrowths are observed adjoining multiple dolomite rhombs but may also be recognized by isopachous edges (Figure 6-26). Typically these laterally linked partial overgrowths display dull to non-luminescence in CL. Compound zoned dolomite cements occur in vugs of the interbedded claystone and dolostone and chaotic facies. These compound zoned cements display non- luminescence in CL and are associated with reduced pore water conditions (Figure 6-27). It is interpreted that these vugs are a result of dissolution associated with meteoric fluids during the unconformity between the upper Three Forks and lower Bakken shale. This is because of the proximity of these vugs to the top of the upper Three Forks where they would be in communication with meteoric waters from the unconformity. The fluids would be of different chemical composition than those associated with the early dolomitization and burial of the upper Three Forks and therefore may cause dissolution. These vugs are only observed in the interbedded claystone and dolostone and chaotic facies of the upper Three Forks. An alternate interpretation for these vugs is that
they are formed as solution vugs when dissolution to create intergranular porosity coalesces (Hiatt and Pufahl, 2014).

Sucrosic dolomitization framework is variable throughout the facies of the upper Three Forks. The tan dolostone sandy dolostone and the dolostone clasts of the brecciated facies display coarse sucrosic dolomite with pervasive cementation. The dolomitic claystone, interbedded claystone and dolostone, and chaotic facies display fine crystalline sucrosic dolomite framework with limited cementation. This indicates mineralogical control on the process of sucrosic dolomitization. Clays prevent the precipitation of pore filling dolomite cement and stop the sucrosic dolomitization model (Figure 6-14) at stage three or four. Clean dolostones have complete sucrosic dolomitization and pervasive pore filling cement.

There are five stages of dolomitization represented in the upper Three Forks (Table 6-5). These are: four pore water changes observed in rhombic overgrowths of contrasting luminescence and late ferroan dolomite cement. The laterally linked partial overgrowths and pore filling dolomite cement indicate primary dolomite precipitation from solution (Humphrey, 1988).

6.4 Anhydrite

There are multiple types of anhydrite present throughout the facies of the upper Three Forks. There are: syndepositional, replacement and pore filling anhydrites. Both petrographic and CL reconnaissance were used for documentation and interpretation of anhydrite. Additional photomicrographs of anhydrite are available in Appendix C: thin section images and Appendix D: cathodoluminescence images. It is recommended the reader view these appendices for more information.

6.4.1 Variation of Anhydrite in the Upper Three Forks

There are five types of anhydrite that occur in the upper Three Forks (Figure 6-28). The syndepositional anhydrites of the upper Three Forks occur in the Tan dolostone facies and the chaotic facies. Poikilitopic nodular anhydrite occurs in the Tan dolostone facies (Figure 6-28-A) and is associated with the tidal flat environment. These poikilitopic
anhydrites are around 500 µm in size and common in the tan dolostone facies. Rare incipient septarian nodules of clays filled with anhydrite occur in the chaotic facies (Figure 6-28-C). These nodules are around 500 µm in size and display common dissolution around the edges of the nodules and within the clays. Rare nodular tabular anhydrites are seen in the interbedded claystone and dolostone facies and chaotic facies (Figure 6-28-B). These nodules are draped by the host rock dolomite and are around 500 µm in size. Rare replacement anhydrite cement occurs in the dolostones of the interbedded claystone and dolostone and chaotic facies (Figure 6-28-E). This cement is patchy and less than 25 µm in size. Rare pore filling tabular anhydrites occur in the interbedded claystone and dolostone facies (Figure 6-28-D). These pore filling anhydrites display common dolomite inclusions and are commonly associated with dissolution. The tabular crystals are between 125 µm and 250 µm in size.

CL observation of these anhydrites demonstrates dolomite ghosts or inclusions within the anhydrite crystals, as well as, any different luminescence characteristics of dolomite crystals in contact with the anhydrite crystals. Poikilotopic anhydrite nodules are non-luminescent in CL and have consumed detrital quartz grains. They do not demonstrate any dolomite inclusions or ghosts (Figure 6-29). Incipient septarian nodules show non-luminescence CL, there are rare dolomite inclusions. The dolomite crystals associated with these incipient septarian nodules display bright yellow luminescence (Figure 6-30). Tabular nodules and pore filling anhydrite are non-luminescent with rare to moderate dolomite inclusions. The dolomite crystals associated with replacement and pore filling anhydrite are bright yellow in CL (Figure 6-31).

6.4.2 Discussion

The presence of syndepositional anhydrite indicates subaerial exposure and hypersaline conditions throughout deposition of the upper Three Forks. The frequency of subaerial exposure decreases throughout the deposition of the upper Three Forks. This is evident based upon the decreasing abundance of anhydrite vertically through the upper Three Forks. Poikilotopic anhydrite nodules are common to abundant in the Tan dolostone facies of the upper Three Forks which is found in the supratidal flat facies association B and experiences the most subaerial exposure of the upper Three Forks. In the interbedded
claystone and dolostone and chaotic facies of the upper Three Forks anhydrite nodules are rare indicating there is less frequent subaerial exposure in the storm dominated mixed flat facies association C. This decrease in frequency of subaerial exposure is a response to the depositional shift in the upper Three Forks between facies association B and C.

The poikilotopic anhydrite of the tan dolostone facies is interpreted to be a syndepositional feature associated with an evaporative environment (Figure 6-28A). The tabular nodular anhydrite is also interpreted to be syndepositional. Murray (1964) states that nodular anhydrites isolated in dolomite with tightly interlocking needle-like tabular crystals with a lack of inclusions did not form by replacement of carbonate rock but are syndepositional evaporite precipitation (Figure 6-28-B). The tabular nodules are interpreted to form during rare episodic hypersaline subaerial exposure between the freshwater influx and storms of the chaotic and interbedded claystone and dolostone facies. The difference between these syndepositional nodules is rate of crystal formation and their abundance. The poikilotopic anhydrites have more rapid formation versus the slow tabular crystal growth of the tabular nodules. The final syndepositional form of anhydrite observed in the upper Three Forks is the incipient septarian nodules of the chaotic facies (Figure 6-28-C). It is interpreted that the formation of these nodules occurred through a combination of dewatering, evaporite precipitation, and storms. Dewatering created small mud cracks within sporadic clays during times of subaerial exposure. During subaerial exposure in the chaotic facies, with increased tidal influence and salinity there is precipitation of evaporites within these mud cracks. During the next storm, high energy creates clay rip ups and clasts. This results in these incipient septarian nodules filled with anhydrite within the chaotic facies of the upper Three Forks (Figure 6-32). The freshwater from storm transportation and meteoric influx cause the common dissolution associated with these incipient septarian nodules.

The other forms of anhydrite in the upper Three Forks are replacement and pore filling tabular anhydrite crystals. Dissolution of syndepositional anhydrite is interpreted to the source for the later replacement and pore filling anhydrite. The meteoric and freshwater fluids associated with the dissolution of the unconformity between the upper Three Forks and lower Bakken shale that created the vugs filled by compound zoned dolomite cement,
are interpreted to be responsible for the dissolution of tabular anhydrite nodules in the interbedded claystone and dolostone and chaotic facies. It is interpreted that in areas where dissolution vugs have been formed and there is proximal dissolution of anhydrite, the precipitation of pore filling anhydrite can occur. Figure 6-33 demonstrates dolomite inclusions within tabular pore filling anhydrites indicating that there is dolomite replacement of secondary anhydrite.

6.5 Pyrite

Pyrite occurs throughout the facies of the upper Three Forks in variable proportions. There are two phases of pyrite observed: an early and secondary pyrite. The early pyrite is associated with the claystone lithology and the secondary pyrite is associated with the silty dolostone lithology. Pyrite is common in the dolomitic claystone, interbedded claystone and dolostone, and chaotic facies. Pyrite is rare in the brecciated and tan dolostone facies.

6.5.1 Early Pyrite

Early pyrite nodules occur in the claystone lithology of the dolomitic claystone, interbedded claystone and dolostone, and chaotic facies (Figure 6-34). These pyrite nodules are common in the claystone lithology and are seen replacing clays and filling pore space. They are less than 10 µm in size. This early pyrite precipitation is associated with early reducing burial conditions in the upper Three Forks.

6.5.2 Secondary Pyrite

Secondary pyrite occurs in the silty dolostone lithology of the interbedded claystone and dolostone and chaotic facies (Figure 6-35). Secondary pyrite is moderate to common and precipitated in and replaces the silty dolostone lithology. CL microscopy demonstrates the dolomite rhombs that have been replaced by this secondary pyrite, and there is associated local dissolution (Figure 6-36). These nodules range in size from 100 µm up to 1000 µm and greater. When these secondary pyrite nodules are present, they occur in dense swaths and can cause local dissolution. This stage of pyrite is associated with later reducing conditions of the upper Three Forks that occurred following reducing of the pore waters.
6.5.3 Discussion

Pyrite plays a crucial role in carbonate and marine sedimentary environments. The importance in the upper Three Forks is seen in multiple settings, from facilitating the precipitation of dolomite, occluding pore space, and causing preferential local dissolution. The mineral formula of pyrite is FeS₂. Iron is associated with reducing conditions in which pyrite is commonly precipitated; sulfur is also associated with pyrite precipitation. Choquette and Hiatt (2014) state that sulfide precipitation associated with pyrite increases the Mg²⁺/Ca²⁺ ratio of pore water. Dolomite forms with Mg²⁺/Ca²⁺ of 5-10:1 in normal salinities (Folk and Land, 1975). Therefore, increased Mg²⁺/Ca²⁺ from sulfide precipitation results in increased rates of dolomite precipitation (Choquette and Hiatt, 2014). The precipitation of pyrite during burial of the upper Three Forks allows for more rapid dolomite precipitation. Early pyrite is damaging to reservoir quality in the upper Three Forks as it is seen replacing clays and occluding porosity. Secondary pyrite replaces dolomite but is interpreted to be associated with local dissolution (Figure 6-37).

Corbella and Ayora (2004) state that carbonate dissolution can be driven by simultaneous precipitation of sulfides. This can be caused by the mixing of diagenetic fluids of different chemistry. With proper chemical mixture of diagenetic fluids, carbonates can be simultaneously precipitated and dissolved (Corbella and Ayora, 2004). The model for this simultaneous pyrite precipitation and carbonate dissolution involves the oxidation of sulfide during the mixing of brine sulfide reduced rich fluid with a surficial or meteoric fluid (Corbella and Ayora, 2004). There are four equations involved with this model:

\[
\begin{align*}
(1) \quad \text{CaCO}_3(s) + 2\text{H}^+ & \rightarrow \text{Ca}^{2+} + \text{CO}_2(aq) + \text{H}_2\text{O} \\
(2) \quad \text{H}_2\text{S}(aq) + 2\text{O}_2(aq) & \rightarrow 2\text{H}^+ + \text{SO}_4^{2-} \\
(3) \quad \text{H}_2\text{S}(aq) + \text{Zn}^{2+} & \rightarrow \text{ZnS}(s) + 2\text{H}^+ \\
(4) \quad \text{SO}_4^{2-}(aq) + \text{Zn}^{2+} + \text{CH}_4(aq) & \rightarrow \text{ZnS}(s) + 2\text{H}_2\text{O} + \text{CO}_2(aq)
\end{align*}
\]

When brine and surficial or meteoric fluids mix; equation (1) and (3) mix 1 mole of carbonate dissolved for each mole of sulfide that precipitates. When an additional meteoric fluid carries sulfate instead of sulfide, the precipitation reaction requires that sulfate
reduction occurs, which will result in the overall precipitation of sulfuric acid that may be responsible for dissolution of carbonate (Corbella and Ayora, 2004). This dissolution of dolomite by precipitation of pyrite results in microporosity which is a critical component to storage capacity and reservoir quality in the upper Three Forks.

6.6 Quartz Cementation

Quartz cementation occurs in the tan dolostone facies of the upper Three Forks (Figure 6-38). This cement is recognized by sutured grain contacts between quartz grains. Quartz cementation is moderate to common in the tan dolostone facies. It is interpreted that this quartz cementation occurs through pressure solution during compaction and burial of the upper Three Forks. The silica source for this quartz cementation is from the dissolved clays and feldspars in the surrounding claystones and dolostones. This cementation is late in the diagenesis of the upper Three Forks. Quartz cementation is only seen in the tan dolostone facies. It is interpreted that the decrease in quartz content and increase in clay content in the other facies of the upper Three Forks prevents quartz cementation. This quartz cement is damaging to reservoir quality as it occludes pore space between quartz grains.

6.7 Dissolution

Dissolution is prevalent in the upper Three Forks and creates microporosity and storage capacity in the upper Three Forks. Dissolution occurs from regional structural movements within microfractures. Regional meteoric diagenetic fluids also cause dissolution. Dissolution is preferential between lithologies and fluid flow conduits. There is also local dissolution based upon mineralization and precipitation of pyrite.

6.7.1 Regional

Regional tectonic activity creates a microfracture network throughout the upper Three Forks. These microfractures serve as a preferential fluid conduit and enhance dissolution (Figure 6-39). There are multiple meteoric diagenetic fluids throughout the burial of the upper Three Forks that cause dissolution. Dissolution more commonly occurs in the interbedded claystone and dolostone and chaotic facies. It is interpreted that
dissolution is more prevalent in these facies for two reasons: 1) the interbedded claystone and dolostone and chaotic facies don’t display pervasive cementation which allows for fluid-rock interaction and causes dissolution, 2) The proximity of the interbedded claystone and dolostone and chaotic facies to the unconformity between the Three Forks and the lower Bakken shale is interpreted as another cause for their more common dissolution. However, in the tan dolostone and brecciated facies, there is pervasive cementation which prevents fluid-rock interaction. The lowstand meteoric fluids during the unconformity are interpreted to cause common dissolution in the interbedded claystone and dolostone and chaotic facies of the upper Three Forks.

6.7.2 Local

Local dissolution is seen in the interbedded claystone and dolostone and chaotic facies and is associated with mineralization and pyrite precipitation. As stated in the pyrite section previously, the precipitation of pyrite can cause simultaneous dissolution of dolomite (Corbella and Ayora, 2004). This extensive local dissolution occurs with swaths of secondary pyrite replacing dolostone (Figure 6-40). This extensive dissolution is moderate in the interbedded claystone and dolostone and chaotic facies. Local dissolution provides microporosity and storage capacity for the upper Three Forks.

6.7.3 Discussion

Dissolution in the upper Three Forks is pervasive, preferential, and complex. Dissolution creates microporosity which is the largest component of storage capacity in the upper Three Forks. Dissolution is preferential based upon mineralogy, conduits for fluid flow, and whether it’s driven by regional or local dissolution. The silty dolostone lithology will be preferentially dissolved over the claystone. The microfracture network of the upper Three Forks provides preferential conduits of fluid flow and experiences preferential dissolution. The combination of multiple types of dissolution and high frequency lithologic contrast in the upper Three Forks causes the complexity of dissolution. It is interpreted that regional dissolution and diagenetic fluids are responsible for the dissolution of clays and claystone. Local dissolution is responsible for the dissolution of dolomite.
Regional dissolution occurs in the upper Three Forks and is associated with tectonics, mixing of meteoric fluids during diagenesis, and meteoric fluids associated with the unconformity between the upper Three Forks and lower Bakken shale.

Local dissolution is associated with mineralization. Plummer et al., (1982) stated that dissolution of dolomite can be driven by evaporite dissolution, accompanied by sulfate reduction, and pyrite precipitation. All of these processes occur in the upper Three Forks. Evaporite dissolution occurs both syndepositional and during burial. Syndepositional evaporite dissolution results from the influx of freshwater in supratidal flat environments and occurs in the brecciated facies. Early burial dissolution of anhydrites occurs in the interbedded claystone and dolostone and chaotic facies with the influx of meteoric fluids associated with the unconformity between the Three Forks and lower Bakken shale. CL microscopy demonstrates multiple changes in the redox state of the pore waters during the diagenesis of the upper Three Forks. This indicates that there is sulfate reduction. Pyrite precipitation occurs commonly in the interbedded claystone and dolostone and chaotic facies. The combination of these three processes causes complex local dissolution of dolomite in the upper Three Forks.

Another complexity associated with dissolution in the upper Three Forks is early and late dissolution. Regional dissolution occurs early in the diagenesis, local dissolution occurs in the mid-to late diagenesis. Early dissolution occurs in clays and along lithology boundaries. CL images show that there is dolomite precipitation associated with early dissolution (Figure 6-41). This early dissolution creates pore space for precipitation of dolomite during continued dolomitization and diagenesis. Local and secondary dissolution occur through mineralization and pyrite precipitation and cause the dissolution of dolomite (Figure 6-42).

This pervasive dissolution both early and late is a control on the complex diagenesis seen in the upper Three Forks. Dissolution changes the elemental composition of the pore waters, which in turn allows for precipitation of later diagenetic stages. Early regional dissolution occurs in clays, detrital feldspars, and muscovite. This provides $\text{Al}^{3+}$, $\text{K}^+$, $\text{Mg}^{2+}$, and $\text{Fe}^{3+}$ to the pore water. Early dissolution also occurs in tabular anhydrite which provides $\text{S}^{2-}$ and $\text{Ca}^{2+}$ to the pore water. This early dissolution causes the chemical and
elemental evolution of the pore water which allows for precipitation of later diagenetic phases. The $S^{2-}$ and $Fe^{3+}$ contribute to the precipitation of secondary pyrite and reduction of pore waters. The $Ca^{2+}$ contributes to the precipitation of pore filling anhydrite, as well as, continued dolomitization. $Mg^{2+}$ is the other contributing element to pervasive dolomitization during the diagenesis of the upper Three Forks. This relationship indicates that early dissolution generates the pore water chemical evolution, which allows for secondary mineral precipitation and causes secondary local dissolution.

6.8 Paragenetic sequence of the upper Three Forks

The paragenetic sequence of the upper Three Forks is a result of all of the diagenetic processes during burial and compaction (Figure 6-43). All of the diagenetic events in this sequence are related. Early events modify pore water chemistry and provide the elements for secondary mineralization. One of the most critical aspects of the paragenesis is the local dissolution from mineralization. This local dissolution is associated with secondary pyrite precipitation commonly followed by pore filling anhydrite (Figure 6-44, Figure 6-45). The CL demonstrates the replacement of dolomite by secondary pyrite. As mentioned in the previous section, this pyrite precipitation is associated with sulfuric acid which leaves sulfur in the pore waters. The dissolution of dolomite provides calcium to the pore waters which is interpreted to account for the precipitation of pore filling anhydrite.

The events in the paragenetic sequence that can be damaging or beneficial to reservoir quality are: (Table 6-6).

Table 6-6: Table listing the diagenetic events of the upper Three Forks and whether they are beneficial or damaging to reservoir quality.

<table>
<thead>
<tr>
<th>Damaging to reservoir quality</th>
<th>Beneficial to reservoir quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomitization, Compaction, Early pyrite, Early and secondary anhydrite, Quartz cementation</td>
<td>Dolomitization, Regional Dissolution, Local Dissolution, Secondary Pyrite</td>
</tr>
</tbody>
</table>
Figure 6-2: Photomicrographs of the claystone lithology demonstrating commonly observed mineralogy, texture, commonly observed microfractures, and abundant pyrite. A) plane polarized light (PPL) image of the interbedded claystone and dolostone facies from the Danks well at 10,688.05 ft. Pyrite nodules (gold triangles), microfracture (FX) and the associated microporosity, and showing the lower dolomite content observed in the claystones of the interbedded claystone and dolostone facies. B) PPL image of the “RT” marker from the Danks well at 10,721.00 ft. Demonstrating the higher dolomite content commonly associated with this interval, as well as a microfracture (FX) and the associated microporosity. C) Cross polarized light (XPL) image of the interbedded claystone and dolostone facies from the Hognose well at 10,403.15 ft, demonstrating low dolomite content of claystone lithology. Orange arrow represents a microfracture with internal mineralization of dolomite, and preferential dissolution around the boundaries of the microfracture as this serves as a conduit for fluid flow; allowing both mineralization and dissolution. D) PPL image of the interbedded claystone and dolostone facies from Henry Bad Gun well at 10,592.15 ft, demonstrating low dolomite content, pyrite nodules (gold triangles), and microfractures (FX). These microfractures demonstrate microporosity resulting from preferential fluid flow and dissolution. E) PPL image of the interbedded claystone and dolostone facies from Roberts Trust well at 10,749.2 ft. Pyrite nodules (gold triangles) which are commonly observed in the Claystone lithology, as well as, a microfracture (FX) showing microporosity. F) PPL image of chaotic facies from Roberts Trust well at 10,754.9 ft. abundant pyrite nodules (gold triangles), and microporosity from preferential dissolution (orange arrows). This dissolution most likely occurred to fine grained dolomite within the claystone lithology. The claystone lithology found in the chaotic facies has a higher dolomite content which allows for preferential fluid flow and dissolution in these claystones.
Figure 6-3: Photomicrographs of silty dolostone lithology demonstrating mineralogy, texture, grain size, and commonly observed porosity types. The compaction, dissolution, and porosity are variable based upon the amount of diagenesis experienced. A) PPL image of the interbedded claystone and dolostone facies from Roberts Trust well at 10,752.00 ft. Silty dolostone lithology dominated by sucrosic dolomite; which is recognized by its rhombic texture, as well as, internal structure and anomalous interference colors in XPL. Detrital mica (MUSC) and quartz (QTZ) grains are also shown. Porosity in the silty dolostone lithology is seen in multiple forms. The most prominent is microporosity (MCP) from dissolution of both dolomite and other minerals. This image demonstrates silty dolostone with higher clay content. B) PPL image of chaotic facies from Roberts Trust well at 10,769.8 ft. Silty dolostone lithology by sucrosic dolomite. The most common type of porosity observed in this lithology is microporosity (MCP) resulting from dissolution. Intercrystalline (IXP) and slot (SP) porosity are also present in the silty dolostone lithology. This image demonstrates clean silty dolostone with a lack of clays.
Figure 6-4: Photomicrographs of the sandy dolostone lithology demonstrating mineralogy, texture, grain size, and porosity types found in this lithology. A) PPL image of tan dolostone facies from Hognose well at 10,428.00 ft. Sucrosic dolomite is observed along with a higher quartz (QTZ) content with fine sand sized quartz grains. It is interpreted that the coarser rock fabric allows for the growth of coarser dolomite rhombs and promotes the development of dolomite cement in this lithology. In this photomicrograph porosity is very limited due to the development of dolomite cement, but microporosity (MCP) from dissolution and slot porosity (SP) are seen. B) PPL image of tan dolostone facies from Roberts Trust well at 10,773.2 ft. Both fine-grained silt sized and very fine sand sized dolomite are observed, as well as fine sand quartz (QTZ) grains. This photo demonstrates more microporosity (MCP) from the result of dissolution, as well as, intercrystalline (IXP) and slot porosity (SP).
Figure 6-5: Photomicrographs of all three distinct lithologies demonstrating variability in mineralogy, texture, grain size, dissolution, and porosity. A) PPL image of interbedded claystone and dolostone facies from Danks well at 10,682.00 ft. Boundary from sandy dolostone and silty dolostone lithology, grain size differential is noticeable with the sandy dolostone lithology being located on the right side of the image and having a very fine sand to fine sand grain size. In this image, there is pervasive dissolution creating microporosity. The microporosity and dissolution are more pervasive in the silty dolostone which is interpreted to be the result of dolomite cement that has developed in the sandy dolostone preventing fluid flow. B) PPL image of the boundary between tan dolostone and interbedded claystone and dolostone facies from Roberts Trust well at 10,773.2 ft. Silty dolostone versus the sandy dolostone demonstrating the contrast in quartz content between the two lithologies, as well as, grain size. Microporosity is seen in both of these lithologies, however the sandy dolostone contains larger intercrystalline and slot porosity. This image shows much less local dissolution than the previous image indicating that fluid flow in the upper Three Forks is preferential based upon depositional and diagenetic pathways. C) PPL image of the chaotic facies from Danks well at 10,686.1 ft. Demonstration of all three lithologies claystone, silty dolostone, and sandy dolostone. This image properly demonstrates the difference in grain size between all three lithology of the upper Three Forks. Variable dissolution is also observed in this image with the silty dolostone showing the most abundant dissolution and accompanied microporosity. In the sandy dolostone, there is visible intercrystalline and slot porosity. D) PPL image of the interbedded claystone and dolostone facies from Henry Bad Gun well at 10,586.00 ft. Another example of all three lithologies in the upper Three Forks, showing the distinct variation in grain size. It is interpreted that this is a syneresis crack infilled with sandy dolostone within the interbedded claystone and dolostone facies. Preferential dissolution is demonstrated in this image with the silty dolostone lithology displaying the most abundant dissolution and microporosity. E) PPL image of interbedded claystone and dolostone facies from Pumpkin well at 10,267.00 ft. Contact between silty dolostone and claystone, showing preferential dissolution at this lithology boundary and the associated microporosity, indicating that lithology boundaries are dominant fluid pathways in the upper Three Forks. The claystone shows no visible porosity and abundant pyrite nodules. The silty dolostone is dominated by sucrosic dolomite and shows microporosity, intercrystalline porosity, and slot porosity. F) PPL image of chaotic facies from Roberts Trust well at 10,767.00 ft. Silty dolostone with limited dissolution and microporosity and silty dolostone with abundant dissolution and microporosity. This image demonstrates the variable amounts of dissolution observed in the upper Three Forks which is interpreted to be controlled by mineralogy, texture, and diagenetic cements. It is also observed that the silty dolostone with abundant dissolution has abundant pyrite nodules which may be a contributing factor to dissolution.
Figure 6-6: Photomicrographs of the dolomitic claystone facies demonstrating common mineralogy, texture, and porosity types. A) PPL image of dolomitic claystone facies from Danks well at 10,682.7 ft. Image showing the dominant mineralogy of the dolomitic claystone facies which is illite and chlorite clays with variation in dolomite content; the dolomite rhombs in this facies are silt to clay sized. This image shows variable dissolution in this facies which is a result of the dolomite content. The two kinds of porosity found in the dolomitic claystone facies are dissolution microporosity (MCP) and microfracture porosity. (FX) B) PPL image of dolomitic claystone facies from Danks well at 10,688.05 ft. Abundant pyrite nodules are observed (Gold Triangles) commonly associated with dissolution, this is interpreted to be a result of pyrite precipitation possibly causing dissolution of dolomite in areas of preferential fluid flow. Both microporosity (MCP) from dissolution and fracture (FX) porosity are seen in this image. In the dolomitic claystone facies dissolution preferentially occurs to the dolomite due to the fact that there is no porosity or fluid pathway throughout the claystone aside from microfractures, causing preferential fluid flow in dolomite rich locations and microfractures.
Figure 6-7: Photomicrographs demonstrating mineralogy, texture, and porosity observed in the brecciated facies. A) PPL image of brecciated facies from Roberts Trust well at 10,779.10 ft. Image showing typical bedding style of brecciated facies with claystone matrix (fill) between two dolostone clasts. The claystone infill is illite and chlorite rich and demonstrates dissolution microporosity (MCP). The dolostone clast to the right of the image has higher quartz content, fine sand grain size, and displays slot (SP) and microporosity (MCP). The dolostone clast to the left of the image shows lower quartz content, silt grain size, and displays slot (SP) and microporosity (MCP). It is also observed that at the lithology boundary between the claystone and dolostone there is prominent microporosity. It is interpreted that this is a result of the contrast in mineralogy, porosity type, and pore throat size at lithology boundaries that there is preferential fluid flow and dissolution. B) XPL image of brecciated facies from Roberts Trust well at 10,779.10 ft. Common sweeping extinction of the illite and chlorite claystone, anomalous birefringence of dolomite, and low first order birefringence of quartz.
Figure 6-8: Additional photomicrographs of the brecciated facies demonstrating mineralogy, texture, porosity, and dissolution. A) PPL image of brecciated facies from Danks well at 10,707.00 ft. This photomicrograph demonstrates the commonly observed bedding nature of the brecciated facies caused by dewatering, dissolution of evaporites, and soft sediment deformation. Fine sand grain size is seen in the brecciated facies, due to the depositional energy of this facies. There is very little dissolution in this image which indicates that dissolution in the UTF is localized and may be attributed to chemical evolution of pore fluids, dissolution through precipitation of pyrite and the associated acids, or organic acids during the migration of hydrocarbons. B) PPL image of brecciated facies from Hognose well at 10,433.35 ft. This image demonstrates a similar relationship between lithologies and bedding nature; however there is pervasive dissolution present. This dissolution seems to have preferentially occurred in the claystone. This is another example of preferential dissolution occurring in the UTF. C) XPL image of brecciated facies from Hognose well at 10,428.00 ft. This image is a further example of the typical contorted bedding nature of the brecciated facies when observed in thin section. Minimal dissolution is present in this image which is five feet above image B in the Hognose well, indicating preferential dissolution. D) PPL image of Brecciated facies from Roberts Trust well at 10,779.1 ft. Another example of contorted bedding nature and upper silt to fine sand grain size of the brecciated facies. There is preferential dissolution at the lithology boundaries and within the microfractures (FX) of the claystone. There is microporosity (MCP) seen in the dolostone clasts.
Figure 6-9: Photomicrographs demonstrating common mineralogy, texture, and porosity seen in the tan dolostone facies. A) PPL image of the tan dolostone facies from Henry Bad Gun well at 10,618.00 ft. High quartz content and very fine to fine sand grain size of the tan dolostone facies. Common poikilotopic anhydrite (ANH) seen in the tan dolostone facies. Sucrosic dolomite is the dominant dolomite in the tan dolostone facies. There is minimal to no dissolution or porosity, which is interpreted to be the result of dolomite cement in this facies. B) XPL image of tan dolostone facies from Henry Bad Gun well at 10,618.00 ft. Poikilotopic anhydrite (ANH) is recognized by high first order birefringence. C) PPL image of tan dolostone facies from Pumpkin well at 10,294.00 ft. Image demonstrating the similarity in the tan dolostone association across the well in the FBR study area. The very fine to fine sand grain size, as well as, the high quartz content is interpreted to be the result of high energy of the storm tides that supply sediment to the supratidal tan dolostone location. Poikilotopic anhydrite (ANH) is also observed. There is no visible dissolution or porosity, which is interpreted to be the result of pervasive dolomite cement. D) XPL image of tan dolostone facies from Pumpkin well at 10,294.00 ft. Poikilotopic anhydrite (ANH) is recognized by high first order birefringence.
Figure 6-10: Additional photomicrographs demonstrating mineralogy, texture, and porosity of the tan dolostone facies. A) PPL image of tan dolostone facies from Henry Bad Gun well at 10,618.00 ft. Demonstration of the typical highly cemented tan dolostone facies, dolomite cement has occluded almost all intercrystalline and slot porosity leaving only slight microporosity in the sand flat facies. The grain size of the tan dolostone facies is very fine to fine sand, which allows for coarser textural development of sucrosic dolomite and dolomite cement. The tan dolostone facies has much higher quartz content than any other facies in the UTF. B) XPL image of tan dolostone facies from Henry Bad Gun well at 10,618.00 ft. Demonstration of anomalous birefringence of dolomite, and low first order interference colors of quartz.
Figure 6-11: Photomicrographs of the interbedded claystone and dolostone facies demonstrating common mineralogy, texture, bedding, and porosity types. A) PPL image of interbedded claystone and dolostone facies from Henry Bad Gun well at 10,600.45 ft. Sharp contacts between lithologies in this facies are observed. It is noted that the dolomite content of the claystones in the interbedded claystone and dolostone facies is lower than in the Dolomitic claystone facies. Variable thickness in lamination is shown, indicating heterogeneity in duration of sedimentation, accommodation space, and sediment supply. Microporosity from dissolution is observed in the silty dolostone sediment of this image. Pyrite nodules (gold triangles) tend to be associated with lithology boundaries, which are interpreted to be a result of these lithology boundaries being pathways for fluid flow and where mineralization and precipitation will preferentially occur. B) PPL image of interbedded claystone and dolostone facies from Henry Bad Gun well at 10,600.45 ft. Demonstration of sharp lithological contacts and variation of lamination thickness indicating heterogeneity in duration of sedimentation, accommodation space, and sediment supply. Microfractures (FX) with porosity are observed in the claystones. Pyrite nodules (gold triangles) are again observed trending along lithology boundaries where fluid pathways exist allowing for dissolution and precipitation. C) PPL image of interbedded claystone and dolostone facies from Hognose well at 10,423.15 ft. This image demonstrates variation in dolomite content of the claystone lithology and the variable dissolution that is a result of this mineralogy. The claystone in the bottom of the image is very illite and chlorite rich and shows little dissolution aside from a microfracture (FX). The claystone at the top of the image has higher dolomite content and is demonstrating abundant dissolution and microporosity. D) PPL image of interbedded claystone and dolostone facies from Pumpkin well at 10,270.00 ft. This image demonstrates sharp contacts between lithologies, illite and chlorite rich claystones. There is the appearance of hummocky cross stratification (HCS) and parallel laminations in the silty dolostone. The silty dolostone also demonstrates microporosity from dissolution. E) PPL image of interbedded claystone and dolostone facies from Hognose well at 10,420.1 ft. Lithology boundary of claystone and silty dolostone, the claystone demonstrates no visible porosity. The silty dolostone also demonstrates microporosity from dissolution. F) XPL image of interbedded claystone and dolostone facies from Henry Bad Gun well at 10,602.05 ft. This image demonstrates a fining upward (Black triangle) sequence in the interbedded claystone and dolostone facies, from claystone to sandy dolostone to silty dolostone back to claystone. There is microporosity from dissolution in both the sandy and silty dolostone; however the most abundant microporosity is observed in the silty dolostone. Pyrite nodules are also observed (gold triangles).
Figure 6-12: Photomicrographs demonstrating common mineralogy, texture, and porosity observed in the chaotic facies. A) XPL image of chaotic facies from Roberts Trust well at 10,774.00 ft. Image showing two silty dolostone clasts and claystone with a much higher quartz and dolomite content than observed in the interbedded claystone and dolostone facies. This is interpreted to be the result of depositional energy in the chaotic facies being higher and mixing coarser sediment with the claystone. Microporosity is observed more abundantly in this facies at the lithology boundaries of the sandy dolostone clasts and the claystone. It is interpreted that these are locations for preferential fluid pathways based upon the difference in mineralogy and porosity. Dissolution can also occur more strongly in the claystones of the chaotic interval due to higher dolomite content. B) PPL image of chaotic facies from Roberts Trust well at 10,750.6 ft. Demonstration of the higher depositional energy of the chaotic facies, showing a clast of the bedded interbedded claystone and dolostone facies (Orange dotted outline). It is interpreted that storm processes are dominant in the deposition of the chaotic facies which yields the scour surfaces, clasts, and other high energy features observed in the chaotic facies. Common microfracture (FX) porosity and microporosity (MCP) from dissolution are observed. Pyrite nodules (gold triangles) are observed in association with dissolution, which is interpreted to be a result of the acid created during the precipitation of pyrite causing dissolution.
Figure 6-13: Photomicrographs showing additional examples of mineralogy, texture, porosity, and variable dissolution seen in the chaotic facies. A) XPL image of chaotic facies from Danks well at 10,687.00 ft. Demonstration of the intensity of microporosity from dissolution that can be present in the chaotic facies. Microfracture (FX) porosity is abundant in the claystone. There is a clast from the interbedded claystone and dolostone facies (orange dotted outline) which indicates a higher energy depositional environment of the chaotic facies. Dissolution is seen at high intensity throughout the entire image however, it’s important to note that in the claystones, dissolution is associated with fractures. There are pyrite nodules (gold triangles) at the lithology boundaries and associated with dissolution within the interbedded claystone and dolostone clast. There is a syneresis crack (blue dotted outline) that penetrates the interbedded claystone and dolostone clast; this is interpreted to be to the rapid sedimentation and dewatering of the chaotic facies. The syneresis crack is filled with the coarse grained sediment transported and put into the water column by the higher energy deposition of the chaotic facies. B) PPL image of chaotic facies from Hognose well at 10,403.15 ft. Demonstration of variability in dissolution seen in the chaotic facies, dissolution is abundant in this image but not of the same intensity as image A. Microporosity is associated with dissolution; this image also demonstrates porosity in microfractures (FX). It is interpreted that the bedding observed in this image is soft sediment deformation at the microscopic scale.
Figure 6-14: Sucrosic dolomitization model showing the five stages and their relation to the processes that drive this style of dolomitization: Nucleus, Cortex, Crystal-Cluster Cortex, Lateral Linkage Cement, Pore-Filling Cement (Choquette and Hiatt, 2014).
Figure 6-15: Photomicrograph of complete sucrosic dolomitization in the tan dolostone facies. A) PPL image from Hognose well at 10,431.00 ft. This image demonstrates complete sucrosic dolomitization and cementation. In the clean tan dolostone facies there are no clays to obstruct growth of dolomite cement allowing for pervasive dolomitization developing rhombic overgrowth cement, lateral linkage cement, and pore-filling cement. This is a case where dolomitization is detrimental to reservoir quality. In the center of this image there is an example of a rhombic overgrowth on a dolomite cortex (orange arrow).

B) XPL image from Hognose well at 10,431.00 ft. Cross polarized view of image.
Figure 6-16: Photomicrograph of compound zoned cement and sucrosic dolomite in chaotic facies. A) PPL image from Pumpkin well at 10,266.00 ft. Compound dolomite cement filling a vug or possibly replacing pre-existing anhydrite, there is competitive growth observed within the compound zoned cement (orange arrows). The textural coarsening of the sucrosic dolomite has been limited by the presence of clays which has preserved microporosity. There is fracture (FX) porosity observed. B) XPL image from Pumpkin well at 10,266.00 ft. Cross polarized view of image A. There is microporosity (MCP) within the fracture on the left of the image along with partial mineralization in the fracture. Competitive crystal growth (Orange arrows) can be observed in the compound dolomite cement by the different extinctions.
Figure 6-17: Photomicrograph of detrital dolomite in the upper Three Forks from chaotic facies. A) PPL image from Henry Bad Gun well at 10,602.05 ft. detrital dolomite grain recognized from: abraded and rounded grain edges, relict internal structure, and grain size. This provides evidence for detrital carbonate in the upper Three Forks and shows there may have been a carbonate source for this mixed siliciclastic and carbonate environment. This image also demonstrates a preserved microporosity network which is interpreted to be a result of the clay content that prevents pore filling dolomite cements. B) XPL image from Henry Bad Gun well at 10,602.05 ft. Cross polarized view of image A demonstrating the anomalous birefringence and cleavage of the detrital dolomite grain.
Figure 6-18: Photomicrograph of vug filling compound zoned dolomite cement from the chaotic facies. A) PPL image from Hognose well at 10,407.20 ft. Compound zoned dolomite cement filling a vug in a highly cemented sucrosic dolomite with minimal microporosity. Competitive growth of crystals is seen in the compound zoned cement (Orange arrows). There is also a high content of laterally linked partial overgrowths in the dolomite cement network observed in this image. B) XPL image from Hognose well at 10,407.20 ft. Cross polarized view of image A.
Figure 6-19: Photomicrograph of dolomicrite in the upper Three Forks from interbedded claystone and dolostone facies. A) XPL image from Pumpkin well at 10,262.50 ft. This dolomicrite may have not had the opportunity to experience textural maturation from early compaction and high quartz content. Sucrosic dolomite is seen occluding porosity in this image.
Figure 6-20: Photomicrograph of limpid dolomites seen filling pores in the tan dolostone facies. A) PPL image from Pumpkin well at 10,296.00 ft. Limpid dolomite crystals (orange arrows) are recognized by near perfect crystal faces and edges, and being inclusion free or relatively inclusion free. Limpid dolomites are indicative of a stressed salinity environment and varying salinity conditions. There is rare microporosity visible and sucrosic dolomitization has created laterally linked overgrowth and pore-filling cements in the tan dolostone facies. B) XPL image from Pumpkin well at 10,296.00 ft. Cross polarized view of image A. Limpid dolomites are highlighted by orange arrows.
Figure 6-21: Photomicrograph of dolomite cement development and possible replacive dolomite from brecciated facies. A) PPL image from Hognose well at 10,426.85 ft. In the center of this image is a dolomite core representing multiple inclusions (Orange arrow). The overgrowth of this dolomite is rhombic overgrowth cement. It is also shown that the clay content of the Brecciated facies has prevented complete cementation via sucrosic dolomitization and has preserved microporosity. B) XPL image from Hognose well at 10,426.85 ft. Cross polarized view of image A.
Figure 6-22: Cathodoluminescence microscopy of the tan dolostone facies A) PPL image from Henry Bad Gun well at 10,617.00 ft. Note pervasive sucrosic dolomite network with limited intercrystalline and slot porosity. B) CL image from Henry Bad Gun well at 10,617.00 ft. Detrital quartz grains are easily identified by their blue luminescence in CL. Dolomite core nuclei are irregular and dull to orange in luminescence. Cortical overgrowths have developed subhedral to euhedral crystals. Continued dolomitization during diagenesis created thin to thick zones that indicated a change in pore water redox conditions. Late ferroan dolomite cement is seen filling pore space between dolomite rhombs and is non-luminescent. Green arrows indicate rhombic overgrowth cements surrounding luminescent dolomite cortices; the rhombic overgrowths display different luminescence than the cortices, indicating varying pore water conditions during dolomitization.
Figure 6-23: Cathodoluminescence microscopy of the claystone in the interbedded claystone and dolostone facies A) PPL image from Henry Bad Gun well at 10,600.45 ft. Note the low percentage of dolomite, moderate pyrite nodules, and microfractures. B) CL image from Henry Bad Gun well at 10,600.45 ft. Quartz grains are easily identifiable from their blue luminescence in CL, note the difference in grain size of quartz in the claystone lithology (less than 10 µm) as compared to the dolostone lithology (up to 50 µm). Dolomite is seen forming irregular to subhedral rhombs. Limited overgrowths are observed due to limited pore space in the claystone lithology preventing fluid-rock interaction and continued dolomitization with burial. Dolomite rhombs are bright yellow in luminescence indicating high Mn$^{2+}$ in the early diagenetic pore water conditions.
Figure 6-24: Cathodoluminescence microscopy of the interbedded claystone and dolostone facies

A) PPL image of a lithology boundary from Henry Bad Gun well at 10,600.45 ft. Note microfracture within claystone lithology, as well as, increased porosity from dissolution in the interbedded claystone and dolostone facies as compared to the tan dolostone facies. B) CL image of a lithology boundary from Henry Bad Gun well at 10,600.45 ft. Detrital quartz grains are easily recognized by their blue luminescence in CL. Note the limited growth of dolomite rhombic overgrowths in the claystone lithology as compared to the dolostone lithology. Dolomite core nuclei are dull to orange luminescent with cortical overgrowths that created subhedral to euhedral crystals. Continued dolomitization during burial has produced fine scale zones in overgrowths indicating change in pore water redox conditions. Green arrows indicate rhombic overgrowth cements surrounding luminescent dolomite cortices; the rhombic overgrowths display different luminescence than the cortices, indicating varying pore water conditions during dolomitization.
Figure 6-25: Cathodoluminescence microscopy of the tan dolostone facies A) PPL image from Henry Bad Gun well at 10,617.00 ft. Note pervasive sucrosic dolomite network with minimal intercrystalline to slot porosity. Pyrite nodules are seen replacing dolomite rhombs.

B) CL image from Henry Bad Gun well at 10,617.00 ft. Detrital quartz grains are recognized by their blue luminescence in CL. There are two dolomite crystals that display intensely bright yellow luminescence indicating that the pore waters were very rich in Mn$^{2+}$ during their precipitation. Core nuclei are irregular and dull to orange in luminescence. Cortical overgrowths have developed subhedral to euhedral dolomite crystals. Continued dolomitization during burial produced thin to thick overgrowths of varying luminescence indicating change in redox pore water conditions during diagenesis. Late ferroan dolomite cement is seen filling pore space between dolomite rhombs and is non-luminescent. Some dolomite rhombs (blue arrow) display at least four changes in pore water redox conditions during dolomitization. Green arrows indicate rhombic overgrowth cements surrounding luminescent dolomite cortices; the rhombic overgrowths display different luminescence than the cortices, indicating varying pore water conditions during dolomitization.
Figure 6-26: Cathodoluminescence microscopy of laterally linked partial overgrowth cement in interbedded claystone and dolostone facies A) PPL image from Hognose well at 10,410.00 ft. Note the vug filling laterally linked partial overgrowth dolomite cement with an isopachous rim (orange arrow). There is microporosity from dissolution visible in the upper portion of the vug. Note sucrosic dolomite network with no visible intercrystalline or slot porosity. B) CL image from Hognose well at 10,410.00 ft. Detrital quartz grains are easily identifiable by their blue luminescence in CL. Note the vug filling laterally linked partial overgrowth dolomite cement is non-luminescent and inclusion pore. The non-luminescence may indicate the vug filling laterally linked partial overgrowth cement is associated with late ferroan dolomite cement. Dolomite rhombs display overgrowths which develop subhedral to euhedral crystals. These overgrowths display thin to thick zones of varying luminescence indicate change in pore water conditions during diagenesis. Note the subhedral non-luminescent dolomite (blue arrow) in the area of partial dissolution. Note the vug demonstrates partial dissolution in the upper region of the image and the dolomite rhombs are much smaller by comparison than in the surrounding areas.
Figure 6-27: Cathodoluminescence microscopy of compound zoned dolomite cement filling a vug in the chaotic facies A) PPL image from Hognose well at 10,407.20 ft. Note the vug filling compound zoned dolomite cement and porosity surrounding the vug. Pervasive sucrosic dolomite network with limited intercrystalline and slot porosity is observed. B) CL image from Hognose well at 10,407.20 ft. Detrital quartz grains are easily identifiable by their blue luminescence. Vug filling compound zoned dolomite cement is non luminescent and shows minimal inclusions. Dolomite rhombs show overgrowths that are subhedral to euhedral. Dolomite overgrowths display thin to thick zones of varying luminescence that indicate a change in pore water redox conditions during diagenesis. There are dolomite rhombs that display bright yellow luminescence and indicate Mn²⁺ rich pore waters.
Figure 6-28: Photomicrographs of the types of anhydrite observed in the upper Three Forks, demonstrating textural differences. A) XPL image of tan dolostone facies from Roberts Trust well at 10,775.20 ft. Poikilotopic anhydrite nodule that is interpreted to be associated with syndepositional evaporite precipitation in the tan dolostone facies. B) XPL image of the interbedded claystone and dolostone facies from Henry Bad Gun well at 10,593.05 ft. Lath anhydrite nodule that is associated with the interbedded claystone and dolostone facies. It is interpreted that these nodules occurred through anhydrite replacement in the second stage of anhydrite of the upper Three Forks. C) XPL image of chaotic facies from Danks well at 10,682.70 ft. Incipient septarian nodule filled with anhydrite. D) XPL image of the interbedded claystone and dolostone facies from Henry Bad Gun well at 10,587.00 ft. Void filling anhydrite interpreted to be associated with the second stage of anhydrite precipitation in the upper Three Forks. E) XPL image of chaotic facies from Hognose well at 10,414.20 ft. Anhydrite cement in the chaotic facies is interpreted to be associated with anhydrite replacement.
Figure 6-29: Cathodoluminescence microscopy of the tan dolostone facies A) PPL image from Danks well at 10,714.00 ft. poikilotopic anhydrite within coarse sucrosic dolomite. Note minimal intercrystalline and slot porosity due to cementation. B) CL image from Danks well at 10,714.00 ft. Poikilotopic anhydrite is non-luminescent. Detrital quartz grains associated with the coarser grained tan dolostone facies are easily identifiable from their blue luminescence in CL. Dolomite core nuclei are dull to non-luminescent. Rhombic overgrowths display an orange to bright yellow luminescence indicating a change in pore water redox conditions during burial. Changing pore water conditions are also demonstrated by some rhombs with a series of thin fine-scale overgrowths of different luminescence. Non-luminescent late ferroan dolomite cement is seen filling pore space between dolomite rhombs indicating late stage dolomitization. Green arrows indicate rhombic overgrowth cements surrounding luminescent dolomite cortices; the rhombic overgrowths display different luminescence than the cortices, indicating varying pore water conditions during dolomitization.
Figure 6-30: Cathodoluminescence microscopy of incipient septarian nodule found in interbedded claystone and dolostone facies A) PPL image from Danks well at 10,682.7 ft. incipient septarian nodule consisting of large tabular anhydrite crystals found within clays clast. Note microporosity and dissolution surrounding the nodule. Dolomite rhombs surrounding the nodule are subhedral to euhedral. B) CL image from Danks well at 10,682.7 ft. Tabular anhydrite crystal is non-luminescent, but few brightly yellow luminescent dolomite rhombs of less than 10 \( \mu m \) can be seen within the anhydrite crystals. Dolomite within the clay is restricted in growth due to lack of pore space for fluid-rock interaction to promote overgrowth cement on the dolomite cortices. Dolomite rhombs that surround the clay clast demonstrate cortical growths of substantial size (close to 50 \( \mu m \)). Due to pore space in the dolomitic sediment, fluid-rock interactions took place allowing for rhombic overgrowths and development of larger crystals during burial. The dolomite in this image is bright yellow suggesting high Mg\(^{2+}\) content in the pore waters during precipitation.
Figure 6-31: Cathodoluminescence microscopy of tabular lath anhydrite in interbedded claystone and dolostone facies A) XPL image from Hognose well at 10,410.00 ft. Note tabular lath replacement anhydrite with minimal dolomite inclusions. There is a pervasive sucrosic dolomite network with no visible intercrystalline or slot porosity. B) CL image from Hognose well at 10,410.00 ft. Detrital quartz grains are easily identifiable by their blue luminescence in CL. The tabular lath anhydrite is non luminescent and has some bright yellow luminescent dolomite inclusions. Dolomite rhombs display overgrowths developing subhedral to euhedral crystals. Overgrowths display thin to thick zones of varying luminescence indicating a change in pore water redox conditions during diagenesis. There are dolomite rhombs with bright yellow luminescence indicating high Mn$^{2+}$ content in the pore water during precipitation.
Figure 6-32: Photomicrographs of syndepositional incipient septarian nodules from chaotic facies throughout the wells of this study. A) PPL image of chaotic facies from Danks well at 10,682.7 ft. B) XPL image of chaotic facies from Danks well at 10,682.70 ft. C) PPL image of chaotic facies from Pumpkin well at 10,299.00 ft. D) XPL image of brecciated facies from Pumpkin well at 10,299.00 ft. E) PPL image of chaotic facies from Roberts Trust well at 10,745.20 ft. F) XPL image of chaotic facies from Roberts Trust well at 10,745.20 ft.
Figure 6-33: Photomicrograph of pore filling anhydrite demonstrating tabular crystal growth. A) XPL image of chaotic facies from Hognose well at 10,406.15 ft. Void filling anhydrite in the chaotic facies. It is interpreted that this anhydrite is associated with later anhydrite precipitation in the upper Three Forks following dissolution which creates these voids. There are dolomite inclusions in these tabular crystals indicating dolomite replacement and further dolomitization following the pore filling anhydrite. B) PPL image of interbedded claystone and dolostone facies from Henry Bad Gun well at 10,587.00 ft. Void filling anhydrite in the chaotic facies. It is interpreted that this anhydrite is associated with later anhydrite precipitation in the upper Three Forks following dissolution which creates these voids. C) XPL image of interbedded claystone and dolostone facies from Henry Bad Gun well at 10,587.00 ft. Cross polarized view of image B. This image demonstrates textural relationships that show dolomitization following the precipitation of pore-filling anhydrite. There are dolomite inclusions and dolomite rhombs growing into the tabular anhydrite crystals indicating dolomite replacement and further dolomitization following the pore filling anhydrite.
Figure 6-34: Photomicrograph of early stage pyrite in the upper Three Forks. A) PPL image of interbedded claystone and dolostone facies from Roberts Trust well at 10,749.2 ft. Early stage pyrite in the upper Three Forks replacing clay and occluding porosity. It is interpreted that this early stage pyrite is associated with early burial reducing conditions in the upper Three Forks.
Figure 6-35: Photomicrographs of second stage pyrite in the upper Three Forks seen replacing dolomite. A) PPL image of interbedded claystone and dolostone facies from Danks well at 10,702.15 ft. Secondary pyrite (orange arrow) replacing dolomite; shown in comparison to first stage pyrite replacing clays and occluding porosity. B) XPL image of interbedded claystone and dolostone facies from Roberts Trust well at 10,763.2 ft. Large secondary pyrite nodule replacing dolomite and causing local dissolution (Orange arrows). C) XPL image of interbedded claystone and dolostone facies from Roberts Trust well at 10,752.00 ft. Secondary pyrite replacing dolomite and causing local dissolution (Orange arrows) surrounding the nodules.
Figure 6-36: Cathodoluminescence microscopy of secondary replacement pyrite and associated dissolution in the chaotic facies A) PPL image from Roberts Trust well at 10,767.00 ft. Note large pyrite nodule and associated dissolution seen in the claystone. There is a microfracture observed in the heavily dissolved claystone. B) CL image from Roberts Trust well at 10,767.00 ft. Detrital quartz grains are easily identifiable by their blue luminescence in CL. Note the size differential between dolomite rhombs in the claystone as compared to the dolostone lithology. This is due to limited pore space in the claystone which prevents dolomite overgrowths and pervasive sucrosic dolomite development by lack of fluid-rock interaction. Note the abundance of dolomite rhombs within the pyrite nodule that can be observed under CL. These rhombs display core nuclei, overgrowths and zonation indicating that dolomitization had occurred before the precipitation of replacement pyrite. Within the dolostone lithology core nuclei are irregular and dull to orange in luminescence. Cortical overgrowths have developed subhedral to euhedral overgrowths. Dolomite overgrowths (blue arrow) display thin to thick zones of varying luminescence indicating change in pore water redox conditions during diagenesis. Late ferroan dolomite cement is seen filling space between dolomite rhombs in the dolostone lithology and is non-luminescent.
Figure 6-37: Photomicrograph of dissolution within a detrital dolomite caused by pyrite replacement of dolomite from the interbedded claystone and dolostone facies. A) PPL image from Pumpkin well at 10,267.00 ft. Second stage pyrite (green arrow) which is observed replacing dolomite. There is local dissolution (orange arrow) associated with the precipitation of pyrite observed within the detrital dolomite grain. B) XPL image from Pumpkin well at 10,267.00 ft. Cross polarized view of image A.
Figure 6-38: Photomicrograph of quartz cement developed through compaction and suturing of grains in the tan dolostone facies. A) PPL image of tan dolostone facies from Pumpkin well at 10,262.50 ft. Quartz cement is recognized by the loss of grain boundaries and suturing of grains. Sutured boundaries (orange arrows) are shown. B) XPL image of tan dolostone facies from Pumpkin well at 10,262.50 ft. Cross polarized view of image A. Quartz cement is recognized by the loss of grain boundaries and suturing of grains. Sutured grain boundaries (orange arrows) are shown. Also seen in this image is rhombic overgrowth (RHO) dolomite cement and laterally linked partial overgrowth (LLP) dolomite cement.
Figure 6-39: Photomicrographs demonstrating regional dissolution from structure and fluids exhibiting both preferential and variable dissolution and microporosity at lithology boundaries, mineralogy contrasts, and within microfractures; which are all conduits of fluid flow. A) PPL image of chaotic facies from Danks well at 10,684.00 ft. Image demonstrating dissolution in the dolomitic clasts (orange dashed outline) creating microporosity, but a lack of dissolution in the claystone rich regions. B) PPL image of chaotic facies from Danks well at 10,701.00 ft. Image showing dissolution in the dolomitic (orange dashed outline) sediment creating microporosity, however, there is no dissolution in the claystone lithology. There are multiple clay clasts (red arrows) within the clay rich matrix indicating the high depositional energy of the chaotic facies. C) XPL image of chaotic facies from Hognose well at 10,428.00 ft. This image shows strong dissolution at the lithology boundary between a dolomitic clast and claystone sediment (orange arrow), as well as, abundant microfractures (FX) with microporosity. There are also pyrite (gold triangles) nodules observed in these microfractures, which are interpreted to serve as conduits for fluid flow allowing mineralization. D) PPL image of chaotic facies from Hognose well at 10,425.00 ft. This image demonstrates microporosity within the dolomitic sediment, but the most prominent porosity observed is microfracture porosity (orange arrows) seen in the claystone clast. E) XPL image of chaotic facies from Hognose well at 10,412.00 ft. This image shows common microporosity from dissolution in both the dolomitic and claystone rich sediments. In the claystone porosity is dominated by microfractures (FX). In the dolomitic sediment dissolution creates microporosity. F) PPL image of chaotic facies from Pumpkin well at 10,263.00 ft. This image shows microfractures (FX) in the claystone interval which provide porosity. There is microporosity (MCP) from dissolution in the dolomitic sediments. There is a dolomitic clast (orange outline) that shows no dissolution due to the development of dolomite cement preventing fluid flow.
Figure 6-40: Photomicrograph demonstrating local dissolution associated with secondary replacement pyrite precipitation, followed by precipitation of pore-filling anhydrite, from the interbedded claystone and dolostone facies: A) PPL image from Roberts Trust well at 10,748.00 ft. This image depicts dissolution associated with the precipitation of pyrite. It is interpreted that during the second stage of pyrite precipitation, which locally replaces dolomite, there is local dissolution. During the precipitation of pyrite, there is the associated precipitation of sulfuric acid which has caused the dissolution of the surrounding dolomite creating local microporosity. Following this pyrite precipitation and dissolution, there is the precipitation of pore-filling anhydrite which is seen in contact with the pyrite nodules. These relationships verify that there were multiple stages of pyrite and anhydrite precipitation in the Upper Three Forks. B) XPL image from Roberts Trust well at 10,748.00 ft. Cross polarized view of image A. Pore-filling anhydrite is recognized by the birefringence colors and tabular crystal texture. It is interpreted that these anhydrites are pore-filling and follow dissolution based upon the tabular nature of the crystals and their lack of dolomitic ghosts or inclusions.
Figure 6-41: Cathodoluminescence microscopy of dissolution and microporosity surrounding clay clasts in chaotic facies A) PPL image from Roberts Trust well at 10,748.00 ft. Note the dissolution and microporosity associated with the clay clasts. There is a pervasive sucrosic dolomite network. B) CL image from Roberts Trust well at 10,748.00 ft. Detrital quartz grains are easily identifiable by their blue luminescence in CL. Dolomite overgrowths have developed subhedral to euhedral crystals. These dolomite overgrowths (yellow arrow) display thin to thick zones of varying luminescence indicating change in pore water conditions during diagenesis. There are inclusion rich cores (green arrow) with thin orange luminescent overgrowths that are inclusion free indicating late replacement dolomitization. Note the dolomite rhombs found within the clay clasts that demonstrate dissolution and microporosity, indicating that dolomitization may have occurred following dissolution of the clay clasts.
Figure 6-42: Photomicrographs demonstrating dissolution associated with secondary replacement pyrite swaths, as well as, pore-filling anhydrite and dolomite following this dissolution; from the interbedded claystone and dolostone facies. A) PPL image from Danks well at 10,690.00 ft. This image depicts dissolution associated with the precipitation of pyrite. It is interpreted that during the second stage of pyrite precipitation, which locally replaces dolomite, there is local dissolution. During the precipitation of pyrite there is the associated precipitation of sulfuric acid which has caused the dissolution of the surrounding dolomite creating local microporosity. Following this pyrite precipitation and dissolution there is the precipitation of pore-filling anhydrite which is seen in contact with the pyrite nodules, as well as, pore-filling dolomite cement. These relationships verify that there were multiple stages of pyrite and anhydrite precipitation in the upper Three Forks, and that the process of dolomitization continued following these diagenetic events and through the complete diagenesis of the upper Three Forks. B) XPL image from Danks well at 10,690.00 ft. Cross polarized view of image A. Dolomite (green arrow) cement and anhydrite (orange arrow) cement surrounding pyrite nodules can be differentiated by birefringence. The red color represents microporosity created by dissolution associated with the precipitation of pyrite.
Figure 6-43: Schematic of the paragenetic sequence of the upper Three Forks formation in Fort Berthold Reservation.
Figure 6-44: Cathodoluminescence microscopy of the chaotic facies A) Cross polarized light (XPL) image from Danks well at 10,690.00 ft. Secondary replacive pyrite nodules and associated dissolution in dolostone of chaotic facies. Note vug filling anhydrite which surrounds pyrite nodules. There is dolomite cement seen associated with this vug filling anhydrite (orange arrow). B) CL image from Danks well at 10,690.00 ft. Dolomite rhombs can be observed within pyrite nodules in CL and display bright orange to yellow luminescence. The vug filling anhydrite is non-luminescent but also displays dolomite rhombs of less than 10 µm, which indicates that anhydrite may have also occurred as a replacement phase following the precipitation of pyrite. The dolomite cement that is seen associated with anhydrite is non-luminescent indicating reduced pore waters during its precipitation. Minimal dolomite is observed in the claystone due to a lack of pore space for the development of dolomite rhombs. CL allows for observation of dolomite rhombs in the area of heavy dissolution. Core nuclei of these rhombs are dull in luminescence; their cortical overgrowths demonstrate a bright yellow to orange luminescence indicating a change in pore water redox conditions during burial.
Figure 6-45: Cathodoluminescence microscopy of secondary replacive pyrite and associated dissolution in chaotic facies A) XPL image from Roberts Trust well at 10,748.00 ft. Note abundant replacement pyrite nodules and associated dissolution and microporosity. There is pore filling anhydrite cement surrounding the pyrite nodules. B) CL image from Roberts Trust well at 10,748.00 ft. Detrital quartz grains are easily identifiable by their blue luminescence in CL. Note the abundance of dolomite inclusions within the pyrite nodules that are visible under CL indicating this pyrite replaces dolomite. The pore filling anhydrite is non-luminescent and displays bright yellow luminescent dolomite rhombs. The dolomite rhombs associated with these pyrite and dissolution are bright yellow in luminescence indicating high Mn$^{2+}$ content during precipitation.
CHAPTER 7 SCANNING ELECTRON MICP TESTING

This chapter uses two methods to classify pore size in the facies of the upper Three Forks: Scanning Electron Microscopy (SEM) and Mercury Injection Capillary Pressure Testing. It is recommended the reader views Appendix E: Scanning Electron Microscopy Images. Appendix E contains additional SEM images that classify the crystalline framework and porosity of the facies in the upper Three Forks. All figures for this chapter can be found following the text. They are displayed in numerical order beginning on page 224.

7.1 SEM analysis of facies in the Upper Three Forks

SEM analysis was conducted to classify the crystalline framework and porosity throughout the facies of the upper Three Forks.

7.1.1 Dolomitic claystone

The dolomitic claystone facies has a fine clay particle framework with individual clay platelets from less than 1 µm to 5 µm in diameter. There are elongate and bladed illite crystals observed, but the dominant morphology of the clay particles are sub rounded plates (Figure 7-1). There are rare to moderate dolomite rhombohedrons present that are dominantly 10 µm in diameter (Figure 7-1).

Pore space between clay grains are sub-rounded to rounded and from less than 0.25 µm in diameter on average but can reach up to 5 µm (Figure 7-2). Pore space between clay grains and dolomite rhombs is angular and elongate ranging from 2 µm to 7 µm in length and 1 µm in width (Figure 7-1). Rare dissolution vugs occur and are up to 10 µm across (Figure 7-3).

7.1.2 Brecciated

The brecciated facies displays a coarse crystalline framework in the sandy dolostone clasts and a fine clay framework in the matrix claystone (Figure 7-4). The claystone is composed of illite and chlorite clay platelets with moderate dolomite rhombohedrons present. The sandy dolostone clasts are composed of dolomite crystals and
quartz. These clasts display pervasive cementation with rhombohedrons ranging from 25 µm to 50 µm in diameter (Figure 7-5). At the boundaries between dolostone clasts and claystone matrix the clay content of the dolostone clast is increased and there is less pervasive dolomite cementation.

The pore network in the claystone matrix displays rare to moderate sub rounded to elongate pores between clay platelets and blades. These pores range from less than .25 µm to 1 µm in diameter (Figure 7-6).

The pore network in the dolostone clasts consists of rare slot and intercrystalline porosity between dolomite rhombohedrons. Pervasive dolomite cementation has occluded a majority of the pore space. Slot pores are elongate, typically less than 1 µm in width and up to 7 µm in length. Intercrystalline pores are angular and range from less than 1 µm to over 10 µm in size (Figure 7-7). Porosity in the dolostone clasts becomes more common the closer in proximity to claystone matrix, as the clays coat the dolomite rhombs and prevent cementation.

7.1.3 Tan dolostone

The Tan dolostone facies has a coarse sucrosic dolomite crystalline framework and displays pervasive dolomite cementation. Dolomite rhombohedrons range from less than 20 µm to slightly larger than 50 µm in diameter (Figure 7-8). Detrital quartz grains are well rounded and up to 50 µm in size. Dolomite cement is abundant and occludes nearly all pore space in this facies. Laterally linked partial overgrowths can be observed with near perfectly plane crystal facies (Figure 7-9).

Porosity is very rare in this facies due to the coarse sucrosic dolomite network and pervasive dolomite cementation. When present, porosity is observed as intercrystalline and slot porosity. These pores are elongate to angular and less than 1 µm in size.

7.1.4 Interbedded claystone and dolostone

The interbedded claystone and dolostone facies displays a well preserved crystalline framework of sucrosic dolomite in the silty dolostone, and a fine-grained clay particle framework in the claystone beds (Figure 7-10). The silty dolostone is composed of sucrosic
dolomite, detrital quartz grains, and rare to moderate clay platelets. The silty dolostone of this facies displays moderate dolomite cementation. Dolomite rhombohedrons within the silty dolostone are from 10 µm to 25 µm in diameter (Figure 7-11). Compound zoned dolomite cements occur filling vugs in the silty dolostone (Figure 7-12). These vugs are over 70 µm in diameter. The compound zoned cements display coarse euhedral dolomite crystals with nearly perfect crystal faces and reach over 30 µm in size. The claystone is composed of illite and chlorite plates and elongate blades. Clay platelets range from less than 1 µm up to 5 µm in diameter (Figure 7-13). The claystone beds of the interbedded claystone and dolostone facies display common microfractures (Figure 7-14). Microfractures can be seen connecting and are commonly over 5-10 µm in width and over 1000’s of µm in length.

The porosity in the silty dolostone ranges from moderate to common depending on clay content and cementation. Figure 7-15 shows common intercrystalline and slot porosity. Intercrystalline pores are angular and range from 1 µm to 8 µm in size. Slot pores are angular and found between dolomite rhombs with widths of less than 1 µm and lengths up to 10 µm.

Figure 7-16 shows moderate intercrystalline and slot porosity in the silty dolostone. The pore network in the claystone beds shows moderate inter-particle porosity. These pores are sub rounded and range from .5 µm to 2 µm in size (Figure 7-17). Microfractures play an intricate role in the pore network and storage capacity of this facies.

### 7.1.5 Chaotic

The chaotic facies displays a well preserved crystalline framework of sucrosic dolomite with moderate to common clay content in the silty dolostone (Figure 7-18). The claystone displays a fine clay platelets framework with rare dolomite grains. The silty dolostone is composed of sucrosic dolomite, detrital quartz grains, and rare to moderate clay platelets. There is rare to common dolomite cementation in the silty dolostone, based upon the clay content. Dolomite rhombs in the silty dolostone range from less than 10 µm to 25 µm in size (Figure 7-19). A secondary replacement pyrite nodule, 100 µm in size, is observed within the silty dolostone (Figure 7-20). The claystone is composed of illite and
chlorite platelets and elongate blades. Clay plates range from less than 1 µm to 5 µm in size. Early replacement pyrite nodules of up to 10 µm in size occur in the claystone, and are associated with dissolution vugs (Figure 7-21). There are moderate to common microfractures observed in this facies. Microfractures are up to 10 µm in width with lengths of 1000’s of µm.

The pore network in the silty dolostone consists of moderate intercrystalline and slot porosity. Intercrystalline pores are angular and from less than 1 µm to 5 µm in size (Figure 7-22). Slot pores are elongate and less than 1 µm in width and lengths up to 10 µm (Figure 7-23). The pore network in the claystone consists of inter particle pores between clay plates. These pores range in size from less than .25 µm to 2 µm (Figure 7-24). Microfractures are also a critical part of the pore network and storage capacity of the storage facies (Figure 7-25).

7.1.6 Discussion

SEM reconnaissance indicates that the porosity is variable throughout the facies of the upper Three Forks based upon grain size and diagenetic processes. The scale of the pore networks in the facies of the upper Three Forks can be classified using a mudrock pore system. Loucks et al., 2012, developed a classification scheme for pores in mudrocks (Figure 7-26). This pore classification scheme will be used to define the pore network for each facies of the upper Three Forks.

The facies of the upper Three Forks each display characteristic pore sizes and shapes. The dolomitic claystone facies shows moderate sub-rounded inter-particle nanopores. The brecciated facies shows bimodal pore networks: the claystone shows rare to moderate sub rounded inter-particle nanopores, the sandy dolostone shows rare elongate to angular slot and intercrystalline micropores. The tan dolostone facies shows very rare elongate to angular slot and intercrystalline nanopores. The interbedded claystone and dolostone facies shows bimodal pore networks: the claystone shows moderate sub-rounded inter-particle nanopores and common microfractures. The silty dolostone shows moderate to common elongate to angular slot and intercrystalline micropores. The chaotic facies shows bimodal pore networks: the claystone shows moderate sub rounded inter-particle
nanopores and common microfractures. The silty dolostone shows moderate to common elongate to angular slot and intercrystalline micropores. Table 7-1 summarizes the pore classification and reservoir quality for each facies of the upper Three Forks.

It is interpreted that the interbedded claystone and dolostone and chaotic facies demonstrate the highest porosity and storage capacity based upon mineralogical balance between dolomite and clay content. As demonstrated previously in chapter 5.2.1 that the best porosity is found in rocks with the balance of dolomite and clay content. The relatively higher clay content of the silty dolostone in these facies prevents pervasive dolomite cementation. Whereas in the brecciated and tan dolostone facies, the lack of clay content allows for pervasive dolomite cementation which occludes pore space. The common microfractures observed in the interbedded claystone and dolostone and chaotic facies are also significant to the storage capacity of these facies as reservoir units.

In summation, the storage capacity of the upper Three Forks is composed of nanopores, micropores and a microfracture network. As discussed in the dissolution section, it is interpreted that much of this microporosity is the result of local dissolution associated with mineralization. The microfracture network is interpreted to be a result of regional tectonic activity associated with the Nesson and Antelope anticlines.

Table 7-1: Pore classification for each facies from SEM observation. Reservoir quality is included as the abundance and size of the pore network in each facies exhibits control on reservoir quality.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Pore network and Abundance</th>
<th>Pore size classification</th>
<th>Reservoir Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomitic claystone</td>
<td>Moderate sub rounded to rounded inter-particle pores Rare vugs</td>
<td>Inter-particle pores are less than 1 µm in size- Nano pore Vugs range from 3 µm- 10 µm- Micropore</td>
<td>There is moderate porosity observed in this facies, however the mineralogy and lack of fracture network results in this facies showing moderate reservoir quality</td>
</tr>
</tbody>
</table>

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Table 7-1 continued:

<table>
<thead>
<tr>
<th>Facies</th>
<th>Bimodal pore network</th>
<th>Claystone inter-particle pores are less than 1 µm in size- Nanopore</th>
<th>Sandy dolostone Clasts- slot and intercrystalline pores range from less than 1 µm up to 10 µm - Micropore</th>
<th>There is rare to moderate porosity observed in this facies. Due to diagenetic dolomite cementation in the dolostone clasts and lack of fracture network this facies shows poor reservoir quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brecciated</td>
<td>Claystones- moderate sub rounded to elongate inter-particle porosity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sandy dolostone Clasts- rare angular and elongate slot and intercrystalline porosity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tan dolostone</td>
<td>Very rare angular to elongate slot and intercrystalline porosity</td>
<td>When pores are observed they are typically less than 1 µm- Nanopore, with occasional 3 µm to 4 µm pores- Micropore</td>
<td></td>
<td>There is very rare porosity as well as pervasive diagenesis in this facies resulting in poor reservoir quality.</td>
</tr>
<tr>
<td>Interbedded claystone and dolostone</td>
<td>Bimodal pore network Claystones- moderate sub rounded inter-particle porosity Silty Dolostone- moderate to common elongate and angular slot and intercrystalline porosity Common microfractures are observed in this facies</td>
<td>Claystone inter-particle pores range from less than .5 µm to 2 µm- Nanopore to very small Micropore Silty dolostone slot pores are less than 1 µm wide and up to 10 µm in length, Intercrystalline pores are between 1 µm and 8 µm- Micropore</td>
<td>Moderate porosity in both lithologies of this facies, limited diagenetic dolomite cementation, and common microfracture network result in this facies having good reservoir quality.</td>
<td></td>
</tr>
<tr>
<td>Chaotic</td>
<td>Bimodal pore network Claystones- moderate sub rounded inter-particle porosity Silty Dolostone- moderate to common elongate and angular slot and intercrystalline porosity Common microfractures are observed in this facies</td>
<td>Claystone inter-particle pores range from less than .25 µm to 2 µm- Nanopore to very small Micropore Silty dolostone slot pores are less than 1 µm in width and up to 10 µm in length, Intercrystalline pores range from 1 µm to 5 µm in size- Micropore</td>
<td>Moderate porosity in both lithologies of this facies, limited diagenetic dolomite cementation, and common microfracture network result in this facies having good reservoir quality.</td>
<td></td>
</tr>
</tbody>
</table>

7.2 Mercury Injection Capillary Pressure testing

Mercury Injection Capillary Pressure (MICP) testing was done at PoroTechnology Lab located in Kingwood Texas. Ten total plugs were tested from three wells in the study area to acquire representative MICP data throughout the facies of the upper Three Forks formation (Table 3-4). This testing was done to acquire porosity and permeability measurements for each facies, as well as, determine pore size distribution.
7.2.1 Dolomitic claystone

The dolomitic claystone facies is represented by sample F from the Pumpkin well at 10,301.00 ft. Results from MICP on the suspension facies yielded average porosity of 4.90%, average permeability of 0.000079 md. The dolomitic claystone facies demonstrates a unimodal pore throat system. It is interpreted that this is a result of the lithologic homogeneity of the dolomitic claystone facies. The pore throat grouping in the dolomitic claystone facies is between 0.001 µm and 0.01 µm. This indicates that the dolomitic claystone facies is dominated by a nanopore system.

7.2.2 Brecciated

The brecciated facies is represented by three samples in attempt to represent the porosity and pore size distribution of both clast supported brecciation and matrix supported brecciation. These samples include two samples from the Henry Bad Gun: sample A at 10,625.15 ft and B at 10,623.20 ft, as well as, sample G from the Pumpkin at 10,297.10 ft. Results from MICP on the brecciated facies yielded average porosity of 5.55%, average permeability of 0.00365 md. The brecciated facies demonstrates a bimodal pore throat system. It is interpreted that this is a result of the lithologic heterogeneity. The smaller pore throat group is 0.01 µm and the larger group is 0.1 µm. This indicates that the brecciated facies is dominated by micro and nano pore systems.

7.2.3 Tan dolostone

The tan dolostone facies is represented by two samples: sample C from the Henry Bad Gun at 10,617.00 ft and sample H from the Pumpkin at 10,294.00 ft. Results from MICP on the tan dolostone facies yielded average porosity of 2.53%, and average permeability of 0.00178 md. The tan dolostone facies shows a unimodal pore throat system. This is interpreted to be a result of the homogeneous lithology of the tan dolostone facies. The pore throat system of the tan dolostone facies is grouped around 0.1 µm indicating the tan dolostone facies is dominated by micropore system.


7.2.4 Interbedded claystone and dolostone

The interbedded claystone and dolostone facies is represented by two samples: sample D from the Henry Bad Gun at 10,592.15 ft., and sample I from the Pumpkin at 10,267.00 ft. Results from MICP on the interbedded claystone and dolostone facies yielded average porosity of 8.83 %, average permeability of 0.00467 md. The interbedded claystone and dolostone facies displays bimodal pore throat system. It is interpreted that this is a result of the lithologic heterogeneity observed in this facies. The smaller group of pores is grouped around 0.01 µm in radius and the large group of pores is 0.1 µm in radius. This indicates that the interbedded claystone and dolostone facies is dominated by micro and nano pore systems.

7.2.5 Chaotic

The chaotic facies is represented by two samples: sample E from the Hognose at 10,416.20 ft., and samples J from the Pumpkin at 10,263.45 ft. Results from MICP on the chaotic facies yielded average porosity of 8.525%, average permeability of 0.00418 md. The Chaotic facies demonstrates a variable pore throat system based upon the amount of lithologic heterogeneity. In locations that are dominantly dolomite or claystone there is a unimodal pore throat system, where as in locations with lithologic heterogeneity there is a bimodal pore throat system. In the chaotic facies the smaller group of pore throats is grouped around .01 µm in radius and the larger group 0.1 µm in radius. Showing that the chaotic facies is dominated by micro and nano pore systems.

7.2.6 Pore throat radius distribution

MICP testing provided pore throat diameter analysis for each sample Table 7-2 demonstrates statistical analysis for the pore throat diameter of each facies.

Table 7-2: Summary table of the pore throat radius in µm for each facies from the upper Three Forks formation in this study. Represented in the statistical analysis are the minimum, quartile 1, median, quartile 3, and maximum pore throat diameter values.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Dolomitic claystone</th>
<th>Brecciated Tan dolostone</th>
<th>Interbedded claystone and dolostone</th>
<th>Chaotic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Table 7-2 continued:

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>0.0009 µm</th>
<th>0.0018 µm</th>
<th>0.0018 µm</th>
<th>0.0018 µm</th>
<th>0.0018 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartile 1</td>
<td>0.0175 µm</td>
<td>0.0138 µm</td>
<td>0.0017 µm</td>
<td>0.0177 µm</td>
<td>0.0176 µm</td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>0.1792 µm</td>
<td>0.1429 µm</td>
<td>0.1792 µm</td>
<td>0.1797 µm</td>
<td>0.1795 µm</td>
<td></td>
</tr>
<tr>
<td>Quartile 3</td>
<td>1.933 µm</td>
<td>1.554 µm</td>
<td>1.933 µm</td>
<td>1.933 µm</td>
<td>1.935 µm</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>19.52 µm</td>
<td>19.48 µm</td>
<td>19.52 µm</td>
<td>19.52 µm</td>
<td>19.52 µm</td>
<td>19.52 µm</td>
</tr>
</tbody>
</table>

This analysis demonstrates that pore throat size and distribution are relatively equal throughout the facies of the upper Three Forks, based on Figure 7-26 all pores in the facies of the upper Three Forks are micro and nano pores. The facies which demonstrate the best reservoir quality in thin section and SEM analysis share the similar pore throat radius as the facies that demonstrate the worst reservoir quality in thin section and SEM analysis. This indicates that pore throat size is not a primary control on reservoir quality, and that mineralogy, diagenesis, dissolution, and microfracture pathways are more dominant controls on reservoir quality than pore throat size.

7.2.7 Discussion

The MICP results demonstrate that pore throat size is consistent throughout the facies of the upper Three Forks and is dominated by micro and nanopores below the size of 40 µm (Table 7-2). These findings correlate with SEM reconnaissance of consistent pore throat size throughout the facies of the upper Three Forks. However, SEM analysis indicates that the abundance of pores and pore shape vary throughout the facies of the upper Three Forks. Table 7-3 demonstrates porosity and permeability values that coincide with the findings of the SEM analysis; that the abundance shape and connectivity of pores is variable throughout the facies of the upper Three Forks. Based upon MICP results the tan dolostone facies shows the lowest porosity and the chaotic and interbedded claystone and dolostone facies show the highest porosity.

The facies of the upper Three Forks display both unimodal and bimodal pore throat size systems. The style of pore throat system is interpreted to be a result of lithology. In
facies with homogeneous lithology such as the dolomitic claystone and tan dolostone facies there are unimodal pore throat systems. In facies with heterogeneous lithologies such as the brecciated, interbedded claystone and dolostone, and chaotic facies there are bimodal pore throat systems. This is interpreted to be related to the contrasting pore styles that develop in clay platelets versus dolomite rhombohedrons. This correlates to what has been observed through previous reconnaissance on the upper Three Forks formation. The higher quality reservoir rocks are the interbedded claystone and dolostone and chaotic facies which have high frequency lithologic variability and bimodal pore throat systems, as well as, the highest porosity and permeability values (Table 7-1, Table 7-3).

Table 7-3: Summary table of porosity and permeability acquired from MICP testing for each facies.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Dolomitic claystone</th>
<th>Brecciated</th>
<th>Tan dolostone</th>
<th>Interbedded claystone and dolostone</th>
<th>Chaotic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity (%)</td>
<td>4.90</td>
<td>5.55</td>
<td>2.53</td>
<td>8.83</td>
<td>8.53</td>
</tr>
<tr>
<td>Permeability (md)</td>
<td>0.000079</td>
<td>0.00365</td>
<td>0.00178</td>
<td>0.00467</td>
<td>0.00428</td>
</tr>
</tbody>
</table>
Figure 7-1: SEM image of dolomitic claystone facies from RT marker from Sample C Pumpkin well at 10,300.6 ft. Dolomite rhomb (green arrow) within the claystone lithology, as well as, inter (crystalline and or particle) porosity (orange arrows) ranging from less than .5 µm to 2 µm.
Figure 7-2: SEM image of dolomitic claystone facies from RT Marker from sample C Pumpkin 10,300.6 ft. The dominant mineralogy observed in the dolomitic claystone facies is illite and chlorite clays with varying dolomite content and trace quartz and mica. There is a moderate amount of inter (crystalline and or particle) porosity (orange arrows) in the dolomitic claystone facies with pores ranging from .5 µm to slightly greater than 1 µm. It is interpreted that the high clay content of the dolomitic claystone facies prevents cementation and preserves the parent pore network.
Figure 7-3: SEM image of dolomitic claystone facies from RT marker from Sample C Pumpkin well at 10,300.6 ft. Vug porosity possibly created by dissolution in RT Marker. A large vug 6 µm (green arrow) possibly caused by the dissolution of a dolomite rhomb. The typical inter-particle porosity (orange arrows) of the dolomitic claystone facies is also observed ranging from less than .5 µm to 1 µm.
Figure 7-4: SEM image of brecciated facies from Sample A Pumpkin well at 10,297.0 ft. Lithology boundary (orange dashed line) between claystones matrix and dolomitic clast. The claystone is significantly finer grained than the dolomitic clast which has crystals that can reach up to over 50 µm. There is rare intercrystalline and slot porosity (orange arrows) observed in the dolomitic clast, particularly in areas with greater clay content. There is also dissolution porosity observed (green arrow).
Figure 7-5: SEM image of brecciated facies from Sample B Henry Bad Gun well at 10,625.0 ft. Dolomitic clast from brecciated facies. It is seen that there is moderate clay content within this dolomitic clast, observed as the much smaller plates. This clast displays pervasive cementation of dolomite with both rhombic and laterally linked partial overgrowth cements which occlude most porosity. At this scale only rare slot porosity (orange arrows) of less than .5 µm can be seen between dolomite crystals.
Figure 7-6: SEM image of brecciated facies from Sample B Henry Bad Gun well at 10,625.0 ft. Pore network in brecciated claystone. Rare inter-particle porosity is observed in the claystone matrix of the brecciated facies. These pores (orange arrows) less than .5 μm to 2 μm and are elongate to sub rounded in shape.
Figure 7-7: SEM image of brecciated facies from Sample A Pumpkin well at 10,297.0 ft. Image of rare intercrystalline pore (orange arrow) observed in a dolomitic clast from the brecciated facies. This pore is one of the larger observed pores in the dolomitic clasts being over 2 µm. The pores in the dolomitic clasts and dolomitic sediments have an angular shape.
Figure 7-8: SEM image of tan dolostone facies from Sample D Henry Bad Gun well at 10,618.0 ft. Pervasive dolomite cementation occluding porosity in the tan dolostone facies. Dolomite rhombs that range from 20 µm to 50 µm or slightly larger and are connected by both rhombic and laterally linked partial overgrowth cements.
Figure 7-9: SEM image of tan dolostone facies from Sample D Henry Bad Gun well at 10,618.0 ft. Laterally linked partial overgrowths (orange arrows) demonstrating nearly perfect crystal facies, and occluding porosity between dolomite crystals in the Tan dolostone facies.
Figure 7-10: SEM image of interbedded claystone and dolostone facies from Sample I Roberts Trust well at 10,757.0 ft. Lithology boundary (orange dashed outline) between claystone and silty dolostone lithology from the interbedded claystone and dolostone facies. It is observed that the crystallinity of the dolostone is much coarser than the claystone. There are two microfractures (red arrow) found within the claystone, these fractures are interpreted to be significant to the storage capacity of the upper Three Forks. Multiple pyrite nodules (gold triangles) are seen in the claystone.
Figure 7-11: SEM image of interbedded claystone and dolostone facies from Sample O Roberts Trust well at 10,767.0 ft. Dolomite rhombs seen around 25 µm in size, and a pervasive dolomite cement network. Slot (orange arrow) and intercrystalline (green arrow) porosity observed in the silty dolostone of the interbedded claystone and dolostone facies, from less than .5 µm to 1 µm. Intercrystalline pores are angular and slot pores are elongate.
Figure 7-12: SEM image of interbedded claystone and dolostone facies from Sample O Roberts Trust well at 10,767.0 ft. Compound zoned (orange dashed outline) dolomite cement seen filling a 30 µm vug. The dolomite crystals in this cement are limpid with perfect crystal faces and limited inclusions. Competitive growth is demonstrated in the compound zoned cement.
Figure 7-13: SEM image of interbedded claystone and dolostone facies from Sample I Roberts Trust well at 10,757.0 ft. Inter-particle (orange arrow) porosity in claystone lithology of interbedded claystone and dolostone facies. These pores are on the scale of 1 µm in length and elongate in shape. In this image a three dimensional view of a clay plate is present demonstrating the plate like nature of illite (green arrow).
Figure 7-14: SEM image of interbedded claystone and dolostone facies from Sample H Pumpkin well at 10,276.8 ft. Multiple microfractures (red arrow) in claystone from interbedded claystone and dolostone facies. It is interpreted that microfractures are significant to the flow network and storage capacity of the upper Three Forks.
Figure 7-15: SEM image of interbedded claystone and dolostone facies from Sample H Pumpkin well at 10,276.8 ft. Intercrystalline (green arrow) and slot (orange arrow) porosity in silty dolostone from interbedded claystone and dolostone facies. It is interpreted that rhombic and laterally linked partial overgrowth cements have not completely occluded pore space due to the presence of clays in the dolostones of the interbedded claystone and dolostone facies. Intercrystalline pores are angular and from less than 1 µm to 5 µm. Slot pores are elongate and less than 1 µm in width.
Figure 7-16: SEM image of interbedded claystone and dolostone facies from Sample O Roberts Trust well at 10,767.0 ft. Rhombic and laterally linked overgrowth cement occlude a majority of pores space. Dolomite overgrowth cements are seen from 5 µm to 20 µm in size. Rare intercrystalline (green arrow) and slot (orange arrow) porosity are observed. Intercrystalline pores have an angular shape and slot pores are elongate.
Figure 7-17: SEM image of interbedded claystone and dolostone facies from Sample H Pumpkin well at 10,276.8 ft. Inter-particle (orange arrow) porosity in the claystone lithology from interbedded claystone and dolostone facies. These pores are on the scale of less than 1 µm in width and 6 µm in length and elongate in shape. There is a microfracture (red arrow) which is commonly associated with the claystone lithology in the interbedded claystone and dolostone facies.
Figure 7-18: SEM image of chaotic facies from Sample M Hognose well at 10,411.0 ft. Intercrystalline (green arrow) and slot (orange arrow) porosity observed in the chaotic facies. Intercrystalline pores have angular shape and slot pores are thin and elongate.
Figure 7-19: SEM image of chaotic facies from Sample L Pumpkin well at 10,284.0 ft. Intercrystalline (green arrow) and slot (orange arrow) porosity in the silty dolostone lithology of the chaotic facies. Intercrystalline pores have an angular shape and are on a scale of less than .5 µm to 2 µm. Slot pores are narrow and elongate and on a scale of less than 1 µm in width but up to 10 µm in length. It is interpreted that the clay content of the dolostone lithology in the chaotic facies prevents complete cementation of rhombic and laterally linked partial overgrowth dolomite cement and preserves pore space.
Figure 7-20: SEM image of chaotic facies from Sample L Pumpkin well at 10,284.0 ft. Large replacement pyrite nodule (gold triangle) in the silty dolostone lithology of the chaotic facies demonstrating dissolution (orange arrows) of the dolomite rhombs it has replaced. It is interpreted that second stage pyrite precipitation caused simultaneous local dissolution of dolomite in the upper Three Forks.
Figure 7-21: SEM image of chaotic facies from Sample M Hognose well at 10,411.0 ft. Solution vug from dissolution (orange dashed outline). It is interpreted that dissolution is highly significant in the fluid flow and porosity of the upper Three Forks. There are dolomite rhombs (blue arrow) observed in the claystone lithology from the chaotic facies. A pyrite nodule is observed (gold triangle) that reaches nearly 10 µm in size. Inter-particle (orange arrow) porosity is observed on a scale of 1 µm or less.
Figure 7-22: SEM image of chaotic facies from Sample M Hognose well at 10,411.0 ft. Intercrystalline (orange arrow) porosity seen in the silty dolostone lithology of the chaotic facies. These intercrystalline pores are angular in shape and from less than .5 µm to 2 µm in size. It is interpreted that the clay content of the dolostone lithology in the chaotic facies prevents complete cementation of rhombic and laterally linked partial overgrowth dolomite cement and preserves pore space.
Figure 7-23: SEM image of chaotic facies from Sample L Pumpkin well at 10,284.0 ft. High magnification image of slot pore in silty dolostone lithology of chaotic facies. This slot pore is narrow and elongate in shape, less than 1 μm in width and 5 μm in length. Clay plates can be seen surrounding and within this pore. It is interpreted that the clay content of the dolostone lithology in the chaotic facies prevents complete cementation of rhombic and laterally linked partial overgrowth dolomite cement and preserves pore space.
Figure 7-24: SEM image of chaotic facies from Sample M Hognose well at 10,411.0 ft. Inter-particle (orange arrow) porosity in claystone lithology from chaotic facies. Inter-particle pores in the claystone lithology are from less than .5 \( \mu \text{m} \) to 1 \( \mu \text{m} \).
Figure 7-25: SEM image of chaotic facies from Sample M Hognose well at 10,411.0 ft. Microfractures (red arrow) meet in chaotic facies, they range from less than 5 µm to over 10 µm in width. It is interpreted that microfractures are significant in fluid flow and storage capacity of the upper Three Forks. This microfracture displays mineralization leaving it partially closed.
Figure 7-26: Pore-size classification for mudrock pores. Classification is modified from the Choquette and Pray (1970) classification. New pore classes include a picopore defined as being less than 1 nm and a nanopore defined as being equal of greater than 1 nm and less than 1 µm. Rouquerol et al. (1994) pore-size classification is also presented because this classification has been suggested as a pore classification for mudrocks. The sizes of methane and water molecules are shown for reference. Loucks et al 2012.
Figure 7-27: Pore throat radius distribution graph of the dolomitic claystone facies from sample F in the Pumpkin well at 10,301 ft. This graph demonstrates that there is unimodal pore throat size in the dolomitic claystone facies.
Figure 7-28: Pore throat radius distribution graphs of the brecciated facies from samples A Henry Bad Gun at 10,625.15 ft, B Henry Bad Gun at 10,623.2 ft, and G Pumpkin at 10,297.1 ft. These distribution plots show that in sample A where the brecciated facies is composed of sandy dolostone clasts and dolomicrite matrix there is a larger grouping to the pore throat system. In samples B and G where there is green claystone matrix and sandy dolostone clasts there is a bimodal pore throat size distribution.
Figure 7-29: Pore throat radius distribution graphs of the tan dolostone facies from sample C Henry Bad Gun at 10,617 ft, and sample H Pumpkin at 10,294 ft. These graphs demonstrate that there is a unimodal pore throat distribution in the tan dolostone facies.
Figure 7-30: Pore throat radius distribution graphs for the interbedded claystone and dolostone facies from sample D Henry Bad Gun at 10,592.15 ft, and sample I Pumpkin at 10,267 ft. These graphs demonstrate that there is a bimodal pore throat radius distribution in the interbedded claystone and dolostone facies.
Figure 7-31: Pore throat radius distribution graph for the chaotic facies from sample E Hognose at 10,416.2 ft, and sample J Pumpkin at 10,263.5 ft. These graphs demonstrate that there can be a variation in the pore throat distribution curve of the chaotic facies based upon the mineralogical composition. Sample J demonstrates bimodal pore throat groups due to the higher dolomite content.
CHAPTER 8 CONCLUSIONS

Research on the upper Three Forks formation in Fort Berthold Reservation demonstrates many important factors about the reservoir quality of this formation and its controls. Perhaps one of the most significant takeaways from research on the upper Three Forks is the high frequency nature of local heterogeneity within this formation. This high frequency heterogeneity is a result of depositional shift and complex diagenesis. Due to this complexity, each field where the upper Three Forks is targeted as a reservoir will have unique and individual controls on reservoir quality.

Depositional Environment

- Though the Three Forks Formation is regionally extensive through the Williston Basin, there are large local heterogeneities based upon eustacy, tectonics, and storms.
- High frequency variations between eustacy, storm and tidal controls in the late Devonian cause lateral migration of depositional environment and create complex vertical facies stacking.
- There is a shift in the depositional environment and climatic conditions moving upward through the stratigraphy of the upper Three Forks.
- This depositional shift is an autogenic response to intrabasinal processes caused by the late Devonian-early Mississippian shift of the Williston Basin.
- Though regionally expansive, the complex relationship between eustacy, storm, and tidal influence create frequent local heterogeneities in the upper Three Forks.
- There are five facies in the upper Three Forks - dolomitic claystone, brecciated, Tan dolostone, interbedded claystone and dolostone, chaotic. These facies are represented in three facies associations
- The three facies associations within the upper Three Forks are A) shallow shelf marine, B) supratidal flat, C) storm dominated mixed flat. There is a depositional environment shift between facies associations B and C.

UV fluorescence
• Hydrocarbon saturation in the upper Three Forks is localized within matrix constituents based upon mineralogy and diagenesis
• Silty dolostones show moderate to good hydrocarbon saturation
• Claystones show very poor hydrocarbon saturation
• Clean sandy dolostones show diagenetic effects which prevent hydrocarbon saturation

Diagenesis and dolomitization

• All the facies of the upper Three Forks display internal heterogeneity and variation of textural relationships, based upon depositional texture or diagenetic fabrics
• Lithologic boundaries have contrast in mineralogy and pore sizes and shapes which are preferential conduits for fluid flow
• Regional and local dissolution occur more preferentially at lithology boundaries due to preferential fluid flow
• Facies with high order frequency in lithologic contrast experience greater dissolution and fluid rock interaction
• Dolomitization throughout the upper Three Forks is pervasive and representative of the complete burial process
• Sucrosic dolomite accounts for over 90% of the dolomite observed in the upper Three Forks, and demonstrates pervasive cementation in the Tan dolostone and brecciated facies which occludes pore space
• In facies with higher claystone content and lithologic heterogeneity, dolomite cementation is prevented and porosity is preserved
• Detrital dolomites are observed in the upper Three Forks
• Three types of dolomite cement are present: rhombic overgrowths, laterally linked partial overgrowths, and compound zoned dolomite cements
• Late ferroan dolomite cement occurs
• CL shows there were five changes in pore water redox conditions during dolomitization of the upper Three Forks
• Anhydrite is present in the upper Three Forks as both a syndepositional and a diagenetic feature
• Syndepositional anhydrite decreases in abundance vertically through section indicating a decrease in subaerial exposure.
• Pore filling anhydrites are observed associated with local dissolution
• Dissolution of evaporites occurs and is associated with regional unconformity fluids between the upper Three Forks and the lower Bakken shale
• There are two stages of pyrite observed in the upper Three Forks
• Early replacement pyrite is seen replacing clays and occurs in nodules of less than 10 µm, associated with early burial reducing conditions
• Secondary replacement pyrite is seen replacing dolostones and occurs in nodules from 100 µm to 1000 µm
• Secondary pyrite causes local dissolution of dolostones due to the associated sulfuric acid
• This local dissolution creates microporosity which is a crucial component of the storage capacity of the upper Three Forks
• Dissolution microporosity is recognized as the most prominent component of storage capacity in the upper Three Forks
• Two types of dissolution are recognized: regional and local
• Regional dissolution is associated with exposure fluid during the unconformity between the upper Three Forks and the lower Bakken shale, as well as, mixing of meteoric fluids during burial
• Regional dissolution is interpreted to be responsible for vugs found in the interbedded claystone and dolostone and chaotic facies of the upper Three Forks.
• Local dissolution occurs due to mineralization in the upper Three Forks- specifically the precipitation of secondary pyrite
• There is a relationship between regional and local dissolution: regional dissolution causes pore water chemical evolution by dissolving detrital clays, micas, and feldspars providing free ions to the pore water. These free elements
allow for mineralization during diagenesis. This mineralization causes local dissolution.

- Facies with high frequency lithologic variability are higher quality reservoirs.

Porosity and Storage capacity

- The upper Three Forks is dominated by microporosity and rarely displays pore spaces over 10 µm.
- Each facies displays variability in the size, shape, and connectivity of pores which controls the reservoir quality.
- Greater variability in pore size and shape creates better connectivity of pores, resulting in facies with higher frequency lithology contrasts having better reservoir quality.
- The dolomitic claystone facies shows moderate sub-rounded intercrystalline micropores with minimal connectivity.
- The brecciated and Tan dolostone facies show rare elongate to angular intercrystalline and slot microporosity with rare connectivity. These facies also demonstrate pervasive dolomite cementation.
- The interbedded claystone and dolostone and chaotic facies show moderate inter-particle, intercrystalline, and slot microporosity. These facies show limited to moderate dolomite cementation.
- Connectivity of pores is seen by dissolution and microfractures. Microfractures are commonly observed in the interbedded claystone and dolostone and chaotic facies.
- Pore throat radius is similar throughout the facies of the upper Three Forks, and is not a primary control on reservoir quality.

Reservoirs

- The highest quality reservoir units of the upper Three Forks are the interbedded claystone and dolostone and the chaotic facies. This is a result of their high frequency lithologic contrasts providing conduits for fluid flow allowing for
greater dissolution, and the higher clay content preventing pervasive dolomite cementation.

- Primary controls on reservoir quality in the upper Three Forks are: mineralogy (i.e. correct ratio of dolomite and clay), diagenesis and mineralization, dissolution (local and regional), and microfracture network.
CHAPTER 9 FUTURE WORK

There is potential for future work on the upper Three Forks in FBR. X-ray fluorescence testing to obtain a manganese (Mn$^{2+}$) curve to be compared to the CL reconnaissance of dolomite throughout the facies of the upper Three Forks. This Mn$^{2+}$ could then be compared to the UV photographs to interpret if Mn$^{2+}$ is contributing to any of the intensity of color in the UV fluorescence. Additional studies on the frequency of storm in the upper Three Forks would be beneficial for greater understanding of the depositional environment. Finally a core study on any fractures in the cores throughout FBR would be beneficial in understanding the hydrocarbon migration pathway throughout the facies of the upper Three Forks.
REFERENCES CITED


Christopher, J. E., 1961, Transitional Devonian-Mississippian formations of southern Saskatchewan: Saskatchewan Department of Mineral Resources Report 66, Regina, Saskatchewan, 103 p.


MacEachern, J.A., Pemberton, S.G., Bann, K.L., Gingras, M.K., 2009, Departures from the archetypal ichnofacies: Effective recognition of physico-chemical stresses in the rock


Mount, J. F., 1984, Mixing of Siliciclastic and Carbonate Sediments in Shallow Shelf Environments, Department of Geology, University of California.


Sandberg, C. A., Poole, F. G., Johnson, J. G, 1988, Upper Devonian of Western United States, Department of Geology, Oregon State University, Corvallis, Oregon, 38p.


Sonnenberg, S. A., and A. Pramudito, 2009, Petroleum geology of the giant Elm Coulee field,


APPENDIX A: CORE DESCRIPTIONS

This appendix contains detailed core descriptions for each well in this study. Each description contains information on: lithology, sedimentary structures, grain size, ichnofossils, facies, cementation, relative sea-level curve, relative tidal influence, and relative storm influence. The purpose of this appendix is to allow the reader to view the vertical stacking pattern and depositional controls of the Upper Three Forks across this study area. Additional core photographs of facies are included in this Appendix as well.

<table>
<thead>
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<th>LITHOLOGY</th>
<th>FACIES</th>
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<td>PINCH AND SWELL LAMINATION</td>
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<td>BRECCIATED</td>
<td>BALL AND PILLOW</td>
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<td>TAN DOLOSTONE</td>
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Figure A-1: Core description key for core logs to follow.
Figure A2: Detailed core log of the Henry Bad Gun well. This image represents the vertical stacking pattern of the upper Three Forks, as well as, relative sea level and storm and tide influence.
Figure A-3: Detailed core log of the Hognose well. This image represents the vertical stacking pattern of the upper Three Forks, as well as, relative sea level and storm and tide influence.
Figure A-4: Detailed core log of the Pumpkin well. This image represents the vertical stacking pattern of the upper Three Forks, as well as, relative sea level and storm and tide influence.
Figure A-5: Detailed core log of the Roberts Trust well. This image represents the vertical stacking pattern of the upper Three Forks, as well as, relative sea level and storm and tide influence.