PETROGRAPHY OF THE TUSCALOOSA AND PALUXY SANDSTONES, DELHI FIELD, LOUISIANA: INFLUENCES ON RESERVOIR QUALITY

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A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

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ABSTRACT

Delhi Field, located in northeastern Louisiana, is undergoing an immiscible CO₂-flood for tertiary hydrocarbon recovery. Phase one of CO₂ injection began in November of 2009, and six future phases of CO₂-flooding have been proposed. The field produces from the Cretaceous-aged Paluxy and Tuscaloosa sandstones. Well-log derived porosity measurements show little variation in porosity between the Tuscaloosa and Paluxy sandstones; however, these sandstones behave quite differently. The underlying Paluxy sandstone acts as a continuous blanket sand, while the Tuscaloosa sandstone is less predictable and more complex. Stratigraphic controls account for much of the observed variation; however, diagenetic features are also influencing reservoir quality. This study contributes fine-scale details about compositional, textural, and diagenetic features that have not previously been evaluated, to understand the controls on permeability variation and connectivity within the reservoir. Furthermore, CO₂-rock interaction and the potential to alter reservoir quality were evaluated. CO₂-rock reactions are of concern, as a number of CO₂ reacting minerals (plagioclase, calcite, rock fragments, and chlorite) were identified via petrographic thin section analysis.

Petrographic thin section analysis supports the previously proposed near-shore, deltaic environment of deposition. Prodelta, delta front, delta plain, and distributary channel facies were identified through core and micro-scale data. Common diagenetic features observed in petrographic thin sections were kaolinite, illite, chlorite, and carbonate precipitation, as well as partial dissolution and leaching of various types of rock fragments and feldspar grains. These diagenetic features have varying effects on porosity and permeability. In the Tuscaloosa sandstone, chlorite and illite clay more adversely affect permeability than a lesser amount of kaolinite, while Fe-dolomite significantly reduces permeability in a number of samples from the Paluxy sandstone. Textural features such as grain size, degree of sorting, and grain packing are also significant contributors to permeability variation.

Additionally, core samples were exposed to a CO₂ and brine solution to determine whether CO₂ exposure would alter reservoir quality. Experimental data suggest a possible increase in permeability in a sample from 3,273, which is attributed to micro-fracturing induced during experimentation rather than mineral dissolution or alteration.
Alternatively, FESEM observations suggest that if reservoir fluid is supersaturated with sodium and chlorine ions, NaCl crystals will precipitate in the presence of CO₂, leading to a slight reduction in permeability; however, no reduction in permeability has been experimentally measured. If reservoir fluid is not supersaturated, it remains unclear as to whether CO₂-rock reactions have the potential to alter reservoir quality.
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ACKNOWLEDGEMENTS

First, I would like to thank Dr. Tom Davis of the Reservoir Characterization Project (RCP) at the Colorado School of Mines. Without his support and encouragement this project would never have been accomplished. I would also like to thank all the RCP sponsors, in particular Marshall and Jane Crouch, for the financial support. I would like to acknowledge the other RCP students, in particular those in the Delhi Group, for all their collaborative efforts and sharing of knowledge. I would like to thank Dr. Sonnenberg and Dr. Aschoff for teaching me so much about the petrography of reservoir sandstones. Thanks goes to John Curtis for serving on this committee. I would also like to thank Denbury Resources Inc., for providing the data for such an interesting project. Many other people played a significant role in helping me accomplish this, and for that I am grateful. Mike Batzle, Najeeb Alharthy, John Skok, Ali in Petroleum Engineering, Al Sami, Mathew Dye, John Chandler, Matt Billingsley, Nick Daniele, and Rachel Vest Woolf have all helped me in one way or another. Finally, I would like to my family for being so supportive. A special thanks goes to my boys Clark and Dexter for making this experience that much more challenging. I now know that I can accomplish anything I set my mind to.
CHAPTER 1
INTRODUCTION

1.1 Purpose

It is estimated that the eastern Texas, Louisiana, and Mississippi region of the Gulf Coast has over 36 billion barrels of oil left in the ground of which a major portion is technically and economically recoverable using CO₂ flooding techniques (Advanced Resources International, Inc., 2006). Delhi Field is a prime target of these recovery practices, as an estimated 60 million bbl of oil are still recoverable. Furthermore, Delhi Field will serve as a site for carbon sequestration, which is sure to become a more widespread practice in the near future. This site has the potential to serve as a model for future immiscible CO₂ flooding, and CO₂ sequestration ventures.

Incremental hydrocarbon recovery is significantly aided by accurate reservoir characterization. This study details reservoir properties and diagenetic features. Given that diagenetic processes alter the composition and texture, as well as porosity and permeability of sediments, this study is of considerable value. At Delhi Field well-log derived porosity measurements show little variation in porosity between the Tuscaloosa and Paluxy sandstones; however, these sandstones behave quite differently. The underlying Paluxy sandstone acts as a continuous blanket sand, while the Tuscaloosa sandstone is less predictable and more complex. Stratigraphic controls account for much of the observed variation. Diagenetic features are also influencing reservoir quality, especially the unpredictable permeability. The causes of permeability variations must be carefully explored for optimal hydrocarbon recovery.

1.2 Location

Delhi Field is located in northeastern Louisiana, United States (Figure 1.1). The field is located within the boundaries of Richland, Madison, and Franklin Parishes near the Mississippi-Louisiana border (Figure 1.2). Field dimensions are roughly 12 by 2.5 miles. The RCP study area is approximately four square miles located on the western side of the field. The Jackson Dome, the source of CO₂ used in the flooding of Delhi Field, is located nearly 80 miles to the east.
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**Figure 1.2:** Map showing the location of Delhi Field (comprised of the Delhi, West Delhi, and Big Creek Fields), within Richmond, Madison, and Franklin parishes. The approximate location of RCP study area is indicated in yellow (modified from Silvis, 2011).

1.3 **Field Introduction**

Delhi Field was discovered by C.H. Murphy, Jr., and Sun Oil Company in December 1944. Various geophysical surveys, including gravity and seismic, were conducted from 1938-1944. The discovery of the Delhi Field is attributed to the integration of geophysical and geological data, as well as “rank wildcat drilling” (Hollingsworth, 1951; Powell, 1972).

The main reservoir is the Holt-Bryant zone, which is composed of the upper Cretaceous Tuscaloosa sandstone and the lower Cretaceous Paluxy sandstones (Powell, 1972). The two types of traps that characterize Delhi Field are the erosional unconformity and those formed by lenticular sand bodies in “deltaic wedges” (Bloomer, 1946). The Tuscaloosa unit in Delhi Field is interpreted as the basal Tuscaloosa, while the other two Tuscaloosa units typically seen in the Gulf region are absent (Powell, 1972). The Tuscaloosa sands are described as marine sands; however, Bloomer (1946) suggested that some of Tuscaloosa sands in Delhi Field look fluvial. Bloomer (1946)
also noted that the absence of units (due to discontinuity) complicates the interpretation process, as lithological and paleontological data present in some areas are absent in others.

The field was originally described as having a relatively simple stratigraphy, and was thought to consist of layered blanket sands. It is now understood that the stratigraphy is quite complex. The issue of compartmentalization will continue to complicate our understanding of fluid flow within the field.

The field has produced 192 million barrels (54%) of an estimated 357 million barrels original oil in place via primary depletion and secondary water-flooding (Figure 1.3). It has been suggested that 225 to 250 bbls of oil and 135 billion cu ft of gas are ultimately recoverable (Powell, 1972). Primary depletion occurred from 1942-1954 and resulted in 14% incremental recovery of OOIP. From 1954-1987, water-flooding resulted in the production of an additional 40% OOIP (Hardy et al., 1972). Recently, a pipeline was built to transport CO₂ from the Jackson Dome in Mississippi to Delhi Field, where a continuous immiscible CO₂ flood for tertiary oil recovery and CO₂ sequestration began in November, 2009.

The CO₂ flood is being conducted by Denbury Resources Inc., and has been separated into six preliminary phases of injection (Figure 1.4). Phase one of injection occurred in the Paluxy and Tusc 7 sandstones, with daily injection rates averaging 10 mmcf CO₂ per injection well. CO₂ breakthrough and oil production began in March, 2010 (Figure 1.5).

This petrographic study determines detailed information about the compositional, textural (grains sizes, grain shapes, degree of sorting), and diagenetic features (precipitation of clay, mineral dissolution and/or alteration) present in the reservoir, and how these features affect overall reservoir quality. In addition, this information contributes fine-scale data to the depositional environment and geologic model proposed by Silvis (2011). This is significant, as multiple depositional environments have been proposed during the history of Delhi Field. Furthermore, this study offers information that can contribute to the accuracy of current and future geologic and reservoir models of the field. More accurate models lead to better prediction of fluid flow paths, and ultimately enhance hydrocarbon recovery.
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1.4 **Data Available**

The RCP (Reservoir Characterization Project), a research consortium in the Department of Geophysics at the Colorado School of Mines, is currently conducting research within Delhi Field, Louisiana. The RCP area is a four square mile area located in the western part of Delhi Field. There are six proposed phases of CO$_2$ flooding. The first CO$_2$ flood (phase one) is currently underway, and is located within the RCP area (Figures 1.4-1.6). The RCP study area contains 50 logged wells. The older wells have SP and resistivity logs, while nine newer wells have SP, resistivity, gamma ray, neutron, density, magnetic resonance image (MRIL), and X-Tended Range Micro Image (XRMI) logs. There is one cored well (159-2) within the designated RCP area, from which 120 ft of core was recovered and 58 petrographic thin sections were produced (Figure 1.6). Additional data includes 2008 3-D seismic data covering the RCP area, and 2010 3-D and 4-D time lapse seismic data.

1.5 **Research Objectives**

This study determines the detailed diagenetic history of the Tuscaloosa and Paluxy sandstones in Delhi Field, and how these features affect reservoir properties. Core-scale observations have determined a depositional environment, placed the field in a stratigraphic framework, and aided in the construction of a preliminary geologic model. This study contributes fine-scale details about compositional, textural, and diagenetic features that have not previously been evaluated (Figure 1.7). This is done with the objective of understanding controls on permeability variation, and connectivity within the reservoir.

In addition, the effect of continuous CO$_2$ exposure on reservoir quality is addressed, as feldspar, volcanic rock fragments, chlorite, and calcite are potential CO$_2$ reacting minerals that have been identified throughout the cored interval. CO$_2$ exposure can produce diagenetic alterations in sandstones which affect porosity and permeability. Understanding potential lithological changes due to CO$_2$ exposure will result in a more accurate geologic model, improved CO$_2$ flow prediction, and ultimately aid in enhanced hydrocarbon recovery.
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CHAPTER 2
BACKGROUND

2.1 Tectonic History

During the Paleozoic and early Mesozoic, continents were joined as a giant landmass known as Pangea. In the Late Triassic and Early Jurassic the North American plate began to drift from the South American and African plates. Concurrently, the area of the Gulf of Mexico Basin was part of an extensive landmass consisting of half grabens and bounded by listric normal faults. In the mid-Jurassic, the area was characterized by rifting, crustal thinning, and alternating basement highs and lows (Mancini et al., 2005; Salvador, 1987). A seafloor-spreading ridge formed as the Yucatan Peninsula drifted southward from the North American plate. Oceanic crustal cooling and subsequent subsidence led to the creation of accommodation space (Mancini et al., 1999b). Widespread salt deposits developed as a result of initial basin flooding in the mid-Jurassic. Eventually, the migration of the Louann salt would play a role in the formation of the Northern Louisiana and Mississippi Interior Salt Basins, important structural lows discussed in section 2.2. During the late Jurassic, marine conditions continued to extend over parts of the Gulf of Mexico Basin. However, the basin was not connected to the Atlantic Ocean until the late Jurassic (Mancini et al., 2005; Salvador, 1987). Subsidence continued into the Early Cretaceous, when a carbonate shelf margin platform developed (Mancini et al., 2005).

2.2 Structure

Figure 2.1 illustrates the prominent structural features in and around the Gulf of Mexico Basin. Figure 2.2 illustrates the proximity of Delhi Field to such features. The Sabine and Monroe Uplifts are positive basement features that influenced the distribution and nature of Mesozoic deposits, and are associated with crustal extensional and rifting (Mancini et al., 2005). The North Louisiana and Mississippi Interior Salt Basins are negative structural features associated with early rifting linked to wrench faulting. They
Figure 2.1: Generalized structure map of the Gulf of Mexico Basin. This map shows the location of the Gulf of Mexico Basin relative to various regional features. The most important features to note are the Sabine uplift (21), North Louisiana salt basin (22), Monroe uplift (23), Mississippi salt basin (26), and Jackson dome (27), as they are most relevant to the area of study (Silvis, 2011).

are extensional basins that experienced subsidence through the Mesozoic and Cenozoic (Mancini et al., 2005).

The Monroe Uplift is the most notable structural feature associated with Delhi Field, as it is the origin of the three to five degrees dip observed in the Holt-Bryan reservoir sediments. The Monroe Uplift has been defined as a “complexly truncated dome that blends into regional structure to the north and northwest” (Johnson, 1958). It is a subsurface structure that is defined largely on the basis of unconformities and stratigraphic pinch-outs of Jurassic through Upper Cretaceous rocks (Crone, 1998). Uplift and truncation first occurred in the area during the Permian. This was followed by
quiescence to form the evaporite basin in which the Luann Salt was deposited. During the Permian to the mid-Cretaceous, the area to the north of the uplift was a structural high, with a slight amount of associated growth. Subsequent uplift during the later part of the Mid-Cretaceous was responsible for the first growth of the Monroe Uplift. Additional erosion at the base of the Monroe Gas rock eliminated Gulf Cretaceous beds over most of the uplift area, which allowed for the development of the Delhi Field trap (Johnson, 1958). Crone (1998) suggests that the uplift is associated with Late Cretaceous igneous activity, that uplifting ended in latest Cretaceous time, and that the feature was buried by Paleocene and younger sediments.

The Sabine Uplift is nearly 200 miles west of Delhi Field, and covers an area 90 miles long and 60 miles wide (Figure 2.2). This uplift is supported by a large rhombic area of basement fault blocks that originated as a mid-rift high during the Triassic rifting phase. Middle to Late Cretaceous Laramide foreland tectonics applied lateral compression from the southwest and formed a foreland fold pair (the Sabine Uplift and the North Louisiana Salt Basin). The uplift was reactivated through additional compression during the Paleocene-Eocene (Adams, 2009). Various gravity anomalies suggest that the high is a result of crustal uplift and shallowing of the Moho and/or upper crust- lower crust boundary. Kruger and Keller (1986) suggested that the uplift occurred as an isostatic or thermal response to cooling and regional subsidence of the crust, and interpreted the presence of Triassic horsts and grabens through gravity anomaly data. Kruger and Keller (1986) further hypothesized that the smaller-scale isolated anomalies in the southern Sabine Uplift area most likely result from igneous intrusion. This is in agreement with a number of previous interpretations, which suggest the Sabine and/or Monroe uplifts are of volcanic origin, caused by various degrees of igneous intrusion (Kidwell, 1965; Harrelson et al., 1992; Johnson et al., 2006).

The Jackson Dome is a buried volcano that consists of both extrusive and intrusive igneous rocks. Stratigraphic relationships suggested that doming of the structure began in the Jurassic, and was caused by plutonism. The doming continued through the mid-Cretaceous until several volcanic vents opened to the surface, causing explosive volcanism. Volcanism continued until the end of the Cretaceous, when the volcano was capped by an ancient reef rock (the Jackson gas rock) (Mancini et al., 1999).
**Figure 2.2:** Map showing the location of Delhi Field within the Gulf Coast region. Note the proximity of the field to the Northern Louisiana and Mississippi Interior Salt Basins, as well as the Monroe and Sabine Uplifts. Also indicated in the location of Jackson Dome (CO₂ source) (Mancini et al., 2008).

The Jackson Dome has produced a significant amount of natural gas and minor crude oil since the 1930's (Saunders and Harrelson, 1992). Vogt and Jung (2007) suggested that hot spot activity may be responsible for the Jackson Dome volcano, and illustrated how the predicted Bermuda hotspot crosses an area of known igneous activity in Mississippi 65 ma (Figure 2.3).

### 2.3 Stratigraphy

The stratigraphy of the Gulf Coast has been well documented as complex and exhibiting abundant lateral heterogeneity. Therefore, both the regional stratigraphy and local stratigraphy are discussed, as significant variability exists between the two.

#### 2.3.1 Regional Stratigraphy

The Smackover Limestone lies stratigraphically below the Paluxy and Tuscaloosa sandstones. The Upper Jurassic Smackover carbonates were deposited in the relatively
Figure 2.3: Map showing the predicted migration of the Bermuda hot spot in black circles, while areas of known volcanic eruptions are marked as white squares. Note the proximity of hot spot migration to known volcanic activity in Mississippi approximately 65 ma (Vogt and Jung, 2007).

shallow marine conditions of the newly formed Gulf basin. The Smackover is one of the most important source rocks in the Central Gulf Coast (Goldthwaite, 2001), and may be the source rock of hydrocarbon accumulations at Delhi Field; however, no study has conclusively identified it as such.

Fourteen T-R sequences in Upper Jurassic and Cretaceous strata of the Gulf coastal plain consisting of a transgressive and a regressive systems tract have been identified (Mancini et al., 2008). Goldthwaite (1991) proposed that the Paluxy sandstone was deposited during a major regression in the Lower Cretaceous time period. This regression was followed by another transgression and subsequent regression during the Upper Cretaceous time period. Later, regional uplift and erosion produced an angular unconformity over much of North Louisiana and marked the end of the Lower Cretaceous (Goldthwaite, 2001). In Louisiana and Southern Mississippi, the Tuscaloosa
is divided into three distinct units (Figure 2.4). The lower Tuscaloosa sandstone is interpreted as aggrading non-marine and coastal deposits, and the lower-middle Tuscaloosa units are interpreted as part of a backstepping facies tract of marine deposits. Both the lower and middle Tuscaloosa sands are interpreted as being deposited during marine transgression. The middle-upper Tuscaloosa sandstones are interpreted as an infilling facies associated with marine to non-marine deposits (Mancini et al., 2008; Goldthwaite, 2001).

**Figure 2.4:** Map showing the three Tuscaloosa members in the Mississippi and Louisiana region. Only the lower and upper Tuscaloosa members are present in Delhi Field, and the middle shale member is absent (Silvis, 2011).

Figure 2.5 illustrates the stratigraphic context of Delhi with respect to the gulf region. With the exception of the Tuscaloosa and Paluxy sandstones, further details about the lithology of the regional formations and their proposed depositional environments are not addressed here. The stratigraphy of Northern Louisiana has been extensively detailed in previous works if a more comprehensive account is preferred (Berryhill et al., 1968; Goldthwaite, 1999; Goldthwaite, 2001; Mancini et al., 2008; Silvis, 2011).
<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Stage</th>
<th>Group</th>
<th>MS</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligocene</td>
<td>Rupelian</td>
<td>Jackson</td>
<td>Yazoo Clay</td>
<td>Moody Branch Formation</td>
<td>Cockfield Formation</td>
</tr>
<tr>
<td></td>
<td>Passianian</td>
<td>Bartonian</td>
<td>Cook Mountain Formation</td>
<td>Koscusko Sand</td>
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</tr>
<tr>
<td></td>
<td>Lutetian</td>
<td>Clabornian</td>
<td>Cane River</td>
<td>Zepha Shale</td>
<td>&quot;lower Lisbon&quot;</td>
</tr>
<tr>
<td></td>
<td>Ypresian</td>
<td>Wilcox</td>
<td>Wilcox</td>
<td>&quot;baffle Island&quot;</td>
<td>&quot;baffle Island&quot;</td>
</tr>
<tr>
<td>Paleocene</td>
<td>Eocene</td>
<td>Selkirk</td>
<td>Wilcox</td>
<td>&quot;baffle Island&quot;</td>
<td>&quot;baffle Island&quot;</td>
</tr>
<tr>
<td></td>
<td>Danian</td>
<td>Midway</td>
<td>Midway Undiff</td>
<td>Nashoba Formation</td>
<td>Nashoba Formation</td>
</tr>
<tr>
<td></td>
<td>Danian</td>
<td>Danian</td>
<td>Danian</td>
<td>Mesozoic Gas Rock</td>
<td>Clayton Chalk</td>
</tr>
</tbody>
</table>

**Figure 2.5:** Regional stratigraphic column. The formations present in Delhi Field are outlined in the red box, while the proposed source rock in outlined in blue (Silvis, 2011). The MS and AL in the formations section refer to Mississippi and Alabama respectively.

### 2.3.2 Local Stratigraphy

The stratigraphy of the Delhi Field and the RCP study area are individually discussed, as there is variability between the two. Copious lateral heterogeneity is observed throughout Delhi Field, resulting in discontinuity and compartmentalization. Therefore, areas within the field may have similar or varying stratigraphy. The red box in Figure 2.5 outlines the stratigraphic units present in Delhi Field. The lowest
stratigraphic formation drilled at Delhi Field is the Glenn Rose Group, which forms a reservoir in various parts of the field. Overlying the Glenn Rose Group is the Paluxy sandstone. Three distinct Paluxy units have been identified and are present in various combinations throughout the field. The lowermost Paluxy unit is the basal Holt sandstone which ranges in thickness from 30 to 60 ft. The middle Paluxy unit is the Murphy sandstone, and the uppermost Paluxy unit goes unnamed. The Tuscaloosa unconformably overlies the Paluxy, and consists of two main units within Delhi Field. The upper marine member of the Tuscaloosa is divided into six distinct units, which are referred to as the Tuse 1, Tuse 3, Tuse 5, Tuse 7, Tuse 8, and Tuse 9, and are present in various combinations and thicknesses. Numerous groupings of these Paluxy and Tuscaloosa sandstones compose the Holt Bryant reservoir (the producing reservoir of Delhi Field). Following deposition of the Tuscaloosa sandstone, significant uplift and erosion occurred, resulting in the angular unconformity that forms the hydrocarbon trap. The reservoir seal consists of 10 ft of Clayton Chalk, and 500 ft of the unconformably overlying Midway shale, both of which are continuous throughout the field. The Monroe Gas Rock underlies the Clayton Chalk in areas of the field, but is an ineffective reservoir seal due to discontinuity.

Within the RCP study area, the Holt Bryant reservoir is limited to that which is formed between the Tuscaloosa and Paluxy contact. Figure 2.6 is a generalized cross section showing the units of the Holt-Bryant reservoir present in the Delhi Field study area, while Figure 2.7 is a stratigraphic column offering a more detailed look at these units. The Glenn Rose Group is not present; therefore, the lowest reservoir sand in the study area is the Paluxy. Approximately 30 ft of the basal Holt Paluxy sandstone is the only Paluxy unit present; however, all six Tuscaloosa sandstone units are present in the study area. Five to ten feet of the Monroe Gas Rock continuously tops the Tuscaloosa in the study area. The Monroe Gas Rock is overlain by both the Clayton Chalk and Midway Shale.
Figure 2.6: Northwest to Southeast generalized cross section through the study area. The actual dip is roughly five degrees SE for the Paluxy and three degrees SE for the Tuscaloosa. The blue box outlines the units of Holt-Bryant reservoir present in the study area. It is important to note the simple “blanket sand” nature of the units depicted in this diagram is unrealistic, as lateral heterogeneity is complicated in this zone (Silvis, 2011).
Figure 2.7: Stratigraphic column depicting the units present in the RCP study area of Delhi Field. Note that the Paluxy is the basal reservoir unit and the reservoir is sealed by the Monroe Gas Rock, Clayton Chalk, and Midway shale. These features are unique to the study area and are not representative of the entire Delhi Field (Silvis, 2011).
2.4 Petrography

The Tuscaloosa and Paluxy sandstones have been extensively detailed in different fields; however, detailed petrographic studies have not been conducted within Delhi Field. Previous work suggests that the diagenetic history of the Tuscaloosa sandstone is quite complex. The precipitation of authigenic chlorite, quartz overgrowths, and carbonate cements, as well as the dissolution of carbonate cements and framework grains are some of the more common diagenetic features observed in the Tuscaloosa Sandstone throughout the Gulf Coast (Hansley, 1996; Hearne and Lock, 1985; Klicman et al., 1988; Weedman et al., 1996). Klicman et al. (1988) noted that the majority of the porosity in the Tuscaloosa Sandstone is secondary porosity due to the dissolution of carbonates and framework grains. Alternatively, Hansley (1996) suggested that the majority of the porosity in the Tuscaloosa is primary porosity preserved at depth by the formation of chlorite rims and quartz overgrowths, while secondary porosity due to the dissolution of carbonates plays only a minor role. Secondary porosity due to dissolution of labile grains is observed in the Tuscaloosa sandstone at Delhi Field; however, it accounts for only a minor amount of total porosity. The majority of porosity appears to be primary in origin. It is most likely primary porosity that has been preserved due to minimal burial and compaction rather than the formation of early clay rims or quartz overgrowths.

Although some similarities exist between the diagenetic features observed in the Tuscaloosa sandstone at Delhi Field and other fields in the region, the type and degree of these features are limited at Delhi Field due to relatively shallow burial depth.
CHAPTER 3
PETROGRAPHIC THIN SECTION ANALYSIS

3.1 Methods

All of the rock observed in this petrographic study was taken from the cored well 159-2. The bulk of this analysis was through observation of petrographic thin sections. At the request of Denbury Resources, thirty-three petrographic thin sections were produced by Lise Brinton of Lithologic Inc. Twenty-five additional thin sections were produced by John Skok, SEM and thin section lab coordinator at the Colorado School of Mines.

Standard thin section making methods were followed (Barber, 1981). All petrographic thin sections were stained with alizarin red S and sodium cobaltinitrite. Alizarin red S stains calcite red and allows for rapid identification of calcite, which is often difficult to distinguish from other carbonate minerals in petrographic thin section (Friedman, 1959). Sodium colbaltinitrite stains potassium feldspar yellow, thereby making potassium feldspar, quartz, and untwinned plagioclase more readily distinguishable (Chayes, 1952; Gabriel and Cox, 1929). Finally, all thin sections were impregnated with a blue stained epoxy which allowed for the rapid identification of pore systems.

Analysis was conducted using a Leica EC3 petrographic microscope and camera. Compositional and textural features were quantified using point counting methods. For most applications at least 300 points must be counted per thin section to ensure an acceptable level of precision (Houseknecht, 1987; Krumbein and Pettijohn, 1938). Therefore, all 58 petrographic thin sections were point counted using four hundred count point counts for modal analysis.

The two primary methods of point counting are the Indiana (traditional) method and the Gazzi–Dickinson method (Weltje, 2002). The primary difference between the two methods lies in the classification of phaneritic polymineralic grains. The traditional method separates grains into quartz, feldspar, and rock fragment percentages. Rock fragments are defined as a grain consisting of two or more crystals, where no crystal may
occupy more than 90% of the total grain, and both crystals must be larger than 0.0625 mm. The Gazzi-Dickinson method separates grains into quartz, feldspar, and lithic fragments, where only aphanitic crystals are classified as lithics. Using the Gazzi-Dickinson method monomineralic crystals that form part of a larger polyminerhalic grain are classified as a monomineralic grain rather than a lithic or rock fragment (Dickinson and Suczek, 1979; Folk, 1974, Weltje, 2002). The Folk classification scheme, based on the Indiana or traditional school of petrography, was used for the point counting portion of this study.

There were rare instances in which the crosshairs of the microscope landed exactly on the boundary between two different points. In these cases, the point directly to the left of the boundary was counted.

Feldspar grains were classified as plagioclase, potassium feldspar, or undetermined feldspar grains. An example of an undetermined feldspar grain is one that has no staining, or twin, but may be partially leached with a typical feldspar shape. Carbonates were categorized as calcite, dolomite, siderite, or an unidentifiable form of carbonate. Rock fragments were categorized as sedimentary, igneous, metamorphic, or of undetermined origin. In a number of cases, rock fragments of undetermined origin were described and illustrated in great detail, and later categorized as sedimentary, igneous, or metamorphic. Clays were identified as kaolinite, chlorite, illite, mixed layer, or undetermined type of clay. XRD data was acquired from a number of samples, and confirms the presence of these four types of clay.

Textural analysis included grain size measurements, degree of grain sorting, type of grain contacts, and grain shapes. Quantitative textural analysis commonly involves measurement of 100 grains so that mean grain size and sorting can be calculated (Houseknecht, 1987). Grain size measurements were performed by first calibrating the microscope. In this case the diameter of the field of view of the microscope was measured at 20X using a micrometer. Appropriate grid spacing was established so that the entire thin section was covered, and one hundred grains were measured in each sample. Only measurements of framework grains were recorded. All authigenic phases were skipped when landed on, and the count simply proceeded to the next framework grain. Measurements of the apparent long axis were recorded for grains that were more
elongate in shape since thin section measurements will generally underestimate true grain size (Smith, 1966) (Figure 3.1). An average grain size was determined, and each sample was classified using the Udden-Wentworth grain size scale (Wentworth, 1922).

Degree of sorting was determined by converting grain size measurements to phi scale measurements using the following equation:

\[ \Phi = - \log_{2}d \], where \( d \) is grain size in mm (Krumbein and Sloss, 1963)

Phi values were then related to sorting based on the parameters listed in Table 3.1.

Core-scale observations were made by Terry Eschner of Sarlan Resources Inc., and Silvis (2011). Sedimentary structures, composition, and grain sizes were noted. In addition, a Schlumberger cluster analysis resolving log-derived facies, was generated by Silvis (2011). The Schlumberger facies model was created using various geophysical well-logs. The core description, photographs, and Schlumberger cluster facies were used as supplemental data. In the following sections, micro-scale observations are repeatedly compared to both the core-scale and geophysically-derived facies models.

3.2 Provenance

Point-counted data were plotted using Folk diagrams for rock classification, and Dickinson diagrams for provenance information (Folk, 1974, Dickinson & Suczek, 1979, Dickinson et al., 1983). Analyzing data that were acquired using Folk’s methods on Dickinson plots may seem questionable. However, valuable results are still yielded since the vast majority of lithics in these samples were very quartz-rich. If the Gazzi-Dickinson method had been used for point counting, the percentage of rock fragments would most certainly be lowered, while the percentage of quartz would increase. If quartz percentages were increased and lithic percentages decreased, samples would still fall into the recycled orogen category on the ternary diagrams (Figure 3.2). Using the Dickinson method would not have significantly affected feldspar percentages, as virtually all samples were depleted in monocrystalline feldspar grains as well as feldspar-rich polymineralic grains.

The point-counted results are plotted on Dickinson diagrams in Figures 3.2 and 3.3. Complete point counting results exist as an archival file with the Reservoir
Figure 3.1: Illustration of grain size measurements taken along the more elongate grain axis.

<table>
<thead>
<tr>
<th>phi (φ) Size Range</th>
<th>Verbal Description of Sorting</th>
</tr>
</thead>
<tbody>
<tr>
<td>under 0.35 phi</td>
<td>very well sorted</td>
</tr>
<tr>
<td>0.35 - 0.50 phi</td>
<td>well sorted</td>
</tr>
<tr>
<td>0.50 - 0.71 phi</td>
<td>moderately well sorted</td>
</tr>
<tr>
<td>0.71 - 1.0 phi</td>
<td>moderately sorted</td>
</tr>
<tr>
<td>1.0 - 2.0 phi</td>
<td>poorly sorted</td>
</tr>
<tr>
<td>2.0 - 4.0 phi</td>
<td>very poorly sorted</td>
</tr>
<tr>
<td>over 4.0 phi</td>
<td>extremely poorly sorted</td>
</tr>
</tbody>
</table>

Table 3.1: Table indicating the ranges in phi values used to categorize degree of sorting (Folk and Ward, 1957). All samples fell somewhere between moderately to very well sorted, further confirming the maturity of the sediments.
Figure 3.2: Dickinson diagram showing provenance. All samples plot in the recycled orogen provenance. The higher quartz content further indicates an increase in continental to oceanic components.

Characterization Project, Department of Geophysics, Colorado School of Mines. The results indicate that the sediment was derived from a recycled orogen provenance. More specifically, a foreland uplift provenance. Foreland fold-thrust belts form highlands from which sediment is shed directly into adjacent foreland basins, which also receive sediment from positive areas on the craton beyond. Sands are typically recycled from sedimentary successions within the fold-thrust belts (Dickinson and Suczek, 1979). For this reason, some quartzose sands from recycled orogen resemble sands from continental block provenances. If samples were counted using Dickinson methods, percent quartz would increase at the expense of percent lithic fragments. If quartz content were increased slightly, some of the samples would plot very close to, or even fall within, the
craton interior provenance. However, the vast majority of samples would continue to plot within the recycled orogen field. Since similarity between the craton interior and recycled orogen provenances is to be expected, it is concluded that these sediments were derived from a recycled orogen, most likely a foreland uplift provenance.

3.3 Composition, Grain Size, and Depositional Environment

All samples from the cored well were quartzarenites, sub-litharenites, or litharenites (Figures 3.3 and 3.4). Overall, samples contained abundant quartz and were depleted in feldspars. The facies identified using the Schlumberger cluster analysis more closely resemble the point-counted data. Gamma Ray, neutron, density, and PE well log curves were used to break out the cluster facies (Silvis, 2011). These logs respond to lithological changes. Core facies were based on sedimentary structures and grain size changes. Therefore, it is no surprise that the cluster facies more closely resemble the point counted data than the core-derived facies do.

This section describes the cored interval of well 159-2 at both the core and microscopic scale. The core-derived facies and depositional environment interpreted by Silvis (2011) (Figure 3.5), and the detailed core description done by Eschner (2010, personal communication) were compared to compositional and textural features observed in petrographic thin sections (Figure 3.6). Furthermore, common sequences of sedimentary structures, texture, and composition observed in reservoir sandstones of different origins, as defined by Berg (1970), were compared to the results acquired from point-counting methods (Figure 3.6). These data were integrated to identify facies and interpret a depositional environment. Results from thin section analysis are consistent with a near-shore environment that has both marine and continental influences. The majority of thin section observations confirm the core-derived facies interpreted by Silvis (2010); with minor modifications.

Silvis (2011) described the interval from 3,296-3,300.7 ft as structureless sandstone, and noted abundant bioturbation. Eschner (2010, personal communication) described vertical, horizontal, oblique, and planolites burrows throughout this interval, as well as carbonaceous debris. The type and abundance of trace fossils described by
Figure 3.3: Point counted results plotted on Folk diagrams (Folk, 1974). The data are color coded to the facies interpretation made by RCP geologist Nick Silvis (2011). The core-derived facies determined by Silvis (2011) are detailed in Figure 3.6.
Figure 3.4: The same point counted data as in figure 3.3; however, the data is now color coded to match the facies interpreted via Schlumberger cluster analysis.
Figure 3.5: Facies and facies associations were interpreted based on core-scale observations of sedimentary structures (Silvis, 2011). Based on micro-scale observations, minor adjustments to these facies associations are suggested.
Figure 3.6: Grain size changes and quartz composition observed in petrographic thin section are related to sedimentary structures observed at the core scale. Core-scale observations include sedimentary structures, and biological features (Eschner, 2010). On the right side of the figure, petrographic thin section and core-scale features are compared to common sequences of sedimentary structures, texture, and composition observed in reservoir sandstones of different origins (Berg, 1979).

Eschner (2010, personal communication) are consistent with the cruziana ichnofacies, which represent mid and distal continental shelf situations, below normal wave base, but which may be affected by storm activity (Benton and Harper, 1997). Silvis (2011)
interpreted this interval as a prodelta front, based on core-scale features. Petrographic thin section analysis identified silt to lower very fine-grained, angular to sub-rounded grains, as well as minor amounts of glauconite (Figure 3.7). Point-counted total quartz was approximately 30%. The limited grain sizes, the presence of glauconite, and the cruziana ichnofacies support the interpretation of this interval as a shelf deposit such as a prodelta.

![Photomicrograph showing the very fine grain size, moderate sorting, and sub-angularity to sub-roundness of quartz grains. Image is characterized by abundant rhombohedral dolomite and other permeability-reducing clay. Glauconite is observed in the upper-central part of the image.](image.jpg)

**Figure 3.7:** Photomicrograph showing the very fine grain size, moderate sorting, and sub-angularity to sub-roundness of quartz grains. Image is characterized by abundant rhombohedral dolomite and other permeability-reducing clay. Glauconite is observed in the upper-central part of the image.

Eschner (2010, personal communication) noted massive sandstones overlain by rippled and cross-beded sandstones in the interval from 3,280-3,295 ft. Silvis (2011) interpreted this interval as a delta plain. Petrographic thin section analysis determined a coarsening upward from very fine to fine-grained sandstone, followed by a fining upward to very fine-grained sediment. A plot of the vertical grain size changes for this interval
show a “blocky” outline, typical of barrier bar deposits (Figure 3.6). Point-counted quartz content remains at just over 50%. The relative increase in quartz content, the sand-sized grains, and the rippled and cross-bedded structures are consistent with an increase in wave or current influence, such as occurs in upper delta front or delta plain deposits. When this interval is analyzed concurrently with the underlying bioturbted silt interval, the entire section (3,280 -3,300 ft) is interpreted as a prograding delta front in which prodelta marine silts are topped by delta plain sands.

Eschner (2010, personal communication) noted cross-stratified, massive, and planar laminated sandstones overlain by heavily bioturbated muds from 3,269 to 3,280 ft. Additionally, Eschner (2010, personal communication) detailed vertical, horizontal, and planolites burrows consistent with the cruziana ichnofacies. Silvis (2011) interpreted this interval as a series of delta plain deposits. Petrographic thin section observations reveal a fining upward sequence with a corresponding decrease in quartz content from approximately 50% at the base to just over 20% at the top of this interval. The overall decrease in quartz composition and change in sedimentary structures are indicative of upward decrease in energy. This is further supported by the upward transition from sand-sized sediment to bioturbated very-fine grained sand and silt. When the interval from 3,269 to 3,295 ft is viewed collectively, it is indicative of marine transgression, during which delta front and/or delta plain sands were overlain by very fine-grained marine sands and silts. A small spike in grain size was noted near 3,270 ft, and marks the only significant outlier to the fining-upward trend. However, this sample remains consistent with transgressive marine deposition, as it is interpreted as a barrier bar between the underlying delta plain channels and overlying marine muds. It is important to note that only a small portion of the complete Paluxy sandstone is represented in the cored interval. While literature consistently describes the Paluxy sandstone as a regressive deposit, the marine transgression interpreted here is likely a small-scale transgressive pulse cause by localized changes in sea level or sediment supply. Therefore, the interpretation that this interval was deposited during transgression remains compatible with previous works concerning the Paluxy in a regional stratigraphic framework, as just a small portion of the Paluxy is represented here.
Eschner (2010, personal communication) noted clay clasts, plant fragments, and carbonaceous debris in the interval from 3,263 to 3,268 ft. Millimeter-scale clay clasts in this interval were further detailed through petrographic thin section analysis (Figure 3.8). From approximately 3,235 to 3,262 ft, Eschner (2010, personal communication) noted a series of cross-stratified and rippled sandstones with variable amounts mudstone intraclasts. Silvis (2011) interpreted the interval from 3,235 to 3,266 ft as a barrier bar facies based on core-scale sedimentary structures. Grain size measurements determined through petrographic thin section analysis show that the interval above the clast-rich base is characterized by a fining upward sequence from fine-grained to silt-sized sediment. Quartz content remains approximately 70% throughout the interval, and a charophyte fossil was identified in the thin section from 3,238.42 ft. The clay rip-up clasts and plant fragments at the base are better interpreted as channel lag. Quartz content, moderate sorting, abundant crossbedding, and the classic fining upward sequence overlying the lag deposits, further support the interpretation of this section as a distributary channel.

Eschner (2010, personal communication) described the interval from 3,210 to 3,234 ft as having a burrowed base (both vertical and horizontal burrows), overlain by thick packages of massive sandstones topped by low angle cross-stratified and rippled sandstones. Berg (1970) described the low angle stratification observed in the upper-part of a coastal barrier sequence as “bedding produced by wave action at the beach face”. Silvis (2011) interpreted this interval as a shoreface beach/barrier bar. Grain sizes measured in petrographic thin sections range from silt to very fine-grained sediment at the base, followed by a coarsening-upward to medium-grained sediment, and a subsequent fining-upward to very fine-grained sediment. Point-counted quartz content ranged from 20% at the base and rapidly increased to over 80% throughout the bulk of the interval. Samples were very well-sorted, well-rounded, and contained virtually no matrix (Figure 3.9). All compositional features, textural features, and sedimentary structures indicate sediment has undergone a significant amount of re-working, and is interpreted here as a barrier bar facies. The sequence observed from 3,210 to 3,234 ft nearly duplicates the idealized sequence of a coastal barrier described by Berg (1970, 1979).
Figure 3.8: a) Photomicrograph showing the large millimeter-scale clay clasts interpreted as channel lag in sample 3268 b) Core photograph of the clay clast interval c) Photomicrograph showing the roundness and well-sorting of quartz grains. In this area of the sample few contacts between framework grains are observed, rather clay occludes pore spaces and exists between framework grains.
Figure 3.9: Photomicrograph showing the well-sorted and well-rounded nature of the grains in a sample from the “barrier bar” facies. Abundant intergranular pore space and minor clay rims are observed. Many quartz grains have recycled quartz overgrowths.

Eschner (2010, personal communication) described the interval from the top of the core to approximately 3,210 ft, as cross-beded sandstone overlain by rippled sandstone, and topped by root traces. This sequence of sedimentary structures is typical of a fluvial channel, showing an upward decrease in energy (cross-stratified to rippled sandstones). The overlying root traces indicate sub-aerial exposure, which implies continental deposition. Petrographic thin section observations show a fining-upward sequence, from medium-grained to very fine-grained sandstone. Point-counted quartz content decreased upward from nearly 60% to 43% throughout the interval. Samples were moderately-well sorted, with an overall upward decrease in grain roundness (Figure 3.10). Compositional and textural features observed in petrographic thin sections suggest an upward decrease in energy throughout this interval. Additionally, charophytes (a fossilized non-marine algae) were identified, further supporting a distributary or fluvial channel facies. Again, similarities to the Berg (1970, 1979, and 1980) model are noted,
as the features in this section nearly duplicate the idealized sequence of a fluvial channel. This interval is interpreted here as a distributary or fluvial channel, suggesting that deposition of the uppermost Tuscaloosa sandstone is associated with delta progradation and/or marine regression.

![Photomicrograph showing the moderate sorting, and variability in grain shapes (angular to rounded) observed in samples from the “distributary channel” facies. This interval is characterized by abundant sedimentary rock fragments, which contribute to reduced permeability.](image)

**Figure 3.10:** Photomicrograph showing the moderate sorting, and variability in grain shapes (angular to rounded) observed in samples from the “distributary channel” facies. This interval is characterized by abundant sedimentary rock fragments, which contribute to reduced permeability.

### 3.4 Diagenetic Features

The most prominent diagenetic features observed throughout petrographic thin section analysis were partial dissolution of labile grains, and the precipitation of carbonates and various clays. The extent and type of diagenetic features varied stratigraphically throughout the cored interval.
3.4.1 Dissolution

At depths of 3,183-3,199 ft, partial dissolution of abundant sedimentary lithics contributes significantly to secondary and microporosity (Figure 3.11). Samples within this interval are very clay-rich due to deformation of sedimentary lithics, which creates abundant pseudo-matrix. Illite, kaolinite and chlorite were identified in petrographic thin sections as composing the clay-rich pseudo matrix. XRD analysis confirms the presence of these clays; albeit with slight variations in the total percentages. From 3,200 to 3,266 ft overall compositions become more quartz-rich, with fewer clays and sedimentary rock fragments. Theses igneous and low grade metamorphic rock fragments compose the bulk of the partially leached grains (Figures 3.12 and 3.13). At 3,267 ft, the transition into the Paluxy sandstone occurs. Partially leached feldspar grains account for a more significant amount of the secondary intragranular porosity within the Paluxy sandstone than in the Tuscaloosa (Figures 3.14 and 3.15). Partial dissolution of rock fragments further contribute to the secondary porosity in this lower-most interval.

![Figure 3.11: Photomicrograph showing the abundant microporosity within partially leached sedimentary rock fragments that is characteristic of the upper part of the core. Note the abundant blue-stained intergranular pore spaces, and how they are adversely affected by the increased sedimentary lithic content. The sedimentary rock fragments in this sample are highly deformed and have created a permeability-reducing pseudo-matrix.](image-url)
Figure 3.12: Photomicrograph showing intragranular secondary porosity within a partially leached rock fragment. Due to the altered nature, it is unclear if the rock is of igneous or metamorphic origin. Note the abundance of blue-stained intergranular pore spaces, which are being filled with various phases of authigenic carbonates. Calcite and dolomite were identified via petrographic microscope, while siderite was identified via XRD.
**Figure 3.13:** a) Photomicrograph of sample 3199 taken in plane polarized light. Intrargranular porosity within partially leached igneous rock fragments account for a significant amount of the secondary porosity. This image also shows calcite precipitated into intergranular pore spaces, and microporosity associated with clay-rich zones within a partially leached igneous or volcanic lithic. b) Image “a” shown in crossed polarized light. Altered igneous and metamorphic rock fragments are most abundant throughout the middle of the core (~3,210-3,255 ft).
Figure 3.14: Secondary porosity within partially leached feldspar grains accounts for a higher percentage of total secondary porosity in the Paluxy sandstone than in the Tuscaloosa. All photomicrographs were taken of sample 3267.33 in PPL. This is the depth at which transition from the Tuscaloosa into the Paluxy sandstone occurs. a) This photomicrograph shows intragranular porosity formed by the partial leaching of a plagioclase grain, as well as abundant intergranular porosity. The unidentified form of carbonate is most likely siderite. b) Secondary intragranular porosity due to partial leaching of a microcline grain c) Secondary intragranular porosity due to partial leaching of potassium feldspar.
Figure 3.15: Partially leached feldspars more frequently contribute to secondary porosity in the Paluxy sandstone than in the Tuscaloosa. Sodium cobaltinitrite imparted a yellow stain on the feldspar grains in this photomicrograph, identifying it as potassium feldspar. This photomicrograph illustrates the variability in porosity and permeability present on sample 3300.5. On the left side of the image, pore spaces are obstructed by illite clay. The right side of the image contains large intergranular pore spaces. Abundant rhombohedral dolomite contributes to permeability reduction.

3.4.2 Carbonates

From 3,194-3,208 ft, various episodes of carbonate precipitation were observed along with continued leaching of labile grains. Upon visual inspection, calcite and dolomite appeared to be the dominant carbonate minerals (Figure 3.16). However, XRD identified siderite as the only form of carbonate present at these depths. In the lowermost part of the core, dolomite was identified visually and via XRD (Figure 3.17). Point counting methods identified over 34% total carbonates at 3,300 ft. In contrast, XRD data taken nearby at 3,299.5 ft, suggest carbonates account for only 22% of the total composition. Visual inspection of the samples identified more than one carbonate suite from 3,296-3,300 ft. Less than half the total carbonates were visually identified as dolomite, while
Figure 3.16: a) Photomicrograph showing both calcite and dolomite phases. It is likely that calcite formed around the quartz grain, which led to local obstruction of pore space. This phase was likely followed by dolomite crystallization in the upper part of the slide. The dolomite is slightly darker in PPL than the calcite and small dolomite rhombs are observed in XPL. The dolomite further occluded porosity, but areas of microporosity associated with the dolomite are present. Finally, a second calcite phase occurred along the lower right rim of the original calcite cement. b) Figure 3.14a shown in crossed polarized light, allows for more rapid identification of multiple phases of carbonates.
Figure 3.17: Photomicrograph showing the rhombic nature of the dolomite in sample 3300.5, suggesting it originated as calcite that was later dolomitized. In the lower-most samples dolomite accounts for a significant percentage of the total composition. Permeability is significantly reduced in these samples, implying a correlation between dolomite content and permeability variation. XRD has identified this as Fe-dolomite. Alignment of heavy minerals, (in this image zircon) creates horizontal laminations.
the rest were classified as an unknown form of carbonate. XRD data identified Fe-dolomite as the only form of carbonate present in this interval.

3.4.3 Kaolinite

Kaolinite clay is the most abundant type of clay present throughout the core. On average, kaolinite accounts for approximately 10% of total composition. From 3,215-3,233 ft, kaolinite content decreases significantly to around 2% (Figure 3.18). At depths of 3,237-3,239 ft, point counting methods indicate an increase to 64% total clay (Figure 3.19). XRD analysis for this interval identified 64% total clay (31% kaolinite, 22% illite, 6% mixed –layer illite/smectite, and 5% chlorite). Leaching and alteration of feldspar grains is a source of the kaolinite in these samples; however, the alteration of muscovite to kaolinite is also observed (Figure 3.20).

Figure 3.18: Kaolinite “booklets” taken with FESEM. This image comes from sample 3231, which has an estimated kaolinite content of only 2%.
**Figure 3.19:** a) Well-developed kaolinite completely obstructing porosity and eliminating permeability in local areas. The image of sample 3239 was taken in plane polarized light. b) Figure 3.16a shown in crossed polarized light.
Figure 3.20: a) Photomicrograph taken in plane polarized light, shows a deformed muscovite grain that is undergoing kaolinitization. The kaolinite in the image illustrates a reduction in local porosity and permeability. However, muscovite alteration can also lead to increased porosity through dissolution, as is evident in the partially leached muscovite grain (left of center). b) Figure 3.18a shown in crossed polarized light.
3.4.4 Quartz Overgrowths

Quartz overgrowths are observed in a number of samples from the upper part of the core. In general, these overgrowths are rounded, indicating they have been recycled (Figures 3.21 and 3.22). Therefore, they are not technically a diagenetic feature of these sandstones. Rather, they are a product of recycled sediment source as is illustrated on the Dickinson diagram in Figure 3.2. In general, quartz overgrowths develop at temperatures of at least 150 degrees C, and 3,500 ft (Wilson and Stanton, 1994). These sandstones have been buried to much shallower depths than is necessary for quartz overgrowth development, which further supports the notion that they are of recycled origin.

![Quartz Overgrowth Image](image)

**Figure 3.21**: Quartz overgrowths with rounded edges are indicative of a recycled sediment source; therefore they are not technically a diagenetic feature of this sandstone. The depth of sediment burial, temperature of reservoir, and appearance of overgrowths, all suggest these quartz overgrowths have been recycled. This image also illustrates the large intergranular pore spaces that are characteristic of samples from this interval. A negligible amount of kaolinite clay exists in between framework grains, and is associated with minor amounts of microporosity.
Figure 3.22: Additional recycled quartz overgrowths, and authigenic clay rims characteristic of sample 3206.

3.4.5 Glauconite

Glauconite is present in the Paluxy sandstone, but was not identified in the Tuscaloosa interval. Glauconite develops in shallow marine environments, but may also develop in brackish waters. The presence of glauconite can help in the determination of a depositional environment, as it only develops under very specific conditions. Glauconite was indentified in very small quantities in sample 3268.5, and was more abundant in samples near 3,284 ft (Figure 3.23).

3.5 Porosity

Porosity was categorized as either intergranular, intragranular, microporosity, or a combination of two porosity types. Intergranular porosity refers to porosity in between grains. Intergranular porosity is usually primary porosity, which develops during
**Figure 3.23:** Photomicrograph showing glauconite identified in the Paluxy sandstone suggests a marine influenced environment of deposition.

sediment deposition. Intergranular pore spaces may also be the result of complete dissolution of minerals. It is often difficult to discern primary from secondary intergranular porosity when complete grain dissolution has occurred. Intragranular porosity develops post-depositionally; therefore, it is referred to as a secondary type of porosity. Chemical diagenesis leads to partial dissolution of minerals, which results in secondary pore spaces within partially leached grains. Microporosity refers to very small pore spaces (typically less than 1 micron) that commonly exist within clay-rich zones. Microporosity is often unobservable via petrographic microscope. Consequently, it is regularly underrepresented in the point counting process. The most common “combination-type” porosity detected was intragranular microporosity. This was commonly observed in samples where sedimentary lithic fragments had been altered into a partially leached pseudo-matrix. The porosity was intragranular in that it resulted from
partial dissolution of a rock fragment, while clay-like nature of the altered rock fragments resulted in micropores.

Primary porosity was the dominant porosity type. Samples with abundant intergranular porosity had minor amounts of microporosity in kaolinite patches, and very minor amounts of secondary porosity within partially leached rock fragments. Samples that contained abundant primary intergranular porosity exhibited the best permeability, and the highest quartz content.

Microporosity played a dominant role in a number of samples in the upper part of the core. The microporosity existed primarily within partially leached sedimentary rock fragments that had been altered into a clay-rich pseudo-matrix. Samples from a depth of 3,183-3,200 ft had the poorest permeability measurements, and plotted in the sub-litharenite to litharenite categories. Microporosity was also commonly observed within kaolinite patches throughout the entire cored interval.

Secondary intragranular porosity due to the partial dissolution of chert, feldspar, monocry stalline quartz, and igneous and metamorphic rock fragments, played only a minor role in the total porosity. In these instances the secondary pore spaces consisted of a significant portion of the partially leached grain, and were not micropores.

3.6 Permeability

Figure 3.24 shows the relationship between experimentally measured porosity and permeability. Samples with higher porosity measurements typically exhibit higher permeability; however, this is not always the case. Porosity and permeability data were derived through standard core testing. This section details the compositional and textural features contributing to permeability variations for a variety of samples that exhibit similar porosity, but varying permeability measurements. Samples are referred to by a sample number that coincides with the depth (in feet) from which the samples were taken.

Sample 3300.5 is plotted in green which represents “facies a” in Figure 3.5. This facies demonstrates consistently low permeability compared to other samples, despite having average percentages of total clay (kaolinite, illite, chlorite). Samples from this facies are circled in Figures 3.25 and 3.26 to emphasize the lower than expected
**Figure 3.24:** Plot showing the relationship between porosity and permeability. Samples with higher porosity measurements typically have higher permeability; however, that is not always the case. Porosity and permeability measurements were acquired through standard SCAL testing of core samples. Samples are color coded according to the core-derived facies determined by Silvis (2011).
**Figure 3.25:** Cross-plot showing a correlation between increased total clay content and reduced permeability. Consistent permeability reduction is observed in samples that have greater than approximately 15% total clay. Total clay includes kaolinite, chlorite, illite, and mixed-layer clays. Clay percentages were determined via point counting. The samples enclosed in the green circle consistently plot with lower than expected permeability for the amount of clay present. Permeability of these “outliers” is being influenced by a high percentage of Fe-dolomite.
Figure 3.26: Plot showing a relationship between increased illite composition and reduced permeability. In samples with less than 5% illite, there is no correlation to reduced permeability. However, samples with greater than 5% total illite display consistently low permeability measurements.
permeability for a given amount of total clay. Something other than the presence of these clays is restricting permeability. Petrographic thin section observations define this sample as a very fine-grained, moderately sorted sandstone. Additionally, point-counting methods identified abundant dolomite, which XRD confirmed as Fe-dolomite. The rhombohedral Fe-dolomite has a consistently negative impact on permeability throughout the sample (Figure 3.27).

**Figure 3.27:** Photomicrograph showing the abundance of dolomite observed in sample 3300.5. The dolomite exhibits a rhombohedral shape and is interpreted as a post-depositional feature. XRD analysis confirmed the presence of Fe-dolomite which consistently inhibits permeability throughout the sample. However, the dolomite does not have such a negative impact on total porosity, as intergranular pore spaces remain abundant.

In contrast, sample 3268.5 consists of clean, well-sorted quartz grains, and large millimeter-scale clay casts. When viewing the photomicrographs in figures 3.27 and 3.28, it is clear that the dolomite in sample 3300.5 has a greater impact on permeability
than the clay clasts in sample 3268.5. The clasts adversely affect permeability in local areas; however, a considerable portion of the sample contains no clay clasts. In these zones, interconnected intergranular pore spaces lead to relatively high permeability (Figure 3.28). The rounded framework grains, increased grain size, moderate to well-sorting of the sample, and nature of the grain contacts (dominantly point contacts) further contribute to the relative increase in permeability in sample 3268.5 compared to sample 3300.5.

![Image](image-url)

**Figure 3.28:** Photomicrograph illustrating how permeability is adversely affected in local areas that contain clay clasts. Note that a significant portion of the sample contains no clasts and consists of clean, quartz-rich sandstone with abundant intergranular pore spaces. In these zones permeability remains high. Porosity consists of intergranular pores, intragranular porosity due to partial dissolution, and microporosity in the clay clast zones. The red line illustrates the interconnectedness of pore spaces in areas with no clay clasts.

XRD data for sample 3183.67 approximates the total clay content as 10% kaolinite, 7% chlorite, and 4% illite. These clays were also identified, in very similar
quantities, with a petrographic microscope. This sample is a fine-grained sub-litharenite with abundant sedimentary rock fragments. The sedimentary rock fragments have been significantly deformed, creating a pseudo-matrix that is associated with abundant microporosity and reduced permeability (Figure 3.29). Framework grains are moderately-well sorted, and sub-angular to sub-rounded. Quartz grains are rarely in contact, as deformed sedimentary rock fragments compose most of the area between quartz grains.

Samples 3183.67 and 3259.33 have comparable amounts of total clay. However, kaolinite, rather than chlorite, accounts for the majority of clay in sample 3259.33. When a large amount of kaolinite (>10%) is present, it can produce significant reductions in permeability (Wilson and Stanton, 1994). Both XRD and point-counting methods identified kaolinite content as less than 8% of the total composition, and quantity of kaolinite is not linked to reduced permeability (Figure 3.30). Sample 3259.33 is a fine-grained, well-sorted, sub-litharenite (Figure 3.31). Grain shapes are predominantly sub-rounded. Long grain contacts are the most abundant type of contacts; however, many point contacts and some concavo-convex contacts are also observed. Porosity is almost completely obstructed in the more clay-rich areas (with the exception of some microporosity), while other areas have abundant, large intergranular pore spaces.

Sample 3183.67 exhibits lower measured permeability than sample 3259.33, despite equal amounts of total measured porosity. The seven percent total chlorite measured in sample 3183.67 (versus trace amounts in sample 3259.33) contributes to a reduction in sample permeability, as chlorite is a high surface area clay that is known to have significantly adverse effects on permeability. Figure 3.32 shows a relationship between increasing chlorite content and reduced permeability. The poorer sorting, finer grain size, and nature of grain packing in sample 3183.67 further contribute to the relative reduction in permeability.

Petrographic thin section analysis identified horizontal laminations in sample 3261.75(Figure 3.33). These laminations were marked by the alignment of heavy minerals (mostly zircon). Clay material also formed horizontal laminations which represent ripple surfaces. These horizontal laminations account for the higher measured horizontal to vertical permeability (463 mD vs. 89.5 mD). This sample was categorized
Figure 3.29: a) Photomicrograph of sample 3183.67 showing abundant microporosity within clay-rich patches b) lower resolution image of sample 3183.67 showing abundant intergranular porosity, as well as clay-rich zones. This sample is a fine-grained sub-litharenite. There are abundant sedimentary rock fragments that have been significantly deformed, creating a pseudo-matrix. The sedimentary rock fragments are associated with abundant microporosity, and reduced permeability. There are equal parts intergranular porosity and intragranular microporosity. Secondary intragranular porosity within partially leached framework grains accounts for a small amount of the total porosity. The quartz grains are moderately-well sorted, and sub-angular to sub-rounded. Quartz grains are rarely in contact, as deformed sedimentary rock fragments compose most of the area between quartz grains.
Figure 3.30: Cross-plot suggesting that only abundant quantities of kaolinite (>10% total composition) adversely affect permeability. The percent kaolinite plotted in this graph was determined via point counting methods. There is no clear correlation between percent kaolinite and permeability for samples with 10% or less total kaolinite. There may be a correlation between reduced permeability and greater than 10% kaolinite; however, sample populations were too sparse to draw any significant conclusions.
Figure 3.31: a) Photomicrograph showing areas of abundant intergranular porosity and some clay clasts b) secondary porosity due to feldspar dissolution and unidentified clay rimming grains. This is a fine-grained, well-sorted sub-litharenite. Grain shapes are predominantly sub-rounded. Long grain contacts are the most abundant type of contacts; however, many point contacts and some concavo-convex contacts are also observed. Porosity is almost completely obstructed in the more clay-rich areas (with the exception of some microporosity), while other areas have abundant, large intergranular pore spaces. There are minor amounts of intragranular porosity, most commonly observed in partially leached k-spar and various types of rock fragments. Grain boundaries look blurred in areas- due to an unidentified form of clay.
Figure 3.32: Chlorite v. permeability cross-plot illustrating the adverse effect increased chlorite content has on permeability. The number of samples with both chlorite content and permeability data was limited; however, a linear trend is still observed.

as a very fine-grained (average grain size of 0.107 mm), well-sorted sub-litharenite., with sub-angular grains, and point contacts between framework grains. There were a number of long grain contacts, offering evidence of slight compaction. Minor kaolinite patches with associated microporosity were observed throughout.

Sample 3234 showed a quartz-dominated composition with clay rimming both pore spaces and rounded framework grains (Figure 3.33). Point-counting methods quantified this sample as a medium-grained, well-sorted quartzarenite. Grain size measurements and phi scale define this as well-sorted, but visually there is a bi-modal grain size distribution. The larger grains are rounded, while the smaller grains are primarily sub-rounded. The majority of contacts between framework grains were point contacts. Minor floating grains and long grain contacts were observed. Many of the
large pore spaces, and some framework grains, had clay rims. There little to no evidence of compaction, and in many areas the sample appears unconsolidated.

Sample 3234 showed a quartz-dominated composition with clay rimming both pore spaces and rounded framework grains (Figure 3.33a). Point-counting methods quantified this sample as a medium-grained, well-sorted quartzarenite. Grain size measurements and phi scale define this as well-sorted, but visually there is a bi-modal grain size distribution. The larger grains are rounded, while the smaller grains are primarily sub-rounded. The majority of contacts between framework grains were point contacts. Minor floating grains and long grain contacts were observed. Many of the large pore spaces, and some framework grains, had clay rims. There little to no evidence of compaction, and in many areas the sample appears unconsolidated.

Samples 3261.75 and 3234.67 were both categorized as well-sorted. However, sample 3234.67 did have a lower phi value than sample 3261.75, indicating it is “more” well-sorted. Again, textural features are influencing permeability, perhaps more so than compositional or diagenetic features.

Figure 3.34 illustrates the relationship between average grain size and permeability, as samples with larger grain sizes typically exhibit higher permeability. Previous work suggests a relationship between grain size, sorting, porosity, and permeability (Pettijohn et al., 1987; Krumbein and Monk, 1943). However, grain size, sorting, packing of framework grains and cementation affect permeability in a complex way that is not fully understood (Pettijohn et al., 1987). Furthermore, there is evidence that depositional processes affect the porosity and permeability distribution of ancient sandstones. Pryor (1972) found that permeability increased with sorting, and porosity increased with sorting in river sands, but not in dune or beach sands.

Textural differences between samples 3256.75 and 3258.58 corroborate the idea that the textural variations observed may be more influential to permeability than compositional variations. Both samples are dominated by very high percentages of monocrystalline quartz and abundant intergranular porosity (Figure 3.35). Sample 3256.75 was categorized as a medium-grained sandstone, while sample 3258.58 was categorized as a lower fine-grained sandstone. The grains in sample 3258.58 were
Figure 3.33: a) Photomicrograph of sample 3234 b) Photomicrograph of sample 3261.75. The horizontal laminations are controlled by the presence of heavy and opaque minerals. Overall, compositions between the two samples are comparable. Textural variations, and/or core-scale features account for permeability variation. The images were taken at the same scale to illustrate the variability in grain size.
**Figure 3.34**: Grain size v. permeability cross-plot. Overall, samples with larger average grain sizes exhibit greater permeability. Permeability is core-derived. Average grain size was calculated through 100-count point counts, during which a micrometer was used to measure individual framework grains.
Figure 3.35: a) Photomicrograph of sample 3256.75 showing abundant intergranular pore spaces, and abundant deformed sedimentary lithics with associated microporosity. Photos were taken at the same scale to illustrate the variation in grain size. Textural features such as grain size variations, sorting, and degree of compaction are contributing to variations in permeability.
predominantly angular, while the majority of grains in sample 3256.75 were rounded. Both samples were categorized as well-sorted; however, sample 3256.75 had a greater phi value, indicating it was better sorted than sample 3258.58. Furthermore, sample 3258.58 exhibited extensive long grain contacts, and local areas in which grains exhibited higher degrees of compaction. Sample 3256.75 was dominated by point contacts, with a minor amount of floating and long grain contacts. The decreased sorting, grain size, and more compact packing of the grains in sample 3258.58 all contribute to the relative reduction in permeability compared to sample 3256.75.
CHAPTER 4
CO$_2$- ROCK INTERACTION

4.1 Pre-CO$_2$ Exposure

Sodium plagioclase, volcanic rock fragments, chlorite and calcite have been described as major CO$_2$-reacting minerals (Watson et al., n.d.). Petrographic thin section observations, as well as QEMSCAN and SEM, have all confirmed the presence of a number of these “reactive” minerals. Chlorite, muscovite, feldspar, and various carbonates are present in well 159-2 samples; therefore, evaluating the effect of CO$_2$ on these reservoir samples is of great interest.

4.1.1 Sample Selection

Three core plugs from well 159-2 were selected to undergo exposure to a CO$_2$ and brine solution (Figure 4.1). These samples were selected because they are compositionally distinct with variable porosity and permeability. Figure 4.2 offers a detailed look at the compositional and textural variations between the samples in Figure 4.1. Figure 4.2a shows the abundance of clay and rock fragments present in sample 3186. Figure 4.2b shows the quartz-rich composition of sample 3231. Figure 4.2c, taken of sample 3273, is finer grained with abundant clay-rich laminations. All images were taken at the same scale to show the variability in grain size.

4.1.2 Porosity and Permeability Measurements

Experimental porosity and permeability were measured using the CMS-300 automated permeameter located in the Department of Petroleum Engineering at the Colorado School of Mines. This instrument uses an integrated form of the combined Darcy, Klinkenberg, and Forchheimer equations to accurately determine permeability from 15 Darcies to 0.05 microdarcies. During analysis, samples are exposed to a requested confining pressure of at least 800 psi. An advanced algorithm allows actual confining pressure to be matched with requested confining pressure. The CMS-300 uses helium as
Figure 4.1: Image showing the core plugs chosen for CO₂ experimentation. Labels on the core plugs indicate the depth from which the plugs were taken. The scale on the left shows both inches (in black) and centimeters (in red).
Figure 4.2: Photomicrographs showing the compositional and textural variations between the samples chosen to undergo CO$_2$ experimentation.  

a) Photomicrograph is from sample 3186 is characterized by abundant sedimentary rock fragments and is very clay-rich. b) Photomicrograph of sample 3231, shows a well-sorted sample characterized my abundant quartz and intergranular pore space c) This image shows the fine-grained nature of sample 3273, which also contains horizontal laminations and carbonate.
its measurement fluid under normal operating conditions (Argosy Technologies Ltd, 2011). For these samples, minimum confining pressure (800 psi) was used due to sample friability. Porosity and permeability results for the experimental samples are summarized in Table 4.1.

<table>
<thead>
<tr>
<th>Sample # (depth ft)</th>
<th>Porosity (%)</th>
<th>Permeability $K_{air}$ (mD)</th>
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</thead>
<tbody>
<tr>
<td>3186.58</td>
<td>21.59</td>
<td>15</td>
</tr>
<tr>
<td>3231.67</td>
<td>27.43</td>
<td>4790</td>
</tr>
<tr>
<td>3273.67</td>
<td>11.16</td>
<td>0.467</td>
</tr>
</tbody>
</table>

Table 4.1: Table summarizing the porosity and permeability measurements acquired for each of the experimental core-plugs. Porosity and permeability were measured using the CMS 300 permeameter.

4.1.3 Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN)

The QEMSCAN Facility at the Colorado School of Mines employs a unique method of quantitative mineralogical evaluation which utilizes a scanning electron microscope linked to a suite of proprietary software produced by FEI Inc. Data are collected using a grid of fields across the face of each sample. Each field is defined by a two-dimensional array of points, the spacing of which is equivalent to the resolution of the scan. During analysis, the electron beam of the SEM is centered on each point. Interaction between the electrons in the beam and the orbital electrons of the atoms in the sample cause several cascading reactions to occur within an excitation volume at the surface of the sample. Within the excitation volume, electronic interactions produce backscatter electrons (BSE), secondary electrons (SE), and characteristic x-radiation. Characteristic x-radiation is used to identify the mineral(s) present at each point, while backscatter electrons are used to produce a grayscale image of the surface of the sample. The brightness of each pixel in the grayscale image is proportional to the atomic weight.
of the mineral(s) present at that point, and is used to verify the mineral identification produced through x-radiation spectral analysis (Dye, 2011, personal communication).

Following data collection, the QEMSCAN software produces a false-color mineral map of the sample. Each mineral is assigned a specific color, which allows for a clear visualization of mineral distribution. Using the data collected during point counting, the QEMSCAN operator is able to produce reports based on quantitative statistical data, such as those pertaining to modal mineral abundance, grain size distribution, and mineral associations (Dye, 2011, personal communication). Results of the QEMSCAN analysis performed on the three experimental samples are summarized in Figure 4.3. It is important to note that QEMSCAN technology does not identify rock fragments, but only their constituent minerals. Therefore, the total quartz percentage identified consists of monomineralic and polymineralic quartz grains, as well as quartz-bearing rock fragments.

4.1.4 **Field Emission Scanning Electron Microscopy (FESEM)**

The FESEM, located in the Metallurgical and Materials Department at the Colorado School of Mines, consists of a traditional scanning electron microscope (SEM) with a field-emission cathode in the electron gun. This provides narrower probing beams at low and high electroenergy. The addition of the field-emission cathode results in both improved spatial resolution and minimized sample charging and damage. The FESEM is typically used instead of the SEM for applications which demand the highest magnification (PhotoMetrics Inc, 2011). This instrument was ideal for the scope of this study, as very high magnification is required to detail possible reactions on the surfaces of individual grains.

A small piece of each core plug was chipped off and mounted for FESEM analysis. Each of the three samples was mounted onto a cylindrical piece of Teflon using conducting epoxy resin (Figure 4.4). Teflon was chosen because it is non-reactive, and would not be affected during exposure to the CO₂-brine solution. Samples were then painted with a small amount of conducting paint. Typically, samples are coated with gold paint prior to SEM analysis. Gold paint was not used on these samples due reaction potential during CO₂ exposure. Since samples lacked gold coating, a low accelerating
Figure 4.3: Summary of the results of QEMSCAN mineralogical analysis conducted pre-CO$_2$ experimentation. The vertical axis shows the sample number, which corresponds to the depth from which the sample was taken.
Figure 4.4: Image showing the smaller samples exposed to experimental solution. Small samples were mounted on Teflon and underwent FESEM analysis. They were placed into a protective plastic container with holes drilled into the lid (lid is off in this photo) before being placed in the experimental vessel for four weeks.
voltage and a reduced number of electrons were used during SEM analysis. Furthermore, copper tape was placed along the edge of each sample which aided proper conduction.

Photomicrographs were taken of grains in each sample with the idea that these exact grains would be re-examined post CO₂ exposure (Figure 4.5). Photomicrographs were taken at low and high resolutions so that identifying markers could be noted.

4.1.5 Experimental Solution

The composition of the experimental solution was based on the May 2011 daily production data from well 159-2. These data were acquired from Raymond Schutte, DRI geochemist. Liquid CO₂ is the only substance being injected into the field; however, oil, gaseous CO₂, methane, and water are all being produced.

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>600 bbls</td>
<td>18.0153 g/mole</td>
<td>5,289,919 moles</td>
<td>78 mole%</td>
</tr>
<tr>
<td>CO₂</td>
<td>1,000,000 cf</td>
<td>44.0095 g/mole</td>
<td>1,201,521 moles</td>
<td>18 mole%</td>
</tr>
<tr>
<td>Oil</td>
<td>250 bbls</td>
<td>119 g/mole</td>
<td>270,282 moles</td>
<td>4 mole%</td>
</tr>
</tbody>
</table>

Table 4.2: Table showing the daily production data for well 159-2 in May 2011. (R. Schutte, 2011, personal communication).

Based on the production data in table 4.2, the following assumptions and calculations were made:

- For experimental purposes the amount of oil produced was neglected.
- Mole % H₂O and CO₂ in the production well were adjusted to 81% and 19% respectively.
- Pure liquid CO₂ is the only substance being injected, therefore, it is assumed that the injection well has 100 mole % CO₂.
- It was assumed that the reservoir contained a mole fraction of H₂O to CO₂ somewhere in between that of the injection and production wells.
- Based on that assumption, the average was taken between the mole fractions of CO₂ and H₂O in the injection and production wells.
Figure 4.5: Images taken using FESEM. The photomicrographs show some of the grains that were imaged pre-experimentation: a) kaolinite clay “booklets” and illite clay observed in sample 3186 b) monocristalline and polycristalline quartz grains, and abundant intergranular porosity were imaged in sample 3231 c) Illite clay and muscovite grains were imaged in sample 3273.
• The average of 19 mole % CO₂ in the production well and 100 mole % CO₂ in the injection well yields an estimated 60 mole % CO₂ in the reservoir.

The remaining 40 mole % H₂O was adjusted to 37 mole % water and 3 mole % salt by means of the following calculations. These calculations were based on water production data from well 159-2 shown if Table 4.3.

<table>
<thead>
<tr>
<th>Anions</th>
<th>mg/l</th>
<th>Cations</th>
<th>mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride</td>
<td>46,000</td>
<td>Sodium</td>
<td>25,213</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>183</td>
<td>Magnesium</td>
<td>1,013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calcium</td>
<td>2,340</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barium</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iron</td>
<td>36</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pH at time of sampling</td>
<td>5.22</td>
</tr>
<tr>
<td>pH at time of analysis</td>
<td><strong>5.22</strong></td>
</tr>
</tbody>
</table>

**Table 4.3:** Table showing the water composition of well 159-2. The sodium and chloride ion data were used to produce the experimental brine solution. Water analysis results are from Jan, 2011 (Denbury Resources Inc, 2011, personal communication).

• 600 bbls = 71,442 L daily H₂O production and 5,289,919 moles of H₂O.
• According to the water analysis report for well 159-2 there is 46 g chloride/L, and 25.213 g sodium/L.
• (71,442 L H₂O) x (46 g Cl/ L H₂O) = 3,286,332 g Cl in the daily production fluid.
• With a molar mass of 35.45 g/ mole, this yields 92,703 moles of Cl in the daily production fluid.
• (71,442 L H₂O) x (25.213 g Na/ L H₂O) = 1,801,267 g Na in the daily production fluid.
• With a molar mass of 22.9898 g/mole, this yields 78,350 moles of Na in the daily production fluid.
• Summing the moles of Na and Cl and dividing them by the total moles of H₂O results in approximately 3 mole % NaCl in the production fluid.

Therefore, the final composition of the experimental solution consisted of 60 mole % CO₂, 37 mole % H₂O, and 3 mole % NaCl. To create the brine solution consisting of the appropriate mole fractions of H₂O and NaCl the following calculations were made:

• With a molar mass of 18 g/ mole, 37 moles H₂O equal 666 g
• With a molar mass of 58 g/mole, 3 moles NaCl equal 174 g
• Based on the previously calculated ratios of H₂O: NaCl, there should be 26 g NaCl per 100 g H₂O in the experimental solution.
• \((100 \text{ g H}_2\text{O}) \times (1 \text{ mole H}_2\text{O} / 18 \text{ g}) = 5.55 \text{ moles H}_2\text{O}\)
  \((26 \text{ NaCl}) \times (1 \text{ mole NaCl} / 58 \text{ g}) = 0.44 \text{ moles NaCl}\)
• Based on the above calculations 100 g of distilled water was measured out, and exactly 26 g of salt was added to it to create the brine solution.
• The brine solution was the poured into a clean, metal transfer vessel that contained pure H₂O on the other end of a sliding piston.

To create the appropriate mixture of CO₂ and brine the following steps were taken:

• An empty transfer vessel was weighed, then filled with CO₂ and re-weighed indicating 245.12 g of CO₂ had been injected into the vessel.
• \((245.12 \text{ g}) \times (1 \text{ mole CO}_2 / 44 \text{ g}) = 5.57 \text{ moles CO}_2\)
• Desired composition consists of 60 mole % CO₂ and 40 mole % brine, therefore 5.57 moles of CO₂ required that 3.71 moles (70 cc’s) of the brine solution be pumped into the CO₂-filled vessel

4.2 Soaking Process

The three core plugs, and three Teflon mounted core-plug pieces were placed into a transfer vessel (Figure 4.6). The Teflon mounted samples were first placed into a small plastic container in an attempt to maintain sample integrity. Four small holes were
drilled into the top of the plastic container so that samples would be properly exposed to experimental solution.

An appropriate amount of the brine solution (3.71 moles or 70 cm³) was then pumped (using the pure water on the other end of the sliding piston) into the transfer vessel containing CO₂. Pressure was continually increased while attempting to get the full 70 cm³ of brine solution into the CO₂-filled vessel. The maximum pressure the transfer vessel can hold is 10,000 psi. At 9,000 psi only 50 cm³ of brine solution had been successfully added to the CO₂, so some of the CO₂-brine mixture was then transferred to the vessel containing the rock samples. The remaining 20 cm³ was then successfully transferred into the CO₂-filled vessel. Once the CO₂-brine solution had been combined into one transfer vessel, the solution was pumped into the vessel containing the rock samples. At this point the pressure in this rock and solution-filled transfer vessel was approximately 900 psi, and needed to be increased to mimic that of the reservoir. A pump was attached to a fluid-filled vessel. Fluid was then pumped into the vessel containing the rock samples, and pressures began to increase very slowly. At about 1100 psi a phase boundary was reached. At this point pressures increased very rapidly to the desired 1700 psi. At 1700 psi the flow rate dropped significantly as fluid began filling the rock. The vessel containing the rock samples and experimental solution was left to “soak” for four weeks.

4.3 Post-CO₂ Exposure

Figure 4.7 shows the samples immediately after being removed from the experimental vessel. Samples were in solution and under pressure for four weeks. The plastic container was moderately successful in maintaining the integrity of the small FESEM samples, as the container was significantly deformed. The surface of the FESEM sample from 3,186 ft was detached. The other two FESEM samples were intact, but displayed significant amounts of copper corrosion on their surfaces. The core plugs were saturated and fragile after being removed from the experimental canister. Again, sample 3186 was the most adversely affected, being fractured into two pieces. Sample 3273 showed evidence of micro-fracturing, but remained intact.
Figure 4.6: Image showing the vessels in which samples were left to soak in experimental solution for four weeks.
Figure 4.7: Image taken immediately after samples were removed from experimental solution after soaking for four weeks. Sample 3286 was most adversely affect, being separated into two pieces. Samples 3273 and 3231 remained intact. The container used to house the SEM samples was significantly deformed and corroded.

Steps were taken to ensure that samples would not be destroyed during analysis performed post-CO₂ experimentation. The exterior of all core plugs were coated with waterproof marine epoxy. Epoxy was left to cure for 24 hours, after which samples were wrapped in surgical tape. Samples were then re-analyzed using CMS-300, QEMSCAN, and FESEM technology.

4.3.1 Porosity and Permeability

Accurate porosity and permeability measurements for all three samples were not acquired post-CO₂ experimentation. During CO₂ exposure, sample 3186 was split into two pieces, rendering it useless to CMS-300 measurements. Samples 3231 and 3273 were both re-analyzed; however, results were unreliable. There was a definite error in the results acquired for sample 3231, as no values were given for either porosity or permeability. Porosity and permeability measurements for sample 3273 were 11.25% and 2.82 mD. This indicates virtually no change in porosity, and a significant increase in permeability (pre-experimentation porosity and permeability measurements were 11.25%
and 0.467 mD). Since samples 3231 and 3273 were simultaneously re-analyzed with the CMS-300, and results for sample 3231 were clearly inaccurate, sample 3273 measurements are also questionable.

If, in fact, permeability in sample 3273 did increase post-experimentation, it is attributed to micro-fracturing incurred by experimental procedures, rather than mineralogical alteration. Observations made via FESEM, suggest that permeability was slightly reduced by the precipitation of sodium chloride; however, this was not quantified using experimental methods.

4.3.2 QEMSCAN

The results of QEMSCAN analysis performed post-CO₂ experimentation are shown in Figure 4.8. Table 4.4 compares the pre- and post- CO₂ QEMSCAN results for each of the three experimental samples. The most notable modal variation is observed in sample 3273. Post- CO₂ experimentation, QEMSCAN identified a six percent decrease in total quartz content, a two percent increase in illite/muscovite, a two percent increase in kaolinite, and a three percent increase in total chlorite. Although a noteworthy change in the total percentage of quartz in sample 3273 was observed, this does not indicate that quartz content in the sample has actually decreased. Rather, the six percent reduction in total quartz is a consequence of small percentage increases of three different types of clay (illite/muscovite, kaolinite, and chlorite). A porous medium such as sandstone can show relatively significant changes in mineralogical content over just a few centimeters; therefore a percentage change merely means there was an increase (or decrease) in other minerals within the face that was scanned during the second run (Dye, 2011, personal communication.) Furthermore, the sample was exposed to a supersaturated solution rather than the targeted reactive solution (discussed further in section 4.3.3). Therefore, it is concluded that the reduction in quartz is a byproduct of the variation expected when using QEMSCAN technology on sandstones. The modal abundances of the other two samples remained virtually unchanged following experimentation. Exposure to the experimental solution did not contribute to the discrepancy between pre- and post-experimental data.
Figure 4.8: Results of QEMSCAN analysis performed post-CO₂ experimentation.
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Pre-CO₂ Exposure</th>
<th>Post-CO₂ Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3186</td>
<td>3231</td>
</tr>
<tr>
<td>Quartz</td>
<td>62</td>
<td>97</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Pyroxene-Augite</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Illite/Muscovite</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Chlorite</td>
<td>1</td>
<td>tr</td>
</tr>
<tr>
<td>Ti-bearing clay</td>
<td>4</td>
<td>tr</td>
</tr>
<tr>
<td>Biotite/Phlogopite</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Dolomite</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Calcite</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Siderite</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Apatite</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Pyrite</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Ca₂SO₄/Anhydrite/Gypsum</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Rutile/Anatase</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Sphene</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Zircon</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Corundum</td>
<td>tr</td>
<td>0</td>
</tr>
<tr>
<td>Others</td>
<td>tr</td>
<td>tr</td>
</tr>
</tbody>
</table>

**Table 4.4:** Table comparing the modal abundances in samples before and after experimentation. Overall, modal abundances appear to be relatively unaffected by the experimental solution. Only minor variations are observed, such as the increase in clays at the expense of percent quartz in sample 3273.

### 4.3.3 FESEM

It was not possible to identify the exact grains photographed pre-CO₂ exposure. Sodium chloride crystals precipitated on the surface of all three samples and rendered them virtually unrecognizable (Figure 4.9). The surface of sample 3186 was displaced during experimentation, so both the exterior and interior of the sample were observed. Sodium chloride crystals were not as prolific on the interior of the sample, as they were on the exterior (Figure 4.10). However, multiple forms of NaCl, and copper had precipitated onto sample surfaces (Figures 4.11, 4.12, and 4.13).
Figure 4.9: a) Photomicrograph showing sample 3231 before CO₂ experimentation. b) The same surface was found post-CO₂ experimentation. However, the sample had been altered by NaCl precipitation and the exact grains images pre-experiment were not identified.
Originally, the experiment was designed to expose samples to a reacting fluid. After post-experimentation analysis, it became clear that samples were actually exposed to a super-saturated solution. It was from this solution that the sodium chloride crystals precipitated. The sodium chloride crystals were observed within previously open pore spaces, and likely result in a slight reduction in porosity and permeability. If in fact, the reservoir fluid at Delhi Field is super-saturated, similar results will be yielded. Increased amounts of CO$_2$ in the system would take water out of solution and leave an excess of sodium chloride. Precipitated sodium chloride could then lead to a decrease in permeability.

Figure 4.10: Image showing the inside of sample 3186. Sodium chloride crystal did not precipitate on the inside of this sample, as abundantly as they did on the surface.
Figure 4.11: Image showing NaCl crystals precipitated into the intergranular pore spaces on the surface of sample 3186.
Figure 4.12: Photomicrograph showing a relatively large NaCl crystal that has precipitated onto a quartz grain in sample 3231.
Figure 4.13: Photomicrographs illustrating some of the alterations made to sample 3273 during experimentation: a) A grain surface that has been detached b) A close-up view of the area circled in figure 4.13a. The higher resolution image shows that copper has precipitated on the newly exposed surface.
CHAPTER 5
SUMMARY, CONCLUSIONS, AND FUTURE WORK

5.1 Summary and Conclusions

Petrographic thin section analysis determined a provenance of recycled orogen, in particular, a foreland uplift provenance. Data acquired through petrographic thin section analysis support the near-shore depositional system proposed by Silvis (2011). Compositional, and textural features identified in petrographic thin sections were coupled with core-scale sedimentary structures to identify distributary channel, barrier bar, transgressive marine, and delta and delta plain facies; all of which are consistent with those deposited as part of a delta system.

The most common diagenetic features observed were: 1) the partial to complete dissolution of labile grains, most notably feldspars and rock fragments 2) precipitation of kaolinite, illite, and chlorite 3) precipitation of carbonates such as dolomite, calcite and siderite. These diagenetic features had varying effects of reservoir quality. A correlation between increased total clay (kaolinite, illite, and chlorite) and decreased permeability was noted. Kaolinite does not adversely affect permeability when present in quantities of less than ten percent, while a much smaller percentage of total chlorite and/or illite is needed to impact permeability. More sample data are needed to fully understand the degree to which these clays are adversely affecting field-wide permeability. Additionally, Fe-dolomite significantly reduces permeability while maintaining a substantial amount of total porosity in core samples.

The barrier bar facies exhibited the highest porosity and permeability. This facies was characterized by the greatest textural maturity, and was not adversely affected by diagenetic features. The distributary channel facies exhibited variable reservoir quality. Intervals within each of the identified distibutary channels contained zones of very high reservoir quality. However, alternate zones within the distributary channel facies contained diagenetic clays and grain compaction/deformation that inhibited effective porosity. The trangressive marine, and prodelta facies were characterized by reduced reservoir quality; however, both facies contained zones of significant reservoir quality. It is important to consider the potential of the “lower permeability” zones during recovery
efforts, as “low/reduced permeability” at Delhi Field has reservoir potential. Ignoring these zones may result in the bypassing of significant resources.

Permeability measurements of sample 3273 suggest that a significant increase in permeability is possible post-CO$_2$ exposure. If such an increase is accurate, it is attributed to micro-fracturing incurred during experimentation rather than mineral alterations. Microfractures were most likely caused by the experimental procedure itself, or by NaCl-induced swelling. Such fracturing in the field could result in conduits for CO$_2$ and/or hydrocarbon migration, and is a topic that should be further investigated.

Alternatively, observations made with the FESEM suggest that if reservoir fluid contains significant amounts of sodium and chlorine ions, NaCl crystals will precipitate in the presence of CO$_2$, leading to a reduction in permeability. However, no reduction in permeability was experimentally measured. If reservoir fluid is not supersaturated, it remains unclear as to whether CO$_2$-rock reactions have the potential to alter reservoir quality.

Tying together the small-scale petrographic data acquired here, to larger-scale well-log and seismic data, is the key to understanding reservoir compartmentalization. These data detail a variety of compositional and textural features that are influencing reservoir quality; however, additional core is needed to confirm that these observations are consistent on a larger scale. This is fundamental for successful hydrocarbon recovery at Delhi Field. The success of future CO$_2$-flood phases will depend on optimal injector-producer placement, which is contingent upon understanding the field geology.

5.2 Future Work

Schlumberger cluster analysis determined petrofacies complementary to those identified by petrographic thin section analysis. Cluster analysis is a reasonable method to delineate zones of common lithology and textures; similar to those acquired through time consuming point-counting methods. Future work should include additional cluster analysis. In particular, analysis involving other geophysical logs, such as SP and resistivity, would allow for more wells to be used in the cluster.

Future construction of a reservoir model that simulates fluid and CO$_2$ flow is vital in optimizing recovery at Delhi Field. The petrographic data acquired here contribute
significant details to any future reservoir model. Any further accurate characterization of Delhi Field will require additional petrographic analysis; therefore, the coring of more wells is necessary. It is recommended that future core is analyzed in a similar manner, at both the core- and micro-scale. Not only are these data useful for the construction of geological and reservoir models; but they offer an understanding of the influences on reservoir quality.

Additionally, further testing of CO\textsubscript{2}-rock interactions could be useful. It is advised that core samples be exposed to a reacting solution, as opposed to the supersaturated solution used during this experiment. Although this supersaturated solution was based on well production data, it is uncertain as to whether this is actually representative of reservoir fluid over the majority of the field. It is well known that the field is defined by lateral heterogeneities; therefore, producing a fluid that accurately represents that which is in the reservoir, is challenging. Consequently, it is advised that more effort be placed on creating a reacting fluid, rather than attempting to mimic reservoir fluid.

Understanding the potential for induced fracturing in shale/clay-rich intervals, such as 3,273 ft, could be imperative to understanding CO\textsubscript{2} migration, as well as optimizing tertiary recovery. Future work should address the issue of potential fracturing as a result of CO\textsubscript{2} flooding, and to what degree this would affect reservoir quality, as well as fluid and gas flow.

Finally, Silvis (2011) mentioned the importance of source rock analysis. Source rock analysis could be carried out to determine source rock potential and provide clues to the existence of other petroleum reservoirs in the area that may have yet to be discovered (Silvis, 2011). During the course of this research, it was dually noted that there is no definitive source rock data for Delhi Field. Therefore, it is agreed that source rock analysis is a favorable topic of future research.
REFERENCES CITED


Berg, R.R., 1979, Reservoir sandstones of the Delaware Mountain Group, southeast New Mexico in N.M. Sullivan, editor, Guadalupian Delaware Mountain Group of West Texas and southeast New Mexico: Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Publication 79-18, p. 75-95.


Folk, R.L., and Ward, W.C., 1957, Brazos River bar, a study in the significance of grain-size parameters: Journal of Sedimentary Petrology v.27, p. 3-27.


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