Peripheral Clay Replacements as the Critical Diagenetic Feature Controlling Matrix Permeability in the Codell Sandstones, Northeastern Colorado

Daniel Alonso Medina
University of Colorado at Boulder, Daniel.A.Medina@colorado.edu

Follow this and additional works at: https://scholar.colorado.edu/geol_gradetds

Part of the Geology Commons, and the Sedimentology Commons

Recommended Citation
https://scholar.colorado.edu/geol_gradetds/131

This Thesis is brought to you for free and open access by Geological Sciences at CU Scholar. It has been accepted for inclusion in Geological Sciences Graduate Theses & Dissertations by an authorized administrator of CU Scholar. For more information, please contact cuscholaradmin@colorado.edu.
PERIPHERAL CLAY REPLACEMENTS AS THE CRITICAL DIAGENETIC FEATURE
CONTROLLING MATRIX PERMEABILITY IN THE CODELL SANDSTONES,
NORTHEASTERN COLORADO

by

DANIEL ALONSO MEDINA

B.S., University of Miami, 2015

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of
Master of Science
Department of Geological Sciences
2017
This thesis entitled:
Peripheral Clay Replacements as the Critical Diagenetic Feature Controlling Matrix Permeability
in the Codell Sandstone, Northeastern Colorado
written by Daniel Alonso Medina
has been approved for the Department of Geological Sciences
by

___________________________________________
David A. Budd

___________________________________________
Paul Weimer

___________________________________________
Edmund Gustason

Date__________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above-mentioned discipline.
ABSTRACT

The Codell Sandstone Member of the Late Cretaceous Carlile Formation is a hydrocarbon-bearing, tight-sand unit and is an active target for unconventional hydrocarbon production in the DJ Basin. The Type 2 sandstone of the Codell Member in northeastern Colorado is a ~30-ft thick, heavily bioturbated, low permeability (<0.1 md) argillaceous sandstone with subordinate amounts of cross-laminated sandstones. The intergranular drainage network within this “tight” sandstone is poorly understood, with the lack of correlation between permeability and lithofacies suggesting a strong diagenetic control. This study focuses on the diagenesis of the Type 2 Codell sands in the Wattenberg and Redtail fields to better comprehend which processes played a role in developing a connected pore network through this clay-rich rock. Five lithofacies were defined using 7 cores, and a paragenetic sequence including 11 features was assembled from thin-section petrographic analysis and electron microprobe mineralogical phase mapping. Quartz cementation, mechanical compaction, precipitation of authigenic clays, and peripheral clay replacements of framework grains are better developed in the laminated lithofacies. Epifluorescence imaging of micropores impregnated with rhodamine dye, coupled with analysis using ImageJ-FIJI, revealed skeletonized flow paths through the clay-rich sands. Cumulative flow-path lengths positively co-vary with permeability, indicating that the skeletonized flow paths capture key aspects of features that control permeability. Imaging of the longest flow paths suggests that peripheral clay replacement of framework grains by illite,
chlorite, and kaolinite was the most important diagenetic feature in creating an efficient drainage network. The microporous network formed along grain boundaries created extensive flow paths characteristic of high permeability samples. Micropores associated with intergranular clay masses were also observed, and this network was utilized for short distances when connecting between peripherally replaced grains. While cementation had a negative impact on primary porosity, the development of quartz cements became beneficial to the drainage system by extending the peripheral micropore network between adjacent grains. Therefore, pore connectivity was most improved during intermediate and deep burial, when pore-filling clays began to replace framework grains and cements and create the connected pore network that facilitates the movement of hydrocarbons from storage in micropores and nanopores to induced fractures.
CONTENTS

CHAPTER

I. INTRODUCTION .................................................................................................................. 1

   Overview of the Codell Sandstone ...................................................................................... 1
   Codell Oil and Gas Production ........................................................................................... 8
   Codell Diagenesis and Pore Networks ................................................................................. 10
   Purpose of this Study ........................................................................................................ 13

II. METHODS .......................................................................................................................... 15

   Sampling ............................................................................................................................ 15
   Core Descriptions .............................................................................................................. 15
   Thin Section Petrography ................................................................................................ 15
   Image Analysis Using ImageJ-FIJI ............................................................................... 23
   Skeletonization & Skeletal Analysis ............................................................................... 29
   Electron Microprobe Analysis ....................................................................................... 37

III. FACIES FRAMEWORK .................................................................................................... 41

   Observed Facies and their Attributes .............................................................................. 41
   Interpretation of Depositional Setting ............................................................................. 46
   Vertical Changes in Facies Types .................................................................................... 48
   Porosity and Permeability Attributes of Facies .............................................................. 51

IV. RESULTS .......................................................................................................................... 58

   Paragenetic sequence ....................................................................................................... 58
     Overview ......................................................................................................................... 58
     Syn-depositional Diagenetic Features ........................................................................... 58
TABLES

1. Core data made available for this study .................................................................16
2. Intensity ranges used to segment pixels into channels ........................................28
3. Ranges used to define the red channel in RF images of all samples .....................30
4. Porosity, permeability, and longest flow paths identified for each sample ..........38
5. Characteristics of the five facies observed in the Codell Sandstone .....................42
6. Abundance of diagenetic features as a function of major lithofacies .................82
FIGURES

1. Map showing the subsurface extent of the Codell Sandstone ........................................... 2
2. Stratigraphic units of the Carlie Shale Formation .............................................................. 3
3. Diagrammatic cross section of the Denver-Julesburg Basin ............................................... 5
4. Cumulative paragenetic sequence for the Codell Sandstone ........................................... 11
5. High-pressure mercury injection data from two Wattenberg cores ................................ 17
6. Range of pore types in the Codell thin-section samples ..................................................... 19
7. Variability in the intensity of purple rhodamine stain ....................................................... 21
8. Areas imaged using epifluorescence microscopy .............................................................. 22
9. BF image, RF image, and pixel-intensity histogram from a high permeability sample .... 24
10. Examples of fluorescence in a clay mass and a mesopore ............................................... 25
11. Frequency histogram showing segmented intensity ranges ............................................. 27
12. Segmented channels for one field of view ....................................................................... 31
13. Red fluorescent image and composite binary threshold image ....................................... 32
14. Segmented image area versus permeability for high-graded sample set ....................... 33
15. Skeletonization of a composite binary image ................................................................. 34
16. Idealized representation of a skeletonized network ....................................................... 36
17. Mineralogical imaging and analysis along a skeletonized flow path ............................... 39
18. Core photographs of laminated Codell facies ............................................................... 43
19. Core photographs of burrowed Codell facies (CDL-4) ................................................... 44
20. Core photographs of burrowed Codell facies (CDL-5) ................................................... 45
21. Simplified descriptions of the Codell sandstone .............................................................. 49
22. Core photograph of basal lag deposit ............................................................................. 50
23. Cross plots of porosity vs permeability for all samples with RCA..............................53
24. Cross plots of porosity vs depth and mineralogy..................................................55
25. Cross plots of permeability vs plagioclase and mixed-layered I/S content ................56
26. Paragenetic sequence for the Codell Sandstone......................................................59
27. Core photograph showing vertical and horizontal trace fossils...............................60
28. Photomicrographs showing pyrite, quartz overgrowths, and calcite .......................62
29. Photomicrographs showing calcite cementation and replacement .......................64
30. Photomicrographs showing evidence of mechanical compaction ..........................66
31. Microprobe images showing I/S mixed layered clay with EDS spectra......................67
32. Microprobe images showing illite-rich fibers in a moldic pore...............................70
33. Microprobe images showing authigenic kaolinite “booklets” in a moldic pore ..........72
34. Microprobe images showing replacive kaolinite, calcite, and albite .........................73
35. Microprobe images showing authigenic kaolinite replacing calcite and quartz ........74
36. Microprobe images showing chlorite and illite replacing quartz, albite, and calcite ....75
37. Images showing quartz and chert being peripherally replaced by authigenic illite ....76
38. BF images of laminated facies with all flow paths greater than 100 µm .................86
39. BF images of bioturbated facies with all flow paths greater than 100 µm .........87
40. Cross plots of permeability versus flow path metrics ............................................89
41. Cumulative frequency plot showing compiled flow path lengths .........................91
42. Partial low-perm flow path in a clay-filled area......................................................94
43. Partial low-perm flow path within a microfracture...............................................95
44. Partial mid-perm flow path traveling along peripherally replaced (illite) quartz ....96
45. Partial high-perm flow path traveling along peripherally replaced (kaolinite) quartz....97
46. Partial low-perm flow path traversing intergranular clay and hugging peripherally replaced (illite) grains
CHAPTER I: INTRODUCTION

Overview of the Codell Sandstone

The Codell Sandstone Member of the Carlile Shale Formation is a Late Cretaceous (middle-late Turonian) rock unit that occurs in the subsurface of eastern Colorado, parts of southeastern Wyoming, northwestern Kansas, and southwestern Nebraska (Fig. 1). It is an argillaceous sandstone with low porosities (≤ 16%) and permeabilities mostly below 0.1 md, which makes it a tight-gas sandstone (Birmingham et al. 2001; Holditch, 2006; Higley and Cox, 2007). The Codell Sandstone is an oil and gas bearing unit that recently has been the target of extensive exploration activity within the northern Denver-Julesburg (DJ) Basin.

The Codell Sandstone Member was deposited on the eastern margin of the Western Interior Seaway, a shallow marine environment that stretched from the Gulf of Mexico to the Arctic during the Cretaceous Period. The seaway was subjected to repeated relative sea-level changes that led to the development of multiple third-order marine transgressive-regressive stratigraphic sequences throughout the Cretaceous (Kauffman, 1969; Glenister and Kauffman, 1985; Krutak, 1996). The Codell sands were deposited during a fourth order transgressive-regressive cycle that was part of the third-order Greenhorn regressive cycle (Kauffman, 1977) (Fig. 2). Weimer and Sonnenberg (1983) identified an erosional surface at the base of the Codell Member that progressively truncates, from east to west, the underlying Fairport and Blue Hill shale members of the Carlile Formation. The Codell Sandstone is disconformably overlain by the Juana Lopez Member in the southern DJ Basin (Rankin, 1944). The Juana Lopez Member thins northward and is completely absent in northern Colorado (Fisher et al. 1985). There, the Codell Member is disconformably overlain by the Fort Hays Member of the Niobrara Formation, a micritic chalky limestone (McLane, 1982; Weimer and Sonnenberg, 1983). The post-Codell
Figure 1. Map showing the subsurface extent of the Codell Sandstone within the DJ Basin (solid red line), structural features that bound the basin (black lines), and distribution of Weimer and Sonnenberg’s (1983) different types of Codell sandstone (dashed red lines). Outlined in yellow are the Wattenberg field to the west (W) and the Redtail field to the east (R). Yellow pins show the locations of the four Wattenberg wells and the three Redtail wells used in this study. Base image from Google Earth.
Figure 2. Stratigraphic units of the Carlile Shale Formation in the northern and southern DJ Basin. In both areas the Codell Sandstone Member is bound by unconformities. The Fairport Chalk and Blue Hill Shale members become progressively truncated in the northern DJ, and there is a complete absence of the Juana Lopez Member in this area. The Codell was deposited during the regressive phase of the third-order Greenhorn cyclothem.
unconformity was interpreted by Weimer (1978) to have been caused by erosion, resulting in variable thicknesses of Codell Sandstone.

Sediments deposited in the Cretaceous Western Interior Seaway were deformed during the Laramide orogeny, resulting in the formation of the numerous basin and mountain ranges that characterize the modern Rocky Mountains. The Denver-Julesburg (DJ) Basin is one of those Laramide features (Kauffman, 1977; Weimer, 1983). It is an asymmetric structural basin whose axis parallels the Colorado Front Range and has a steep west flank and a significantly gentler dipping east flank (Fig. 3). It is bounded by the Hartville uplift to the northwest, the Chadron arch to the northeast, the Las Animas arch to the southeast, and the Apishapa uplift to the southwest (Higley and Cox, 2007) (Fig. 1).

Within the DJ Basin, the Codell Sandstone has been divided into three geographically-distinct types of sandstone, each reflective of different depositional processes in separate and unique depositional environments (Weimer and Sonnenberg, 1983) (Fig. 1). The Type 1 and Type 2 sandstones are separated from one another by an approximately 90 km wide region in the central DJ Basin where the Codell Sandstone is absent.

Type 1 Codell sandstone is a fine- to medium-grained, poor- to well-sorted, mineralogically mature sandstone (Lewis, 2013). It occurs in the southern DJ basin and is well developed in Kansas (Fig. 1). This unit thickens southward from a northern wedge edge to over 60 feet (Sonnenberg, 2014). Type 1 Codell sandstones lack significant amounts of detrital clay but instead have abundant intergranular pore-filling quartz and calcite cement (Lewis, 2013). Bioturbation is present throughout most of these sandstones and can range from minimal to pervasive. Intervals with little to no bioturbation display well preserved planar bedding, low-angle cross-bedding, and hummocky cross-stratification (Lewis, 2013). The most commonly
Figure 3. Diagrammatic cross section highlighting the east-west asymmetric nature of the Denver-Julesburg Basin and the occurrence of the Codell Sandstone. From Gustason and Sonnenberg, 2003.
observed ichnogenera are *Ophiomorpha* and *Thalassinoides*, with *Zoophycos*, *Teichichnus*, and *Palaeophycus* occurring less frequently (Lewis, 2013). The tops of the Type 1 sandstones are extensively bioturbated and contain *Glossifungites*, a firm ground ichnofacies. Weimer and Sonnenberg (1983) interpreted the Type 1 sandstones to be a marine shelf or shoreline bar with sheet-like distribution. More recently, Lewis (2013) interpreted the lower Type 1 Codell Sandstone to represent deposition near fair-weather wave base and the upper Type 1 sandstone to reflect deposition in the lower shoreface to lowermost upper shoreface. Lewis (2013) argued that the shelf to lower shoreface transition was preserved while shallower deposits were eroded before and during the Juana Lopez transgression.

Type 2 Codell sandstone is a bioturbated, medium to very-fine grained, argillaceous sandstone and is the main focus of this thesis. It is distributed across northeast Colorado and into southeast Wyoming (Fig. 1). It thickens to the northwest from a wedge edge to approximately 30 ft, with a typical thickness of about 20 ft in northern Colorado (Weimer and Sonnenberg, 1983). The Type 2 sandstone is composed primarily of quartz with small amounts of chert (3-20%) and plagioclase feldspar (<7.5%). Sablina (1993) classified the sands as mainly argillaceous sublithic arenites although she also noted a few argillaceous quartz arenites. In contrast, Henningsgaard’s (1986) data indicate a mix of sublithic and subfeldspathic sands. However, albitization and replacements of framework grains by clay and calcite (Henningsgaard, 1986; Caraway, 1990; Sablina, 1993; this study) means that those classifications reflect the post-diagenetic composition of framework grains, not the mineralogy of the framework grains at the time of deposition. Clay content is relatively high, forming up to 22% (Caraway, 1990) or 33% (Henningsgaard, 1986) of the total composition. The clays occupy intergranular pores and are both detrital and authigenic (Henningsgaard, 1986; Caraway, 1990; Sablina, 1993). The detrital clays are derived from the
mixing of originally interbedded sand and mud layers by bioturbation on the seafloor (Weimer and Sonnenberg, 1983); authigenic clays formed with burial and diagenesis (Henningsgaard, 1986; Caraway, 1990; Sablina, 1993).

Type 2 sand beds are heavily bioturbated and preserved sedimentary structures are uncommon. Where present those structures are mainly horizontally to hummocky cross-stratified sandstone lenses (Caraway, 1990). Caraway (1990) also observed small-scale, angle-of-repose (i.e., trough or tabular) cross-bedded sandstone beds near the top of the Codell Member in the Type 2 sands. Trace fossils within the Type 2 sandstones are represented by mixed “Skolithos-Cruziana” and “Cruziana-Zoophycos” ichnofacies, which represent marine shelf settings (Sablina, 1993). Originally, the Type 2 sand was interpreted to be a marine shelf sandstone lacking a central-bar lithofacies (Weimer and Sonnenberg, 1983). Henningsgaard (1986) reinterpreted the Type 2 sandstone to be a shelf ridge sandstone near storm weather wave base. In contrast, Caraway (1990) concluded that these sands were a nearshore inner shelf deposit, with the hummocky and angle-of-repose beds indicating major fluctuations in current regime associated with episodic storms. Sablina (1993) interpreted the Type 2 sands to have been deposited in an offshore environment below fair weather wave base. She argued that the presence of the Cruziana-Zoophycos ichnofacies throughout most of the Type 2 sandstone interval indicated a marine shelf environment with low to moderate energy levels, with the occasionally preserved cross-strata implying periodic storm deposits.

Type 3 Codell sandstone is burrowed, fine-grained, and cross-bedded to ripple laminated. It is found in Wyoming and Nebraska (Fig. 1), and constitutes the thickest Codell deposits with increasing thickness (up to 100 ft) to the northwest (Weimer and Sonnenberg, 1983; Anderson, 2011; Sonnenberg, 2014) where it is known as the Wall Creek Sandstone (E. Gustason, personal
communication). Type 3 sandstones are composed primarily of quartz, minor amounts of feldspars, and clay contents of 15–25% (Anderson, 2011; Smith, 2015; Sterling et al. 2015). The sandstone is heterogeneous, containing both bioturbated and laminated lithofacies (Smith, 2015). Bioturbation is present throughout the entire interval, with bioturbation decreasing in abundance northward from the Colorado-Wyoming state lines (E. Gustason, personal communication). However, no studies have attempted to identify ichnofacies. Sections where sedimentary structures are preserved show horizontal cross bedding, hummocky cross stratification, and some tabular cross bedding (Sterling et al. 2015). Weimer and Sonnenberg (1983) interpreted the Type 3 sandstone to be deposited in either an intertidal (brackish water) or marine environment. More recently, Anderson (2011) interpreted two depositional environments. The first was a middle to lower wave dominated delta in eastern Wyoming, just south of the Powder River Basin, as evidenced by cross-bedding, massive bedding and a larger grain size. Anderson’s (2011) second Type 3 depositional setting was an inner ramp environment in the southeast corner of Wyoming, as suggested by lower energy mud and silt deposits as well as a smaller sand grain size.

**Codell Oil and Gas Production**

Most historical hydrocarbon production from the Codell Sandstone occurred from the Type 2 sands in northern Colorado. Codell production began in 1955 with the discovery of the Soda Lake Field southeast of Morrison, Colorado (Krutak, 1996). During the 1960s and 1970s the Codell Sandstone was exploited in conjunction with wells going through the Niobrara, Terry, Sussex, and/or Shannon formations (Kennedy, 1983). Byron Oil developed the Spindle Field in the mid-1970s and produced hydrocarbons from the Terry, Niobrara and Codell sandstones (Weimer and Sonnenberg, 1983; Milne and Cumella, 2014). A few years later, Martin Oil made
further discoveries in the Boulder Valley Field, and Energy Oil made a Codell discovery in the Hambert Field in 1981 (Weimer and Sonnenberg, 1983).

The escalation in hydrocarbon prices in the early 1980s renewed interests in the Codell Sandstone across the central DJ Basin. Exploration wells indicated the existence of Codell hydrocarbon reserves in northeastern Colorado, and it was deemed economic enough for development until the oil market crash of 1985 (Krutak, 1996). Actual development of the Codell-hosted resources within the Wattenberg Field was renewed in the 1990s and early 2000s in association with advances in fracture stimulation technology (Ladd, 2001; Milne and Cumella, 2014). By 2005, over 6,600 wells were producing hydrocarbons from the Codell Member in Wattenberg Field alone (Birmingham et al. 2001).

Critical developments in horizontal drilling and multistage hydraulic fracturing were applied to Codell development beginning in 2009. This resulted in yet another Codell boom throughout Wattenberg Field, and extended exploration to the north and northeast (Higley and Cox, 2007; Milne and Cumella, 2014). Today, the Codell Sandstone is one of the primary targets in the DJ Basin, with most of the production coming from the Wattenberg Field (Sonnenberg, 2014) and some from the Redtail Field (Volker et al. 2014). Between 2009 and 2015, horizontal drilling in Wattenberg Field resulted in an increase in oil production from 192,000 BOEPD to 448,000 BOEPD (Smith, 2015; Sterling et al. 2015). It’s been estimated that there is over 6 BCFG in reserves in Wattenberg Field (Higley and Cox, 2007), and every year more and more horizontal wells are successfully being completed (Sterling et al. 2015).

Since 2013, Codell discoveries have also been recorded in southeastern Wyoming (from Type 3 sands in Laramie County) starting with the SM Tomahawk 1-30, Cirque Warren 17-1, Kaiser Francis Roadrunner 1-6, and EOG Jubilee 80-09 horizontal wells (Sterling et al. 2015).
As of 2015, approximately 90 wells have been drilled into the Type 3 Codell sandstone in Laramie County, with 68 of those being completed (Sterling et al. 2015).

**Codell Diagenesis and Pore Networks**

The low permeabilities of tight-gas sandstones are generally the result of diagenesis (Rushing et al. 2008), thus an understanding of those sandstones diagenetic history is advantageous to understanding the reservoir. The diagenesis of the Codell Sandstone has been the subject of just three prior MS theses by Henningsgaard (1986), Caraway (1990), and Sablina (1993). Each presented an interpretation of the paragenesis (Fig. 4), with those interpretations having some shared attributes and some significant differences. Bioturbation and precipitation of quartz overgrowths are the only two features noted in all three prior studies as early-formed features. Precipitation of calcite, authigenic clay growth, and feldspar replacement and dissolution are the only three features interpreted by all three prior workers as features of the middle stage of the paragenesis. No later-stage, deeper burial features are shared between the three paragenetic sequences.

Beyond those commonalities, the paragenesis presented in the three prior theses varies with respect to the timing of processes and observed features (Fig. 4). Henningsgaard (1986) observed hematite rims and euhedral quartz precipitation into secondary pores, two diagenetic features not observed in the other theses. Henningsgaard (1986) also linked the maturation of organic matter to the dissolution of aluminosilicates, the preservation of calcite cements, and precipitation of clays into secondary pores. Caraway (1990) mentioned sericitization of feldspars, a feature not shared by Henningsgaard or Sablina, and minor authigenic clay precipitation, but Caraway did not mention which clay minerals formed. Sablina (1993) mentioned calcite replacing framework grains beginning with shallow burial and precipitating
Figure 4. A cumulative paragenetic sequence showing the diagenetic features observed in the Codell by Henningsgaard (1986), Caraway (1990), Sablina (1993). Several features were observed by all three authors, other features by just one or two of those authors. Differences in relative timing are also noted. Caraway (1990) listed diagenetic processes in order of occurrence, but with no relative timing (early to late) or depth (shallow to deep). Timing of Caraway’s events in the cumulative paragenetic sequence are based on the relative timing of features given by the other two theses.
into secondary pores at the end of her interpreted paragenetic sequence. Sablina (1993) is also
the only author who mentioned albitization, conversion of kaolinite to chlorite, and illite
precipitation. Sablina (1993) interpreted those processes to have occurred during intermediate
burial, and since illitization had not gone to completion, Sablina (1993) concluded that the
Codell Sandstone never reached “deep burial”. Some processes, like late pyrite precipitation and
peripheral replacement of framework grains by clay, are not mentioned in any of the three prior
studies.

The effects of all diagenetic processes on permeability was only treated in a qualitative
fashion in the prior diagenetic studies of the Codell sandstones. Henningsgaard (1986), Caraway
(1990), and Sablina (1993) assumed that the Codell’s porosity and permeability were less than
adequate because of clays, cements, and lack of obvious mesopores. Other authors (e.g., Weimer
and Sonnenberg, 1984; Birmingham et al. 2001; Smith, 2015; Sterling et al. 2015) have stated
that it is a known fact that clays and cements adversely affect permeability in the Codell
sandstones. Caraway (1990) argued that the secondary pores created by dissolution of
aluminosilicates appeared isolated, thus implying a poorly connected pore network.

Documentation and discussion of the Codell’s pore network has been similarly minimal.
All three prior studies (Henningsgaard, 1986; Caraway, 1990; Sablina, 1993) restricted their
efforts to transmitted light microscopy, which limited resolution for viewing micropores. Those
prior used SEM imaging to document clay types and cements, not to focus on small-scale pores.
The best prior assessment of cumulative effects of diagenesis on pore network comes from
Birmingham et al (2001). Those authors stated that the Codell’s reservoir quality has been
reduced due to “diagenetic precipitation of clay, and to a lesser extent, carbonate and sulfide
minerals that effectively reduce pore throat size and permeability.” Furthermore, Birmingham et
al (2001) wrote, “Clay, carbonate, and sulfide accessories reduce permeability through depositional admixing, intense bioturbation fabrics, and intrastratal alteration of feldspars and rock fragments creating authigenic pore-lining and pore-plugging cements.”

**Purpose of this Study**

This study focuses on the diagenesis of the Type 2 sandstone of the Codell Member in northeastern Colorado to better understand which processes played a role in developing a connected pore network. Detrital and authigenic clays in intergranular space certainly had an adverse effect on permeability (Weimer and Sonnenberg, 1984; Caraway, 1990; Sablina, 1993; Birmingham, 2001), but that is not to say that a pore network does not exist between clay particles. The Codell Sandstone is very productive, so there must be some type of connected pore network that facilitates the movement of hydrocarbons from storage in micropores and nanopores to induced fractures. The specific questions pursued are thus:

1. What are the permeable pathways through these low-permeability, clay-dominated sandstones?
2. How do those permeable pathways relate to the various diagenetic features observed within the Codell Sandstone?

Addressing these questions required, first and foremost, an understanding of the Codell’s paragenetic sequence as revealed by transmitted light microscopy and mineralogical phase mapping. Following this, flow paths through the argillaceous sands were imaged using epifluorescence microscopy of pores impregnated with rhodamine dye and were quantitatively characterized using petrographic image analysis techniques. Finally, relationships were established between diagenetic features and optimum flow paths using back-scattered electron imaging and mineral phase mapping. This last step helped determine which features hindered
and promoted continuous flow paths. Those insights, in turn, led to an improved understanding of the “critical events” within the Codell’s paragenetic sequence that affected its permeability.
CHAPTER II: METHODS

Sampling

These objectives of this thesis were met using core samples from the Wattenberg and Redtail areas (Fig. 1). The cores utilized were all proprietary cores owned by operators within the study area. Samples were provided from seven cores, with samples derived from existing core plugs (four Wattenberg cores) or trims (three Redtail cores). Routine core analyses, and in some cases x-ray diffraction analyses for mineralogy, had already been performed on some of those plugs by third party service companies, and those data were made available for this study (Table 1).

Core Descriptions

The four cores from Wattenberg and three cores from Redtail (Fig. 1) were described at sub-foot intervals for lithology, color, contacts, grain size, sedimentary structures, bioturbation intensity, and relative occurrence of vertical and horizontal burrows. Lithofacies were chosen based on types of sedimentary structures, bioturbation intensity, and grain size. The core descriptions are in Appendix A.

Thin Section Petrography

Twelve thin sections (all from the Narco Devore core) were provided for the study by that core’s owner. Thirty thin sections were prepared from the other core materials made available by the cores’ owners. Those 30 samples were selected to insure coverage of different lithofacies and the full range of porosity and permeabilities reported for each core. The 30 subsamples were impregnated with blue-dyed epoxy mixed with rhodamine B fluorescent dye. Samples were subjected to a vacuum, pressurized to 1500 psi, and were left overnight to cure. High-pressure mercury intrusion curves (Fig. 5) indicate that 10% to 58% (average 29 ± 17%) of
Table 1. Core data made available for this study.

<table>
<thead>
<tr>
<th>Well name</th>
<th>Abbreviation</th>
<th>Core Photos</th>
<th>Mineralogy Data</th>
<th>Routine core porosity &amp; permeability</th>
<th>Oil and water saturations</th>
<th>Thin sections</th>
<th>Borehole Logs</th>
<th>Rock Eval</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wattenberg cores</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Narco Devore</td>
<td>ND</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Puritan</td>
<td>P</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Rissler State</td>
<td>RS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miracle</td>
<td>M</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td><strong>Redtail cores</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrace</td>
<td>T</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Razor</td>
<td>RZ</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>CW</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Figure 5. Examples of high-pressure mercury injection data from two of the Wattenberg cores utilized in this study. A) Representative mercury injection curves that depict the range of relationships observed between injection pressures, pore throat radii, and percent of pore volume invaded. Horizontal dashed line represents injection pressure used for epoxy impregnation. B) Histogram of the relative abundance of porosity behind specific pore throat sizes. Plot averages data from multiple samples and facies – it is a composite of the entire Codell Sandstone.
the pore space was likely impregnated, representing pores accessed by pore-throats greater than 70 nm. All thin sections were glass mounted, 30-microns thick, and optically polished.

The blue epoxy was observed in meso- and micropores in transmitted light, and the rhodamine dye produced a purple-hued stain in micropores associated with intergranular clay, grain boundaries, and some grain surfaces (Fig. 6). This purple coloring was not seen in mesopores (e.g., moldic pores) that were filled with blue epoxy. The differential impregnation is hypothesized to result from the epoxy-rhodamine mixture separating into two phases during impregnation, resulting in a heterogeneous distribution of the rhodamine dye. The blue epoxy penetrated meso- and larger micro-pores, but its higher viscosity meant it did not penetrate into smaller pores between clay minerals and at the boundaries between clay and framework grains. In contrast, the rhodamine, which was dissolved in ether, would have had a lower viscosity and thus successfully penetrated sub-micron pore throats. At the point that pore throats were too small for even the rhodamine-ether mixture, the rhodamine may have “clogged” the throat and caused the surrounding areas to concentrate the most rhodamine and the epoxy to thus appear the darkest purple in transmitted light.

All forty-two thin sections (33 from the Wattenberg cores; 9 from the Redtail cores) were used for petrographic analysis. Each was imaged in plane and polarized transmitted light using an Olympus BH-2 petrographic microscope and attached AmScope FMA050 digital camera. Most photography was done at 200x and 400x total magnifications. Sedimentary structures, mineralogy, spatial distribution of detrital and authigenic phases, and cross-cutting relations indicative of paragenetic relations were all documented. In addition, average grain sizes were visually assessed.
Figure 6. Thin-section photomicrograph showing range of pore types present. Blue epoxy is visible in mesopores (M) and micropores (yellow arrows) in transmitted light. Rhodamine dye within micropores associated with intergranular clay and grain boundaries appears as a pervasive reddish to purple hue (yellow circles). Scale bar at lower right is 100 µm. Sample is from the Miracle well.
Point counts to establish mineralogies of framework grains, and thus classification on QRF plots, were not done because the prior work of Henningsgaard (1986) and Sablina (1993) had already established the sublithic nature of the Codell sands. The extents of grain replacements (described in results) also raises the question as to the value of model compositions. In addition, the research questions being pursued relate to diagenetic controls on permeability, for which a classification of framework grain compositions may have little relevance.

The lithofacies groups established by core observations and petrographic analyses, as well as the porosity and permeability data, were used to high-grade 19 samples for fluorescence imaging of the rhodamine dye. This imaging was done using a Nikon inverted spinning disk confocal microscope equipped with a Hamamatsu ImagEM EM-CCD digital camera. The light source was a SOLA light engine, which provides solid state white light for photographing in bright field. A Texas Red filter allowed for light at a wavelength of 558 nm to pass through to the sample and excite the rhodamine B dye. The dye fluoresces bright red at a wavelength of 645.5 nm.

Three areas were selected for imaging in each thin section based on staining patterns from the rhodamine (Fig. 7). The three areas were chosen on the assumption that capturing a representative range of fluorescing intensities would collectively subsample the heterogeneity in each sample’s porosity and permeability. Each of the three areas was imaged with a montage of 5x5 photos with stitched dimensions of approximately 2200 µm by 2200 µm. Both bright field and red fluorescent images were captured using the same parameters (brightness, contrast) for all three imaged areas in each of the 19 high-graded samples (Fig. 8).
Figure 7. Thin-section image (transmitted light) showing variability in the intensity of purple rhodamine stain. Based on the variability in that light purple coloration, three areas were chosen and imaged using epifluorescence microscopy (red boxes). Each area is approximately 2.2 mm by 2.2 mm. Scale bar at lower right is 5 mm. Sample is from the Miracle core.
Figure 8. A). Thin-section image (transmitted light; same as Figure 6) showing areas (red boxes) that were imaged using epifluorescence microscopy. B, C, D) Bright field (upper) and red fluorescent (lower) images for each of the three areas highlighted by the red box in image A. Each area in B, C, and D is a montage of 5x5 photos with stitched dimensions of approximately 2.2 mm by 2.2 mm. Sample is from the Miracle core.
**Image Analysis Using ImageJ-FIJI**

The red-fluorescent (RF) images capture the spatial attributes of the rhodamine-impregnated pore network. Those images were analyzed using ImageJ-FIJI, a free Java-based image processing program (https://imagej.net/Welcome). ImageJ was used to segment objects based on pixel intensity-thresholding and then calculate area and shape metrics for each object.

For each RF image, the histogram depicting the number of pixels with any particular fluorescing intensity (Fig. 9) did not exhibit any discrete peaks that would indicate a significant number of fluorescent pixels of a specific intensity. Rather, the histograms all showed one discrete peak of essentially non-fluorescent pixels belonging to framework grains and pyrite clusters (red arrow, Fig. 9C) and a broad range of fluorescent pixels that steadily decrease in number as intensity increases. The total area indicated by the fluorescent pixels severely overestimates the total porosity measured in the core plugs associated with each sample. Yet thresholding only for the pixels with the highest intensities vastly underestimates the measured porosity.

The broad range in observed fluorescence intensities is probably the result of a number of factors. First, within clay masses that contain microporosity, the intense fluorescence generated in the small pores probably “bleeds” over the adjacent non-fluorescent minerals. The photographic image thus records more apparent pore volume than is really present (Fig. 10A, B). Second, a micropore that is smaller than a pixel in the photographic image may not fluoresce as brightly as a micropore that is as large as a pixel because the later might contain more rhodamine dye. Thirdly, mesopores (e.g., secondary pores after dissolved framework grains) that were impregnated with blue epoxy do not display any visible purple hue, indicating low rhodamine
Figure 9. Bright field (A) and red fluorescent (B) images from a sample with relatively high permeability (same field of view as Fig. 7C). C) Frequency histogram showing the number of pixels at any particular fluorescing intensity for the image in B. Peak denoted by red arrow are the non-fluorescent pixels that occur over framework grains and pyrite clusters. Peak denoted by blue arrow indicates a high number of low-intensity pixels that are adjacent to grain boundaries. At still greater intensities, the pixel count steadily decreases as intensity goes up.
Figure 10. Bright field (left) and red fluorescent (right) images. A,B) An example of a dark clay mass in the center of the image (A) that contains abundant microporosity, as revealed by the rhodamine dye (B). The intense fluorescence generated in the micropores within the clay mass “bled” over the adjacent clay particles (especially in the rim of the clay mass), making the entire clay mass fluoresce red. If red is equated to porous, then all pixels in the microporous clay mass are classified as pore, when in fact they are a mixture of micropores and clay minerals. C,D) An example of a secondary mesopore (center) that was successfully impregnated with blue dyed epoxy, but not rhodamine, thus does not display a red fluorescence (D). The mesopore has some of the lowest pixel intensities in the RF image, but the intensity of those pixels are still higher than the framework grains’ pixels. Both samples are from the Terrace well.
concentrations. As a result, the mesopores have very low red fluorescence, albeit still greater than framework grains (Fig. 10C, D).

Because of the above described scenarios, it was assumed that a pore could be represented by any fluorescence intensity, but not all pixels exhibiting fluorescence at any one intensity would necessarily be a pore. Thus, rather than label all pixels that exhibit some level of fluorescence a “pore”, the full spectrum of intensities was subsampled. Five subsamples of the intensity range were used, with each subsample defined as a “channel”. Each channel was informally referred to as red, green, yellow, purple, and blue (Fig. 11). The range of intensities covered by each channel was selected after experimenting with different ranges across multiple samples that spanned different porosities. The goal of those experiments was to determine a uniform range of intensities for each channel that would result in the segmented pixel areas approximating each sample’s porosity (as determined by core analysis). Each channel, with the exception of blue, was given a small range (Table 2). The blue channel was set to cover the highest fluorescent intensities, which corresponded to gray scales of 145 or more. In most of the high-graded samples, the blue channel was non-existent due to a lack of pixels that fluoresce within that range. For samples that did display a blue channel, the area of the image represented by that blue channel was two orders of magnitude smaller than the areas represented by all of the other areas combined.

The range of intensities for all channels except for red were kept the same for all images across all samples. The red channel, which has the lowest gray scale range, corresponds to the least fluorescent pixels in mesopores and surrounding grain boundaries. It could not be set to a single range for all samples, probably because of differences in how much the rhodamine and epoxy separated during impregnation. However, the same intensity range was used for the red
Figure 11. Frequency histogram shown in Figure 8C. Five intensity ranges, outlined by red, green, yellow, purple, and blue boxes (and coded by those colors), were subsampled to define the pore network.
<table>
<thead>
<tr>
<th>Channel #</th>
<th>Channel Label</th>
<th>Intensity range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Red</td>
<td>Variable, but total range ≤ 5</td>
</tr>
<tr>
<td>2</td>
<td>Green</td>
<td>45-50</td>
</tr>
<tr>
<td>3</td>
<td>Yellow</td>
<td>70-75</td>
</tr>
<tr>
<td>4</td>
<td>Purple</td>
<td>115-120</td>
</tr>
<tr>
<td>5</td>
<td>Blue</td>
<td>145-255</td>
</tr>
</tbody>
</table>

Table 2. Intensity ranges used to segment pixels on the RF images into channels.
channel in all fields of view within an individual thin section. In all samples, the intensity ranges for the red channel never exceeded 5 (Table 3).

Once the intensity range of each channel was defined for a sample, all pixels covering each range were segmented (Fig. 12). Then the five images representing each channel were merged into a “composite binary threshold image” (Fig. 13) that depicts “connected areas” as white and solid material as black. This composite binary threshold image does NOT represent the actual pores in a sample. Rather, the image is a network of connected areas in a single plane that is ASSUMED to represent the pore network. That assumption was evaluated by plotting the total area of the composite image segmented as connected pores against the actual plug permeability of the sample (Fig. 14). A strong positive correlation ($r^2=0.89$) was determined, indicating that each segmented “composite binary threshold image” did indeed capture a valid representation of each sample’s connected pore network. A one-to-one relationship was not expected as the segmented pore network for each sample is derived from an area representing about 14.5 mm$^2$ whereas the core plug permeabilities represent about 13 cm$^3$ orders of magnitude greater volume. What is most important is that the more permeability in the core plug, the greater the segmented area in the thin-section images.

**Skeletonization & Skeletal Analysis**

Each composite thresholded binary image was skeletonized using ImageJ. The skeletonization process computes the center point along the length of each 2D object, which in the case of a pore network, means it defines a one-pixel wide central flow path through each discrete “connected area”. Skeletonization does not connect separate objects (i.e., separate pore networks). The result is a skeletal network that depicts all separate connected flow paths in a “composite skeletal image” (Fig. 15).
<table>
<thead>
<tr>
<th>Sample</th>
<th>Red Channel Intensity Range</th>
<th>Total # of Segmented Paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narco Devore 7441.8</td>
<td>20–25</td>
<td>5</td>
</tr>
<tr>
<td>Miracle 7234.85</td>
<td>23–28</td>
<td>5</td>
</tr>
<tr>
<td>Terrace 6195.8</td>
<td>15–19</td>
<td>4</td>
</tr>
<tr>
<td>Narco Devore 7435.2</td>
<td>15–19</td>
<td>3</td>
</tr>
<tr>
<td>Narco Devore 7442.1</td>
<td>22–25</td>
<td>3</td>
</tr>
<tr>
<td>Terrace 6189.0</td>
<td>19–24</td>
<td>5</td>
</tr>
<tr>
<td>Miracle 7225.65</td>
<td>27–32</td>
<td>5</td>
</tr>
<tr>
<td>Razor 5887.25</td>
<td>30–35</td>
<td>5</td>
</tr>
<tr>
<td>Miracle 7237.55</td>
<td>32–37</td>
<td>5</td>
</tr>
<tr>
<td>Miracle 7230.65</td>
<td>27–32</td>
<td>5</td>
</tr>
<tr>
<td>Terrace 6190.8</td>
<td>30–35</td>
<td>5</td>
</tr>
<tr>
<td>Rissler State 7329.1</td>
<td>25–30</td>
<td>5</td>
</tr>
<tr>
<td>Miracle 7222.25</td>
<td>30–35</td>
<td>5</td>
</tr>
<tr>
<td>Cottonwood 5881.25</td>
<td>20–25</td>
<td>5</td>
</tr>
<tr>
<td>Rissler State 7321.0</td>
<td>25–30</td>
<td>5</td>
</tr>
<tr>
<td>Puritan 7820.2</td>
<td>23–28</td>
<td>5</td>
</tr>
<tr>
<td>Rissler State 7319.1</td>
<td>27–30</td>
<td>3</td>
</tr>
<tr>
<td>Rissler State 7332.6</td>
<td>29–34</td>
<td>5</td>
</tr>
<tr>
<td>Rissler State 7335.1</td>
<td>25–30</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3. Ranges used to define the red channel in RF images of all samples. The red channel, which covers the lowest fluorescence intensities in mesopores and around grain boundaries, had to be adjusted for each thin-section sample. Each field of view (3 per thin section) was segmented using the intensity range chosen for that sample.
Figure 12. Example of segmented channels for one field of view (Fig. 7C) in a Miracle sample with relatively high permeability. The pixel intensity histogram for this field of view is shown in Figures 8C and 10. A) Red fluorescent image prior to segmentation; B) red channel (intensities of 23-28); C) green channel (intensities of 45-50); D) yellow channel (intensities of 70-75); E) purple channel (intensities of 115-120); and F) blue channel (intensities of 145-255). Most of the red fluorescing pixels are in the red and green channels. The red channel has the most segmented area despite having a small range, and it is outlining grain boundaries.
Figure 13. The same field of view as Figures 11 and 7C. A) RF image prior to segmentation. B) The composite binary threshold image generated by taking all 5 channels (Figures 11B to 11F) and merging them into a single binary image. Porous areas are white, and solid material is black. The composite binary threshold image does NOT represent porosity in a sample, but rather a network of connected areas in a single plane that can be used to represent the pore network.
Figure 14. Covariance of segmented image area versus permeability for the 19 high-graded sample set. The strong covariance indicates that the segmentation process captured features that correlate to permeability.
Figure 15. The same field of view as Figures 13, 11 and 7C. A) Composite binary threshold image prior to skeletonization. B) Composite skeletal image depicting all connected flow paths for thresholded (white) objects. Skeletonization defines a central path that is 1 pixel wide through each object, and separate objects do not connect to each other.
To characterize these skeletal networks (i.e., flow paths), another ImageJ plugin was used to analyze the “composite skeletal image”. This plugin employs a graph analysis algorithm to give metrics that characterize each skeletal network. Those metrics include the number of junctions, triple and quadruple points, endpoint, and branches in each skeletal network, and the maximum and average branch length in pixel lengths (Polder et al. 2010). Furthermore, the plugin uses the Floyd–Warshall algorithm to perform multiple iterations to find and measure the shortest connected path between the two furthest points in each skeletal network (Floyd, 1962; Warshall, 1962). Figure 16A is an idealized representation of a skeletal network with junctions (including triple- and quadruple-points), branches, and endpoints labeled. A junction (black dot) is where two or more branches intersect, with triple- and quadruple-points referring to the number of branches connecting at one point. A branch is defined as a continuous line of pixels that terminates at either an endpoint or a junction. In red (Fig. 16A) are the branches that are part of the single skeletal unit connected via junctions. In green (Fig. 16B) is the shortest continuous path between the two furthest endpoints in this skeleton. These paths, hereon called “flow paths”, are measured in pixels by summing the lengths of only the branches that make up the shortest path.

For each sample, the graph analysis yielded a data table containing thousands of flow paths, ranging in length from tens to thousands of pixels. Exploring for relations between the flow paths and diagenetic features meant correlating the two suites of observations. However, imaging hundreds or thousands of paths in each sample was impossible. A cumulative frequency plot of all the flow paths greater than 100 pixels long was constructed for each of the 19 skeletonized composite binary images. From this plot, the longest flow paths were identified, overlaid, and traced on their respective bright field image. The number of flow paths selected
Figure 16. A) Idealized representation of a skeletonized network. The skeleton depicts the connected center point pathway within each object (e.g., white pixels in Figure 12B) of the composite binary threshold image. Herein, the skeletonized network is interpreted to represent the generalized flow path through the pore network represented by each skeletonized object. Branches are skeletonized paths that terminate at either an endpoint (green dots) or a junction. Junctions (black dots) are points where two or more branches intersect. Triple-points and quadruple-points are types of junctions where three and four branches connect, respectively. A single skeleton is continuous until endpoints are reached on all sides and may contain one branch or thousands of branches. B) Same image as A. Highlighted in green is the shortest continuous path between the two furthest endpoints in this skeleton. Its length is determined by summing the lengths of just those branches that make up the shortest path.
varied from sample to sample (Table 4). The five longest paths in each sample were also chosen for imaging and mineral phase mapping via an electron microprobe.

**Electron Microprobe Analysis**

An electron microprobe was used to identify the minerals present in the Codell Sandstone, constrain the relative timing of digenetic processes, and assess mineralogical heterogeneity along the flow paths defined by skeletonization of the pore network. All electron microscopy was conducted in the Department of Geological Sciences, University of Colorado, Boulder. The optically polished thin sections were carbon-coated and analyzed using a JEOL JXA-8230 electron microprobe. Initially, a lanthanum (LaB$_6$) cathode electron gun was used, but midway through the analyses that was changed to a tungsten filament. Operating conditions were 15 kV and 2.0 nA.

Samples were initially imaged at 600x to 800x magnifications using secondary electron (SE) and back-scattered electron (BSE) modes to document textural and mineralogical relations. Elemental maps were also made of select fields of view using a Thermo Scientific UltraDry silicon drift Energy-dispersive X-ray spectrometer (EDS). The elemental maps were converted to mineralogical phase maps using the Pathfinder X-ray Microanalysis software. The COMPASS phase mapping algorithm was used to classify distinct phases in a sample based on x-ray spectrum information collected by the microprobe. These phases depict which minerals are present in a field of view, and the spatial relations between those different mineral phases. Phase maps allowed for high-resolution analysis of the paragenetic sequence.

The endpoints of the 5 longest paths in each sample were captured, as well as an area where the path was continuous (Fig. 17). Paths were imaged with the electron microprobe at 1000x to 1500x using BSE mode, and elemental x-ray energy information was collected for
<table>
<thead>
<tr>
<th>Sample</th>
<th>Porosity (%)</th>
<th>Permeability (md)</th>
<th># of Paths Identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narco Devore 7441.8</td>
<td>12.300</td>
<td>0.13000</td>
<td>10</td>
</tr>
<tr>
<td>Miracle 7234.85</td>
<td>9.055</td>
<td>0.11056</td>
<td>5</td>
</tr>
<tr>
<td>Terrace 6195.8</td>
<td>14.495</td>
<td>0.0968</td>
<td>5</td>
</tr>
<tr>
<td>Narco Devore 7435.2</td>
<td>13.200</td>
<td>0.09000</td>
<td>9</td>
</tr>
<tr>
<td>Narco Devore 7442.1</td>
<td>10.200</td>
<td>0.03000</td>
<td>8</td>
</tr>
<tr>
<td>Terrace 6189.0</td>
<td>13.015</td>
<td>0.02905</td>
<td>6</td>
</tr>
<tr>
<td>Miracle 7225.65</td>
<td>12.273</td>
<td>0.02905</td>
<td>8</td>
</tr>
<tr>
<td>Razor 5887.25</td>
<td>16.010</td>
<td>0.023</td>
<td>8</td>
</tr>
<tr>
<td>Miracle 7237.55</td>
<td>11.213</td>
<td>0.02110</td>
<td>8</td>
</tr>
<tr>
<td>Miracle 7230.65</td>
<td>14.325</td>
<td>0.02005</td>
<td>5</td>
</tr>
<tr>
<td>Terrace 6190.8</td>
<td>14.225</td>
<td>0.01890</td>
<td>10</td>
</tr>
<tr>
<td>Rissler State 7329.1</td>
<td>13.850</td>
<td>0.01729</td>
<td>6</td>
</tr>
<tr>
<td>Miracle 7222.25</td>
<td>10.336</td>
<td>0.01565</td>
<td>8</td>
</tr>
<tr>
<td>Cottonwood 5881.25</td>
<td>12.941</td>
<td>0.01527</td>
<td>6</td>
</tr>
<tr>
<td>Rissler State 7321.0</td>
<td>11.245</td>
<td>0.01176</td>
<td>6</td>
</tr>
<tr>
<td>Puritan 7820.2</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Rissler State 7319.1</td>
<td>4.474</td>
<td>0.00922</td>
<td>5</td>
</tr>
<tr>
<td>Rissler State 7332.6</td>
<td>10.135</td>
<td>0.00887</td>
<td>11</td>
</tr>
<tr>
<td>Rissler State 7335.1</td>
<td>9.010</td>
<td>0.00584</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4. Porosity, permeability, and number of longest flow paths identified for each sample.
Figure 17. Various images illustrating the mineralogical imaging and analysis along a skeletonized flow path. A) Bright field image showing one of the longest flow paths (red squiggly line) revealed by skeletal analysis. B, C, D) Paired transmitted light photomicrograph and mineralogical maps (from EDS mapping on the electron microprobe) at the flow paths’ endpoints (C, D) and in a continuous section of the path (B). Key to mineralogical colors to the right.
COMPASS phase mapping as described above. The objective was to assess the relation between skeletonized flow paths and mineralogical features. The specific goals were to determine (1) if there were any unique petrographic associations with where paths terminated, or (2) if there were any diagenetic differences between paths present in high permeability samples versus those in low permeability samples.
CHAPTER III: LITHOFACIES FRAMEWORK

**Observed Lithofacies and their Attributes**

A total of five lithofacies was observed in the Codell Member (Table 5). The five Codell lithofacies include three characterized by cross stratification and two characterized by bioturbation. CDL-1 is a tabular to trough cross-stratified sandstone with a bioturbation index of 0 or 1 (Fig. 18A). This lithofacies only occurs in the Redtail cores. CDL-2 is a thinly-laminated, low angle horizontal to hummocky cross-stratified sandstone with minimal to no bioturbation (Fig. 18B). Symmetrical ripple laminae may occur in this lithofacies, as well as mud drapes (the latter only in Redtail cores). This lithofacies has a bioturbation index of 0 or 1. CDL-3 is a thinly laminated, low-angle horizontal to hummocky cross-stratified sandstone with moderate bioturbation (Fig. 18C). Mud drapes in the Redtail cores are also observed in this lithofacies. It exhibits a bioturbation index of 2 to 4, which is the main distinguishing feature from lithofacies CDL-2. CDL-4 (Fig. 19) is a fine to lower medium grained sandstone with pervasive amounts of bioturbation (bioturbation index of 5 or 6). CDL-5 (Fig. 20) is a silty to upper very fine grained sandstone also with pervasive amounts of bioturbation (bioturbation index of 5 or 6). Based on x-ray diffraction data from three Wattenberg cores (Table 1), total clay content in the burrowed lithofacies ranges from 12.7 to 35.0%, whereas total clay content in laminated lithofacies ranges from 13.3 to 31.0%.

There are several important differences in lithofacies between the Wattenberg and Redtail areas (Table 5). First, and perhaps most obvious, is that laminated lithofacies (CDL-1, 2, and 3) occur more often in Redtail Field than in Wattenberg Field. In fact, laminated lithofacies are six times more common in the Redtail cores than in the Wattenberg cores, with the tabular to trough cross stratified sandstone (CDL-1) only occurring in the Redtail area. Bioturbated finer grained
<table>
<thead>
<tr>
<th>Facies name</th>
<th>Characteristic sedimentary structures</th>
<th>Grain size</th>
<th>UV fluorescence</th>
<th>Bioturbation Index</th>
<th>Relative abundance</th>
<th>Porosity</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDL-1</td>
<td>Tabular-trough cross-stratified</td>
<td>Medium sand</td>
<td>Fluoresces brightly</td>
<td>1</td>
<td>Not present in Wattenberg cores; 7% in Redtail cores</td>
<td>Redtail: 14.5%</td>
<td>Redtail: 0.09 md</td>
</tr>
<tr>
<td>CDL-2</td>
<td>Low angle horizontal cross beds, symmetrical ripples, hummock cross strata, and mud drapes</td>
<td>Very fine to fine sand</td>
<td>Fluoresces brightly</td>
<td>0-1</td>
<td>2% in Wattenberg cores; 33% in Redtail cores</td>
<td>Wattenberg: 10.2%-11.2%</td>
<td>Wattenberg: 0.02-0.03 md</td>
</tr>
<tr>
<td>CDL-3</td>
<td>Same as CDL-2, but also with distinct burrows</td>
<td>Very fine to upper fine sand</td>
<td>Fluoresces brightly</td>
<td>2-4</td>
<td>8% in Wattenberg cores; 20% in Redtail cores</td>
<td>Wattenberg: 10.1%-13.8%</td>
<td>Wattenberg: 0.008-0.013 md</td>
</tr>
<tr>
<td>CDL-4</td>
<td>Extensive bioturbation</td>
<td>Fine to lower medium sand</td>
<td>Generally does not fluoresce</td>
<td>5-6</td>
<td>45% in Wattenberg cores; 14% in Redtail cores</td>
<td>Wattenberg: 4.5%-14.3%</td>
<td>Wattenberg: 0.009-0.440 md</td>
</tr>
<tr>
<td>CDL-5</td>
<td>Extensive bioturbation</td>
<td>Silt to very fine sand</td>
<td>Generally does not fluoresce</td>
<td>5-6</td>
<td>45% in Wattenberg cores; 26% in Redtail cores</td>
<td>Wattenberg: 7.3%-13.2%</td>
<td>Wattenberg: 0.005-0.25 md</td>
</tr>
</tbody>
</table>

Table 5. Characteristics of the five facies observed in the Codell Sandstone.
Figure 18. Core photographs showing examples of laminated Codell lithofacies. For scale, all cores are 4 inches (10.1 cm) wide. A) Lithofacies CDL-1, a tabular to trough cross-stratified sandstone with a bioturbation index of 0 to 1. This lithofacies type is found only in the Terrace core. B) Lithofacies CDL-2, a thinly-laminated, low-angle horizontal to hummocky cross-stratified (top of the image) sandstone with minimal to no bioturbation. Yellow arrows point to mud drapes (Cottonwood core). C) Lithofacies CDL-3, a thinly-laminated low-angle horizontal to hummocky cross-stratified sandstone with moderate bioturbation (white arrows) and mud drapes (yellow arrows) (Miracle core).
Figure 19. Core photographs showing examples of burrowed Codell lithofacies 4. For scale, all cores are 4 inches (10.1 cm) wide. To the left are reflected light images; to the right are UV fluorescent images. A, B) Example of lithofacies CDL-4a (Cottonwood core), a fine- to lower medium-grained sandstone with pervasive amounts of bioturbation (bioturbation index of 5 or 6). This lithofacies is characterized by burrows that fluoresce under UV light (B). C, D) Example of lithofacies CDL-4b (Puritan core), whose burrows do not fluoresce under UV light (D).
Figure 20. Core photographs showing examples of burrowed Codell lithofacies 5. For scale, all cores are 4 inches (10.1 cm) wide. To the left are reflected light images; to the right are UV fluorescent images. A, B) Example of lithofacies CDL-5a (Razor core), a silty to upper very fine grained sandstone with pervasive amounts of bioturbation (bioturbation index of 5 or 6). This lithofacies is characterized by burrows that fluoresce under UV light (B) C, D). Example of lithofacies CDL-5b (Razor core), whose burrows do not fluoresce under UV light (D).
CDL-5 sands are also more common than bioturbated coarser grained CDL-4 sands in the Redtail cores. In contrast, there is an equal abundance of finer and coarser bioturbated sands in the Wattenberg cores.

The types of ichnofossils observed within lithofacies CDL-3, CDL-4, and CDL-5 are a mixed association of vertical, inclined, and horizontal structures. The pervasively bioturbated lithofacies, CDL-4 and CDL-5, exhibit high diversity and abundance of burrowing structures. Vertical traces include Diplocraterion, Thalassinoides, Teichichnus, and minor Ophiomorpha and Skolithos. Horizontal traces include Palaeophycus, Chondrites, Planolites, and Zoophycus. These trace fossils are mainly associated with the Cruziana and Zoophycus ichnofacies (MacEachern et al., 2010), with the latter being more common in the Wattenberg cores. Sablina (1993) identified a few of the same ichnogenera in her study and concluded that the Codell sandstones had a mixed “Cruziana-Zoophycos” ichnofacies. More recently, Krueger (2015) concluded the Codell sandstones in the Wattenberg area were dominated by a Cruziana ichnofacies assemblage, with a prevailing Zoophycus ichnofacies in horizontally burrowed deeper-water lithofacies. When Ophiomorpha and Skolithos were observed, it was mainly in lithofacies CDL-3, at the exclusion of horizontal traces, and was associated with a Skolithos ichnofacies. In the Redtail cores, there is also a clear preference for unlined vertical traces, and their abundance indicates a Glossifungites ichnofacies. This assemblage reflects firm but unlithified substrates and demarcates a number of discontinuities in deposition (MacEachern et al., 2010).

**Interpretation of Depositional Setting**

As marine trace fossils occur across 98% and 60% of the Codell section in the Wattenberg and Redtail cores, respectively, those traces are key to interpreting the depositional processes and setting of the Codell sandstones. The Cruziana and Glossifungites ichnofacies
indicate deposition of the Codell sediments as subtidal, poorly sorted, semi-cohesive to firm substrates (MacEachern et al., 2010). Depositional settings would have been on a sloping shelf profile below fair-weather wave base and above storm wave base where these two ichnofacies dominate (MacEachern et al., 2010). Moreover, the presence of the Zoophycus ichnofacies indicates deposition in possibly deeper and/or calmer waters with lowered oxygen levels (MacEachern et al., 2010). In contrast, the Skolithos ichnofacies, when present in lithofacies CDL-3, is indicative of higher wave energy. These traces often occur in clean, well-sorted, shifting substrates—conditions commonly occurring above fair-weather storm base in foreshore settings (MacEachern et al., 2010).

The subtidal, shallow marine shelf depositional setting indicated by the ichnofacies constrains the depositional processes of the cross-stratified lithofacies (CDL-1, 2, and 3). The tabular to trough cross bedding in lithofacies CDL-1 indicates traction transport of sands under unidirectional flow, probably by marine currents in the shallowest depositional setting represented (e.g., foreshore). In contrast, the hummock and symmetrical ripples of lithofacies CDL-2 and CDL-3 indicate combined and oscillatory flow, respectively, on the offshore marine shelf. The combined flow that produced the hummocky cross strata was the result of storms and could represent deposition at or above storm wave base. Offshore transport of the sands now in the bioturbated lithofacies (CDL-4 and CDL-5) was probably also driven by storm and normal marine currents. It is assumed that the sediments were originally deposited as alternating laminae of sand (higher energy current deposits) and mud (lower energy deposits). Those original sand laminae were likely similar to those observed in lithofacies CDL-2 and CDL-3. Subsequent to deposition, the different laminae were destroyed by organisms living at or slightly below the sediment-water interface, resulting in the extensively bioturbated muddy sands seen in the cores.
Bioturbation was so extensive that no original physical sedimentary structures were preserved in lithofacies CDL-4 and CDL-5. Lithofacies CDL-3 would be the intermediary condition in that it exhibits both preservation of the original cross-stratified sandstones and partial bioturbation.

**Vertical Changes in Facies Types**

Average sand sizes and ichnofacies indicate an overall regressive sequence with increasing depositional energy (Fig. 21). A low angle, coarse-grained lag deposit was observed near the base of the Codell Member in one of the Redtail wells (Fig. 22) but was not seen in any other core. However, Henningsgaard (1986) and Sablina (1993) recorded this type of feature in two of their Wattenberg wells, and Caraway (1990) noted coarser-grained, angle-of-repose basal deposits in two Codell outcrops. Krueger (2015) also recorded an interval of lower coarse sand at the bottom of one of her Wattenberg cores. This coarse lag is interpreted to mark erosion and reworking of material in association with the basal unconformity between the Codell Sandstone and the underlying shale. Deeply burrowing organisms could have reworked some of the coarser sand upwards into overlying bioturbated lithofacies.

Sand-size changes within the Codell are often summarized as gradually coarsening upward (Henningsgaard, 1986; Caraway, 1990 Sablina, 1993; Krueger, 2015), and this trend was also documented in the Wattenberg cores. In that area, the Codell Sandstone gradually coarsens upward from a very fine, silty sandstone to an upper fine- to lower medium-grained sandstone (Fig. 21A). The finer-grained basal sand is compatible with initial deposition offshore. As Codell deposition progressed, accommodation decreased, energy levels increased, and the fine- to lower medium-grained sands were deposited. The evolution in trace fossil assemblages, from a more Zoophycus ichnofacies at the bottom to a more Cruziana ichnofacies at the top, further suggests an overall shallowing-upward, regressive sequence. Lower energy and a more stable
Figure 21. Simplified descriptions of the Codell sandstone in a Wattenberg core (left) and a Redtail core (right) showing just lithology and grain size. A) Upper 10 feet of the Narco Devore shows a coarsening-upward trend from a very fine, silty sandstone to a medium grained sandstone. B) Complete Codell section in the Cottonwood core shows a fining-upward trend from a medium-grained sandstone to a very fine sandstone. Carbonate is present in the upper foot of both cores.
Figure 22. Low-angle cross-stratified coarse-grained sandstone lag deposit near the base of the Codell Sandstone in the Razor core. This sublithofacies was only noted in this one Redtail well. Conglomeratic mud clasts (red arrows) and erosional truncation suggest an association with the unconformity between the Codell Sandstone and underlying Carlile shale.
environment during early Codell deposition promoted higher abundance and diversity of organisms.

In the Redtail cores, the grain size gradually fines upward from a medium sandstone to a lower fine sandstone (Fig. 21B). This would indicate decreasing depositional energy moving up through the section. Large intervals of laminated lithofacies (CDL 1, 2, and 3) are preferentially concentrated in the lower half of the Codell Sandstone that could indicate higher energy and shallower waters during deposition of the lower Codell sands in the Redtail area. Alternately, the greater amounts of bioturbation in the upper half of the Codell sands could also mean the lack of cross laminations in that interval is due to a preservation bias more so than a trend in depositional water depths and settings. The occurrence of mud drapes within the laminated lithofacies indicates quiescence after transient high-energy events. Within the burrowed lithofacies (CDL 3, 4 and 5), vertical traces belonging to the Glossifungites-Cruziana ichnofacies appear consistently, but horizontal burrows occur more frequently in the upper half of the Codell Sandstone than in the lower half. This suggests lower-energy deposition of the upper Codell sands in the Redtail area relative to the upper Codell sands in the Wattenberg area. The lower energy may have been the result of either deeper water or a more restricted depositional setting (Anderson, 2011).

Porosity and Permeability Attributes of Lithofacies

Core photos taken with UV light indicate the presence of hydrocarbons in both the laminated and burrowed lithofacies of the Codell Sandstone. The distribution of UV fluorescence hints at the location of effective pore networks in this heavily bioturbated, low-permeability reservoir sand. Nearly all laminated lithofacies fluoresce under UV light, even those with moderate bioturbation (i.e. CDL-3), and almost half of the intensely bioturbated lithofacies
(CDL-4 and CDL-5) exhibit UV fluorescence in some burrow traces (Figs. 19, 20). Therefore, an effective pore network exists within all laminated lithofacies, but that network can be variable in its occurrence and connectivity within bioturbated lithofacies. Furthermore, in Wattenberg and Redtail fields, burrows in coarser sands are more likely to fluoresce in UV light (i.e. CDL-4a) than burrows going through finer sands (i.e. CDL-5b).

When porosity and permeability data for the Codell Sandstone are cross plotted (Fig. 23), several relationships are revealed as a function of lithofacies. First, the burrowed lithofacies (CDL-4 and CDL-5) generally have lower porosities (average 10.6 ± 2.6 %, range 5-15%) than laminated lithofacies (CDL-1, 2, and 3), which average 13.7 ± 2.6% (range 9-18%). All of the higher porosity laminated lithofacies, however, are from the Redtail area. Regardless of location, burrowed lithofacies also exhibit a larger range in permeability than the laminated lithofacies (Fig. 23A).

Individual lithofacies do not have as much variability in porosity and permeability (Fig. 23B) as the larger lithofacies groupings. The most porous lithofacies tend to be CDL-2 and CDL-3 in the Redtail cores, whereas the most permeable tend to be examples of lithofacies CDL-4 and CDL-5 in the Wattenberg core. The latter observation, however, may be a measurement artifact as those more permeable samples are mostly from the Narco Devore core, which is about three decades older than all others studied.

Porosity and permeability as a function of depth and mineral abundances generally show no covariant relations. In particular, permeability exhibited no trend with depth, and most of the minerals analyzed via XRD and FTIR lacked any sort of trend with either porosity or permeability (Appendix B). However, some exceptions occur. A slight increase in porosity occurs with decreasing depth ($R^2=0.25$) in samples from both Wattenberg and Redtail areas, and
Figure 23. Cross plots of porosity and permeability for all samples with routine core analysis. A) Data grouped into laminated (yellow) and bioturbated (green) lithofacies. Squares represent Redtail samples, and circles represent Wattenberg samples. B) Same data, but sorted by specific lithofacies as well as area.
Porosity increases with quartz content ($R^2=0.21$) in samples from the Wattenberg cores (Figs. 24A, 24B). These relationships would indicate that porosity is better developed in the shallower Codell intervals, perhaps due to the coarsening upward grain-size trend, and in areas where quartz content is higher. It is assumed that these relatively quartz-rich intervals also have lower total clay content, and indeed, quartz content and total clay content display a strong inverse relationship ($R^2=0.64$) (Fig. 24C); but, the latter has almost no effect on porosity ($R^2=0.03$) (Fig. 24B).

Permeability displays very weak positive covariance with the abundance of plagioclase ($R^2=0.18$) and mixed-layered illite-smectite ($R^2=0.26$) (Fig. 25). The weakness of the covariance with plagioclase makes any definitive statements regarding an effect of on permeability purely speculative. The relationship with mixed I/S clays, which means with detrital as well as potentially authigenic I/S, might mean that more permeable samples have more detrital smectitic clay that is undergoing illitization, and perhaps more restructuring of the clays’s fabric to create better pathways for fluid flow. However, such an inference is purely speculative as the covariance between permeability and mixed I/S is too weak to draw any absolute conclusions.

The variability in porosity and permeability, and the overlap in values between lithofacies and general groupings of lithofacies, indicates that there is more to the porosity and permeability variability in the Codell Sandstone than just major lithofacies differences. In addition, much of the permeability data for the fluorescing burrowed lithofacies falls within the same range as the permeabilities for the laminated lithofacies (Fig. 23). This would suggest an effective pore network is present within the burrowed lithofacies that can match the laminated lithofacies in connectivity and possibly production capability. Porosity and permeability within the Codell Sandstone also cannot be defined simply by mineralogical and depth trends (Figs. 24, 25,
Figure 24. A) Cross plot of porosity versus depth below the top of the Codell for samples in Wattenberg and Redtail cores. B) Cross plot of mineral content (from XRD or FTIR analyses) versus porosity for Wattenberg samples. Quartz content indicated by blue and total clay content indicated by red. C) Cross plot of quartz content versus total clay content for Wattenberg samples.
Figure 25. Cross plots of permeability (log scale) versus A) plagioclase feldspar content and B) mixed-layered illite-smectite content. Samples are all from the Wattenberg cores. The weak covariance indicates that permeability cannot be defined simply by mineralogical trends, and that diagenesis is playing a significant role in creating more permeable pathways.
Appendix B). Furthermore, porosity and permeability lack any sort of correlation (Fig. 23).

Collectively, the lack of correlation of those petrophysical variables as a function of lithofacies, mineralogy, or depth suggest that diagenetic processes are controlling permeability. Furthermore, this lack of relationships all suggest that permeability, rather than porosity, is the key variable to understanding the relationships between the Codell’s pore networks, lithofacies, and diagenetic processes.
CHAPTER IV: RESULTS

Paragenetic sequence

Overview.—Twelve diagenetic features were identified in the Codell sandstones based on thin-section analysis and mineral phase mapping done with the electron microprobe. The relative timing of those twelve features with respect to each other, which defines the paragenetic sequence (Fig. 26), was constrained by cross-cutting relationships. The entire paragenetic sequence was divided into four major intervals: syn-depositional, shallow, intermediate, and deep-burial diagenesis. Herein, syn-depositional diagenesis refers to diagenetic features that occurred shortly after burial and probably within meters of the sediment-water interface. Shallow-burial diagenetic processes are defined herein as any process that must have formed more than several meters below the seafloor, but does not post-date the end of mechanical compaction. Intermediate burial processes are those that clearly post-date mechanical compaction, but precede the formation of illite, chlorite and cubic pyrite. Deep burial, the “late” stage of Codell diagenesis includes features that post-date feldspar dissolution.

Syn-depositional Diagenetic Features.—Syn-depositional diagenesis is characterized by alterations that occurred while the sediment was still near the sediment-water interface. Any diagenetic alterations occurring at this time can be related in some form or fashion to the overlying depositional surface. Thus, syn-depositional features probably occurred within a meter or less of the depositional surface. During this time, sediments are unconsolidated and initially composed of alternating layers of sand (storm) and mud (fair weather) deposits.

Although not a diagenetic feature, bioturbation is included as a syn-depositional feature because of its effect on pore systems. Evidence for bioturbation are the trace fossils observed in the Codell cores (Figs. 18, 19, 27). Burrowing organisms moved in all directions and, in the
Figure 26. Paragenetic sequence for the Codell Sandstone showing all authigenic features observed with their relative timing to each other denoted by horizontal black lines (dashed where uncertain). Burial stages were defined by diagenetic processes and mineral alterations that typically occur within known depth-related chemical and temperature regimes (see text). The timing of diagenetic processes was constrained by cross-cutting relationships. Text in red refers to features that were observed only in the Redtail samples; all other features were observed in samples from both Redtail and Wattenberg fields.

<table>
<thead>
<tr>
<th>Diagenetic feature</th>
<th>Syn-Dep</th>
<th>Shallow</th>
<th>Intermediate</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioturbation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrite precipitation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz cementation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical compaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcite cementation and replacement of framework grains and matrix</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early clay replacement of feldspar and quartz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feldspar dissolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kaolinite precipitation in secondary pores and as a replacement of feldspars, quartz, and calcite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illitization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Albition of feldspars</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illite and chlorite precipitation in secondary pores and as a replacement of feldspars, quartz, and calcite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 27. Core photo from the Miracle well showing trace fossils left by organisms (blue arrows) burrowing vertically and horizontally through Codell sediments. Bioturbation of the alternating sand and mud layers resulted in a homogenized muddy sandstone above the red line. Burrowing organisms have introduced additional clays to these intervals, making bioturbation the first diagenetic process to have occurred in the Codell.
process, destroyed the originally alternating sand and mud layers. The mixing of the sediments would have placed detrital clay minerals into originally clay-free (or at least clay poor) sand layers. The result would have been conversion of originally open intergranular pore space to clay-filled voids between sand grains.

The other syn-depositional feature is initial pyrite precipitation, which is represented by micron-sized (10-20 µm) and isolated pyrite framboilds. These small crystals contrast sharply with large crystalline pyrite clusters that formed later (Fig. 28). The isolated pyrite framboilds are not commonly observed in the Codell, but when they are, the framboilds are typically encased in authigenic calcite and quartz.

Bioturbation and formation of pyrite framboilds are interpreted as occurring syn-depositionally because they require continuous fluxes of oxygen and sulfur, respectively, both of which occur at and generally within a meter of the sediment surface. Organisms living in the substrate required oxygen, which would have been more than adequate at the sediment-water interface, and up to many tens of centimeters into the substrate. Also, the lack of preserved sedimentary structures in the cores indicates that they were destroyed by burrowers almost immediately after deposition. Framboidal pyrites are known to be an early diagenetic feature in marine sandstones (Burley, 1987; Larsen and Friss 1991; Karim et al. 2010; Aplin and Macquaker, 2011; García-García, 2013) and are interpreted here to have formed with very shallow burial, probably once the sediments were below the oxic to suboxic zone associated with bioturbation. Pyrite formation is dependent on the availability of sulfate ions that can diffuse downward from seawater (Larsen and Friss 1991). Under anoxic condition, that sulfate is reduced to sulfide by chemosynthetic microbes. The iron for the pyrite is derived from iron-
Figure 28. Paired thin-section photomicrographs (A–plane light; B–cross polars) showing micron-sized isolated pyrite framboïds (red circles) encased in quartz overgrowths (Qo) and intergranular calcite cement (IGC). Also shown in lower right is, calcite partially replacing quartz (CRQ) and completely replacing a feldspar (C). Blue epoxy in upper image fills moldic pores (MP) created by feldspar dissolution. Large pyrite clusters that have replaced portions of cements, detrital grains, or clays, and have precipitated into moldic pores following dissolution of framework grains are denoted by the green circles. Chert grains are also present here (Ch). Sample is from the Terrace core.
oxyhydroxide that is associated with detrital clays and organic matter (Larsen and Friss 1991; Loucks and Ruppel, 2007; Aplin and Macquaker, 2011).

**Shallow Burial Diagenetic Features.**—Diagenetic processes interpreted as occurring during shallow burial are quartz cementation, calcite cementation and replacement, mechanical compaction, and clay replacement of framework grains. Evidence for quartz cementation occurs as overgrowths observed on detrital quartz grains (Fig. 28). The overgrowths terminate in sharp euhedral edges that either face into what was an open intragranular pore, or abut euhedral overgrowths from adjacent grains. Those relations indicate that these cements initiated and grew before most compaction.

Evidence for calcite replacement and cementation consists of framework grains that have been replaced by calcite and carbonate cements filling intergranular pore space (Fig. 29). Detrital quartz grains show partial replacement by calcite (Fig. 28). Feldspars may be partially to completely replaced as indicated by a rectangular “ghost” of the precursor grain’s morphology (Fig. 29). Calcite cement grew concurrent with the replacive calcite and proceeded to fill intergranular voids (Fig. 29). The size of the intergranular spaces filled by calcite are approximately what one might expect in uncompacted sediment, indicating that the calcite formed before significant compaction had occurred. In the thin sections studied herein, the calcite cements abut quartz overgrowths (Fig. 29), indicating the overgrowths formed before the calcites. However, calcite is also known to occur as a first-generation cement within cleaner, sandier burrow fills (*Thalassinoides* and *Ophiomorpha*) and as a first-generation cement in some laminated sands (E. Gustason, personal communication). In the latter case, the calcite cement can occlude all pore space, as evidenced by the lack of any subsequent oil staining (e.g., 3-inch thick white laminated sands in Fig. 18C).
Figure 29. Paired thin section photomicrographs (A–plane light; B–cross polars) showing authigenic calcite (C) replacing framework grains (feldspars (F) and quartz (Qtz). At least one framework grain is completely replaced (R). Calcite also fills original pore space between grains (red arrows). The latter indicates calcite formed before that pore space was destroyed by mechanical compaction. The calcite cement also overlies quartz overgrowths (white arrows) indicating calcite formed after the onset of quartz cementation. Sample is from the Puritan core.
Evidence for mechanical compaction is the deformation of mica grains, longitudinal grain contacts, and a visually overly close packing of framework grains in sandstones. Quartz grains with overgrowths are observed impacting and slightly deforming micas (Fig. 30), indicating that this deformation post-dates onset of the quartz cementation. Micas did not break from the increased stress, but instead bent slightly, and only at the point that is in contact with the framework grain. This suggests the amount of compaction affecting the micas was minor. However, overly close packing of framework grains is also prevalent, as evidenced by grain densities that visually appear greater than 60% in many samples (Figs. 28A, 29B). At a finer scale, additional evidence is the juxtaposition of quartz grains and their thin overgrowths next to each other (Fig. 30) with complete loss of all intervening original primary pore space. These observations suggest that although mechanical compaction may have initiated before quartz cementation, most compaction post-dates both the quartz and calcite cementation.

Evidence for early framework grain replacement comes from phase maps that show feldspars and chert (Fig. 31) that have been heavily replaced by mixed-layered illite-smectite (I/S). This is a common feature in Wattenberg samples, but rarer in Redtail samples. This replacement is considered shallow burial because it includes smectitic clays, thus occurring before the onset of illitization (i.e., once illitization began, illite, not smectite would be the replacive phase). Relative timing of this feature as compared to the other shallow burial features, or even later formed features, is difficult due to the absence of cross-cutting relations. However, clays replacing feldspar or chert were never observed encased in the calcites that replaced feldspars, suggesting that these initial clay replacements post-date the formation of calcites. That in turn places the clay replacements at the end of shallow burial and possibly at the onset of intermediate burial.
Figure 30. Paired thin section photomicrographs (A–plane light; B–cross polars) showing evidence of mechanical compaction. In upper image, quartz grains have thin overgrowths, but they are closely packed, indicating grain reorientation and loss of primary porosity by compaction. A quartz grain (Q) with overgrowths (Qo) also slightly deformed a mica grain (M). The mica is resting on a grain, presumably feldspar, that has been partially replaced by calcite (C) and clays (cl/F). This implies that quartz overgrowths had to happen before compaction. Clays also peripherally replace quartz grains and overgrowths (cl/Q). Sample is from the Rissler State core.
Figure 31. Paired backscatter image (A) and phase map (B) showing mixed-layered illite-smectite (I/S-pink) partially replacing a chert grain (Ch-grey). The EDS spectra (C) for the I/S in the upper images shows peaks for Fe, Na and Mg cations, which can occur in smectites, and a peak for K, which is characteristic of illite. Authigenic illite fibers also grew from the replacive I/S clays and began to peripherally replace the surrounding quartz, evidenced by clay embayments (red arrows). Sample is from the Miracle well.
The four features described above are interpreted as occurring during shallow burial because of conceptual and temperature constraints established in the literature that support the observed cross-cutting relationships. First, mechanical compaction is dominant at shallow depths (Ehrenberg, 1990; Crossey and Larsen, 1992; Nygård et al. 2004) and begins as soon as overburden accumulates and the effective stress is increased (Bjørlykke, 2014). This process is reported to begin at depths as shallow as 700 m (Dutton and Loucks, 2010). It has been suggested that initial porosity loss in sandstones is controlled by mechanical compaction down to burial depths of 2.0-3.0 km (Ramm and Bjørlykke, 1994; Bjørlykke and Høeg, 1997). Early precipitated cements, such as quartz overgrowths and calcite, have been shown to be influential in limiting the effects of compaction (Crossey and Larsen, 1992; Stroker et al, 2013). Thus, mechanical compaction, or at least its onset, is a shallow-burial phenomenon.

If the compaction features are the product of shallow burial, it then follows that the features that pre-date compaction – the precipitation of both quartz and calcite – must also be the product of shallow burial. An early phase of calcite formation that predates compaction is common in many sandstones (Lundegard, 1992; Bjørlykke and Høeg, 1997; Salem et al. 2000; Kim et al. 2007; Bjørlykke, 2014; Lai et al. 2016). In marine sandstones such as the Codell member, early calcites are often derived from Ca and CO$_3$ ions found in marine and mixed-marine pore waters (Simpson and Hutcheon, 1995; McBride et al. 2003; Okwese et al., 2012). Other sources of calcium and carbonate ions are from seawater diffusion through the sediment prior to significant overburden and from dissolution of biogenic carbonates (Morad et al. 2000). The latter processes could explain pre-quartz calcite cementation of burrows and laminated sands. Oxygen isotope data from other Cretaceous marine sandstones have shown that calcite
cements precipitate favorably in relatively lower temperatures that can be found at the sea floor (McBride et al. 2003; Nyman et al. 2014).

What does seem anomalous is the early quartz cementation. It is clearly post syndepositional pyrite, and it clearly preceded the formation of some calcite and most compaction. Yet isotopic evidence suggests quartz cementation in sandstones usually begins to form around 80°C (Bjørlykke and Egeberg, 1993; Thyberg et al. 2010; Taylor et al, 2010). This is not a temperature typically associated with “shallow” burial; rather approximately 1.6 km (5150 ft) of burial would be indicated assuming a surface temperature of 25°C and an elevated geothermal gradient of 35°C per km for the Wattenberg thermal anomaly. The pre-compaction origin of the Codell quartz overgrowths suggests that they must be a lower temperature precipitate relative to most other observations of quartz cements in sandstones.

**Intermediate Burial Diagenetic Features.**—With increasing burial depth, rising subsurface temperatures initiated and drove multiple mineral alterations that are interpreted to have occurred at intermediate burial depths. These features are feldspar dissolution, precipitation of kaolinite, and onset of illitization and albitization. Evidence for feldspar dissolution is large moldic pores that are outlined by clay rims and/or quartz overgrowths (Fig. 28A). These secondary pores are rare in Wattenberg samples, but are more pervasive in sandstones from the Redtail area. In all cases, the moldic pores contain no evidence of the precursor grain. The scarcity of feldspars throughout the Codell member, and the rectilinear shapes of some moldic pores, implies that feldspars were the dissolved grains. Some moldic pores have delicate arrangements of clays running through the pore (Fig. 32). The linear arrangement of those clays suggests that they had previously partially replaced a feldspar along twin boundaries and/or cleavage planes (e.g., “guided replacements”). If so, this not only supports feldspar as the
Figure 32. Paired backscatter image (A) and phase map (B) showing delicate fibers of illitic clay (I-red) in a moldic pore (Por-blue) formed by the dissolution of feldspar grains. Prior to dissolution, the feldspars were subjected to partial replacement by earlier authigenic clays along cleavage planes (guided replacement). Evidence of this is the linear arrangement of clay fibers within the moldic pore (white arrows). Rhombic shapes for some of the clay in the middle of the image suggests that the clay may also have replaced calcite that had also partially replaced the feldspar. Feldspar remnants were later albitized (Alb-green). Quartz grains and quartz overgrowths (Qtz-grey) also display peripheral replacement by the clay, as evidenced by embayments of clay into the quartz (black arrows). Sample is from the Miracle well.
precursor grain, but also times the dissolution to be after the earlier clay replacement of framework grains.

Evidence for kaolinite precipitation is multifold, but was only seen in Redtail samples; authigenic kaolinite was not observed in any Wattenberg sample. Three habits of kaolinite were noted. First, booklets of kaolinite cements occur in, and often fill, moldic pores created by feldspar dissolution (Figs. 33, 35). Masses of replacive kaolinite are the second expression of kaolinite precipitation. The evidence for replacement, as opposed to pore-filling is that the kaolinite masses exhibit blocky patterns that are indicative of the clay preserving the precursor’s overall morphology (Fig. 34). This replacive kaolinite may be replacing feldspar directly or replacing calcite that had already replaced feldspar. The third type of kaolinite is also replacive, but it peripherally replaces quartz and albite (Fig. 33), as well as some of the shallow-burial calcite (Fig. 35). The replacive nature of this kaolinite is indicated by the fact that the kaolinite crystals penetrate into the periphery of their hosts. All three kaolinite habits – cements and replacements – are assumed to have formed concurrently. Furthermore, when kaolinite replaced feldspars, those were obviously feldspars that had not previously dissolved.

Albite is the only feldspar detected in all phase maps collected in this study (Figs. 32, 33, 34, 36, 37). No Ca-bearing plagioclase or K-feldspars were observed. This implies that all the feldspar in the Codell Sandstones that were not previously dissolved or replaced by clay minerals were albitized. This explains why XRD analysis registers only plagioclase in Codell samples.

Illitization – the replacement of mixed layer illite-smectites by more crystalline illite – is a process also interpreted to have initiated during intermediate burial. Prior workers (Pollastro, 1985; Elliot et al. 1991) used x-ray crystallography to demonstrate that illitization of smectite is a common phenomenon in the DJ Basin, and illitization was documented in the Codell previously
Figure 33. Paired backscatter image (A) and phase map (B) showing authigenic kaolinite “booklets” (AK-orange) precipitating within a secondary pore formed by the dissolution of a feldspar grain. Feldspar remnants have been albitized (Alb-green). Embayments into the quartz grains and quartz overgrowths (Qtz-grey) indicate peripheral replacement by the kaolinite. Sample is from the Terrace well.
Figure 34. Paired backscatter image (A) and phase map (B) showing large masses of fine crystalline kaolinite (RK-orange) that either directly replaced feldspars, or calcite that had originally replaced feldspar. Replacement is evidenced by the blocky nature of the kaolinite masses (i.e., dashed red lines in A). The tight packing of those former grains indicates kaolinite replacement was post compaction. Calcite (C-yellow) has partially replaced a feldspar, with the remnant feldspar being subsequently albitized (Alb-green). To the far left, illite-rich clay (I) occurs in a partially replaced chert grain, as evidenced by some remaining quartz (Qtz-grey). Whether this is direct replacement by late illite, or illitization of an earlier illite/smectite replacement phase is unknown. Sample is from the Razor well.
Figure 35. Paired backscatter image (A) and phase map (B) showing a secondary pore (Por-blue) partially filled by authigenic kaolinite (AK-orange) and earlier-formed calcite (C-yellow). The calcite partially replaced a feldspar (now completely dissolved), evidenced by the euhedral crystal shape (i.e., remnant automorphic penetration), and grew as cement that abutted quartz overgrowths (Qtz-grey, red arrows). Then the feldspar dissolved, and kaolinite formed in the secondary pore and began to replace the calcite, evidenced by penetration of kaolinite into the calcite (black arrows). Sample from the Terrace core.
Figure 36. Paired backscatter image (A) and phase map (B) showing a secondary pore (Por-blue) partially filled by authigenic chlorite (Cl-rust orange) and illite-rich clay (red). The clay mass in the lower left contains inclusions of quartz crystallites, suggesting the precursor was chert. Pore-filling authigenic illite appears as characteristic fibers (AI), and illitized detrital smectitic clay (I) appears as a finer-crystalline honeycomb textured clay mass. Pore-filling chlorite appears as branching plates that also partially replace quartz (Qtz-grey), albite (Alb-green), and calcite (C-yellow). Both clay types are embaying into the quartz along the grain boundaries. Sample from the Rissler State core.
Figure 37. A) SEM image of a broken face showing quartz grains (Qtz) and chert (Ch) being peripherally replaced by authigenic fibrous illite (I). The illite leaves embayments along the grain boundary (white arrows) and has demonstrated guided replacement along the contact between quartz and chert. The fibrous illite is growing on an earlier-replacement clay phase that has been illitized. B) Phase map shows quartz grains (grey) being peripherally replaced by an illite-rich clay mass (red), as evidenced by embayments along the grain boundary (black arrows). The honeycomb-textured mass is interpreted to be a combination of illitized detrital clay and an accumulation of small illite fibers like those in the SEM image. Albite (Alb-green) is also being replaced by the illite. Both samples are from the Rissler State core.
by Henningsgaard (1986). It is a well-documented process known to occur in sandstones with kaolinite and/or smectite clays (Shelton, 1964; Bjørlykke, 1998; Higgs et al. 2007; Stroker et al. 2013). In this study, direct evidence for illitization would seemingly be the presence of illite in most phase maps collected (Figs. 32, 34, 36, 37). However, XRD analyses performed by third-party companies registered mixed-layered illite-smectite (I/S) as the overwhelmingly dominant clay in the bulk rock mineralogy of all samples. Therefore, the phase maps must be misleading, with the COMPASS algorithm used to process the EDS data unable to distinguish differences between illite-smectite and pure illite. Pure illite is generally described as having a fibrous growth form; however, a majority of the clay identified as illite had a “honeycomb” texture with small, but resolvable pores between the crystals (Figs. 32, 36). The BSE images and phase maps can only be reconciled with the XRD data if it is assumed that the honeycomb texture of what the phase maps indicate is illitic clay masses are actually the mixed-layered illite-smectite that is captured by bulk-rock XRD analysis.

Evidence for the relative timing of the four features interpreted as forming at intermediate burial depths is related to both cross-cutting relations and consideration of diagenetic concepts established by prior workers. First, the secondary pores formed by feldspar dissolution have not collapsed, indicating that feldspar dissolution occurred after compaction had ceased. Kaolinite in those secondary pores, and by inference all other kaolinite, must post-date the feldspar dissolution. As intermediate burial diagenesis is defined herein to be post-mechanical compaction, both feldspar diagenesis and kaolinite precipitation are assigned to intermediate burial diagenesis.

Illitization is also interpreted as a process that initiated during intermediate burial diagenesis. Crosscutting relationships could not be used to constrain the timing of illitization due
to a lack of photographic evidence. Instead, cation exchanges and temperature regimes limit the onset of illitization to depths greater than those of the shallow-burial realm. Illitization is controlled almost entirely by $K^+$ availability (Thyberg et al. 2010) and initiates around 100-110°C (Hower et al. 1976; Pollastro, 1990; Elliott et al. 1991; Cuadros, 2006; Stroker et al. 2013; Wilson et al. 2014); these temperatures would occur at depths below mechanical compaction. Hence illitization is interpreted to be a product of intermediate diagenesis. Furthermore, the potassium for illitization is thought to come from preferential dissolution of K-feldspar, which suggests a timing concurrent with the dissolution of Codell feldspars. It has been noted that illitization generally does not go to completion due to either a lack of $K^+$ or a reduced reaction rate (Pollastro, 1990; Cuadros, 2006); thus, illitization is a process that likely has continued into the realm of deep burial diagenesis (Fig. 26).

Albitization can begin at ~60°C, but complete conversion of feldspars to “pure” albite is favored at higher temperatures (120°C-150°C) and goes to completion relatively quickly once it has begun (Saigal, 1988; Baccar et al., 1993). Herein, albitization is interpreted as a feature initiated during intermediate burial not so much on the basis of those temperatures, but on the assumption that it was linked to the onset of illitization. The conversion of smectite to illite releases significant amounts of sodium and silica (Boles and Franks, 1979; Bjørlykke, 1998; Thyne et al. 2001; Peltonen et al. 2009), which likely drove the albitization. However, as both illitization and albitization continue to higher temperatures, albitization is likely to have continued into the deeper burial realm (Fig. 26).

**Deep Burial Diagenetic Features.**—Deep burial diagenesis is characterized by clays (different from those reacting during shallow burial) precipitating within secondary pores and further replacing framework grains. Features interpreted as formed during deep burial are illite
and chlorite precipitation in secondary pores and as partial, dominantly peripheral, replacements of quartz, chert, albite, and calcite, plus formation of large pyrite clusters (~200-300 µm) composed of cubic crystals many tens of microns in size. The chlorite is more abundant in Wattenberg samples, whereas the cubic pyrite is more common in Redtail samples. This may indicate regional differences in the sink of iron during late burial diagenesis.

The late burial illite is distinguished from earlier formed illite in that it is pure illite with no evidence for associated smectite. This pore-filling authigenic illite appears as characteristic fibers growing primarily across moldic pores (Fig. 36). There is porosity observed between individual crystal fibers. Illite peripherally replacing framework grains was a common observation in the phase maps (Figs. 32, 36, 37B). That this later illite peripherally replaces grains already compacted together (Figs. 34, 37), means the illite is post shallow burial. As it also attacks albite (Fig. 36), the formation of the pure authigenic illite is also post intermediate burial, hence deep burial.

Chlorite occurs in association with the late illite. Pore-filling chlorite appears as branching plates that can either intersect each other or grow side by side in a fan-like texture (Fig. 36). There is a high amount of microporosity associated with the intersecting plates. Chlorite was also observed branching into and peripherally replacing quartz, albite, and calcite (Fig. 36).

Finally, clusters of euhedral cubic pyrite crystals cross-cut quartz grains, quartz overgrowths, and illitized clays matrix, and are also observed growing into moldic pores formed by feldspar dissolution (Fig. 28). These clusters are much larger (up to hundreds of times larger) than the isolated, syn-depositional frambooidal pyrites. This late-stage pyrite is thought to be the final authigenic phase to have formed within the Codell sandstone.
The illite, chlorite, and cubic pyrite are interpreted as deep burial features for a number of reasons. First and foremost, the late illite replaces albite; thus, it must have post-dated the albitization that occurred at the intermediate stage. Late illitization of smectite was probably concurrent as the smectite could have provided the cations that led to the precipitation of both illite (K sink) and chlorite (Mg and Fe sink) (Hazen et al. 2013). The conversion of detrital smectite to a mixed layered I/S with a higher proportion of illite layers is a process that continues until temperatures are high enough to promote growth of fibrous, pore-filling illite (Higgs et al. 2007; Stroker et al. 2013; Wilson et al. 2014; Suchý et al. 2015; Weibel et al. 2017). The smectite-to-illite content of mixed layered I/S has been used as a proxy geothermometer for constraining the diagenetic stages of sedimentary basins (Pollastro, 1993; Sachsenhofer et al. 1998; Dellisanti et al. 2010; Stroker et al. 2013). Non-interlayered authigenic illite (pore-filling, fibrous growth pattern) begins to form at depths greater than 3 km (Hower et al, 1976; Liu, 2003; Dutton and Loucks, 2010; Suchý et al. 2015). The high geothermal gradient associated with the Wattenberg high would explain the formation of illite at even shallower depths.

A similar geochemical cycle takes place for chlorite growth in deeply buried, high-temperature sediments in that chlorite content has been observed as increasing along with illite content (Hower et al. 1976). Iron and magnesium lost by detrital smectite converting to illite is incorporated into chlorite (Hower et al. 1976; Day-Stirrat et al. 2010). Temperatures for chlorite formation are variable due to the clay recrystallizing as burial depth and temperature increases (Spötl et al. 1994). However, authigenic pore-filling chlorite has been shown to be stable at temperatures comparable to those that promote growth of fibrous illite (Spötl et al. 1994; Day-Stirrat et al. 2010; Blamey et al. 2014). Finally, the late cubic pyrite would have required sulfur, which could have been provided by the catagenesis of sulphur-bearing hydrocarbon compounds.
Hydrocarbon maturation in the overlying Niobrara Formation, and underlying Greenhorn Formation, tended to occur near maximum burial (Clayton and Swetland, 1980; Pollastro, 1990; Birmingham et al. 2001; Higley and Cox, 2007; Milne and Cumella, 2014), which limits the formation of the late pyrite to the deeper burial environment.

**Diagenetic Variations as a Function of Lithofacies**

Table 6 lists the relative abundance of diagenetic features in laminated and bioturbated samples. Only the 19 high-graded samples are considered because they were the only ones examined in detail with electron microprobe phase maps, which was critical to identifying mineralogical differences. Illitization and albitization are not included in Table 6 because it was impossible to ascertain how far along illitization had progressed in each sample, and albite was the only feldspar observed, so there was no variation in how well- or poorly-developed the latter process was. Early clay replacement of framework grains is also excluded because this process was observed in only one phase map, and so it would not have provided any information on diagenetic variations between lithofacies.

Quartz overgrowths, mechanical compaction, precipitation of authigenic clays (illite, chlorite, kaolinite in the case of Redtail), and peripheral clay replacements of framework grains are all diagenetic processes that are better developed in the laminated samples. Each is well-developed in anywhere from 63% to 100% of the laminated facies, but well-developed in only 9% to 40% of the burrowed facies. Most of the laminated samples (75%) had calcite (both as a cement and replacement) as a well-developed diagenetic feature, but calcite was equally as common in the bioturbated samples (72%). Finally, pyrite (including both shallow and deep burial precipitation events) and feldspar dissolution exhibited no significant variation between
### Table 6. Qualitative abundances of diagenetic features as a function of major lithofacies groupings.

Sample codes are RS=Rissler State, M=Miracle, P=Puritan, ND=Narco Devore, T=Terrace, RZ=Razor, CW=Cottonwood. Abbreviations for diagenetic features are Pyr=Pyrite precipitation, QO=Quartz overgrowths, Cal=Calcite precipitation, Com=Mechanical compaction, FD=Feldspar dissolution, RK/AK=Replacive kaolinite/Authigenic kaolinite, AI/Chl=Authigenic Illite/Chlorite, PR=Peripheral Replacement.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Facies</th>
<th>Permeability (md)</th>
<th>Diagenetic Features</th>
<th>Well-developed</th>
<th>Uncommon but Present</th>
<th>Not Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laminated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ND7441.8</td>
<td>CDL-3</td>
<td>0.130</td>
<td>QO, Com, AI/Chl, PR</td>
<td>Pyr, Cal, FD</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td>M7234.85</td>
<td>CDL-3</td>
<td>0.111</td>
<td>Com, FD, AI/Chl, PR</td>
<td>Pyr, QO, Cal</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td>T6195.8</td>
<td>CDL-1</td>
<td>0.097</td>
<td>Pyr, QO, Cal, FD, AK/RK, PR</td>
<td></td>
<td>Com</td>
<td>AI/Chl</td>
</tr>
<tr>
<td>ND7442.1</td>
<td>CDL-2</td>
<td>0.030</td>
<td>Cal, Com, AI/Chl, PR</td>
<td>Pyr, QO, Cal</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td>RZ5887.25</td>
<td>CDL-2</td>
<td>0.023</td>
<td>Pyr, QO, Cal, Com, RK/AK, PR</td>
<td></td>
<td>FD, AI/Chl</td>
<td></td>
</tr>
<tr>
<td>M7237.55</td>
<td>CDL-2</td>
<td>0.021</td>
<td>QO, Cal, Com, PR</td>
<td>Pyr, FD, AI/Chl</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td>T6190.8</td>
<td>CDL-3</td>
<td>0.019</td>
<td>Pyr, Cal, Com, FD, AI/Chl, PR</td>
<td></td>
<td>QO, RK/AK</td>
<td></td>
</tr>
<tr>
<td>RS7329.1</td>
<td>CDL-3</td>
<td>0.017</td>
<td>QO, Cal, FD, AI/Chl, PR</td>
<td>Pyr, Com</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td><strong>Bioturbated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ND7435.2</td>
<td>CDL-4</td>
<td>0.090</td>
<td>Pyr, QO, Cal, PR</td>
<td>Com, FD, AI/Chl</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td>M7225.65</td>
<td>CDL-4</td>
<td>0.029</td>
<td>Cal, FD, AI/Chl, PR</td>
<td>Pyr, QO, Com</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td>T6189.0</td>
<td>CDL-5</td>
<td>0.029</td>
<td>Pyr, Cal</td>
<td>QO, Com, FD, RK/AK, AI/Chl, PR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M7230.65</td>
<td>CDL-4</td>
<td>0.020</td>
<td>FD, AI/Chl, PR</td>
<td>Pyr, QO, Cal, Com</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td>M7222.25</td>
<td>CDL-4</td>
<td>0.016</td>
<td>Pyr, Cal, FD, AI/Chl</td>
<td>QO, Com, PR</td>
<td>RK/AK</td>
<td></td>
</tr>
<tr>
<td>CW5881.25</td>
<td>CDL-4</td>
<td>0.015</td>
<td>Pyr, RK/AK, AI/Chl</td>
<td>QO, Cal, Com, FD, PR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS7321.0</td>
<td>CDL-4</td>
<td>0.012</td>
<td>Cal, FD</td>
<td>Pyr, QO, Com, AI/Chl, PR</td>
<td></td>
<td>RK/AK</td>
</tr>
<tr>
<td>RS7319.1</td>
<td>CDL-4</td>
<td>0.009</td>
<td>Cal</td>
<td>Pyr, QO, Com, PR</td>
<td>FD, RK/AK, AI/Chl</td>
<td></td>
</tr>
<tr>
<td>RS7332.6</td>
<td>CDL-5</td>
<td>0.009</td>
<td>Pyr, Cal</td>
<td>QO, Com, FD, AI/Chl, PR</td>
<td></td>
<td>RK/AK</td>
</tr>
<tr>
<td>RS7335.1</td>
<td>CDL-5</td>
<td>0.006</td>
<td>Pyr, PR</td>
<td>QO, Cal, Com, FD, AI/Chl</td>
<td></td>
<td>RK/AK</td>
</tr>
<tr>
<td>P7820.2</td>
<td>CDL-4</td>
<td>N/A</td>
<td>Cal, Com</td>
<td>Pyr, QO, FD, AI/Chl, PR</td>
<td></td>
<td>RK/AK</td>
</tr>
</tbody>
</table>
laminated and bioturbated samples, implying that the prevalence of these two diagenetic features is independent of lithofacies.

Early quartz overgrowths and mechanical compaction are inferred to be better developed in the laminated lithofacies because of the lack of intergranular clay introduced by burrowing organisms. In undisturbed sediments, quartz cements had an opportunity to grow and occlude primary pores before they were filled with clays. In contrast, burrowed lithofacies had clays that filled intergranular pores, and this limited the development of quartz overgrowths but did not completely prevent it (Table 6). Occluding intergranular pores with detrital clays also limited compaction, which resulted in more point contacts between grains and quartz and feldspars “floating” in the clay matrix. On the other hand, laminated samples had preferentially closer packing of detrital grains and a higher occurrence of long contacts between framework grains, indicating relatively more compaction.

Authigenic clays precipitating in open voids were likely better developed in the laminated lithofacies because a higher percentage of primary pores survived into the later stages of diagenesis than in the bioturbated lithofacies. Earlier cementation may have preserved some of these primary intergranular pores, albeit with a significantly reduced volume, and clays began to grow within them and replace the surrounding grains. A majority of samples with well-developed authigenic clay precipitation also displayed better development of feldspar dissolution (Table 6), indicating that the two processes are related. Peripheral clay replacements were well-developed in all the laminated samples and in a few bioturbated samples (Table 6). A reason for this disparity could be linked to the precipitation of pore-filling clays, since most samples with both diagenetic features display good development of the two, and pore-filling clays occur more often in the laminated samples. Another interesting relationship is that peripheral clay
replacements are likely to be better developed in samples with either quartz overgrowths or compaction, both of which are also better developed in the laminated lithofacies.

*Evolution of the Codell’s Pore Network*

The pore networks of the Codell sandstone evolved in conjunction with the diagenetic evolution of minerals. Most diagenetic processes resulted in reduction in porosity and thus a deterioration of the pore networks. The most significant processes destroying porosity were bioturbation, compaction, and the various cementation events.

Bioturbation reduced the amount of laminated sands (lithofacies CDL-1, CDL-2) containing primary intergranular porosity and produced burrowed argillaceous sandstones (lithofacies CDL-4, CDL-5) in which the intergranular space was filled with mud (Fig. 27). Compaction, by definition, destroyed porosity. It is a common process in sandstones and is typically the main destroyer of original porosity (e.g., Lundegard, 1992). In Codell sandstones, it eliminated intergranular porosity through repacking and reorientation of grains, and resulted in overly close packing of grains in most laminated sandstones (Figs. 29, 30). By its very nature, cements of any type that fill open void space reduce pore volume and increase the complexity of the remaining pore space. The early formed quartz and calcite cements led to early reduction of primary porosity (e.g., Figs. 28, 29, 30). The addition of later clay cements primarily affected reduction of secondary porosity formed by feldspar dissolution. Although microporosity typically remains between the clays infilling secondary pores, there was still a reduction in the secondary pores’ volume and a decrease in connectivity due to the clay minerals (e.g., Fig. 30).

Only two processes tended to improve porosity and/or pore connectivity. These were feldspar dissolution and the replacement of framework grains by clays. Feldspar dissolution involved the removal of the solid precursor grain and thus created an open void. Because this
dissolution occurred after the rocks had become rigid and resistant to compaction, the secondary pores did not collapse. This type of secondary porosity is particularly well developed in the Redtail samples (Fig. 28) but also present in lesser amounts in Wattenberg (Fig. 32). Clay replacement of framework grains tended to produce microporosity between the clay crystals where no porosity formally existed (Figs. 33, 36). However, it is also possible that the replacement was complete and no microporosity developed, as is the case where feldspars (or calcites that had already replaced the feldspars) were replaced by kaolinite (Fig. 34). Of potentially greater importance was the peripheral replacement of grains, which created microporosity along the grain-clay contact (Figs. 32, 33, 37). In three-dimensions, that microporosity around all framework grains has the potential to create an effectively continuous drainage network that links all other micro and mesopores in the Codell sandstones.

All other processes – calcite replacement of framework grains, albitization of feldspars, and illitization of smectitic clays – were neutral with respect to the evolution of porosity and pore networks. In the case of replacements by calcite and albite, a solid mineral with no associated porosity was replaced by another solid mineral with no associated porosity. In the case of illitization, one clay (smectite) was replaced by another (illite) and presumably any microporosity that might have existed in the precursor clay mass was preserved, albeit restructured due to differences in crystal habits between the precursor and replacement product.

**Characteristics of Flow Paths**

**Imaged Paths.**—Hundreds to thousands of skeletonized flow paths occur in each sample (Fig. 38, 39), with lengths that vary from just a few microns to ~7.0 mm. The longest flow path within individual sample might just be hundreds of microns and cover a relatively small area, or be millimeters long and span the entire length of an image (Figs. 38, 39). Some flow paths can be
Figure 38. Bright field (BF) thin-section images in three laminated lithofacies showing all skeletonized paths greater than 100 µm (red lines) and examples of the shortest and longest paths traced in yellow lines. Scale bar in A is applicable to all three images. A) Terrace well, lithofacies CDL-1 (tabular to trough cross-stratified sandstone with minimal to no bioturbation). B) Miracle well, lithofacies CDL-2 (thinly-laminated low angle horizontal to hummocky cross-stratified sandstone with minimal to no bioturbation). C) Miracle well, lithofacies CDL-3 (thinly laminated, low-angle horizontal to hummocky cross-stratified sandstone with moderate bioturbation). In all three samples, flow paths commonly travel along grain boundaries. The flow path length is based on pixel connectivity through a single slice, and so flow paths can, in reality, be longer than they appear here.
Figure 39. Bright field (BF) thin-section images of four bioturbated lithofacies. All skeletonized paths greater than 100 µm are shown (red lines), as are examples of the shortest and longest paths (yellow lines). Scale bar in A is applicable to all three images. A) Cottonwood well, lithofacies CDL-4a (fine- to lower medium-grained sandstone with burrows exhibiting fluorescence). B) Miracle well, lithofacies CDL-4b (fine- to lower medium-grained sandstone with burrows that exhibit no fluorescence). C) Rissler State well, lithofacies CDL-5a (silty to very fine-grained sandstone with burrows exhibiting fluorescence). Burrow lining is marked by green lines. Notice that flow paths are nearly all within the burrow fill. D) Rissler State well, lithofacies CDL-5b (silty to very fine-grained sandstone with burrows that exhibit no fluorescence). Flow paths in image D are more scattered compared to image C. In all four samples, flow paths are through clay-filled areas and along grain boundaries. Flow paths become smaller as grain size decreases, and samples with fluorescing burrows (A, C) have a larger number of slightly longer flow paths.
seen going through epoxy-filled mesopores, but the majority of paths travel through fluorescent areas associated with clays. Generally, all flow paths imaged within each field of view collectively covered that entire field of view. One exception is an imaged sample of lithofacies CDL-5 (Fig. 39C), where the majority of skeletonized flow paths are concentrated within a single burrow fill.

**Multivariate Analysis of Paths.**—The analysis of the skeletonized flow paths yielded thousands of lengths as well as multiple metrics for each path. Those metrics include number of branches, average branch length, maximum branch length, number of junctions, and flow path length. Only three of those metrics were independent of each other: the flow path length, number of branches, and the average branch length. Each of these variables showed some degree of bivariate correlation to permeability (Fig. 40). The cumulative length of all flow paths in a sample displayed the best correlation (largest $R^2$ value) with a positive exponential covariance (Fig. 40A). The cumulative number of branches and the average branch length in a sample also displayed good power law covariance with permeability (Figs. 40B and C, respectively).

All three of the flow path metrics that correlate to permeability form non-parametric populations, and so they were transformed to parametric populations. A multivariate regression analysis using the parametric transformations of the three metrics and log of permeability resulted in a multivariate regression that predicts the high-graded samples’ permeabilities with an $R^2$ value of 0.902:

$$\log k = 0.087(X_1) - 0.628(X_2)$$

where $X_1 = e^{0.0000114 \times \text{Sum of flow path lengths}}$  
and $X_2 = (\text{sum number of branches})^{0.0115}$

(p-value = $3 \times 10^{-4}$)  
(p-value = $7 \times 10^{-11}$)
Figure 40. Cross plots of permeability (log scale) versus A) cumulative flow path lengths, B) cumulative number of branches, and C) cumulative average branch length. Data are grouped by high permeability (red), middle permeability (green), and low permeability (blue) samples. Best-fit lines are linear (A) and exponentials (B, C).
The addition of the average branch length actually lowered the $R^2$ to 0.896, and thus it contributes no additional predictive value to the multivariate regression and was excluded from the final regression model.

The significance of the above regression model is that it shows that the combination of the flow path lengths and the total number of branches in a sample very strongly relate to permeability. It is a logical result as the regression shows that longer lengths and fewer branches equate to greater permeability. This result means that the skeletonization processes successfully captured critical elements of the permeable networks within each sample. This in turn means that these two variables, and particularly the “flow path length” variable, can be used to investigate the potential relations between permeability and diagenesis.

**Flow Path Length Analysis.**—A cumulative frequency plot of all the flow paths longer than 100 pixels (~105 µm) across all of the 19 high-graded samples (n=13,113) reveals a distribution of flow path lengths that is reflected by a samples’ permeability (Fig. 41). Individual samples had anywhere from 149 to 1133 total paths greater than 100 pixels (105 µm). Samples with higher permeabilities ($\geq 0.09$ md) have the longest cumulative flow paths, with the upper 25% of the cumulative length represented by no more than 8.5% of the paths. That is, a lot of the cumulative flow path is in a small percentage of the total number of paths. In contrast, the lower permeability samples ($\leq 0.001$ md) have shorter cumulative flow paths and 75–100% of the cumulative path lengths are distributed across paths between 9% and 14% of the cumulative lengths. That is, most the cumulative flow path length is in the shorter paths.

In both high and low permeability samples, a few long outliers represent a relatively larger percentage of the cumulative flow path length in each sample. These outliers are seen in Figure 41 as discrete points at high cumulative lengths. The long path outliers (Fig. 41) are also
Figure 41. Cumulative frequency plot showing the compiled flow path lengths for all 19 high-graded samples. Data grouped by high permeability (red), middle permeability (green), and low permeability (blue). A length of 100 pixels was chosen as the minimum threshold because paths smaller than this would not have helped in understanding the Codell’s pore network.
key attributes of permeability. The longest flow paths in low permeability samples have similar length measurements to “short” paths identified in high permeability samples. Therefore, some diagenetic features may be hindering flow path length in the low permeability samples, and these features may be lacking in the higher permeability samples.

Understanding the differences in the distribution of flow path lengths requires a closer examination of petrographic characteristics along flow paths. However, it is not possible to observe the tens of thousands of lengths across all samples, so an alternative strategy was devised. The strong correlation between permeability and flow path length suggested that an analysis of diagenetic features along the longest flow paths might be productive. The long path outliers of Figure 41 were thus used to select a reduced population of flow paths for microprobe imaging.

**Diagenetic Features Observed at Endpoints of Flow Paths.**—From the heavily reduced population of measured lengths, five of the longest flow paths in each sample were imaged for relationships between the path length and diagenetic features. Diagenetic features typically observed at flow path endpoints are ones interpreted to have occurred during intermediate and deep burial (Fig. 26). Those features are kaolinite replacement of feldspar, kaolinite precipitation in secondary pores, and peripheral replacement of quartz by kaolinite (all in Redtail samples). The deep burial features found at the end of flow paths include illite and chlorite precipitation in secondary pores and late peripheral replacements of calcite, albite, quartz, and chert by illite and chlorite. These deep burial diagenetic features were imaged at the flow path endpoints in both Wattenberg and Redtail samples.

Regardless of a sample’s permeability, imaged flow paths almost always terminated in areas that appeared microporous in BSE images. These microporous areas include peripherally
replaced framework grains (Fig. 42) and micropores within a clay mass (Fig. 43). Termination in microporous areas indicates that the paths are, in reality, just exiting the plane of the thin section and continuing through the rock. Thus, whether short or long, it is likely that the longest paths observed in any sample are longer than they appear to be within the 2D images. Thus, analysis of the end-points of flow paths do not elucidate why longer and more effective flow paths are present in some samples.

**Diagenetic Features Observed Along Continuous Flow Path Segments.**—The same diagenetic features imaged at the flow paths’ endpoints were also observed to dominate along continuous segments of the paths. In low-permeability samples, flow paths preferentially pass through microporous intergranular clay matrix and masses (Figs. 42, 43). If matrix, the clays are typically detrital. In contrast, the masses of clay are typically pore-filling replacements of framework grains (Fig 42). Other flow paths in low permeability samples preferentially travel through microfractures that were located within mud-rich areas or travel along grain boundaries (Fig. 43). In one low-permeability sample from the Rissler State core that had fluorescing burrows, the flow paths were concentrated within the burrow fill (Fig. 39C). The flow paths in that burrow fill, though short, were the longest for that sample and were observed traveling through clay matrix and along some grain boundaries.

In mid to high-permeability samples, flow paths preferentially follow microporosity associated with peripherally replaced grain boundaries (Figs. 44, 45), be it dominantly illite (all samples) or kaolinite (Redtail only). Micropores associated with these authigenic clay replacements are clearly seen in BSE images (Figs. 44, 45). Flow paths along grain boundaries are longer in mid to high permeability samples, and they are also more tortuous than the shorter flow paths that go through microporous clay masses. It is worth noting that the presence of
Figure 42. Paired backscatter image (A), phase map (B), and bright field (BF) thin section image (C) with a flow path identified via skeletal analysis (yellow line). Red box in the BF image is the area shown in the paired images to the left. In the BF image, the skeletonized flow path (yellow line) travels along grain boundaries left by quartz (Qtz-grey) and albite (Alb-green) and terminates in a small porous area along a peripherally replaced quartz grain. Illite-rich clay (I-red), likely illitized detrital clay, and chlorite (Cl-rust-orange) have replaced quartz and albite and have begun to fill the secondary pore. With porosity present on the other side of the quartz grain, it is likely that the path continues out of this plane of view. Sample is a low permeability sample from the Rissler State well.
Figure 43. Paired backscatter image (A), phase map (B), and bright field (BF) thin section image (C) with a flow path identified via skeletal analysis (yellow line). Red box in the BF image is the area shown in the paired images to the left. In the BF image, the skeletonized flow path (yellow line) is following a microfracture along grain boundaries that has created a connection between microporosity in clay-rich areas. The flow path terminates within a pore (Por-blue) located between some chlorite plates (Cl-rust-orange) and illite-rich (I-red) matrix, likely illitized detrital clay. Quartz (Qtz-grey) and albite (Alb-green) show less replacement by clay, and there is minimal microporosity within the illite-rich matrix. The flow path is therefore confined to the microfractures that have extended the pore network. Sample is a low permeability sample from the Rissler State well.
Figure 44. Paired backscatter image (A), phase map (B), and bright field (BF) thin section image (C) with a flow path identified via skeletal analysis (yellow line). Red box in the BF image is the area shown in the paired images to the left. In the BF image, the skeletonized flow path (yellow line) is traveling along peripherally replaced quartz (Qtz-grey), where large amounts of microporosity (Por-blue) seem to be located (as shown by the black areas in image A). The illite/chlorite clay mass (I/Cl-red/rust-orange) has pervasively replaced albite (Alb-green) and quartz grains, creating more porosity in place of solid grains and promoting a longer flow path in mid to high permeability samples. Notice that while the flow path is longer here, it is also more tortuous because it is following grain boundaries rather than going directly through the clay matrix. Sample is a middle permeability sample from the Miracle well.
Figure 45. Paired backscatter image (A), phase map (B), and bright field (BF) thin section image (C) with a flow path identified via skeletal analysis (yellow line). Red box in the BF image is the area shown in the paired images to the left. Notice that the skeletonized flow path in the BF image is very long, but it is also tortuous. As seen in images to the right, the flow path (yellow line) travels along quartz overgrowths (Qtz-grey) that are being peripherally replaced by authigenic kaolinite (AK-orange). Notice the flow path nicely follows the carries and embayments into the quartz created by the kaolinite; the path does not travel through the microporous clay in the secondary pore (Por-blue). This indicates a better connected pore network at the grain-clay contact. Sample is a high permeability sample from the Terrace well.
secondary pores, kaolinite in those pores, or replacive kaolinite in mid to high-permeability samples from the Redtail area had little effect on flow paths. Flow paths might or might not go through secondary pores, but never transect replacive kaolinite or pore-filling booklets. What is more important in the Redtail sandstones is that the larger grain size and more extensive quartz cementation results in more continuous quartz surfaces. When those surfaces are peripherally replaced, as is the case in Figure 45, the resultant flow paths are very long.

**Diagenetic Effects on Flow Path Length.**—Based on imaging of the longest flow paths across all samples, it is inferred that the intensity of peripheral clay replacements is the main control on flow path length because it promotes longer paths. Lower permeability samples (<0.02 md), and especially those from bioturbated lithofacies, have less development of peripheral clay replacement of framework grains (Table 6). Quartz grains and overgrowths do display peripheral replacement in the low permeability samples, but albite and chert are not as affected by that type of replacement (Fig. 46). Assuming no large differences in the relative amounts of feldspars across the sample set, less replacement of albite by clays would mean a reduction in the amount of microporous clay masses.

Cumulatively, the above features mean less connected microporosity in low permeability samples, thus shorter flow paths. The presence of a longest flow path going through a microfracture (Fig. 43) suggests that low permeability samples can have the flow path lengths enhanced by fractures going through mud-rich areas. However, the length of the flow path is limited to the extent of the microfracture. The concentration of flow paths within burrow fills (Fig. 39C) suggests that a better-connected pore network exists within some burrows, but not others. The proximity of these flow paths to each other could mean that they are in fact parts of a longer single flow path that is continuous in a 3D space. However, the UV fluorescence of
Figure 46. Paired backscatter image (A), phase map (B), and bright field (BF) thin section image (C) with a flow path identified via skeletal analysis (yellow line). Red box in the BF image is the area shown in the paired images to the left. The skeletonized flow path (yellow line) goes through illite-rich clay (I-red), likely illitized detrital matrix, with microporosity (perhaps a replaced grain) and along peripherally replaced quartz. The path terminates at a peripherally replaced albite grain with micropores (Por-blue) located along the boundary. This is a low permeability sample with more carbonate (C-yellow), quartz (Qtz-grey), and albite (Alb-green) preserved than in samples with longer flow paths. Chlorite (Cl-rust orange) is also present as it replaces albite. The increased amount of non-porous material (grains and cements) may be limiting the flow path length. Sample is a low permeability sample from the Rissler State well.
burrows (Figs. 19, 20) indicates flow path lengths are limited to the size and shape of the burrow and do not necessarily continue through the rock.

In contrast, 92% of mid to high-permeability samples (permeability $\geq$ 0.02 md) display more extensive peripheral replacement of quartz by illite, chlorite, and kaolinite (in Redtail samples) than in low permeability samples (Table 6), as evidenced by large carries and deeper embayments into the quartz (Figs. 44, 45). The mineral phase maps collected for the 5 longest flow paths in the high-graded sample set revealed less preserved albite and chert in the mid to high-permeability samples with longer flow paths (e.g., Figs. 44, 45). It is inferred that both chert and albite were more successfully replaced by clays in these samples because of their susceptibility to guided replacement, and this increased the amount of microporous clay. The clays that replaced the chert and albite also meant greater amounts of clay within the samples that could serve as the “seeds” for the clays that would subsequently grow and peripherally replace adjacent grains.

All of the above factors mean more microporous masses between grains that are connected by microporosity associated with clays that peripherally replace grains in mid- to high-permeability samples. The combination leads to longer flow paths that travel through micropores located at grain-clay contacts, regardless of whether it is illite, chlorite, or kaolinite. The increased presence of clay replacement in samples with longer flow paths implies that the clay replacements, particularly along grain boundaries, are the most important diagenetic feature determining flow path length. The passage of the longest flow paths along peripherally replaced grains further implies that the micropores along those grain boundaries are larger and/or more connected than those within the clay matrix. The same long flow paths can go through clay matrix when connecting between peripherally replaced grains. However, without the portion of
the path traveling along the periphery of grains, the microporous network would be limited in its connectivity and would be shorter, essentially the same as the shorter paths in the low permeability samples.
CHAPTER V: DISCUSSION

Phase Maps Help to Better Understand the Paragenesis of the Codell

Whereas previous diagenetic studies of the Codell sandstones (Henningsgaard, 1986; Caraway, 1990; Sablina, 1993) relied on thin-section petrography for creating a paragenetic sequence, this study also used higher-resolution imaging technology to identify diagenetic phases and their cross-cutting relationships. As a result, the recognition and relative timing of diagenetic processes was more accurately constrained than in previous diagenetic studies of the Codell Type 2 sandstones. For example, many of the diagenetic processes mentioned by previous authors focused on framework-grain dissolution, calcite cement dissolution, and authigenic clays filling secondary pores. Those prior studies failed to fully distinguish the complexities of mineral replacements.

The only mineral phase identified by Henningsgaard (1986), Caraway (1990) or Sablina (1993) as a replacement of detrital material was calcite. Clays were never mentioned as a replacement. In this study, clays (illite, chlorite, and kaolinite) were observed replacing quartz, feldspars, and calcite even after they had filled secondary pores. Identification of these extensive clay replacements sheds light on important diagenetic processes that influence Codell rock properties. Furthermore, the timing of clay replacements, elucidated herein with the help of phase maps, indicates that the deep burial realm is when the best connected micropores were created. This is a contrast to interpretations made by the previous authors, who stated that most secondary porosity was formed earlier in the paragenesis by feldspar and calcite dissolution.

Albitization was also a diagenetic feature previously mentioned only by Sablina (1993), but the evidence for her observation was not clearly given. Her paragenesis groups albitization with feldspar dissolution in the intermediate burial realm, but with no clear relative timing. The
EDS phase maps collected in this study confirms that albitization did indeed take place, and did so after feldspars were initially dissolved and/or replaced by calcite and early clays. Microprobe imaging and phase maps also helped distinguish different clay growth morphologies associated with replacive and pore-filling phases. Prior to this study, mentions of kaolinite were strictly of the vermiform booklets that filled secondary pores left by the dissolution of feldspars (Henningsgaard, 1986; Sablina, 1993). Phase maps used herein revealed “grains” of replacive kaolinite that preserved the shape of precursor feldspars and or calcite, indicating a replacement phase that is distinctly different from the pore-filling booklets.

**Comparison of Paragenesis to Previous Studies of the Codell**

Most of the diagenetic features observed in this study were also mentioned in the previous Codell paragenetic studies by Henningsgaard (1986), Caraway (1990) and Sablina (1993). However, there are some divergences in relative ordering of features and interpreted burial stages. The significant differences between the paragenetic sequence defined in this study (Fig. 26) and those of the prior workers (Fig. 4) are discussed below.

The first difference is syn-depositional pyrite precipitation noted herein. Previous Codell studies have not included pyrite precipitation so early in their parageneses. Henningsgaard (1986) defined pyrite precipitation as an early burial feature that followed quartz cementation and compaction and occurred concurrently with calcite precipitation. Sablina (1993) interpreted pyrite precipitation as a strictly shallow burial feature with no clear timing in relation to the other shallow diagenetic features she observed in thin sections and SEM images. In this study, individual, micron-sized pyrite frambooids were seen encased in quartz overgrowths, indicating pyrite preceded quartz cementation. This pyrite probably formed once the sediments passed
through the oxic and suboxic zones associated with bioturbation and entered the underlying zone of anoxic pore-water, all of which occurs with very shallow burial.

A few major differences in the ordering and timing of shallow burial features also occur between this study (Fig. 26) and the three preceding Codell theses (Fig. 4). There is agreement that mechanical compaction did take place in the Codell, as indicated by the overly close packing of grains and deformation of ductile micas. Henningsgaard (1986) interpreted mechanical compaction as a shallow burial feature that preceded cementation by quartz and calcite. Sablina (1993) distinguished between two phases of compaction: a minor component that occurred syn-depositionally with bioturbation, and a major component that took place during shallow burial at the same time as quartz and calcite cementation. In this study, it was noted that quartz overgrowths abut overgrowths on adjacent grains and that calcite had filled some intergranular pores; cementation must have initiated before the onset of compaction, with the calcite cementation in some samples finishing before compaction began. If compaction had occurred beforehand, as Henningsgaard (1986) proposed, the detrital grain boundaries would be in contact, more pseudomatrix would be found in intergranular pores, and there would be diminished quartz overgrowths. The sequence of events proposed herein is more similar to Sablina’s (1993) interpretation, with the exception of two phases of compaction. The evidence presented herein would indicate that compaction within the Codell was relatively minor, as its effects were minimized by quartz overgrowths and calcite precipitation providing stability to the sediments.

Calcite cementation and replacement was observed by all three previous authors, but its timing is not well constrained and its placement within the paragenetic sequence is variable (Fig. 4). Henningsgaard (1986) observed calcite replacing framework grains and clay, as well as
occluding primary pores. He interprets it to be post-compaction and precipitation of quartz overgrowths. Caraway (1990) observed calcite replacing feldspars and quartz overgrowths and implied it was a shallow to intermediate burial feature. Sablina (1993) interpreted two calcite precipitation events in her Codell samples: cementation of intergranular pores during shallow burial that preceded major compaction, and cementation of secondary pores and replacement of framework grains during intermediate burial. This study presents evidence for calcite cements precipitating within intergranular pores and replacing quartz overgrowths, feldspars, and intergranular matrix. The timing of calcite cementation given here is in alignment with Sablina’s (1993) interpretation in that pore-filling calcite had to begin forming just before the onset of compaction. Otherwise, pseudomatrix and the surrounding grains would have filled the primary pores, leaving no room for calcite cementation. Calcite replacement is interpreted herein to be a shallow burial feature, just as Henningsgaard (1986) proposed, but the main difference is its timing with respect to compaction. Because calcite precipitation is viewed as a single diagenetic feature, it is assumed that replacement happened within the same time as cementation. Since cementation began just before compaction, replacement would have taken place just as compaction began to take effect.

One diagenetic feature documented in this study, but not by Sablina (1993) or Henningsgaard (1986), is the early clay replacement of feldspar and quartz. Only Caraway (1990) noted clay replacement (sericitization, Fig. 4) of feldspars, but she simply calls it an early diagenetic feature with no clear relative timing. A precursor detrital clay is mentioned by Sablina (1993) and Henningsgaard (1986); however, it appears they assumed that the clay did not replace any framework grains. In this study, an authigenic partially-smectitic clay was observed replacing chert, implying that it had to have grown before illitization began, thus making it
relatively early in the paragenetic sequence. The early smectitic clays may have also begun to
replace quartz and feldspars before being illitized. The timing of this event is better constrained
herein than was the case with Caraway (1990), but it is still uncertain how pervasive the early
clay replacements were or for how long they attacked framework grains. Regardless, the
placement of this diagenetic event in the paragenesis presented here means that peripheral and
guided replacement of framework grains by clays began as early as shallow burial.

The paragenetic sequence presented herein also distinguishes between three burial stages
for the Codell sandstone, a feat not done in the previous Codell diagenetic studies.
Henningsgaard (1986) defined early diagenetic events as those happening below 50 m of burial
and late diagenetic events as those related to hydrocarbon maturation and higher subsurface
temperatures. He did not formally define an intermediate stage, but some features are seen
starting in the middle of his paragenetic sequence. Caraway (1990) simply listed the major
diagenetic features she observed without any interpretation of each features’ development with
respect to burial depths. Sablina (1993) distinguished shallow and intermediate burial, but
concluded the incomplete conversion of smectite to illite meant the Codell sandstone never
experienced deep burial alteration. In this study, recognition of features typically formed
proximal to the seafloor and placement of features between mechanical compaction and
formation of illite and chlorite were the keys to distinguishing three stages of diagenesis.

Kaolinite was noted by Henningsgaard (1986) and Sablina (1993) mainly as a cement;
both authors observed kaolinite booklets growing in moldic pores. Herein, it is assumed that
kaolinite was able to precipitate because of the aluminum and silica released during feldspar
dissolution, a hypothesis shared by Henningsgaard (1986). Henningsgaard (1986) classified
kaolinite precipitation as a late diagenetic feature, whereas this study places it in intermediate
burial, an interpretation similar to Sablina’s (1993). Additionally, phase maps and high-resolution imaging revealed kaolinites that completely replaced feldspars and peripherally replaced quartz, two clay interactions not mentioned in previous Codell studies. The addition of kaolinite replacement within the paragenetic sequence highlights the importance of clays that interact with detrital grains and previously-formed cements. These interactions are, in turn, modifying the pore network within the Codell. An example of this is the pore-filling kaolinite that peripherally replaces quartz and calcite, a process that is creating microporosity in areas previously inhabited by solid minerals.

Authigenic illite and chlorite were observed in the Codell samples analyzed in this study, and they characterize the onset of deep burial in the paragenetic sequence herein. Henningsgaard (1986) and Sablina (1993) distinguish separate timings for illite and chlorite precipitation, whereas Caraway (1990) simply notes the precipitation of minor authigenic clays during deep burial. In this study, the two clays are grouped as a single feature in the paragenesis. Both clay types were observed inhabiting the same void space with no evidence for one clay attempting to replace the other, making it impossible to distinguish their relative timing. Pure fibrous illite precipitates at high temperatures, hence its placement in the deep burial realm. Chlorite, on the other hand, can form at a variety of burial depths and temperatures, and so its timing cannot be defined in the same way as illite. However, chlorite requires iron and magnesium to precipitate, and these cations were likely released by smectitic clays during illitization, a hypothesis shared by Henningsgaard (1986) and Sablina (1993). This relationship could mean that chlorite precipitation began as early as intermediate burial, when illitization had also begun, and before temperatures were hot enough to drive significant amounts of illite precipitation.
Microprobe images and phase maps presented herein show evidence of illite and chlorite peripherally replacing quartz, albite, and calcite. This diagenetic event was not mentioned in the three previous studies. Illite and chlorite are considered to be the main peripheral replacement phases in the Codell and were observed attacking framework grains and calcite with equal intensity in all samples. This indicates that environmental conditions (heat and cation supply) during deeper burial favored the continued growth of clays and fueled their replacement of grains and cements. The addition of illite and chlorite peripherally replacing grains to the Codell paragenetic sequence highlights an important role of microporous clays when they were previously deemed destructive to porosity by Henningsgaard (1986), Caraway (1990), and Sablina (1993).

Finally, large pyrite clusters were observed precipitating on late authigenic clays, making it the last diagenetic feature to form in the Codell samples. Pyrite precipitation during deep burial is a diagenetic feature that has not been noted in previous Codell studies. These clusters are significantly larger than the micron-sized pyrite frambois interpreted to be syndepositional features, reflecting a major difference in iron and sulfur availability during deep burial. The iron was likely sourced from smectites undergoing illitization, implying that the precursor smectitic clay was rich in metal cations, especially iron. The sulfur probably came from the maturation of hydrocarbon compounds within the formations enclosing the Codell. Type II organic matter is found in the underlying Greenhorn Formation and the overlying Niobrara Formation (Sonnenberg, 2014). Thermal maturation of bitumen broke the weak carbon-sulfur bonds within the organic matter (Horsfield and Rullkotter, 1994), and free sulfur ions could have infiltrated the Codell to combined with iron to form the large pyrite clusters.
**Diagenetic Evolution of the Drainage Network**

The flow paths analyzed in this study illustrate the optimal drainage paths in samples and reveal the relationships between connected pores and certain diagenetic features. Shorter flow paths indicate restricted pore connectivity limited by inaccessible micropores, whereas longer flow paths are an indication of well-connected pathways containing easily-navigable channels. Bioturbation, although not considered a diagenetic feature, was a key depositional process that destroyed primary intergranular porosity. The relative abundance of diagenetic features, independent of lithofacies, indicates that early quartz overgrowths, precipitation of pore-filling clays, feldspar dissolution, and peripheral clay replacement of framework grains frequently occur in almost all of the mid- to high-permeability samples (Table 6). In contrast, these four features have a minor presence in low-permeability samples. Lastly, the correlation of flow paths and phase maps show that intergranular clay masses impact the connectivity of micropores associated with peripheral replacements within the Codell.

Bioturbation set the stage for the micropore drainage system that dominates the Codell today. Previous authors (Weimer and Sonnenberg, 1983; Henningsgaard, 1986; Caraway, 1990; Sablina, 1993; Birmingham et al. 2001) agreed that bioturbation negatively impacted the Codell pore network. The reasoning is that organisms moved through stratified sand and mud layers and mixed those sediments, effectively reducing the amount of laminated sands and increasing the amount of muddy sands. Primary porosity that existed within the laminated sands was destroyed as intergranular pores were clogged with detrital clays and silt-sized particles. The initial pore network that included an abundance of intergranular mesopores was transformed into one dominated by micropores between intergranular clays.
In one sample from the Rissler State well, a majority of flow paths were observed within a burrow, including the longest three for that sample (Fig. 39C). This concentration of flow paths would indicate that burrows can be a primary drainage network, perhaps reflecting better connectivity of micropores in the burrow fill than in the surrounding matrix. However, the flow paths for this sample are some of the shortest in the high-graded set. It is inferred that the detrital clay may have inhibited compaction and formation of quartz overgrowths, which in turn means framework grains just touch each other at points, or even float in the clay matrix. This would result in flow paths that could not easily extend through peripheral grain replacements, and instead only connect for short distances through the microporous detrital clays.

The precipitation of impermeable mineral phases and pore-filling clays are also important diagenetic features in the alteration of the original Codell pore network. Quartz overgrowths and calcite cements eliminated primary porosity and created barriers to potential flow paths very early in the paragenesis. Similarly, kaolinite cements have a negative impact on the pore network because they occlude secondary pores. Even when there is microporosity within the kaolinite masses, no flow paths were observed going through pores, implying that these microporous areas may not be well connected or are difficult to navigate. Fibrous illite and platy chlorite were also observed growing into moldic pores. These minerals were not as effective at filling secondary pores as kaolinite, and so more microporosity is observed in these areas. In fact, flow paths were observed going through secondary pores filled with these clay cements. A reason for this may be that illite and chlorite have less intricate growth patterns than pore-filling kaolinite, making it easier for a flow path to navigate a pore cemented by these two clay types. However, flow paths that were confined to these clay-filled areas continued to be some of the shortest in the sample.
set, reflecting the limiting nature of illite and chlorite cemented voids with respect to pore connectivity.

The creation of large secondary mesopores by feldspar dissolution (e.g., Figs. 5, 10C, 28A, 33) certainly improved storage capacity within the Codell sandstones, but its importance with respect to the drainage network may have been overstated by prior workers. While secondary mesopores were more pervasive in the more porous Redtail samples (14-16%), most of the longest flow paths occurred in Wattenberg samples, which also had lower porosities (9-13%) and few, if any, mesopores. Furthermore, in samples with large mesopores, skeletonized flow paths almost never traveled through those void spaces. Rather, the flow paths continued along the clay-lined edge of moldic pores, suggesting that the drainage network does not necessarily rely on empty secondary mesopores. This would imply that the secondary mesopores do not improve pore connectivity as much as prior Codell workers thought.

Clays that peripherally replaced framework grains are considered here to be the key diagenetic features controlling flow path length, making them vital to the creation of an effective drainage system in the Codell. Clays created embayments along grain and cement boundaries (e.g., Figs. 33, 35, 37, 44, 45, 46) replacing the solid mineral phases and creating microporosity where none previously existed (e.g., Fig. 37). The longest flow paths are located in mid- to high-permeability samples, and they typically follow the edges of grains peripherally replaced by illite, chlorite, and/or kaolinite. This implies that the micropores created by peripheral clay replacements associate with larger pore throats (Fig. 5) that were easily accessed by rhodamine during impregnation. From this, it is inferred that the primary drainage system for a fluid traveling through highly permeable sediments is along the clay-replaced grain boundaries. While
porosity may not have been vastly improved by the addition of these micropores, these clay replacements certainly improved pore connectivity.

Two features that are inferred to have improved flow path length are the proximity of framework grains (especially quartz) to each other, and the amount of clay between peripherally replaced grains. Mechanical compaction, which reduced primary porosity within the Codell, had beneficial effects on pore connectivity in that it increased the contact area between framework grains. The closer packing of grains meant better connectivity of the microporosity associated with the subsequent peripheral grain replacements by clay. In the absence of compaction, those peripheral networks can only connect from one grain to another where the hosts touch at points. With compaction, the framework grains were in contact with one another over greater surface areas. That, in turn, meant the peripheral network of micropores could connect over large surface areas between grains, improving the overall flow paths.

The same argument applies to the quartz overgrowths in that they reduced primary porosity early in the paragenesis, but it also increased the contact area between adjacent quartz grains. Quartz overgrowths were observed in most of the phase maps of the continuous section of flow paths in mid to high permeability samples, implying that this diagenetic feature is vital in the creation of an effective drainage network. Quartz overgrowths resulted in longer contacts between adjacent quartz grains. While this reduced primary porosity and permeability, the effect on permeability was reversed when clays replaced the periphery of the quartz overgrowths. Micropores were created along the continuous boundaries of the “conjoined” quartz grains, resulting in a connected micropore network as evidenced by longer flow paths.

Finally, intergranular clay masses played a role in promoting long flow paths, regardless of a sample’s permeability. It should be noted that the long flow paths in mid to high
permeability samples do not solely rely on peripherally replaced grains for achieving such extensive lengths. The flow paths in higher-permeability samples were sometimes observed traversing small areas where clays had replaced entire framework grains or filled spaces between framework grains (i.e., cement or detrital clays). In either case, those masses of clay were associated with small but resolvable porosity in phase maps. This relationship was also observed in the longest flow paths in low permeability samples. The interpretation here is that while rhodamine relied heavily on peripheral clay replacement to successfully penetrate samples, it was still able to flow through clay masses that separated these better-connected micropores. It is inferred that the clay masses link the micropore networks within the grain boundaries into longer, continuous flow paths.

**Limitations and Future Work**

Phase maps are an effective means of quickly identifying various minerals in thin sections, which allowed for better understanding of diagenetic features and processes. However, the identification of mineral phases was based on EDS (energy dispersive) rather than WDS (wavelength dispersive) measurements. EDS is faster and less expensive, but WDS is superior—it has better resolution of individual elements and lower detection limits. For framework grains, calcite, and simple clays like kaolinite, EDS analysis worked fine because their elemental constitution is relatively simple. But, the resolution of the collected data made it difficult to distinguish pure illite from illite-smectite mixtures. The mixed-layered illite-smectite that was repeatedly registered by XRD was observed by previous authors (Henningsgaard, 1986; Sablina, 1993), but could not be identified as a separate phase during the conversion of the EDS spectra to mineralogical maps. Because of this, almost all of the phase maps appear to have pure illite, despite the fact that different clay morphologies were observed (fibrous vs honeycomb). Thus,
future work utilizing phase mapping should rely primarily on WDS data rather than EDS data for more accurate identification of mixed-layered illite-smectite and pure illite.

Higher-resolution imaging technology has shed light on new diagenetic features not previously mentioned and has revealed microporosity associated with clay masses that were previously deemed impermeable. However, these images still cover a relatively large area (100-200 µm across). At that scale, the details of the clay morphologies, like illite (fibrous versus honeycomb) and kaolinite (blocky versus booklets), and the micropores in clay-filled areas, are not well resolved. Furthermore, imaging on a 2D plane limits our perception of the actual size and depth of micropores associated with clays. This makes it difficult to accurately assess if pore sizes are larger along peripherally replaced grain boundaries than between pore-filling clay particles. More SEM work on broken rock faces, done at high resolutions, would certainly provide greater insights.

The flow paths imaged and analyzed in this study were an inexpensive and effective means of capturing the drainage system in clay-rich sandstones at the thin section level. Furthermore, the integration of high-resolution microprobe imaging and mineralogical phase mapping with flow paths has generated new ideas about the controls on permeability in the Codell. Future work in the Codell Type 2 sands should focus on corroborating the results given here by implementing the same staining method and using epifluorescence microscopy to image micropores. This will verify if the rhodamine, once again, preferentially stains a large percentage of micropores based on the permeability (more staining with higher permeabilities).

Thresholding on 5 channels, perhaps with a slightly different pixel intensity range, and skeletonizing will confirm if flow path lengths are controlled by permeability and if the longest flow paths are continually being identified along peripherally replaced grain boundaries. Such
work should also consider using more than 3 fields of view to image the attributes of each of the longest flow paths. This would be particularly true for mid to high permeability samples, since flow paths in these samples can have lengths up to 7 mm.

Further analysis of the micropores at the grain-clay contact is also needed in order to better understand why peripheral clay replacements are the primary flow paths in the Codell. Quantitative analyses of the abundance of peripheral replacements, and the evaluation of that data in the context of data on pore volumes and pore-throat sizes (e.g., capillary pressures from mercury injection and nuclear magnetic resonance analyses), might prove the most useful for this type of study. FIB-SEM would also be advantageous in this venture because it would provide 3D visualizations of the micropores along grain boundaries, thus yielding a more complete picture of that specific drainage network. Also, 3D imaging of fluorescing bioturbated samples would expand on the interpretation given here that burrows may serve as a conduit for preferential fluid flow. A comparison of the pore network within a burrow that has a high concentration of flow paths to the pore network in the surrounding homogenized matrix may reveal other diagenetic features that promote a more effective drainage system.

Finally, a more detailed look at the micropores within clay assemblages will also shed light on how effective intergranular clay masses are in promoting longer flow paths. While it was noted that the longest flow paths in all samples relied on clay masses to connect between adjacent peripherally replaced grains, it is still unknown why lower permeability samples only have short flow paths. More high-resolution images and phase maps collected along the lengths of the flow paths in higher permeability samples may reveal a difference in clay types or morphologies from those found in lower permeability samples. Understanding the micropores in these clay assemblages will expand on the ideas presented herein.
CHAPTER VI: CONCLUSIONS

This study focused on the diagenesis of the Codell Type 2 sandstone in the Wattenberg and Redtail fields, Denver Basin, to better comprehend which diagenetic processes played a role in developing a connected pore network. Electron microprobe imaging and phase mapping revealed diagenetic features not described in previous Codell studies and helped constrain the relative timing of features identified previously. This new information has led to an improved understanding of the Codell’s diagenetic history. Epifluorescence microscopy and flow paths analysis successfully generated a representation of the intergranular drainage system that exists within this “tight” sandstone at various permeabilities. Furthermore, phase maps acquired of the longest two-dimensional flow paths in all samples shed light on the key diagenetic features that improved permeability. This, in conjunction with the new paragenetic sequence, yields a better understanding of the critical diagenetic events impacting permeability in the Codell sandstones.

Clays are an important feature in the development of the Codell sands. Bioturbation mixed the sediment, introduced detrital clays into intergranular pores and reduced primary porosity. These clays set the stage for a low-permeability reservoir sandstone that utilizes a micropore-dominated drainage system for fluid transport. Authigenic clays formed during intermediate and deep burial, and they interacted in various ways with quartz, feldspars, and calcite. This included complete replacements of framework grains, cementation in primary and secondary pores, and peripheral replacement of detrital grains and quartz overgrowths. The latter feature, which included replacements by illite, chlorite, and kaolinite, is particularly important to this study because it has not been discussed by prior workers as a diagenetic process within the Codell.
Most of the diagenetic processes inferred as being detrimental to the Codell pore network have been discussed in prior studies, but some differences exist for features interpreted as positive influences on pore connectivity. Diagenetic processes that destroyed primary intergranular porosity within the Codell (introduction of clays by bioturbation, quartz and calcite cementation, compaction) all occurred early in the paragenesis, making shallow burial the time when the pore network was most heavily diminished. Porosity was improved by feldspar dissolution, but the resultant secondary mesopores are not connected to each other and were not observed to contribute significantly to pore connectivity. Mechanical compaction and the development of quartz overgrowths played a role in improving the pore network by increasing the contact area between framework grains. Subsequent clay replacement along those contacts and the periphery of framework grains created additional microporosity in areas previously inhabited by impermeable mineral phases.

The imaging of rhodamine dye within micropores, and subsequent skeletonization of the micropore system revealed by that dye, defined permeable pathways through these clay-dominated sandstones. Based on impregnation pressures and high-pressure mercury injection data, the identified pathways are connected by pore throats greater than 70 nm and represent 10% to nearly 60% of all pores in the Codell samples. The longest flow paths relied primarily on micropores created by the peripheral clay replacement of framework grains and quartz cements. Micropores associated with intergranular clay masses provided secondary connections between peripherally replaced grains. The increased contact area between grains brought about by compaction and quartz cementation promoted a longer, continuous micropore network when clays peripherally replaced framework grains and cements that met along planes rather than points. The flow paths were able to achieve longer lengths in higher permeability samples.
because these easily-accessible channels connected over larger surface areas between grains. Therefore, intermediate and deep burial diagenetic events were key to the development of effective pore connectivity and creation of the thin-section scale drainage networks being exploited today for hydrocarbon recovery.
REFERENCES


Smith, K.H., 2015, Codell Sandstone, DJ Basin: AAPG Annual Convention & Exhibition, Denver, Colorado, USA.


Sterling, R., Bottjer, R. and Smith, K.H., 2015, Codell SS: a review of the northern DJ oil resource play in Laramie County, WY & Weld County, CO: AAPG Annual Convention & Exhibition, Denver, Colorado, USA.


APPENDIX A

Wattenberg and Redtail Core Logs

Four cores from the Wattenberg Field and three cores from the Redtail Field were described. All cores captured the entirety of the Codell Sandstone Member, and all cores were slabbed and 4” in diameter. Core descriptions focused solely on the Codell, with the underlying 1-2 feet of Blue Hill Shale and overlying 0.5-1 feet of Fort Hays simply noted by their depths. Cores were described at sub-foot intervals for lithology, color, lithofacies (as described herein), contacts, relative grain size, physical sedimentary structures when present, bioturbation intensity (after MacEachern et al. 2010), and relative occurrence of vertical and horizontal burrows. Sedimentary structures were drawn as they appeared in cores.

Individual core descriptions can be found on the following pages:

<table>
<thead>
<tr>
<th>Core Name</th>
<th>Location</th>
<th>Unit</th>
<th>Interval (ft)</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rissler State</td>
<td>Wattenberg</td>
<td>Codell</td>
<td>7318-7337</td>
<td>126</td>
</tr>
<tr>
<td>Miracle</td>
<td>Wattenberg</td>
<td>Codell</td>
<td>7218-7249</td>
<td>128</td>
</tr>
<tr>
<td>Puritan</td>
<td>Wattenberg</td>
<td>Codell</td>
<td>7812-7836</td>
<td>130</td>
</tr>
<tr>
<td>Narco Devore</td>
<td>Wattenberg</td>
<td>Codell</td>
<td>7428-7447</td>
<td>132</td>
</tr>
<tr>
<td>Terrace</td>
<td>Redtail</td>
<td>Codell</td>
<td>6184-6199</td>
<td>134</td>
</tr>
<tr>
<td>Razor</td>
<td>Redtail</td>
<td>Codell</td>
<td>5880-5895</td>
<td>135</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>Redtail</td>
<td>Codell</td>
<td>5872-5883</td>
<td>136</td>
</tr>
<tr>
<td>Facies</td>
<td>Color</td>
<td>Lithology</td>
<td>Contacts</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------</td>
<td>------------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>CDL-1</td>
<td>LLGr: Light-light grey</td>
<td>Sand</td>
<td>S: Sharp</td>
<td></td>
</tr>
<tr>
<td>CDL-2</td>
<td>LGr: Light grey</td>
<td>Mud</td>
<td>E: Erosional</td>
<td></td>
</tr>
<tr>
<td>CDL-3</td>
<td>DLGr (w/Br): Dark-light grey</td>
<td>Carbonate</td>
<td>G: Gradational</td>
<td></td>
</tr>
<tr>
<td>CDL-4</td>
<td>LDGr (w/Br): Light-dark grey</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDL-5</td>
<td>DDGr (w/Br): Dark-dark grey</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DDGr w/Bl: Dark-dark grey</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>GrBr: Grey-brown</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LGBr w/Bl: Light-grey brown</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tan w/DG: Tan with little dark-grey</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burrows</td>
<td>Horizontal bedding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low-angle horizontal bedding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alternating sand and mud</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mud drape</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cross-stratified bedding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hummocky beds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coarse grained bedding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BI</td>
<td>Bioturbation Index (BI)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0: No bioturbation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-2: Minimal bioturbation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-4: Moderate bioturbation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-6: Pervasive bioturbation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sedimentary Structures

- Horizontal bedding
- Low-angle horizontal bedding
- Alternating sand and mud
- Mud drape
- Cross-stratified bedding
- Hummocky beds
- Coarse grained bedding
<table>
<thead>
<tr>
<th>Interval (ft)</th>
<th>Lithology</th>
<th>Color</th>
<th>Facies</th>
<th>Contacts</th>
<th>Grain size</th>
<th>Structures</th>
<th>Bioturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td>7318</td>
<td>LLGr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7320</td>
<td>DLGr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7322</td>
<td>DBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7324</td>
<td>w/Bl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7326</td>
<td>LGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7328</td>
<td>LGBr w/Bl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7330</td>
<td>SDG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7332</td>
<td>DBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
WELL NAME: MIRACLE
INTERVAL DESCRIBED: 7218-7233
LOCATION: WATTENBERG
PAGE: 1 OF 2

<table>
<thead>
<tr>
<th>Interval (ft)</th>
<th>Lithology</th>
<th>Color</th>
<th>Facies</th>
<th>Contacts</th>
<th>Grain size</th>
<th>Structures</th>
<th>Bioturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td>7218</td>
<td>LLGr</td>
<td>DBr</td>
<td></td>
<td>G</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7220</td>
<td>DLGr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>7222</td>
<td>LGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>7222</td>
<td>DGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7224</td>
<td>DBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>7224</td>
<td>DGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7226</td>
<td>DGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>7226</td>
<td>DGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7228</td>
<td>DBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>7230</td>
<td>DBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>7232</td>
<td>DGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Interval (ft)</td>
<td>Lithology</td>
<td>Color</td>
<td>Fades</td>
<td>Contacts</td>
<td>Grain size</td>
<td>Structures</td>
<td>Bioturbation</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td>-------</td>
<td>-------</td>
<td>----------</td>
<td>------------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td>7234</td>
<td>LBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7236</td>
<td>LGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7238</td>
<td>LGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7240</td>
<td>DGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7242</td>
<td>LBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7244</td>
<td>LGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7246</td>
<td>LGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Lithology Structures**

**Facies**

**Color**

**Interval**

**BI Index**

**Vertical**

**Horizontal**

**Grain size**

**Contacts**

**Clay Silt VF F M C**
<table>
<thead>
<tr>
<th>Interval (ft)</th>
<th>Lithology</th>
<th>Color</th>
<th>Facies</th>
<th>Contacts</th>
<th>Grain size</th>
<th>Structures</th>
<th>Bioturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td>7812</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7814</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7816</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7818</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7820</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7822</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7824</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7826</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interval (ft)</td>
<td>Lithology</td>
<td>Color</td>
<td>Facies</td>
<td>Contacts</td>
<td>Grain size</td>
<td>Structures</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td>-------</td>
<td>--------</td>
<td>----------</td>
<td>------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>7828</td>
<td>LGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7830</td>
<td>DGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7832</td>
<td>DGBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7834</td>
<td>DDGr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7836</td>
<td>LBl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Lithology**

- LGBr: Lithified Gray Bioturbated
- DGBr: Diagenetic Gray Bioturbated
- DDGr: Diagenetic Dark Gray
- LBl: Lithified Black

**Contact**

- S: Soft
- G: Graded

**Grain size**

- VF: Very Fine
- F: Fine
- M: Medium
- C: Coarse

**Bioturbation**

- BI Index: Vertical Index
- Vertical: 1 to 6
- Horizontal: 0 to 6
<table>
<thead>
<tr>
<th>Interval (ft)</th>
<th>Lithology</th>
<th>Color</th>
<th>Facies</th>
<th>Contacts</th>
<th>Grain size</th>
<th>Structures</th>
<th>Bioturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td>7444</td>
<td>DDGr</td>
<td>Black</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7446</td>
<td>LDGr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interval (ft)</td>
<td>Lithology</td>
<td>Color</td>
<td>Facies</td>
<td>Contacts</td>
<td>Grain size</td>
<td>Structures</td>
<td>Bioturbation</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td>-------</td>
<td>--------</td>
<td>----------</td>
<td>------------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td>6184</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6186</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6188</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6190</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6192</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6194</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6196</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6198</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

WELL NAME: TERRACE
INTerval DESCRibED: 6184-6199

LOCATION: REDTAIL
PAGE: 1 OF 1
<table>
<thead>
<tr>
<th>Interval (ft)</th>
<th>Lithology</th>
<th>Color</th>
<th>Facies</th>
<th>Contacts</th>
<th>Grain size</th>
<th>Structures</th>
<th>Bioturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5880</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5882</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5884</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5886</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5888</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5892</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5894</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**WELL NAME:** RAZOR  
**LOCATION:** REDTAIL  
**INTERVAL DESCRIBED:** 5880-5895  
**PAGE:** 1 OF 1
APPENDIX B
Porosity and Permeability vs Mineralogy and Depth Plots

K-feldspar vs Porosity (%) (Wattenberg)

Plagioclase vs Porosity (%) (Wattenberg)
$R^2 = 0.08$

Calcite vs Porosity (%) (Wattenberg)

$R^2 = 0.04$

Pyrite vs Porosity (%) (Wattenberg)

Total Clay vs Porosity (%) (Wattenberg)

$R^2 = 0.03$
Chlorite vs Porosity (%) (Wattenberg)

R² = 0.04

Mixed-layered I/S vs Porosity (%) (Wattenberg)

R² = 0.002

Illite vs Porosity (%) (Wattenberg)

R² = 0.005
Perm (md) vs Depth Below Top Codell (Wattenberg and Redtail)

Quartz vs Permeability (md) (Wattenberg)

K-feldspar vs Permeability (md) (Wattenberg)
Calcite vs Permeability (md) (Wattenberg)

Pyrite vs Permeability (md) (Wattenberg)

Total Clay vs Permeability (md) (Wattenberg)
Illite vs Permeability (md) (Wattenberg)

\[ R^2 = 0.12 \]

Chlorite vs Permeability (md) (Wattenberg)

\[ R^2 = 0.002 \]