RESERVOIR CHARACTERIZATION OF THE FRONTIER FORMATION, POWELL FIELD,

POWDER RIVER BASIN WY

by

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ABSTRACT

The Upper Cretaceous Wall Creek Member of the Frontier Formation is a prolific oil and gas producer in the Powder River Basin of north east Wyoming. It has been a focus for drillers in recent years as horizontal drilling and hydraulic fracturing help exploit the hydrocarbon resource of the tight sandstone reservoir. Millions of barrels of oil have been produced from this oil prone formation since the late 19th century.

The Upper Cretaceous, Turonian Wall Creek Member of the Frontier Formation represents the distal reaches of a progradational clastic wedge that formed in response to the Sevier Orogeny. Sediments were shed from the Sevier Highlands into the Western Interior Basin (WIB). The Wall Creek Member of the Frontier Formation produces at Powell Field in the center of the Powder River Basin near the deep basin axis. Vertical well production originates from reworked, medium to coarse grained sandstones.

This research integrates data and interpretations to characterize the Wall Creek Member of the Frontier Formation at Powell Field. Petrophysical evaluation, well production, X-Ray diffraction, core analysis, and petrographic analysis were used to characterize the Wall Creek Member of the Frontier Formation. The Simandoux shaly sand petrophysical model matches core derived water saturation values best and was used to produce subsurface maps that highlight areas for further unconventional well development. Eight total core facies are identified as part of the core analysis that suggest a shallow marine, wave and tidal influenced delta front environment. Petrographic observations of the main reservoir facies indicate primary porosity is preserved from early chlorite coating of quartz grains prior to calcite cementation and quartz overgrowths forming.
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CHAPTER 1: INTRODUCTION

1.1 Overview

The Powder River Basin was developed during the Laramide Orogeny and is comprised of sediments from the Sevier Highlands. The Powder River Basin, situated in Wyoming and Montana, is a historic sedimentary basin in the United States providing vast quantities of natural resources. Natural resources such as uranium, bentonite, coal, oil, and natural gas are produced out of a basin comprised of more than 34,000 square miles (Dolton et al., 1990). The Powder River Basin is a northerly trending, asymmetrical basin that is approximately 250 miles long and 100 miles wide. The basin axis, and deepest part of the basin is situated along the western margin.

In the deepest parts of the basin over 17,000 ft of sediments have accumulated and range in age from Paleozoic to Tertiary (Anna, 2009). The current configuration is constrained by many prominent structural features such as the Bighorn Mountains and Casper Arch to the west. The Laramie Range and Hartville uplift surround the basin to the south, the Black Hills Uplift encompasses the basin to the east, and the Porcupine dome and Miles City Arch to the north (Figure 1.1).

The focus of this study will be the Upper Cretaceous, Turonian Wall Creek Member of the Frontier Formation (Figure 1.2). The Frontier Formation represents the distal reaches of a progradational clastic wedge that formed in response to the Sevier Orogeny. It is a prolific tight oil producer in the Powder River Basin. In 2017 alone, the Frontier Formation, and its equivalent Turner Member produced over 17,000,000 barrels of oil and is the largest horizontal target (Figure 1.3).
Oil and gas industry activity in the Powder River Basin has been extremely focused on the Frontier Formation, with 1,500 state permits requested for horizontal wells since January 2019. The focus area of this thesis is Powell Field in Converse and Campbell counties Wyoming. Vertical well production dominates the area, however, with the advent of horizontal drilling and hydraulic fracturing, hydrocarbons can be produced from the tighter, elevated clay intervals below the higher porosity and permeability reservoir. A shaly sand petrophysical model is used to generate subsurface maps highlighting areas for further unconventional well development.
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Figure 1.3  Powder River Basin monthly horizontal well oil production colored by producing horizon. Plot starts in the year 2010 and goes through 2016 (Finley, 2017).
1.2 Purpose and Objectives

The purpose of this research is to integrate data and interpretations to characterize the Wall Creek Member of the Frontier Formation at Powell Field and highlight areas for further unconventional well development. Wireline logs, well production, X-Ray diffraction, core analysis, thin sections, and scan electron microscopy are all examples of data that was interpreted and integrated into a final product. The objective of this study is to provide a reservoir characterization of the Frontier Formation at Powell Field in order to better understand the Upper Cretaceous, tight oil potential of the Frontier system in the Powder River Basin.

1.3 Research and Methods

As with many geologic studies, I chose to research using a top-down approach (i.e. regional maps -> sequence stratigraphic framework -> petrophysical evaluation -> core description -> petrographic evaluation -> FE-SEM evaluation. Five representative cores in the project area were described in detail to gain a better understanding of facies distribution and depositional environment.

A petrophysical evaluation was completed and a model was built for the Wall Creek Member using established methods for analyzing shaly sandstone and thinly bedded reservoirs. Over 100 digital well logs were used for the petrophysical evaluation. Routine core analysis, and X-Ray diffraction data were used to calibrate the petrophysical model. Water saturation, volume of clay, effective and total porosities, and hydrocarbon pore volume are all computations completed for the digital well logs available.

A petrographic analysis was completed including thin section evaluation and FE-SEM photographs to better understand the compositional makeup of the Wall Creek Member and
better understand the pore system and its distribution. Diagenetic order was also identified in the 
petrographic analysis.

A sequence stratigraphic framework was built identifying key surfaces that were tied back to core to give a better understanding of the reservoir compartmentalization and depositional environment. All work products were combined to generate a series of subsurface maps for the Powell Field area. Reservoir isopachs, average petrophysical property maps, as well as hydrocarbon pore volume maps were generated.

1.4 Area of Investigation

The study area for this project is comprised of 12 townships in southern Campbell and northern Converse counties. It consists of townships 41N-38N and ranges of 73W-75W. Powell Field makes up most of the area but also includes Spearhead Ranch Field, Manning Field, parts of Buck Draw Field, and Pine Tree Field (Figure 1.4). The study area captures the synclinal basin axis and includes some of the deepest parts of the basin. Multiple horizons have produced in this area including the Dakota and Muddy, the Niobrara, Shannon, Sussex Parkman, and Teapot Formations.

1.5 Data Set

A combination of core data, well log data, and production data were all evaluated as part of this research. Five slabbed cores, core photos, thin sections, SEM photo micrographs and core analysis were evaluated. The cores were located at the USGS Core Research Center or housed at the Colorado School of Mines core repository. Core descriptions were generated using EasyCore Software.
Digital well logs from over 100 wells were used as part of the petrophysical evaluation for this study. Prizm, part of the GeoGraphix software platform, was the primary software for the petrophysical modeling. The primary logs used for evaluation were the gamma ray (GR), resistivity (ILD & LLD), density and neutron porosity (DPHI_268 & NPHI respectively), calculated on a shaly sandstone matrix (2.68 g/cc). Sonic porosity (SPHI) was used as available to better constrain the porosity model.

Figure 1.4 Location map of study area outlined in red. Well spots colored by major producing horizon. Major fields outlined in green. 100 ft contour lines are drawn on the top of the Frontier Formation in depths sub-sea feet.
CHAPTER 2: GEOLOGIC BACKGROUND

2.1 Background Geology

The Powder River Basin is located in eastern Wyoming and developed during the Laramide Orogeny which took place from about 75 to 40 Ma (Lawton, 2008), and consists of sediments sourced by the Sevier Orogeny into a region known as the Western Interior Basin (WIB) (Figure 2.1). The WIB was established in the Late Jurassic and accumulated sediments up until the start of the Laramide Orogeny. There are two main source rocks that supplied hydrocarbons to the Cretaceous system. The Mowry and Niobrara Formations. The Frontier Formation was likely sourced from a combination of the two source rocks, but the Mowry Formation is the main source rock for the study area (Momper & Williams, 1982). The Frontier Formation consists of sediments deposited in the WIB during the Cenomanian to late Turonian situated between the Mowry below and Carlile Formation above. The Frontier Formation represents the distal reaches of a progradational clastic wedge that formed in response to the Sevier Orogeny. It was deposited in the forebulge and backbulge of the foreland basin system (DeCelles, 2004). Deposition occurred during rising eustatic sea level (Kauffman, 1977) during which sedimentation rates ranged from 0.08 in/1,000 years to over 10 in/1,000 years (Merewether et al, 1996). Kauffman (1985) describes up to four orders of sea-level cycles. First order cycles lasted 90-100 m.y., second order cycles lasted 30-40 m.y. and fourth order cycles lasted 1-3 m.y.
Figure 2.1  Map showing the extent of the Western Interior Basin (WIB) and the location of the Sevier Thrust Belt (Martinsen, 2003).
2.2 Structural Framework

The Powder River Basin (PRB) is a northerly trending, asymmetrical foreland basin, approximately 250 miles long and 100 miles wide. The basin axis, and deepest part of the basin, is situated along the western margin. It is surrounded by major uplifts on all sides, including the Big Horn Mountain and Casper Arch to the west, the Black Hills Uplift to the east, the Porcupine Dome and Miles City Arch to the north, and the Laramie Range and Hartville uplift to the south. The basin axis is situated just west of center with gentle structural dips to the north east and steep, almost vertical structural dips south west of the basin axis (Figure 2.2). The PRB was formed during the Laramide Orogeny (35-75 Ma). The PRB is made up of Paleozoic to Tertiary strata to depths of nearly 17,000 ft below the surface at the basin axis. The Wall Creek Member of the Frontier Formation, at the study area, is encountered around 12,500 ft below the surface.

2.3 Stratigraphy

The Powder River Basin contains a thick section of Cretaceous strata including the Cenomanian – Turonian Frontier Formation. The Frontier Formation in the study area is a prograding clastic wedge that is encased in marine shales and mudstones above and below. It is situated, unconformable on top of the Clay Spur Bentonite of the Mowry Shale and is sealed by the conformably overlying Sage Breaks Member of the Carlile Formation. Anna (2009) divided the Frontier Formation into three main members (Figure 1.2). The Wall Creek Member and Emigrant Gap Member are separated by an erosional boundary. The Emigrant Gap Member is not present in the study area but is present further to the west in a more proximal setting. In the study area the Wall Creek Member sits uncomfortably on the Belle Fourche Member which is primarily made up of marine shales and several bentonite beds with occasional sandstones.
Figure 2.2  West to East cross section across the asymmetric Powder River Basin highlighting major sedimentary horizons. Steep dips to the west towards the Casper arch and Bighorn Mountains, shallow dips to the east towards the Black Hills (modified from Anna, 2009).
Prionocyclus macombi and Scaphites preventicosus (88.5 Ma) are the main ammonites present in the Wall Creek Member (Cobban et al., 2006; Kirschbaum and Mercier, 2013). Chronostratigraphic equivalents of the Frontier Formation across the region include the Bridge Creek Limestone, Fairport Chalky Shale, and Blue Hill Shale of south east South Dakota and north east Nebraska, Carlile Shale, Greenhorn Formation, and Codell Sandstone of south east Colorado, and Pool Creek, and Turner Sandstone of north east Wyoming (Merewether et al., 2017, Fig 2.3).

2.4 Previous Work

A substantial amount of research has been completed in the past for the Frontier Formation in the PRB. Work has been completed on the outcrop belt near Kaycee, Wyoming and many studies have been completed to carry correlative surfaces from outcrop to the subsurface. Multiple depositional environments have been interpreted of the Frontier system, ranging from top truncated deltaic deposits to offshore bar deposits. As early as the 1950’s the Wall Creek Member was described as a deltaic deposit (Masters, 1952; Goodell, 1962). In the 1970’s and 1980’s the offshore bar and shelf sand ridge models were introduced (Tillman & Almon, 1979; Winn, 1983; Weimer, Porter, & Land, 1985). Starting in the mid 1990’s to present, a variety of deltaic depositional models were introduced; ranging from wave dominated, tide dominated, and fluvial dominated to a combination of the three (Bergman, 1994; Gani and Bhattacharya, 2007; Sadeque et al. 2009). However, little has been completed for the Powell Field area. Tillman and Almon (1979) published a paper for this area describing core and observing the pore preserving chlorite rims on quartz grains in a reworked sand facies.
Figure 2.3 Frontier Correlative surfaces across central Wyoming, north east Wyoming, south east Colorado/north east New Mexico, central Kansas, and south east South Dakota/North east Nebraska (Merewether et al., 2017).

Figure 2.4 Monthly Production graph for Powell Field showing production from 1978 through 2017 for all producing horizons (WOGCC).
2.5 Greater Powell Field Area

Powell Field is situated just to the north east of the basin axis in Converse County, WY. To date it has produced almost 30 million BO, and 326 BCF of gas from over 120 producing wells (Figure 2.4). Production comes from several Cretaceous horizons, but the Wall Creek Member of the Frontier Formation is the primary target. Powell Field was discovered in 1975 by Woods Petroleum Corporation when they drilled the Powell II Unit No. 1 well. The well initially flowed 888 BO and 8,008 MCFPD from the Wall Creek Member. During early development, operators of the field determined the Wall Creek Member was producing a retrograde condensate and had steep pressure declines. The reservoir had a dew point of 4,968 psig and early development of the field indicated reservoir pressures were approaching this dew point sooner than anticipated. In response to this discovery, the Wyoming Oil and Gas Conservation Commission (WOGCC) implemented field rules limiting gas production to 15 MMCFD of gas per well per month. This allowed time for further assessment of reservoir pressures and to evaluate a pressure maintenance program to maintain pressure and support liquids production. In 1980 the commission enacted a field wide shut in as reservoir pressures were getting extremely close to dew point. In September of 1983, the WOGCC established a pressure maintenance unit. Produced gas was to be reinjected into the field in order to maintain reservoir pressures above dew point. This allowed the field to maintain its liquids production.

In the study area, the Frontier Formation at Powell Field has an average porosity of 14.5%, an average pay thickness of 5 ft, and an initial formation bottom hole pressure greater than 8,000 psi. Perforations are usually placed at the top of a parasequences where chlorite clay rims have preserved primary porosity. This diagenetic feature will be addressed in more detail by my research. Core permeabilities average 100 mD with reservoir depths exceeding 12,000 ft.
TVD. In 1983 when the pressure maintenance unit was established, six pressure maintenance wells were implemented. Total injected volumes totaled more than 134 BCF of field gas back into the reservoir to support liquids production. To date the field has produced over 29 million barrels of oil, and over 320 BCF of natural gas from more than 120 vertical wells (Figure 2.4). In the last 10 years horizontal producers have been introduced, exploiting multiple different horizons.

Other major vertical producing fields in the greater Powell Field area include: Pine Tree Field to the north west producing mostly out of the Shannon Formation, Buck Draw Field to the north east, producing from the Dakota Formation, Manning Field to the east, producing from the Parkman Formation, Hornbuckle Field to the south east, and Spearhead Ranch Field which produces mainly from the Frontier Formation (Figure 1.4). Spearhead Ranch Field has been included in the evaluation of the Frontier Formation in this study. The study area is also very active with horizontal well activity. Twenty-two horizontal wells have spud in 2019 thus far, nine of them targeting the Frontier Formation.
CHAPTER 3: CORE ANALYSIS

3.1 Core Observation Method

Five cores were viewed and described in detail in the study area (Figure 3.1) resulting in eight different facies. These facies were identified based on bed to bed contacts, lithology, grain size, sedimentary structures, and ichnology. All described cores penetrate the Wall Creek Member of the Frontier Formation and observe the contact with the overlying Carlile Shale. Routing core analysis (RCA), thin sections, SEM photomicrographs, and bioturbation index, were all used to describe the five cores.

Figure 3.1  Map with locations of five described cores designated by red stars.
3.2 Ichnology and Bioturbation Index

Ichnology is the study of trace fossils that have been generated by microbes, plants, and animals. The process by which these traces are left is called bioturbation. Identifying bioturbation in an ancient sedimentary setting can help to identify, in core and outcrop, the environment in which organisms lived. Since trace fossils are considered a biogenic sedimentary structure, they are preserved intact, and in place, rarely transported away from their origin unlike some body fossils can be. Changes in sedimentation rate, water depths, oxygen levels, and energy levels will all influence the type of organisms living in a particular setting, which in turn affects the types of trace fossils observed and preserved (Bromley, 1996). When trace fossils are formed in a similar depositional environment, they can be grouped into ichnofacies. Seilacher (1954) developed a series of ichnofacies and associated ichnofauna then placed them into likely depositional settings (Figure 3.2). There are eight main ichnofacies that correspond with rocky coast lines all the way to the abyssal zone. The two main ichnofacies associated with the Wall Creek Member at Powell Field are the Skolithos and Cruziana ichnofacies. These two are associated with sandy shores and the sublittoral zone, respectively.

A bioturbation index (BI) was used in core descriptions to establish a measure of the abundance of trace fossils. BI ranges from 0-6 (no occurrence – high occurrence) as described in Figure 3.3, and developed by Reineck (1963), Taylor and Goldring (1993), Taylor et al, (2003), and MacEachern and Bann (2008). Key stratigraphic surfaces can also be identified due to organism’s preference for a particular type of substrate. Taylor et al (2003) describes soupground, softground, and stiffground surfaces that can be associated with certain ichnofauna. Soupground and softground substrates are often associated with muddy lithologies that have been compacted and dewatered. Planolites, Zoophycos, and Chondrites are some common
ichnofauna observed with soupground and softground substrates (Taylor et al., 2003). Stiffground substrates however are typically observed with sandier lithologies that have been compacted and dewatered. These surfaces may have been subaerially exposed representing a time of non-deposition or erosion. *Thalassinoides* is the primary ichnofauna observed with stiffground substrates (Sadeque, 2009).

Figure 3.2  Ichnofacies and ichnofauna as they exist from rocky coast settings to abyssal zone settings (Seilacher, 1954).
Figure 3.3  Key to bioturbation index modified from Reineck (1963), Taylor and Goldring (1993) and Taylor et al. (2003) by MacEachern and Bann (2008). The bioturbation index ranges from 0 (no visible bioturbation) to 6 (complete bioturbation, no visible sedimentary structures).
3.3 Key Stratigraphic Surfaces

Four key stratigraphic surfaces were observed in the five cores described at Powell Field. Flooding surfaces (FS), minor erosional surfaces (ES), regressive surfaces of erosion (RSE), and transgressive surfaces of erosion (TSE) are described in this section as observed in core.

Figure 3.4 Core photo from Spearhead Ranch 2 well displaying a flooding surface at 12,435 ft core depth. Coarser-grain sandstone sit below finer-grained sandstone above.
3.3.1 Flooding Surfaces (FS)

A flooding surface is the most common surface observed in the five cores at Powell Field. These surfaces represent an increase in water depth or major current influence and are observed in core where there is an abrupt change from a sandy lithology below, to a siltstone or mudstone above (Figure 3.4). These flooding surfaces can occur at the top or base of a parasequence. A FS can also be identified on wireline logs. When the gamma ray log has an abrupt shift from a low api count to a high api count, along with a resistivity change from high to low, a FS can be interpreted. When a FS could be identified in core and on open hole log, the correlation on the well log was carried across the Powell Field area for field scale correlations.

Figure 3.5 Core photo from Powell Fed 1-13 well displaying transgressive surface of erosion at 12,313 ft core depth. A coarse-grained transgressive lag can be observed between two blue lines. Above the top blue line is the Carlile Formation.
3.3.2 Transgressive Surface of Erosion

In each core described, a transgressive surface of erosion (TSE) can be identified at the very top of the Wall Creek Member. It represents a ravinement surface due to flooding over sandstones at the top of the Wall Creek Member. In many cases, a transgressive lag can be observed in core on top of the TSE (Figure 3.5). Transgressive lag deposition can be the result of wave ravinement in a nearshore setting. On well logs this surface is easily identified by the low api gamma ray count of the Wall Creek Member, drastically increases greatly into the Carlile Shale above.

3.3.3 Regressive Surface of Erosion

A regressive surface of erosion is a subaqueous surface of marine erosion formed during a relative sea-level fall. As sea level falls, wave base and the upper-shoreface drops and erodes off the sediments that were formerly below wave base. This fall results in the superposition of coarser-grained sediment sharply overlying finer-grained marine sediments. The basal contact of the Wall Creek Member reservoir interval with the underlying non-reservoir shales and siltstones below is represented by a regressive surface of erosion (RSE). This is observed in core by the coarser-grained Wall Creek sands overlaying fine-grained muddy-to silty sandstones and shales (Figure 3.6). On well logs this surface is distinguishable in gamma ray log as a sudden drop in api count.
Figure 3.6  Core photo from Spearhead Ranch 2 displaying the regressive surface of erosion at 12,521 ft core depth. The green line represents the contact of the wall creek member above with the non-reservoir siltstone below.

Figure 3.7  Core photo from Spearhead Ranch 4 displaying an erosional surface at 12,583 ft core depth. The orange line represents a surface for erosion of a sandy lens and finer-grained bioturbated sediments deposited above.
3.3.4 Erosional Surfaces

Several erosional surfaces can be observed throughout the cores described. These surfaces have been observed where medium-grained sandstones overlie finer-grained sandstones as well as where finer-grained sandstones overlie coarser-grained sandstones (Figure 3.7). These surfaces are not always present in well logs since the features of the erosional surface are below the resolution of well logs. But when they do, there is an abrupt change in gamma ray values and occasionally resistivity values.

3.4 Core Facies Descriptions

This section describes the unique facies observed in the five cores used in this study. Eight unique facies were identified and will be discussed along with any XRD information available. All cores were described and digitized using EasyCore software. Each core description can be found in the appendix.

3.4.1 Facies 1: Flaser Bedded Siltstone and Shale

Facies 1 is made up of light grey flaser bedded siltstones and shales (Figure 3.8). Lower very fine to upper fine-grained sandstone make up most of this facies. Occasional mud rip-up clasts are observed. Wave and flaser bedding along with slight ripple laminations are common with interbedded siltstone and shale. The siltstone laminae tend to be thicker than the shale laminae. A bioturbation index (BI) ranges from 1-2 with low ichnodiversity. Planolites is the most common ichnofauna present.
Figure 3.8  Example of Facies 1: Flaser bedded siltstone and shale.

Figure 3.9  Example of Facies 2: Heterolithic muddy sandstone.
3.4.2 Facies 2: Heterolithic Muddy Sandstone

Facies 2 is observed as an interbedded muddy sandstone (Figure 3.9). Laminae of the very fine-grain light grey sand are thicker (~5mm) than the dark grey and black mudstone laminae (~1mm). Grain size is typically muddy to very fine-grained sandstone that displays sub-planar parallel laminations along with wavy and lenticular bedding. Facies 2 contains low levels of bioturbation with a BI of 1-2. Ichnodiversity is slightly greater in Facies 2 than Facies 1 with trace fossils such as *Paleophycus*, *Thallassinoides*, and *Planolites*. XRD results for a sample from Facies 2 include 18 vol% quartz, 1 vol% calcite, 2 vol% plagioclase, and 75 vol% clay.

3.4.3 Facies 3: Ripple Laminated, Very Fine-Grained Sandstone

Facies 3 consist of very light grey, very fine to fine-grained sandstone. Mud drapes are occasionally present along with wave and current ripples. Wispy laminae are observed along ripple foresets (Figure 3.10). Mud clasts were observed but very rare. Facies 3 BI is low (BI=0-2) as well as the ichnodiversity. The most common ichnofauna observed were *Ophiomorpha* with occasional *Skolithos*. XRD results taken in Facies 3 consists of 65 vol% quartz, 16 vol% plagioclase, 1 vol% calcite, and 15 vol% clay.

3.4.4 Facies 4: Moderately Angled, Cross Stratified, Fine-Grained Sandstone

Facies 4 is composed of a very light grey to tan, fine to lower medium-grained sandstone (Figure 3.11). The sandstone is cross-stratified with moderate to high angle cross sets. Hummocky cross-stratification is also present. Structureless bedding is present in Facies 4 but is less common than the cross-stratified sedimentary structure. Bioturbation in Facies 4 is very low (BI=0-1), with *Macaronichnus* being the most common trace fossil. XRD results available for Facies 4 show 83 vol% quartz, 7 vol% plagioclase, 3 vol% calcite, and 6 vol% clay.
Figure 3.10  Example of Facies 3: ripple laminated, very fine-grained sandstone.

Figure 3.11  Example of Facies 4: moderately angled, cross stratified, fine-grained sandstone.
3.4.5 Facies 5: Reworked, Medium to Coarse-Grained Sandstone

Facies 5 represents a grey and tan, medium to coarse-grained sandstone (Figure 3.12). This facies is mostly observed at the top of the Wall Creek Member and at the top of coarsening upward sequences. The transgressive lag just above the TSE is included in Facies 5 and was observed to be four to six inches thick in the cores described. This facies is mostly structureless with occasional faint parallel laminations. Silt/shale stringers can also be observed but are rare. Based on RCA, Facies 5 tends to have the highest porosity and permeability. Bioturbation is low with a BI=0-2. XRD results for Facies 5 consists of 86 vol% quartz, 2 vol% plagioclase, 2 vol% calcite, and 2 vol% clay. Chert is also most abundant in facies 5 than any other core facies. Also observed in Facies 5 from SEM micrographs are chlorite clay coatings on quartz grains. This is a reservoir feature and is discussed in further detail later in the study.

3.4.6 Facies 6: Bioturbated, Slightly Laminated, Fine-Grained Sandstone

Facies 6 is composed of light to dark grey, fine to very fine-grained sandstones. Faint laminations and mud drapes are present along with mottled bedding (Figure 3.13). Scour surfaces are present in Facies 6 and has a medium amount of bioturbation (BI=2-3). Ichnodiversity is medium as well with Macaroninhus, Planolites, Thalassinoides, and Paleophycus making up the common ichnofauna. XRD results consists of 65 vol% quartz, 13 vol% plagioclase, 2 vol% calcite, and 18 vol% clay.

3.4.7 Facies 7: Highly Bioturbated, Muddy Sandstone

Facies 7 is composed of a grey to dark grey highly bioturbated muddy siltstone (Figure 3.14). This facies is the most bioturbated facies observed in the Wall Creek Member at Powell Field with a BI=3-5. This mud rich siltstone has a superimposed ichnofabric showing individual
burrows. This results in little to no sedimentary structures that are identifiable. Many of the burrows have been filled with a slightly coarser-grained material than the surrounding matrix. Facies 7 contains the most diverse ichnofauna as well with trace fossils such as *Macaronichnus, Asterosoma, Planolites, Paleophycus, and Thalassinoides* present.

![Image](image_url)

Figure 3.12 Example of Facies 5: reworked, medium to coarse-grained sandstone. Main reservoir facies.

### 3.4.8 Facies 8: Laminated, Fine to Lower Medium-Grained Sandstone

Facies 8 is composed of a white to light grey fine- to lower medium-grained sandstone. In most cases, it appears Facies 8 has been cemented by calcite after deposition and does not have visible porosity. Sedimentary structures are preserved however with parallel and non-parallel laminations. Wave and ripple laminae sets are also present (Figure 3.15). Bioturbation in
Facies 8 is generally low with a BI=1-2. *Ophiomorpha* and *Skolithos* are common ichnofauna present. XRD results for Facies 8 show 65 vol% quartz, 10 vol% plagioclase, 7 vol% calcite, and 15 vol% clay.

Figure 3.13  Example of Facies 6: bioturbated, slightly laminated, fine-grained sandstone.

Figure 3.14  Example of Facies 7: highly bioturbated, muddy sandstone.
3.5 Ichnofacies

A variety of ichnofauna and ichnodiversity were observed in the 8 core facies described. BI ranged from 0-5 with core Facies 7 being the most bioturbated and having the greatest diversity out of the 8 core facies.

As mentioned previously, when trace fossils are formed in a similar depositional environment, they can be grouped into ichnofacies. *Ophiomorpha, Paleophycus, Astersoma, Diplocrterion, Skolithos, Conichnus, Planolites, Arenicolites, Cylindrichnus, Macaronichnus, Thalassinoides*, are the eleven trace fossils identified in core as part of this study but are not inclusive to all trace fossils present (Figures 3.16 and 3.17). These eleven trace fossils are commonly associated with the *Cruziana* and *Skolithos* ichnofacies (Figure 3.2). They suggest these trace fossils were deposited within the sand shore to sublittoral zone, respectively. The *Skolithos* ichnofacies typically is a high energy environment where organisms need to be able to
withstand the stressful conditions. Foreshore, shoreface, estuarine point bars, and tidal deltas are all settings for the *Skolithos* ichnofacies. The *Cruziana* ichnofacies is generally associated with a deeper, calmer depositional environment than the *Skolithos* ichnofacies. A shallow marine with tidal influence settings is most common for the *Cruziana* ichnofacies (Seilacher, 1954).

Figure 3.16 Core photos from the study area showing the variety of ichnofauna observed in the core descriptions. *Asterosoma* (AS), *Conichnus* (co), *diplocraterion* (DI), *macaronichnus* (ma), and *Paleophycus* (Pa). For scale, note that all core is approximately 4 in. wide and that each photo is scaled differently.
Figure 3.17  Core photos from the study area showing the variety of ichnofauna observed in the core descriptions. *Asterosoma* (AS), *arenicolites* (Ar), *cylindrichnus* (CY), *ophiomorpha* (Op), and *planolites* (Pl).
Figure 3.18  Core photos from the study area showing the variety of sedimentary structures observed in the Wall Creek Member.
Table 3.1  Table listing each of the eight facies observed in core and associated sedimentary structure and bioturbation index.

<table>
<thead>
<tr>
<th>Core Facies #</th>
<th>Facies Description</th>
<th>Sedimentary Structures</th>
<th>Bioturbation Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flaser Bedded Siltstone and Shale</td>
<td>Wave and current, bi-directional laminations, interbedded siltstone and shale, slight riffle lamination, mud drapes</td>
<td>1-2</td>
</tr>
<tr>
<td>2</td>
<td>Heterolithic muddy sandstone</td>
<td>Sub-planar parallel laminations, wavy and lenticular bedding</td>
<td>1-2</td>
</tr>
<tr>
<td>3</td>
<td>Ripple Laminated, very fine to fine grained sandstone</td>
<td>Mud drapes, wave and current ripples, wispy laminations</td>
<td>0-2</td>
</tr>
<tr>
<td>4</td>
<td>Moderately angled, cross stratified, fine grained sandstone</td>
<td>Cross stratified, moderate to high angle cross stratification, hummocky cross stratification</td>
<td>0-1</td>
</tr>
<tr>
<td>5</td>
<td>Medium to coarse grained sandstone</td>
<td>Structureless, silt/shale stringers, faint parallel laminations, reworked transgressive lag</td>
<td>0-2</td>
</tr>
<tr>
<td>6</td>
<td>Bioturbated, Slightly laminated, fine grained sandstone</td>
<td>Burrow mottled bedding, faint laminations, and mud drapes</td>
<td>2-3</td>
</tr>
<tr>
<td>7</td>
<td>Highly bioturbated, muddy sandstone</td>
<td>Tube shaped burrows, mud drapes</td>
<td>3-5</td>
</tr>
<tr>
<td>8</td>
<td>Laminated, fine to lower medium grained sandstone</td>
<td>Parallel laminated, and ripple laminated, occasional burrow</td>
<td>1-2</td>
</tr>
</tbody>
</table>

3.6 Sedimentary Structures

Several different types of sedimentary structures were observed and recorded in the five cores described as a part of this study (Figure 3.18). The sedimentary structures outlined in Figure 3.18 are some of the structures that assisted in the interpretation of depositional environments of the Wall Creek Member at Powell Field. The main processes responsible for generating the structures observed include wave, tide, current, and storm processes as part of a delta front system.

The presence of planar cross stratification, trough-cross stratification and asymmetrical ripples indicate subaqueous dune formation from strong currents and wave-influence or storm
events. Sub-planar laminations and wavy lenticular bedding, as seen in core Facies 2, as well as mud-draped foresets, point to tidal processes possibly taking place in a lagonal setting. The presence of a structure-less, coarse-grained, well sorted sandstone suggests reworking during a transgression and provide the best reservoir quality in the Powell Field area. Table 3.1 provides a description of each facies and the common sedimentary structures they are associated with.

### 3.7 Facies Association

After the observation of the eight facies identification, along with sedimentary structure and bioturbation observations, a depositional environment was interpreted for each core facies. The eight core facies can be grouped into three different facies associations that belong to similar depositional environments.

#### 3.7.1 Facies Association 1: Prodelta to Offshore

Facies Association 1 (FA1) represents a prodelta to offshore depositional environment. It represents deposition, basin ward, beyond the delta front. Mudstones and siltstones make up the majority of FA1 but sandstones can be found as well. Silts and muds fall out of suspension to form parallel laminations along with lenticular bedding suggesting tidal and wave influences. Wavy and flaser bedding are also sedimentary structures found in FA1 suggesting some tidal influence. Hyperpycnal flows can occur in the prodelta to offshore setting. When this occurs, any open bioturbated burrows become filled with coarser sediments than the surrounding finer-grained sediments that were burrowed due to the coarser sediments rapidly falling out of suspension (Bhattacharya and MacEachern, 2009). BI for FA1 range from 1-5 with the *Cruziana* ichnofacies being most prevalent. The presents of increasingly finer grained sediments in FA1 make it the most distal depositional environment in this study. The prodelta to offshore setting
falls mainly within storm-wave base and partially in the fair weather wave-base. Core facies 2, 6, and 7 make up FA1.

3.7.2 Facies Association 2: Delta Front

Facies association 2 (FA2) is described as the delta front and is the intertidal shoreline and gently dipping subtidal platform. FA2 represents the zone above fair weather wave-base and mean low tide level. Wave and current, bi-directional laminations, along with mud rip-ups and moderately angled, cross stratified sandstones are all observed in FA2. These sedimentary structures suggest wave and tidally influenced processes. BI is usually below a 2 suggesting a higher energy environment than FA1. The *skolithos* ichnofacies is most prevalent in FA2 with ichnofauna such as *Ophiomorpha*, *Diplocraterion*, and *Arenicolites* present. Due to the bi-directional laminations and tidally influenced flaser bedding observed, the delta front systems at Powell Field is interpreted to be mainly a wave and tidally influenced delta front system. FA2 is comprised of core facies 1, 3, 4, 5 and 8.

3.7.3 Facies Association 3: Reworked Transgressive Deposits

Facies association 3 (FA3) is described as a reworked transgressive deposit. Core facies 5 is the only core facies that makes up FA3 which is a medium to coarse grained, well-sorted sandstone, mostly structureless with occasional faint parallel laminations. It is the main hydrocarbon producing interval in the Powell Field area from vertical wells and was deposited at the very top of the Wall Creek Member. The lack of fine-grained sediments, well-sorted nature of core facies 5, and lack of bioturbation, suggest it was reworked by a transgressive event. This event, as described earlier, is correlated across the field as the transgressive surface of erosion (TSE) which separates the Carlile Shale above from the Frontier Formation below.
3.8 Diagenesis

Diagenetic features were recognized in thin sections and FE-SEM photomicrographs to better understand reservoir quality. Individual stages of diagenesis play a critical role in reservoir quality, especially as it pertains to the Wall Creek Member at Powell Field. Previous work has been completed by Tillman and Almon (1979) and Winn, Stonecipher, and Bishop (1983) as it relates to the Wall Creek Member in the Powell Field area. Similar observations and conclusions from those studies are made in this study with additional FE-SEM analysis.

Table 3.2  Diagenetic sequence for reworked and non reworked marine bar facies as defined by Tillman and Almon (1979)

<table>
<thead>
<tr>
<th></th>
<th>Reworked Marine Bar Facies</th>
<th>Non Reworked Marine Bar Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chlorite</td>
<td>Quartz</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
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<tr>
<td>III</td>
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<td>IV</td>
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<td></td>
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<td>V</td>
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</tbody>
</table>

Tillman and Almon (1979) describe five different stages of diagenesis (Table 3.2) starting with chlorite clay rims forming on quartz grains followed by quartz cementation,
feldspar leaching, illite/smectite formation, calcite cementation, and finally hydrocarbon emplacement. A similar sequence was observed in this study. Especially in coarser grained core facies (Core Facies 5) where early pore fluids and lack of compaction aided in the formation of chlorite rims, while also preventing quartz overgrowths. In finer-grained core facies, chlorite development was hindered, and quartz cement was more prevalent, reducing any primary porosity. Weaver and Pollard (1973) suggest that Mg-rich chlorite forms at higher temperatures than Fe-rich chlorite. This supports that chlorite clay rims were developed early in the diagenetic process.

3.9 FE-SEM Analysis

Field emission scanning electron microscope (FE-SEM) analysis was performed on multiple Wall Creek Member samples to observe certain diagenetic features, clay types, and minerology. The images were taken by Stolper Geologic, Inc. Samples from core D473 and core B136 were examined. The chlorite rimming of quartz grains is an important feature observed in these samples. Figure 3.19 shows a quartz grain in core B136, core facies 5, that has the chlorite clay rim. Figure 3.20 shows a close up of this feature. These chlorite rims on the quartz grains have prevented quartz overgrowth from occurring and preserve the primary porosity. In some cases, euhedral quartz overgrowths can be observed occurring adjacent to the chlorite clay rims. Figure 3.21 is an example of this in core D473, core facies 5.

In certain core facies that are more bioturbated, or have smaller grain sizes, quartz overgrowths and other authigenic clays are present, reducing the reservoir quality. The authigenic clays are likely formed after chlorite and quartz overgrowth formation, but before calcite cementation. Figure 3.22 shows an example from core D473, core facies 7, of pore throat
plugging illite clay and quartz overgrowths that are abundant in finer-grained more bioturbated facies. Some of the observed quartz overgrowths may have formed in conjunction with chlorite clay rims, and not directly after chlorite clay rim formation, as suggested by Tillman and Almon (1979). Energy dispersive x-ray spectrography (EDS) analysis indicate that the chlorite observed in FE-SEM samples is iron rich (Figure 3.23). This suggests that dissolution of the biotite observed in thin section (Figure 3.24), could be the source for the chlorite formation. Winn, Stonecipher, and Bishop (1983) also observed this and postulate that biotite dissolution could have provided the silica needed to form some of the quartz overgrowth as well.

Figure 3.19 FE-SEM photo from core B136 (11,777 ft) showing a quartz grain with a chlorite clay rim 200x. Focus of Figure 3.20 is within the yellow box.
Overall the diagenetic features observed in this study confirm the observations made by Tillman and Almon (1979) as well as Winn, Stonecipher, and Bishop (1983). Starting with sediment consolidation and compaction, then biotite dissolution, then chlorite clay rims forming on quartz grains followed by quartz overgrowth and cementation, then feldspar leaching, illite/smectite formation, calcite cementation, and finally hydrocarbon emplacement. These diagenetic features have been observed to have positively affected the coarser grained facies and negatively impacted the finer grained facies as it relates to reservoir quality.

Figure 3.20 FE-SEM photo from core B136 (11,777 ft) showing a quartz grain with a chlorite clay rim 2000x
Figure 3.21  FE-SEM photo from core D473 (12,054’’) showing a quartz overgrowth with a chlorite on either side 2000x.

Figure 3.22  FE-SEM photo from core D473 (12,069 ft) showing a quartz overgrowth with pore plugging illite clay 2000x.
Figure 3.23  Energy Dispersive X-Ray spectroscopy (EDS) analysis from core B136 (11,777 ft) showing high levels of iron in a chlorite sample.

Figure 3.24  Thin section from core D473 (12,071 ft) showing high level of cementation and biotite.
CHAPTER 4: PETROPHYSICAL EVALUATION

Major sedimentary basins across the world have been evaluated using open hole logs as a major tool for finding hydrocarbon accumulations and characterizing reservoirs. It has long been an issue to evaluate thinly bedded clastic reservoirs and shaly sand clastic reservoirs due to the limits of logging tools. Modern open hole logging tools are achieving higher vertical resolutions to deal with thin bed effects, but shaly sand systems still pose issues due to elevated clay content. When clays are disseminated or laminated throughout the reservoir rock, log-derived measurements of porosity, and water saturation are influenced. Typically, shaly sandstone systems have high enough clay content that the deep resistivity measurements are subdued. This in turn generates a higher calculated water saturation using an Archie based water saturation model (Asquith, 1990). Therefore, a shaly sandstone water saturation model was established and calibrated to core data for the purpose of this research.

In the 1950’s only electric resistivity logs were available to calculate porosity. Therefore, a combination of the gamma ray log, resistivity log, and SP log were used in shaly sand models. In the 1960’s the density log was introduced and was incorporated in dispersed clay and shaly sand models. Then in the late 1960’s and early 1970’s neutron logs were developed and incorporated allowing the Simandoux and Indonesian models to be developed (Asquith, 1990). The vintage of digital logs available for evaluation range from 1970 to 2017.

In the greater Powell Field area, well log data is abundant. The majority of vertical wells penetrated through the Frontier Formation. A combination of raster logs and digital LAS files were used in this study. Over 100 wells had digital LAS files that were used in the petrophysical evaluation. A complete list of subsurface well log locations can be found in
Appendix A. The well log combinations involved in the evaluation all have at least the following log curves: gamma ray, deep resistivity, density, and neutron porosity. A few wells also have sonic porosity curves that aided in the porosity model. Figure 4.1 shows the location of wells with digital LAS files that were used as part of the petrophysical evaluation. A series of subsurface maps were generated as part of the evaluation. Average density porosity (DPHI_268), average deep resistivity, net reservoir, average volume of clay (Vclay), average water saturation (Sw), and hydrocarbon pore thickness (SoPhiH), were mapped across the greater Powell Field area to identify high reservoir quality and highlight undeveloped hydrocarbon accumulations.

Figure 4.1  Location map of wells that have digital well logs and were used in the petrophysical model.
4.1 Porosity Model

Due to the presence of clay in the Wall Creek Member of the Frontier Formation in the study area, petrophysical porosity readings are generally overestimated. This is the case for sonic, neutron, and density porosity readings. Neutron logs measure hydrogen ion concentrations. Clay types present in the reservoir all have elevated hydrogen ion concentrations due to the hydroxyl (OH) associated with a clay’s composition. This causes the neutron log to record the clay as porosity. The density porosity, on a clean sandstone matrix (2.65g/cc), measures an elevated porosity when the matrix density of the clay is less than the reservoir’s matrix density. Due to the presence of clay, a higher matrix density is used to compute density porosity. A clean sandstone matrix density of 2.65 g/cc underestimates the density porosity of the system. Grain densities, observed in core analysis, measure closer to 2.68 g/cc and this was the matrix density used in the density porosity computation. Figure 4.2 shows how the core porosity compares to the log calculated density porosity in the Moore Ranch 12-13 and the Nutcracker D1 well.

Effective porosity (PhiE) was calculated for the field area to better characterize the moveable fluid pore space in the system. Effective porosity is defined by the density porosity minus the clay bound water volume. This is because the clay bound water is assumed to be immobile and not a major contributor to reservoir moveable volumes. Effective porosity is connected pore volume and is the porosity proxy used in this model.
Figure 4.2 Two well logs showing density porosity in red match to core porosity data points in the far right track.

4.2 Vclay Model

In a shaly sand petrophysical model, the volume of clay (Vclay) or volume of shale (Vshl) is a critical component of the model, and the terms Vclay and Vshl have been used interchangeably throughout literature. For the purposes of this study, Vclay is the pneumonic used, and it was calibrated to volume of clay measured by x-ray diffraction (XRD) on cores in the study area. A total of four cores in the study area had XRD data available to calibrate the Vclay
model. After a calibrated computation of $V_{clay}$ can be established, an effective porosity can be computed.

There are several methods for calculating the volume of clay, and most methods involve four different well logs: spontaneous potential, gamma ray, neutron, and density are the common well logs used to compute $V_{clay}$. Johnson and Linke (1977) provided research that showed the gamma ray method provided great correlation to the volume of clay as well as with the cation exchange capacity (CEC) values measured on core in the lab. Dewan (1983) found the neutron-density method matched to core clay values where there were clays with low CEC such as chlorite and kaolinite. This is the case in the Wall Creek Member. Equations [4.1] and [4.2] show the gamma ray, neutron-density methods used to compute $V_{clay}$. The combination provides a good match to XRD derived total clay volumes. $V_{clay}$ was computed separately using the GR and neutron-density method. Then the lowest obtained value from each method is used for $V_{clay}$ (Eq [4.3]).

\[
V_{clayGR} = \frac{(GR-GR_{cln})}{(GR_{shl}-GR_{cln})} \tag{4.1}
\]

\[
V_{clayND} = \frac{(PHIN-PHID)}{(PHIN_{shl}-PHID_{shl})} \tag{4.2}
\]

\[
V_{clay} = \text{Minimum of (} V_{shlGR}, V_{shlND} \text{)} \tag{4.3}
\]

In the equations above, the inputs for $GR_{cln}$ and $GR_{shl}$ are baseline values picked from a “clean”, shale free interval for $GR_{cln}$, and a shale baseline selected at the nearest shale interval. The same is true for $PHIN_{shl}$ and $PHID_{shl}$ in equation [3.2]. For this model, the best match to $V_{clay}$ from XRD used a $GR_{cln}=30$, $GR_{shl}=130$, $PHIN_{shl}=0.19$, $PHID_{shl}=0.02$. 

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4.3 Sw Model

In the 1940’s Archie developed an empirical formula for water saturation that was best suited for shale free sandstones (Eq [4.4]). This equation is commonly used in well log analysis today but does not fit the needs of a shaly sand system, such as the Wall Creek Member of the Frontier Formation.

\[ Sw^n = \frac{1/\varnothing^{m}R_w}{R_t} \]

[4.4]

where:

- \( Sw \) = formation water saturation
- \( n \) = saturation exponent
- \( \varnothing \) = porosity of formation, v/v
- \( m \) = cementation exponent
- \( R_w \) = resistivity of formation water at reservoir temperatures, ohm/m
- \( R_t \) = deep resistivity of formation rock, ohm/m

Models that incorporate the volume of clay into the model came about in the 1960s and 1970s. They were developed because traditional water saturation computations were overestimating the water in a shaly sand system. The effects of clay in a sandstone reservoir not only overestimate the total porosity, but also affects the resistivity readings. Because clays can
exchange cations in their structure, they cause an increase in electrical conductivity, lowering resistivity readings. This suppressed resistivity reading has a negative effect on the water saturation computation and must be accounted for as well (Asquith, 1990). Two commonly used models today for a shaly sand system are the Simandoux (Eq [3.5]) and Indonesian model (Eq [3.6]). The Simandoux model was developed by Simandoux (1963) with Poupon and Leveaux developing the Indonesian model (1971). Both models account for the volume of clay as well as the resistivity of the shale.

\[
SwS = \frac{(\sqrt{\frac{V_{clay}}{R_{shl}}})^2 + \frac{4 \times \varnothing^m}{(R_w \times (1 - V_{clay}) \times R_t) - V_{clay} \times R_{shl})}}{2 \times \varnothing^m \times (R_w \times (1 - V_{clay}))}
\]

[4.5]

\[
SwIND = \frac{\sqrt{\frac{1}{R_t}}}{V_{clay}^{(1 - 0.5 \times V_{clay})}} \left( \frac{1}{\sqrt{R_{shl}} + \left(\varnothing^m / a \times R_w\right)} \right)
\]

[4.6]

where:

\(SwS\) = formation water saturation, Simandoux

\(SwIND\) = formation water saturation, Indonesian

\(a\) = saturation exponent

\(\varnothing\) = porosity of formation, v/v

\(R_w\) = resistivity of formation water at reservoir temperatures, ohm/m
Rt = deep resistivity of formation rock, ohm/m

Vclay = volume of clay, v/v

Rshl = resistivity of nearest shale, ohm/m

The constant Rshl is a specific one to shaly sand models and helps constrain water saturation in high clay intervals. Rshl is established for each individual well by cross plotting Vclay and Rt. Figure 4.3 shows this for the Moore Ranch 12-13 well. A line of best fit is drawn through the data. Where the line intersects the top of the chart at Vclay=1 (6 ohm/m in the case of the Moore Ranch 12-13 well), the resistivity at that point is recorded and used for Rshl in the water saturation computation.

The resistivity of formation water (Rw) is another constant that is a part of most water saturation calculations. Rw values can be hard to come by in the public domain since they depend on operator reported formation water analysis from produced waters or waters from drill stem tests (DST). It is also possible to compute Rw using a Picket plot. The Pickett plot is a graphical representation of Archie’s equation in terms of resistivity. On a log-log scale, deep resistivity (Rt) and porosity are cross plotted. Rw in the study area is assumed to be around 0.15 ohm/m based on water analysis gathered.

Figure 4.4 shows how the Archie (SwA), Simandoux (SwS), and Indonesian (SwIND) water saturation models compare to core derived water saturation on two wells in Powell Field. The Archie model overestimates water saturation in the shale rich intervals of the Wall Creek, whereas the Simandoux and Indonesian models calculate closer to the core analysis values. For this study area, the Simandoux water saturation model appeared to match closest to core derived
water saturations most consistently and was the water saturation model used for subsurface mapping.

Figure 4.3 Cross plot of deep resistivity and log calculated Vclay. Where a line of best fit intersects the top of the chart at Vclay=1, the corresponding deep resistivity value is used for Rshl. In this single well plot for the Moore Ranch 12-13 well, the line of best fit intersects the top of the plot at a deep resistivity reading of 6 ohm/m. This is the value used for Rshl in the Simandoux and Indonesian equations [4.5] & [4.6].
Figure 4.4  Cross sections showing water saturation comparison between the Archie (SwA), Simandoux (SwS), and Indonesian (SwIND) on two wells in Powell field. The Archie model overestimates water saturation in the shale rich intervals of the Wall Creek, whereas the Simandoux and Indonesian models calculate closer to the core analysis values. For this study area, the Simandoux water saturation model matched closest to core derived water saturations and was the water saturation model used for subsurface mapping.
CHAPTER 5: RESERVOIR CHARACTERIZATION

5.1 Stratigraphic Correlation

Major stratigraphic surfaces were observed in the described cores of this study and were correlated to well logs to aid in field wide correlations. Observed in cored intervals were two major flooding surfaces (FS_30 & FS_40), the transgressive surface at the top of the Wall Creek Member (TSE), and the regressive surface of erosion (RSE) observed at the base of the Wall Creek reservoir interval (Figure 5.1). Figure 5.2 shows the logged interval of cored wells where more flooding surface were identified. Most of these flooding surfaces occur where there is an abrupt change in gamma ray value from low to high and occasionally a corresponding change in resistivity values from high to low. This can be seen in more detail in Figure 5.3 which is a dip cross section, flattened on the Belle Fourche sequence boundary, highlighting the major flooding surfaces observed in the Powell Field area. Up to four major coarsening upward sand assemblages can be identified in the middle of Powell Field. The major producing reservoir interval occurs between the TSE at the top of the Wall Creek Member, and above the RSE. This reservoir interval thins from the south west to the north east and will be discussed further in the Reservoir Characterization Chapter. The cross-section in Figure 5.3 also shows that the major coarsening upward sand assemblages are not continuous across the field area. This has implications for reservoir fluid movement and compartmentalization.
Figure 5.1  Core photos from Spearhead Ranch #2 well showing major flooding surfaces (FS), the transgressive surface of erosion (TSE) at the top of the Wall Creek Member of the Frontier Formation, and the regressive surface of erosion (RSE) at the base of the Wall Creek Member reservoir interval. These surfaces were carried to the well logs and correlated across the field area.
Figure 5.2  Cross section N-S is a five well cross section of the core analysis wells. Major flooding surfaces identified in the cored intervals are RSE, FS_30, FS_40, and tse. Most of these flooding surfaces occur where there is an abrupt change in gamma-ray value from low to high and occasionally a corresponding change in resistivity value from high to low. The cored interval is noted by the cyan bar on the left side of the track. The perforated interval is noted in red. An index map is in the upper left portion of the figure.
Figure 5.3 Cross section A-A’ is an eight well dip cross section, flattened on the Belle Fourche sequence boundary, from south west to north east. The index map is in the upper right portion of the figure. The gamma ray log is in the left track while the deep resistivity log is in the right track for each respective well. This cross section shows major flooding surfaces (FS), the transgressive surface of erosion (TSE) at the top of the Frontier Formation, the regressive surface of erosion (RSE) at the base of the Wall Creek Member reservoir interval, and the base of the Wall Creek Member and top of Belle Fourche (BLFC_SB). The reservoir thins up dip to the north east providing a stratigraphic trap for hydrocarbon accumulation.
5.2 Core Porosity and Permeability

Porosity and permeability measurements were available for ten wells in the study area (Figure 5.4). Porosity values ranged from 1.0% porosity up to 22.0% porosity. Permeability values ranged from 0.02 mD to more than 400 mD. Generally, the highest porosity and permeability values occurred in the upper five feet of the coarsening upwards sequences. These intervals also corresponded to core faces 5, which is the main reservoir faces. Porosity and permeability were cross plotted (Figure 5.4) to distinguish the pore throat size. Most data points fell within the micropores category while most of the porosity values above 10% fell in the macropores and megapores category.

![Figure 5.4](image)

Figure 5.4 A cross plot of core porosity vs core permeability with data points colored by gamma ray for ten wells with routine core analysis totaling 102 data points. Lines represent a constant ratio between permeability and porosity and divide the plot into pore size categories. Permeability is plotted on a log scale while porosity is plotted on a linear scale. The core data has been depth shifted to log depths. The data points are colored by corresponding gamma ray api count.
5.3 Subsurface Maps

With a core calibrated petrophysical model, a series of subsurface maps were generated to better define the reservoir quality of the Wall Creek Member in the Powell Field area. Over 100 wells with digital well log data were used to generate maps of the following attributes: Gross and net isopach, average density porosity, average volume of clay, average deep resistivity, average water saturation, and hydrocarbon pore thickness (SoPhiH).

All reservoir computations were made on the stratigraphic interval defined by the top of the Wall Creek Member of the Frontier Formation observed as a transgressive surface of erosion (TSE) and the regressive surface of erosion (RSE) as correlated across the area (Figure 5.5). This interval was the main target for vertical well development. Figure 5.6 shows the gross isopach for the TSE to RSE interval. It is thickest to the south west at around 140 feet and thins to the north east to around 30 feet likely providing a stratigraphic trap for the Powell Field area. This is indicative of the delta front of the Wall Creek Member building out from the Sevier Highlands from the south west to the north east. Further to the south west the gross interval is upwards of 200 feet.

Figure 5.7 shows an average density porosity map for the reservoir interval. The density porosity calculated on a 2.68 g/cc matrix density corresponded to the core porosities the best. Average density porosities in the study area ranged from less than 4 percent to greater than 6.5 percent. The greatest average exists in the south west part of the study area as well as a north west – south east trend through the middle of the study area. Figure 5.8 is a map with the average calculated volume of clay (Vclay) in the study area. The method used to calculate Vclay was a combination of the gamma ray, neutron, and density methods. This computation was calibrated
Figure 5.5  Well log of the Spearhead Ranch 4 well showing the interval used for reservoir computations noted in green on the left side of the track. The cored interval in this well is noted by the cyan bar on the left side of the track. The perforated interval is noted in red just below the top of Wall Creek. This perforated interval corresponds to core facies 5.
Figure 5.6  Gross isopach map from top of Wall Creek Member reservoir interval (TSE surface) to RSE. The interval thickens to the south west and thins to the north east. The contour interval is 10 feet.
Figure 5.7  Map showing the average density porosity on a 2.68 g/cc matrix density. The highest values appear in the middle of the study area in a north west – south east trend. The contour interval is 5 percent.
Figure 5.8  Map showing the well log calculated average volume of clay using the combination of gamma ray, neutron porosity, and density porosity methods. The contour interval is 10 percent.
to wells with XRD results for total clay volume. For the reservoir interval, the lowest Vclay values of around 20 percent occur in the south west part of the study area as well through the middle of the study area with a north-south trend. Higher Vclay values, greater than 40 percent occur to the north and east.

A map for Net Reservoir was generated and is shown in Figure 5.9. Net Reservoir was defined as the portion of the gross reservoir that had Vclay less than 40 percent and density porosity greater than 4 percent. The thickest net reservoir of up to 100 feet occur in the south west portion of the study area as well as a thick trend through the middle of the study area. This map is a good indicator of reservoir quality and corresponds well with historical vertical production. Figure 5.10 is a map showing the average deep resistivity of the reservoir interval. Higher resistivity values can be an indicator of greater hydrocarbon saturations. As observed on previous maps, the highest resistivity values occur in the south west part of the study area as well as through the middle part of the study area.

Average water saturation, using the modified Simandoux equation, is what makes up Figure 5.11. Average water saturation values range from less than 50 percent to greater than 90 percent in the extreme north east part of the study area. The lowest water saturations occur in the south west part of the study area and through the middle of the study area and correspond well with historical vertical production.

To characterize the areas of the study area that have the highest potential for hydrocarbon production, a hydrocarbon pore thickness (SoPhiH) map was generated by combining the net reservoir map with oil saturation (1-Sw). This can be seen in Figure 5.12 where the largest SoPhiH values occurring in the south west part of the study area as well as
through the middle of the study area. These areas, as seen on previous maps, have the best potential for hydrocarbon production. An SoPhiH of 1 calculates to around 5 million reservoir barrels of oil per section, or around 7,813 barrels per acre.

Figure 5.9 Map showing the net reservoir. Computed from Vclay less than 40 percent and porosity greater than 4 percent. The contour interval is 10 feet. The thickest net reservoir is present in the south west part of the map area and through the middle where most vertical well production occurs.
Figure 5.10  Map showing average deep resistivity. Values are largest through the middle of the study area indicating higher hydrocarbon saturations. The contour interval is 2 ohm/m.
Figure 5.11  Map showing average water saturation using the Simandoux method [eq 4.5]. Water saturation values are lowest in the south west portion of the study area and increase to the north east portion of the study area. Contour interval is 5 percent.
Figure 5.12 Map showing hydrocarbon pore thickness (SoPhiH). The highest values occur in the south west part of the study area as well as through the middle of the study area. An SoPhiH of 1 calculates to around 5 million reservoir barrels of oil per section. The contour interval is 0.5 SoPhiH.
The main source rock that has generated the hydrocarbons for the Wall Creek Member in the study area is the Mowry Shale. A thermal maturity map of the Mowry Shale, using vitrinite reflectance (Ro), is shown in Figure 5.13. For most of the study area, Ro values exceed 1.0 – 1.2 (Modica and Lapierre, 2012). This is in the peak to late oil generating window. The high level of thermal maturity likely aided in the higher reservoir pressures observed when the field was originally developed.

Figure 5.13  Vitrinite Reflectance (Ro) map for the Mowry Formation. The Mowry Formation is the main source rock for the Wall Creek Member. The highest Ro values occur in the center and south west part of the study area which corresponds to thermally mature source rocks in the late oil window. It also corresponds positively with calculated SoPhiH values. Map was modified and updated from Modica and Lapierre (2012). The contour interval is 0.1 Ro
5.4 Production

Vertical production from the Wall Creek Member in the study area started in early 1970’s and continues to this day along with new horizontal production (Figure 5.14). Horizontal production began in the study area in the early 2000’s and new wells are brought on every year, targeting the Wall Creek Member.

Figure 5.14  Production bubble map showing cumulative three phase production for the study area. Production bubbles plot at the bottom hole location for horizontal wells. The injection wells are colored in yellow.
Most vertical wells are perforated and hydraulically fractured in the upper five to ten feet of the coarsening up sequences observed in the reservoir interval. Horizontal wells in the area target the flooding surfaces of these coarsening up sequences and hydraulically stimulate lateral lengths up to two miles. The largest cumulative oil vertical producer in the study area is the Spearhead Ranch 15 well that completed in 1979 and has produced over 1.7 million barrels of oil to date. It was perforated and completed in 12-foot interval at the top of the Wall Creek Member. The largest cumulative oil horizontal producer in the study area is the Roger Leo Federal well. It was completed in 2015 and has produced just over 174,000 barrels of oil to date. Currently there are more than 45 approved state permits to drill horizontal wells in the study area targeting the Wall Creek Member.
CHAPTER 6: CONCLUSIONS

1) Log-derived measurements of porosity, and water saturation are influenced where clay is disseminated or dispersed in the reservoir rock.

2) The Simandoux shaly sand petrophysical model calibrated to core is necessary to evaluate the hydrocarbon potential of the tighter, clay rich facies which provide additional resources for unconventional development.

3) Eight total core facies were established based on bed to bed contacts, lithology, grain size, sedimentary structures, and ichnology.

4) Three key stratigraphic surfaces were identified including the transgressive surface of erosion, flooding surfaces, and regressive surface of erosion.

5) *Cruziana* and *Skolithos* are the ichnofacies associated with the Wall Creek Member.

6) Three facies associations were established including prodelta to offshore, delta front, and reworked transgressive deposits.

7) The Wall Creek Member was deposited in a wave and tidal dominated delta system.

8) Core facies 5 is the main reservoir facies in the study area due to low clay content, coarse-grained, well sorted, and diagenetic features that help preserve primary porosity.

9) Fe-rich chlorite formed early in the diagenetic sequence, coating quartz grains which prevented quartz overgrowths and calcite cement from reducing pore space.

10) Five major flooding surfaces were interpreted and separated out major coarsening upward sandstone sequences.

11) The thickest Wall Creek reservoir is in the south west of the study area and thins to the north east of the study area providing a stratigraphic trap for hydrocarbons.
12) Hydrocarbon thickness map (SoPhiH) shows the best hydrocarbon potential resides in the middle and south west part of the study area where there is up to 23,000 barrels of original oil in place per acre.
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Figure A. 1  Core description of the Moore Ranch 12-13 well (USGS core D473) showing grain size and sedimentary structures in the first track. Gamma ray log in the second track. Facies number in the third track. Core analysis in the fourth track. Bioturbation index in the final track.
Figure A. 2  Core description, gamma ray, facies, core porosity, and bioturbation index for the Dilts 7-1 well. (USGS core B136).
Figure A. 3  Core description, gamma ray, facies, core porosity, and bioturbation index for the Spearhead Ranch 2 well.
Figure A. 4  Core description, gamma ray, facies, core porosity, and bioturbation index for the Spearhead Ranch 4 well.
Figure A. 5  Core description, gamma ray, facies, and bioturbation index for the South Powell 1-13 well.
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**Figure A.6** Table of wells with digital las data used in the petrophysical model. Listed is the api number, well name and number, original operator, location (T-R-S-QTR), driller total depth in feet, spud date (yyy-mm-dd), completion date (yyy-mm-dd), and kb elevation in feet.