SEQUENCE STRATIGRAPHY OF THE LOWER PIERRE SHALE IN SOUTHERN
POWDER RIVER BASIN, WYOMING, USA

By

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ABSTRACT

Powder River Basin is one of the biggest interior sedimentary basins in the Rocky Mountain region. The Upper Cretaceous section of the southern Powder River Basin includes the Niobrara Formation, which is one of the most significant source rocks of the Western Interior Cretaceous Seaway, and it is overlain by lower Pierre Shale which consists mostly of progradational shale sequences and two productive sandstone members encased in these shales.

In the southern Powder River Basin, the lower Pierre Shale is made up of eight members. These members are progradational highstand deposits of the Gammon Ferruginous Member; lowstand prograding wedge deposits consisting of the Shannon Sandstone, the Unnamed Member, and the Sussex Sandstone; transgressional Ardmore Pedro Bentonite Beds and Sharon Springs members; and highstand deposits of the Mitten Black Shale and Red Bird Silty members. The Shannon and Sussex sandstone members are known targets for oil production. The Sharon Springs Member of the lower Pierre shale has relatively high organic carbon content. Therefore, determining its continuity throughout the study area and its source rock potential was one of the main focuses of this study in addition to building the sequence stratigraphic framework for the lower Pierre Shale interval.

Based on an integrated research of 1490 raster well-log data with three cores, this study demonstrates that the lower Pierre Shale interval is a Type 1 Ramp Margin Sequence. While previous studies were primarily focused on individual sandstone members or parts of the lower Pierre Shale section in relatively limited areas, this study provides an in depth sequence stratigraphic analysis of the lower Pierre Shale interval. The sequence stratigraphic framework was built based on well-log correlations, core descriptions, isopach maps and three-dimensional
surface maps of each member, and one master west east oriented cross section throughout the study area.

According to this sequence stratigraphic analysis, a depositional model connecting the Bighorn Basin to the Southern Powder River Basin was created. The depositional model demonstrates that the Shannon Sandstone, Unnamed, and Sussex Sandstone Members were deposited as an encased lowstand prograding wedge between the progradational Gammon Ferruginous Member and the transgressional Ardmore Pedro Bentonite Beds and Sharon Springs members hundreds of miles basinward from the stratigraphically equal Mesaverde lowstand sandstones of the Bighorn Basin. The shift of facies across such long distances is explained with the forced regression that has taken place during the deposition of the uppermost Gammon Ferruginous Member and the following deposition of Shannon and Sussex sandstone members farther in the basin compared to the synchronous shoreline sands.

Source rock analyses within the Sharon Springs interval demonstrate that member is moderately organic rich (TOC wt. % 1.27-2.72) and it is thermally mature (Tmax 437-440 °C) within the study area. However, the kerogen type within the member is Type III and the organic matter is gas prone. Based on these data, there is no evidence for the contribution of the Sharon Springs Member to the oil accumulations found in the Shannon and Sussex Sandstone Members.
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CHAPTER 1
INTRODUCTION

The Powder River Basin is an intermontane basin of Laramide origin and is located in the northern Rocky Mountains. The basin occupies northeastern Wyoming and a part of southeastern Montana. It comprises more than 34,000 sq. mi. (Dolton et al., 1988). The deepest part is up to 17,000 ft or more to the top of the Precambrian basement. On the east flank regional dip is about 100 ft/mi and on the west flank regional dip is about 500 ft/mi (Figure 1.1) (Anna, 2009). In the southeastern part of the Powder River Basin, Upper Cretaceous rocks dip southwest almost uniformly at 140-220 ft/mi (Asquith, 1970). Oil production comes from (1) the stratigraphic traps in the Lower Cretaceous Fall River (Dakota) and Newcastle Sandstones (Stapp, 1967), (2) both stratigraphic and structural traps in the Permo-Pennsylvanian Minnelusa Formation, and (3) Upper Cretaceous sandstones at Dead Horse Creek, Barber Creek, and other fields which are located along the southwest flank of the basin.

![Figure 1.1 Generalized east-west cross section of Powder River Basin illustrating the basin's asymmetrical shape. Basin axis is located in the west (modified from Anna, 2009).](image-url)
The Niobrara Formation and the lower Pierre Shale of the southern Powder River Basin are examples of the wide shelf configuration, in which subsidence is relatively slow, progradation is rapid, and sand is largely confined to the shelf (Asquith, 1970). The Sharon Springs Member of the lower Pierre Shale has high source rock potential (Gautier et al., 1984). Figure 1.2 shows a generalized stratigraphic column of the Powder River Basin. In the Figure 1.2, the study interval is magnified and each member within the study interval is shown in a separate box.

This study is focused on the sequence stratigraphy of the lower Pierre Shale within southern Powder River Basin with an emphasis on understanding the mechanisms that lead the deposition of the two sandstone members within the study interval far away from the synchronous shoreline deposits. Another focus of this study is to understand the source rock potential of the organic-rich Sharon Springs Member and answering the question whether or not Sharon Springs Member is continuous across the study area.

1.1 Objectives and Purpose

The objective of this study was to investigate the stratigraphy of Pierre Shale, to identify the individual clinoform packages and thickness of these clinoform packages by using sequence stratigraphic approach. In order to understand the sudden depositional change from the calcareous shale and marlstone beds of the Niobrara Formation (Asquith, 1970) to clastics, correlations and interpretations within the lower Pierre Shale interval were made. Therefore, the sequence stratigraphic framework was built by making correlations between geophysical logs by using IHS Petra software and creating isopach maps and three-dimensional models. Finally, a depositional model for the lower Pierre Shale interval was created which explains the deposition of the two sandstone members within the study interval farther in the basin from the synchronous shoreline deposits. The organic carbon rich Sharon Springs Member was a focus in this study. The question of whether or not the Sharon Springs Member is continuous across
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the study area was answered. Three core samples which were taken from the lower part of Pierre Shale Unit were described, and source rock analyses were made on them. This study includes an expanded and detailed analysis of the lower Pierre Shale compared to the previous studies since an adequate number of well-logs and three cores in the southern Powder River Basin were analyzed. Therefore, it has a significant contribution to the previous studies and the understanding of the mechanisms that caused the lower Pierre Shale to overlay the Niobrara Formation and cut the Niobrara carbonate factory off.

1.2 Study Area

Powder River Basin is a structural and topographic basin. The basin is bounded by the Bighorn Mountains on the west, the Casper arch on the southwest, the Laramie Mountains and the Hartville uplift on the south, the Black Hills on the east, and the Miles City arch on the northeast. The basin is separated by the Bull Mountain Basin on the northwest by a low arch within the Ashland syncline (Beikman, 1962).

The Powder River Basin is approximately 230 miles in length and 100 miles in width which makes it one of the biggest intermontane basins of the Rocky Mountain Region. The basin has an asymmetrical syncline shape, which has a steeply dipping west flank and a gently dipping east flank (Figure 1.1). The synclinal axis of the basin trends N. 15° to N. 20° W. and is parallel to the central Bighorn Mountains (Beikman, 1962). The deepest part of the basin is located on the west, adjacent to the central Bighorn Mountains. There is a structural relief of about 21,000 ft defined by the Paleozoic Rocks which are in some places about 21,000 ft higher in the elevation on the east flank of the Bighorn Mountains than they are in the deepest part of the trough of the basin (Beikman, 1962).

The study area for this project is located in the southern portion of the Powder River Basin which is located in the northeastern part of Wyoming. It covers southern parts of both
Campbell and Weston counties and northern parts of Converse and Niobrara counties (Figure 1.3). The dataset used for this study was included in the Figure 1.3. The stars show the locations of the cores. The red colored star shows the location of the 11 Highland Flats Federal (Sec.11, T37N R73W) which was sampled for the geochemistry analyses, and the red circles show the wells from which the cutting data was taken. The green boxes show the location of the well logs used as type logs for correlations. The blue line on the Figure 1.3 shows the location of the master cross section (see Appendix D).

1.3 Research and Methods

Interpretation of well log data is the one of the primary methods for development of a sequence stratigraphic framework. Sequence stratigraphic approach is based on identifying the “rock relationships within a chronostratigraphic framework of repetitive, genetically related strata, bounded by surfaces of erosion or nondeposition, or their correlative conformities” (Van Wagoner et al., 1988).

Research methods for this study consist of sequence stratigraphic analysis which was conducted by correlating wireline well logs and describing cores within the southern Powder River Basin in the lower Pierre Shale interval. Isopach maps and three-dimensional surface maps were created in order to understand the depositional patterns and thickness trends related to the basin subsidence during the sedimentation. Based on these thickness trends and well log patterns, directions for overall sediment supply were interpreted. One master cross section was created to illustrate the stratigraphic trend of each member within the lower Pierre Shale and the sequence stratigraphic interpretation.

1.3.1 Raster Wireline Logs

A digital well database which has a total of 102,092 wells was provided through the Colorado School of Mines Niobrara Consortium for this study. Well information within this
Figure 1.3 Generalized geology map of the southern Powder River Basin with the well log data used for this study. The stars mark the locations of the cores. The red colored symbols are the locations for the geochemistry data. The green boxes show the locations of the type logs. The blue line marks the location of the master cross section (see Appendix D) (map courtesy of http://ims.wsgs.uwyo.edu/PRB/).
database included well locations, general well data, and raster logs (if available). 1,490 raster well logs were analyzed and used to determine the geometries and thickness trends of the six members of the lower Pierre Shale interval and the two sandstone members which are involved in the sequence in the western half of the study area (Figure 1.2). However, at some places in the study area there are insufficient well data which lead to poor well control.

IHS Petra database management software was used to make correlations on well log database across the basin for this project. Top selections, isopach maps, and the master cross section were created with the use of this software. Furthermore, three-dimensional surface maps which show the positions and shapes of each member of the lower Pierre Shale using the Red Bird Silty Member as the datum were created with the use of Schlumberger Petrel.

1.3.2 Cores

Three cores, which were taken from the western half of the study area, were examined and described in order to understand the relationships and the nature of the surfaces between the Gammon Ferruginous Member, Shannon Sandstone, the Unnamed Member and Ardmore Pedro Bentonite Beds members. Locations of the cores are shown on the Figure 1.3. Furthermore, facies analyses for the sandstones within the cored intervals and source rock analyses for the lower Sharon Springs Member were made. These cores were obtained from the wells 13-11 Highland Flats Federal (Sec.11, T37N R73W), 20-11 Ione (Sec.20, T44N R75W), and 1 Pfister-D (Sec.23, T44N R76W). 13-11 Highland Flats Federal (Sec.11, T37N R73W) core was sampled and SRA analyses were made on these samples in order to understand the source rock potential of the Sharon Springs Member.

In addition to the samples obtained from 13-11 Highland Flats Federal (Sec.11, T37N R73W), source rock analyses data of cutting samples coming from 22-6 Parker Sparks (Sec.6, T37N R68W) and 1-29 Carshon Federal (Sec.29, T37N R65W) wells were examined. Locations
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CHAPTER 2
GEOLeOGIC BACKGROUdN

In this chapter, the structural background for the Powder River Basin and stratigraphic background for the late Cretaceous strata in the Powder River Basin is reviewed based on the former publications.

2.1 Regional Setting and Structure

The Powder River Basin is one of the most significant interior sedimentary basins in the USA (Rasco, 1999). The basin is located in northeastern Wyoming and southeastern Montana and it was developed during the Laramide Orogeny similar to other Rocky Mountain foreland structural basins (Anna, 2009). Its present shape is mostly formed during late Laramide Orogeny, which took place during the Late Cretaceous - Early Tertiary (Sharp, 1948). The basin has an asymmetric shape, and its orientation is north-south with its axis on the western side. The basin is surrounded by uplifts on all sides, and all of these uplifts influenced the formation and evolution of the basin at some time (Rasco, 1999). These major uplifts are the Bighorn Mountains, Hardin Platform and Porcupine Dome to the northwest; the Miles City Arch to the north and northeast, the Black Hills uplift and monocline to the east, the Hartville Uplift to the southeast, the Laramie Range to the south, and the Casper Arch to the southwest (Figure 2.1) (Anna 2009).

Based on the asymmetric sediment thickness pattern, the Cretaceous Western Interior Basin has commonly been interpreted as a characteristic foreland basin (Liu et al., 2005). The driving mechanism for the asymmetric subsidence pattern in the basin is interpreted by several authors to be the Sevier thrust belt which is located on the western margin of the basin (Price 1973; Dickinson, 1974; Kauffman, 1977). According to Pang (1994), Pang and Nummedal (1995), and Liu and Nummedal (2004) the two components of the regional subsidence in the
Figure 2.1 The major structural elements that bound and the major basins that surround the Powder River Basin (modified from Anna, 2009) (map courtesy of http://ims.wsgs.uwyo.edu/PRB/)
basin were “a short-wavelength flexural loading component that changed on time-scales of a few million years and a long-wavelength dynamic subsidence component that changed slowly over 10 s of million of years” (Liu et al., 2005). Pang and Nummedal (1995), and Liu and Nummedal (2004) showed that subsidence related to the load of the Sevier fault and thrust belt has taken place within approximately only 75-112 mi. band east of the Sevier thrust belt. Based on this observation, Liu et al. (2011) proposed that most of the Western Interior Basin subsidence is formed in response to mantle flow affects which are related to the Farallon plate subduction in addition to the subsidence component caused by foreland basin configuration associated with the shortening in the Sevier fold and thrust belt. Dynamic subsidence that has taken place across the Northern America starting from Late Cretaceous was suggested by Liu et al. (2008) by using inverse mantle convection model, and Liu et al. (2011) by using backstripping analyses across both Utah-Colorado and Wyoming sections. Liu et al. (2011) suggested that in addition to the subsidence which was driven by the Sevier thrust belt and the related sediment loads, there is a long wavelength continuously evolving residual subsidence during the deposition of Late Cretaceous succession of central Utah, Colorado and southern Wyoming. Furthermore, reconstructions that were made using quantitative inverse models in the same study show that there’s an eastward movement of the “loci of maximum rates of this residual subsidence” from approximately 98 to 74 Ma” (Liu et al., 2011). This long wavelength subsidence across the central Rocky Mountains starts with an initial subsidence in the west and was subsequently followed by a trough shaped subsidence profile. Liu et al. (2011) coupled the inverse convection model, which was suggested in Liu et al. (2008) study, with the backstripping analyses and showed that the inverse convection model underpredicts the dynamic subsidence along the Wyoming section. Liu et al. (2011) suggest an “increasing maximum cumulative residual subsidence” which is approximately from 1300 to 3050 ft “between 98.8 and 75 Ma with an eastward migrating depocenter” across Utah-Colorado section, and a dynamic subsidence of approximately 3280 ft in the Wyoming section.
Based on inverse convection model for Farallon subduction, Liu et al. (2008) suggested that during Late Cretaceous a thick and cool oceanic slab, which has an arch shape with dips in all directions, migrated eastward beneath North America. According to Liu et al. (2011) the dynamic surface subsidence was caused by the negative buoyancy of the sinking Farallón slab. At 98 Ma, the leading edge of the Farallón slab reached Utah and western Wyoming causing a high rate of subsidence. Before 90 Ma, the highest rate of subsidence, which was caused by the shallow part of the eastward dipping slab, was in the west; whereas, the subsidence in the east was widespread with a low magnitude. Approximately at 84 Ma, the whole slab started to affect the Western Interior Basin. In the west, where the slab crest is located, the viscous pull was at maximum with a progressive weakening eastward which is caused by the deepening of the slab. At approximately 80 Ma, the center of residual subsidence moved to western Colorado and middle Wyoming. After 80 Ma the migration direction of the Farallón plate relative to the North America changed from eastward to northeastward. Synchronously, the Farallón slab sank deeper into the mantle which created an overall decrease in the viscous pull (Liu et al., 2008). Therefore, Liu et al. (2011) concluded that the dynamic subsidence of the Western Interior Basin during Late Cretaceous “is characterized by an initial rapid subsidence in the west that subsequently migrated to the east, forming a trough-shaped subsidence profile.”

By combining the inverse convection models with plate motion reconstructions Liu et al. (2010) identified the Shatsky conjugate plateau as a seismic anomaly on the recovered Farallón Plate that subducted beneath the North America. Liu et al. (2010) proposed that “continued subduction caused the oceanic crust to undergo the basalt–eclogite phase transformation, during which the Shatsky conjugate lost its extra buoyancy and was effectively removed”, and the “increases in slab density and coupling between the overriding and subducting plates initially dragged the surface downward, followed by regional-scale surface rebound”. Therefore, Liu et
al. (2010) suggested that the Laramide uplift was formed as a consequence of the removal of the Shatsky conjugate.

According to Rasco (1999) many geological features including major uplifts, faults, fractures, and folds in the southern Powder River Basin are linearly arranged. Strong structural control is suggested by the linear arrangement of many of the reservoirs belonging to producing intervals and their orientation to the northwest (Rasco, 1999). Figure 2.2 illustrates the linear arrangement of the reservoirs within the southern Powder River Basin and the Pennsylvanian-Permian reservoirs are shown in blue, the Lower Cretaceous in green, and the Upper Cretaceous in yellow (Rasco, 1999). This linear arrangement includes the Clareton, Fiddler Creek, House Creek, Dead Horse Creek-Barber, Hartzog Draw and the South Coyote fields (Slack, 1981).

A major continental seaway existed in Mesozoic and terminated in Late Cretaceous. A counterclockwise rotation of stress related to the Laramide Orogeny is represented by the reactivation of many basement faults and formation of new structures, which have north-south, northwest-southeast, and east-west trends in that order of age (Rasco, 1999).

2.2 Stratigraphy

According to Beikman (1962) sedimentary rocks reach a maximum thickness of about 17,000 feet in the Powder River Basin and rocks of all geologic systems are represented. Different nomenclature is used for several outcropping units, which are in fact equivalent, on the major uplifts surrounding the basin (Beikman, 1962). The reason for that is the existence of variations in lithologies, thicknesses, and ages of these rock units (Beikman, 1962).

During the deposition of the lower Pierre Shale within the Southern Powder River Basin rapid progradation accompanied with relatively slow subsidence has taken place, and the sand bodies are restricted to the shelf (Asquith, 1970). In addition to the shale, there are significant
amounts of siltstone, silty sandstone, and lesser amounts of sandstone and marlstone within the southern Powder River Basin (Asquith, 1970).

According to Asquith (1970) the Niobrara Formation, which is the basinal equivalent of terrigenous clastic material deposited on the western part of the Powder River Basin, lies below the Pierre Shale. According to Asquith (1970) and Gill and Cobban (1966) the lowermost Pierre Shale has an interfingering relationship with the uppermost calcareous shale and marlstone beds of the Niobrara Formation. The Niobrara Formation in the Black Hills area is recognized as soft, white weathering chalky shale by Gill and Cobban (1966). The formation has thin beds of bentonite in the middle part and its thickness ranges from 150 to 225 feet on the eastern side of the basin (Beikman, 1962).

According to Beikman (1962) the Pierre Shale is observed as a sequence of marine shale, sandstone, and bentonite beds in the Black Hills; it is underlain by the Niobrara, and overlain by the Fox Hills Sandstone. The equivalents on the western side of the basin include

Figure 2.2 Generalized tectonic map showing the linear arrangement of the reservoirs emphasizing the strong structural control on the formation of the basin. Pennsylvanian-Permian reservoirs are shown in blue, Lower Cretaceous in green, and Upper Cretaceous in yellow (modified from Rasco, 1999).
several sandstone beds (Beikman, 1962). The Fox Hills Sandstone lies above the Pierre Shale and it is interpreted by Gill and Cobban (1966) as a shallow marine sand body which has a gradational contact with the Pierre Shale.

The Gammon Ferruginous Member is the lowermost member of the lower Pierre Shale and it was named by Rubey in 1930 for its exposures of dark gray mudstone and bentonitic claystone containing red weathering siderite concretions along Gammon Creek on the northwest flank of the Black Hills in T. 57 N., Rs. 67 and 68 W., Crook County, Wyoming (Gill and Cobban, 1966). According to Asquith (1970) and Gill and Cobban (1966) the Gammon Ferruginous Member has an interfingering relationship with the Niobrara Formation at the bottom. The lithology of this member is silty shale (Asquith, 1970), and the adjective “ferruginous” indicates that the member has abundant siderite concretions (Gill and Cobban, 1966). The sediments of Gammon Ferruginous Member entered the area from the northwest with a shelf progradation direction towards southeast, and the depositional surfaces have a present inclination of $\frac{1}{2}^\circ$ to $1^\circ$ (Asquith, 1970). The member has a westward thickening trend which is accompanied by a decrease in hardness and increase in abundance of siderite concretions (Gill and Cobban, 1966). Gill and Cobban (1966) recognized Gammon Ferruginous Member at Red Bird as dark hard platy-weathering non-calcareous shale, and they noted the locally observed banded appearance of Gammon due to rusty-weathering siderite concretions.

The Shannon Sandstone lies above the progradational sequence of the Gammon Ferruginous Member which is composed of offshore mud deposits. There is a sharp basal contact between Shannon Sandstone beds and the progressive offshore marine muds. There are several different interpretations about the depositional mechanisms of the Shannon Sandstone (Suter and Clifton, 1999 for a detailed summary of the interpretations). According to Spearing (1976) following the period of nondeposition, discrete sand bodies which make up Shannon Sandstone were carried and deposited by storm waves and oceanic currents with a
constant southward transport direction. According to Spearing (1976), having flat base and convex tops, Shannon Sandstone shows no evidence in shape and sedimentary structure for erosion. Sands in the Shannon interval are thickest at the Salt Creek area and they thin both eastward and westward (Spearing, 1976). Similar to Spearing (1976), Tillman and Martinsen (1984) and Swift and Parsons (1999) interpreted Shannon Sandstone as storm dominated shelf sand deposits. Sullivan et al. (1997) interpreted the unit as a tide dominated delta deposited as an incised valley infill. Another interpretation is based on explaining the deposition of this unit as tidal sand ridges deposited in a mixed wave-tidal regime estuary (Elliott, 1995). Bergman (1994) suggested there are several problems with the shelf ridge interpretation such as the transportation of sediment from shoreline to the shelf; the suggested reworking model of the sands into approximately 65 ft thick coarsening upward sand bodies which are encased in mudstones; the stacking patterns; assemblages of trace fossils; the existence of glauconite and siderite in the same facies; the absence of sand between the synchronous shoreline deposits; and the suggested shelf ridge complex. Instead, another interpretation which explains these problems with sea level fluctuations and interpreting Shannon Sandstone as a lowstand deposit was suggested by Bergman (1994). Furthermore, Bergman (1994) defined eight different facies within the Shannon Sandstone and presented the depositional relationships among these facies in Hartzog Draw – Heldt Draw fields. According to Steel et al. (2012), during Campanian, there was significant tidal influence on the southwestern shoreline of the Western Interior Seaway. The Shannon Sandstone is one of the many sandstone members which were deposited farther basinward, and these sandstone bodies were deposited as a result of relative sea level fall and they have dominantly but not exclusively tidal origin (Steel et al., 2012). Since they don't have downcutting distributary channels the middle and distal parts of these sandstone bodies are interpreted to be subaqueous (Steel et al., 2012).

The Unnamed Member of the lower Pierre Shale prograded on the Shannon Sandstone
in the western half of the study area and on Gammon Ferruginous Member where Shannon Sandstone does not exist. According to Asquith (1970), the member prograded eastward and deposited on Gammon Ferruginous Member after a period of ceased sedimentation. As a result of insufficient sediment supply the member is restricted to the submerged shelf and a part of the upper slope of Gammon Ferruginous Member on the western half of the study area which resulted in increase of the submarine topographic relief between the top of the Unnamed Member and the eastern half of the study area (Asquith, 1970).

According to Wilson (1951), the Sussex Sandstone is best developed in Sussex and Meadow Creek oil fields. The member is observed as 40-foot thick light greenish-gray, fine-grained, subangular, glauconitic, marine sandstone which contains shark teeth and black chert pebbles (Wilson, 1951). Being deposited in offshore positions, the Sussex interval deposits in the Powder River Basin were interpreted by Brenner (1978) as a part of a sandy mud sheet which is characterized by a southward and eastward progradation from a siliciclastic source on the northwest. According to Brenner (1978), both storm generated and tidal currents created and shaped sand ridges within the prograding sandy mud sheet. The Sussex Sandstone and its shaly equivalents can be recognized on well-logs for a distance of 75 miles along the west and the south margins of the Powder River Basin; however, it is a well-developed sandstone for only about 15 miles (Wilson, 1951). On the other hand, the tide-dominated, wave-dominated, and mixed-energy (tides and waves) deposition interpretations made by Steel et al., (2012) for the Upper Cretaceous sandstone bodies along the southwestern shore of the Western Interior Seaway. These interpretations lead to new interpretations for the deposition of the Sussex Sandstone Member. Steel et al. (2012) included the Sussex Sandstone in the tidally influenced sandstones deposited in northern Wyoming.

The Ardmore Bed is named by Spivey (1940) after the three-foot thick bentonite bed being commercially quarried at Ardmore and Ardmore Bed is one of the eight to twelve
bentonite beds which are separated by shale. These beds have thicknesses varying from 1 inch to 20 inches in south and southeast of the Black Hills, Fall River County, South Dakota (Spivey, 1940). Gill and Cobban (1966) recognized the same bed as the Ardmore Bentonite Bed of the Sharon Springs Member of the Pierre Shale at Red Bird and they designated it as the basal unit of the Sharon Springs Member where the member can be recognized in South Dakota, Wyoming, and Montana. The exposures of the equivalent member of Ardmore Bentonite Bed near Pedro, sec. 5, T. 45 N., R. 63 W., Weston County, Wyoming was named by Rubey (1930) as the Pedro Bentonite Bed. Asquith (1970) defined these Bentonite beds as Ardmore Pedro Bentonite Beds and showed that these beds are locally absent on the upper part of the submarine topographic slopes of the Gammon Ferruginous Member and the Unnamed Member of the lower Pierre Shale. According to Asquith (1970) the time surface at the base of the Sharon Springs Member, which is the base of Ardmore Pedro Bentonite Beds since these beds are defined as the basal unit of the Sharon Springs, approximates one of the most significant transgressions of the Pierre Sea. According to Asquith (1970) the absence of bentonite beds on the slope along with the existence of a basinward southeast projecting lobe of these beds suggest that the submarine erosion has taken place during a period in which deposition was only limited to bentonite accumulation and during this erosional event the eroded sediments of the bentonite beds moved downslope. During these movements, slump scars which are seen as local irregularities on the upper parts of the submarine slopes of the Gammon Ferruginous Member and the Unnamed Member were created (Asquith, 1970).

The Sharon Springs Member was named by Elias (1931) after exposures of hard buttress-forming organic-rich shale in Wallace and Logan Counties, Kansas. Defining Sharon Springs as “dark, nearly black beds of bituminous fissile shale which weather to dark brown”; Moxon et al. (1939) suggested that “the Sharon Springs of South Dakota is correlated with that of Kansas and Colorado”; and “beds in southeastern Wyoming, Weston County, are an
extension of the Sharon Springs”. Due to the organic material content, the Sharon Springs Member has abnormally high radioactivity (Gill and Cobban, 1966). Therefore, Sharon Springs and lateral equivalent members can be recognized on gamma ray logs and electric logs of oil and gas test holes throughout much of eastern Colorado, western Kansas, Nebraska, North and South Dakota, and eastern Wyoming and Montana (Gill and Cobban, 1966).

The Mitten Black Shale Member was first defined and named by Rubey (1930) at Mitten Prong in sec. 22 T. 56N, R. 68 W., Crook County, Wyoming as blue to black fissile shale with calcareous concretions which are stained by iron and marine fossils. Mitten Black Shale lies conformably and gradationally on the Sharon Springs Member and these two members are differentiated by the change from silver-gray papery weathering shale to black-gray limonite-stained shale (Gill and Cobban, 1966). The lowermost part of the Mitten at its type locality contains a thin bed of polished black phosphate pebbles and rounded bone fragments, and above it hard dark gray brownish weathering shale lies (Gill and Cobban, 1966). The upper part of the Mitten is black flaky shale which contains siderite concretions on the lower part and rusty weathering limestone concretions on the upper part (Gill and Cobban, 1966).

Following the deposition of the Mitten Black Shale Member, siltstone and silty shale of the Red Bird Silty Member was deposited (Asquith, 1970). The contact between Mitten Black Shale and Red Bird Silty Member is gradational and it is recognized as a change from dark flaky shale to lighter colored silty shale (Gill and Cobban 1966). The member was first named by Gill and Cobban (1962) for the exposures of light to medium gray, soft, silty shale at Red Bird. Being deposited marginal to the nearshore marine sandstones, the Red Bird Silty Member is recognized in west-central Colorado, eastern Wyoming, western South Dakota, western North Dakota and eastern Montana (Gill and Cobban, 1966). The member becomes less silty eastward. Eventually, it grades into the Gregory Member of the Pierre Shale of Missouri River valley of South Dakota (Gill and Cobban 1966). According to Gill and Cobban (1966) the
member contains abundant silty limestone concretions which are yellow, orange, or brown
colored. These concretions can be as big as 1 to 2 feet in diameter and many of them contain
invertebrate fossils. The Red Bird Silty Member in Wyoming is characterized by a variable but
sharp increase in resistivity curve on electric logs (Gill and Cobban, 1966).

It is important to note that the Shannon Sandstone is not the equivalent of Hygiene
Sandstone and Sussex Sandstone is not the equivalent of Terry Sandstone as they are used in
the nomenclature for the Denver Basin in order to prevent a possible confusion.

Based on the aforementioned relationships among the members of the lower Pierre
Shale Asquith (1970), built a cross section (FIGURE 2.3) showing all of these members and
their depositional geometries. Later Brenner (1978) and Van Wagoner et al. (1990) modified this
cross section and carried the model that Asquith suggested further with different interpretations.

Rubey (1930) and Gill and Cobban (1966) expressed different opinions about the water
depth during the deposition of the lower Pierre Shale interval. Having examined 30
petrographic thin sections of the marine shales taken from the Black Hills area, Rubey (1930)
concluded that the light and dark layers of clay and silt were not destroyed by waves and were
deposited below effective wave base. On the other hand, Gill and Cobban (1966) suggested
that the “Mitten Black Shale and younger members of the Pierre were deposited at depths less
than 200 feet”, and “the Gammon and Sharon Springs Members were deposited at depths
greater than 200 feet” based on several indirect evidences such as the distance to shore and
bioturbation.
Figure 2.3 Electric log cross section showing the six members of the lower Pierre Shale in the southeastern Powder River Basin (modified from Asquith, 1970). Each member in this cross section were colored and the same colors are used for the correlations and 3D models within this study.
CHAPTER 3
SEQUENCE STRATIGRAPHY

In this chapter the sequence stratigraphy interpretation was made and the sequence stratigraphy framework was built based on wireline well log correlations and core descriptions by creating isopach maps, three-dimensional surface maps and one master cross section.

3.1 Well-Log Correlations and Interpretations

An abundant number of well logs are available in the southern portion of the Powder River Basin which provides a robust dataset for building the sequence stratigraphy framework.

3.1.1 Correlation Strategies

The correlations within the study area were made on wireline well-logs. Finding cores which cut the whole study interval has been a problem since the lithology within the study interval consists of mostly shale. On the other hand, there are two significant sandstone members within the sequence on the western half of the study area and the cores cutting these sandstone intervals are abundant. Although these sandstones are not the main focus of the study, three cores are described in order to understand the nature of these sandstone members; how they were deposited farther basinward; and the nature of the bounding surfaces of these sandstones. Some of the bounding surfaces of the sandstone members are significant for sequence stratigraphic interpretation. Along with the well log correlations, making these descriptions and interpretations was a significant step on building the sequence stratigraphic framework.

Since the study area is wide and some of the members do not exist in the eastern half of the study area, four type logs were created which represent both eastern and western half of the southern Powder River Basin (Figures 3.1A and 3.1B). Using Asquith’s (1970) study, one type
log is created as the representative of the easternmost part of the study area. This type log was picked on the east since the Unnamed Member and the two sandstone members are pinching out eastward and don’t exist in the eastern half of the study area. The second type log is picked in the central part of the study area, where the Shannon Sandstone pinches out and the Sussex Sandstone is about to pinch out. The third and fourth type logs are picked on the western half of the study area in order to represent the area where the Shannon Sandstone, the Unnamed Member and the Sussex Sandstone are thicker. The four type logs show that the lower Pierre Shale section shows dominantly coarsening upwards trend which indicates the progradational nature of the members. There are irregular and fining upwards packages which will be defined as the transgressive systems tract in the following sections. Sandstones within the study interval usually show blocky to hour glass patterns and they will be defined as part of lowstand systems tract deposits in the following sections (Figure 3.1A and 3.1B).

The correlations are based on these well-log patterns and the well-log patterns on the western half of the study area are crosschecked with the cross sections created by Merewether et al. (1977) in order to provide consistency with the literature. In this study, the thickness values that will be mentioned in the following sections for each member of the lower Pierre Shale are measured through the well-log correlations.

Datum picking has been a challenge among the units within the study interval. The best candidate for being a consistent datum across the study area is Ardmore Pedro Bentonite Beds. However, the unit was eroded in a NNE-SSW trending corridor in the study area where the dip of the progradational Gammon Ferruginous Member deposits increase about ½ to 1 degree and the eroded sediments were redeposited eastward, further in the downdip direction as a southeast projecting lobe (Asquith, 1970). This absence eliminates the Ardmore Pedro Bentonite Beds as a candidate. Another significant candidate is the Niobrara Formation. The reason that the Niobrara formation was not picked as a datum is that it has sharp folding and/or
Figure 3.1A Type logs representing the western half of the study area.
Figure 3.1B Type logs representing the central part and eastern half of the study area.
faulting after its deposition in the northeastern part of the study area which was defined by Asquith (1970). This folding and/or faulting created an accommodation space for the incoming Gammon Ferruginous Member sediments which is clearly represented in the isopach map of the Gammon Ferruginous Member as a thickness change in the Gammon at the aforementioned location. Asquith (1970) picked the Red Bird Silty Member as the datum for the cross section he built and this study follows Asquith’s (1970) work by means of datum picking. In order to crosscheck the accuracy of Red Bird Silty Member as the datum, a flooding surface within the lower Lewis Shale was picked across the master cross section and this flooding surface was set as the new datum (Figure 3.2). After flattening the members of the lower Pierre Shale to this new datum, it was seen that there’s no significant difference with the onlapping, downlapping, and truncation patterns of each member within the study interval. It is not applicable to use this horizon as the datum in the whole study area since it is above the logged interval on the easternmost part based on the reason that the logging starts from 200 ft below the surface on each well.

3.1.2 Members of the lower Pierre Shale

Within this study, 1490 wireline well-logs were correlated in the study area. Eight different formation tops were picked in all 1490 well logs in order to create the 3D surface maps and isopach maps for each member of the lower Pierre Shale. However, some of these members don’t exist in some of the well logs due to the reasons that either the whole study interval was not completely logged or the top of the member is located at depths so close to the surface that it is not logged.

3.1.2.1 Gammon Ferruginous Member

The Gammon Ferruginous Member is the lowermost member of the lower Pierre Shale in the southern Powder River Basin. This member is characterized by an eastward progradation
Figure 3.2 Alternative datum within lower Lewis Shale interval is shown. This datum was picked and all members within lower Pierre Shale interval were flattened on the new datum in order to cross check the accuracy of the Red Bird Silty Member as the datum and no difference in the patterns was recognized.

and it has a consistent thinning trend towards the eastern boundary of the study area.

Depositional dip values of the Gammon Ferruginous Member deposits increase along a roughly north south trending corridor in the central part of the study area. This increase in depositional dips was interpreted by Asquith (1970) as a shelf, slope, basin geometry. However, Van Wagoner (1990) showed that the present dips shown by Asquith (1970) are too shallow for such interpretation. Based on the well-log correlations an isopach map was created for the Gammon Ferruginous Member within the limits of the well-log data (Figure 3.3). This isopach map shows
that the thickness of the member changes from 30 ft to 1270 ft within the study area. Although Asquith (1970) and Gill and Cobban (1966) argued that the Gammon Ferruginous Member has an interfingering lower contact with the Niobrara Formation, a sharp contact between these two members was recognized on the well log correlations. Therefore, there’s no evidence that the Niobrara Formation has an interfingering relationship with the Gammon Ferruginous Member within the study area. The member is directly overlain by the Ardmore Pedro Bentonite Beds on the eastern half of the study area. The contact between the Gammon and Ardmore is seen as a sharp contact which is defined by a sharp decrease in resistivity on the well-log patterns (Figure 3.1B). On the western half of the study area, the Gammon Ferruginous Member is overlain by the Shannon Sandstone. On the well-logs, this contact is characterized by a peak that shows sudden decrease in resistivity and this peak is followed above by the Shannon Sandstone interval which shows blocky to hour glass trends (Figure 3.1A). The Gammon Shannon contact is seen on the cores as a sharp erosive surface having abundant sideritized mud clasts which can be up to 4 inches long on their long axes (Figure 3.18A). The Gammon Ferruginous Member has a characteristically coarsening up well-log pattern which shows its progradational nature. On the eastern half and the central part of the of the study area, the uppermost horizons of the Gammon Ferruginous Member show distinct truncation patterns which are interpreted as indicators of a large scale erosion within the upper parts of the Gammon Ferruginous Member interval. The well-logs located on the westernmost part of the study area show decrease in resistivity at the uppermost part of the Gammon. This decrease in resistivity is followed by irregular patterns which slightly coarsen upwards for a few tens of feet. These patterns are interpreted to be the bottom parts of a progradational parasequence which lost its distinct coarsening upwards trend as the upper parts of the parasequence eroded.

3.1.2.2 Shannon Sandstone Member

The Shannon Sandstone lies above the Gammon Ferruginous Member with a sharp
Figure 3.3 Isopach map for the Gammon Ferruginous Member. The member reaches its highest thickness values on the westernmost part of the study area.

erosional basal contact which is interpreted to be the forced regressive surface of erosion and this interpretation is explained in the following sections in detail. The sediment supply during the deposition of the Shannon Sandstone was from the west and the member is restricted to the western half of the study area. Based on the well-log correlations an isopach map is created for the Shannon Sandstone Member within the limits of the well-log data (Figure 3.4). On some of the wells, the Shannon Sandstone pinches out completely having the 0ft value. In other cases, the thickness value is forced to zero between the wells that Shannon Sandstone exists and does not exist in order to prevent further extrapolation that will be made by IHS Petra software. In such cases, the zero isopach line is situated at an equal distance to both wells, which emphasizes the pinching out geometry that the member has. The isopach map shows that the thickness of the member changes from 0 ft to 200 ft within the study area. Although the thickness trends of the member are irregular within the study area, there’s an overall thickening
towards west-southwest. The thickest values are reached at the southwesternmost part of the study area where the synclinal axis of the basin is located. The characteristic well-log response for the Shannon sandstone throughout the study area is an increase in resistivity, characterized by hour glass to blocky shaped trends (Figure 3.1A).

Figure 3.4 The isopach map for the Shannon Sandstone Member. The member doesn't have a regular thickness trend and it pinches out towards east.

3.1.2.3 The Unnamed Member

The Unnamed Member of the lower Pierre Shale lies above the Shannon Sandstone on the eastern half of the study area, and directly above the Gammon Ferruginous Member at the central part of the study area where Shannon Sandstone pinches out. This member is characterized by an eastward progradation indicated by downlaps on electric log correlations. An isopach map was created for the Unnamed Member based on the well-log correlations (Figure 3.5). This isopach map shows that the member abruptly pinches out eastward along the central part of the study area indicating the sediment supply was insufficient. The minimum and maximum thickness values of the member based on this isopach map are 0 ft and 500 ft.
Although there are local minor irregularities in the thickness trends, the overall thickening of the member is towards west-southwest with the thickest values located at the east of the basin axis. The Unnamed Member is characterized by an irregular response on electric logs with a slightly coarsening upwards trend which emphasizes its progradational nature (Figures 3.1A and 3.1B). The lower contact of the Unnamed Member is characterized with a decrease in resistivity above the Shannon Sandstone.

![Isopach map for the Unnamed Member of the lower Pierre Shale. The member pinches out towards east.](image)

**3.1.2.4 Sussex Sandstone Member**

The Sussex Sandstone lies above the Unnamed Member of the lower Pierre Shale with a sharp contact. An isopach map is created for the Sussex Sandstone Member based on the well-log correlations (Figure 3.6). The maximum and minimum thickness values of the member based on this isopach map are 0 ft and 110 ft. Sussex thins constantly eastward with some thickness irregularities especially at the central and northern part of the area where the member is seen, and it abruptly pinches out. The zero line has roughly northeast to southwest
orientation. The member reaches the maximum thickness at the southwesternmost part of the study area where the basin axis is located. The Sussex Sandstone mostly shows hour glass to coarsening upward trend throughout the study area; on the other hand, fining upwards trend is seen on the logs which are close to the point where the member pinches out (Figures 3.1A and 3.1B).

Figure 3.6 Isopach map for the Sussex Sandstone. The member does not have a regular thickness trend and pinches out towards east.

3.1.2.5 Ardmore Pedro Bentonite Beds

The Ardmore Pedro Bentonite Beds Member lies above the Sussex Sandstone on the western half of the study area and directly on the Gammon Ferruginous Member on the eastern half. Both contacts are characterized by an abrupt decrease in the resistivity which is seen as a sharp peak on the resistivity logs. The member is characterized by an onlapping pattern towards west which indicates the transgressional nature of the member. An isopach map is created for the Ardmore Pedro Bentonite Beds based on the well-log correlations (Figure 3.7). The isopach map shows that the member is locally absent along a corridor which has a north-northeast to
south-southwest orientation in the central part of the study area. This absence is interpreted as erosion that has taken place where a topographic relief existed between western half and the eastern half of the study area prior to the deposition of the Ardmore Pedro Bentonite Beds (Asquith, 1970). This topographic relief is formed by the depositional dip increase seen in the Gammon Ferruginous Member interval and eastward pinching out geometries of the Shannon Sandstone, the Unnamed, and the Sussex Sandstone members (Asquith, 1970). There is a southeast-projecting lobe on the eastern half of the study area which is about 50 ft thicker from the surrounding deposits and it is interpreted by Asquith (1970) to be created by the redeposition of the eroded Ardmore beds in the basinward direction (Figure 3.7). The maximum and minimum thickness values of the member based on the isopach map are 0 ft and 170 ft. The overall thickness of the Ardmore is greater on the western side of the study area and it does not have a regular thickness trend. The characteristic well-log response for Ardmore is an irregular pattern which is interrupted by sharp decreases in the resistivity which are expressed by sharp peaks (Figures 3.1A and 3.1B).

3.1.2.6 Sharon Springs Member

The Sharon Springs Member of the lower Pierre Shale lies above the Ardmore Pedro Bentonite Beds and it covers the eroded corridor located at the center of the basin. The member is interpreted to be transgressional based on the onlapping patterns which are more distinct on the eastern half of the study area. Characteristic well-log response for the member within the study area is slightly to distinctly fining upwards trend with some irregular peaks (Figures 3.1A and 3.1B). The isopach map created for the member based on the well-log correlations show that the maximum and minimum thickness values are 50 ft and 380 ft (Figure 3.8). The Sharon Springs Member reaches the thickest values along a corridor at the central part of the study area where the sandstone members and the Unnamed Member pinches out and the Ardmore Pedro Bentonite Beds member is locally absent. The Ardmore Pedro Bentonite Beds are
Figure 3.7 Isopach map for the Ardmore Pedro Bentonite Beds. The member does not exist along a corridor in the central part of the study area. This absence is interpreted by Asquith (1970) to be the consequence of erosion.

defined as the basal unit of the Sharon Springs Member (Gill and Cobban, 1966; Asquith, 1970); therefore, the lower contact of the Sharon Springs with the Ardmore is gradational.

3.1.2.7 Mitten Black Shale Member

The Mitten Black Shale Member lies above the Sharon Springs Member. On the eastern half of the study area, the lowermost deposits of the member onlap towards west where there is a slight dip increase in the central part of the study area. The horizons above these onlaps show a progradational pattern towards the east. The maximum flooding surface is interpreted to be at the turning point of the onlapping pattern to the progradational pattern on the eastern half of the basin. On the western half of the basin, this surface coincides with the surface between the Sharon Springs Member and Mitten Black Shale Member which marks the top of the Sharon Springs Member. These interpretations will be explained in the following sections in detail. The characteristic well-log response for the member shows an overall coarsening upwards pattern to
Figure 3.8 Isopach map for the Sharon Springs Member. The member reaches its thickest values along a corridor in the central part of the study area where Ardmore does not exist. The half of the total thickness of the member from the lower contact. Above this coarsening upwards package there is a moderately sharp decrease in resistivity which is followed by an irregular to slightly coarsening upwards trend (Figures 3.1A and 3.1B). Based on the well-log correlations an isopach map for the member is created which shows the maximum and minimum thickness for the member as 210 ft and 1090 ft (Figure 3.9). The Mitten Black Shale Member has a constant thickening trend towards east with a slight thinning at the easternmost part of the study area. The thickening rate increases in the central part of the study area where there is topographic relief between the western and the eastern halves of the study area. The deposition of Mitten Black Shale Member significantly reduces this topographic relief. The member reaches its greatest thickness values at the southeastern part of the study area.

3.1.2.8 Red Bird Silty Member

The Red Bird Silty Member lies above the Mitten Black Shale and it is the uppermost member in the study interval. The member is characterized by an eastward progradation which
is not as distinct as the Mitten Black Shale Member. The isopach map for the member is created based on the well-log correlations within the study area. This isopach map shows that the maximum and minimum thickness values for this member are 135 ft and 565 ft (Figure 3.10). The member is constantly thickening towards the east with its thickest values are reached at the easternmost part of the study area. The rate of increase in thickness is the highest at the easternmost part of the study area. On the well-logs, an abrupt increase in resistivity above the contact with Mitten Black Shale is recognized. The characteristic well-log pattern for the member is a slight overall increase in resistivity indicating a coarsening upwards trend and this overall increasing pattern is interrupted by two relatively sharp peaks showing drops in resistivity (Figures 3.1A and 3.1B).

3.2 Cores

Cores recovered from the wells 13-11 Highland Flats Federal (Sec.11, T37N R73W), 20-11 Ione (Sec.20, T44N R75W), and 1 Pfister-D (Sec.23, T44N R76W) were analyzed, and core
descriptions were made in order to understand the depositional relationships among the members of lower Pierre Shale (see Appendix A). These core descriptions include the grain size and sedimentary structures, lithology, shale contents, and facies distribution of each core (Appendix A.2 through A.4). Appendix A.2A and Appendix A.2B illustrate the core description for the 13-11 Highland Flats Federal (Sec.11, T37N R73W) core; Appendix A.3A and Appendix A.3B illustrate the core descriptions for the 20-11 Ione (Sec.20, T44N R75W) core; and Appendix A.4 illustrates the core description for the 1 Pfister-D (Sec.23, T44N R76W) core. These cores are mostly cutting the Shannon and Sussex sandstone intervals. The main focus when the core descriptions were being made was examining and defining the boundaries that are significant for the low order sequence stratigraphic interpretation. Higher-order sequences within the Shannon sandstone interval were defined by Bergman and Walker (1995) in their detailed work on higher degree sequences in the Shannon Sandstone. However, higher degree sequence boundaries were not defined within this study since such high resolution sequence
stratigraphic interpretation within the Shannon and Sussex sandstone intervals is beyond the scope of this study. Facies analyses were made and some bioturbation patterns were defined within the cored intervals in order to make more accurate interpretations about the depositional environments which are significant steps in building the sequence stratigraphic framework of the whole lower Pierre Shale interval.

Core photos showing the sedimentary structures, bioturbation patterns, facies distribution on whole cored sections, facies, and significant surfaces are included in following sections. Figure 3.11 shows the symbol legend used on these core photos.

![Symbol Legend for Core Photos](image)

Figure 3.11 Symbol legend for the core photos.

### 3.2.1 Sedimentary Structures

Flaser bedding is defined as cross-bedded sandstones with several interbedds of mud flasers (Reineck and Wunderlich, 1968). When the crests of the ripples are overlain by the mud layers and the ripple troughs are filled with mud, the bedding is named as wavy bedding (Reineck and Wunderlich, 1968). According to Reineck and Wunderlich, (1968), the main contrast between wavy bedding and flaser bedding is, in wavy bedding there is no contact
among the rippled sandstones vertically. Lenticular bedding is seen when there is both vertical and horizontal discontinuity among the rippled sandstone lenses, in some cases the lenses seem to float in the mud (Reineck and Wunderlich, 1968).

These bedding types are formed by alternating current or wave action and slackwater (Reineck 1960a,b). The rippled sands are deposited by current and the mud is deposited during slackwater periods (Reineck and Wunderlich, 1968). These bedding types are seen in environments where there is a change between slackwater and water turbulence (Reineck and Wunderlich, 1968). Mainly, these environments are subtidal zones (Reineck, 1963; Reineck et al., 1968) and intertidal zones (Hantzschel, 1936). The ripples which are formed by tides are mostly current ripples (Reineck and Wunderlich, 1968).

Heterolithic bedding is observed on each three of the three cores that were analyzed for this project. Abundant flaser, wavy, and lenticular bedding distribution is recognized within the sandstone facies of the cores (Figure 3.12). The type of heterolithic bedding is one of the criteria used for the differentiation of the facies where it is seen in the sandstone intervals of the cores. This criterion has been extremely significant when the interpretations for the depositional environments for each facies were being made.

In addition to the heterolithic bedding, abundant cross stratification of the sandstones was recognized especially in the Shannon Sandstone interval. Sussex Sandstone is mostly bioturbated and as a consequence of this bioturbation, most of the cored interval has lost its stratification patterns; however, at some places cross stratification was still recognized.

### 3.2.2 Bioturbation

Making a detailed biostratigraphic interpretation within the sandstone facies is beyond the scope of this study. However, the bioturbation in these sandstone facies is a key feature to understand the depositional environment, facies relationships, and eventually to build the
Figure 3.12 Heterolithic bedding features seen in the Shannon and Sussex sandstone intervals of the cores. A) Lenticular bedding seen in Facies 8. B) Wavy bedding seen in Facies 2. C) Flaser bedding seen in Facies 5 (scale is 1 inch).

sequence stratigraphic framework. According to the general appearance of the bioturbated intervals, a low diversity in the bioturbation was recognized within the sandstone intervals. In order to better understand the relationships among the facies and support the earlier interpretations made based on well log correlations, Skolithos trace fossil is identified on each of the three cores that were examined. This bioturbation type was chosen, since it is easy to recognize and abundantly distributed throughout the sandstone intervals of the cores.

Pemberton et al. (1992) described the Skolithos ichnofacies as predominantly vertical, cylindrical, or u-shaped burrows constructed mostly by suspension feeders or passive
carnivores which typically construct deeply penetrating traces. Being characteristically
developed in slightly muddy to clean, well sorted substrates, these trace fossils are indicators of
high levels of wave or current energy (Pemberton et al., 1992). The necessary conditions for
these trace fossils commonly occur on foreshore and shoreface of beaches, and sometimes on
tidal deltas and submarine fans (Pemberton et al., 1992).

Skolithos traces are recognized in 13-11 Highland Flats Federal (Sec.11, T37N R73W)
and 20-11 Ione (Sec.20, T44N R75W) cores that were studied (Figure 3.13). Skolithos traces
seen in the cores are 1/8 inch in diameter and they are up to 3 1/2 inches in length. The traces
are vertical and some of them are slightly curved to the bottom. In addition to the recognized
sedimentary structures, the existence of Skolithos trace fossil as an indicator of shallow marine
deposition has created a basis for making interpretations for the depositional environment of
Shannon and Sussex sandstone members.

In addition to these fossils Bergman (1994) recognized Teichichnus and Chondrites in
the Shannon Sandstone interval. The existence of such limited diversity of bioturbation is
interpreted to be an indicator of considerably stressed ichnofacies assemblage. Steel et al.
(2012) defined the existence of such stressed ichnofacies assemblage as one of the indicators
of prodelta and lower delta front deposits in the western shores of Western Interior Seaway.

3.2.3 Facies and Facies Associations

The facies descriptions within the cored intervals are adopted from Bergman’s (1994)
study and applied to both sandstone bodies and the adjacent mudstone units. Bergman (1994)
defined eight different facies within the Shannon Sandstone. Some additions and modifications
were made to Bergman’s (1994) facies descriptions and two new facies which are recognized
within the 13-11 Highland Flats Federal core that cuts the Sussex Sandstone interval were
defined (Table 3.1). Facies 7, which was defined by Bergman (1994), is not recognized in the
Figure 3.13 Bioturbation features are shown on the cores. A) Skolithos in 20-11 Ione, B) Skolithos in 20-11 Ione, C) Skolithos in 13-11 Highland Flats Federal cores (scale is 1 inch).

studied cores. However, Bergman’s (1994) definition for the Facies 7 is summarized both in the facies descriptions section and the Tables 3.1.

Table 3.1 shows the summarized explanations for facies and interpretations for their depositional environments. The main criteria when differentiating the facies shown on the table are: (1) the lithology, (2) sedimentary structures, and (3) descriptive trends. Interpretations about the depositional environments and facies relationships were made based on these criteria and other observations that were made on the cores such as the maturity of the framework grains, mud and silt content, and bioturbation intensity.

Within this study three facies associations were defined and these facies associations include all adopted and newly defined facies. These facies associations are: (1) marine mudstone facies association which includes Facies 1; (2) tide dominated deltaic sandstone deposited in subaqueous environment facies association which includes Facies 2, Facies 3,
Table 3.1 Table showing the facies descriptions, sedimentary structures and trends within the facies, and interpretations about the depositional environments for each facies.

<table>
<thead>
<tr>
<th>FACIES NAME</th>
<th>DESCRIPTION</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>TRENDS</th>
<th>INTERPRETATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACIES 1 BLACK MUDSTONE</td>
<td>-Black massive mudstone with minor silt component. -Silt is seen as very thin beds (0.04 to 0.12 inches). -At some places very thin ripple laminated very fine sandy intervals up to 1/8 inch thick.</td>
<td>-Mudstone is bioturbated. -No burrow forms are recognizable. -Very thin, ripple laminated, horizontally discontinuous, very fine-grained sand layers.</td>
<td>-Sideritized mudstone clasts up to 2-3 inches at their longer axes in diameter.</td>
<td>-Low energy deposition. -Basin floor deposits.</td>
</tr>
<tr>
<td>FACIES 2 THIN BEDDED BIOTURBATED SANDSTONE</td>
<td>- Very thin to thin (average 0.8-1.2-inch, max 2-inch thick) layered, sharp based fine-grained sandstone interbedded with light gray, bioturbated mudstone. -Quartz grains are subangular and subrounded.</td>
<td>-Sandstone is ripple cross stratified. -Mud drapes are abundant and distinct. -Wavy Bedding. -Bioturbation is distinct.</td>
<td>-Glaucnite is disseminated throughout. -Skolithos recognized.</td>
<td>-Existence of abundant mud drapes and the subangular to subrounded quartz grains are indicating that the deposition took place as tide dominated marine deltas in subaqueous environment.</td>
</tr>
<tr>
<td>FACIES 3 BIOTURBATED SANDSTONE</td>
<td>- Very thin to thin, sharp based, ripple laminated very fine-grained sandstone interbedded with dark gray, thoroughly bioturbated mudstone. The mud content is higher compared to Facies 2. -Quartz grains are subangular to subrounded.</td>
<td>-Sandstone is ripple cross stratified -Bioturbation exists in both muddy and sandy intervals. -Wavy bedding</td>
<td>-Glaucnite is disseminated throughout.</td>
<td>-Very similar to Facies 2, the most significant difference is that the degree of bioturbation is notably higher and the mud content is higher.</td>
</tr>
</tbody>
</table>
Table 3.1 Table showing the facies descriptions, sedimentary structures and trends within the facies, and interpretations about the depositional environments for each facies (cont.).

<table>
<thead>
<tr>
<th>FACIES NAME</th>
<th>DESCRIPTION</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>TRENDS</th>
<th>INTERPRETATION</th>
</tr>
</thead>
</table>
| **FACIES 4 GLAUCONITIC MEDIUM TO COARSE SANDSTONE** | -Glaucitic fine-grained sandstone.  
-Abundant rip up clasts of mudstone and sideritized mud clasts  
-Quartz grains are subangular.  
-Some mud drapes can be seen. | -Cross stratification.  
-Some mud drapes. | -Rip up clasts are preserved in cross bed foresets.  
-Sideritized mud clasts seen up to 3 ½ inches. | -Subaqueous deposition of the tide dominated, deltaic sourced sands. |
| **FACIES 5 THIN BEDDED SANDSTONE** | -Thin bedded to medium bedded, fine- to medium-grained sandstone.  
-Beds separated by shale laminae (< 0.2 inches) | -Ripple cross laminated.  
-Cross bedded  
-Mud drapes between the clean sandy intervals.  
-Flaser Bedding. | -Glaucomite is disseminated throughout isolated mudstone rip up clasts and siderite pebbles (0.4 inches)  
-Fining upwards trend.  
-Skololiths recognized. | -Tide dominated deltaic deposition in subaqueous environment.  
The most distinct feature in this facies is the mud drapes which can be seen throughout the facies. |
| **FACIES 6 CROSS BEDDED SANDSTONE** | -Gray, medium-grained sandstone.  
Quartz grains are sub angular to sub rounded. | -Cross bedding.  
-Some bioturbation.  
-Some mud drapes. | -Coarsening upward  
-Few mudstone partings  
-Sideritized mud clasts (up to 2 inches) and mudstone rip up clasts | -Based on the existence of glauconite, mud drapes, and the immature subangular quartz grains this facies is a part of the tidal influenced deposition in subaqueous environment system. |
Table 3.1 Table showing the facies descriptions, sedimentary structures and trends within the facies, and interpretations about the depositional environments for each facies (cont.).

<table>
<thead>
<tr>
<th>FACIES NAME</th>
<th>DESCRIPTION</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>TRENDS</th>
<th>INTERPRETATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACIES 7</td>
<td><strong>COARSE BIOTURBATED SANDY MUDSTONE</strong></td>
<td>- Bioturbated with no recognizable burrows.</td>
<td>- Glaucopite is disseminated throughout.</td>
<td>- This facies does not exist in the cores that are studied.</td>
</tr>
<tr>
<td>8</td>
<td>Mudstone interbedded with thin (0.4 to 1.2 inches) laminated very fine grained sandstone.</td>
<td>- Lenticular bedding. - Bioturbation is rare. - Burrows are vertical. - No recognizable bioturbation in mudstone intervals. - Sandstone intervals are ripple laminated.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FACIES 9</td>
<td><strong>BIOTURBATED MUDDY SANDSTONE</strong></td>
<td>- Dark gray very fine sandstone with major silt and shale component. - Sand proportion is low. - Quartz grains are subangular to subrounded.</td>
<td>- Thoroughly bioturbated. - Thin interlayers of silty sand.</td>
<td>- Deposited in a wave dominated environment rather than tide dominated based on higher silt content, more stressed ichnofacies, and the absence of the mud drapes compared to the other sandstone facies.</td>
</tr>
<tr>
<td>10</td>
<td>Gray, very fine to fine sandstone with major silt component. - Quartz grains are mostly subrounded.</td>
<td>- Thoroughly bioturbated. - Mud is reworked with sand. - Some elongate mud rip up clasts few of them are sideritized.</td>
<td></td>
<td>- Wave dominated environment with even higher energy deposition than Facies 9 based on the lower amount of mud and higher amount of silt.</td>
</tr>
</tbody>
</table>
Facies 4, Facies 5, Facies 6, and Facies 8; and (3) wave-dominated deltaic sandstone deposited in subaqueous environment facies association which includes Facies 9 and Facies 10. Facies 7 was excluded from these facies associations since it was not seen on any of the three cores that were examined for this study.

All of the cores that were described have a similar pattern. They start with the finer-grained facies, continue with the coarser-grained facies, and eventually end with finer-grained facies. The coarsest grained sandstone facies with the least mud content on each core is either in the middle or close to the middle of the cored interval. Figures 3.14 through 3.16 show the whole core photos and the facies distributions on them.

3.2.3.1 Facies 1: Black Mudstone

Facies 1 is composed of black colored massive mudstone which has minor silt component in it (Bergman, 1994) (Figure 3.17). Silt is mostly seen as very thin, horizontal beds which are one to few millimeters scale within the massive mudstone. The mudstone is bioturbated; however, recognizable burrow forms do not exist (Bergman, 1994). Bioturbation reworking is recognized in some of the silt beds. At some places very thin ripple laminated, very fine sand layers which have thicknesses up to 1/8 inch are recognized especially in the upper part of 20-11 Ione (Sec.20, T44N R75W) core. The distinctive characteristic of these sandy layers is, they are not horizontally continuous and they are completely isolated. Few sideritized mud clasts which are as big as 2-3 inches at their longer axes were recognized within this facies. According to these criteria and composition, the unit is interpreted to be deposited in or close to the basin floor, in a low energy environment. Facies 1 exists in all 13-11 Highland Flats Federal (Sec.11, T37N R73W), 20-11 Ione (Sec.20, T44N R75W), and 1 Pfister-D (Sec.23, T44N R76W) cores (Figures 3.14 through 3.16).
Figure 3.14 Core box photo of the 13-11 Highland Flats Federal well showing the facies distribution. Stratigraphic top is to the upper left. F, facies number; arrowheads, facies boundaries; scale is 3 ½ inches.
Figure 3.15A Core box photo of upper half of the 20-11 lone well showing the facies distribution. Stratigraphic top is to the upper left. F, facies number; arrowheads, facies boundaries; scale is 3 ½ inches.
Figure 3.15B Core box photo of lower half of the 20-11 lone well showing the facies distribution. Stratigraphic top is to the upper left. F, facies number; arrowheads, facies boundaries; scale is 3 ½ inches (cont.).
3.2.3.2 Facies 2: Thin Bedded, Bioturbated Sandstone

This facies is composed of very thin to thin fine-grained sandstone layers with sharp bases which have average thickness of 0.8 to 1.2 inches and a maximum thickness of 2 inches.
These sandstones are interbedded with light gray colored, bioturbated mudstone (Bergman, 1994). The glauconite is disseminated throughout the facies (Bergman, 1994) (Figure 3.17). The sandstone layers are ripple cross laminated and mostly reworked by bioturbation. Recognizable burrow forms include Skolithos (Bergman 1994). The subangular to subrounded quartz grains indicate the immaturity of the sandstone. The distribution and shapes of the abundant mud drapes within this facies are interpreted as wavy bedding. The existence of disseminated glauconite within the facies (Bergman, 1994) indicates that the deposition has taken place in shallow marine to tidal environment. The sandstone is not clean; therefore, the deposition is not likely to be taken place in a storm influenced environment. Based on all these observations the deposition for this facies is interpreted to be as tide dominated marine deltas in subaqueous environment. Facies 2 is seen on 20-11 Ione (Sec.20, T44N R75W) core (Figures 3.15A and 3.15B).

3.2.3.3 Facies 3: Bioturbated Sandstone

Facies 3 is highly similar to Facies 2 (Bergman, 1994). This facies is composed of very thin to thin, sharp based, ripple laminated, very fine-grained sandstone interbedded with dark gray, thoroughly bioturbated mudstone (Figure 3.17). This facies has fewer sandstone beds compared to Facies 2, and the glauconite is disseminated throughout the facies (Bergman, 1994). Some of the ripple laminated sandstone layers were reworked by bioturbation. However, there are no recognizable burrow forms (Bergman, 1994). There are horizontally oriented sideritized mud clasts which are bigger than 3 ½ inches in their long axes. Similarity of this facies with Facies 2 and the existence of wavy bedding, glauconite, and the subangular to subrounded shaped immature quartz grains yield the interpretation that the Facies 3 sands were deposited as tide dominated marine deltas in subaqueous environment. The abundant mud layers were deposited during slackwater periods, and they create the distinct wavy bedding
3.2.3.4 Facies 4: Glaucnotic Medium to Coarse Sandstone

This facies consists of light gray, glauconitic fine-grained sandstone which has abundant mudstone rip up clasts and sideritized mud clasts (Bergman, 1994) (Figure 3.17). Another characteristic feature of this facies is that the sands are showing cross stratification (Bergman, 1994). Sideritized mud clasts can be up to 3 ½ inches in size. There are some mud drapes within the facies which indicates that the deposition is still under tidal influence. The sand input was interpreted to be deltaic based on the immature, subangular quartz grains. The existence of abundant glauconite is an indicator of the shallow marine deposition. Facies 4 is seen on 1 Pfister-D (Sec.23, T44N R76W) core (Figure 3.16).

3.2.3.5 Facies 5: Thin Bedded Sandstone

This facies is composed of light gray, thin bedded to medium bedded, fine- to medium-grained, cross-bedded sandstone (Bergman, 1994) (Figure 3.17). The beds are separated by shale laminae which are thinner than 0.2 inches (Bergman, 1994). There are several mud drapes within the facies which form distinct flaser heterolithic bedding pattern. Bioturbation is seen throughout the facies, and Skolithos and Macaronichnus traces are dominant (Bergman, 1994). There are sideritized mud clasts, and abundant glauconite is seen as disseminated throughout the facies. The subangularity of the quartz grains are indicators of the immaturity of the sands which lead to the interpretation that the sediment input was deltaic similar to the adjacent facies and the existence of the flaser bedding indicates that the system is a part of the tidally influenced deltaic deposition in subaqueous environment system. This facies is seen in all 13-11 Highland Flats Federal (Sec.11, T37N R73W), 20-11 Ione (Sec.20, T44N R75W), and 1 Pfister-D (Sec.23, T44N R76W) cores (Figures 3.14 through 3.16).
3.2.3.6 **Facies 6: Cross Bedded Sandstone**

This facies is composed of gray colored, medium-grained sandstone (Figure 3.17). This facies shows distinct cross bedding. Compared to the other facies relatively fewer mudstone partings exist (Bergman, 1994). Some mud rip up clasts are recognized within the facies (Bergman, 1994). The glauconite content is the highest in this facies. There are sideritized mud clasts which are as big as 2 inches. There are few very thin mud drapes recognized within the facies. One of the distinct features of this facies is coarsening upwards trend. This facies has the coarsest grains within the analyzed cores and the quartz grains are subangular to subrounded which is an indicator of their immaturity. Bioturbation is not a distinct feature in this facies. Based on the existence of glauconite, mud drapes, and the immature subangular quartz grains this facies is interpreted to be a part of the tidal influenced deposition in subaqueous environment system. Facies 6 is seen on 1 Pfister-D (Sec.23, T44N R76W) core (Figure 3.16).

3.2.3.7 **Facies 7: Coarse Bioturbated Sandy Mudstone**

Facies 7 is characterized as medium- to coarse-grained sand grains in a mud matrix which does not have preserved bedding (Bergman, 1994). There’s bioturbation but there are no recognizable traces (Bergman, 1994). The facies has glauconite which is disseminated throughout the section (Bergman, 1994). This facies has not been recognized in the cores that were analyzed for this study. Therefore, the description was taken from Bergman’s (1994) study.

3.2.3.8 **Facies 8: Laminated Mudstone**

This facies consists of mudstone which is interbedded with thin laminated sandstone (Bergman, 1994) (Figure 3.17). The sandstone is ripple laminated and the sandstone beds are 0.4 to 1.2 inches in thickness (Bergman, 1994). Bioturbation is relatively rare in this facies and the type of bioturbation is not recognizable in the mudstone interval (Bergman, 1994). The burrowing is commonly vertical where the bioturbation exists (Bergman, 1994). The amount and
distribution of sandstone lenses in muddy intervals show the characteristic features of lenticular bedding. Therefore, the deposition is interpreted to be tide-dominated deltaic deposition in subaqueous environment. This facies is seen in 1 Pfister-D (Sec.23, T44N R76W) core (Figure 3.16).

3.2.3.9 Facies 9: Bioturbated Muddy Sandstone

This facies consists of dark gray-colored very fine-grained sandstone that has major silt and shale content in it (Figure 3.17). The sand proportion is low compared to the other sandstone facies. The interval is thoroughly bioturbated; however, there are no recognizable burrow forms. Another distinct feature is that there are very thin layers of silty sandstone which contain significantly lesser mud amount compared to the rest of the facies. The lower contact for this facies is recognized with Facies 10 as it is marked with an interval consisting of very coarse sand grains which is interpreted as transgressive lag (Figure 3.18B). This feature will be discussed in the following sections in detail. The bioturbation patterns within this facies have more limited diversity compared to the other facies which is interpreted to show stressed ichnofacies assemblage according to the higher energy environment. This facies is interpreted to be deposited in a wave-dominated environment rather than tide dominated based on the higher silt content, more stressed ichnofacies assemblage, and the absence of the mud drapes compared to the other sandstone facies. This facies is recognized only in 13-11 Highland Flats Federal (Sec.11, T37N R73W) core which cut the Sussex Sandstone (Figure 3.14).

3.2.3.10 Facies 10: Bioturbated Silty Sandstone

This facies consists of gray-colored, very fine- to fine-grained sandstone which has major silt component in it (Figure 3.17). The facies is thoroughly bioturbated and mud and silt is reworked with sand. The limited diversity in bioturbation patterns is similar to the Facies 9. Some elongate mud rip up clasts exist within the facies and some of these are sideritized. The quartz grains are mostly subrounded. Lower amount of mud content and higher amount of silt
content compared to Facies 9 are observed and are interpreted to show the energy of the depositional environment is higher than Facies 9. This facies is interpreted to be deposited in a wave-dominated environment rather than tide dominated environment based on higher silt content, more stressed ichnofacies, and the absence of the mud drapes compared to the other sandstone facies. Facies 10 is seen only in 13-11 Highland Flats Federal (Sec.11, T37N R73W) core which cut the Sussex Sandstone (Figure 3.14).

3.2.4 Interpretations

Interpretations about the depositional environments and the nature of the contacts were made based on the sedimentary structures, bioturbation patterns, and facies relationships within the studied core intervals. Recognizing these features and making the following interpretations based on them is a significant step on making accurate interpretations when building the sequence stratigraphic framework.

All of the sandstone facies mostly consist of subangular to subrounded framework grains which is interpreted to indicate the relative immaturity of the sand grains. Based on this observation the sand input is interpreted to be deltaic. Existence of significant amount of heterolithic bedding especially within the Shannon Sandstone interval indicates that these sandstone facies were deposited in a tide-dominated environment. However, the Sussex Sandstone does not have mud drapes except for the very thin Facies 5 interval seen on the core. There’s significant amount of silt in the sandstone facies within the Sussex Sandstone. Therefore, this member is more likely to be deposited in a higher energy environment compared to the Shannon Sandstone. The Shannon Sandstone was interpreted to be deposited as tide-dominated subaqueous marine deltas. Based on these observations, the deltaic sourced sands of the Sussex Sandstone were interpreted to be deposited in wave-dominated environment. It was argued by some authors that these sandstones were deposited in a storm wave-dominated depositional environment (Spearing, 1976; Tillman and Martinsen, 1984; Swift and Parsons,
Figure 3.17 Detail core photos of the facies and facies boundaries. F, facies number; FB, facies boundary (scale is 1 inch).
However, the lack of cleanliness within the sandstone facies, which is indicated by high glauconite content and several muddy intervals, create discrepancies for this interpretation.

Distinct trace fossils are defined within the study in order to support the previous interpretations about the depositional environment. These trace fossils are recognized as Skolithos trace fossils and they are seen both in Shannon and Sussex sandstone intervals. It has been harder to recognize these trace fossils within the Sussex Sandstone interval, since the interval has gone through intense bioturbation and almost all of the facies contain significant amount of silt. The interpretations made based on the sedimentary structures are supported by the existence of low diversity of the bioturbation patterns. This low diversity in bioturbation patterns is the indicator of the existence of stressed ichnofacies assemblages. The depositional environments of the two sandstone members change from lower energy tidal influenced to higher energy wave influenced environment. Although there is no significant change in grain roundness, the increasing amount of silt content and reducing amount of mud content along with the absence of distinct heterolithic bedding features indicate that the deposition of Sussex Sandstone shows the features of wave-dominated environment rather than of tide dominated environment.

Bergman (1994) stated that no positive evidence exist to suggest that the Shannon Sandstone Member is deposited as a shelf ridge complex which is some 100 miles farther basinward from the contemporaneous shoreline which was shown by Gill and Cobban (1973). Furthermore, the questions about (1) sediment transport, (2) ridge formation, and (3) ridge stacking patterns remain unanswered (Bergman, 1994). Another discrepancy for the shelf ridge sands explanation for these two members is that Plint (2010) listed some modern examples for the shelf ridge sands and stated that in all cases these shelf ridge sands lie immediately above a marine transgressive surface. However, the marine transgressive surface in the study area lies above the Sussex Sandstone and it is indicated by onlapping horizons and transgressive
lag seen on 13-11 Highland Flats Federal (Sec.11, T37N R73W) core (Figure 3.18B).
Furthermore, the existence of the tidal and wave influence; the bioturbation patterns; and relatively immature grains are indicators of a close shoreline during the deposition of Shannon and Sussex sandstone members.

It is generally agreed that based on the localized funneling of tidal currents, shoaling patterns and the effects of Coriolis force; the tidal influence can become significant even in large epicontinental seas (Dalrymple, 2010). The interpretations based on the existence of the storm wave conditions within the southwestern Western Interior Seaway stratigraphic record are applied mostly to the western highstand shorelines instead of the lowstand shorelines (Steel et al., 2012). Steel et al. (2012) suggested a rapidly changing paleotopography and bathymetry as a result of regressions and transgressions with shoreline migrations of hundreds of kilometers. As a result of these changes regressive deltas and strandplains, estuaries, and barrier lagoon systems were formed (Steel et al., 2012). As a result of these regressions, “distally situated, tide-dominated, subaqueous marine deltas, or deltas variably reworked by tidal currents in the seaway” were formed (Steel et al., 2012). One of the characteristic features for tide dominated delta deposits is the stressed ichnofacies assemblages seen within the prodelta and lower delta front deposits in the Western Interior Seaway (Steel et al., 2012).

The interpretations that were made within this study are aiming to have better understanding on the depositional relationships among the members and nature of the bounding surfaces between each member within the lower Pierre Shale. The existence of these sand bodies with abundant heterolithic bedding and relatively immature grains are interpreted to be indicators of a close shoreline on the western side of the study area. This interpretation is supported by the shoreline positions which were presented in Gill and Cobban’s (1973) study. However, since both making detailed interpretations on the depositional environments of these sandstones and building the higher degree sequence stratigraphic framework within these
sandstones are beyond the scope of this study; the interpretations made are grounded on the limited core and well log data and thorough literature review.

One of the main objectives of the core descriptions was identifying the significant surfaces for building the sequence stratigraphy framework. Based on the interpretations on the depositional environments, the sandstone members within the cored intervals represent the most basinward shift of the facies. The contact between the Gammon Ferruginous Member and the Shannon sandstone is recognized on the 1 Pfister-D (Sec.23, T44N R76W) core as a distinct erosional surface which is represented as a sudden change from the mudstone facies to the tide dominated subaqueous sandstone facies (Figure 3.18A). Sideritized mud clasts exist immediately above the contact. This surface is interpreted to be the forced regressive surface of erosion based on these interpretations, the basinward shift of facies, and the erosion patterns recognized on the electric log patterns. Another significant surface within the cored interval is recognized between the wave-dominated Sussex Sandstone and the transgressive Ardmore Pedro Bentonite Beds (Figure 3.18B). There is a muddy interval which is about 1 inch thick followed by a very coarse grained transgressive lag immediately above this contact. This contact was interpreted as the transgressive surface based on these observations and the onlapping patterns on the well logs. The transgressive surface picked on the well-logs is located about 10 feet above this transgressive lag since the transgressive lag is interpreted to be located at one of the several transgressive surfaces formed during the relative sea level rise. These interpretations will further be discussed in the Sequence Stratigraphy Framework section.

3.3 Sequence Stratigraphy Framework

The thick Upper Cretaceous section of the Southern Powder River Basin is dominated by marine silty and non-silty shales. There are two sandstone members deposited in tide-dominated subaqueous to wave-dominated environment getting involved in the sequence in the western half of the study area. During Early Campanian, the deposition of the lower Pierre
Figure 3.18 Detail core photo showing the forced regressive surface of erosion (FRSE) marked with sharp facies change and the transgressive surface (TS) marked with transgressive lag. SM, sideritized mud clast; scale is 1 inch.
Shale initiated with the silty shale of the Gammon Ferruginous Member. High sediment influx of the Gammon Ferruginous Member along with the widespread regression stopped the Niobrara carbonate factory.

Starting from the four type logs introduced in the previous chapters (Figures 3.1A and 3.1B), all members of the lower Pierre Shale were correlated in 1490 raster well logs. Based on these correlations that were made using IHS Petra software and the core descriptions, a sequence stratigraphic framework is created within the study interval. Thirty-four of these 1490 wells were chosen to create a northwest to southeast oriented master cross section in order to illustrate all the significant surfaces; onlapping, downlapping, truncation patterns; systems tracts definitions; and the sequence stratigraphy interpretation (see Appendix D). A schematic cross section based on this 34 well master cross section is created in order to be able to show all of the depositional relationships and sequence stratigraphy interpretations without the inconvenience and complexity of including that many raster well logs in the same figure. The original 34 well cross section is provided within the Appendix (see Appendix D). Figure 3.19 illustrates both this master and the schematic cross sections together. This schematic cross section is vertically exaggerated to clearly show the interpretations made on the relatively thinner members compared to the whole section (Figure 3.20). This same vertically exaggerated schematic cross section is included on the top left side of the Figures 3.21 through 3.25, which show the significant well-log patterns, in order to illustrate the locations of these logs on the master cross section.

Based on the well-log correlations made within the study, three-dimensional surface maps were created in addition to the isopach maps that were explained in the previous sections in detail Figures 3.26 through 3.33). These three-dimensional surface maps are flattened on the Red Bird Silty Member which is set as the datum. The detailed explanation of the systems tracts were made with the aid of these three-dimensional surface maps as they show the depositional
Figure 3.19 The schematic cross section is shown together with the master cross section which is provided in full scale in the appendices (see Appendix D). Minor differences between two figures exist since the well spacing on the master cross section was intentionally set constant. The upper figure does not have a horizontal scale since the well spacing was intentionally constant.
Figure 3.20 Vertically exaggerated schematic cross section showing the depositional relationships among each member, the depositional trends, and the sequence stratigraphic interpretation. System tracts and important surfaces are shown.
sequence of each member in a consecutive way. The age charts which were formed based on Gill and Cobban’s (1973) study and the sea level curves were provided in the same figures with the three-dimensional surface maps (Figures 3.26 through 3.33). The question marks that were put near some age intervals show that these age intervals are approximate.

Surfaces were picked on the master cross section within each member interval to illustrate the stacking patterns within each systems tract. These surfaces were picked based on the distinguishable features on the electric logs through all wells on the master cross section. The following observations showing the depositional characteristics of each member were made with the aid of these surfaces.

The lower Pierre Shale interval consists of mostly progradational shale sequences and two productive sandstone members encased in these thick shale packages. The first step for interpreting the progradational nature of the thick shale members of the lower Pierre Shale was the recognition of the overall coarsening up patterns of these thick shale intervals on each of the 1490 raster well logs. As these coarsening up packages were correlated throughout the study area (see Appendix D), it was recognized that these thick shale packages show distinct downlapping patterns towards east (see Appendix D) which emphasize their progradational nature.

The uppermost horizons of the progradational Gammon Ferruginous Member, which is the lowermost member of the lower Pierre Shale, show truncation patterns towards its upper boundary located between the Gammon Ferruginous Member and the Shannon Sandstone (Figures 3.22, 3.23, 3.25). These truncation patterns are either seen as truncating horizons towards east (Figures 3.22 and 3.25) and truncating horizons on both east and west sides (Figure 3.23). The truncations are interpreted to be the indicators of the erosion which has taken place on the upper parts of the member.
Above the Gammon Ferruginous Member, the Shannon Sandstone pinches out
eastward with downlapping pattern (Figure 3.23). Higher degree sequences were defined by
Bergman and Walker (1995) within this member. These higher degree sequences are beyond
the scope of this study; therefore, no further interpretations within the Shannon Sandstone
interval were made.

The Shannon Sandstone is overlain by the Unnamed Member of the Lower Pierre Shale
which shows distinct progradational patterns indicated by series of downlapping horizons
eastward (Figures 3.21 through 3.25). The member also pinches out with downlaps (Figure
3.25)

Following the deposition of the Unnamed Member, the Sussex Sandstone Member was
deposited and it shows a pinching out geometry eastward with downlapping pattern above the
Unnamed Member (Figure 3.23). Similar to Shannon Sandstone, possible higher degree
sequences were recognized within the Sussex Sandstone; however, these are beyond the
scope of this study. Therefore, no further sequence stratigraphic interpretations were made
within this sandstone interval.

The Ardmore Pedro Bentonite Beds Member is characterized by onlapping patterns
westward (Figures 3.21 and 3.25). Along a corridor in the central part of the study area the
member does not exist. This absence of the Ardmore Pedro Bentonite Beds is interpreted to be
as the consequence of a local erosion which has taken place along the corridor where there is a
regional topographic relief, which was defined by Asquith (1970), between the western half and
the eastern half of the study area. This regional topographic relief is formed by the slight
increase of the depositional dips of the top of the Gammon Ferruginous Member and the
existence of the Shannon Sandstone, the Unnamed Member, and the Sussex Sandstone on the
western half of the study area (Asquith, 1970). Further evidence for this erosion is the existence
of a southeastward projecting lobe deposited further on the east which is interpreted to be formed by the deposition of the eroded sediments of the Ardmore Pedro Bentonite Beds (Asquith, 1970). On well logs, this erosion is indicated by eastward truncation of the horizons within the Ardmore Pedro Bentonite Beds interval (Figure 3.23), and absence of the member on the well logs in the central part of the study area (Figure 3.24). On the eastern half of the study area, the member is seen again with onlapping patterns which indicate the transgressive nature of the member (Figure 3.25).

The Sharon Springs Member overlies the Ardmore Pedro Bentonite Beds and it shows onlapping patterns towards west (Figure 3.24). It reaches its greatest thickness values along the corridor where the Ardmore Pedro Bentonite Beds Member does not exist, and it directly overlies the Unnamed Member of the lower Pierre Shale along this corridor with onlapping patterns (Figure 3.24).

The Mitten Black Shale Member overlies the Sharon Springs Member. The lowermost horizons of the Mitten Black Shale on the eastern half of the study area show onlapping patterns (Figure 3.24), and above these horizons the member shows progradational features indicated with downlapping patterns eastward (see Appendix D).

The Red Bird Silty Member was deposited as the last member of the lower Pierre Shale interval and it directly overlies the Mitten Black Shale Member showing progradational patterns. It is interpreted that the progradation gradually slows down since there is not any downlapping horizons towards the upper boundary of the Mitten Black Shale Member (see Appendix D).

Based on all of these observations within each member following interpretations were made, the systems tracts were defined, and the sequence stratigraphic surfaces were picked within the lower Pierre Shale interval.
Figure 3.21 Figure showing the significant well log patterns. Downlaps within the lowstand prograding wedge and onlaps within the transgressive systems tract are shown.

Figure 3.22 Figure showing the significant well log patterns. Truncations within the highstand systems tract and downlaps within the lowstand prograding wedge are shown.
Figure 3.23 Figure showing the significant well log patterns. Truncations within the highstand systems tract and downlaps within the lowstand prograding wedge are shown. Shannon and Sussex sandstone members of the lowstand prograding wedge pinch out and the Ardmore is showing truncational patterns indicating erosion.

Figure 3.24 Figure showing the significant well log patterns. Downlaps within the lowstand prograding wedge and onlaps within the transgressive systems tract are shown. The onlapping patterns within the lower Mitten Black Shale define the maximum flooding surface.
Figure 3.25 Figure showing the significant well log patterns. Truncations within the highstand systems tract and onlaps within the transgressive systems tract are shown. The lowstand prograding wedge pinches out with downlaps.

3.3.1 Highstand and Forced Regressive Systems Tract

The highstand systems tract consists of the Gammon Ferruginous Member, which is the lowermost member of the lower Pierre Shale. The recognition of the Gammon Ferruginous Member as the highstand systems tract is based on (1) the overall progradational pattern of the member, which is interpreted by using the correlations of the coarsening upwards packages on the raster logs within the study area; (2) the existence of the major, widespread erosion surface bounds the member at the top; and (3) the major shift of facies that has taken place after the deposition of the Gammon. Asquith (1970) and Gill and Cobban (1963) argued that the Gammon Ferruginous Member has an interfingering relationship with the Niobrara Formation at its bottom contact; however, no evidence for an interfingering relationship was recognized on the well log correlations. Instead, the contact between two members is recognized as a sharp contact on the well logs which indicates a sudden change from carbonates to clastics with high sediment influx during the deposition of the lowermost part of the Gammon Ferruginous
Member. The Gammon Ferruginous Member shows distinct progradational patterns indicated by coarsening upwards patterns on the well logs within the study area (see Appendix D). Based on the well log correlations a three-dimensional surface map which is flattened to the datum Red Bird Silty Member is created for the Gammon Ferruginous Member (Figure 3.26). The upper boundary of the Gammon Ferruginous Member is recognized as an erosional surface on the western half and central part of the study area and it is conformable on the easternmost part. This erosion is indicated with the existence of several truncating horizons on the eastern and central parts of the study area. This erosional surface, which can also be seen on the cores as a sharp change from mudstones to sandstones, is interpreted to be formed during a rapid relative sea level fall, is interpreted as the forced regressive surface of erosion (Figure 3.18A). Within the study area, the forced regressive systems tract is expressed as the erosional upper boundary of the Gammon Ferruginous Member that is recognized on the western half and the central part of the study area. The recognition of the forced regressive systems tract is based on the existence of the major erosional surface recognized during the well log correlations.

Asquith (1970) interpreted sharp folding and/or faulting which has taken place after the deposition of the Niobrara Formation on the northeastern part of the study area. This sharp folding and/or faulting created accommodation space for the deposition of the Gammon Ferruginous Member. This accommodation space is indicated on the isopach maps as an area where the Gammon Ferruginous Member deposits are up to a hundred feet thicker compared to its surrounding area (Figure 3.3). Because of the paleotopographic relief change caused by this sharp folding and/or faulting, there are some irregular patterns in the lower horizons of the Gammon Ferruginous Member which are recognized by the restriction of the deposition of some horizons to the western half of the study area for a period of time (see Appendix D).
3.3.2 Lowstand Systems Tract

The lowstand systems tract within the study area consists of the Shannon Sandstone, the Unnamed Member, and the Sussex Sandstone. The recognition of the lowstand systems tract is based on (1) the major basinward shift in the facies which is expressed by the deposition of sandstone packages in thick shale packages farther in the basin; and (2) the erosional lower boundary that separates the thick shales from the sandstone packages. Three-dimensional surface maps were created for each member based on the well-log correlations (Figures 3.27 through 3.29). The glauconitic, bioturbated Shannon Sandstone, which shows strong tidal influence indicated by the appearance of abundant heterolithic bedding, is deposited as the lowermost member of the lowstand systems tract. The member is deposited above the forced regressive surface of erosion during the most basinward shift of the facies (Figure 3.27).

Bergman and Walker (1995) defined higher degree sequences within the Shannon Sandstone interval. The Unnamed Member of the lower Pierre Shale is deposited above the Shannon Sandstone and it shows progradational patterns indicated by several downlapping horizons (Figure 3.28). The bioturbated, glauconitic, silty Sussex Sandstone, which is interpreted to be deposited in a higher energy environment compared to the Shannon Sandstone, was deposited above the Unnamed Member (Figure 3.29). This higher energy environment is interpreted to be wave-dominated environment.

3.3.3 Transgressive Systems Tract

The transgressive systems tract consists of the Ardmore Pedro Bentonite Beds, the Sharon Springs Member, and the lowermost horizons within the Mitten Black Shale on the eastern part of the study area. The recognition of the transgressive systems tract is based on the (1) onlapping patterns recognized during well log correlations; (2) immediate change from the sandstone packages to organic-rich marine shales; and (3) the transgressive lag recognized on the 13-11 Highland Flats Federal (Sec.11, T37N R73W) core located at the lower boundary.
of the systems tract. Three-dimensional surface maps were created for the Ardmore and Sharon Springs members based on the well-log correlations (Figures 3.30 and 3.31). The Ardmore Pedro Bentonite Beds Member is deposited after the deposition of the Sussex Sandstone Member (Figure 3.30). Following the deposition of the Ardmore, the Sharon Springs Member was deposited (Figure 3.31). Tansgressive systems tract is defined by several onlapping horizons towards west. The lower boundary of the transgressive systems tract is marked by a transgressive lag on the 13-11 Highland Flats Federal (Sec.11, T37N R73W) core (Figure 3.18B). The lowermost horizons of the Mitten Black Shale on the eastern half of the study area show onlapping horizons towards west and they are located below the maximum flooding surface; therefore, these horizons are included in the transgressive systems tract (Figure 3.24).

### 3.3.4 Highstand Systems Tract

The maximum flooding surface is located above the onlapping lowermost horizons of the Mitten Black Shale on the eastern half of the study area, and at the top of the Sharon Springs Member on the western half. Above this maximum flooding surface the highstand systems tract consisting of the Mitten Black Shale and the Red Bird Silty Member of the lower Pierre Shale was deposited. The recognition of the highstand systems tract is based on (1) the change form onlapping patterns to downlapping patterns above the maximum flooding surface and (2) overall coarsening upward patterns of the members recognized during log correlations. The interval of the Mitten Black Shale above the maximum flooding surface shows progradational patterns within the study area. Three-dimensional surface maps based on the well-log correlations were created for the Mitten and Red Bird members (Figures 3.32 and 3.33). The contact between the Mitten Black Shale and the Red Bird Silty Member is gradational (Gill and Cobban, 1966) and the Red Bird Silty Member is characterized by progradational patterns. The top of the Red Bird Silty Member is picked as the datum for the study interval and all of the other tops are flattened to the top of the Red Bird Silty Member.
Figure 3.26 3D surface map for the Gammon Ferruginous Member of the highstand systems tract. Depositional dip increase about 1 degree is shown at the central part of the study area.
Figure 3.27 3D surface map for the Shannon Sandstone of the lowstand systems tract. The member is restricted to the western half of the study area.
Figure 3.28 3D surface map for the Unnamed Member of the lowstand systems tract. The member is restricted to the western half of the area.
Figure 3.29 3D surface map for the Sussex Sandstone of the lowstand systems tract. The member is restricted to the western half of the study area.
Figure 3.30 3D surface map for the Ardmore Pedro Bentonite Beds of the transgressive systems tract. The member has gone through erosion along a corridor in the central part of the study area.
Figure 3.31 3D surface map for the Sharon Springs Member of the transgressive systems tract
Figure 3.32 3D surface map for the Mitten Black Shale Member of the highstand systems tract. The member shows distinct progradational patterns.
Figure 3.33 3D map for the Red Bird Silty Member of the highstand systems tract. The top of this member is set as datum and flattened.
3.4 Depositional Model

Based on the interpretations listed in the previous sections, a depositional model for the lower Pierre Shale interval which also ties the Bighorn Basin to the Southern Powder River Basin is suggested within this study. Figure 3.34 illustrates the sequence stratigraphy interpretation along with the depositional model. The western side of this figure is modified from Brenner’s study (1978) and the eastern part, which shows the depositional sequence in the southern Powder River Basin, is formed based on the interpretations within this study.

According to Van Wagoner et al. (1990), the key characteristics of the Type 1 Ramp Margin Sequence are: (1) uniform dips which have low angles less than 1° with most dips less then ½° (2) clinoforms show shingled to sigmoidal patterns (Mitchum et al., 1977), and (3) “deposition of lowstand deltas and other shoreline sandstones in response to the relative sea level fall” exist. Both Asquith’s (1970) study and well-log correlations show that most of the depositional dips within the lower Pierre Shale interval are uniform and ½ to 1°. Based on Asquith’s (1970) study, Van Wagoner et al. (1990) suggest another evidence for the ramp margin interpretation for the lower Pierre Shale as the erosional features of the upper boundary of the Gammon Ferruginous Member indicate that the steepest dips that exist are caused by erosion instead of being depositional. Furthermore, the well log correlations within this study show that the clinoform packages within the interval show sigmoidal shapes and shingled patterns. Deposition of lowstand sandstones, which were deposited as tide dominated marine deltas in subaqueous environment, in response to relative sea level fall exist farther in the basin. These lowstand sandstones were deposited as the lowstand prograding wedge. According to the Van Wagoner et al.’s (1990) definition, the lower Pierre Shale interval in the southern Powder River basin is a Type 1 Ramp Margin Sequence which shows rapid progradational patterns within most of the interval.

The highstand systems tract deposits of the Gammon Ferruginous Member started to
prograde towards east (Asquith, 1970) with the initiation of high sediment influx above the 
Niobrara Formation. This high sediment influx accompanied with regression cut the Niobrara 
carbonate factory off during early Campanian. According to Gill and Cobban (1973) the 
deposition of the Gammon Ferruginous Member took place 81±2 Ma based on potassium-argon 
dating. As the lowermost horizons of the Gammon Ferruginous Member were deposited, 
faulting and/or sharp folding defined by Asquith (1970) has taken place within the Niobrara 
Formation which caused some paleotopographic irregularities. These paleotopographic 
irregularities were concluded with the restriction of some lower horizons of the Gammon 
Ferruginous interval to the western half of the study area (see Appendix D). This faulting and/or 
sharp folding created accommodation space for the deposition of the Gammon Ferruginous 
Member and as the Gammon fills the accommodation space, a thickness increase up to 100 
feet has taken place in the eastern half of the study area, which is clearly seen in the isopach 
map of the Gammon (Figure 3.3). Based on Gill and Cobban’s (1973) study on ammonite 
sequences, deposition of the prograding Gammon Ferruginous Member is synchronous with the 
Telegraph Creek – Eagle Regression which started about 83.5 Ma and stopped around 80 Ma. 
According to Bergman (1994), this regression is consistent with the third-order-sea-level-curve 
of Haq et al. (1988). During this regression the lowstand Mesaverde shoreline sands were 
 deposited in the Bighorn Basin before a rapid large scale relative sea level fall occurred. This 
rapid, large scale relative sea level fall is suggested by the truncating patterns of the upper 
horizons of Gammon Ferruginous Member. This sea level fall is interpreted as forced 
regression, and it is defined by the shift of facies over long distances basinward. The upper 
boundary of the Gammon Ferruginous Member is interpreted as the forced regressive surface 
of erosion and this surface is indicated by a large scale erosion. The forced regressive surface 
of erosion is defined as the sequence boundary since it is a large scale erosion surface, and it 
represents the most basinward shift of facies. This interpretation is consistent with Hunt and 
Tucker’s (1992) explanation of the hiatus of the sequence boundary which can be seen as a
significant unconformity being represented between the late highstand through the transgressive systems tract of the next sequence. However, this unconformity is seen as a correlative conformity in the basin which may not be seen as a hialtal surface at all (Hunt and Tucker, 1992). Martinsen (2003b) placed a hiatus within the Gammon Ferruginous Member on the stratigraphic column and this hiatus reaches up to the equivalents of the Shannon Sandstone Member.

The forced regressive systems tract within the study area is recognized as the truncational upper boundary of the Gammon Ferruginous Member in the western half and central part of the study area. This erosion was caused by the forced regression event and the eroded sediments are expected to be deposited farther basinward; however, these redeposited sediments were not recognized within the limits of the study area in the well log correlations.

As a result of this forced regression, the late lowstand deposits of tide dominated Shannon Sandstone, progradationalUnnamed Member, and wave influenced Sussex Sandstone were deposited as the lowstand prograding wedge hundreds of miles basinward from the stratigraphically equal Mesaverde lowstand sandstones (Bergman, 1994) of the Bighorn Basin. This shift of facies across long distances is compatible with the lowstand prograding wedge definition made by Hunt and Tucker (1992). The Shannon Sandstone was deposited as tide-dominated deltaic deposits in subaqueous environment at the lowest point of the sea level. Above the Shannon Sandstone, the progradational Unnamed Member of the lower Pierre Shale was deposited during a period of limited sediment supply. Following the deposition of the Unnamed Member, the Sussex Sandstone was deposited in a wave-dominated environment which indicates a gradual deepening. This interpretation is also consistent with the study made by Steel et al. (2012) in which they explained the depositional mechanisms of Campanian aged lowstand tide-dominated sandstones deposited at the maximum regressive position in their host sequence along the western shorelines of Western
Interior Seaway. These sandstones are deposited as the most basinward increments of the regression associated sand deposition at the regressive-transgressive turnaround of the clastic wedges as a consequence of the forcing aid of a falling relative sea level (Steel et al., 2012).

The transgressive systems tract indicated by the westward onlapping patterns started with the deposition of the sediments of the Ardmore Pedro Bentonite Beds. The Ardmore was deposited above the lowstand prograding wedge on the western half of the study area, and directly above the Gammon Ferruginous Member on the eastern half. The bottom surface of the Ardmore is defined as the transgressive surface and it is indicated by the existence of transgressive lag on the 13-11 Highland Flats Federal (Sec.11, T37N R73W) core (Figure 3.18B). The actual transgressive surface was picked about 10 feet above this transgressive lag on the well log since the transgressive lag is located at one of the several transgressive surfaces formed during the relative sea level rise. During transgression, the sediments of the Ardmore were eroded along a corridor where there is a topographic relief. This topographic relief was caused by the depositional dip increase seen in the Gammon Ferruginous Member interval; and eastward pinching out geometries of the Shannon, Unnamed, and Sussex members (Asquith, 1970). The eroded sediments were redeposited basinward forming a southeastern projecting lobe in the eastern half of the study area (Asquith, 1970). Above Ardmore, transgressive systems tract continues with the deposition of the relatively organic-rich Sharon Springs Member which shows onlapping patterns towards west. The lowermost horizons of the Mitten Black Shale Member which continued being deposited with onlapping patterns in the eastern half of the study area were included in the transgressive systems tract (Figure 3.24). The maximum flooding surface, which is shown with the dashed line in the Figure 3.24, is located above these onlapping horizons on the eastern half of the study area and it onlaps the top of the Sharon Springs Member on the western half (see Appendix D). According to Gill and Cobban’s (1973) study on ammonite sequences, the transgressive systems tract
deposits of Ardmore Pedro Bentonite Beds and the Sharon Springs Member are synchronous with the Clagett Transgression which is dated 79.5 Ma based on potassium-argon dating.

The highstand systems tract deposits of the Mitten Black Shale Member show progradational patterns above the maximum flooding surface and the progradational Red Bird Silty Member is deposited above the Mitten Black Shale Member with gradational contact (Gill and Cobban, 1966) (see Appendix D). Deposition of these two members is synchronous with the Judith River Regression according to Gill and Cobban's (1973) study on ammonite sequences.

3.4.1 Why Forced Regression

The deposition of the Shannon and Sussex sandstone members as encased in mostly progradational lower Pierre Shale mud sequence is explained as a consequence of forced regression that has taken place during the deposition of the upper part of the Gammon Ferruginous Member.

Within this study, the Shannon Sandstone, the Unnamed Member, and the Sussex Sandstone are suggested to be deposited as the lowstand prograding wedge. According to the definition; the lowstand prograding wedge is part of the lowstand systems tract and it is deposited above the sequence boundary at or after the sea level has reached its lowest point and beginning to rise, but before the transgressive systems tract (Hunt and Tucker, 1992). The lowstand prograding wedge of Shannon, Unnamed and Sussex members shows eastward downlapping patterns towards the sequence boundary within the study area. These progradational patterns are consistent with Hunt and Tucker’s (1992) explanation as the lowstand prograding wedge shows typically a parasequence stacking pattern and clinoform geometry of progradation to aggradation as the accommodation space begins to increase. It downlaps the sequence boundary basinward and onlaps it landward (Hunt and Tucker, 1992).
Another significant feature of the lowstand prograding wedge is that its size is an indicator of the ratio of rate of relative sea level rise to rate of sedimentation. The upper surface of the lowstand prograding wedge is the transgressive surface which marks the beginning of the transgressive systems tract (Hunt and Tucker, 1992). In the study interval this surface is defined by the onlapping patterns that Ardmore Pedro Bentonite Beds Member has towards west.

The main reasons that lead the interpretation of the Shannon Sandstone, the Unnamed Member, and the Sussex Sandstone as the lowstand prograding wedge deposited as a consequence of a forced regression event are: (1) during the progradation of the Gammon Ferruginous Member, the upper horizons of Gammon were being eroded on the eastern half of the study area, and this erosion was indicated with the truncation patterns on the master cross section (see Appendix D); (2) the regression was driven by a rapid relative sea level fall instead of sediment influx which is expressed by distinct erosion in the upper parts of the Gammon; (3) the Shannon Sandstone directly overlies the Gammon Ferruginous Member and it is deposited as tide-dominated subaqueous sandstone which indicates the most basinward position of the shoreline; (4) deposition of the stranded lowstand prograding wedge is a characteristic feature of the forced regressive systems (Hunt and Tucker, 1992); and (5) the deposits of the lowstand prograding wedge is located more than hundreds of miles basinward from the stratigraphically equal Mesaverde lowstand sandstones (Bergman, 1994) in the Bighorn Basin, which shows the rapid relative sea level fall.

3.4.2 Sediment Supply Directions

The overall sediment supply directions for the study interval is inferred to be from a source in the west by the use of the progradational log patterns on the master cross section (see Appendix D), and the isopach maps which show consistent thickness changes from west to east especially in the progradational members of the lower Pierre Shale (Figures 3.3 through 3.10). This inference is supported by the studies made by Liu et al. (2008), and Liu et al. (2011),
which present that there is an eastward change in the position of the maximum rates of subsidence that concluded with an eastward migrating depocenter approximately from 98 to 74 Ma caused by the migration of the Farallon plate.
Figure 3.34 Schematic cross section showing the depositional model and the sequence stratigraphic interpretation which ties the southern Powder River Basin to the Bighorn Basin. The age chart based on K-Ar dating is provided on the left (western part of the cross section is modified from Brenner, 1978).
Usage of organic geochemistry contributes to sedimentary basin analysis by providing analytical data for identifying and mapping source rocks (Peters and Cassa, 1994). The data acquired by using organic geochemistry are mainly richness, type, and thermal maturity of the source rock (Peters and Cassa, 1994). The next step is building maps using these data which have high significance on determining the three-dimensional extent of a source rock in a petroleum system (Peters and Cassa, 1994). Furthermore, the calculations that are made using the volume, richness, and thermal maturity of the source rock contribute to the determination of the amount of oil and gas produced. Eventually, the risk of exploration is reduced (Peters and Cassa, 1994).

Peters and Cassa (1994) defined the source rocks as “sedimentary rocks that are, or may become, or have been able to generate petroleum”; effective source rock as a sedimentary rock that “is generating or has generated and expelled petroleum”; and a potential source rock as a sedimentary rock which “contains adequate quantities of organic matter to generate petroleum, but only becomes an effective source rock when it generates bacterial gas at low temperatures or it reaches the proper level of thermal maturity to generate petroleum.”

Atomic H/C and O/C ratios of different kerogen types are used for the classification of the kerogens (Tissot et al., 1974). Rock-Eval pyrolysis and TOC analyses of rocks lead to the generation of hydrogen index (HI) versus oxygen index (OI) graphs, and obtaining the HI and OI data are faster and less expensive compared to the determination of atomic H/C and O/C values (Peters and Cassa, 1994). The key Rock-Eval pyrolysis and TOC parameters that are presented and used for determination of kerogen type in this study are S1, S2, Production or Productivity Index, Hydrogen Index, Oxygen Index, and Tmax.
According to Peter and Cassa (1994) “S1 measures the hydrocarbon shows as the amount of free hydrocarbons that can be volatilized out of the rock without cracking the kerogen (mg HC/g rock)”, and “S2 measures the hydrocarbon yield from cracking of kerogen (mg HC/g rock) and heavy hydrocarbons and represents the existing potential of rock to generate petroleum.”

Production or Productivity Index (PI) values are calculated based on the S1 and S2 values. In fine-grained rocks, PI values increase gradually as the depth increases (Peters and Cassa, 1994). This increase in PI values is a result of the conversion of thermally labile components of the kerogen (S2) to free hydrocarbons (S1) (Peters and Cassa, 1994). The equation that is used for the calculation of production or productivity index is as follows (Peters and Cassa, 1994).

\[ PI = \frac{S1}{S1 + S2} \]

Tmax is the measurement of the thermal maturity and it partly is determined by the type of the organic matter (Peters and Cassa, 1994). According to Peters and Cassa (1994), Tmax “corresponds to the Rock-Eval pyrolysis oven temperature (C˚) at maximum S2 generation”.

Hydrogen index (HI) (mg HC/g TOC) indicates the oil generation potential of the rock and it is proportional to the hydrogen amount in the kerogen and the following equation is used to calculate the hydrogen index (HI) (Peters and Cassa, 1994).

\[ HI = \frac{S2}{TOC} \times 100 \]

Oxygen index (mg CO2/g TOC) is dependent on the amount of oxygen in the kerogen and is calculated by using the following equation (Peters and Cassa, 1994).

\[ OI = \frac{S3}{TOC} \times 100 \]
According to Peters and Cassa (1994) four main types of kerogens were defined by using both atomic H/C versus O/C diagrams and hydrogen index (HI) versus oxygen index (OI) diagrams. Type I kerogens have high atomic H/C and low atomic O/C values and they are oil prone. Type I kerogens generally have low sulfur content and they can be derived from both lacustrine and marine settings. Type II kerogens are oil prone and they have high atomic H/C and low atomic O/C. Type II kerogens have higher sulfur amount than other kerogens. Type III kerogens are gas prone, and they have low atomic H/C and high O/C values. Type IV kerogens are named dead carbon since they have very low atomic H/C values and low to high O/C values and they generate little or no hydrocarbons during maturation.

Geochemical analyses were made within this study in order to have a general idea about the source rock potential and source rock properties of the Sharon Springs Member of the lower Pierre Shale, and its possible contribution to the Niobrara Petroleum System in the southern Powder River Basin. The data for the geochemical analyses come from one core, and two cutting samples. In total, there are six data points. Four of these data points were obtained from the samples which were taken from the 13-11 Highland Flats Federal (Sec.11, T37N R73W) well. The other two data points were obtained from the cutting samples which were taken from the wells 22-6 Parker Sparks (Sec.6, T37N R68W) and 1-29 Carshon Federal (Sec.29, T37N R65W).

The core recovered from 13-11 Highland Flats Federal (Sec.11, T37N R73W) well is the only sampled core within this study for geochemical analyses. The samples were taken within the Ardmore Pedro Bentonite Beds interval which is defined as the basal unit of the Sharon Springs Member (Gill and Cobban, 1966; Asquith 1970). The samples were taken from every one foot starting from the top of the core which is at 10,030 ft and sampling was stopped at one foot above the bottom of the Ardmore Pedro Bentonite Beds interval which is at 10,034 ft.
Therefore, the four samples were taken exactly from 10,030 ft, 10,031 ft, 10,032 ft, and 10,033 ft depths.

Cutting sample values are taken from 22-6 Parker Sparks (Sec.6, T37N R68W) and 1-29 Carshon Federal (Sec.29, T37N R65W) wells. There is only one data point from each well within the Sharon Springs Member interval. The cutting sample obtained from 22-6 Parker Sparks (Sec.6, T37N R68W) well was taken at 7,950 ft and the one obtained from 1-29 Carshon Federal (Sec.29, T37N R65W) well was taken at 6,310 ft depth.

Table 4.1 illustrates the TOC, S1, S2, S3, and Tmax values obtained from the analyses for each sample and the hydrogen index (HI) oxygen index (OI) and productivity index (PI) values calculated using the equations given above. TOC values for Sharon Springs Member differ between 1.27 and 2.72 weight percent. One significant remarkable trend is that there’s a consistent increase of TOC values of the samples, which were taken from the 13-11 Highland Flats Federal (Sec.11, T37N R73W) well, from 1.27 weight percent at 10,033 ft to 1.54 weight percent at 10,030 ft. This is interpreted to be an indicator of possible higher TOC values that could be reached with the shallower depths into the Sharon Springs Member interval. The hydrogen index (HI) and oxygen index (OI) values for each member were calculated in order to plot the kerogen type graph. According to the graph, which was plotted based on the calculated HI and OI values, the kerogen is Type III (Figure 4.1). The Remaining Hydrocarbon Potential (S2) versus Total Organic Carbon (TOC) graph shows that the Sharon Springs Member has Type III, gas prone kerogen (Figure 4.2). The kerogen type and maturity graph (HI versus Tmax graph) shows that the Sharon Springs of lower Pierre Shale has reached the oil window (Figure 4.3).

These results indicate that the Sharon Springs Member of the lower Pierre Shale does not have significant source rock quality where sampled for these study. Therefore, there is no
evidence that the oil which was accumulated in the Shannon and Sussex sandstone members of the lower Pierre Shale was sourced by the Sharon Springs Member. However, all of the data points are located within southern half of the study area and further investigation of a bigger dataset which is more representative of the whole study area will provide further information and will provide a better insight for the source rock potential of the member. There are no geochemistry logs or maps for richness, type, and thermal maturity created for the Sharon Springs Member within this study since the dataset used was too small and does not allow such detailed work.
Table 4.1 Table showing the SRA results and calculated values for both core and cutting samples (cutting data is taken from http://my.usgs.gov/crcwc/cutting/report/29138).

<table>
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<tr>
<th>API NUMBER</th>
<th>Depth (ft)</th>
<th>SRA TOC</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>Tmax (°C)</th>
<th>Calculated % Ro</th>
<th>HI</th>
<th>OI</th>
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<td>18.18</td>
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<td>103</td>
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<td>0.11</td>
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</table>

Figure 4.1 Kerogen Type Graph (Hydrogen Index versus Tmax) shows that the kerogen in Sharon Springs Member is Type III.
Figure 4.2 Kerogen Quality Graph (Remaining Hydrocarbon Potential versus Total Organic Carbon) shows that the kerogen is Type III gas prone.
Figure 4.3 Kerogen Type and Maturity graph (Hydrogen Index versus Tmax) shows that the Sharon Springs Member has reached the oil window.
CHAPTER 5

SUMMARY AND CONCLUSIONS

In order to build the sequence stratigraphic framework within the lower Pierre Shale interval in the southern Powder River Basin, six shale and two sandstone tops were correlated on 1490 electric well logs. The list of the API numbers of these wells with their coordinates is provided in appendix (see Appendix B). The list of the TVD values for each member top, with the API numbers of the wells on which they were picked is provided as a list in appendix (see Appendix C).

Core analyses including core descriptions and facies analyses were made on three cores in addition to the well log correlations to better understand the depositional relationships of the Shannon and Sussex sandstone members and their bounding surfaces. Based on these correlations and core descriptions: (1) isopach maps for each member; (2) three-dimensional surface maps for each member; and (3) the master cross section that shows the sequence stratigraphic interpretation (see Appendix D) were created. Schematic cross section based on the master cross section, and the schematic cross section showing the depositional model were created in order to illustrate sequence stratigraphic framework for the lower Pierre Shale.

In addition to the sequence stratigraphic analysis, source rock analyses on four samples taken from 13-11 Highland Flats Federal (Sec.11, T37N R73W) well were made and source rock analysis data for the cuttings taken from 22-6 Parker Sparks (Sec.6, T37N R68W) and 1-29 Carshon Federal (Sec.29, T37N R65W) wells were obtained. These source rock analysis data was collected in order to understand the source rock potential of the Sharon Springs Member within the study area. Therefore, possible contribution of the Sharon Springs Member to the oil found in the Shannon and Sussex sandstone members was evaluated.
Based on these observations, interpretations and analyses, following conclusions were reached within this study.

1. The lower Pierre Shale interval in the southern Powder River basin is a Type 1 Ramp Margin Sequence which shows rapid progradational patterns within most of the interval. The depositional dips are uniform and less than or about 1 degree. The clinoform packages within the interval show shingled to sigmoidal patterns. There is deposition of lowstand sandstones in response to relative sea level fall hundreds of miles basinward from the stratigraphically equal Mesaverde lowstand sandstones (Bergman, 1994) in the Bighorn Basin.

2. Rapid relative sea level fall during the deposition of the uppermost Gammon Ferruginous Member deposits took place. This rapid relative sea level fall was concluded with a wide spread erosion indicated by truncational patterns of the uppermost horizons within the Gammon Ferruginous Member interval on the western half and the central part of the study area. This rapid relative sea level fall shows the characteristics of a forced regressive system and as a consequence of this forced regression the deposition of a lowstand prograding wedge took place. The sandstone members within the study interval are confined to this lowstand prograding wedge and they were deposited as encased in the progradational shale members hundreds of miles basinward from the stratigraphically equal Mesaverde lowstand sandstones (Bergman, 1994) of the Bighorn Basin.

3. One of the main contributions of this study is that it shows that the deposition of Shannon and Sussex sandstone members has taken place as the consequence of a rapid relative sea level fall at about 80 Ma ago as the lowstand prograding wedge within the study interval. Shannon Sandstone which is interpreted to be
deposited as as tide dominated marine deltas in subaqueous environment and Sussex Sandstone which is interpreted to be deposited under wave-dominated environment are indicators of a close shoreline position which emphasizes this rapid relative sea level fall.

4. This study shows that the Sharon Springs Member of the lower Pierre Shale is continuous throughout the study area. The TOC values of the member differ between 1.27 and 2.72 weight percent. According to the Kerogen Type and Kerogen Quality graphs the Sharon Springs Member has Type III kerogen and the organic matter within this member is gas prone. Therefore, the member does not have significant source rock potential and there is no evidence that the oil accumulated in the Shannon and Sussex sandstone members of the lower Pierre Shale was sourced from the Sharon Springs Member.
CHAPTER 6
FUTURE WORK

This study explains the detailed sequence stratigraphic framework of the lower Pierre Shale, which consists of six shale members and two sandstone members, in the southern Powder River Basin. These sandstone members have become significant targets for oil production lately. Being separated from each other by the Unnamed Member of the lower Pierre Shale, these sandstone members were deposited as an encased lowstand prograding wedge between the progradational Gammon Ferruginous Member and the transgressional Ardmore Pedro Bentonite Beds and Sharon Springs members. The following recommendations for the future researchers to contribute to the understanding of the Niobrara Petroleum System in the southern Powder River Basin are listed.

1. Detailed structural analyses using high resolution 3D seismic data will aid determination of possible structural features within this section and it will contribute to the understanding of minor thickness irregularities seen on the isopach maps of especially the sandstone members.

2. Determining the source rock potential of each member of the lower Pierre Shale by making SRA analyses on cutting and core samples from future wells will contribute to the determination of whether or not any of these significantly thick shale sequences have contribution to the Niobrara Petroleum System. Creating geochemistry logs and maps for richness, type, and thermal maturity for the Sharon Springs Member by using a more representative dataset of the southern portion of the Powder River Badin will provide further information on the possible contribution of the Sharon Springs Member to the Niobrara Petroleum System.
3. Since the two sandstone members within the sequence have become the focus of interest as they have significant oil accumulations, electron microscopy and XRF analyses will contribute to the understanding of their inner structures and provide more accurate data about their provenance.

4. Provenance analyses including the usage of electron microscopy and XRF will contribute to provenance identification for the sediments of each member of the lower Pierre Shale.
REFERENCES CITED


Reineck, H.E., 1960a, Uber Zeitlücken in rezenten Flachsee-Sedimenten: Geol. Rundschau, v. 49, p. 149-161


APPENDIX

To provide the oversized master cross section, raw data and data sources the supplemental electronic files are compiled here. These files include core descriptions, source rock analysis results and graphs, a list of all wells correlated within this study by API numbers and coordinates, depth of interpreted tops for each member of the lower Pierre Shale interval on each well by API numbers, the master cross section that shows the detailed sequence stratigraphy interpretation. Supplemental files appear in the order they are listed above. This data is included so that the reader may see each step of the process on making the interpretations, building the sequence stratigraphic framework, and reaching the conclusions listed within this study.

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>Supplemental File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPENDIX A</td>
<td>Core_Descriptions.pdf</td>
<td>The core descriptions of the three cores made within the study. The symbol legend is included.</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>Raster_log_APIs.pdf</td>
<td>API numbers of the wells correlated within the study including their coordinates.</td>
</tr>
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<td>APPENDIX C</td>
<td>Formation_Tops_by_API.pdf</td>
<td>All interpreted formation tops by API and TVD values.</td>
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<tr>
<td>APPENDIX D</td>
<td>Master_Cross_Section.pdf</td>
<td>The master cross section that shows the detailed sequence stratigraphy interpretation.</td>
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