STRATIGRAPHY AND RESERVOIR CHARACTERIZATION OF THE TURNER SANDSTONE, SOUTHERN POWDER RIVER BASIN, WYOMING

by

Andrew W. Heger
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Golden, Colorado

Date__________________________

Signed: ________________________________
Andrew W. Heger

Signed: ________________________________
Dr. Stephen Sonnenberg
Thesis Advisor

Golden, Colorado

Date__________________________

Signed: ________________________________
M. Stephen Enders
Interim Department Head
Department of Geology and Geological Engineering
ABSTRACT

The upper Turonian Turner Sandy Member of the Carlile Shale has long been a historic producer of hydrocarbons, and recently has become a significant horizontal target in the southern Powder River Basin. Although the Turner has a robust drilling past and currently is one of the most prolific producers in the basin, relatively little has been published on the interval. Questions regarding depositional environment, facies successions, sediment transport processes, sediment sources, and origin of unconformities still remain generally unanswered.

This aim of this research is to interpret facies relationships, depositional processes and environments, and to identify potential unconventional reservoirs in the Turner.

Detailed mapping indicates the Turner can be separated into informal upper and lower units based on biostratigraphic constraints associated with the *Scaphites whitfieldi* Western Interior Ammonite zone. Core analysis suggests the lower and upper Turner were deposited by contrasting depositional processes in different shallow marine environments.

Bioturbation is one of the most important diagenetic processes in the Turner. The burrow type and degree of biological reworking are two of the controlling factors that either destroy or enhance the reservoir quality in the Turner. Additionally, bioturbation in conjunction with sedimentology play a significant role in differentiating the depositional processes and environments of the Turner.
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1.1 Overview

The upper Turonian Turner Sandy Member (Turner) of the Carlile Shale is a productive low-resistivity, tight sandstone reservoir associated with the Niobrara Petroleum System (Anna, 2009). Historically, vertical production from the Turner Sandstone was restricted to isolated fields located generally along the eastern margin of the Powder River Basin (PRB) and from the most favorable reservoir facies. Advancing technologies such as horizontal drilling and multi-stage hydraulic fracturing have enabled operators to target the less attractive, low-porosity low-permeability facies. The majority of the horizontal wells that have been drilled are adjacent to existing vertical production. To date, over 200 horizontal wells have been drilled targeting the Turner, with cumulative production (vertical and horizontal) at approximately 47.6 MMBO and 165 BCFG.

The Turner is described as a stratigraphic equivalent to: the Wall Creek Member of the Frontier in central Wyoming, the Juana Lopez in southeast Colorado and northeast New Mexico, and the upper portion of the Codell Sandstone in Kansas, southeast South Dakota, and northeast Nebraska (Merewether et al., 2007). Renewed interest in the Turner by the oil and gas industry has created new research opportunities for academia. However, unlike its stratigraphic equivalents, very little work has been published on the Turner despite being one of the most frequently targeted and prolific intervals in the PRB (Figure 1.1). Questions regarding depositional environment, facies successions, sediment transport processes, sediment sources, and origin of
unconformities still remain generally unanswered or, undecided upon and thus a significant research opportunity exists.

In this study, previously unpublished core, well-log, and petrographic data and nearly 25+ years of advancing concepts in sedimentology, stratigraphy, and petroleum geology are applied toward interpreting facies relationships, depositional processes, depositional environments, and potential “unconventional” reservoirs of the Turner.

Figure 1.1 A) Powder River Basin horizontal completions by interval. B) Production from the top three horizontally completed intervals.
1.2 Study Objectives
The objective of this study is to integrate modern concepts and previously unpublished data to 1) document spatial and temporal facies relationships, 2) interpret sediment transport processes, 3) link facies relationships and transport processes to depositional environment(s), and 4) describe reservoir properties and their relationships to reservoir units in the Turner.

1.3 Study Area
The PRB is located in southeastern Montana and northeastern Wyoming. In Wyoming, the PRB is bound to the west and southwest by the Bighorn Mountains and Casper Arch, the Laramie Uplift and Hartville Uplift to the south, and the Black Hills Uplift to the east. Specifically, the study area covers parts of Johnson, Campbell, Weston, Niobrara, and Converse counties, Wyoming (Figure 1.2).

1.4 Dataset and Methods
The dataset for this project includes; 1) outcrop observations along the eastern and western margins of the PRB, 2) core descriptions and analysis, and 3) well-log data from MJ Systems and the Wyoming Oil and Gas Conservation Commission.

1.4.1 Outcrop Observations
Outcrops along the margins of the PRB (Figure 1.3) were used to better understand the lateral character of the Turner. Specific detail was placed on bed thickness, continuity and geometry, lithology, texture, fossils, diagenetic alterations, and ichnology. Turner outcrops along the eastern margin were used primarily for this study, whereas supplementary outcrops along the western margin were used to make stratigraphic comparisons between the age partially equivalent Wall Creek and Turner.
1.4.2 Core Descriptions

A total of 25 cores were used in this study, 23 from the USGS, one from Abraxis Petroleum, and one from Yates Petroleum (Figure 1.4). Core descriptions consisted of describing and documenting bed thickness, lithology, texture, primary and secondary sedimentary structures, ichnology, fossils, diagenetic alterations (oil staining, pervasive calcite cementation), and facies relationships. Additional effort was made to document any surfaces (contacts) that separate distinctly different lithofacies successions or ichnofacies. A bioturbation index (BI) modified from Taylor and Goldring (1993) was used to document and quantify the degree of biological disturbance within the rock. The data was compiled into spreadsheets and used to generate a digitized, vertical profile of the core.
1.4.3 Thin Section Petrography

Petrographic thin sections from cores were used to observe and document composition and mineral percentages, texture, cementation, porosity, and diagenetic alterations. Additional petrographic thin sections were made at Weatherford Labs in Golden, Colorado. Thin sections were stained for calcite, ferroan dolomite, and potassium feldspar. Point counting techniques (300 count/thin section) were used to determine the percentages of 1) minerals, 2) cements, and 3) porosity, and 4) intergranular volume (IGV%). Pettijohn et al. (1972) suggests counts of 200-500 per sample are statistically reasonable for a semi-quantitative to quantitative measurement of composition.
1.4.4 Mineralogical Analysis

This study utilized publically available x-ray diffraction data that has been submitted to the USGS CRC, and data donated by operators. Data was downloaded from the USGS CRC website for all of the Turner cores for which the analysis had been run. Several caveats are associates with this data: 1) data sources vary, and in some cases are unknown, 2) the range of minerals being analyzed in some case varies, and 3) there is an inherited assumption that the sample depths being reported are accurate. All efforts were made to minimize induced error.

1.4.5 Subsurface Mapping

Well-log data, primarily electric logs, acquired from MJ Systems served as the foundation for correlations. Because of the incomplete log suites inherent to older electric logs and the low resistivity nature of the Turner, additional well-logs were downloaded, imported into IHS Petra, and depth calibrated. Additional log suites include; gamma ray (GR), neutron-density porosity (NPHI-DPHI), photoelectric effect (PEF), and bulk density (RHOB). Well-log vintage was taken into consideration when evaluating log signatures. Primarily log suites from 1980-present were used for correlations and log digitization.

Acquiring additional log suites, along with the existing deep induction (ILD) logs enabled core and outcrop data to be directly tied to the subsurface well-log data. Core descriptions were depth shifted to match log depths, digitized, and imported as raster images into IHS Petra for the respective wells. Facies described in core were then tied to the corresponding well-log signatures, allowing the core facies to be interpreted in adjacent wells and correlated between control points (cores). Additionally, detailed
facies successions, grain size, and lithologic descriptions were imported and stored into IHS Petra. These data was plotted along the wellbore of the control-wells to assist with facies interpretation and correlation in adjacent wells. A similar method was used for outcrop descriptions, and correlated to a neighboring well.
CHAPTER 2: GEOLOGIC HISTORY

The following chapter outlines the geologic evolution of the study area by explaining the structural framework and timing of events related to the generation of the Powder River Basin, and describes the stratigraphic elements pertaining to this study. The Turner section was intentionally kept brief as much of the material will be discussed in subsequent chapters.

2.1 Overview

Located in northeastern Wyoming and southeastern Montana, the PRB is a Laramide structural feature that originated in the earliest middle Paleocene (Ayers, 1986). Prior to the Laramide Orogeny (~80-35 Ma) this region occupied a portion of the Western Interior Basin (WIB). The WIB is a large composite foreland basin that spanned an east-west distance of over 620 miles (~1,000 km) and a north-south distance of over 3,000 miles (>5,000 km). The WIB began forming during the Late Jurassic with the emplacement of the Sevier orogenic thrust sheets, in response to the Farallon plate colliding and then subducting under the western margin of the North American plate (Kauffman and Caldwell, 1993). Flooding of the North American continent occurred during the Barremian-Aptian as the Boreal Sea inundated from the north, and the Tethys Ocean from the south, joining for the first time during the late Albian (Kauffman, 1985; Kauffman and Caldwell, 1993; DeCelles, 2004). Pertinent to this study are the 3rd order Greenhorn and Niobrara marine cycles lasting from latest Albian-early Upper Turonian (Greenhorn Cycle), and from latest Upper Turonian-Lower Campanian (Niobrara Cycle) (Kauffman, 1985; Figure 2.1). Kauffman (1985) defined 1st through 4th order sea-level cycles as: 1st order ~ 90-100 m.y., 2nd order ~ 30-40 m.y., 3rd order ~ 9-
10 m.y., and 4\textsuperscript{th} order ~ 1-3 m.y. Flexural subsidence continued east of the Sevier fold and thrust belt and sediment continued to accumulate in the WIB until approximately 80 Ma and the onset of the Laramide Orogeny which began partitioning the WIB. Laramide partitioning resulted in upwards of 20 intermountain basins present throughout the Rocky Mountain region (White et al., 2002; DeCelles, 2004; Liu et al., 2014).

2.2 Structural Framework

The PRB is a Laramide structural feature that formed during the earliest middle Paleocene (Ayers, 1986). The basin covers an area approximately 34,000 mi\textsuperscript{2} (8,800 km\textsuperscript{2}) across northeastern Wyoming and southeastern Montana. Basin geometry is asymmetrical with a steeply dipping western flank and gentler dipping eastern flank, with the basin axis trending roughly north-south near the western side. Regional dip along the west flank varies between 1.0° and 8.0° with steeper dips occurring toward the south; along the eastern margin, regional dip is greatest proximal to the Black Hills Uplift and then decreases to approximately 1° to 2° westward into the basin (Anna, 2009). The deepest portions of the basin follow the structural axis where nearly 18,000 ft (~5,500 m) of Phanerozoic sedimentary rocks separate the land surface from the Precambrian basement (Figure 2.2; Anna, 2009).

The PRB comprises multiple structural features that vary in size and subdivide the basin into several rectangular blocks. The blocks are bounded by faults rooted in the Precambrian basement and correlate with lineaments visible at the surface. The majority of the lineaments have a strong northeast strike; however a secondary northwest oriented set is also present (Figure 2.3; Marrs and Rains, 1984).
Figure 2.1 Regional sea-level cycles (up to 4\textsuperscript{th} order) for the Late Cretaceous Western Interior stratigraphy. Greenhorn and Niobrara 3\textsuperscript{rd} order cycles are highlighted with red box. Regional sea level from Kauffman and Caldwell (1993). Global eustatic curve from Haq et al. (1989). Radiometric ages from Obradovich (1993). Modified from Drake and Hawkins (2012).
Figure 2.2 Simplified structural cross section of the Powder River Basin. From Anna (2009).

Figure 2.3 Distribution of oil and gas fields and structural lineaments in the PRB. Lineaments BC=Bell Creek, SR=Springen Ranch, RZ=Rozet, SCC=South Coyote Creek, GB=Gose Butte, FC=Fiddler Creek, CT=Clareton Trend, PB=Parkman-Baker, BHC=Bighorn-Custer, BD=Buffalo-Douglas, BB=Black Butte, LC=Lightening Creek. Modified from Martinsen (2003).
A subtle yet important structural feature in the PRB is the Belle Fourche arch, a paleotopographic feature that trends northeast across the central portion of the basin. Displacement along the arch is approximately 200 ft and primarily occurred during the Cretaceous (Slack, 1981). Although structural relief is subtle across the arch, it is believed to have had significant impacts on facies distributions and depositional environments. Slack (1981) reported what he interpreted to be Turner channel deposits superimposed along channel trends in the Muddy Formation. He concluded that reactivation along faults bounding the arch were responsible. Slack (1981) stated that throughout the Phanerozoic subtle movements along the bounding faults have affected depositional environments and hydrocarbon accumulations in many of the reservoirs in the northern portion of the basin. Sonnenberg (1980) and Weimer (1980, 1984) demonstrated that recurrent movement along basement faults within the Denver Basin (a Laramide basin) occurred throughout the Paleozoic and Mesozoic and that these movements had an impact on the distribution of hydrocarbon reservoirs. Pratsch (1986) applied Bouguer gravity data to show the relationship between producing conventional fields and anomalies in the gravity data associated with Precambrian basement structures in the PRB. Marrs and Rains (1984) suggested that recurrent movement along the basement faults could have influence sediment dispersal patterns, transport directions, and facies distributions within Cretaceous strata. Weimer and Flexer (1985) supported the concept of basement fault reactivation in the PRB. Where based on gross interval isopach maps of the Upper Cretaceous, areas of thinning within the Turner corresponded to areas of thinning in the Lower Cretaceous and it was interpreted to indicate recurrent movement on the same paleo-highs. They also noted thinning on a
broader scale in the Belle Fourche, Pool Creek, and Turner in southern Campbell, southwestern Weston, and northeastern Converse counties and speculate the thinning may be related to movement along lineaments bounding the Belle Fourche arch.

2.3 Stratigraphy

The late Albian-Lower Campanian (approximately 100.5-83.0 Ma) sedimentary rocks of the southern and eastern PRB consist of marine shales, siltstones, sandstones, chalks, and limestones. Marine transgressions and subsequent regressions associated with relative fluctuations in sea level and sediment supply caused lateral shifts in depositional environments throughout this time, resulting in an intertonguing relationship between marine-derived sediments and continental sediment sourced from Cordilleran highlands. The intertonguing nature of the sediments resulted in facies variability along depositional strike and shallow marine sandstones encased in organic-rich marine shales (Forzoni et al., 2015).

Several authors have recognized unconformities within the Upper Cretaceous strata in the PRB (Cobban, 1951; Cobban and Reeside, 1951, 1952a, 1952b; Weimer and Haun, 1960; McGookey, 1972; Weimer, 1984; Weimer and Flexer, 1985; Merewether et al., 1979; Merewether et al., 2007). Pertinent to this study are the Turonian and Coniacian disconformities as reported by Merewether et al. (2007).

2.3.1 Mowry Shale

The Mowry Shale is the oldest stratigraphic unit included in this study. Previous studies of the fauna found in the Mowry have yielded contradicting results on the age of the unit. Reeside and Cobban (1960) found the Mowry to be entirely Albian age based on their studies on the ammonite genus *Neogastroplites*. Conversely, Obradovich et al.

The Mowry Shale is characterized as a siliceous, radiolarian-rich, dark-gray to black organic-rich mudrock. Numerous bentonites have been documented within the unit in outcrop and core, as well as well-log. The Clay Spur Bentonite which serves to cap the Mowry Shale is reported to be a combination of multiple thin-bentonite beds, and serves as a regionally correlatable datum throughout the PRB (Slaughter and Earley, 1965).

2.3.3 Greenhorn Formation

The late middle Cenomanian-early Turonian Greenhorn Formation consists predominantly of organic-rich, calcareous, marine shales, limestones, and bentonites deposited during the inundation of the Greenhorn Sea into the WIB (Haun, 1958; Weimer and Flexer, 1985). The interval transitions upward from marine shales to silty limestones near the top. The upper contact with the Carlile Shale is conformable along the eastern portion of the basin. To the west, the Greenhorn Formation pinches out and age equivalent strata are incorporated into the Belle Fourche Member of the Frontier Formation (Fox, 1993; Figure 2.4).

2.3.4 Carlile Shale: Pool Creek Member

The early Middle Turonian Pool Creek is the youngest of the three Carlile Shale members. It is present in the subsurface and crops out along the eastern margin of the PRB. The Pool Creek ranges in thickness from 0 to 140 ft and consists of dark gray,
silty shales (Rubey, 1930; Haun, 1958; Weimer and Flexer, 1985). The upper contact with the overlying Turner Sandstone is disconformable, and towards the western portion of the basin the unconformity completely removes the Pool Creek leaving the Turner Sandstone resting atop the Greenhorn Formation or age equivalent strata. Weimer and Flexer (1985) interpreted the Pool Creek to have been deposited during the early stages of the Greenhorn Sea regression.

2.3.5 Carlile Shale: Turner Member

The Turner generally consists of very fine- to medium-grained sandstone with thin interbedded organic shales and localized conglomeratic lenses (Sawyer, 1990). The basal contact of the Turner is disconformable with the Pool Creek, and generally conformable with the overlying Sage Breaks. Chronostratigraphic equivalents of the Turner include the Wall Creek Member of the Frontier in central Wyoming; the Juana Lopez in southeast Colorado and northeast New Mexico; and the upper portion of the Codell Sandstone in Kansas, southeast South Dakota, and northeast Nebraska (Merewether et al., 2007; Figure 3.3).

2.3.6 Carlile Shale: Sage Breaks Member

Along the eastern margin of the PRB and adjacent areas the Sage Breaks consists of 100-300 ft of poorly exposed non-calcareous to calcareous, dark-gray fissile shale, calcareous light-gray to light-brown shale, and multiple zones of calcareous concretions (Haun, 1958). Although not as significant of a source rock as the Mowry or Niobrara Formation, Merewether and Claypool (1980) measured TOC wt.% within the Sage Breaks that ranged from 1-2 wt.% from core on the eastern margin of the PRB.
The age of the Sage Breaks as well as relationship with the overlying Niobrara Formation has been debated by workers since first being described. Rubey (1930) reported the Sage Breaks as the basal member of the Niobrara Formation. Cobban and Reeside (1952b) showed that the sparse megafauna within the Sage Breaks were more “Carlile-like” than Niobrara, although similar species of foraminifera were found in both the Sage Breaks and Fort Hays in the Denver Basin. Additionally Cobban and Reeside (1952b) reported that fauna within the Sage Breaks represented an intermediate form between *Prionocyclus wyomingensis* (Carlile) and the *Inoceramus deformis* (Niobrara). They concluded that based on faunal relationships, the “knife-edge sharpness” of the contact between the Sage Breaks and the overlying Niobrara, and gradational relationship with the underlying Turner Sandstone, that the Sage Breaks should be assigned to the Carlile of latest Turonian age. Evetts (1976) reported the occurrence of planktonic species *Archaeoglobigerina cretacea, Hastigerinoides subdigitata,* and *Marginotruncana concavata* in the upper portions of the Sage Breaks, all of which are known to occur in Coniacian, Santonian, and early Campanian aged strata from the Western Interior of the United States.

### 2.3.7 Niobrara Formation

Regionally, the Niobrara Formation consists of two members, the lower Coniacian Fort Hays Member and the middle Coniacian to lower Campanian Smoky Hill Member (Kauffman, 1969). In the Denver Basin, the Fort Hays Member consists of 15-40 ft of limestone, and the Smoky Hill Member consists of 250-650 ft of alternating calcareous shale, marl, and chalk. In the western portion of the PRB the Niobrara Formation is included in the Cody Shale (Figure 2.5). In the PRB, only the Smoky Hill
Member is present and based on XRD data from Taylor (2012), the interval becomes increasingly enriched in clays northward, and carbonates toward the southern portion of the basin.

The Niobrara is a significant source of hydrocarbons produced from Upper Cretaceous reservoirs within the Rockies. Momper and Williams (1984) reported that combined the Niobrara and Sage Breaks have expelled over 7.5 billion barrels of oil, with the vast majority coming from the Niobrara. Although the PRB has not seen the drilling activity that the neighboring Denver Basin has (IHS, 2015), it is likely that activity will continue as the formation continues to be evaluated. Currently the majority of the drilling is taking place along the basin axis, in the southern portion of the basin.
Figure 2.4 Generalized stratigraphic column of the Powder River Basin showing variations in nomenclature related to geographic position within the basin. Red box indicates known or potential source rocks. Green dot indicates a known productive interval. Modified from Anna (2009).
Figure 2.5 Type log for the western portion of the Powder River Basin. From Bhattachara and Willis (2001).
CHAPTER 3: TURNER STRATIGRAPHY AND KEY STRATIGRAPHIC SURFACES

3.1 Previous Work

Rubey (1930) studied the Upper Cretaceous strata along the northwestern flank of the Black Hills. Rubey named the Turner Sandy Member (Turner) of the Carlile Shale from exposures along Turner Creek, T46N and T47N, R64W, Weston County, Wyoming. Rubey (1930) described the Turner as 150-200 ft of sandy shales, siltstones, thin bedded sandstones, and conglomeratic and phosphatic units. Abundant shark teeth were locally present within lower portions of the section. Rubey also documented a distinct faunal break and possible unconformity at the base of the Turner.

Cobban (1951a) and Cobban and Reeside (1952b) studied the Carlile Shale along the northern flank of the Black Hills Uplift. They described the interval as consisting of three members, in ascending order; the unnamed shale member, the Turner Sandstone Member, and the Sage Breaks Member. Additionally, their correlations, based on the occurrence of Prionocyclus wyomingensis and Scaphites whitfieldi, showed the Turner occupying a similar biostratigraphic position as the Wall Creek Member of the Frontier Formation in the western PRB.

Haun (1958) measured outcrop sections of early Upper Cretaceous strata on the western and eastern margins of the PRB. His work supported that of Cobban and Reeside (1952b) that the Turner occupied a similar stratigraphic position as the Wall Creek.

Following the work by Cobban (1951a), Knechtel and Patterson (1962) described and mapped the basal member of the Carlile Shale. This interval was previously
referred to as the “unnamed member of the Carlile Shale”. Knechtel and Patterson (1962) named the interval the Pool Creek Member of the Carlile Shale for exposures along Highway 85 near Pool Creek, north of Belle Fourche, South Dakota.

Robinson et al. (1964) measured multiple stratigraphic sections of the Carlile Shale, six of which included the Turner. Thicknesses, detailed lithologic descriptions, fossil types, and sampling locations for each member of the Carlile Shale were reported. Robinson et al. (1964) reported that the Turner became sandier south of the Black Hills specifically in Weston County, Wyoming.

Merewether et al. (1979) and Merewether (1980) described the Frontier Formation along the western margin of the PRB and partial age equivalent strata west of the Black Hills. In the report, the Frontier Formation was subdivided into informal units, from older to younger, unit I through VIII. Pertinent to this study are units VI and VII, both belonging to the Wall Creek Member of the Frontier. Unit VI was correlated through the PRB to outcrops near Osage, WY where it forms the basal sandstone of the Turner. *Scaphites warreni* is present in both Unit VI and the basal sandstone of the Turner. Unit VII is represented by sandstone and siltstone present in the upper portion of the Turner near Osage, WY and the presence of *Scaphites whitfieldi*. According to their interpretation, sediments of the Turner and Wall Creek were interpreted to have entered the PRB as a “high-destructive, tide-dominated delta” between Ervay and Douglas, Wyoming. Sediments were subsequently transported to the north-north east as a complex of channel and bar deposits while the delta prograded to the Black Hills. Merewether et al. (1979) stated that although isopach trends indicate transport from the
southwest to northeast, themselves and others have documented paleocurrents (Towse, 1952; Merewether et al. 1979) toward the southeast and southwest.

Weimer and Flexer (1985) described three sandstone types within the Turner along the eastern margin of the PRB and west of the Black Hills. Type 1 are parallel-laminated or low-angle cross-stratified, medium-grained pebbly-conglomeratic sandstones typically from 1-2 ft thick. Trace fossils are rare to absent. Type 2 sandstones are ripple and planar laminated, fine-grained, and interbedded with shales and siltstones. Trace fossils are of low diversity. Type 3 sandstones are fine-grained and heavily bioturbated. Occasionally, cross-stratification is present in the upper portion of the sandstones. Weimer and Flexer (1985) interpreted Type 1 sandstones as being transported through incised valleys in the underlying Pool Creek, and subsequently deposited near the shelf edge during sea level lowstand around 90Ma. Type 2 sandstones were deposited within the valleys as estuarine or intertidal deposits during subsequent transgression. Continued sea level rise resulted in Type 3 sandstones being deposited in the remaining accommodation space within the valleys as normal marine shelf sands.

Merewether and Cobban (1986a) noted that the ammonite and inoceramid fossil zones in Turner and Wall Creek onlap the basal disconformity with the underlying Pool Creek and equivalent strata toward the southwest and west. Based on this observation, Merewether and Cobban (1986a) interpreted the Turner-Wall Creek as a transgressive deposit.
Rice and Gaskill (1988) and Rice and Keighin (1989) reported on the Turner southwest of Osage, Wyoming at Osage Oil Field, and north of Lusk, Wyoming at exposure along the flanks of Old Woman Anticline. They divided the Turner into an “upper” (contains Scaphites whitfieldi) and “lower” (contains Scaphites warreni), separated by a marine shale. Within their “lower” Turner, two types of sandstone were present, both of which overlie a regional unconformity with the Pool Creek and were interpreted to be deposited during a sea-level lowstand and subsequent transgressions. Type 1 sandstones are very fine- to fine-grained, planar laminated, wave-ripple cross-laminated, occasionally hummocky cross-stratified. Shale interbeds decrease up section as the interval forms a shoaling upward sequence. The authors interpreted Type 1 sandstones to have been deposited on a wave-dominated shelf with occasional storm activity. The shoaling upward character is attributed to progradation during an overall transgression. Type 2 sandstones of the “lower” Turner interval are medium- to coarse-grained, tabular and planar cross-stratified with sets less than five ft thick. Type 2 sandstones were interpreted to be deposited by eastward directed, offshore-flowing submarine, channelized currents. Channel location was interpreted to be controlled by recurrent movement of basement fault blocks. Locally, type 2 sandstones contain conglomeratic lenses of black chert pebbles and granules, shark and stingray teeth, fish vertebrae, and wood fragments. Conglomeratic lenses were interpreted as lags that were concentrated as sea-level periodically rose. The “upper” Turner interval was reported to consist of a lower and upper unit. The authors describe the lower unit as interbedded shale with planar laminated sandstone and hummocky cross-stratified sandstone. The upper unit of the “upper” Turner interval is heavily burrowed by
Skolithos ichnofacies with occasionally preserved planar laminated and hummocky cross-stratified sandstone. The interpreted depositional environment for the “upper” Turner interval is on a storm-dominated shelf, below fair-weather wave base, during a sea-level highstand. The heavily bioturbated upper unit of the “upper” Turner interval was interpreted to represent times where biological colonization and reworking of the sediment was not disrupted by storm activity.

Sawyer (1990) studied outcrops of the Turner located northwest of Provo, South Dakota, southeast of the Black Hills Uplift. The Turner was subdivided into a lower, middle, and upper unit based on mappable lithologic differences between the units. The lower unit lies disconformably over the Pool Creek, and consists of wavy, flaser, and lenticularly bedded sandstone and shale overlain by conglomeratic, medium- to coarse-grained sandstone. The lower unit was reported to represent post-regression deposition, in a wave-dominated upper shoreface environment. The middle unit was interpreted to lie disconformably above the lower, and consists of lenticular bedded shales and siltstone, with hummocky cross-stratified and cross-laminated sandstones. The middle unit was interpreted to have been deposited in a lower shoreface to inner shelf environment. The hummocky cross-stratified and cross-laminated sandstone were thought to represent high energy storm events. The upper unit consists of amalgamated, hummocky cross-stratified, lenticular sandy siltstones also interpreted to represent high energy storm events along the lower shoreface. The increased degree of amalgamation within the upper unit was interpreted to represent shallower water depths during time of deposition.
Winn (1991) studied the Wall Creek and Turner, specifically Unit VII of Merewether et al. (1979) in the southern PRB. He interpreted the Wall Creek and Turner to be deposited as shelf sand sheets 20-50 ft thick. In his interpretation, sediments of the Wall Creek and Turner were transported primarily by storm-generated currents. He describes a scenario where clastic sediments shed from the Sevier Orogenic Belt were transported through fluvial processes eastward to the WIB and initially deposited in a delta-strandplain system located near the present day Big Horn Mountains (Figure 1.2). Winter storms subsequently transported sediment offshore and then toward the south, away from the delta-strandplain system.

Merewether’s (1996) compilation summarized previous interpretations of the authors as well as other researchers. Some statements by Merewether (1996, p.T33) regarding the depositional environment of the Turner: “The Turner was deposited in shallow-water marine environments on a shelf and, particularly where the member is sandy, as distal parts of a delta lobe”; “the Turner in Weston County was deposited in a nearshore-marine environment close to an area of lowland vegetation”. In a sequence stratigraphic model the Turner includes a “progradational parasequence in a lowstand systems tract and an overlying retrogradational parasequence in a transgressive systems tract” Merewether, 1996 p.T34).

Based on an outcrop- and core-facies analysis, Gustason (2015) interpreted the Wall Creek and Upper Turner as elongate; “isolated sand bodies” or “sand ridges” deposited in shallow marine shelf environment, detached from coeval deltaic and shoreface deposits. Gustason (2015) proposed storm-generated shelf currents as a mechanism for “sand ridge” migration toward the south-southeast. Gustason (2015)
noted that large storms occasionally reworked the “sand ridge” tops, however hummocky cross stratification is reported as being rare.

### 3.3 Age, Biostratigraphy, and Chronostratigraphic Equivalents

The Turner was deposited in the WIS following a global sea-level drop at approximately 90.3 Ma (Figure 3.1). Fossils collected from the Turner along the western flank of the Black Hills uplift place the Turner between the *Prionocyclus macombi* and *Prionocyclus germari* Western Interior ammonite zones. This range corresponds to an age between 90.21 Ma to 89.30 Ma (Figure 3.2; Merewether et al., 2007, 2011).

The Turner is a partial age equivalent to the Wall Creek member of the Frontier Formation in central Wyoming, the Juana Lopez in southeast Colorado and northeast New Mexico, and portions of the Codell Sandstone (Codell) and Blue Hill Shale in central Kansas, southeast South Dakota, and northeast Nebraska (Merewether, 2007; Figure 3.3).

### 3.4 Key Stratigraphic Surfaces

Key stratigraphic surfaces (KSS) were identified in outcrop and core (Table 3.2). This study defines KSS as a lithologic contact where the observed facies juxtaposition is inferred to have resulted from variations in 1) depositional environment, 2) depositional processes, and 3) environmental conditions. Biostratigraphic and radiometric age data were used to constrain depositional cycles and the hiatus between the Turner and Pool Creek.

The following sections describe the KSS that were observed and interpreted in the Turner.
### 3.2 Summary of Interpretations

Table 3.1 Summary of the nomenclature and varying interpretations of depositional environment and sediment transport.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Interpreted Depositional Environment</th>
<th>Sediment Transport Processes &amp; Mechanism</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Creek-Turner: Unit VII, Unit VII, Unit VI</td>
<td>Channels, nearshore bars, offshore bars</td>
<td>Destructive tide-dominated delta</td>
<td>Merewether et al.1979, p.68, 91</td>
</tr>
<tr>
<td>Turner: Type 1 SS</td>
<td>Lowstand shelf edge sands</td>
<td>Sea level drop</td>
<td>Weimer and Flexer 1985, p. 138, 144-145</td>
</tr>
<tr>
<td>Turner: Type 2 SS</td>
<td>Intertidal or estuarine valley fill</td>
<td>Sea level rise</td>
<td></td>
</tr>
<tr>
<td>Turner: Type 3 SS</td>
<td>Valley fill, normal marine shelf sand</td>
<td>Sea level rise</td>
<td></td>
</tr>
<tr>
<td>Lower Turner: Type 1 SS</td>
<td>Wave-dominated Shelf</td>
<td>Major river-dominated delta; minor storm</td>
<td>Rice and Gaskill 1988, p.69-70, 72</td>
</tr>
<tr>
<td>Lower Turner: Type 2 SS</td>
<td>Wave-dominated shelf</td>
<td>Offshore-flowing submarine channelized</td>
<td></td>
</tr>
<tr>
<td>Upper Turner</td>
<td>Storm-dominated shelf, below fwwb</td>
<td>Storm currents</td>
<td></td>
</tr>
<tr>
<td>Lower Turner</td>
<td>Wave-dominated, tide-influenced upper shoreface</td>
<td>Wave-generated currents, tidal currents, minor storm influence</td>
<td>Sawyer 1990, p. 198-202</td>
</tr>
<tr>
<td>Middle Turner</td>
<td>Lower shoreface to inner shelf</td>
<td>Reworking by storm currents</td>
<td></td>
</tr>
<tr>
<td>Upper Turner</td>
<td>Lower shoreface to inner shelf</td>
<td>Reworking by storm currents</td>
<td></td>
</tr>
<tr>
<td>Wall Creek-Turner: Unit VII</td>
<td>Middle to outer shelf sand sheet</td>
<td>Storm-generated currents, minor wave-generated currents</td>
<td>Winn 1991, p. 97-99</td>
</tr>
<tr>
<td>Wall Creek-Turner</td>
<td>Wall Creek: strand line, reworked shoreface</td>
<td>Wall Creek: long-shore currents, storm waves</td>
<td>Melick 2013, p. 156</td>
</tr>
<tr>
<td></td>
<td>Turner: proximal - distal shelf hyperpycnites</td>
<td>Turner: sediment gravity flows</td>
<td></td>
</tr>
<tr>
<td>Upper Turner-Wall Creek</td>
<td>Isolated shelf sand body, sand ridge</td>
<td>Storm-generated currents</td>
<td>Gustason 2015, abs.</td>
</tr>
</tbody>
</table>
Figure 3.1 Western Interior stratigraphic framework for the Albian through Santonian. Biozones correspond to Merewether et al., 2007 (Figure 3.2). Time scale from Ogg et al., 2004. Eustatic curve from Haq et al. (1989). Black diagonal lines indicates hiatus. Modified from Melick (2013).
Figure 3.2 Biostratigraphic chart for the Western Interior United States. Red box highlights the ammonite and inoceramid zones corresponding to the Turner. Modified from Merewether et al. (2007).
3.4.1 Regressive Surface of Erosion

An interpreted regressive surface of erosion (RSE) is present at the base of the Turner and demarcates heterolithic or medium-grained facies from silty, argillaceous mudstones of the underlying Pool Creek. The RSE is believed to have formed due to forced regression in association with the regressing Greenhorn Sea, and corresponds to a hiatus of approximately 2.42 Ma. No evidence for subaerial exposure was observed at this surface in core or outcrop. As such, the RSE is interpreted to have formed within the marine realm. It should be noted that previous authors have suggested subaerial exposure may have occurred (Weimer and Flexer, 1985).

3.4.2 Flooding Surfaces

Flooding surfaces (FS) are interpreted as being associated with an increase in water depth, but within the subaqueous realm (i.e. shelf). Three FS were identified in the Turner and each correlates to a Western Interior ammonite biozone. The three
biozones are, from oldest to youngest, *Scaphites warreni*, *Scaphites whitfieldi*, and *Prionocyclus germari* (zones 8, 10-11, and 13 from Merewether et al. 2007; Figure 3.2).

### 3.4.2.1 Scaphites warreni

The *Scaphites warreni* FS caps the first depositional cycle in the lower Turner, spanning approximately 250 k.y. The surface was identified in outcrop based on previous studies by Rubey (1930), Haun (1958), Robinson et al. (1964), Merewether et al. (1979, 1980) and it can be traced into the subsurface and correlated on a semi-regional scale throughout the eastern portion of the study area. To the west and southwest the *Scaphites warreni* FS onlaps the disconformity (RSE) between the Turner and the underlying Pool Creek.

### 3.4.2.2 Scaphites whitfieldi

The *Scaphites whitfieldi* FS caps the second depositional cycle in the lower Turner, spanning approximately 375 k.y. The surface was identified in outcrop based on previous studies by Rubey (1930), Haun (1958), Robinson et al. (1964), Merewether et al. (1979, 1980) and it can be traced into the subsurface and correlated throughout the study area.

*Scaphites whitfieldi* is used to divide the Turner into lower and upper units. This FS demarcates archetypal *Cruziana* ichnofacies from the underlying restricted and juvenile distal *Skolithos* assemblage. Additional characteristics associated with the surface are an observed and interpreted variability between facies, sediment transport processes, and depositional environment across the FS.
3.4.2.3 *Prionocyclus germari*

The *Prionocyclus germari* FS caps the upper Turner depositional cycle spanning approximately 375 k.y. The surface was identified in outcrop based on previous studies by Ruby (1930), Haun (1958), Robinson et al. (1964), Merewether et al. (1979, 1980) and it can be traced into the subsurface and correlated throughout the study area. The *Prionocyclus germari* FS serves as the lithostratigraphic top of the Turner. A variable amount of erosion or non-deposition associated with this surface was observed across the study area, particularly in the area of the Porcupine and Crossbow fields. This erosion is believed to have occurred in the marine environment during a time of relative sea-level rise.

3.4.3 Additional Surfaces

3.4.3.1 Minor Flooding Surfaces

Minor flooding surfaces (MnFS) identified in core occur frequently within longer duration depositional cycles. MnFS observed in the Turner are subtle where the mechanism of “deepening or drowning” could be related to allo- or autogenic processes. Differentiating between the two is beyond the scope of this study. MnFS are predominantly associated with the upper Turner, and constitute the lowest magnitude surface juxtaposing relatively distal above relatively proximal facies.

3.4.3.2 Minor Erosional Surfaces

A minor erosional surface (MnES) occurs locally around Porcupine, Tuit Draw, and K Bar fields. Below the surface a *Glossifungites* ichnofacies and a bioturbated sandstone facies are present, and a medium-grained sandstone facies overlies.
*Skolithos* burrows are passively filled with medium-grained sand grains below the surface. This indicates a period of non-deposition or a pause in sedimentation.

### 3.4.4 Additional Comments on Key Stratigraphic Surfaces

It should be noted that within the upper Turner outcrops at OWA, sandstone packages containing a basal concentration of shell fragments are common and believed to be a type of lag. Because a facies of concentrated shell fragments was not observed in any core, it is possible that this surface crosscuts lithology and juxtaposes various facies in different locations. The degree of erosion associated with the surface is not uniform and changes quickly over short distances and corresponds to the *Prionocyclus germari* biozone.

In outcrop KSS and minor surfaces are more easily recognized due the interaction between lithologic composition, lithologic competency, and weathering. The RSE is identified below resistant ledges and overlies marine shale of the Pool Creek. MnFS are identified above competent sandstone ledges and below weaker shale and interbedded sandstone. These surfaces bound packages of shale capped by sandstone (Figure 4.14).

### 3.5 Lithofacies

A total of 15 subfacies were identified and combined into 7 facies groups in cores from the Turner. Subfacies were differentiated based on composition, grain size, sedimentary structures, and degree of bioturbation and then placed into 7 facies groups based similarities (Table 3.3).
Table 3.2 Summary of the key surfaces observed in cores and outcrops of the Turner.

<table>
<thead>
<tr>
<th>Key Surface</th>
<th>Nature of Contact</th>
<th>Facies Below</th>
<th>Facies Above</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regressive surface of erosion (RSE)</td>
<td>Conformable or scoured</td>
<td>Silty, argillaceous mudstone of the Pool Creek or equiv.</td>
<td>Heterolithic; Medium-grained sandstone</td>
<td>Regional Disconformity; Lithostratigraphic base of Turner Coarser above finer</td>
</tr>
<tr>
<td>Flooding surface (FS)</td>
<td>Conformable or scoured</td>
<td>Variable; often heterolithic and thin bedded sandstones</td>
<td>Bioturbated muddy siltstone and sandstone</td>
<td>Correspond to biozones S. warreni, S. whitfieldi, P. germari Cap ~250 – 400 k.y depositional cycles Finer above coarser</td>
</tr>
<tr>
<td>Minor flooding surfaces (MnFS)</td>
<td>Conformable or scoured</td>
<td>Variable; Heterolithic; Bioturbated muddy siltstone and sandstone</td>
<td>Variable; Silty, argillaceous mudstone, Bioturbated muddy siltstone and sandstone</td>
<td>May represent short periods of progradation during overall transgression</td>
</tr>
<tr>
<td>Minor erosional surface (MnES)</td>
<td>Scoured</td>
<td>Variable bioturbated facies</td>
<td>Medium-grained structureless</td>
<td>Stalled sedimentation or non-deposition, very sharp contact Coarser above finer</td>
</tr>
</tbody>
</table>
Table 3.3 Various facies observed in core of the Turner Sandstone.

<table>
<thead>
<tr>
<th>Group</th>
<th>Facies</th>
<th>Sedimentary Structures</th>
<th>Bioturbation</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Medium-grained sandstone</td>
<td>Cross stratified</td>
<td>0-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subfacies</td>
<td>Structureless</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1) cross-stratified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1) structureless</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Very fine- to fine-grained</td>
<td>Laminations:</td>
<td>0-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sandstone</td>
<td>Planar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subfacies</td>
<td>Ripple</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2) structureless</td>
<td>Wavy-flaser</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.1) planar laminated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.2) ripple laminated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.3) wavy-flaser laminated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>Bioturbated sandstone</td>
<td>Faint, low-angle crossbeds to</td>
<td>3-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subfacies</td>
<td>structureless</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Paleophycus</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Ophiomorpha</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>Facies</td>
<td>Sedimentary Structures</td>
<td>Bioturbation</td>
<td>Example</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
<td>------------------------</td>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>3</td>
<td>Laminated siltstone, sandstone, and mudstone</td>
<td>Laminations: Sub-planar parallel Ripple Wavy-flaser Contains organic-rich mud drapes</td>
<td>0-1</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td><strong>Subfacies</strong></td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Heterolithic shaly sandstone, siltstone, and mudstone</td>
<td>Laminations and organic-rich mud drapes are preserved in less bioturbated (btb) beds.</td>
<td>1-2</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td><strong>Subfacies</strong></td>
<td>4) sandy, mod. btb 4.1) org. muds, low btb 4.2) mod. btb</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>Facies</td>
<td>Sedimentary Structures</td>
<td>Bioturbation</td>
<td>Example</td>
</tr>
<tr>
<td>-------</td>
<td>------------------------------</td>
<td>-------------------------------------------------------------</td>
<td>-------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>5</td>
<td>Bioturbated shaly siltstone</td>
<td>Nearly no preserved sedimentary structures.</td>
<td>3-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subfacies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5) laminated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.1) sandy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.2) muddy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Silty, argillaceous mudstone</td>
<td>Very thin to thin laminated siltstone beds occur irregularly</td>
<td>Rare to Sparse (BI=1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subfacies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Of the seven facies groups described below, three can be considered as “sand prone” and four “mud prone”. Facies groups 1, 2, and 2.5 are sand prone, whereas 3, 4, 5, and 6 are mud prone.

3.5.1 Facies Group 1: medium-grained sandstone

Facies group 1 consists of medium-grained sandstones either structureless or cross bedded to faintly cross bedded. Facies group 1 predominantly occurs in the upper Turner, mostly commonly in the Tuit Draw and Porcupine fields. Evidence for bioturbation is generally absent, although cryptic bioturbation by meiofauna could be responsible for the observed faintness of cross bedding and structureless nature of the facies (Howard and Frey, 1975).

3.5.2 Facies Group 2: very fine- to fine-grained sandstone

Facies group 2 consists of laminated very fine- to fine-grained sandstones. Laminations include plane-parallel, ripple, and wavy-flaser forms. Bioturbation is absent to sparse. Facies group 2 is present in both the upper and lower Turner, and typically forms event-like beds that are generally 2-5 cm. Thin beds consisting of facies group 2 are often carbonate cemented.

3.5.3 Facies Group 2.5: bioturbated sandstone

Facies group 2.5 consists of fine-grained bioturbated sandstone. This facies is predominantly present in the upper Turner, most commonly in the K Bar, Tuit Draw, and Porcupine fields. Bioturbation ranges from moderate to heavy, predominantly of *Skolithos, Thalassinoides, and Ophiomorpha* trace fossils.
Oil staining is a common occurrence in this facies in the K Bar, Tuit Draw, and Porcupine areas.

### 3.5.4 Facies Group 3: laminated siltstone, sandstone, and mudstone

Facies group 3 consists of laminated siltstone, sandstone, and mudstone. Sandstone is very fine- to fine-grained with plane-parallel, ripple and wavy-flaser laminations. Mudstone may or may not be laminated, and range in thickness from single laminations to 1-2 cm. Bioturbation is absent to sparse. Facies group 3 predominantly occurs in the lower Turner, and is a minor contributor to the overall facies succession.

### 3.5.5 Facies Group 4: heterolithic shaly sandstone, siltstone, and mudstone

Facies group 4 consists of heterolithic shaly sandstone, siltstone, and mudstone. Sandstone is mostly very fine- to fine-grained, although coarser grains do occur locally at the base of some normally graded beds in the lower Turner. This is especially common in the southeastern portion of the study area in cores from Finn Shurley and neighboring areas. Sedimentary structures include plane-parallel and sub-parallel laminations; combined flow and oscillatory ripple laminations; micro-hummocky cross stratification; and organic-rich mud drapes <3 cm thick. Bioturbation is sparse to low, and consists predominantly of a restricted *Skolithos* and *Cruziana* ichnofacies.

### 3.5.6 Facies Group 5: bioturbated shaly siltstone to sandstone

Facies group 5 consists of bioturbated shaly siltstone and mudstone, and silty sandstones. Facies group 5 is the most commonly occurring and abundant facies in the Turner. Bioturbation is moderate to intense, and generally dominated by *Cruziana* and *Cruziana* overprinting *Skolithos*. Occasionally some laminated sandstones are
preserved and are interbedded with moderately to highly burrowed shaly siltstones and mudstone.

Facies group 5 consists of a sand-rich (5.1) and clay-rich (5.2) subfacies. Although in core and well log the differences may seem slight, the mineralogical variations have implications toward hydrocarbon storage and migration.

### 3.5.7 Facies Group 6: silty argillaceous mudstone

Facies group 6 consists of silty, argillaceous mudstone with pinstripe and lenticular bedded siltstones. This facies is typically present above deepening and flooding surfaces found in both the lower and upper Turner. Bioturbation is sparse and consists of small *Chondrites* burrows.

### 3.6 Bioturbation

Bioturbation is the process by which the primary consistency and structure of a sediment are modified by the activity of the organisms living within it (Richter, 1952). The abundance and diversity of the organisms are directly tied to the environmental conditions of that particular location. Thus, trace fossils can be a good record of the environment and changes that occurred based on factors that influence the individual species, or entire community (Bromley, 1996). Stressful (also referred to as restricted) environments typically yield low diversity, but high abundance populations. Two of the most ecologically limiting factors are the availability of oxygen and salinity. Additional environmental processes such as sedimentation rates and hydraulic energy at the sea floor will also have an effect on the organisms.
Modifiers such as archetypal, proximal, distal, robust, juvenile, restricted, and diverse are used when the author felt appropriate to further characterize the ichnofacies assemblages, facies, or key stratigraphic surfaces. For example, “This interpretation is based on juxtaposition of archetypal Cruziana ichnofacies above a restricted and juvenile, distal Skolithos assemblage”, where archetypal refers to typical, restricted refers to lacking diversity, juvenile refers to small in size compared to a healthy adult assemblage, and distal refers to a seaward expression of the typical, or archetypal Skolithos.

Secondary biogenic structures in the Turner range from absent or cryptic to pervasive. Cryptic bioturbation is a result of meiofauna or very small macrofauna displacing grains a very short distance. The result is a blurring of the sediment fabric which leads to homogeneity (Howard and Frey, 1975). Trace fossils present in the Turner include Arenicolites, Planolites, Thalassinoides, Cylindrichnus, Teichichnus, Ophiomorpha, Phycosiphon, and Chondrites.

Arenicolites form small U-shaped tubes, typically only one of the vertical parts of the U is observed in core. Tubes lack spreiten and vary between being lined or not lined. Generally Arenicolites occurs in low diversity assemblages associated with the heterolithic shaly siltstone, sandstone, and mudstones of facies group 4 (Figure 3.4). Planolites are feeding burrows, commonly found in facies group 4. Planolites form unlined, oval to elliptical burrows in cross-section, typically non-branching (Figure 3.4). Both Arenicolites and Planolites can be associated with the Skolithos ichnofacies, although Planolites can be found in nearly all environments from freshwater to deep marine (Pemberton, 2009).
Figure 3.4 *Arenicolites* and *Planolites* from the heterolithic shaly siltstone, sandstone, and mudstones of facies group 4. White arrows are *Arenicolites*, blue arrows are *Planolites*. Perpetual Finn #8, Finn Shurley.

*Cylindrichnus* and *Ophiomorpha* are commonly associated with the *Skolithos* ichnofacies, but *Cylindrichnus* can also found in the proximal *Cruziana* ichnofacies. Both have unique burrow characteristics that make recognition straightforward. *Ophiomorpha* have a pelleted, almost bulbous look associated with the rim, or wall of the burrow. *Cylindrichnus* are recognized as a cylindrical, to sub-cylindrical burrow consisting of multiple concentric layers. Burrows are often sub-vertical to sub-horizontal in core.
Figure 3.5 *Cylindrichnus* (white arrow) and *Ophiomorpha* burrows (blue arrows). Note pelletal rim, black to dark-gray rim surrounding *Ophiomorpha*. Cosner 29-1, Tuit Draw.

*Thalassinoides* and *Teichichnus* are dwelling/feeding burrows formed by deposit-feeding organisms. *Teichichnus* form stacked concave-up laminae that may be oriented horizontally, sub-horizontally, or vertically, but are never branched. *Thalassinoides* form branching burrow systems, and display a range of shapes in cross-section. Cylindrical, half-moon, and elliptical burrows typically have smooth walls. Both *Thalassinoides* and *Teichichnus* are associated with the *Cruziana* ichnofacies found in lower shoreface to
offshore environments (Figure 3.6). However, both are also found in brackish-water environments such as lagoons and bays (Pemberton, 2009).

Figure 3.6 *Cylindrichnus*=white arrow, *Thalassinoides*=green arrow, *Teichichnus*=blue arrow. Cosner 29-1, Tuit Draw.

*Phycosiphon* form irregular, black-cored burrows with a silt or very fine-grained sand halo. In core the traces are most easily seen as tiny dark pin-head sized spots and are easily overlooked (Pemberton, 2009).
Figure 3.7 *Phycosiphon* form small, irregular burrows that appear as tiny black specks. This example is completely overprinted by *Phycosiphon*.

Because there is an intimate connection between the distribution of trace fossils and the physical sedimentary process present in the depositional system, inference can be made about sedimentation rates, water chemistry, and the general depositional environment (Gingras et al., 2009). To understand this connection, a method of semi-quantifying the degree of bioturbation established by Taylor and Goldring (1993) and modified by Gani et al. (2009) was used for the Turner. The method utilizes a bioturbation index (BI) ranging from 0 to 6 (Table 3.4). By plotting the BI data similar to well-log form and knowing a connection exists between the trace fossil distribution and the acting, physical sedimentary processes, the resulting trend of the BI log should
provide useful data for understanding the depositional history throughout a vertical
facies succession (Gani et al. 2009; Gingras et al. 2009, Figure 3.8)

Table 3.4 Classification scheme for analyzing the degree of bioturbation present in core. The bioturbation index (BI) refers to the sharpness of the primary sedimentary fabric, burrow abundance, and amount of burrow overlap (modified after Taylor and Goldring, 1993).

<table>
<thead>
<tr>
<th>BI</th>
<th>Percent Bioturbated</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No bioturbation</td>
</tr>
<tr>
<td>1</td>
<td>1-4</td>
<td>Sparse bioturbation, bedding distinct, few discrete traces and/or escape structures</td>
</tr>
<tr>
<td>2</td>
<td>5-30</td>
<td>Low bioturbation, bedding distinct, low trace density, escape structures common</td>
</tr>
<tr>
<td>3</td>
<td>31-60</td>
<td>Moderate bioturbation, bedding boundaries sharp, traces discrete, overlap rare</td>
</tr>
<tr>
<td>4</td>
<td>61-90</td>
<td>High bioturbation, bedding boundaries indistinct, high trace density with overlap</td>
</tr>
<tr>
<td>5</td>
<td>91-99</td>
<td>Intense bioturbation, bedding completely disturbed (just visible), limited reworking, later burrows discrete</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>Complete bioturbation, sediment reworking due to repeated overprinting</td>
</tr>
</tbody>
</table>
Figure 3.8 Example of a bioturbation index (BI) log using the method described by Taylor and Goldring (1993) and the associated bedding fabrics (modified after Taylor and Goldring, 1993; Droser and Bottjer, 1986; Gani et al. 2009; Pemberton, 2009; and Marenco and Bottjer, 2011).
CHAPTER 4: OUTCROP AND CORE ANALYSIS

This chapter outlines the sedimentary features and overall stratigraphy of the Turner observed in this study. Outcrop and core data were used for evaluating and interpreting facies successions, stratigraphic continuity, and depositional history.

4.1 Outcrop Analysis

Outcrops of the Turner generally consisted of two to four resistant sandstone ledges underlain by interbedded shale and thin lenticular siltstones and very fine-grained sandstones. At each of the outcrop locations along the eastern margin of the PRB, the Greenhorn, Pool Creek, Turner, and part of Sage Breaks were present. Exposures are fairly poor in most areas, especially the less competent shale successions in the Pool Creek, Turner, and Sage Breaks. However, resistant limestone beds at the top of the Greenhorn, as well as sandstone beds and concretions near the top of the Turner are moderately well exposed and can be traced for several tens of miles along the southwestern flanks of the Black Hills Uplift.

4.1.1 Old Woman Anticline, Wyoming

Old Woman Anticline (OWA) is located approximately 30 mi (48 km) north of Lusk, Wyoming in east-central Niobrara County. OWA is the southeastern most exposure incorporated in this study. Outcrops of the Greenhorn Formation, Pool Creek, Turner, Sage Breaks, and Niobrara are exposed along the eastern flank of the north plunging anticline. Outcrops were described at two locations, one in the southern part of the structure and the other approximately four miles to the north.
The Greenhorn Formation forms moderately steep slopes capped with a resistant, thinly bedded limestone to silty limestone 2-3 ft (0.6-0.9 m) thick (Figure 4.1). Upper beds are fossiliferous and contain abundant *Mytiloides mytiloides* of late lower Turonian age.

Figure 4.1 Thinly bedded fossiliferous limestone and silty limestone at the top of the Greenhorn Formation, southern Old Woman Anticline, Wyoming. Hammer is 16 inches (0.4 m).

The Pool Creek is poorly exposed and forms a grass covered slope, occasionally concretions can be found weathering from the hillsides. The concretions are light to medium-gray with yellow-brown calcite veins radiating from the center. The contact between the Pool Creek and Turner is not well exposed. The lower most sandstone of
the Turner is a light-gray, cross-stratified, medium-grained sandstone as much as 3 ft (0.9 m) thick (Figure 4.2) and is similar to the type 2 sandstone of Rice and Gaskill (1988). This sandstone facies was only observed at the outcrops along the northern portion of OWA although it was reported to be well developed and up to 4 ft (1.2 m) thick (Rice and Gaskill, 1988).

Overlying the medium-grained sandstone is approximately 50 ft (15 m) of dark-gray, lenticular bedded shale and siltstone that range from 0.4-1.2 in. (<1-3 cm) thick (Figure 4.3). Concretionary, sandy siltstones approximately 12 ft (3.7 m) wide and 3.5 ft (1.1 m) tall are intercalated with the lenticular bedded shales and siltstone (Figure 4.4). This facies is present in both the southern and northern portions of OWA and maintains nearly equal thickness between locations. The lenticular bedded shale and siltstones are directly overlain by light-gray to tan-gray, very fine- to fine-grained sandstones. The sandstones range in thickness from 3-12 in. (7.6-30 cm) and are laterally discontinuous over several tens of feet, with individual beds ranging from 0.4-2.4 in. (1-6 cm) thick. A concentration of shell fragments is present at the base of many of the sandstones and is typically overlain by ripple or planar laminations (Figure 4.5). The dominant sedimentary structures are cross-stratification, planar and ripple laminations, and occasionally hummocky cross-stratification (Figure 4.6). This facies is present in both the southern and northern portions of OWA. Hummocky cross-stratification was interpreted based on the presence of a scoured and concave down lower boundary, where laminations are parallel to the lower bounding surface (Compton, 1985).
Figure 4.2 Cross-stratified medium-grained sandstone at the base of the lower Turner at the northern outcrops of Old Woman Anticline, Wyoming. Hammer is 13 in. (0.3 m).
Figure 4.3 Lenticular bedded shale and siltstone in the lower Turner, Old Woman Anticline, Wyoming. Hammer is 13 in. (0.3 m).
The uppermost portion of the Turner is similar to the previous mentioned facies, but is concretionary and highly bioturbated by *Ophiomorpha* and *Thalassinoides*. This facies forms prominent weather-resistant ridges throughout the area. Two types of vertical succession are present in the uppermost sandstones. The first, from the base upward includes; 1) concentrated shell fragments, 2) low angle planar laminations that grade upward into, 3) symmetrical ripple laminations, 4) bioturbated sandstone (Figure 4.7). The second, from the base upward includes; 1) concentrated shell fragments, 2) trough cross-stratification, 3) low angle planar laminations that truncate underlying trough cross-stratification, 4) bioturbated sandstone (not always present; Figure 4.8). The upper 10 in. (25.4 cm) of the sandstones are heavily bioturbated in the southern outcrops, but less so to the north. Occasionally, a thin <2 in. (<5 cm) ripple laminated
sandstone is present above the bioturbated package. Ripples include symmetrical, asymmetrical, and interference forms. Ammonite shells and imprints are fairly common in the upper concretionary beds, and are believed to be of *Prionocyclus wyomingensis* (early Upper Turonian).

Figure 4.5 Concentrations of shell fragments are present at the base of many sandstones in the upper Turner. Southern Old Woman Anticline, Wyoming. Hammer handle is 8 in. (0.2 m) long.
Figure 4.6 Hummocky cross-stratification in the upper Turner, southern Old Woman Anticline, Wyoming. Hammer is 13 in. (0.3 m).
Figure 4.7 Typical vertical succession present in the uppermost sandstones in the southern portion of OWA. Starting at the base; 1) concentrated shell fragments, 2) low angle planar laminations, 3) symmetric ripple laminations, 4) bioturbated sandstone. Southern Old Woman Anticline, Wyoming. Hammer is 13 in. (0.3 m).
Figure 4.8 Typical vertical succession present in the uppermost sandstones in the northern portion of OWA. Starting at the base; 1) concentration of shell fragments, 2) trough cross-stratification, 3) low-angle planar laminations. Northern Old Woman Anticline, Wyoming. Hammer is 13 in. (0.3 m).

4.1.2 Newcastle, Wyoming

Newcastle, Wyoming is located along the west-southwest flank of the Black Hills Uplift, approximately 50 mi (80.5 km) north of the exposures at OWA (Figure 1.3). Due to limited public access and quality of the exposures, multiple outcrop locations were tied together to make a composite description for the Newcastle area. The Turner and other members of the Carlile Shale are exposed to the west, southwest, and southeast of Newcastle (Figure 4.9).
Figure 4.9 Outcrop locations used in the Newcastle, Wyoming area to develop a composite description for the Turner. Red star indicates the town of Newcastle, Wy. Green points indicate outcrop locations.

The contact between the Pool Creek and overlying Turner is best observed west of Newcastle approximately 2 mi (3.2 km) along Highway 16. The Pool Creek consists of interbedded dark-gray to light-gray shale and silty shale with thin, lenticular bedded light-gray siltstones. The contact with the overlying Turner was placed were interbedded siltstones of the Pool Creek was overlain by thin, calcareous, medium-grained sandstone (Figure 4.10). The Pool Creek is approximately 90-100 ft (27-30.5 m) thick (Robinson et al., 1964).
Figure 4.10 Contact between the Pool Creek and overlying Turner. Beds are dipping 52° to the southwest. Highway 16 roadcut, Newcastle area, Wyoming.
The lowermost portion of the Turner consists of a light-gray, calcareous, medium-grained sandstone directly overlying the interbedded shales and thin lenticular bedded siltstones of the Pool Creek. Thickness ranges from 0-4 in. (10 cm). The medium-grained sandstone pinches out into the under- and overlying interbedded shale and siltstone (Figure 4.11). Iron concretions less than 0.8 in. (<2 cm) diameter are present and no sedimentary structures were observed. The medium-grained sandstone has a sharp basal and irregular upper contact. Overlying the medium-grained sandstone are medium-gray, interbedded lenticular shales and thin bedded, very fine- to fine-grained sandstones. Sandstone lenses are thin, less than 2 in. (<5 cm) and discontinuous across the outcrop. This facies appears to be gradational with the overlying fine-grained sandstones, as the ratio of sandstone to shale beds, as well as sandstone thickness, increase up section.

Overlying the interbedded lenticular shales and thin bedded sandstones are light-gray, fine-grained sandstones. Sedimentary structures include ripple and planar parallel laminations. The uppermost beds of the fine-grained sandstones are concretionary, tan-yellow, and resistant to weathering. Concretions south of Newcastle along Old Highway 85 are approximately 15 ft (4.5 m) wide and 4 ft (1.2 m) tall. West of Newcastle along Highway 16, concretions are smaller and are approximately 5 ft (1.5 m) wide and 2 ft (0.6 m) tall. Sandstone beds at the base of the concretions and at the top of the ripple and planar parallel laminated sandstones are burrowed by Arenicolites. The contact between the Turner and the overlying shale of the Sage Breaks is sharp. A thin bedded, ripple laminated, fine-grained sandstone was locally observed just below the contact with the Sage Breaks.
Figure 4.11 Calcareous medium-grained sandstone approximately 15 ft above the base of the Turner. Highway 16 roadcut, Newcastle area, Wyoming. Hammer is 13 inches (0.3 m).
4.1.3 Oil Creek Road (WY County Road 10)

Approximately halfway between Newcastle and Osage along Oil Creek Road (OCR) are outcrops of the Greenhorn, Pool Creek, and Turner. This location is on private land and permission should be granted before accessing the outcrops.

The Greenhorn forms gentle slopes capped by a resistant ridge of thin bedded calcareous siltstone and silty limestone. Skeletal fragments of bivalves are abundant at the top of individual beds. Individual bed thicknesses range from 0.7-2.0 in. (2-5 cm) and are discontinuous over a few feet, whereas the bed sets as a whole are more continuous (Figure 4.12).

Figure 4.12 Thin bedded calcareous, fossiliferous silty limestone of the Upper Greenhorn. Individual beds are discontinuous over a few feet, but beds as a whole are continuous across the entire outcrop. Oil Creek Road (WY CR 10), Wyoming.
The contact between the Greenhorn and Pool Creek is not well exposed at this location. The Pool Creek was observed as gentle slope forming medium-gray shales below the lowermost sandstone of the Turner. At this location the Pool Creek is approximately 20-40 ft (6.0-12 m) thick (Robinson et al., 1964). The variability in thickness of the Pool Creek is interpreted to be related to post-depositional erosion associated with the regression of the Greenhorn Sea. This is consistent with the interpretations of Weimer and Flexer (1985), and Rice and Gaskill (1988).

The contact between the Pool Creek and Turner was placed where medium-gray shale and lenticular siltstone are directly overlain by a tan, cross-stratified, medium- to very coarse-grained sandstone (Figure 4.13).

The lowermost Turner consists of a tan, calcareous, cross-bedded, medium- to very coarse-grained sandstone. Granules are common and include igneous and volcanic rock fragments, and black chert. Sedimentary structures include faint cross-stratification, sub-parallel planar lamination, and asymmetric ripple laminations. Sandstone beds are discontinuous and up to 9 in. (up to 23 cm) thick, and thin either direction away from a point of maximum thickness. The contact between the medium- to very coarse-grained sandstone facies and the overlying shale is irregular. About 2 ft of shale separate the basal medium-grained sandstone from the next overlying sandstone package.

Above the basal sandstone in the Turner are three sequences consisting of light- to medium-gray, lenticular shale and very fine-grained sandstone that are capped by tabular fine-grained sandstones. Within each successively younger sequence, the shale
intervals become thicker and sandstones become thicker and more amalgamated (Figure 4.14). Ripple laminations and planar parallel laminations are the dominant sedimentary structures. The sandstone capping the third sequence can be heavily bioturbated near the top. Sandstones are discontinuous within the lower two sequences, the third is concretionary and forms a resistant ridge that can be traced several miles.

Figure 4.13 Contact between the Pool Creek and lowermost Turner is represented interbedded shale and lenticular siltstones overlain by medium- to very coarse-grained sandstone. Oil Creek Road (WY CR 10), Wyoming.
Figure 4.14 Shale intervals increase in thickness and sandstones become more amalgamated and thicker with successively younger sequences. Dashed white line indicates the contact between the Pool Creek and Turner. Black dashed lines separate the sequences represented by red arrows. Oil Creek Road (WY CR 10), Wyoming.
4.1.4 Osage, Wyoming

Osage, Wyoming is located approximate 14 mi (22.5 km) northwest of the Newcastle, and 8 mi (12.9 km) northwest of Oil Creek Road (OCR). Exposures of the Greenhorn, Pool Creek, Turner, and Sage Breaks are present at Osage Oil Field (OOF) which is accessed along Highway 451, approximately 2 mi (3.2 km) southwest of the Highway 16 junction.

Along the northern edge of the field, the Greenhorn forms a prominent ridge capped by white to light-gray limestone and silty limestone. Individual beds are thin and laterally discontinuous similar to those exposed at OCR, but are heavily bioturbated. *Inoceramus labiatus* and *Ostrea sp.* are abundant in beds near the top of the section (Robinson et al., 1964)

The Greenhorn is overlain by poorly exposed dark-gray, calcareous shale and thin, lenticular siltstones of the Pool Creek. The Pool Creek is approximately 10-15 ft (3.0-4.6 m) thick. The contact with the overlying Turner occurs as an increase in thinly bedded fine-grained sandstones that contain abundant black chert grains, or as a bed of medium-grained sandstone also containing abundant black chert grains (Figure 4.15).

The medium-grained sandstone facies forms a dip slope with limited exposures and appears to be discontinuous along strike. Conglomeratic lenses containing black chert granules, and teeth of *Ptychodus sp.*, *Isurus sp.* (Robinson et al., 1964) occur locally near the top of beds. Conglomerates were observed strictly in the eastern portion of the OOF outcrop belt. Cross-stratification is the primary sedimentary structure, however much of the sandstone is also structureless. The medium-grained sandstone
facies is overlain by approximately 30-35 ft (9.1-10.6 m) of dark-gray, silty shale and thin, lenticular, very fine-grained sandstone and siltstone (Figure 4.16). Lenticular sandstone and siltstone beds are < 1.5 in. (4 cm) thick and are typically < 10 ft (3.0 m) wide (Figure 4.17). Sandstones are planar parallel and ripple laminated. The ratio of sandstone to shale increases up section and is gradational with tabular, very fine- to fine-grained sandstones (Figure 4.18). White to light-gray, very fine- to fine-grained sandstones are approximately 9 ft (2.7 m) thick. Individual sandstones are tabular and more continuous than the underlying lenticular sandstones. Individual bed thickness ranges from 1-6 in. (3-15 cm). Sedimentary structures and bedding features include plane-parallel and symmetrical ripple laminations, low-angle crossbeds, minor scour and fill, and burrowing by *Arenicolites*, *Thalassinoides*, and *Ophiomorpha*.

Concretionary, very fine- to fine-grained sandstones conformably overlie the tabular, very fine- to fine-grained sandstones. Beds are thicker and more amalgamated. Sedimentary structures and bedding features include symmetrical ripple laminations, low-angle crossbeds, increased occurrence of scour and fill, and heavy bioturbation. Trace fossils include *Arenicolites*, *Thalassinoides*, and *Ophiomorpha*. Concretions can be up to 15 ft (1.5 m) tall and 250 ft (6.1 m) wide, and form prominent lenticular ridges (Figure 4.19).

Overlying the concretionary sandstones are interbedded dark-gray shales and lenticular sandstones. This facies is similar to the interbedded shale and lenticular sandstones described previously, but contain large, oval calcareous concretions (Figure 4.20). Lenticular sandstones are very fine-grained, primarily planar parallel laminated, and typically less than 3 in. (<7.6 cm) thick. Fossils identified within the concretions
include *Inoceramus perplexus* Whitfield, *Scaphites nigricollensis* Cobban (Robinson et al., 1964). This fossil assemblage places the uppermost Turner in the *Scaphites whitfieldi* Western Interior ammonite zone and of early Upper Turonian age.

### 4.1.5 Summary

At a sub-regional scale (i.e. eastern margin of PRB) the Turner generally consists of a similar facies succession at each location. Thin interbedded shale, siltstone, and sandstone are typically overlain by thicker bedded, more amalgamated sandstone packages. Common sedimentary structures are wavy, ripple, and planar laminations in the interbedded heterolithic facies of the outcrops. In the upper portions, where the Turner is more sandstone dominated, low angle cross-bedding, planar and ripple laminations, and hummocky cross-stratification are present. The upper Turner is characterized by large, reddish brown to tan concretionary sandstone beds that can be followed on the surface for several tens of miles. At smaller scales such as between 1-10 miles, variations in the thickness individual sandstone, lack of certain facies of variations in facies stacking patterns were most noticeable. For instance, the lowermost shale and interbedded interval, between OCR and OOF, ranged from 2-3 ft to more than 30 ft over 8 mi. Successively younger coarsening upward signatures at OCR and to a lesser degree OOF, became thicker and more amalgamated with each overlying sequence. This pattern was not observed at OWA, instead exposures of the upper Turner are thin, hummocky cross-stratified, and contained abundant ammonite fossils and skeletal fragments at the base of bed.
Figure 4.15 Contact between the Pool Creek and Turner is marked by an increase in thin bedded fine-grained sandstone containing abundant black chert grains. Dogs are 2 ft (0.6 m) tall. Osage Oil Field, Osage, Wyoming.
Figure 4.16 Upper contact of the cross-stratified medium-grained sandstone is placed at the base of the dip slope where slope angle shallows, soil color changes from light-gray to dark-gray, and vegetation density increases. Osage Oil Field, Osage, Wyoming.
Figure 4.17 Dark gray, silty shales and thin, lenticular, very fine-grained sandstone and siltstone. Sandstones are planar parallel and ripple laminated, <4 cm thick, and <10 ft wide. Osage Oil Field, Osage, Wyoming. Hammer is 13 in. (0.3 m).
Figure 4.18 Silty shales and thin, lenticular sandstone and siltstone are gradational with overlying tabular, very fine- to fine-grained sandstone. Sandstone to shale ratio increase upward through the succession. Osage Oil Field, Osage, Wyoming. Hammer is 13 in. (0.3 m).
Figure 4.19 Concretionary sandstones in the upper portion of the Turner weather tan to orange and from prominent lenticular ridges. White to light-gray sandstone at the base of the outcrop thickens and becomes more amalgamated up-section. Substantial bioturbation is present in many beds and gives the rock a crumbled rough appearance. Osage Oil Field, Osage, Wyoming.
Figure 4.20 Concretions in the uppermost interbedded shale and lenticular sandstone facies of the Turner are approximately 9.5 ft (2.9 m) wide and 5.5 ft (1.7 m) tall. The hammer on the right concretion is 16 in. (0.4 m). Osage Oil Field, Osage, Wyoming.
4.2 Core Analysis

A total of 25 cores were used to describe and characterize the facies succession and key surfaces in the Turner. Observations and descriptions are summarized for each field containing core data used in this study.

4.2.1 K Bar Field

K Bar is located in south-central Campbell County and hosts the northwestern most data used in this study (Figure 1.4). Sixty feet of core from the Groves 4 was graciously donated to this study by Yates Petroleum.

The Turner essentially consists of three coarsening upward successions capped by MnFS and separated by bioturbated shaly siltstone to sandstone (Figure 4.21). The sandstone facies within the coarsening upward sections consists of very fine- to fine-grained sandstone, bioturbated sandstone, and minor heterolithic shaly sandstone, siltstone to mudstone. The percentage of sandstone prone facies increases with each individual coarsening upward succession, although the total thickness of individual succession does not. The uppermost six feet of the core consists of at least four MnES and two MnFS. Occasionally a medium- to coarse-grained, granular sandstone lag occurs above the MnES, in beds approximately 1-2 in. thick (Figure 4.22). This is the coarsest material documented in core from the Turner.

The Turner at K Bar is predominantly fine-grained with the exception of the coarser grained lags above the MnES mentioned in the previous paragraph. Grains are subangular to subrounded and well sorted. The majority of samples from the Groves 4 core plot as lithic arkose or feldspathic litharenite, with two samples plotting in the sub arkose portion of the QFR diagram (Figure 4.23).
Figure 4.21 Core description of the Groves 4, K Bar field.
Figure 4.22 Core photograph from the upper nine feet of the Groves 4 core. Interpreted MnFS (blue) and MnES (red) have been annotated on the core to show the complex facies succession in of the upper Turner at K Bar field. Core +2ft = log.
Figure 4.23 Point count data from the Groves 4 plots the majority of the samples as lithic arkose or feldspatic litharenite on the Folk QFR diagram.
4.2.2 Tuit Draw Field

Tuit Draw field is located approximately 10 mi (16 km) southeast of the Groves 4, between K Bar and Porcupine fields (Figure 1.4). Five cores from the field were used in the study. Cores taken from the Turner were often at different stratigraphic levels where neighboring cores would be used side by side to describe a greater portion of the interval (Figure 4.24). Well spacing is fairly tight. The maximum distance between any two wells is about 2 mi (3.2 km).

The Turner consists of two to three coarsening upward successions typically capped by MnFS. Each succession generally grades from bioturbated shaly siltstone to sandstone upward into various sand-prone facies (Figure 4.24). Bioturbation is dominated by Thalassinoides, Cylindrichnus, and Phycosiphon of the Cruziana ichnofacies, with some Skolithos overprinting.

The uppermost coarsening up succession is capped by a MnES that demarcates bioturbated sandstone from the overlying medium-grained sandstone facies (10,035.1 MD in Figure 4.25). The MnES is correlable throughout Tuit Draw. Below the erosional surface, burrows are passively filled by medium-grained sediment of the overlying facies (Figure 4.25 and Figure 4.26). This surface has implications on sedimentation rates, as well as the evolutionary history of the deposit.

The Prionocyclus germari FS separates faintly cross-bedded to structureless, medium-grained, carbonate cemented sandstone from the overlying argillaceous silty mudstone and mudstone of the Sage Breaks. Within the Tuit Draw cores, the FS is more erosive and truncates bedding surfaces and laminations of the underlying facies.
Figure 4.24 Core descriptions of the Underwood Ranch 11-33 (core-1ft =log) and Wilmot Fee 33-1 (core-4ft =log), Tuit Draw field.
Figure 4.25 Core photo of the Underwood Ranch 11-33, Tuit Draw field. Note the oil staining below the MnES within the *Glossiofungites* ichnofacies/bioturbated sandstone lithofacies. EB=event bed, MnES= minor erosional surface, FS=flooding surface.
Figure 4.26 Core photo of the Wilmot Fee 33-1, Tuit Draw field. Typical facies succession for the field has an overall coarsening upward signature, truncated by the bounding flooding surface. Key surfaces and features include: EB=event bed, MnES=minor erosional surface, FS=flooding surface.
4.2.3 Porcupine Field

Porcupine field is located immediately to the southeast of Tuit Draw and Crossbow fields (Figure 1.4). Crossbow field was discovered by EOG in 2008 and has been a successful target for horizontal drilling within the Turner.

In northwestern Porcupine, the lower 1/3 of the cored interval from the Birdsall 12-10 (Figure 4.27) consists predominately of bioturbated muddy siltstone to sandstone. Carbonate cementation occurs in the medium-grained sandstone facies near the top of the succession. Bioturbation is dominated by Thalassinoïdes and Phycosiphon. In the overlying bioturbated sandstone facies Ophiomorpha, Thalassinoïdes, and occasional Skolithos burrows become more abundant (Figure 4.28). An interpreted MnES separates the bioturbated sandstone from the overlying medium-grained sandstone facies. Similar to Tuit Draw, carbonate cement has preferentially occluded the porosity in the medium-grained sandstone facies of the Turner.

Two miles south, the Quillback 2-33 consists of planar laminated to structureless, very fine-to fine-grained sandstone irregularly overlying bioturbated shaly siltstone and sandstone (Figure 4.29 and Figure 4.30). Individual beds appear scoured at the base, and are normally graded over a few inches. Fugichnia is present in several of the sandstone beds where bioturbation is otherwise rare. Facies boundaries are more gradational, specifically those associated with the bounding FS near the top of the Turner.
Figure 4.27 Core description of the Birdsall 12-10, Porcupine field. Note the oil staining strictly present within the bioturbated sandstone faces. Core-11.5 ft=log.
Figure 4.28 Core photo of the Birdsall 12-10, Porcupine field. Note that the facies and stratigraphic position of oil staining is similar to the cores from Tuit Draw. Note the presence of very fine-grained and heterolithic facies at 9388.5' and 9385.8', respectively. EB=event bed. MnES=minor erosion surface, FS=flooding surface. Core-11.5=log.
Figure 4.29 Core description for the Quillback 2-33, Porcupine field. Core+5 ft=log.
Figure 4.30 Core photos of Quillback Federal 2-33, Porcupine field. Note subtleness of the flooding surface at the top of the Turner. FS=flooding surface, MnES=minor erosional surface. Core+5=log.
4.2.4 SE Porcupine Wildcat

Eleven miles southeast of Porcupine is a wildcat drilled and cored by Davis Oil Company. The Connelly Federal 1 cored through 104 ft of the Turner, covering the entire lower Turner, and the majority of the upper Turner. Although geographically closer to the Porcupine area, the stratigraphy at this location resembles that of the Brooks Draw area approximately 20 mi to the south-southeast.

The basal portion of the lower Turner consists of laminated siltstone, sandstone, and interbedded mudstone. Wavy, flaser, ripple, and planar parallel laminations are all present in the thinly bedded sandstones and siltstone. Approximately 25 ft of heterolithic shaly sandstone, siltstone, and mudstone conformably overlie the laminated and thinly bedded facies in the lowermost portion of the lower Turner. The heterolithic facies are capped by an interpreted FS associated with the top of the Scaphites warreni fossil zone. Overlying the Scaphites warreni FS are argillaceous mudstones and pin stripe siltstone laminations. Log signatures (high GR, low resistivity, low DPHI, and high NPHI) and stacking patterns suggest the argillaceous mudstones may represent the “deepest water” or most distal facies present in the lower Turner. This interpretation would then make the Scaphites warreni surface a transgressive surface and the overlying argillaceous mudstones may correspond to a time maximum flooding in this area.

Bioturbation in the lower Turner is indicative of a stressful or restricted marine environment. Traces are small in size, moderately abundant, and of low species diversity. This suggests that the organisms colonizing the sediments at that time were at least partially adapted to the environmental conditions. Argillaceous mudstones grade upward into heterolithic shaly sandstone, siltstone, and mudstone facies. The
succession continues coarsen upward before being capped by the *Scaphites whitfieldi* FS. The *Scaphites whitfieldi* FS is a regionally correlatable surface and is used to divide the Turner in to a lower and upper unit.

The remaining cored portion of the upper Turner is moderately to heavily bioturbated where all primary sedimentary structures have been biologically overprinted. *Thalassinoides, Arenicolites*, and *Planolites* form a transitional ichnofabric between the less bioturbated argillaceous mudstones and the heavily bioturbated shaly siltstone to sandstones above. Within the bioturbated shaly siltstone to sandstone facies of the upper Turner, subtle coarsening or shallowing upward signatures were documented. A repetitive altering between facies subgroups 5.1 and 5.2 provide enough contrast in grains size and clay content that the gamma ray log can resolve the sequences, and correlate well with detailed facies descriptions (Figure 4.31). Three very subtle coarsening upward successions capped by MnFS are present in upper Turner from the Connelly Federal 1 core. The overall thickness of each is roughly equal; however the ratio sandstone to shale increases successively (Figure 4.31 and Figure 4.32).

Sandstones within the Connelly Federal 1 are predominantly very fine-grained. Grains are subangular to subrounded and well sorted and plot as feldspathic litharenite and litharenite on the QFR diagram (Figure 4.33).

**4.2.5 Finn Shurley Field**

Finn Shurley is located along the eastern flank of the PRB, approximately 30 miles east northeast from the Connelly Federal 1, and 40-45 mi east of Porcupine and Tuit Draw (Figure 1.4).
Figure 4.31 Core description for the Connelly Federal 1, wildcat, SE Porcupine. Two flooding surfaces correspond to the top of the *Scaphites warreni* and *Scaphites whitfieldi* fossil zones, *Prionocyclus germari* was not cored in this well. Note the three coarsening upward successions in the upper Turner and the progressive increase in sandstone to shale in each. Core+3 ft=lg.
Figure 4.32 Core photograph of the Connelly Federal 1, wildcat, SE Porcupine. Base of the core is lower right, top is uppermost left. MnFS=minor flooding surface, FS=flooding surface. Core+3 ft=log.
Figure 4.33 Point count data from the Connelly Federal 1.
Cores from Finn Shurley were all taken from the lower Turner, and consist of 3-4 coarsening upward successions capped by 1) silty, argillaceous mudstones, 2) bioturbated shaly siltstone to sandstone, or 3) a heterolithic shaly siltstones and mudstones (subfacies 4.1; Table 3.3). The *Scaphites warreni* FS is present in four of the five cores from Finn Shurley, whereas the *Scaphites whitfieldi* FS was only present in the Perpetual Finn #8 (Figure 4.34). The *Prionocyclus germari* surface was not sampled in any of the cores from this area.

The predominant facies in the lower Turner at Finn Shurley are heterolithic shaly sandstones, siltstones, and mudstones (and associated subfacies). Other facies include 1) silty, argillaceous mudstones, 2) very fine- to fine-grained laminated sandstone, and 3) bioturbated shaly siltstone to sandstone (Figure 4.34). Additionally, there are some coarser beds that contain granule size chert grains and smaller skeletal fragments. Coarse beds range in thickness from 0.4-0.7 in. (1-2 cm) up to 10 in (24.4 cm). The coarser facies makes up a rather small percentage of the overall interval, but is unique in that it was only documented in lower Turner on the eastern side of the study area. Beds associated with the laminated and heterolithic facies range from <0.5 in. (1.2 cm) to < 4 in. (10 cm), and are normally graded (Figure 4.35). Mudstone rip up-clasts are also present along the base of many of these beds (Figure 4.36).

The lower Turner is thicker in this part of the basin and more heterolithic compared to the western portion of the study area. Coarsening upward facies successions match those shown on geophysical logs and are unique to the lower Turner at Finn Shurley.
Figure 4.34 Core descriptions for the Colen 10-10 (core+7 ft=log) and Perpetual Finn #8 (core+12 ft=log), Finn Shurley. Only the lower Turner was cored at Finn Shurley, and primarily is composed of a heterolithic facies (shown in green).
Additionally, the coarsest grain size in the lower Turner was recognized in the heterolithic facies, which was not present in core from the lower Turner to the west and southwest near Porcupine and Brooks Draw, respectively.

Figure 4.35 Sandstone bed within the heterolithic facies of the lower Turner at Finn Shurley. Massive or structureless sandstone with granules that is overlain by sub planar laminations. These are interpreted to have been deposited during the same event.
Figure 4.36 Mudstone rip up clasts and coarse grains at the base grade into massive or structureless fine-grained sandstone, and then into planar laminated sandstone.

4.2.6 Brooks Draw Field

Brooks Draw is located along the border of Converse and Niobrara counties (Figure 1.4). Production from the field has been predominantly restricted to the lower Turner. The Abraxas Lakeside 1H and City Services Cow Creek #3 are located 2 mi (3.2 km) apart. The Lakeside 1H covers 106 ft (32.3 m) of the Turner, and the Cow Creek #3 covers the entire interval. In this area, the Turner is approximately 133 ft (40 m) thick.

The lower Turner disconformably overlies argillaceous mudstones of the Pool Creek. The contact was observed in both the Lakeside 1H and Cow Creek #3 cores,
and varies from scoured to gradational. The disconformity is interpreted as a regressive surface of erosion (Figure 4.37, Figure 4.38), and constitutes a 2.42 Ma hiatus based on missing faunal zones for eastern Wyoming. No evidence for subaerial exposure was observed at the disconformity in either core.

Above the regressive surface of erosion, the lower Turner consists of predominantly heterolithic, shaly sandstone and siltstone, and very fine- to fine-grained sandstone, with minor amounts of thinly laminated siltstone, sandstone, and mudstone. The *Scaphites warreni* and *Scaphites whitfieldi* FS each cap a coarsening upward sequence from silty, argillaceous shale into heterolithic, shaly sandstone and siltstone (Figure 4.38). The *Scaphites whitfieldi* FS separating the lower and upper Turner demarcates very fine-to fine-grained sandstone from the overlying bioturbated shaly siltstone to sandstone.

The upper Turner consists predominantly of a bioturbated shaly siltstone to sandstone facies at Brooks Draw. Multiple MnFS are present in the upper Turner, similar to those observed in the Connely Federal 1. The *Prionocyclus germari* FS denotes the lithostratigraphic top of the Turner and demarcates bioturbated shaly siltstone to sandstone facies from the overlying silty, argillaceous mudstone facies of the Sage Breaks (Figure 4.37, Figure 4.38).

The Turner at Brooks Draw is predominantly very fine-grained sandstone. Grains are subangular to subrounded and well sorted. Samples from the Cow Creek #3 and Lakeside 1H consist of sublitharenite, feldspathic litharenite, and litharenite (Figure 4.39).
Figure 4.37 Core photographs for the entire City Services Cow Creek #3. Note the color variation within the bioturbated shaly siltstone and sandstone, below the uppermost flooding surface. RSE=regressive surface of erosion, FS=flooding surface, MnFS=minor flooding surface. Core-2 ft=log.
Figure 4.38 Core description of the Cow Creek #3, Brooks Draw field. The entire Turner was cored in this well. Core-2 ft=log.
Figure 4.39 Point count data from the Cow Creek #3 and Lakeside 1H cores from Brooks Draw field.
4.3 Discussion

The following sections discuss depositional processes and environments based on observed sedimentology, facies successions, and facies distributions.

4.3.1 Lithofacies Distribution

Net to gross plots show a non-uniform facies distribution across the study area. From west to east, facies transition from being more sand prone to being more interbedded and mud prone (Figure 4.40).

Medium-grained sandstone and bioturbated sandstone facies occur in the upper Turner and are generally restricted to the K Bar, Tuit Draw, and Porcupine areas. Toward the east, age equivalent facies consist of bioturbated shaly siltstone to sandstone (Figure 4.41, Figure 4.42), and are interpreted as the distal equivalents to the sand-rich facies in the Porcupine, Tuit Draw, and K-Bar areas.

The lower Turner consists of bioturbated shaly siltstone to sandstone in the K Bar, Tuit Draw, and Porcupine areas. Toward the east, the lower Turner is thicker and becomes more interbedded, consisting predominantly of facies groups 2, 3, and 4 (Figure 4.43, Figure 4.44).

Merewether et al. (2007) reported progressive truncation and removal of biozones toward the west, below the Turner-Pool Creek disconformity and suggested that paleohighs may have resulted in increased erosion and a subsequently irregular depositional surface. The aforementioned thicker, lower Turner that is present in the eastern portion of the study area is interpreted to onlap the RSE toward the west.
(Figure 4.42). It is possible that the onlapping observed in the lower Turner is a result of reactivation of the paleohigh proposed by Merewether et al. (2007).

**4.3.2 Lower Turner**

In decreasing order of abundance, heterolithic (facies group 4), laminated siltstone and sandstone (facies group 3), and very fine-to fine-grained sandstone (facies group 2) dominate the facies succession at Brooks Draw, in the Connelly Federal 1, and at Finn Shurley. This facies succession in the lower Turner is unique to those areas (Figure 4.40).
Figure 4.41 Index map showing facies correlation panel cross sections.
Figure 4.42 Facies correlation panel A-A’. Medium-grained sandstone and bioturbated sandstone appear to be coeval with the bioturbated shaly siltstone to sandstone in the upper Turner to the southeast (A’). Note facies present in the lower Turner, below the *Scaphites whitfieldi* flooding surface thin toward and onlap the RSE at the base of the Turner.
Figure 4.43 Facies correlation panel B-B'). Note facies present in the lower Turner, below the Scaphites whitfieldi flooding surface thin toward and onlap the RSE at the base of the Turner toward the west (B).
Figure 4.44 Facies correlation panel C-C’. Note facies present in the lower Turner, below the *Scaphites whitfieldi* flooding surface thin toward and onlap the RSE at the base of the Turner toward the west (C).
4.3.2.1 Trace Fossils

Bioturbation within lower Turner facies can range from $BI=0$ to $BI=4$ within centimeters. Colonization is primarily by opportunistic burrowers of a low diversity and low population ichnogenra consisting of small *Arenicolites* and *Planolites*. Low species diversity and population are an indication that the depositional environment was stressful and hard on the organisms and as such certain facies of the lower Turner are not widely colonized (Bromley, 1996).

A cross section of lower Turner core descriptions and Bioturbation Index (BI) shows the temporal and spatial relationships between lithofacies and degree of bioturbation (Figure 4.45). In the Connelly Federal 1 and Lakeside 1H, the lowermost Turner is characterized as by a low, non-uniform BI that shifts to moderate, non-uniform at measured depths of 8,990 ft and 8478 ft. This shift toward an increased degree of bioturbation occurs along a boundary between laminated and very fine- to fine-grained facies and the overlying heterolithic facies. This relationship suggests there may be a link between depositional processes and environmental stress during deposition of the lower Turner. A possible explanation for the increase in BI from the very fine- to fine-grained facies into the overlying heterolithic facies and up to the *Scaphites warreni* FS is that a relative sea-level rise resulted in decreased sedimentation rates in that area.

Between the *Scaphites warreni* and *Scaphites whitfieldi* FS an upward increasing BI trend is present in the Connelly Federal 1, Lakeside 1H, and Colen 10-10 indicating a spatial improvement in the environmental conditions.
Above the *Scaphites whitfieldi* FS the upper Turner is characterized by a uniform and high BI trend that suggests stable environmental conditions capable of supporting an abundant and diverse colony was spatially extensive across much of the study area during upper Turner deposition (Figure 4.45).

### 4.3.2.2 Sedimentology

**Fining-Upward Successions**

It is important to note that numerous depositional processes can result in fining-upward successions of normally graded and event-like beds. Boggs (2009) notes that dissipating river flooding events, turbidity currents and other sediment gravity flows, storm event-beds, periodic silting on delta distributaries, settling ash from volcanic eruptions can all result in normally graded bed and fining-upward deposits. Macquaker et al. 2010 recognized another process referred to as wave-enhanced sediment-gravity flows (WESGFs). WESGFs consist of a three-part microfabric that exhibit upward fining throughout the bedded succession.

Primary sedimentary structures in the lower Turner include plane-parallel, ripple, wavy, and flaser laminations. Typically beds range from thin to medium, are normally graded, and contain organic-rich mud drapes. Common to the lower Turner at Finn Shurley are bedding successions consisting of (+/-) mudstone rip-up clasts, (+/-) “floating” coarse sand and granules in otherwise finer-grained sandstone, a structureless or disorganized basal bed gradationally overlain by plane-parallel to sub-parallel laminations, and then combined-flow ripple laminations (Figure 4.46).
Figure 4.45 Northwest to southeast cross section of the lower Turner. BI plots showing a non-uniform signature in the lowermost Turner, an upward increasing trend between the *Scaphites warreni* and *Scaphites whitfieldi* flooding surfaces, and a uniform and high trend in the upper Turner above the *Scaphites whitfieldi* flooding surface. For explanation of BI trends and resulting environmental conditions see Figure 3.8.
Plane-parallel to sub-parallel and combined-flow ripple laminations also may be present or absent. Capping the successions are organic-rich mud drapes and mudstone beds up to 0.8 in. (2 cm) thick. Combined, the observed succession of sedimentary structures and vertical reduction in grain size suggests that lower Turner sedimentation is linked to depositional processes resulting from waning flow energy. Of the aforementioned processes resulting in fining-upward successions, storm-generated flows and turbidity currents are interpreted to be the dominant depositional processes involved in Turner sedimentation.

**Storm-influenced Successions**

Sedimentary features common in the lower Turner, specifically noted in the Cow Creek #3 (Brooks Draw field) and Colen 10-10 (Finn Shurley field) cores are beds consisting of curved or concave laminations with low-angle, wavy truncation surfaces. Beds range from 2-5 cm thick and are typically capped up to a centimeter or more of organic mud (Figure 4.47). These bed forms were originally interpreted as ripple cross-laminations or climbing ripples where only foresets were preserved (Figure 4.47). The thin bedded nature of the structures does not agree with the rapid sedimentation central to the formation of ripple cross-laminated bed forms. Additionally there should be some evidence for waxing or waning flow energy associates with ripple cross-laminated bed forms such as underlying plane-parallel laminations, or upward decreasing ripple amplitude due to suspension sedimentation and reduced traction sedimentation rates (Boggs, 2009). Neither of which were observed in cores from the lower Turner.

Alternatively, these bed forms have been interpreted as micro-hummocky cross-stratification (MHCS). Comparatively, HCS forms larger, sand-rich, bedding structures in
the distal shoreface-proximal offshore environments, whereas MHCS typically occurs in thin interbedded sandstones and mudstones deposited near storm wave base (Dott and Bourgeois, 1982).

Another type of storm-influenced sedimentation are interpreted as storm-generated sedimentary gravity flows (SGSGFs). SGSGFs are herein described as “surge-type” flows, where vertical successions of sedimentary structures indicate deposition from decelerating erosive storm currents. Walker (1985) reported a number of storm-related mechanisms that could initiate sediment gravity flows (SGFs) including storm-surge relaxation, cyclic storm-wave loading, and river flooding due to heavy precipitation inland. The important storm-related forces responsible for transporting sediment include 1) frictional forces associated with the sea floor that act opposite to water movement directions, 2) the generation of an offshore pressure gradient due to coastal setup or setdown, 3) the Coriolis effect that acts at 90° to the water movement direction, and 4) the downslope dispersion of excess weight associated with increased sediment concentrations (Myrow and Southard, 1996).

A key component of SGSGFs is the relationship between shore-parallel geostrophic currents and the formation of a bottom boundary layer. Shore-parallel geostrophic currents form due to the combined effects of the Coriolis effect and offshore directed pressure gradient. The resulting geostrophic currents flow parallel to bathymetric contours and subsequently apply shear stress to the sea floor resulting in the formation of the bottom boundary layer (Myrow and Southard, 1996).
Figure 4.46 Lower Turner interbedded heterolithic and laminated facies from Finn Shurley. Common sedimentary structures and textures include 1) mudstone rip-up clasts, or coarse sand and granules at the base of beds, 2) coarse sand and granules “floating” in otherwise finer-grained sandstone, 3) bedding is disturbed, and rip-up clasts present, 4) plane-parallel to sub-parallel laminations, and 5) combined-flow ripple laminations. Beds are typically graded, but rip-up clasts are not always present. At Brooks Draw and in the Connelly Federal 1 core, no rip-up clasts were documented.
Figure 4.47 Curved to convex laminations with low-angle truncation surfaces. Note that in (A) the event bed has an irregular basal contact and has scoured into the underlying heterolithic siltstone and mudstone. B) Note that the truncation and depositional lee surfaces are at lower angles, but show similar overall geometries as in (A). Additionally, notice the nature of the contact between the mudstone drapes and the underlying bed form in A) the contact is erosional, whereas in B) the contact is gradational. Both examples are from the Cow Creek #3, Brooks Draw.
Walker et al. (1983) described a succession of sedimentary structures of a storm bed as consisting of, from older to younger, 1) massive/graded, 2) parallel laminaions, 3) HCS, and 4) wave ripple cross-lamination. The divisions by Walker et al. (1983) resemble those ascribed to the Bouma Sequence with respect toward the depositional nature and relationship to waning flow energy. It is understandable how deciphering the two could be challenging especially if the succession were missing certain sedimentary structures. Myrow and Southard (1996) proposed a tripartite model that predicts sedimentary successions based on possible combinations of storm processes. Similar to the triangle models used to describe the modifying influences of deltas, storm deposits can occur in numerous forms depending on the relative influence of depositional processes (Figure 4.48).

Deposits of the lower Turner, specifically the heterolithic shaly sandstone, siltstone, and mudstone, and the laminated siltstone, sandstone, and mudstone facies show evidence for being deposited by SGSGFs (Figure 4.46, Figure 4.47). Distinguishning characteristic of SGSGFs include the presence of oscillation ripples, combined-flow structures, and HCS/MHCS.

**Bouma-like Sequences**

Many of the beds in the lower Turner do not contain diagnostic HCS/MHCS, but do consist of vertical successions exhibiting waning flow structures similar to those of a Bouma sequence (Figure 4.49). Bouma-like sequences in the lower Turner are interpreted as turbidity currents that aided in the across-shelf transport of the fine-grained sediments.
Figure 4.48 Tripartite model for predicting the possible sedimentary outcomes based on the relative influence and combination of storm processes. It should be noted that the “classical turbidite” succession formed by purely density-induced flow, essentially defines non-storm conditions, as sediment suspension occurs independent of wave and current activity. From Myrow and Southard 1996.
Figure 4.49 Bouma-like sequence in the lower Turner characterized by a) sub-planar laminations, b) ripple laminations, c) sub-planar laminations, d) mudstone. Deposits such as this resemble Tbcde successions of the Bouma Sequence.

**Mudstone Layers**

Ichaso and Dalrymple (2009) suggested that any mudstone layers greater that 5 mm thick may have been deposited as fluid muds. Aplin and Macquaker (2011) summarized the substantial catalog of previous work related to mud transport and deposition on continental shelves, and note that transport predominantly occurs as dense fluid muds within the boundary layer. The slope of most continental shelves (<0.5°) is generally too low to effectively generate purely density driven sediment gravity flows, and additional energy supplied by wave activity is necessary to initiate flow (Myrow and Southard, 1996; Ogston et al., 2000; Wright et al., 2001; Macquaker et al., 2010; Aplin and Macquaker, 2011).
Mudstones observed in the lower Turner range from single laminations to less than 0.8 in. (<2cm) thick, and may be gradational with underlying siltstones and sandstone, or are sharp based and erosional. Two mechanisms are proposed to explain the observed mudstones based on thickness, sedimentary structures, and basal contact; 1) suspension settling, and 2) dynamic deposition via sediment gravity flow.

Thin mudstone laminations forming drapes capping sub-planar, ripple, and wavy-flaser siltstone and sandstone bed forms are interpreted as suspension deposits. It is possible that mudstones and associated siltstone and sandstone were affected by tidal processes. However, diagnostic tidal indicators are rare, but bidirectional ripples and reactivation surfaces were observed (Figure 4.50). Thicker mudstones that are gradational with underlying siltstone and sandstone are also interpreted as a result of suspension settling associated with waning flow energies (Figure 4.47b and Figure 4.49).

Thick mudstone beds 0.4-0.8 in. (1-2 cm) that discordantly overlie siltstones and sandstones are interpreted as fluid muds deposited by wave-enhanced sedimentary gravity flows. These deposits may overlie interpreted SGSGFs (Figure 4.47a) and seem to indicate a hydrodynamic jump and dynamic deposition rather than suspension settling, or occur seemingly randomly within very fine-grained sandstones (Figure 4.51).

4.3.3 Upper Turner

4.3.3.1 Trace Fossils

Bioturbation in the upper Turner is generally more pervasive than in the lower Turner, particularly in the southern and southeastern portions of the study area.
Figure 4.50 Thin mudstone laminations capping sub-planar, ripple, and wavy-flaser bedding in the lower Turner. Mudstone has been interpreted as a result of suspension settling.
In this area the upper Turner consists primarily of shaly bioturbated siltstone and sandstone dominated by archetypal *Cruziana*. Toward the northwest, lithofacies are predominantly sandstone dominated and *Cruziana* and *Skolithos* are the dominant ichnofacies (Figure 4.40).

In the areas of K Bar, Tuit Draw, and Porcupine *Cruziana* ichnofacies are gradationally overlain by *Skolithos*. Locally, *Glossifungites* is present in the bioturbated sandstone facies and is recognized by *Skolithos* burrows that have been passively filled with medium-grained sediments from facies group 1. The contact between the bioturbated sandstone and overlying medium-grained facies is sharp and discordant. The lack of MnFS capping the uppermost coarsening upward successions at Tuit Draw suggests that some degree of erosion has occurred along this surface. The
interpretation that erosion has occurred between the two aforementioned facies suggests the two are not genetically linked. As such, the surface may have sequence stratigraphic implications that could be helpful in fully understanding the depositional history of the upper Turner.

BI plots show a uniform and high signature throughout the upper Turner in the southern and southeastern portion of the study area. The uniform and high BI trend indicates stable environmental conditions capable of supporting an abundant and diverse ichnofauna assemblage.

4.3.3.2 Sedimentology

In the southeastern and southern portion of the study area, the upper Turner consists primarily of shaly bioturbated siltstone and sandstone. Color variations in the upper Turner shaly bioturbated siltstone and sandstone facies are a result of mineralogical variations between sand- and clay-rich subfacies 5.1 and 5.2, respectively. The light-gray color of subfacies 5.1 is enhanced when carbonate cement is present. Besides color variation, Subfacies 5.1 can also be identified on well logs by an upward decreasing gamma ray response capped by a deepening surface (Figure 4.37, Figure 4.38).

Toward the northwestern portion of the study area, within K Bar, Tuit Draw, and Porcupine fields, the upper Turner is dominated by structureless and faintly cross stratified medium-grained sandstone, bioturbated sandstone, and bioturbated shaly siltstone and sandstone. Lesser amounts of very fine- to fine-grained sandstone and heterolithic shaly sandstone, siltstone, and mudstone facies occur sporadically (Figure
4.28). The general lack of thin bedded heterolithic facies, the presence of abundant sand-prone facies, and overall coarser nature of the sediments is interpreted to correspond to deposition in a more proximal location along the shelf compared to the more distal shelf deposits in the Brooks Draw and Finn Shurley areas.

The presence of *Glossifungites* ichnofacies at Tuit Draw suggests a break in sedimentation prior to deposition of the faintly cross-bedded medium-grained sandstones. Lewis (2012) documented the several subaqueous unconformities notably a *Glossifungites* assemblage between the Codell Sandstone-Juana Lopez, and the Juana Lopez-Fort Hays Limestone, and concluded that transgressive reworking aided in erosion and removal.
CHAPTER 5: RESERVOIR CHARACTERIZATION

5.1 Reservoir Analysis

Routine core analysis (RCA), core description, x-ray diffraction (XRD), and petrographic data were integrated and utilized to interpret reservoir intervals and possible controls on hydrocarbon production from the Turner.

5.1.1 K Bar Field

Reservoir facies at K Bar field were identified from the Groves 4 core and include very fine- to fine-grained sandstones and bioturbated sandstones.

Core porosity and permeability values for the very fine- to fine-grained sandstones range from 8 to 12 % and 0.06 to 1.2 mD, respectively. Water saturations are low compared to the over- and underlying facies. The very fine- to fine-grained sandstones in the Groves 4 occurs as thin beds within thicker facies successions, or as thin discrete event beds in otherwise bioturbated silty sandstones.

Core porosity and permeability values for the bioturbated sandstone facies range from 8 to 12 % and 0.07 to 0.15 mD, respectively. Oil staining was observed between 10,469 and 10,458 ft MD, and was only present in that facies. The occurrence of oil staining correlates well with the measured water and oil saturation data (Figure 5.1). RCA data for intrinsic properties is somewhat similar between the two interpreted reservoir facies. However, the bioturbated sandstone facies is thicker and tends to form more “amalgamate-like” beds as opposed to thin, interbedded or discrete beds. Porosity and permeability cross plots show a direct correlation and highest values for the
bioturbated sandstones, indicating the good reservoir quality associated with this facies (Figure 5.2).

XRD data from the Groves 4 record similar compositional trends between the bioturbated sandstone and very fine- to fine-grained sandstone facies. Each interpreted reservoir interval is characterized by an upward increase in weight percent quartz, an upward decrease in weight percent mixed-layer illite/smectite, and less than 15 wt. % total clays (Figure 5.3).

Porosity within the reservoir facies occurs as both primary and secondary. Primary porosity appears to be preserved due to early cementation by grain coating clays. Secondary porosity results from partial and complete dissolution of feldspar and lithic grains, and from fractured grains (Figure 5.4).

5.1.2 Tuit Draw Field

Potential reservoir intervals were identified from core analysis data from the Wilmott Fee 33-1. At Tuit Draw, the most favorable reservoir facies consist of bioturbated sandstones. Porosity and permeability data from the bioturbated sandstones range from 9 to 11 % and 0.01 to 0.09 mD, respectively. Saturation data from this facies shows decreased water saturation and increased oil saturation and correlated well with oil staining observed in the core (Figure 5.5). Medium-grained sandstones present at the top of the upper Turner (9,695 MD) have favorable saturations, but slightly lower porosity and permeability compared to the bioturbated sandstones. Within the medium-grained sandstones carbonate cement was present and may be responsible for the lower porosity and permeability, and lack of oil staining.
Figure 5.1 Core description and core analysis data from the Groves 4, K Bar field. Interpreted reservoir intervals are highlighted by red dash-dot boxes. Shaded in red is a zone of increased hydrocarbon saturation, porosity, and permeability within the bioturbated sandstone facies of the upper Turner.
Figure 5.2 Cross plot of porosity and permeability data from the Groves 4, K Bar field. Note the direct correlation and highest measured values for the bioturbated sandstone facies.
Figure 5.3 X-ray diffraction data from the Groves 4 core, K Bar field. Interpreted reservoir intervals are characterized by an upward increase in weight percent quartz, an upward decrease in weight percent mixed-layer illite/smectite, and less than fifteen weight percent total clay. Interpreted reservoir intervals are highlighted by red dash-dot boxes.
Figure 5.4 Examples of the different porosity types in reservoir facies from the Groves 4, K Bar field. A) primary intergranular porosity has been preserved due to early cementation by grain coating clays. B) Secondary porosity due to grain dissolution and grain fracturing.
Figure 5.5 Core description and core analysis data from the Wilmot Fee 33-1, Tuit Draw field. Interpreted reservoir interval is highlighted by red dash-dot boxes.
Cross plotted porosity and permeability data show a loose correlation, but indicate the bioturbated sandstones have the highest reservoir quality (Figure 5.6). The loose correlation between porosity and permeability in the Wilmot Fee 33-1 could be related to poor data quality.

Figure 5.6 Cross plot of porosity and permeability data from the Wilmot Fee 33-1, Tuit Draw field. Note the loose correlation between porosity and permeability. This may be related to poor data quality.
5.1.3 Porcupine Field

Potential reservoir intervals were identified from core analysis data from the Quillback Federal 2-33. Porosity and permeability data for this well were limited, but do indicate that the medium-grained sandstones and the bioturbated sandstones have the highest reservoir quality. Oil staining was observed in the core only in the bioturbated sandstones in the upper portion of the upper Turner (Figure 5.7).

Cross plotted porosity and permeability data show there is a correlation between the two properties. Although data are limited, bioturbated sandstones had the highest values and best correlation of porosity and permeability of any facies measured (Figure 5.8).

5.1.4 Finn Shurley Field

Core analysis data from the McTuillin-Federal1 and XRD data from the Colen 10-10 were utilized to identify and evaluate potential reservoir intervals at Finn Shurley. Heterolithic shaly sandstones and very fine- to fine-grained sandstones tend to have the highest porosity and permeability values of the facies sampled. Values for those facies range from 12 to 15 % and 0.2 to 0.7 mD. Oil staining in the McTuillin-Federal 1 was confined to the heterolithic shaly sandstones below the *Scaphites warreni* FS (Figure 5.9). Between the oil stained intervals, carbonate cement is pervasive and the boundary between the two is distinct. The heterolithic shaly sandstones have the best correlation between porosity and permeability, and the highest values of the facies sampled (Figure 5.10).
Figure 5.7 Core description and core analysis data from the Quillback Federal 33-2, Porcupine Field. Interpreted reservoir interval is highlighted by red dash-dot boxes.
Figure 5.8 Cross plot of porosity and permeability data from the Quillback Federal 33-2, Porcupine field. Both the medium-grained sandstones and bioturbated sandstones have good porosity and permeability values, with the later correlating the best.
X-ray diffraction data from the Colen 10-10 indicate that the interpreted potential reservoir intervals have less than 4 wt. % illite/mica, up to 20 wt. % plagioclase, and up to 6 wt. % kaolinite (Figure 5.11).

### 5.1.5 Brooks Draw

Core analysis and XRD data from the Lakeside 1H and Cow Creek #3 was utilized to identify and evaluate potential reservoir intervals at Brooks Draw field. The best reservoir intervals appear to be in the very fine- to fine-grained sandstones in the basal portion of the lower Turner, with porosity values are up to 8 % (Figure 5.12).

XRD data indicate that the potential reservoirs consist of up to 17 wt. % plagioclase, greater than 60 wt. % quartz, and less than 20 wt. % total clay (Figure 5.13). Petrographic data indicate the potential reservoirs contain abundant lithic fragments (rigid and ductile), and both silica and calcite cementation, the latter being fairly pervasive in some samples. Porosity is entirely secondary and resulted from the dissolution of potassium feldspar and lithic fragments (Figure 5.14).

Photographs taken under ultraviolet light of the Lakeside 1H indicate the presence of hydrocarbon within the very fine- to fine-grained sandstone facies. Additionally, the photos indicate the presence of hydrocarbons in the sand-rich bioturbated shaly siltstone to sandstone facies (subgroup 5.1, Figure 5.15).

### 5.2 Discussion

A summary of petrographic data documents a change in the compositional maturity of the Turner from west to east across the study area.
Figure 5.9 Core description and analysis data from the McTuillin-Federal 1, Finn Shurley field. Interpreted potential reservoir intervals are highlighted by red dash-dot boxes.
Figure 5.10 Cross plot of porosity and permeability data from the McTuillin-Federal 1, Finn Shurley field. The heterolithic shaly sandstones have the best correlation between porosity and permeability, and the highest values of the facies sampled.
Figure 5.11 Core description and X-ray diffraction data for the Colen 10-10, Finn Shurley field. Interpreted potential reservoir intervals are highlighted by red dash-dot boxes.
Figure 5.12 Core description and analysis of the Lakeside 1H and Cow Creek 3, Brooks Draw field. Potential reservoir intervals consist of very fine- to fine-grained sandstones present in the lower portion of the lower Turner. Interpreted potential reservoir intervals are highlighted by red dash-dot boxes.
Figure 5.13 X-ray diffraction data from the Cow Creek 3, Brooks Draw field. Interpreted potential reservoir interval is highlighted by red dash-dot box.
Figure 5.14 Petrographic photos taken from the very fine- to fine-grained sandstone present in the lower Turner at Brooks Draw. A & B) Lithic fragments consisting of both ridged and ductile forms are abundant, no primary porosity is present. The only porosity present is secondary intrgranular associated with partial feldspar dissolution. C) Pervasively calcite cementation. D) SEM image of grain coating chlorite. Illite is also commonly present.
Figure 5.15 Ultraviolet photographs taken of the A) very fine- to fine-grained sandstone and B) bioturbated shaly siltstone to sandstone facies in the Lakeside 1H.
On the eastern side of the study area, the Turner at Brooks Draw and Finn Shurley show an increase in lithic and feldspathic constituent minerals compared to samples from the K Bar and SE Porcupine areas (Figure 5.16). Compositional maturity is referred to in this study as the amount of separation between the uppermost Q.A section of a standard Folk QFR and a data point plotted on the Folk tri-plot. For example a quartz arenite would be more compositionally mature than a litharenite. The change in compositional maturity is accompanied by a decrease in grain size to the east. Lindquist (1986) documented a similar west to east decrease in the grain size in the Turner. The changes in compositional maturity and decreasing grain size likely have a negative effect on the reservoir quality of the Turner in the eastern portion of the study area.

Bioturbation has long been considered a mechanism for decreasing porosity and permeability within a reservoir by reducing grain sorting and homogenizing laminated sediment. Recent studies have shown that depending on burrow type and resulting textural heterogeneities reservoir porosity and permeability can actually be enhanced by bioturbation (Gingras et al., 2012; Hsieh et al., 2015; Pemberton and Gingras, 2005; Tonkin et al., 2010). At K Bar, Tuit Draw, and Porcupine fields the best reservoirs are interpreted to be within the bioturbated sandstone facies. The bioturbation is believed to be one of the controlling factors for reservoir quality within the aforementioned fields. Reservoirs within the Sussex, Shannon, and Codell also produce from a similar facies as that of the Turner (Bottjer and Hendricks, 2013).
Figure 5.16 Folk classification diagram for Turner point count data.
CHAPTER 6: CONCLUSIONS

1) The combined presence of normally graded beds containing combined-flow ripple laminations, mudstone layers, and MHCS, and general successions of waning flow structures suggest the lower Turner was deposited near storm wave base in an offshore environment distal to the age equivalent shoreline.

2) Sediments of the lower Turner are interpreted to have been transported from nearshore environments by storm-generated sediment gravity flows, wave-enhanced sediment gravity flows, and probably turbidity currents.

3) Bioturbation Index plots show an overall increase through the lower Turner. This increase is interpreted to correspond to a decreasing rate of sedimentation as a result of relative sea-level rise.

4) Facies successions, trace fossil assemblages, and BI plots suggest the upper Turner was deposited under relatively ambient marine conditions possibly related to continued relative sea-level rise.

5) In the K Bar, Tuit Draw, and Porcupine areas the upper Turner consists of 2-3 coarsening upward successions that are interpreted to represent short progradational episodes. These fine- and medium-grained sediments may have been sequestered in a proximal location on the shelf due to continued rise or possibly still stand of relative sea-level.

6) Toward the east at Brooks Draw and Finn Shurley the upper Turner consist of bioturbated shaly siltstone to sandstone deposited on the distal shelf under ambient marine conditions.
7) A *Glossifungites* ichnofacies assemblage at the top of the bioturbated sandstone facies in the upper Turner at Tuit Draw indicates a break in sedimentation. The disconformably overlain medium-grained sandstones are interpreted as reworked transgressive deposits. The surface demarcating the two facies is interpreted as an erosional surface formed during transgression.

8) The best reservoir intervals are found in the bioturbated sandstone facies of the upper Turner and are limited to the K Bar, Tuit Draw, and Porcupine areas. This facies has the highest measured porosity and permeability of any of the facies sampled in the Turner.

9) Decreasing grain size and compositional maturity is believed to be a limiting factor on reservoir quality of the Turner in the eastern portion of the study area. At Brooks Draw and Finn Shurley fields interpreted reservoir intervals consist of heterolithic shaly sandstones and very fine- to fine-grained sandstones, both of which have lower porosity and permeability than the bioturbated sandstone reservoirs in the western portion of the study area.
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