DEPOSITIONAL AND DIAGENETIC CONTROLS ON THE
DISTRIBUTION OF POROSITY IN THE LOWER
CRETACEOUS FALL RIVER SANDSTONE,
SOUTHERN POWDER RIVER BASIN,
WYOMING

by

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

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The Lower Cretaceous (Albian) Fall River Sandstone is an important hydrocarbon producing horizon in the Powder River Basin of northeast Wyoming. This formation is encountered at depths exceeding 11,000 feet (3,353 m) in the southwest part of this basin. Buck Draw field is the only significant Fall River oil accumulation in this area. This field has recoverable reserves exceeding 22 million barrels of oil. Since its discovery in 1983, approximately exploratory 100 wells have been drilled searching for another Buck Draw-type accumulation. However, no new significant discoveries have been made. Thick Fall River sandstones have been penetrated, but porosity and permeability have been too low for commercial production.

Cores were examined to determine facies relationships and to identify sequence boundaries. The identified facies and key surfaces were correlated to electric logs, and mapped throughout the study area. Seismic data were also integrated to map the paleotopography. A petrographic study was completed to relate sedimentary facies and the depositional setting to diagenesis, and porosity distribution.
The study area is located at the intersection of a Fall River fluvial system and the Cretaceous Epeiric Sea. At this intersection, a valley that had been formed by the fluvial system was drowned by rising sea level, creating a large estuary. The active fluvial system formed a bayhead-delta complex where it entered this estuary. Buck Draw field is located at the seaward termination of a distributary channel in the bayhead delta complex.

This relative position allowed marine waters to invade the intergranular pore space of the high porosity fluvial deposit. The displacement of fresh water by marine waters allowed chlorite clay coats to form over the framework grains during early diagenesis. These clay coats inhibited silica cementation during later diagenesis, thereby preserving porosity. The high-energy channel deposits that are not located in the estuary lack complete chlorite clay coats. As a result, pervasive silica cementation has destroyed the porosity and permeability of these deposits. The estuarine and marine sediments north of Buck Draw do contain chlorite clay coats but lack reservoir quality rock. The porosity of these lower energy deposits was primarily lost by compaction. Additional Buck Draw-type accumulations should be found at the seaward termination of other fluvial channels.
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Introduction

Purpose and Scope

This study reports results of the examination of depositional facies, diagenetic modifications, and porosity distribution in the valley-fill system of the Lower Cretaceous Fall River Sandstone (Figure 1). This formation is referred to as the "Dakota" by many authors and petroleum geologists working this sedimentary section in the Powder River Basin. The Fall River Sandstone consists primarily of fluvial, estuarine, and shallow-marine clastic deposits. It was deposited during the first major transgression of the Cretaceous Epeiric Sea into the Western Interior (Figure 2). A hypothesis explaining the prolific hydrocarbon production from Buck Draw field has been developed. The greater Buck Draw Area, located in the southern part of Wyoming's Powder River Basin, has ultimate recoverable reserves exceeding 27 million barrels of oil (MMBO) and 73 billion cubic feet of gas (BCFG). An exploration fairway that may contain other Buck Draw-type hydrocarbon accumulations has been identified. Research is confined to the southern Powder River Basin where the Fall River Sandstone has an average thickness of 55 feet (16.8 m), is overpressured, and is encountered at depths from 10,000 to 14,000 feet (3,048 to 4,267 m), (Figure 3).

The approach and interpretations of authors that have
Figure 1. Stratigraphic nomenclature correlation chart (modified from Laudon et al., 1976).
Figure 2. Map of the Western Interior Cretaceous Seaway representing Early Cretaceous Skull Creek time, showing sea-level high-stand conditions (modified from Rice and Shurr, 1983).
Figure 3. Regional structure map of the Powder River Basin, Wyoming, contoured on top of the Fall River Sandstone showing oil fields and location of study area, contour interval is 1,000 feet (305 m), (modified from Reservoirs Inc., 1987).
previously described the stratigraphy of the Fall River Sandstone will be examined. Alternative interpretations of the Fall River depositional system will be evaluated as a stratigraphic model is developed for this formation. This model will apply sequence stratigraphic concepts to identify and map erosional surfaces. A paragenetic interpretation describing the diagenesis of the Fall River will be developed by integrating the depositional model with the burial history, and with the petrographic characteristics of each facies in this formation. The sedimentary and diagenetic processes that ultimately control the destruction and preservation of porosity in this formation will be identified.

LOCATION

The study area is located in the southern Powder River Basin of northeast Wyoming. It encompasses 756 square miles including parts of Converse, Campbell, and Johnson Counties. The area covers Townships 37 through 42 North and Ranges 73 (west half) through 76 West (Figure 4).

METHODS

Drill stem tests have not been consistently conclusive and are prone to failure where the Fall River Sandstone is very deep, overpressured, and has very low permeability.
Figure 4. Map identifying limits of study area, subsurface control, and field names. Larger well symbols identify Fall River penetrations. Circled well symbols indicate Fall River interval was cored.
Therefore, very few drill stem tests have been run to evaluate the productive potential of the Fall River Sandstone in this part of the basin. Conventional core analysis is generally used to make casing-point decisions. For this reason, the Fall River oil play in this part of the Powder River Basin is one of the most densely cored formations in the Rocky Mountain Region. The Fall River section has been cored in a total of 74 of the 230 penetrations in the study area. Ten Fall River cores were selected for detailed description (Appendix A). These cores represent each mapped facies in the study area, as well as sandstones with low, moderate, and high porosity development. An additional 24 cores were examined in less detail. However, stratigraphic relationships and differences with the detailed core descriptions were noted. In particular, any stratigraphic evidence of sequence boundaries was recorded.

Each core was correlated to its corresponding electric log to relate characteristic facies and erosion surfaces identified in the cores with characteristics on the electric logs. Based on these correlations, specific facies and erosive surfaces in the Fall River Sandstone were identified for subsurface correlation. In addition, the formation tops of the Mowry, Muddy, Skull Creek, Dakota Silt member, Fuson Shale member, Lakota Sandstone, and Morrison were identified
(Figure 5). These horizons were correlated in the electric logs of every Fall River penetration in the study area, a total of 230 wells. These subsurface data were used to generate structure and isopach maps of the Lower Cretaceous sedimentary rocks in the study area. Isochron intervals and seismic anomalies from proprietary seismic data were incorporated into the subsurface interpretations.

Buck Draw field was studied in detail to determine its stratigraphic and productive characteristics (Figure 6). The production history of each well was compared with core descriptions, core analyses, and mapped distribution of net sandstone and net porosity.

A total of 70 thin-sections from 24 wells in the study area were examined to determine the relationships between porosity, facies, and mineral paragenesis (Appendix B). From this group, core samples from eight wells were selected for X-Ray diffraction (XRD) analysis, and scanning electron microscope (SEM) examination. These samples represented the major facies identified in this formation, including sandstones with poor, moderate, and good porosity development. A total of ten samples were selected for XRD analysis, and nine samples were selected for SEM examination (Appendix B).
Figure 5. Type log for the Lower Cretaceous in the southern Powder River Basin, Wyoming.
Figure 6. Channel Map of the greater Buck Draw Area. Cumulative Fall River production, in thousands of barrels of oil, is posted (Petroleum Information, 1992). Larger well symbols signify well penetrated the Fall River Sandstone. Oil well symbols without posted production, are completed in other formations. Circled well symbols identify the wells completed prior to the discovery of Buck Draw field.
PREVIOUS WORK

The Lower Cretaceous (Albian) Fall River Sandstone is a sandstone and shale sequence that ranges in thickness from 41 to 71 feet (12.5 to 21.6 m) in the study area. The Fall River overlies the Fuson Shale member of the Lakota Sandstone and underlies the Skull Creek Shale (Figure 1). The Fall River was originally labeled the Dakota Formation by Darton in a 1901, report describing a rock sequence that outcropped in the Black Hills of South Dakota. The described unit was interpreted as correlative with the upper Cretaceous Dakota Sandstone of northeastern Nebraska (Burk, 1957). Years later, Russell used fossil evidence to demonstrate that the Dakota described by Darton was not age equivalent to the type Dakota section in Nebraska (in Burk, 1957). At that time, the term Dakota was being applied to any sandstone deposit underlying a thick Cretaceous marine shale, regardless of its time-stratigraphic position (McGookey, 1972). Therefore, Russell introduced the name Fall River to replace the term Dakota in the Black Hills of South Dakota and Wyoming (Waage, 1959). In 1930, Rubey combined the Fall River with the underlying Fuson Shale, and Lakota Sandstone to form a more mappable unit called the Inyan Kara Group. The history of the Lower Cretaceous nomenclature and the correlation of these stratigraphic units was summarized by K. M. Waage
(1959). Many authors have subsequently introduced stratigraphic nomenclature, described the stratigraphy, and correlated the Lower Cretaceous sedimentary rocks in the Powder River Basin including: Davis and Izett, (1958); Hooper, (1961); Hooper, (1962); MacKenzie and Ryan, (1962); Curry, (1962); Gries, (1962); Wulf, (1962); Haun and Barlow, (1962); Dondanville, (1963); Bolyard and McGregor, (1966); Young, (1970); Gott et al., (1974); Dolson et al., (1991).

Additional publications describing the geology of oil fields in the Powder River Basin that produce from the Fall River Sandstone include: Curry and Curry, (1954); Barkley and Gosman, (1958); Trotter, (1962); Truchot, (1963); Miles, (1963); Runge, (1968); Stone and Hoeger, (1973); Hando, (1976); Lawyer, Newcomer, and Eger, (1981); Moore, (1984); Hawkins and Formhals, (1985); Sonnenberg and Meissner, (1986); Sellars and Hawkins, (1992). Most authors described the Fall River sedimentary rocks as marginal-marine deposits associated with the transgression of the Early Cretaceous seaway. This conclusion is supported by regional biostratigraphy and palynology studies of the Cretaceous Western Interior (Kauffman, 1977), and by the identification of both plant fragments and marine fossils in Fall River cores (Curry and Curry, 1954; Waage, 1959; Dondanville, 1963; Hawkins and Formhals, 1985; Sellars and Hawkins, 1992). The
more porous reservoir sandstones have been described as marine barrier bar deposits (Miller, 1962; Miller, 1963; Stapp, 1967), or as tidal channel deposits (Chisholm, 1970). However, both marine and non-marine sedimentary rocks were identified in outcrops of the Fall River Sandstone in the Black Hills (Ryan, 1958; Waage, 1959; Dondanville, 1963). These data supported other authors' interpretations that the Fall River reservoir sandstones were fluvial channel point-bar deposits (Mettler, 1966; Bolyard and McGregor, 1966; Berg, 1968; Berg, 1979). Based on outcrop work in the Black Hills of South Dakota, Ryan (1958) described the Fall River as a fluvial valley-fill deposit. Until 1973, most of the literature was directed toward determining if the productive Fall River facies was a continental or a marine deposit.

Alternative depositional models for the Fall River Sandstone continued to be proposed. Based on outcrop work in the northeastern Black Hills, the Fall River was described as fluvial deposits that grade seaward into estuarine sediments that filled tidal scours (Campbell and Oaks, 1973). A depositional model describing a shoreface deposit that was paralleled by a fluvial channel was proposed by Harris (1976). Other authors used a classic bird-foot delta model to explain the distribution of facies in this formation (RPI Inc., 1983; Rasmussen, et al., 1985; and Reservoirs Inc.,
1987). The Fall River reservoir sandstones in the southern Powder River Basin were described as low sinuosity, fluvial valley-fill deposits that had incised older deltaic sediments (Davies, 1986). Ryer (1990) described the Fall River sedimentary rocks as deposits of northwest flowing fluvial channels that supplied sediment to a prograding shoreline. Sonnenberg (1992) described the productive Fall River sandstones in the southern Powder River Basin as fluvial point bars that were deposited in an incised valley.

Structural Setting

The Powder River Basin is a strongly asymmetric basin that is flanked by the Black Hills Uplift, the Hartville Uplift, the Laramie Range, the Casper Arch, and the Bighorn Mountains (Figure 3). The timing of the basin deformation is post-Maestrichtian and pre-Oligocene (Laramide orogeny) as recorded by the deposition of nearly 8,000 feet (2,438 m) of non-marine sediments in the study area during this time interval (Curry, 1971).

The study area encompasses the southwestern and deepest portion of this basin. The major structural feature in this area is the basin axis with a steeply dipping west flank, and a gently dipping east flank. The east flank has a homoclinal dip of 90 feet (27 m) per mile to the southwest and strikes north 30 degrees west. The west flank has homoclinal dip of 350 feet (107 m) per mile to the northeast, also striking north 30 degrees west (Figure 7).

All hydrocarbon production in the study area is trapped stratigraphically; structure plays no apparent role in the trapping of these fields. However, seismic data and isopach maps indicate that basement fault blocks may have influenced sedimentation during the Jurassic and Cretaceous. This interpretation is analogous to other areas in the Powder River Basin where authors have cited recurrent fault block
Figure 7. Computer generated structure map of the study area on the Fall River Sandstone, contour interval: 500 feet (152 m). Larger well symbols signify that the well penetrated the Fall River Sandstone.
movement controlling sedimentation (Emme, 1981; Farmer, 1981; Weimer et al., 1982; and Rasmussen and Bean, 1984).

Recurrent movement of basement fault blocks may have enhanced reservoir porosity and permeability by creating natural fracturing in the Lower Cretaceous sedimentary rocks. This process may have also opened pathways for vertical fluid movement, including hydrocarbon migration when the overlying organic rich shales became thermally mature. This interpretation is supported by the identification of natural fractures in cores from wells located over the hinge line of interpreted basement fault blocks (Appendix A) and by the identification of faults on seismic lines. The fractures observed in core are open, indicating they post-date silica cementation. Therefore, the fractures are unrelated to the early dissolution of Permian-age salts. The Fall River oil fields are not highly fractured reservoirs, as evidenced by the performance of the tertiary gas flood in North Buck Draw Unit (Sellars and Hawkins, 1992). Most fractures observed in core are near vertical and short, their lengths average less than six inches. However, the identification of fractures helps explain the high production rates recorded from many Fall River wells. Sonnenberg and Meissner (1986) interpreted the fractures as tensional, created when overpressuring (caused by hydrocarbon generation) exceeded the compressive
stress of the sandstone.

Slack (1981) proposed that virtually all stratigraphic production from the Permian and Cretaceous sedimentary rocks in the Powder River Basin is related to recurrent movement of major northeast-trending structural lineaments. This interpretation was based on an apparent coincidence of present-day drainage patterns on Tertiary strata and the location and orientation of oil fields in the Powder River Basin. Isopach maps, structure maps, seismic, and aeromagnetic data have been examined to evaluate Slack’s theory. These data indicate paleo-structures do exist in the study area, but a south to north orientation is indicated. Slack’s theory of northeast-trending lineaments was not supported by the evaluation completed in this portion of the Powder River Basin.

**Sequence Stratigraphy**

Sequence stratigraphy is a relatively new approach to mapping sedimentary units. It is based on the identification and correlation of time-equivalent surfaces. Generally, previous workers who described the geology of the Fall River Sandstone in this area have applied a conventional stratigraphic approach. Sequence stratigraphy concepts were applied in this study to reconstruct the depositional setting and the distribution of facies in this unit. A summary of
sequence stratigraphy has been included in this report to clarify what sequence stratigraphy is and how it differs from a more conventional stratigraphic evaluation.

Vail et al. (1977) defined sequence stratigraphy as the study of genetically related strata which are bounded by unconformities or their correlative conformities. A conformity is defined as "a bedding surface separating younger from older strata, along which there is no evidence of erosion or non-deposition, and along which no significant hiatus is indicated" (Van Wagoner et al., 1988). Weimer (1992) describes sequence stratigraphy as "a specialized study of litho-stratigraphy that emphasizes the association of unconformities, key surfaces, facies, and condensed sections". Weimer (1992) defines an unconformity as a "sedimentary structure in which two groups of rocks are separated by an erosional surface" that was formed by either subaerial or submarine processes. Facies are defined as "the local lithologic or biologic aspect of a chrono-stratigraphic unit" (Weimer, 1992). Key surfaces are "associated with major changes in relative sea level" (Weimer, 1992). One such key surface is a sequence boundary, which is a lowstand surface of erosion (LSE). This surface is "related to a lowering of base level, which caused subaerial exposure and incisement of drainages into older deposits". Another key
surface, that may also be a sequence boundary, is a transgressive surface of erosion (TSE). This surface is related to marine shoreface erosion that resulted from a rise in relative sea level (Weimer, 1992). A third key surface is the maximum flooding surface (MFS) which is associated with the maximum transgression of the shoreline and is equivalent to a marine condensed shale section. This deposit is recognized on electric logs by highly radioactive shales, due to high total organic carbon content. The shales may also contain abundant fossils, glauconite or phosphate grains (Weimer, 1992).

Classic delta progradation is recorded in the rock record during high-stand depositional conditions (Weimer, 1992). Textures fine seaward, and sedimentation rates are low in the deep basin. During a lowstand, the shelf is exposed to subaerial erosion. Rivers bypass the shelf, and deposit sediment directly onto the slope (Vail et al., 1977). The sedimentary cycles associated with both high-stand and low-stand conditions may have resulted from eustatic sea-level fluctuations, tectonic movement, changes in sediment supply, climatic changes, or any combination thereof. The unconformities are the result of eustatic sea-level changes and/or syn-depositional tectonics (Weimer, 1992). Recognizing the "interplay between relative sea level,
subidence, and sediment supply' is a basic concept of sequence stratigraphy (Boyd et al., 1989).

In order to apply sequence stratigraphy, one must recognize key erosional surfaces and use them to determine the relative age of units. To recognize lowstand surfaces of erosion in outcrop and core, one should first look for evidence of subaerial exposure. Lithologic criteria used to recognize a lowstand unconformity include: coals, root zones, paleosols, or oxidized zones above an erosional surface. Chemical changes due to early cementation by kaolinite, silica, siderite, or calcite may be identified below the erosional surface (Weimer, 1992). An LSE may also be identified by a missing facies tract due to erosional scour. In many cases, the only evidence of an LSE is a coarse-grained lag directly overlying a scoured marine shale or sandstone. Transgressive surfaces of erosion are identified as a thin relict deposit (less than 30 cm. thick) composed of: a "coarse-grained or conglomeratic lag with clay clasts, an intensively burrowed sandstone, a concentration of phosphate grains, shark's teeth, fish bones, or glauconite" (Weimer, 1992). A TSE may also be recognized by the overlying calcareous cemented, poorly sorted reworked marine bar, up to six feet (2 m) thick that unconformably overlays continental deposits. The top of a TSE may have a sharp
contact, and be overlain by low resistivity marine shale.

Without the recognition of unconformities, sequence stratigraphy is no different than conventional stratigraphy. However, geologists have always mapped unconformities when they have been recognized. From this standpoint, many geologists maintain that conventional stratigraphy is no different than sequence stratigraphy. None the less, stratigraphic evidence of an unconformity can be very subtle, and has often been unrecognized. Application of the basic concepts of sequence stratigraphy is serving to enhance petroleum exploration and production efforts. Using conventional stratigraphy a coal, root zone, paleosol, oxidized sandstone or pebble lag zone were often considered as evidence of local subaerial exposure. Using sequence stratigraphy, the geologist correlates these zones to determine the areal extent, angular discordance, and the nature of this contact in a paleo-bathymetric framework to determine the relative age of units. Once this evaluation is completed, the geologist can determine if the zone was formed by an isolated event or by a change in relative base-level. In recent years, geologist have re-examined core and outcrop data, and have commonly found that early workers did not recognize unconformities in the rock record. Once these key surfaces are recognized and mapped, significantly different
interpretations may be developed concerning depositional setting and prospective exploration areas.

**Facies of the Fall River Sandstone**

Most Fall River exploration in the study area has been based on a depositional model describing a prograding shoreline composed of a series of classic bird-foot delta deposits. This model was supported by published and proprietary studies of the Fall River Sandstone (RPI Inc., 1983, Rasmussen et al., 1985; Reservoirs Inc., 1987). These workers used distinguishing sedimentary features to identify environments of deposition that are characteristic of a classic deltaic depositional system. Listed below is an abbreviated summary of the sedimentary characteristics and the interpreted depositional environments that represent the facies described by previous workers.

Based on the geographic distribution of each of these deposits, a northeast trending paleoshoreline was documented in the Powder River Basin (Figure 8), (RPI Inc., 1983; Rasmussen et al., 1985). Fall River sedimentary rocks in the eastern portion of the basin are predominantly sandy, interpreted as alluvial to delta plain deposits (Bolyard and McGregor, 1966). In the western portion of the basin, the Fall River pinches out to a siltstone and thin marine sandstone unit (Hooper, 1961).
**Delta Front Deposit** - interbedded shale and very fine to fine-grained, coarsening-upward, ripple-laminated, bioturbated sandstone, with planar tabular cross beds.

**Distributary Channel Deposit** - non-bioturbated, fine-grained trough cross-stratified sandstone, with rip-up clasts overlying a scoured basal contact.

**Abandoned Channel Deposit** - mudstones and ripple-laminated sandstones with a scoured basal contact.

**Interdistributary Bay Deposit** - mudstone and very fine-grained sandstones with moderate to extensive bioturbation.

**Swamp and Marsh Deposit** - thin beds of coal, carbonaceous shale and rooted zones.

**Core Descriptions**

Of the 34 cores examined in the study area, ten were selected for presentation in this report. These wells represent a geographic distribution of each mapped facies identified in the study area, good examples of sequence boundaries, and a wide range of porosity development from both productive wells and dry holes. The stratigraphic examination of the remaining 24 cores ranged from cursory to detailed, depending on the facies that was cored and the geographic location of the well. The core examination was initiated by reviewing core descriptions completed by
Figure 8. Generalized Cretaceous structure map of the Powder River Basin, contour interval is 1,000 feet (305 m), with the approximate position of the Fall River shoreline (modified from Rasmussen et al., 1985).
previous workers. The Reservoirs Inc. (1987) study of the Dakota (Fall River) Formation included core descriptions of 27 wells in the Powder River Basin. In addition, measured sections completed by RPI/Colorado describing Fall River outcrops in the Powder River Basin were studied in detail.

Marine Tidal Flat

The electric logs and an abbreviated core description for cores number 1 and 2 are displayed in Figures 9 and 10. The facies described by previous workers as delta front deposits, are interpreted in these cores as tidal flat deposits. This sedimentary unit is very widespread and is commonly penetrated throughout the southern Powder River Basin.

This facies is described as a light gray to very light gray, very fine-grained to fine-grained sandstones and local siltstones. Petrographic examination of this facies identifies rare to moderate amounts of glauconite. Typically this unit is composed of two cycles. The lower cycle is a coarsening upward, ripple-laminated sandstone, interbedded with wavy bedded and finely laminated mudstones. The sandstone may also have thin low angle planar tabular cross bed sets that are capped by clay drapes. Burrowing in the lower cycle is moderate and locally intensive; identified trace fossils include Chondrites, Planolites, and Skolithos.
Mudstone, moderately bioturbated, pyritic.

Silty sandstone overlying carbonaceous shale.
Sandstone, massive to horizontally bedded with a conglomeratic lag over an erosive basal contact.

Sandstone, thin planar tabular cross beds, and ripple laminations, trace bioturbation.
Siltstone, ripple laminated, slightly bioturbated.
Mudstone, black, fissile.

Figure 9. Electric log and summary core description of core number 1, interpreted as a marine tidal flat deposit.
Mudstone, bioturbated, pyritic.

Sandstone, cross bedded, scoured basal contact.
Siltstone, bioturbated, overlying thin carbonaceous shale.
Sandstone, horizontal bedding and planar tabular cross beds, non-bioturbated.
Sandstone, ripple laminated, bioturbated.

Sandstone, oxidation stains, ripple laminations.
Siltstone, ripple laminated, trace bioturbation.

Figure 10. Electric log and summary core description of core number 2, interpreted as a marine tidal flat deposit.
The basal contact of the lower cycle is generally gradational, its upper contact is usually sharp. The lower unit is typically capped by a light gray shale or a fine-grained sandstone of the upper cycle. Locally, the lower cycle may be thin or absent due to removal by erosion.

The sedimentary structures of the upper cycle indicate that it was deposited in a higher energy environment than the underlying unit. It is a fairly well sorted, highly silica cemented sandstone. The primary sedimentary structure in the sandstone is ripple-lamination, but thin bedded planar tabular (two dimensional, "2D") and trough cross stratifications (three dimensional, "3D") as well as massive bedding overlying reactivation surfaces are also common. Thin clay drapes typically overly the bedsets. The sandstone is highly silica cemented, locally pyritic, and commonly contains styolites. Locally, biogenic sedimentary structures such as Chondrites, Planolites, and Skolithos trace fossils are identified. Typically, both the basal and upper contact are sharp. The lower contact may be marked by angular shale rip-up clasts. In the southern two thirds of the study area, the upper cycle is commonly capped by a light gray shale, carbonaceous shale, coal, or a rooted zone. In the northern third of the study area, this cycle is overlain by the estuarine facies described below. Biogenic sedimentary
structures in the upper unit are rare or absent. The only commercial wells completed in this facies in the study area, are interpreted to be in fracture communication with active channel-fill deposits. By comparing conventional core analysis from wells completed in this facies, porosity is estimated to average less than five percent, permeability averages approximately 0.1 md.

Active Valley-Fill

Cores number 3, 4, and the lowermost portion of cores number 5 and 6 (Figures 11, 12, 13 and 14) are interpreted as low-sinuosity point bar deposits. These sediments were deposited as active fill in an incised valley by rivers with fluctuating discharge rates. Previous workers have interpreted this facies as distributary channel deposits.

Light to medium brownish gray, mostly fine-grained to very fine-grained, highly silica cemented sandstones characterize active valley-fill deposits. The overall unit typically fines upward above a scoured basal contact and is composed of multiple scour and fill fining-upward units. Scour surfaces may be overlain by black, angular shale rip-up clasts indicating short distance of transport. Sedimentary structures include thick, massive (structureless) bedding, large and small scale, high angle 3D cross stratifications, large and small scale 2D cross beds and thin ripple-laminated
Mudstone, bioturbated, pyritic.
Siltstone, bioturbated, ripple laminated, scoured basal contact.
Sandstone, massive with stacked sets of scour and fill planar tabular and trough cross beds bounded by shale rip-up clasts, non-bioturbated.

Figure 11. Electric log and summary core description of core number 3, interpreted as an active valley-fill deposit.
CITIES SERVICE  BT FEDERAL #1
SENW 20-T41N-R73W  (Cored interval + 2 foot correction = log depth 12,556 to 12,615)

Conglomeratic Sandstone, fine grained sandstone with shale rip-up clasts, massive, reactivation surfaces, non-bioturbated, silica cemented, scoured basal contact.
Shale, black, fissile, bioturbated.

Siltstone, ripple laminated, extensively bioturbated.
Mudstone, silty, extensively bioturbated.

Figure 12. Electric log and summary core description of core number 4, interpreted as an active valley-fill deposit.
Mudstone, bioturbated, pyritic.
Sandstone, silty to very fine-grained, ripple laminated, slightly bioturbated.

Sandstone, very fine grained, ripple laminated, carbonaceous, silica cemented, non-bioturbated with thin black mudstone interbeds.

Sandstone, fine grained, planar tabular cross beds or massive, silica cemented, non-bioturbated

Figure 13. Electric log and summary core description of core number 5, interpreted as representing both partial-abandonment and active valley-fill facies.
CITIES SERVICE NINE MILE CREEK #2
NESW 14-T40N-R75W (Cored interval - 6 foot correction = log depth 13,544 to 13,596)

Mudstone, bioturbated, pyritic.

Sandstone, very fine grained, ripple laminated, some very thin planar tabular cross beds, carbonaceous, numerous scour surfaces overlain by shale rip-up clasts, mudstone interbeds, thin silty zones. Sandstone, fine grained, thin planar tabular and trough cross bed sets, some shale rip-up clasts, silica cemented, non-bioturbated, scour basal contact.

Figure 14. Electric log and summary core description of core number 6, interpreted as an abandonment valley-fill deposit.
stratification. This facies is commonly capped by abandonment and partial-abandonment deposits, detailed in the facies description below. Biogenic sedimentary structures are extremely rare. The sandstone is locally pyritic, and contains spotty carbonaceous debris within the ripple-laminated portions. The active valley-fill deposit is the principal oil-producing facies in this formation. A review of conventional core analysis from wells in the Buck Draw area, indicates that porosity in this facies ranges from less than 4% to over 14%, permeability ranges from 0.01 md. to 90 md. Based on visual core examination, the sedimentary structures and textures of the active valley-fill deposits having higher porosity and permeability values are indistinguishable from the active valley-fill deposits with low porosity and permeability. Therefore, porosity and permeability distribution within this facies is interpreted to not be controlled by primary sedimentary characteristics. Diagenetic modifications must be responsible for the variable distribution of porosity within this high-energy deposit.

Abandonment Valley-Fill

The upper portion of cores number 5 and 6 (Figure 13 and 14) are interpreted as lower energy point bar deposits that represent abandonment and partial-abandonment deposition in an incised valley. Within the deltaic model of previous
workers, this facies was interpreted as low energy distributary channel deposits.

This facies contains both partial-abandonment and abandonment deposits. The partial-abandonment deposits are very light gray to light brownish gray, very fine-grained sandstones. The dominant sedimentary structure in this deposit is small-scale ripple-lamination. The abandonment deposits contain light gray ripple-laminated sandstone that is interbedded with wavy bedded, light gray siltstones and gray mudstones. Mudstones with rare trace fossils interbedded with thin lenticular siltstones and sandstones are also common. Both the abandonment and partial-abandonment deposits overlay a scoured basal contact. Scour and reactivation surfaces are common within the deposit, as is spotty carbonaceous debris, rooted intervals, and local pyritic zones. These sediments are interpreted to have been deposited in low flow regime, in shallow water during abandonment or partial-abandonment of individual fluvial channels. Comparing conventional core analysis indicates that core porosity averages approximately 4%, permeability averages less than 0.1 md. This facies is not commercially productive in the study area.

Estuarine

Following the Rasmussen et al. (1987) approach of using
characteristic electric log curves to identify facies, cores number 7 and 8 were previously interpreted as distributary channel deposits (Figure 15 and 16). A 20 foot thick sandstone is developed in the lower portion of the Fall River interval. This clean (low radioactivity) sandstone has a sharp basal contact and has the same electric log character as the active valley fill deposits. However, the sedimentary structures and characteristics identified in core are very similar to the higher energy tidal flat deposits described previously. In particular, the recognition of biogenic sedimentary structures (*Skolithos* trace fossils). The sedimentary structures described are not characteristic of the active valley fill deposits. This interpretation is additionally supported by the petrographic identification of glauconite in this sandstone. Since the precursor of glauconite is fish feces it is considered an indicator of a marine depositional environment. Glauconite was conspicuously absent in every high-energy, fluvial valley fill sample examined. The basal sandstone in cores number 7 and 8 is identified as a higher energy marine tidal flat deposit, that is bounded by regional unconformities.

Based solely on electric log character, cores number 9 and 10 would be interpreted as distributary channel clay plug deposits (Figures 17 and 18). However, the sedimentary
Sandstone, siltstone and mudstone, interbedded, mottled, ripple laminated, lenticular and wavy bedding, moderate to locally extensive biogenic sedimentary structures. Sandstone, very fine to fine grained, ripple laminations, planar tabular and trough cross stratification, reactivation surfaces, silica cemented, rare skolithos trace fossils.

Figure 15. Electric log and summary core description of core number 7, interpreted a tidal channel deposit overlying a regional unconformity.
Sandstone, siltstone and mudstone, interbedded, mottled, ripple laminated, lenticular and wavy bedding, moderate to locally extensive biogenic sedimentary structures.

Sandstone, very fine grained, ripple laminated, mudstone clay drapes, local to moderate biogenic sedimentary structures, silica cemented.

Figure 16. Electric log and summary core description of core number 8, interpreted a tidal channel deposit overlying a regional unconformity.

Shale, black, fissile.

Figure 17. Electric log and summary core description of core number 9 interpreted as an estuarine deposit overlying a regional unconformity.
Siltstone, bioturbated, pyritic.

Sandstone, plane bedded, scoured base. Siltstone, ripple laminated, locally extensive bioturbation, mudstone interbeds. Mudstone, wavy bedded, some trace fossils. Siltstone, as above.

Sandstone, ripple laminated, planar tabular cross beds, some trace fossils, silica cemented, scoured base. Siltstone, ripple laminated, moderately bioturbated, mudstone interbeds. Mudstone, black, fissile, moderately bioturbated.

Siltstone, ripple laminated, moderately bioturbated.

Figure 18. Electric log and summary core description of core number 10, interpreted as an estuarine deposit overlying a regional unconformity.
characteristics observed are not indicative of a fresh water fluvial depositional setting. The lower Fall River interval in these two cores is very similar to the marine tidal flat deposits described previously. Therefore, the basal 14 foot Fall River interval in these two cores is interpreted as marine tidal flat deposits that are overlain by a regional unconformity surface.

The mudstone, siltstone and sandstone deposits that overly the upper regional unconformity surface in cores number 7, 8, 9 and 10 have an electric log profile that is similar to the partial abandonment and abandonment facies described previously. However, the sedimentary features described in these core intervals are not similar to the sedimentary features described previously for low energy fluvial deposits. The estuarine sediments are characterized by interstratified dark gray to black mudstone, light gray siltstones and very fine-grained to fine-grained thinly bedded white sandstones. Horizontal, siltstone and sandstone filled burrows are common, identified trace fossils include Chondrites, Skolithos, Planolites, Arenicolites, Astersoma, Conichnus, and fecal strings. Climbing ripples and ripple cross stratification are very common as are thin pyritic zones. Reactivation surfaces and graded bedding are also common. High-energy sedimentary structures and carbonaceous
debris are absent. These sediments were deposited in a lower flow regime setting. Upper contacts may be gradational however, the lower contacts are sharp.

These deposits are interpreted as estuarine, based on a comparison with classic estuarine deposits. Clifton (1982) described estuary deposits as mud and well-sorted, ripple-laminated and cross-bedded sandstone, interlayered in sharply contrasting strata, with locally intense bioturbated zones. Layers of siltstone and clay in otherwise clean, well sorted sandstone constitute one of the most characteristic features of this deposit.

Conventional core analysis is not performed on the estuarine facies, because the sandstones are generally thin and interbedded with shales. This facies is not commercially productive.

Transgressive Marine Sandstone

A relatively thin transgressive sandstone was commonly deposited above a TSE, capping the Fall River Sandstone. Previous workers have described this facies as a storm deposit.

Transgressive sandstones are typically light gray, very fine to fine-grained sandstone. This deposit may contain ripple laminations or small scale thinly bedded 2D and 3D cross stratification. Locally, biogenic sedimentary
structures may be abundant. Pyrite concretions are also locally abundant. This deposit may contain interbedded siltstones, mudstones, and rare shale clasts. This deposit caps the Fall River Sandstone with an erosive basal contact (TSE). Its upper contact is sharply overlain by marine shales. In the study area, one commercial well has been completed in this facies. This well was interpreted to be in fracture communication with an active valley-fill deposit. Based on a comparison of conventional core analysis, core porosity averages approximately 3% to 5%, permeabilities are typically less than 0.1 md.

Sequence Boundaries

After the erosional surfaces were identified in core, these surfaces were marked on all corresponding electric logs. Generally, the surfaces were recognized by characteristic electric log responses. The unconformities were often identified on electric logs by a thin low resistivity zone, a sharp deflection on the gamma ray curve, and an abrupt change in porosity. Correlation of the described cores revealed that the unconformities were consistently identified within specific stratigraphic intervals. For example, in paleotopographic low areas, the basal unconformity was encountered very low in the section. Using these relationships and criteria, the key surfaces were
correlated to the electric logs of every well in the study area. However, on many electric logs, the exact depth of one or both of the unconformities was subject to interpretation. Therefore, subsurface maps on the unconformity surfaces are highly interpretive in areas lacking core control.

The sedimentary structures and key surfaces identified in cores number 1 and 2 are representative of a common Fall River depositional cycle in the Powder River Basin. Previous workers have referred to this sedimentary cycle as the "regional" marine sequence (Hawkins and Formhals, 1985). Core number 11 also penetrated the "regional" marine sequence. This well is located just east of the study area, 12 miles east of core number 2. Photographs of sequence boundaries in this core are displayed in Figure 19. Core number 12 also penetrated the "regional" marine section. This well is located six miles south of the southern border of the study area and 19 miles southwest of core number 1. A photograph of the lower Fall River sequence boundary in this core is displayed in Figure 20. After integrating all the well logs and examined core in the area, the unconformities identified in cores number 1, 2, 11, and 12 were recognized as chronostratigraphic-equivalent sequence boundaries (Figure 21). These two sequence boundaries are consistently identified in cores and electric logs over a
Figure 19. Electric log of Fall River interval in Core Number 11, and photographs of LSE #1 and LSE #2.
Figure 20. Electric log of Fall River interval in Core Number 12, and photograph of LSE #1. LSE #2 is above the cored interval.
Figure 21. Stratigraphic cross section A-A' that extends outside of the study area to the south and east, showing electric log correlation of the unconformities, key surfaces, and formation contacts that have been identified in core.
large portion of the southern Powder River Basin. Therefore, these two unconformities are interpreted as significant surfaces representing relative drops in sea level that affected Fall River sedimentation in a large regional area. LSE #1 (lowstand surface of erosion) is interpreted as a brief and not extreme drop in sea level. This lowstand is not associated with a fluvial valley-fill deposit in the study area. This interpretation is based on isopach mapping, and on the stratigraphic evidence of this unconformity in core. In many cores, the unconformity surface of LSE #1 has merged with the overlying TSE surface. LSE #2 is interpreted as a longer duration lowstand, related to a more significant drop in sea level. This lowstand is associated with the deposition of thick valley fill deposits in the study area.

It is beyond the scope of this report to correlate these two unconformities throughout the Powder River Basin. However, additional evidence of these two surfaces was repeatedly identified in cores, core descriptions by previous workers, electric logs and measured outcrop sections in other portions of the Powder River Basin. This additional evidence will be discussed in more detail later in this report. LSE #1 is dated at 100 million years before present based on correlation with a basal Fall River unconformity that has been described in the eastern Powder River Basin (Weimer et
Subsurface Mapping

The objective of the subsurface mapping was to map paleotopography in order to reconstruct the drainage system that was formed due to erosion during the Fall River lowstands. Stratigraphic analysis (core descriptions, cross sections, isopach maps and litho facies maps) was performed on the entire Lower Cretaceous section to meet these objectives. As a result, paleotopographic highs and lows were identified and a relation between facies and paleotopographic position was defined.

Table 1 lists the subsurface maps completed in the study area. Excluding the computer generated structure map presented in Figure 7, all of the maps were hand contoured. These maps are displayed in Appendix D. Some maps were not conclusive due to the subjective nature of the stratigraphic correlations where insufficient core data made reliable correlations impossible. Due to the lack of subsurface control, no isopach maps were made of the Jurassic or older sedimentary rocks.

The Fall River structure map identifies structural strike at North 30 degrees West, and dip 90 feet (27 m) per mile to the southwest (Figure 7). No relationship between structural position and hydrocarbon production is evident.
Fall River Structure Map
Mowry to Muddy Isopach Map
Muddy to Fall River Isopach Map
Fall River to Fuson Shale Isopach Map
Fall River to LSE #2 Isopach Map
Fall River to LSE #1 Isopach Map
LSE #1 to Fuson Shale Isopach Map
Fuson Shale to Lakota Sandstone Isopach Map
Lakota Sandstone to Morrison Isopach Map
Map of the Fall River Channel and Bayhead-delta Complex
Buck Draw Area, Net Porosity Isopach Map of Channel
Buck Draw Area, Production Map

Table 1. Subsurface Maps completed in the study area.

The Muddy to Fall River isopach map displays a pronounced
south to north trend (Figure 22). This isopach map is
interpreted as an accurate representation of topography
during early Cretaceous time. The topography is interpreted
to have been influenced by salt dissolution and recurrent
basement fault block movement. This interpretation will be
discussed in detail in a later section of this report.

An examination of the location of Cretaceous oil fields
in the study area reveals a paleotopographic correlation
throughout Cretaceous time. Sand Dunes field is located at
Figure 22. Muddy to Fall River Isopach Map (Skull Creek Shale), contour interval: 10 feet (3 m). The productive area of the First Frontier Sandstone is shaded, production from other horizons is not identified. See text for detailed discussion relating paleotopography to oil production.
the southern border of the study area (Figure 22). This field will ultimately produce in excess of 28 million BO, and 28 BCFG from a Muddy Sandstone valley-fill deposit (Formhals, 1991). Subsurface and seismic control support an interpretation that the reservoir was deposited in a south to north oriented graben fault block. This field is located in the axis of the valley defined by the Muddy to Fall River Isopach Map.

Powell and Spearhead Ranch fields are located in the center of the study area (Figure 22). Together, these two fields have cumulative production of 30 million BO, and 200 BCFG from a Frontier Formation marine sandstone deposit (Petroleum Information, 1992). The south to north oriented reservoir sandstones in these fields have been described as marine deposits that have been reworked by storm events (Tillman and Almon, 1979; Winn, 1991). The best reservoir sandstone is a high porosity zone that averages less than ten feet (3 m) in thickness, and is only developed on paleo-bathymetric high areas (Figure 23). This sandstone can be correlated off the paleo-bathymetric high areas where it has poor porosity development. In these areas, the sandstone was deposited below effective storm wave base. The isopach map of the Skull Creek Shale (Figure 22) effectively delineates the limits of production in the First Frontier Sandstone.
Figure 23. Rising sea level, marine sands on bathymetric highs are reworked by storm waves. High-energy reservoir sands are deposited in these areas. Low energy sands and shales are deposited in the bathymetric lows. This is analogous to Weimer’s (1983) valley-fill model.
This indicates the topography that was developed during lower Cretaceous Skull Creek time was nearly identical to the topography during upper Cretaceous Frontier time. The geometry of sand bodies, the distribution and orientation of isopach thicks and thins, and the geographic location of Cretaceous oil fields indicates that basement fault blocks and Ervay salt dissolution have similarly influenced sedimentation during both lower and upper Cretaceous time. In the study area, this relationship explains sandstone distribution in the Lakota, Fall River, Muddy, Frontier, and Shannon intervals.

The Fall River to Fuson isopach map (Figure 24) and the Fall River to LSE #2 isopach map (Figure 25) both display a south to north orientation with the location of paleo-highs and paleo-lows corresponding to the Muddy to Fall River isopach map. The interpretation of a south to north paleodrainage system is strongly supported by these and other isopach maps (Appendix D).

**Seismic Interpretation**

Of the 210 wells drilled in the study area, only three wells have penetrated the Permian Ervay Member of the Goose Egg Formation. In the southern Powder River Basin, this is a salt that varies from 0 to 250 feet (76 m) in thickness and is penetrated approximately 1,000 feet (305 m) below the base
Figure 24. Fall River to Fuson Shale Isopach Map, contour interval: 10 feet (3 m). The location of two representative seismic lines (BTS 1-83 and W 83-47) are posted.
Figure 25. Fall River to LSE #2 Isopach Map, contour interval: 20 feet (6 m). The relative location of cross section B-B' is posted.
of the Fall River Sandstone. The lack of deeper drilling in the study area is due to the depth to the next objective reservoir, the Pennsylvanian Minnelusa Formation, in this portion of the basin. Due to the lack of deeper drilling, subsurface control cannot be used to map the dissolution of the Ervay salt in the study area. However, seismic modeling using sonic and density logs indicates seismic data can be used to estimate the thickness of the Ervay salt (Figure 26).

Seismic data have been used to map the dissolution of the Ervay salt section in the eastern Powder River Basin (Rasmussen and Bean, 1984). Previous workers have documented that the variations in the Ervay salt thickness were due to post-depositional salt removal by solution, and not due to original variations in thickness of salt deposition (Parker, 1967). These workers conclude that salt dissolution was initiated during the Late Jurassic and continued during the Early Cretaceous. Rasmussen and Bean (1984) postulate that dissolution was initiated by fracturing related to recurrent movement along basement fault blocks. This fracturing created conduits which allowed groundwater circulation to remove the Ervay salt. This caused subsidence of the overlying sediments and the development of, or amplification of, paleotopographic low areas at the surface. Rasmussen and Bean (1984) used both subsurface control and seismic data to
Figure 26. Seismic model of the Sinclair Wind Creek #1 (SE SW 17-T40N-R76W) displaying Permian, Ervay salt dissolution. The right and left extremes represent a 250 foot thick salt section, this section is 70 feet (21 m) thick in the center of the model. Dissolution is identified by an character anomaly in the Goose Egg interval and by a sag in the overlying sediments.
identify the areas of Ervay salt dissolution. The Ervay salt was not completely removed throughout the area. Subsurface mapping identified remnant areas with thick Ervay salt. In these areas, fluid flow was insufficient for dissolution. These salt remnants were evident as topographic high areas at the surface during early Cretaceous time. Rasmussen and Bean (1984) used subsurface control and seismic data to demonstrate a relationship between compensatory thickening in overlying syndepositional strata and dissolution of the Ervay salt.

An examination of multi-fold CDP seismic data in the study area documents Ervay salt dissolution anomalies and coincident Lower Cretaceous isopach thick anomalies similar to those described by Rasmussen and Bean (1984). As part of this seismic investigation, isochron intervals were evaluated to determine the interval that best demonstrates the paleotopography during early Cretaceous time. The following isochron intervals were examined: Sussex to Fall River, Sussex to Madison, Frontier to Fall River, Muddy to Fall River, Fall River to Spearfish, and Spearfish to Madison (Figure 1). While most of these isochron intervals showed anomalies over Buck Draw field, only the Fall River to Triassic Spearfish isochron interval consistently agreed with the subsurface control throughout the study area.
Identifiable salt dissolution anomalies are recognized on seismic lines underlying isochron thickhs in the Fall River to Spearfish interval (Figure 27). Where a complete Ervay salt section is identified, the overlying Spearfish to Fall River isochron is comparatively thin. The isochron variations identified on seismic lines were integrated into the subsurface maps presented in Appendix D.

A Goose Egg salt dissolution feature has been identified below Buck Draw field (Figure 28). A top-loaded doublet character anomaly at the Fall River interval coincides with the location of productive wells in this field (Figure 29). The character anomaly is related to a thick Fall River channel deposit overlying a thin Lakota section. Seismic modeling indicates that this top-loaded doublet and other character anomalies are caused by changes in lithology and thickness in the Lakota to Fall River interval. Many unsuccessful exploratory wells have been drilled on top-loaded doublet character anomalies in the Fall River that overlie Ervay salt dissolution features. Generally, these wells penetrated a thick Fall River section that was tight, or a thin Fall River section overlying a thick Lakota Sandstone. Modeling indicates that various combinations of thicknesses and lithology in the Fall River-Lakota interval can create a top-loaded doublet character anomaly.
ENERGY SOURCE: DYNAMITE  GROUP INTERVAL: 110 FEET  SHOT POINT INTERVAL: 660 FEET
FOLD: 8  CHARGE SIZE: 20 POUNDS  HOLE DEPTH: 140 FEET  DATE SHOT: MAY, 1983

Figure 27. Portion of seismic line W 83-47; see Figure 24 for location of line. Eight milliseconds of thickening have been identified in the Spearfish to Fall River isochron interval. This thickening is developed in the sag overlying the Ervay salt dissolution anomaly (colored red).
Figure 28. Portion of seismic line BTS 1-83 over Buck Draw field; see Figure 24 for location of line. Ten milliseconds of thickening have been identified in the Spearfish to Fall River isochron interval. A weak Ervay salt dissolution is identified.
Figure 29. Enlarged portion of seismic line BTS 1-83 over Buck Draw field; A top loaded doublet character anomaly is identified where the Fall River interval is productive. Note identified sag in paleo-low area.
Additional modeling indicates phase problems and noise can create character variations that are not related to the sedimentary rocks. This modeling indicates that a thick Fall River and Lakota package can be identified, but seismic character changes cannot reliably delineate high-energy channel deposits.

Seismic data support the interpretation of a south to north oriented paleodrainage system. When seismic data were of sufficient quality, evidence of syndepositional basement fault block activity were identified. However, the shooting and processing parameters of this seismic data were insufficient to consistently identify Precambrian fault block movement at depths of 15,500 feet, (4,724 m). The distribution of Lower Cretaceous thicks and thins in subsurface maps and seismic data supports an interpretation that the orientation of Cretaceous sedimentation was ultimately controlled by basement fault block movement.

Fall River Oil Exploration

The exploration approach used by many oil companies drilling for Fall River hydrocarbon accumulations in the Powder River Basin was summarized by Rasmussen et al. (1985) and followed by other workers (Hawkins and Formhals, 1985; Reservoirs Inc., 1987; Schultz and Coppinger, 1989; Sellars and Hawkins, 1992). Based on characteristic electric log
patterns, each well is determined to have penetrated a particular depositional environment within a classic bird-foot delta system (Figure 30). Once a well is assigned an environment of deposition, it is grouped with other wells that have similar electric log patterns. After each well in the area of interest is assigned to a group, the distribution of each group is posted on a map. The deltaic system is then reconstructed, by connecting equivalent log facies. Seismic data are integrated into this approach by posting channel anomalies on the map where identified on seismic lines. Most of the Fall River exploratory wells drilled in the study area were justified by using this type of exploration approach.

Since the discovery of Buck Draw field, a total of 100 wildcat tests have penetrated the Fall River Sandstone in the deeper, overpressured portion of the southern Powder River Basin. A majority of these exploratory wells were drilled on seismic anomalies. Due to poor casing point decisions, many wildcat tests were completed as non-commercial wells. Only six wildcat wells, drilled since the Buck Draw discovery, have produced economic quantities of oil from the Fall River Sandstone. The average cumulative production from these six commercial wells is 70 MBO per well (Petroleum Information, 1992). By comparison, the reserves in North Buck Draw Unit average 750 MBO per well. The oil industry has expended over
Figure 30. Characteristic E-logs of the Fall River interval, from selected wells. Depositional environment is labeled using the Rasmussen et al., (1985) approach. In parentheses, is the depositional environment interpreted in this report, based on sequence stratigraphy and core descriptions.
$100 million during a nine year exploration effort to discover another Buck Draw-type accumulation. No significant Fall River field discoveries have been made. An examination of this extremely poor success ratio indicates the exploration model used by industry is not effective.

The Discovery of Buck Draw Field

Prior to the development of a new exploration model for the Fall River Sandstone, the successful exploration approach that led to the discovery of Buck Draw field was examined. Additionally, the production history of wells in this field were studied to determine the most significant controls on productivity. To determine if Buck Draw was a typical Fall River oil accumulation, these production data were compared with other Fall River oil fields in the Powder River Basin.

Prolific production of gas and light, low-sulfur oil from the Fall River Sandstone is well established in the Powder River Basin. The trend of producing fields from Coyote Creek to Miller Creek, located 50 miles northeast of the study area, has produced in excess of 80 million barrels of oil from stratigraphic traps. Over 80 million barrels of oil has also been produced from fields discovered on small structural closures on the west flank of the basin, southwest of the study area (Moore, 1984). Due to deeper drilling depths, exploration in the study area was relatively limited
until the early 1980's. Fall River production was well established in the Powell field (Figure 6). Buck Draw field was discovered in 1983, when Louisiana Land and Exploration Company drilled the M & M 33-18 well (located in the NW/4 SE/4 18-T41N-R73W) in an attempt to extend oil production from wells completed in a Fall River channel sandstone (Figure 6). This well was completed naturally for an initial production rate of 2,360 BO and 5.5 MMCFG per day. The main portion of the field was incorporated into a tertiary gas flood unit. This unit was named North Buck Draw (NBDU), and was still undergoing development during 1992 by the drilling of gas injection wells. As of May, 1992 the NBDU had cumulative production of 14.8 million BO, 15 BCFG, and was producing 7,000 BOPD from 17 wells with 8 gas injection wells. The estimated ultimate recoverable reserves for NBDU will exceed 22 MMBO and 53 BCFG (Sellars and Hawkins, 1992). Kerr-McGee (1987) estimated the ultimate recovery factor for NBDU to be 50% of the original oil in place (after miscible gas flood) and 65% of the original gas in place. Twenty other Fall River wells have been completed outside of the NBDU boundary, but within the immediate vicinity of this field. As of June, 1992, these wells had cumulative production of approximately 5 million BO, and 20 BCFG (Petroleum Information, 1992). The thickness of the
reservoir ranges from 10 to 59 feet (3 to 18 m), based on a six percent porosity cutoff. Permeability ranges from less than .01 md to over 80 md. The field is overpressured, with an original bottom hole pressure of 8,100 psi (0.64 psi/ft.). There is no water leg, significant water production, or gas cap in the field. The producing mechanism is a depletion drive. The oil is 41.6 API gravity; the original gas-oil ratio was 2,000:1; and the calculated BTU of the gas is 1,232 (Hawkins and Formhals, 1985).

Louisiana Land and Exploration had accurately predicted the extension of the Fall River channel, but the production rates and per well reserves of the successful wells were three times greater than expected. The high production rates in Buck Draw field initiated significant exploration activity in the southern Powder River Basin.

**Depositional Model**

The identification of two regional unconformities in the Fall River Sandstone requires a re-evaluation of the previously proposed depositional setting. As described previously, there was reasonable stratigraphic evidence to support a birds-foot delta depositional model for the Fall River Sandstone. The stratigraphic data compiled by previous workers are still valuable. These data only need to be viewed from a new perspective. The previous work describing
the position and orientation of the Fall River shoreline is still valid. Fluvial channel deposits are recognized in the eastern Powder River Basin, and thin silty marine deposits are recognized in the western part of this basin (Figure 8). Therefore, a revised depositional model must still position the study area near the shoreline during a stage of Fall River deposition.

The Lakota Sandstone is a continental pediment deposit composed of conglomeratic sandstones and variegated mudstones that unconformably overlays the Jurassic Morrison Formation (Young, 1970). The basal Lakota unconformity is dated at 112 million years before present (Weimer, 1983). Based on isopach mapping, the Lakota Sandstone is interpreted to be deposited by northward flowing braided streams (Appendix D). In the study area, this sandstone ranges from less than 10 feet (3 m) to over 100 feet (30 m) in thickness. At or near the beginning of Albian time, the Boreal Sea transgressed southward through a narrow trough from the Arctic Ocean (Young, 1970). This sea-level rise is the first transgression of the Western Interior Cretaceous Seaway (Stapp, 1967). As the study area was drowned by the marine transgression, shoreface waves eroded and reworked the uppermost Lakota sandstones. A transgressive surface of erosion (TSE) developed, capping the Lakota sandstones.
The seaway then transgressed and deposited the Fuson Shale Member of the Lakota Sandstone (Figure 1). The Fuson Shale in the Powder River Basin has been described as a brackish water deposit containing both marine and fresh-water fossils (Curry, 1962). Depositionally, the Fuson Shale is unrelated to the underlying Lakota Sandstone. It is distinct on the basis of color, bedding, composition, texture, trace fossils, sedimentary structures, and is separated from the Lakota continental sandstones by a transgressive surface of erosion (TSE). Within the study area, the Fuson Shale is recognized as depositionally related to the lowest Fall River depositional cycle. The upper Fuson and the lower Fall River share the same general color, bedding, composition, and biogenic sedimentary structures along their gradational contact. This relationship is difficult to recognize in the eastern part of the basin, where the lowest Fall River depositional cycle has been removed by erosion. Based on work completed in the eastern Powder River Basin, previous workers included the Fuson Shale as a member of the Lakota Sandstone. This is a reasonable conclusion based on the units' contact in this part of the basin. However, subsequent regional work indicates the Fuson Shale should be classified as a member of the Fall River Sandstone.

Examination of selected cores in the study area
documents the gradational contact between the Fuson Shale and the Fall River Sandstone (Figures 9 and 10). Previous workers have also described the contact between the Fuson Shale and Fall River Sandstone as gradational in other portions of the Powder River Basin (Hooper, 1961; Rasmussen et al., 1985). The gradational contact suggests a slow regression of the epeiric sea, and initiation of Fall River deposition by coarsening-upward, shallow-marine clastic sedimentation.

The sediments deposited during the initial Fall River depositional cycle are extremely widespread. This coarsening-upward unit, composed of marine siltstones and sandstones, was deposited during the continuation of the marine regression. The sedimentary structures present in this deposit (described previously) are representative of a tidal flat environment. An unknown thickness of these sediments was deposited as the sea regressed. Any upper shoreface sediments which may have been deposited were subsequently eroded. This depositional cycle was terminated by a rapid drop in sea level (LSE #1).

This base-level drop is recorded in cores by a scour surface, locally by a missing lower shoreface facies tract, and locally by an oxidized zone capping the marine sediments. The basal Fall River unconformity is identifiable in a large

The magnitude of the relative sea-level drop was sufficient to expose the shelf causing the incisionment of northward flowing fluvial drainage systems into the underlying marine sediments. The position and orientation of the valleys was controlled by paleotopography. Valleys formed in low areas that were created in response to syndepositional basement fault block movement, and dissolution of Permian salts (Figure 31). This interpretation is based on isopach and seismic analogies with Fall River deposits in the eastern Powder River Basin described previously in this report. The amount of erosion into the underlying sediments during a falling relative sea level depended on the local and regional paleotopographic position. Therefore, paleotopography controlled the nature of the Fuson to Fall River contact. The relative paleotopographic position explains the variable thickness of this depositional cycle observed in cores number 1, 2, 7, 8, 9, and 10. However, an isopach map of the Fuson Shale demonstrates that erosion in the study area was not severe.
Figure 31. Sea-level lowstand, subaerial exposure of shelf is recorded by a basin wide erosional surface. Equivalent to the Weimer (1983) valley-fill model.
Evidence of subaerial exposure in core is rare, and in some cores subtle (Appendix A). Within the paleo-low areas in the study area, the depth of erosional scour is estimated to average ten feet (3 m). Vail et al., (1977) explains that "the greater the sea-level fall the easier it is to recognize sequence boundaries". The minor amount of scour suggests the drop in base level relative to the study area was not extreme, and that the regression was of short duration. Regions south and east of the study area are interpreted as being paleotopographically higher than the study area. In these portions of the Powder River Basin, the lower Fall River marine deposits were completely removed and the Fuson to Fall River contact is not gradational. In these areas the contact is marked by a distinct unconformity (Hooper, 1961; Hooper, 1962; Gott et al., 1974). This explains why previous workers did not include the Fuson Shale as a member of the Fall River Sandstone. Previous workers have mapped the limit of the Fuson Shale in the eastern Powder River Basin (Figure 8). This limit identifies the edge of the paleotopographic highest areas where the Fuson Shale was completely removed by erosion. In areas east of this line, the Fall River has been identified as unconformably overlying the Lakota Sandstone (Bolyard and McGregor, 1966; Young, 1970; Campbell and Oaks, 1973).
Relative sea-level gradually rose as the basin was drowned by a southeasterly transgressing marine shoreline. Shoreface waves eroded and reworked the uppermost portion of the previous Fall River depositional cycle. This process removed much of the evidence of subaerial exposure, and additional amounts of the underlying sediments. In many cores, a thin, high-energy transgressive marine sandstone can be identified capping the unconformity. This deposit is a shallow-marine sandstone deposit that locally coarsens upward. The sandstone above the TSE is interpreted as a tidal flat deposit associated with a slowly transgressing seaway. This unit can be correlated over 50 miles to the northwest (seaward) where it gradually thins and grades into marine siltstones. The seaway did not transgress over a perfectly flat surface. Topography was originally influenced by Permian salt dissolution, then further modified by subaerial exposure. This topography controlled the thickness, type of lithology (siltstone versus sandstone), and the sedimentary structures within the depositional cycle that directly overlays the unconformity surface (LSE #1). The relative topographic position explains the occurrence of cross bedded marine sandstones directly overlying an unconformity surface in cores number 7 and 8 (Figures 15 and 16).
Extensive tidal channel deposits that display scoured bases and a fining-upward textural trend are common in tidal flat settings (Weimer et al., 1982). However, many cores from this depositional cycle are described as coarsening-upward. A review of modern coastal environments demonstrates that tidal channels, bays and estuaries are confined to bathymetric low areas along the coastline. If the low areas are controlled by underlying structural features, the tidal channels and bay sediments will be confined, and will not migrate out of these areas. Along the paleotopographic higher areas, a simple marine coarsening-upward cycle that is dissected by tidal creeks is deposited. This is analogous to the Georgia coast on the Atlantic Ocean (Figure 32) where large estuaries, bays, and tidal channel complexes are confined to topographic low areas. A general marine coarsening-upward unit that is dissected by tidal creeks is deposited along the tidal flats. The lithology and sedimentary structures described in this Fall River depositional cycle are representative of this depositional setting. This interpretation is supported by previous workers that have described the Fall River marine cycle in the Powder River Basin as a tidal flat deposit (Chisholm, 1970; Campbell and Oaks, 1973). The coeval Plainview Formation in the Denver Basin has also been described as a
Figure 32. ERTS false color of the Georgia coast (U.S.A.), large estuaries form at each intersection of a valley and the shoreline (from Weimer et al., 1982).
tidal flat deposit (Weimer, et al., 1982). After deposition of an unknown thickness of marine and marginal-marine deposits, a second significant relative drop in sea level (LSE #2) exposed the shelf to repeated erosion.

Many workers however have interpreted the two marine depositional cycles in the Fall River as a prodelta deposit. This interpretation was based on Walther's Law of Facies, which states that vertical facies changes reflect lateral facies changes. The prodelta interpretation assumes the fluvial channels in the area were a time-equivalent deposit. The recognition of a regional unconformity that separates the fluvial deposits from the marine deposits suggests that the marine facies does not have a time-equivalent fluvial deposit in the study area. Lacking a delta and understanding the environment of deposition with respect to the unconformity, the unit cannot be a prodelta deposit.

After the second drop in relative sea level, the marine shelf was exposed to repeated erosion (LSE #2). Active fluvial systems again formed south to north flowing streams superimposed on the valleys formed during the first Fall River sea-level lowstand. Based on isopach maps, this younger valley was approximately ten miles wide (Appendix D). Erosion within the valley was deeper during the second lowstand than during the first Fall River lowstand. Within
the valleys, the tidal flat, tidal channel, bay, and
estuarine sediments deposited during the previous Fall River
cycle were largely removed. Additionally, evidence of the
first Fall River lowstand was locally removed due to the
deeper erosional scour of the second Fall River lowstand
(Figure 33). In excess of 50 feet (15 m) of sediment was
eroded in the valley areas. The generally coarsening-upward
cycles deposited on the paleotopographic high areas during
the previous Fall River depositional cycles were not as
severely eroded.

Sea level is interpreted to have dropped at least 60
feet (18 m), relative to the study area. This magnitude is
estimated by assuming a water depth of ten feet (3 m) during
deposition of the tidal flat deposits, and adding 50 feet (15
m) of incision into the lower Fall River sedimentary rocks.

Sea level subsequently rose until a stillstand occurred,
and developed a northeast-trending shoreline which crossed
the Powder River Basin. The location and orientation of this
shoreline has been identified by other workers and described
previously (Figure 8). The fluvial systems that eroded
valleys on the Fall River shelf and supplied sediment to the
shoreline were still active. As sea-level rose, the stream
gradient was radically reduced, and sediment began to be
deposited aggradationally as valley-fill (Figure 33). These
Figure 33. Stratigraphic cross section B-B' displaying the relative positions of LSE #1, LSE #2, and the fluvial valley-fill sediments. The location of wells in cross section B-B', is posted in Figure 25.
fluvial sediments were deposited as low sinuosity point bar deposits. Because of fluctuating discharge rates, the high-energy cross bedded sandstones are interbedded with low-energy ripple laminated siltstones. The underlying tidal flat deposits were eroded and reworked as a coarse clastic sediment source. The valleys were primarily filled with fine-grained sandstone, due to an abundant supply. In the paleotopographic high areas, thin coals and carbonaceous shales cap the unconformity surface, indicating that large swamps formed on coastal plains behind the shoreline. Coals are absent in the northern portion of the study area, where estuarine deposits overlie the second Fall River unconformity surface (LSE #2).

North and east of the study area, the Fall River is composed of relatively thick marine sandstones that are oriented in a northeasterly direction. These sediments are interpreted to be barrier-bar deposits, formed during the sea-level stillstand. The absence of reservoir quality porosity and permeability in the barrier bar deposits, is attributed to low wave energy and to the erosion of upper shoreface deposits during the final Fall River transgression.

An estuary formed at each intersection of a valley and the shoreline (Figure 32). Bayhead deltas formed where active fluvial systems entered each estuary. Modern-day
analogies can be found along the coastal plain of the Gulf of Mexico. This coastal plain was dissected by rivers during the late Wisconsin sea-level lowstand (Wilkinson and Byrne, 1977). "During the Holocene transgression, as these Pleistocene paleovalleys were flooded, fluvial-deltaic sands and muddy sands, and bay-estuarine muds and sandy muds progressively filled the drowned valleys" (Wilkinson and Byrne, 1977). These drowned valleys are now identified as bays along the Gulf of Mexico coastline. Bayhead deltas are formed where active fluvial systems have prograded into these bays. Lavaca Bay, located along the Texas coastal plain has been described as a valley-fill, bayhead delta complex (Wilkinson and Byrne, 1977). The sedimentary units described in Lavaca Bay are similar to the sedimentary units described in the mapped bay located just north of Buck Draw field. In Lavaca Bay, the Tertiary unconformity is overlain by a deltaic sandstone that is overlain by a relatively thick sequence of estuarine mud (Wilkinson and Byrne, 1977). North of Buck Draw, the first Fall River unconformity (LSE #1) is overlain by tidal flat sandstones of variable thickness. The second Fall River unconformity (LSE #2) is overlain by locally thick estuarine mudstones and siltstones (Figure 34).

Mobile Bay, Alabama has been compared to Lavaca Bay and has also been described as a valley-fill, bayhead delta
Figure 34. The upper diagram displays a strike section across Lavaca Bay, Texas (Wilkinson and Byrne, 1977). The lower diagram displays a strike section across the postulated bay just north of Buck Draw field. In both sections, an unconformity is overlain by sandstone that is overlain by estuarine mudstones and siltstones.
complex (Warme, 1992). Mobile Valley is approximately ten miles wide and is filled with fluvial valley-fill deposits. Swamps and vegetation now cover the topographically higher areas that were not as severely eroded during the sea-level lowstand (Figures 35 and 36). A bayhead delta was formed by the progradation of distributary channels over previously deposited delta mouth bar and estuarine deposits in Mobile Bay.

Using Mobile Bay as a depositional model, the Fall River fluvial system was re-constructed. Cored wells were used to identify fluvial channel deposits. These wells were then used as a basis to identify channels in other wells by recognition of distinct electric log character. Net sandstone thickness from each well was posted, and the distribution of the fluvial system was interpreted after honoring all core data, isopach maps and seismic data (Figure 37). An examination of the area southwest of Buck Draw field reveals that three separate fluvial channels are located within the valley. The distribution of these channels corresponds to coincident thins and thicks in the Fall River to Fuson Shale Isopach Map (Figure 24) and on the Fall River to LSE #2 Isopach Map (Figure 25). By comparison with Mobile Bay, one would expect multiple channels in a bayhead-delta complex. There is sufficient subsurface control to map one
Figure 35. Infrared Landstat image of the Mobile Bay, Alabama area. A valley was cut by the Mobile River during the late Wisconsin sea-level lowstand, Mobile Bay was formed after this valley was drowned during the Holocene transgression. The relative position of Buck Draw field in the bayhead delta complex is identified.
Figure 36. Topographic map of the Mobile Bay, Alabama area.
Figure 37. Subsurface map of the Fall River channel, bayhead delta, and estuary.
of these channels terminating at Buck Draw field.

The Fall River reservoir sandstone at Buck Draw field is interpreted as a bayhead-delta channel deposit overlying a regional unconformity. The position and orientation of the channel is confined by the paleotopography within the valley and by the valley walls. The reservoir sandstone is composed of a series of stacked fluvial scour and fill deposits. Individual units range from less than 5 to 15 feet (1.5 to 4.5 m) in thickness and they typically fine upward. The width and thickness of individual sedimentary units indicate the fluvial sediments were deposited as low sinuosity point bars. The anomalous width of the fluvial sandstone body at Buck Draw field is due to the accretion and amalgamation of sandstone lobes. This width is due to the progradation of the channel into the bay. The commercial wells in this field are completed in high-energy, fluvial sandstone deposits. These sediments had excellent primary porosity development, which is a prerequisite for commercial production due to significant loss of porosity by compaction and cementation.

Several wells in the field have penetrated stacked partial-abandonment fill deposits. The sandstones of this facies were deposited as the finer grained sediments associated with the upper portions of individual point bars. Because of the lower energy depositional environment, these
sediments contain more fines and had poor primary porosity
development. The available porosity was detrimentally
occluded by subsequent burial and diagenesis. No commercial
production has been established from this facies, due to its
extremely low porosity and permeability. Offset wells,
located less than one half mile away, and completed in high-
energy fluvial facies will produce over 1 million BOP per
well.

Dry holes immediately north of the field have penetrated
lower energy delta mouth bar facies with extremely low
porosity and permeability development. Due to its small
areal extent, the depositional setting of this facies has not
been recognized by previous workers. Based on analogy with
modern sediments described by (Van Heerden and Roberts,
1988), the absence of extensive "distributary-mouth bar
deposits indicates rapid channel advancement". The
distribution and geometry of the mouth bar deposit will also
be influenced by the ambient water, water depths, bottom
slope seaward of the mouth, and tidal range (Coleman, 1981).
From this data, it can be concluded that the delta mouth bar
was deposited under low energy conditions which resulted in
poor reservoir development.

This interpretation is supported by examining cores,
electric logs, and production data from the area. Operators
have drilled 12 dry or non-commercial wells in an attempt to extend Buck Draw field to the north (Figure 6). The abrupt termination of prolific production at this end of the field is due to the facies change from high-energy fluvial deposits to lower energy delta mouth bar deposits. The energy level of the depositional environment significantly influences the potential for commercial production. This interpretation is supported by the poor production rates from wells completed in the lower energy, partial-abandonment facies in the middle of Buck Draw field.

The wells north and west of Buck Draw field have penetrated estuarine and tidal flat deposits. Because these sediments overly a regional unconformity, they have been incorrectly interpreted by previous workers as fluvial channel, clay plug, and crevasse splay deposits. Once the basal scour surface is identified as a regional unconformity, the sedimentary structures and trace fossils described in these cores are recognized as estuarine (Figures 17 and 18). Estuarine sediments are extremely variable because they are influenced by a complex combination of tidal currents, waves, river discharge, flora, and fauna (Clifton, 1982). Characteristically, estuary deposits become increasingly muddy landward. This is due to the abundant silt and clay sized material supplied by the fluvial system, and the lack
of high-energy wave activity. Coleman (1988) described how turbid, fresh water flows from the distributary mouth over denser marine waters. As this effluent plume spreads, velocity is reduced, and sedimentation proceeds by hydraulic sorting. This process results in the deposition of fines by suspension under waning energy conditions.

The lower reaches of the estuary are dominated by tides, currents, waves, and an oceanic sand supply (Clifton, 1982). Therefore, the sediments in this portion of the estuary are relatively sandy. This geographic distribution of sandstone and shale is recognized in the Fall River estuary, north of Buck Draw field. Cores from the small delta mouth bar are sandy. Slightly to the north, the estuarine sediment overlying LSE #2 is primarily shaly (cores number 8 and 9). Further north, sediment deposited over LSE #2 in wells located at the northern edge of the study area and beyond has a higher sandstone content (core number 8).

Additional distributary channel and delta mouth bar deposits, analogous to the deposit at Buck Draw field can be expected where the other channels located in the mapped valley prograde northward into the bay. Isopach maps, seismic data, and sedimentary structures observed in core document the existence of other distributary channels in the valley southwest of Buck Draw field. Additional Buck Draw-
type delta mouth bar complexes will be encountered at the seaward termination of these fluvial channels. These deposits will be located north of the documented fluvial channel deposits, and south of the documented estuarine deposits. Other south to north oriented Fall River valleys have been mapped in the Powder River Basin, outside of the study area. A similar depositional pattern can be expected in these areas.

The termination of Fall River deposition is marked by a relative rise of sea level, and coastal onlap. During this transgression, the energy of shoreface waves eroded and reworked the uppermost sediments deposited during Fall River time. Many of the features that characterize the period of subaerial exposure were removed during this transgression. Even the widespread coals, which are commonly resistant to erosion, are typically only a few inches thick. A transgressive marine sandstone was deposited, capping the Fall River Sandstone. This unit is overlain by open-marine shales deposited below effective wave base in the Skull Creek Seaway (Weimer et al., 1982). The lower Skull Creek shales are interpreted as brackish water deposits, based on the presence of diagnostic invertebrate fauna (Kauffman, 1977). A regressive episode during this overall marine transgression is marked by the deposition of the Dakota Silt during early
Skull Creek time (Figure 5). With continued rise in sea level, the Boreal Sea and the Austral Sea joined and the Western Interior Cretaceous Seaway extended from the Arctic Ocean to the Gulf of Mexico (Figure 2). During this sea-level high-stand a maximum flooding surface (MFS) was formed within a marine condensed shale section of the Skull Creek Shale.

**Depositional Summary**

The transition from fluvial to estuarine is not apparent by comparing the characteristic electric log curves of wells in the area. However, this transition can be recognized by comparing the sedimentary structures and characteristics typical of fluvial deposits in Buck Draw field with the sedimentary features observed in cores located north of this field. Many of the wells north of Buck Draw have been incorrectly identified as clay plugs deposited by distributary channels. These wells are now identified as marine and estuarine deposits overlying regional unconformities. This study demonstrates that relying on characteristic electric log profiles is not completely reliable unless sufficient core is available. Cores must be integrated with electric logs to accurately determine the presence and nature of erosional contacts. The difference between local channel scour and regional unconformity
surfaces must be recognized.

An examination of sequence boundaries and facies distribution supports Mobile Bay as an analogy for the Fall River Sandstone in the Powder River Basin. Cores recovered from mapped paleotopographic high areas document limited erosion and evidence of subaerial exposure. Cores recovered from mapped paleotopographic low areas in the southern half of the study area document deep erosion and deposition of thick fluvial channel deposits. Subsurface control and seismic data identify where the fluvial system formed a bayhead-delta complex by dividing into multiple distributary channel deposits (Figure 37). Cores recovered from wells north of the mapped bayhead delta are described as estuarine deposits overlying regional unconformities. Cores recovered from paleotopographic high areas, south of the mapped shoreline, consistently exhibit coals or carbonaceous shales capping the upper unconformity. To the north, these same unconformities are capped by marine and estuarine deposits. Coals are distinctly absent in these areas.

It is beyond the scope of this report to document in detail the unconformities and the distribution of facies in the Fall River Sandstone throughout the Powder River Basin. However, a brief examination of the Fall River channel deposits in the northeastern Powder River Basin indicate that
these sediments were deposited in a similar depositional setting. The productive trend from Coyote Creek to Miller Creek field (Figure 38) is interpreted as a south to north oriented fluvial valley-fill deposit. This is based on the identification of two unconformities overlying marine sediments from wells drilled in paleotopographic high areas adjacent to the valley (Figure 39). These surfaces have been described in outcrop and core by previous workers, but have been unrecognized as regional unconformity surfaces (Davis and Izett, 1958; Waage, 1959; Miller, 1963; Dondanville, 1963; Bolyard and McGregor, 1966; Mettler, 1965; Campbell and Oaks, 1973; Gott et al., 1974; Berg, 1977). Thick fluvial channel deposits identified in cores overly a single unconformity in paleotopographic low areas. At Miller Creek, the channel system forms a bayhead delta and divides into several separate distributary channels (Figure 39). The north edge of Miller Creek and Moorcroft fields is marked by a transition from fluvial to delta mouth bar and estuarine deposits. No Fall River channel production is found north of these fields.

The Plainview Sandstone in the Denver Basin (a Fall River equivalent) has a basal unconformity and is composed of two separate units (MacKenzie, 1971; Chamberlain, 1976). This author speculates that the basal unconformity and the
Figure 38. Map of the Fall River valley-fill channel deposit, and bayhead delta in the Coyote Creek to Miller Creek producing trend. The extent of each Fall River field is shaded. Fall River Structure Map (contour interval: 500’).
Figure 39. Fall River Type Log for the northeastern Powder River Basin (modified from Berg, 1979).

surface that separates the upper and lower Plainview are related to the sequence boundaries identified in the study area.

Other analogies are documented in outcrop studies. Ryan (1958) recognized an erosional surface and described Fall River channels as fluvial valley-fill deposits in the Black Hills of South Dakota. Campbell and Oaks (1973) completed an outcrop study of the Fall River Sandstone in the Black Hills of Wyoming. This work was completed prior to the wide-spread application of sequence stratigraphy concepts and a widely applied valley-fill model. The Fall River was described as a widespread tidal-flat deposit that was capped by rooted zones and paleosols. The paleosols were recognized as carbonaceous shales overlying "ochre-colored mudstone" and
reddish sandstones. Fluvial and estuarine sandstones were mapped filling large channels that cut through the tidal-flat deposits. These sandstone bodies were mapped as occupying the mouths of former streams. They are scoop shaped, and up to 100 feet (30 m) thick (Figure 40). The base of the channel filling deposit is marked by a conglomeratic lag. Campbell and Oaks (1973) described in great detail the exact criteria indicative of a fluvial-estuarine valley-fill system. These criteria include identification of paleotopographic highs with a subaerial exposure surface, valley erosion, and filling of the valley with fluvial sediments that grade seaward into estuarine sediments. Their outcrop work strongly supports the proposed depositional model and interpreted processes described in this report.

Following the Weimer et al. (1982) approach, the stratigraphic model for the Fall River Sandstone incorporates relative sea-level fluctuations, local tectonics that influenced paleotopography, and distribution of facies controlled by environments of deposition. The fluvial-estuarine valley-fill setting is supported by the identification of unconformities, characteristic sedimentary structures, the distribution of biogenic sedimentary structures, facies distribution, orientation of isopach thickness trends, and similarity to a modern analog. Buck
Figure 40. Geometry and facies distribution of the fluvial-estuarine complex that fills a deep scour in tidal-flat deposits (described by Campbell and Oaks, 1973).

Draw field is anomalous in two respects. First, its location at the exact seaward termination of the Fall River fluvial system. Secondly, good reservoir porosity and permeability enable wells in this field to produce oil at sustained flow rates exceeding 2,000 BOPD. The following petrographic study will establish a relationship between these two anomalous characteristics.

**Petrographic Study**

Thin sections were examined to compare and contrast the petrographic characteristics of each Fall River sandstone facies described previously. The selection of samples was based on: availability of core, facies, geographic distribution, porosity, and permeability development. Core plugs were not available for thin section examination or
analysis. The samples examined were taken within six inches of the actual core plug. The core plug porosity and permeability is assumed to represent one linear foot of core. This assumption is not always correct, due to the heterogeneous nature of this formation. The well names, locations, and sample depths are listed in Appendix C. Below is a detailed petrographic description of each sandstone facies.

Previous workers have completed point count analysis to determine the composition of each sedimentary facies in the Fall River Sandstone (Davies, 1986; Reservoirs Inc., 1987). Reservoirs Inc. examined 143 thin sections from 27 cores; many of these same cores were examined in this study. Each of the 70 thin-sections examined in the study area revealed that the Fall River Sandstone is a clean quartz arenite, typically containing over 90% monocrystalline quartz. Since a thorough point count study of the Fall River sandstones had already been performed by previous workers, a single sandstone sample representing each facies described earlier in this report was selected for point count examination. This examination revealed that these samples were essentially identical in composition to Fall River samples that were described by previous workers. Since the point count data from this comparison was in such close agreement and because
there is little compositional variation from facies to facies, no additional point count analysis was performed.

**Active Valley-Fill (High Porosity)**

This sandstone is a fine-grained, sub-angular, well sorted clean quartz arenite (Figures 41 and 42). Examination of 30 thin sections representing valley-fill deposits reveals that the compositional variation between wells is very slight. A representative sample of this facies is composed of 94% monocryalline quartz, 3% chert fragments, 2% plagioclase feldspar, and a trace amount of mica. Authigenic-clay coats are observed coating many of the framework grains. Authigenic-clay coats are "also commonly referred to as clay coatings, clay rims, or pore-lining clay" and they "originate as newly formed or regenerated clay minerals and typically have a radial morphology" (Pittman et al., 1992). The clay coats range from absent to thin and spotty to thick and well developed. In thin section examination, this sandstone demonstrates good development of moderately interconnected, intergranular porosity (Figure 41). Dissolution and microporosity are rare, but have also been observed (Figure 42).

Sandstones of this depositional facies range from slightly to highly silica cemented. The silica cement occurs as coalesced syntactical quartz overgrowths (Figure 43). The
Figure 41. Thin section photomicrograph of a representative Fall River quartz arenite sandstone from a zone with commercial production. Blue epoxy represents porosity. Quartz overgrowths can be identified where dust rims are developed. The green arrow (located at G-5) identifies a clay coat that covers a framework grain, the clay coats are black in color due to staining by oil. This specific clay coat has been enveloped by a quartz overgrowth. Generally, well-developed intergranular and interconnected porosity is developed in this facies. The green arrow (located at C-1) identifies rare dissolution porosity.
Operator: Kerr-McGee  
Well Name: NBDU 33-18  
Location: SE/4 18-T41N-R73W  
Depth: 12,596 feet (3,839 m)  
Core Porosity: 10%  
Core Permeability: 37 md.  
Facies: Channel (Bayhead delta)  
Magnification: 1.0 cm = 0.2 mm  
Light: Crossed Nicols

Figure 42. Different view of same thin section displayed in Figure 41. This sandstone is primarily composed of monocrysaline quartz framework grains. The green arrows identify chert fragments located at B-1 and G-3 where a trace amount of dissolution porosity is developed.
Operator: Presidio
Well Name: Sara Armstrong Federal 2-23
Location: SE/4 23-T41N-R74W
Depth: 12,895 feet (3,930 m)
Core Porosity: 9.8 %
Core Permeability: 11.5 md.
Facies: Channel (Bayhead delta)
Magnification: 1.0 cm = 0.07 mm
Light: Plane

Figure 43. Thin section photomicrograph showing significant silica cementation in this portion of thin section. The green arrow located at C-3 identifies an isolated clay coat that has been completely enveloped by quartz overgrowths. The large intergranular pore spaces located at F-3 to F-4 are bounded by quartz framework grains that are covered by well-developed clay coats. Rare kaolinite is developed at G-5 (green arrow), where a feldspar grain has been altered.
quartz grains generally form point and line contacts. Reliable evidence of pressure solution was not observed. Thick well-developed clay coats are present on the framework grains that border open pore spaces (Figure 44). Because the clay coats have been stained by hydrocarbons, they have a dark brown to black color. Therefore, the specific clay type can not be identified in thin section by a characteristic color. By comparison with dust rims and quartz overgrowths, the formation of these clay coats are interpreted to have preceded silica cementation (Figure 41 and 44). Therefore, they are interpreted as being formed during early diagenesis. Thick, well-developed clay coats appear to inhibit the growth of quartz overgrowths. Where clay coats are absent, thin, or spotty, over-saturated silica bearing solutions precipitated quartz on the framework grains thereby occluding the entire intergranular pore space (Figure 43). Not withstanding the detrimental effects of silica cementation in this facies, sufficient intergranular pore space remains interconnected for the reservoir to contain adequate porosity and permeability for commercial production.

Trace amounts of porosity development can be attributed to porosity enhancement by partial grain dissolution. Most commonly feldspar grains are leached, but chert fragments may also be partially dissolved. Typically, only a small fraction
Figure 44. Thin section photomicrograph of a monocrystalline quartz arenite with silica cementation. Thick, well-developed clay coats cover many of the framework grains. Intergranular porosity and microporosity are associated with the clay coats. The green arrow at G-1 identifies spotty clay coat development that covers a quartz framework grain. During later diagenesis, quartz overgrowth enveloped this spotty clay coat and has partially filled the intergranular pore space.
of the framework grain has been dissolved (Figures 41 and 42). As described previously, feldspar and chert fragments constitute less than eight percent of the total framework grains. Dissolution porosity accounts for less than two percent of the total porosity. Although dissolution porosity may serve to enhance porosity, it plays a minor role in overall reservoir development. Precipitated calcite is only present in small amounts. Calcite precipitation and subsequent dissolution does not appear to have a significant effect in porosity development. Likewise, quartz dissolution was not observed.

Active Valley-Fill (Low Porosity)

The sandstones in this facies are also a fine-grained, sub-angular, well sorted, quartz arenite (Figure 45). The framework grain composition of this sandstone is essentially identical to the active valley-fill, high porosity facies. A representative sample of this facies is composed of approximately 94% monocrystalline quartz, 3% chert fragments, 2% plagioclase feldspar, and trace amounts of mica. However, silica cementation is more extensive in this sandstone, filling most of the intergranular pore space. The silica cement is present as coalesced syntaxial quartz overgrowths (Figure 45). Additionally, the clay coat development in this sandstone is not as effective preventing quartz
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Operator: Bass Enterprises
Well Name: Pogo Woodward State 1-16
Location: NW/4 16-T40N-R74W
Depth: 13,082 feet (3,987 m)
Core Porosity: 7.1 %
Core Permeability: 0.4 md.
Facies: Channel (Bayhead delta)
Magnification: 1.0 cm = 0.07 mm
Light: Plane

Figure 45. Thin section photomicrograph showing extensive silica cementation completely filling most intergranular pore spaces. Clay coat development is spotty, and thin. The green arrows (located at E-7 and H-4) identify poor intergranular porosity and microporosity that is associated with clays.
precipitation. This is due to the thickness and extent of the clay coat development. The clay coats are not absent, but are typically thin or spotty. There are sufficient nucleation sites available for the extensive formation of quartz overgrowths. In many intergranular areas, quartz overgrowths have filled the pore space enveloping the nearby clay coat (Figure 46). Locally, clay coats are well developed and intergranular porosity can be identified (Figure 45). However, this porosity is isolated and in poor communication with other sites of preserved porosity. The sandstones in this facies have lower porosity and permeability because most of the pore space has been occluded by quartz overgrowths.

Partial Abandonment-Fill

This facies is also a quartz arenite sandstone, but is slightly less quartz rich, has poorer sorting, and a smaller average grain size than the active-fill sandstones (Figure 47 and 48). The framework grain composition of the point counted sandstone sample that represents this facies is 91% monocrystalline quartz, 7% chert fragments, 2% plagioclase feldspar, and trace amounts of mica. Due to the poorer sorting and finer grain size, this sandstone was subjected to additional porosity loss by compaction during early diagenesis. Additionally, the ripple-laminations associated
Figure 46. Thin section photomicrograph under higher magnification of thin and uneven clay coats covering quartz framework grains. These clay coats have been ineffective at inhibiting silica cementation. Green arrows point to quartz overgrowths that have filled intergranular pore spaces. Quartz overgrowths have formed on available nucleation sites and enveloped clay coats. The black arrow located at F-6 identifies preserved microporosity that is associated with clay coats.
Operator: Kerr-McGee
Well Name: NBDU 23-8
Location: SW/4 8-T41N-R73W
Depth: 12,310 feet (3,752 m)
Core Porosity: 4%
Core Permeability: 0.3 md.
Facies: Channel - Partial-Abandonment Fill
Magnification: 1.0 cm = 0.2 mm
Light: Plane

Figure 47. Thin section photomicrograph of a very fine-grained, monocrystalline quartz arenite. Well-developed clay coats, covering the framework grains are absent. Slightly higher detrital clay content. No visible porosity at this magnification. This facies is not commercially productive and is not considered prospective in the study area.
Operator: Kerr-McGee
Well Name: NBDU 23-8
Location: SW/4 8-T41N-R73W
Depth: 12,310 feet (3,752 m)
Core Porosity: 4 %
Core Permeability: 0.3 md.
Facies: Channel - Partial-Abandonment Fill
Magnification: 1.0 cm = 0.2 mm
Light: Crossed Nicols

Figure 48. Thin section photomicrograph displaying same view as presented in Figure 47. Sandstone is primarily composed of monocrystalline quartz framework grains. Slightly higher concentration of chert rock fragments are identified in this sandstone, see green arrows located at G-1, B-2, and D-3. The orange colored fragment located at D-5 is calcite. The black arrow located at A-4 identifies mica.
with this sandstone reduce permeability. The small pore spaces that remained after early compaction are partially filled with detrital clays. During later diagenesis, minor amounts of silica cementation filled intergranular pore space (Figure 47). The only porosity identified petrographically in this sandstone is ineffective microporosity, associated with clays.

**Marine Tidal Flat**

Examination of 34 thin-section samples representing this facies reveals that this facies has a smaller overall grain size, poorer sorting, and a higher ductile grain content than the active valley-fill sandstones (Figure 49). Additionally, glauconite can also be identified in select samples, supporting the interpretation of a marine depositional environment (Figure 50). These characteristics indicate that sandstones in this facies were deposited in a lower energy environment compared to the active valley-fill deposits. The point counted sandstone sample that represents this facies has 88% monocrystalline quartz, 7% chert fragments, 5% plagioclase feldspar. Additionally, a slightly larger percentage of ductile grains (mica) was observed in the sandstones representing this facies (Figure 51). Significant porosity loss is attributed to early compaction, related to grain size, sorting, and ductile grain deformation. The
Figure 49. Thin section photomicrograph from a dry hole located just north of the northern border of the study area. This highly silica cemented sandstone had been interpreted as a fluvial channel deposit by previous workers. For comparison with a commercially productive well, view Figure 44. Green arrows located at I-5 and F-1 identify thin, and spotty clay coats over quartz framework grains. These clay coats are interpreted as chlorite. The intergranular porosity is associated with these clay coats. The porosity is rare, poorly developed, and isolated. Black arrows point to microporosity that is also associated with these clays.
Figure 50. Thin section photomicrograph of microporosity associated with clays. Chlorite clay coats are identified by their characteristic green color. The black arrow located at D-4 identifies a dark green, round grain of glauconite. The black opaque mineral located at F-5 is pyrite.
Operator: Diamond Shamrock
Well Name: Peterson 33-29
Location: SE/4 29-T42N-R73W
Depth: 12,364 feet (3,769 m)
Core Porosity: 6.6 %
Core Permeability: < 0.01 md.
Facies: Marine Tidal Flat
Magnification: 1.0 cm = 0.2 mm
Light: Crossed Nicols

Figure 51. Thin section photomicrograph displaying the same view presented in Figure 50. This sandstone is primarily composed of monocrystalline quartz framework grains. The green arrow identifies rare calcite cementation located at C-4. Mica is more common in sandstones representing this facies, and can be identified at locations F-3, C-5, and F-7. The black arrow identifies an un-altered feldspar grain located at D-3.
prominent porosity type is microporosity, with isolated intergranular porosity. As observed in other Fall River sandstones, porosity is developed in association with clay coats. Since clay coat development is spotty, silica cementation is uniform and extensive.

The samples representing this sedimentary facies are from dry holes. Therefore, the clays in these samples have not been stained by hydrocarbons. This allows the identification of these clays as chlorite, due to its characteristic green color, habit, and low anisotropism.

**Scanning Electron Microscope Examinations**

A total of twelve samples were examined in the scanning electron microscope. These samples represent each of the Fall River facies described above. Based on the thin section examination, recognizable characteristics were expected with the SEM analysis. Specifically, the majority of the framework grains were known to be monocrystalline quartz. Extensive quartz overgrowths were known to form the major amount of pore filling material. Intergranular porosity was expected to be observed in association with well-developed clay coats. Within the marine tidal flat sandstones, the clay coats were identified as chlorite by characteristic color and morphology. The morphology of the clays observed by SEM examination in conjunction with energy dispersive
survey analysis (EDS) confirmed mineralogical identification and allowed the identification of the specific clay types in the other Fall River sandstones.

**Active Valley-Fill (High Porosity)**

Using EDS analysis, monocrystalline quartz was confirmed as the primary framework grain in this sandstone. Well-developed intergranular and interconnected porosity was observed between the quartz framework grains (Figure 52). Examination under increased magnification revealed that the well-developed clay coats that cover the quartz framework grains are chlorite (Figure 53). EDS confirmed that the clay coats are iron-rich chlorite. This specific clay type is diagnostic of a marine depositional environment, and will be discussed further in a later section of this report. In many intergranular areas, chlorite clay coats are very well developed and completely cover the framework grains (Figure 53). In these areas, the quartz overgrowths are sparse to non-existent. These thick clay coats reduce effective permeability and form less-effective microporosity at the expense of intergranular porosity. However, this porosity and permeability reduction is not significant when compared to the porosity loss due to silica cementation.

Quartz overgrowths are common in sandstones representing this facies. These overgrowths form on portions of framework
Operator: Kerr-McGee
Well Name: NBDU 23-8
Location: SW/4 8-T41N-R73W
Depth: 12,334 feet (3,759 m)
Core Porosity: 12%
Core Permeability: 30 md.
Facies: Channel (Bayhead delta)
Magnification: 101 X

Figure 52. SEM photomicrograph displaying optimum development of intergranular porosity and permeability. Well-developed quartz overgrowths can be identified by the euhedral crystal shape covering the quartz framework grains.
Operator: Kerr-McGee  
Well Name: NBDU 23-8  
Location: SW/4 8-T41N-R73W  
Depth: 12,334 feet (3,759 m)  
Core Porosity: 12%  
Core Permeability: 30 md.  
Facies: Channel (Bayhead delta)  
Magnification: 460X

Figure 53. SEM photomicrograph of thick, and well-developed chlorite clay coats covering quartz framework grains. The chlorite forms radiating blades and flakes oriented normal to the surface of the framework grain. Nucleation sites for silica cementation are nearly absent. Quartz overgrowths occur as very small, poorly defined crystals faces, attached to the host grain at isolated points. Porosity loss due to silica cementation is minor.
grains that are not covered by chlorite (Figure 54). In this manner, quartz overgrowths partially fill intergranular pore space, even where chlorite clay coats are present. This demonstrates how even the most porous Fall River sandstones in the study area have undergone significant porosity reduction by silica cementation.

**Active Valley-Fill (Low Porosity)**

The sandstones in this facies have been significantly silica cemented. Examination under increased magnification reveals that chlorite clay coats are present, but these clay coats are not as well developed as the clay coats in the high porosity channel samples. Illite clay coats have also been identified in these sandstones (Figure 55). The quartz overgrowths have nucleated on the framework grains around the incomplete and thin clay coats. These overgrowths extend from multiple nucleation sites and meet in an interlocking fashion (Figure 55). This cementation completely fills many intergranular pore areas nearly eliminating intergranular porosity and severely reducing permeability. Rare open pore spaces were identified, but pathways connecting the pore spaces were tortuous.

**Partial Abandonment-Fill**

Based on thin-section examination, rare porosity
Figure 54. SEM photomicrograph of an intergranular pore space with a well-developed chlorite clay coat on the framework grain in the left side of the photograph. The framework grain on the right side of the photograph was not completely covered by chlorite clay. Quartz nucleation sites were available on this grain. Quartz crystals grew outward from these nucleation sites and partially fill the intergranular pore space. Thick, well-developed chlorite clay coats must completely cover all of the framework grains to effectively inhibit silica cementation. This photograph represents spotty chlorite clay coat development.
Figure 55. SEM photomicrograph of illite clay coats covering the framework grains of an extensively silica cemented interval. The morphology of this clay does not effectively cover the quartz framework grain. Nucleation sites for silica precipitation are generally available.
development and moderate silica cementation were expected in the sandstones representing this facies. Intergranular pore spaces were rare, and filled with detrital clays (Figure 56). Any porosity development was microporosity, associated with the clays. The grains appear molded together because of early porosity loss due to compaction. Silica cementation is absent only where detrital clays and clay coats are formed. SEM examination conclusively demonstrates that this facies is not a potential reservoir in the study area.

**Marine Tidal Flat**

Under SEM examination, sandstones representing this facies are similar to the low-energy channel deposits. Intergranular pore space is very limited; interconnection of pore space appears non-existent (Figure 57). Only ineffective microporosity could consistently be identified in the pore spaces. The intergranular areas are filled with detrital clays, clay coats, and silica cement. This poor porosity development is due to poorer sorting, higher detrital clay content, and to the slightly finer grain size of sandstones representing this facies. In addition, many framework grains are covered by very thin and poorly developed clay coats which did not inhibit silica cementation (Figure 58). The effectiveness of this facies as an updip hydrocarbon trap is obvious in Figures 57 and 58.
Operator: Kerr-McGee
Well Name: NBDU 33-13
Location: SE/4 13-T41N-R74W
Depth: 12,605 feet (3,842 m)
Core Porosity: 4 %
Core Permeability: 0.3 md.
Facies: Channel - Partial-Abandonment Fill
Magnification: 270 X

Figure 56. SEM photomicrograph of a non-prospective reservoir sandstone deposited in a low-energy fluvial environment. Rare and isolated intergranular porosity is present at location E-3. This porosity is associated with well-developed chlorite clay coats (located at E-3, and G-3). In other areas in this sample, primary porosity was too low for the formation of well-developed chlorite clay coats. Significant porosity loss is attributed to compaction. Clays have completely filled the intergranular pore space at locations C-4, and C-5. A quartz overgrowth can be identified by its euhedral shape at location E-3.
Figure 57. SEM photomicrograph displaying clay filled intergranular pore spaces. Microporosity and minor intergranular porosity are developed at locations C-2, and F-5. Porosity loss due to compaction and silica cementation. This photomicrograph displays the effectiveness of this facies as an updip hydrocarbon trap.
X-Ray Diffraction Analysis

The possibility of using X-Ray diffraction analysis to identify depositional facies and the related potential for porosity preservation in the Fall River Sandstone was examined. A total of eight samples were analyzed using X-Ray diffraction techniques: two high-energy/high porosity channel samples, two high-energy/low porosity channel samples, two delta mouth-bar samples, one estuarine sandstone sample, and one "regional" marine tidal flat sandstone sample. All the samples were prepared at the same time using identical procedures.

The previous examination indicated that the amount and distribution of chlorite clay coats, illite clay coats and detrital clays (kaolinite) were not uniform in the Fall River sandstones. Therefore, the magnitude of these diffraction clay peaks was expected to vary from facies to facies. A modest amount of chlorite clay was expected in the high-porosity channel sandstone facies. Diminished chlorite peaks accompanied by trace amounts of illite and kaolinite clays were expected in the other Fall River facies. These data confirmed the previously observed relationship between porosity preservation, chlorite clay coat development and silica cementation. A silica peak was expected in each sandstone facies, due to the pervasive silica cementation in
Operator: Bass
Well Name: UTC Unit #1
Location: NE/4 23-T42N-R74W
Depth: 12,508 feet (3,812 m)
Core Porosity: 3.1 %
Core Permeability: 0.32 md.
Facies: Marine Tidal Flat
Magnification: 1040 X

Figure 58. SEM photomicrograph of thin and poorly developed clay coats over quartz framework grains. These clay coats did not effectively cover quartz nucleation sites. Silica bound on top of these thin clays and formed multiple overgrowths. These individual quartz overgrowths grew into the intergranular pore space, then merged to form larger planar surfaces. The overgrowths meet in the intergranular pore space in an interlocking fashion. This cementation has significantly reduced porosity; permeability is extremely low.
all of the Fall River sandstones.

Each of the eight samples displayed nearly identical XRD diffractograms (see Appendix C). A trace amount of illite clay, a small amount of chlorite clay, and a moderate amount of quartz were identified in each sample. A representative diffractogram is displayed in Figure 59. To check for consistency, multiple samples of different facies were prepared. Each pair of analysis matched very well, indicating reliable data. No strong correlation was apparent between the magnitude of the quartz and the chlorite diffraction peaks, and porosity development in the Fall River sandstones.

This evaluation indicates that the magnitude of the variation in clay type and clay content in the Fall River sandstones is insufficient for differentiation by X-Ray diffraction analysis. No correlation was made between facies, porosity preservation and XRD analysis data. Therefore, the use of XRD analysis as an exploration tool for Fall River oil exploration in the southern Powder River Basin was discounted.

**Paragenetic Interpretations**

Based on analogy with modern coastal environments, one may expect to locate high-energy facies within the marine and estuarine deposits that are prospective reservoirs. However,
Figure 59. Clay fraction X-Ray diffraction diffractogram of a Fall River Sandstone. Additional diffractograms are displayed in Appendix C.
the wells completed in the Fall River marine and estuarine deposits have all been non-commercial. Low wave energy and a microtidal environment (0 to 2 meter tidal range) is interpreted along this portion of the Western Interior coastline (RPI/Colorado, 1983). This low depositional energy partially explains why the marine facies have slightly smaller grain size, slightly poorer sorting, higher detrital clay content, and more ductile grains. These factors are sufficient to prevent the retention of commercial reservoir-quality porosity after compaction and silica cementation.

Only wells completed in the fluvial facies of the bayhead-delta complex have been consistently commercial. The diagenetic processes that influenced the preservation of porosity in this facies will be examined. These processes will then be compared with the diagenetic processes in other Fall River facies.

During early diagenesis, several chemical and physical transformations were ongoing concurrently. These events include: the alteration of authigenic clays, formation of pyrite, and the initiation of porosity loss by compaction. These processes are described separately, but are recognized as concurrent events.

Formation of Pyrite

The Fall River Sandstone contains locally abundant
pyrite nodules and well developed chlorite clay coats. Petrographic examination indicates both of these pore fillers formed during very early diagenesis. Anoxic conditions are required for the formation of these minerals. Therefore, the Fall River sedimentary rocks are interpreted to have completed the transition from aerobic to anoxic conditions during very early diagenesis. Once anoxic conditions were established, anaerobic micro-organisms reduced sulfate to hydrogen sulfide as they consumed organic matter. Disseminated pyrite and pyrite nodules formed when this hydrogen sulfide complexed with iron (Waples, 1985). Core descriptions document that carbonaceous debris was widely available and locally abundant, which is also shown by the wide distribution of pyrite in the Fall River sedimentary rocks. The chemical equation for the formation of pyrite is listed below in Table 2.

\[
2 \text{SO}_4^{2-} + \text{Fe}^{2+} + 16 \text{H}^+ + 14 \text{e}^- = \text{FeS}_2 + 8 \text{H}_2\text{O}
\]

Table 2. Chemical equation for the formation of pyrite (Drever, 1988).

Porosity Loss Due to Compaction

It is beyond the scope of this report to develop a detailed porosity versus depth profile for the Fall River valley-fill deposits in the Powder River Basin. However, by
performing spot checks, compaction has been identified as a significant cause of porosity loss in the Fall River Sandstone. This was determined by using McBride's (1982) formula, which states that porosity loss by compaction is equal to initial porosity minus present day porosity plus the percentage of pore-filling cement. This calculation, listed below in Table 3 indicates that 15 percent of the original rock porosity was reduced by compaction. This value assumes 44% primary porosity for the valley-fill deposits, and averaged estimates of pore fillers based on point count data.

\[
15\% \text{ LOSS} = 44\% \varnothing - (9\% \varnothing + 15\% \text{ Silica} + 4\% \text{ Clays} + 1\% \text{ Other})
\]

Compaction = original porosity - (current porosity + all pore fillers)

Table 3. Equation describing the method for determining porosity loss by compaction (from McBride, 1982).

The active valley-fill deposits in the Coyote Creek to Miller Creek trend are encountered at average depths of 6,200 feet (1,890 m). At this depth, porosity loss due to mechanical compaction is not as extreme. The reservoir sandstones have average porosities of 18.5% and permeabilities may be as high as 200 md (Truchot, 1963). In the study area, the Fall River Sandstone is encountered at an average depth exceeding 13,200 feet (4,023 m). The best porosity at this depth is developed in Buck Draw field. The commercially productive fluvial sandstones in this field have
average porosities less than 9% and average permeabilities less than 3 md (Hawkins and Formhals, 1985). Petrographic examinations indicate porosity loss is attributed to mechanical compaction and silica cementation. The high energy channel deposits outside of the Buck Draw Area have even lower porosity than that recorded in Buck Draw field. Based on petrographic examinations, this is attributed to higher amounts of silica cementation. The porosity loss is difficult to quantify, because the volume of rock is decreased, resulting in a relative increase in all mineral phases, including cement (McBride, 1989). A comparison showing increased grain packing and cementation from fluvial channel deposits in Buck Draw field compared to Coyote Creek field is presented in Figure 60.

Formation of Chlorite Clay Coats

In this report, and in previous studies, workers have described the occurrence of well developed, iron-rich chlorite clay coats in the high-energy, fluvial sandstone samples from Buck Draw field (Hawkins and Formhals, 1985; Reservoirs Inc., 1987). Other high-energy, fluvial sandstone samples examined from dry holes outside of the Buck Draw area lack these well developed clay coats. The chlorite clay coats are interpreted as an authigenic clay formed during early diagenesis since they coincide with dust rims and
Figure 60. Upper photomicrograph displays porosity development in the Fall River valley-fill channel deposit at a depth of 6,847 feet (2,087 m). Most grain contacts are point to point, silica cementation is modest. The lower photomicrograph displays the porosity development in the same Fall River facies at a depth of 12,596 feet (3,839 m). Grain contacts are point and line, silica cementation is higher.
precede the emplacement of other pore filling materials. Following Wilson and Pittmans' (1977) criteria, the chlorite clay coats are interpreted to be authigenic because of their delicate morphology. They occur as pore linings of radiating clusters of small flakes and blades oriented normal to the surface of the framework grain (Figure 53). This morphology demonstrates that the clay development formed in open pore space during early diagenesis prior to significant porosity loss by compaction.

There are multiple chemical reactions that form chlorite. These reactions can occur at any time after burial (Hayes, 1970). Dunoyer De Segonzac (1970) explained that "detrital particles can be aggraded to chlorite during early diagenesis" but that massive chlorite growth may also occur during late diagenesis. The polytypism of chlorite is dependent on temperature, pressure, growth rate, and the nature of the reactants (Hayes, 1970). Secondary stages of chlorite formation during later diagenesis were not observed during petrographic examination. Therefore, only reactions that formed iron-rich chlorite clay coats during early diagenesis were examined.

Iron-rich authigenic chlorite forms during very early diagenesis when argillaceous sands are deposited in marine waters (Hayes, 1970; Land and Dutton, 1978). This well
documented relationship is the basis for the interpretation of iron-rich chlorite clay coats as a diagnostic indicator of a marine depositional environment. In studies of Gulf Coast sedimentary rocks, Loucks et al. (1984) reported that chlorite clay coats form at shallow burial depths, generally within the first 130 feet (40 m). Similar chlorite clay coats have been described in modern quartz-rich shoreface sandstones, at depths of 34 feet (10.4 m), (Burns and Ethridge, 1979).

A model for the formation of early diagenetic chlorite was described by Dunoyer De Segonzac (1970) and is presented in Figure 61. This model summarizes how "montmorillonite can be markedly altered during early diagenesis, at very moderate temperatures and pressures". This reaction requires montmorillonite-rich clay assemblages to be present in the fluvial and marine waters as grain coatings on the sand, or as detrital clay in the silts and shales. The aqueous medium in which sediments are deposited will either be magnesium-rich (marine), or potassium-rich (fluvial). Dunoyer De Segonzac (1970) explains that "the chemical composition of the interstitial solution is the important factor in the transformation of montmorillonites". In a magnesium-rich environment, montmorillonite alters to corrensite, and then to chlorite. In a potassium-rich environment, montmorillonite
Figure 61. The transformation of montmorillonite to chlorite and illite (from Dunoyer De Segonzac, 1970).
alters to alleuvarite, and then to illite.

An activity diagram identifying the transition from montmorillonite to chlorite is presented in Figure 62. The chemical reactions that form iron-rich chlorite and illite are detailed in Table 4. The reaction path for this model is simply controlled by the presence or absence of marine waters. "The theoretical Mg/K ratio of sea water is 3.34", this high ratio is why "magnesium is preferentially absorbed between the expanded clay layers" of montmorillonite (Weaver, 1959). The high total dissolved solids (TDS) in sea water supply a unique chemical environment favorable for the alteration of montmorillonite to chlorite. The alteration of montmorillonite cannot follow these same reaction paths in a fresh water (low TDS) environment.

The formation of chlorite clay coats during early diagenesis had been recognized and well documented by previous workers. Milne and Earley (1958) concluded that clays in sandstones are greatly altered when sufficient time is available for chemical equilibria to be reached between sea water and the clay minerals. This work coincides with Weaver's (1959) observation that montmorillonite alters to either chlorite or illite. Hayes (1970) demonstrated that chlorite forms under low temperatures in a reducing environment, in sediments with high porosity and
1.8Ca. Mont.+1.85Mg^{2+}+1.85Fe^{2+}+14.8H_{2}O =

Chlorite+0.29Ca^{2+}+4.6H_{4}SiO_{4}+6.8H^{+}

Ca. Mont.+0.41K^{+}+0.57H^{+}+2.64H_{2}O =

0.68Illite+0.08Mg^{2+}+0.25Fe^{2+}+0.16Ca^{2+}+1.6-2H_{4}SiO_{4}

Where: Ca-Montmorillonite=Ca_{1.6}(Al_{1.56}Mg_{2.5}Fe_{0.5})Si_{4}O_{10}(OH)_{2}

Chlorite = Mg_{2.3}Fe_{2.3}Al_{1.4}(Al_{1.4}Si_{2.6}O_{10})(OH)_{8}

Illite = K_{2}Mg_{2.5}Al_{1.8}(Al_{3}Si_{3.5}O_{10})(OH)_{8}

Table 4. Chemical reaction for the transformation of montmorillonite to chlorite and illite (From Kaiser, 1984).
permeability. The abundance of pyrite nodules in the Fall River sedimentary rocks is a diagnostic indicator of a reducing environment during early diagenesis. The formation of chlorite clay rims is also controlled by primary porosity and permeability. Burns and Ethridge (1979) explain that the morphology of chlorite clay requires sufficient pore space to form radiating clusters of clay laths, this pore space is available in high porosity sandstones but is not available in low porosity sandstones. The thick, well-developed chlorite clay coats from samples in Buck Draw field, are characterized by radiating clusters of small flakes and blades (Figure 53). The large intergranular pore space that is required for the formation of this clay morphology was available. Chlorite clay coats have also been identified in the "regional" marine and estuarine deposits. However, these deposits had significantly lower primary porosity. Due to smaller primary pore spaces, chlorite clay coats in these deposits are not as thick and well developed.

The quality of the chlorite clay development was controlled by many variables, other than porosity and permeability. Clay development was also controlled by the original distribution of the argillaceous clay, the level of dilution of the invaded marine waters (the pore water chemistry), and the residence time of these fluids. Under
ideal conditions, the formation of the chlorite clay continued until the clays were in chemical equilibria with the saline waters. However, ground water flow can modify the water chemistry and thereby alter the chemical reaction.

This diagenetic model assumes that the climate and provenance were favorable for montmorillonite-rich clay assemblages to have formed. Montmorillonite is a predominant clay mineral in arid regions where the leaching of soils is greatly reduced (Milne and Earley, 1958). A study of the Mississippi delta demonstrates that given a favorable (arid) provenance, montmorillonite clays are common in fluvial, deltaic, and estuarine sediments (Figure 63). It appears reasonable to apply these assumptions when modeling the Fall River sandstones. These assumptions are supported by the presence of chlorite clays in the Fall River marine

![Diagram](image)

**Figure 63.** Major clay mineral types of northeastern Gulf of Mexico. Arbitrary scale of amounts. (From Milne and Earley, 1958).
sediments, and by illite in the fluvial sediments. In a study of Eocene sandstones in the Gulf of Mexico, Weaver (1959) reported an abundance of illite in deltaic sandstones and chlorite in beach sandstones.

In order to completely apply this model to explain the presence of chlorite clay coats in the Fall River sandstones in Buck Draw field, marine (magnesium-rich) waters must be introduced syndepositionally into the intergranular pore space of the fluvial sandstones. As described previously, Buck Draw field is located where the Fall River valley-fill system formed a bayhead-delta complex. These fluvial sediments were deposited in or adjacent to marine waters. Due to the proximity to the ocean, marine waters were driven onto these fluvial deposits during high tides and storms. Wright and Coleman (1974) describe distinct wedges of saline water that migrate up the distributaries of the Mississippi delta during low and normal river stages. Due to the large density contrast, the fresh fluvial waters flow downstream above the saline waters. The only time these wedges of saline water are completely flushed from the channels is during flood stage. Through this same process, saline waters may have moved up the Fall River fluvial system. The saline waters were more dense than fresh waters so they could invade the intergranular pore space by vertical migration. The
gradational upstream migration of saline water is evident in the Wilcox sandstones in the Texas Gulf Coast, where the distal distributary channel sandstones contain more chlorite than the proximal channel deposits (Stonecipher and May, 1990).

Conventional core analysis documents the extreme heterogeneity of porosity and permeability in the high-energy channel deposits in Buck Draw field. Porosity ranges from 4 to 12 percent, permeability ranges from less than 0.01 md to over 80 md. However, a general relationship can be recognized between the stratigraphic position of clean sandstones and the development of permeability. A case can be made for "windows" in the upper part of the Fall River channel deposit that acted as high permeability vertical conduits for the introduction of marine waters into the reservoir (Figure 64). Permeability windows were developed where high-energy fluvial sandstones were deposited in the upper portions of the channel deposit. These sandstones acted as conduits for vertical migration when distinct wedges of comparatively dense marine waters migrated up the distributary channels. As the marine waters invaded the fluvial deposits, they mixed with and displaced the fresh water in the intergranular pore spaces. Through this syndepositional process that is unique to the bayhead delta
Figure 64. Schematic cross section of permeability barriers and the invasion of marine waters during deposition of the Fall River channel deposits in Buck Draw field.
channel deposits, the intergranular pore water chemistry in the high-energy sandstones was altered from fresh to marine.

The presence of comparatively impermeable shale layers prevented the complete displacement of the original fresh pore waters throughout the fluvial deposits. Many compartments in the distributary channel deposit retained fresh water in the intergranular pore spaces. These areas of banked fresh water are now recognized in core as high-energy fluvial deposits with extremely low permeability. As expected, these low-porosity sandstones have poorly developed chlorite clay coats covering the framework grains.

The thoroughness of the displacement of intergranular pore waters is also related to the distance the distinct wedge of marine water migrated up the distributary channels. A mixing zone of fresh and marine waters can be recognized by the lower productivity of Fall River wells completed in the fluvial channel five to eight miles southwest of North Buck Draw Unit. In this area, the chlorite formation was not as widespread and complete. However, sufficient chlorite clay coats were developed to locally preserve porosity during later diagenesis.

The distinct marine water wedge did not migrate great distances upstream of the bayhead delta complex. High-energy fluvial valley-fill sediments further to the south (landward)
retained fresh water in the intergranular pore space and lack well-developed chlorite clay coats on the framework grains. In these sandstones, illite is the dominant clay and was formed during early diagenesis. During later diagenesis, compaction-driven marine waters sourced from dewatering marine sediments migrated through these sediments. However, much of the original montmorillonite had previously been altered to illite. In these sandstones, the amount of well-developed chlorite clay coats is minor.

Another assumption with respect to this model is that the chemistry of the water in the Cretaceous Epeiric Seaway was favorable for the alteration of montmorillonite to chlorite. The salinity of the Cretaceous Seaway during Fall River time has been interpreted as brackish (Waage, 1959; Harris, 1976; Kauffman, 1977). The diagenetic model described earlier is based on the chemistry of standard mean ocean water. Therefore, these models are only analogies and are not necessarily directly correlatable.

However, chlorite clay coats are developed in the Fall River "regional" marine facies. Additionally, anomalous amounts of well-developed chlorite clay coats are developed in the high-energy fluvial deposits at the exact termination of the bayhead-delta system. Therefore, the water chemistry of the Early Cretaceous Sea must have been conducive for the
formation of chlorite clay coats.

As previously described, chlorite clay coats are of variable thickness, partially or completely cover framework grains, and slightly reduce the sandstones' permeability. Additionally, the large surface area of the thin blades create microporosity and increase tortuosity at the expense of intergranular porosity. Although the chlorite is detrimental to the overall porosity, its presence is critical to the preservation of intergranular porosity.

Porosity Loss Due to Silica Cementation

Based on thin section and SEM examination of Fall River samples from the study area, silica cementation is consistently recognized as the second most important cause of porosity loss. Every high-energy fluvial sandstone sample that had poor porosity and permeability development was extensively silica cemented. Based on point count analysis, some Fall River sandstones have over 20% quartz overgrowths. Conversely, every high-energy fluvial sandstone sample that had relatively good porosity and permeability development was only slightly to moderately silica cemented. The silica cement occurs as overgrowths that form well-developed euhedral crystals over the framework grains (Figure 52).

Tremendous pore volumes of silica-saturated formation water are required to develop extensive quartz overgrowths
(Land and Dutton, 1978). The paleohydrology of the Fall River valley-fill system is an ideal setting to meet this requirement. These deposits had high primary porosity and permeability and formed an effective aquifer system that was continuous and extensive. The channel facies was bounded on all sides by water saturated shales, siltstones and low-permeability sandstones that were deposited in a lower-energy environment. Compaction-driven fluids containing dissolved silica from dewatering siliceous sediments migrated to the high-permeability fluvial deposits. Copious amounts of formation water were flushed through these conduits as water migrated out of the subsiding basin. McBride (1989) reports that fluid flux is one of the most important factors that causes an increase in the volume of quartz cement in a sandstone. Therefore, the high-porosity valley-fill deposits were the most likely facies to sequester silica cement.

Fluids expelled from compacting and dewatering siliceous sediments contain silica in solution. The silica is supplied by the transformation of dewatering clays (McBride, 1982; McBride, 1989). By volume, most of the formation water is expelled after the sediments are buried one to two kilometers, and are subjected to temperatures greater than 122° F (50° C) (McBride, 1989). The rate of expulsion is controlled by the amount of water in the sediments and by the
burial rate. Because of the depth, the expelled fluids are comparatively hot. At these higher temperatures, the fluids are undersaturated or normally saturated with respect to silica. This is due to the high solubilities of quartz and other low-temperature silica polymorphs at high temperatures (McBride, 1989). The compaction-driven fluids migrate updip to areas of lower potentiometric pressure. As these fluids migrate out of the deeper portion of the basin, their temperature cools.

A drop in fluid temperature will cause fluids to become oversaturated with respect to silica and to precipitate syntaxial quartz cement (Land and Dutton, 1978). This analysis was supported by McBride (1982 and 1989). Furthermore, he explained that with the cooling of formation fluid, the solubility product of quartz is exceeded, so silica will preferentially precipitate where detrital quartz grains are available as seeds (McBride, 1989). McBride (1982) concluded that this stage of quartz cementation typically takes place in a window between burial depths of 1,800 feet (549 m) and 6,000 feet (1,829 m). In a later study of the Gulf Coast and North Sea basins it was observed that quartz precipitated from ascending formation waters between temperatures of 140° and 212° F (60° and 100° C) (McBride 1989). Work completed by Blatt (1979) concluded
that silica cementation is controlled by fluid flow, and occurs at a relatively shallow depth prior to significant compaction of detrital grains.

A burial history curve (Figure 65) was constructed using the type log displayed in Figure 5 as representative of the study area. The data and assumptions used to reconstruct the burial history of this portion of the Powder River Basin are summarized in Appendix E. Based on the current geothermal gradient calculated for this well, the Fall River Sandstone would enter the temperature window for silica precipitation (140°F or 60°C) at a burial depth of approximately 4,500 feet (1,370 m). The majority of silica cementation is interpreted to have taken place between 66 and 70 million years before present. This assumes most of the formation water is expelled prior to a burial depth of 6,000 feet (1,829 m).

This model assumes that dewatering fluids will retain their heat content while migrating out of the deep basin. However, fluid flow models indicate compaction-driven waters in homogeneous sandstones move too slowly to avoid conductive cooling, and are therefore an ineffective heat transfer mechanism (Bethke, 1986). Heat transfer by compaction-driven flow is controlled by high permeability, high porosity and high heat flows (Deming et al., 1990). Model simulations
Figure 65. Burial history curve representing the study area. The hydrocarbon maturity windows are shaded (see Appendix E for supporting data).
indicate effective thermal perturbations may occur in heterogeneous sandstones, if an impermeable layer prevents fluids from escaping upward while fluid flow is concentrated through a high-permeability pathway (Deming et al., 1990). As described previously, the fluvial valley fill deposits in the Fall River Sandstone formed a continuous and extensive aquifer system. These aquifers acted as high permeability conduits for the migration of copious amounts of compaction-driven fluids. The highly porous and permeable aquifer systems in this heterogeneous sandstone address both the water volume problem and the heat perturbation problem associated with the proposed silica cementation model.

It should be noted that grain size, primary porosity and permeability, availability of quartz nucleation sites, formation pressure, and formation water chemistry combine to influence the depth and width of the silica precipitation window. Subsidence alters these variables, so that the region of quartz precipitation can continuously shift. Through the shifting of this precipitation window, the Fall River sedimentary rocks throughout the Powder River Basin received silica cementation. The amount of cementation is variable, due to the length of time spent within the precipitation window. This serves to explain the occurrence of severely cemented valley fill deposits in the study area,
when compared to the equivalent facies in the Coyote Creek to Miller Creek trend (Figure 60). This stage of silica cementation terminated when the supply of fluids from dewatering shales was exhausted.

Quartz overgrowths precipitate directly from aqueous solution as well ordered, low (alpha) quartz (McBride, 1989). Silica will only precipitate where it can locate a nucleation site on a quartz framework grain. At this site, the silica forms "an initial layer of regular atomic pattern (the monolayer)", whose structure is in optical continuity with that of the substrate (Waugh, 1970). Once such a layer is established, the basic structure is preserved and the overgrowth will grow rapidly. With continued growth, the crystalline projections become so numerous on grain surfaces that the crystals merge and overlap until a single crystal face with recognizable form is developed (Waugh, 1970). This process commences simultaneously (in the precipitation window) at all available nucleation sites on the framework grains. Dust rims and thin clay coats covering the quartz framework grains do not effectively cover the nucleation sites. In these areas, the silica bearing solutions will bind on top of the clay and still grow secondary quartz (Waugh, 1970).

Quartz nucleation sites are effectively covered, if
authigenic clay coats are thick, well developed, and completely cover the quartz framework grain. The type of clay that coats the framework grain is also important. Iron-rich chlorite clay coats have been described in the Fall River Sandstones. These clays are composed of thick coats of radiating clusters of small flakes and blades oriented normal to the surface of the framework grain (Figure 53). This particular morphology effectively covers quartz nucleation sites significantly inhibiting the precipitation of quartz overgrowths. On these grains, no sites were available for the initial quartz monolayer to form. Quartz overgrowths will not form on these grains, even if all of the conditions are ideal for the precipitation of silica.

Calcite Cementation

During late diagenesis, calcite cement formed over quartz overgrowths. At this late stage of diagenesis, the carbon may have been supplied by the thermal breakdown of organic molecules. Blatt (1979) explained that calcite solubility decreases with increasing temperature and is therefore more likely to precipitate at depth. Calcite cementation is not extensive, it is characteristically scattered and constitutes a small percentage of the pore space.
Kaolinite Formation

Kaolinite clay has also been identified in the Fall River Sandstone. It is present as stacked plates and aggregates of booklets that partially fill open pore spaces. Under ideal conditions, this clay may also inhibit the formation of quartz overgrowths (Shelton, 1964). However, in the study area, the formation of this clay post-dates silica cementation. This clay is interpreted as a late diagenetic mineral, associated with the partial dissolution of feldspars.

Hydrocarbon Generation

The final stage of diagenesis began with the release of CO₂ by the thermal breakdown of bitumen. The CO₂ formed acids that partially dissolved calcite, minor amounts of plagioclase feldspar, and chert fragments. The extent of secondary porosity development is controlled by the texture and composition of the sandstone, and by the availability of acidic waters and their flow paths (McBride, 1982). The porosity and permeability of the Fall River sedimentary rocks in the study area had already been significantly reduced by compaction and silica cementation. This severely limited fluid flow during later diagenesis which in turn limited grain dissolution.
The final stage of diagenesis involved the generation, expulsion, and migration of hydrocarbons. The Powder River Basin is a relatively cool basin as documented by the relatively low volumes of thermogenic gas production, and by oil production at depths exceeding 13,000 feet (3,962 m). Analysis of Fall River samples from the study area, document thermal alteration index (TAI) values ranging from 2.9 to 3.4, indicating an oil to wet gas generative zone (Waples, 1985). Momper and Williams (1979) identify the ceiling of the oil-expulsion window at depths approaching 11,000 feet (3,353 m), in this portion of the basin. They calculate the timing of oil expulsion at Early Eocene through Miocene. The burial history curve constructed for this study (Figure 65) indicates peak oil expulsion at a depth of 8,400 feet (2,560 m). Based on this burial history curve, the timing of peak oil expulsion is estimated at 56 million years ago through present. Due to the extreme depth of the oil window, porosity and permeability in the Fall River sedimentary rocks was significantly reduced by compaction prior to hydrocarbon emplacement. Based on the burial history curve (Figure 65) silica cementation is dated to have been completed 10 million years before peak oil expulsion began. Therefore, the valley-fill deposits that acted as conduits during early diagenesis were essentially sealed to hydrocarbon migration by previous
silica cementation and compaction. However, based on the large hydrocarbon accumulation at Buck Draw field, there were no problems with hydrocarbon migration pathways in this portion of the basin. The hydrocarbon migration pathways are interpreted to be well-developed fracture systems that are related to recurrent basement fault block movement. Hydrocarbons migrated vertically, down fracture systems from the overlying organic-rich marine shales (type II kerogen) in the Skull Creek and Mowry Shales. This interpretation is supported by the common identification of natural fractures in the Fall River cores. The Shannon Sandstone at Hartzog Draw field (just north of the study area) as well as most of the Upper Cretaceous reservoirs in the Powder River Basin, are interpreted to have been charged by hydrocarbons migrating up vertical fracture systems (Momper and Williams, 1979). Hydrocarbon migration continued as the thick organic-rich shales of the Mowry Shale entered and remained in the hydrocarbon generation window. Hydrocarbons were generated at sufficient rates to cause overpressuring in the Fall River Sandstone below depths of 11,000 feet (3,353 m).

The entrapment and accumulation of oil displaced pore fluids that were in the intergranular pore spaces with hydrocarbons. This effectively terminated diagenetic processes within the hydrocarbon reservoirs.
Summary

This study describes how the depositional setting controls the development of primary porosity and the initial chemistry of the intergranular pore fluid which controls early diagenesis. These two factors strongly influence later diagenesis and essentially control the distribution of porosity in the Fall River Sandstone. Three paragenetic sequences are detailed in Figure 66. This figure summarizes the relative timing and sequence of diagenetic events previously described. One paragenetic sequence describes the high-energy fluvial deposits in the bayhead delta complex, where chlorite clay coats can form during early diagenesis. The second paragenetic sequence describes the high-energy fluvial deposits landward of the Epeiric sea, where marine (magnesium rich) waters are not available. The third paragenetic sequence generically describes the low-energy fluvial, estuarine, and marine deposits.

The ability of authigenic clay coats to inhibit the formation of quartz overgrowths during basin subsidence thereby preserving primary intergranular porosity is a well-recognized and documented relationship (Heald and Anderegg, 1960; Shelton, 1964; Pittman and Lumsden, 1968; Pittman, 1972; Heald and Larese, 1974; Land and Dutton, 1978; Tillman and Almon, 1979; Wescott, 1983; Johnston and Johnson, 1987;
Bayhead Delta Distributary Channel Deposits

**DIAGENETIC STAGE:** Very Early    Middle    Very Late

PYRITE
CHLORITE
ILLITE
COMPACITION
SILICA CEMENTATION
CALCITE CEMENTATION
KAOLINITE FORMATION
HYDROCARBON EMPLACEMENT

Valley-Fill Fluvial Channel Deposits

**DIAGENETIC STAGE:** Very Early    Middle    Very Late

PYRITE
CHLORITE
ILLITE
COMPACITION
SILICA CEMENTATION
CALCITE CEMENTATION
KAOLINITE FORMATION
HYDROCARBON EMPLACEMENT

Low-Energy Fluvial, Estuarine, and Marine Deposits

**DIAGENETIC STAGE:** Very Early    Middle    Very Late

PYRITE
CHLORITE
ILLITE
COMPACITION
SILICA CEMENTATION
CALCITE CEMENTATION
KAOLINITE FORMATION
HYDROCARBON EMPLACEMENT

Figure 66. General summary of paragenetic sequences interpreted for select facies of the Fall River Sandstone.
McBride, 1989; Pittman et al., 1992). This relationship was cited by previous workers to explain the anomalous amount of porosity development in the Fall River Sandstone at Buck Draw field (Hawkins and Formhals, 1985; Reservoirs Inc., 1987). However, previous workers did not offer an explanation for the anomalous occurrence of iron-rich chlorite clay coats in fluvial deposits.

Chlorite clay coat development inhibits silica cementation, but does not necessarily prevent it. Nucleation sites are formed where chlorite clays are absent, discontinuous, or thin. The quartz overgrowths will extend from the nucleation site, into the open pore space and partially envelop the clay coat (Figures 44, and 54). McBride (1989) described in general terms how the thickness and continuity of clay coats influence the effectiveness of the coats in inhibiting quartz overgrowths. By comparison, illite forms delicate, fibrous clays, and long lath-like projections that extend into the pore space (Figure 55). In the Fall River Sandstone, this clay has a sheet-like appearance of irregular flakes at its base, where it covers the framework grain. Due to this morphology, open nucleation sites are generally available for the formation of quartz overgrowths. Typically, illite clay coats are less effective than iron-rich chlorite clay coats at inhibiting silica
cementation (Heald and Larese, 1974). However, if the illite clay coats are relatively thick, well developed, and formed during early diagenesis, they may effectively inhibit the nucleation of quartz overgrowths.

A transition can be recognized, from the fluvial valley-fill deposits that were saturated with fresh water to the fluvial bayhead-delta deposits that were saturated with marine waters. This mixing zone is similar to the saltwater-freshwater transition zone that is currently present in the northern Atlantic coastal plain, where saltwater has invaded sediments and mixed with fresh water (Meisler et al., 1985). This transition is represented by the level of chlorite clay coat development in the Fall River fluvial deposits. This clay coat development is responsible for the high degree of porosity preservation, which is reflected in the cumulative production of oil wells completed in the fluvial channel. This production trend can be observed in Figure 6. Wells drilled in abandonment-fill deposits should be discounted as well as low cumulative production due to a short production history. Disregarding these anomalies, a south to north production increase can be recognized. There are dry holes to the extreme south, that penetrated thick, high-energy, fluvial channel deposits (Figure 37). This same channel to the north, is characterized by wells with average cumulative
production of 200 MBO (Figure 6). Four miles farther north, the wells have average cumulative production of 600 MBO. Three miles farther north, in North Buck Draw Unit, the wells average over 1 MMBO per well. Due to a facies change to estuarine deposits, there are no commercial wells north of North Buck Draw Unit. Once this production profile is recognized and understood, it can be used as an exploration tool to determine a "show wells" relative position to another Buck Draw-type accumulation.

Alternative Interpretations

In proprietary studies, geologists have proposed that the porosity in Buck Draw field was preserved by oil emplacement. This requires the early generation and migration of oil or extremely late silica cementation. A tremendous volume of fluid is required for extensive silica cementation (McBride, 1989). Due to the known hydrologic controls on this formation, the only opportunity for extensive silica cementation was during earlier diagenesis. Blatt (1976) explains that pressure solution may provide minor silica during late diagenesis. Reliable identification of extensive pressure solution was not observed during the petrographic examination.

As described previously in this report, the Fall River channel deposits lose porosity and permeability to the south,
in a structurally downdip direction. If early hydrocarbon emplacement was responsible for the preservation of porosity, then workers should have been able to identify a verifiable oil/water contact; however one has not been confirmed. Additionally, using this model there should be a consistent relationship between structural position and productivity of high-energy sandstone deposits. There are structurally high wells that are poor producers, and structurally low wells that have excellent production.

In other proprietary studies, geologists have proposed the early emplacement and the late dissolution of calcite to explain the porosity preservation in Buck Draw field. This interpretation is not supported by petrographic examination, or by chemical and fluid flow models. These alternative interpretations ignore the anomalous distribution of chlorite clay coats in the productive wells, and the documented relationship between chlorite clay coats and silica cementation. This relationship cannot be applied to calcite cementation since "clay coats do not affect the precipitation of epitaxial cements such as carbonates" (Pittman et al., 1992).

Additional Research

It is beyond the scope of this thesis to extend the stratigraphic interpretations formulated in this report
beyond the limits of the study area. However, random sampling of cores and electric logs in other parts of the Powder River Basin indicates the depositional model and integrated mapping approach described in this report are applicable outside of the study area. Isopach maps in the eastern Powder River Basin presented by Weimer and Flexer (1985), indicated that the orientation of basement fault blocks control the facies and thickness of formations in the Upper Cretaceous. The mapped orientation and position of basement fault blocks in the study area may be supported by mapping the Upper Cretaceous formations. The depositional models proposed in this report could be further evaluated by examining the Fall River outcrops on the west and east flank of the Powder River Basin.

Picking the exact depth of the lowstand surface of erosion in some wells is difficult, due to the similarity of facies above and below the erosional surface. Typically, there is not a weathering profile below the lowstand surface of erosion that can be observed in core examination. Clay analysis to determine the presence of kaolinite in the cores may identify a chemical weathering profile, thereby defining the erosional surface.

Additional petrographic analysis could be performed to further the understanding of diagenesis in the Fall River
Sandstone. In conjunction with this, cathodoluminescence microscopy could be performed to determine the extent of pressure solution of the quartz framework grains. Additionally, the oxygen isotope composition of the quartz overgrowths could be determined in order to estimate the temperature range of quartz cementation. Bracketing the temperature range for quartz cementation could be incorporated and compared with a detailed burial history curve of the Fall River Sandstone, to better understand the relative timing of silica cementation. However, to accomplish this, the quartz overgrowths must be separated from the quartz framework grain. It is unlikely this can be accomplished, because the sandstones are very fine-grained, very well cemented and extremely compacted.

The Fall River oil production in the northeastern Powder River Basin from Coyote Creek to Miller Creek field, has been described as being in the same depositional setting as the study area. Chisholm (1970) described the presence of illite clays in the reservoir sandstone at Coyote Creek field. RPI Inc. (1983) described chlorite in Fall River cores from wells in the northeastern Powder River Basin. The diagenetic model presented in this study could be tested by comparing the types and distribution of authigenic clays, relative to the Fall River depositional environments in the northeastern
Powder River Basin.

**Conclusion**

Hayes (1979) stated that to understand and to predict sandstone porosity, reconstruction of the flow paths and timing of fluid flow through a formation is required. In addition, it is necessary to understand the water's origin, chemical composition, and its chemical evolution as it flowed through the sandstone. A hypothesis has been presented and supported that follows this approach by describing the chemistry and fluid flow in the Fall River Sandstone in the southern Powder River Basin. This hypothesis explains the depositional and diagenetic controls on the distribution of porosity in this formation. Stonecipher and May (1990) described how the depositional environment influences diagenesis of the Wilcox Group of the Texas Gulf Coast by controlling original water chemistry, sediment texture, detrital composition, and organic content. This study also demonstrates how depositional setting controls the diagenesis of a sedimentary facies.

Only the distal portions of the fluvial bayhead-delta deposits have both excellent primary porosity, and a mechanism for the early introduction of marine waters into the intergranular pore space. The estuarine and marine deposits have the marine waters available, but poor primary
porosity due to the low wave energy of the Early Cretaceous seaway. Samples from the high-energy fluvial valley-fill deposits south of the bayhead delta had excellent primary porosity. Because these sediments were saturated with fresh water, chlorite coats which cover the framework grains are poorly developed. The illite clay coats that are developed in this facies did not effectively inhibit extensive silica cementation.

Oil exploration efforts for the Fall River Sandstone in the southern Powder River Basin should be concentrated on mapping and exploring for the seaward termination of the fluvial system. These targets are encountered in the bayhead-delta complex which average one mile in width and five to ten miles in length. They can be mapped using a sequence stratigraphy depositional model with the Gulf of Mexico shoreline as a modern-day analogy. However, core descriptions, petrographic examinations and seismic data must be integrated with the subsurface control to accurately map these deposits.

In the past, the major exploration risk associated with the Fall River oil play in the southern Powder River Basin has been the prediction of permeability. The depositional and diagenetic model presented in this study is the first model that adequately explains the distribution of Fall River
sandstones and porosity development in the southern Powder River Basin. This exploration approach may have applications in other petroleum provinces where silica cementation destroys the porosity of quartz-arenite sandstones.
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APPENDIX A

INVENTORY OF EXAMINED CORES

AND

CORE DESCRIPTIONS
Cores Described In Detail

Core Number 1
Louisiana Land and Exploration
B&B Federal 23-12
NESC 12-T38N-R74W
Cored Interval: 13,544-13,576

Core Number 2
True Oil Company
Moore Flynn 1-11
SENW 11-T40N-R74W
Cored Interval: 12,720-12,776

Core Number 3
Bass Enterprises
Pogo Woodward State 1-16
SENW 16-T40N-R74W
Cored Interval: 13,035-13,090

Core Number 4
Cities Service
BT Federal #1
SENW 20-T41N-R73W
Cored Interval: 12,554-12,581

Core Number 5
Presidio Oil
Sara Armstrong Federal 2-23
NESE 23-T41N-R74W
Cored Interval: 12,849-12,897

Core Number 6
Cities Service
Nine Mile Creek #2
NESC 14-T40N-R75W
Cored Interval: 13,550-13,593

Core Number 7
Louisiana Land and Exploration
Bassinger Federal 34-15
SWSE 15-T42N-R74W
Cored Interval: 12,589-12,639
Core Number 8  
Louisiana Land and Exploration  
Laur 33-26  
NWSE 26-T43N-R74W  
Cored Interval: 12,267-12,295

Core Number 9  
Champlin Petroleum  
Moore 12A-13  
SWNW 13-T41N-R75W  
Cored Interval: 13,307-13,368

Core Number 10  
Apache Corporation  
Neeley 30-10  
NWSE 30-T42N-R73W  
Cored Interval: 12,034-12,096

Cores That Were Examined

Marathon  
Wright Federal 1-14  
NWNE 14-T43N-R73W  
Cored Interval: 11,635-11,715

Diamond Shamrock  
Rattlesnake 23-32  
NESW 32-T42N-R72W  
Cored Interval: 11,699-11,757

Apache Corporation  
Moore 19-15  
SWSE 19-T42N-R73W  
Cored Interval: 12,406-12,465

Diamond Shamrock  
Petersen 33-29  
NWSE 29-T42N-R73W  
Cored Interval: 12,322-12,382

Woods  
Turner 31-1  
NESW 31-T42N-R73W  
Cored Interval: 12,342-12,393
Apache Corporation
Federal 34-9
NESE 34-T42N-R73W
Cored Interval: 12,034-12,096

Bass Enterprises
UTC Unit #1
SWNE 23-T42N-R74W
Cored Interval: 12,470-12,521

Moncrief
Turner 25-2
NWSE 25-T42N-R74W
Cored Interval: 12,350-12,410

Kerr-McGee
NBDU 33-7
NWSE 7-T41N-R73W
Cored Interval: 12,384-12,468

Kerr-McGee
NBDU 31-18
NWNE 18-T41N-R73W
Cored Interval: 12,444-12,500

Kerr-McGee
NBDU 33-18
NWSE 18-T41N-R73W
Cored Interval: 12,538-12,599

Kerr-McGee
NBDU 33-12
NWSE 12-T41N-R74W
Cored Interval: 12,570-12,626

Diamond Shamrock
Everett Fee 33-13
NWSE 13-T41N-R74W
Cored Interval: 12,571-12,625

Kerr-McGee
NBDU 32-24
SWNE 24-T41N-R74W
Cored Interval: 12,708-12,772
Home Petroleum
Powell 1-26
NESC 26-T41N-R74W
Cored Interval: 12,932-12,975

Home Petroleum
Powell 2-26
NWSE 26-T41N-R74W
Cored Interval: 12,969-13,007

Bass Enterprises
Moore Ranch 12-13
SENW 12-T40N-R75W
Cored Interval: 13,342-13,370

Bass Enterprises
Moore Ranch 13-13
SENW 13-T40N-R75W
Cored Interval: 13,433-13,505

Louisiana Land and Exploration
William Fee 33-13
NWSE 13-T40N-R75W
Cored Interval: 13,354-13,397

Cities Service
Nine Mile Creek #2
NESC 14-T40N-R75W
Cored Interval: 13,550-13,602

Louisiana Land and Exploration
GGN Fee 32-13
SWNE 13-T38N-R76W
Cored Interval: 13,708-13,723

Diamond Shamrock
Pine Ridge Unit #1
SESE 22-T38N-R76W
Cored Interval: 13,365-13,423

Diamond Shamrock
Snake Charmer Draw #1
NESC 24-T38N-R76W
Cored Interval: 13,870-13,919
Amoco
Ormsby Draw #3
SWSE 8-T37N-R76W
Cored Interval: 12,250-12,301
CORE #1: B&B FEDERAL 23-12 NESW 12-T33N-R74W
Cored Interval: 13,545 to 13,602 feet

13,545.0 - 13,549.0  Mudstone, medium to dark gray, horizontal laminated to wavy bedded, locally fissile, slightly to moderate amount of biogenic sedimentary structures (small horizontal trace fossils), locally silty, locally pyritic, non-calcareous, gradational basal contact.

13,549.0 - 13,556.5  Mudstone, light to medium gray, silty, fining-upward, local trace fossils, silty zones are horizontally laminated, with some ripple-laminations, locally calcareous, sharp basal contact.

13,556.5 - 13,557.7  Sandstone, light gray, silty to mostly very fine, ripple-laminated, contains abundant carbonaceous debris, and thin clay drapes, non-calcareous, sharp basal contact.

13,557.7 - 13,558.0  Carbonaceous shale, black

13,558.0 - 13,559.0  Siltstone, medium gray, carbonaceous, rooted, motiled, non-calcareous, moderate pyrite concretions, gradational basal contact.

13,559.0 - 13,564.5  Siltstone, light to dark gray, interbedded with dark gray to black mudstone, large Skolithos trace fossils from 13,563.5 to 13,564.5, slight to locally moderate amount of biogenic sedimentary structures including Skolithos, Planolites and Arenicolites, siltstone is wavy bedded to ripple-laminated, numerous reactivation surfaces, non-calcareous, gradational basal contact, open vertical fracture at 13,559.0, 13,561.0 to 13,563.0 feet.

13,567.5 - 13,574.8  Sandstone, light gray, fining-upward from silty to very fine, some vertical trace fossils in upper section, horizontally bedded with some wavy bedding, and ripple-laminations, some thin clay drapes, some stromatolites, non-calcareous, gradational basal contact.

13,574.8 - 13,577.3  Sandstone, light gray to light brownish gray, fine-grained, well sorted, extensively silica cemented, non-calcareous, generally massive with some horizontal bedding, spotty silica concretions, some very thin clay laminations, trace pyrite, sharp basal contact.

13,577.3 - 13,578.9  Sandstone, very light gray, silty to very fine, horizontally bedded to massive, abundant light gray (oxidized) shale rip-up clasts, extensive silica cementation, non-calcareous, erosive basal contact.

13,578.9 - 13,583.8  Sandstone, very light gray, interbedded with light gray siltstone, and medium gray mudstone, sandstone is coarsening-upward from silty to very fine grained, parallel laminated with some low angle D2 cross beds, HCS bedding common, siltstone is wavy bedded to ripple-laminated, trace fossils in local areas, some stromatolites, locally pyritic, gradational basal contact.

13,583.8 - 13,586.4  Siltstone, light to medium gray, coarsens upward, ripple-laminated to wavy bedded, interbedded with medium to dark gray, wavy bedded mudstone, slight to locally moderate vertical and horizontal trace fossils, non-calcareous, gradational basal contact.

13,586.4 - 13,602.5  Mudstone, light to medium gray, wavy bedded and parallel laminated, locally fissile, interbedded with thin lenticular light gray siltstone containing trace fossils, silt content increases upward, locally pyritic.

END OF CORE
CORE #2: SNP MOORE FLYNN 1-11 SENW 11-T40N-R74W
Cored Interval: 12,720 to 12,776.4 feet

12,720.0 - 12,738.5 Mudstone, black, wavy bedded, locally fissile, some thin light gray siltstone laminations, bioturbated, locally pyritic.

12,738.5 - 12,739.0 Siltstone, light gray, extensively bioturbated, with thin mudstone laminations, sharp basal contact is overlain by well rounded black shale rip-up clasts, and pyrite concretions.

12,739.0 - 12,743.7 Sandstone, light to medium gray, very fine to mostly fine-grained, stacked thin bed sets (average 6 inches thick) of high angle 2D and 3D cross beds, with some thin ripple-laminated intervals, locally some poorly stratified small, angular black, and well rounded light brown shale rip-up clasts, trace calcareous cement, extensively silica cemented, non-bioturbated, scooped basal contact.

12,743.7 - 12,754.0 Siltstone to very fine-grained sandstone, fining-upward, light to medium gray, interbedded with dark gray and black mudstone, siltstone is wavy bedded to ripple-laminated, graded beds are common, moderately to locally extensive bioturbation (primarily horizontal Chondrites, isolated pyrite nodules are common (ranging from 1 mm to 20 mm in diameter), sharp basal contact.

12,754.0 - 12,754.3 Carbonaceous Shale, mixed with very fine-grained sand, pyritic, sharp basal contact.

12,754.3 - 12,758.6 Sandstone, light to medium gray, very fine to fine-grained, coarsening-upward, horizontally bedded, with low to medium angle 2D cross bed sets (averaging 4 inches in thickness), top 2 inches is rooted, non-bioturbated, gradational basal contact.

12,758.6 - 12,765.8 Siltstone coarsening upward to very fine-grained sandstone, light to medium gray, primarily ripple-laminated with some wavy and horizontal bedding, slight to locally moderate bioturbation (Skolithos burrows averaging 1 mm in diameter and 10 mm in length), moderately carbonaceous, non-calcareous, extensively silica cemented, gradational basal contact.

12,765.8 - 12,767.4 Siltstone to very fine-grained sandstone, light to medium gray, ripple-laminated, with medium gray mudstone interbeds, moderate amount of biogenic sedimentary structures (Chondrites and Planolites), sharp basal contact.

12,767.4 - 12,768.1 Sandstone, light gray, very fine-grained, ripple-laminated to locally massive, brownish red and yellowish brown oxidation staining, non-bioturbated, non-calcareous, gradational basal contact.

12,768.1 - 12,769.3 Sandstone, light to medium gray, very fine-grained, ripple-laminated, moderately calcareous, non-bioturbated, gradational basal contact.

12,769.3 - 12,775.6 Siltstone to very fine-grained sandstone, coarsening-upward, light to medium gray, ripple-laminated with some wavy and contorted beds, non-calcareous, trace bioturbation, sharp basal contact.

12,775.6 - 12,776.4 Siltstone, medium gray, ripple-laminated, interbedded with black mudstone laminations, moderately to locally extensively bioturbated, some small pyrite nodules.

END OF CORE
CORE #3: POGO WOODWARD STATE 1-16 SENW 16-T40N-R74W
Cored Interval: 13,035.0 to 13,090.3 feet

13,050.0 - 13,061.0  Mudstone, dark gray to black, locally fissile, with some very thin light gray, lenticular siltstone lamination, bioturbation by small horizontal burrows is restricted to silty intervals and increases downward, non-calcareous, basal contact is gradational.

13,061.0 - 13,066.0  Siltstone, light gray, ripple-laminated, interbedded with wavy bedded black mudstone, siltstone contains moderate to locally extensively biogenic sedimentary structures (Chondrites and Planolites), non-calcareous, isolated pyrite nodules (up to 15 mm in diameter), sharp basal contact.

13,066.0 - 13,068.1  Sandstone, light gray, very fine-grained, ripple-laminated, with some very thin wavy bedded mudstone laminae, upper and lower contacts contain moderate amounts of vertical Skolithos burrows, stylolites are common, non-calcareous, scoured basal contact.

13,068.1 - 13,090.0  Sandstone, light brown, fine-grained, well sorted, massive with stacked sets of 2D and 3D cross beds (averaging 6 inches thick), with sharp basal contacts, well rounded, light brown shale rip-up clasts are common, locally carbonaceous, non-bioturbated, trace calcareous cement, extensively silica cemented, numerous reactivation surfaces, interbedded with:

- Siltstone and very fine-grained sandstone, light gray, ripple-laminated, with very thin clay laminations on bedding surfaces, non-bioturbated, non-calcareous, interbedded with:

- Mudstone, dark gray to black, non-calcareous, trace horizontal worm burrows in some silty zones, numerous reactivation surfaces, sharp basal contact.

Vertical hairline fractures, that are open and lack cements on fracture surfaces were identified at 13,072.2, 13,073.8, 13,075.3, 13,079 to 13,082, 13,082.5 to 13,086, and at 13,087 feet.

END OF CORE
CORE #4: BT FEDERAL #1 SENW 20-T41N-R73W
Cored Interval: 12,554.0 to 12,612.8 feet

12,554.0 - 12,555.1 Conglomeratic Sandstone, very light gray with black angular shale clasts, sandstone is very fine to fine-grained, massive, shale rip-up clasts are poorly stratified, and may be as large as 10 mm in width and 60 mm in length, averaging 5 mm by 20 mm, some stylolites, non-bioturbated, non-calcareous, silica cemented, isolated pyrite nodules averaging 10 mm in diameter, scoured basal contact.

12,555.1 - 12,558.6 Sandstone, light gray to light brownish gray, very fine to fine-grained, ripple-laminated (climbing ripples), some thin wavy bedded mudstone clay drapes, some stylolites, non-bioturbated, non-calcareous, extensively silica cemented, sharp basal contact.

12,558.6 - 12,559.8 Conglomeratic Sandstone, as above.

12,559.8 - 12,561.3 Sandstone, light gray to light brownish gray, fine-grained, massive, reactivation surfaces are common, very well silica cemented, non-calcareous, non-bioturbated, some stylolites, small angular black shale rip-up clasts are common (up to 10 mm in width by 25 mm in length, averaging 5 mm by 10 mm), sharp basal contact.

12,561.3 - 12,561.8 Conglomeratic Sandstone, as above.

12,561.8 - 12,569.5 Sandstone, as above, with open vertical fracture at 12,564.5 feet.

12,569.5 - 12,570.2 Conglomeratic Sandstone, as above.

12,570.2 - 12,597.1 Shale, dark gray to black, fissile, non-calcareous, locally silty, silty zones are bioturbated with horizontal burrows, gradational basal contact.

12,597.1 - 12,608.9 Siltstone, light gray, ripple-laminated, moderately to locally extensively bioturbated with horizontal and vertical burrows, abundant pyrite nodules (up to 25 mm in diameter), non-calcareous, numerous reactivation surfaces that may be marked by conglomeratic lag, gradational basal contact.

12,608.9 - 12,612.8 Mudstone, medium gray, silty, extensively bioturbated with mottled appearance, non-calcareous, locally pyritic.

END OF CORE
CORE #5: SARA ARMSTRONG FEDERAL 2-23 NESE 23-T41N-R74W
Cored Interval: 12,849.0 to 12,897.0 feet

12,849.0 - 12,859.1 Mudstone, dark gray to black, containing some horizontal silt filled burrows, thin bedded, ripple laminated siltstone interbeds, and pyrite concretions (up to 20 mm in diameter)

12,859.1 - 12,861.0 Not cored.

12,861.0 - 12,866.1 Sandstone, light gray, silty to very-fine grained, ripple laminated, slight to locally moderate amount of small vertical Skolithos burrows, rare pyrite concretions (up to 25 mm in diameter), interbedded with thin, lenticular, light gray siltstone and black mudstone laminations containing small horizontal silt-filled burrows, sharp basal contact.

12,866.1 - 12,870.0 Sandstone, light to medium gray, very-fine grained, ripple laminated, very rare biogenic sedimentary structures (short vertical Skolithos burrows), some thin black mudstone clay drapes, sharp basal contact.

12,870.0 - 12,871.1 Siltstone, light gray, lenticular ripple laminations, moderately bioturbated with horizontal burrows, interbedded with thinly bedded black mudstone laminations, gradational basal contact.

12,871.1 - 12,875.5 Sandstone, light gray, silty to very-fine grained, ripple laminated, trace Skolithos burrows, interbedded with very thin black clay drapes and thin, light gray, ripple laminated, slightly bioturbated (horizontal) siltstones, interlayered with black mudstone laminations, sharp basal contact.

12,875.5 - 12,877.2 Mudstone, dark gray, silty, interbedded with very thin bedded, ripple laminated, siltstone and light gray silt to very-fine grained sandstones, with some horizontal bioturbation in silty zones.

12,877.2 - 12,884.0 Sandstone, light to medium gray, very fine, ripple laminated, carbonaceous, with some small black angular shale rip-up clasts, silica cemented, non-bioturbated, with some thin black mudstone interbeds, gradational basal contact.

12,884.0 - 12,885.5 Sandstone, medium gray, very-fine to fine grained, 2D cross bedded, moderate dark brown carbonaceous debris, silica cemented, non-bioturbated, gradational basal contact.

12,885.5 - 12,892.0 Sandstone, medium gray, very-fine to fine grained, ripple laminated, moderately carbonaceous, non-bioturbated, silica cemented, gradational basal contact.

12,892.0 - 12,895.7 Sandstone, medium gray, fine grained, 2D cross bedding, non-bioturbated, silica cemented, some siltstone, open vertical fracture from 12,893.5 to 12,894.0, gradational basal contact.

12,895.7 - 12,897.0 Sandstone, medium gray, fine grained, massive, silica cemented, non-bioturbated.

END OF CORE
CORE #6: NINE MILE FEDERAL #2 NESW T40N R75W
Cored Interval: 13,550 to 13,602.5 feet

13,550.0 - 13,562.7 Mudstone, medium to dark gray, wavy bedded, ripple-laminated, lenticular siltstones, small horizontal burrows, locally calcareous, isolated pyrite nodules, bioturbation and silt content increases downward, sharp basal contact.

13,562.7 - 13,564.6 Sandstone, very light gray, very fine-grained, ripple-laminated, extensively silica cemented, non-calcareous, sharp basal contact.

13,564.6 - 13,567.1 Mudstone, black parallel laminated, interbedded with light gray ripple-laminated siltstone, very pyritic, local biogenic sedimentary structures composed of small vertical and horizontal burrows.

13,567.1 - 13,577.6 Sandy siltstone, light gray to light brownish gray, very fine grained, ripple-laminated, capped by thin shale laminae, trace bioturbation in shales, possible rooted zone at 13,576.1 feet, locally pyritic, sharp basal contact.

13,577.6 - 13,580.0 Conglomeratic sandstone, light gray, very fine grained, massive sandstone with abundant black, poorly stratified, angular, shale rip-up clasts (up to 10 mm by 60 mm, averaging 5 mm by 10 mm), erosive basal contact.

13,580.0 - 13,586.4 Sandstone, light gray, fining-upward from very fine to fine, ripple-laminated, with mudstone interbeds and ripple-laminated silty zones, non-calcareous, rare bioturbation in silty zones, some well rounded rip-up clasts in thin 2D cross stratified beds, numerous reactivation surfaces, extensively silica cemented, sharp basal contact.

13,586.4 - 13,587.9 Mudstone, dark gray to black, interbedded with thin bioturbated and ripple-laminated siltstones.

13,587.9 - 13,589.0 Sandstone, as above.

13,589.0 - 13,590.5 Mudstone, as above.

13,590.5 - 13,594.1 Sandstone, light gray, fine-grained, ripple-laminated with some thin 2D cross beds, occasional rip-up clasts, carbonaceous, some very thin clay laminae, non-bioturbated, non-calcareous, sharp basal contact.

13,594.1 - 13,600.4 Sandstone, light to medium gray, fine-grained, stacked sequences of 2D and 3D cross bed sets, with each bed set averaging 3 to 6 inches in thickness, some small shale rip-up clasts, locally pyritic, extensively silica cemented, non-bioturbated, non-calcareous, scoured basal contact, healed vertical fracture at 13,598.3 feet.

13,600.4 - 13,602.5 Shale, dark gray to black, fissile, locally pyritic, some thin lenticular bioturbated silty zones.

END OF CORE
CORE #7: BASSINGER FEDERAL 34-15 SWSE 15-T42N-R74W
Cored Interval: 12,579.0 to 12,629.0 feet

12,579.0 - 12,594.3  Interbedded and convoluted thin beds sandstone, siltstone and mudstone: very light gray, silty to very-fine grained sandstone, lenticular, ripple laminated, light gray siltstone, and medium gray, wavy bedded mudstone. Moderate to extensive biogenic sedimentary structures, horizontal, angular and vertical silt-filled burrows (Skolithos and Chondrites), locally pyritic, sharp basal contact.

12,594.3 - 12,612.4  Sandstone, very-light gray, fine grained, ripple laminated, 2D cross stratification, locally massive, very thin medium gray mudstone laminae drapes, reactivation and scour surfaces are common, rare small shale clasts, stromatolites, rare bioturbation, short vertical Skolithos burrows, extensively silica cemented, locally pyritic, open vertical fractures at 12,596, 12,603, 12,608, 12,611 feet, scour basal contact.

12,612.4 - 12,629.0  Mudstone, light to medium gray, wavy bedded and parallel laminated, fossiliferous, interbedded with thin lenticular light gray siltstone containing trace fossils, silt content increases upward, locally pyritic.

END OF CORE
CORE #8: LAUR 33-26 NWSE 26-T43N-R74W
Cored Interval: 12,267.0 to 12,271.6 and 12,276.0 to 12,295.9 feet

12,267.0 - 12,271.6 Interbedded and mottled sandstone, siltstone and mudstone: very light gray, thin-bedded, silty to very-fine grained sandstone, lenticular, ripple laminated, light gray siltstone, and medium gray, wavy bedded mudstone. Moderate to extensive biogenic sedimentary structures, horizontal, angular and vertical silt-filled burrows (Skolithos Chondrites, Anconichnus, and Fecal String), basal contact was not cored.

12,271.6 - 12,276.0 This interval was not cored.

12,276.0 - 12,286.0 Interbedded siltstone, mudstone and sandstone, as above.

12,286.0 - 12,295.9 Sandstone, very light gray, very-fine grained, ripple laminated, with some very thin medium gray mudstone laminae drapes, some styolites, slight to locally moderate bioturbation with small, short vertical Skolithos burrows and clay filled horizontal Chondrites burrows, extensively silica cemented, basal contact was not cored.

END OF CORE
CORE #9: 1 MOORE 12A-13 SWNW 13-T41N-R75W
Cored Interval: 13,307.0 to 13,368.5 feet

13,307.0 - 13,308.5 Siltstone, light gray, ripple laminated, sharp basal contact overlying mudstone, dark gray, silty, bioturbated, gradational basal contact overlying sandstone and conglomeratic lag, light to medium gray, silty to pebbly shale clasts, sandstone is ripple laminated, calcareous, scour basal contact.

13,308.5 - 13,309.7 Mudstone, black with some lenticular silty bioturbated zones.

13,309.7 - 13,318.2 Siltstone, light to medium gray, lenticular, wavy bedded, thin mudstone interbeds, slightly to moderately bioturbated with horizontal burrows, locally pyritic, sharp basal contact.

13,318.2 - 13,321.1 Sandstone, light gray, silty to very-fine grained, ripple laminated, graded beds, extensive Arenicolites and Skolithus burrows, black wavy bedded mudstone laminae, silica cemented, gradational basal contact.

13,321.1 - 13,322.9 Mudstone, black, light gray lenticular siltstones, wavy bedded, bioturbated, sharp basal contact.

13,322.9 - 13,325.7 Sandstone, light gray, silty to very-fine grained, ripple laminated, small light brown siderite clasts (up to 5 mm in diameter), local biogenic sedimentary structures include Skolithus and Planolites burrows, silica cemented, interbedded with wavy bedded black mudstones, numerous reactivation surfaces, sharp basal contact.

13,325.7 - 13,330.7 Interbedded Mudstone and Sandstone, as above with Concholepas burrows.

13,330.7 - 13,331.7 Sandstone, medium gray, very-fine to fine grained, trace ripple lamination, small black well rounded shale clasts (average 5 mm in diameter), silica cemented, nonbioturbated, sharp basal contact.

13,331.7 - 13,333.0 Mudstone, as above, with scour basal contact.

13,333.0 - 13,334.6 Sandstone, light gray, very-fine grained, interbedded with medium gray siltstone, and black mudstone clay draperies, distorted and overturned bedding with scour surfaces, nonbioturbated, accreted basal contact.

13,334.6 - 13,345.2 Siltstone, light to medium gray, wavy bedded, ripple laminated, locally pyritic, with small horizontal burrows, and thin black mudstone clay drapes, small sand dikes at 13,341, gradational basal contact.

13,345.2 - 13,350.0 Siltstone, light gray, grading downward to silty mudstone, medium gray, slightly to moderately bioturbated with horizontal silt filled burrows, silty zones are lenticular and ripple laminated, gradational basal contact.

13,350.0 - 13,363.0 Mudstone, black, fissile, with horizontal silt filled burrows, gradational basal contact.

13,363.0 - 13,368.5 Mudstone and siltstone, black, fissile, moderate to locally abundant silt filled horizontal burrows.

END OF CORE
CORE #10: NEELY 30-10 NWSE 30-T42N-R73W
Cored Interval: 12,360.0 to 12,432.8 feet

12,360.0 - 12,363.9  Siltstone, light to medium gray, some wavy bedding, and lenticular ripple laminations, locally extensive bioturbation, some large pyrite concretions (up to 20 mm in diameter), numerous reactivation surfaces, sharp basal contact, interbedded with black mudstone containing silt filled Planolites burrows.

12,363.9 - 12,366.4  Sandstone, light gray, silty to very fine-grained, plane bedded, sharp basal contact, interbedded with light gray, ripple laminated, bioturbated, siltstone laminations and dark gray mudstones with graded bedding.

12,366.4 - 12,373.4  Siltstone, light gray, extensive Chondrites burrows, graded bedding, and ripple laminations. Interbedded with dark gray silty mudstone, containing horizontal silt filled burrows, and thin ripple laminations, some pyrite concretions (up to 25 mm in diameter), gradational basal contact.

12,373.4 - 12,390.8  Mudstone, medium to dark gray, wavy bedded, horizontal silt filled Astartoma and Conichnus burrows, slightly fissile. Interbedded with light gray, ripple laminated siltstones with a sharp basal contact. Thin sandstone interbeds, light gray, silt to very fine, ripple laminated, silica cemented, locally pyritic, sharp basal contact.

12,390.8 - 12,397.0  Sandstone, very light gray, silty to very fine, ripple laminated, silica cemented, containing styloids, thin black mudstone clay drapes and clay laminations, locally bioturbated (horizontal), 2D cross beds at 12,395.8 to 12,397.0, well rounded light brown siltite clasts <1mm to 5 mm in diameter, scoured basal contact.

12,397.0 - 12,401.0  Siltstone, medium to dark gray, coarsening upward, ripple laminated, slightly to locally moderately bioturbated (Planolites and Astartoma), interbedded with dark gray to black mudstone, containing horizontal silt filled burrows, gradational basal contact.

12,401.0 - 12,427.4  Mudstone, black, fissile, locally interbedded with thin light gray, lenticular, moderately bioturbated (horizontal) siltstone laminations.

12,427.4 - 12,432.8  Siltstone, medium gray, thin bedded, ripple laminated, interbedded with black mudstone containing abundant horizontal silt filled burrows.

END OF CORE
APPENDIX B

SAMPLES EXAMINED PETROGRAPHICALLY
Valley-Fill Channel Deposits

Krause F-32-33-P
NE/4 33-T49N-R68W
Thin section depth: 6499 feet

Krause F-21-3-P
NW/4 3-T48N-R68W
Thin section depth: 6513 feet, 6524 feet

Mohawk Federal B 6
SW/4 26-T48N-R68W
Thin section depth: 6847 feet

NBDU 23-31
SW/4 31-T42N-R73W
Thin section depth: 12,364 feet, 12,386 feet
X-Ray diffraction depth: 12,364 feet, 12,386 feet
SEM depth: 12,364 feet, 12,386 feet

NBDU 33-7
SE/4 7-T41N-R73W
Thin section depth: 12,411 feet, 12,434 feet
X-Ray diffraction depth: 12,434 feet (tested twice)
SEM depth: 12,434 feet

NBDU 23-8
SW/4 8-T41N-R73W
Thin section depth: 12,310 feet, 12,327 feet, 12,334 feet
X-Ray diffraction depth: 12,310 feet, 12,334 feet
SEM depth: 12,327 feet

NBDU 33-18
SE/4 18-T41N-R73W
Thin section depth: 12,575 feet, 12596 feet
X-Ray diffraction depth: 12,596 feet
SEM depth: 12,596 feet
NBDU 33-13
SE/4 13-T41N-R74W
Thin section depth: 12,582 feet, 12,605 feet, 12,612 feet
X-Ray diffraction depth: 12,605 feet, 12,612 feet
SEM depth: 12,612 feet

Sara Armstrong Federal 2-23
SE/4 23-T41N-R74W
Thin section depth: 12,867 feet, 12,892 feet, 12,895 feet, 12,896 feet

Powell USA 1-26
SW/4 26-T41N-R74W
Thin section depth: 12,985 feet, 12,997 feet, 13,004.0 feet, 13,004.1 feet, 13,007 feet

Pogo Woodward State 1-16
NW/4 16-T40N-R74W
Thin section depth: 13,067 feet, 13,079 feet, 13,080 feet, 13,082 feet
SEM depth: 13,082 feet

Moore Ranch Federal 13-13
NW/4 13-T40N-R75W
Thin section depth: 13,461.7 feet, 13,467.8 feet

Estuarine Deposits

Wright Federal 1-14
NE/4 14-T43N-R73W
Thin section depth: 11,702.2 feet, 11,705 feet, 11,709.5 feet, 11,710.0 feet

Neeley 30-10
SE/4 30-T42N-R73W
Thin section depth: 12,364 feet, 12,388 feet, 12,391 feet
Bassinger 34-15  
SE/4 15-T42N-R74W  
Thin section depth: 12,587 feet, 12,596 feet, 12,608 feet

Moore Minerals Trust 14-1  
SW/4 14-T41N-R74W  
Thin section depth: 12,854.5 feet

Pine Tree 26-69  
NW/4 26-T41N-R75W  
Thin section depth: 13,578

"Regional" Marine Deposits

Rattlesnake Unit 23-32  
SW/4 32-T42N-R72W  
Thin section depth: 11,731

Moore 19-15  
SE/4 19-T42N-R73W  
Thin section depth: 12,409 feet, 12,416 feet, 12,423 feet, 12,427 feet

Peterson 33-29  
SE/4 29-T42N-R73W  
Thin section depth: 12,364 feet  
X-Ray diffraction Depth: 12,364 feet  
SEM depth: 12,364 feet

Neeley 30-10  
SE/4 30-T42N-R73W  
Thin section depth: 12,392 feet, 12,393.5 feet, 12,396 feet

UTC Unit #1  
SW/4 32-T42N-R73W  
Thin section depth: 12,508 feet  
X-Ray diffraction depth: 12,508 feet  
SEM depth: 12,508 feet
Moore #1  
NW/4 13-T41N-R75W  
Thin section depth: 13,327 feet

Virg Federal 1-2  
NW/4 2-T40N-R74W  
Thin section depth: 12,826.5 feet, 12,827 feet, 12,829.9 feet, 12,830 feet, 12,830.7 feet, 12,832.5 feet, 12,835 feet, 12,843.5 feet

Moore Federal 2-3  
NW/4 3-T40N-R74W  
Thin section depth: 12,838.7 feet, 12,856.7 feet, 12,860 feet, 12,863 feet, 12,871.5 feet, 12,871.5 feet, 12,874.4 feet

Moore 4-9  
SE/4 4-T40N-R74W  
Thin section depth: 12,902 feet, 12,913 feet

Moore Flynn 1-11  
NW/4 11-T40N-R74W  
Thin section depth: 12,735.0 feet, 12,736 feet, 12,739.5 feet, 12,741.6 feet, 12,751.5 feet, 12,768 feet

Transgressive Marine Sand (TSE)  

Peterson 33-29  
SE/4 29-T42N-R73W  
Thin section depth: 12,337 feet  
X-Ray diffraction depth: 12,337 feet
APPENDIX C

CLAY FRACTION

X-RAY DIFFRACTION DIFFRACTOGRAMS
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<tr>
<th>Intensity</th>
<th>2 Theta</th>
<th>Matched &quot;d&quot;</th>
<th>Matched I</th>
<th>hkl Pattern</th>
<th>Phase</th>
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Kerr-McGee NBDU 23-31  
Depth: 12,386 feet  
Starting Two Theta: 4.0  
Intensity Oriented Sample  

Nesw 31-T42N-R73W  
Porosity: 4 %  
Permeability: 9 md.

Facies: Channel
### Sample Information
- **Facies:** Marine
- **Depth:** 12,508 feet
- **Porosity:** 3.1%
- **Permeability:** 0.32 md
- **Starting Two Theta:** 4.0
- **Oriented Sample**

### Intensity Data

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Dwell: 2400 msec

Acquire: Off
Display: 1024
Overlap: Off
Scale: 512
Group: E1
Roi No: None
Roi: Off
Ram: 301K
Port: 528
Dac: Saw
Calc: On
Synch: Int

deg: 32.49
Cts: 68

Kerr-McGee NBDU 23-31
Depth: 12,364 feet
Starting Two Theta: 4.0
 Oriented Sample

N E S W 31-T42N-R73W
Porosity: 3 %
Permeability: 0.2 md.

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**Parameters:**
- **Dwell:** 2400 msec
- **Acquire:** Off
- **Display:** 1024
- **Overlap:** Off
- **Scale:** 512
- **Group:** E1
- **Roi No:** None
- **Roi:** Off
- **Ram:** 301K
- **Port:** 528
- **Dac:** Saw
- **Calc:** On
- **Synch:** Int

**Sample Details:**
- **Kerr-McGee NBDU 23-8**
- **Depth:** 12,327 feet
- **Starting Two Theta:** 4.0

**Facies:** Channel
- **Porosity:** 6%
- **Permeability:** 0.2 md.

**XRD Data:**

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Dia-Shmrck. Peterson 33-29
NWSE 29-T42N-R73W
Facies: Marine
Depth: 12,364 feet
Porosity: 6.6 %
Starting Two Theta: 4.0
Oriented Sample
Permeability: <0.01 md.

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- Acquire: Off
- Display: 1024
- Overlap: Off
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- Group: E1
- Roi No: None
- Roi: Off
- Ram: 381K
- Port: 520
- Dac: Saw
- Calc: On
- Synch: Int

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Kerr-McGee NBDU 33-7  
NWSE 7-T41N-R73W  
Facies: Channel  
Depth: 12,434 feet  
Porosity: 13 %  
Permeability: 90 md.  
Starting Two Theta: 4.0  
Oriented Sample

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<table>
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<th>Kerr-McGee NBDU 33-18</th>
<th>NWSE 18-T41N-R73W</th>
<th>Facies: Channel</th>
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<tr>
<td>Depth: 12,596 feet</td>
<td>Porosity: 10 %</td>
<td>Permeability: 37 md.</td>
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<td>Starting Two Theta: 4.0</td>
<td>Oriented Sample</td>
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<tr>
<th>Intensity</th>
<th>2 Theta</th>
<th>Matched &quot;d&quot;</th>
<th>Matched I</th>
<th>hkl Pattern</th>
<th>Phase</th>
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<tr>
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<td>Matched &quot;d&quot;</td>
<td>Matched I</td>
<td>hkl Pattern</td>
<td>Phase</td>
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<td>-------------</td>
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<td>Illite</td>
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<tr>
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<td>62-30 =32</td>
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<td>67-34 =33</td>
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<td>4.74</td>
<td>50</td>
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<td>Chlorite</td>
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<td>35</td>
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<td>35</td>
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<td>391-60=331</td>
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Kerr-McGee NBDU 33-13
NWSE 13-T41N-R74W
Facies: Channel
Depth: 12,612 feet
Porosity: 6%
Permeability: 0.1 md
Starting Two Theta: 4.0
Oriented Sample
APPENDIX D

SUBSURFACE MAPS
Channel Map of the greater Buck Draw Area. Larger well symbols signify well penetrated Fall River Sandstone. Cumulative Fall River production, in thousands of BO is posted (Petroleum Information, 1992). Oil well symbols without posted production, are completed in other formations. Circled well symbols identify the wells that were completed prior to the discovery of Buck Draw field.
Structure Map on the Fall River Sandstone, contour interval: 500 feet. Larger well symbols signify that the well penetrated the Fall River Sandstone.
Mowry Shale Interval Isopach Map, contour interval: 10 feet.
Muddy to Fall River Isopach Map, contour interval: 10 feet. The Frontier Formation production is shaded. The Shannon Sandstone production is stippled.
Fall River to Fuson Shale Isopach Map, contour interval: 10 feet.
Fall River to LSE #2 Isopach Map, contour interval: 20 feet. The relative location of cross section B-B' is posted.
Fall River to LSE #1 Isopach Map, contour interval: 10 feet.
LSE #1 to Fuson Shale Isopach Map, contour interval: 10 feet.
Fuson Shale to Lakota Sandstone Interval Isopach Map, contour interval: 5 feet.
Lakota Sandstone to Morrison Formation Interval Isopach Map, contour interval: 10 feet.
Subsurface map of the Fall River channel, bayhead delta, and estuary.
Buck Draw Area, Fall River Channel Net 6% Porosity Isopach Map, contour interval: 10 feet.
APPENDIX E

BURIAL HISTORY CURVE

DATA AND ASSUMPTIONS
### Stratigraphy Table

<table>
<thead>
<tr>
<th>Formation Type or Event Name</th>
<th>Age (Ma)</th>
<th>Begin Well Top (feet)</th>
<th>Present Thickness (feet)</th>
<th>Missing Thickness (feet)</th>
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<tbody>
<tr>
<td>White River-Olig</td>
<td>E</td>
<td>25</td>
<td>-600</td>
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<td>Wasatch-Eocene</td>
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<td>-1600</td>
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<td>Tongue Rvr-Paleo</td>
<td>D</td>
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<tr>
<td>Lebo-Paleocene</td>
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<tr>
<td>Tullock-Paleocene</td>
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<td>1326</td>
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<tr>
<td>Lance</td>
<td>F</td>
<td>66</td>
<td>4596</td>
<td>2568</td>
</tr>
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<td>Lewis</td>
<td>F</td>
<td>70.5</td>
<td>7164</td>
<td>1296</td>
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<td>Parkman</td>
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<td>77.5</td>
<td>8460</td>
<td>1145</td>
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<td>Sussex</td>
<td>F</td>
<td>80</td>
<td>9605</td>
<td>497</td>
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<td>Shannon</td>
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<td>81</td>
<td>10102</td>
<td>1174</td>
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<td>Basal Niobrara</td>
<td>F</td>
<td>89</td>
<td>11276</td>
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<td>Upper Frontier</td>
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<tr>
<td>Lower Frontier</td>
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<td>Mowry</td>
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<td>Muddy</td>
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<td>Fall River</td>
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<td>100</td>
<td>12850</td>
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<td>Lakota</td>
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<td>112</td>
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</table>

Note: The ages of select formations were based on work completed by Asquith (1970), and Weimer (1983).
### Lithology Table

<table>
<thead>
<tr>
<th>Lithology Name</th>
<th>Lithology Pattern</th>
<th>Initial Porosity</th>
<th>Compaction Factor (FM)</th>
<th>Exponential Factor (SC)</th>
<th>Density (g/cm³)</th>
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<tr>
<td>Sandstone</td>
<td>1</td>
<td>0.45</td>
<td>1.75</td>
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<td>2.20</td>
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<td>3</td>
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<td>2.40</td>
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### Lithology Table

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<tr>
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<th>Grain Size (mm)</th>
<th>Matrix Cond (W/m²K)</th>
<th>Heat Cap (kJ/m²K) Sandstone %</th>
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<td>4.80</td>
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### Lithology Table

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<td>100.0</td>
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<td>100.0</td>
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### Lithology Table

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<tr>
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<td>Coal</td>
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<tr>
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### Time Values Table

- Surface
- Time: 25 Ma
- Temp: 68 °F
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<th>Temp Factor (°F)</th>
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Maturity conversion method: Table
TTI = 1.817512 + 4.191876 * log10(%Ro)

### Maturity Conversion Table

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<th>TTI</th>
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<th>TMAX</th>
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### Expulsion Efficiency Table

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<td>Efficiency (0.0 - 1.0)</td>
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<td>0.00</td>
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<td>0.05</td>
</tr>
<tr>
<td>Depth (feet)</td>
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<tr>
<td>-------------</td>
<td>-----</td>
</tr>
<tr>
<td>Distance (mi)</td>
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</tr>
<tr>
<td>Temperature (°F)</td>
<td>1.3</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m°C)</td>
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<tr>
<td>Heat Capacity (kJ/m°C)</td>
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</tr>
<tr>
<td>Heat Flow (mW/m²)</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Model Units

- Depth = (feet)
- Distance = (mi)
- Temperature = (°F)
- Thermal Conductivity = (W/m°C)
- Heat Capacity = (kJ/m°C)
- Heat Flow = (mW/m²)
- Gradient = (°F/100 ft)
- Activation Energy = (kcal/mole)
- Arrhenius = (1/my)
- Pressure = (MPa)
- Mud Weight = (lbs/gal)
- Density = (g/cm³)
- Seismic Velocity = (m/s)
- Event Time = (msec)
- Maturity = (%Ro)
- HC Generation = (mg/g TOC)

Model Parameters

- Compaction = Off
- Use Delta Thickness = No
- Thermal Calculation = Gradient
- Thermal Gain = 1.000
- Use BHT's = Smooth
- Maturity Calculation = LLNL
- Kinetics Calculation = Quick
- Time Interval = 1.00
- Depth Interval = 3280.80
- Integrate Depth = No
- Rock-Eval Correction = 35.00
- TTI Reference Temp = 105.00
- TTI Doubling Temp = 10.00
- Kerogen Mode = LLNL

Present Day Info

- Model Name = Sara Arm. Fed. 2-23
- Model Description = Powder River Basin
- Current Surface Temp = 68.00
- Current Elevation = 5258.00
- Current Heat Flow = 0.00

Seismic Parameters

- Shot Point = 0
- X = 0.000000000
- Y = 0.000000000