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Sequence Stratigraphy, Depositional Environments, and Regional Mapping of the Late Devonian Interval, Upper Three Forks Formation, Sanish Member, and Lower Bakken Shale, U.S. Portion of the Williston Basin

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Sequence Stratigraphy, Depositional Environments, and Regional Mapping of the Late Devonian Interval, Upper Three Forks Formation, Sanish Member, and Lower Bakken Shale, U.S. Portion of the Williston Basin

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Thesis submitted to the
College of Arts and Sciences
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in Geology

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2011

Keywords: Sanish; Three Forks; Lower Bakken; Sequence Stratigraphy; Williston Basin; Late Devonian

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ABSTRACT

Sequence Stratigraphy, Depositional Environments, and Regional Mapping of the Late Devonian Interval, Upper Three Forks Formation, Sanish Member, and Lower Bakken Shale, U.S. Portion of the Williston Basin

Steven A. Sesack

Cores of the Late Devonian upper Three Forks, Sanish, and lower Bakken units from eight wells were examined and described at the North Dakota core depository. Core descriptions, wireline log correlation and mapping, and X-ray diffraction (XRD) data were integrated to recognize seven facies: The Three Forks D and the (600-900API) lower Bakken Shale, four facies belonging to the Sanish, and a basal siltstone facies assigned to the Lower Bakken. Facies identified were then grouped into separate systems tracts based on the identification of several significant sequence stratigraphic surfaces.

The four facies identified in the Sanish include: Facies A, a dolomitic and *Skolithos* burrowed sandstone with a hard-ground at the base as originally defined in the Antelope Field; the widely distributed Facies B, a dolomitic siltstone characterized by burrows of the *Cruziana* ichnofacies with periodic silty dolostone event beds (interpreted as of storm origin); Facies C, an argillaceous siltstone containing *Planolites* burrows; and Facies D, a fossiliferous wackestone to packstone resting above an interpreted maximum flooding surface (MFS) characterized by *Glossifungites*. A silty shale to siltstone assigned to the Bakken Formation with a total organic carbon (TOC) averaging 8.2% and a gamma ray reading of approximately 130 to 170 API was identified in cores and logs and was interpreted as the first phase of a transgression, showing the progression toward a stratified water column and accumulation of the Lower Bakken organic-rich shale.

The Sanish Facies A, B, and C are grouped into the transgressive systems tract (TST) of the Sanish, Facies C&D overlying the maximum flooding surface (MFS) composes the highstand systems tract (HST) with a depositional hiatus resulting in a corrosion surface (phosphatic pebble lag) capping off the sequence. The lower Bakken is considered its own depositional sequence with the Basal Bakken as the LST, the bottom half of the lower Bakken Shale (up to the highest gamma ray) as the TST, and from the highest gamma ray to the sequence boundary between the lower and middle Bakken as the HST.

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CHAPTER 1

Introduction

The Bakken Formation petroleum system of the Williston basin consists of two world class source rocks (informal upper and lower shale members) that sandwich a middle member which can be fracture stimulated (LeFever, 1991). The middle Bakken member is composed of a variety of facies and lithologies including sandstone, dolostone, and carbonate. Underlying the lower Bakken Shale member, the upper Three Forks Formation is an additional exploration target with a significant quantity of recoverable oil, which has intensified pursuit of petroleum in the Williston basin.

In recently drilled wells, the target reservoirs are facies of the middle Bakken member, and the upper Three Forks. The existence of two viable reservoirs in such a thin stratigraphic interval has led producers to complete dual lateral wells and co-mingle production in the upper Three Forks and the middle Bakken. This completion practice has made it necessary to expand the Bakken petroleum system to include the underlying Three Forks Formation. At the top of the Three Forks Formation rests the informally defined Sanish member, which is an important reservoir target.

1.1 Purpose and Scope

The purpose of my study is to provide an analysis of the stratigraphy, depositional environments and extent of the informal Sanish in eastern Montana and western North Dakota. A stratigraphic framework will be constructed to better understand the distribution and sequence stratigraphy of the Sanish member and its relationship to the remainder of the underlying Three

Forks Formation and the overlying lower Bakken Shale member. Understanding the distribution of facies in this interval will contribute to improved understanding of depositional processes, sequence stratigraphy and help to define drilling targets in a play that is increasingly dependent on facies as opposed to structure (Flannery & Krauss, 2006). Improved definitions of facies relationships and boundaries will help to better define original oil in place (OOIP), and other reservoir properties.

Figure 1.1: Stratigraphic column of the Williston basin showing oil and gas producing units. Modified from Gerhard et al. (1988).

1.2 Location of the Study Area

The study area encompasses approximately 47,000 square miles (~120,000 km²) across western North Dakota, and eastern Montana, and is located in the southern portion of the Williston basin (Figure 1.2).

Study Area

1.3 History of the Sanish

Previous workers of the Three Forks Formation recognize the presence of the Sanish (Dumonceaux, 1984; Berwick, 2008; LeFever, 2009 & 2011). Dumonceaux (1984) recognized that the Sanish is locally present at the Nesson anticline, but suggested that no comprehensive study has been undertaken.

The Sanish dolomitic sandstone has been recognized since its discovery in the 1950's in Antelope field (LeFever, 1991), unfortunately the nomenclature of the Sanish does not always

include the Sanish itself. Several companies and other workers do not constrain the Sanish member to its original definition within the Williston basin and informally assign parts of the Three Forks Formation to the Sanish member (Berwick, 2008).

Dumonceaux (1984), groups the Sanish member in with the Three Forks D interval. Berwick (2008) takes Dumonceaux's Three Forks D interval and transforms it wholly into what he calls the Sanish member, then subdivides it into a C, D, and E interval. LeFever (2009) recognizes that there is a Sanish member, but groups it within the Three Forks Formation. LeFever describes the Sanish as consisting of an argillaceous siltstone to sandstone, with a dolomitic component, and characterized by *Skolithos* burrows, storm wave deposits, and in some cases displaying ripples or laminations (LeFever, 2008).

All workers document the presence of the Acadian unconformity at the base of the lower Bakken Shale member, and at the top of the Three Forks Formation, and by nature of the log contact they place the unconformity at the top of the Sanish. In LeFever's most recent work (2011), she recognizes the Sanish, and calls the Basal Bakken (as defined by the writer) the distal equivalent of the Sanish.

1.4 Research Objectives

The goals of this study are to describe the depositional environment, mineralogy, and sequence stratigraphy of the upper Three Forks, Sanish, and lower Bakken units. To provide such an interpretation, the following research objectives were completed:

- 1) Description and interpretation of eight subsurface cores in the study area;

- 2) Identification of facies, significant surfaces and collection of samples from identified facies for XRD analysis;
- 3) Determination of depositional environments;
- 4) Interpretation of the sequence stratigraphic framework of the Sanish and lower Bakken; and
- 5) Correlation of cores to logs and extrapolated to common logs to compile isopach maps of identified systems tracts.

1.5 Research Contributions

The main contributions of this study are:

- 1) Identification of facies and significant surfaces of the Sanish and lower Bakken Shale;
- 2) Development of a sequence stratigraphic model of the Sanish and lower Bakken Shale; and
- 3) Demonstration that the Sanish is its own mappable entity above the Acadian unconformity, separate from the Three Forks Formation.

1.6 Data and Methods

This study included eight Late Devonian core descriptions encompassing the upper Three Forks, the Sanish, and the lower Bakken Shale member. The cores are housed at the State of North Dakota's core depository in Grand Forks, North Dakota and were described with permission from Julie LeFever of the North Dakota Geological Survey (NDGS). The remaining

core examined in this thesis was available through the North Dakota Oil and Gas commission website (Figure 1.3). Facies identified in core descriptions were analyzed for their mineralogical components using XRD analysis. Significant stratigraphic surfaces were identified in the core descriptions to place the Sanish into a sequence stratigraphic framework.

Raster logs were downloaded from a commercial source (TGS) and available digital log ASCII standard (LAS) files were downloaded from the North Dakota Oil and Gas Commission. Facies were integrated with significant surfaces through the use of core descriptions, photographs, raster and LAS logs. Approximately 1000 logs were correlated basin wide to produce a sequence stratigraphic framework for the upper Three Forks, Sanish, and lower Bakken units.

Figure 1.3: Map of the study area (outlined in blue) with locations of all North Dakota Geological Survey (NDGS) cores in red. Cores that are described are numbered. (For core names please refer to Table 3.1 in Chapter 3)

CHAPTER 2

Geologic Setting

The Williston basin is an elliptical shaped depression in the western North America occupying most of North Dakota, northwestern South Dakota, eastern Montana, and parts of southern Manitoba and Saskatchewan, Canada (Gerhard and Anderson, 1988). It is the result of shallow epeiric seas covering a portion of the North American craton in what is now North Dakota, South Dakota, Montana, Saskatchewan, and Manitoba (Dumonceaux, 1984)(Figure 2.1). This intracratonic sag contains approximately 16,000 feet (4,878 m) of sedimentary rocks, underlain by two Archean terranes indicated by core and geophysical data (Gerhard and Anderson, 1988; Berwick, 2008).

Figure 2.1: Location of the Williston basin highlighted in tan, spanning North Dakota, South Dakota, Montana, Manitoba, and Saskatchewan. Red line indicates approximate location of cross section in Figure 2.3 (image from Encyclopedia of Saskatchewan)

2.1 Paleogeography

The Phanerozoic stratigraphic section has been broken into six major sequences bounded by unconformities (Sloss, 1963). These six sequences include the Sauk (Cambro-Ordovician), Tippecanoe (Ordovician-Silurian), Kaskaskia (Devonian-Mississippian), Absaroka (Pennsylvanian-Permian-Triassic), Zuni (Cretaceous-Tertiary), and Tejas (Tertiary-Cretaceous) (Gerhard et al., 1990).

During the Devonian (417-360Ma), tectonic activity along several paleotectonic elements changed the major communication from the Cordilleran shelf (the central Rockies depression) to a new access route via the Elk Point basin of the Prairie provinces of western Canada joining the Alberta and Williston basins (Figure 2.2) (Gerhard and Anderson, 1988). Gerhard et al., (1982) attribute the change to the last major uplift of the Transcontinental arch, which tilted the basin northward. The basin originated as a craton-margin basin, and evolved into an intracratonic basin during the Cordilleran orogeny (Gerhard et al., 1990). Intracratonic subsidence was most likely due to extension along weaknesses in the basement associated with the Trans-Hudson orogen and the Dakota block provinces (Heck et al., 2004).

Subsidence of the Williston basin continued during the lower Kaskaskia. Sediments thickened northward, allowing for thick Tippecanoe sediments to be overlain by upper Kaskaskia rocks, with thin lower Kaskaskia rocks in the central Williston basin (Gerhard and Anderson, 1988). The lower Kaskaskia and the very lower upper Kaskaskia sequences represent the stratigraphic interval of interest. Figure 2.3 displays the intracratonic “sag” configuration of the Bakken Formation (Meissner, 1978).

Figure 2.2: Late Devonian reconstruction of the Williston basin, arrows showing Alberta and Williston basins, Sweetgrass-Battle River arch in red (center)(modified from Ron Blakely).

Figure 2.3: Schematic cross section of the Bakken formation from Meissner (1978), displaying the bowl type geometry of the Williston basin.

2.2 Devonian Basin History

Capping the Kaskaskia I sequence, carbonate-evaporite cycles of the Birdbear (Nisku) were overlain by mixed carbonate and clastic pulses of the Three Forks Formation in a shallow eperic sea (Gerhard and Anderson, 1988). According to Dumonceaux (1984), the Three Forks Formation consists of interbedded greenish-gray and reddish-brown micrite and dolomicrite with anhydrite nodules scattered throughout. The Kaskaskia's upper and lower division is the contact between the Bakken Formation and the Three Forks Formation. The stratigraphic unit that is the focus of this study lies between the lower Bakken Shale and Three Forks Formation and is termed the Sanish.

The Three Forks & Bakken formations are thought to be separated by a large basin-wide unconformity termed by many authors as the Acadian unconformity. According to Julie LeFever (1991), the Acadian unconformity is between the Three Forks and Bakken formations in the center of the Williston basin. During the Late Devonian as a result of a drop in relative sea level the Three Forks Formation underwent a period of erosion before deposition of the Bakken Formation (Smith and Bustin, 2000). Growth of the Transcontinental arch is suspected to be the cause of subaerial erosion, coinciding with the Acadian event. During this time, depositional environments were predominantly shallow marine, encompassing subtidal, intertidal and sabkha deposits (Gerhard and Anderson, 1988).

2.3 Lithostratigraphy

The stratigraphic interval covered in this thesis spans the upper Three Forks Formation, the informal Sanish member and the lower Bakken Shale member. The majority of rock types are

marine limestone, dolostone, siltstone, sandstone, shale and minor evaporate. The lithostratigraphy section will begin with (but will not include) the Birdbear Formation of the Jefferson Group (Late Devonian) upwards through the Three Forks Formation and ending with the lower Bakken Shale member (Late Devonian).

2.3.1 Three Forks Formation

Following deposition of the Nisku platform carbonate units (Birdbear), mixed carbonate and clastic pulses of the Three Forks Formation were deposited by a shallow epeiric sea (Gerhard and Anderson, 1988). According to Dumonceaux (1984), the Three Forks Formation consists of interbedded greenish-gray and reddish-brown micrite and dolomicrite with anhydrite nodules scattered throughout. The Three Forks Formation is present in the Williston basin in North Dakota, adjacent parts of Montana, Wyoming, South Dakota and Canada (Dumonceaux, 1984).

Originally described by Peale (1893) for exposures at its type section in Logan, Montana, the Three Forks derives its name from the junction of the three forks of the Missouri River near Three Forks, Montana (Dumonceaux, 1984). Because of its presence in different states and provinces of Canada, the Three Forks has many time and facies equivalents.

According to the North Dakota Geological Survey, the term Three Forks Formation is preferable for several reasons: 1) Since 1951 when oil was discovered in the Williston Basin, the name Three Forks has been in use; 2) The Three Forks Formation has been traced from outcrops at its type section in Montana into the subsurface; and 3) The Three Forks Formation has been

described from core chips at its standard subsurface section and has been formally established in the basin (North Dakota Geological Survey, 1961).

2.3.2 Three Forks Facies Terminology

Three previous workers of the Three Forks Formation: Dumonceaux (1984), Berwick (2008), and LeFever (2009) have used core, various thin-section, XRD analysis, and well logs to divide the Three Forks Formation into facies representing differing depositional environments. Dumonceaux divided the Three Forks Formation into four representative facies A through D, including the Sanish as the D interval.

Berwick (2008) went a step further, and took what was Dumonceaux's unit D and separated it into his C & D intervals then terming the Dumonceaux's Three Forks D unit the Sanish and briefly touching on the lower intervals only for context, yet never actually defining the boundaries or lithologies of the Three Forks A and the B. Terming the upper unit of the Three Forks Sanish is not in accordance with tying it to its originally defined stratigraphic position as dolomitic sandstone to siltstone resting between the lower Bakken Shale member and the Three Forks Formation.

LeFever (2009) divided the entire Three Forks package into six units closely corresponding to the divisions of Dumonceaux, with unit 6 being the equivalent of Dumonceaux's D interval. LeFever's unit 6 includes the Sanish, and is the equivalent to Berwick's C, D, and E interval (which he also labels Sanish). Units 4 and 5 correspond with Dumonceaux's C interval, units 2 and 3 correspond to Dumonceaux's B interval, and LeFever's unit 1 corresponds to Dumonceaux's unit A (Figure 2.4).

Figure 2.4: Translation of units between the three previous workers of the Three Forks Formation

For the purpose of the proposed study, I will start by retaining Dumonceaux's correlation of the A, B, C, and most of the D interval and focus my work on the original Sanish and its adjacent units (upper Three Forks Formation, and lower Bakken Shale). I intend to demonstrate that it is a mappable entity separate from the Three Forks Formation. Dumonceaux states the advantages of splitting the Three Forks Formation into four members A-D in order to display the truncation of the units along the flanks of the basin and the angular Acadian unconformity.

Dumonceaux states that although the vertical succession of lithofacies is similar from one core to another, throughout the area, the Three Forks Formation exhibits extreme lateral and

vertical variability, making correlation within the formation a difficult process. Dumonceaux breaks down the Three Forks Formation into the different lithologies, representing supralittoral, littoral, and sublittoral depositional environments: micrite, argillaceous micrite, dolomicrite, argillaceous dolomicrite, and argillaceous biomicrite. Although she defines five lithologies, she does not give them a specific stratigraphic assignment to her A,B,C, and D intervals.

Through personal communication with Dr. John C. Hohman, the Three Forks Formation displays a cyclic nature with alternating coastal plain and tidal flat deposits (John C. Hohman, pers.comm, 2011). LeFever (2009) makes note that at the top of her unit 3, which is the top of Dumonceaux's unit B, there is marked decrease in the photoelectric curve, due to the decrease in the amount of anhydrite (LeFever, 2009). Dr. John C. Hohman attributes this to a climatic shift from a more arid environment of the A & B units, to a more humid environment which ensued during deposition of the C & D units. Instead of breaking down the Three Forks Formation into its A, B, C, and D subdivisions and giving each a specific description, I will use the observed petrophysical and interpreted climatic shift to define a composite set of subdivisions (Three Forks A&B and C&D), respectively.

2.3.3 Three Forks A & B

The lower portion of the Three Forks Formation consists of massive, faintly bedded to brecciated rocks containing locally abundant anhydrite in the form of nodules and vug filling cement (LeFever, 2009). These features suggest deposition and/or early diagenesis in an arid, restricted marine or sabhka environment that allowed for seawater to evaporate forming anhydrite and possibly even dolomitizing pre-existing limestone (LeFever, 2009).

2.3.4 Three Forks C&D

According to LeFever (2009), the upper portion of the Three Forks Formation differs in the frequency and detail of primary sedimentary structures. The Three Forks above unit 3 (the base of C for Dumonceaux) contains couplets of thin layers of reddish or greenish clay-sized material alternating with thin layers of light-tan silt to very-fine sand-sized material that sometimes contains ripple cross-laminations (LeFever, 2009). The upper Three Forks (Dumonceaux's C-D) interval consists of mainly argillaceous dolomicrite, dolomicrite, and argillaceous micrite (Dumonceaux, 1984). As mentioned before, Dumonceaux (1984) has just recognized facies, and has not constrained them to wireline log picks. For the purpose of this study, the only the upper-most portion of the Three Forks Formation will be examined because of the distinct nature of the contact between the Three Forks D tidal flat, and the Sanish representing the Acadian unconformity.

2.3.5 The Sanish Member

All three previous workers on Three Forks Formation (Dumonceaux, 1984; Berwick, 2008; and LeFever, 2009) recognize the presence of the Sanish. Dumonceaux recognizes that the Sanish is locally present on the Nesson anticline, but indicates that no comprehensive study has been undertaken. Just as all three workers recognize that the Sanish does exist, no one recognize it as a mappable entity until the 2011 work by Julie LeFever of the NDGS.

The Sanish dolomitic sandstone has been recognized since its discovery in the 1950's in Antelope field, unfortunately the nomenclature of the Sanish does not always include the Sanish itself. Several companies and workers within the Williston basin informally call parts of the

Three Forks Formation Sanish member, and do not follow the original definition of the Sanish member.

Dumonceaux (1984), groups the Sanish member in the Three Forks D interval. Berwick (2008) transforms Dumonceaux's Three Forks D interval and the Sanish member then subdivides it into a C, D, and E interval. Lastly, LeFever (2009) recognizes the Sanish member, while grouping it within the Three Forks Formation.

As originally defined, the Sanish member consists of an argillaceous siltstone to sandstone, with a dolomitic component, and is characterized by *Skolithos* burrows, storm wave deposits, and in some cases displays ripples or laminations (LeFever, 2008). In 2011, the interpretation of the Sanish member was revised and the Basal Bakken was referred to as the distal equivalent to the Sanish member (LeFever et al., 2011).

2.3.6 Lower Bakken Shale

Upper Devonian and Lower Mississippian black shale formations composed of thin, condensed, organic-rich strata are widespread throughout the interior of North America. They include the Bakken Formation in the Williston basin, the Exshaw Formation in the western Canada sedimentary basin of Alberta, The Pilot Shale of Utah, the Chattanooga Shale in the eastern mid-continent and southern Appalachian basin, the Antrim Shale in the Michigan basin and the New Albany Shale in the Illinois basin. The age and facies equivalent of the Bakken is the Exshaw Shale of the Alberta basin (Smith and Bustin, 1996). At the end of Three Forks Formation / Sanish deposition, a basin wide transgression and/or basin subsidence ensued depositing the lower Bakken Shale.

The lower Bakken Shale member consists of a dark grey to brownish-black, non-calcareous, fissile, slightly to highly organic-rich shale. The color of the shale varies depending on the amount of silt, clay, and organic carbon present in the rock. The shale is finely laminated to massive and can be hard or soft (wax-like) (LeFever, 1991). Pyrite is also abundant and occurs in thin, wispy laminae, lenses or nodules, or can be disseminated. LeFever also notes two parts to the lower Bakken package, a lower basal siltstone, and a shale. It is in her latest interpretation that the Basal Bakken siltstone is defined as the distal equivalent of the Sanish (LeFever et al., 2011).

Due to its very high gamma ray readings (200-900 API), the informal upper and lower Bakken Shale members are used as prominent marker beds within the Williston basin. The lower Bakken Shale member is wide spread throughout the basin and reaches a maximum thickness just east of the Nesson anticline of about 17m (55ft). Deposition of the lower Bakken Shale member is believed to have taken place in a stratified water column with anoxic bottom waters allowing for preservation of organic matter in the lower Bakken Shale member (Smith and Bustin, 1996).

The end of deposition of the lower Bakken Shale member was the result of a regression and a significant change in overall environment (Smith and Bustin, 2000). The lower-middle Bakken member consists of several lithofacies interpreted as high and low energy deposits in a shoreline environment (LeFever et al., 1991). According to Smith and Bustin, the transitional gray sandstone and mudstone lithofacies of the middle Bakken member were deposited in a well oxygenated, intertidal or shallow sublittoral setting (Smith and Bustin, 1996).

2.4 Late Devonian Sanish Member

The Late Devonian Sanish member at the top of the Three Forks Formation, is currently interpreted to be deposited during lowered sea-level as a beach or nearshore deposit (Dumonceaux, 1984; LeFever, 1991). As previously stated, the boundary between the Kaskaskia I and Kaskaskia II sequences is represented by the regional Acadian unconformity that occurs across most of North America. Smith et al., 1995 (Figure 2.5) interpret this unconformity as a sequence boundary that separates the Torquay / Big Valley from the Exshaw Formation in the western Canadian sedimentary basin. In the Williston basin, the sequence boundary separates the Three Forks Formation from the Bakken Formation. The Sanish straddles this boundary and is interpreted by workers to rest below the Acadian Unconformity.

Banff Fm.	Banff carbonates		Highstand Systems Tract (partial)		Lodgepole Formation	
	basal Banff black shale		Maximum flooding surface		Upper Member	
Exshaw Formation	Siltstone Member	Sub-unit B-ex	Transgressive Systems Tract		Sub-unit C-bk	Middle Member
		Sub-unit A-ex	Marine flooding surface		Sub-unit B-bk	
	Black Shale Member	Mb-2	Lowstand Systems Tract		Sub-unit A-bk	
		Mb-1	Devonian-Mississippian boundary			
	Palliser/Big Valley Formations		Sequence boundary or its conformable equivalent		Lower Member	
		Transgressive Systems Tract		Big Valley/Torquay Lyleton/Threeforks Formations		
		Marine flooding surface/sequence boundary				

Figure 2.5: Comparison of the sequence stratigraphy of the Exshaw-Bakken Formation between the Foreland basin of Canada and the Williston basin of the United States from Smith et al.(2000).

Smith and Bustin (2000) state that low sedimentation rates as a result of the geographical isolation of much of the Western Canada sedimentary basin may have been responsible for the absence of a regionally continuous lowstand systems tract at the base of the Bakken and Exshaw formations. This study will look to characterize the Sanish member and distinguish it from the upper Three Forks Formation and the Acadian unconformity will be placed below the Sanish.

2.5 Petroleum Geology

According to Berwick (2008), there are three main types of source rocks within the Williston basin. These source rocks are Type I, lacustrine lipid-rich algae oil-prone source rocks of the Winnipeg Formation (Ordovician); Type II marine phytoplankton, zooplankton, and bacteria oil and gas-prone source rocks of the Bakken Formation (Late Devonian-Early Mississippian); and Type III terrestrial vascular plants gas-prone source rocks of the Tyler Formation (Pennsylvanian). The most prolific of these source rocks are the highly organic-rich upper and lower shale units of the Bakken Formation. As Berwick points out, the prolific lower Bakken Shale lies directly above the Sanish, and where mature, may produce productive source and trap configurations.

2.6 Related Work

Despite the proximity of the upper Three Forks Formation, and the informal Sanish member to the well-studied Bakken Formation, the Sanish member is still poorly understood. To date, only a few papers have addressed the Sanish.

Murray (1968) takes a quantitative look at the nature of fractures within the Sanish relating it to production within McKenzie County, North Dakota, yet does not touch on the stratigraphic relationships or the significance of the Sanish.

Dumonceaux (1984) takes a look at the Three Forks Formation as a whole, defining five lithofacies, and dividing the Three Forks into an A, B, C, and D units. The D unit includes the Sanish, however she never defines the Sanish. Stratigraphic horizons for the Three Forks Formation, provided courtesy of the Hess Corporation, correspond with Dumonceaux's A, B, C, and D interval. These picks are retained. However, the D interval was modified to represent the Sanish as its own unit and to locate the Acadian unconformity with knowledge of the Three Forks Formation defining the setting for the pre-Sanish depositional environment.

Berwick (2008) examines the upper Three Forks Formation (unit D) yet defines the entire unit D as the Sanish, which is in discordance with recognition of the Sanish.

Julie LeFever and Stephan Nordeng (1991, 2008, 2009, & 2011) of the North Dakota Geological Survey also touch on the Three Forks Formation and Sanish. They divide the Three Forks Formation into six units in which the Sanish is included into her upper-most unit 6 of the Three Forks Formation. This interpretation is in discordance with the idea that the Sanish is a separate unit from the Three Forks Formation, resting on an unconformity which is mappable basin-wide (LeFever & Nordeng, 2009). In 2011, LeFever, LeFever & Nordeng revised their interpretation and they recognize the Sanish and Basal Bakken intervals referring to the Basal Bakken as the distal equivalent to the Sanish member (Figure 2.6).

Figure 2.6: Previous and current interpretations of the Late Devonian interval from the AHLE et al Grassy Butte 12-31 H3 well.

CHAPTER 3

Core Descriptions and Definition of Facies

A facies is “a body of rock characterized by a particular combination of lithology, physical, and biological structures that exhibits an aspect different from the bodies of rock above, below, and laterally adjacent” (Walker et al. 1992). The first step in determining the origin of the Sanish member is a detailed core description and facies analysis. Each recognized facies and significant surface was defined and, depositional environments and stratigraphic boundaries are inferred.

3.1 Methods

Eight cores from the upper Three Forks, Sanish, and lower Bakken units spanning the western portion of North Dakota’s Williston basin were described (Figure 3.1a). All eight cores are public domain data, and are housed at the North Dakota Geological Survey’s core depository. Each core was examined for lithology, significant surfaces, sedimentary structures, and biogenic structures.

Biogenic structures were identified using an in-field geology hand book (Compton, 1995) as well as the work done by Pemberton, Van Wagoner, and Wach (1992) in which several ichnofacies related to a wave dominated shoreline were identified. A Core Lab™ grain size comparator and a Wards™ 10X hand lens were used to aid in the identification of differing lithologies. Rock color was compared to a rock color chart produced by Munsell™ color. A bottle of 10% hydrochloric acid was provided by the NDGS core laboratory to determine the type of matrix, grain composition, or cement. A partings classification from Lazar et al., 2010; modified after Campbell (1967) was used in classification of shale lithology. Also, core

photographs were available from the NDGS website (<https://www.dmr.nd.gov-oilgas/>).

Figure 3.1a: Map displaying the eight locations of the core descriptions, for the names of the cores, refer to Table 3.1 in the proceeding text.

In addition to the dolomitic and argillaceous Three Forks D and the classic high gamma ray lower Bakken Shale, four facies were defined from the top of the Three Forks unit D, to the base of the high gamma ray lower Bakken Shale. Representative samples from all six facies were prepared for XRD analysis and log characteristics which are discussed under each facies description.

3.1.1 X-Ray Diffraction (XRD) & Total Organic Carbon (TOC) Methods

Upper Three Forks, Sanish, and lower Bakken facies were sampled for their mineral proportions disregarding organic carbon content. Only four samples were analyzed for TOC (two in the Basal Bakken, and two in the lower Bakken Shale). If more than one lithology was present in a particular sequence, each lithology was sampled. Twenty seven samples from a total of 6 facies were obtained from cores described. Data can be found in Appendix C.

Once samples were selected from representative facies, samples were crushed using a cast-iron mortar and pestle and transferred to sample bags. The mortar and pestle were thoroughly cleaned to rid of any excess minerals using an air-compressor and an alcohol solution. When all samples were crushed and labeled they were analyzed by Dr. Vivek Singh of the WVU physics department.

The powdered sample was placed onto a silica sample holder and treated with an acetone/ethanol solution. Each sample was analyzed at 5° - 100° 2Θ over a span of 2 ½ hours in order to determine the dominant mineral assemblage not including organic carbon. The resultant diffraction pattern was then copied to Jade 9TM software in which the Rietveld Refinement Method was used to match diffraction peaks to standard minerals in the database.

Iterations to determine the proportion of minerals in each sample were run until the expected values and resultant values showed no change and the best solution was achieved. XRD Results are discussed in each facies description.

To measure for total organic carbon (TOC) powdered samples of the shale facies were heated at a 10oC/min to 650oC and maintained for 20 min. Samples were measured for amount water loss and the remaining weight loss was assumed to be organic carbon.

3.2 Core Descriptions

Custom core description templates were constructed, and applied to all eight cores. Each core description has a hand drawn graphic lithology, followed by the identification of any diagnostic criteria (Figure 3.1b), XRD sample locations, photo locations, and a description of any significant surfaces or facies changes. All core descriptions may be found in Appendix A. A glossary of core photographs is available in Appendix B and XRD samples and results are listed in Appendix C.

Figure 3.1b: Example core description depicting lithology, graphic lithology, significant structures and surfaces and a synopsis of each facies encountered.

3.2.1 Facies Occurrences in Core Samples

Core	TFD	Sanish Facies A	Sanish Facies B	Sanish Facies C	Sanish Facies D	Basal Bakken	Lower Bakken Shale
1. Prairie Rose 24-31	X	X	X	X	X		X
2. Sadowsky 24-14	X		X	X	X		X
3. Erickson 11-1 H	X	X		X	X	X	X
4. Grassey Buttes 12-31 H3	Not Cored		X	X	X	X	X
5. Duncan Rose 1	X	X				X	X
6. USA 42-24A	X		X				
7. Miller 34-9x	X		X				X
8. Brigham Olson 10-15 H	X			X		X	X

Table 3.1: Summary of facies occurrences in examined cores.

3.3 Facies Descriptions

Variations in the lithologies include thicknesses and presence or absence of a facies. However all cores had a consistent stratigraphic succession. The Three Forks D with either Sanish Facies A,B, or C rested on an abrupt hard-ground unconformity. Some cored wells contained Sanish Facies D capping the sequence with a flooding surface represented by Facies C grading into the base of Facies D. The Sanish is overlain by a pebble lag (corrosion/omission surface), with the next facies being either the Basal Bakken siltstone, or the classic lower Bakken Shale. Figure 3.2 is a composite stratigraphic column displaying a complete stratigraphic succession.

Figure 3.2: Composite stratigraphic column showing the typical stacking pattern of the Three Forks (Dumonceaux, 1984), Sanish, Lower Bakken, and Middle Bakken.

The following facies descriptions and identified surfaces start in the uppermost Three Forks Unit D, include the major unconformity, the Sanish, include the gravel lag resting at the top of the Sanish, the Basal Bakken, and finish in the lower Bakken Shale.

3.3.1 Three Forks D

The Three Forks unit D is the uppermost division of Gayle Dumonceaux's (1984) four-part division (A,B,C and D) of the Three Forks Formation. Horizons were based on wireline log signatures. Unit D was observed in each core except for the AHSL et al. Grassy Butte 12-31 H3, in which core was not taken below the Sanish.

Unit D of the Three Forks includes two facies: 1) a wavy-bedded alternating moderate yellowish green (10GY 6/4) to grayish green (10GY 5/2) mudstone and pale yellowish orange (10YR 8/6) to grayish orange (10YR 7/4) microcrystalline dolostone (Figure 3.3) and 2) a light green (5G 8-1) to greenish-gray (5G 6-1) doloclastic conglomerate (Figure 3.4).

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: USA 42-24A

DEPTH: 10869'

NDIC#: 7579

WELL: SAKAKAWEA FEDERAL 13x-35

DEPTH: 9862'

NDIC#: 17067

WELL: SADOWSKY 24-14

DEPTH: 10531'

NDIC#: 17808

FACIES: THREE FORKS "D"

SYNOPSIS: Wavy bedded, alternating tan and green dolostone and mudstone.

Figure 3.3: Core photographs of the Three Forks "D" interval. (Courtesy of the NDGS)

Figure 3.4: Core photographs of the brecciated sections of the Three Forks "D" interval.
(Courtesy of the NDGS)

Silt detritus is moderately to well sorted in the dolostone of the first facies in unit D. Current ripples, scoured surfaces, bi-directional flow indicators were observed. The yellowish-green to grayish-green mudstone displays parallel laminations, desiccation cracks, fluid escape structures, halite casts, soft sediment deformation with disseminated pyrite throughout (Figures 3.5 & 3.6). The conglomerate of unit D is characterized by soft sediment deformation and brecciated sections from 3 inches to 1 foot thick (.08 to .3 m) obscuring any other sedimentary structures (Figure 3.7).

Figure 3.5: Core photograph from Jorgenson 1-15 (10,066.5'), displaying soft sediment deformation (SSD), bi-directional flow directions (FD), parallel laminations and mud cracks. (Courtesy of the NDGS)

Figure 3.6: Core photograph from Young Bear 32-4 (10,519') displaying the Three Forks "D" interval. Note halite casts, mud drapes and scoured surfaces. (Courtesy of the NDGS)

Figure 3.7: Core photograph from Erickson 11-1H (11,343') displaying doloclastic conglomerate of the Three Forks "D". Soft sediment deformation is abundant. (Courtesy of the NDGS)

Important diagnostic characteristics used for interpretation of the two facies in unit D of the Three Forks Formation include: current ripples, directional flow indicators, fluid escape structures, desiccation cracks, and scour surfaces.

3.3.1.1 XRD Results

Samples for XRD were taken from both lithologies which encompass the Three Forks D (tan dolostone & green mudstone). As expected, mineral compositions varied mainly in the dolomite and illite compositions. For depths and wells, please refer to Appendix C.

Dolostone: Four samples of the dolostone intervals averaged 29.0% quartz (25% min, 38.9% max), 67.0% dolomite (52.8% min, 73% max), 2.8% illite (0.3% min, 7.4% max), and 1.2% kaolinite (0.7% min, 1.9% max).

Mudstone: Only one mudstone sample was analyzed, the mineralogical composition is as follows: 20.8% quartz, 10.2% dolomite, 60.6% illite, 4.4% kaolinite, and 4.0% pyrite. One mixed sample containing equal portions of dolostone and mudstone ended up with a composition between that of the dolostone lithology and mudstone lithology as follows: 26% quartz, 34.2% dolomite, 37.7% illite and 2.1% kaolinite.

3.3.1.2 Identification on Wireline Log

The Three Forks D displayed an serrated signature on both the gamma ray and the neutron porosity, reflecting the bedding of alternating dolostone and mudstone. Presumably, higher gamma ray inflections (100+ API) and higher inflections of the neutron porosity tool (NPHI) reflect an interval of mudstone due to detection of bound water on the clay minerals.

Lower gamma ray or “clean” (60-100 API) and lower inflections of the NPHI tool reflect an interval of dolostone relatively free of clay (Figure 3.8).

3.3.1.3 Interpretation of Three Forks D

The Three Forks D interval was deposited in an inter-tidal to supratidal environment; several diagnostic characteristics are present in this lithofacies to aid in the interpretation. According to Berwick (2008), this facies displays shallowing upward cycles capped by tidal ripples and scoured surfaces (Figure 3.5). Current ripples display bi-directional flow, and bi-directional cross-stratification is an end product of this flow (Figure 3.5) (Berwick et al. 2008; Tucker et al. 1990; Pratt et al. 1992). Brecciated sections are common throughout the Three Forks D lithofacies containing fragments of dolostone and mudstone from tidal reworking and deposition during storm episodes (Figure 3.7) (Smosna, pers. comm.; Berwick, 2008; Tucker et al. 1990; Pratt et al. 1992). According to Berwick, any rare parallel laminations identified are

preserved remnants of cyanobacteria that were trapped and shaped into sediment as hardgrounds (Figure 3.5) (Berwick, 2008).

Figure 3.9: Depositional model for the Three Forks "D" (arid, tidal flat). (Pratt and James, 1992)

Mud drapes and flame structures (type II) are also abundant in the Three Forks D lithofacies. Mud drapes form when muddy sediment is deposited along a migrating ripple, if no instability occurs, the mud drape is deposited and preserved (Figure 3.6) (Berwick, 2008). Flame structures (type II) were identified and formed when less dense sediment (mudstone) is overlain by denser sediment (dolostone) producing flame shaped wisps projected into the denser material (Figure 3.10) (Berwick, 2008).

Figure 3.10: Core photograph of the Minnie Kummer #1 (10,981') well displaying a type II flame structure. Note the less dense green mudstone projected into the denser overlying dolostone. (Courtesy of the NDGS)

Halite casts are present, but not abundant in the Three Forks D, due to instability and the ease of the dissolution of salt (Figure 3.6) (Tucker et al. 1990; Pratt et al. 1992). Halite casts coupled with multiple scoured surfaces, soft sediment deformation (SSD) and mud cracks and lack of bioturbation indicate an environment, exposed sub-aerially at times, arid, stressed environment which is consistent with a tidal flat (Figure 3.9) (Berwick, 2008; Tucker et al. 1990; Pratt et al. 1992).

3.3.2 Three Forks Unconformity

Truncating the units from the Three Forks to the Birdbear, this unconformity underlies the Sanish in all examined cores and exists as a torn-up, hardground surface exposed to weathering and overlain by either the Sanish, or lower Bakken Shale (Figure 3.11).

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: SOLOMON BIRD BEAR F-22-22-1

DEPTH: 10090'

NDIC#: 793

WELL: SADOWSKY 24-14

DEPTH: 10529'

NDIC#: 17808

WELL: MILLER 34x-9

DEPTH: 9519'

NDIC#: 17723

SURFACE: THREE FORKS UNCONFORMITY (ACADIAN UNCONFORMITY?)

Figure 3.11: Core photographs of the unconformity (Acadian?) at the base of the Sanish and top of the Three Forks D, surface boundary shown in red. (Courtesy of the NDGS)

3.3.2.1 Identification on Wireline Log

This unconformity can be identified through the aid of cored intervals, which correspond to a “baseline” shift in the neutron and density porosity tools. Because there is a relative lack of clay minerals in the Sanish, a decrease in the neutron porosity and loss of the serrated signature of the log indicates the presence of the Sanish (Figure 3.12).

Figure 3.12: Raster image of the unconformity in the Murphy Creek State 1 well, note baseline shift (decrease) in the NPHI readings indicating a break in the lithology.

3.3.2.2 Interpretation of the Unconformity

Currently, the unconformity, which separates the Bakken Formation from the Three Forks Formation is accepted as being located at the base of the lower Bakken Shale (Smith and Bustin, 2000). After careful core examination, the presence of an abrupt, erosional contact at the base of every examined Sanish section indicates otherwise. This unconformity (Figure 3.11) is a torn up, hardground surface, sometimes displaying clasts from the underlying Three Forks D suspended in a Sanish matrix.

At the end of Three Forks deposition, there was a major scale regression corresponding to the boundary of the Kaskaskia I and II sequences, exposing this surface to sub aerial weathering and reworking. After a period of (millions of years?) the Sanish was deposited as a part of the ensuing transgression.

3.3.3 Sanish Facies A

Sanish Facies A encompasses facies of the original definition of the Sanish as defined in Antelope Field. Facies A was identified in three described cores (Erickson 11-1H, Prairie Rose 24-31 and Duncan Rose #1). Facies A was also observed in core photographs from wells throughout the basin.

Facies A is described as a pale yellowish brown (10YR 6/2) to grayish orange (10YR 7/4) to dusky yellowish brown (10YR 2/2) argillaceous and dolomitic sandstone (Figure 3.9). This facies is always below Facies C & D where they are present. It is best characterized by its coarser grain size (fine to very fine) and abundant vertical burrowing (*Skolithos*) and bioturbation (Figures 3.13 & 14) (*Skolithos* burrows are present in Sanish Facies B, however Facies A, consists of coarser grained quartz sand as well as more extensive burrowing).

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: JORGENSEN 1-15 H

DEPTH: 10655' NDIC#: 17086

WELL: DUNCAN ROSE 1

DEPTH: 10602' NDIC#: 12019

WELL: PRAIRIE ROSE 24-31

DEPTH: 11127.6' NDIC#: 16798

FACIES: "SANISH" FACIES A

SYNOPSIS: Intensely burrowed (*Skolithos*) dolomitic and argillaceous sandstone.

Figure 3.13: Core photographs of Sanish Facies A. (Courtesy of the NDGS)

Figure 3.14: Core photograph of Sanish Facies A, from the Jorgenson 1-15 H well (11,045'). Note the sedimentary structures are obscured by the *Skolithos* ichnofacies and extensive bioturbation. (Courtesy of the NDGS)

3.3.3.1 XRD Results

Three samples were taken from the Sanish Facies A lithofacies and analyzed for their dominant mineral assemblage. Facies A is dominated by the minerals quartz and dolomite with no other subsidiary minerals identified. The average mineral assemblages from the three samples are as follows (minimum and maximum measured values in parentheses): 81.3% quartz (68% min, 90.4% max) and 18.7% dolomite (9.6% min, 32.0% max). Full XRD results for Facies A can be found in Appendix C.

3.3.3.2 Identification on Wireline Log

Sanish Facies A is best characterized by a “clean” blocky pattern on the gamma ray log, due to the abundance of quartz and dolomite and relative lack of clay material or organics (Figure 3.15). In newer wells with a photoelectric effect (PE) curve, there is a decrease in the PE value due to the presence of quartz.

Figure 3.15: Raster log from the Duncan Rose #1 well displaying the signature of Sanish facies A sitting on top of the Three Forks “D”, note the cross-over in the neutron and density as the Sanish in this area (Antelope) is a known producer of oil and gas (LeFever, 1991).

3.3.3.3 Interpretation of Sanish Facies A

The *Skolithos* ichnofacies is indicative of relatively high levels of wave or current energy and is typically developed in a well-sorted, loose or shifting particulate substrate (Pemberton et al., 2001). There can be abrupt changes in rates of deposition, erosion, and physical reworking of sediments is frequent. The *Skolithos* ichnofacies ordinarily grades landward into supratidal or terrestrial zones and seaward into the *Cruziana* ichnofacies, (e.g., Facies B of the Sanish). The landward boundary of the *Skolithos* ichnofacies tends to be more abrupt than the boundary with

the *Cruziana* ichnofacies, possibly explaining why Facies A is much less prevalent in the basin than Facies B (Pemberton et al., 2001).

The Sanish Facies A has virtually no sedimentary structure preserved and is characterized by extensive burrowing and bioturbation mainly of the *Skolithos* ichnofacies. Two major components help to classify this depositional environment: grain size, and ichnofacies. A slightly larger grain size (VF to F), abundance of quartz sand, and extensive bioturbation place this facies into the lower to middle shoreface environment (Figure 3.16) (Prothero and Schwab, 1996).

Figure 3.16: Depositional environment of Sanish Facies A, indicated in blue (lower to middle shoreface). Modified from Walker and Plint (1992).

3.3.4 Sanish Facies B

Sanish Facies B comprises the bulk of what is defined as the Sanish, and is by far the most abundant of the Sanish facies. Sanish Facies B was identified in all cores examined except for Duncan Rose #1, Erickson 11-1H (only Facies A) and the Olson 10-15H (only Basal Bakken).

Facies B is best described as a two part lithology: 1) a grayish orange (10YR 7/4) to pale yellowish brown (10YR 6/2) dolomitic and slightly argillaceous siltstone, containing 2) periodic yellowish gray (5Y 8/1) dolostone/quartz silt event beds (Figure 3.17). Part 1 of Facies B is rather non-descript displays some soft sediment deformation (SSD) and scoured surfaces. Part 2 of Facies B (event beds) display vertical and horizontal burrows of the *Thalassinoides*, *Asterosoma*, *Teichichnus*, and *Chondrites* ichnofacies (Pemberton et. al., 1992), scoured surfaces and rarely planar cross bedding (Figures 3.18,19, & 20). The event beds in core are typically harder than that of the surrounding siltstone.

Figure 3.17: Core photographs of the Sanish Facies B (courtesy of the NDGS).

Figure 3.18: Core photograph of Sanish Facies B from the MOI Elkhorn 33-11 well (10,414'). Note the dolostone event bed, with soft sediment deformation (SSD), scoured surface, Asterosoma, and Thalassinoides trace fossils. (Courtesy of the NDGS)

Figure 3.19: Core photograph of the Sanish Facies B from Grassey Butte 12-31 (11,322.5'). Note the planar cross-bedding in the dolostone event bed (storm generated?). (Courtesy of the NDGS)

Figure 3.20: Core photograph from the MOI Elkhorn 33-11 well (10,417.4'). Note the *Teichichnus*, *Thalassinoides*, and *Chondrites* trace fossils. (Courtesy of the NDGS)

Important diagnostic characteristics of this facies used for interpretation are the burrows of the *Thalassinoides*, *Asterosoma*, *Teichichnus* and *Chondrites* trace fossils, SSD, scour surfaces, and rare laminations.

3.3.4.1 XRD Results

Six samples from the Sanish Facies B interval were analyzed for their dominant mineral compositions. The dominant mineral portions are quartz and dolomite, however in different proportions than that of the Sanish Facies A (Facies A is approximately 80% quartz and 20% dolomite). The average mineral proportions for Facies B are as follows (min and max in

parentheses): 29% quartz (39.9% max, 18.8% min), 67.9% dolomite (81.2% max, 49.2% min), 0.9% calcite (5.1% max, 0% min), and 2.3% illite (10.9% max, 0% min).

3.3.4.2 Identification on Wireline Log

Sanish Facies B was the most abundant of the Sanish facies. Its gamma ray character ranged from blocky with little undulation to some undulation likely due to the periodic dolomitic siltstone event beds (Figure 3.21). Overall the Sanish displayed a fining upward log character within the range of 60 to 120 API compared to the Sanish Facies A with an API of <60.

Figure 3.21: Typical log character of the Sanish facies B from the Sadowsky 24-14 H well, displaying an aggradational to fining upwards character of the gamma ray tool.

3.3.4.3 Interpretation of Sanish Facies B

Unlike Facies A, which was characterized by extensive bioturbation, Facies B contains multiple sedimentary structures and burrows of the *Cruziana* ichnofacies placing this facies into an offshore environment, at or slightly above storm wave base. Overall, Facies B has a smaller grain size than that of Facies A, indicating a lower energy environment. In more transitional settings (between lower shore face and offshore), “floating sand” may be present such an occurrence may be found in the core description of the USA 42-24A (core 8). In the Ben Nevis and Avalon formations of the Jeanne d’Arc Basin, “the overall fine grained nature and occurrence of thin, storm-scoured sandstone beds support placement of the deposit below fair weather wave base, but above storm wave base” (Figure 3.22) (Pemberton et. al, 2001).

Sedimentary structures of Facies B include: soft sediment deformation (SSD), scoured surfaces, and planar x-bedded event beds interpreted to be storm generated. Scoured surfaces normally occurred at the base of the storm generated event beds, with SSD normally occurring post storm deposition (Figure 3.18). Planar x-beds (Figure 3.19) are rarely preserved due to burrowing of the *Cruziana* ichnofacies.

The *Cruziana* ichnofacies is most characteristic of subtidal, unconsolidated substrates with energy levels typically ranging from moderate (above wave base) to low (below wave base) (Pemberton et al., 2001). Burrows of the *Cruziana* have a horizontal orientation due to lowered energy and shifts in temperature and salinity levels (Pemberton et al., 2001). In shallow waters periodic scour by storm waves and renewed deposition following their cessation may incorporate storm layers within a sequence of otherwise low-energy deposits (Pemberton et. al, 2001). Indicative of Facies B, Pemberton states that storm layers are eventually overprinted by the *Cruziana*-type traces (Pemberton et al., 2001). Burrows of the *Cruziana* type ichnofacies were identified and include, however are not limited to: *Asterosoma*, *Chondrites*, *Teichichnus*, and *Thalassinoides* (Figure 3.18 & 20).

3.3.5 Sanish Facies C

The Sanish Facies C is least common of the Sanish facies. It is recognized as a thin veneer of argillaceous siltstone approaching the distal portion of the basin during Sanish deposition, and as a thin deposit at the base of the flooding surface grading into Sanish Facies D. Sanish Facies C is an grayish olive (10Y 4/2) argillaceous siltstone, characterized by burrows of the distal *Cruziana* ichnofacies (Figures 3.23 & 24).

CORE PHOTOGRAPHS : FACIES PHOTOS
WELL: FARHART 11-11		
	DEPTH: 9714'	NDIC#: 17096
WELL: MERTES 1-32		
	DEPTH: 7228.4'	NDIC#: 08819
WELL: BRIGHAM OLSON 10-15 H		
	DEPTH: 10680'	NDIC#: 17513	
FACIES: "SANISH" FACIES C		SYNOPSIS: Olive green to gray, argillaceous siltstone. Contains <i>Planolites</i> burrows.	

Figure 3.23: Core photographs of the Sanish facies C. (Courtesy of the NDGS)

Figure 3.24: Core photograph of the Sanish Facies C from the Mertes 1-32 well (7228.4'). Note the horizontally oriented *Planolites* burrow. (Courtesy of the NDGS)

3.3.5.1 XRD Results

No XRD samples were analyzed from this facies.

3.3.5.2 Identification on Wireline Log

The Sanish Facies C was one of the more difficult facies to recognize on logs because of two factors: increased clay content, and location in the basin. Because Facies C is extremely argillaceous, and exists as a thin veneer in the distal portion of the basin during Sanish deposition it is often masked by the extreme inflection of the gamma ray in the lower Bakken Shale. An example of this —“masking effect”— is shown in Figure 3.25. However, one can recognize Sanish Facies C based on the higher resolution pad based tools and curves (e.g. density-neutron & photoelectric effect).

Figure 3.25: Typical log character of the Sanish facies C, displaying a shoulder-like, gradational boundary at the base of the highly radioactive Lower Bakken shale (LBS) from the Mertes 1-32. Note: Facies D is not present due to either corrosion or non-deposition.

3.3.5.3 Interpretation of Sanish Facies C

The lack of any real sedimentary structures and amount of argillaceous material within this facies indicate deposition in offshore quiescent waters below storm wave base (Prothero and Schwab 1996). Pemberton states that the lower offshore comprises dark silty shale beds, with very fine sandstone beds in low abundance (Figure 3.24). Sanish Facies C is present to the north, in the more distal portion of the basin..

Rare *Planolites* burrows were observed in Facies C, and are indicative of an offshore ichnofacies (Figure 3.26) (Pemberton et al. 2001). *Planolites* is described as an unlined burrow that is straight to tortuous, with the fillings essentially structureless and differing from the surrounding rock due to reprocessing by the trace maker (Figure 3.24). *Planolites* are found in virtually every environment from fresh water to deep marine (Pemberton et al. 2001).

Figure 3.26: Proposed depositional environment for Sanish facies C (distal *Cruziana*). Modified from Walker and Plint (1992).

3.3.6 Sanish Flooding Surface

Facies D is always at the top of the Sanish sequence and overlies a marine flooding surface. This flooding surface is characterized by a laminated argillaceous siltstone to mudstone (Facies C?) ranging from 1'' to 2' thick grading into the limestone facies of Sanish Facies D (Figure 3.27). This argillaceous flooding surface is only present in cores with Sanish Facies D; the deepest facies of the Sanish and is interpreted to be the maximum flooding surface.

3.3.6.1 Interpretation of Sanish Flooding Surface

This flooding surface was observed above the Sanish Facies A, B & C, and below the Sanish Facies D as indicated in Figure 3.15. In the Grassey Butte 12-31 (Core 4) core description, this boundary was identified as belonging to the *Glossifungites* ichnofacies. The *Glossifungites* ichnofacies is characterized by sharp-walled, unlined, vertical to sub-vertical domiciles which are passively filled by the overlying sediment (Pemberton et al., 2001). In the Grassey Butte 12-31 core, some burrows have maintained their identity, while others have collapsed or been subject to further bioturbation indicating the facies below was firm-ground (Figure 3.28).

Figure 3.28: *Glossifungites* flooding surface between facies B and facies C in the Grassey Butte 12-31 well (11,318.5'). Note: Burrows filled with argillaceous siltstone of facies C highlighted in yellow. (Photo courtesy of the NDGS)

According to Pemberton et al., a marine flooding surface is typically an abrupt contact across which there is evidence of an increase in water depth (Pemberton et al., 2001). This surface is normally characterized by the juxtaposition of prodelta mud on marine sandstone however, in this case it is Facies A of the shoreface, and Facies B of the offshore overlain by deeper water silty shale grading into the wackestone to packstone of Facies D.

3.3.7 Sanish Facies D

Sanish Facies D is best identified as a “clean” gamma ray ($<60\text{API}$), the overlap of the neutron and density tools and a $\text{PE} > 5$ characteristic of a limestone on wireline logs. Facies D is always at the top of the Sanish sequence, and rests on a marine flooding surface with an argillaceous siltstone to mudstone (Facies C?) grading into the base of Facies D.

In core, Facies D is recognized as a light brownish gray (5YR 6/1) to brownish gray (5YR 4/1) argillaceous and fossiliferous wackestone to packstone (Figure 3.29). Facies D tends to be microcrystalline and mottled in nature containing brachiopod, crinoid and other calcareous skeletal fragments, and some wispy mudstone laminations.

Figure 3.29: Core photographs of the Sanish Facies D. (Courtesy of the NDGS)

3.3.7.1 XRD Results

Four samples from the Sanish Facies D were analyzed for their mineral assemblage. The dominant mineral in Facies D is calcite, with some quartz, dolomite, and clay present. The average mineral assemblages from the three samples are as follows (minimum and maximum measured values in parentheses): 86.3% calcite (59.6% min, 99.9% max), 7.2% quartz (0.1% min, 21.2% max), 4.7% illite (0% min, 5.5% max), 4.4% dolomite (0% min, 13.7% max), and 0.7% kaolinite (0% min, 2.8% max). A full table of Facies D XRD results may be found in Appendix C.

3.3.7.2 Identification on Wireline Log

The Sanish Facies D is the easiest of the facies to identify on wireline log in the study area. On the gamma ray it displays a “clean” (30-80 API) signature, with the tracing effect of the density and neutron tools characteristic of a limestone (Figure 3.30). On newer wells complete with a PE curve, an abrupt increase in value (~ 5 b/e) also characteristic of a limestone interval indicates the Sanish Facies D.

Figure 3.30: Characteristic wireline log signature from the Sadowsky 24-14 H well of the Sanish facies D.

3.3.7.3 Interpretation of Sanish Facies D

The Sanish Facies D is largely absent of sedimentary structures, and composed mainly of carbonate skeletal material and particles. The shallow illuminated seafloor is the place where carbonate is fixed most rapidly by plants and animals, and where carbonate particles precipitate

most easily (Jones and Desrochers, 1992). These sediments may be preserved as what would be called a subtidal limestone (Jones and Desrochers, 1992).

Facies D is a wackestone to packestone and is transitional between low-energy mudstone and high-energy grainstone (Jones and Desrochers, 1992). Crinoid and brachiopod fragments are the most common bioclastic grain type in this facies, and indicate deposition in a shallow sea with normal salinities and oxygenation (Prothero, 1998). Brachiopods are incapable of burrowing and must always stay where currents are strong enough to bring them fresh food and oxygen and eliminate wastes, while crinoids are more prevalent in quieter waters where they may passively filter from suspended food in the water column (Prothero, 1998).

Facies D is interpreted as being deposited on a shallow epeiric platform as a result of the shut off in clastic sediments and lack of turbidity. The term “carbonate platform” is used as a very general and loose term, potentially forming in a vast range of geotectonic settings. Epeiric platforms, however are classified as very extensive (100-10,000km wide), quite flat, cratonic areas covered by a shallow sea (Tucker, 1990).

3.3.8 Corrosion / Omission Surface / Unconformity

Basin wide, resting at the top of the Sanish is a sandy to phosphatic and skeletal lag / omission surface, that caps the Sanish sequence and marks the start of the lower Bakken Shale. This pebble lag (Figure 3.31) tends to have clasts ranging from .25’’ (.08m) to fine sand containing phosphate nodules, quartz sand, fish scales (Smith and Bustin, 1996), calcareous skeletal debris (crinoids and brachiopods only when above Facies D) and pyritic in nature. At the base of the lag, there is evidence of corrosion (Figures 3.33 & 34) based on personal

communication with Dr. John C. Hohman and Dr. Richard Smosna. Moving outward from the Sanish depocenter, this pebble lag merges with the unconformity resting at the top of the Three Forks Formation (Figure 3.32).

Figure 3.31: Core photographs of the gravel lag capping the Sanish. Pebble Lag is highlighted by the red box. (Courtesy of the NDGS)

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: NORDSTOG 14-23-161-98 H-V

DEPTH: 10711'

NDIC#: 16089

WELL: ANDERSON SMITH 1-26

DEPTH: 9794.1'

NDIC#: 16083

WELL: McALMOND 1-05

DEPTH: 8871'

NDIC#: 16862

CONVERGENCE OF PEBBLE LAG
AND THE UNCONFORMITY AT THE
TOP OF THE THREE FORKS

SYNOPSIS: Three Forks unconformity with Lower Bakken shale overlying, note
the remnants of the pebble lag / corrosion surface from the top of the Sanish.

Figure 3.32: Core photographs displaying the convergence of the Three Forks unconformity (Acadian?) with the pebble lag resting at the top of the Sanish sequence. (Courtesy of the NDGS)

3.3.8.1 Interpretation of Corrosion Surface

According to the AGI Glossary of Geology, a corrosion surface is a ~~p~~itted, irregular bedding surface found only in certain carbonate sediments, characterized by a black manganiferous stain, and presumed to result from cessation of lime deposition and from submarine solution”(AGI Glossary of Geology, 2005). The term corrosion surface will be used in tandem with the term ~~o~~mission surface” to emphasize the break in deposition between the Sanish and lower Bakken. An omission surface is a ~~d~~iscontinuity surface of the most minor

nature, which marks a temporary halt in deposition but little or no erosion” (AGI Glossary of Geology, 2005).

This skeletal, sandy to phosphatic pebble lag/ corrosion surface which overlies the entire Sanish depositional sequence indicates transgression of the lower Bakken. It also marks a major rise in sea level and an elongated hiatus in deposition. When the Sanish Facies D is absent, the primarily dolomitic sediments with quartz sand and silt were exposed to chemical dissolution (Figures 3.33 & 34). The dissolution of dolomite is interpreted to account for the amount of concentrated quartz sand and silt observed along the corrosion surface.

Figure 3.33: Photograph of the corrosion surface at the top of the Sanish from the MOI Elkhorn 33-11 well (10,412.4'). (Courtesy of the NDGS).

Figure 3.34: Photograph of the corrosion surface at the top of the Sanish from the USA 33-23-154 well (10,604'). (Courtesy of the NDGS)

Facies D of the Sanish has been interpreted as an epeiric platform which was likely drowned by the ensuing lower Bakken transgression. Such drowning is marked by a transition from shallow to deep-water facies, a change from benthic to pelagic organisms, cementation forming hardgrounds, production of Fe- and Mn- oxides and phosphate formation (Jones and Desrochers, 1992) and was observed in core (Figure 3.34). Dawson and Reaser (1996) observed a discontinuity surface within the Austin Chalk in North-Central Texas which they described as having “abundant phosphatized and pyritized nodules, bioclasts, fish teeth and bones”. Baird (1978) observed similar pebbly phosphorite deposits in the Middle Devonian of New York helping to shed light on submarine discontinuities (Baird, 1978).

In 1991, Baird and Brett took the analysis of these lag deposits further where they focused their study on the black (organic-rich) shale units of the Paleozoic of North America. This study concluded that many black shale units are characterized by “acid-insoluble lag concentrations of reworked pyrite, phosphatic debris, and siliceous material.” Further, these lag

deposits marked widespread disconformities (typically marine flooding surfaces) to local, within outcrop –scale, scour features (Baird and Brett, 1991). Interestingly, their findings show that at the base of the Exshaw shale (distal equivalent of the lower Bakken Shale) there is a widespread discontinuity/lag between the Palliser limestone consisting of phosphate nodules, quartz sand, and dolomite, which may correlate to this lag observed in North Dakota (Baird and Brett, 1991).

The skeletal, sandy to phosphatic pebble lag/ corrosion surface overlies the entire Sanish depositional sequence and indicates transgression of the lower Bakken. Dissolution of carbonate debris under conditions of carbonate understaturation and/or low pH in bottom waters was generally complete (Baird and Brett, 1991). Hydraulic transport coupled with dissolution led to the formation of lags composed of pyritic grains, debris, conodonts, quartz sand, and phosphate nodules (Baird and Brett, 1991) (Figures 3.33 & 34). The dissolution of the primarily dolomite and quartz-rich Sanish Facies B is interpreted as accounting for the concentrated quartzose sand and silt observed within this deposit.

3.3.9 Basal Bakken Siltstone

The Basal Bakken siltstone is mainly constrained to the southwest and western portions of the Williston basin and around the Nesson and Antelope anticlines, northward approaching Canada. The lithology is best described as a pale brown (5YR 5/2) to grayish-brown (5Y 3/2), soft to firm argillaceous and dolomitic siltstone and shale (Figure 3.36) with planar and parallel partings to wavy, non-parallel and discontinuous, wavy, non-parallel as defined by Lazar (2010) (Figure 3.35). In core, this lithology was only distinguished from the lower Bakken Shale through powdering with a mortar and pestle, and aid of the gamma ray tool. Values on the

gamma ray tool tend to run from 130 to 170 API, compared to the lower Bakken Shale displaying much higher values of 600 to 900 API.

Figure 3.35: Shale lamina classification from Lazar et al., 2010; modified after Campbell, 1967(above).

Figure 3.36: Core photographs of the "Basal" Bakken Siltstone. (Courtesy of the NDGS)

3.3.9.1 XRD Results

Three samples were taken from the Basal Bakken interval, and analyzed for their dominant mineral assemblage and total organic carbon (TOC). Two samples were from the actual Basal Bakken interval, while one sample was from a silty bed contained within the Basal Bakken (Sample X4B). The average mineral assemblages from the two samples (excluding sample X4B) are as follows (minimum and maximum measured values in parentheses): 8.2% TOC (7.7% min, 8.7% max), 43.6% quartz (39.5% min, 47.6% max), 25.7% illite (15.3% min, 36.2% max), 17.8% dolomite (17.4% min, 18.2% max), 4.7% kaolinite (3.1% min, 5.9% max).

3.3.9.2 Identification on Wireline Log

The Basal Bakken is identified on wireline log as having an aggradational character, with a definite contrast from the underlying and overlying units (Figure 3.37). The gamma ray reads a consistent 130 to 170 API contrasting with the overlying lower Bakken Shale (LBS) (>>200 API). Neutron and density porosity tools read slightly lower than that of the highly organic LBS, however since it is an argillaceous siltstone, it reads higher than that of the underlying Sanish and Three Forks D.

Figure 3.37: Characteristic wireline log signature of the Basal Bakken from the Knute Hagen #1

3.3.9.3 Interpretation of the Basal Bakken

The Basal Bakken was largely devoid of any sedimentary structures and/or ichnofacies to help interpret the depositional environment. In a few silt beds of the Basal Bakken there were non-descript burrows likely of the *Nereites* or *Zoophycos* ichnofacies (anoxic, restricted environment), however lack of overall burrow structure prevented certain identification (Figure 3.38). The Basal Bakken is a dark brown to grayish brown or black siltstone to silty mudstone or shale, however it lacks the fissile nature possessed by the lower Bakken Shale. Based on the work of Lazar et al. (2010), the partings can best be classified as wavy, parallel to wavy, non-parallel. Total organic carbon (TOC) values from two samples of the Basal Bakken averaging 8.2% demonstrate that this unit was deposited in waters with conditions amenable to preservation of the organic carbon (Smith and Bustin 1996). The amount of illite also supports deposition from a settling water column, in quiescent waters and below storm wave base (Smith and Bustin 1996).

The Basal Bakken is interpreted to be the first phase of the lower Bakken transgression, with a lower overall TOC (8.2%) than that of the overlying lower Bakken Shale (16.6%). Silt content is likely of aeolian origin, or radiolarians composing skeletons of siliceous material (Hohman, pers. comm.). Aeolian quartz and dolomite was noted in the Montney, Baldonnel, and Pardonet formations in the Triassic of western Canada (Davies, 1997).

3.3.10 Lower Bakken Flooding Surface

This flooding surface is widely recognized by those working in the basin due to the stark contrast of the gamma ray readings for the lower Bakken Shale in comparison to other units. It is only a noticeable contact in the core from the Grassey Butte 12-31 well in which there are wispy silt laminae resting at the contact between the two (Figure 3.38). In all other cores examined, the contact of the lower Bakken Shale and Basal Bakken siltstone is defined by lack of silt and increased fissility. This flooding surface is visible in nearly every well with a wireline log and represents a deepening in the water column. It shows the progression from the slightly stratified water column of the Basal Bakken with some detrital input to a fully stratified and anoxic water column with very low detrital input of the lower Bakken Shale.

Figure 3.38: Flooding surface between the Basal Bakken and Lower Bakken shale from the Grassey Butte 12-31 H3 well (11,284'). (Photo courtesy of the NDGS).

3.3.11 Lower Bakken Shale

The lower Bakken Shale is widely recognized in the area due to its high gamma ray readings (600-900 API). This lithology is a brownish black (5YR 2/1) to grayish black (N2) highly organic-rich and fissile shale with planar and parallel partings as described by Lazar et al. (2010) (Figure 3.39). Disseminated and laminated pyrite is common throughout the interval. The lower Bakken Shale may contain some shell hash; calcite cemented veins and fractures, and or

quartz sand injectites (rare). Smith et al. (1995) describe the lower Bakken Shale as a “finely laminated, organic-rich, hemi-pelagic, black marine mudstone in which body fossils and bioturbation are rare.” It should be noted that when correlating the lower Bakken Shale, there was a lower gamma ray interval at the top of the interval (only observed in logs, not core), toward the northeast approaching Canada (increased silt content?) possibly indicating a regression at some point leading into Middle Bakken deposition.

Figure 3.39: Core photographs of the Lower Bakken shale. (Courtesy of the NDGS)

3.3.11.1 XRD Results

Samples of the lower Bakken Shale were analyzed for their mineral components, and two samples were chosen for TOC data (Erickson 11-1 & Grassey Butte 12-31). Samples analyzed for TOC were normalized to account for the amount of organic carbon. Samples not analyzed for TOC were only analyzed for their mineral proportions with organic carbon ignored. The samples of the lower Bakken Shale were analyzed and normalized to the amount of TOC have the following mineral composition: 16.6% TOC (16.5% min, 16.7% max), 65.6% quartz (64.5% min, 66.6% max), 8.6% dolomite (4.2% min, 12.9% max), 7.5% illite (2.6% min, 12.4% max), 1.7% kaolinite (0.0% min, 3.4% max). Three other samples from the lower Bakken were taken and analyzed, with organic carbon ignored these samples showed: 44.3% quartz (33.0% min, 62.3% max), 41.4% illite (21.3% min, 62.2% max), 4.6% pyrite (0.0% min, 13.7% max), 8.2% dolomite (0.0% min, 12.9% max), 1.5% kaolinite (0.1% min, 3.5% max).

3.3.11.2 Identification on Wireline Log

Identification of the lower Bakken Shale was straightforward, with gamma ray readings greater than 600 API. In newer wells complete with digital log suites, it is possible to have a continuous log signature when the gamma ray scale is set from 0 to 900 API. In older logs (without digital curves) and raster logs, it is not uncommon to have no gamma ray signature, as the counts are too great for the scale which can cause problems when trying to correlate the lower shale. Along with higher gamma ray readings, the LBS is characterized by very high resistivity and neutron porosity readings and low bulk density readings due to high organic content (Figure 3.40).

Figure 3.40: Characteristic digital and raster logs of the Lower Bakken shale from the Deadwood Canyon Ranch 43-28H well.

3.3.11.3 Interpretation of Lower Bakken Shale

The proposed depositional environments for the lower Bakken Shale have varied from a marine swamp with restricted circulation, a stagnant marginal marine lagoonal environment, and an offshore marine environment with a layered water column. Offshore with stratified water column is the commonly accepted interpretation (LeFever, 1991).

Figure 3.41: Depositional environment for the Lower Bakken shale from Brown and Kenig (2004).

A position along the equator during the Devonian could have inhibited waters from cooling and allowing for water column mixing (Ettensohn, 1998). The dark, highly organic and laminated nature, high TOC (~16%), abundant pyrite, and rare benthic fauna give further evidence that this was deposited under anoxic bottom conditions (LeFever, 1991, Smith and Bustin, 2000). High quartz contents revealed in XRD analysis (40-60%) are attributed to a Radiolarian ooze (Hohman, pers. comm.). Water depths for the lower Bakken Sea range from 60 to 200+ meters depending on the author and are evidenced by the absence of any storm generated deposits or surfaces of erosion, suggesting it was persistently below storm wave base during lower Bakken deposition (Figure 3.41) (Smith and Bustin, 2000). Maximum effective anoxia on

modern shelves occurs mostly in waters approximately 60 meters deep and the maximum depth of winter mixing in the semi-enclosed Black Sea is less than 60 meters (Tyson and Pearson, 1991; Kara et al., 2009).

3.3.12 Lower Bakken Unconformity

The lower Bakken unconformity was recognized as an abrupt and erosional surface in which siltstones of the middle Bakken directly overlay the shale of the lower Bakken. It was widely recognized in wireline logs as there was an abrupt change in the gamma ray count from the range of 600-900 API to about 90 or 100 API (Figure 3.42) as well as an increase in density indicating an increase in silt content and decrease in organic content. In core, it was recognized as an abrupt erosional unconformity (Figure 3.42).

Figure 3.42: Expression on wireline log and in core of the Lower Bakken unconformity from the Knute Hagen 1 and the Blue Buttes Madison Unit G-105 (10,632'). Core photograph provided courtesy of the NDGS.

3.4 Summary of Depositional Environments

Table 3.2 summarizes the depositional environments for each facies from the upper Three Forks, through the Sanish up to the lower Bakken Shale.

Facies	Label	Typical Gamma Ray	Sedimentary Structures	Ichnofacies/ Biofossils	Average Mineral Assemblage	Depositional Environment
Lower Bakken Shale	LBS	600-900 API	Finely laminated, organic rich, pyrite lags common, planar and parallel partings.	Rare benthic fauna.	16.6% TOC, 65.6% Quartz, 8.6% Dolomite, 7.5% Illite, 1.7% Kaolinite	Open marine (anoxic, stratified water column)
"Basal" Bakken	BB	130-170 API	Planar and parallel partings, to wavy, non-parallel, and discontinuous wavy, non-parallel, rare silty storm? events	None recognized, few storm events of calcareous skeletal debris.	8.2% TOC, 43.6% Quartz, 25.7% Illite, 17.8% Dolomite, 4.7% Kaolinite	Offshore quiescent waters below storm wave base (slightly stratified water column)
Sanish Facies D	SFD	30-80 API	Microcrystalline to mottled in nature, some wispy and muddy laminations and storm scours.	Rests on <i>Glossifungites</i> surface, contains Brachiopods & Crinoid pieces.	86.3% Calcite, 7.2% Quartz, 4.7% Illite, 0.7% Kaolinite	Shallow Epeiric Platform, (normal oxygen and salinities)
Sanish Facies C	SFC	120-200 API	Laminated olive green to gray silty shale with thin event beds	<i>Planolites</i>	No XRD	Offshore (Slightly below storm wave base)
Sanish Facies B	SFB	60-120 API	Soft Sediment Deformation, Scoured Surfaces, Rare Planar Cross-Bedding	<i>Thalassinoides</i> , <i>Asterosoma</i> , <i>Teichichnus</i> , <i>Chondrites</i>	29% Quartz, 67.9% Dolomite, 0.9% Calcite, and 2.3% Illite	Offshore (below fair-weather wave base, but above storm wave base)
Sanish Facies A	SFA	20-60 API	Sedimentary structures obscured from extensive bioturbation.	Burrows mainly of the <i>Skolithos</i> ichnofacies.	81.3% Quartz, 18.7% Dolomite	Lower to Middle Shoreface
Three Forks "D" (Dolostone)	TFD	100-200 API	Current Ripples, Scoured Surfaces, Bi-Directional Flow	None	29% Quartz, 67% Dolomite, 2.8% Illite, 1.2% Kaolinite	Tidal Flats, (extremely shallow and arid)
Three Forks "D" (Mudstone)	TFD	100-200 API	Parallel Laminations, Dessication Cracks, Flame Structures, Halite Casts, & Soft Sediment Deformation	None	20.8% Quartz, 10.2% Dolomite, 60.6% Illite, 4.4% Kaolinite, 4.0% Pyrite	Tidal Flats, (extremely shallow and arid)

Table 3.2 : Summary table of facies and corresponding depositional environment.

CHAPTER 4

Significant Surfaces and Sequence Stratigraphy of the Sanish and Lower Bakken

4.1 Methods

The methods used to place the Sanish into a sequence stratigraphic framework began with detailed core descriptions noting any lithofacies, and ichnofacies and significant surfaces based off the work of Walker et al. (1992), and Pemberton et al. (1985 & 2001). Depositional environments were inferred from the resulting lithofacies and ichnofacies, and significant surfaces were characterized as flooding, corrosion / omission (flooding), or subaerial erosion surfaces.

Once depositional environments and surfaces were inferred, they were placed into a sequence stratigraphic framework. The sequence stratigraphic framework used here is the ExxonMobil™ methodology (Abreu et. al., 2010). The ExxonMobil™ methodology is composed of a low stand systems tract (LST), transgressive systems tract (TST), and a high stand system tract (HST). Within this framework, there are four types of surfaces: 1) Sequence Boundary (SB) 2) Transgressive Surface (TS) 3) Maximum Flooding Surface (MFS) and 4) Flooding Surface (parasequence boundary) (FS) (Abreu et. al, 2010).

The LST is characterized by a sequence boundary at its base, and a transgressive surface at the top. The TST is characterized by a transgressive surface (the first major flooding across the shelf) at the base, and a MFS at the top, indicating the maximum landward extent of basinal facies. Lastly, the HST is characterized by the MFS at its base and a sequence boundary at the top (Figure 4.1) (Abreu et. al, 2010).

4.1.1 Implications of the Sanish in a Sequence Stratigraphic Framework

An interpretation of this set of strata and the nomenclature used hinges on one significant discontinuity surface: the corrosion / omission surface separating the top of the Sanish from the base of the lower Bakken Shale. If this corrosion / omission surface is viewed as a sequence boundary, it makes the Sanish its own depositional sequence as Mitchum (1977) states that: —a sequence is a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities” (Mitchum, 1977). Based on the definition of sequence stratigraphy by Posamentier et al., (1988) and Van Wagoner, (1995), sequence

stratigraphy is the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or *non deposition*, or their correlative conformities” (Posamentier et al., 1988, and Van Wagoner, 1995).

Due to the nature of this definition, I will view the Sanish as its own depositional sequence, and not as the LST of the lower Bakken. The benefits of such an interpretation are as follows: 1) it allows for the accountability of the Basal Bakken as a different and separate LST of the lower Bakken; 2) it allows for each parasequence to become its own systems tract bounded by major surfaces rather than having multiple parasequences composing a systems tract; and 3) it separates two completely different depositional environments (shallow environment from deep marine environment). The two scenarios are shown schematically below in Figure 4.2.

Figure 4.2: The two different stratigraphic framework scenarios stemming from whether to consider the omission/corrosion surface at the top of the Sanish a sequence boundary. Scenario 1 will be used in this study based off the work of Posamentier et al. (1988) and Van Wagoner (1995).

4.2 Previous Sequence Stratigraphic Interpretation

Only two previous authors have placed this interval into a sequence stratigraphic framework: Smith and Bustin (2000) and Berwick (2008). Smith and Bustin detailed the sequence stratigraphy of the Bakken and Exshaw formations in Canada and the United States. He recognizes the Sanish Sand however this unit is placed into the Three Forks Formation. Also excluded from placement in a sequence stratigraphic framework is the Basal Bakken siltstone at the base of the lower Bakken. With the Sanish and Basal Bakken excluded from their interpretation, the Bakken and Exshaw shale units are divided into three major stratigraphic sequences, beginning at the base of the classic high gamma ray lower Bakken. The lower Bakken Shale is placed into a transgressive systems tract with a sequence boundary at the base of the LBS, and a sequence boundary at the lower Bakken / middle Bakken contact (Figure 4.3).

Banff Fm.	Banff carbonates		Highstand Systems Tract (partial)		Lodgepole Formation	
	basal Banff black shale		Maximum flooding surface		Upper Member	
Exshaw Formation	Siltstone Member	Sub-unit B-ex	Transgressive Systems Tract		Sub-unit C-bk	Middle Member
		Sub-unit A-ex	Marine flooding surface		Sub-unit B-bk	
	Black Shale Member	Mb-2	Lowstand Systems Tract		Sub-unit A-bk	
		Mb-1	Devonian-Mississippian boundary Sequence boundary or its conformable equivalent		Lower Member	
Palliser/Big Valley Formations		Transgressive Systems Tract Marine flooding surface/ sequence boundary		Big Valley/Torquay Lyleton/Threeforks Formations		

Figure 4.3: Sequence stratigraphic interpretation of the Bakken from Smith and Bustin (2000).

Figure 4.3: Sequence stratigraphic interpretation of the Bakken from Smith and Bustin (2000).

Similarly to Smith and Bustin (2000), Berwick (2008) placed the Sanish into the Three Forks Formation, and did not identify the Basal Bakken component of the lower Bakken Shale. Berwick states that the Three Forks Formation through the Sanish is part of a ~~deepening~~ or transgression from tidal flat deposits to shallow marine deposits as a part of a transgression, with the contact above the Sanish being a transgressive surface of erosion (TSE). Of importance to this study is the fact that both Smith and Bustin (2000) and Berwick (2008) indicate the base of the classic high gamma ray lower Bakken to be a transgressive surface. Through examination of core, I have recognized additional stratigraphic discontinuities at the top of the Three Forks Formation (not including the Sanish), and at the top of the Sanish / base of the lower Bakken Shale.

4.3 Significant Stratigraphic Surfaces

4.3.1 Three Forks Sequence Boundary / Sanish Transgressive Surface

At the top of the Three Forks Formation, truncating units of the entire Three Forks to the Birdbear is a regional hardground unconformity identified in every core examined that penetrated through the Three Forks D lithofacies (Figure 4.4). According to Smith and Bustin (2000), during the Late Devonian, a drop in sea level exposed the Williston basin and eastern cratonic platform to extensive erosion and reworking (Smith and Bustin, 2000). This reworked and hardground unconformity becomes the transgressive surface for the ensuing Sanish deposition which is largely absent of a lowstand systems tract. The lack of a LST is attributed to the Williston basin at the time being ~~sediment starved~~” and arid with lack of a fluvial input (Smith and Bustin, 2000).

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: SOLOMON BIRD BEAR F-22-22-1

DEPTH: 10090'

NDIC#: 793

WELL: SADOWSKY 24-14

DEPTH: 10529'

NDIC#: 17808

WELL: MILLER 34x-9

DEPTH: 9519'

NDIC#: 17723

SURFACE: THREE FORKS UNCONFORMITY (ACADIAN UNCONFORMITY?)

Figure 4.4: Core photographs of the unconformity (Acadian?) at the base of the Sanish and top of the Three Forks "D", surface boundary shown in red. (Courtesy of the NDGS)

4.3.2 Sanish Maximum Flooding Surface

This flooding surface is the only major flooding surface recognized between the hardground unconformity at the top of the Three Forks Formation, and the omission/corrosion surface on top of the Sanish. According to Abreu et al. (2010), the MFS represents the maximum landward extent of basinal facies, and indicates the top of the TST. Facies C (argillaceous siltstone) of the Sanish directly overlies this *Glossifungites* boundary (Figure 4.5) and indicates the most landward extent of the basinal facies. Above this flooding surface, Facies C grades into Facies D indicating an end in sediment supply and the beginning of carbonate production (Emery and Meyers, 1997).

Figure 4.5: *Glossifungites* flooding surface (interpreted MFS) between facies B and facies C in the Grassey Butte 12-31 well (11,284.5') indicating a landward movement of basinal facies. Note: Burrows filled with argillaceous siltstone of facies C highlighted in yellow. (Photo courtesy of the NDGS)

4.3.3 Sanish Sequence Boundary

Resting atop the Sanish, and merging with the Three Forks unconformity moving radially outward from the Sanish TST depocenter is an omission/corrosion surface indicating a depositional hiatus. This pitted, irregularly shaped surface (AGI Glossary of Geology, 2005) coupled with a pyritic, phosphatic, and quartzose lag indicates prolonged dissolution in low pH water leaving behind a condensed lag (Figures 4.6 & 4.7) (Baird and Brett, 1991). Although there is no subaerial exposure or evidence of substantial erosion, this omission/corrosion surface is considered to be a sequence boundary based on the definition of sequence stratigraphy by Posamentier et al., (1988) and Van Wagoner, (1995), where sequence stratigraphy is the study

of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or *non deposition*, or their correlative conformities”

(Posamentier et al., 1988, and Van Wagoner, 1995).

Figure 4.6: Photograph of the corrosion surface (interpreted sequence boundary) at the top of the Sanish from the MOI Elkhorn 33-11 well (10,412.4'). (Courtesy of the NDGS)

Figure 4.7: Photograph of the corrosion surface (interpreted sequence boundary) at the top of the Sanish from the USA 33-23-154 well (10,604'). (Courtesy of the NDGS)

4.3.4 Lower Bakken Flooding Surface / Transgressive Surface

The surface noted in Figure 4.8 was deemed to be a flooding surface based on the observation that “deeper” anoxic black shale of the lower Bakken is abruptly overlaying a somewhat shallower siltstone deposit of the Basal Bakken (Abreu, et al., 2010). Furthermore, the flooding surface is not just a parasequence boundary flooding surface, but is interpreted as the beginning of a transgressive systems tract, defining the top of the lowstand systems tract that “separates aggradationally stacked parasequences below and retrogradationally stacked parasequences above” (Abreu et al., 2010) (Figure 4.8). The lower Bakken transgressive surface was most easily observed in wireline logs due to the sharp contrast between the overlying organic rich lower Bakken Shale, and the underlying silty Basal Bakken (Figure 4.8). This surface was only observed in one core (Grassey Butte 12-31 H3) and is pictured below (Figure 4.8).

Figure 4.8: Wireline log from the Knute Hagen #1 and core photograph from the Grassey Butte 12-31 H3 well (11,284') shown in tandem to display the transgressive surface of the Lower Bakken. Note the transgressive surface separates aggradational patterns of the “Basal” Bakken from a retrogradational pattern above.

4.3.5 Lower Bakken Maximum Flooding Surface

The lower Bakken maximum flooding surface is a difficult horizon to map due to lack of a consistent log character. The MFS is interpreted as corresponding to the highest gamma ray peak, indicating the furthest landward extent of basinal facies (Abreu et al., 2010). This log character is present in newer wells complete with digital logs and spectral gamma ray suites (Figure 4.9).

In spectral gamma ray logs, the MFS is represented by a peak in Uranium, with suppressed Thorium and Potassium values, and from the highest Uranium peak, Thorium and Potassium increase, indicating the regressive state of the HST and increased detrital influence

(Adams and Weaver, 1958). However, when trying to correlate basin wide with older raster logs, the API count is too great and leaves a blank spot in the log representing the lower Bakken Shale (Figure 4.10). For this reason, the lower Bakken TST/HST was combined into a composite isopach.

Figure 4.10: Comparison between digital LAS logs and raster logs displaying the degree of difficulty encountered when trying to correlate a MFS in the Lower Bakken sequence (from the Deadwood Canyon Ranch 43-28 H well).

4.3.6 Lower Bakken Sequence Boundary

The lower Bakken sequence boundary is represented in core as an abrupt and unconformable surface (Figure 4.11). This sequence boundary would be classified as a regressive surface of erosion (Catuneau, 2006) leading into deposition of the Middle Bakken siltstone, and marks the end of the study in the vertical dimension.

Figure 4.11: Wireline log to core correlation of the Lower Bakken sequence boundary. Core photograph provided courtesy of the NDGS.

4.4 System Tracts

The Sanish and lower Bakken were divided into sequence stratigraphic systems tracts based upon significant surfaces identified in cores and at times with the aid of wireline logs.

4.4.1 Sanish Transgressive Systems Tract

The Sanish transgressive systems tract is composed of three Sanish facies: Facies A; of the lower to middle shoreface, Facies B; of the lower shoreface to upper offshore, and Facies C; of the distal offshore. The transgressive systems tract includes these facies and is bounded by the Three Forks sequence boundary (Figure 4.4) and the Sanish maximum flooding surface (Figure 4.5). Indicated by the wireline logs, the Sanish TST displays an onlapping relationship onto the underlying Three Forks sequence boundary (Acadian Unconformity) (Figure 4.12). The lack of a Sanish lowstand systems tract is likely attributed to the lack of a fluvial input in what is

considered a “sediment starved” basin (Smith and Bustin, 2000). This relationship allows for the Three Forks sequence boundary to be interpreted as the transgressive surface of the Sanish as mentioned previously.

4.4.2 Sanish Highstand Systems Tract

The Sanish highstand systems tract is composed of two facies: the distal Facies C, and the wackestone to packstone of Facies D. The Sanish HST consists of everything between the Sanish MFS (Figure 4.5) to the Sanish sequence boundary (phosphatic and pyritic lag) (Figure 4.6 & 4.7). The Sanish HST generally consists of about 1 ½' to 1" of the silty shale of Facies C overlying the *Glossifungites* MFS which grades into the wackestone to packstone of Facies D. Although the Sanish HST is relatively thin compared to the previous successions, the depositional pattern is one of a downlapping nature onto the MFS (Figure 4.13). The upper bounding surfaces of the Sanish HST (phosphatic and pyritic lag) merges and is superimposed onto the Three Forks SB northward, at which point the Sanish HST pinches out and is overlain by the lower Bakken Shale (lower Bakken TST) or Basal Bakken siltstone (lower Bakken LST). Examples of convergence of the two surfaces can be seen in Figure 3.32 in the preceeding chapter as well as in Appendix B (2). These surfaces also merge to the south due to erosion where the middle Bakken member can be seen overlying the Sanish. An example of this is seen in the USA 42-24A core description in which the intervening lower Bakken systems tracts and Sanish HST is removed or non-deposited, making the shale in that particular core description the upper Bakken Shale.

Figure 4.13: Cross section displaying the thin but downlapping Sanish HST composed of the Sanish facies C & D onto the Sanish MFS. The Sanish HST is bounded below by the Sanish MFS, and above by the Sanish SB (phosphatic & pyritic pebble lag).

4.4.3 Lower Bakken Lowstand Systems Tract

The lower Bakken lowstand systems tract (LST) is composed of the Basal Bakken siltstone facies. In cross-section, the significant surfaces bounding the lower Bakken LST are the Sanish sequence boundary (phosphatic & pyritic pebble lag) (Figures 4.6 & 4.7), and the lower Bakken transgressive surface (Figure 4.14). The lower Bakken LST generally displays an aggradational pattern on wireline log, and represents a basin-ward shift in facies over the Sanish sequence boundary with onlap and downlap above the Sanish sequence boundary as defined by Abreu et. al (2010). The lower Bakken LST is displayed in cross-section as a “lowstand wedge” and may represent a drop in base level that was ultimately masked by local tectonics.

Figure 4.14: Cross section displaying the aggradational pattern of the Lower Bakken LST onlapping to the Southeast and downlapping basinward to the Northwest. The Lower Bakken LST consists of everything between the Sanish SB and the Lower Bakken TS.

4.4.4 Lower Bakken Transgressive Systems Tract / Highstand Systems Tract

The lower Bakken transgressive systems tract (TST) and highstand systems tract (HST) consist of the classic lower Bakken Shale facies. Ideally, the highstand systems tract and the transgressive systems tract should be separated by the maximum flooding surface indicating the most landward extent of the basinal facies, however due to lack of sufficient spectral gamma ray logs and lack of overall log character on raster logs, the lower Bakken TST and HST were combined on cross section and in isopach maps. When, the MFS of the lower Bakken is approximated, it laps onto the lower Bakken LST wedge confirming its position within the sequence stratigraphic framework (Figure 4.15).

4.5 Stratigraphic Placement of the Sanish

Due to recognition of mappable facies, I believe that the Sanish is a valid stratigraphic term that can be tied to the original definition in Antelope Field. The Sanish can be removed from the Three Forks Formation and could become a formation or a member of the Bakken Formation. The Sanish is recognized as a depositional sequence bounded above and below by unconformities or discontinuity surfaces.

CHAPTER 5

Regional Mapping of the Sanish and Lower Bakken

5.1 Methods

After defining all significant surfaces and placing them into a sequence stratigraphic framework, the products were sequence stratigraphic systems tracts as defined in Chapter 4. Each sequence stratigraphic systems tract was bounded by significant surfaces, and these surfaces were related to the common log and correlated basin-wide in Geographix™ to produce four isopach maps of each identified systems tract. Only one cross-section is displayed (A-A'). However, additional cross sections are available in Appendix D.

5.1.1 Three Forks Sequence Boundary (Structure)

A structure map was generated of the Three Forks SB (Acadian unconformity) erosional hardground unconformity (Figure 5.1). This map was generated to compare to the Sanish TST isopach map in order to determine if there were paleo-lows which corresponded to thicker sections of the Sanish TST. The general geometry of this structure map shows the “~~bowl~~” shape of the basin during Sanish deposition, with its deepest portions to the west of the Nesson anticline approximately 11,500 feet (~3,500m) deep, increasing radially to approximately 8,500 feet (2,600m) deep. The three yellow dashed lines correspond to the “~~thicker~~” portions of the Sanish TST, and show a good correlation to paleo-lows likely related to erosional topography.

Figure 5.1: Structure map of the Three Forks SB (Acadian unconformity) displaying the “bowl” shaped geometry of the basin during Sanish deposition. The yellow dashed lines correspond to the thicker trends in the Sanish TST and show a good correlation to lower areas on the structure map.

5.1.2 Sanish Transgressive Systems Tract

The Sanish TST is approximately 47.5 feet (14.5m) thick at its thickest, in a linear northwest to southeast trend to the southwest of the Nesson and Antelope anticlines (Figure 5.2). From this linear thick, the Sanish TST thins in all directions eventually to a zeroed edge in the southern portion and thinning basin-ward toward Canada to anywhere from 3 feet (0.9m) to a few inches. Thinning is more gradual to the east, northeast, north and northwest and more abrupt to the southwest. Because the Sanish TST was deposited on a hard-ground unconformity likely exposed to prolonged sub-aerial weathering, thick sections and thin sections correspond to topographic lows and highs resulting in variations of thickness. Sediment sourcing of the Sanish TST is likely aeolian in origin judging by a dominant composition of silt sized grains and overall low clay content of the rock (primarily quartz and dolomite). Davies (1997) refers to the Triassic Montney Formation of the Western Canada Sedimentary Basin in which “hot tight silts” were sourced by aeolian processes from the exposed Canadian Shield (Davies, 1997). Conversely, at the time of Sanish deposition to the west, southwest, south and southeast of the Sanish depocenter were the exposed hardground sediments of the Three Forks possibly providing an alternative source for Sanish sediments. This may account for the high amount of detrital dolomite in the Sanish Facies B in particular.

Figure 5.2: Isopach map of the Sanish TST stratigraphic sequence. The sequence is approximately 47.5 feet (14.5m) at its thickest and decreases to a zeroed edge in the southern portion and to about 3 feet (0.9m) to a few inches basin-ward toward Canada. Thick areas of the Sanish are noted by the yellow dashed lines, and correspond to the Three Forks SB structure map's interpreted paleo-lows.

5.1.3 Sanish Highstand Systems Tract

The Sanish HST stratigraphic sequence reaches an approximate thickness of 13 feet (~4m) at its thickest, decreasing asymmetrically to a few inches (0.1m) or zero. It is a very isolated deposit which is interpreted to be where waters were sufficiently oxygenated and deep enough to form an epeiric carbonate platform. There is an abrupt decrease in thickness to the southwest in which the Sanish HST disappears along a NW-SE trend. The author interprets this thickness change to a paleo-shelf defined by the Sanish TST in which the carbonates of the HST were eroded or non-deposited (Figure 5.3). The bounding surfaces of the Sanish HST are the *Glossifungites* MFS, and the Sanish SB (phosphatic & pyritic pebble lag/omission surface) that merges with the Three Forks sequence boundary moving outward in all directions from the Sanish HST. Figure 5.4 displays the composite isopach of the entire Sanish interval which is everything between the Three Forks SB and the Sanish SB.

Figure 5.3: Isopach Map of the Sanish HST, displaying thicknesses ranging from 0 to 13 feet (~4m). Note the NW to SE trend of abrupt thickness decrease interpreted to indicate the location of the paleo-shelf at which the HST was either eroded or non-deposited.

Figure 5.4: Composite isopach map of the Sanish displaying thicknesses ranging from 0 to 50 feet (~15m). This isopach is representative of the entire Sanish depositional sequence of both the Sanish TST and HST.

5.1.4 Lower Bakken Lowstand Systems Tract

The lower Bakken LST stratigraphic sequence is an elongate NW to SE trending wedge like deposit ranging from approximately 33 feet (10 m) to anywhere from 0 to 10 feet (3 m) distally in patchy, isolated thicks (Figure 5.5). This stratigraphic sequence encompasses everything between the Sanish sequence boundary and the lower Bakken transgressive surface. The lower Bakken LST is interpreted to be deposited during a drop in base level that may have been masked by local tectonics. Silt within the lower Bakken LST may be attributed to aeolian delivery bringing along nutrients allowing for organic productivity resulting in about (8.2% TOC).

Figure 5.5: Isopach map of the Lower Bakken LST displaying an elongate NW to SE trending deposit that rapidly changes in thickness from east to west.

5.1.5 Lower Bakken TST/HST

The lower Bakken TST & HST were grouped into one isopach map due to difficulty in correlating the MFS through older raster logs and without aid of spectral gamma ray suites. The lower Bakken TST & HST isopach encompasses everything between the lower Bakken transgressive surface and the lower Bakken sequence boundary. This stratigraphic sequence reaches a maximum thickness of 55 feet (16.7m) at the basin center to non existence at the basin margins (Figure 5.6). This isopach map is interpreted to represent a relative sea level rise which led to the deposition of the first of the two world class source rocks of the Bakken. The depocenter for the lower Bakken TST/HST has moved progressively further northward from the previous three mapped systems tracts (Figures 5.1, 5.3, 5.5, & 5.6) and this northward movement in depocenter is interpreted to be a result of decreased accommodation space to the south with a resulting northward movement in depocenter. Radial thinning of the lower Bakken TST & HST from the basin center (near the Nesson and Antelope anticlines) are interpreted to represent shallowing waters which reduced production and accumulation of organic-rich material and increased the probability of erosion by the ensuing RSE (Regressive Surface of Erosion or lower Bakken sequence boundary).

Figure 5.6: Isopach map of the combined lower Bakken TST & HST displaying a thickness of 55 feet (16.7m) at its depocenter and thinning radially outward from the basin center due to either non deposition or removal from the resulting lower Bakken sequence boundary (regressive surface of erosion).

CHAPTER 6

Conclusions and Recommendations

The main purpose of this study was to identify and map the Sanish based on the original definition in Antelope field, and to determine its relationship to the Three Forks Formation and Bakken Formation. In order to accomplish this task it was necessary to identify all Sanish facies, determining the depositional environments, mineralogical components, and significant surfaces to define separate systems tracts and construct a sequence stratigraphic framework. The results of the study are as follows:

6.1 Conclusions

- The Sanish appears to be a depositional sequence separate from the Three Forks Formation and Bakken formations bounded above and below by unconformities or discontinuity surfaces and includes four different facies:
 - **A:** A *Skolithos* burrowed dolomitic sandstone of the lower to middle shoreface environment. XRD averages: (81.3% Quartz, 18.7% Dolomite)
 - **B:** A dolomitic siltstone displaying storm bed events with rare planar X-bedding preserved, scoured surfaces, and soft sediment deformation characterized by the *Cruziana* ichnofacies of the upper offshore environment. XRD averages: (67.9% Dolomite, 29% Quartz, 2.3% Illite, 0.9% Calcite)
 - **C:** A silty shale with sparse and thin event beds displaying laminations, and characterized by the distal *Cruziana* ichnofacies. No XRD.

- **D:** A microcrystalline to mottled skeletal wackestone to packstone composed of brachiopods and crinoids indicating an onset of sediment starvation and deposition in well oxygenated waters. XRD averages: (86.3% Calcite, 7.2% Quartz, 4.7% Illite, 0.7% Kaolinite)
- The Sanish can be divided into two systems tracts: TST & HST separated by a MFS characterized by a *Glossifungites* surface.
 - Lack of a Sanish LST is likely attributed to a lack in fluvial input in what is considered to be a “sediment starved” basin.
- An additional facies was identified and was assigned to the lower Bakken shale.
 - Basal Bakken siltstone composed of quartz and dolomite silt possibly delivered through aeolian processes. XRD averages: (8.2% TOC, 43.6% Quartz, 25.7% Illite, 17.8% Dolomite, 4.7% Kaolinite).
- The lower Bakken was grouped into a three component sequence composed of a LST, TST, & HST.
 - LST of the lower Bakken is composed of the Basal Bakken siltstone.
 - TST is composed of the lower Bakken Shale from the lower Bakken transgressive surface up to the MFS of the lower Bakken delineated in spectral gamma ray logs.
 - The HST is then composed of the classic lower Bakken Shale from the MFS up to the sequence boundary (unconformity) separating the lower Bakken Shale and middle Bakken member.
- The Sanish is interpreted as a depositional sequence separate from the lower Bakken Shale. This interpretation has three benefits:

- It allows for each parasequence composing its own systems tract.
- It allows for the accountability of the Basal Bakken as the LST of the lower Bakken sequence.
- It separates depositional environments of shallow marine and deep marine.
- Deposition of the Basal Bakken may have been influenced through continued subsidence along the Heart River Fault and/or dissolution of the underlying Prairie Evaporite (LeFever et al., 2011) however further investigation is necessary.

6.2 Recommendations

- Reservoir characterization of the Sanish completed through updated LAS logs:
 - Calibrate with porosity and permeability measurements from core plugs.
 - Water saturation of the Sanish
 - Hydrocarbon saturation
- Thin section analysis of each of the Sanish facies & Basal Bakken to :
 - Confirm depositional environments
 - Confirm mineralogy
 - Attempt to determine a provenance and transport mechanism (aeolian or fluvial)
- Petroleum systems analysis to determine flow direction and potential source charge.
- Zircon age dating for two unconformities (hardground unconformity below Sanish, and corrosion/omission surface above the Sanish)

- Extend the interpretations into Canada, and compare and contrast the Sanish with the Big Valley Formation of Canada.
- A Further investigation into the depositional & structural controls of the Sanish and Basal Bakken.

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APPENDIX A

Core Descriptions

FOSSILIFEROUS MATERIAL	BIOGENIC STRUCTURES	LITHOLOGIES
<p>© CRINOIDS</p> <p>β BRACHIOPODS</p> <p>Δ PHOSPHATIC NODULES</p>	<p>‡ BURROWS (UNDIFFERENTIATED)</p> <p>Sk SKOLITHOS ICHNOFACIES</p> <p>Cr CRUZIANA ICHNOFACIES (Thalassinoides (Th), Asterosoma (As), Teichichnus (Te), Chondrites (Ch), Planolites (Pl), or Helminthopsis (He))</p> <p>Ne NEREITES ICHNOFACIES</p>	<p> DOLOSTONE WITH MUDSTONE/SHALE INTERBEDS</p> <p> DOLOCLASTIC CONGLOMERATE</p> <p> DOLOMITIC SANDSTONE SLIGHTLY ARGILLACEOUS</p> <p> DOLOMITIC SILTSTONE WITH DOLOMITE EVENT BEDS</p> <p> ARGILLACEOUS, SILTY FOSSILIFEROUS WACKESTONE TO PACKSTONE</p> <p> SILTY SHALE/MUDSTONE</p> <p> CALCAREOUS SILTSTONE SLIGHTLY FOSSILIFEROUS</p> <p> LAMINATED BLACK SHALE</p> <p> SILTSTONE (Dolomitic to Calcareous)</p>
SEDIMENTARY STRUCTURES	DIAGENETIC FEATURES	
<p> CURRENT RIPPLES</p> <p> PLANAR CROSS BEDDING</p> <p> SYMMETRICAL RIPPLES</p> <p> PARALLEL LAMINATIONS</p> <p> MUD CRACK</p> <p> SOFT SEDIMENT DEFORMATION</p> <p> FRACTURE (VERTICAL OR HORIZONTAL)</p> <p> FLUID ESCAPE (FLAME STRUCTURE)</p> <p> SYNERESIS CRACK</p>	<p>PYR PYR DISSEMINATED PYRITE</p> <p> NODULAR PYRITE</p> <p> CALCAREOUS NODULES</p> <p> DOLOMITIC CEMENT</p> <p> CALCITIC CEMENT</p> <p>SIGNIFICANT SURFACES</p> <p> FLOODING SURFACE</p> <p> UNCONFORMITY</p> <p> CORROSION/OMISSION SURFACE</p>

APPENDIX B (1)

Core Photographs Corresponding to Core Descriptions

CORE PHOTOGRAPHS		P1
P1A	DEPTH: 10482'
	P1B	DEPTH: 10484'
	P1C	DEPTH: 10485'
CORE: PRAIRIE ROSE 24-31		COUNTY: DUNN
		SEC/TWP/RNG: 31/147/95
		NDIC #: 16798

CORE PHOTOGRAPHS		P1

	P1D	DEPTH: 11119'
	P1E	DEPTH: 11119'
CORE: PRAIRIE ROSE 24-31		SEC/TWP/RNG: 31/147/95
COUNTY: DUNN		NDIC #: 16798

CORE PHOTOGRAPHS		P1
P1G	DEPTH: 11124'
P1H	DEPTH: 11127'
P1I	DEPTH: 11128'
CORE: PRAIRIE ROSE 24-31		COUNTY: DUNN
SEC/TWP/RNG: 31/147/95		NDIC #: 16798

CORE PHOTOGRAPHS		P1
P1J	DEPTH: 11130'

CORE: PRAIRIE ROSE 24-31		COUNTY: DUNN
		SEC/TWP/RNG: 31/147/95
		NDIC #: 16798

CORE PHOTOGRAPHS		P2
P2A	DEPTH: 10482'

	P2B	DEPTH: 10484'
P2C	DEPTH: 10485'
	<div> <div>CORE: SADOWSKY 24-14 H</div> <div>COUNTY: DUNN</div> <div>SEC/TWP/RNG: 14/141/96</div> <div>NDIC #: 17808</div> </div>	

CORE PHOTOGRAPHS		P2
P2D	DEPTH: 10487'
P2E	DEPTH: 10489'
P2F	DEPTH: 10505'	
CORE: SADOWSKY 24-14 H	COUNTY: DUNN	SEC/TWP/RNG: 14/141/96	NDIC #: 17808

CORE PHOTOGRAPHS		P2
P2G	DEPTH: 10521'
	P2H	DEPTH: 10529'
	P2I	DEPTH: 10531'
CORE: SADOWSKY 24-14 H		COUNTY: DUNN
		SEC/TWP/RNG: 14/141/96
		NDIC #: 17808

CORE PHOTOGRAPHS		P3
P3A	DEPTH: 11303'	
			P3B	DEPTH: 11305'	
			P3C	DEPTH: 11313'	
CORE: ERICKSON 11-1 H			COUNTY: DUNN	SEC/TWP/RNG: 11/147/97	NDIC #: 17881

CORE PHOTOGRAPHS		P3
P3D	DEPTH: 11320'

	P3E	DEPTH: 11326'
P3F	DEPTH: 11332'
	CORE: ERICKSON 11-1 H	
	COUNTY: DUNN	SEC/TWP/RNG: 11/147/97
		NDIC #: 17881

CORE PHOTOGRAPHS		P3
P3G	DEPTH: 11335'
	P3H	DEPTH: 11337.5'
	P3I	DEPTH: 11339'
CORE: ERICKSON 11-1 H		COUNTY: DUNN
		SEC/TWP/RNG: 11/147/97
		NDIC #: 17881

CORE PHOTOGRAPHS	<div data-bbox="203 1213 284 1352">P3</div> <div data-bbox="511 1119 1156 1505"> <div data-bbox="1075 1119 1156 1505"> <div>P3J</div> <div>DEPTH: 11341'</div> </div> </div> <div data-bbox="457 533 1156 945"> <div data-bbox="1075 533 1156 945"> <div>P3K</div> <div>DEPTH: 11343'</div> </div> </div>	<div data-bbox="1347 1213 1427 1866">CORE: ERICKSON 11-1 H</div> <div data-bbox="1347 865 1427 1213">COUNTY: DUNN</div> <div data-bbox="1347 441 1427 865">SEC/TWP/RNG: 11/147/97</div> <div data-bbox="1347 195 1427 441">NDIC #: 17881</div>
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CORE PHOTOGRAPHS		P4
<div> <div> <div>P4A</div> <div>DEPTH: 11281'</div> </div> <div> <div>P4B</div> <div>DEPTH: 11284'</div> </div> <div> <div>P4C</div> <div>DEPTH: 11293'</div> </div> </div>		
CORE: AHEL ET AL GRASSEY BUTTE 12-31 H3		COUNTY: MCKENZIE
TWP/SEC/RNG: 12/146/99		NDIC #: 12772

CORE PHOTOGRAPHS		P4

CORE: AH EL ET AL GRASSEY BUTTE 12-31 H3		COUNTY: MCKENZIE
		LOCATION: 12/146/99
		NDIC #: 12772

CORE PHOTOGRAPHS		P4
P4F	DEPTH: 11318'
	P4G	DEPTH: 11325'
CORE: AH EL ET AL GRASSEY BUTTE 12-31 H3		COUNTY: MCKENZIE
		LOCATION: 12/146/99
		NDIC #: 12772

CORE PHOTOGRAPHS		P5
P5A	DEPTH: 10587'
	P5B	DEPTH: 10594'
	P5C	DEPTH: 10595.5'
CORE: DUNCAN ROSE 1		COUNTY: MCKENZIE
		SEC/TWP/RNG: 33/152/94
		NDIC #: 12019

CORE PHOTOGRAPHS		P5
P5D	DEPTH: 10598.5'			
	P5E	DEPTH: 10602'			
	P5F	DEPTH: 10605'			
CORE: DUNCAN ROSE 1			COUNTY: MCKENZIE	SEC/TWP/RNG: 33/152/94	NDIC #: 12019

CORE PHOTOGRAPHS	P5			

CORE PHOTOGRAPHS		P6
P6A	DEPTH: 10857'
	P6B	DEPTH: 10859'
	P6C	DEPTH: 10860'
CORE: USA 42-24A		COUNTY: MCKENZIE
LOCATION: 24/145/104		NDIC #: 7579

CORE PHOTOGRAPHS		P6
P6D	DEPTH: 10857'

	P6F	DEPTH: 10860'
CORE: USA 42-24A		COUNTY: MCKENZIE
SEC/TWP/RNG: 24/145/104		NDIC #: 7579

CORE PHOTOGRAPHS	P7
<div data-bbox="1078 1381 1149 1772"> P7A DEPTH: 9507' </div>	<div data-bbox="1078 848 1149 1218"> P7B DEPTH: 9509' </div>	<div data-bbox="1078 300 1149 678"> P7C DEPTH: 9513' </div>
CORE: MILLER 34x-9	COUNTY: MERCER	SEC/TWP/RNG: 9/145/90 NDIC #: 17723

CORE PHOTOGRAPHS		P7
P7D	DEPTH: 9519'
	P7E	DEPTH: 9532'
CORE: MILLER 34x-9	COUNTY: MERCER	SEC/TWP/RNG: 9/145/90	NDIC #: 17723

CORE PHOTOGRAPHS		P8
P8A	DEPTH: 10655'
P8C	DEPTH: 10673'
CORE: OLSON 10-15 1-V	COUNTY: WILLIAMS	SEC/TWP/RNG: 10/154/102
		NDIC #: 17513

CORE PHOTOGRAPHS		P8
P8A	DEPTH: 10681'
	P8C	DEPTH: 10682'	
CORE: OLSON 10-15 1-V		COUNTY: WILLIAMS	SEC/TWP/RNG: 10/154/102	NDIC #: 17513

APPENDIX B (2)

Core Photographs Corresponding Identified Facies & Sanish Significant Surfaces

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: USA 42-24A

DEPTH: 10869'

NDIC#: 7579

WELL: SAKAKAWEA FEDERAL 13x-35

DEPTH: 9862'

NDIC#: 17067

WELL: SADOWSKY 24-14

DEPTH: 10531'

NDIC#: 17808

FACIES: THREE FORKS "D"

SYNOPSIS: Wavy bedded, alternating tan and green dolostone and mudstone.

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: DUNCAN ROSE 1	
DEPTH: 10484'	NDIC#: 12019

WELL: ERICKSON 11-1 H	
DEPTH: 11343'	NDIC#: 17881

WELL: PRAIRIE ROSE 24-31	
DEPTH: 11130'	NDIC#: 16798

FACIES: THREE FORKS "D" (CONGLOMERATE)

SYNOPSIS: Doloclastic conglomerate (ranges from 3" to 1'+ thick).

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: JORGENSEN 1-15H

DEPTH: 10655' NDIC#: 17086

WELL: DUNCAN ROSE 1

DEPTH: 10602' NDIC#: 12019

WELL: PRAIRIE ROSE 24-31

DEPTH: 11127.6' NDIC#: 16798

FACIES: "SANISH" FACIES A

SYNOPSIS: Intensely burrowed (*Skolithos*) dolomitic and argillaceous sandstone.

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: CONNELL 24-27

DEPTH: 10547' NDIC#: 12886

WELL: SADOWSKY 24-14

DEPTH: 10514.5' NDIC#: 17808

WELL: AHELE ET AL GRASSEY BUTTE 12-31 H3

DEPTH: 11325.5' NDIC#: 12772

FACIES: "SANISH" FACIES B

SYNOPSIS: Argillaceous siltstone with periodic silty dolostone event beds. *Thalassinoides*, *Asterosoma*, *Teichichnus*, *Chondrites*, and rare *Skolithos* are common ichnofacies.

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: FARHART 11-11

DEPTH: 9714'

NDIC#: 17096

WELL: MERTES 1-32

DEPTH: 7228.4'

NDIC#: 08819

WELL: BRIGHAM OLSON 10-15 H

DEPTH: 10680'

NDIC#: 17513

FACIES: "SANISH" FACIES C

SYNOPSIS: Olive green to gray, argillaceous siltstone. Contains *Planolites* burrows.

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: GRASSEY BUTTE 12-31 H3

DEPTH: 11315' NDIC#: 12772

WELL: SADOWSKY 24-14

DEPTH: 10487' NDIC#: 17808

WELL: PRAIRIEROSE 24-31

DEPTH: 11119' NDIC#: 16798

FACIES: "SANISH" FACIES D

SYNOPSIS: Brown to gray, argillaceous and fossiliferous wackestone to packstone, microcrystalline to mottled texture containing brachiopods, crinoids, and other calcareous skeletal remains.

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: GRASSEY BUTTE 12-31

DEPTH: 11304' NDIC#: 12772

WELL: ERICKSON 11-1

DEPTH: 11326' NDIC#: 17881

WELL: OLSON 10-15 1-V

DEPTH: 10673' NDIC#: 17513

FACIES: "BASAL" BAKKEN

SYNOPSIS: Pale brown to grayish brown argillaceous and dolomitic siltstone/shale with planar and parallel partings to wavy, non-parallel and discontinuous, wavy, non-parallel partings.

CORE PHOTOGRAPHS : FACIES PHOTOS

WELL: OLSON 10-15 1-V	
DEPTH: 10655'	NDIC#: 17513

WELL: GRASSEY BUTTE 12-31	
DEPTH: 11281'	NDIC#: 12772

WELL: MILLER 34X-9	
DEPTH: 9507'	NDIC#: 17723

FACIES: LOWER BAKKEN SHALE

SYNOPSIS: Brownish black to grayish black, highly organic and fissile shale with planar and parallel partings

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: SOLOMON BIRD BEAR F-22-22-1

DEPTH: 10090' NDIC#: 793

WELL: SADOWSKY 24-14

DEPTH: 10529' NDIC#: 17808

WELL: MILLER 34x-9

DEPTH: 9519' NDIC#: 17723

SURFACE: THREE FORKS UNCONFORMITY (ACADIAN UNCONFORMITY?)

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: BN 15-22 (FLAT TOP BUTTE)

DEPTH: 11015' NDIC#: 7494

WELL: OLSON 10-15 1-V

DEPTH: 10680.5' NDIC#: 17513

WELL: RAUSCH SHAPIRO FEE 32-9

DEPTH: 10517' NDIC#: 12873

SURFACE: THREE FORKS UNCONFORMITY (ACADIAN UNCONFORMITY?)

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: NORDSTOG 14-23-161-98 H-V

DEPTH: 11309' NDIC#: 16089

WELL: USA 42-24A

DEPTH: 10867' NDIC#: 7579

WELL: FEDERAL 34-1

DEPTH: 10533' NDIC#: 10803

SURFACE: THREE FORKS UNCONFORMITY (ACADIAN UNCONFORMITY?)

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: SADOWSKY 24-14

DEPTH: 10489' NDIC#: 17808

WELL: ERICKSON 11-1-H

DEPTH: 11337.5' NDIC#: 17881

WELL: GRASSEY BUTTE 12-31 H3

DEPTH: 11318.5' NDIC#: 12772

FLOODING SURFACE @
BASE OF SANISH FACIES D

SYNOPSIS: Marine flooding surface (indicated by yellow dashed line) marked by .25" to 2' thick argillaceous siltstone (facies C?) grading into the limestone facies of Sanish facies D.

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: TITAN F-WP 32-14-H

DEPTH: 10711' NDIC#: 16174

WELL: MOI ELKHORN 33-11

DEPTH: 10412.4' NDIC#: 12072

WELL: AH EL ET AL GRASSEY BUTTE 12-31 H3

DEPTH: 11308' NDIC#: 12772

PEBBLE LAG / OMISSION
SURFACE @ TOP OF SANISH

SYNOPSIS: Pebble lag / omission surface capping the Sanish. Lag contains quartzose sand, carbonate skeletal debris , phosphate nodules, pyritic in nature, and fish scales (Smith and Bustin, 1996).

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: PRAIRIE ROSE 24-31

DEPTH: 11119' NDIC#: 16798

WELL: ERICKSON 11-1 H

DEPTH: 11332' NDIC#: 17881

WELL: SPRING CREEK 27X-31 BN

DEPTH: 10833.8' NDIC#: 12983

PEBBLE LAG / OMISSION SURFACE @ TOP OF SANISH

SYNOPSIS: Pebble lag / omission surface capping the Sanish. Lag contains quartzose sand, carbonate skeletal debris, phosphate nodules, pyritic in nature, and fish scales (Smith and Bustin, 1996).

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: NORDSTOG 14-23-161-98 H-V

DEPTH: 10711' NDIC#: 16089

WELL: SADOWSKY 24-14

DEPTH: 10485' NDIC#: 17808

WELL: BN 15-22 (FLAT TOP BUTTE)

DEPTH: 10994.5' NDIC#: 7494

PEBBLE LAG / OMISSION
SURFACE @ TOP OF SANISH

SYNOPSIS: Pebble lag / omission surface capping the Sanish. Lag contains quartzose sand, carbonate skeletal debris, phosphate nodules, pyritic in nature, and fish scales (Smith and Bustin, 1996).

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

PEBBLE LAG / CORROSION SURFACE @ TOP OF SANISH

SYNOPSIS: Pebble lag / corrosion surface capping the Sanish. Lag contains quartzose sand, carbonate skeletal debris, phosphate nodules, pyritic in nature, and fish scales (Smith and Bustin, 1996).

CORE PHOTOGRAPHS : SIGNIFICANT SURFACES

WELL: NORDSTOG 14-23-161-98 H-V	
DEPTH: 10711'	NDIC#: 16089

WELL: ANDERSON SMITH 1-26	
DEPTH: 9794.1'	NDIC#: 16083

WELL: McALMOND 1-05	
DEPTH: 8871'	NDIC#: 16862

CONVERGENCE OF PEBBLE LAG
AND THE UNCONFORMITY AT THE
TOP OF THE THREE FORKS

SYNOPSIS: Three Forks unconformity with Lower Bakken shale overlying, note
the remnants of the pebble lag / corrosion surface from the top of the Three
Forks.

APPENDIX C

XRD Results

Sanish Subfacies "A"																
Sample Number	Well Name	Facies	Depth	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR(+/-)	% CALCITE	ERROR(+/-)	% ILLITE	ERROR(+/-)	% KAOLINITE	ERROR(+/-)	% PYRITE	ERROR(+/-)	
X1C	PRARIE ROSE 24-31	SAN 'A'	11127.0	85.5	5.7	14.5	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
X3D	ERICKSON 11-1	SAN 'A'	11338.0	68.0	4.3	32.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
X5B	DUNCAN ROSE 1	SAN 'A'	10601.0	90.4	6.2	9.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
		min	low Av.	68.0	75.9	9.6	17.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
		max	hi Av.	90.4	86.7	32.0	19.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
			tot Av.		81.3		18.7		0.0		0.0		0.0		0.0	
Sanish Subfacies "B"																
Sample Number	Well Name	Facies	Depth	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR(+/-)	% CALCITE	ERROR(+/-)	% ILLITE	ERROR(+/-)	% KAOLINITE	ERROR(+/-)	% PYRITE	ERROR(+/-)	
X2C	SADOWSKY 24-14	SAN'B'	10491.1	18.8	1.1	81.2	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
X2D	SADOWSKY 24-14	SAN 'B'	10512.0	26.9	4.4	72.4	0.0	0.0	0.0	0.0	0.6	0.0	0.1	0.0	0.0	
X2E	SADOWSKY 24-14	SAN'B'	10528.5	35.6	2.1	64.4	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
X4E	AHELET AL GRASSEY BUTTE 12-31	SAN 'B'	11317.0	24.2	1.4	70.7	1.5	5.1	0.5	0.0	0.0	0.0	0.0	0.0	0.0	
X4F	AHELET AL GRASSEY BUTTE 12-31	SAN 'B'	11325.5	28.4	1.7	69.5	2.0	0.0	0.0	2.0	2.0	1.1	0.1	0.0	0.0	
X6A	USA 42-24 A	SAN 'B'	10867.0	39.9	2.4	49.2	1.6	0.0	0.0	0.0	10.9	1.4	0.0	0.0	0.0	
		min	low Av.	18.8	26.8	49.2	66.5	0.0	0.8	0.0	0.0	1.8	0.0	0.0	0.0	
		max	hi Av.	39.9	31.2	81.2	69.3	5.1	0.9	10.9	2.7	0.1	0.0	0.0	0.0	
			tot Av.		29.0		67.9		0.9		2.3		0.0		0.0	
Sanish Subfacies "C"																
Sample Number	Well Name	Facies	Depth	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR(+/-)	% CALCITE	ERROR(+/-)	% ILLITE	ERROR(+/-)	% KAOLINITE	ERROR(+/-)	% PYRITE	ERROR(+/-)	
X1B	PRARIE ROSE 24-31	SAN 'C'	11119.0	21.2	7.0	13.7	4.4	59.6	19.6	5.5	32.3	0.0	0.0	0.0	0.0	
X2B	SADOWSKY 24-14	SAN 'C'	10485.5	0.1	0.0	0.0	0.0	99.9	7.4	0.0	0.0	0.0	0.0	0.0	0.0	
X3C	ERICKSON 11-1	SAN 'C'	11334.0	5.4	0.4	3.7	0.3	90.8	6.2	0.0	0.0	0.0	0.0	0.0	0.0	
X4D	AHELET AL GRASSEY BUTTE 12-31	SAN 'C'	11312.0	2.2	0.3	0.0	0.0	95.0	6.8	0.0	0.0	2.8	0.6	0.0	0.0	
		min	low Av.	0.1	5.3	0.0	3.2	59.6	76.3	0.0	0.0	0.0	0.6	0.0	0.0	
		max	hi Av.	21.2	9.2	13.7	5.5	99.9	96.3	5.5	9.5	2.8	0.9	0.0	0.0	
			tot Av.		7.2		4.4		86.3		4.7		0.7		0.0	
"Basal" Bakken Siltstone (NORM TO TOC)																
Sample Number	Well Name	Facies	Depth	% TOC	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR(+/-)	% CALCITE	ERROR(+/-)	% ILLITE	ERROR(+/-)	% KAOLINITE	ERROR(+/-)	% PYRITE	ERROR(+/-)
X3B	ERICKSON 11-1	BB	11322.0	7.7	52.5	5.5	18.2	2.5	0.0	0.0	0.0	15.3	4.5	6.3	1.7	0.0
X4C	AHELET AL GRASSEY BUTTE 12-31	BB	11305.0	8.7	34.6	2.6	17.4	1.1	0.0	0.0	0.0	36.2	3.6	3.1	0.8	0.0
		min	low Av.	7.7	34.6	39.5	17.4	16.0	0.0	0.0	0.0	15.3	21.7	3.1	3.4	0.0
		max	hi Av.	8.7	52.5	47.6	18.2	19.6	0.0	0.0	0.0	36.2	29.8	6.3	5.9	0.0
			tot Av.	8.2		43.6		17.8		0.0			25.7		4.7	0.0
Sandy bed in "Basal" Bakken Siltstone																
Sample Number	Well Name	Facies	Depth	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR(+/-)	% CALCITE	ERROR(+/-)	% ILLITE	ERROR(+/-)	% KAOLINITE	ERROR(+/-)	% PYRITE	ERROR(+/-)	
X4B	AHELET AL GRASSEY BUTTE 12-31	BB(Sandy)	11284.0	78.7	5.1	21.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Lower Bakken Shale (No TOC)																
Sample Number	Well Name	Facies	Depth	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR (+/-)	% CALCITE	ERROR (+/-)	% ILLITE	ERROR (+/-)	% KAOLINITE	ERROR (+/-)	% PYRITE	ERROR (+/-)	
X1A	PRARIE ROSE 24-31	LBS	11115.6	62.3	5.7	12.9	1.5	0.0	0.0	21.3	5.9	3.5	1.3	0.0	0.0	
X2A	SADOWSKY 24-14	LBS	10484.5	37.7	3.5	0.0	0.0	0.0	0.0	62.2	7.3	0.1	0.0	0.0	0.0	
X5A	DUNCAN ROSE 1	LBS	10594.0	33.0	2.2	11.7	0.8	0.0	0.0	40.8	3.7	0.9	0.3	13.7	1.0	
		min	low Av.	33.0	40.5	0.0	7.4	0.0	0.0	21.3	35.8	0.1	1.0	0.0	4.2	
		max	hi Av.	62.3	48.1	12.9	9.0	0.0	0.0	62.2	47.1	3.5	2.0	13.7	4.9	
			tot Av.		44.3		8.2		0.0		41.4		1.5		4.6	
Lower Bakken Shale (Normalized to TOC)																
Sample Number	Well Name	Facies	Depth	% TOC	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR (+/-)	% CALCITE	ERROR (+/-)	% ILLITE	ERROR (+/-)	% KAOLINITE	ERROR (+/-)	% PYRITE	ERROR (+/-)
X3A	ERICKSON 11-1	LBS	11308.0	16.7	66.6	6.3	4.2	0.9	0.0	0.0	12.4	3.1	0.0	0.0	0.0	0.0
X4A	AHEL ET AL GRASSEY BUTTE 12-31	LBS	11281.0	16.5	64.5	5.6	12.9	1.3	0.0	0.0	2.6	1.3	3.4	1.1	0.0	0.0
		min	low Av.	16.5	64.5	59.6	4.2	7.5	0.0	0.0	0.0	5.3	0.0	1.2	0.0	0.0
		max	hi Av.	16.7	66.6	71.5	12.9	9.7	0.0	0.0	12.4	9.7	3.4	2.3	0.0	0.0
			tot Av.	16.6		65.6		8.6		0.0		7.5		1.7		0.0
Three Forks "D" (Dolostone)																
Sample Number	Well Name	Facies	Depth	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR (+/-)	% CALCITE	ERROR (+/-)	% ILLITE	ERROR (+/-)	% KAOLINITE	ERROR (+/-)	% PYRITE	ERROR (+/-)	
X1D	PRARIE ROSE 24-31	TFD(DOLO)	11132.0	25.6	3.7	73.0	9.8	0.0	0.0	0.8	0.0	0.7	0.5	0.0	0.0	
X2F	SADOWSKY 24-14	TFD(DOLO)	10530.5	26.5	2.8	71.2	6.6	0.0	0.0	0.3	0.0	1.9	0.5	0.0	0.0	
X3E	ERICKSON 11-1	TFD(DOLO)	11341.0	25.0	7.4	70.8	0.0	0.0	0.0	2.8	0.0	1.4	0.7	0.0	0.0	
X5C	DUNCAN ROSE 1	TFD(DOLO)	10606.0	38.9	2.4	52.8	1.8	0.0	0.0	7.4	1.3	0.8	0.5	0.1	0.0	
		min	low Av.	25.0	24.9	52.8	62.4	0.0	0.0	0.3	2.5	0.7	0.7	0.0	0.0	
		max	hi Av.	38.9	33.1	73.0	71.5	0.0	0.0	7.4	3.2	1.9	1.8	0.1	0.0	
			tot Av.		29.0		67.0			0.0		2.8			0.0	
Three Forks "D" (Mudstone)																
Sample Number	Well Name	Facies	Depth	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR (+/-)	% CALCITE	ERROR (+/-)	% ILLITE	ERROR (+/-)	% KAOLINITE	ERROR (+/-)	% PYRITE	ERROR (+/-)	
X6B	DUNCAN ROSE 1	TFD (MUD)	10607.0	20.8	1.5	10.2	0.8	0.0	0.0	60.6	4.7	4.4	0.8	4.0	0.6	
Three Forks "D" (Mixed)																
Sample Number	Well Name	Facies	Depth	% QUARTZ	ERROR(+/-)	% DOLOMITE	ERROR (+/-)	% CALCITE	ERROR (+/-)	% ILLITE	ERROR (+/-)	% KAOLINITE	ERROR (+/-)	% PYRITE	ERROR (+/-)	
X5D	USA 42-24 A	TFD(Mixed)	10868.0	26.0	1.6	34.2	1.2	0.0	0.0	37.7	2.8	2.1	0.6	0.0	0.0	

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03017.RAW] PRAIRIE ROSE-1A
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1060, 05/11/11 03:52a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.179579(0.031463)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	62.3 (5.7)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.47(0%)	12.9 (1.5)	73
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	21.3 (5.9)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.95(0%)	3.5 (1.3)	596

XRF(Wt%): Ca=2.8%, K=2.1%, Si=34.4%, Al=5.1%, Mg=1.7%, O=52.1%, C=1.7%, H=0.1%

NOTE: Fitting Halted at Iteration 19(4): R=28.69% (E=15.14%, R/E=1.9, P=40, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03018.RAW] PRAIRIE ROSE-1B
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1028, 05/12/11 02:13a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.174299(0.007012)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	21.2 (7.0)	34
Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.47(0%)	13.7 (4.4)	74
Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	5.5 (?)	50
Calcite - CaCO ₃	PDF#00-005-0586	2.00(5%)	59.6 (?)	36

XRF(Wt%): Ca=26.8%, K=0.5%, Si=11.1%, Al=1.1%, Mg=1.8%, O=49.7%, C=8.9%, H=0.0%

NOTE: Fitting Halted at Iteration 25(4): R=17.47% (E=14.97%, R/E=1.17, P=41, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03019.RAW] PRAIRIE ROSE-1C
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=7289, 05/12/11 05:15a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.286558(0.002639)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (2)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	85.5 (5.7)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.44(0%)	14.5 (0.7)	74

XRF(Wt%): Ca=3.2%, Si=40.0%, Mg=1.9%, O=53.1%, C=1.9%

NOTE: Fitting Converged at Iteration 26(4): R=24.42% (E=12.05%, R/E=2.03, P=27, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03020.RAW] PRAIRIE ROSE -1D
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1653, 05/13/11 02:47a
 PROC: [WPF Control File]

- ☒ K-alpha2 Peak Present [Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B ☒ Specimen Displacement - Cos(Theta) = 0.281422(0.008969)
☒ Allow Negative Occupancy ☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering ☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	25.6 (3.7)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.45(0%)	73.0 (9.8)	74
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	0.8 (?)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.93(0%)	0.7 (0.5)	622

XRF(Wt%): Ca=15.9%, K=0.1%, Si=12.3%, Al=0.3%, Mg=9.6%, O=52.4%, C=9.5%, H=0.0%

NOTE: Fitting Halted at Iteration 34(4): R=22.42% (E=14.33%, R/E=1.57, P=41, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03021.RAW] SADOWSKY-2A

SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=689.0, 05/16/11 03:34a

PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = -0.308113(0.060308)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (3)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	37.7 (3.5)	33
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	62.2 (7.3)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.97(0%)	0.1 (?)	674

XRF(Wt%): K=6.1%, Si=30.8%, Al=12.7%, O=50.1%, H=0.3%

NOTE: Fitting Halted at Iteration 27(4): R=26.32% (E=14.56%, R/E=1.81, P=36, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03022.RAW] SADOWSKY-2B

SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1180, 05/17/11 02:09a

PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.239229(0.011143)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (2)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	0.1 (?)	33
■ Calcite - CaCO ₃	PDF#00-005-0586	2.00(5%)	99.9 (7.4)	36
XRF(Wt%): Ca=40.0%, Si=0.1%, O=48.0%, C=12.0%				

NOTE: Fitting Halted at Iteration 22(4): R=25.29% (E=17.36%, R/E=1.46, P=27, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03023.RAW] SADOWSKY-2C
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1926, 05/17/11 05:03a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.41047(0.005588)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (2)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	18.8 (1.1)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.42(0%)	81.2 (1.4)	74

XRF(Wt%): Ca=17.6%, Si=8.8%, Mg=10.7%, O=52.3%, C=10.6%

NOTE: Fitting Converged at Iteration 26(4): R=20.64% (E=15.08%, R/E=1.37, P=28, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03024.RAW] SADOWSKY-2D
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1083, 05/18/11 03:25a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present
☒ Allow Negative Isotropic B
☒ Allow Negative Occupancy
☒ Apply Anomalous Scattering | [Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Specimen Displacement - Cos(Theta) = 0.426409(0.009446)
☐ Monochromator Correction for LP Factor = 1.0
☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5 |
|---|---|

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	26.9 (4.4)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.42(0%)	72.4 (?)	74
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	0.6 (?)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.88(0%)	0.1 (?)	614

XRF(Wt%): Ca=15.7%, K=0.1%, Si=12.7%, Al=0.1%, Mg=9.5%, O=52.4%, C=9.4%, H=0.0%

NOTE: Fitting Halted at Iteration 25(4): R=23.57% (E=15.95%, R/E=1.48, P=41, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03025.RAW] SADOWSKY-2E

SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=674.0, 05/19/11 02:43a

PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.240017(0.012204)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (2)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	35.6 (2.1)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.45(0%)	64.4 (2.0)	74

XRF(Wt%): Ca=14.0%, Si=16.6%, Mg=8.5%, O=52.5%, C=8.4%

NOTE: Fitting Halted at Iteration 31(4): R=24.69% (E=15.8%, R/E=1.56, P=29, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03026.RAW] SADOWSKY-2F
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1723, 05/19/11 06:05a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.311054(0.00696)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	26.5 (2.8)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.44(0%)	71.2 (6.6)	74
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	0.3 (?)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.93(0%)	1.9 (0.5)	614

XRF(Wt%): Ca=15.5%, K=0.0%, Si=12.9%, Al=0.5%, Mg=9.4%, O=52.5%, C=9.3%, H=0.0%

NOTE: Fitting Halted at Iteration 26(4): R=21.66% (E=14.3%, R/E=1.51, P=40, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03027.RAW] ERICKSON-3A

SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=2077, 05/20/11 03:09a

PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.263969(0.021466)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (3)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	80.0 (6.3)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.46(0%)	5.1 (0.9)	73
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	14.9 (3.1)	50

XRF(Wt%): Ca=1.1%, K=1.5%, Si=40.6%, Al=3.0%, Mg=0.7%, O=52.4%, C=0.7%, H=0.1%

NOTE: Fitting Halted at Iteration 26(4): R=30.17% (E=14.34%, R/E=2.1, P=34, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03029.RAW] ERICKSON-3B

SCAN: 10.0/79.96/0.06/5(sec), Cu(40kV,30mA), I(p)=977.0, 05/23/11 01:52a

PROC: [WPF Control File]

☒ K-alpha2 Peak Present
☒ Allow Negative Isotropic B
☒ Allow Negative Occupancy
☒ Apply Anomalous Scattering | [Diffractometer LP] Two-Theta Range of Fit = 10.0 - 80.0(deg)
☒ Specimen Displacement - Cos(Theta) = -0.012071(0.043796)
☐ Monochromator Correction for LP Factor = 1.0
☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5 |
|---|--|

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	56.9 (5.5)	21
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.51(0%)	19.7 (2.5)	43
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	16.6 (4.5)	49
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.95(0%)	6.8 (1.7)	352

XRF(Wt%): Ca=4.3%, K=1.6%, Si=31.6%, Al=4.8%, Mg=2.6%, O=52.4%, C=2.6%, H=0.1%

NOTE: Fitting Halted at Iteration 26(4): R=32.18% (E=14.08%, R/E=2.29, P=42, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03031.RAW] ERICKSON-3C
 SCAN: 10.0/79.96/0.06/5(sec), Cu(40kV,30mA), I(p)=2467, 05/24/11 01:13a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 10.0 - 80.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.051855(0.008566)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (3)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	5.4 (0.4)	22
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.48(0%)	3.7 (0.3)	44
■ Calcite - CaCO ₃	PDF#00-005-0586	2.00(5%)	90.8 (6.2)	24

XRF(Wt%): Ca=37.2%, Si=2.5%, Mg=0.5%, O=48.4%, C=11.4%

NOTE: Fitting Halted at Iteration 21(4): R=18.49% (E=13.48%, R/E=1.37, P=31, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03032.RAW] ERICKSON-3D
 SCAN: 10.0/79.96/0.06/5(sec), Cu(40kV,30mA), I(p)=3096, 05/24/11 04:29a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 10.0 - 80.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.588221(0.004036)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (2)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	68.0 (4.3)	21
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.40(0%)	32.0 (1.4)	44

XRF(Wt%): Ca=6.9%, Si=31.8%, Mg=4.2%, O=52.9%, C=4.2%

NOTE: Fitting Converged at Iteration 25(4): R=27.87% (E=15.59%, R/E=1.79, P=27, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03034.RAW] ERICKSON-3E
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1133, 05/25/11 04:57a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.185177(0.01219)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	25.0 (7.4)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.46(0%)	70.8 (?)	73
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	2.8 (?)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.93(0%)	1.4 (0.7)	612

XRF(Wt%): Ca=15.4%, K=0.3%, Si=12.6%, Al=0.9%, Mg=9.3%, O=52.3%, C=9.2%, H=0.0%

NOTE: Fitting Halted at Iteration 32(4): R=20.81% (E=15.07%, R/E=1.38, P=42, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03035.RAW] GRASSEY BUTTE-4A
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=2049, 05/26/11 02:03a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.149755(0.011367)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	77.4 (5.6)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.47(0%)	15.4 (1.3)	73
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	3.1 (1.3)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.94(0%)	4.1 (1.1)	616

XRF(Wt%): Ca=3.3%, K=0.3%, Si=37.8%, Al=1.5%, Mg=2.0%, O=53.1%, C=2.0%, H=0.0%

NOTE: Fitting Halted at Iteration 28(4): R=25.8% (E=12.83%, R/E=2.01, P=42, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03040.RAW] GRASSEY BUTTE-4B
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=5342, 05/31/11 04:43a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.014217(0.004125)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (2)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	78.7 (5.1)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.49(0%)	21.3 (1.0)	74

XRF(Wt%): Ca=4.6%, Si=36.8%, Mg=2.8%, O=53.0%, C=2.8%

NOTE: Fitting Halted at Iteration 24(4): R=22.04% (E=12.12%, R/E=1.82, P=29, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03039.RAW] GRASSEY BUTTE-4C
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=728.0, 05/31/11 01:04a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present
☒ Allow Negative Isotropic B
☒ Allow Negative Occupancy
☒ Apply Anomalous Scattering | [Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Specimen Displacement - Cos(Theta) = 0.173656(0.013185)
☐ Monochromator Correction for LP Factor = 1.0
☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5 |
|---|---|

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	37.9 (2.6)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.47(0%)	19.1 (1.1)	75
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	39.6 (3.6)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.96(0%)	3.4 (0.8)	612

XRF(Wt%): Ca=4.2%, K=3.9%, Si=26.8%, Al=8.8%, Mg=2.5%, O=51.1%, C=2.5%, H=0.2%

NOTE: Fitting Halted at Iteration 26(4): R=20.53% (E=14.2%, R/E=1.45, P=43, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03042.RAW] GRASSEY BUTTE-4D

SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1436, 06/01/11 11:54p

PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.07426(0.010332)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (3)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	2.2 (0.3)	34
■ Calcite - CaCO ₃	PDF#00-005-0586	2.00(5%)	95.0 (6.8)	36
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.91(0%)	2.8 (0.6)	636

XRF(Wt%): Ca=38.1%, Si=1.6%, Al=0.6%, O=48.3%, C=11.4%

NOTE: Fitting Halted at Iteration 21(4): R=24.36% (E=15.4%, R/E=1.58, P=33, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03043.RAW] GRASSEY BUTTE-4E
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1460, 06/02/11 02:58a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = -0.054253(0.006936)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (3)	Source	I/Ic	Wt%	#L
Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	24.2 (1.4)	34
Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.50(0%)	70.7 (1.5)	74
Calcite - CaCO ₃	PDF#00-005-0586	2.00(5%)	5.1 (0.5)	36

XRF(Wt%): Ca=17.4%, Si=11.3%, Mg=9.3%, O=52.1%, C=9.8%

NOTE: Fitting Halted at Iteration 27(4): R=20.61% (E=13.7%, R/E=1.5, P=34, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03044.RAW] GRASSEY BUTTE-4F
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1446, 06/03/11 01:39a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.240718(0.011067)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	28.4 (1.7)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.45(0%)	69.5 (2.0)	74
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	2.0 (1.1)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.91(0%)	0.1 (?)	614

XRF(Wt%): Ca=15.1%, K=0.2%, Si=13.7%, Al=0.4%, Mg=9.2%, O=52.3%, C=9.1%, H=0.0%

NOTE: Fitting Halted at Iteration 25(4): R=21.46% (E=13.72%, R/E=1.56, P=41, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03047.RAW] ROSE-5A
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1508, 06/07/11 04:40a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.135403(0.006423)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (5)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	33.0 (2.2)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.48(0%)	11.7 (0.8)	75
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	40.8 (3.7)	50
■ Pyrite - FeS ₂	PDF#00-042-1340	1.60(5%)	13.7 (1.0)	20
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.95(0%)	0.9 (0.3)	618

XRF(Wt%): Fe=6.4%, Ca=2.5%, K=4.0%, S=7.3%, Si=24.2%, Al=8.5%, Mg=1.5%, O=43.8%, C=1.5%, H=0.2%

NOTE: Fitting Halted at Iteration 34(4): R=21.87% (E=12.95%, R/E=1.69, P=46, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03048.RAW] ROSE-5B
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=9377, 06/08/11 01:11a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.25976(0.004212)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (2)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	90.4 (6.2)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.45(0%)	9.6 (0.6)	74

XRF(Wt%): Ca=2.1%, Si=42.3%, Mg=1.3%, O=53.1%, C=1.3%

NOTE: Fitting Halted at Iteration 27(4): R=31.79% (E=11.21%, R/E=2.84, P=28, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03049.RAW] ROSE-5C
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=2123, 06/09/11 01:37a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present
☒ Allow Negative Isotropic B
☒ Allow Negative Occupancy
☒ Apply Anomalous Scattering | [Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Specimen Displacement - Cos(Theta) = -0.065518(0.008278)
☐ Monochromator Correction for LP Factor = 1.0
☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5 |
|---|--|

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (5)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	38.9 (2.4)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.50(0%)	52.8 (1.8)	74
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	7.4 (1.3)	50
■ Pyrite - FeS ₂	PDF#00-042-1340	1.60(5%)	0.1 (?)	20
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.97(0%)	0.8 (0.5)	612

XRF(Wt%): Fe=0.0%, Ca=11.5%, K=0.7%, S=0.0%, Si=19.9%, Al=1.7%, Mg=7.0%, O=52.2%, C=6.9%, H=0.0%

NOTE: Fitting Halted at Iteration 29(4): R=22.31% (E=12.63%, R/E=1.77, P=44, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03050.RAW] ROSE-5D
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=649.0, 06/13/11 12:42a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.11768(0.023722)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(4), Lambda=1.54187Å (Cu/K-average)

Phase ID (5)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	20.8 (1.5)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.48(0%)	10.2 (0.8)	74
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	60.6 (4.7)	50
■ Pyrite - FeS ₂	PDF#00-042-1340	1.60(5%)	4.0 (0.6)	21
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	1.00(0%)	4.4 (0.8)	594

XRF(Wt%): Fe=1.9%, Ca=2.2%, K=5.9%, S=2.1%, Si=23.5%, Al=13.2%, Mg=1.3%, O=48.1%, C=1.3%, H=0.3%

NOTE: Fitting Halted at Iteration 25(4): R=22.47% (E=13.37%, R/E=1.68, P=45, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03052.RAW] USA-6A
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=1198, 06/14/11 12:52a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.193425(0.013465)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (3)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	39.9 (2.4)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.46(0%)	49.2 (1.6)	74
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	10.9 (1.4)	50

XRF(Wt%): Ca=10.7%, K=1.1%, Si=21.0%, Al=2.2%, Mg=6.5%, O=52.1%, C=6.4%, H=0.1%

NOTE: Fitting Converged at Iteration 24(4): R=23.21% (E=12.85%, R/E=1.81, P=36, EPS=0.5)

Whole Pattern Fitting and Rietveld Refinement

FILE: [Z03053.RAW] USA-6B
 SCAN: 5.0/99.98/0.06/5(sec), Cu(40kV,30mA), I(p)=772.0, 06/14/11 04:16a
 PROC: [WPF Control File]

☒ K-alpha2 Peak Present	[Diffractometer LP] Two-Theta Range of Fit = 5.0 - 100.0(deg)
☒ Allow Negative Isotropic B	☒ Specimen Displacement - Cos(Theta) = 0.036069(0.011486)
☒ Allow Negative Occupancy	☐ Monochromator Correction for LP Factor = 1.0
☒ Apply Anomalous Scattering	☐ K-alpha2/K-alpha1 Intensity Ratio = 0.5

Profile Shape Function (PSF) for All Phases: pseudo-Voigt, Polynomial(9), Lambda=1.54187Å (Cu/K-average)

Phase ID (4)	Source	I/Ic	Wt%	#L
■ Quartz - SiO ₂	PDF#00-046-1045	3.41(5%)	26.0 (1.6)	34
■ Dolomite - CaMg(CO ₃) ₂	PDF#01-074-1687	2.49(0%)	34.2 (1.2)	74
■ Illite - KAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	PDF#00-043-0685	0.36(5%)	37.7 (2.8)	50
■ Kaolinite 2M - Al ₂ Si ₂ O ₅ (OH) ₄	PDF#01-075-0938	0.92(0%)	2.1 (0.6)	640

XRF(Wt%): Ca=7.4%, K=3.7%, Si=20.6%, Al=8.1%, Mg=4.5%, O=51.0%, C=4.5%, H=0.2%

NOTE: Fitting Halted at Iteration 21(4): R=17.24% (E=14.4%, R/E=1.2, P=42, EPS=0.5)

APPENDIX D

Regional Cross-Sections

APPENDIX E

REFERENCED WELLS USED IN THE STUDY

(Core Descriptions, Core Photographs, Example Logs, Cross Sections, Type Logs)

NUMBER	UWI/API	WELLNAME	Operator	County	Section	Tship	Range
1	33025006690000	PRAIRIE ROSE 24-31H	Burlington	Dunn	31	147	95
2	33025008680000	SADOWSKY 24-14	Anschultz	Dunn	14	141	96
3	33025008840000	ERICKSON 11-1	Hess	Dunn	11	147	97
4	33053023080000	AHEL ET AL GRASSEY Butte 12-31	American Hunter	McKenzie	12	146	99
5	33053021630000	DUNCAN ROSE 1	Continental	McKenzie	33	152	94
6	33053010580000	USA 42-24A	Slawson	McKenzie	24	145	104
7	33057000350000	MILLER 34X-9 V	XTO	Mercer	9	145	90
8	33105016930000	OLSON 10-15 1-V	Brigham	Williams	10	154	102
9	33105015570000	ANDERSON SMITH 1-26V	Hess	Williams	26	155	96
10	33061004890000	NELSON FARMS 1-24V	Hess	Mountrail	24	156	92
11	33053023400000	BN SPRING CREEK 27X-31	Abraxas	McKenzie	27	148	102
12	33023004890000	NORDSTOG 14-23-161-98 H-V	Baytex	Divide	14	161	98
13	33007011090000	MOI-ELKHORN 33-11	Whiting	Billings	11	143	102
14	33013008620000	MERTES 1-32	Clarion	Burke	32	162	89
15	33053027110000	TITAN F-WP 32-14-H	Enerplus	McKenzie	32	148	103
16	33025006640000	ROGNE 44-34H	Encore	Dunn	34	145	95
17	33061005810000	DEADWOOD CANYON RANCH 43-28H-V	Fidelity	Mountrail	28	154	92
18	33025003470000	YOUNG BEAR BIA 32-4	Geolinear	Dunn	4	148	92
19	33053003420000	MINNIE KUMMER TRACT	Hess	McKenzie	25	150	96
20	33025007290000	JORGENSEN 1-15V	Newfield	Dunn	15	148	96
21	33061006800000	FARHART 11-11V	Oasis	Mountrail	11	157	92
22	33061005870000	MCALMOND 1-05H	Landtech	Mountrail	5	155	89
23	33007012130000	CONNELL 24-27H	Ranch	Billings	27	144	102
24	33053010300000	BN 15-22 (Flat Top Butte)	Sequel	McKenzie	15	146	101
25	33053013910000	USA 33-23-154	Slawson	McKenzie	23	146	104
26	33025000050000	BIRD BEAR ETAL F-22-22-1	Socony Vacuum	Dunn	22	149	91
27	33053021880000	BICENTENNIAL 44-13	St Mary	McKenzie	13	145	104
28	33007012100000	RAUSCH SHAPIRO-FEE 32-9	Summit	Billings	9	142	102
29	33053004770000	BBMU G-105	Texaco	McKenzie	5	151	95
30	33007009970000	FEDERAL 34-1	Union Texas	Billings	34	141	100

31	33053028580000	SAKAKAWEA FEDERAL 13X-35	XTO	McKenzie	35	154	95
32	33089005860000	KUBAS 11-13 TFH	Whiting	Stark	13	140	99
33	33007005220000	SCHWARTZ 2-21	Tom Brown, Inc.	Billings	2	137	100
34	33105008660000	SEATON 14-30	Brent Exploration, Inc.	Williams	30	155	98
35	33007004410000	HECKER 1 SWD	Missouri Basin Well Service, Inc.	Billings	2	143	99
36	33053014950000	ROY MOEN 1	Mobil Oil Corp.	McKenzie	35	150	100
37	33089002080000	MARTIN-KILZER 1	Energetics Operating	Stark	26	137	92
38	33089002490000	LAWRENCE 1	BMG, INC.	Stark	36	140	95
39	33053013590000	ROLFSON 1	Hilliard Oil and Gas, Inc.	McKenzie	4	150	98
40	33025003760000	MURPHY CREEK STATE 1	Davis Oil Co.	Dunn	16	144	96
41	33053014290000	KNUTE HAGEN 1	W. H. Hunt Trust Estate	McKenzie	12	148	99
42	25083217230000	AMESTOY 1	Intermountain	Richland	6	25	54
43	25083211560000	SIGURD RUDIE 1	Slawson	Richland	7	24	59
44	25091212710000	VERA JENSEN 25-1	Citation Oil & Gas	Sheridan	25	34	56