EVALUATION OF X-RAY DIFFRACTION OF BIT CUTTINGS AS A PROXY FOR CORE DATA IN DETERMINING BULK MINERALOGY AND CLAY SPECIES, BAKKEN FORMATION, WILLISTON BASIN

By

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CHAPTER I

INTRODUCTION

Problem Statement

The Williston Basin, which is located primarily in North Dakota and Eastern Montana (Figure 1), has been an important source of domestic oil production since the advent of horizontal drilling. This increase in oil production is mainly from an Upper Devonian/Lower Mississippian unit known as the Bakken Formation. The Bakken Formation consists of a black upper shale, a sandy/silty middle member sometimes referred in the field as the middle dolomite, and a lower black shale. The United States Geological Survey (USGS) recently reported that the Bakken Formation contains 4.3 billion barrels of oil equivalent in reserves (Pollastro, 2008). Continued drilling in the Bakken Formation is occurring in both North Dakota and Montana despite the collapse of oil and gas prices in the fall of 2008. As exploration companies try to adjust to falling profits, drilling costs have yet to reflect the adjustment in the market. As such, expenditures in drilling programs, such as coring potentially productive intervals are some of the “science projects” that some smaller companies are eliminating from their drilling budgets. Although an integral part of all drilling activities, coring is a source of information many companies are willing to forego to obtain important rock data, such as lithotypes and clay mineralogy. The principal question addressed in this study concerns the applicability of x-ray diffractometry to determine bulk rock mineralogy and clay species in the absence of core. This problem is complicated by the use of modern bits, which essentially powder the cuttings and thereby reduce the size of rock fragments available for analysis.

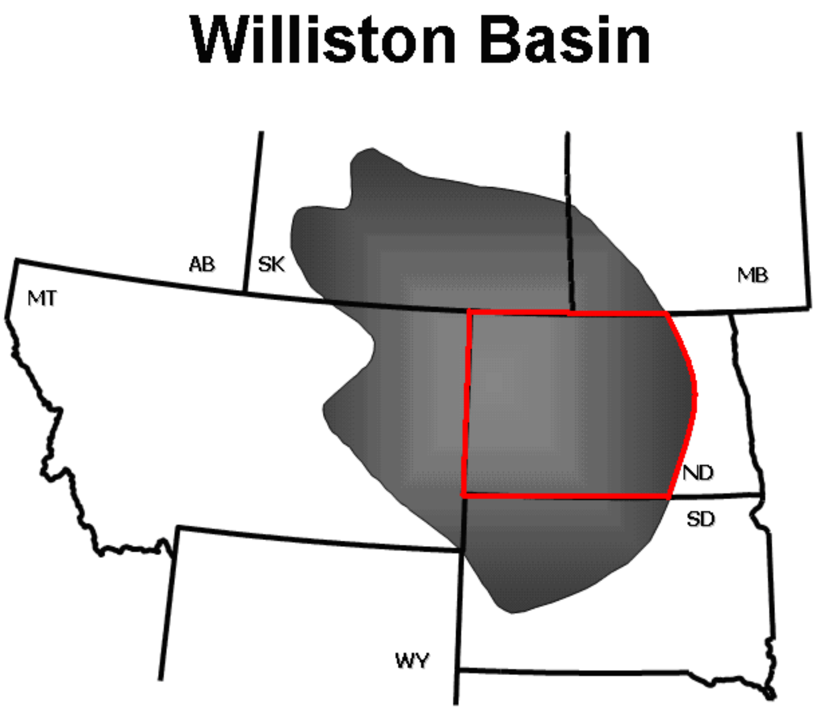

Figure 1. Map of the Williston Basin with study area outlined in red (Department of Energy, 2009)

For this study, samples of bit cuttings and thin sections from core obtained from the North Dakota Geological Survey were analyzed and the results compared to determine if cuttings are a viable substitute for core. The study area (Figure 2) from which the samples were obtained is located in western North Dakota.

Purpose and Objectives

In order to mineralogically characterize the Bakken Formation and evaluate the effectiveness of substituting bit cuttings for core samples in determining bulk mineralogy, the following objectives were formulated.

1. Establish a stratigraphic framework for the Bakken Formation using the accepted industry convention (Pitman et al., 2001).
2. Describe each member on the basis of lithologic and petrophysical properties using thin section petrography and wireline logs.
3. Analyze bit cuttings of the Bakken Formation using powder x-ray diffraction to establish bulk and clay mineralogy.
4. Compare the results of the petrographic and x-ray analyses to x-ray spectra of core samples to determine if bit cuttings can serve as an adequate proxy for core samples.

This study should provide sufficient data to determine if bit cuttings are capable of serving as a substitute for core. This comparison is particularly significant in a play like the Bakken Formation as most wells in the oil-producing zone are horizontal and the opportunity for coring is rare.

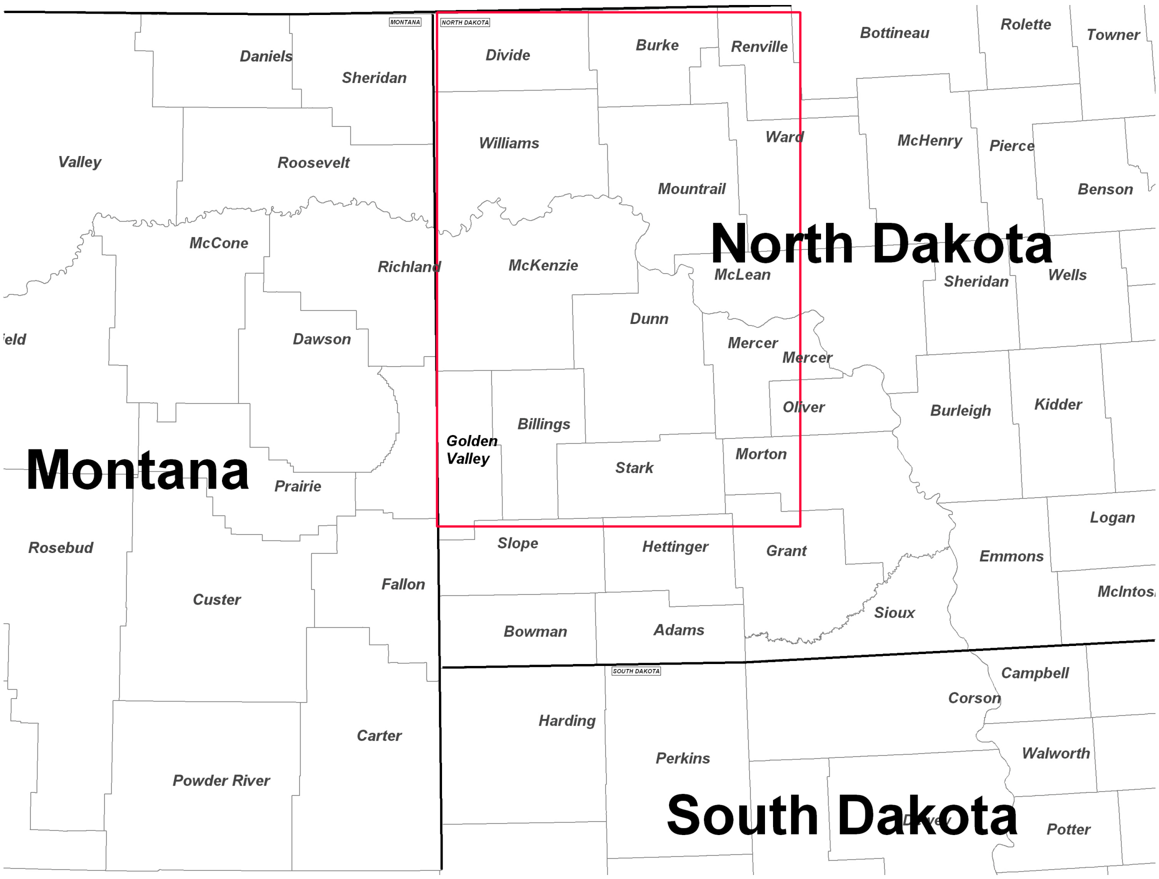

Figure 2. Detail map of study area outlined in western North Dakota.

Location of Study

In order to capitalize on the most recently available and abundant geologic and engineering information, the chosen study area consists of the majority of 14 counties in North Dakota: Divide, Burke, Renville, Williams, Mountrail, Ward, McKenzie, Dunn, McLean, Mercer, Golden Valley, Billings, Stark and Morton. The study area can be defined by governmental townships and includes: T.152N., R.104W. to T.152N., R.89W. and T.164N., R.95W. to T.140N., 95W. The area including these townships is known by the petroleum industry as the Norse, Galaxy, Rocket and Normandy fields. The study location was chosen to include the Nesson Anticline (Figure 3) and also due to this area being the center of drilling activity to produce oil and gas from the Bakken Formation.

Overview of Bakken Play

The Bakken Formation is a siliciclastic unit that consists of three members: upper and lower organic-rich shales and a middle calcareous sandstone and siltstone. Production from the middle member comes from areas where there is a significant amount of total organic carbon (TOC%) in the bounding upper and lower shales and an adequate thermal maturity to generate hydrocarbons from these known source rocks (LeFever et al., 1991). The history of oil production from the Bakken Formation began with reported occurrences (“shows”) of oil in vertical wellbores, and subsequent oil and gas production occurred in three distinct cycles. The first cycle began with the completion of the Bakken Formation in an oil well in 1963. This well produced only 774 barrels of oil (bbls) before abandonment. This initial well was considered to be uneconomic because of its low volume production and the low commodity prices of the time ($2/bbl), which

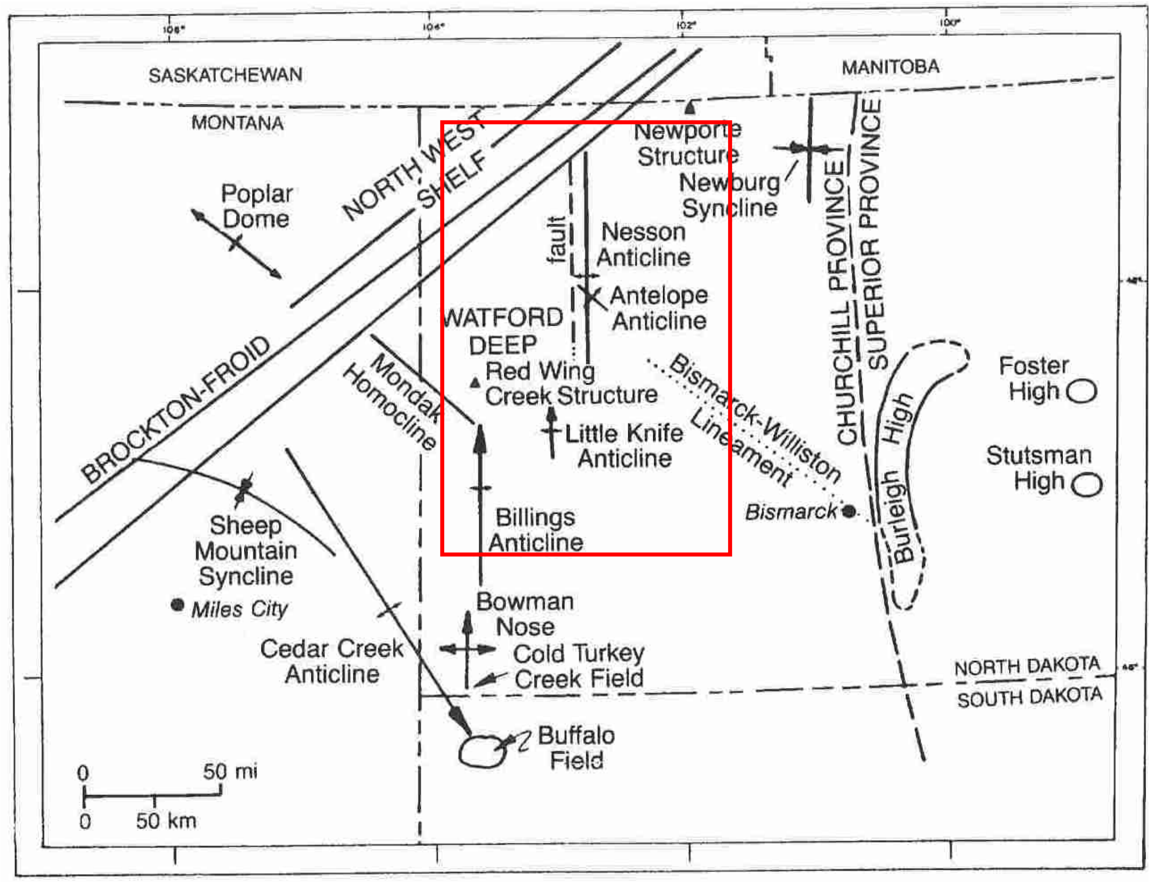

Figure 3. Location map of the Williston Basin showing major structural features in relation to the study area in red (after Gerhard et al., 1991).

discouraged exploration for oil and gas production from the Bakken Formation until the late 1970’s when prices had risen substantially to drive the 2nd cycle. The subsequent depression in price and downcycle of the 1980-90 decade further discouraged drilling for Bakken Formation oil and gas production. This downturn lasted until the early 1990’s, when the combination of horizontal drilling and higher oil and gas prices launched the present third cycle of drilling and production.

Stratigraphy

The Bakken Formation is a Devonian to Mississippian age siliciclastic unit that contains three informal members. In the study area, the Bakken Formation rests unconformably on the underlying Three Forks Formation (Figure 4). The Lodgepole Formation of the Madison Group overlies the Bakken Formation. Widespread flooding during the upper Devonian was responsible for deposition of the Lower Bakken sediments, which accumulated on the erosional surface of the Three Forks Formation. The end of the Devonian is marked by an unconformity between the Devonian and Mississippian, as uplift and erosion exposed the Devonian strata along the basin flanks, while deposition in deeper parts of the basin continued (Pitman et al., 2001). It was during this time that the orientation of the seaway that occupied the study area shifted to the north due to the tectonic activity along the Transcontinental Arch (Pitman et al., 2001). Basinal Devonian-Mississippian sediments represent repeated periods of transgression and regression and a subsequent reorientation of the basin during Mississippian time shifted the depocenter of the middle and upper Bakken westward to the central Montana trough (Pitman et al., 2001). The boundary between the Devonian and Mississippian is placed within the Middle Bakken interval, whereas the Upper Bakken shale is considered to be exclusively Mississippian (Pitman et al., 2001).

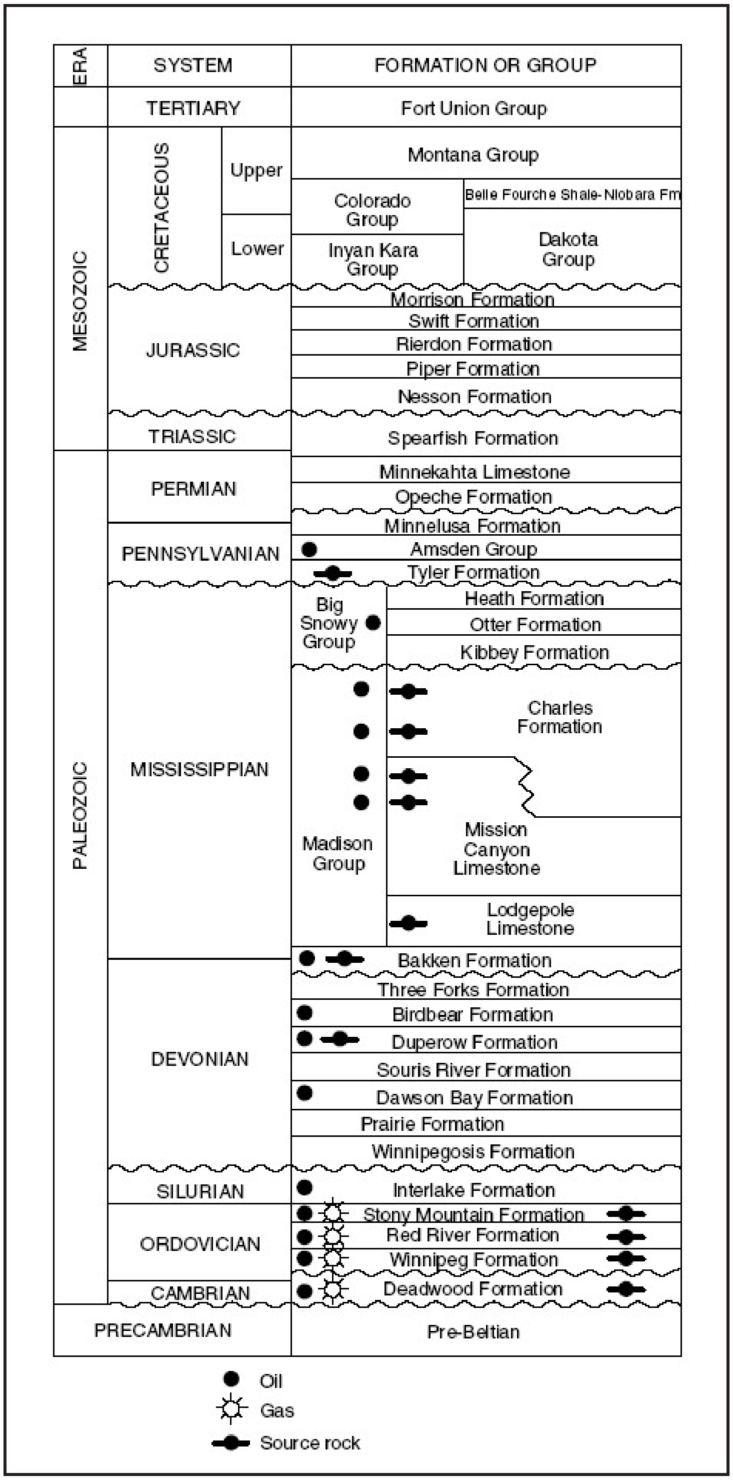

Figure 4. Subsurface stratigraphic nomenclature of the Williston Basin (Moss, 2009).

CHAPTER II

REVIEW OF LITERATURE

The Bakken Formation was studied initially as a potential source rock for oil and gas that accumulated in older carbonate units. In the last ten to fifteen years interest in the Bakken Formation increased as it became a target for horizontal drilling techniques, which made oil and gas production economically feasible.

According to Pitman, et al. (2001) the Bakken Formation is a closed, low permeability petroleum system that generated approximately 200 to 400 billion barrels of oil in place. Most of this oil was expelled into very fine grained sandstones and siltstones within the middle member, which is bounded by lower and upper organic-rich shales that are considered both sources and seals (Pitman et al., 2001).

The general tectonic setting of the region was addressed by LeFever, et al. (1991), who described the geologic setting of the Williston Basin and discussed the evolution of the basin (and other major structural features, including the Nesson, Cedar Creek and Billings Anticlines). The impact of structure on oil and gas production was established by Shurr (1995), who related horizontal production from the Bakken Formation in southwestern North to lineament block tectonics.

Meissner (1978) established a relationship between the petrophysical characteristics of the Upper and Lower Bakken shales and thermal maturity. Shales high in total organic carbon (TOC) and located towards the center of the basin are thermally mature and register higher values of resistivity than shales in areas where the shales are less thermally mature and not capable of producing hydrocarbons (Meissner, 1978).

Smith and Bustin (1995) described the sedimentology of the Bakken Formation as a set of thinly laminated, fine grained, organic rich mudstones in the upper and lower shales with a gray mudstone middle member that contains ichnofacies including populations of *nerites, skolithos* and *cruziana*. These ichnofacies were used to interpret the cyclical depositional processes a deeper offshore setting for the lower Bakken, shallower shoreface for the middle Bakken and offshore setting for the upper Bakken.

The bulk mineralogy of dark shales in other basins has been examined to determine the impact of mineral composition of engineering issues. Matthews et al. (2007) discussed the mineralogy of shales in the Fort Worth Basin and West Texas Basin and the effect of shale mineralogy on hydraulic fracturing and the success of oil and gas well completions in these shales. Matthews et al. (2007) stated that the shales of the Barnett Shale contain approximately equal parts of silica, clay and carbonate material and that this composition directly relates to the brittle nature and the enhanced response to hydraulic fracturing. When shales in the Fort Worth Basin were compared to those in West Texas, the percentages of clay and silica were found to be closer to 50:50 and that associated carbonate material was minimal to absent. The absence of silica or carbonate material creates a more elastic and less brittle reservoir rock that is resistant to hydraulic fracturing (Matthews et al., 2007).

Xu and Pruess (2004) conducted a study on the effect of swelling clays on fracture stimulation. They tested many different applications for using geothermal fluid mixed with a variety of fresh water and chemical treatments to test the extent of mineral scaling and clay swelling on well performance. Results indicated that increased amounts of smectite in shales led to an increase in swelling when exposed to aqueous solutions of low ionic strength and that cations bond with water molecules and the molecular thickness increases as bulk density decreases (Xu and Pruess, 2004).

Depositional History

There are many interpretations as to the paleoenvironmental settings under which Bakken sediments were deposited (Pitman et al., 2001; Sandberg, 1982; McCabe, 1959; Christopher, 1961; Smith 1996). Sandberg (1982) proposed a model based on the eustatic sea-level changes that indicated that the deposition of Bakken sediments was initiated by a marine transgression that developed due to the Antler and Acadian orogenic events. This interpretation is based on evidence in the sharp contact between the Lower Bakken and Three Forks Formation. This eustatic sea-level model was expanded by Smith (1996) who demonstrated that the Saskatchewan portion of the Williston basin formed in part due to the dissolution of the Devonian Prairie Salt and erosion of the Three Forks Formation.

The black shales of the upper and lower members of the Bakken Formation are interpreted to represent deposition during a widespread rise in sea level (Pitman et al., 2001). Webster (1982) detailed how the upper and lower shales represent deposition in a stratified hydrologic regime with anaerobic bottom-water conditions as evidenced by the presence high organic-matter content, pyrite and the lack of benthic fauna.

LeFever et al. (1991) proposed that sediments of the middle member were deposited in a coastal regime and displays a wider variety of facies, varying depositional conditions and ichnofossils. In the central basin region, the middle member contains argillaceous, greenish-gray, highly fossiliferous, pyritic siltstones in the lower part, suggesting that it was deposited in a shallow marine environment. The shoreline prograded basinward as evidenced by highly burrowed, interbedded shale and sandstone. The presence of *cruziana* suggests a lower shoreface deposition. The middle part of the member contains *skolithos* and begins to grade into massive and tabular crossbedded sandstones that produces hydrocarbons in the Canadian portion of the basin (LeFever et al, 1991). Finally the upper part of the middle member was determined to be deposited in a marine environment with strong current action based on the evidence of disarticulated brachiopods that occur in thin, well-sorted siltstone and sandstone beds (LeFever et al., 1991).

Structural Setting

Pitman et al. (2001) describes the structural setting of the Williston Basin as being an intracratonic, structural, and sedimentary feature that overlies the Superior craton, the Trans-Hudson orogenic belt, and the Wyoming craton in the United States and Canada. The basin occupies portions of North Dakota, South Dakota, Montana, Saskatchewan, and Manitoba (Pitman et al., 2001)

The Williston basin (Figures 5 and 6) is a structurally simple “bowl shaped” basin with the only major structural feature being the Nesson Anticline which trends northward from the Kildeer Mountains in Dunn County to the Canadian border. The anticline is associated with the western Nesson fault, which extends along the western flank of the fold (Pitman et al., 2001). Movement along this fault and the development of the Nesson

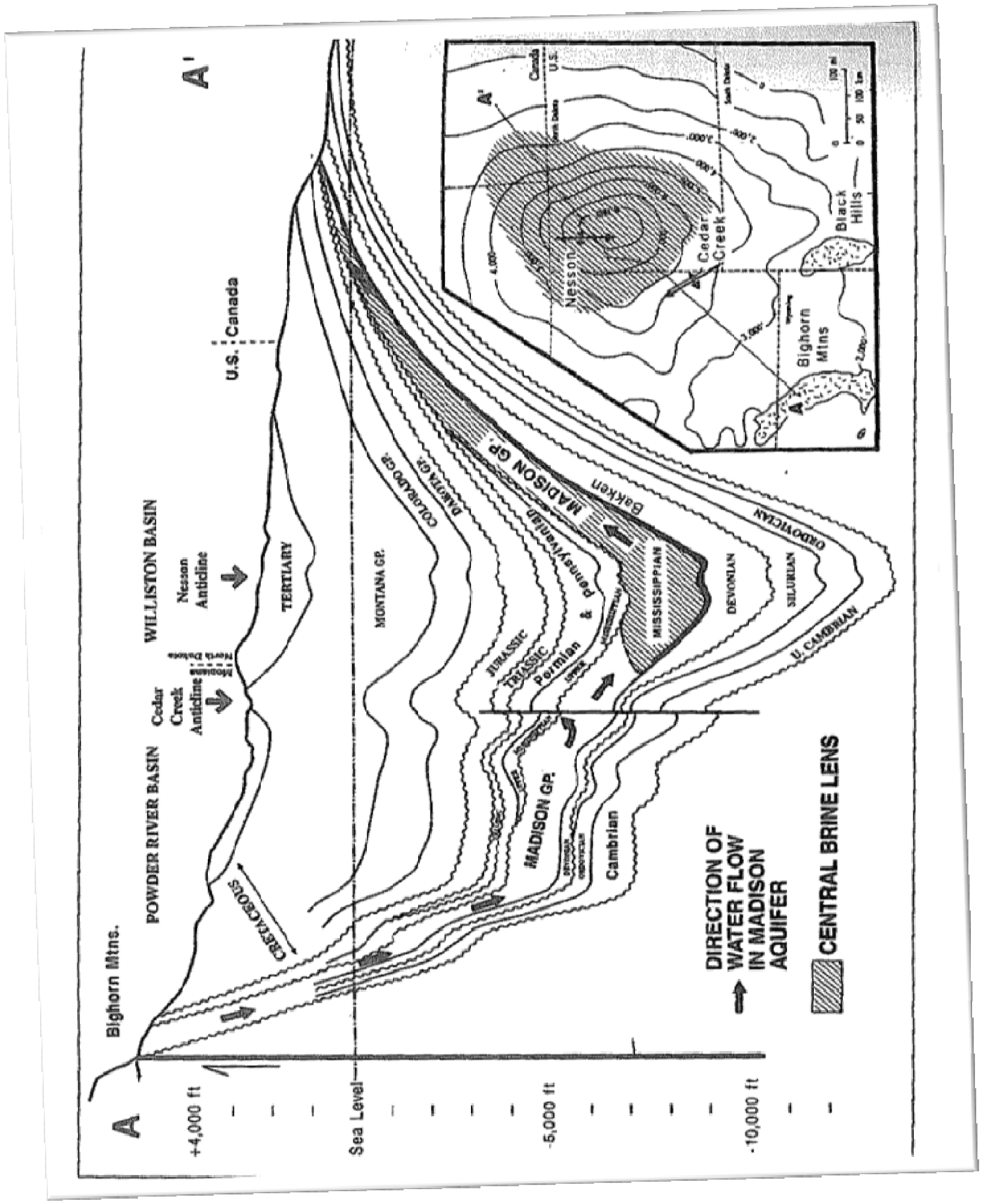

Figure 5. Cross section showing the stratigraphy and present structural configuration of the Williston Basin (highly vertically exagerated) (DeMis, 1994).

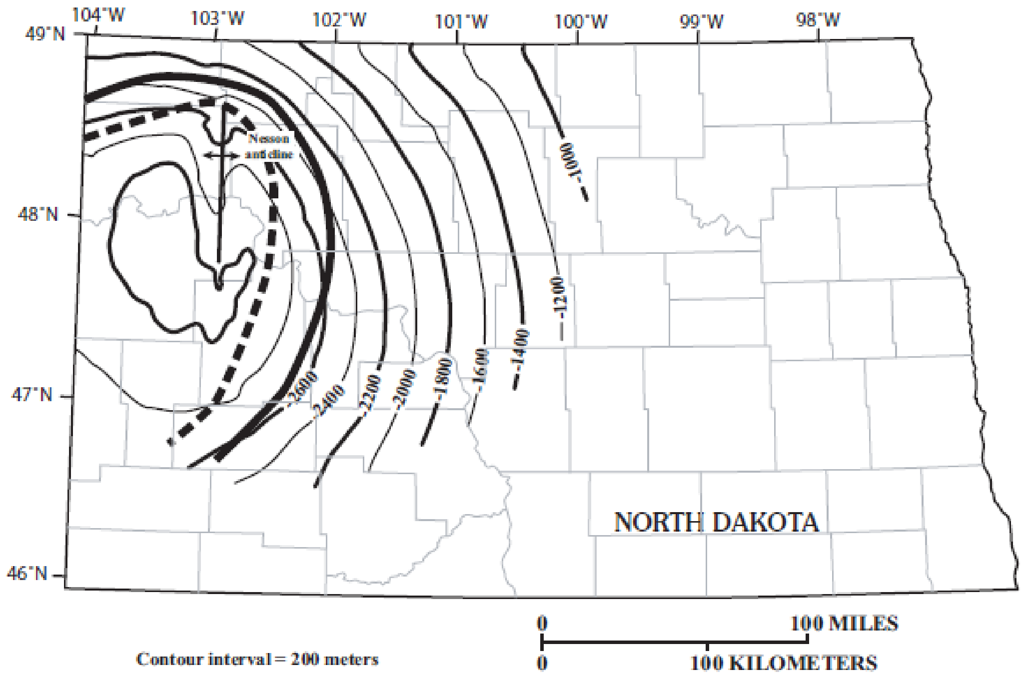

Figure 6. Structure map of the Bakken Formation (Pitman et al., 2001).

Anticline has been attributed to basement tectonics, which also caused the dissolution of the Prairie Salt Formation (LeFever 1987).

Reservoir Potential

Based on the previously referenced 4.3 billion barrels of oil equivalent reserves (Pollastro, 2008), the middle Bakken is an important contributor to domestic oil production. Pitman et al. (2001) provided a concise account of reservoir evolution. The thermal conditions, maturation levels and the high concentrations of organic matter in the upper and lower Bakken shales are consistent with the development of organic acids during the onset of hydrocarbon production in conjunction with maximum burial. These acids explain the dissolution of carbonate cement in the rock matrix and adjacent hydraulic fractures. While porosities and permeabilites remain low (5% and .04 millidarcies respectively) the middle Bakken maintains a high residual oil saturation and high incidence of hydraulically induced fractures (Pitman et al., 2001). Most oil produced from the Bakken comes from open, horizontal fractures and in secondary micro-porosity adjacent to fractures (Figure 7). Only small amounts of oil reside in matrix pores. These horizontal fractures form a pervasive network in deeply buried reservoir rocks and result in high residual oil saturations. The converse is true for portions of the Bakken that are shallower and contain little to no residual oil saturation. The fractures that hold the oil in the Bakken are the result of superlithostatic pressures that formed in response to increased fluid volumes from the generation of hydrocarbons (Pitman et al.,2001). Of note is the observation that if these fractures are mineralized, they are incapable of transmitting fluids. On the other hand, the porous and permeable open horizontal fractures laterally focus hydrocarbons and enhance the production of the reservoir (Figure 8).

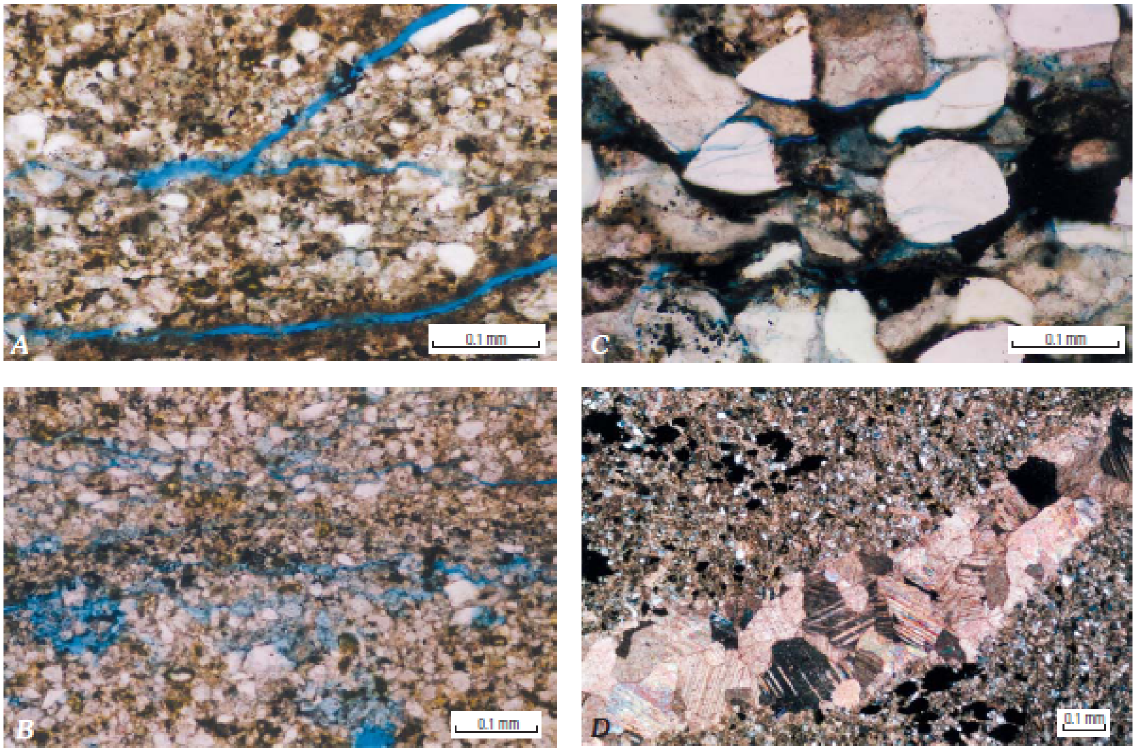

Figure 7. Thin section photomicrographs of sandstones depicting *A*, open (noncemented), discontinuous fractures parallel to bedding. Such fractures are abundant and form a pervasive network in sandstones adjacent to mature shales, NDGS 607, 3,223 m; *B*, secondary porosity associated with horizontal fracture swarms, NDGS 9707, 3,184 m; *C*, microscopic fractures cross-cutting framework quartz grains. Note bitumen filling secondary intergranular pores, NDGS 105, 2,312 m, and *D*, calcite cemented vertical fracture, NDGD 9707, 3,186 m. From Pitman et al., 2001

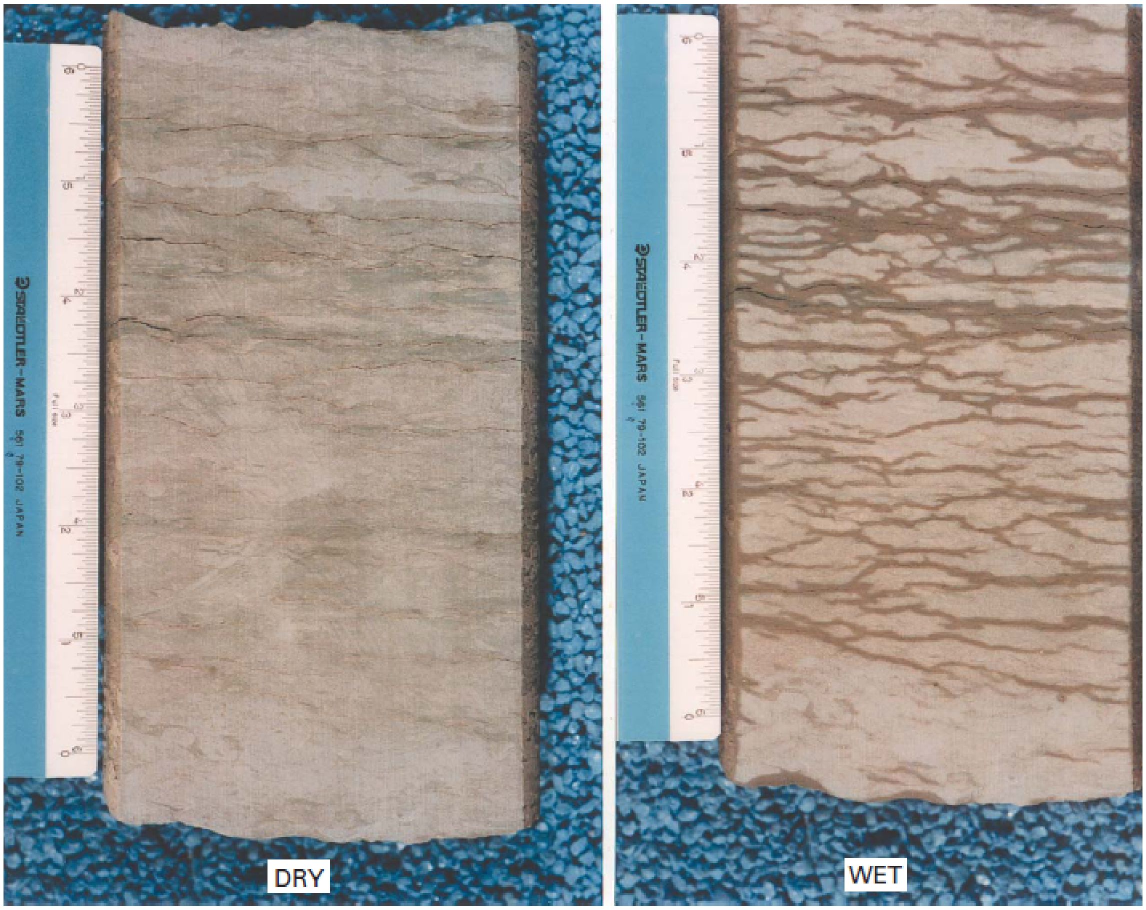

Figure 8. Slabbed sandstone displaying reticulated fracture network on wet surface. Note that the permeable nature and distribution of fractures are not apparent when surface is dry. NDGS 8902, 3,186 m. From Pitman et al., 2001

CHAPTER III

METHODOLOGY

This study is designed to examine several types of data that can be utilized to characterize and analyze bulk mineralogy of the Bakken Formation of the Williston Basin. Before characterization is described, the stratigraphic and structural attitude of the basin must be presented to ensure that the subsurface stratigraphy is established with confidence and that correlations across the basin are not compromised by deformation or unconformities.

The first feature of the Bakken Formation examined was thickness. An isopoach map was constructed that shows the extent of the Bakken Formation across the Williston Basin (Figure 9). Features of note are the thicknesses of the Bakken to the east of the Nesson Anticline, which is interpreted to have been an active positive feature during Bakken deposition. This map is noteworthy for the gradual thickening of the Bakken and its apparent uniform thickness and continuity across the study area.

The second stage of the Bakken pre-characterization study involved the construction of cross sections using wireline logs (Figure 10) to establish an electrostratigraphic framework to which cores and cuttings could be correlated. Based on this framework and the distinct wireline log curves exhibited therein, the correlation of

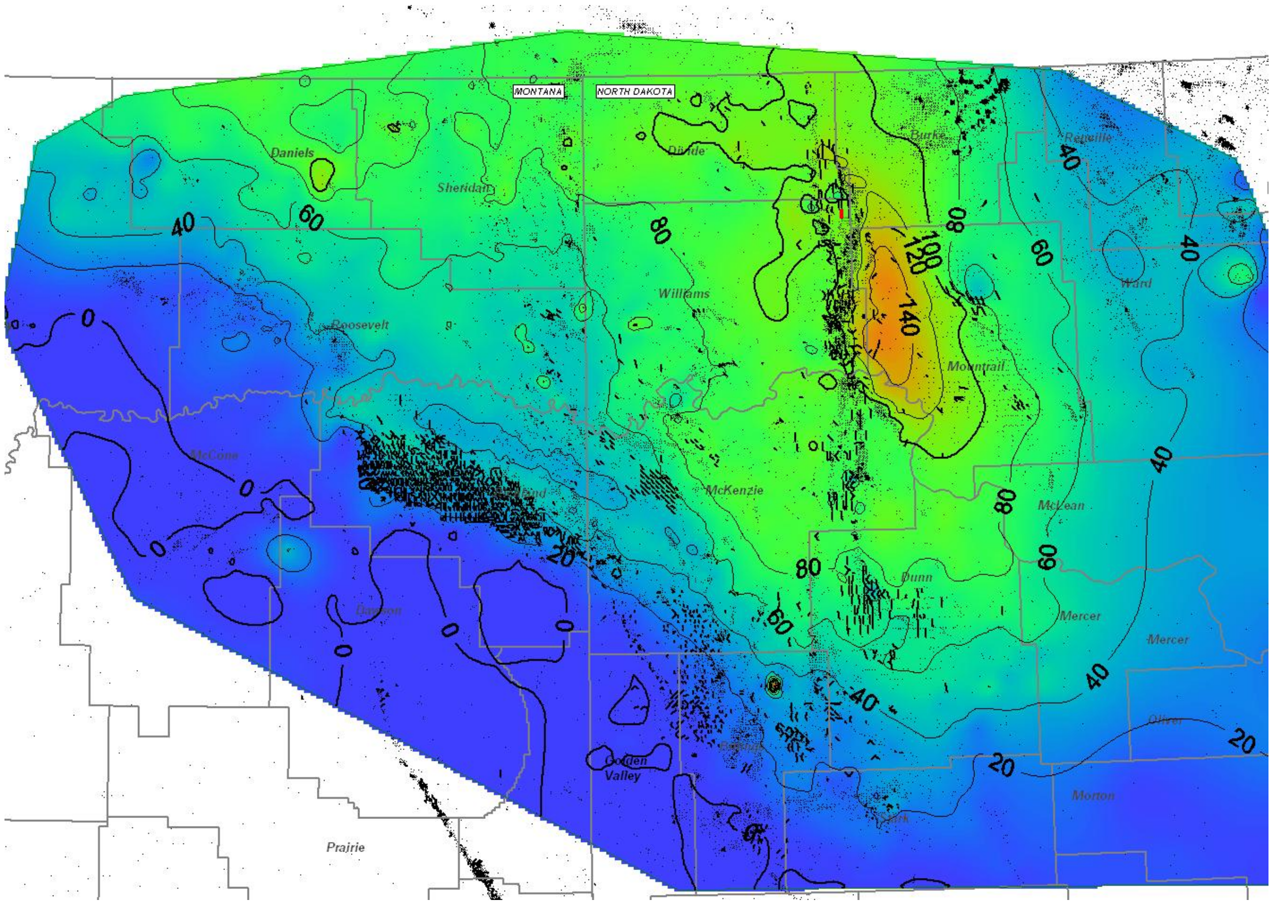

Figure 9. Isopach of the Bakken Formation showing the gradual thinning towards the margins of the basin. The thicker north to south trend isolated immediately east of the Nesson Anticline.

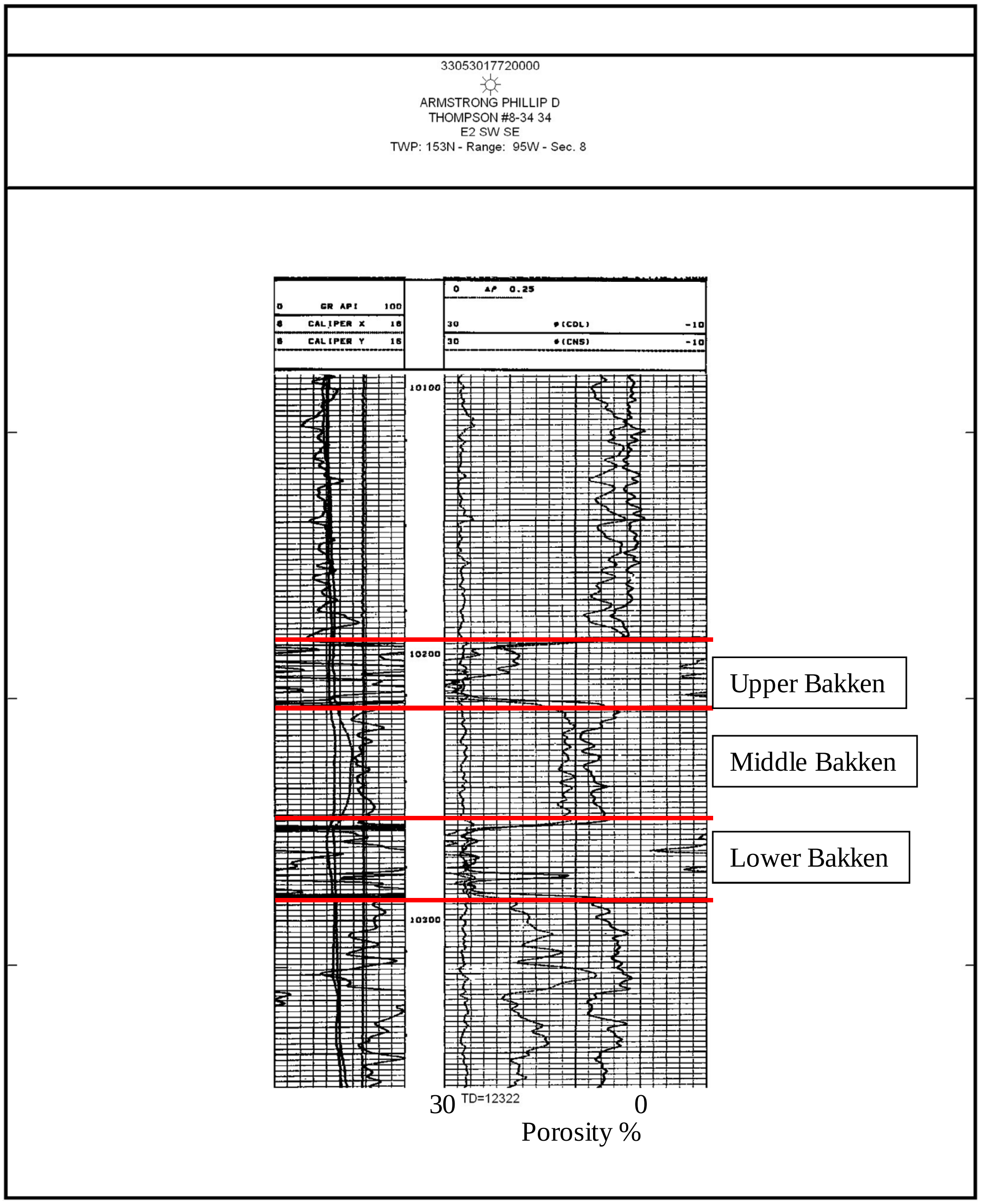

Figure 10. Example “type log” showing the characteristic log signature across the Bakken Formation interval. The upper and lower members exhibit off scale gamma-ray values and high neutron/density porosity.

the upper, middle and lower Bakken member across the basin was achieved with confidence.

Gamma-ray Signature

The three separate units within the Bakken are easily identifiable by their gamma-ray log signature and thus correlative across the basin. The gamma-ray evidence for subdividing the Bakken Formation is distinctive, as seen in the “Typelog” (Figure 10). The petrophysical characteristics, or log signature, for the Bakken Formation is immediately recognizable based on the intensity of the gamma-ray curve, which responds to natural radioactivity in the rock. The gamma-ray curve across the Bakken Formation gives higher readings (>150 API units) in the two “hot” shales that represent the upper and lower members and lower or “cooler” readings in the cleaner middle member that has lower gamma-ray values (90-120 API units). These log signatures are consistent and can be traced with ease across the basin up to and including the flanks, where the formation is onlapping and pinching out against the unconformity on top of the Three Forks Formation.

The upper Bakken, as stated above, is a “hot” high gamma-ray reading shale and generally has gamma-ray readings in excess of 300 API units, or the limits of the more common 300 count scale which causes the gamma-ray curve to wrap or be traced over itself in log track one. The Bakken Formation is separated from the overlying Lodgepole Formation by a thin hot shale, which is called the false Bakken (Figure 10). The upper Bakken exhibits a sharp contact with the underlying middle Bakken. The high gamma-ray values for the upper Bakken are attributed to the presence of radioactive material in the shale that became incorporated at the time of deposition.

The Middle Bakken is a zone with a reduced gamma-ray value that is positioned stratigraphically between the two shales. The middle member is richer in silt and sand and can be dolomitized (Pitman et al., 2001). The decrease in clay content and variable lithology results in the gamma signature varying internally from as low as 40 API counts to as high as 90 API counts. The variance in gamma-ray values between the middle member and the adjacent "hotter" shales make the gamma-ray signature useful diagnostic tools used in horizontal drilling to determine wellbore position within the Bakken Formation.

The lower Bakken shale is similar in its response to the gamma-ray tool as the upper Bakken. It has a sharp contact with the Middle Bakken and also with the underlying Three Forks Formation. The gamma-ray curve will record an average reading of over 300 API units, causing the curve to go off scale and wrap around on the standard gamma-ray log chart (Figure 10).

Resistivity Curve

Resistivity in the Bakken Formation displays a consistent pattern across the basin. However, a trend of decreasing resistivity with shallowing is evident. Where the Bakken is thermally mature, the resistivity will register up to 1000 ohm-m (Meissner, 1978). Conversely, where these Bakken Formation shales are thermally immature the resistivity curve will read lower and give values close to those of the middle Bakken, which makes correlation difficult when a gamma-ray curve is not available. The resistivity curve is considered important to Bakken Formation oil and gas development because it is considered an indicator of areas where thermal maturity is sufficient to produce oil and gas (Meissner, 1978).

Thickness of the Bakken Formation

The Williston basin has been called the structurally simplest basin in the world (Price, 1999). There are only two obvious faulted regions in the Williston Basin: the Nesson Anticline and the Brockton-Froid Fault Zone. As a result of this overall large scale undeformed nature, the thickness of the Bakken Formation does not change drastically or quickly from the center of the basin to the outer flanks, until it starts to pinch out along those edges. This “pancake” style of deposition is evident when cross section log correlations are tied back to structure and isopach (thickness) maps. As shown by the Bakken Formation Isopach map (Figure 9), with the only exception to the very gradual change in thickness occurs on the eastern edge of the Nesson Anticline, and in general, the Bakken Formation is relatively laterally continuous and uniform thickness. The total thickness of the Bakken Formation reaches a maximum of 149 ft near the east edge of the Nesson Anticline and a minimum of 21 feet in the mapped areas as it begins to pinch out toward the edge of the basin.

The upper Bakken shale changes thickness similar to the total formation in that it has a maximum thickness of over 30ft to the east of the Nesson Anticline and ultimately is truncated along the edge of the basin (Figure 11).

The middle Bakken also displays a uniform distribution throughout the Williston Basin and is thickest in the deepest part of the basin near the Nesson Anticline where it reaches a thickness of 90ft. In the study area, the middle Bakken is a maximum of 60-70ft thick. Abrupt changes in the thickness of the middle Bakken are attributed mainly to the dissolution of the Prairie Salt Formation and ultimately the collapse of overlying strata (Pitman et al., 2001).

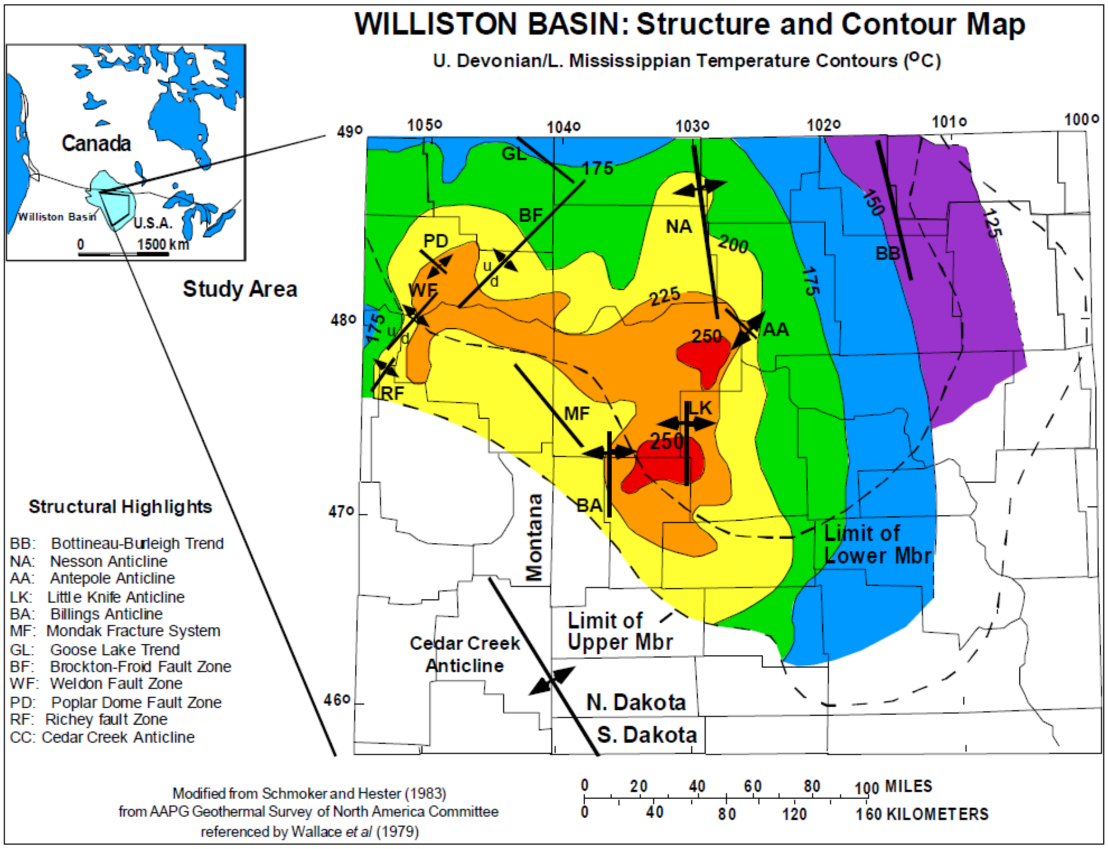

Figure 11. Structure map of the Bakken Formation. Note: the two dashed contours are the upper and lower Bakken pinchouts, colored countours represent temperature in °F. From Jarvie 2001.

The lower Bakken has a maximum thickness of approximately 30ft thick in the deeper part of the basin and thins to zero where it pinches out along the basin margin (Figure 11).

Once an understanding of the stratigraphic and structural framework for the Bakken Formation was established, sampling was conducted across the Bakken interval. Samples from each of the three members were included in the sample set. Wells were selected that met certain criteria: (1) vertical boreholes of recent vintage that were surveyed with a modern log suite, (2) depth of penetration that included the complete Bakken Formation section and (3) locations near the wells for which cores are available

After reviewing the list of potential candidate wells, bit cuttings were selected for four type wells. These wells were conventional vertical wells in which samples were collected at intervals of ten feet vertical depth (TVD). Vertical wells were chosen to ensure the most accurate sampling of the rock units in the stratigraphic column. Samples taken from horizontal wells would have introduced a higher amount of potential error concerning the true stratigraphic position. Bit cuttings are transported to the surface in the slurry of drilling mud and the fluid dynamics in horizontal wells are not as predictable as the dynamics for vertical holes. While the samples from horizontal wells are quite sufficient for geo-steering and determining host rock unit for drilling purposes, the position of origin for vertical well cuttings is much more predictable and appropriate for this study.

The bit cuttings used in the study samples were field separated, cleaned and dried. Their stratigraphic position was predicted and depth corrected, which allowed correlation to the wells electric logs. A split sample of each cutting was powdered in a mortar and pestle to ensure consistency of texture, random orientation of grains and ease of mounting in the sample trays. Each tray was appropriately marked denoting the well information, depth and stratigraphic unit. For example, the first well and the first sample interval was labeled Bakken 1.1, the second Bakken 1.2, etc. Each sample tray was placed into the sample holder of a Philips powder x-ray diffractometer and scanned across a 2θ range of 5 º to 50 º, using a Cu x-ray tube, 45kilovolts and 40miliamps. The x-ray instrument is housed in the Boone Pickens School of Geology at Oklahoma State University.

The resultant peaks, which reflect d-spacings in the crystal lattice of the minerals contained in the samples, were adjusted for background interference and analyzed using the Philips software suite. Once the major peaks were identified, a list of possible candidate compounds was generated from the software's database. Each major peak was identified, and a print out of the diffractogram was obtained for each sample. These diffractograms are presented in Appendix A.

An aliquot of each sample was analyzed four times. The first was a bulk sample to identify all mineral species within the survey range of 2θ 5º-50 º. Samples from the three Bakken Formation subunits, upper, middle and lower, were analyzed. Samples from the upper and lower Bakken Shales, were prepared for clay extraction following the procedure of Kittrick and Hope (1963). Approximately 20 grams of sample was placed in a 250ml centrifuge bottle and treated with 100ml +/- 5ml of sodium acetate solution (Kittrick and Hope, 1963). Samples were stirred and heated to accelerate the removal of carbonate and soluble salts. Each sample was washed multiple times with lab (de-ionized) water and centrifuged for five minutes at 1500 rpm to remove the sodium acetate solution and separate clays from silt and larger grains. The process of washing and centrifuging was repeated until clays remained suspended in the solution and could not be forced to the bottom of the tube by centrifuging.

Bulk Sample Run

The bulk samples returned high intensity silica and calcite peaks. The silica peaks in the upper and lower Bakken shales are pronounced, possibly due to the presence of detrital sand and silt. The high intensity of carbonate peaks reflect calcite.

The samples were then pared down to only the upper and lower Bakken shales. This was done to target the shales for the next step in the process: clay extraction. The samples were placed in a plastic test tube and mixed with sodium acetate solution. This solution contains 82g sodium acetate, glacial acetic acid and water that were mixed according to procedure outlined by Kittrick and Hope (1963). The glacial acid is used to dissolve carbonate material that may be present. All samples were then heated to 80° C to provide a catalyst to the reaction. Most samples effervesced vigorously as the acid was added. As a result, these samples were soaked overnight. The following day samples were stirred to suspend all particles and placed in a centrifuge. Samples were centrifuged at 1500 rpm for approximately five minutes. This process separated clays from the silt and sand-sized quartz material. Samples were decanted and treated again with sodium acetate solution to remove carbonate material. This process was repeated if carbonate effervesces were detected.

After the samples no longer showed any presence of carbonate minerals, i.e. they no longer effervesced, they were washed, stirred and centrifuged. This process was repeated until a clay suspension was present. A pipette was used to extract suspended clay in solution and small drops of water were applied slowly and neatly on two ceramic plates that were heated on a hot plate. This process was repeated until a visible smear accumulated on the test plates. One sample plate was identified as “normal” and a second as a “glycolated”. They were labeled as N and G respectively.

Extracted (Normal) Clay Analysis

The plates marked (N) were allowed to cool before being scanned. Each sample was scanned from 2θ 0° to 30° to determine the mineralogy of clays in the sample. The upper limit of scanning range was chosen to include the location of the 100% quartz peak, which serves as a point of reference on the diffractogram.

Glycolated Sample Analysis

The samples split for glycolation were placed in a glass jar containing ethyleneglycol for a 24 hour period. Glycolation facilitates the expansion of clays in the sample. The samples were scanned in the XRD and showed very little change from the extracted (Normal) diffractograms.

Heated Sample Analysis

Following X-ray analysis, the glycolated samples were placed in a furnace and heated to 500^{o} C for 30 minutes to destroy any expanded clay structure that may have formed as a result of glycolation. These samples were given an H designation, to indicate that they had been heated, and scanned one final time. No change in diffractogram patterns of the heated samples indicates that only illite is present and swelling clays such as smectite are not present in detectable amounts. The importance of this will be described in the following chapter.

Thin Section Analysis

Whole cores were not available for this study, but thin sections from selected existing cores were made available by the North Dakota Department of Natural Resources. Each thin section was photographed three times using an Olympus BX51 microscope with a digital camera attachment. Each image was covered by a grid of 100 squares to facilitate point counting. Magnification was kept constant at 50x to ensure that each thin section was somewhat randomly sampled over multiple regions to give the maximum amount of information and to prevent skewing the data. Appendix B contains the tabulated data for each thin section.

Each thin section was imaged in normal light and again in crosspolarized light to improve mineral identification and especially to differentiate between calcite and silica. Clay-rich regions in thin sections are represented by low light transmission in plane-polarized light.

CHAPTER IV

FINDINGS

This study generated over 75 x-ray diffractograms from the bulk, clay extraction, glycolated and heated sample analyses. A total of 42 thin sections were provided from the North Dakota Geological Survey, from which over 320 thin section photomicrographs were generated and point counted. These results comprise Appendix A.

Petrography

The analysis of 32 selected thin sections generated approximately 200 photos of the three subunits of the Bakken Formation. Each photo was point counted to identify constituents and calculate the percentages of clay, quartz and carbonate. Based on thin section analyses, four microfacies were established. The compositions of representative examples of these microfacies are shown in Table 1:

Thin Section #	Facies Identifier	Facies Description	%Clay	%Carbonate	%Silt
183	SC	Silty Claystone	58	27	15
134	CSC	Calcareous, silty claystone, carbonate matrix	11	27	62
145	SSC	Silty or sandy, carbonate	14	32	54
137	CSS	Calcareous Sandstone	28	41	31

Table 1. Representative composition of the 4 microfacies described from thin section analyses.

Facies 1 (Figure 12) (silty claystone) is dominant in the upper and lower members. In thin section it is a dark-colored rock containing abundant clay, with lesser amounts of detrital silt and carbonate, which occurs as distinct euhedral crystals that align along bedding planes. The example thin section comes from the Supron Energy Corp. Federal F-6, at a depth of 10,456ft.

The representative x-ray diffractogram of cuttings (Figure 12a) for this facies is from the Texaco Eisenlohr Trust #1-1 at a depth of approximately 10,760ft. Based on the correlation of wireline log to cutting sample depth, the x-rayed sample is of the upper member of the Bakken Formation and contains mostly quartz (Q), calcite (C), ankerite/dolomite (A) and illite (I). The representative peaks for these minerals are labeled in Figure 12.

The representative x-ray diffractograms (Figure 12b,c) of this facies are from cores of the upper and lower Bakken. The upper Bakken sample in the Amerada Petroleum Co, H.H. Shelvic Tr 1-1 in Section 35, T.150N., R.97W., at a depth of 10,950ft. The lower Bakken core sample is from the Northern Pump Co., Louis Peterson #1 in Section 7, T.161N., R.90W. The lower Bakken sample is from a depth of 7545ft. In both of these spectra, illite is a prominent peak at 2θ 8.8º. Other minerals include quartz and dolomite.

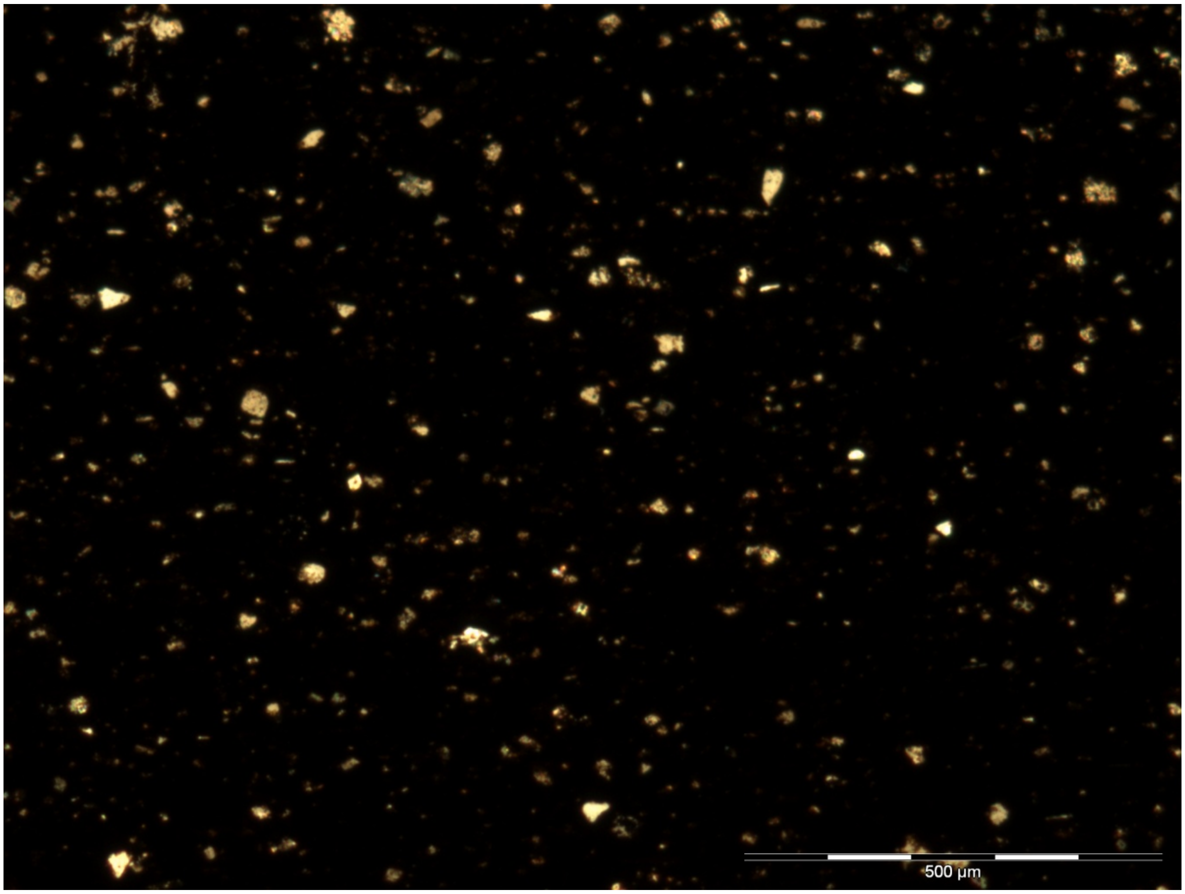

Figure 12. Photomicrograph of microfacies 1 of the Bakken Formation. This rock is clay-rich, silt deficient mudrock with minimal carbonate cement, silt grains occur scattered in clay matrix. Silt aligned along bedding planes is not evident in this image, but was observed in other samples. Bakken Formation upper member. Supron Energy Corp., Federal F-6, depth: 10,456ft. Cross-polarized light, CPL.

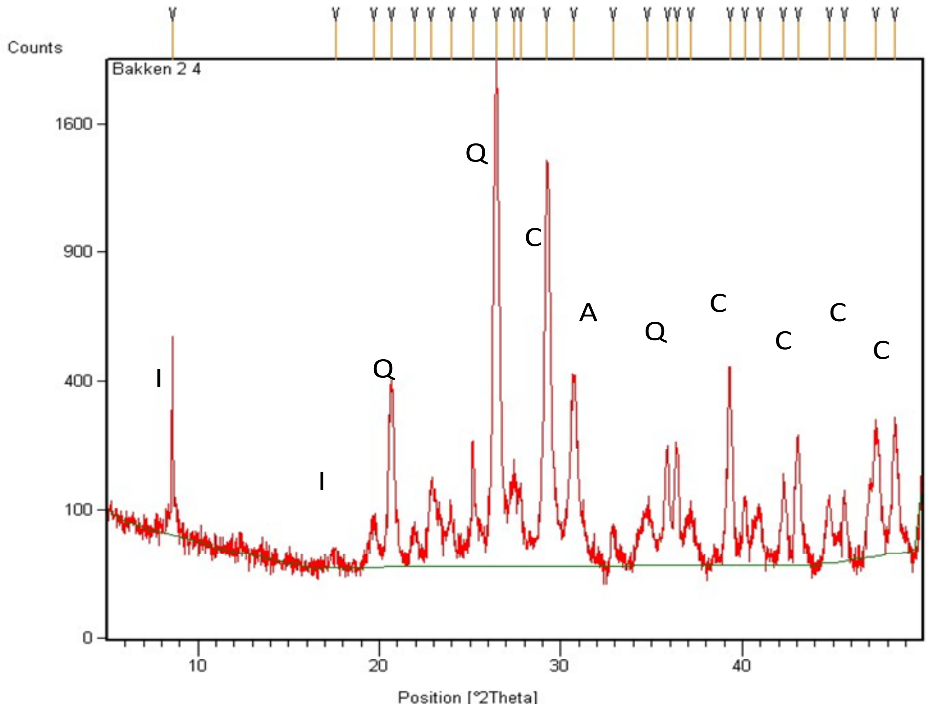

Figure 12a. Powder x-ray diffractogram of bit cuttings represents Microfacies 1 showing the presence of illite at 2θ 8.8º. The relative intensity of illite (I) relative to quartz (Q) and calcite (C) highlights the abundance of the clay. Bakken Formation upper member. Texaco, Eisenlohr trust #1-1. Depth: 10,760ft.

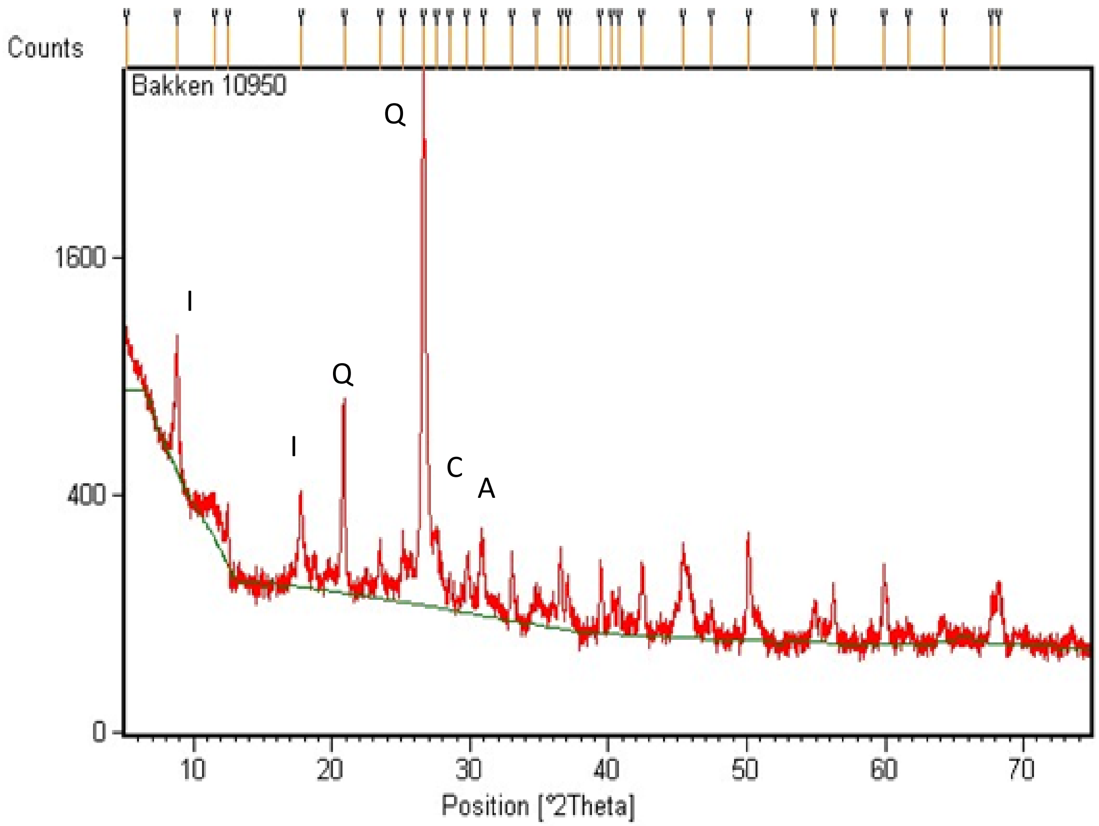

Figure 12b. Powdered x-ray diffractogram of a thin section from core of Microfacies 1 showing the presence of illite (I) in relative abundance to quartz (Q) and ankerite/dolomite (A). Bakken Formation upper member. Amerada Petroleum Co., H.H. Shelvic Tract 1-1. Depth: 10,950ft.

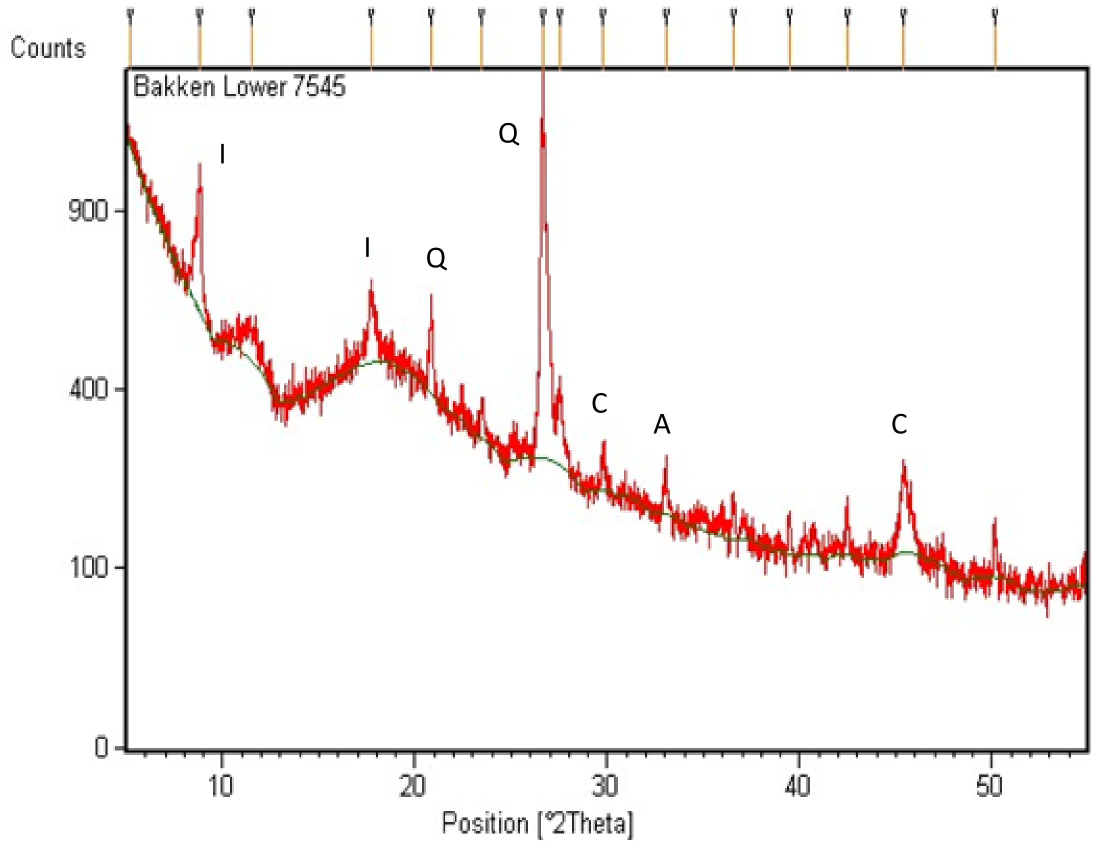

Figure 12 c. Powdered x-ray diffractogram of cored Microfaices 1 showing the presence of illite (I) in relative intensity to quartz (Q). Bakken Formation lower member. Northern Pump Co., Louis Peterson #1. Depth: 7545ft.

Facies 2 (Figure 13) (calcareous, silty claystone, carbonate matrix). In thin section this microfacies is a medium to dark colored rock rich in carbonate and clay. Silt is common, but somewhat minor compared to carbonate and clay. The example thin section is from the middle Bakken in the Clarion Resources, Nelson #1-29, from a depth of 7403ft.

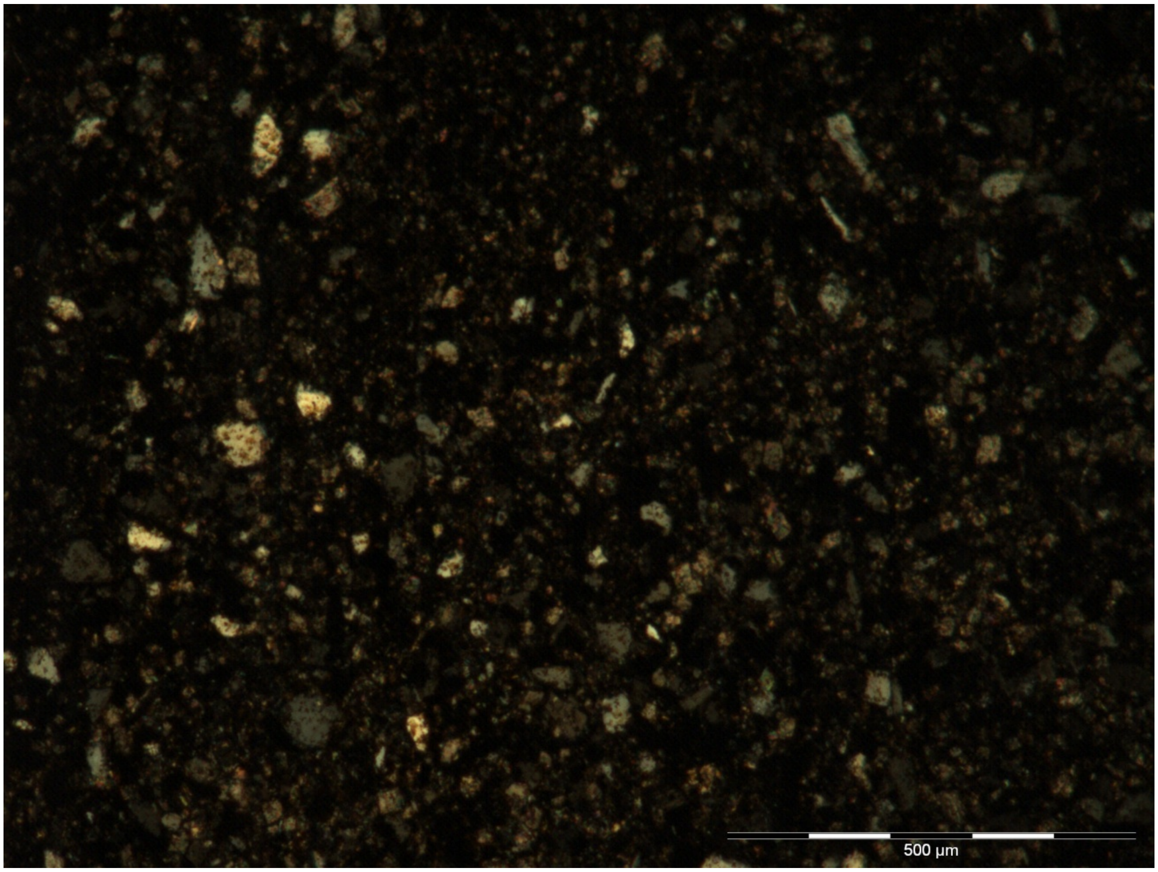

Figure 13. Photomicrograph of microfacies 2 consists of silty mudrock with a carbonate-rich matrix. Calcite and dolomite occur as distinct crystals and as fine-crystalline matrix. Bakken Formation, middle member. Clarion Resources, Nelson #1-29. Depth: 7403ft. CPL

The representative x-ray diffractogram of microfacies 2 (Figure 13a) is dominated by quartz (Q) and calcite (C), which suppress the peaks of minor minerals such as illite. The ankerite/dolomite (A) peak is generated by small (silt sized) rhombohedra. This diffractogram is from the Chesapeake Operating Osborne #1-1 at a depth of 8762ft. A representative core sample of microfacies 2 was not available for x-ray diffraction.

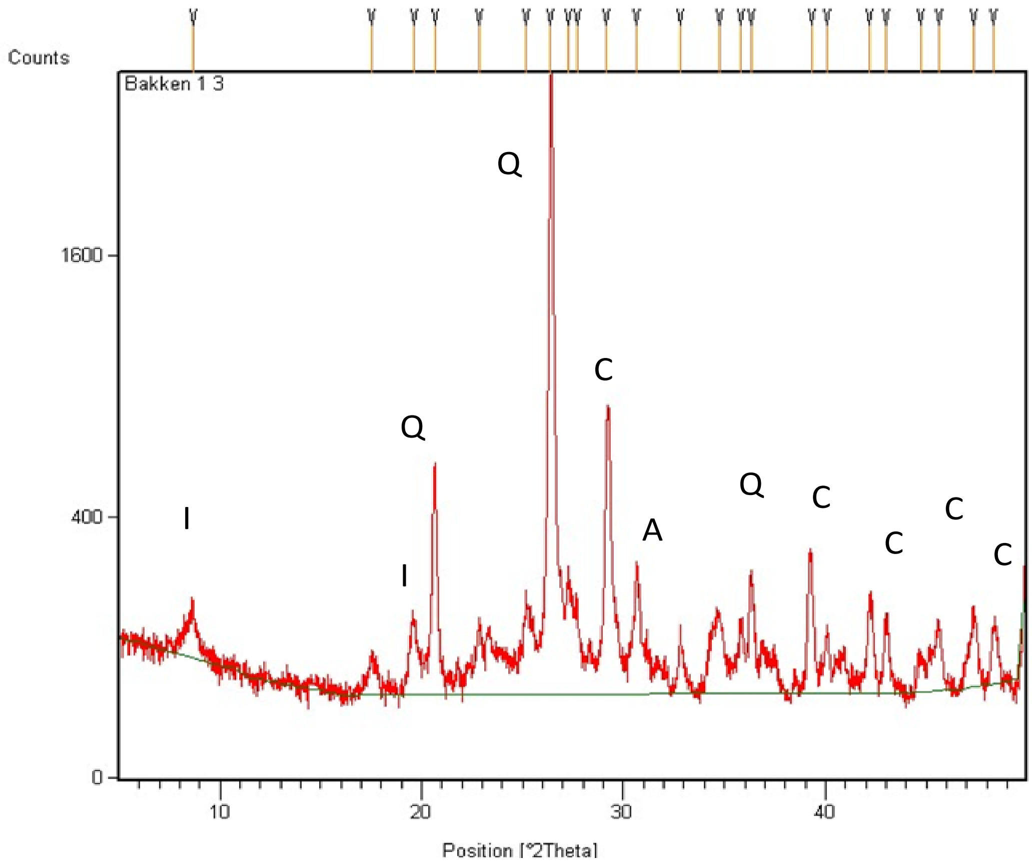

Figure 13a. Powder x-ray diffractogram of Microfacies 2. The quartz peak at 2θ 26.6º is most intense, reflecting the abundance of detrital silt in the samples. Bakken Formation, middle member. Amoco Production, Thompson C #1, 11,401ft.

Facies 3 (Figure 14) (silty or sandy carbonate) occurs in the middle Bakken. In thin section it is a light-colored rock containing abundant calcite and dolomite. Detrital sand and silt grains are common, but clay matrix is scarce. The example thin section is from the Clarion Resources, Nelson #1-29 at a depth of 7424ft.

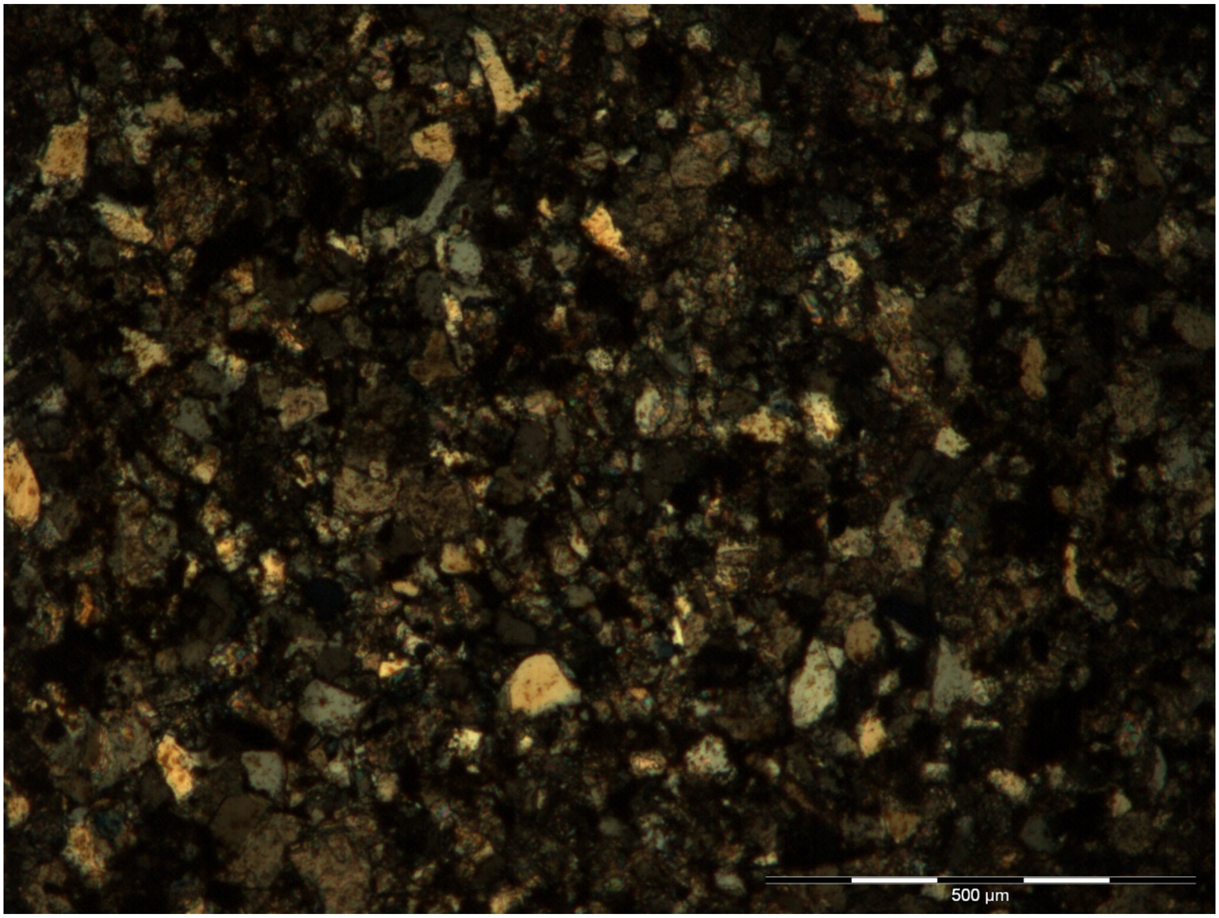

Figure 14. Photomicrograph of microfacies 3. This rock is carbonate-rich with fine crystalline matrix and dolomite rhombohedrons. Detrital quartz is angular to subrounded silt to very fine grained sand and gray colored in cross-polarized light. Bakken Formation, middle member. Clarion Resources, Nelson #1-29. Depth: 7424ft. CPL

The x-ray diffractogram for the cuttings of microfacies 3 (Figure 14a) comes from a depth of 8772ft in the Chesapeake Operating, Osborne #1-1, and shows the relative intensity of quartz (Q), calcite (C) and ankerite/dolomite (A). Illite is likely suppressed as evidenced by an absence of peaks at the positions marked by (I). The representative x-ray diffractogram of core is from the middle Bakken in the Northern Pump Co., L. Peterson #1 at a depth of 7531ft (Figure 14b). This sample is carbonate as evidenced by the dominance of calcite (C) over quartz (Q). Illite (I) is not apparent.

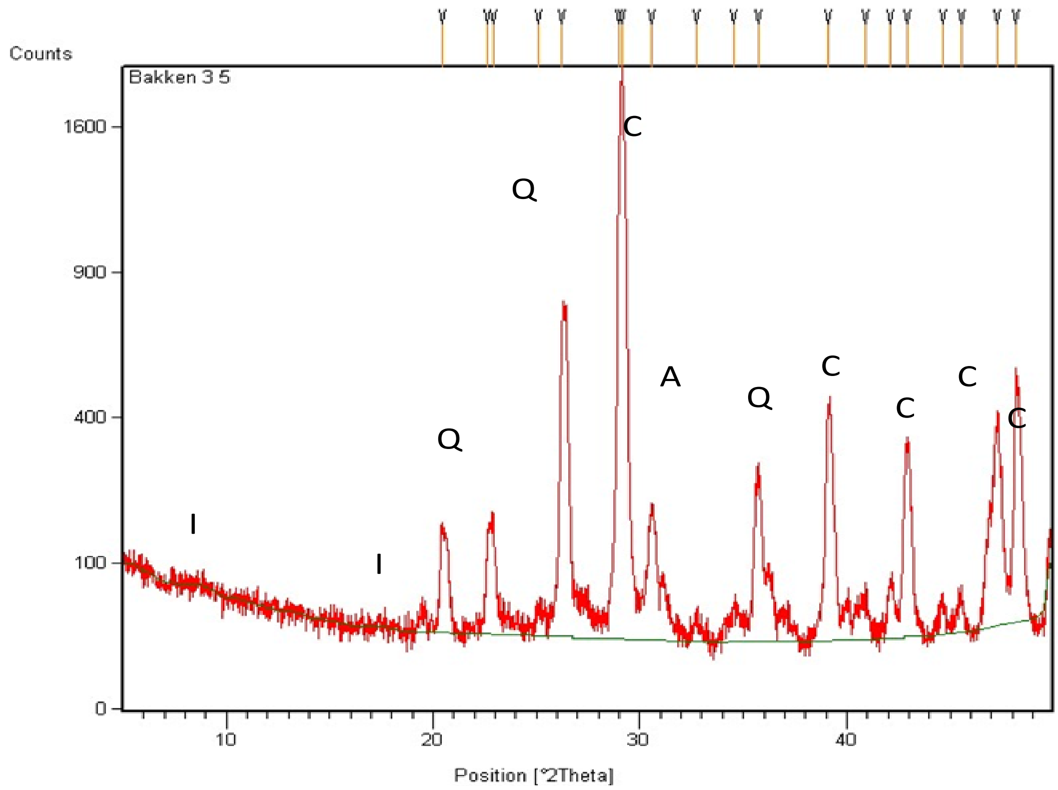

Figure 14a. Powdered x-ray diffractogram of microfacies 3 showing the presence of quartz (Q) dominated by calcite (C). Ankerite/dolomite (A) is a minor constituent. Bakken Formation, middle member. Chesapeake Operating, Osborne #1-1, 8762ft.

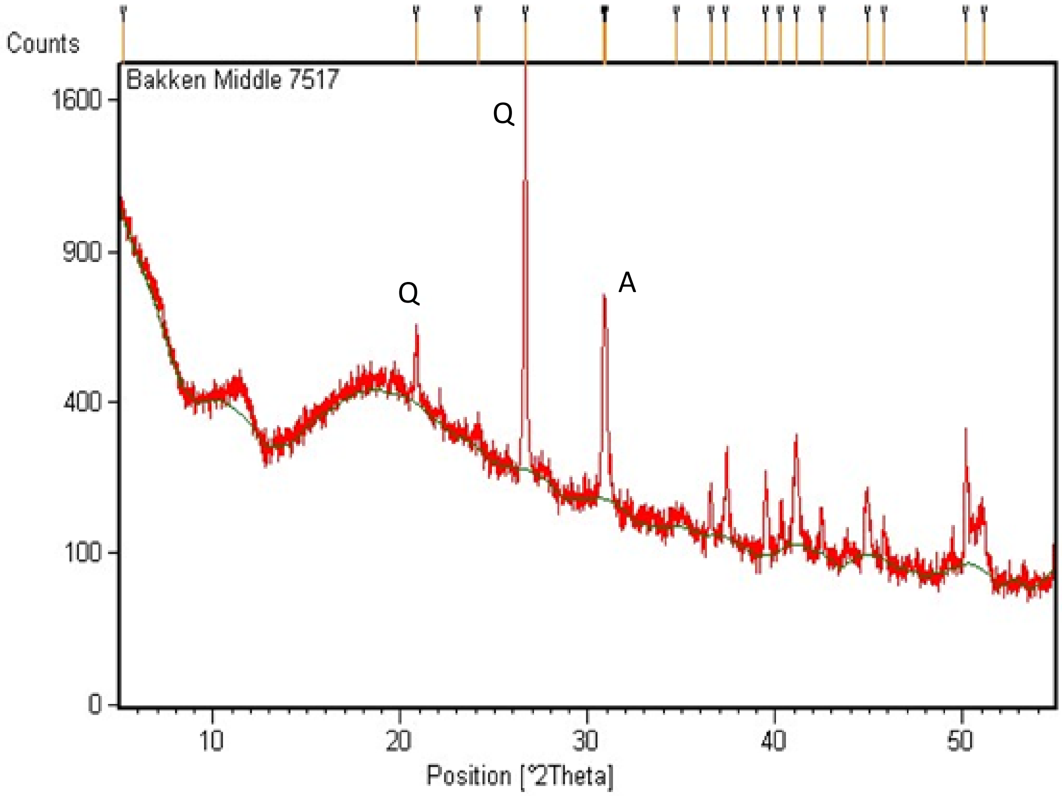

Figure 14b. Powdered x-ray diffractogram of cored Microfacies 3 showing the presence of quartz (Q) in relative intensity to ankerite/dolomite (A). Bakken Formation middle member. Northern Pump Co., Louis Peterson #1. Depth: 7517ft.

Facies 4 (Figure 15) (calcareous sandstone) occurs sparingly in the middle Bakken. In thin section it is light colored and consists of angular to subrounded quartz grains. Euhedral dolomite rhombohedra are evident in some samples and detrital clay is a minor component. The representative thin section is from the Clarion Resources, Nelson #1-29.

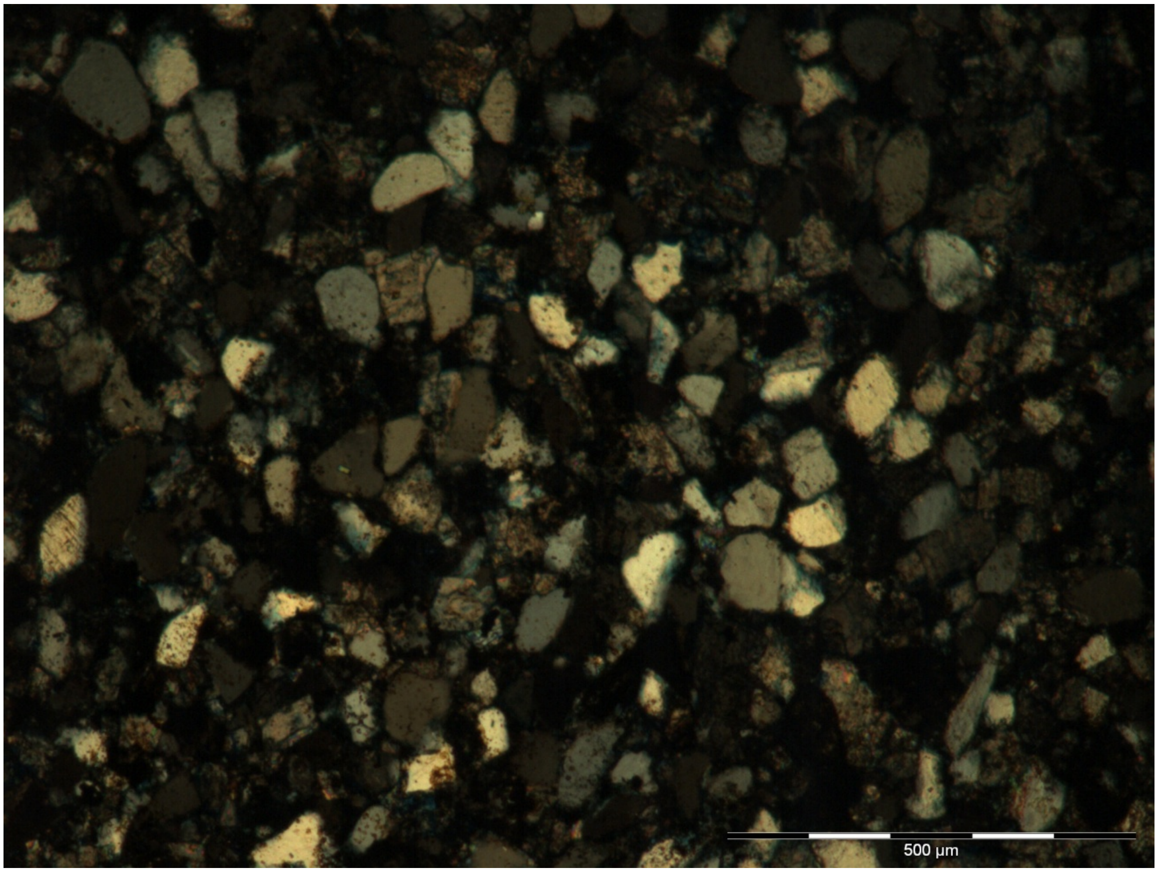

Figure 15. Photomicrograph of microfacies 4 showing the sandstone microfacies with fine to very fine-grain detrital quartz. Silt is common and calcite and dolomite occur as cement. Bakken Formation, middle member. Clarion Resources Nelson #1-29. Depth: 7413ft. CPL

The representative x-ray diffractogram of cuttings (Figure 15a) comes from the Chesapeake Operating Osborne #1-1, from a depth of approximately 8782ft. It shows near equal peak intensities for quartz (Q) and calcite (C). Ankerite/dolomite (A) is also present as cement and is represented by a moderately intense peak. Illite (I) is identified by the small peak at 2θ 8.8º. The representative x-ray diffractogram of core comes from the Northern Pump Co., L. Peterson #1 at a depth of 7542ft.

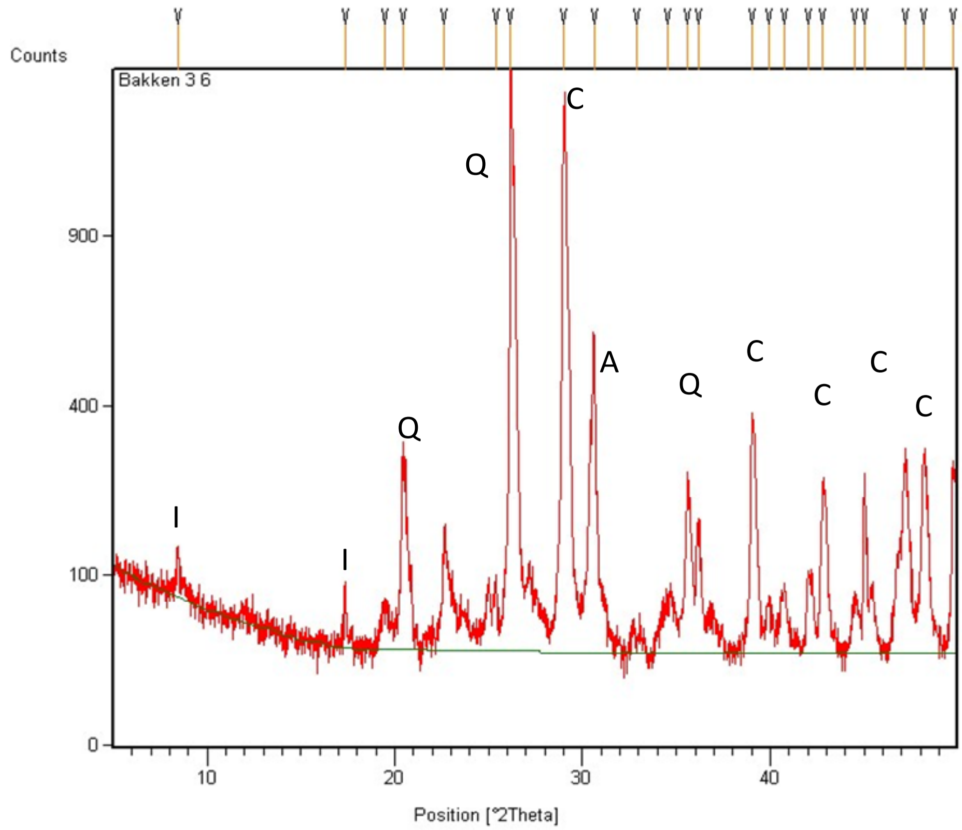

Figure 15a. Powdered x-ray diffractogram of cuttings from sandstone Microfacies 4. The relative peak intensities are interpreted to indicate abundant quartz (Q) and calcite (C), with lesser amounts of illite (I) and ankerite/dolomite (A). Bakken Formation, middle member. Chesapeake Operating, Osborne #1-1. Depth: 8782ft.

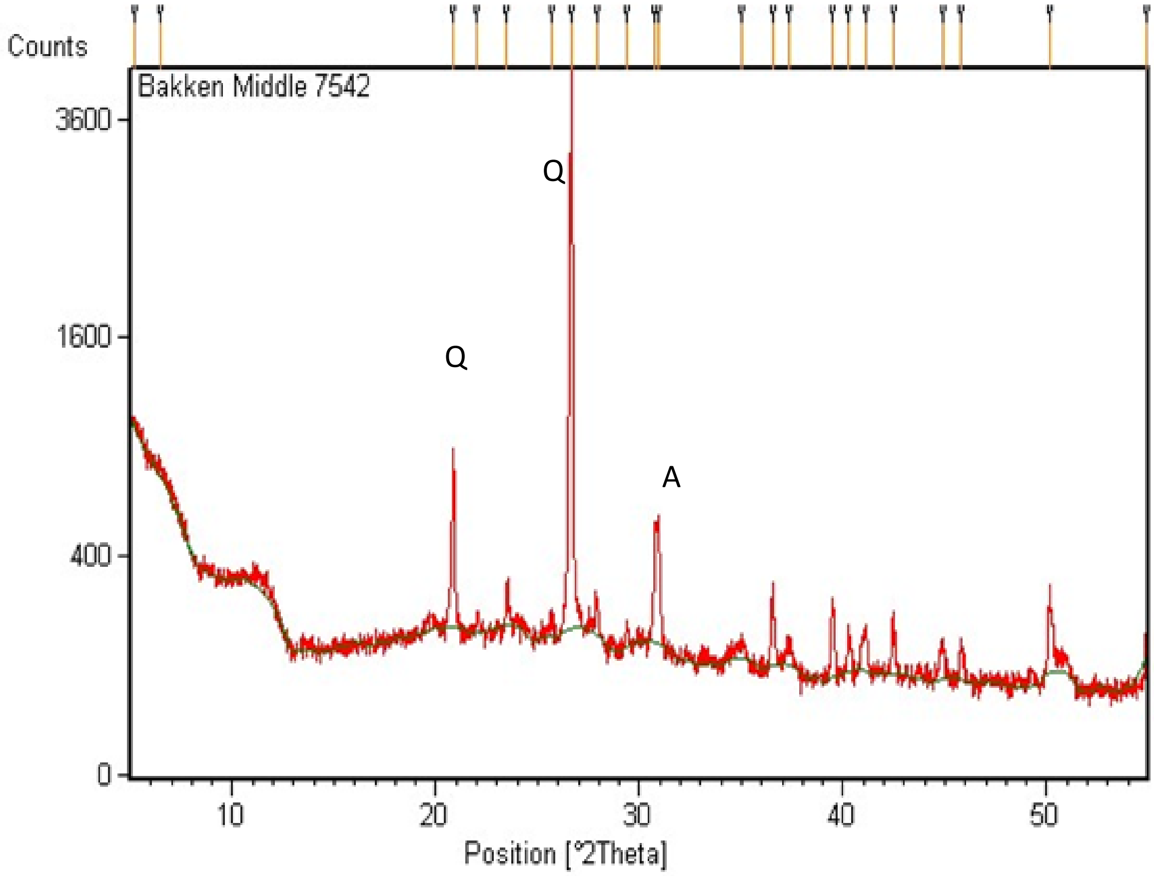

Figure 15b. Powdered x-ray diffractogram of cored sandstone Microfacies 4 showing the presence of quartz (Q) in relative intensity to ankerite/dolomite (A). Northern Pump Co., Louis Peterson #1. Depth: 7542ft.

The x-ray results were analyzed for bit cuttings from four wells that form a north to south transect across the study area along the Nesson Anticline (Figure 16). In some instances proximity of wells whose cuttings were analyzed was within one mile of a cored well, for others the analyzed cuttings were for a well greater than six miles from the nearest cored Bakken Formation. The location of cores and bit cuttings are shown in Figure 12, where the blue icons represent the analyzed thin sections, red icons represent sample cuttings locations and yellow icons show locations of logs.

SLB WILLISTON - Williston Basin

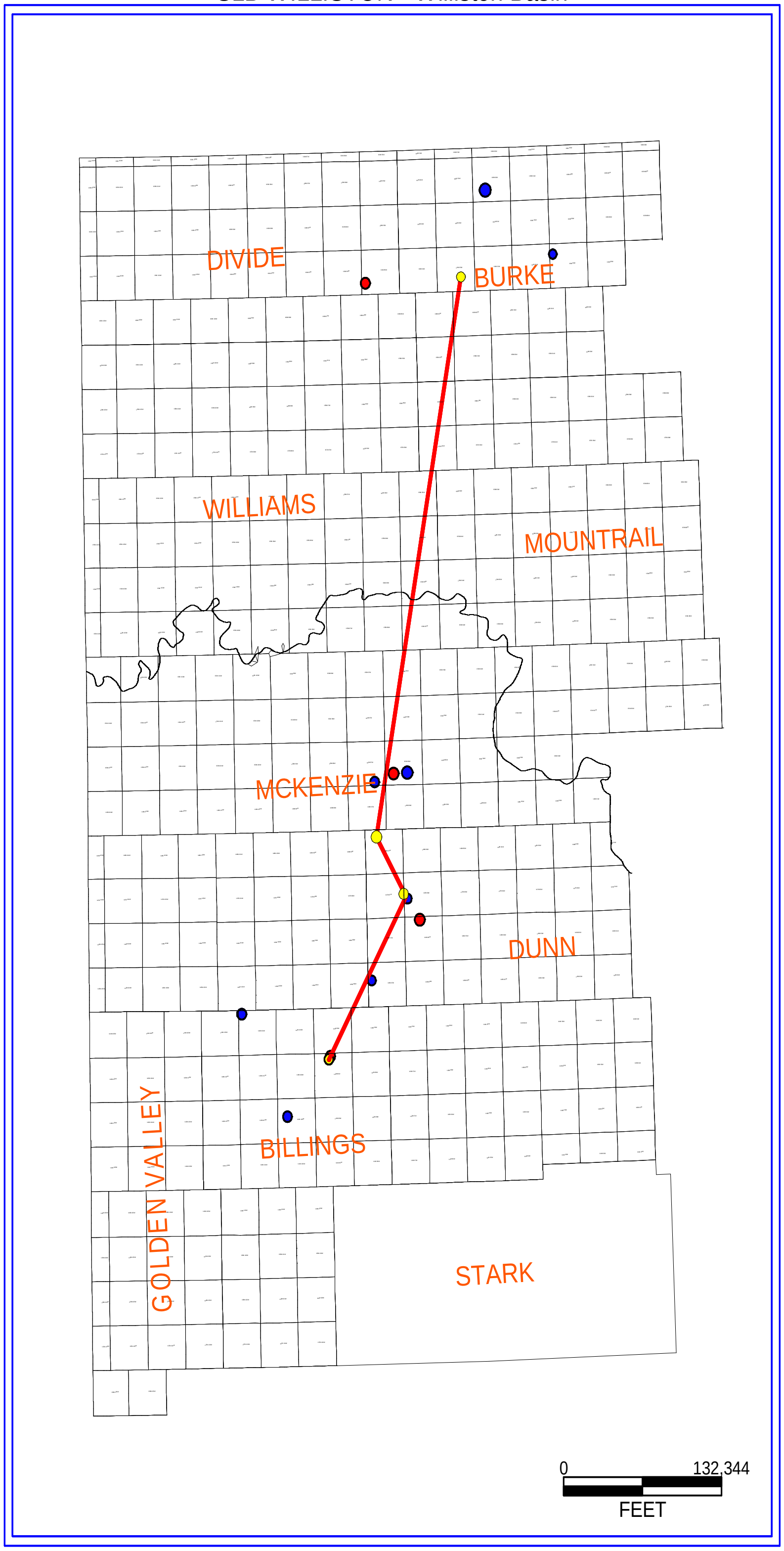

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Figure 16. Map showing locations of sample wells. Red icons are sample wells with bit cuttings, blue icons are thin section locations, yellow are wireline logs.

Well #1:

The Amoco Production, Thompson C 1 was drilled in T.143N., R.93W. and is located along the Nesson Anticline along the southern flank of the basin. The Thompson C-1 has the thinnest section of the Bakken Formation of all the sample wells and the thinning is apparent in all three members. As such, this well has the least amount of rock data to correlate to the other sample wells. X-ray results of the Thompson C-1 cuttings indicate rocks relatively rich in carbonate and quartz. The distinction between the intensities of the carbonate and silica peaks is not as strong as for the other three sample wells. Illite is present in all the samples as the major clay type, but the peaks are suppressed. The reported interval of the sample collections, 11,080 to 11,100ft, is shown on the wireline log for the Thompson C-1 in Figure 18.

Well #2:

The second well in the transect (moving from south to north) is the Amoco Production, Bang 1-33 that was drilled in T.146N., R.96W. The Bang 1-33 has thick upper and lower shales, with a slightly thicker middle member (Figure 19). The bulk x-ray samples have quartz with the highest intensity, calcite as the second highest intensity and lesser intensity peaks for albite and illite. The illite peak increases in diffractograms of sample cuttings from the middle member.

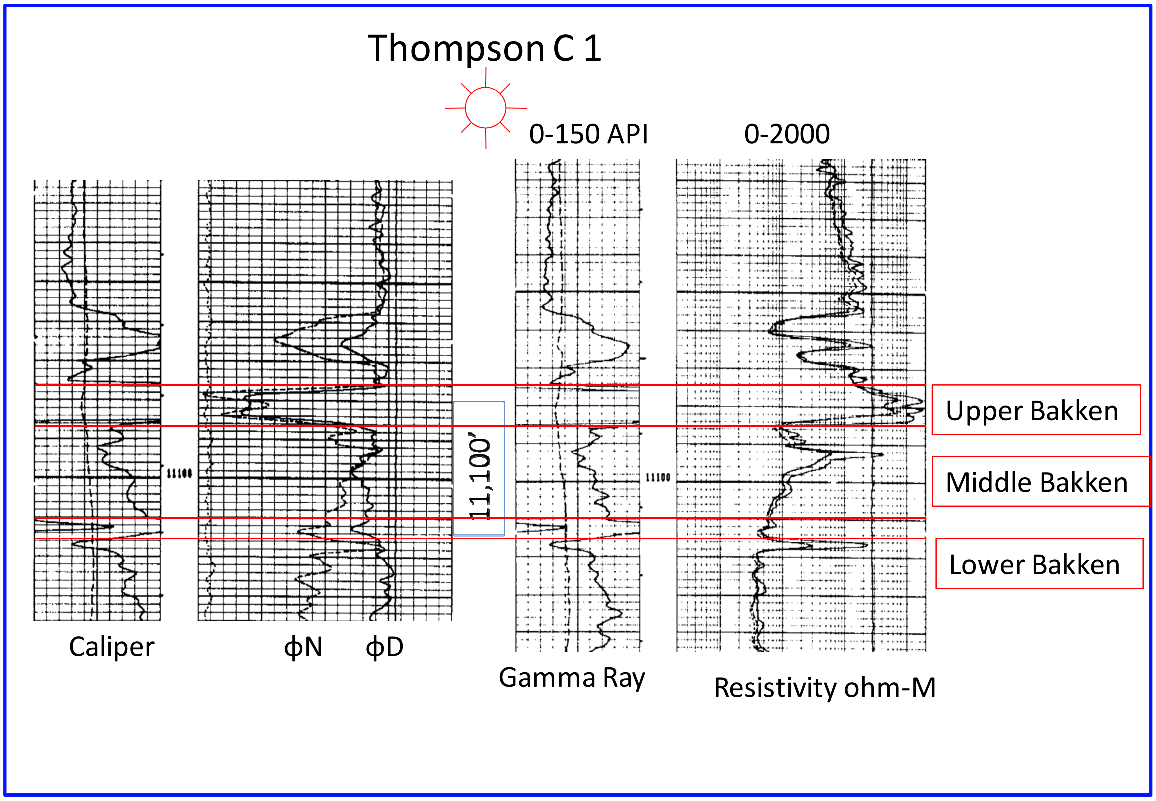

Figure 18. Portion of the wireline log of the Amoco, Thompson C-1, showing the gamma-ray and signatures across the Bakken Formation. The bit cuttings sampling interval ranged from 10,080 to 11,110ft.

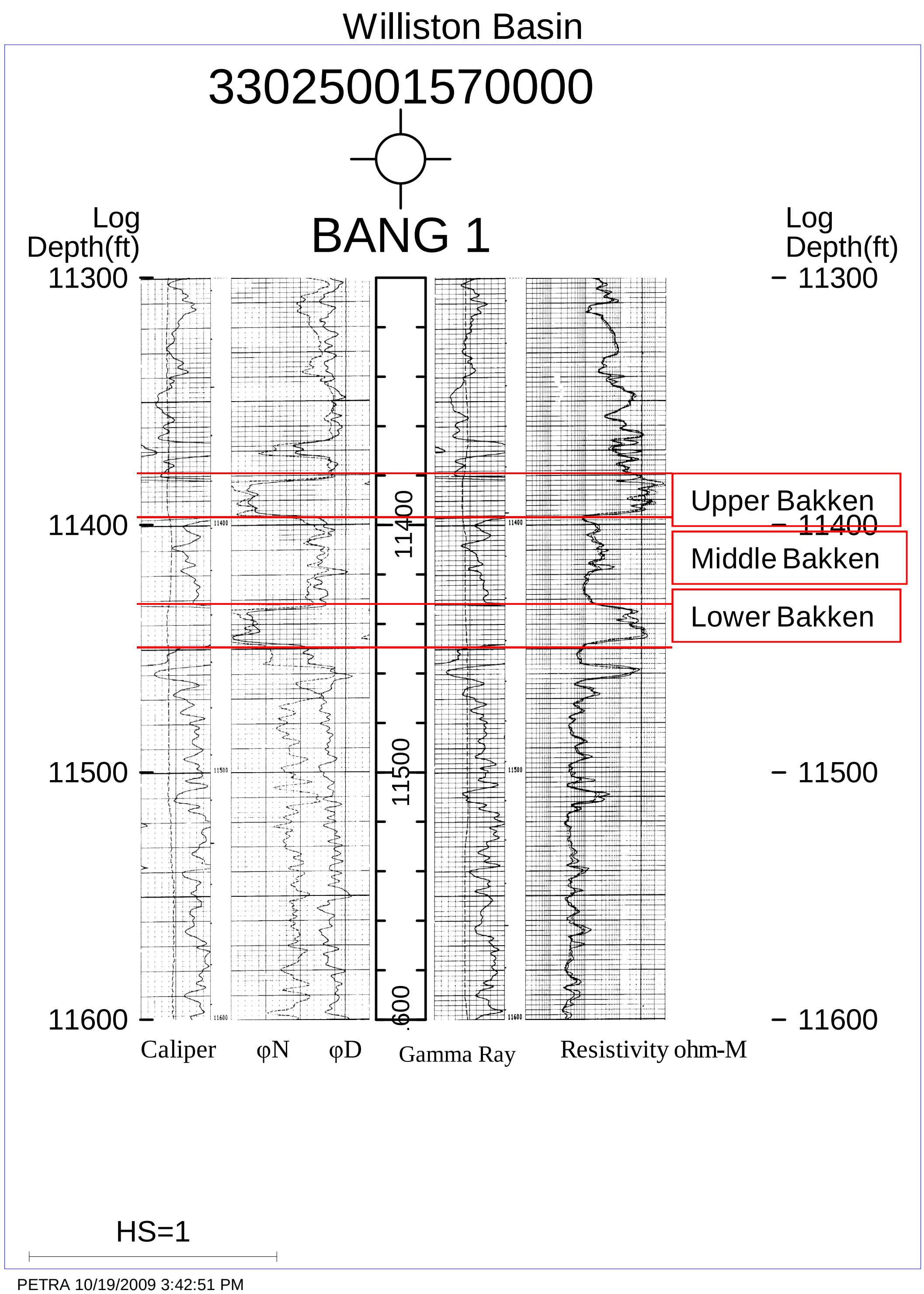

Figure 19. Portion of the wireline logs of the Amoco Bang 1-33 across the interval of sampling (11,390 to 11,440ft.) and log characteristics of the Bakken Formation.

Well #3:

The third well in the transect is the Texaco, Eisenlohr Trust #1-1 drilled in T.150N., R.96W. The Eisenlohr Trust 1-1 had a thicker upper, middle, and lower sections (Figure 20). All x-ray results of bulk samples from the Eisenlohr indicate silica dominance with the quartz peak most intense in all samples. The 100% calcite peak came close to parity with the silica peak in two samples but never surpassed it. Illite is present in all samples, however, the stronger intensity peaks occur in diffractograms of samples from the middle member.

Well #4:

The fourth and northernmost well in the transect is the Chesapeake Operating, Osborne #1-1 was drilled in T.161N., R.95W. The upper member is thinner in this well but the middle and lower members thicken (Figure 21). The bulk analysis shows a calcite-rich sample at the top of the sampling interval, with an increase in quartz in sample 3.2. The intensity of the calcite and quartz remain similar in sample 3.3, 3.4, 3.6, 3.7, and 3.9. Calcite is higher in intensity in most samples. The illite peak is in several samples, and distinctive in 3.1, 3.8, and 3.9.

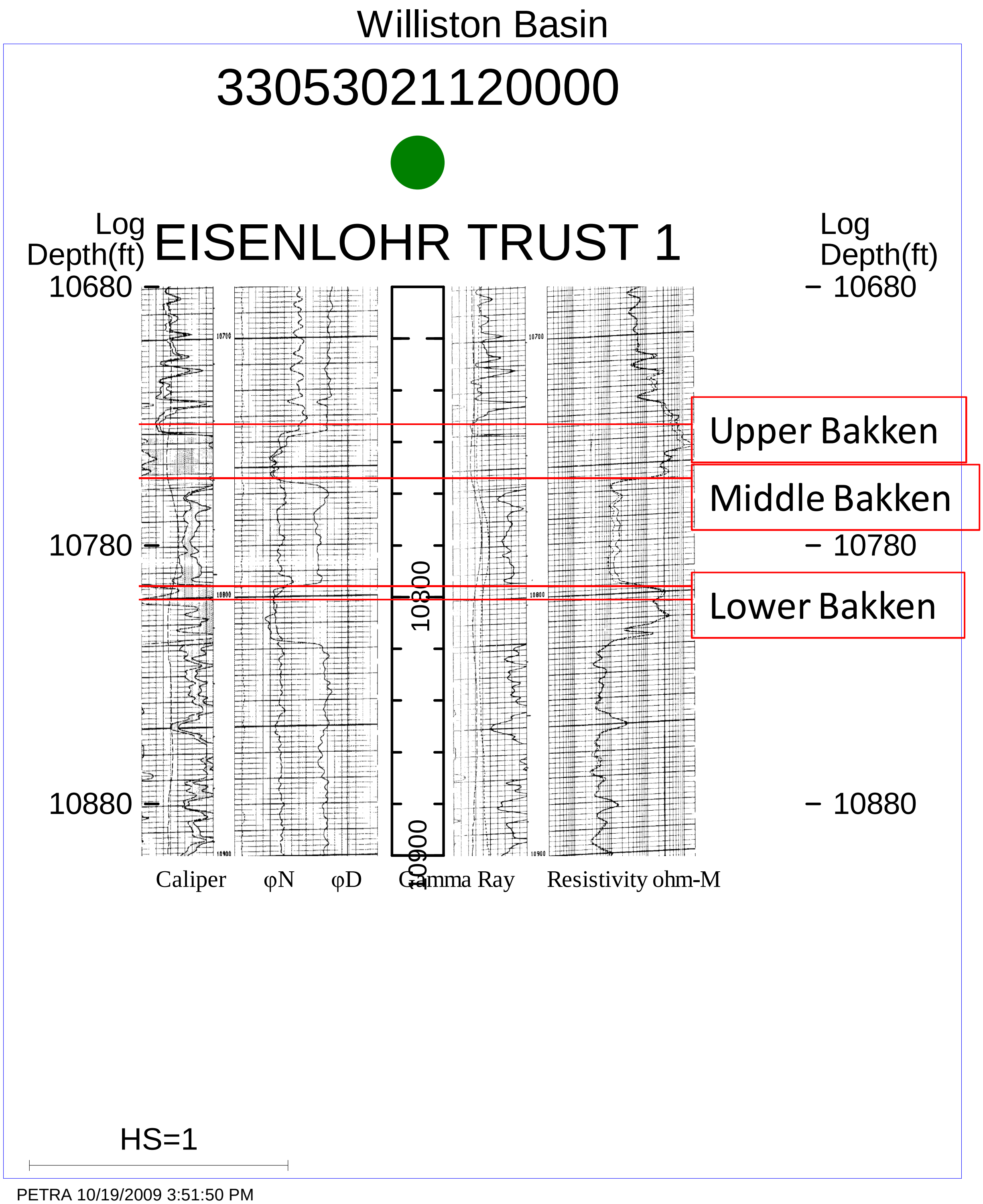

Figure 20. Portion of the wireline logs of the Texaco, Eisenlohr Trust 1 showing the interval of sampling (10,470 to 10810ft) and log characteristics of the Bakken Formation.

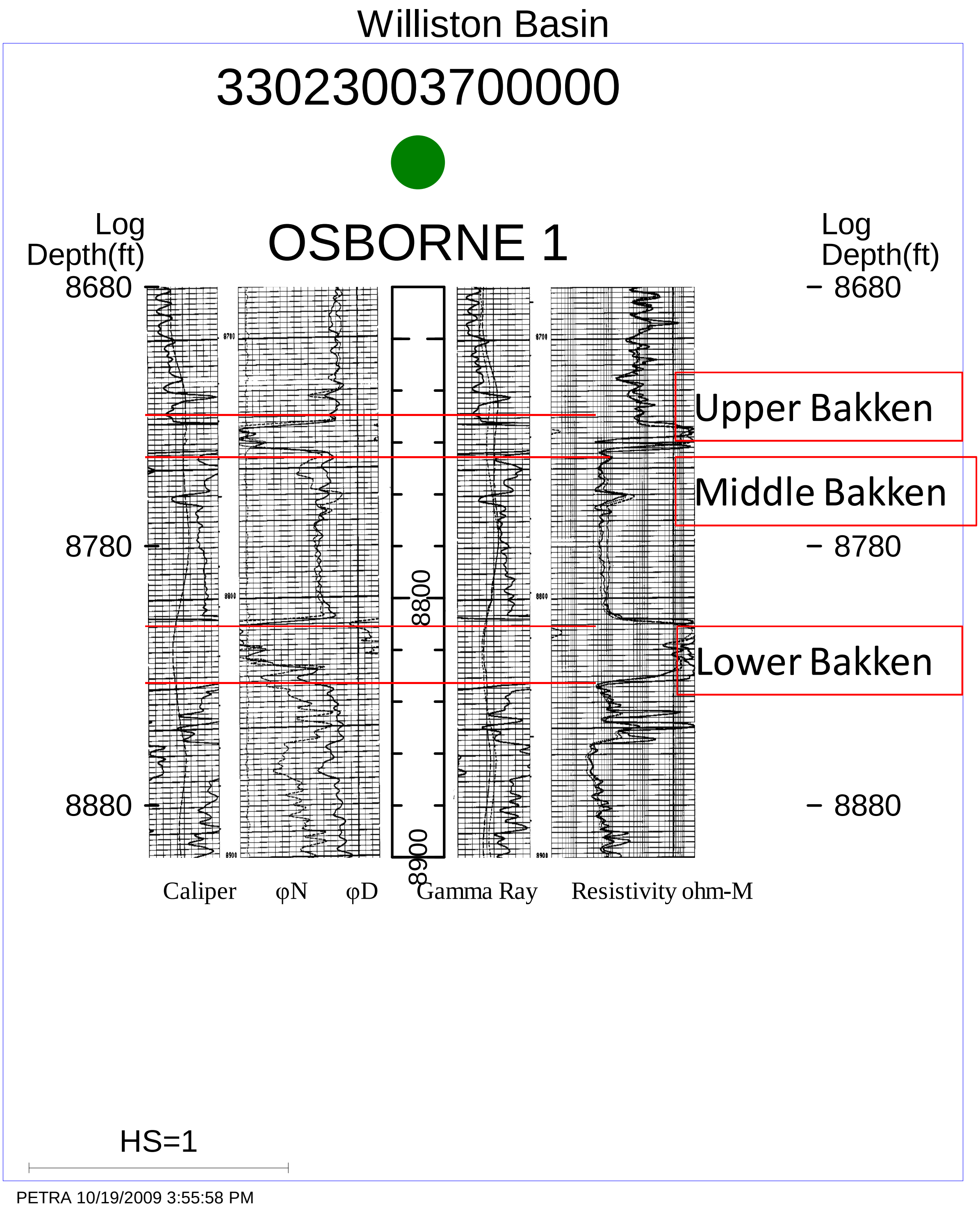

Figure 21. Portion of the wireline logs of the Chesapeake, Osborne 1 showing the interval of sampling (8740 to 8830ft) and log characteristics of the Bakken Formation.

Discussion

Core examination by thin section analysis revealed distinct microfacies in the Bakken Formation. The microfacies consist of (1) silty claystone, (2) calcareous, silty claystone, with carbonate matrix, (3) silty or sandy, carbonate, and (4) calcareous sandstone. Powder X-ray diffractograms from bit cutting samples correlated to these microfacies show distinct changes in the intensity of the quartz, calcite and illite peaks that are interpreted to represent bulk mineralogy. When the position of samples collected for x-ray analysis and thin section are plotted on wireline logs for the respective wells, correlation between microfacies, bulk x-ray and log characteristics become evident. However, it should be noted that correlation between log-recognized units and bulk x-ray samples are not as evident in wells with thin subunits of the Bakken Formation.

For example, distinct changes in the intensity of the illite peak can be evident in the diffractograms of samples collected within and immediately below the upper member. Samples collected at depths corresponding to the upper member contain limestone fragments from the Lodgepole Formation, whereas as a result of lag time, samples collected at depths immediately below the upper member contain samples of the shales. Assuming samples were collected timely, the drilling fluid system was proper and the rate of penetration normal, the lag time for cuttings to reach the surface can be estimated. This lag time was factored into the cuttings to log and core correlation.

<u>Sample Well 1</u>

The Amoco Thompson C-1 was sampled four times across the Bakken interval. Samples 4.1 (11,080ft.) and 4.2 (11,090ft.) are calcite dominant, which can be interpreted as samples from the overlying Scallion and Lodgepole Limestone. Samples 4.3 (11,100ft.) shows a shift to quartz dominance, but the differences in the intensity of the quartz and calcite peaks are not great. Illite is present in all samples, but prominent in 4-4 (11,110ft.). The slight increase in the illite peak in 4-4 may reflect the lag time for the upper Bakken shale cuttings to the surface, but this cannot be stated with confidence. The thinning of the Bakken in this well exacerbates the difficulty in correlating cuttings to the wireline logs.

Sample Well 2

The Amoco, Bang 1-33 was sampled six times across the Bakken interval. Sample 1.1 (11,390ft.), which according to log depth (Figure 19) was collected during drilling of the upper shale. Sample 1.1 is calcite dominated and contains abundant carbonate from the shallower Lodgepole Limestone. Using a normal lag time, the upper shale should be present in sample 1.3 (11,410ft.) and 1.4 (11,420ft.). The illite peak increases in 1.3 and 1.4, which may reflect the presence of upper Bakken shale in the cuttings. More significantly, quartz becomes the dominant peak in 1.2 (11,400ft.) and remains so in the remaining samples. This change is interpreted to reflect the transition from the Lodgepole Limestone to the Bakken siliciclastic units. The abundance of quartz in middle Bakken microfacies 2, 3 and 4 is seemingly apparent in samples 1.3 to 1.6 (11,410 to 11,440ft.).

Well 3:

The Texaco Exploration, Eislenohr Trust 1-1 was sampled beginning in the upper Bakken shale and ending in the lower Bakken shale (Figure 20). Quartz dominated the mineralogy in the sampled intervals. The illite peak is present in all samples, but becomes prominent in 2.4 (10,770ft.). Sample 2.4 can be logged back to the upper Bakken shale. The dominance of quartz and minimalization of calcite in samples 2.5 to 2.8 (10,780 to 10,810ft.) suggest a sandy middle Bakken as represented by microfacies 4. An x-ray diffractogram of the upper Bakken shale in the nearby Amerada Petroleum, Shelvic Tract 1-1 (Figure 12b) shows a similar profile with prominent illite and quartz peaks.

Well 4:

Chesapeake Operating, Osborne #1-1 was sampled ten times across the Bakken Formation. Bulk mineralogy for samples 3.1, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8 and 3.9 (8740 to 8830ft.) is interpreted to be calcite and quartz-rich. Samples 3.1 and 3.10 are quartz-rich, with calcite being less abundant. Illite becomes apparent in samples 3.2 (8750ft.), but decreases in 3.3 (8760ft.) and 3.4 (8770 ft.) and is not evident in 3.5 (8780ft.). The illite peak reappears in 3.6 (8790ft.) and is prominent in 3.7, 3.8, 3.9, and 3.10.

If expected lag times are used to correlate these samples to the log, illite would be expected to peak in sample 3.2 to 3.4 (8750 to 8770ft.). There is a slight peak in 3.2 and 3.3 that is gone by sample 3.4. The reemergence of the illite peak in sample 3.6 (8790 ft.) cannot be explained by the log-sample correlation. There are a number of possible explanations for this discrepancy including difference between driller’s depths and log depths, the available data are not sufficient to address this problem.

Clay Series

The presence of illite in most samples of the Bakken Formation is evidenced by a 2θ 8.8 ^{o} on X-ray diffractograms. Since previous studies have shown the shales to be organic rich and thermally mature (Meissner, 1978) we would expect to see illite in most, if not all samples. However, to determine the type of clay present in these cuttings, bulk samples were divided, clay extracted, and analyzed. The results include no evidence for swelling clays such as smectite following glycolation and heating, only illite. These results (Figures 22-24) confirm that illite is the dominant clay in the Bakken Formation.

A graph representing the relative intensities of illite, calcite, quartz and dolomite is shown in Figure 25. The increase in illite intensity in the upper and lower members of the Bakken Formation is evident. Quartz is dominant in all samples except for one in the middle Bakken in the carbonate microfacies.

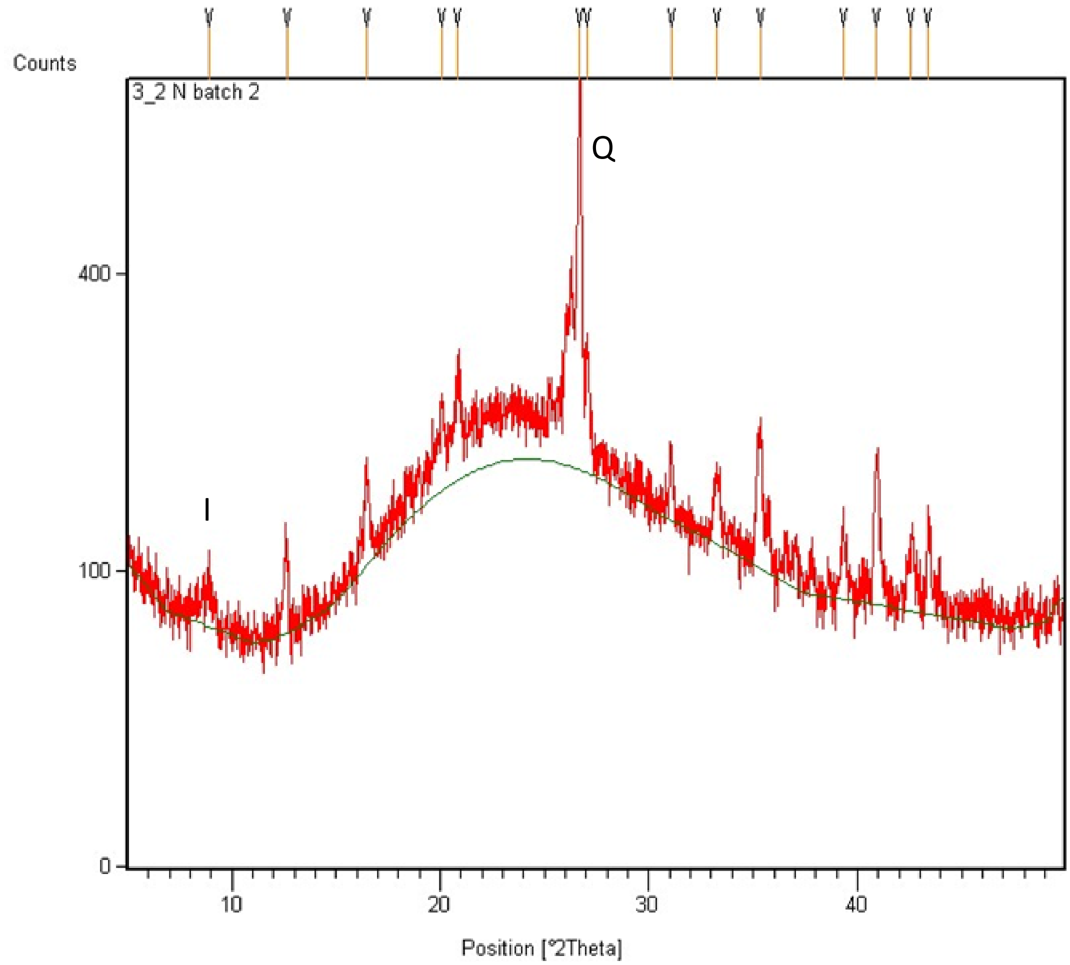

Figure 22. Powdered x-ray diffractogram of clay extracted sample showing illite (I) and quartz (Q) peaks. Chesapeake Operating, Osborne #1-1. Depth: 8750ft.

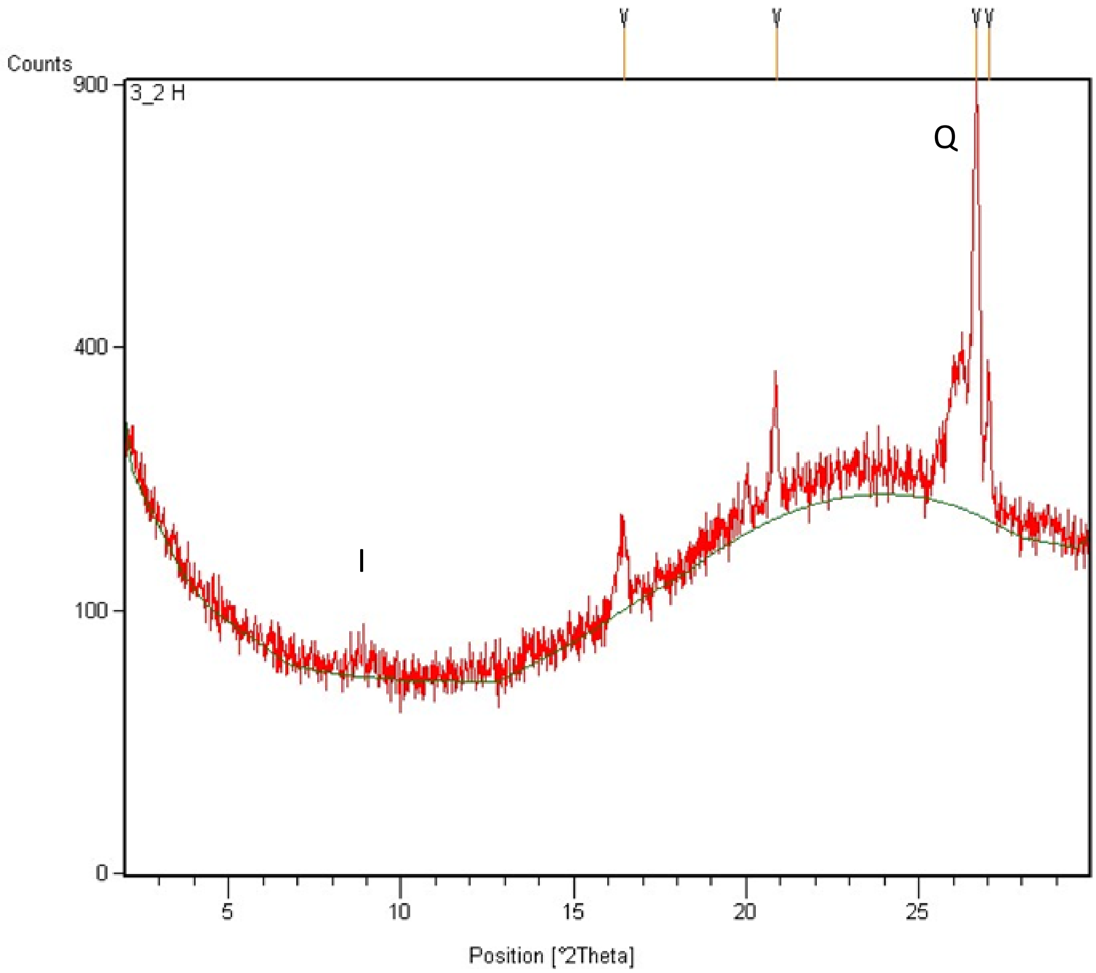

Figure 23. Powdered x-ray diffractogram of heated sample showing illite (I) and quartz (Q) peaks. Chesapeake Operating, Osborne #1-1. Depth: 8750ft.

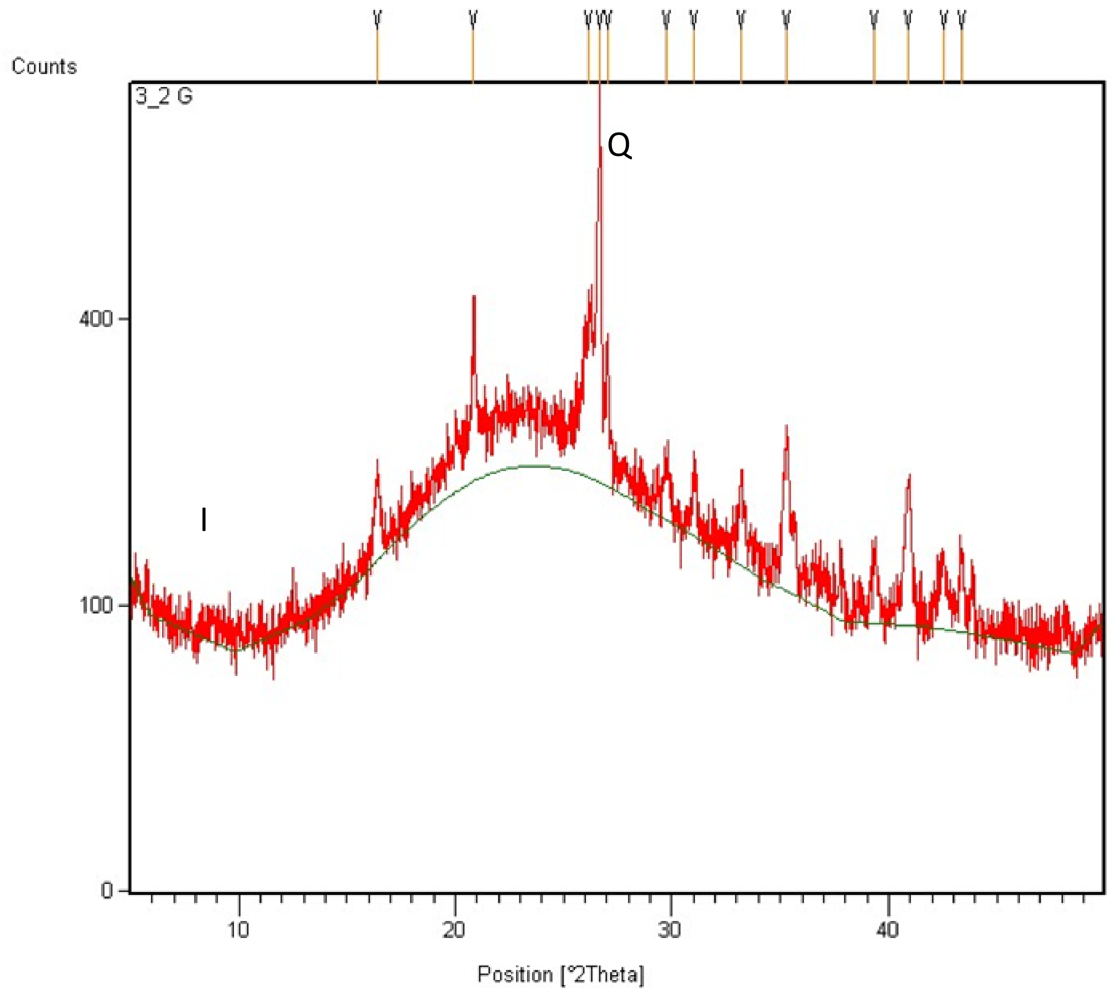

Figure 24. Powdered x-ray diffractogram of glycolated sample showing illite (I) and quartz (Q) peaks. Chesapeake Operating, Osborne #1-1. Depth: 8950ft.

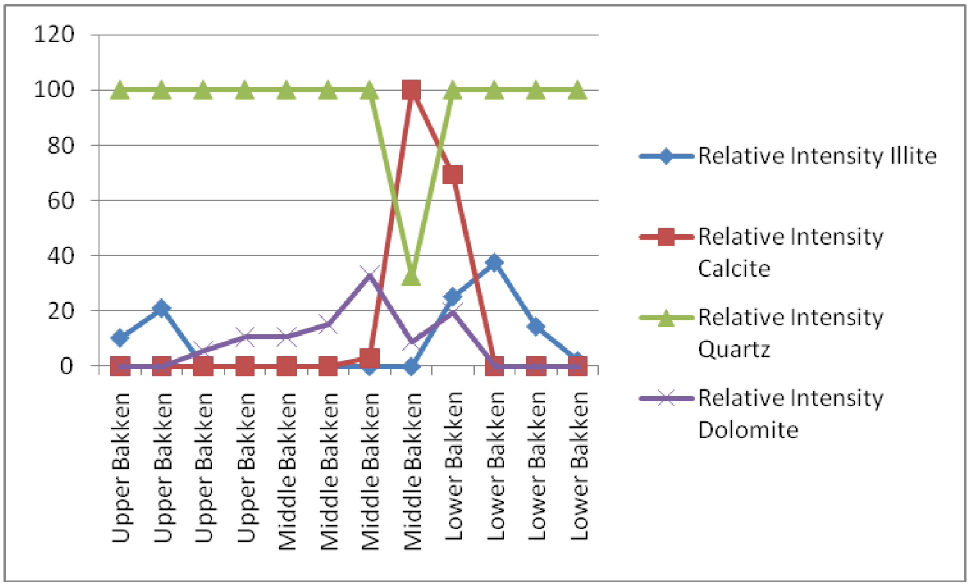

Figure 25. Graph illustrating the relative intensities of illite, calcite, quartz and dolomite.

CHAPTER V

CONCLUSION

The problem statement of this thesis addresses the question "can XRD data derived from powdered bit cuttings serve as a proxy for core data in determining the bulk mineralogic composition and clay mineralogy"? The results discussed in the previous chapter illustrate that often there is not a sufficient enough correlation between the XRD, log and thin section data to conclude that XRD can serve as a universal substitute for core data. However the findings supported the following conclusions, which were based on the mapping and analytical techniques used in this study:

(1) The Bakken Formation has distinct wireline log characteristics that allow it to be separated into upper, middle and lower subunits, which in informal petroleum industry nomenclature are called members.

(2) The Bakken Formation is thicker to the east of the Nesson Anticline and thins uniformly toward the margins of the basin.

(3) The three subunits (members) and formation boundaries of the Bakken Formation can be correlated across the basin, allowing for correlation of bit cuttings to thin section from core and logs.

(4) The x-ray analysis of bulk, clay extracted, glycolated and heated samples demonstrate that the Bakken Formation contains illite as the dominant clay species.

(5) Thin section analysis allowed the Bakken formation to be subdivided into 4 distinct microfacies. These are silty claystone in the upper and lower shales, and calcareous, silty claystone with carbonate matrix, silty or sandy carbonate, calcareous sandstone in the middle member.

(6) Powder x-ray diffraction of properly correlated samples showed bulk mineralogic patterns that were consistent with thin section analyses. The similarities improved in cuttings from thicker sections of the Bakken Formation. A close correlation of x-ray mineralogy to thin section mineralogy was more difficult to establish in wells with thin Bakken Formation intervals.

(7) Cleaned, but further unprocessed bit cuttings are useful in determining mineralogy of the drilled units under most conditions if the correction for cutting lag times and the stratigraphy of the studied interval are known.

Implications

The importance of clay mineralogy to drilling and stimulating of argillaceous rocks is summarized by Matthews et. al. (2007) and Xu and Pruess (2004). Bit cuttings analysis may provide a less-expensive technique to determine bulk and clay mineralogy, that in turn may be used to predict drilling hazards associated with swelling clays and elasticity of rocks to be stimulated for oil and gas production. Furthermore, bulk mineralogy, coupled with visual examination of cuttings should strengthen correlations of x-ray derived data to lithofacies.

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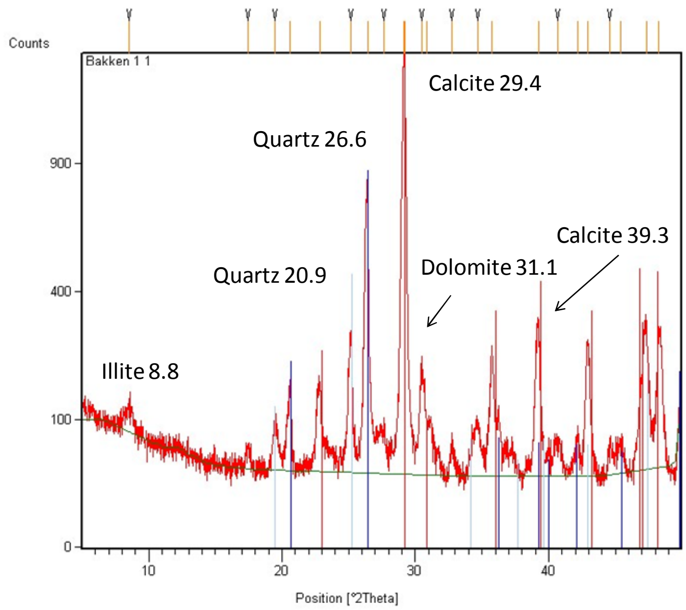
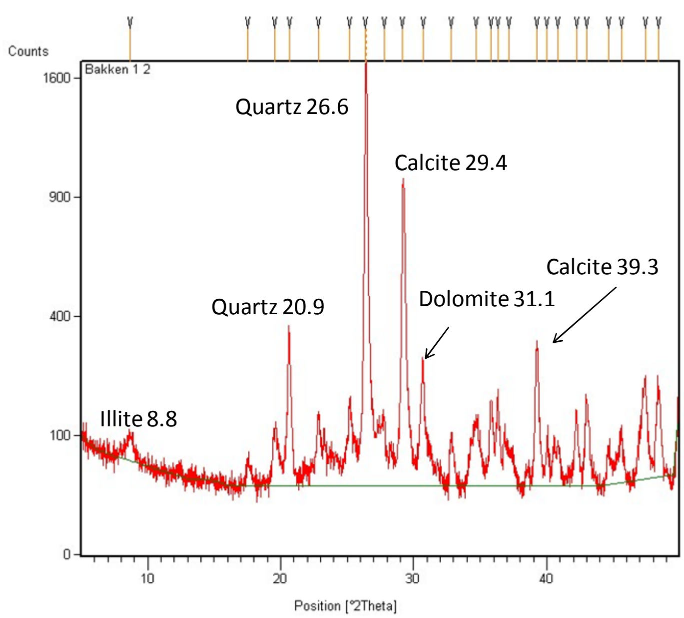
APPENDICES

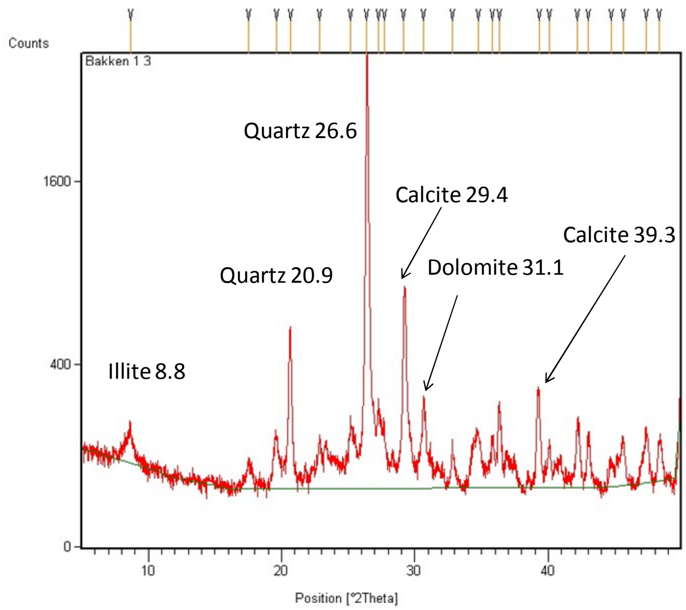
APPENDIX A



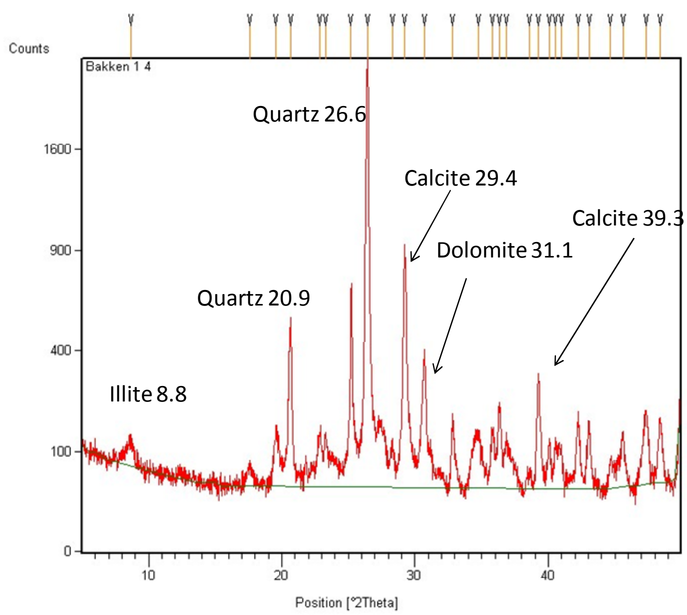
This diffractogram contains high amounts of calcite and is characteristic of the upper Bakken that contains some Lodgepole



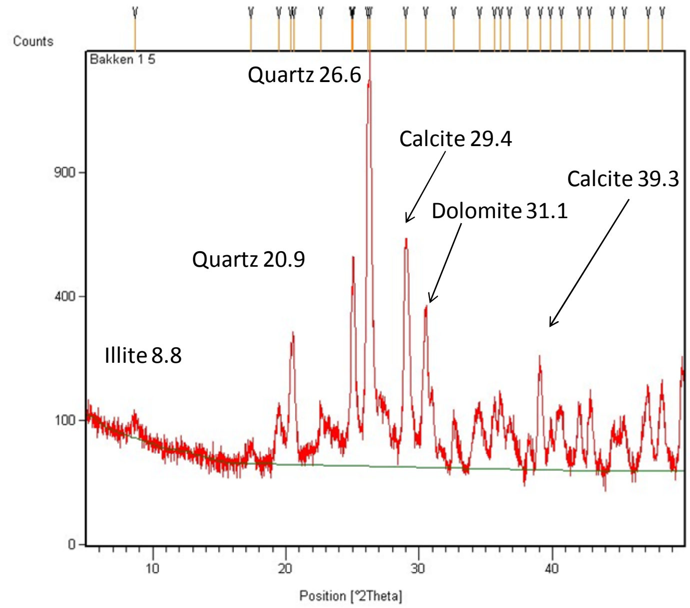
This diffractogram contains high amounts of quartz and is characteristic of the upper Bakken



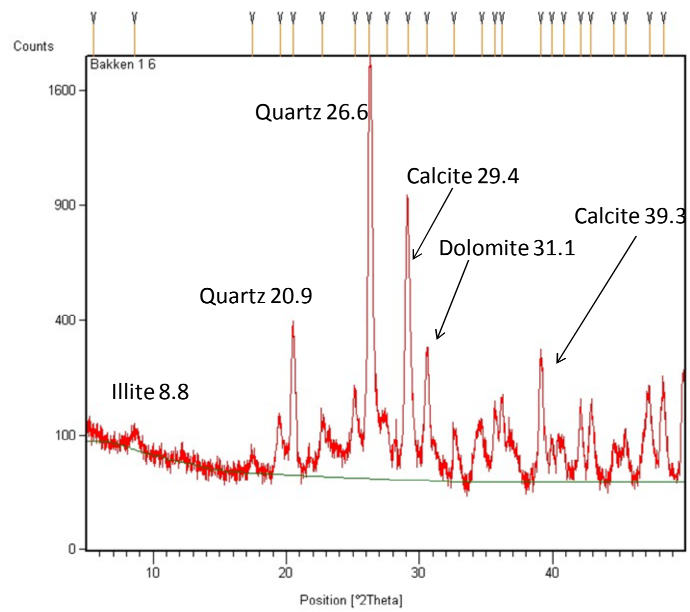
This diffractogram contains high amounts of quartz, calcite and some dolomite and is characteristic of the middle Bakken



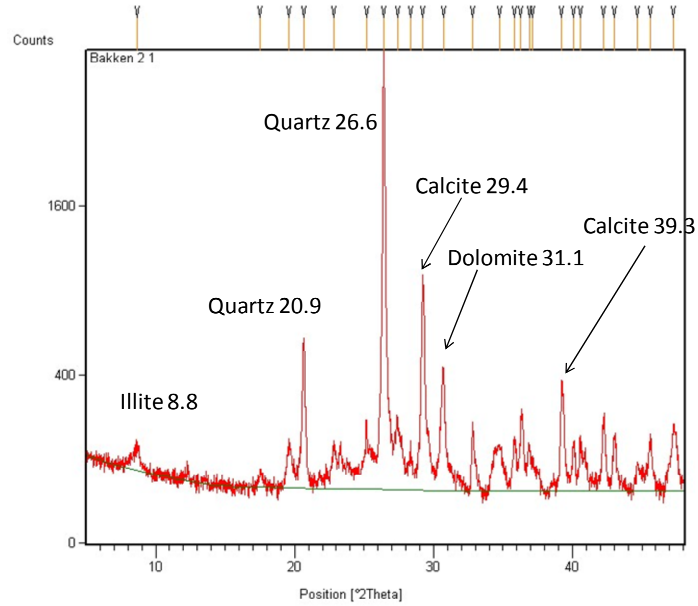
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



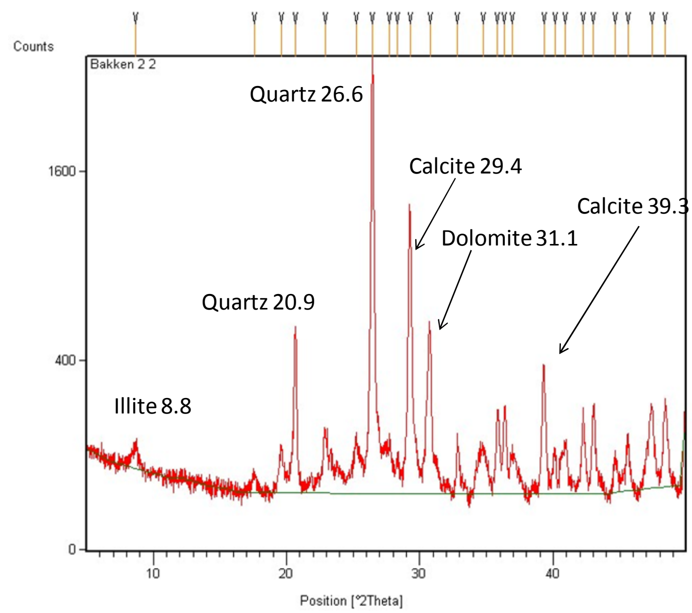
This diffractogram contains his amounts of quartz and is characteristic of the lower Bakken



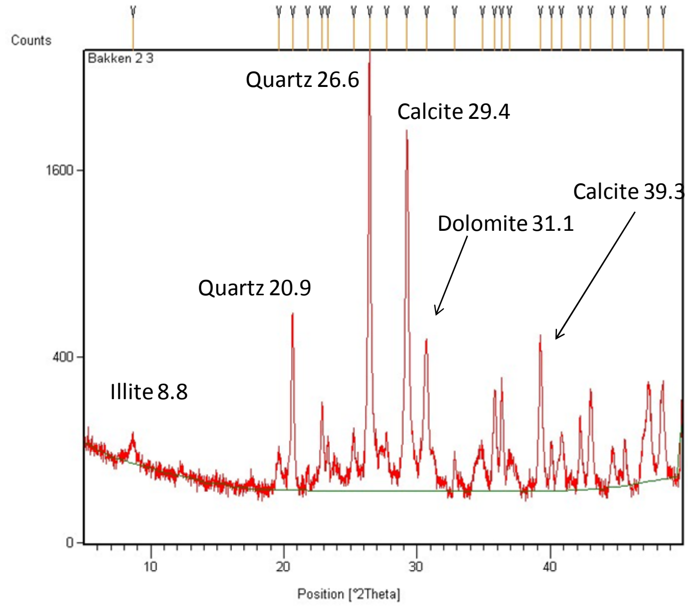
This diffractogram contains high amounts of quartz and some calcite and dolomite and is characteristic of the lower Bakken



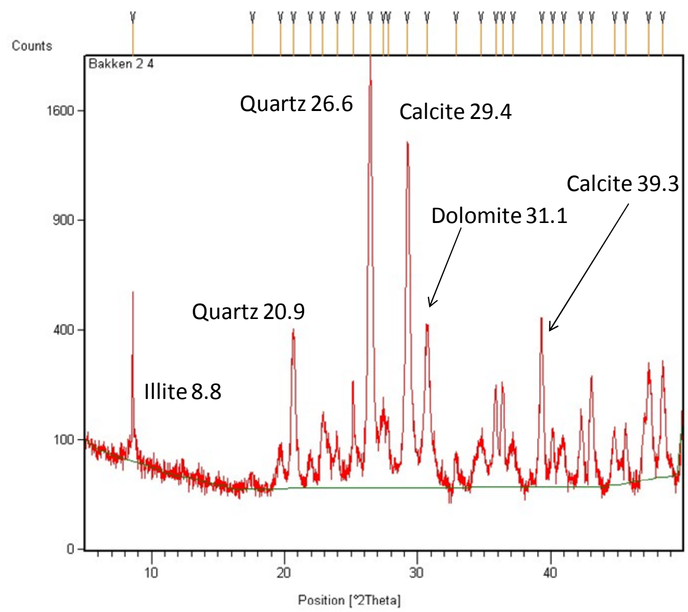
This diffractogram contains high amounts of quartz and is characteristic of the upper Bakken



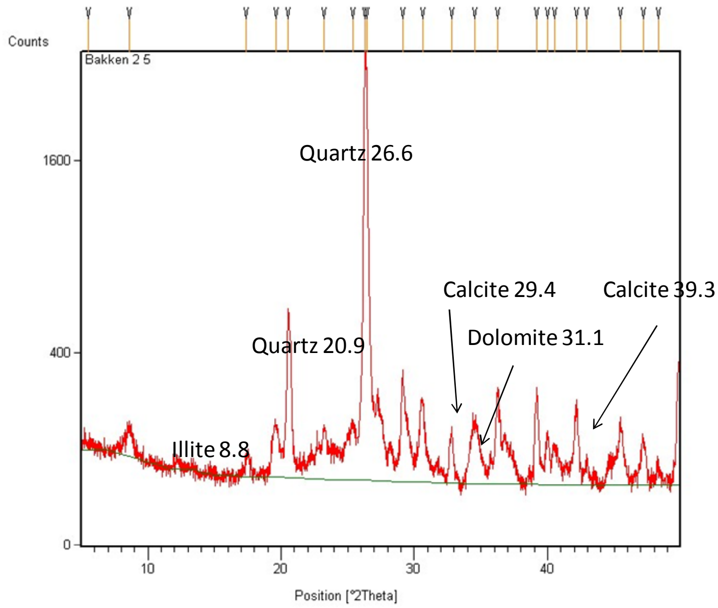
This diffractogram contains high amounts of quartz and is characteristic of the upper Bakken



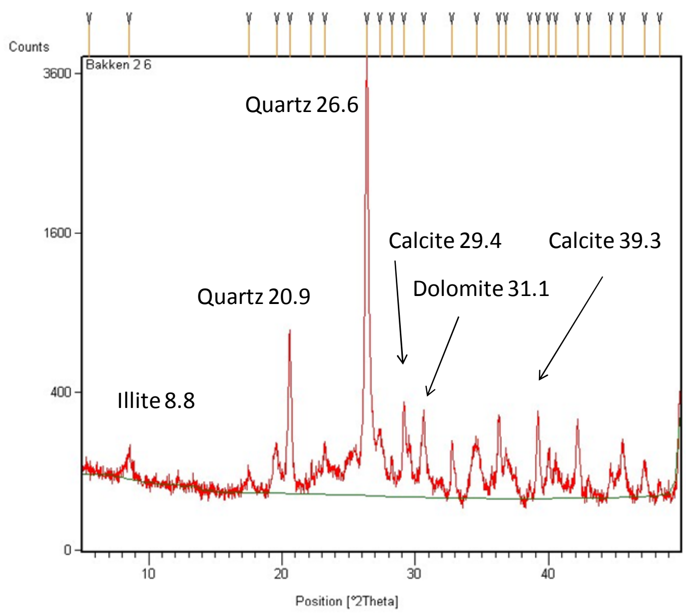
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



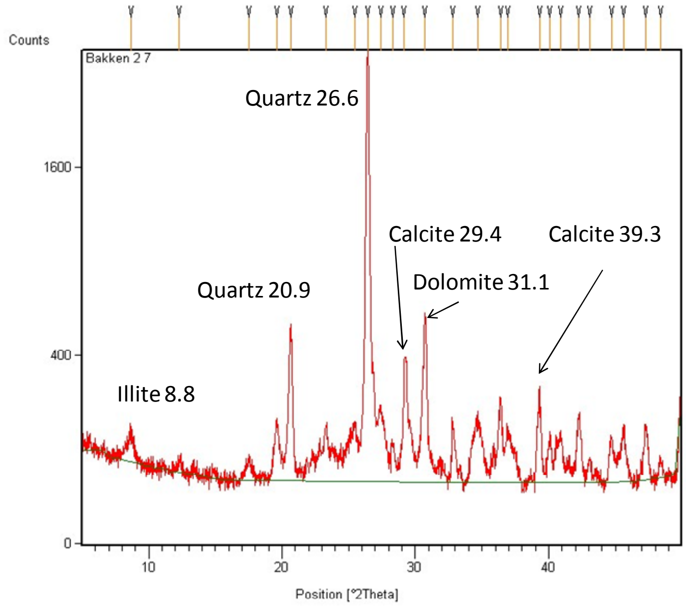
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



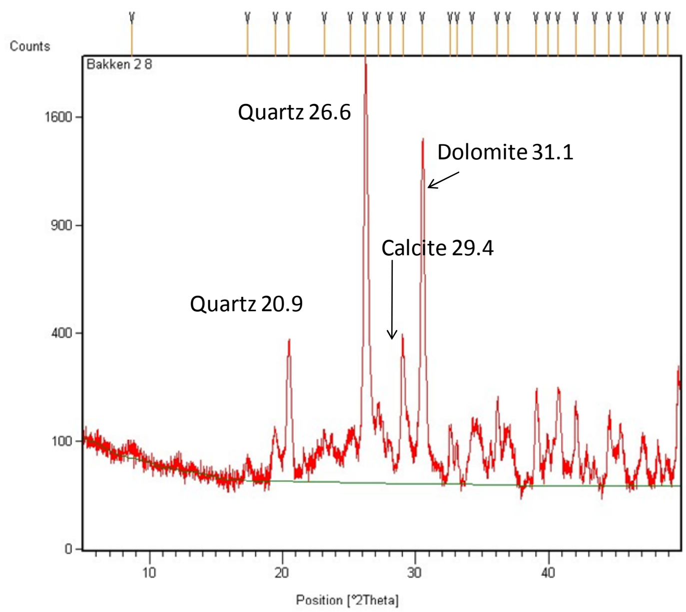
This diffractogram contains high amounts of quartz, however calcite and dolomite are barely present and is uncharacteristic of the middle Bakken



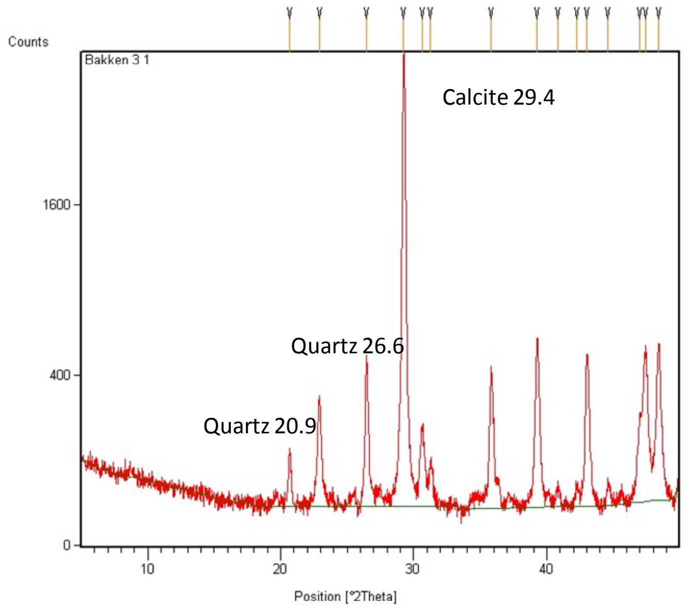
This diffractogram contains high amounts of quartz, however calcite and dolomite are barely present and is uncharacteristic of the middle Bakken



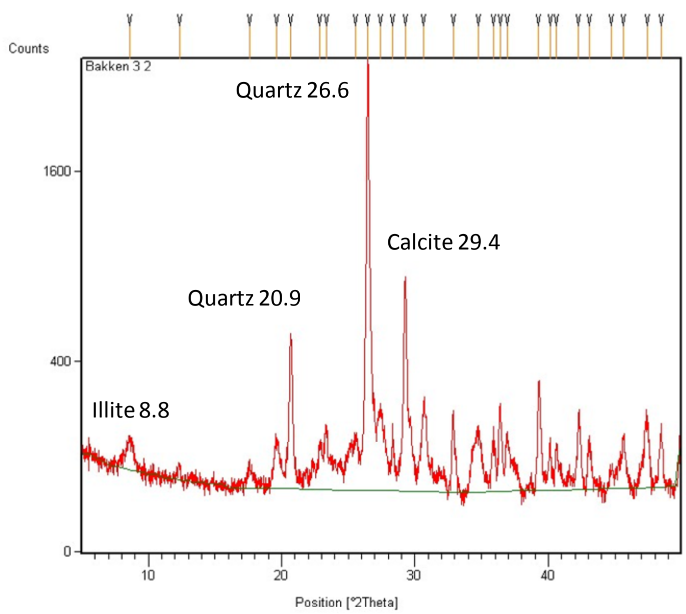
This diffractogram contains high amounts of quartz and is characteristic of the lower Bakken



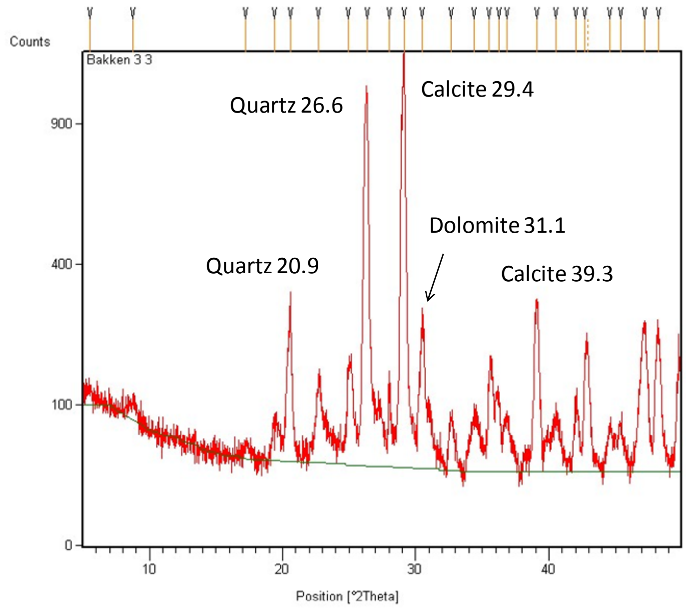
This diffractogram contains high amounts of quartz and dolomite and is uncharacteristic of the lower Bakken



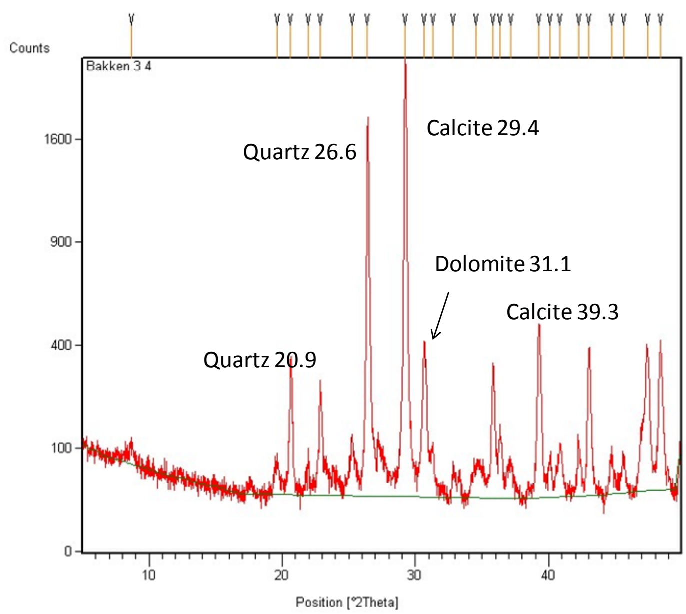
This diffractogram contains low amounts of quartz, however calcite is very high and is uncharacteristic of the upper Bakken, this sample possibly contains some Lodgepole



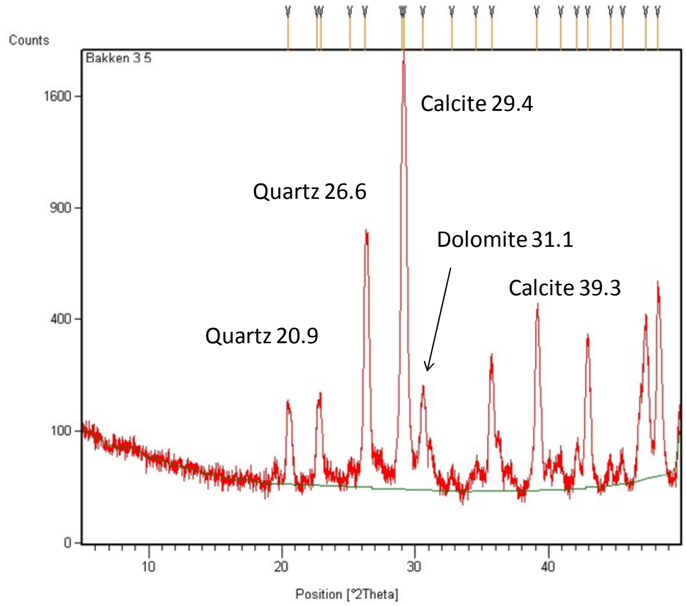
This diffractogram contains high amounts of quartz, and is characteristic of the upper Bakken



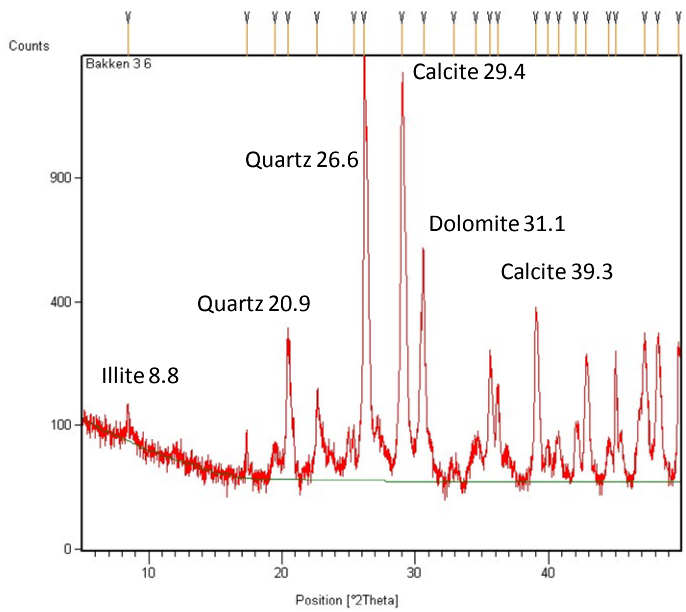
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



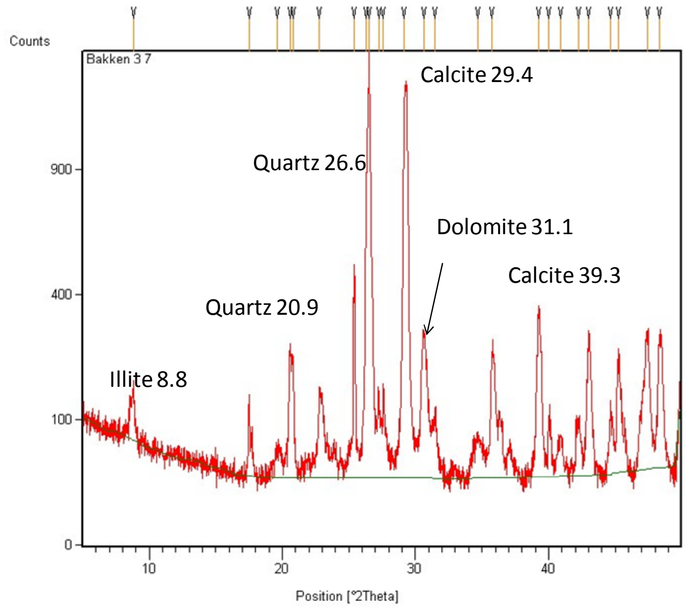
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



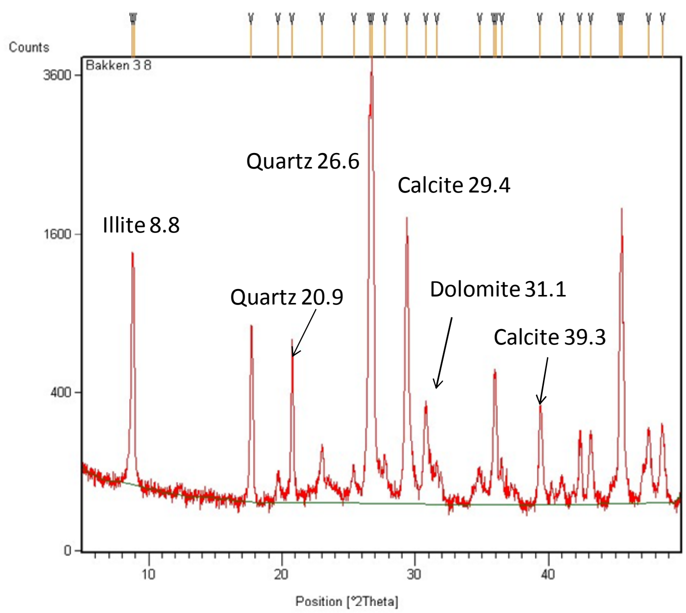
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



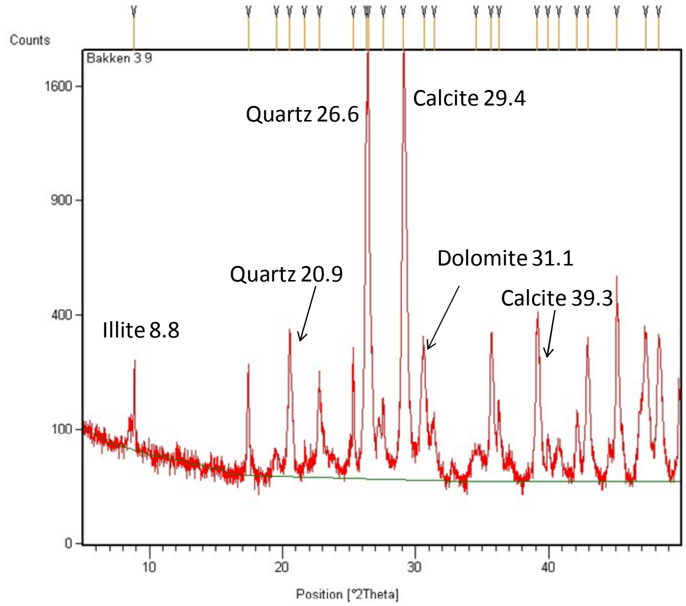
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



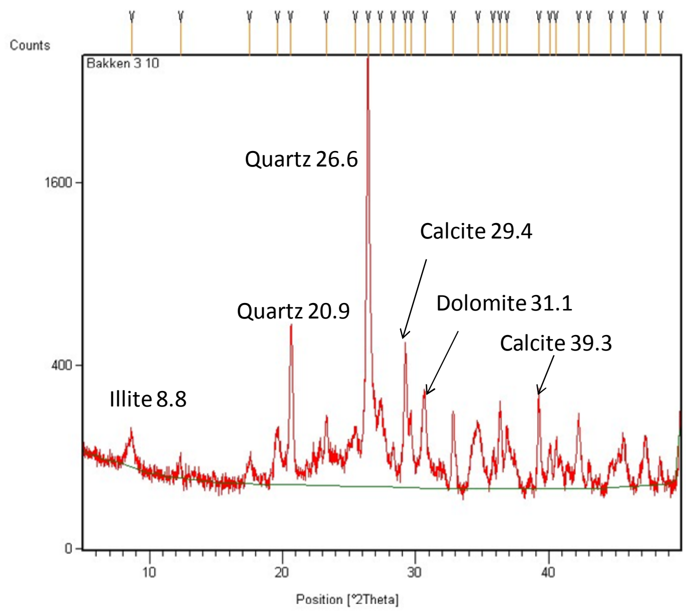
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



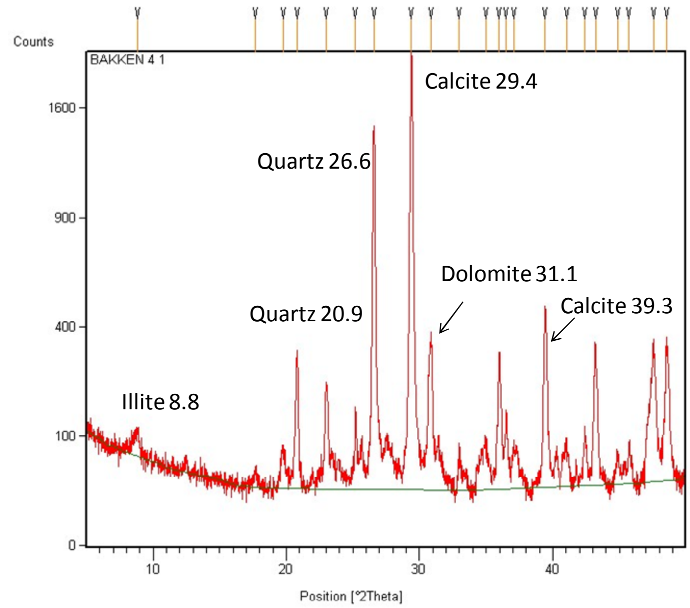
This diffractogram contains high amounts of quartz, calcite and some dolomite and is characteristic of the middle Bakken, illite is high showing the possible presence of lower Bakken in the sample



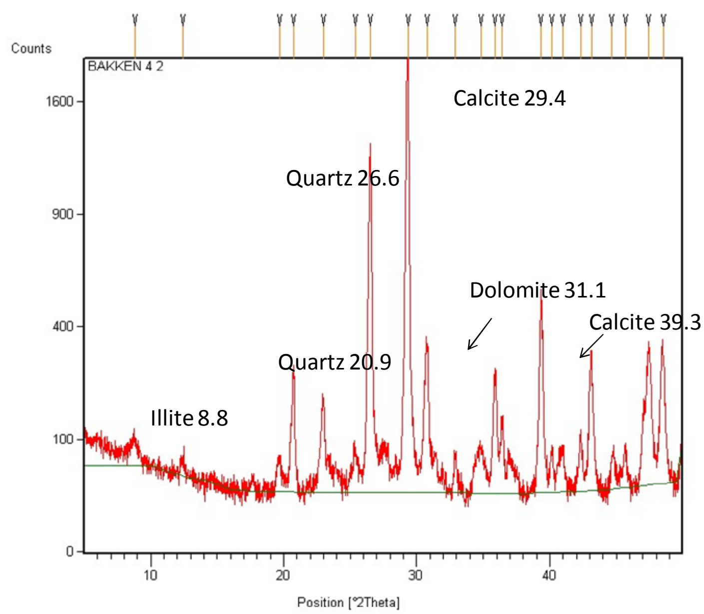
This diffractogram contains high amounts of quartz but has high calcite content and is uncharacteristic of the lower Bakken



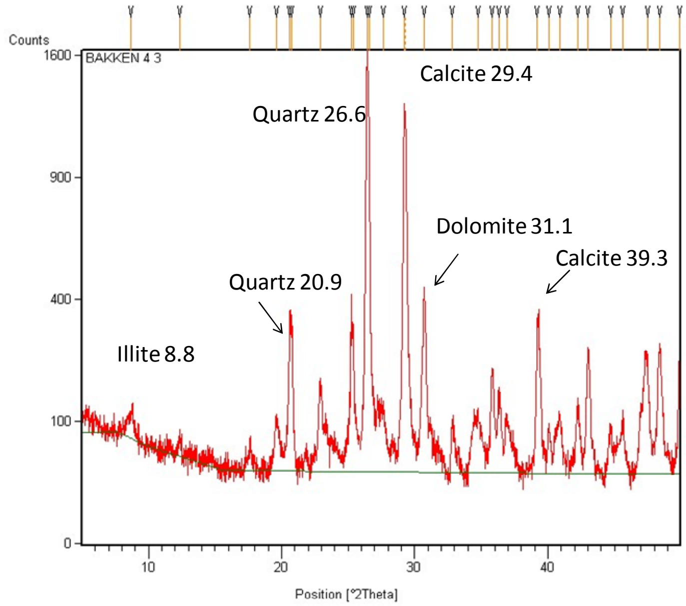
This diffractogram contains high amounts of quartz and is characteristic of the lower Bakken



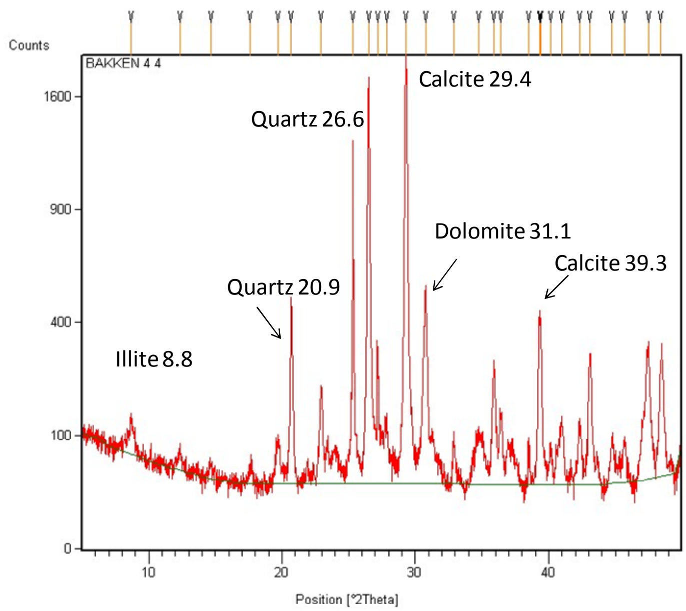
This diffractogram contains high amounts of quartz; calcite and dolomite are present and is uncharacteristic of the upper Bakken, Lodgepole presence could be the source of the aberrant data



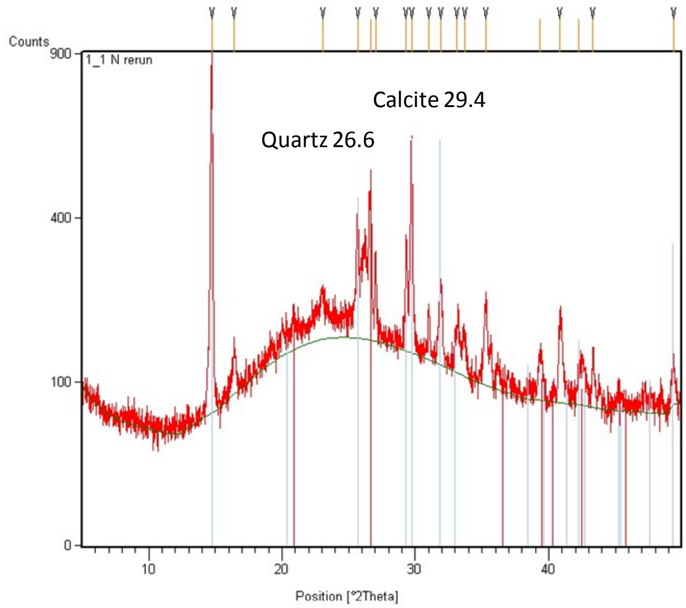
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



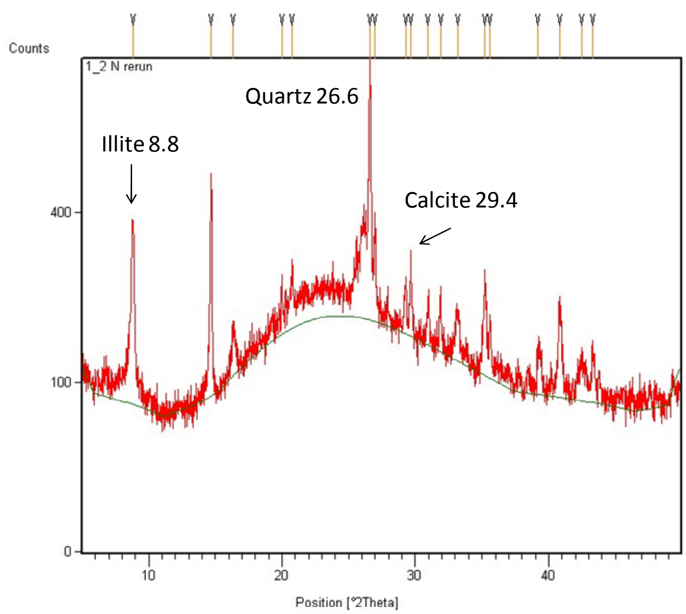
This diffractogram contains high amounts of quartz, calcite and dolomite and is characteristic of the middle Bakken



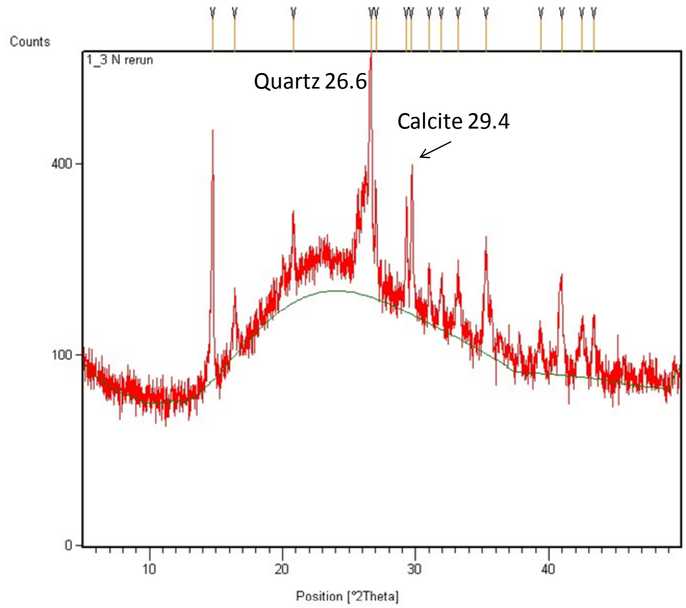
This diffractogram contains high amounts of quartz, calcite and dolomite and is uncharacteristic of the lower Bakken, the presence of the middle Bakken could be the source of the aberrant data



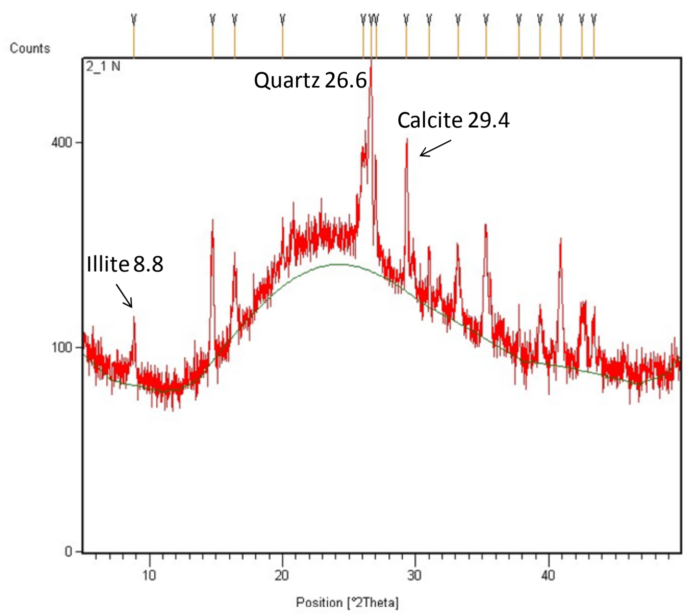
This diffractogram contains no illite and some calcite and is uncharacteristic of the upper Bakken



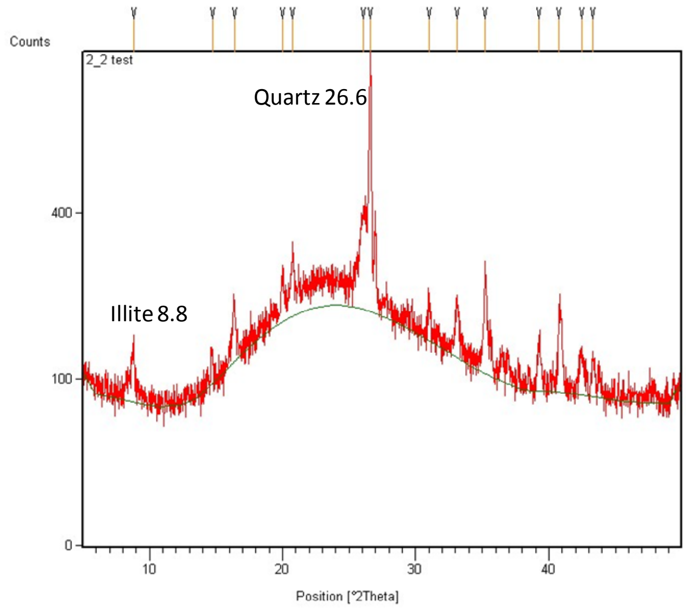
This diffractogram contains illite and quartz and is characteristic of the upper Bakken



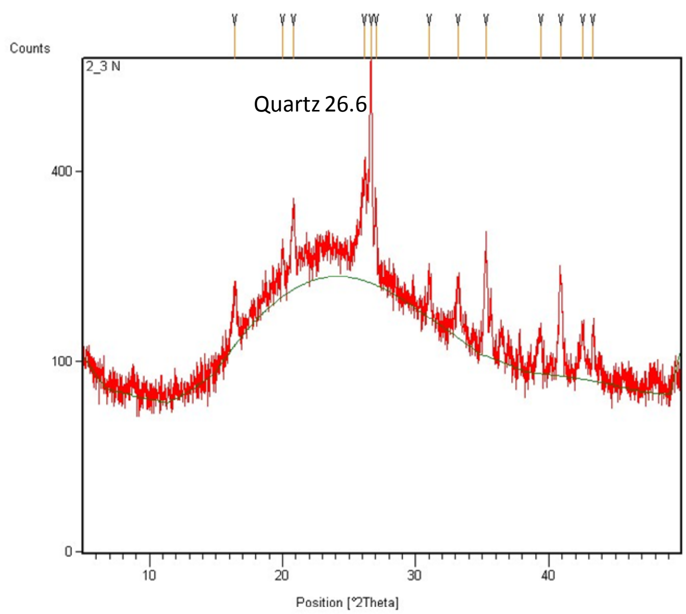
This diffractogram contains no illite and some calcite and is uncharacteristic of the lower Bakken



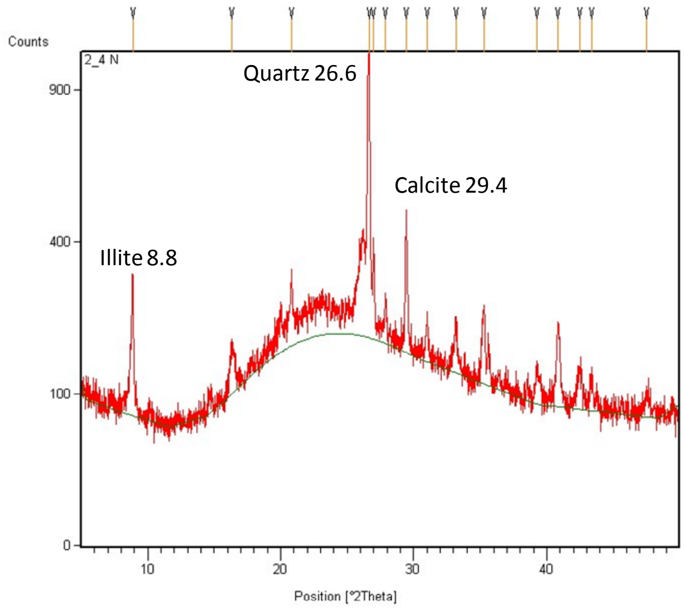
This diffractogram contains some illite, calcite is also present and is uncharacteristic of the upper Bakken



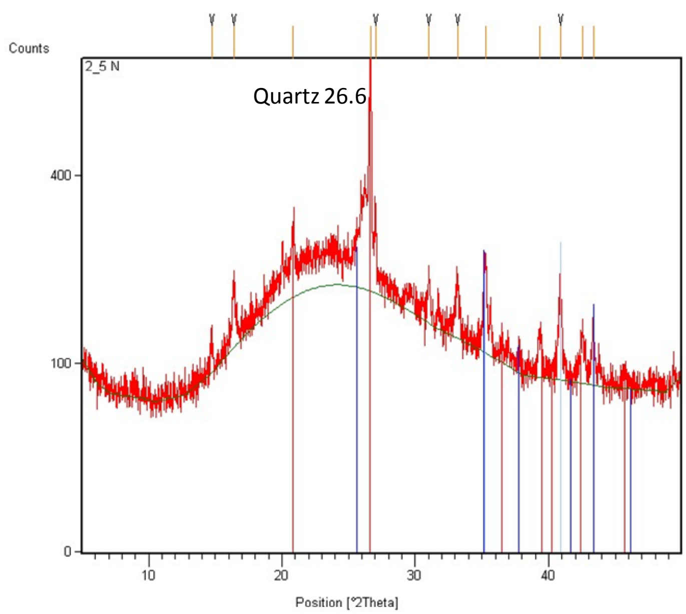
This diffractogram contains some illite and quartz and is characteristic of the upper Bakken



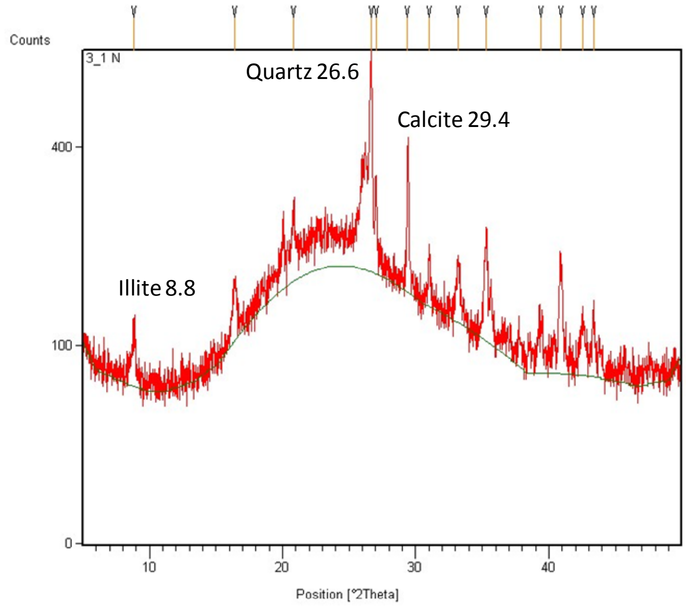
This diffractogram contains no illite and is uncharacteristic of the lower Bakken



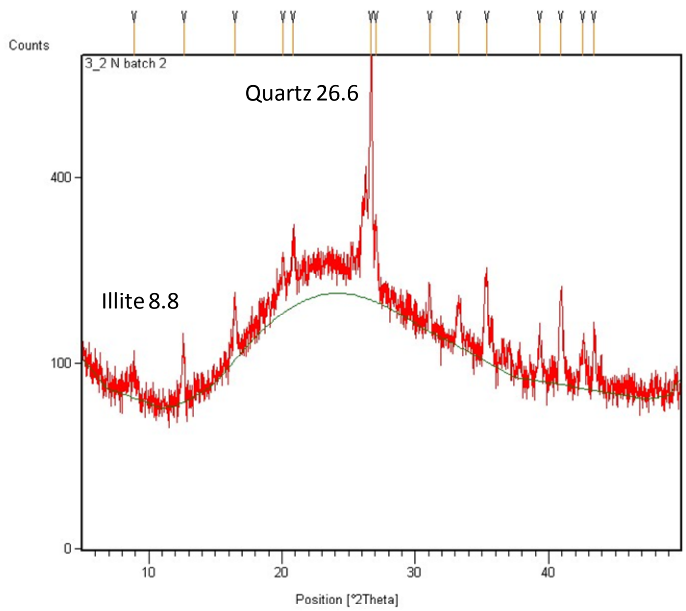
This diffractogram contains some illite, calcite is also present and is uncharacteristic of the lower Bakken



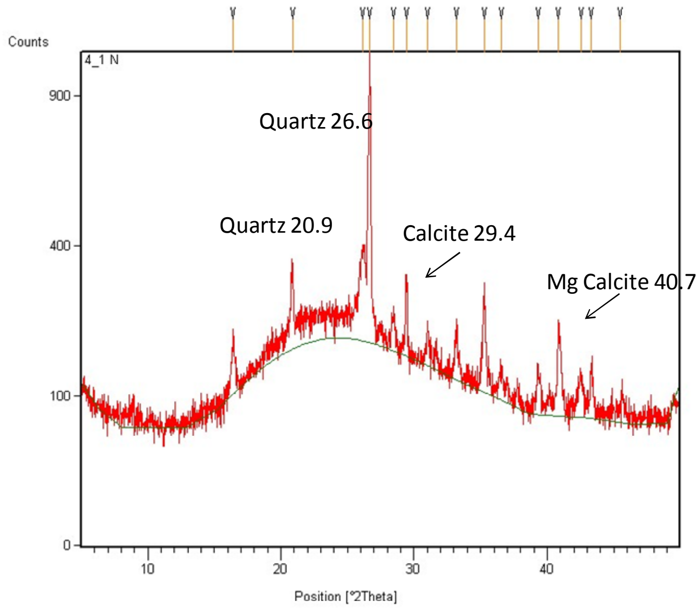
This diffractogram contains no illite and is uncharacteristic of the lower Bakken



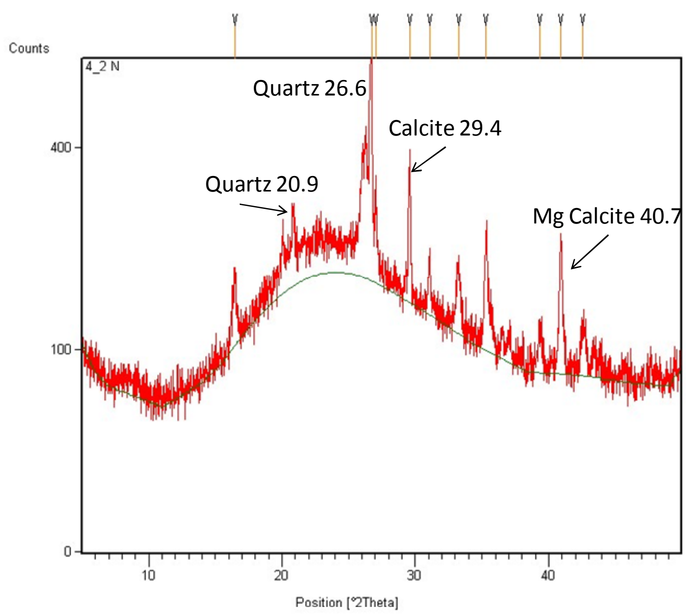
This diffractogram contains some illite, calcite is also present and is uncharacteristic of the upper Bakken



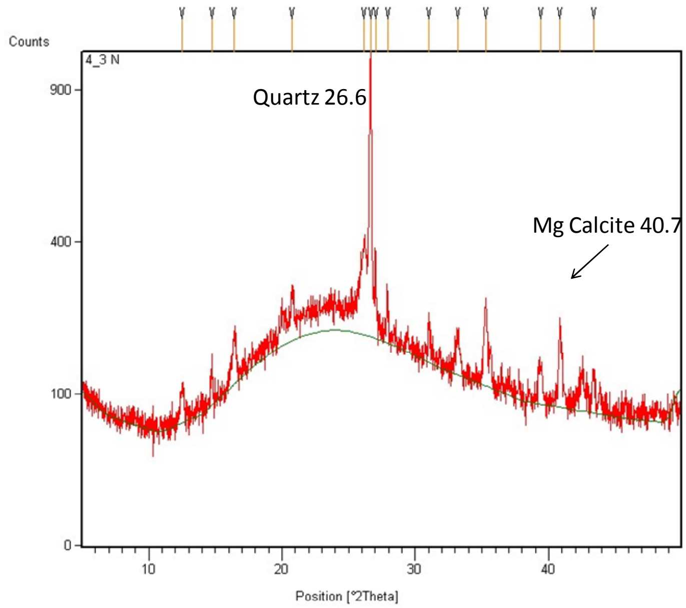
This diffractogram contains some illite and is characteristic of the lower Bakken



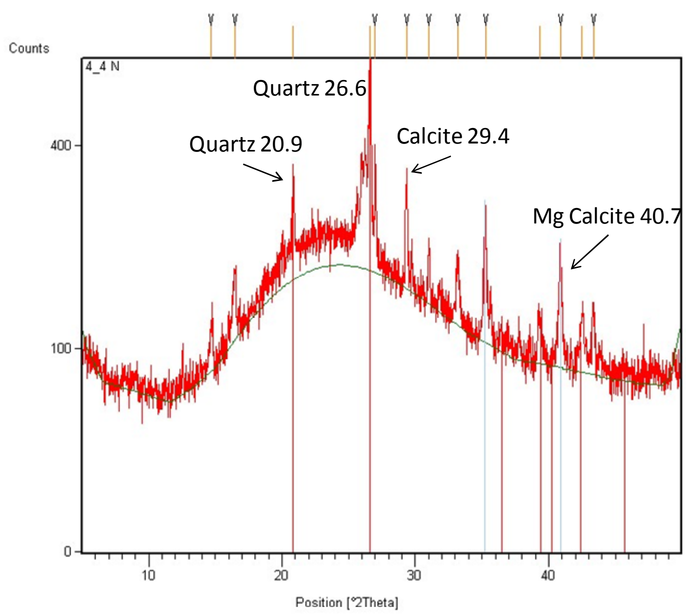
This diffractogram contains no illite, calcite is also present and is uncharacteristic of the upper Bakken



This diffractogram contains no illite, calcite is also present and is uncharacteristic of the upper Bakken



This diffractogram contains no illite and is uncharacteristic of the lower Bakken



This diffractogram contains no illite, calcite is also present and is uncharacteristic of the lower Bakken

APPENDIX B

Sample #	Slide #	Description	Lithology	%S	%C	%Q	Tot
EC113		same w/xpolar	MB	24	53	23	100
EC114		C-R	MB				0
EC115		same w/xpolar	MB	15	58	27	100
EC116		L	MB				0
EC117		same w/xpolar	MB	20	48	32	100
EC118	9351 10447.7	L	MB				0
EC119		same w/xpolar	MB	22	54	24	100
EC120		C	MB				0
EC121		same w/xpolar	MB	18	49	33	100
EC122		R w/xpolar	MB				0
EC123		R w/o xpolar	MB	14	36	50	100
EC124	9351 10480	C	MB				0
EC125		same w/xpolar	MB	12	21	67	100
EC126		L	MB				0
EC127		same w/xpolar	MB	12	43	45	100
EC128		R	MB				0
EC129		same w/xpolar	MB	23	24	53	100
EC130	8850 7403	U	MB				0
EC131		same w/xpolar	MB	28	30	42	100
EC132		M	MB				0
EC133		same w/xpolar	MB	11	27	62	100
EC134		L	MB				0
EC135		same w/xpolar	MB	28	41	31	100
EC136	8850 7413	U	MB				0
EC137		same w/xpolar	MB	8	17	75	100
EC138		M	MB				0
EC139		same w/xpolar	MB	9	23	68	100
EC140		L	MB				0
EC141		same w/xpolar	MB	12	16	72	100
EC142	8850 7424	U	MB				0
EC143		same w/xpolar	MB	17	38	45	100
EC144		M	MB				0
EC145		same w/xpolar	MB	14	32	54	100
EC146		L	MB				0
EC147		same w/xpolar	MB	14	23	63	100
EC148	Gone		MB				0

EC149	Gone		MB				0
EC150	Florida 3F6 10449-131	U	SH				0
EC151		same w/xpolar	SH	47	27	26	100
EC152		M	SH				0
EC153		same w/xpolar	SH	39	24	37	100
EC154	Image Bad	L	SH				0
EC155	Image Bad		SH				0
EC156	Image Bad	same w/xpolar	SH				0
EC157	Florida 3F6 10452.5-132	U	SH				0
EC159		same w/xpolar	SH	29	37	34	100
EC160		M	SH				0
EC161		same w/xpolar	SH	33	38	29	100
EC162		L	SH				0
EC163		same w/xpolar	SH	38	42	20	100
EC164	Florida 3F6 10456.5-134	U	SH				0
EC165		same w/xpolar	SH	31	30	39	100
EC166		M	SH				0
EC167		same w/xpolar	SH	28	34	38	100
EC168		L	SH				0
EC169		same w/xpolar	SH	22	33	45	100
EC170	7787 10795	C-RD	MB				0
EC171		same w/xpolar	MB	14	39	47	100
EC172	Gone		MB				0
EC173	Gone		MB				0
EC174	Gone		MB				0
EC175	Gone		MB				0
EC176		L	MB				0
EC177		same w/xpolar	MB	9	54	37	100
EC178		U-RD	MB				0
EC179		same w/xpolar	MB	13	67	20	100
EC180	gone						0
EC181	gone						0
EC182	9351 10456	U	SH				0
EC183		same w/xpolar	SH	38	33	29	100
EC184		M	SH				0
EC185		same w/xpolar	SH	34	45	21	100
EC186		L	SH				0
EC187	Image Bad		SH				0
EC188	Image Bad		SH				0
EC189		same w/xpolar	SH	46	32	22	100
EC190			SH				0

EC191	9351 10458	U w/xpolar	MB	19	41	40	100
EC192		U	MB				0
EC193		M	MB	23	37	40	100
EC194		same w/xpolar	MB				0
EC195		Retake M	MB				0
EC196		Retake M w/xpolar	MB				0
EC197		L	MB				0
EC198		same w/xpolar	MB	18	63	19	100
EC199	9351 10460	U	MB				0
EC200		same w/xpolar	MB	11	73	16	100
EC201		M	MB				0
EC202		same w/xpolar	MB	24	71	5	100
EC203		L	MB				0
EC204		same w/xpolar	MB	16	71	13	100
EC205	9351 10464	U	MB				0
EC206		same w/xpolar	MB	7	67	26	100
EC207		M-R	MB				0
EC208		Retake	MB	9	79	12	100
EC209		same w/xpolar	MB				0
EC210		L-L	MB	6	82	12	100
EC211		same w/xpolar	MB				0
EC212	9351 10467	U	MB	12	77	11	100
EC213		same w/xpolar	MB				0
EC214		M-L	MB	23	55	22	100
EC215		same w/xpolar	MB				0
EC216		L	MB	18	54	28	100
EC217		same w/xpolar	MB				0
EC218	12785 11261	U	MB	6	80	14	100
EC220		same w/xpolar	MB				0
EC221		M	MB	9	82	9	100
EC222		same w/xpolar	MB				0
EC223		L	MB	7	80	13	100
EC224			MB				0
EC225			MB				0
EC226		same w/xpolar	MB				0
EC227	12785 11270.5	U	MB	9	86	5	100
EC228		same w/xpolar	MB				0
EC229		L-L	MB	8	89	3	100
EC230		same w/xpolar	MB				0
EC231	12785 11282	U-R	MB	10	86	4	100
EC232		same w/xpolar	MB				0
EC233		M	MB	6	92	2	100

EC234		same w/xpolar	MB				0
EC235		L	MB	11	82	4	97
EC236		same w/xpolar	MB				0
EC237	12785 11304	U	MB	16	73	11	100
EC238		same w/xpolar	MB				0
EC239		M	MB	9	83	8	100
EC240		same w/xpolar	MB				0
EC241		L	MB	12	72	16	100
EC242		same w/xpolar	MB				0
EC243	12785 11314	L	SH	27	52	21	100
EC244		same w/xpolar	SH				0
EC245		M	SH	22	50	28	100
EC246		same w/xpolar	SH				0
EC247		U	SH	19	48	33	100
EC248		same w/xpolar	SH				0
EC249	12785 11324	U	MB	14	28	58	100
EC250		same w/xpolar	MB				0
EC251		M	MB	10	18	72	100
EC252		same w/xpolar	MB				0
EC253		L	MB	11	42	47	100
EC254		same w/xpolar	MB				0
EC255	12785 11340	U	MB	21	46	33	100
EC256		same w/xpolar	MB				0
EC257		M	MB	13	40	47	100
EC258		same w/xpolar	MB				0
EC259		L	MB	17	29	54	100
EC260		same w/xpolar	MB				0
EC261	12785 11347.5	U-R	SH	28	42	30	100
EC262		same w/xpolar	SH				0
EC263		M	SH	31	60	9	100
EC264		same w/xpolar	SH				0
EC265		L-R	SH	41	40	19	100
EC266		same w/xpolar	SH				0
EC267	12785 11358.5	U	SH	24	54	22	100
EC268		same w/xpolar	SH				0
EC269		M	SH	16	66	18	100
EC270		same w/xpolar	SH				0
EC271		L	SH	19	72	9	100
EC272		same w/xpolar	SH				0
EC273	4508 7515	U	MB	4	12	84	100
EC274		same w/xpolar	MB				0
EC275		M	MB	6	18	76	100
EC276	Image Bad	same w/xpolar	MB				0

EC277	Image Bad	L	MB				0
EC278	Image Bad	same w/xpolar	MB				0
EC279		L	MB	8	24	68	100
EC280		same w/xpolar	MB				0
EC281	4508 7504	U	MB	9	19	72	100
EC282		same w/xpolar	MB				0
EC283		M	MB	14	31	55	100
EC284		same w/xpolar	MB				0
EC285		L	MB	16	40	44	100
EC286		same w/xpolar	MB				0
EC287	4508 7517	U	MB	8	33	59	100
EC288		same w/xpolar	MB				0
EC289		M	MB	11	23	66	100
EC290		same w/xpolar	MB				0
EC291		L	MB	16	31	53	100
EC292		same w/xpolar	MB				0
EC293	4508 7503-04	U	SH	24	62	14	100
EC294		same w/xpolar	SH				0
EC295		M	SH	8	84	8	100
EC296		same w/xpolar	SH				0
EC297		L	SH	11	82	7	100
EC298		same w/xpolar	SH				0
EC299	4508 7504-05	U	SH	29	52	19	100
EC300		same w/xpolar	SH				0
EC301		M	SH	24	65	11	100
EC302		same w/xpolar	SH				0
EC303		L	SH	19	55	26	100
EC304		same w/xpolar	SH				0
EC305	4508 7545	U w/xpolar	SH	21	74	5	100
EC306		U	SH				0
EC307		Ua	SH	31	51	18	100
EC308		same w/xpolar	SH				0
EC309	4508 7546	UL	SH	65	28	7	100
EC310		same w/xpolar	SH				0
EC311		UR	SH	80	15	5	100
EC312		same w/xpolar	SH				0
EC313		L	SH	85	13	2	100
EC314		same w/xpolar	SH				0
EC315	4508 7529	U-L	SH	85	10	5	100
EC316		same w/xpolar	SH				0
EC319		L-R	SH	86	12	2	100
EC320		same w/xpolar	SH				0

APPENDIX C

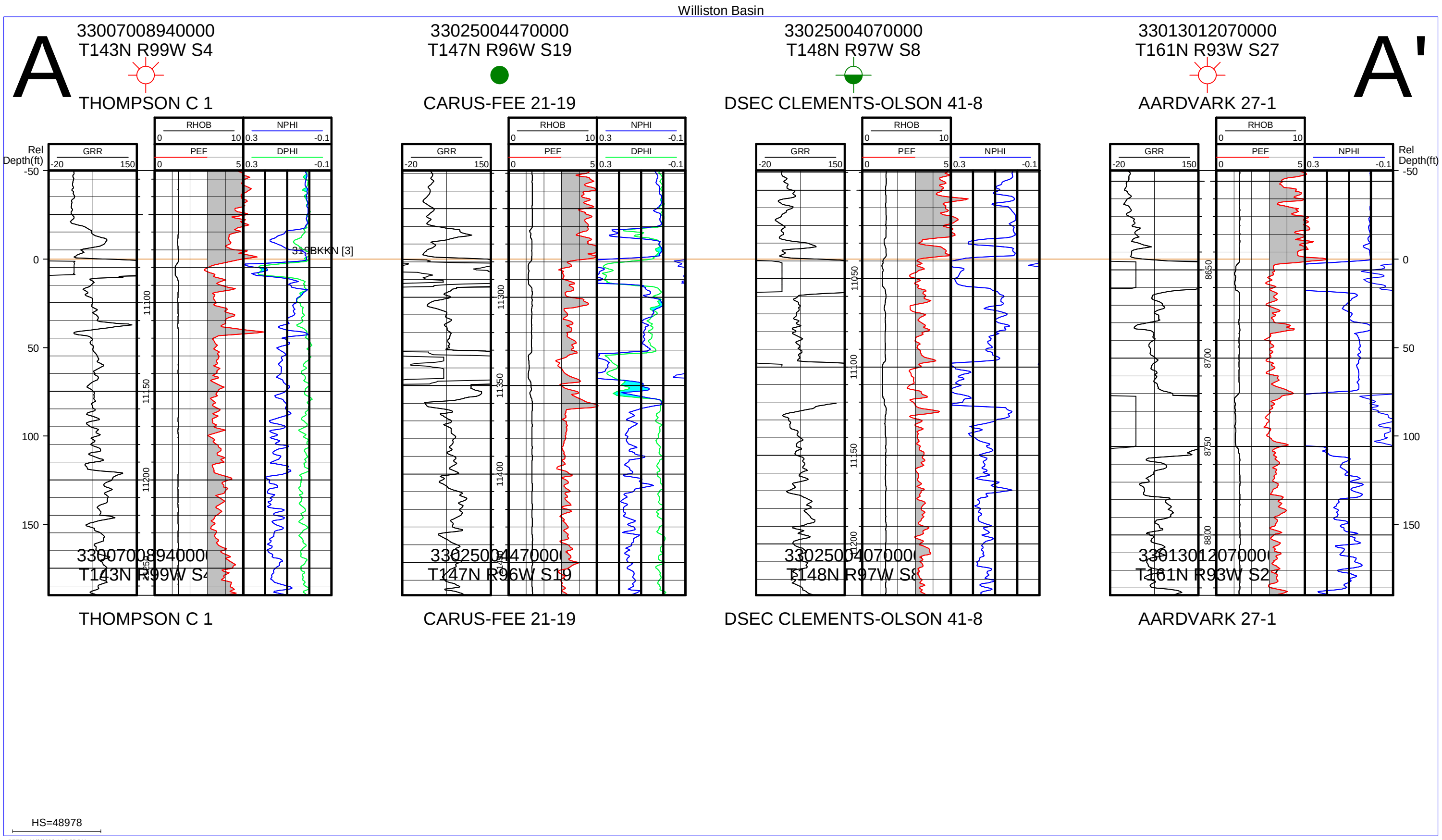


Figure 17. Cross section showing portions of the wireline logs of wells in the study area. The stratigraphy of the Bakken Formation interval is marked.

VITA

Stuart Lee Barnes

Candidate for the Degree of

Master of Science

Thesis: EVALUATION OF X-RAY DIFFRACTION OF BIT CUTTINGS AS A PROXY FOR CORE DATA IN DETERMINING BULK MINERALOGY AND CLAY SPECIES, BAKKEN FORMATION, WILLISTON BASIN

Major Field: Geology

Biographical:

Personal Data:
Married for 12 years with three sons. Captain in the Army Reserves and have deployed to both Iraq and Afghanistan

Education:
Completed the requirements for the Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in May 2011

Experience:
One year developmental geology experience with Continental Resources, Inc., one year exploration geology with Devon Energy, Inc.

Professional Memberships: AAPG

Name: Stuart Lee Barnes Date of Degree: May, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: EVALUATION OF X-RAY DIFFRACTION OF BIT CUTTINGS AS A PROXY FOR CORE DATA IN DETERMINING BULK MINERALOGY AND CLAY SPECIES, BAKKEN FORMATION, WILLISTON BASIN

Pages in Study: 103 Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study: The principal question addressed in this study concerns the applicability of x-ray diffractometry to determine bulk rock mineralogy and clay species in the absence of core in the Bakken Formation. For this study, samples of bit cuttings and thin sections from core obtained from the North Dakota Geological Survey were analyzed and the results compared to determine if cuttings are a viable substitute for core.

Findings and Conclusions: The results illustrate that often there is not a sufficient enough correlation between the XRD, log and thin section data to conclude that XRD can serve as a universal substitute for core data. However, the implication of bit cuttings analysis may provide a less-expensive technique to determine bulk and clay mineralogy, that in turn may be used to predict drilling hazards associated with swelling clays and elasticity of rocks to be stimulated for oil and gas production. Furthermore, bulk mineralogy, coupled with visual examination of cuttings should strengthen correlations of x-ray derived data to lithofacies.

ADVISER’S APPROVAL: Dr. James Puckette