

**SEDIMENTOLOGY AND DIAGENESIS OF THE BAKKEN FORMATION
IN DALY FIELD, SOUTHWEST MANITOBA**

BY

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A Thesis

Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree of

MASTER OF SCIENCE

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Abstract

The Bakken Formation (Devonian-Mississippian) is a relatively thin unit that can be found throughout the Williston Basin. The unit consists of upper and lower black, organic-rich shales separated by a calcareous siltstone. These units have been informally defined as the Upper, Lower, and Middle Bakken respectively.

In the Daly field, southwestern Manitoba, the Lower Bakken is absent and the Middle Bakken has a sharp erosional contact with the underlying Devonian Lyleton Formation. The Upper Bakken has a conformable contact with the overlying Mississippian Lodgepole Formation.

The Middle Bakken is subdivided into three subunits: 1) the Massive Unit, 2) the Horizontal Laminated Unit, and 3) the Wavy Laminated Unit. These subunits are composed mainly of quartz, dolomite, and clay minerals, with variable amounts of anhydrite, gypsum, K-feldspar, pyrite, plagioclase, calcite, and halite. The amount of quartz decreases upwards in the section whereas the clay mineral content increase.

The Bakken Formation was deposited on a shallow marine, non-barred, low wave energy shoreline. The Lower Bakken was deposited during a transgression and then later eroded from the Daly field area during a period of regression. The Middle and Upper Bakken were then deposited during a subsequent transgression.

After deposition, the Bakken Formation experienced a series of chemical diagenetic changes. Shortly after deposition, there was the formation of authigenic pyrite and dolomite which was later followed by the formation of authigenic illite and the

dissolution of detrital K-feldspar. Later in diagenesis, there was continued formation of authigenic illite and formation of quartz overgrowths on detrital quartz grains. Somewhat later in diagenesis illite stopped precipitating and authigenic K-feldspar precipitation occurred. Towards the end of the diagenetic history of the Bakken Formation there was formation of coarsely crystalline, pore-lining dolomite, conversion of pyrite into hematite, and precipitation of anhydrite, gypsum, and halite.

Acknowledgements

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Chapter 1: Introduction

1.1 General Introduction

The Bakken Formation was named by Nordquist (1953), who defined the type section as "the strata occurring between the depths of 9615 and 9720 feet in the Amerada Petroleum Corporation-H. O. Bakken No. 1 deep test, C SW NW sec. 12, T. 157 N., R. 95 W., Williams County, North Dakota." He described the unit as a black, fissile, very slightly calcareous shale underlain by a light grey to grey-brown, very fine-grained, calcareous sandstone, interbedded with minor amounts of grey-brown cryptocrystalline limestone. This was, in turn, underlain by another black, fissile, very slightly calcareous shale. These units have been defined informally as the Upper, Middle, and Lower Bakken respectively. In North Dakota and Montana, the Bakken Formation ranges in thickness from a maximum of 44 m in western Mountrail County, North Dakota, to a feather edge along its depositional limit (Figure 1) (Webster, 1984). Webster (1984) and Meissner (1978) demonstrate that the three members of the Bakken Formation show an onlapping relationship, with the progressively younger units being more aerially extensive than the previous ones and with each unit thinning to a feather edge to the east in North Dakota. The depositional edge of the Bakken is not found in Manitoba as the formation is truncated by the Mississippian-Jurassic unconformity (McCabe, 1959). The Lower Bakken is almost entirely missing in Manitoba, except for a small area in the southernmost part of the province in the Waskada area (McCabe, 1959).

The age of the Bakken Formation has been determined to be Late Devonian to

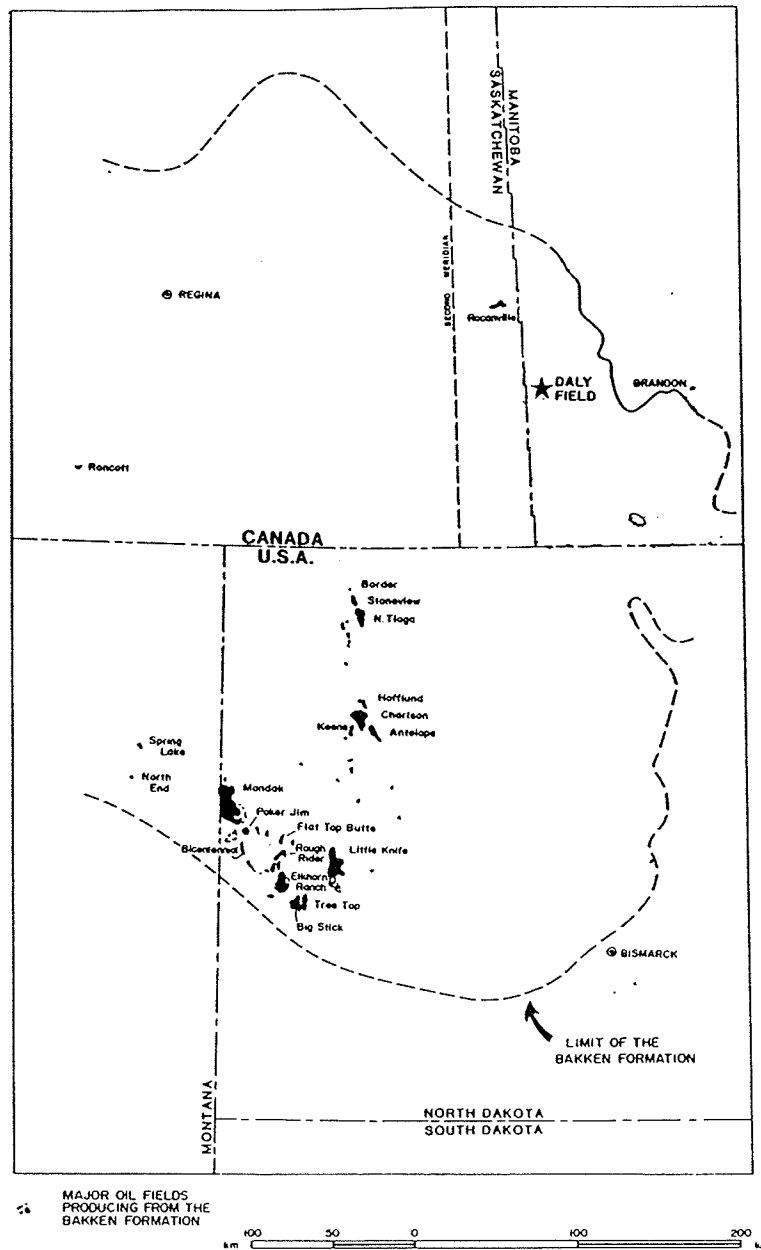


Figure 1

Map showing the limit of the Bakken Formation, which in North Dakota is the depositional limit and in Manitoba is an erosional truncation. Also shown are the major oil fields producing from the Bakken Formation. The star denotes the Daly Field, which is the study area for this project. (Modified from Martiniuk, 1988).

Early Mississippian. The Devonian-Mississippian boundary in North Dakota, which was determined through the study of conodonts (Holland *et al.*, 1987) and brachiopods (Thrasher, 1987), is placed in the upper part of the Middle Bakken.

1.2 Stratigraphy

The stratigraphy in the Bakken Formation is similar to that of the general stratigraphic sequence which covers the Devonian-Mississippian boundary in North America (Gutschick and Moreman, 1967). Devonian carbonates, overlain by Late Devonian-Early Mississippian black shales and light coloured clastic sediments, followed by Early Mississippian dark shales and silt- or sandstones overlain by Mississippian carbonates comprise the general Devonian-Mississippian sequence. This corresponds with the sequence in the Bakken Formation in which the shales and carbonates of the Lyleton/Three Forks are overlain by the black shales and light coloured clastic sediments of the Lower and Middle Bakken followed by the dark shales and silt- and sandstones of the Middle and Upper Bakken. This is, in turn, overlain by the Mississippian Lodgepole carbonates.

In Manitoba, the Bakken Formation unconformably overlies the Devonian Lyleton Formation (known as the Three Forks Group in North Dakota, Montana, and Saskatchewan), a green and red shale with dolomitic bands. The contact between the Bakken Formation and the Lyleton Formation is identified in core by the presence of a sudden change in lithology from shale to sandstone and the presence of a breccia at the top of the Lyleton Formation. The Bakken Formation is, in turn, overlain by the Mississippian Lodgepole Formation, a cherty argillaceous limestone. The contact

between the Lodgepole and the Bakken is conformable in Manitoba but Kent (1984) has reported that the contact becomes unconformable in western Saskatchewan.

1.3 Correlations

Meissner (1978) indicates that the formations correlative to the Bakken Formation include the Exshaw/Banff Formations in the Alberta Basin/northern Rocky Mountains; the Pilot Formation in the Cordilleran area; the "Lower Mississippian Black Shale" in the Permian Basin; the Woodford Formation in the Anadarko Basin/Arbuckle Mountains; the Chattanooga Shale in the eastern Mid-Continent/Southern Appalachian Basin; the Antrim Formation in the Michigan Basin; and the New Albany Formation in the northern Appalachian Basin. As formally defined by Nordquist (1953), however, the Bakken Formation only appears in the subsurface in Manitoba, Saskatchewan, North Dakota, and Montana (Figure 1).

Sandberg and Klapper (1967) suggest that the Lower and Middle Members of the Bakken Formation are laterally continuous with the Exshaw Formation in Alberta (Figure 2), with the Upper shale having been eroded away. They also propose that the black shales of the Exshaw and the Sappington Member of the Three Forks Formation in Montana are also laterally continuous, with the siltstone units being separated by an erosional area approximately 65 kilometres wide in northwestern Montana.

1.4 Objectives of Study

Previously, little work had been done specifically on the lithology and diagenesis of Bakken Formation. Most of these previous studies have concentrated mainly on the petroleum source rock characteristics and potential of the unit (Dembicki and Pirkle,

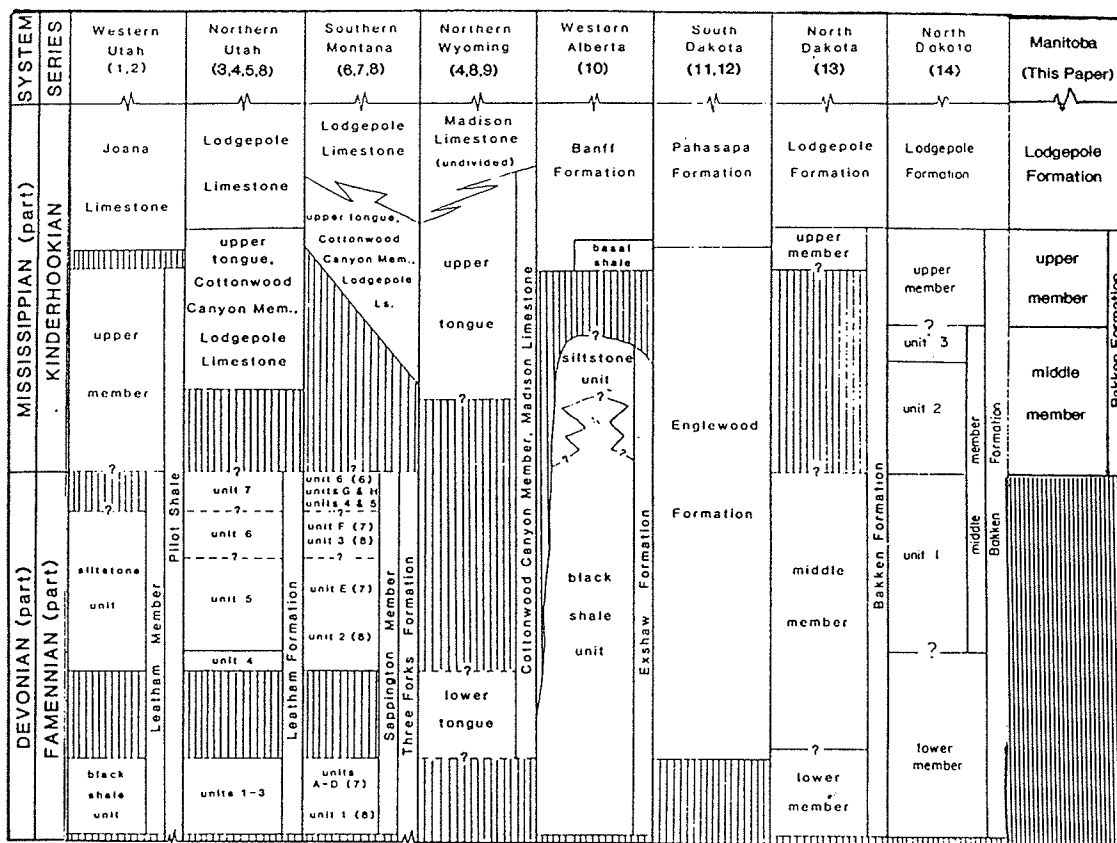


Figure 2

Correlation of the Bakken Formation with other units in its depositional complex in the Western Interior of North America. Sources of information for each column correspond to numbers enclosed in parentheses as follows: (1) Gutschick and Rodriguez (1979), (2) Sandberg *et al.* (1980), (3) Sandberg and Gutschick (1969), (4) Sandberg and Poole (1977), (5) Sandberg and Gutschick (1979), (6) Gutschick *et al.* (1962), (7) Sandberg (1965), (8) Sandberg and Klapper (1967), (9) Sando (1967), (10) Macqueen and Sandberg (1970), (11) Klapper and Furnish (1962), (12) Klapper (1966), (13) Hayes (1985), (14) Holland *et al.* (1987). Modified from Holland *et al.* (1987).

1985, Price *et al.*, 1984, Webster, 1984, Schmoker and Hester, 1983, Meissner, 1978, Dow, 1974, and Williams, 1974) and on the sedimentology of the unit (Martiniuk, 1988, Webster, 1984, Meissner, 1978, Christopher, 1961, McCabe, 1959, and Fuller, 1956). The purpose of this study is to further refine the depositional model of the Bakken Formation in the Daly field in Manitoba, and to understand the diagenesis, as well as some of the reservoir characteristics of the Middle Member of the Bakken Formation. The results of this study will further the understanding of the deposition and diagenesis of the Mississippian strata in Manitoba as well as assist in defining possible targets for further petroleum exploration in the basin.

Chapter 2: Study Area and Methodology

2.1 Study Area

The study area is the region contained between townships 8 and 11 and ranges 27 and 29¹, which includes the Daly field (Figure 3). This is the only area in Manitoba in which the Bakken Formation has been found to contain economic quantities of oil.

2.2 Open Hole Logs and Core Analyses

One way in which the Bakken Formation is being studied is through the use of open hole geophysical logs. The well logs for all of the 87 wells that had penetrated the Bakken Formation up to July, 1988 were obtained from the files at the Petroleum Division of the Manitoba Department of Energy and Mines. The compensated neutron logs were then photocopied if these logs were present and if not, the gamma ray logs were copied. Core analyses for 23 Bakken cores were also copied from the files of the Petroleum Division of the Manitoba Department of Energy and Mines.

2.3 Core Examination

All of the available cores from the study area (Table 1) have been logged, sampled, and photographed. During the visual logging, sedimentary structures, zones of macroscopic porosity, and lithologic variations were recorded. The colour of the core was determined using a Munsell Soil Colour Chart. The sampling locations on the cores were at the contacts between the different units and toward the centre of the units. Some samples were also taken of features such as unique sedimentary structures and areas of

¹ All ranges in this document are West Prime Meridian unless otherwise noted.

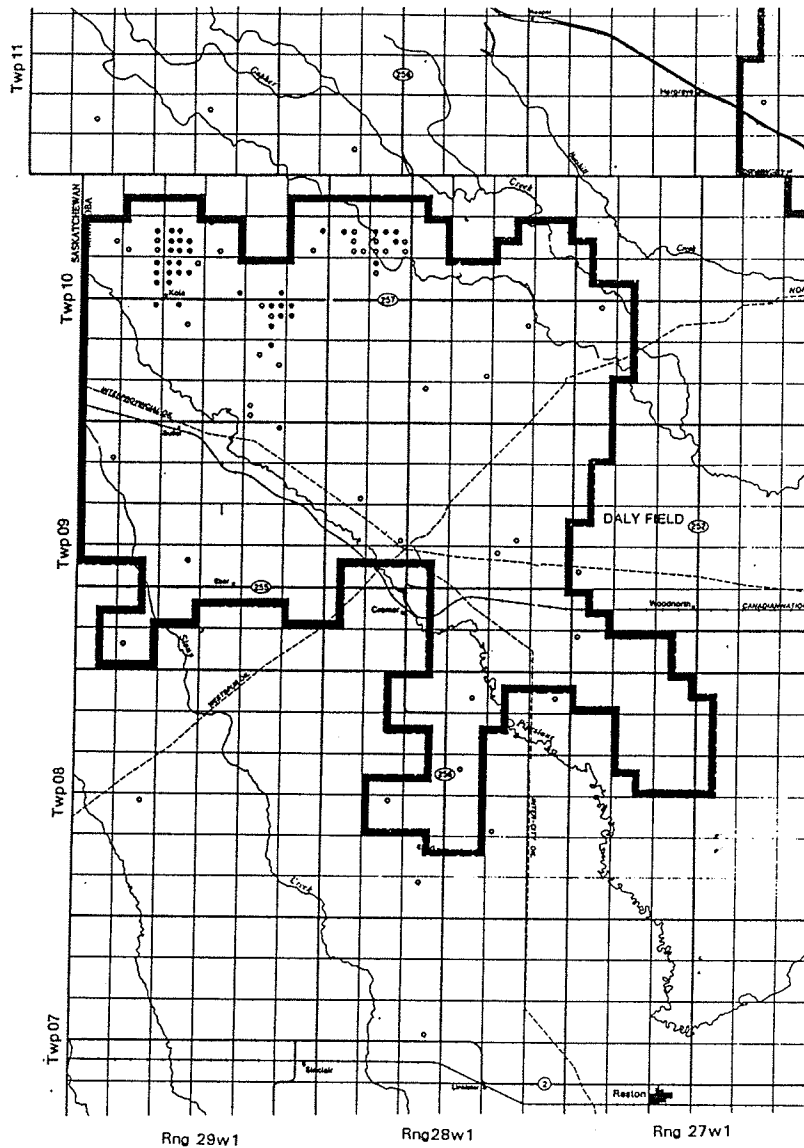


Figure 3

Map of the study area showing the Dominion Land Survey (DLS) lines, geographic, and cultural features. Also included are the locations of the wells drilled previously to July, 1988 that have penetrated the Bakken Formation. Wells which are producing oil are shown as solid circles, dry wells are shown as open circles. Modified from Manitoba Department of Energy and Mines, Petroleum Division Map No. 7.

Table 1: Cores Logged

The core locations are shown in the form of Legal Subdivision (LSD) - Section - Township - Range.

| | | |
|-------------|-------------|-------------|
| 05-18-09-27 | 08-14-10-28 | 11-21-10-29 |
| 15-18-10-27 | 12-20-10-28 | 01-23-10-29 |
| 15-12-11-27 | 03-29-10-28 | 02-25-10-29 |
| 02-21-07-28 | 10-29-10-28 | 13-27-10-29 |
| 14-04-08-28 | 11-29-10-28 | 03-28-10-29 |
| 15-17-08-28 | 12-29-10-28 | 04-28-10-29 |
| 11-22-08-28 | 10-30-10-28 | 05-28-10-29 |
| 07-36-08-28 | 09-05-11-28 | 01-29-10-29 |
| 13-14-09-28 | 01-31-09-29 | 04-29-10-29 |
| 01-20-09-28 | 11-11-10-29 | 08-29-10-29 |
| 02-23-09-28 | 14-16-10-29 | 09-29-10-29 |
| 01-30-09-28 | 09-20-10-29 | 7A-08-11-29 |
| 14-04-10-28 | 05-21-10-29 | 11-11-11-29 |

strong lithologic variation, such as pyrite bands. Samples from a few of cores were then subsampled for petrographic thin section and scanning electron microscopic examination, as well as X-ray diffraction analysis. Core descriptions can be found in Appendix 1 and sampling locations in Appendix 2.

2.3.1 X-Ray Diffraction Analysis

The bulk mineralogy of the rocks of the Bakken Formation was determined by the use of X-ray diffraction techniques. Chips were taken from the core, ground to a powder, and mounted on a standard petrographic slide (Klug and Alexander, 1974). The samples were then irradiated in one direction from 5 degrees two theta to 65 degrees two theta using a Philips PW1710 Powder Diffractometer. Scanning speed was set at 6 degrees two theta per minute with a sampling interval of 0.4 seconds. Other instrument settings were: 1 degree beam slit, 0.01 cm detector slit, and a 0.01 degree two theta step size.

By comparing the X-ray diffraction data to the table produced by Chen (1977) the different minerals present in the bulk samples were determined. Subsequent to determining the minerals that were present, the X-ray diffraction data were quantified by the method described by Schultz (1964). This technique involves measuring the intensity of the main X-ray diffraction peak of a mineral and then comparing this to the intensity of the main peak of a pure sample, in effect, applying an "intensity factor" (see Appendix 3). The values for all the minerals in the sample were then totalled and normalized to one hundred to give percentage values. Replicate analyses using this procedure give results within ± 8 percent (Last, 1980).

2.3.2 Petrography

Core samples were studied by two different petrologic techniques: thin section petrography and scanning electron microscope petrography. The nomenclature system used (Figure 4) is based loosely on Selley (1988), and Shepard (1954).

2.3.2.1 Thin Section Petrography

Samples from some of the cores were studied by thin section petrography. In order to produce thin sections, small slabs (2cm x 3cm) were cut from the core samples. The slabs were then impregnated with an epoxy which had been dyed blue, so that the porosity present in the rock would be easy to see in the thin section. The slabs were then polished and the polished surface was epoxied to a standard petrographic slide. The rock was then ground down to a 30 μm thickness to produce a thin section for use with a standard petrographic microscope. The thin sections were coated with a removable clear coating so that they could be studied under a cathode luminescence microscope. An uncoated sample is required for cathode luminescence microscopy.

2.3.2.2 SEM Petrography

The scanning electron microscope (SEM) is an instrument that allows the user to look at a three dimensional surface at very high magnifications (up to approximately 400,000X). A Cambridge Instruments Stereoscan 120 coupled with a Kevex Unispec 7000 energy dispersive X-ray (EDX) spectrometer was used in this study. The SEM was used with a 20 kV setting on the electron gun. The EDX allows for the qualitative identification of the elemental composition of a mineral under study by producing X-Ray energy spectrum of the grain under investigation. The element is identified by comparing

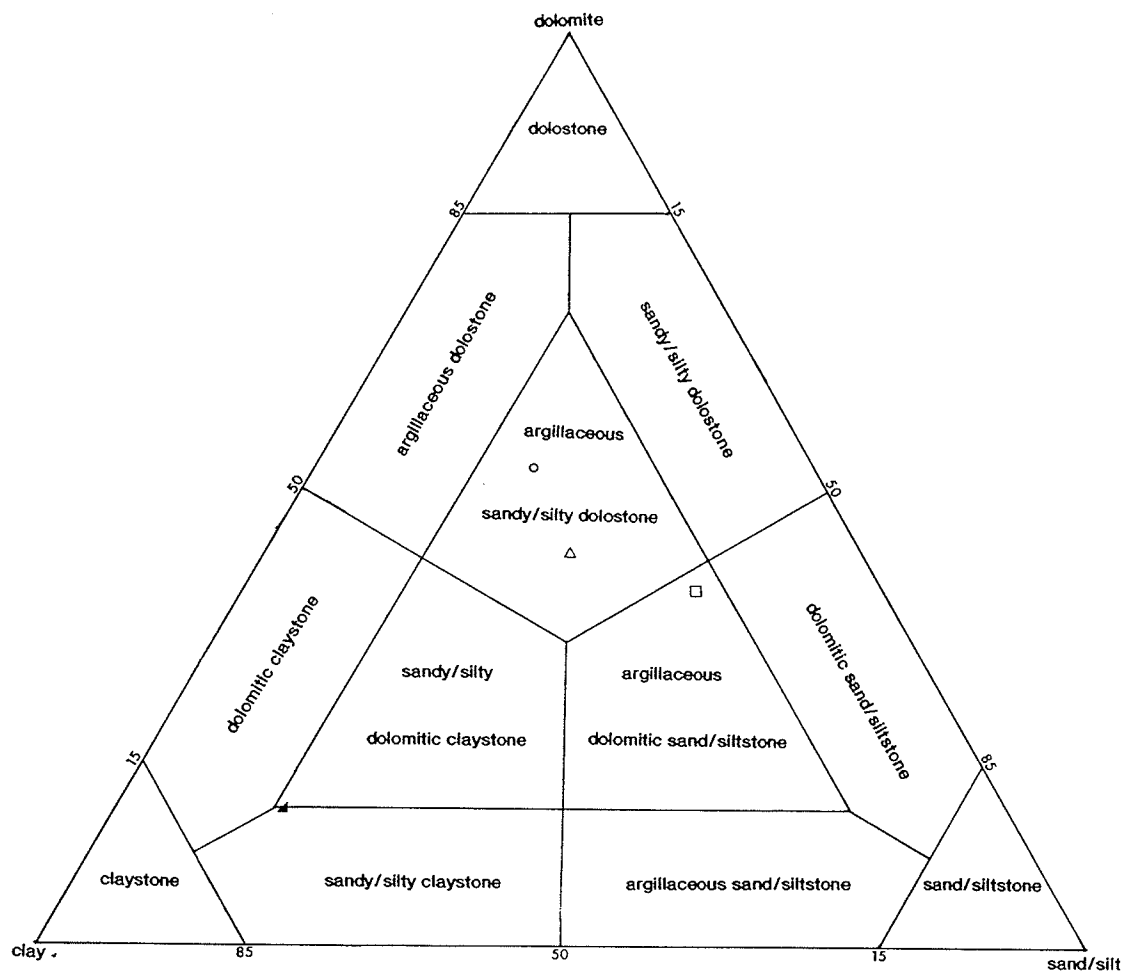


Figure 4

Diagram showing the classification of sedimentary rocks based on the proportions of dolomite, clay minerals and silt/sand. Based loosely upon Selley (1988) and Shepard (1954). The average composition of the units of the Bakken are plotted as follows: (▲) Shale Unit, (●) Massive Unit, (△) Horizontal Laminated Unit, and (□) Wavy Laminated Unit.

the position of the peaks in the energy spectrum to a table of the energy spectra of all the naturally occurring elements.

To analyze the core, small chips (averaging 5mm x 5mm) were removed from selected core samples and then cemented to 1 cm round aluminum stubs with silver cement. The stubs with the samples were then sputter coated with a gold-palladium alloy to provide a conductive coating. The conductive coating and cement are required in order to avoid charging of the sample under the electron beam of the SEM, as charging severely degrades the image quality.

A total of 46 samples from 8 cores were examined. Sample locations are listed in Table 2. The technique used was to scan the sample horizontally with a separation between scan lines of approximately 150 μm . Magnification was set to about 1000X, producing a field of view of about 100 μm . During the scanning procedure, variations in the grain morphology, grain size, and the arrangement of grains were noted. Photographs were taken of both typical and unique grain morphologies and textures. The EDX spectra, which gives a qualitative elemental analysis, was used in combination with grain morphologies to determine the mineralogy of the grains.

Table 2: SEM Samples

See Appendix 2 for sample depths. Letters after the sample number indicates that more than one subsample was taken from that core sample.

| Core | Samples |
|-------------|-------------------|
| 11-22-08-28 | : 1,2,3,4,5,6,7,8 |
| 08-14-10-28 | : 1A,1B,2A,2B,3,4 |
| 12-20-10-28 | : 1A,1B,3,4,5 |
| 11-29-10-28 | : 1,2,3,4,5,6 |
| 11-11-10-29 | : 3 |
| 11-21-10-29 | : 2,3,4,5,6,7,8,9 |
| 02-25-10-29 | : 1,3,4,5,6,7 |
| 11-11-11-29 | : 1,2,3,4,5,7 |

Chapter 3: Previous Work

3.1 Sedimentology

Some of the earliest work done on the Bakken Formation in Canada was by Fuller (1956) who divided the Bakken Formation in southeastern Saskatchewan and southwestern Manitoba into three different regions: 1) the central area of "normal" succession and lithology, 2) the eastern, or Manitoba shelf of attenuated succession; and 3) the northwestern area of beds with variegated colour (Figure 5). In the "normal" succession, the Bakken Formation is very similar to the type section in North Dakota as defined by Nordquist (1953). The lowermost unit is a black shale (the Lower Bakken) that is organic-rich with some fossils (*Lingula*, conodonts and "spore" cases). This shale is overlain by arenaceous beds (the Middle Bakken) consisting mostly of grey siltstone and fine grained sandstone that are uniform in colour and texture and cemented by calcareous material. These beds have sparse fauna, most of which is slightly to heavily pyritized, finely ribbed brachiopods, *Lingula*, and occasional crinoid ossicles. Fuller (1956) suggests that most of the fluctuations in the thickness of the Bakken Formation in southeastern Saskatchewan and southwestern Manitoba are due to thickness changes in the arenaceous beds. The upper shale (the Upper Bakken), in most respects, closely resembles the lower shale, but extends over a greater area, with its thickness nowhere exceeding 4m in the area studied by Fuller (1956).

In the marginal areas described by Fuller (1956), the lower shale is absent on the eastern shelf and the arenaceous beds lie directly on top of the Three Forks Group

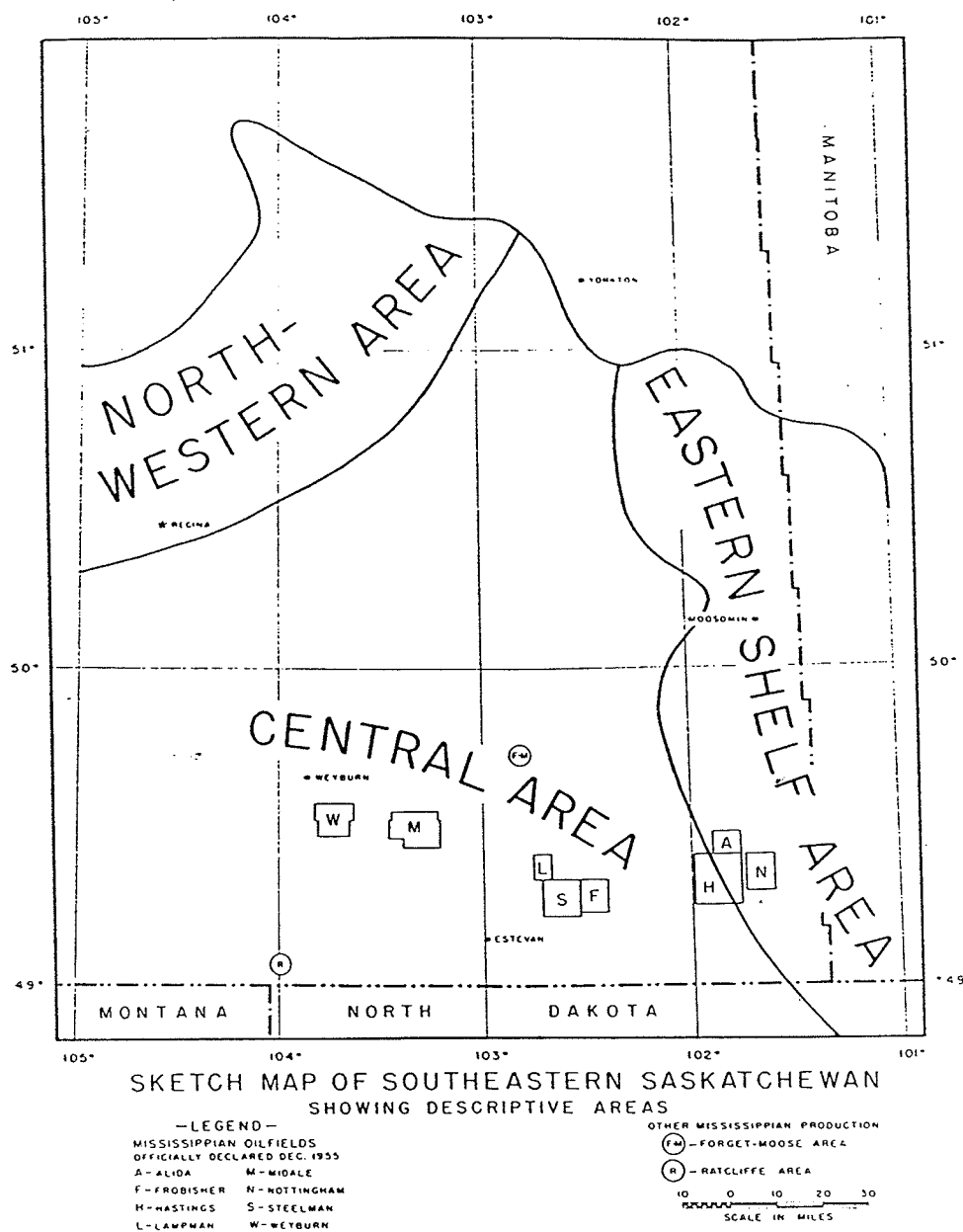


Figure 5

Map showing the northwestern, central, and eastern shelf areas defined by Fuller (1956). Also shown are the Mississippian oil fields in Saskatchewan known up to December, 1955. From Fuller (1956).

(referred to as the Qu'Appelle Group by Fuller (1956)). In the northwest, however, the expected stratigraphic position of the lower black shale is occupied by pale-green and ochreous variegated shales, which closely resemble those of the Three Forks Group. Among the arenaceous beds of the marginal areas, variations in texture and bedding become more pronounced with strong lamination, abrupt variations in the grain size between silt and sand, and numerous grey-shale seams.

Fuller (1956) proposes that the Lyleton Formation of Manitoba is the lowermost portion of the Three Forks Group, in which the upper members have been eroded away. He also found a pebble conglomerate under the Bakken Formation in parts of Saskatchewan. The pebble bed is not only under the area where the lower shale is missing, but it also extends under the lower shale, indicating a period of erosion before the deposition of the lower shale. Fuller (1956) did not find the pebble conglomerate between the Middle and Lower Members of the Bakken Formation.

McCabe (1959) found the Bakken Formation in Manitoba was similar to what was observed by Fuller (1956) in Saskatchewan. The Lower Bakken, however, was generally missing except for in some wells in the Waskada area. McCabe (1959) noted a large thickness (up to 10 metres) of intraformational breccia near the top of the Lyleton Formation. He also observed that the grain size of the Middle Bakken clastic sediments increases to the north and east and that there is a prominent red coloration in some of the wells to the north. His petrographic study of the Middle Bakken showed that the sands and silts are composed primarily of quartz, with up to 5% feldspars. The maximum grain size of the quartz and feldspar is about 0.2 mm (fine sand), but most of the

material is very fine sand or coarse silt. The coarser sand grains are predominantly sub-rounded. In samples from one well (10-8-15-27), McCabe (1959) observed what appeared to be irregular, eroded quartz overgrowths on rounded grains, indicating that the sediment had been reworked from a pre-existing sedimentary rock. The Upper Bakken thins considerably to the north to only one metre of medium grey to slightly reddish and yellow shale, showing a bright red streak.

Christopher (1961) describes the Bakken Formation in a manner similar to Fuller (1956) and McCabe (1959) but indicates there are some minor differences. Whereas Fuller (1956) and McCabe (1959) did not interpret a hiatus in deposition between the Lower Bakken and the Middle Bakken, Christopher (1961) found evidence of an erosional contact between the two units. Another difference in the description by Christopher (1961) is that he divides the Middle Bakken into two major subdivisions which are designated the "A" beds and the "B" beds.

The "A" beds consist of a massive, very calcareous, greenish grey, pyritiferous, fossiliferous, very fine grained to silty sandstone about 3 to 10 metres thick. Bedding, though present in some locations, is generally disrupted by bioturbation, and fossils, mostly brachiopods, are generally restricted to the lower 1.5 to 3 metres. The "A" beds pinch out to the east.

The "B" beds are further subdivided into B₁, B₂, B₃, and B₄ from the bottom to the top of a shale-sandstone alternation (Figure 6). The shale tongues emerge eastward, northward and southward from an argillaceous depositional area located between Swift Current and Old Wives Lake, where the "B" beds consist wholly of dark grey to grey-

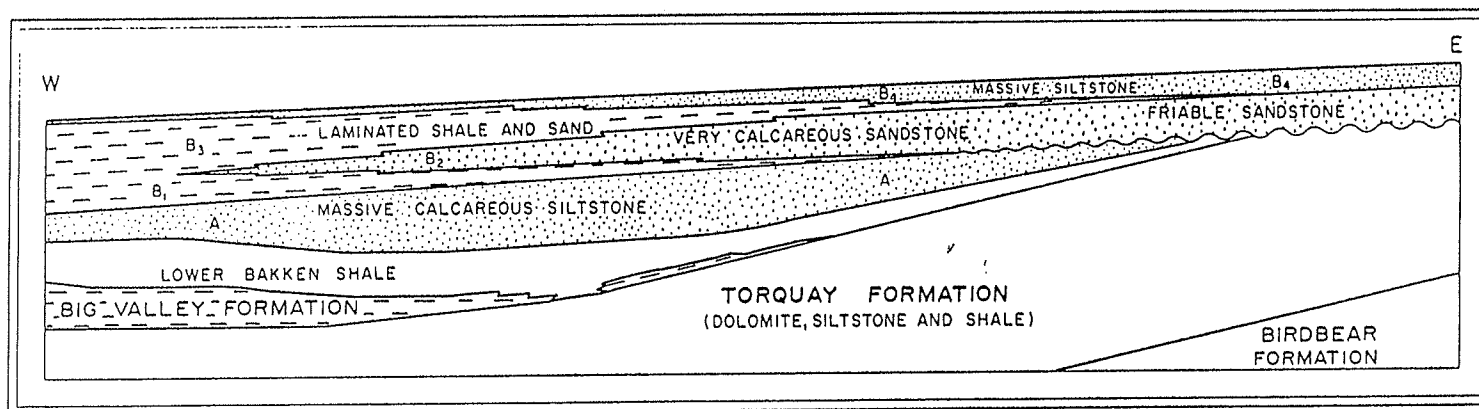


Figure 6

Generalized west to east stratigraphic cross-section south of latitude 50 degrees from western Saskatchewan to the Manitoba border showing facies relationships within the Middle Bakken sandstone member (Units A, B₁, B₂, B₃ and B₄). From Christopher (1961).

black shale with minor silty bodies. Away from this area, especially toward the east on the extreme eastern shelf area near range 1 W2M, the two shale tongues (B_1 and B_3), feather out into sandstone and siltstone. Thus, in this eastern area the two sandstone bodies (B_2 and B_4) constitute the Middle Bakken Member, and are characterized by massive, fossiliferous, silty sandstones or coarse siltstone bodies (B_4), 1.5 to 4.5 metres thick, resting on bedded, friable, fine to medium sandstone (B_2), 3 to 4.5 metres thick. The B_2 unit projects westward across the southeastern part of Saskatchewan as a well-cemented, calcareous, medium grained sandstone and oolitic calcarenite. The B_2 unit loses its identity by passing into silty sandstone, then into laminated grey-black shale and sandstone west of the Roncott area between ranges 1 and 3 W3M. Throughout its extent, the B_2 unit exhibits well developed cross-bedding, ripple marks, current scour marks, and numerous diastems. The upper contact of the B_2 unit is usually gradational, passing through silty sandstone with rolled and broken bedding into laminated sandstone and grey-black shale of the B_3 unit. The upper unit of the eastern shelf area (B_4) thins irregularly westward and its basal contact grades downward into the B_3 unit.

The upper contact of the Bakken Formation was further defined by Kent (1974), who found that the contact varies from conformable in southeastern Saskatchewan to unconformable in the west where progressively older Bakken strata are overlain by basal Madison Group rocks. In extreme southwestern Saskatchewan, the Madison Group rests on the lowermost beds of the Bakken Formation.

Meissner (1978) further studied the Upper and Lower Members of the Bakken Formation, finding that in thin section the shales are composed mostly of indistinct

organic material with lesser amounts of clay minerals, silt, and dolomite grains. The Lower Bakken shale becomes less organic-rich and more clay-rich, silty, and dolomitic near its depositional edge, particularly on the western flank of the basin.

The Upper and Lower Bakken in North Dakota are hard, siliceous, pyritic, fissile, generally noncalcareous, and organic-rich shales, averaging 11.33 wt% organic carbon (Webster, 1984). In thin section, Webster (1984) found that the shales are composed mostly of dark indeterminate material of which a large percentage is organic matter. The organic matter is distributed uniformly in the shales and not concentrated in lenses or laminations. Webster (1984) used X-ray diffraction analysis to determine that the predominant mineral in the shales in North Dakota is quartz, with lesser amounts of clay minerals than would be expected. Some calcite and dolomite exists in thin section, with the dolomite forming euhedral rhombs. Webster (1984) also states that in North Dakota, all the lithologies in the Middle Bakken are very well cemented with calcite and silica, and have low permeabilities (less than 0.1 millidarcy) and porosities (between 1 and 6 percent).

3.2 Thickness

Isopach maps of the Bakken Formation in Manitoba (Figure 7) show the average total thickness of the Bakken Formation in Manitoba to be 6 metres. The maximum thickness of the Bakken Formation is 35 metres in the Waskada field area where the Lower Bakken is locally present. The Lower Bakken, which is present in only a small area, reaches a maximum thickness of 13 metres. The Middle Bakken has an average thickness of 4 metres with a maximum thickness of 16 metres, again reached in the

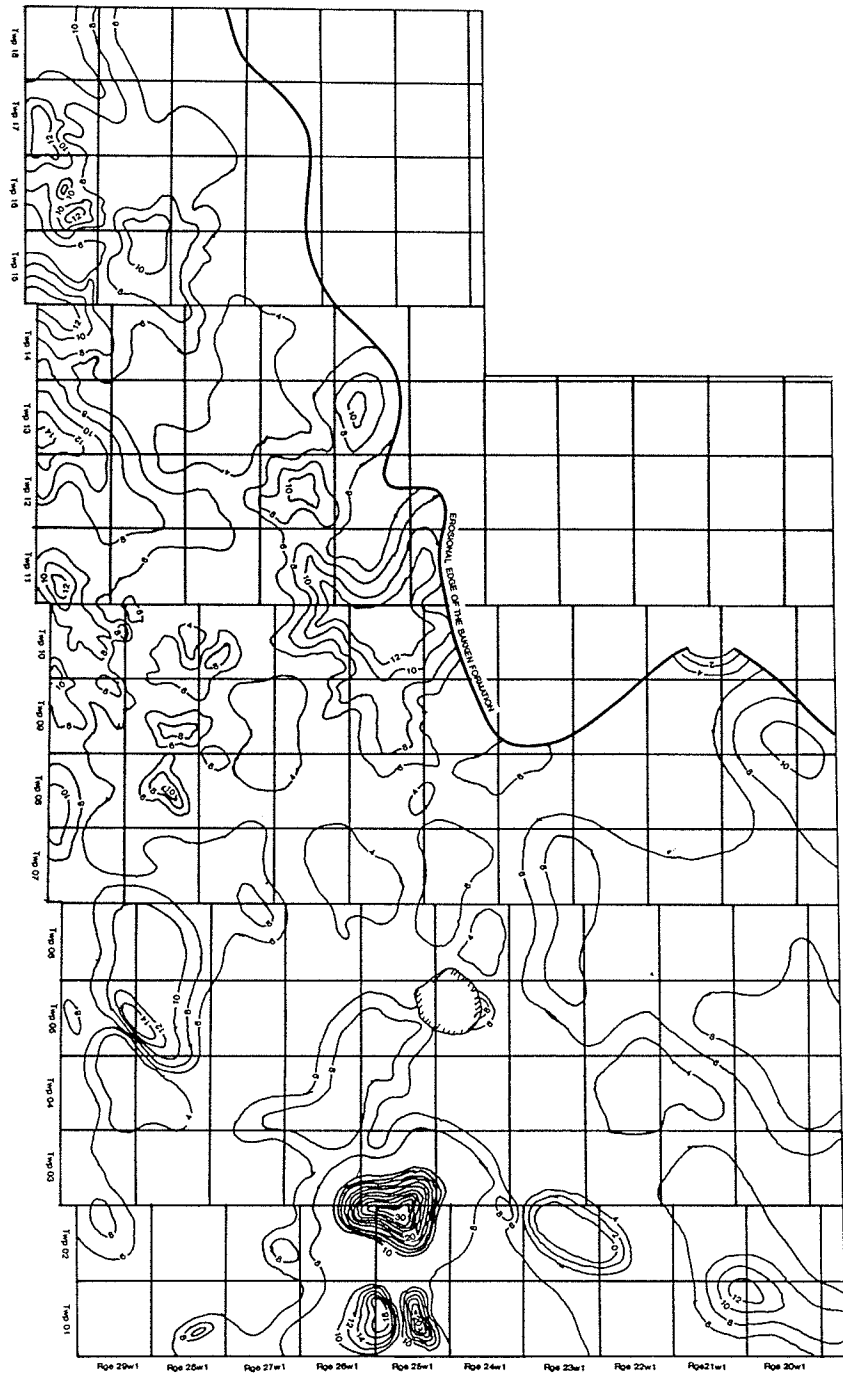


Figure 7

Isopach map of the total Bakken Formation in Manitoba. Modified from Martiniuk (1988). Contour interval is 2 metres.

Waskada area. The average thickness of the Upper Bakken is 2 metres, and is relatively uniform throughout southwestern Manitoba; it is also thickest in the Waskada area, at 18 metres.

In North Dakota, the Bakken Formation reaches a maximum thickness of 44 metres in western Mountrail County (Webster, 1984). The Lower Bakken has an average thickness of 6 metres with maximum of 15 metres. The average thickness of the Middle Bakken is 10 metres and a maximum thickness of 26 metres. The Upper Bakken, as in Manitoba, is quite uniform in its thickness with an average thickness of 4 metres and a maximum thickness of 7 metres. In North Dakota all of the members reached their maximum thicknesses in western Mountrail County.

3.3 Depositional Models

The depositional model proposed by Fuller (1956) is that the sediments of the Devonian Three Forks Group were deposited on a nearly flat surface. A series of evaporites, silts, and clays were formed in this shallow marine environment. These sediments were also rich in sulphates and iron oxides. Later, as the surface of the sediments was weathered and eroded, the clays were re-worked in a vast "marine swamp", and the iron oxides and sulphates therein were chemically reduced to form iron sulphides in the black Bakken muds. A marine transgression caused the deposition of the arenaceous beds and then a return to the deposition of the black shale as the water column stagnated, returning to a "marine swamp" environment.

McCabe (1959) suggests that the depositional environment for the Lower Bakken was an extensive "marine swamp" with restriction of circulation due to prolific organic

productivity. Rather than having the Middle Bakken deposited during a transgression, McCabe (1959) proposes that the black shale swamp which deposited the Lower Bakken was apparently drowned or flooded during the time of Middle Bakken deposition by an influx of shallow marine clastics throughout the area due to a minor tectonic uplift in the peripheral areas. McCabe (1956) contends that restricted, stagnant conditions persisted in most places during Middle Bakken time, as indicated by the presence of abundant pyrite in the Middle Bakken. Following deposition of the Middle Bakken sediments, the peripheral tectonism apparently ceased; no further coarse clastic material was supplied to the basin, and stagnant swampy conditions under which the Upper Bakken black shale was deposited were re-established.

The depositional model proposed by Christopher (1961) is somewhat similar to that of Fuller (1956) and McCabe (1959), in that Christopher (1961) proposes deposition of the lower black shale in a swamp/lagoon type of environment. The Middle Bakken was then deposited during a transgression, starting with deposition of the "A" beds. Subsidence of the eastern area then deepened the platform and allowed the sea to spread over the nearly flat shelf to the east. The strandline and the concurrent band of erosion advanced well into Manitoba from Saskatchewan to erode the Lyleton Formation. The fine sands and silts of the "B" beds were then deposited over the broad shelf. There was then a slow regression which resulted in the end of deposition of the Middle Bakken. As the overall depth of the sea decreased, sedimentation became reduced to the slow influx of clay minerals and the generation of a black mud (the Upper Bakken) in a repetition of the Lower Bakken swamp/lagoon environment. This was followed by a

major marine transgression which resulted in the deposition of the argillaceous limestones of the Madison Group.

In contrast, the depositional model that was put forward by Lineback and Davidson (1982) and Hayes and Holland (1983) is that the finely laminated, organic rich, black shales of the Bakken Formation were deposited in an anoxic, marine environment that was offshore, sediment-starved, and below wave base. They suggest that the Middle Bakken contains bedding features and fossil evidence indicative of a slightly dysaerobic, current influenced marine environment.

A shallow water, marine depositional model for the Bakken Formation is proposed by Kent (1984), who states that considerable fluctuation in sea level would be required to sandwich the medial silts and sands, which represent deposition in shallow water, between the two shales which could be interpreted as deeper water deposits. He proposes that it is more likely that the shales were formed on a broad open marine platform over which wave intensity was dampened because of the shallow water depth; fine clastic sediments would have been virtually undisturbed and any organic material deposited with the mud would not have been winnowed (Kent, 1984).

Webster (1984) proposes that a transgression of the Williston sea began in Late Devonian time, coinciding with the deposition of the Lower Bakken shale. The nature of the Bakken shales indicates a pronounced basin-wide change in the depositional environment, from oxygen-rich conditions during Three Forks time, to highly anoxic conditions during part of Bakken time. As the sea transgressed in early Bakken time, Webster (1984) proposes that some type of change occurred in basin geometry, climate,

or water circulation, causing anoxic, possibly stagnated conditions. These anoxic conditions ended in Middle Bakken time during an influx of coarser clastics into the basin. Webster (1984) states that the Middle Bakken has fauna and bedding features indicative of a normal shallow marine to nearshore marine depositional environment. He also states that the transgression of the sea continued in Middle and Upper Bakken time as evidenced by the onlapping relationship of the Bakken Members upon the unconformity at the top of the Three Forks Group. Several minor regressions probably occurred during Middle Bakken time, as bedding features, oolitic carbonate grains, and trace fossils indicate very shallow water conditions during part of Middle Bakken time. He proposes that anoxic conditions returned to the basin with the deposition of the Upper Bakken as the transgression continued.

Webster (1984) suggests that the black shales were deposited in a deep water, offshore environment. The evidence he uses for this is the predominance of algal organic matter over terrestrial organic matter, as well as the widespread lithologic similarity of the shales which would require interconnection of the black shale depositing system. He proposes the existence of a stratified water column due to the presence of a pycnocline, with the oxygenated surface waters being separated from the anaerobic bottom waters. He submits the idea that the stratification is due to the surface waters rarely cooling enough to sink to deeper levels and displace the colder bottom waters due to a temperate climate as suggested by Byers (1977). Webster (1984) further proposes that a minimum depth of about 45 metres would be necessary in order to have the bottom waters below both the photic zone and wave action. Webster (1984) does not give any reason for the

breakdown of the anoxic conditions during the deposition of the Middle Bakken.

3.4 Maturation of Organic Material

A study of the oil in the Williston Basin by Williams (1974) found that there are three different types of oil present, which are proposed to have originated from different formations. The first type of oil originated from the Ordovician Winnipeg shale and is found primarily in Ordovician reservoirs but is occasionally also found in Silurian, Devonian and Mississippian reservoirs as well. The second type of oil, which originated from the Mississippian-Devonian Bakken shales is found in Mississippian Madison reservoirs. The third type of oil originated from the Pennsylvanian Tyler shales and is found only in Pennsylvanian Tyler reservoirs.

The amount of oil expelled from the mature Bakken shales was estimated to be about 10 billion barrels by Dow (1974). The estimate of the oil expelled from the Bakken shales was increased to 132 billion barrels by Schmoker and Hester (1983).

An intensive study of the maturation of organic material in the Bakken Formation was done by Price *et al.* (1984). They reported that the depth of the threshold of intense hydrocarbon generation in the Bakken shale in the higher paleogeothermal gradient areas towards the centre of the Williston basin was somewhere between 2,230 and 2,440 metres, with the best estimate being 2,440 metres. This is close to the estimate of 2,130 metres used by Dow (1974) for the depth required for the Bakken shales to reach maturity.

Another study of the maturation of organic materials in the Bakken shales was done by Webster (1984) in which he suggests that the onset of hydrocarbon generation

and intense hydrocarbon generation occur at average depths of 2,740 metres and 3,050 metres respectively. These figures are significantly deeper than the depths postulated by Price *et al.* (1984).

Chapter 4: Geologic Setting

4.1 Regional Geology

Southwestern Manitoba is on the northeastern flank of the Williston Basin, an intracratonic basin that covers much of North Dakota and parts of South Dakota, Montana, Saskatchewan, and Manitoba (Figure 8). In the study area, rocks of Mesozoic and Paleozoic age form a basin-ward thickening wedge dipping to the southwest. Strata within the Mesozoic and Paleozoic of Manitoba are truncated by several unconformities.

The Williston Basin forms an irregularly shaped depression on the western edge of the Canadian Shield. Sedimentation in the basin has been relatively continuous through Phanerozoic time, with carbonate deposition dominating the Paleozoic and clastics dominating the Mesozoic and Cenozoic eras (Gerhard *et al.*, 1982).

The following synopsis of deposition within the Williston Basin is summarized from Gerhard *et al.* (1982). Sedimentation within the basin is characterized by cyclical transgressions and regressions evidenced by repeating sequences of clastics and carbonates. Initial sedimentation occurred over an irregular Precambrian crystalline surface, beginning with deposition of Sauk sequence (Cambrian-Lower Ordovician) rocks which show a change from clastics to carbonates up-section. Tippecanoe sequence (Ordovician-Silurian) rocks represent the second cycle of transgression, sedimentation, and regression. By the Ordovician the basin was a well-defined structural depression with marine waters from the southwest depositing clastics followed by carbonates. Seaways developed northward during Devonian time, as a result of activity on the

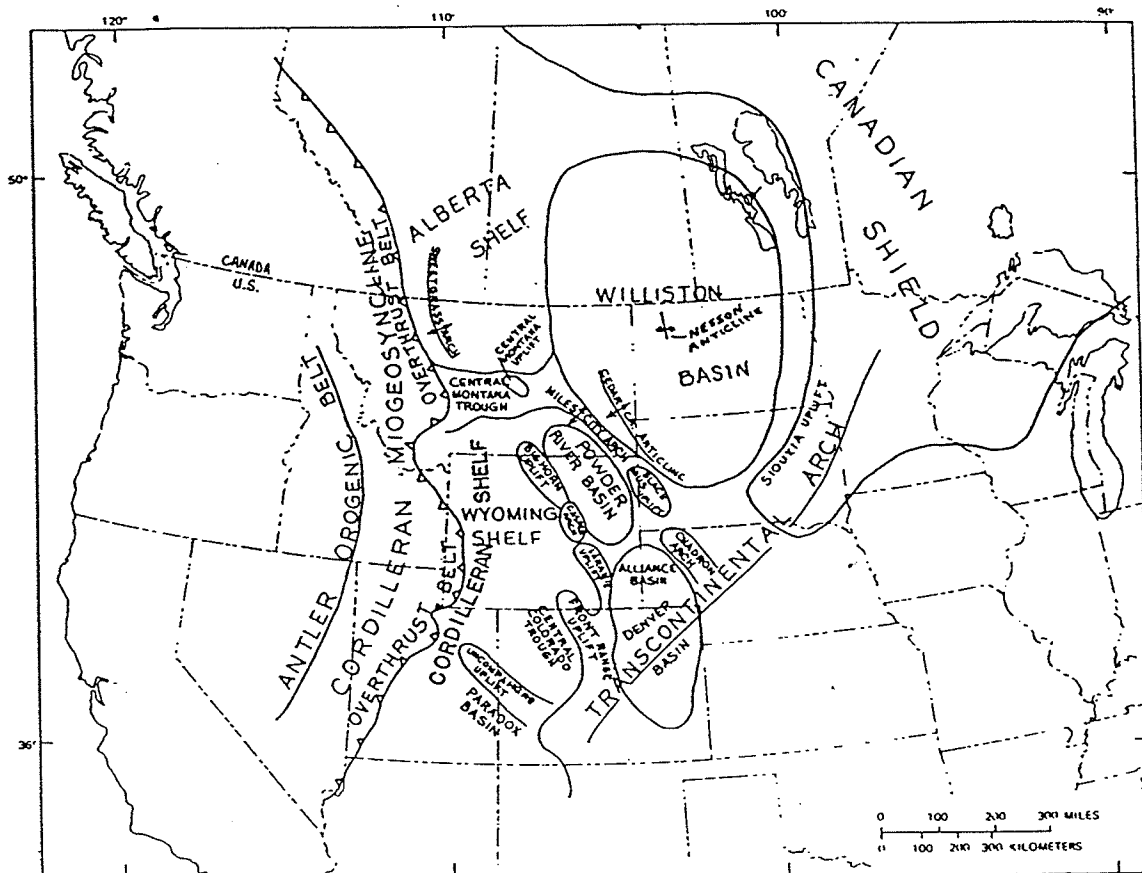


Figure 8

Regional paleogeography and paleostructure during Paleozoic time, Western Interior, United States. Position of Mesozoic thrust belt is also shown. From Peterson (1987).

Transcontinental arch which tilted the basin and its structures northward. Again during the Kaskaskia sequence (Devonian-Mississippian), a transgressive and regressive sequence of sediments were deposited. A reorientation of seaways also occurred during deposition of the Madison Group as the basin opened to the west. This reorientation is related to the development of shear systems in Montana. Terrestrial clastics interbedded with marginal marine clastics and carbonates and evaporite sediments are characteristic of Absaroka sequence (Pennsylvanian-Triassic) rocks. The setting for deposition of the last sequence of marine clastic sediments occurred during Zuni (Jurassic-Cretaceous) time with a deepening of the western interior Cretaceous seaway. Uplift, erosion and volcanism occurred during this time in the Laramide Rockies supplying extensive quantities of detritus to the basin. Tejas sequence (Tertiary-Quaternary) rocks generally consist of shaley sandstones and lignites, with some limestone and volcanic ash.

A major angular unconformity separates the Paleozoic section from the Mesozoic section in Manitoba and represents one or more periods of erosion or non-deposition that occurred between Late Mississippian and Early Jurassic time. During this interval, Paleozoic strata in the northeastern part of the basin were uplifted and differentially eroded, while strata in the southern portion of the basin experienced slight uplift (McCabe, 1959). Successively older strata extend further towards the edge of the basin before being truncated. Deposition resumed in Mesozoic time with the deposition of thick Jurassic and Cretaceous strata on the eroded Paleozoic surface.

Within the Paleozoic sequence there is an unconformity that separates the Devonian and Mississippian strata and represents a period of regression. During this

time the Devonian age rocks experienced erosion or non-deposition from Late Devonian to Early Mississippian time at the edges of the basin; meanwhile, the period of erosion or non-deposition was much shorter, or non-existent, in the deeper central portion of the basin. Mississippian sediments were then deposited on the eroded Devonian surface (Sandberg, 1964) during a transgression that began in Late Devonian time (Webster, 1984).

4.2 Stratigraphy

The Bakken Formation in Manitoba consists of two members: the Upper Bakken (a black shale) and the Middle Bakken (ranging from a silty dolostone to an argillaceous dolomitic silt- or sandstone), with the Lower Bakken (another black shale) being absent except for a small subcrop in the Waskada area (McCabe, 1959).

The Bakken Formation overlies the Devonian Lyleton Formation, a unit that is correlative with the Three Forks Group of North Dakota, Montana and Saskatchewan. The type section of the Lyleton Formation, in the Robert Moore No. 1 Well, 5-20-1-27 WPM was described by Allan and Kerr (1950) as the dolomitic shales and siltstones that overlie the carbonate strata of the Devonian and underlie the bituminous black shales of the Bakken Formation (referred to as the Exshaw Formation by Allen and Kerr (1950)). The term Lyleton, as used here, is limited to Manitoba.

The Lodgepole Formation, named after Lodgepole Creek, the type section of which is in Little Chief Canyon, 4 km south of the Lodgepole Subagency, Ft. Belknap Indian Reservation, Little Rocky Mountains, Montana (Collier and Cathcart, 1922), is the unit that immediately overlies the Bakken Formation. The basal part of the

Lodgepole Formation in the Daly Field consists of a dark grey argillaceous limestone. A thin bed of relatively clean limestone separates the shaley Lodgepole Formation from the Bakken shale (McCabe, 1959).

The general stratigraphy of the Phanerozoic in southwestern Manitoba is shown in Figure 9.

4.3 Structure

In general, the Bakken Formation has fairly little local structure and follows the Paleozoic tilt with a regional dip to the southwest of approximately 6 metres/km (Figure 10). Martiniuk (1988), however, noted that there are some areas in which the Middle Bakken departs from the norm. For example, within the Daly field, there are several minor closed structural highs which are coincident with areas in which oil is produced from the Bakken.

GEOLOGICAL FORMATIONS IN MANITOBA

| AGE Millions of years before present | ERA | PERIOD | EPOCH | FORMATION | MEMBER | MAX. THICK (m) | BASIC LITHOLOGY | | |
|--|-----------|------------------|-----------------|----------------|---|---|---|---|---|
| 50 | CENOZOIC | QUATERNARY | RECENT | | | | TOP SOIL, DUNE SANDS | | |
| | | | PLEISTOCENE | GLACIAL DRIFT | 140 | CLAY, SAND, GRAVEL, BOULDERS, PEAT | | | |
| | | TERTIARY | PLIOCENE | | | | | | |
| | | | MIOCENE | | | | | | |
| | | | OLIGOCENE | | | | | | |
| 65 | | | Eocene | | | | | | |
| | | | PALEOCENE | TURTLE MTN. | PEACE GARDEN GOODLANDS | 120 | SHALE, CLAY AND SAND, LIGHT BEDS LOCATED ONLY IN TURTLE MOUNTAIN | | |
| 100 | MESOZOIC | CRETACEOUS | UPPER | BOISSEvain | | 30 | SAND AND SANDSTONE, GREENISH GREY, LOCATED ONLY IN TURTLE MOUNTAIN | | |
| | | | | RIDING MTN. | COLLIER WILLIAM MILLWOOD | 310 | GREY SHALES—NON-CALC., LOCAL IRONSTONE BENTONITE NEAR BASE, GAS FOUND | | |
| | | | VERMILION RIVER | PEMBINA | 155 | SHALE DARK GREY CARBONACEOUS NON-CALC. BENTONITE BANDS | | | |
| | | | | BOYNE | | SHALE GREY SPECKLED CALC. BENTONITIC SLIGHTLY PETROLIFEROUS | | | |
| | | | | MORGEN | | SHALE DARK GREY NON-CALC. CONCRETIONS, LOCAL AND SILT | | | |
| | | | FAVEL | 40 | GREY SHALE WITH HEAVY CALCAREOUS SPECKS BANDS LIMESTONE AND BENTONITE | | | | |
| | | | ASHVILLE | 115 | SHALE, DARK GREY, NON-CALC. SILTY "SAND ZONE" 27m F.G. Q.T.Z. S. OR SS. | | | | |
| | | ASHVILLE SAND | | | | | | | |
| | | LOWER CRETACEOUS | SWAN RIVER | 75 | SANDSTONE AND SAND, Q.T.Z. PYRITIC SHALE—GREY, NON-CALC. | | | | |
| | | 150 | | JURASSIC | UPPER JURASSIC | WASKADA | 200 | BANDED-GREEN SHALE AND CALC. SANDSTONE BANDS OF LIMESTONE, VARI-COLORED SHALE | |
| | | | | | | MELITA | | | |
| MIDDLE JURASSIC | RESTON | | | | 45 | LIMESTONE, BUFF, AND SHALES, GREY | | | |
| | AMARANTH | | | | UPPER: EVAPORITE LOWER: RED BEDS | 45 40 | WHITE ANHYDRITE AND/OR GYPSUM AND BANDED COLOMITE AND SHALE RED SHALE TO SALTSTONE-DOLOMITIC OIL PRODUCING | | |
| 200 | | | TRIASSIC | | | | | | |
| 250 | | | PERMIAN | | | | | | |
| 300 | | | PENNSYLVANIAN | (?) | ST. MARTIN COMPLEX | 200 | CARBONATE BRECCIA, TRACHYANDESITE (CRYPTO-EXPLOSION STRUCTURE) | | |
| 350 | PALEOZOIC | MISSISSIPPIAN | | MADISON GROUP | CHARLES | 20 | MASSIVE ANHYDRITE AND DOLOMITE | | |
| | | | | | MISSION | MC-3 | | | |
| | | | | | CANYON | MC-2 MC-1 | 120 | LIMESTONE—LIGHT BUFF, OOLITIC, FOSS. FRAG., CHERTY, BANDS SHALE AND ANHYDRITE OIL PRODUCING | |
| | | | | | LODGEPOLE | FLOSSIE LAKE WHITEWATER LAKE VIRDEN | 185 | LIMESTONE & ARG. LIMESTONE LIGHT BROWN AND REDDISH MOTTLED ZONES OF SHALEY, OOLITIC, CRINOIDAL & CHERTY OIL PRODUCING | |
| | | | | BAKKEN | SCALDON TROUT LAKE | | | | |
| | | | | | UPPER | 20 | 2 BLACK SHALE ZONES - SEPARATED BY SALTSTONE OIL PRODUCING | | |
| | | | | | MIDDLE LOWER | | | | |
| | | | | BASKIN GROUP | LYLETON | 35 | RED SALTSTONE AND SHALE DOLOMITIC | | |
| | | | | | NISKU | 40 | LIMESTONE & DOLOMITE, YELLOW-GREY FOSS. POROUS, SOME ANHYD | | |
| | | | | | DUPEROW | 170 | LIMESTONE & DOLOMITE, ARG. & ANHYDRITIC IN PLACES | | |
| 400 | | DEVONIAN | | MAIN GROUP | SQUARE RIVER | 120 | CYCICAL SHALE, LIMESTONE & DOLOMITE ANHYDRITE | | |
| | | | | | 1ST RED | 85 | LIMESTONE & DOLOMITE, POROUS, ANHYDRITE—LOCAL SHALE RED & GREEN | | |
| | | | | | DAWSON BAY | 120 | SALT POTASH & ANHYDRITE, DOLOMITE INTER-BEDDED | | |
| | | | | | 2ND RED | | | | |
| | | | | ELK POINT G. | PRAIRIE EVAP. | | | | |
| | | | | | WINNIPEGOSIS | 75 | DOLOMITE, LIGHT YELLOWISH BROWN REEFY | | |
| | | | | | ELM POINT | | LIMESTONE—FOSS. HIGH CALCIUM | | |
| | | | | | ASHERN | 12 | DOLOMITE AND SHALE—BRICK RED | | |
| | | | | SILURIAN | | INTERLAKE GROUP | | 135 | DOLOMITE YELLOWISH—ORANGE TO GREYISH—YELLOW FOSS. SILTY ZONES |
| | | | | | | | STONEWALL | 15 | DOLOSTONE, GRAYISH YELLOW, BEDDED |
| 450 | | ORDOVICIAN | | STONY MOUNTAIN | WILLIAMS | 30 | DOLOMITE—YELLOWISH—GREY SHALEY | | |
| | | | | | GURTON | | | | |
| | | | | | PENITENTIARY | 20 | DOLOMITE—DUSKY—YELLOW FOSS. | | |
| | | | | | GUNN | SHALE RED—GREEN FOSS. LIMESTONE BANDS | | | |
| | | | RED RIVER | FOOT CLIFF | 170 | DOLOMITIC LIMESTONE, MOTTLED AND DOLOMITE | | | |
| | | | | SELMER | | | | | |
| | | | | CATHEDRAL | | | | | |
| | | | | MOOREHEAD | | | | | |
| | | | WINNIPEG | UPPER UNIT | 80 | SHALE, GREEN, WAXY, SANDSTONE INTERBEDDED | | | |
| | | | | SANDSTONE | | SAND, SANDSTONE, QUARTZOSE | | | |
| 500 | | | | | | | | | |
| 550 | | CAMBRIAN | | DEADWOOD | | 80 | SAND, BLACK TO GREEN—GREY WAXY, GLAUCONITIC SALTSTONE & SHALE, GREEN—GREY TO BLACK, VERY EDGE OF S.W. MANITOBA ONLY | | |
| | | | | | | | | | |
| | | PRECAMBRIAN | | | | | ACID & BASIC CRYSTALLINES & METAMORPHICS | | |

Figure 9

Geological Formations in Manitoba. From Oil in Manitoba, Mineral Education Series, Manitoba Department of Energy and Mines.

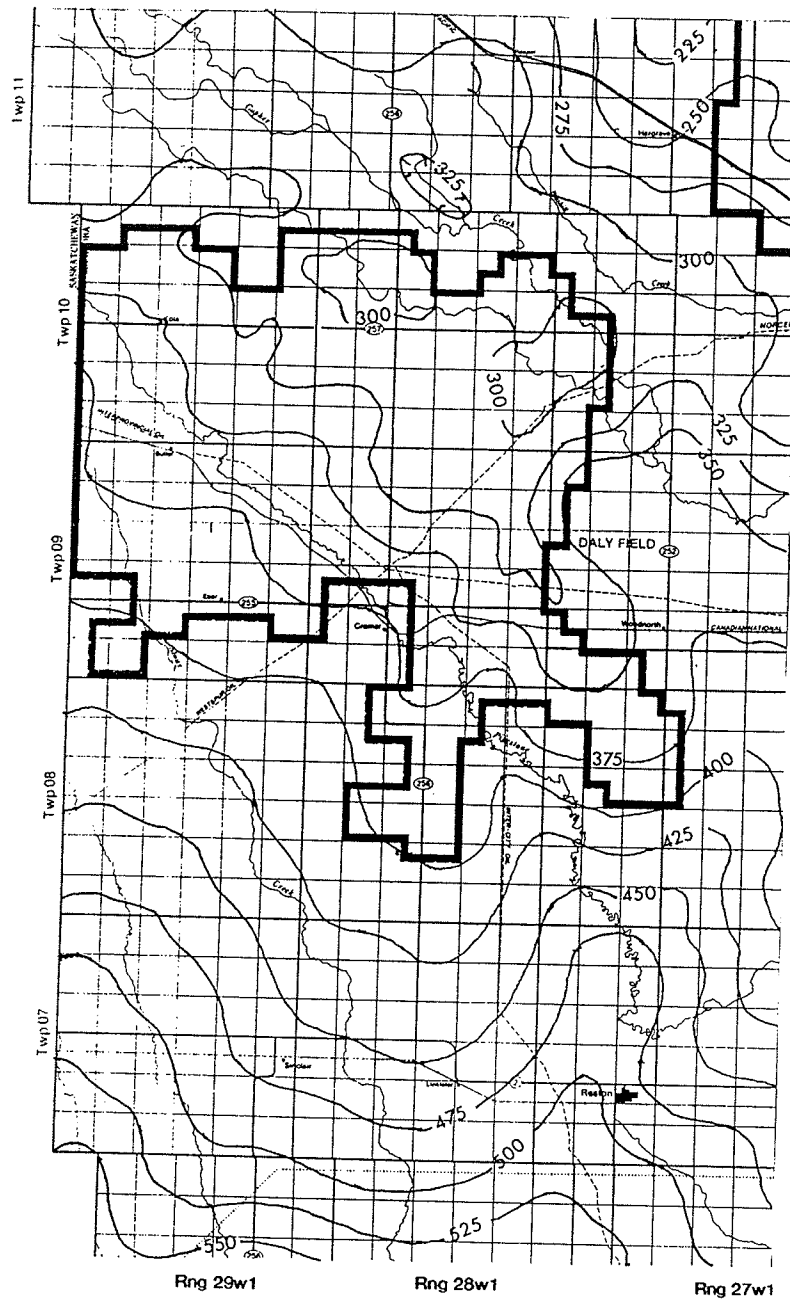


Figure 10

Map of the structure of the Middle Bakken Member in the Daly Field area. The contours are in metres below sea level. Also shown are the Dominion Land Survey lines, geographic and cultural features. Modified from Martiniuk (1988).

Chapter 5: Results of Analyses

5.1 Open Hole Log and Core Analysis

On open hole geophysical logs the stratigraphic position of the Upper Member of the Bakken Formation is easily identified by a very strong response (over 200 API) on the gamma ray logs. The base of the Middle Bakken is more difficult to discern. The base of the Middle Bakken is inferred to be at the point where the density porosity log and the neutron porosity logs diverge (Figure 11). Recognition of the members of the Bakken Formation on the logs and on the core are in good agreement, confirming that the depths determined on the logs for the base of the Bakken Formation are valid for wells without core.

It was also noted that if there is a pyrite band in the core, there is a peak on the photoelectric (P_e) log at the corresponding depth. This peak was also noted on several logs without cores.

Core analyses reveal that porosity of the Middle Bakken in Manitoba generally is quite high, in the 13 to 20% range. The permeability of the rocks of the Middle Bakken, however, varies considerably, both vertically and horizontally, from less than 0.1 millidarcy to over 100 millidarcies. In the wells which had no oil production, the permeability is generally less than 1 millidarcy throughout the Middle Bakken, whereas in the wells producing oil there are zones with permeabilities over 100 millidarcies. When highly permeable zones were found in the Middle Bakken, the zones were concentrated in two bands, one near the top of the member and a second at the base of

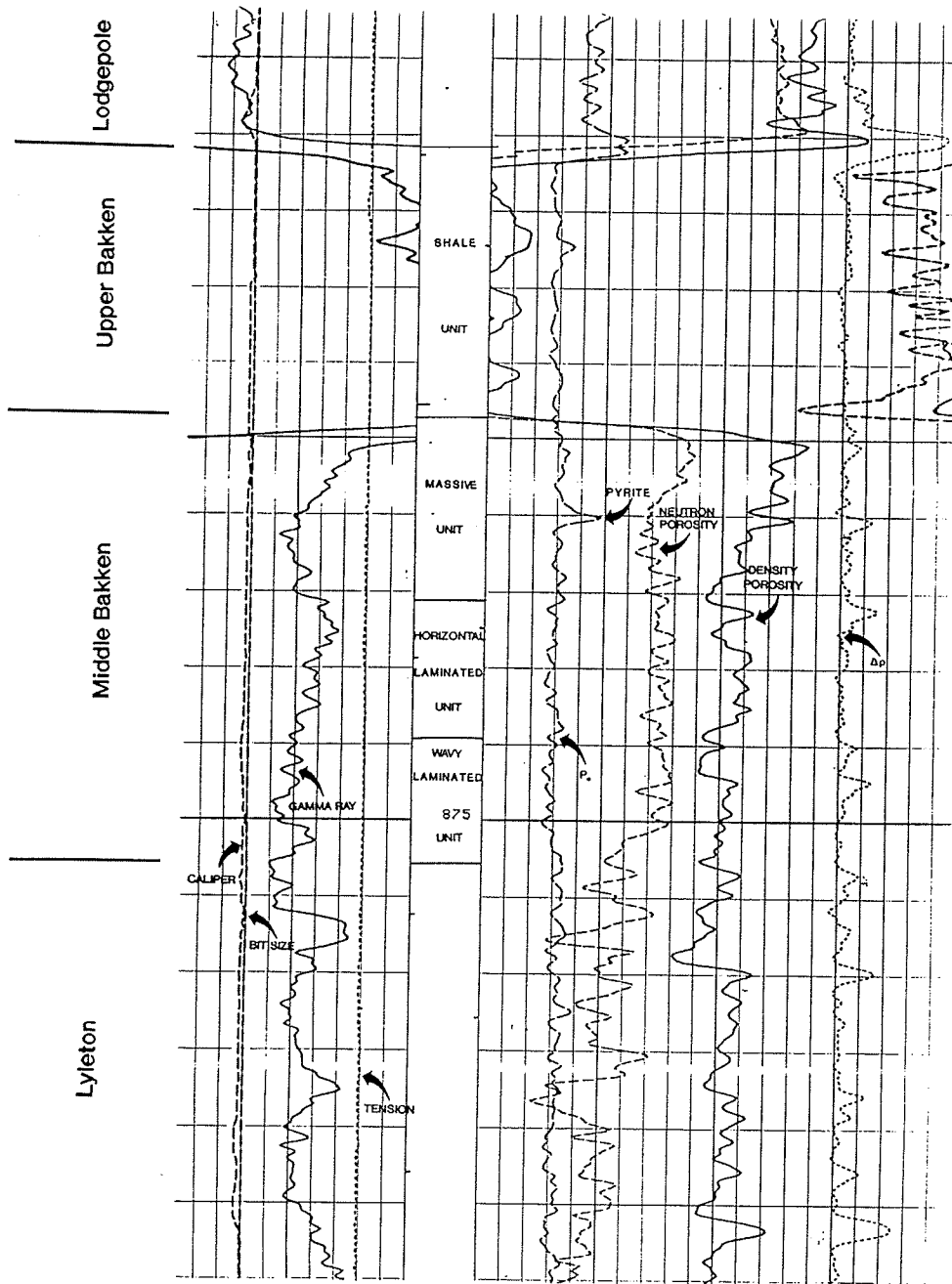


Figure 11

Compensated neutron log suite from the Newscope Opnac Daly Prov 08-29-10-29 well. Depths of units, as identified in core, are shown. Also identified is the photoelectric (P_e) log response indicating a pyrite band.

the member. In comparison, the Middle Bakken in North Dakota has porosities in the range of one to six percent and a permeability less than 0.1 millidarcy (Webster, 1984).

5.2 Lithology

The lithology of the Bakken Formation was determined through the examination of all of the available core (Table 1) by both visual logging, and by X-ray diffraction (XRD) analysis of samples taken from the cores. Detailed descriptions of the core can be found in Appendix 1.

The sediments of the Bakken Formation in the study area can be subdivided into two members; the Middle Bakken, which is subdivided into the Wavy Laminated Unit, the Horizontal Laminated Unit, and the Massive Unit; and the Upper Bakken consisting of the Shale Unit. These units are defined on the basis of the sedimentary structures that are present in the rock, the presence or absence of fossils, and grain size.

It was also noted that there was a tendency in the cores to have an increase in the degree of red coloration to the north and to the east in the study area.

In the following sections, which describe the units of the Bakken Formation, the amount of the unit that each mineral constitutes on average is shown in brackets after the mineral name. These values are average percentages from the all the samples that have been analyzed in each unit. A table with the results of the X-ray diffraction analysis of each individual sample and averages for each unit can be found in Appendix 4. Table 3 shows the average percentage of each mineral that was present in each unit. Table 4 shows the standard deviation for the data in Table 3.

Table 3
Average Mineralogic Composition of the Lithologic Units (in percent)

| | Quartz | Plag | K-Spar | Calcite | Dolomite | Clay | Pyrite | Gypsum | Anhydrite | Halite |
|----------------------------------|--------|------|--------|---------|----------|-------|--------|--------|-----------|--------|
| Shale Unit (n=17) | 9.25 | 2.68 | 9.23 | 14.79 | 9.00 | 40.47 | 7.37 | 0.32 | 4.91 | 1.93 |
| Massive Unit (n=52) | 15.95 | 4.01 | 5.26 | 2.15 | 39.00 | 20.45 | 3.35 | 1.78 | 5.85 | 2.15 |
| Horizontal Laminated Unit (n=41) | 22.35 | 4.14 | 6.29 | 1.69 | 33.65 | 21.27 | 1.18 | 2.11 | 4.73 | 2.54 |
| Wavy Laminated Unit (n=28) | 24.23 | 2.37 | 5.22 | 1.21 | 22.21 | 10.24 | 1.91 | 15.53 | 15.52 | 1.51 |

Table 4
Standard Deviation of the Mineralogic Composition of the Lithologic Units (in percent)

| | Quartz | Plag | K-Spar | Calcite | Dolomite | Clay | Pyrite | Gypsum | Anhydrite | Halite |
|----------------------------------|--------|------|--------|---------|----------|-------|--------|--------|-----------|--------|
| Shale Unit (n=17) | 3.27 | 2.90 | 3.42 | 2.20 | 7.16 | 10.84 | 7.38 | 1.28 | 5.60 | 2.14 |
| Massive Unit (n=52) | 4.48 | 2.15 | 1.79 | 1.86 | 12.65 | 12.83 | 8.12 | 5.08 | 13.10 | 2.32 |
| Horizontal Laminated Unit (n=41) | 4.40 | 1.69 | 1.86 | 0.62 | 7.46 | 7.81 | 1.95 | 4.46 | 7.03 | 2.07 |
| Wavy Laminated Unit (n=28) | 8.57 | 1.50 | 2.38 | 0.89 | 17.54 | 8.69 | 8.59 | 20.18 | 23.04 | 1.51 |

5.2.1 Wavy Laminated Unit

The Wavy Laminated Unit, is a relatively coarse grained, wavy laminated, grey to olive grey argillaceous dolomitic silt- or sandstone (Figure 12). This unit exhibits common macroscopic intergranular porosity in some of the cores. The Wavy Laminated Unit is presently composed of almost equal amounts of dolomite (22.2%) and quartz (24.2%), and minor amounts of clay minerals (10.2%) and K-feldspar (5.2%), with highly variable amounts of gypsum (15.5%) and anhydrite (15.5%).

5.2.2 Horizontal Laminated Unit

The Horizontal Laminated Unit is a thinly laminated to cross bedded argillaceous silty dolostone (Figure 13). The laminations vary from olive grey to dusky red, often within a few centimetres in the same core. The laminations are generally a few millimetres thick, but vary from less than a millimetre to nearly a centimetre. The Horizontal Laminated Unit commonly grades from wavy laminated to flat horizontal lamination upward in the section. This unit is presently composed primarily of dolomite (33.7%), quartz (22.4%), and clay minerals (21.3%), with minor but highly variable amounts of K-feldspar (6.3%) and anhydrite (4.7%).

5.2.3 Massive Unit

The Massive Unit is a homogeneous grey to olive grey argillaceous silty dolostone (Figure 14) in which sedimentary structures have been obliterated by bioturbation. The unit also contains abundant fossils, primarily brachiopods and occasional crinoid stem fragments. The fossils are preserved as pyrite or hematite casts. Although the majority of the porosity in the core is microscopic, in several of the cores examined this unit



Figure 12

Photograph of an example of the Wavy Laminated Unit (Sample 14-16-10-29:6). The scale is in centimetres. The sample was taken along the vertical axis of the core.



Figure 13

Photograph of an example of the Horizontal Laminated Unit (Sample 05-28-10-29:5).

The scale is in centimetres. The sample was taken along the vertical axis of the core.



Figure 14

Photograph of an example of the Massive Unit (Sample 11-11-11-29:1). The scale is in centimetres. The sample was taken along the vertical axis of the core.

exhibited a small band (2-10 cm) of macroscopic porosity (Figure 15). In some cores, there are bands (2-5 cm) of coarser material, mostly shell fragments (Figure 16). There is also a 2-3 cm thick pyrite band in some of the cores. The Massive Unit is presently composed primarily of dolomite (39.0%), with major amounts of clay minerals (20.5%) and quartz (16.0%), and minor but highly variable amounts of anhydrite (5.9%), K - feldspar (5.3%), plagioclase (4.0%), and pyrite (3.4%). In some cores, generally from the north and east, this unit is dusky red, however, within these dusky red sections there are occasionally patches that have an olive grey coloration (Figure 17).

5.2.4 Shale Unit

The Shale Unit is a finely laminated to massive, black to dark dusky red silty shale (Figure 18). In general, the Shale Unit presently consists primarily of clay minerals (40.5%) with minor amounts of calcite (14.8%), quartz (9.3%), K - feldspar (9.2%), dolomite (9.0%), pyrite (7.4%), and anhydrite (4.9%). In North Dakota the shale has an average of 11.3 wt% organic carbon (Webster, 1984) and similar values were found in the small number of samples from the study area that were analyzed (Last pers. comm.). In some cores the Shale Unit contains thin (5-10 cm) bands of calcareous material (Figure 19), which contain up to 60% calcite, with the remainder being primarily clay minerals. Analysis of organic matter maturity was done on a small number of samples from the study area. The analyses show that the Bakken Formation is near its maximum depth of burial (approximately 800-900 m subsurface) with a current bottom hole temperature of approximately 35°C in the Bakken Formation (Last, pers.

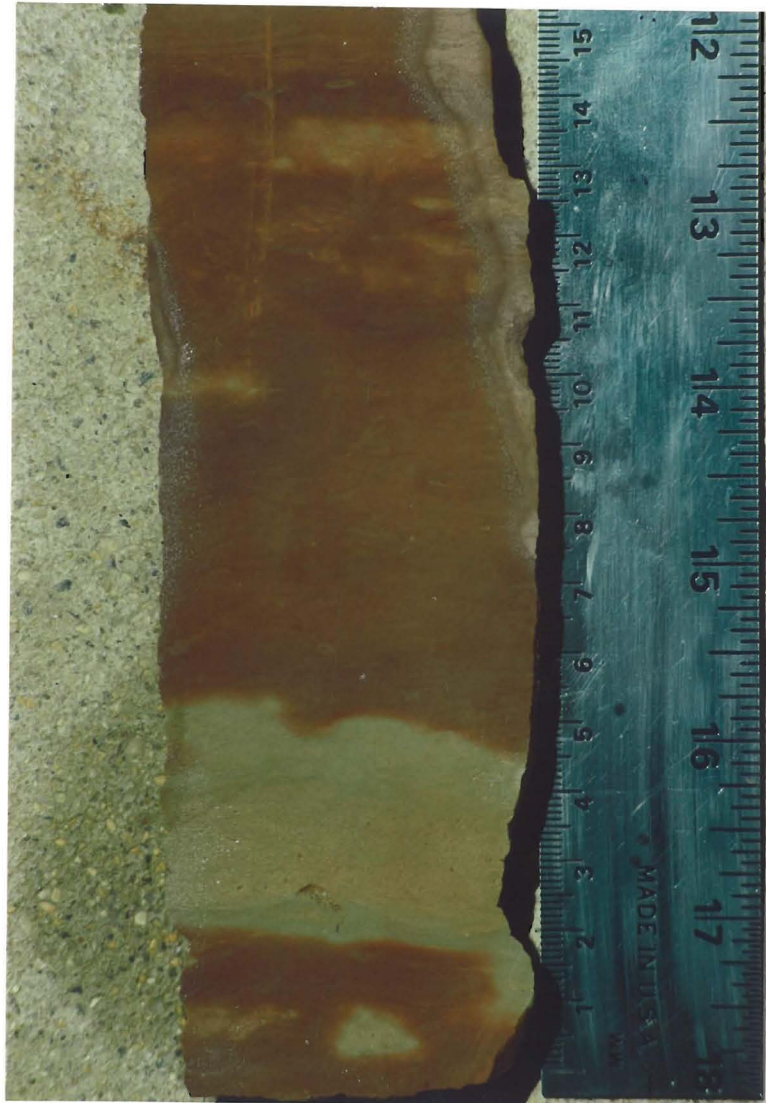


Figure 15

Photograph of macroscopic porosity (tan zone) within the Massive Unit (Sample 09-14-10-28:1). The scale is in centimetres. The sample was taken along the vertical axis of the core.



Figure 16

Photograph of a band of coarse material in the Massive Unit (Sample 02-21-07-28:1).
The scale is in centimetres. The sample was taken along the vertical axis of the core.

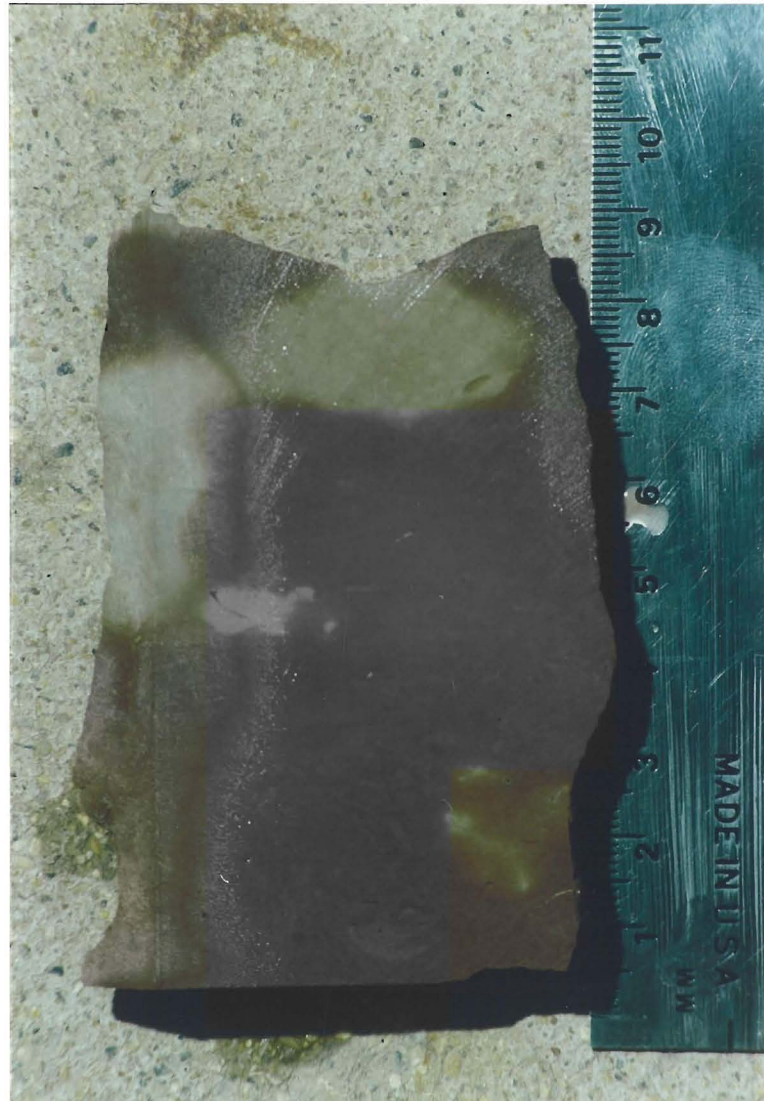


Figure 17

Photograph of an area of patchy coloration within the Massive Unit (Sample 10-30-10-28:2). The scale is in centimetres. The sample was taken along the vertical axis of the core.

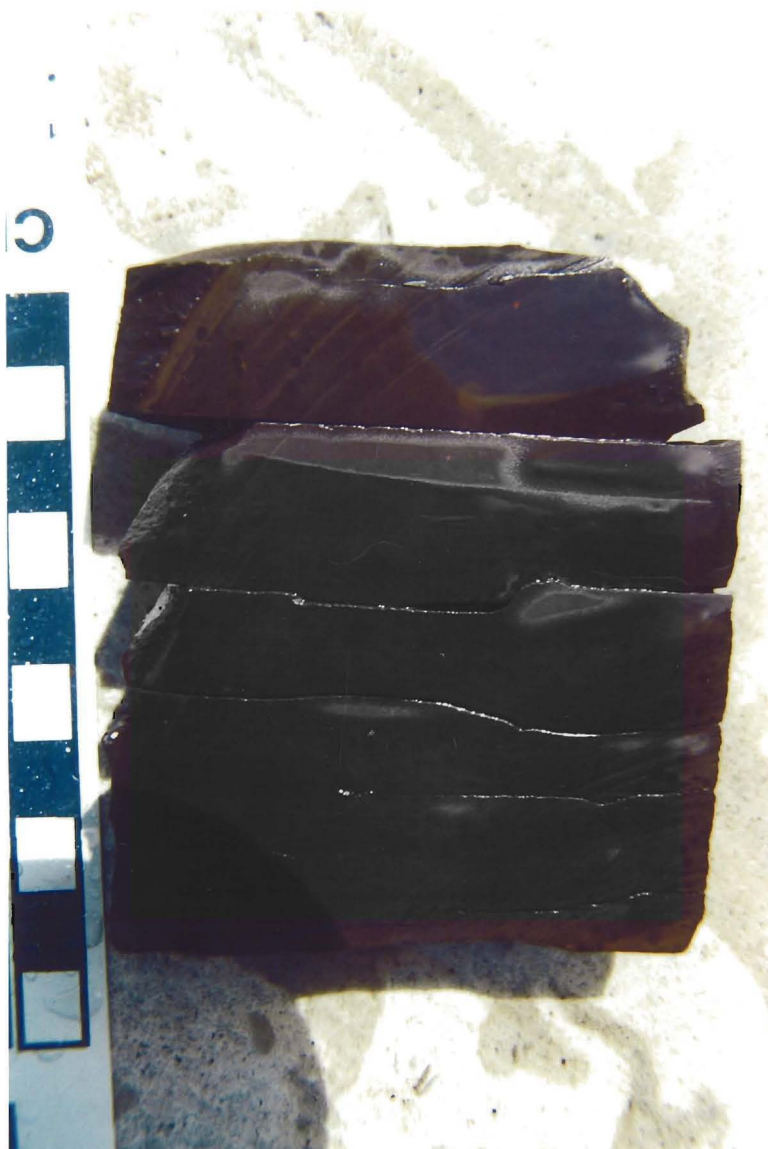


Figure 18

Photograph of an example of the Shale Unit (Sample 13-14-09-28:2). The scale is in centimetres. The sample was taken along the vertical axis of the core.



Figure 19

Photograph of a calcareous bed within the Shale Unit (Sample 11-11-10-29:1). The scale is in centimetres. The sample was taken along the vertical axis of the core.

comm.).

5.2.5 Contacts

The contacts between the units within the Middle Bakken are gradational with no definite sharp breaks. The contact between the Bakken Formation and the underlying Lyleton Formation, however, is sharp and is associated with a pebble conglomerate in some cores and with a pebble breccia in other cores. The pebble conglomerate or breccia is usually present at the base of the Wavy Laminated Unit (Figure 20). The pebble conglomerate or breccia consists of pebbles of Lyleton material, primarily green shale or massive tan dolomite, in a matrix of Wavy Laminated Unit material; the pebbles range from rounded to angular. In one well (04-29-10-29) there is a pebble breccia over 4.5 metres thick.

The contact between the Middle Bakken and the Upper Bakken is gradational over a short distance from grey siltstone to black shale (Figure 21). The contact between the Upper Bakken and the Lodgepole Formation also show a rapid change from black shale to carbonates over a 10 cm interval.

5.2.6 Stratigraphy

In the study area it was found that the Bakken Formation has a relatively uniform stratigraphy, with a pebble conglomerate or breccia at the base of the unit, overlain by the Wavy Laminated Unit. The Wavy Laminated Unit is then overlain by the Horizontal Laminated Unit which in turn is overlain by the Massive Unit. Above the Massive Unit is the Shale Unit.

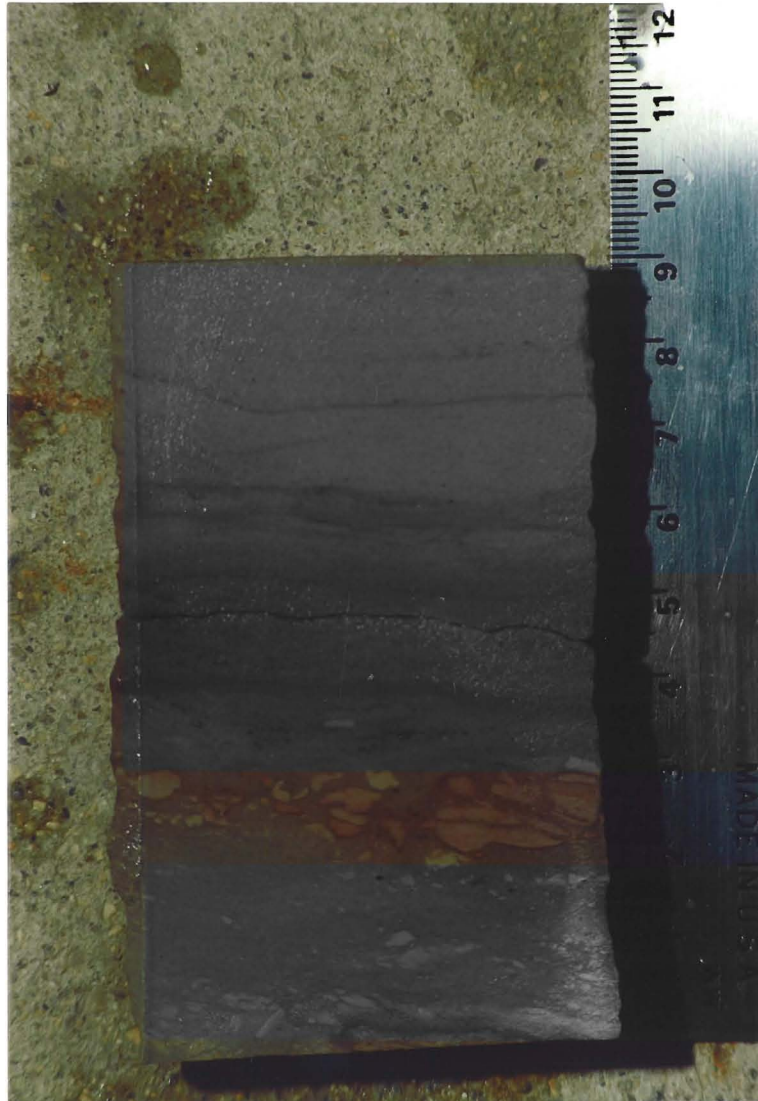


Figure 20

Photograph of the pebble conglomerate at the base of the Wavy Laminated Unit (Sample 07-34-08-28:9). The scale is in centimetres. The sample was taken along the vertical axis of the core.



Figure 21

Photograph of the contact between the Upper and Middle Bakken (Sample 16-16-10-29:1). The scale is in centimetres. The sample was taken along the vertical axis of the core.

5.3 Petrography

5.3.1 Thin Section Petrography

The thin sections that were prepared for this study were impregnated with a dyed epoxy in order to enhance the visibility of porosity in the rock. The resulting thin sections were generally not suitable for study, as a large number of grains were dislodged from the epoxy when the thin sections were ground.

An intensive thin section petrographic study of the Bakken Formation was not undertaken as it was decided that a scanning electron microscopic petrographic study would produce more useful results.

Petrographic examination revealed that the rocks were very fine grained (50 μm and finer). In some thin sections, dolomite crystal sizes were large enough to identify rhomb shapes. Also, there are small grains of organic material dispersed throughout the sediments of the Middle Bakken. Petrographic examination also showed that the lamination in both the Horizontal and Wavy Laminated Units is due to variation in the concentration of quartz grains. The laminations are nearly pure quartz at the bottom of the lamination and grade upward into almost pure matrix, mostly dolomite and clay. The quartz grains also show a slight fining upwards in the Middle Bakken with sizes ranging from a mean of 80 μm in the Wavy Laminated Unit to a mean of 40 μm in the Massive Unit. The quartz grains also grade from subrounded to rounded in the Wavy Laminated Unit to subangular to subrounded in the Massive Unit.

5.3.2 SEM Petrography

SEM petrography was deemed to be more useful because it is possible to look at

the three dimensional structure of the samples, as well as examine the finer features with very high magnification.

5.3.2.1 Description of Minerals

The minerals described in the following section are from the Middle Member of the Bakken Formation unless it is otherwise specified. A total of 46 samples from 8 cores were examined using the SEM (see table 2). Mineral identification was done by energy dispersive x-ray (EDX) analysis.

5.3.2.1.1 Illite

The vast majority of the clay minerals in the Bakken Formation are illite. Some of the illite grains are often found as small (1-5 μm) platy grains with random orientations (Figure 22). The platy grains of illite are found as coatings on larger grains, usually quartz (Figure 23), or as intergrowths with other grains, such as quartz overgrowths (Figure 24) or dolomite grains (Figure 25). There are large areas in which individual grains are not identifiable but the EDX spectra indicates the presence of illite. In the Upper Bakken the illite grains form a sheetlike structure (Figure 26) in which individual grains cannot be identified. The platy illite is interpreted to be authigenic due to its fragility, however, in the areas that the individual grains are not identifiable the illite may be detrital or the grains may have been disrupted during the drilling process.

5.3.2.1.2 Quartz

The quartz grains in the Middle Bakken are moderately well sorted with a particle size mode of about 60 μm (coarse silt) and are subangular to subrounded. The quartz grains are generally coated with very fine (1-5 μm) illite (Figure 22). Many of the

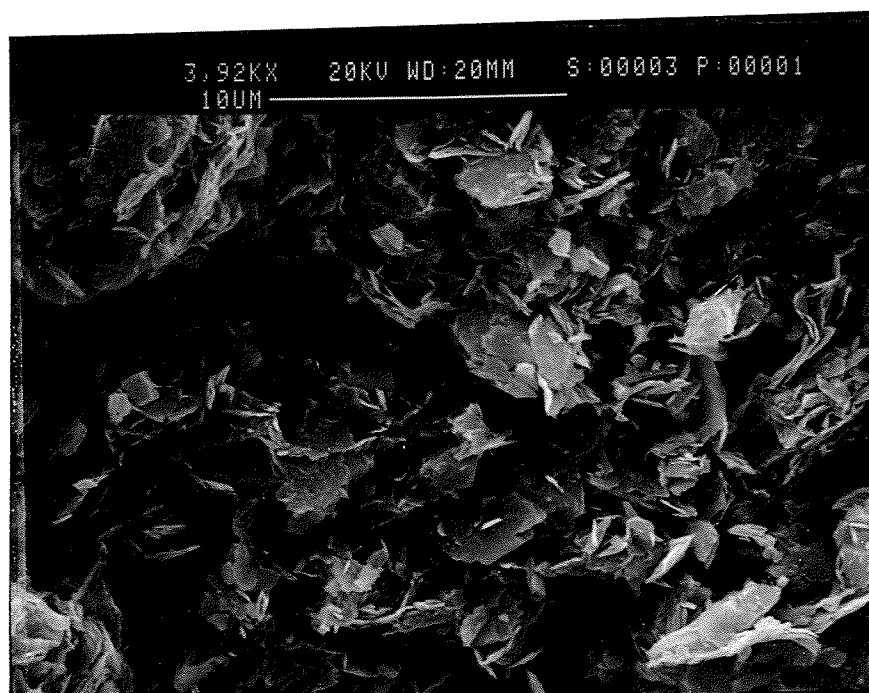


Figure 22

Scanning electron photomicrograph showing randomly oriented plates of illite (Sample 11-29-10-28:3). The sample is from the Middle Bakken.

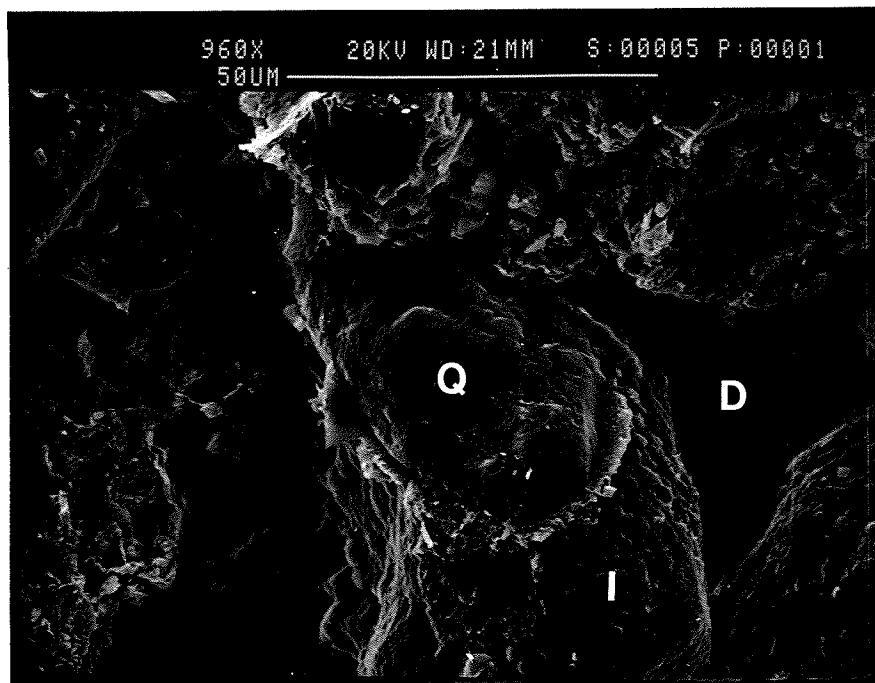


Figure 23

Scanning electron photomicrograph showing a detrital quartz grain coated with authigenic illite (Sample 11-21-10-29:5). The sample is from the Middle Bakken.

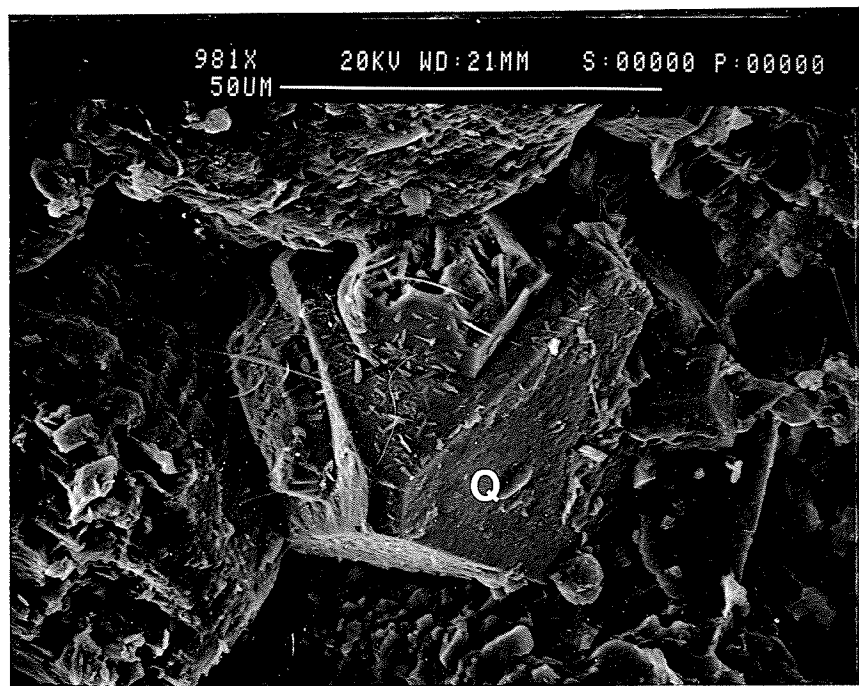


Figure 24

Scanning electron photomicrograph showing a quartz overgrowth with illite inclusions (Sample 11-21-10-29:6). The sample is from the Middle Bakken.

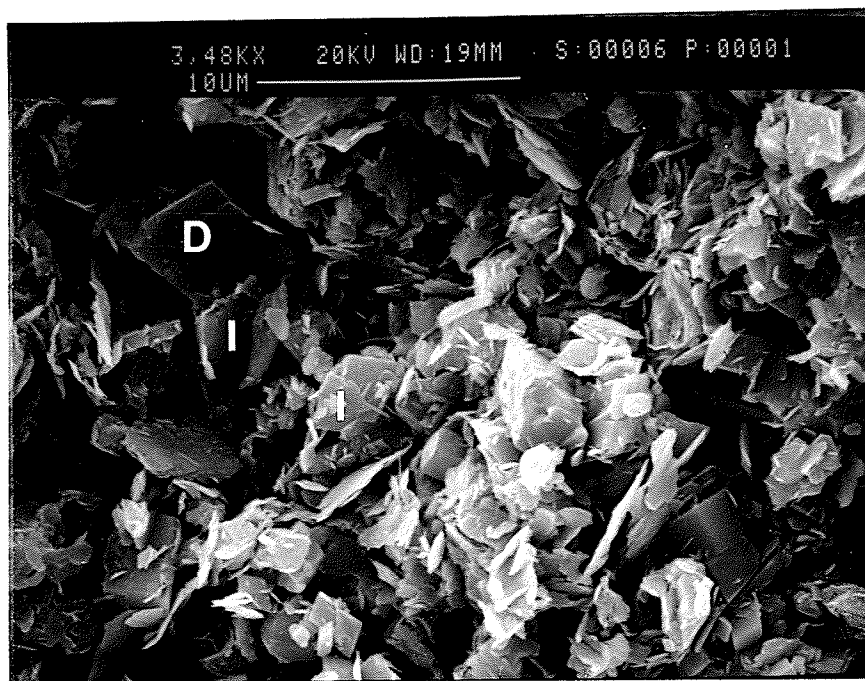


Figure 25

Scanning electron photomicrograph showing small dolomite rhombs (D) with illite (I) intergrowths (Sample 11-29-10-28:6). The sample is from the Middle Bakken.

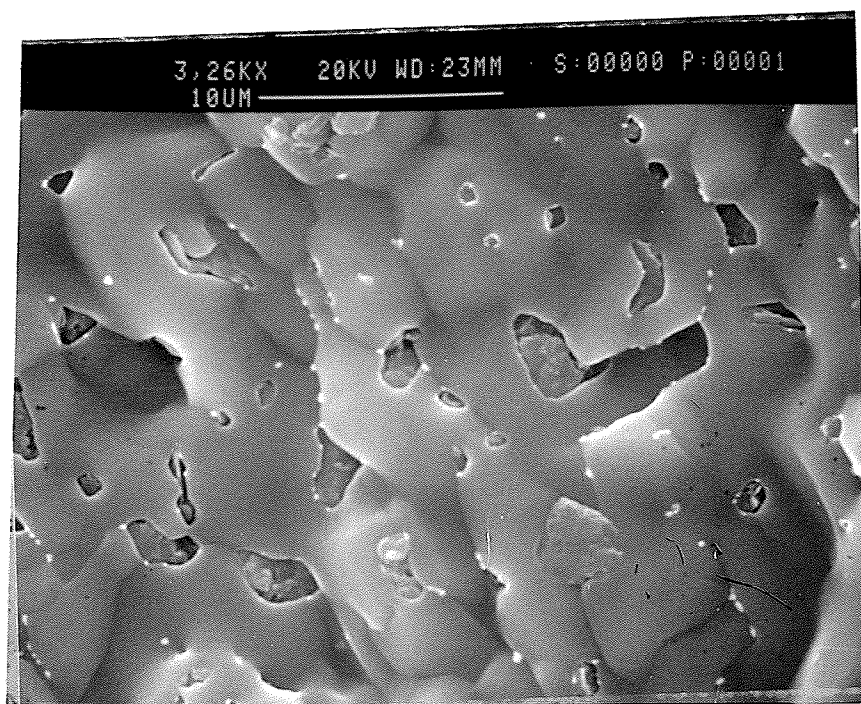


Figure 26

Scanning electron photomicrograph showing sheetlike illite grains from the Upper Bakken (Sample 11-22-08-28:1).

grains also have an euhedral, terminating overgrowth of quartz. These quartz overgrowths often have inclusions of illite (Figure 24), however, there are some grains which do not have the illite inclusions (Figures 27). The quartz is interpreted to be detrital in origin with authigenic overgrowths of quartz and illite.

5.3.2.1.3 Dolomite

The dolomite occurs as euhedral rhombs that have a large size range (1-50 μm). The rhombs of dolomite are commonly intergrown with each other (Figure 28) and also with illite (Figure 25). The larger dolomite rhombs (20-50 μm) are often found interlocked with quartz grains and quartz overgrowths (Figure 29). Some of the larger crystals are zoned (Figure 30). In areas of macroscopic porosity there is often a concentration of larger (20-50 μm) dolomite crystals (Figure 28). There are some dolomite crystals which are pitted (Figure 31). There are also some small (1-20 μm) dolomite crystals in the Upper Bakken (Figure 32). The dolomite is interpreted to be an authigenic replacement as the dolomite grains are euhedral and show no evidence of being transported (i.e., they are not abraded).

5.3.2.1.4 Pyrite and Hematite

Pyrite and hematite are discussed together as they are morphologically similar; the identity of each mineral can only be determined by the presence or absence of a sulphur peak in the EDX spectra. Both minerals are found in the form of small (0.5-1 μm) octahedra and larger (5-15 μm) aggregates and framboids (Figure 33). The pyrite and hematite are interpreted to be authigenic on the basis of the euhedral morphology and lack of rounding and corrosion.

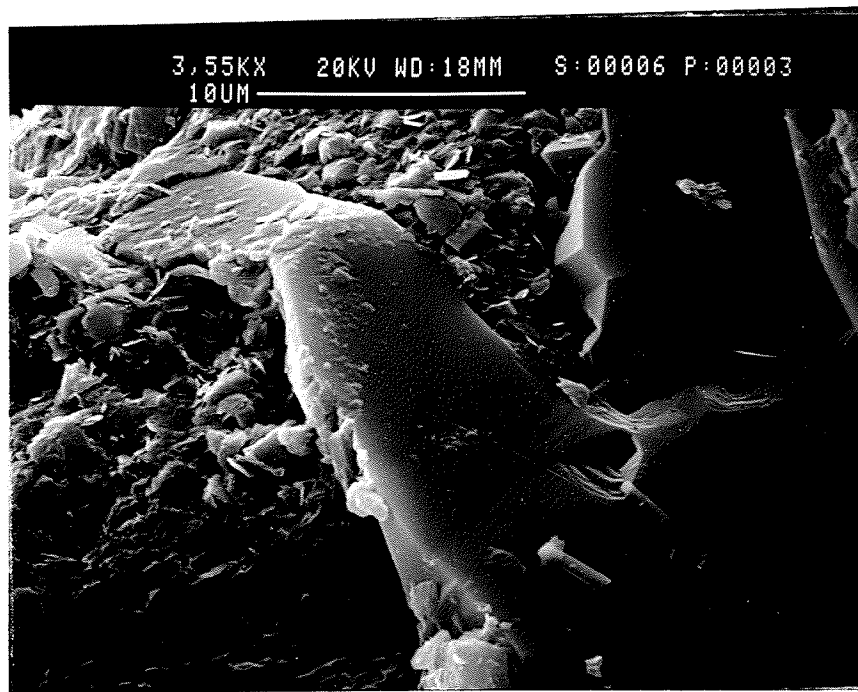


Figure 27

Scanning electron photomicrograph showing a quartz overgrowth lacking illite inclusions (Sample 11-29-10-28:6). The sample is from the Middle Bakken.

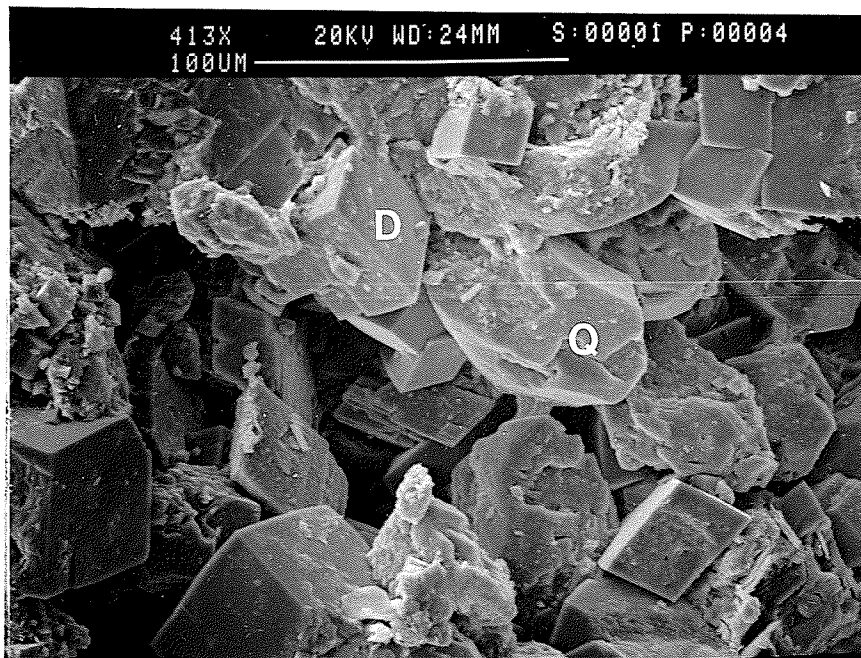


Figure 28

Scanning electron photomicrograph showing euheedral dolomite grains lining a pore. Note the intergrown nature of the dolomite (Sample 08-14-10-28:1). The sample is from the Middle Bakken.

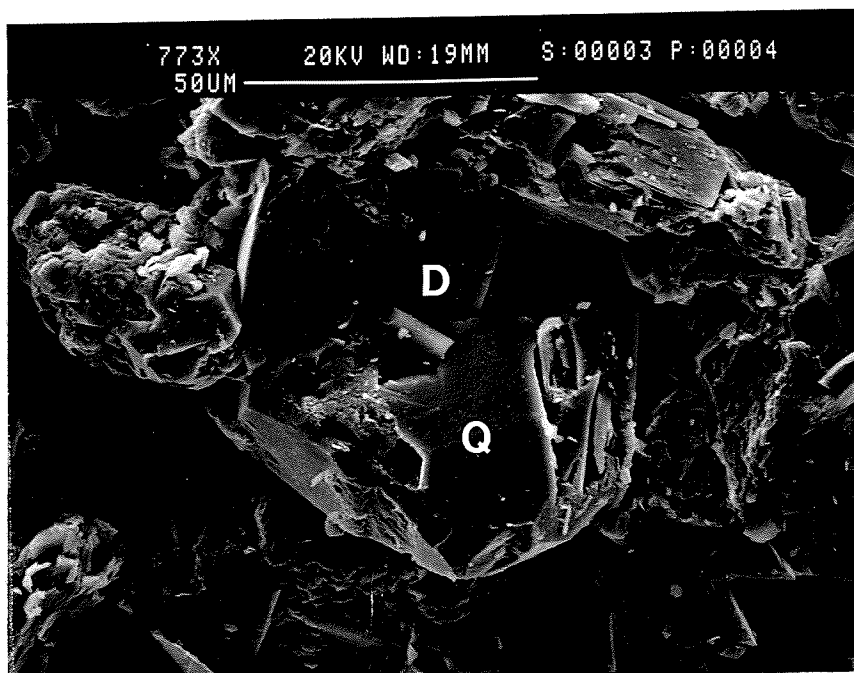


Figure 29

Scanning electron photomicrograph showing interlocking growth of authigenic quartz (Q) and dolomite (D) grains (Sample 11-29-10-28:3). The sample is from the Middle Bakken.

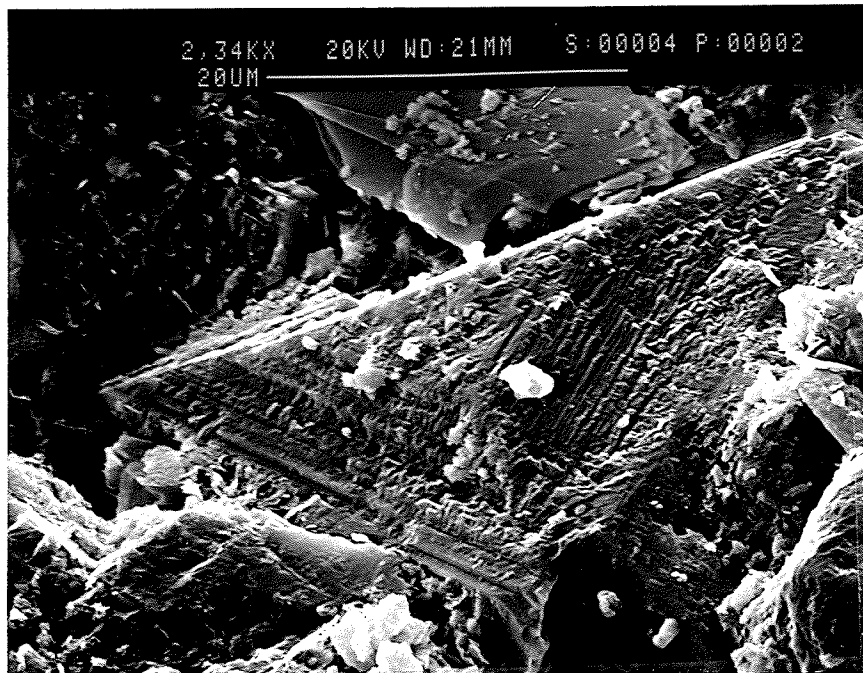


Figure 30

Scanning electron photomicrograph showing zoning in a dolomite grain (Sample 11-21-10-29:4). The sample is from the Middle Bakken.

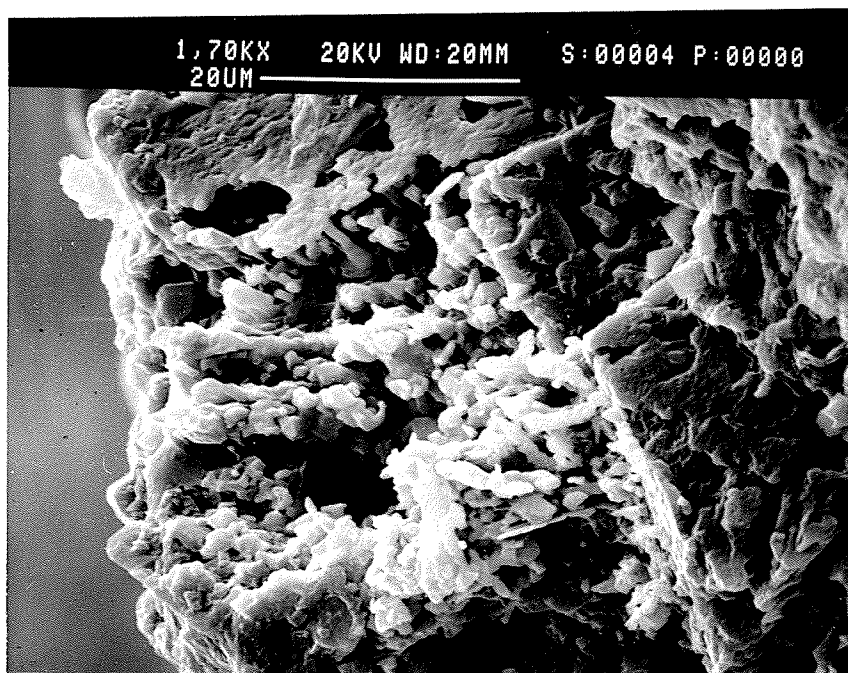


Figure 31

Scanning electron photomicrograph showing solution pitting within dolomite grains (Sample 12-20-10-28:4). The sample is from the Middle Bakken.

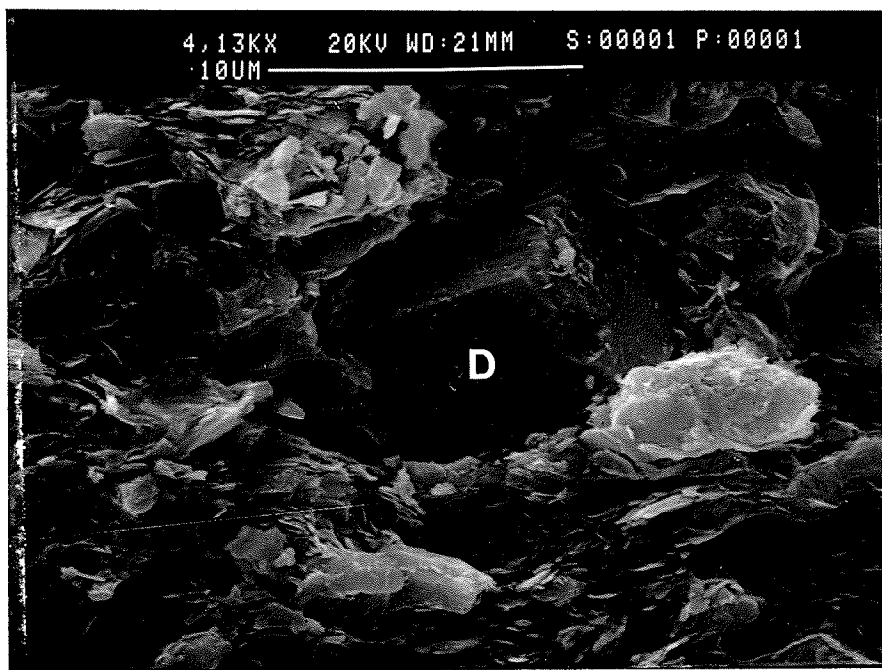


Figure 32

Scanning electron photomicrograph showing an authigenic dolomite (D) grain surrounded by illite within the Upper Bakken (Sample 11-29-10-28:1).

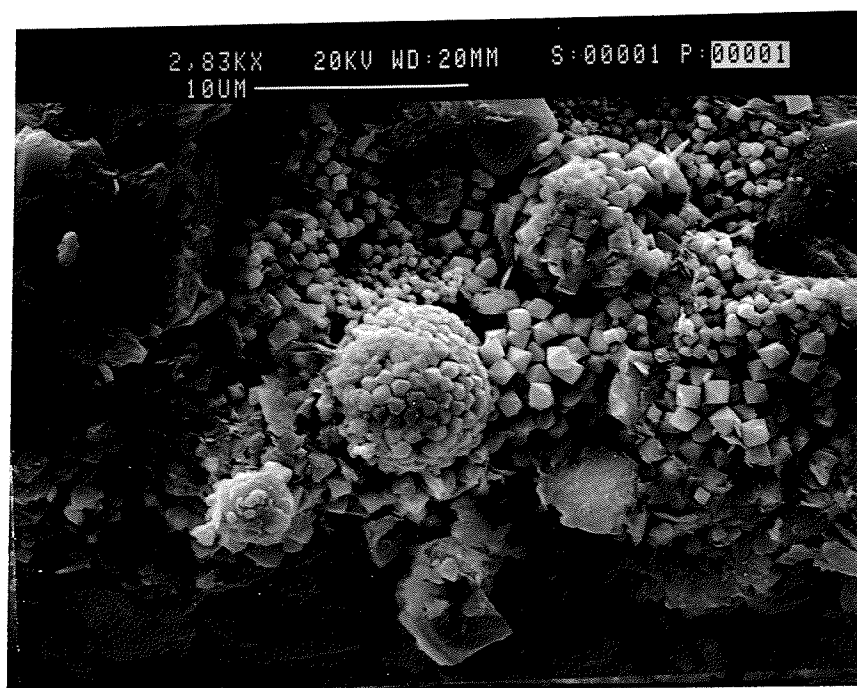


Figure 33

Scanning electron photomicrograph showing octahedra and framboids of hematite (Sample 11-11-11-29:1). The sample is from the Middle Bakken.

5.3.2.1.5 K-Feldspar

K-feldspar, which occurs in minor amounts, is found in two forms: 1) as slightly to severely corroded, angular to subangular grains that are generally 20-50 μm in size (Figure 34), and 2) aggregates (15-30 μm) of small (5-20 μm) euhedral grains (Figure 35). The aggregates of euhedral grains are often present as overgrowths on quartz and dolomite. The corroded grains are interpreted to be detrital grains that have undergone partial dissolution. The aggregates of smaller euhedral grains are interpreted to be authigenic on the basis of their morphology and fragility.

5.3.2.1.6 Anhydrite and Gypsum

Anhydrite and gypsum cannot be differentiated in the SEM image or by the EDX spectra, and so, can only be identified as being anhydrite and/or gypsum. In the Bakken Formation, anhydrite and gypsum are found as a pore filling minerals (Figure 36). They have also undergone dissolution in some areas, as can be seen by the stair-step pattern (Figure 36) (see Schenk and Richardson, 1985). They are interpreted as an authigenic minerals as they are found filling pores and surrounding previously deposited minerals (Figure 37).

5.3.2.1.7 Halite

Halite is an uncommon pore filling mineral in the Bakken Formation. When present it usually occurs as a bulbous anhedral mass (Figure 38). In some locations it has also undergone dissolution (Figure 39). It is interpreted to be authigenic in origin because it fills pores and surrounds previously deposited minerals (Figure 38).

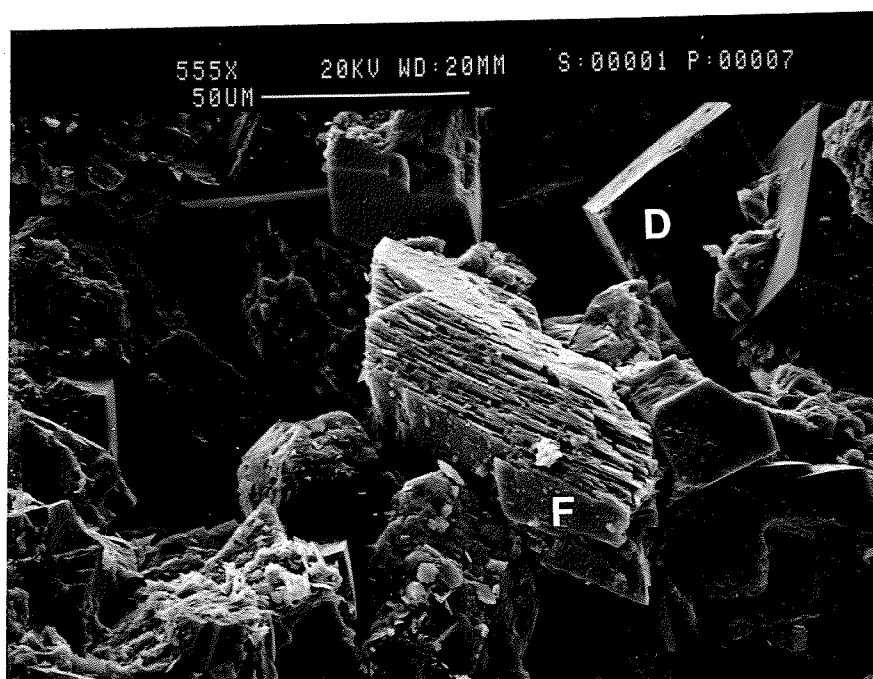


Figure 34

Scanning electron photomicrograph showing a skeletal (corroded) K-feldspar grain (Sample 08-14-10-28:1). The sample is from the Middle Bakken.

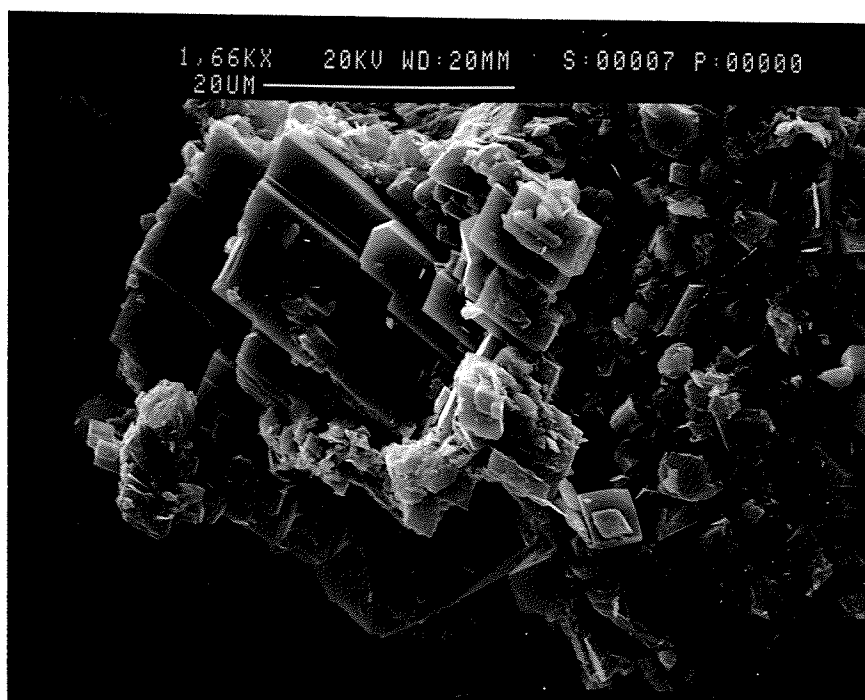


Figure 35

Scanning electron photomicrograph showing an aggregate of euhedral K-feldspar grains (Sample 02-25-10-29:7). The sample is from the Middle Bakken.

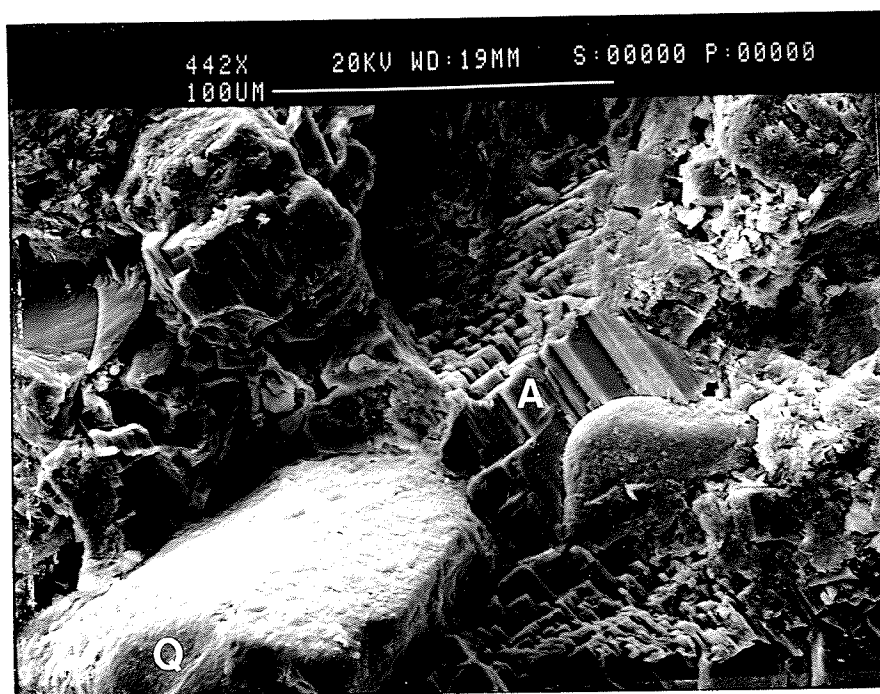


Figure 36

Scanning electron photomicrograph showing anhydrite and/or gypsum (A) filling pores. Note the stair-step dissolution. Adjacent quartz grains indicated by Q. (Sample 11-11-11-29:5). The sample is from the Middle Bakken.

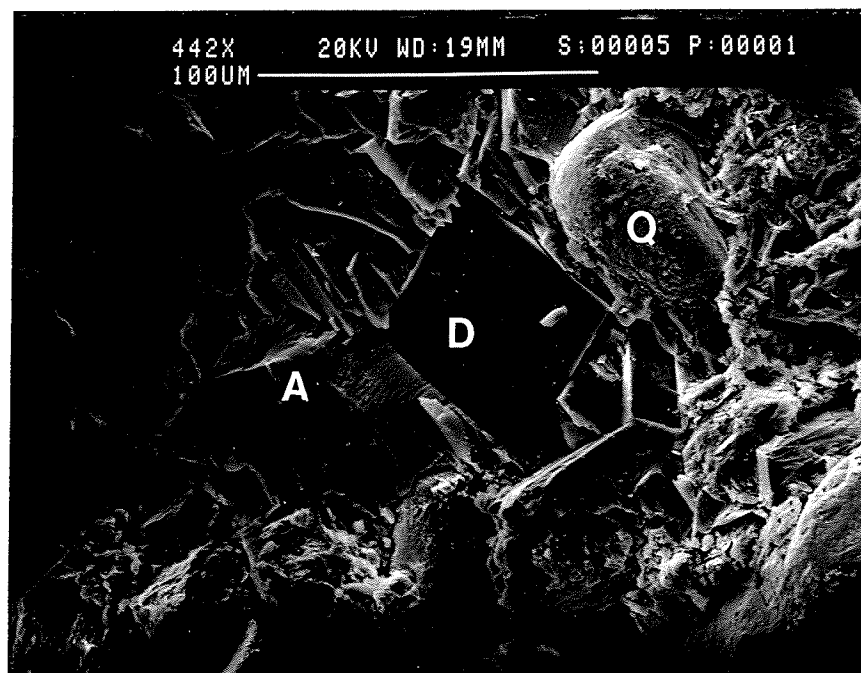


Figure 37

Scanning electron photomicrograph showing pore filling anhydrite and/or gypsum (A) surrounding dolomite (D) and quartz (Q) grains (Sample 11-11-11-29:5). The sample is from the Middle Bakken.

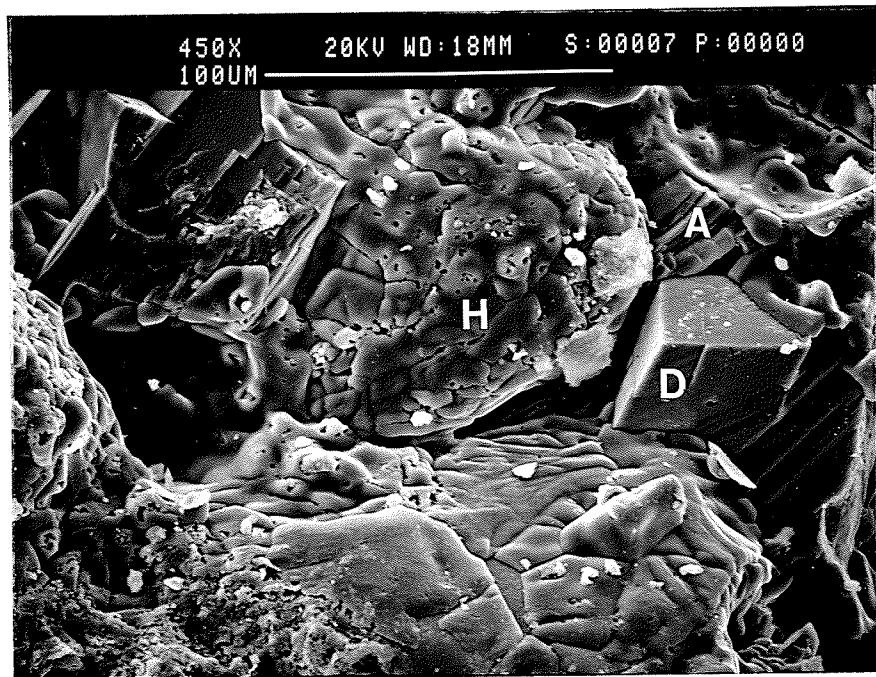


Figure 38

Scanning electron photomicrograph showing a bulbous mass of halite. Also note stair-step anhydrite and/or gypsum surrounding dolomite grain (Sample 11-11-11-29:7). The sample is from the Middle Bakken.

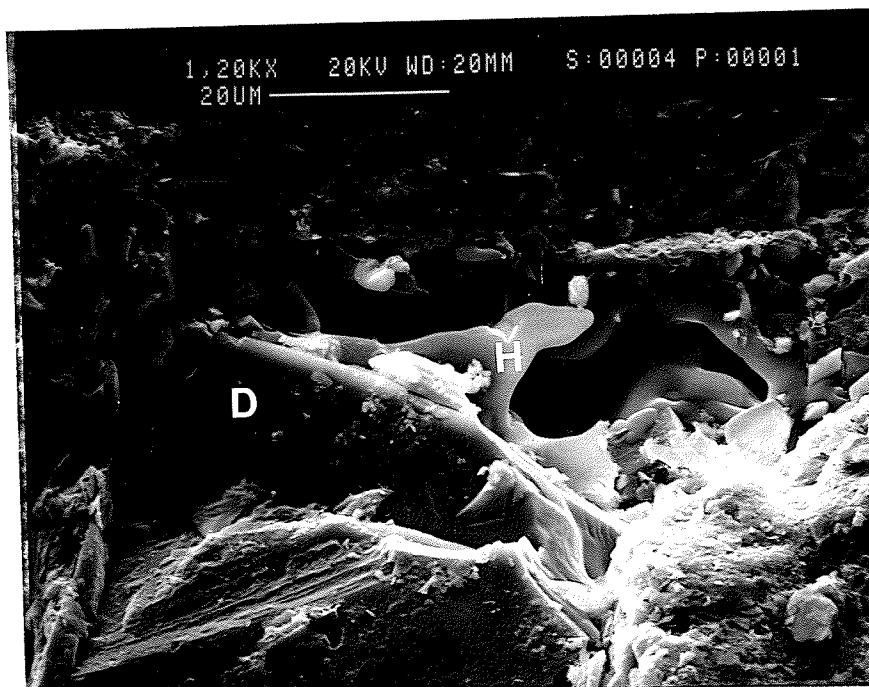


Figure 39

Scanning electron photomicrograph showing dissolution of halite which is filling a pore between dolomite grains (Sample 11-11-11-29:4). The sample is from the Middle Bakken.

Chapter 6: Discussion

6.1 Deposition

6.1.1 Introduction

In the previous work done on the Bakken Formation, the depositional models have concentrated on the environment of deposition for the black shales of the Upper and Lower Bakken and have virtually ignored the Middle Bakken depositional environment. The depositional environment proposed by Fuller (1956), McCabe (1959), Christopher (1961), and Kent (1984) for the Upper and Lower Bakken is a shallow water "marine swamp". The main evidence against this model is the work of Webster (1984), which shows that the main source of organic material for the Upper and Lower Bakken is algal material, rather than the woody material that would be expected in a swampy environment. Lineback and Davidson (1982), Holland and Hayes (1983), and Webster (1984), however, propose that the Upper and Lower Bakken were deposited in a deeper marine environment in which there was a chemically or physically stratified water column. None of the previous work done on the Bakken Formation gave a detailed depositional model for the Middle Bakken. Most only state that the Middle Bakken was deposited during a transgression (Fuller, 1956, Christopher, 1961) or a slight regression (Webster, 1984) or due to a sudden influx of clastics due to uplift in the periphery (McCabe, 1959, Kent, 1984).

In determining a detailed depositional model for the Bakken Formation, the model must satisfy several criteria. First, a marine environment is required for the model

because there are marine fossils, mostly brachiopods, found primarily in the Massive Unit of the Middle Bakken. Any model that is proposed must also explain the uniformity and large regional extent of the Bakken Formation. The model must account for the type and sequence of sedimentary structures in the Bakken Formation, specifically a wavy laminated sandstone followed by parallel laminated siltstone, followed by a massive bioturbated siltstone which is overlain by a finely laminated black shale. The model must also explain the fining upwards in grain size of the Bakken, from a fine sand in the Wavy Laminated Unit to a shale in the Upper Bakken. Sedimentary environments that have most of these qualities are: 1) a regressing beach with a backshore lagoon, 2) an onlapping nearshore marine environment, 3) and a shallow marine shelf. The beach and backshore lagoon model is not acceptable because this model would require the Massive unit to be at the base of the Middle Bakken and the Wavy laminated unit to be at the top of the Middle Bakken, with the lagoonal shale deposited directly on top of the Wavy Laminated Unit, whereas in the Middle Bakken the exact opposite stratigraphy exists.

I feel that depositional environment of the Bakken Formation is a combination of the nearshore environment and the nearshore portion of the shallow marine shelf, with the Middle Bakken being deposited in the nearshore environment and the Upper Bakken being deposited on the marine shelf.

6.1.2 Depositional Model

In order to find a depositional model for the Bakken Formation, the lithology and stratigraphy of the Bakken Formation was compared to the facies models describe in several texts (Pettijohn *et al.*, 1987, Reading, H.G., 1986, Walker, R.G., 1984, Blatt

et al., 1980, Reineck and Singh, 1980).

A modern depositional environment that satisfies most of the above criteria for a depositional model for the Middle and Upper Bakken in the study area is a non-barred, low wave energy clastic shoreline, such as that presented by Elliot (1986) (Figure 40). This type of shoreline occurs on the margin of lakes and restricted seas with limited wave fetch, and on the leeward sides of major continents. Modern examples presented by Elliot (1986) of this type of shoreline include the Gulf of Gaeta in the Mediterranean Sea (Reineck and Singh, 1971, 1980) and the shore of Sapelo Island on the east coast of the United States (Howard *et al.*, 1972, as cited in Elliot, 1986).

The sediments of the Middle and Upper Bakken are similar to the lower shoreface, offshore-transition, and offshore relict sand facies of Elliot's (1986) model (Figure 40). These facies are represented in the Middle and Upper Bakken by the Wavy Laminated Unit, the Horizontal Laminated and Massive Units, and the Shale Unit respectively. The upper shoreface and foreshore facies of the non-barred, low wave energy shoreline model as presented by Elliot (1986) are missing in the Bakken Formation in the study area perhaps because these sediments were reworked offshore into the lower shoreface facies (the Wavy Laminated Unit) during a transgression. The upper shoreface and foreshore facies may appear to the east of the study area or may have been removed during the formation of the Mississippian-Jurassic unconformity.

The stratigraphy of the Bakken Formation has deeper water sediments (the Upper Bakken) deposited on top of shallow water deposits (the Middle Bakken). This stratigraphic sequence indicates that the Bakken Formation was deposited during a

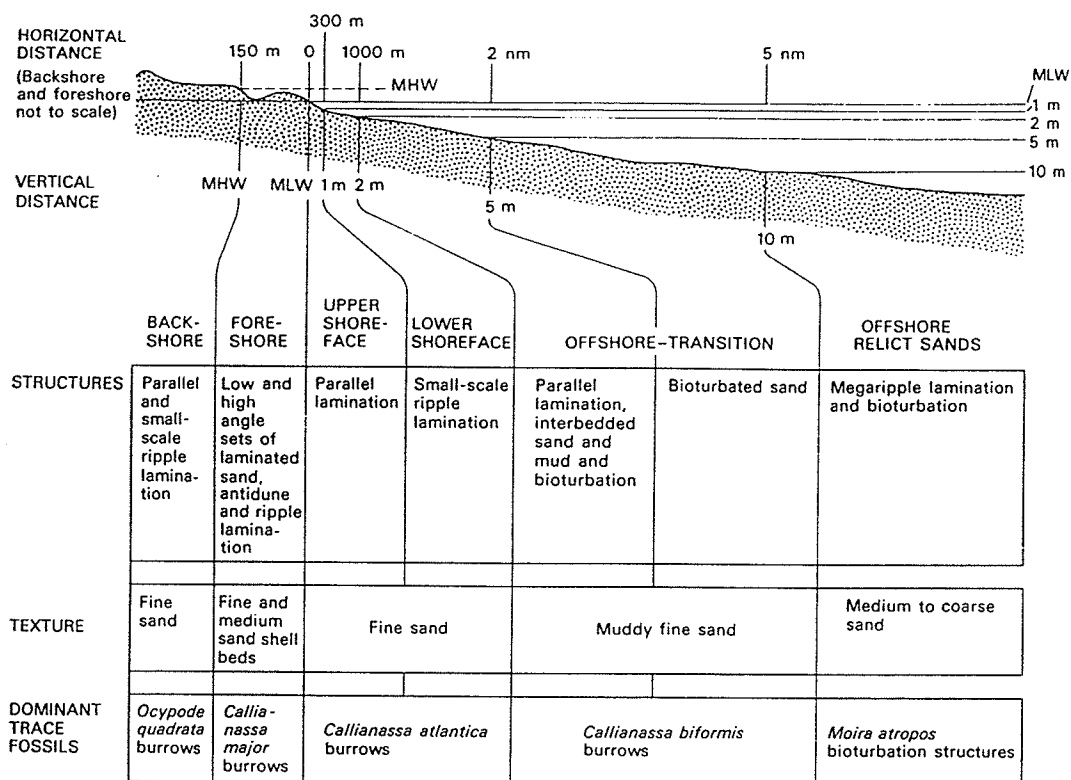


Figure 40

Facies characteristics in Elliot's (1986) model of a non-barred low wave energy shoreline
(Sapelo Island beach face after Howard *et al.*, 1972 from Elliot, 1986)

transgression in which the shoreline receded. In contrast, during a regression or stillstand the deposition of sediment would have resulted in a prograding shoreline with shallow water sediments being deposited over deeper water sediments.

There is much evidence to support the theory that the Middle and Upper Bakken were deposited during a transgression. One indication of deposition during a transgression is that in North Dakota the Lower, Middle, and Upper Members of the Bakken Formation show an onlapping relationship, with each of the successively younger members being more laterally extensive than the previous ones (Webster, 1984). Baum and Vail (1988) state that transgressive deposits are bracketed at the base by a transgressive surface (e.g. an unconformity) and at the top by a surface of maximum starvation, which is a point of minimal coarse clastic input. These are shown respectively in the Bakken Formation by the erosional pebble conglomerates and breccias at the base of the Bakken Formation, and the shale of the Upper Bakken, which was formed during a period of minimal coarse clastic input. Furthermore, a plot of eustatic sea level changes by Ross and Ross (1988) shows a regression at the end of the Devonian, followed by a transgression at the beginning of the Mississippian, which is the period of Middle and Upper Bakken deposition.

6.1.3 Pre-Bakken Time

Before deposition of the Bakken Formation, the Lyleton Formation was deposited in a sea with little organic productivity as indicated by the green colour and the lack of organic matter or its residues. The Lyleton Formation is characterized by green shales and buff coloured dolomites. In some localities the Lyleton shales are a deep red to

purple colour. The green colour of the shales is probably due to the inherent colour of the clay minerals in the shale but may be also partially due to the presence of green ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) (Christopher, 1961). In the wells in which the shales are deep red to purple in colour, it is possible that this coloration is due to the diagenetic oxidation of green ferrous sulphate to hematite. The uniformity of the Lyleton over a large region suggests that similar conditions prevailed over the area during the time of Lyleton deposition - probably on a broad, gently sloping shelf. A regression, which exposed the Lyleton Formation to erosion, resulted in the formation of a pebble bed between the Lower Bakken and the Lyleton toward the eastern edge of the basin in Saskatchewan and Manitoba (Christopher, 1961). The extent of the pre-Bakken erosion in Manitoba is not known because any evidence was removed when the Lower Bakken was removed during a later erosional episode. On the deeper parts of the gently dipping shelf in North Dakota there is no evidence of a break in sedimentation (Webster, 1984), indicating that the regression was minor, extending only into eastern Saskatchewan.

6.1.4 Lower Bakken Deposition

The unit deposited on top of the Lyleton is the black shale of the Lower Bakken. The Lower Bakken was deposited during a transgression, as evidenced by the fact that the Lower Bakken is found on top of an eroded Lyleton surface toward the edges of the basin (McCabe, 1959, Christopher, 1961). It is suggested that the sea that deposited the Lower Bakken extended east past the Waskada area because there is an isolated remnant of the Lower Bakken in that area (McCabe, 1959).

Whereas most authors agree that both the Upper and Lower Bakken shales were deposited in a shallow water environment (Martiniuk, 1988, Kent, 1984, McCabe, 1959), there are some who propose deep marine deposition (Webster, 1984, MacDonald, 1956). Those who favour the shallow water depositional model variably describe the environment of deposition for the black shale as a vast "marine swamp" with restricted circulation due to prolific organic productivity and resulting in anoxic conditions (Martiniuk, 1988, McCabe, 1959) or a broad open marine platform over which wave intensity was dampened due to shallow water depth (Kent, 1984).

Another possible explanation for the presence of the black shales of the Upper and Lower Bakken Formation is that these sediments were deposited in a chemically and/or thermally stratified water column (Lineback and Davidson, 1982, Holland and Hayes, 1983, and Webster, 1984), similar to the environment described by Ettensohn and Barron (1981) for much of the Devonian-Mississippian "Black Shale Sea" of North America. In a stratified water column, the surface water and the deeper water are separated by a strong chemical or temperature gradient and the two water strata do not mix, resulting in an oxygenated surficial water strata and an anoxic deep water strata, allowing for the deposition of unoxidized organic material and iron sulphides.

Supporting the idea of a strong temperature stratification is the fact that the area of Bakken deposition was less than 10 degrees from the equator during the Late Devonian-Early Mississippian (Khramov, 1987)(Figure 41); in this warm climate, surface waters do not cool enough to sink and displace the colder bottom waters (Byers, 1977). In contrast, in cold waters, mixing of the water strata is relatively easy. This is because



Figure 41

Paleomagnetic base map of Earth for the Mississippian Period. From Khramov (1987).

the density difference caused by a 1 degree temperature difference is much greater in warm water than it is in cold water.

Another possibility is a strong chemical stratification of the Bakken Sea by the creation of a halocline in the Williston Basin during the deposition of the Bakken Formation. In this scenario, the normal marine waters of the Williston Basin would float on top of a denser hypersaline brine in the lower parts of the basin. The separation of the surface waters from the deeper waters due to the density differences would result in a stratified sea, similar to the conditions present in the Black Sea today (Emery and Hunt, 1974).

It is proposed that the hypersaline brines would originate from the dissolution of evaporite beds in formations below the Bakken Formation and fed into the Williston Basin by underwater springs. Possible evidence to support this hypothesis is the presence of solution collapse structures that formed before or during the deposition of the Lower Bakken. These solution collapse structures, which are found in the Waskada area, have a relief of over 13 metres (McCabe, 1959, Martiniuk, 1988). The thickness of the hypersaline brine would likely be controlled by the height of the outlet of the Williston Basin. Webster (1984) states that the oxygen stratification is due to a change in basin geometry, climate, or water circulation. Lineback and Davidson (1982) and Holland and Hayes (1983) do not give a reason for the origin of the stratification.

A problem with both of the models proposed for the stratification of the Williston Basin during the deposition of the black shale is that in a shallow sea, storm waves would likely disrupt the stratification. A possible solution to this problem is that the

stratification was strong enough that the storm waves could not destroy the stratification. It is also possible that the stratification occurred in waters that were too deep to be affected by storm waves, however, this poses the problem of having drastic changes in sea level between deposition of the black shale of the Lower Bakken and the clastic material of the Middle Bakken and again between the deposition of the Middle and Upper Bakken. Webster (1984) states that 45 metres is the minimum depth necessary to get the bottom waters below wave base.

At the end of Lower Bakken time, there was a regression which caused erosion of the Lower Bakken from most of Manitoba, except in the Waskada area where it had been deposited in a topographic low (McCabe, 1959). This erosional event also removed part of the upper Lyleton Formation from the study area, and there is now a pebble conglomerate/breccia at the top of Lyleton. The present eastern erosional edge of the Lower Bakken is in eastern Saskatchewan. The erosion on the top of the Lower Bakken does not extend very far west toward the centre of the basin. This is supported by Christopher (1961) who found a pebble bed on the top of the Lower Bakken only in easterly Saskatchewan wells.

6.1.5 Middle and Upper Bakken Deposition

After erosion of the Lower Bakken and Lyleton Formations, the sea once again began to deepen and transgress eastward. This would have resulted in deposition of fine and medium sands with antidune, ripple and parallel lamination of the foreshore and upper shoreface facies according to Elliot's (1986) model. As the transgression continued, these foreshore and upper shoreface facies (Figure 40) were reworked seaward

into the lower shoreface environment, resulting in deposition of the Wavy Laminated Unit, which contains small-scale ripple lamination, just as Elliot's (1986) model indicates.

The source of the detrital material in the Wavy Laminated Unit is probably from erosion of the underlying formations at the shallower margins of the sea. Erosion from previously existing (pre-Bakken) sedimentary rocks is evidenced primarily by the maturity (sorting and rounding) of the detrital quartz found in the Middle Bakken. Also, some of the detrital quartz grains have abraded overgrowths (McCabe, 1959), indicating that they were reworked from previously existing sedimentary rocks. However, there was little coarse clastic sediment available as most of the units below the Bakken are carbonates (i.e. Nisku, Duperow) and shale (Lyleton) containing only a small clastic component. This may account for the relative thinness of the Middle Bakken.

The carbonate content of the Bakken Formation may have originally been detrital residues from the older carbonates; alternatively, they could have been formed by the primary chemical or biochemical precipitation of calcite, or a combination of the two. Both the original crystal nature and the source of the carbonate is difficult to discern due to extensive dolomitization. The fine grained nature of the dolomite and the sparsity of macrofossils suggests that primary carbonates were either chemical precipitates or microscopic detrital shell material.

The grain size of the quartz fines upward, indicating a drop in energy in the environment of deposition from the base of the Middle Bakken to the top of the Upper Bakken. Also, there is a general trend in the percent concentration of quartz vs all other

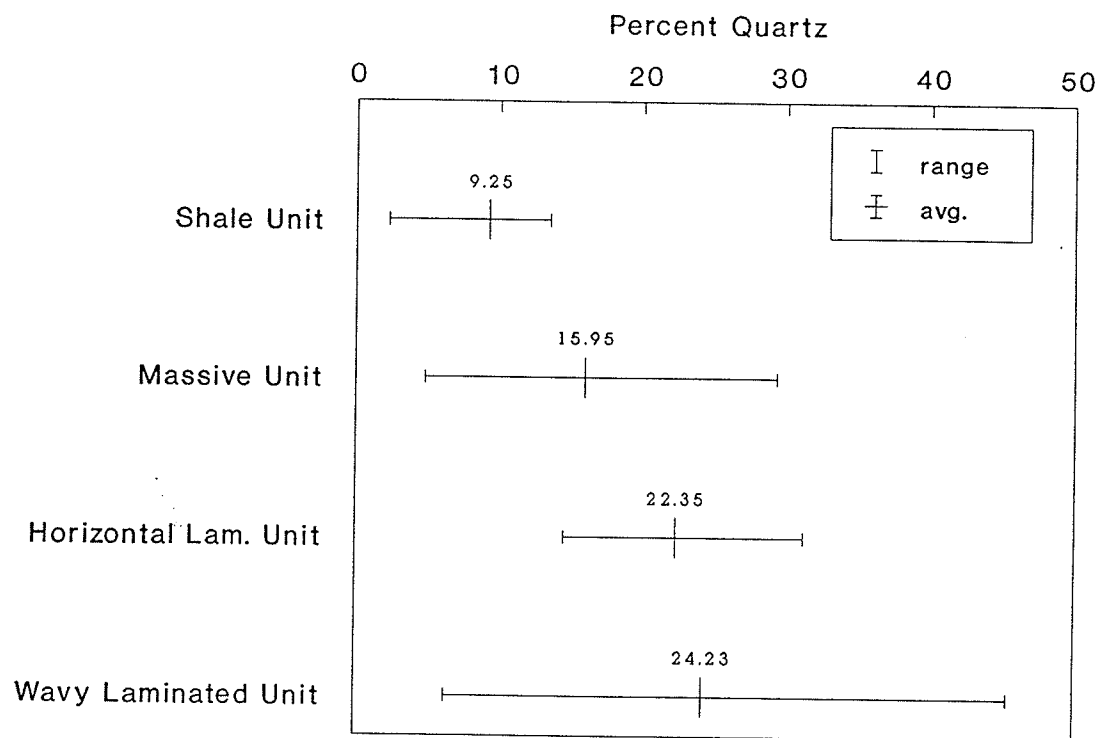


Figure 42

Quartz content in the various units within the Bakken Formation. The bar indicates the range of values observed and the tick mark indicates the mean.

minerals in the samples (see Appendix 4) in the Middle and Upper Bakken (Figure 42), which shows a decrease in the amount of quartz upward in the section. Because the range of the quartz grain size is relatively small, this trend in quartz concentration may also indicate a drop in maximum energy available in the depositional environment during Bakken time. The concentration of clay minerals in the Bakken shows an increasing trend upward in the Bakken section (Figure 43), which may further indicate a decrease in energy of deposition from the base to the top of the Bakken section. Although some portion of the clay minerals (primarily illite) are authigenic precipitates, it is possible that the trend evident in Figure 43 is due to an increase in the amount of detrital clay minerals present.

Using the trends indicated above, it is suggested that the Wavy Laminated Unit is the most shoreward of the deposits found in the Bakken Formation in the study area, and it reflects the highest energy conditions. This relatively higher energy depositional environment is further evidenced by the presence of wavy laminations, which are probably cross sections of current ripples, in the Wavy Laminated Unit.

With further transgression to the northeast, the waters over the study area deepened. Wave energy decreased and beds become thinner, forming parallel horizontal laminae (the Horizontal Laminated Unit). The drop in wave energy is further shown by the trends in the concentration of quartz (Figure 42) and clay minerals (Figure 43) mentioned previously. Petrographic examination of the parallel laminations show that each laminae has grains of silt and sand sized quartz at the bottom and grades upwards into finer grained carbonate and clay at the top.

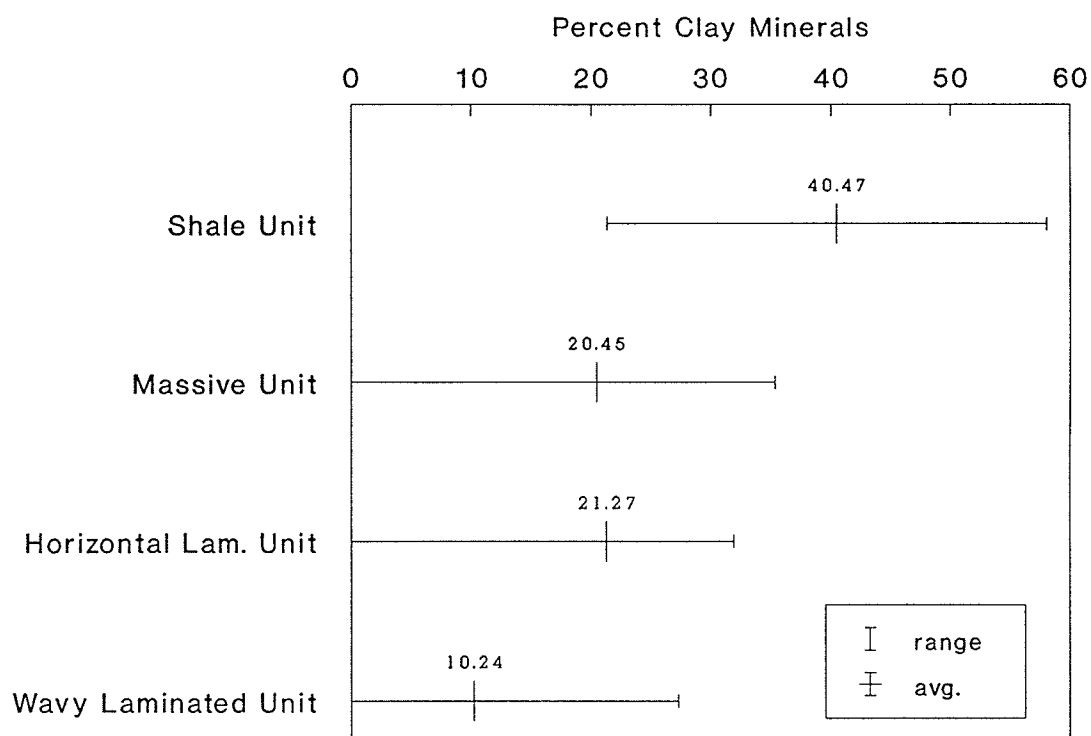


Figure 43

Clay mineral content in the various units within the Bakken Formation. The bar indicates the range of values observed and the tick mark indicates the mean.

As the transgression continued, the bottom of the Bakken Sea in the study area went below fair weather wave base, but remained above storm wave base. This is suggested by the presence of a few relatively coarse grained beds in some of the cores (Figure 16). These coarse beds are interpreted to be storm sheets. The drop below fair weather wave base allowed the area to be colonized by brachiopods, crinoids, and other biota. The organisms churned up the sediments, destroying any structure that was present.

With further transgression, the surface of deposition in the study area dropped below storm wave base and a strongly stratified water column may have become established due to development of either a thermocline or halocline. The reasons and processes which led to the stratification would have been similar to those discussed for the deposition of the Lower Bakken. Due to the stratification in the water column, the oxygen in the water at the sediment-water interface was depleted before all the organic matter could be oxidized, resulting in the black shales of the Upper Bakken. The clastic sediments became predominantly fine grained clay minerals (Figure 43) which could be carried in suspension for some distance. The amount of dolomite found in the Upper Bakken shale is quite low relative to the amount found in the Middle Bakken. This may be due to the fine grained sediments restricting the circulation of porewater and cutting off the supply of Mg^{2+} needed for the transformation of calcite to dolomite. Most of the carbonate in the Upper Bakken is found in thin bands of nearly pure calcite which have no discernable relict structure, possibly due to remobilization. The lower amount of carbonate in the Upper Bakken, as compared to the Middle Bakken, may be due to a

reduction in the production of carbonate in the water column above the seafloor during the deposition of the black shales.

At the end of deposition of the Upper Bakken, there was an increase in the amount of carbonate produced in the water column, resulting in deposition of the Lodgepole carbonates.

6.2 Diagenesis

A suite of authigenic minerals was identified in the Bakken Formation, and I have used this to interpret the occurrence of several chemical diagenetic events. Authigenic minerals were identified by their euhedral crystal form and intergrowth with other crystals. If these minerals had been detrital, they probably would have exhibited a more rounded morphology due to abrasion during transportation and would not exhibit the intricate intergrowths that are present. The chemical diagenetic events recognized in the Middle Bakken include the dissolution of some minerals and the precipitation of others. The authigenic minerals identified in the Middle Bakken are illite, dolomite, pyrite, quartz, K-feldspar, hematite, anhydrite, gypsum, and halite. In the Upper Bakken the only authigenic mineral found during scanning electron microscopic study was dolomite, however, the X-ray diffraction analysis indicates the presence of pyrite and anhydrite.

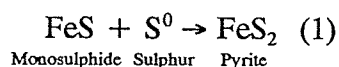
It is proposed that the solutions that precipitated the authigenic minerals had a low degree of supersaturation. This is supported by the statements by Berner (1980) that both the rates of crystal growth and crystal nucleation is a function of the degree of supersaturation of the solution. At low levels of supersaturation, crystal nucleation is very slow, and excess dissolved material is consumed by crystal growth on a limited

number of nuclei. This results in a high degree of crystallinity of the authigenic phase and will tend to favour growth on existing mineral phased as syntaxial overgrowths. In contrast, with high supersaturation, the rate of nucleation may be so fast that virtually all the excess solute is rapidly precipitated as nuclei (in the order of 10-100 Å), effectively decreasing the saturation so that little solute remains for crystal growth. The result will tend to be very poorly crystallized, often fine grained precipitate.

6.2.1 Pyritization

Pyrite formed relatively early in the diagenesis of the Bakken Formation, possibly in the sulphate reducing zone within a few metres of the sediment-water interface. The probable presence of conditions optimal (i.e. sulphate from the seawater and the likely presence of sulphate reducing bacteria) for pyritization during early burial suggests that formation of pyrite in the sulphate reducing zone would account for the majority of the pyrite found in the Bakken Formation. In the presence of soluble ferrous iron, the sulphate produced in the sulphate reducing zone will immediately precipitate as metastable iron monosulphides and pyrite that forms from the transformation from these precursor phases displays a characteristic framboidal structure (Hesse, 1990) as seen in Figure 33. Berner (1970, 1984) states that most pyrite found in the sedimentary record was formed in the sulphate reducing zone during early burial. The first stage in the production of early diagenetic pyrite is the creation of a reducing environment. This is accomplished by the oxidation of organic matter in sediments which consumes all of the available oxygen. The pyrite forms in the sediment from anaerobic sulphate reducing bacteria forming H_2S (i.e., $\text{SO}_4^{2-} + 2\text{CH}_2\text{O} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{S} + 2\text{HCO}_3^-$). The H_2S then

reacts with dissolved reduced iron to form monosulphides which react with elemental sulphur to form pyrite (Berner, 1970, 1984).



Because the amount of sulphate found in marine waters is in excess of what is needed to form pyrite (Berner, 1984), the limiting factor in the formation of pyrite would be the availability of dissolved iron or reactive organic matter. If insufficient iron is present, the H₂S which is produced by the sulphate reducing bacteria would escape from the sediment without forming pyrite. If not enough reactive organic matter is present, the sulphate reducing bacteria do not produce enough H₂S to react with the iron that is present because the bacteria use the organic matter as a food source (Berner, 1984). The formation of pyrite is so extensive that some wells have a 2-3 cm thick pyrite band in the Massive Unit. This pyrite band can be traced through much of the study area (Figure 44) by the use of P_e well logs. The pyrite bands may have formed in topographic lows where the bottom waters stagnated and the oxidation of organic matter created anoxic conditions above the sediment/water interface and allowed for an open system sulphate reduction in the water column. Disseminated pyrite is found throughout many of the cores. Most of the brachiopod shells that were present were also replaced by pyrite which in some localities was later pseudomorphically replaced by hematite.

6.2.2 Dolomitization

In the current literature there are many models proposed for the formation of the dolomite found in the geologic record. Some of the models that have been proposed (as presented in Morrow, 1982, Baker and Burns, 1985, and Hardie, 1987) are the

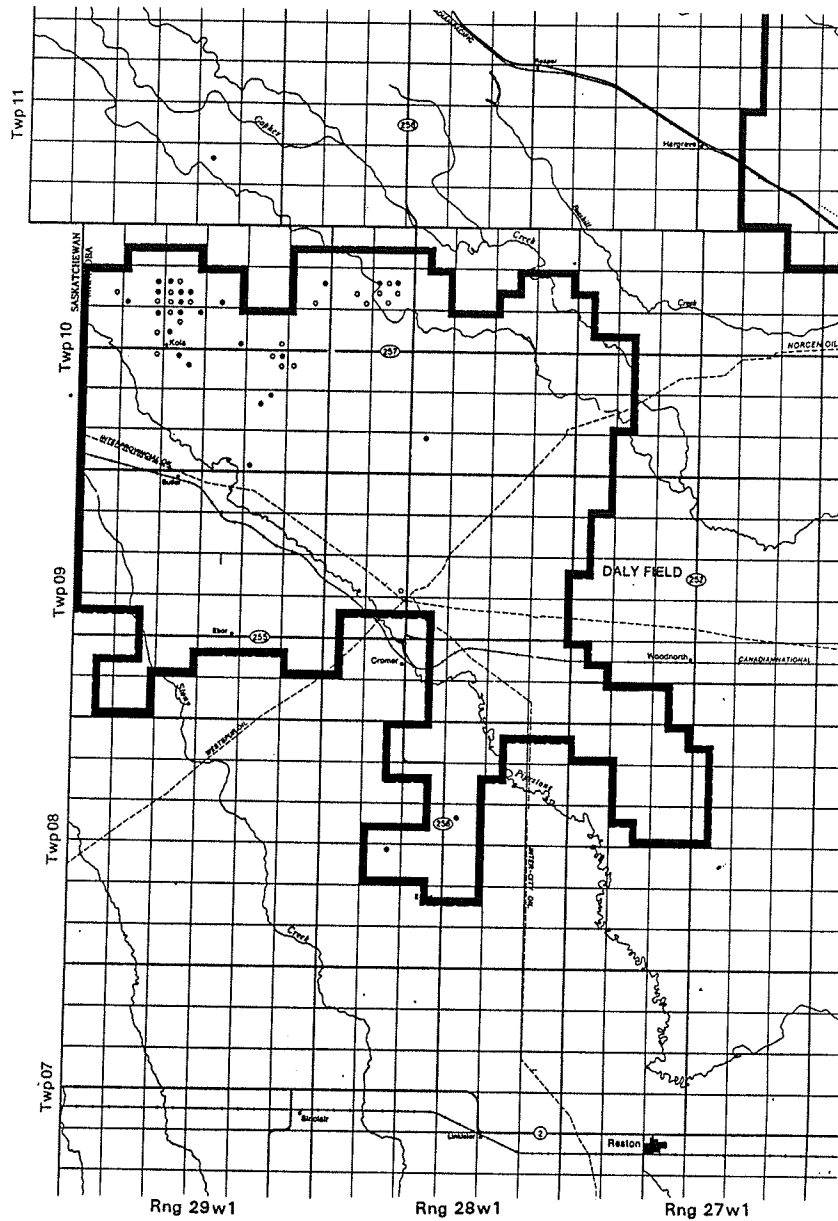


Figure 44

Map showing wells with a pyrite band in the Massive Unit. Solid dots indicate wells with core or P_e logs showing a pyrite band, open dots indicate a well which does not have a pyrite band on the core or P_e logs. Modified from Manitoba Department of Energy and Mines, Petroleum Division Map No. 7.

hypersaline lagoon and reflux model (known as the seepage reflux model), the burial compaction model, the mixed water or dilution model, solution cannibalization and pressure solution model, the tectonic or hydrothermal model, the sabkha model (a variation on the seepage reflux model), and the Coorong model, which is a variation on the mixed water model.

In the study of the Bakken Formation, the solution cannibalization and pressure solution model, as well as the tectonic or hydrothermal models, have been eliminated as they require that the sediments be buried to depths greater than 1 km (Morrow, 1982), whereas a study of organic matter maturity of the Upper Bakken in the study area indicate a maximum burial of 800-900 m (see section 5.2.4). The seepage reflux model and sabkha models are not used, as the dolomites formed by these models are associated with substantial deposits of evaporite minerals (Morrow, 1982, Hardie, 1987), and only a small amount has been found in the Bakken Formation. Furthermore, this model requires an extensive, very shallow (< 1 m) lagoon or shelf, and this type of geometry is not indicated for the Williston Basin at this time.

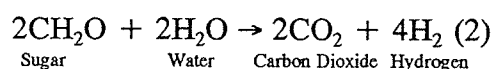
The mixed water model, also known as the Coorong and Dorag models, was first proposed by Henshaw *et al.* (1971) but is more widely known as the Dorag model (Badiozamani, 1973). In this model, dolomitization can take place shortly after deposition or after lithification. The dolomitization occurs due to the mixing of seawater with meteoric water. The mixing of these two waters causes the salinity of the water to drop while the Ca/Mg ratio stays essentially unchanged, making it more thermodynamically and kinetically favourable for the formation of dolomite

(Badiozamani, 1973, Folk and Land, 1975).

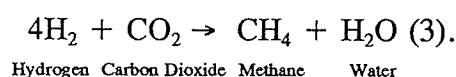
In the Bakken Formation, post lithification dolomitization may have occurred during the exposure of the edge of the Bakken during the formation of the Mississippian-Jurassic unconformity. At that time, meteoric waters could have percolated down from the unconformity to mix with the saline formation waters, resulting in favourable conditions for the replacement of calcite by dolomite. Evidence in the Bakken Formation for the formation of dolomite in this way is the presence of clear, well formed, pore-lining dolomite, particularly in the areas of high permeability. It was proposed by Folk and Land (1975) that clear, well formed dolomite would form in the mixed water environment. There is some question as to the validity of the mixed water model, and Hardie (1987) even states that dolomite has not been shown to be forming in areas in which fresh and saline waters are mixing in the modern environment. The arguments that Hardie (1987) makes against the model include the fact that Badiozamani (1973) used the thermodynamic data for ordered dolomite rather than the values for disordered dolomite and it is disordered dolomite that is forming in the modern environment.

A more recent model for the formation of dolomite has been proposed in which conditions in normal seawater are favourable for the formation of dolomite by the decomposition of organic matter and the concurrent destruction of sulphate by sulphate reducing bacteria (Baker and Burns, 1985). This process allows calcite to be altered to dolomite because sulphate is generally considered to inhibit dolomite formation (Baker and Kastner, 1981). Another condition that favours early diagenetic dolomite formation is an increase in porewater alkalinity (HCO_3^-) due to the action of the sulphate reducing

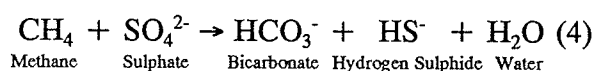
bacteria. Methanogenic bacteria, which digest simple organic compounds, may also be a source for the bicarbonate needed for dolomite formation (Friedman, 1991). The methanogenic bacteria form methane by a CO₂ reduction pathway (Claypool and Kaplan, 1974):



and



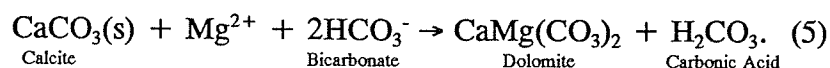
The methane is then microbiologically oxidized anaerobically with sulphate as the oxidant to produce bicarbonate (Friedman, 1991):



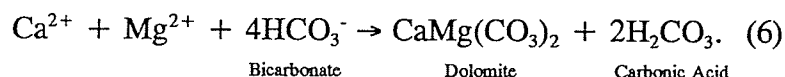
It has also been proposed that the enzymatic degradation of the protein found in marine algae results in the formation of relatively high concentrations of ammonia (NH₃), which would increase the pH of the system and promote the replacement of calcite by dolomite (Slaughter and Hill, 1991). The large increase the pH of the porewaters due to the carbonate alkalinity and ammonia may result in porewaters that are highly supersaturated with respect to dolomite (Baker and Burns, 1985) causing precipitation of dolomite.

Dolomite precipitation may occur with or without a precursor calcite. The increased HCO₃⁻ concentrations resulting from the sulphate reduction may first cause calcite or magnesian calcite to form. This early formed calcite could then be converted into diagenetic dolomite through a reaction such as that proposed by Baker and Burns

(1985):



Alternatively, the dolomite may have formed with no calcite precursor by the following reaction (Burns *et al.*, 1988):



In both reactions, Ca and Mg both came ultimately from sea water and the bicarbonate from the sulphate reducing bacteria. The Ca and Mg ions that are necessary for the formation of dolomite are supplied by diffusion into the sediment from the overlying seawater. The shallow depth of diffusion of the Ca and Mg ions constrain significant dolomite precipitation to the uppermost sediments, as many volumes of porewater with seawater concentrations of Ca and Mg are required for dolomitization (Baker and Burns, 1985). This model has been shown to have operated in several DSDP drill holes in which dolomite was found (Baker and Burns, 1985).

Conditions in the Bakken formation during early burial appear to be favourable for the formation of organogenic dolomite, particularly the presence of large amounts of organic matter and the presence of pyrite, which suggest that sulphate reducing conditions existed. The evidence against the formation of organogenic dolomite in the Bakken is that in the DSDP cores, only a small amount of dolomite is found (at most 40%) and is almost always found with calcite. In the Bakken Formation, dolomite forms as much as 74% of the sediment and is found with only a trace of calcite. In the Bakken Formation, these problems may be resolved by the fact that the sediments of the Bakken

show evidence of a very large source of organic matter (i.e the high organic content of the shales) and so may have had conditions favourable for the conversion of all the available calcite to dolomite.

Another possibility is that the dolomite that is present in the Bakken Formation is due to the recrystallization of a clastic dolomite. Because many of the formations that are stratigraphically below the Bakken Formation are also dolomitic, some of the sediment of the Bakken may be detrital dolomite, having been eroded from these dolomitic units; later recrystallization may have occurred to form the authigenic dolomites found in the Bakken. The evidence against this is that the clastic dolomite grains would have had a maximum size in the same order of the quartz grains (i.e. fine silt) and it is difficult to explain how much of the very fine (1-5 μm) dolomite would have formed from this. Further evidence against the recrystallization of clastic dolomite is the lack of relict structures, such as grain boundaries, which would be expected.

It is my opinion that the organogenic model of dolomitization has the most evidence in its favour, and so it is suggested that the majority of the dolomite found in the Bakken Formation was formed by transformation of precursor calcite to dolomite by this process. A small amount of the dolomite, particularly the larger pore lining dolomites in the permeable zones, however, may have formed by the mixed waters process.

6.2.3 Diagenesis of Silicic Minerals

Although much of the silicate minerals found in the Bakken Formation, primarily quartz, illite and K-feldspar, are detrital, an unknown portion of these minerals formed

authigenically. All of the silicate minerals found in the Bakken Formation are chemically related. The silicate mineral formation and stability relationships can be described by the $K_2O-Al_2O_3-SiO_2-H_2O$ system. The stability fields of the silicate minerals found in the Bakken Formation can be shown in a diagram relating $\log[K^+]/[H^+]$ and $\log[H_4SiO_4]$ (Figure 45) (Garrels and Christ, 1965). Initially the porewater had a $\log[K^+]/[H^+]$ and $\log[H_4SiO_4]$ in the range of sea water but with the $\log[K^+]/[H^+]$ at the high end of the range (approximately 6.5). At these values of $\log[K^+]/[H^+]$ and $\log[H_4SiO_4]$ illite is stable, however, K-feldspar is unstable. As a result of the different stabilities, illite may have started to precipitate while K-feldspar was undergoing dissolution. Harder (1974) suggests that illite can form as a "direct" precipitate from seawater if there is a sufficiently high concentration of K (0.05 to 0.5%). The dissolution of K-feldspar along with the potassium in seawater acted as a source for potassium during the precipitation of illite. The dissolution of K-feldspar also increased the H_4SiO_4 concentration in the porewater. The rise in the concentration of H_4SiO_4 of the water increased from the normal sea water levels (approximately -4.3) to -4 resulted in the precipitation of quartz overgrowths (Figure 29). These authigenic quartz overgrowths act as a cement in some parts of the Bakken Formation. There is also some authigenic K-feldspar found in the Bakken Formation. The change from dissolution to precipitation of K-feldspar indicates that the concentration of H_4SiO_4 in the porewater had entered the K-feldspar stability field.

The overall trend in the silicate system shows a change in the chemistry of the porewaters, starting with a concentration of H_4SiO_4 similar to sea water and gradually

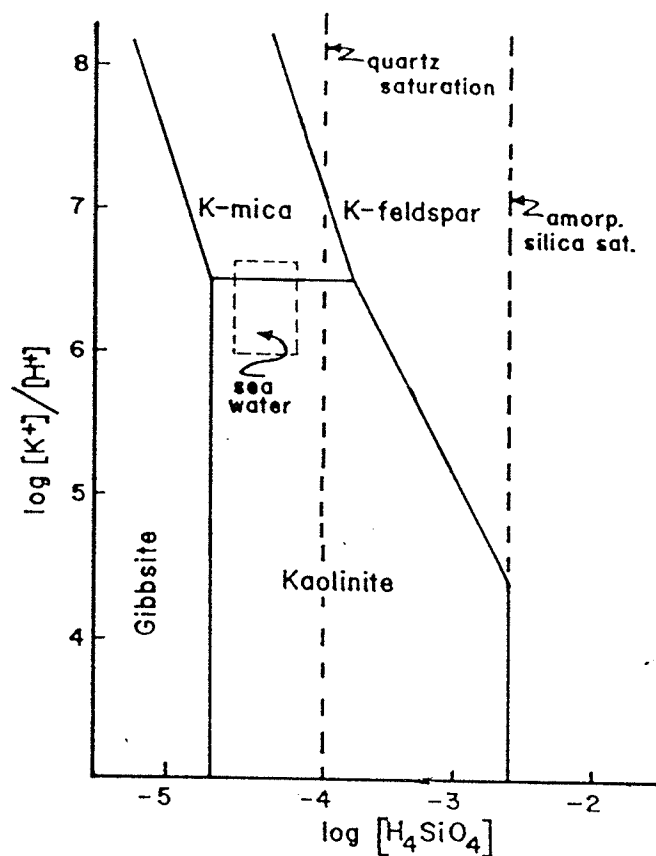


Figure 45

Stability relations of some phases in the system $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ at 25°C and one atmosphere, as functions of $\log[\text{K}^+]/[\text{H}^+]$ and $\log [\text{H}_4\text{SiO}_4]$. Modified from Garrels and Christ (1965).

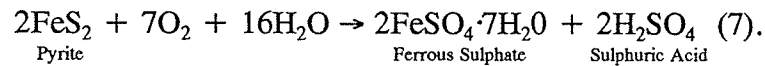
increasing to the point where the chemistry plots in the K-feldspar stability field.

It does not seem possible that illite formed as a result of alteration of kaolinite or smectite because the Bakken Formation has not been buried deeply enough to produce these types of alteration. In order to alter kaolinite or smectite to illite temperatures of over 150°C are required (Eberl, 1984) and in the Bakken Formation the maximum temperatures that have been experienced are in the range of 35-40°C. A further possible mechanism for the precipitation of the authigenic illite is through the dissolution and reprecipitation of detrital illite.

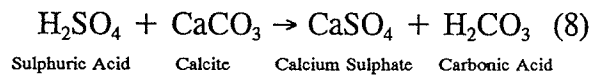
6.2.4 Formation of Hematite and Evaporite Minerals

Another diagenetic event of the Bakken Formation was the conversion of pyrite to hematite. Both the hematite and the pyrite occur in the form of small octahedra (Figure 33), an isometric crystal morphology. Pyrite is an isometric mineral, however, hematite is a hexagonal mineral and should not form octahedra. Thus, the crystal morphology of the hematite in the Bakken Formation suggests that it formed as a pseudomorphic replacement of pyrite, preserving the pyrite morphology. The oxidation of pyrite to hematite is a late stage event, likely due to oxygenated waters from the surface percolating down from the outcrop of the Bakken Formation during the exposure of the Mississippian-Jurassic unconformity. This is further supported by the fact that the cores increase in the degree of oxidation (red coloration) to the north and east which is where the Bakken Formation would have cropped out during the time of the formation of the Mississippian-Jurassic unconformity. The oxidation of pyrite to hematite may also explain the presence small pockets of anhydrite and gypsum in the formation. Anhydrite

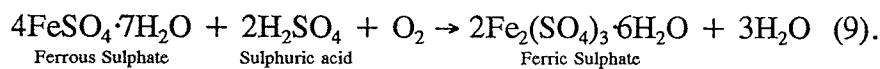
and gypsum were among the last minerals to form as indicated by their pore filling relations (Figure 36). The formation of anhydrite and/or gypsum from the oxidation of pyrite in the presence of carbonates is described by Christopher (1961):



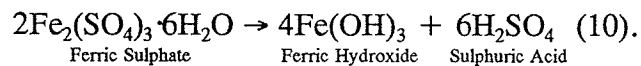
The sulphuric acid reacts with the carbonate



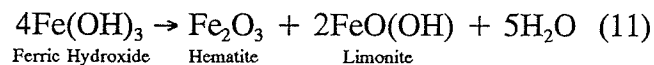
to form anhydrite and/or gypsum and carbonic acid. The green ferrous sulphate produced by reaction (7) can be further oxidized



This brown ferric sulphate is readily broken down by hydrolysis to form brown ferric hydroxide and sulphuric acid



Further reacting of the acid with carbonate by reaction (8) forms more anhydrite and/or gypsum. The ferric hydroxide is readily dehydrated to form hematite



Some of the anhydrite, gypsum, and halite in the Bakken Formation may be due to the dissolution and re-precipitation of salts from the evaporite deposits that are found above and below the Bakken Formation (e.g., the Mississippian Charles Formation and the Devonian Prairie Evaporite).

6.2.5 Sequence of Diagenetic Events

By the study of the grain relations between the different minerals found in the Bakken Formation, a sequence of chemical diagenetic events can be interpreted (Figure 46).

In the Bakken Formation it is suggested that the first chemical diagenetic event to take place was the formation of pyrite within the sulphate reducing zone. There is little direct evidence for this in the Bakken, however, Berner (1984) suggests that most pyrite found in sedimentary rocks form during early burial, particularly in organic rich sediments, such as the Bakken.

The next mineral to form during diagenesis of the Bakken is the fine crystalline dolomite, which is proposed to be of organogenic origin. The presence of pyrite in the same unit suggests that sulphate reducing conditions existed, and this may have provided the conditions for the transformation of a precursor calcite into organogenic dolomite. In addition, the formation of dolomite is placed as an early diagenetic event because the organogenic model requires the diffusion of Mg from the overlying seawater, and thus this process is limited to the top few metres of sediment (Baker and Burns, 1985). Diffusion of seawater Mg into the sediments is required as the entrapped porewater would contain insufficient Mg to allow dolomitization to occur (Baker and Burns, 1985).

The intergrowth of dolomite crystals with illite flakes (Figure 25) indicates that at least some of the illite is formed diagenetically and probably started to form early in the diagenesis of the Bakken Formation. Further evidence for the early formation of illite is that the porewaters necessary to precipitate illite are nearly the same as seawater

| EVENT | EARLY | INTERMEDIATE | LATE |
|--------------------------|-------|--------------|-------|
| PYRITE PRECIPITATION | ----- | | |
| DOLOMITE PRECIPITATION | ----- | ----- | |
| ILLITE PRECIPITATION | ----- | | |
| K-FELDSPAR DISSOLUTION | ----- | | |
| QUARTZ PRECIPITATION | | ----- | |
| K-FELDSPAR PRECIPITATION | | ----- | |
| HEMATITE PRECIPITATION | | | ----- |
| DOLOMITE DISSOLUTION | | | ----- |
| ANHYDRITE PRECIPITATION | | | ----- |
| GYP SUM PRECIPITATION | | | ----- |
| HALITE PRECIPITATION | | | ----- |

Figure 46

Timing of the various diagenetic events in the Middle Member of the Bakken Formation.

Solid bars indicate most probable timing of event, dashed bars indicate possible timing of events.

(Figure 45) and, as suggested earlier, the porewaters in the Bakken had a trend away from seawater composition. Concurrent with the precipitation of illite was the dissolution of K-feldspar, because it is unstable in the porewaters that could precipitate illite (Figure 45).

The formation of quartz overgrowths occurred later in the diagenesis of the Bakken Formation due to the increase in the H_4SiO_4 concentration in the porewaters. A study of the grain relations shows that the quartz overgrowths formed after dolomite precipitation. This is demonstrated in Figure 47, where it can be seen that the quartz overgrowth forms a mould of a dolomite grain, indicating growth of the quartz around a dolomite grain which was later removed. Some of the quartz overgrowths contain intergrowths of illite (Figure 24), others do not (Figure 27), indicating that the formation of illite ceased at some point during the time that quartz overgrowths were forming.

Authigenic K-feldspar was formed later in the diagenesis of the Bakken Formation due to the continued increase in the H_4SiO_4 concentration as porewaters entered the K-feldspar stability field (Figure 45). This is indicated by the overgrowth of a K-feldspar crystal on a previously formed quartz overgrowth (Figure 48).

The pore lining dolomite is generally coarsely crystalline (20-50 μm) and forms only in the areas of high permeability in the Horizontal Laminated and Wavy Laminated Units. The areas of high permeability are coincident with areas of macroscopic porosity. This dolomite may have formed through the process involved in the mixed water model for dolomitization. The saline waters would have been the marine water trapped in the pores or deep groundwater and the fresh water may have been oxygenated meteoric

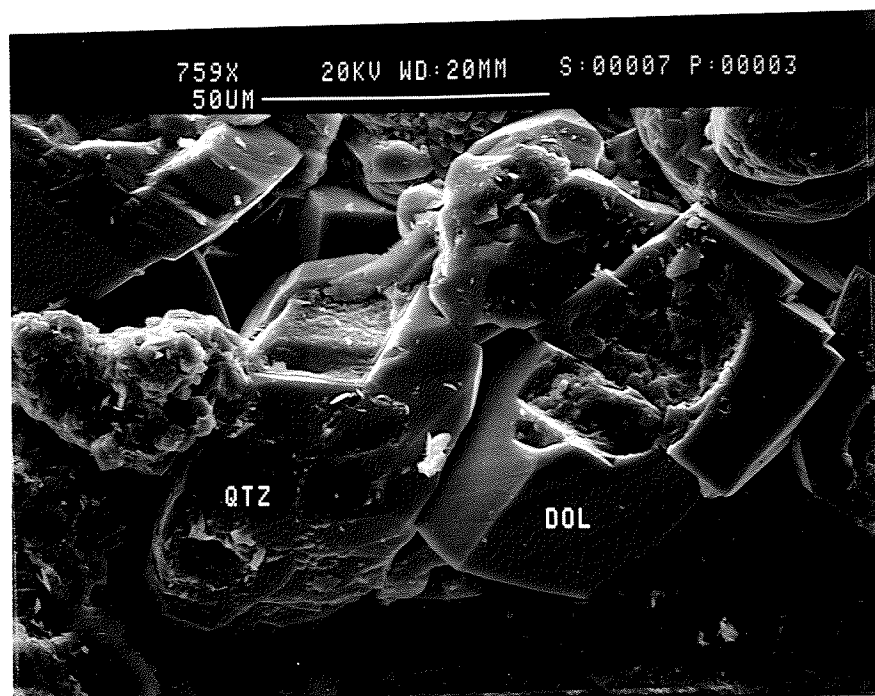


Figure 47

Scanning electron photomicrograph of a quartz overgrowths from which the dolomite rhombs have been removed to show that the quartz grows around the dolomite (Sample 02-25-10-29:7).

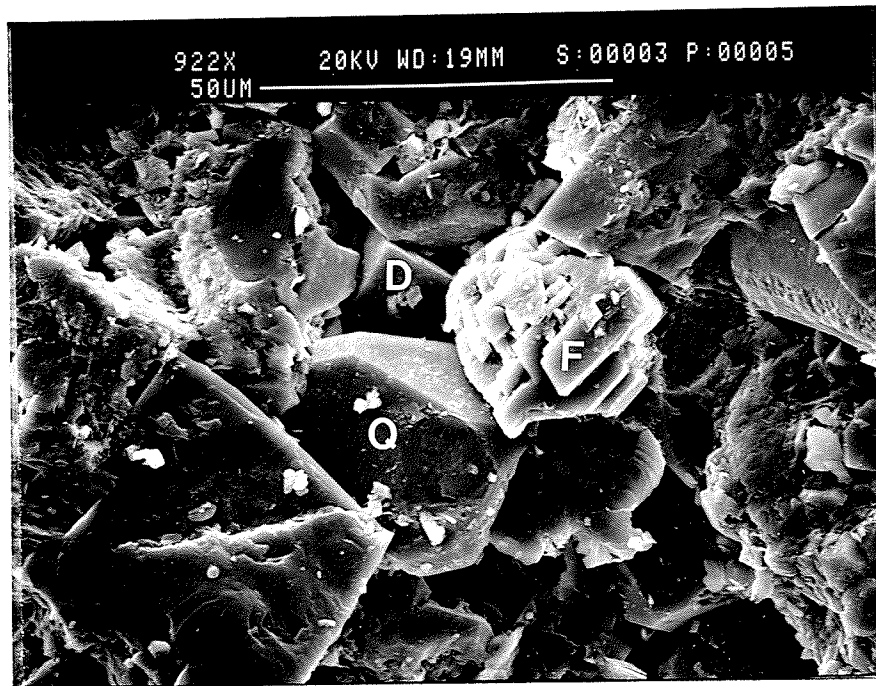


Figure 48

Scanning electron photomicrograph of a K-feldspar overgrowth on top of previously formed quartz overgrowths and dolomite rhombs (Sample 11-29-10-28:3).

waters percolating down from the Mississippian-Jurassic unconformity. Evidence for the dolomite forming in a later stage of diagenesis is the lack of illite inclusions, indicating that the dolomite formed after the illite stopped precipitating. Through SEM examination, it was found that some of the large (20-50 μm) dolomite grains are zoned (Figure 30), suggesting that the grains formed in disequilibrium with the porewater. This indicates a change in the porewater composition during crystallization, or rapid crystallization which did not allow the crystal to come into equilibrium with the porewater. Formation of the pore lining dolomite during late diagenesis is further evidenced by the fact that it is only found in zones of high permeability and not in the other areas of the formation.

The oxidation of pyrite to hematite and the resulting formation of gypsum and anhydrite is thought to be very late in the diagenesis of the Bakken Formation. The waters which oxidized the pyrite are proposed to have come from the outcrop of the Bakken during the formation of the Mississippian-Jurassic unconformity.

6.3 Reservoir Quality

At some point after deposition, oil migrated into the Bakken Formation in the study area. It is proposed by several authors (Dembicki and Pirkle, 1985, Price *et al.*, 1984, Webster, 1984, Dow, 1974, and Williams, 1974) that the source of the Bakken oil is the Bakken Formation itself. The shales are mature approximately 150 kilometres to the southwest.

The porosity of the Middle Bakken, which is possibly related to dolomitization, is consistently high throughout the area, however, the permeability is quite variable. In

some areas of the Daly field, the permeabilities reach in excess of 100 millidarcies in some horizons. The variability in the permeability is due to two factors. In some zones the pore throats have been plugged with anhydrite and/or gypsum, blocking communication between the pores. The other factor is that some of the illite and fine grained dolomite may have broken loose and have lodged in the pore throats, also blocking communication between the pores. This latter factor is evidenced by the fact that a waterflood well injecting into the Bakken has had decreasing injectability, most likely due to fines migration (Barchyn, pers. comm., 1991). Unfortunately, this type of variation in permeability is very difficult to predict.

Chapter 7: Summary and Conclusions

The Bakken Formation in the Daly field of southwestern Manitoba was studied by the use of core logging to determine the sedimentary structures and subdivisions, X-ray diffraction analysis to determine the mineral content and by thin section and scanning electron microscope petrography to determine the distribution and morphology of the minerals

In the Williston Basin overall, the Devonian-Mississippian Bakken Formation is divided into three members: 1) the Lower Bakken, a black shale, 2) the Middle Bakken, generally considered a clastic unit, and 3) the Upper Bakken, another black shale. In the area studied in this report, however, the Lower Bakken is missing.

In the study area, the Bakken formation can be divided into the Upper Bakken, which is an organic rich black shale which is composed primarily of clay minerals with trace amounts of quartz, K-feldspar, calcite, dolomite, and pyrite, and the Middle Bakken, which can be subdivided into three units (from the base toward the top): 1) the Wavy Laminated Unit, a wavy laminated grey to olive grey argillaceous dolomitic sandstone to siltstone 2) the Horizontal Laminated Unit, a horizontal laminated, olive grey to dusky red, argillaceous silty dolostone, and 3) the Massive Unit, a homogeneous grey to olive grey argillaceous silty dolostone. The laminations in the Wavy Laminated Unit are interpreted to be cross sections of current ripples. The Massive Unit is also bioturbated and is fossiliferous in some localities. The overall grain size of the units decreases from the Wavy Laminated unit to the Massive Unit. There is also a trend of

decreasing quartz content and increasing clay mineral content from the Wavy Laminated Unit up to the Massive Unit.

The thin section petrographic examination of the rocks of the Bakken Formation showed the presence of dolomite rhombs and organic material. It was also observed that lamination in the Horizontal Laminated Unit was due to an upward grading from quartz and feldspar to dolomite and illite within each laminae.

The scanning electron microscope (SEM) petrography which showed the presence of detrital quartz and feldspar grains with the quartz grains often having diagenetic quartz overgrowths and the feldspars showing signs of dissolution. The SEM petrography also showed the presence of euhedral dolomite crystals with a wide size range from 1 to 50 μm and were commonly intergrown. Fine platy illite grains were also observed. These grains usually coated grains of quartz or dolomite, but were commonly intergrown with the quartz or dolomite crystals. Pyrite was also present in the form of small (0.5 - 1 μm) octahedra and occasionally as framboids. Hematite, which was morphologically identical to the pyrite, was determined to be present by energy dispersive X-ray analysis. Anhydrite, gypsum, and halite occur as pore filling cements.

After the data from the core was collected and studied a depositional model for the Bakken Formation was synthesised and it was determined that during the period from the deposition of the pre-Bakken Lyleton Formation (interbedded shales and dolostones) to the deposition of the post Bakken Lodgepole Formation (an argillaceous limestone), the sea in the Williston Basin had undergone a number of sea level changes. After the shales and dolostones of the Lyleton Formation were deposited there was a regression

which resulted in partial erosion of the Lyleton Formation in Manitoba and Saskatchewan. The Lower Bakken (a black shale) was deposited over this unconformity as the sea again transgressed. After deposition of the Lower Bakken there was a regression during which all but a small remnant of the Lower Bakken in the Waskada area was eroded from Manitoba. The Lower Bakken, however, was not eroded in the centre of the basin in North Dakota and Saskatchewan. This period of erosion was followed by a transgression, which resulted in the deposition of the Middle and Upper Bakken.

The deposition of the Middle Bakken occurred on a shoreline without a barrier bar during a transgression. The base of the Middle Bakken was deposited in the nearshore zone and is represented by the Wavy Laminated Unit. It was determined to have been deposited in this environment due to its slightly coarser grain size and higher quartz content and lower clay mineral content. This is overlain by a slightly more offshore deposit represented by the finer grained Horizontal Laminated Unit and the Massive Laminated Unit. The offshore position of the Horizontal Laminated Unit and the Massive Unit is indicated by the decrease in quartz content and increase in clay mineral content. With increasing water depth there was a change in the depositional environment, resulting in deposition of the black shales of the Upper Bakken, which are very fine grained and have a low quartz content and a high clay mineral content. The trend towards a lower quartz content and higher clay mineral content is proposed to be related to a decrease in the energy in the depositional environment.

Following the deposition of the Massive Unit, there was a change to deposition of the black shale of the Upper Bakken. Deposition of the black shales is due to one or a combination of the following: 1) the water became temperature stratified, 2) the water became chemically stratified, or 3) the sediment surface went below storm wave base and the bottom waters stagnated. As a result of the stratification or the stagnation or a combination of the two effects, the lower water strata in the Williston basin became oxygen depleted, resulting in the deposition of the black shales of the Bakken Formation.

During and after deposition, the Bakken Formation underwent a series of chemical diagenetic changes. Shortly after deposition there was the precipitation of pyrite and illite, the transformation of calcite to dolomite, and the dissolution of K-feldspar. Later in the diagenetic history there was a continued precipitation of illite and transformation of calcite to dolomite, as well as the precipitation of quartz overgrowths. Late in the diagenetic history of the Bakken Formation there was continued precipitation of quartz and possible precipitation of more dolomite; there was also the precipitation of K-feldspar, anhydrite, gypsum, and halite, and the pseudomorphic conversion of pyrite to hematite. At some point there was also a slight dissolution of dolomite, halite, and anhydrite.

Pyritization is proposed to have occurred very early in the history of the Bakken Formation, possibly in the sulphate reducing zone just below the sediment/water interface. Sulphate reducing bacteria produce H_2S which reacts with the iron in the sediments to form monosulphides which are eventually transformed into pyrite. There is a band of pyrite in the Massive unit in some wells and most of the fossils in the

Massive Unit, which is the only fossiliferous unit, are replaced by pyrite; in some localities this pyrite has been pseudomorphically replaced by hematite.

Most of the dolomite found in the Bakken Formation is proposed to be organogenic dolomite which formed by the replacement of calcite in the sulphate reducing zone early in diagenesis. The high pH, due to the high HCO_3^- (resulting from the action of sulphate reducing bacteria) and high NH_3 concentrations (due to the enzymatic degradation of protein), in combination with the low sulphate would provide conditions suitable for the transformation of calcite into dolomite. Some of the larger pore filling dolomite is proposed to have precipitated at a later time due to the mixing of entrapped sea water with fresher waters percolating down from the Mississippian-Jurassic unconformity.

The diagenesis of the silicic minerals (illite, quartz, and K-feldspar) can be explained by the stability relations of the $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ system. The initial porewater probably had K and H_4SiO_4 concentrations similar to that of seawater, a point at which illite is stable and K-feldspar is unstable, resulting in the precipitation of illite and the dissolution of K-feldspar. An increase in the concentration of H_4SiO_4 would have resulted in the precipitation of quartz overgrowths. With a further increase in H_4SiO_4 the porewater entered the K-feldspar stability field and resulted in the precipitation of K-feldspar.

The diagenetic formation of anhydrite and gypsum may be related to the pseudomorphic replacement of some of the pyrite by hematite. In the oxidation of the pyrite to hematite, sulphate is released, and the sulphate reacts with Ca to form gypsum

and anhydrite. Some of the evaporite minerals may also be due to the dissolution and re-precipitation of salts from evaporite deposits that are found above and below the Bakken Formation.

The Bakken Formation has a significant amount of porosity (13 - 20%) in most areas, possibly due to dolomitization. The permeability of the rock, however, is quite variable. The cause of the permeability variation appears to be a combination of anhydrite, gypsum, and halite cements blocking the pore throats and a migration of fine grained material plugging the pore throats.

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Appendix 1
Core Descriptions

Core Descriptions

05-18-09-27

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|---|
| 811.38 - 814.43 m | 3.05 m | Greyish green shale with occasional light mottles: Lyleton |

15-18-10-27

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|--|
| 765.66 - 767.18 m | 1.52 m | Dusky red shale that appears mottled, possibly bioturbated: Lyleton |

15-12-11-27

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|--|
| 733.96 - 735.61 m | 1.65 m | Dusky red siltstone with bioturbation and bands of lamination and cross bedding, occasional patches of green and dark red in the lower part: Massive Unit |

| | | |
|-------------------|--------|--|
| 735.61 - 736.60 m | 0.99 m | Dark reddish grey laminated siltstone with bands of green and brown: Horizontal Laminated Unit |
| 736.60 - 736.93 m | 0.33 m | Olive green laminated siltstone with some cross bedding, in sharp contact with Lyleton: Wavy Laminated Unit |
| 736.93 - 741.58 m | 4.65 m | Dark red shale, becomes mottled approximately 1 m from contact with Bakken: Lyleton |

02-21-07-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 935.12 - 936.75 m | 1.63 m | Black shale with very fine laminae, core is discing at lamiae: Shale |
| 936.75 - 937.82 m | 1.07 m | Dark greenish grey homogeneous siltstone with minor calcite, brachiopods |

present: **Massive Unit**

| | | |
|-------------------|--------|---|
| 937.82 - 937.85 m | 0.03 m | Dark grey coarse grained bed with disseminated pyrite, has identifiable crinoid stem pieces, contains calcite, apparent storm bed: Massive Unit |
| 937.85 - 938.89 m | 1.04 m | Dark grey homogeneous siltstone with some laminated beds, contains some brachiopod shells and crinoid debris, coarser grained towards base: Massive Unit |
| 938.89 - 941.05 m | 2.16 m | Dark grey and olive green laminated siltstone showing occasional slumps and cross bedding, more olive green towards base, no fossils, major slump at base: Horizontal Laminated Unit |
| 941.05 - 942.41 m | 1.36 m | Greenish grey massive shale: Lyleton |

14-04-08-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|---|
| 883.61 - 884.03 m | 0.42 m | Dark olive grey laminated siltstone with minor cross bedding: Horizontal Laminated Unit |
| 884.03 - 884.43 m | 0.40 m | Interbedded light brownish grey and dark olive grey laminated siltstones, changes cyclicly from cross-bedded to wavy lamination: Wavy Laminated Unit |
| 884.43 - 884.76 m | 0.33 m | Olive grey wavy laminated siltstone, coarser than previous unit, lag is present at the base of the laminations: Wavy Laminated Unit |
| 884.76 - 886.87 m | 2.11 m | Interbedded pale olive and greyish green shales and dolostone, dolostone shows well developed cross bedding: Lyleton |

15-17-08-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|--|
| 903.00 - 904.15 m | 1.15 m | Laminated black shale: Shale |
| 904.15 - 905.08 m | 0.93 m | Dark greenish grey homogeneous siltstone with faint laminations in some zones, bioturbation evident, fossiliferous towards top, sharp contact at base: Massive Unit |
| 905.08 - 905.12 m | 0.04 m | Massive pyrite band: Massive Unit |
| 905.12 - 905.46 m | 0.34 m | Olive grey homogeneous siltstone with faint lamination, slight oil staining: Massive Unit |
| 905.46 - 906.43 m | 0.97 m | Dark olive grey and pale brown interbedded laminated siltstones, slight oil staining: Horizontal Laminated Unit |

| | | |
|---------------------------|-------------------------|---|
| 906.43 - 906.73 m | 0.30 m | Olive grey laminated siltstone, coarser grained towards base, sight oil staining: Horizontal Laminated Unit |
| 906.73 - 907.26 m | 0.53 m | Olive grey wavy laminated siltstone to fine sandstone, rare bands of pyrite, coarser grained towards base, erosional breccia at base: Wavy Laminated Unit |
| 907.64 - 913.00 m | 5.36 m | Interbedded olive shale and pale brown silts: Lyleton |
| <u>11-22-08-28</u> | | |
| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
| 871.00 - 871.70 m | 0.70 m | Laminated black shale with some carbonate bands: Shale |
| 871.70 - 873.04 m | 1.34 m | Dark reddish grey homogeneous siltstone with thin carbonate band at 872.55 m (4 cm) and thin (1 cm) pyrite band at 872.46 m: Massive Unit |

| | | |
|-------------------|--------|--|
| 873.04 - 874.42 m | 1.38 m | Dark grey laminated siltstone with occasional carbonate bands, slightly coarser towards base, erosional contact with Lyleton: Horizontal Laminated Unit |
|-------------------|--------|--|

| | | |
|--------------|-------|--|
| 874.42 - EOC | -.- m | Light olive green shales: Lyleton |
|--------------|-------|--|

07-36-08-28

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| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|--|
| 846.06 - 848.35 m | 2.29 m | Black shale with gradational contacts on upper and lower surface, occasional carbonate bands: Shale |
| 848.35 - 849.66 m | 1.31 m | Olive grey homogeneous siltstone, slightly lighter and coarser towards base, visible porosity at base: Massive Unit |
| 849.66 - 851.52 m | 1.86 m | Brown laminated siltstone with rare clay bands, wavy laminated towards base: Horizontal Laminated Unit |

| | | |
|-------------------|--------|---|
| 851.52 - 852.08 m | 0.56 m | Dark Brown wavy laminated sandstone with erosional contact at base, possible angular unconformity: Wavy Laminated Unit |
|-------------------|--------|---|

| | | |
|-------------------|--------|--|
| 852.08 - 855.56 m | 3.48 m | Light olive green brecciated Lyleton, various amounts of breccia: Lyleton |
|-------------------|--------|--|

13-14-09-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|---|
| 832.10 - 832.40 m | 0.30 m | Light yellowish brown carbonate, stylolite near contact with the Bakken, contact may be bioturbated: Lodgepole |
| 832.40 - 834.04 m | 1.64 m | Laminated black shale, becomes redder towards base, base slightly coarser grained: Shale |
| 834.04 - 834.59 m | 0.55 m | Weak red homogeneous siltstone, faintly laminated, grades into lighter coloured |

mottled siltstone: **Massive Unit**

| | | |
|-------------------|--------|---|
| 834.59 - 835.57 m | 0.98 m | Weak red and brown mottled siltstone, slight oil staining, occasional faint wavy laminations: Massive Unit |
| 835.57 - 836.04 m | 0.47 m | Dusky red laminated siltstone with some faint wavy lamination: Horizontal Laminated Unit |
| 836.04 - 836.38 m | 0.34 m | Dusky red homogeneous siltstone: Massive Unit |
| 836.38 - 838.02 m | 1.64 m | Dark reddish grey laminated siltstone with rare wavy lamination towards base: Horizontal Laminated Unit |
| 838.02 - 838.39 m | 0.37 m | Brown wavy laminated siltstone with oil staining, visible porosity, sharp contact at base: Wavy Laminated Unit |

| | | |
|-------------------|--------|--|
| 838.39 - 838.73 m | 0.34 m | Light brownish grey wavy laminated sandstone with occasional finer beds, some oil staining along finer bands, contact with Lyleton indeterminate: Wavy Laminated Unit |
|-------------------|--------|--|

| | | |
|-------------------|--------|-------------------------------------|
| 838.73 - 839.72 m | 0.99 m | Green massive shale: Lyleton |
|-------------------|--------|-------------------------------------|

01-20-09-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 861.05 - 862.00 m | 0.50 m | Weak red dolomite, grades into Bakken: Lodgepole |
| 862.00 - 864.39 m | 2.39 m | Laminated reddish black shale, slight lighter colour towards base, two calcite bands present: Shale |
| 864.39 - 865.83 m | 1.44 m | Olive grey homogeneous siltstone with faint laminations, some beds have more |

prominent lamination, slightly redder towards top, small amount of calcareous material near top: **Massive Unit**

| | | |
|-------------------|--------|--|
| 856.83 - 867.86 m | 2.03 m | Olive grey, finely laminated siltstone, coarser grained towards base, with minor cross bedding towards base, slight erosional breccia at contact with Lyleton: Horizontal Laminated Unit |
|-------------------|--------|--|

- 135 -

| | | |
|----------------|--------|--|
| 876.86 m - EOC | -.-- m | Massive green and red shales: Lyleton |
|----------------|--------|--|

02-23-09-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|--|
| ---.-- - 830.58 m | -.-- m | Laminated black shale, part of core is missing: Shale |
| 830.58 - 832.04 m | 1.46 m | Dusky red grading to olive grey homogeneous siltstone, slightly fossiliferous, |

occasional shale bands, coarser grained towards base, visible porosity towards base: **Massive Unit**

| | | |
|-------------------|--------|--|
| 832.04 - 833.83 m | 1.79 m | Dusky red to reddish brown laminated siltstone with occasional bands of wavy lamination, occasional non-oxidized (green) bands: Horizontal Laminated Unit |
|-------------------|--------|--|

| | | |
|-------------------|--------|---|
| 833.83 - 834.50 m | 0.67 m | Greenish brown wavy laminated fine grained sandstone with occasional shaley bands, erosional contact with Lyleton: Wavy Laminated Unit |
|-------------------|--------|---|

| | | |
|-------------------|--------|--------------------------------------|
| 834.50 - 837.00 m | 2.50 m | Red and green shales: Lyleton |
|-------------------|--------|--------------------------------------|

01-30-09-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|---|
| 847.34 - 869.45 m | 24.11 m | Pale olive limestone and dolomite, stylolite and possible breccia at base: Lodgepole |

| | | |
|-------------------|--------|---|
| 869.45 - 871.39 m | 1.94 m | Laminated reddish black shale, slightly lighter in colour towards base: Shale |
| 871.39 - 872.20 m | 0.81 m | Dark reddish grey homogeneous siltstone, darker towards base, contains brachiopods: Massive Unit |
| 872.20 - 872.63 m | 0.43 m | Dusky red and olive grey mottled siltstone, no apparent fossils, faint oil staining: Massive Unit |
| 872.63 - 874.62 m | 0.99 m | Dark reddish grey laminated siltstone with rare deformation, core becomes greyer towards base faint wavy lamination towards top, possible desiccation cracks at 872.71 m: Wavy Laminated Unit |
| 874.62 - 875.44 m | 0.82 m | Yellowish brown siltstone to fine sandstone with faint laminations and ripple marks, structure more prominent towards top, slight oil staining, erosional breccia at contact with Lyleton: Wavy Laminated Unit |

| | | |
|-------------------|---------|---|
| 875.44 - 890.00 m | 14.58 m | Banded green and dusky red shales: Lyleton |
|-------------------|---------|---|

14-04-10-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 822.00 - 822.20 m | 0.20 m | Laminated reddish black shale, (depth questionable): Shale |
| 822.20 - 822.96 m | 0.76 m | Missing core |
| 822.96 - 823.84 m | 0.88 m | Olive grey and dusky red mottled siltstone, contains brachiopod fragments: Massive Unit |
| 823.84 - 823.90 m | 0.06 m | Olive brown siltstone, faintly laminated, oil stained, visible intergranular porosity, sharp contact at base: Massive Unit |
| 823.90 - 824.28 m | 0.38 m | Olive grey, homogeneous siltstone, possible oil staining: Massive Unit |

| | | |
|---------------------------|-------------------------|--|
| 824.28 - 825.60 m | 1.32 m | Dark reddish grey laminated siltstone: Horizontal Laminated Unit |
| 825.60 - 825.98 m | 0.38 m | Olive grey siltstone to fine sandstone, wavy laminated, occasional clay stringers, erosional breccia at base: Wavy Laminated Unit |
| 825.98 - 831.19 m | 5.21 m | Massive dusky red and olive shale: Lyleton |
| <u>08-14-10-28</u> | | |
| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
| 792.48 - 792.87 m | 0.39 m | Weak red homogeneous siltstone with bands of yellowish brown oil stained bands: Massive Unit |
| 792.87 - 793.55 m | 0.68 m | Weak red laminated siltstone with occasional olive grey bands: Horizontal Laminated Unit |

| | | |
|-------------------|--------|--|
| 793.55 - 793.89 m | 0.34 m | Weak red and olive grey mottled siltstone, angular unconformity with Lyleton: Massive Unit |
|-------------------|--------|--|

| | | |
|-----------------|--------|--|
| 793.89 - 800.10 | 6.21 m | Dusky red cross bedded shales and silts, brecciated near top: Lyleton |
|-----------------|--------|--|

12-20-10-28

- 140 -

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|---|
| 811.09 - 812.86 m | 1.77 m | Laminated black shale, becomes redder towards base: Shale |
| 812.86 - 814.30 m | 1.44 m | Weak red homogeneous siltstone, coarser towards base, visible porosity near base: Massive Unit |
| 814.30 - 815.87 m | 1.57 m | Weak red laminated siltstone, erosional breccia at base: Horizontal Laminated Unit |

| | | |
|-------------------|--------|---|
| 815.87 - 816.37 m | 0.50 m | Weak red erosional breccia within the Lyleton: Lyleton |
|-------------------|--------|---|

| | | |
|--------------|--------|---------------------------------|
| 816.37 - EOC | -.-- m | Weak red shales: Lyleton |
|--------------|--------|---------------------------------|

03-29-10-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 806.57 - 808.40 m | 1.83 m | Black laminated shale: Shale |
| 808.40 - 809.99 m | 1.59 m | Dusky red homogeneous shale with light olive grey patches towards base, some visible porosity near base, contains brachiopods: Massive Unit |
| 809.99 - 811.59 m | 1.60 m | Dusky red laminated siltstone: Horizontal Laminated Unit |
| 811.59 - 811.82 m | 0.23 m | Light olive brown wavy laminated very fine grained sandstone, possible erosional |

breccia at base: **Wavy Laminated Unit**

811.82 m - EOC -- m Dusky red and greenish grey shales with light olive brown bands: **Lyleton**

10-29-10-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 809.75 - 811.57 m | 1.82 m | Black shale, badly broken by drilling: Shale |
| 811.57 - 813.21 m | 1.64 m | Weak red homogeneous siltstone, mostly red with some green patches, carbonate bands and 812.68 m and 813.17 m: Massive Unit |
| 813.21 - 814.93 m | 1.72 m | Dark reddish brown laminated siltstone, slightly darker towards base: Horizontal Laminated Unit |
| 814.93 - 815.25 m | 0.32 m | Olive brown wavy laminated sandstone, oil stained, lower contact missing: Wavy |

Laminated Unit

815.25 m - EOC -- m Red shales with approximately 1 m of breccia: **Lyleton**

11-29-10-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 810.51 - 812.17 m | 1.66 m | Black shale , discing, calcareous near base: Shale |
| 812.17 - 813.94 m | 1.77 m | Weak red homogeneous siltstone, contains brachiopods which are concentrated in bands, slightly coarser towards base, visible porosity near base: Massive Unit |
| 813.94 - 815.47 m | 1.53 m | Weak red horizontal laminated siltstone, indeterminate contact with Lyleton: Horizontal Laminated Unit |
| 815.47 m - EOC | -- m | Red and green shales with dolomite stringers: Lyleton |

12-29-10-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|---|
| 809.60 - 811.36 m | 1.76 m | Laminated black shale: Shale |
| 811.36 - 813.14 m | 1.78 m | Reddish brown homogeneous siltstone, possible rootlets, mottled towards base, occasional thin (3 cm) dolomite bands, visible porosity towards base: Massive Unit |
| 813.14 - 814.82 m | 1.68 m | Dark reddish brown horizontal laminated siltstone: Horizontal Laminated Unit |
| 814.82 - 815.13 m | 0.31 m | Dark brown wavy laminated sandstone, breccia in Lyleton underneath, contact indistinct: Wavy Laminated Unit |
| 815.13 - 816.00 m | 0.87 m | Breccia within Lyleton: Lyleton |

816.00 m - EOC -.-- m Red and green shales: **Lyleton**

10-30-10-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 812.38 - 814.23 m | 1.89 m | Dark red shale, discing with conchoidal fracture: Shale |
| 814.23 - 816.05 m | 1.82 m | Dark reddish brown homogeneous siltstone with brachiopod molds, heavily oxidized with some green mottles, slightly coarser towards base, visible porosity at base: Massive Unit |
| 816.05 - 817.67 m | 1.62 m | Dark reddish brown horizontal laminated siltstone, slight wavy lamination towards base: Horizontal Laminated Unit |
| 817.67 - 818.07 m | 0.40 m | Olive grey wavy laminated siltstone, contact with Lyleton missing: Horizontal Laminated Unit |

| | | |
|----------------|--------|---|
| 818.07 m - EOC | -.-- m | Banded red and green shales with dolomite bands: Lyleton |
|----------------|--------|---|

09-05-11-28

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|--|
| 843.08 - 846.12 m | 3.04 m | Interbedded olive shales and light olive brown silts: Lyleton |

01-31-09-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|--|
| 913.18 - 914.46 m | 1.28 m | Laminated black shale with bands of bright yellow alteration: Shale |
| 914.46 - 915.88 m | 1.42 m | Olive grey homogeneous siltstone, coarser and more bioturbated towards base, rare anhydrite blebs, slightly fossiliferous: Massive Unit |
| 915.88 - 916.91 m | 1.03 m | Olive grey horizontal laminated siltstone, slightly wavy laminated towards base: Horizontal Laminated Unit |

| | | |
|-------------------|--------|--|
| 916.91 - 917.82 m | 0.91 m | Olive grey wavy laminated fine grey sandstone with occasional shale stringers: Wavy Laminated Unit |
| 917.82 - 917.98 m | 0.16 m | Homogeneous grey shale to siltstone in sharp (erosional ?) contact with Lyleton: Massive Unit |
| 917.98 m - EOC | -.-- m | Light olive brown cross bedded dolostone with shale stringers grading into green shales: Lyleton |

11-11-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 861.50 - 862.89 m | 1.39 m | Laminated black shale, occasional band of calcareous material: Shale |
| 862.89 - 864.50 m | 1.61 m | Olive grey homogeneous siltstone, rare pyrite bands, coarser grained towards base: Massive Unit |

| | | |
|-------------------|--------|---|
| 864.50 - 866.03 m | 1.53 m | Olive grey horizontal laminated siltstone with occasional wavy lamination: Horizontal Laminated Unit |
| 866.03 - 867.30 m | 1.27 m | Light olive brown siltstone, rare bands of lamination, oil stained, oil stain increases towards base, some visible vuggy porosity: Wavy Laminated Unit |
| 867.30 - 867.60 m | 0.30 m | Olive grey interbedded shales and silts: Horizontal Laminated Unit |
| 867.60 - 867.84 m | 0.24 m | Light olive brown siltstone, rare bands of lamination, oil stained, possible erosional breccia at base: Wavy Laminated Unit |
| 867.84 - 870.50 m | 2.66 m | Interbedded olive shales and laminated light olive brown siltstone: Lyleton |

14-16-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 881.00 - 881.36 m | 0.36 m | Laminated black shale: Shale |
| 881.36 - 883.38 m | 2.02 m | Grey homogeneous siltstone, slightly coarser towards base, numerous brachiopod molds and casts, pyrite band at 882.35 m: Massive Unit |
| 883.38 - 884.78 m | 1.40 m | Dark grey laminated siltstone with rare deformation and wavy lamination: Horizontal Laminated Unit |
| 884.78 - 885.95 m | 1.17 m | Dark greyish brown wavy laminated sandstone, oil stained with increase in intensity towards base, occasional coarse bands present, erosional breccia at base: Wavy Laminated Unit |
| 885.95 - 899.00 m | 13.05 m | Interbedded olive shales and light olive brown siltstone: Lyleton |

09-20-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|------------------------------|------------------|--|
| 879.00 - 880.53 m | 1.53 m | Black laminated shale: Shale |
| 880.53 - 882.46 m | 1.93 m | Dark olive grey homogeneous siltstone, slightly coarser towards base, visible porosity at base, highly fossiliferous: Massive Unit |
| - 150 - 882.46 - 885.18 m | 2.72 m | Dark grey horizontal laminated siltstone with rare coarser grained wavy laminated beds, coarser grained towards base: Horizontal Laminated Unit |
| 885.18 - 887.22 m | 2.04 m | Olive grey wavy laminated sandstone, some bands coarser material, oil stained, slightly coarser at base with visible intergranular porosity, erosional contact at base: Wavy Laminated Unit |
| 887.22 m - EOC | -.-- m | Olive brown dolostone grading into green shales: Lyleton |

05-21-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 874.00 - 876.28 m | 2.28 m | Laminated black shale: Shale |
| 876.28 - 878.01 m | 1.73 m | Olive to olive grey homogeneous siltstone, fossiliferous, pyrite band at 877.23 m (1 cm) and 887.35 m (1 cm), slightly coarser with visible porosity towards base: Massive Unit |
| 878.01 - 880.78 m | 2.77 m | Olive grey horizontal laminated siltstone, nonfossiliferous, slightly wavy laminated towards base, strongly oil stained band at 878.74 m (5 cm): Horizontal Laminated Unit |
| 880.78 - 882.34 m | 1.56 m | Olive grey wavy laminated, fine grained sandstone, coarser grained towards base with fine visible porosity, possible erosional contact with Lyleton: Wavy Laminated Unit |

| | | |
|----------------|-------|---|
| 882.34 m - EOC | --- m | Cross bedded dolostone grading into laminated grey shales: Lyleton |
|----------------|-------|---|

11-21-10-29

| <u>depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|---|
| 872.00 - 873.94 m | 1.94 m | Black shale, gradational contact at base: Shale |
| 873.94 - 875.72 m | 1.78 m | Dark olive grey homogeneous siltstone, small fossil trails, slightly coarser towards base: Massive Unit |
| 875.72 - 877.63 m | 1.91 m | Dark olive grey horizontal laminated siltstone, slightly coarser towards base, gradational contacts: Horizontal Laminated Unit |
| 877.63 - 879.79 m | 2.16 m | Dark olive grey wavy laminated sandstone, coarser towards base, erosional contact, oil stained: Wavy Laminated Unit |

879.79 - 880.10 m 0.31 m Grey shale to siltstone: **Massive Unit**

880.10 m - EOC -.-- m Dolostone and green shale: **Lyleton**

01-23-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|---------------------------|
|---------------------|-------------------------|---------------------------|

| | | |
|-------------------|--------|-------------------------------------|
| 849.00 - 849.60 m | 0.60 m | Laminated black shale: Shale |
|-------------------|--------|-------------------------------------|

| | | |
|-------------------|--------|---|
| 849.60 - 851.51 m | 1.91 m | Olive grey to light dusky red homogeneous siltstone, slightly fossiliferous, red towards base, heavily oil stained at 850.67 m: Massive Unit |
|-------------------|--------|---|

| | | |
|-------------------|--------|--|
| 851.51 - 853.03 m | 1.52 m | Light dusky red horizontal laminated siltstone: Horizontal Laminated Unit |
|-------------------|--------|--|

| | | |
|-------------------|--------|--|
| 853.03 - 853.59 m | 0.56 m | Light dusky red wavy laminated sandstone, coarser towards base: Wavy Laminated Unit |
|-------------------|--------|--|

| | | |
|-------------------|--------|--|
| 853.59 - 853.79 m | 0.20 m | Light dusky red homogeneous siltstone with visible porosity, erosional contact with Lyleton: Massive Unit |
|-------------------|--------|--|

| | | |
|----------------|--------|---|
| 853.79 m - EOC | -.-- m | Dusky red with bands of fenestral porosity near the top, possible erosional breccia: Lyleton |
|----------------|--------|---|

- 154 -

02-25-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|---|
| 826.30 - 829.01 m | 2.71 m | Black shale with slight reddening towards base, minor calcarious bands near base: Shale |
| 829.01 - 830.15 m | 1.14 m | Grey homogeneous siltstone, slightly darker towards base: Massive Unit |
| 830.15 - 830.74 m | 0.59 m | Olive dolostone with fenestral porosity, oil stained: Massive Unit |

| | | |
|-------------------|--------|---|
| 830.74 - 832.77 m | 2.03 m | Olive homogeneous siltstone with occasional bands of red oxidation: Massive Unit |
| 832.77 - 833.13 m | 0.36 m | Reddish brown wavy laminated sandstone with oil staining: Wavy Laminated Unit |
| 833.13 - 834.98 m | 1.85 m | Interlaminated silts and shales, strong red oxidation: Lyleton |
| 834.98 m - EOC | --- m | Green shales: Lyleton |

13-27-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 847.34 - 848.19 m | 0.85 m | Olive grey homogeneous siltstone with occasional faint lamination, fossiliferous towards base: Massive Unit |

| | | |
|-------------------|--------|---|
| 848.19 - 848.71 m | 0.52 m | Olive horizontal laminated siltstone, rare coarser bands: Horizontal Laminated Unit |
| 848.71 - 848.91 m | 0.20 m | Olive grey wavy laminated sandstone, very friable, finer material may have desiccation cracks: Wavy Laminated Unit |

03-28-10-29

| | | | |
|---------|---------------------|-------------------------|--|
| - 156 - | <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
| | 865.50 - 866.98 m | 1.48 m | Laminated black shale: Shale |
| | 866.98 - 868.64 m | 1.66 m | Dark grey homogeneous siltstone, pyrite band at 867.93 m, fossiliferous: Massive Unit |
| | 868.64 - 870.62 m | 1.98 m | Dark grey horizontal laminated siltstone, occasional wavy lamination: Horizontal Laminated Unit |

| | | |
|-------------------|--------|--|
| 870.62 - 872.81 m | 2.19 m | Dark grey wavy laminated fine grained sandstone, occasional shale stringers, slightly coarser towards base, may be erosional breccia: Wavy Laminated Unit |
|-------------------|--------|--|

| | | |
|----------------|-------|--|
| 872.81 m - EOC | -.- m | Grey homogeneous siltstone, nonfossiliferous: Lyleton ? |
|----------------|-------|--|

04-28-10-29

- 157 -

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 871.00 - 872.19 m | 1.19 m | Moderately laminated black shale: Shale |
| 872.19 - 873.36 m | 1.17 m | Dark olive grey homogeneous siltstone with brachiopod fossils (molds and casts), gradational contact at top: Massive Unit |
| 873.36 - 873.88 m | 0.52 m | Dark olive grey homogeneous siltstone with more fossils than above and some visible porosity: Massive Unit |

| | | |
|---------------------------|-------------------------|--|
| 873.88 - 876.04 m | 2.16 m | Dark olive grey horizontal laminated siltstone, slightly coarser towards base: Horizontal Laminated Unit |
| 876.04 - 878.40 m | 2.36 m | Olive grey wavy laminated sandstone, disseminated pyrite, oil stained, erosional breccia at base: Wavy Laminated Unit |
| <u>05-28-10-29</u> | | |
| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
| 865.00 - 866.18 m | 1.18 m | Laminated black shale: Shale |
| 866.18 - 867.78 m | 1.60 m | Olive grey homogeneous siltstone, fossil brachiopods, some bioturbation: Massive Unit |
| 867.78 - 870.10 m | 2.32 m | Olive grey horizontal laminated siltstone, slightly coarser towards base, sandstone band between 868.20 m and 868.50 m: Horizontal Laminated Unit |

| | | |
|-------------------|--------|---|
| 870.10 - 871.66 m | 1.56 m | Olive grey strongly wavy laminated sandstone, slightly coarser towards base, grades into grey shale: Wavy Laminated Unit |
|-------------------|--------|---|

| | | |
|-------------------|--------|--------------------------------------|
| 871.66 - 871.92 m | 0.26 m | Hard grey shale: Massive Unit |
|-------------------|--------|--------------------------------------|

| | | |
|----------------|-------|---|
| 871.92 m - EOC | -.- m | Dolomite and green and red shales: Lyleton |
|----------------|-------|---|

- 159 -

01-29-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|---|
| 876.00 - 877.49 m | 1.49 m | Laminated black shale: Shale |
| 877.49 - 878.96 m | 1.47 m | Dark greenish grey homogeneous siltstone, some faint horizontal and wavy lamination, occasional brachiopod shells, slightly coarser towards base, slightly darker towards base: Massive Unit |

| | | |
|-------------------|---------|--|
| 878.96 - 879.84 m | 0.88 m | Olive grey homogeneous siltstone with rare bands of horizontal lamination, coarser than previous interval: Massive Unit |
| 879.84 - 881.78 m | 1.94 m | Olive grey horizontal laminated siltstone, coarser laminations towards base, slight wavy lamination throughout, slight oil staining: Horizontal Laminated Unit |
| 881.78 - 883.06 m | 1.28 m | Olive grey wavy laminated sandstone, occasional shale bands and disseminated pyrite: Wavy Laminated Unit |
| 883.06 - 895.00 m | 11.94 m | Top of interval is a grey shale followed by an oil stained, light olive brown dolostone, followed by and interbedded olive shale and light olive brown siltstone: Lyleton |

04-29-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 878.00 - 879.49 m | 1.49 m | Black shale, core is broken into discs: Shale |
| 879.49 - 880.00 m | 0.51 m | Dark olive grey homogeneous siltstone with possible rootlets, pyrite band near base, erosional contact with Lyleton: Massive Unit |
| 880.00 - 884.68 m | 4.68 m | Brecciated shale and dolostone: Lyleton |

08-29-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|---|
| 867.50 - 869.57 m | 2.07 m | Laminated black shale: Shale |
| 869.57 - 871.85 m | 2.28 m | Olive grey homogeneous siltstone, fossiliferous, pyrite band at 870.73 m, coarser grained towards base, visible porosity at base: Massive Unit |

| | | |
|-------------------|--------|---|
| 871.85 - 873.63 m | 1.78 m | Olive grey horizontal laminated siltstone, nonfossiliferous, slightly coarser towards base, slight wavy lamination towards base: Horizontal Laminated Unit |
| 873.63 - 875.16 m | 1.53 m | Olive grey wavy laminated fine grained sandstone, occasional disseminated pyrite coarser towards base, indeterminate contact with Lyleton: Wavy Laminated Unit |
| 875.16 - 876.33 m | 1.17 m | Light olive brown cross bedded dolostone with fenestral porosity: Lyleton |
| 876.33 m - EOC | -.-- m | Interbedded light and dark green shales: Lyleton |

09-29-10-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|---------------------|-------------------------|--|
| 861.50 - 863.49 m | 1.99 m | Laminated black shale: Shale |
| 863.49 - 865.74 m | 2.25 m | Grey homogeneous siltstone, fossiliferous, pyrite band ant 868.84 m, beneath the |

pyrite band become coarser grained and has visible porosity: **Massive Unit**

| | | |
|-------------------|--------|--|
| 865.74 - 867.46 m | 1.72 m | Grey horizontal laminated siltstone, wavy lamination increases towards the base: Horizontal Laminated Unit |
| 867.46 - 869.38 m | 1.92 m | Grey wavy laminated fine grained sandstone, occasional shale stringers, coarser towards base, slight breccia at base: Wavy Laminated Unit |
| 869.38 m - EOC | -.-- m | Green shale with dolomite bands: Lyleton |

7A-08-11-29

| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
|-------------------|------------------|---|
| 850.39 - 850.50 m | 0.11 m | Dark olive grey homogeneous siltstone, rare fossil fragments: Massive Unit |
| 850.50 - 852.77 m | 2.27 m | Dark greenish grey horizontal laminated siltstone, rare wavy lamination towards |

top: **Horizontal Laminated Unit**

| | | |
|-------------------|--------|---|
| 852.77 - 853.45 m | 0.68 m | Dark greenish grey wavy laminated siltstone to fine sandstone: Wavy Laminated Unit |
|-------------------|--------|---|

11-11-11-29

| | | |
|-------------------|------------------|--|
| <u>Depth</u> | <u>Thickness</u> | <u>Description</u> |
| 846.20 - 850.07 m | 3.87 m | Laminated black shale, discing: Shale |
| 850.07 - 852.21 m | 2.14 m | Olive grey homogeneous siltstone, contains abundant brachiopods, coarser towards base, visible porosity at base: Massive Unit |
| 852.21 - 853.75 m | 1.54 m | Dark olive grey horizontal laminated siltstone, pyrite band at 852.31 m: Horizontal Laminated Unit |

| | | |
|-------------------|--------|---|
| 853.75 - 854.25 m | 0.50 m | Grey wavy laminated sandstone with disseminated pyrite and pyrite bands: Wavy Laminated Unit |
| 854.25 - 855.36 m | 1.11 m | Homogeneous grey shale, breccia at base: Massive Unit |
| 855.36 m - EOC | -.-- m | Green shales: Lyleton |

Appendix 2

Sampling Locations

Sampling Locations

The sample numbers throughout this document are constructed as follows: LSD-Section-Township-Range:number of sample in individual core. The samples taken average 10 cm in length. This section gives the depth, measured in meters, from the kelly bushing to the top of the sample.

| | | | | | |
|-------------|--------|--------|-------------|----|--------|
| Core | Sample | Depth | 02-21-07-28 | :3 | 939.00 |
| 05-18-09-27 | :1 | 812.0 | | :4 | 939.60 |
| | | | | :5 | 940.70 |
| 15-18-10-27 | :1 | 766.9 | | :6 | 942.00 |
| 15-12-11-27 | :1 | 734.74 | 14-04-08-28 | :1 | 883.61 |
| | :2 | 735.38 | | :2 | 884.03 |
| | :3 | 736.14 | | :3 | 884.20 |
| | :4 | 736.52 | | :4 | 884.58 |
| | :5 | 739.87 | | :5 | 885.66 |
| | | | | :6 | 886.58 |
| 02-21-07-28 | :1 | 937.35 | | | |
| | :2 | 937.82 | 15-17-08-28 | :1 | 904.15 |

| | | | | | |
|-------------|-----|--------|-------------|-----|--------|
| 15-17-08-28 | :2 | 905.09 | 07-36-08-28 | :3 | 849.56 |
| | :3 | 905.47 | | :4 | 849.86 |
| | :4 | 905.80 | | :5 | 850.54 |
| | :5 | 906.46 | | :6 | 851.10 |
| | :6 | 906.73 | | :7 | 851.65 |
| | :7 | 907.35 | | :8 | 851.90 |
| | :8 | 907.55 | | :9 | 852.03 |
| | :9 | 907.79 | | :10 | 852.47 |
| | :10 | 908.15 | | | |
| | | | 13-14-09-28 | :1 | 832.75 |
| 11-22-08-28 | :1 | 871.45 | | :2 | 833.71 |
| | :2 | 871.96 | | :3 | 833.97 |
| | :3 | 872.57 | | :4 | 834.52 |
| | :4 | 872.60 | | :5 | 835.23 |
| | :5 | 872.75 | | :6 | 835.59 |
| | :6 | 873.31 | | :7 | 836.44 |
| | :7 | 873.41 | | :8 | 837.05 |
| | :8 | 873.56 | | :9 | 837.89 |
| | :9 | 874.33 | | :10 | 838.30 |
| | | | | :11 | 838.59 |
| 07-36-08-28 | :1 | 847.51 | | :12 | 838.70 |
| | :2 | 847.36 | | | |

| | | | | | |
|-------------|----|--------|-------------|-----|--------|
| 01-20-09-28 | :1 | 862.00 | 01-30-09-28 | :4 | 872.32 |
| | :2 | 863.23 | | :5 | 872.55 |
| | :3 | 864.37 | | :6 | 873.17 |
| | :4 | 864.69 | | :7 | 873.53 |
| | :5 | 865.38 | | :8 | 874.69 |
| | :6 | 865.93 | | :9 | 875.16 |
| | :7 | 866.79 | | :10 | 875.41 |
| | :8 | 867.80 | | | |
| | :9 | 863.91 | 14-04-10-28 | :1 | 822.10 |
| | | | | :2 | 823.61 |
| 02-23-09-28 | :1 | 830.22 | | :3 | 823.87 |
| | :2 | 830.83 | | :4 | 824.49 |
| | :3 | 831.91 | | :5 | 825.70 |
| | :4 | 832.38 | | :6 | 825.96 |
| | :5 | 833.37 | | | |
| | :6 | 834.16 | 08-14-10-28 | :1 | 792.97 |
| | :7 | 834.39 | | :2 | 793.07 |
| | :8 | 834.65 | | :3 | 793.68 |
| | | | | :4 | 794.14 |
| 01-30-09-28 | :1 | 869.45 | | :5 | 793.89 |
| | :2 | 871.39 | | | |
| | :3 | 871.72 | 12-20-10-28 | :1 | 811.48 |

| | | | | | |
|-------------|----|--------|-------------|----|--------|
| 12-20-10-28 | :2 | 812.26 | 11-29-10-28 | :3 | 813.72 |
| | :3 | 813.98 | | :4 | 813.82 |
| | :4 | 814.28 | | :5 | 814.29 |
| | :5 | 814.86 | | :6 | 815.44 |
| | | | | :7 | 815.50 |
| 03-29-10-28 | :1 | 807.07 | | | |
| | :2 | 808.55 | 12-29-10-28 | :1 | 811.99 |
| | :3 | 809.67 | | :2 | 812.76 |
| | :4 | 810.40 | | :3 | 812.94 |
| | :5 | 811.67 | | :4 | 814.32 |
| | | | | :5 | 814.82 |
| 10-29-10-28 | :1 | 812.17 | | :6 | 815.16 |
| | :2 | 812.71 | | :7 | 815.30 |
| | :3 | 813.02 | | | |
| | :4 | 813.17 | 10-30-10-28 | :1 | 813.48 |
| | :5 | 813.55 | | :2 | 815.49 |
| | :6 | 814.22 | | :3 | 815.97 |
| | :7 | 815.03 | | :4 | 816.30 |
| | :8 | 815.25 | | :5 | 817.84 |
| | | | | :6 | 818.11 |
| 11-29-10-28 | :1 | 812.01 | | | |
| | :2 | 812.50 | 09-05-11-28 | :1 | 843.30 |

| | | | | | |
|-------------|-----|--------|-------------|----|--------|
| 09-05-11-28 | :2 | 843.63 | 14-16-10-29 | :4 | 883.64 |
| | | | | :5 | 884.51 |
| 01-31-09-29 | :1 | 914.76 | | :6 | 885.82 |
| | :2 | 916.25 | | :7 | 885.94 |
| | :3 | 917.57 | | :8 | 886.16 |
| | :4 | 917.82 | | | |
| | :5 | 917.98 | 09-20-10-29 | :1 | 881.98 |
| | | | | :2 | 882.35 |
| 11-11-10-29 | :1 | 862.00 | | :3 | 883.47 |
| | :2 | 862.89 | | :4 | 883.63 |
| | :3 | 863.88 | | :5 | 884.55 |
| | :4 | 865.86 | | :6 | 885.90 |
| | :5 | 865.95 | | :7 | 887.10 |
| | :6 | 866.32 | | :8 | 887.22 |
| | :7 | 866.69 | | | |
| | :8 | 867.24 | 05-21-10-29 | :1 | 875.59 |
| | :9 | 867.61 | | :2 | 876.52 |
| | :10 | 867.76 | | :3 | 887.23 |
| | | | | :4 | 887.35 |
| 14-16-10-29 | :1 | 881.61 | | :5 | 887.76 |
| | :2 | 882.42 | | :6 | 878.14 |
| | :3 | 882.57 | | :7 | 878.76 |

| | | | | | |
|-------------|-----|--------|-------------|----|--------|
| 05-21-10-29 | :8 | 880.30 | 02-25-10-29 | :2 | 828.39 |
| | :9 | 881.30 | | :3 | 829.02 |
| | :10 | 882.14 | | :4 | 829.36 |
| | | | | :5 | 830.63 |
| 11-21-10-29 | :1 | 874.64 | | :6 | 832.40 |
| | :2 | 875.42 | | :7 | 832.95 |
| | :3 | 876.17 | | :8 | 833.14 |
| | :4 | 876.82 | | | |
| | :5 | 877.63 | 13-27-10-29 | :1 | 847.44 |
| | :6 | 877.97 | | :2 | 847.90 |
| | :7 | 878.78 | | :3 | 848.43 |
| | :8 | 879.66 | | :4 | 848.63 |
| | :9 | 879.79 | | :5 | 848.50 |
| 01-23-10-29 | :1 | 850.29 | 03-28-10-29 | :1 | 865.62 |
| | :2 | 850.70 | | :2 | 867.97 |
| | :3 | 851.71 | | :3 | 868.83 |
| | :4 | 853.14 | | :4 | 869.14 |
| | :5 | 853.46 | | :5 | 870.78 |
| | :6 | 853.74 | | :6 | 871.85 |
| | | | | :7 | 872.65 |
| 02-25-10-29 | :1 | 826.30 | | :8 | 872.91 |

| | | | | | |
|-------------|----|--------|-------------|-----|--------|
| 04-28-10-29 | :1 | 872.49 | 01-29-10-29 | :4 | 879.58 |
| | :2 | 873.81 | | :5 | 881.19 |
| | :3 | 873.99 | | :6 | 881.46 |
| | :4 | 876.45 | | :7 | 881.83 |
| | :5 | 876.72 | | :8 | 882.22 |
| | :6 | 876.88 | | :9 | 883.03 |
| | :7 | 877.30 | | :10 | 883.13 |
| | :8 | 878.33 | | | |
| | | | 04-29-10-29 | :1 | 879.50 |
| 05-28-10-29 | :1 | 866.43 | | :2 | 879.91 |
| | :2 | 867.72 | | :3 | 880.23 |
| | :3 | 867.96 | | :4 | 880.88 |
| | :4 | 868.27 | | :5 | 881.69 |
| | :5 | 896.46 | | :6 | 883.80 |
| | :6 | 870.32 | | :7 | 884.43 |
| | :7 | 870.87 | | | |
| | :8 | 871.55 | 08-29-10-29 | :1 | 869.86 |
| | :9 | 871.66 | | :2 | 871.49 |
| | | | | :3 | 872.33 |
| 01-29-10-29 | :1 | 877.45 | | :4 | 874.59 |
| | :2 | 878.25 | | :5 | 875.05 |
| | :3 | 878.55 | | :6 | 875.61 |

| | | |
|-------------|----|--------|
| 09-29-10-29 | :1 | 862.89 |
| | :2 | 864.20 |
| | :3 | 864.82 |
| | :4 | 865.42 |
| | :5 | 866.57 |
| | :6 | 868.09 |
| | :7 | 869.12 |

| | | |
|-------------|----|--------|
| 7A-08-11-29 | :1 | 850.40 |
| | :2 | 851.16 |
| | :3 | 851.94 |
| | :4 | 853.25 |

| | | |
|-------------|----|--------|
| 11-11-11-29 | :1 | 850.91 |
| | :2 | 852.09 |
| | :3 | 852.24 |
| | :4 | 853.02 |
| | :5 | 853.75 |
| | :6 | 853.88 |
| | :7 | 854.08 |
| | :8 | 855.31 |

Appendix 3
Intensity Factors

| <u>Mineral</u> | <u>Main Identification</u> <u>Peak(s)</u> <u>(Degrees two theta,</u> <u>CuK alpha)</u> | <u>Intensity Factor</u> |
|----------------|---|-------------------------|
| Quartz | 26.7 | .0000333 |
| Plagioclase | 27.8 - 27.9 | .000143 |
| K - Feldspar | 27.4 - 27.5 | .000167 |
| Calcite | 29.4 - 29.8 | .0000917 |
| Dolomite | 30.9 | .000128 |
| Clay Minerals | 19.9 - 20.1 | .00128 |
| Pyrite | 33.1 | .000357 |
| Gypsum | 11.7 | .000536 |
| Anhydrite | 24.5 | .000417 |
| Halite | 31.7 | .000167 |

Appendix 4

X-Ray Diffraction Analysis Results

Legend

The sample numbers are set up as follows: LSD-Section-Township-Range:Sample. The number in sample is the sample number (see Appendix 2), the letters are coded as follows: 1) A and B: two subsamples from the same core sample, 2) C: coarse grained material, 3) F: Fine grained material, 4) S: shaley material, 5) L: limestone.

Qtz: quartz

Plag: plagioclase

K-Spar: K-Feldspar

Cc: Calcite

Dol: Dolomite

Clay: Clay minerals

Pyr: Pyrite

Gyp: Gypsum

Anh: Anhydrite

Hal: Halite

Bdepth: Depth within the Bakken Formation (from top of the black shale).

Numbers represent the percentage of that particular mineral of the 10 minerals analyzed.

Shale Unit

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|------|--------|-------|-------|-------|-------|------|-------|------|--------|
| 11-22-08-28:01 | 9.84 | 0.00 | 8.41 | 3.72 | 4.66 | 42.85 | 27.29 | 0.00 | 0.00 | 3.20 | 0.45 |
| 07-36-08-28:01 | 4.18 | 0.00 | 5.45 | 61.52 | 2.66 | 26.17 | 0.00 | 0.00 | 0.00 | 0.00 | 1.45 |
| 13-14-09-28:01 | 10.19 | 0.00 | 10.37 | 3.79 | 4.88 | 50.21 | 7.57 | 0.00 | 9.27 | 3.67 | 0.35 |
| 13-14-09-28:02 | 11.81 | 4.50 | 13.74 | 4.81 | 5.72 | 39.31 | 14.00 | 0.00 | 0.00 | 6.07 | 1.31 |
| 13-14-09-28:03 | 12.28 | 0.00 | 12.33 | 4.53 | 9.96 | 32.85 | 8.17 | 0.00 | 16.37 | 3.48 | 1.57 |
| 01-20-09-28:09 | 8.45 | 5.49 | 9.99 | 3.92 | 6.46 | 44.55 | 6.74 | 0.00 | 14.36 | 0.00 | 1.91 |
| 01-20-09-28:01 | 10.92 | 5.40 | 12.24 | 4.72 | 8.91 | 39.63 | 18.14 | 0.00 | 0.00 | 0.00 | 0.00 |
| 01-20-09-28:02 | 6.51 | 3.23 | 8.12 | 21.37 | 4.34 | 40.21 | 6.33 | 0.00 | 9.84 | 0.00 | 1.23 |
| 01-20-09-28:03 | 9.96 | 4.06 | 10.64 | 5.01 | 12.68 | 32.36 | 12.34 | 0.00 | 9.47 | 3.43 | 2.37 |
| 01-30-09-28:1L | 2.24 | 0.00 | 0.00 | 45.27 | 27.66 | 24.81 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 01-30-09-28:1S | 8.51 | 2.60 | 6.57 | 7.73 | 26.93 | 33.84 | 5.39 | 0.00 | 8.40 | 0.00 | 0.00 |
| 11-29-10-28:01 | 13.50 | 0.00 | 9.88 | 4.25 | 6.13 | 51.54 | 10.64 | 0.00 | 0.00 | 4.02 | 1.50 |
| 14-04-10-28:01 | 10.35 | 9.72 | 10.59 | 4.24 | 7.08 | 57.99 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 |
| 11-11-10-29:1C | 3.12 | 0.00 | 4.12 | 61.59 | 2.35 | 21.33 | 0.00 | 0.00 | 7.47 | 0.00 | 3.00 |
| 11-11-10-29:1S | 10.83 | 6.01 | 13.09 | 5.24 | 5.98 | 53.35 | 0.00 | 5.46 | 0.00 | 0.00 | 3.00 |
| 02-25-10-29:01 | 12.37 | 0.00 | 10.55 | 4.12 | 10.11 | 57.77 | 0.00 | 0.00 | 0.00 | 5.05 | 0.00 |
| 02-25-10-29:02 | 12.25 | 4.58 | 10.76 | 5.63 | 6.57 | 39.26 | 8.63 | 0.00 | 8.34 | 3.93 | 2.09 |
| | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | |
| MIN | 2.24 | 0.00 | 0.00 | 3.72 | 2.35 | 21.33 | 0.00 | 0.00 | 0.00 | 0.00 | |
| MAX | 13.50 | 9.72 | 13.74 | 61.59 | 27.66 | 57.99 | 27.29 | 5.46 | 16.37 | 6.07 | |
| AVG | 9.25 | 2.68 | 9.23 | 14.79 | 9.00 | 40.47 | 7.37 | 0.32 | 4.91 | 1.93 | |
| SD | 3.27 | 2.90 | 3.42 | 2.20 | 7.16 | 10.84 | 7.38 | 1.28 | 5.60 | 2.14 | |

Massive Unit

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|-------|--------|-------|-------|-------|-------|-------|-------|------|--------|
| 15-12-11-27:01 | 9.49 | 6.31 | 5.72 | 1.88 | 33.00 | 23.07 | 0.00 | 0.00 | 7.25 | 3.24 | 2.74 |
| 15-12-11-27:02 | 15.54 | 4.04 | 4.76 | 1.64 | 35.84 | 24.58 | 0.00 | 0.00 | 11.09 | 2.48 | 3.38 |
| 02-21-07-28:01 | 15.82 | 6.17 | 4.29 | 2.67 | 36.16 | 26.84 | 0.00 | 0.00 | 5.19 | 2.82 | 2.23 |
| 02-21-07-28:02 | 12.08 | 2.29 | 3.59 | 15.78 | 30.28 | 19.61 | 4.18 | 4.47 | 5.36 | 2.30 | 2.70 |
| 14-04-08-28:01 | 21.76 | 0.00 | 6.72 | 2.17 | 37.04 | 28.99 | 3.29 | 0.00 | 0.00 | 0.00 | 3.61 |
| 14-04-08-28:02 | 17.90 | 3.80 | 7.67 | 1.59 | 25.70 | 33.03 | 0.00 | 0.00 | 6.30 | 3.97 | 4.03 |
| 15-17-08-28:01 | 10.27 | 4.10 | 6.03 | 1.85 | 46.05 | 28.75 | 0.00 | 0.00 | 0.00 | 2.91 | 1.15 |
| 15-17-08-28:2A | 12.78 | 2.79 | 3.58 | 1.98 | 32.55 | 22.27 | 4.51 | 7.21 | 5.10 | 7.19 | 2.09 |
| 15-17-08-28:2B | 20.60 | 5.44 | 3.37 | 0.00 | 33.87 | 0.00 | 27.78 | 8.91 | 0.00 | 0.00 | 2.09 |
| 15-17-08-28:3A | 6.49 | 1.42 | 1.76 | 0.74 | 14.59 | 9.43 | 0.00 | 22.62 | 39.88 | 3.03 | 2.47 |
| 15-17-08-28:3B | 7.96 | 2.18 | 2.08 | 0.67 | 13.59 | 0.00 | 0.00 | 0.00 | 73.50 | 0.00 | 2.47 |
| 11-22-08-28:02 | 6.42 | 3.00 | 4.60 | 2.36 | 38.00 | 26.04 | 0.00 | 0.00 | 6.63 | 2.91 | 0.96 |
| 11-22-08-28:03 | 15.01 | 2.78 | 4.98 | 1.94 | 61.10 | 14.16 | 0.00 | 0.00 | 0.00 | 0.00 | 1.57 |
| 11-22-08-28:04 | 22.98 | 3.53 | 5.31 | 2.22 | 52.05 | 0.00 | 0.00 | 0.00 | 13.89 | 0.00 | 1.60 |
| 07-36-08-28:02 | 13.21 | 3.25 | 5.11 | 2.36 | 37.12 | 35.33 | 0.00 | 0.00 | 3.58 | 0.00 | 2.30 |
| 07-36-08-28:03 | 19.87 | 4.73 | 5.97 | 1.88 | 34.33 | 22.17 | 6.24 | 0.00 | 4.78 | 0.00 | 3.50 |
| 13-14-09-28:04 | 14.09 | 5.43 | 3.87 | 1.95 | 33.95 | 28.59 | 0.00 | 0.00 | 5.71 | 6.37 | 1.85 |
| 13-14-09-28:05 | 17.24 | 2.81 | 4.11 | 1.56 | 58.40 | 0.00 | 0.00 | 0.00 | 15.85 | 0.00 | 2.83 |
| 13-14-09-28:06 | 20.68 | 4.26 | 5.25 | 1.15 | 47.83 | 12.99 | 0.00 | 0.00 | 7.80 | 0.00 | 3.19 |
| 01-30-09-28:02 | 16.10 | 4.51 | 4.87 | 2.63 | 38.59 | 33.27 | 0.00 | 0.00 | 0.00 | 0.00 | 1.94 |
| 01-30-09-28:04 | 14.47 | 2.17 | 7.84 | 2.01 | 50.39 | 16.09 | 0.00 | 0.00 | 0.00 | 7.00 | 2.87 |
| 01-30-09-28:05 | 13.27 | 3.66 | 3.83 | 1.18 | 27.60 | 0.00 | 0.00 | 0.00 | 50.43 | 0.00 | 3.10 |
| 14-04-10-28:02 | 18.97 | 4.49 | 6.52 | 2.13 | 33.45 | 28.46 | 0.00 | 0.00 | 3.66 | 2.27 | 2.51 |
| 14-04-10-28:3C | 10.77 | 2.44 | 2.50 | 0.00 | 18.86 | 0.00 | 3.06 | 0.00 | 62.33 | 0.00 | 2.77 |
| 14-04-10-28:3F | 15.14 | 3.50 | 5.85 | 1.89 | 39.67 | 31.20 | 0.00 | 0.00 | 0.00 | 2.72 | 2.77 |
| 08-14-10-28:01 | 16.53 | 4.15 | 5.76 | 1.95 | 43.32 | 20.97 | 0.00 | 0.00 | 5.26 | 2.03 | 2.97 |
| 08-14-10-28:1C | 21.42 | 13.09 | 6.92 | 1.31 | 53.25 | 0.00 | 0.00 | 0.00 | 3.97 | 0.00 | 2.97 |
| 08-14-10-28:2C | 19.82 | 3.38 | 5.42 | 1.98 | 52.96 | 11.96 | 0.00 | 0.00 | 4.45 | 0.00 | 3.07 |
| 08-14-10-28:2F | 17.04 | 6.32 | 7.40 | 2.18 | 33.19 | 26.43 | 0.00 | 0.00 | 3.27 | 4.13 | 3.07 |

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|-------|--------|------|-------|-------|-------|------|------|-------|--------|
| 10-29-10-28:01 | 13.17 | 0.00 | 6.36 | 2.50 | 34.32 | 35.35 | 0.00 | 0.00 | 4.56 | 3.70 | 2.42 |
| 10-29-10-28:02 | 20.87 | 6.10 | 6.87 | 1.66 | 42.86 | 16.49 | 0.00 | 0.00 | 5.13 | 0.00 | 2.96 |
| 10-29-10-28:03 | 16.80 | 4.67 | 6.05 | 1.95 | 37.89 | 23.94 | 0.00 | 0.00 | 5.75 | 2.90 | 3.27 |
| 11-29-10-28:02 | 17.62 | 3.35 | 6.02 | 2.45 | 39.37 | 27.05 | 0.00 | 0.00 | 0.00 | 4.10 | 1.99 |
| 11-29-10-28:03 | 24.94 | 11.67 | 9.48 | 1.70 | 52.18 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.21 |
| 11-29-10-28:04 | 20.13 | 5.82 | 8.94 | 2.56 | 44.15 | 13.23 | 0.00 | 0.00 | 0.00 | 5.13 | 3.31 |
| 10-30-10-28:02 | 15.26 | 3.25 | 4.84 | 2.05 | 48.71 | 19.93 | 0.00 | 0.00 | 0.00 | 5.92 | 2.95 |
| 10-30-10-28:03 | 17.89 | 3.46 | 7.86 | 3.35 | 44.76 | 18.25 | 0.00 | 0.00 | 0.00 | 4.38 | 3.63 |
| 01-20-09-29:04 | 10.46 | 2.43 | 4.01 | 1.63 | 52.29 | 23.33 | 0.00 | 0.00 | 5.82 | 0.00 | 2.69 |
| 01-20-09-29:05 | 11.57 | 3.41 | 4.62 | 1.67 | 54.95 | 14.55 | 0.00 | 0.00 | 5.41 | 3.78 | 3.38 |
| 11-11-10-29:2C | 10.65 | 3.70 | 3.70 | 1.75 | 48.57 | 23.58 | 3.89 | 4.13 | 0.00 | 0.00 | 3.89 |
| 11-11-10-29:2F | 15.21 | 3.64 | 7.19 | 3.38 | 18.60 | 31.18 | 11.48 | 9.28 | 0.00 | 0.00 | 3.89 |
| 11-11-10-29:3A | 9.10 | 2.56 | 3.68 | 6.24 | 58.67 | 13.83 | 0.00 | 0.00 | 2.64 | 3.25 | 4.88 |
| 11-11-10-29:3B | 12.56 | 2.13 | 2.90 | 0.00 | 28.88 | 0.00 | 46.06 | 7.44 | 0.00 | 0.00 | 4.88 |
| 11-11-10-29:3C | 10.43 | 3.63 | 3.71 | 5.28 | 47.58 | 16.30 | 4.37 | 4.42 | 2.18 | 2.04 | 4.88 |
| 14-16-10-29:01 | 12.35 | 3.41 | 4.38 | 1.64 | 42.35 | 30.12 | 5.71 | 0.00 | 0.00 | 0.00 | 1.91 |
| 14-16-10-29:3A | 19.64 | 0.00 | 5.34 | 2.46 | 51.78 | 11.88 | 4.99 | 0.00 | 3.88 | 0.00 | 2.87 |
| 14-16-10-29:3B | 4.81 | 1.51 | 1.31 | 1.70 | 6.38 | 82.69 | 1.57 | 0.00 | 0.00 | 0.00 | 2.87 |
| 14-16-10-29:3C | 9.99 | 2.40 | 4.02 | 1.54 | 62.72 | 13.35 | 3.51 | 0.00 | 0.00 | 2.43 | 2.87 |
| 09-20-10-29:01 | 17.62 | 4.18 | 3.77 | 1.88 | 48.80 | 18.76 | 0.00 | 4.96 | 0.00 | 0.00 | 2.98 |
| 09-20-10-29:02 | 29.35 | 3.93 | 5.57 | 1.88 | 39.00 | 17.37 | 0.00 | 0.00 | 0.00 | 2.88 | 3.35 |
| 11-21-10-29:01 | 16.84 | 5.64 | 5.49 | 2.29 | 33.23 | 32.74 | 0.00 | 0.00 | 0.00 | 3.73 | 2.64 |
| 11-21-10-29:02 | 14.78 | 4.59 | 4.87 | 1.55 | 40.35 | 23.52 | 0.00 | 0.00 | 0.00 | 10.30 | 3.42 |
| 02-25-10-29:04 | 16.74 | 4.09 | 6.22 | 2.05 | 36.89 | 31.49 | 0.00 | 0.00 | 0.00 | 2.48 | 3.06 |
| 02-25-10-29:06 | 16.59 | 6.47 | 5.10 | 1.78 | 45.31 | 21.66 | 0.00 | 0.00 | 0.00 | 3.05 | 6.10 |
| 13-27-10-29:01 | 29.36 | 7.13 | 10.51 | 2.29 | 24.08 | 22.18 | 0.00 | 0.00 | 4.41 | 0.00 | 4.44 |
| 13-27-10-29:02 | 14.59 | 3.92 | 5.31 | 2.33 | 50.43 | 19.62 | 0.00 | 0.00 | 0.00 | 3.76 | 4.90 |
| 04-28-10-29:01 | 14.46 | 4.99 | 4.66 | 1.89 | 36.30 | 24.25 | 3.13 | 4.13 | 4.35 | 1.79 | 2.99 |
| 04-28-10-29:02 | 12.29 | 3.21 | 4.77 | 1.76 | 60.18 | 12.28 | 5.48 | 0.00 | 0.00 | 0.00 | 4.31 |
| 05-28-10-29:01 | 16.08 | 0.00 | 5.07 | 2.05 | 43.90 | 25.21 | 0.00 | 0.00 | 5.09 | 2.55 | 1.43 |
| 05-28-10-29:02 | 15.89 | 4.95 | 5.64 | 1.49 | 43.90 | 14.32 | 6.10 | 0.00 | 4.28 | 3.40 | 2.72 |

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|------|--------|------|-------|-------|-------|-------|------|------|--------|
| 01-29-10-29:1C | 18.59 | 4.51 | 5.63 | 2.73 | 23.39 | 29.36 | 13.48 | 0.00 | 0.00 | 2.26 | 1.45 |
| 01-29-10-29:1F | 10.80 | 3.72 | 6.37 | 2.70 | 3.70 | 41.95 | 14.65 | 7.95 | 8.12 | 0.00 | 1.45 |
| 01-29-10-29:02 | 17.20 | 6.80 | 0.00 | 2.26 | 40.13 | 28.33 | 0.00 | 0.00 | 5.26 | 0.00 | 2.25 |
| 01-29-10-29:3A | 18.18 | 3.97 | 5.80 | 2.41 | 41.97 | 24.60 | 0.00 | 0.00 | 0.00 | 3.03 | 2.55 |
| 01-29-10-29:3B | 13.44 | 2.84 | 4.04 | 0.00 | 7.87 | 0.00 | 38.68 | 33.09 | 0.00 | 0.00 | 2.55 |
| 01-29-10-29:3C | 14.98 | 8.35 | 4.84 | 1.33 | 31.30 | 25.35 | 0.00 | 6.14 | 0.00 | 7.66 | 2.55 |
| 01-29-10-29:04 | 19.26 | 3.62 | 5.83 | 1.67 | 40.12 | 18.31 | 4.19 | 0.00 | 4.80 | 2.15 | 3.58 |
| 04-29-10-29:01 | 17.26 | 3.24 | 6.00 | 2.10 | 29.33 | 26.47 | 8.70 | 3.80 | 0.00 | 3.07 | 1.50 |
| 04-29-10-29:02 | 21.60 | 2.61 | 4.91 | 1.62 | 52.87 | 0.00 | 16.24 | 0.10 | 0.00 | 0.00 | 1.91 |
| 7A-08-11-29:01 | 16.26 | 4.59 | 5.77 | 1.75 | 43.76 | 23.18 | 0.00 | 0.00 | 4.66 | 0.00 | 3.40 |
| 11-11-11-29:01 | 14.53 | 4.31 | 8.92 | 1.32 | 40.57 | 26.61 | 0.00 | 0.00 | 0.00 | 3.70 | 4.71 |
| 11-11-11-29:02 | 14.79 | 3.77 | 6.74 | 2.29 | 40.55 | 25.55 | 0.00 | 0.00 | 0.00 | 6.27 | 5.89 |

| | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | |
|-----|-------|-------|--------|-------|-------|-------|-------|-------|-------|-------|--|
| MIN | 4.81 | 0.00 | 0.00 | 0.00 | 3.70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| MAX | 29.36 | 13.09 | 10.51 | 15.78 | 62.72 | 82.69 | 46.06 | 33.09 | 73.50 | 10.30 | |
| AVG | 15.95 | 4.01 | 5.26 | 2.15 | 39.00 | 20.45 | 3.35 | 1.78 | 5.85 | 2.15 | |
| SD | 4.48 | 2.15 | 1.79 | 1.86 | 12.65 | 12.83 | 8.12 | 5.08 | 13.10 | 2.32 | |

Horizontal Laminated Unit

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|------|--------|------|-------|-------|------|------|------|------|--------|
| 15-12-11-27:03 | 21.49 | 4.28 | 5.50 | 1.75 | 34.31 | 22.78 | 0.00 | 0.00 | 7.57 | 2.27 | 4.14 |
| 15-12-11-27:04 | 19.02 | 2.63 | 3.71 | 1.54 | 33.23 | 25.64 | 0.00 | 7.86 | 3.91 | 2.41 | 4.52 |
| 02-21-07-28:03 | 21.04 | 4.84 | 6.29 | 0.00 | 35.92 | 28.61 | 0.00 | 0.00 | 0.00 | 3.26 | 3.88 |
| 02-21-07-28:04 | 20.96 | 4.58 | 5.02 | 1.82 | 36.33 | 26.97 | 4.28 | 0.00 | 0.00 | 0.00 | 4.48 |
| 15-17-08-28:04 | 19.55 | 4.67 | 0.00 | 2.30 | 32.63 | 22.51 | 3.39 | 7.55 | 4.36 | 3.00 | 2.80 |
| 15-17-08-28:05 | 23.58 | 5.68 | 6.32 | 1.44 | 24.20 | 23.01 | 2.95 | 4.55 | 5.58 | 2.63 | 3.46 |

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|-------|--------|------|-------|-------|------|-------|-------|------|--------|
| 15-17-08-28:06 | 18.63 | 3.51 | 6.72 | 1.81 | 34.25 | 20.86 | 0.00 | 6.98 | 4.12 | 3.09 | 3.73 |
| 11-22-08-28:06 | 26.21 | 3.48 | 4.83 | 1.86 | 33.09 | 26.23 | 0.00 | 0.00 | 0.00 | 4.26 | 2.31 |
| 11-22-08-28:07 | 27.00 | 3.11 | 6.74 | 1.71 | 25.69 | 24.72 | 0.00 | 0.00 | 8.51 | 2.49 | 2.41 |
| 07-34-08-28:05 | 19.47 | 5.96 | 8.26 | 1.73 | 34.47 | 30.07 | 0.00 | 0.00 | 0.00 | 0.00 | 4.48 |
| 07-34-08-28:06 | 19.56 | 3.94 | 8.80 | 1.72 | 30.50 | 21.22 | 0.00 | 0.00 | 10.85 | 3.38 | 5.04 |
| 07-36-08-28:4A | 19.31 | 4.17 | 7.89 | 1.81 | 44.29 | 13.49 | 0.00 | 0.00 | 9.00 | 0.00 | 3.80 |
| 07-36-08-28:4B | 18.09 | 4.28 | 5.58 | 2.21 | 37.18 | 29.74 | 0.00 | 0.00 | 0.00 | 2.89 | 3.80 |
| 03-14-09-28:07 | 26.74 | 2.67 | 8.01 | 0.00 | 33.92 | 23.43 | 0.00 | 0.00 | 5.19 | 0.00 | 4.04 |
| 13-14-09-28:08 | 23.91 | 3.74 | 9.24 | 1.56 | 30.94 | 25.45 | 0.00 | 0.00 | 0.00 | 5.12 | 4.65 |
| 01-20-09-28:07 | 20.62 | 2.89 | 7.40 | 1.37 | 32.35 | 27.70 | 0.00 | 0.00 | 5.53 | 2.09 | 4.79 |
| 01-30-09-28:06 | 21.18 | 4.84 | 5.47 | 2.87 | 31.45 | 25.51 | 0.00 | 3.03 | 2.95 | 2.66 | 3.72 |
| 01-30-09-28:08 | 31.08 | 2.81 | 9.07 | 1.19 | 25.06 | 0.00 | 0.00 | 4.25 | 23.37 | 3.12 | 5.24 |
| 14-04-10-28:04 | 19.40 | 4.27 | 4.52 | 2.15 | 41.52 | 23.05 | 0.00 | 0.00 | 0.00 | 5.07 | 3.39 |
| 08-14-10-28:03 | 31.07 | 4.68 | 7.21 | 1.61 | 25.18 | 20.39 | 3.20 | 0.00 | 6.63 | 0.00 | 3.68 |
| 10-29-10-28:05 | 25.68 | 0.00 | 8.58 | 2.13 | 35.36 | 28.23 | 0.00 | 0.00 | 0.00 | 0.00 | 3.80 |
| 11-29-10-28:05 | 22.43 | 5.10 | 6.57 | 1.78 | 35.36 | 24.47 | 0.00 | 0.00 | 0.00 | 4.26 | 3.78 |
| 11-29-10-28:06 | 23.77 | 3.56 | 12.13 | 2.13 | 19.94 | 0.00 | 0.00 | 0.00 | 38.45 | 0.00 | 4.93 |
| 10-30-10-28:04 | 21.40 | 4.89 | 6.48 | 2.69 | 28.90 | 28.94 | 0.00 | 0.00 | 0.00 | 6.67 | 3.96 |
| 11-11-10-29:04 | 17.49 | 2.09 | 6.53 | 1.45 | 39.31 | 16.46 | 3.35 | 5.03 | 5.81 | 2.44 | 6.86 |
| 14-16-10-29:04 | 17.39 | 2.81 | 5.04 | 1.88 | 63.00 | 0.00 | 2.14 | 0.00 | 7.70 | 0.00 | 3.94 |
| 14-16-10-29:05 | 19.80 | 3.89 | 5.26 | 1.55 | 41.95 | 22.39 | 0.00 | 0.00 | 5.13 | 0.00 | 4.81 |
| 09-20-10-29:03 | 29.76 | 0.00 | 6.33 | 1.98 | 25.88 | 29.22 | 3.91 | 0.00 | 0.00 | 2.88 | 4.47 |
| 09-20-10-29:05 | 22.00 | 3.97 | 6.70 | 2.16 | 34.01 | 28.64 | 0.00 | 0.00 | 0.00 | 2.49 | 5.55 |
| 11-21-10-29:03 | 25.50 | 4.87 | 4.99 | 1.51 | 22.98 | 22.73 | 6.01 | 0.00 | 6.55 | 4.83 | 4.17 |
| 11-21-10-29:04 | 19.77 | 6.15 | 5.51 | 1.89 | 35.56 | 25.67 | 0.00 | 0.00 | 0.00 | 5.41 | 4.82 |
| 02-25-10-29:05 | 18.48 | 3.35 | 6.70 | 2.23 | 49.02 | 18.35 | 0.00 | 0.00 | 0.00 | 1.83 | 4.33 |
| 13-27-10-29:03 | 16.85 | 10.76 | 6.21 | 1.03 | 29.19 | 16.21 | 0.00 | 14.43 | 5.28 | 0.00 | 5.43 |
| 04-28-10-29:03 | 24.34 | 3.37 | 4.66 | 1.24 | 39.27 | 15.09 | 6.16 | 5.84 | 0.00 | 0.00 | 4.49 |
| 05-28-10-29:03 | 21.16 | 5.10 | 5.84 | 2.07 | 39.21 | 14.42 | 3.59 | 0.00 | 0.00 | 8.56 | 2.96 |
| 05-28-10-29:04 | 14.54 | 3.60 | 5.90 | 1.54 | 30.50 | 8.78 | 0.00 | 22.17 | 9.11 | 3.82 | 3.27 |
| 05-28-10-29:05 | 30.88 | 6.09 | 6.26 | 0.00 | 32.48 | 19.10 | 0.00 | 0.00 | 0.00 | 5.16 | 4.46 |

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|------|--------|------|-------|-------|------|------|------|------|--------|
| 01-29-10-29:05 | 20.20 | 5.39 | 4.73 | 2.02 | 32.92 | 16.78 | 5.08 | 4.94 | 5.59 | 2.31 | 5.19 |
| 7A-08-11-29:02 | 31.22 | 5.10 | 4.80 | 1.13 | 26.87 | 21.72 | 0.00 | 0.00 | 9.12 | 0.00 | 4.16 |
| 7A-08-11-29:03 | 16.47 | 4.23 | 5.79 | 1.75 | 28.83 | 31.95 | 4.60 | 0.00 | 3.74 | 2.59 | 4.94 |
| 11-11-11-29:03 | 29.18 | 4.50 | 6.27 | 2.61 | 32.72 | 21.50 | 0.00 | 0.00 | 0.00 | 3.19 | 6.04 |

| | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | |
|-----|-------|-------|--------|------|-------|-------|------|-------|-------|------|--|
| MIN | 14.54 | 0.00 | 0.00 | 0.00 | 19.94 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| MAX | 31.22 | 10.76 | 12.13 | 2.87 | 63.00 | 31.95 | 6.16 | 22.17 | 38.45 | 8.56 | |
| AVG | 22.35 | 4.14 | 6.29 | 1.69 | 33.65 | 21.27 | 1.18 | 2.11 | 4.73 | 2.54 | |
| SD | 4.40 | 1.69 | 1.86 | 0.62 | 7.46 | 7.81 | 1.95 | 4.46 | 7.03 | 2.07 | |

Wavy Laminated Unit

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|------|--------|------|-------|-------|------|-------|-------|------|--------|
| 14-04-08-28:03 | 26.43 | 3.81 | 6.44 | 2.94 | 25.79 | 27.29 | 0.00 | 0.00 | 5.14 | 2.12 | 4.20 |
| 14-04-08-28:04 | 20.47 | 1.36 | 2.67 | 0.84 | 10.42 | 7.91 | 0.00 | 3.43 | 52.86 | 0.00 | 4.58 |
| 07-34-08-28:07 | 24.35 | 4.07 | 8.13 | 1.51 | 24.06 | 24.17 | 0.00 | 0.00 | 9.31 | 4.35 | 5.59 |
| 07-34-08-28:08 | 11.66 | 1.65 | 4.00 | 0.00 | 9.32 | 11.65 | 0.00 | 2.78 | 55.04 | 3.87 | 5.84 |
| 13-14-09-28:11 | 19.68 | 1.67 | 1.70 | 0.00 | 3.55 | 0.00 | 0.00 | 0.00 | 72.53 | 0.84 | 6.19 |
| 01-20-09-28:08 | 21.76 | 2.42 | 4.71 | 1.76 | 37.61 | 21.74 | 0.00 | 0.00 | 8.24 | 1.72 | 5.80 |
| 01-30-09-28:09 | 45.35 | 2.93 | 8.98 | 1.67 | 26.98 | 0.00 | 0.00 | 5.23 | 5.90 | 2.93 | 5.71 |
| 01-30-09-28:AC | 29.16 | 1.86 | 6.22 | 1.03 | 17.21 | 8.61 | 0.00 | 34.03 | 1.85 | 0.00 | 5.96 |
| 01-30-09-28:AF | 6.57 | 2.28 | 3.38 | 0.00 | 69.81 | 12.50 | 0.00 | 0.00 | 3.45 | 1.97 | 5.96 |
| 14-04-10-28:05 | 26.95 | 4.62 | 3.55 | 0.98 | 9.15 | 0.00 | 0.00 | 39.70 | 15.03 | 0.00 | 4.60 |
| 15-17-10-28:07 | 26.30 | 1.72 | 4.41 | 1.14 | 12.43 | 13.64 | 4.23 | 0.00 | 34.32 | 1.77 | 4.35 |
| 15-17-10-28:09 | 15.07 | 0.00 | 1.13 | 0.64 | 2.84 | 0.00 | 0.00 | 0.00 | 80.30 | 0.00 | 4.79 |
| 10-29-10-28:07 | 19.43 | 2.40 | 11.13 | 1.12 | 15.31 | 15.98 | 0.00 | 0.00 | 32.75 | 1.85 | 5.28 |
| 10-30-10-28:05 | 29.72 | 4.83 | 9.25 | 1.91 | 29.96 | 21.35 | 0.00 | 0.00 | 0.00 | 2.94 | 5.50 |

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|------|--------|------|-------|-------|-------|-------|-------|------|--------|
| 11-11-10-29:06 | 6.27 | 2.15 | 4.96 | 1.64 | 69.42 | 7.87 | 0.00 | 3.26 | 2.05 | 2.33 | 7.37 |
| 11-11-10-29:07 | 20.27 | 1.56 | 4.17 | 0.00 | 73.98 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 7.69 |
| 14-16-10-29:06 | 17.61 | 1.99 | 3.76 | 1.64 | 10.61 | 0.00 | 0.00 | 59.73 | 4.63 | 0.00 | 6.12 |
| 14-16-10-29:07 | 27.07 | 1.57 | 2.54 | 1.01 | 8.80 | 0.00 | 0.00 | 54.29 | 4.69 | 0.00 | 6.24 |
| 09-20-10-29:06 | 23.04 | 3.19 | 4.36 | 4.44 | 14.41 | 0.00 | 0.00 | 48.90 | 0.00 | 1.63 | 6.90 |
| 09-20-10-29:07 | 31.40 | 2.07 | 7.58 | 1.15 | 10.70 | 0.00 | 0.00 | 38.81 | 6.37 | 1.88 | 8.10 |
| 11-21-10-29:05 | 30.93 | 3.17 | 8.75 | 1.18 | 27.25 | 16.96 | 2.86 | 3.63 | 0.00 | 5.23 | 5.63 |
| 11-21-10-29:07 | 16.77 | 1.51 | 3.96 | 0.75 | 11.14 | 7.61 | 0.00 | 56.63 | 0.00 | 1.59 | 6.78 |
| 11-21-10-29:08 | 26.59 | 0.00 | 3.95 | 0.90 | 9.05 | 9.67 | 0.00 | 31.10 | 18.71 | 0.00 | 7.66 |
| 02-25-10-29:07 | 31.34 | 5.56 | 7.96 | 1.49 | 39.93 | 13.70 | 0.00 | 0.00 | 0.00 | 0.00 | 6.65 |
| 13-27-10-29:04 | 14.54 | 0.00 | 1.83 | 0.00 | 14.08 | 0.00 | 0.00 | 59.58 | 9.94 | 0.00 | 5.63 |
| 13-27-10-29:05 | 17.46 | 0.00 | 2.32 | 0.00 | 4.66 | 0.00 | 0.00 | 21.98 | 53.56 | 0.00 | 5.80 |
| 04-28-10-29:05 | 40.27 | 0.00 | 8.75 | 1.42 | 27.72 | 16.11 | 4.05 | 0.00 | 0.00 | 1.66 | 7.22 |
| 04-28-10-29:07 | 33.67 | 1.98 | 5.30 | 1.15 | 18.41 | 10.59 | 0.00 | 26.58 | 0.00 | 2.29 | 7.80 |
| 05-28-10-29:07 | 32.47 | 4.90 | 7.22 | 1.85 | 28.50 | 22.60 | 0.00 | 0.00 | 0.00 | 2.42 | 5.87 |
| 05-28-10-29:08 | 30.21 | 3.23 | 5.79 | 2.29 | 26.68 | 17.91 | 0.00 | 8.87 | 0.00 | 4.97 | 6.55 |
| 01-29-10-29:07 | 29.45 | 3.94 | 6.62 | 2.08 | 26.29 | 16.65 | 0.00 | 14.93 | 0.00 | 0.00 | 5.83 |
| 01-29-10-29:09 | 17.54 | 1.73 | 3.22 | 1.20 | 11.62 | 13.11 | 0.00 | 41.20 | 6.99 | 3.33 | 7.03 |
| 01-29-10-29:6P | 29.43 | 1.49 | 5.05 | 0.00 | 2.53 | 0.00 | 53.49 | 7.99 | 0.00 | 0.00 | 5.46 |
| 01-29-10-29:6S | 26.14 | 3.23 | 6.61 | 1.94 | 21.52 | 12.12 | 0.00 | 20.22 | 6.58 | 1.58 | 5.46 |
| 7A-08-11-29:4C | 40.36 | 5.52 | 4.88 | 1.63 | 29.27 | 15.97 | 2.35 | 0.00 | 0.00 | 0.00 | 6.25 |
| 7A-08-11-29:4F | 18.92 | 2.93 | 4.78 | 1.21 | 40.05 | 26.16 | 5.90 | 0.00 | 0.00 | 0.00 | 6.25 |
| 11-11-11-29:05 | 16.45 | 1.88 | 6.26 | 1.08 | 17.29 | 17.19 | 0.00 | 5.15 | 32.00 | 2.66 | 7.55 |
| 11-11-11-29:06 | 19.65 | 1.03 | 2.11 | 0.48 | 5.66 | 0.00 | 0.00 | 2.10 | 67.58 | 1.34 | 7.68 |

| | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal |
|-----|-------|------|--------|------|-------|-------|-------|-------|-------|------|
| MIN | 6.27 | 0.00 | 1.13 | 0.00 | 2.53 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MAX | 45.35 | 5.56 | 11.13 | 4.44 | 73.98 | 27.29 | 53.49 | 59.73 | 80.30 | 5.23 |
| AVG | 24.23 | 2.37 | 5.22 | 1.21 | 22.21 | 10.24 | 1.91 | 15.53 | 15.52 | 1.51 |
| SD | 8.57 | 1.50 | 2.38 | 0.89 | 17.54 | 8.69 | 8.59 | 20.18 | 23.04 | 1.51 |

Lyleton

| Sample | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | Bdepth |
|----------------|-------|------|--------|------|-------|-------|------|------|------|-------|--------|
| 05-18-09-27:01 | 5.93 | 1.75 | 3.19 | 1.53 | 62.90 | 17.55 | 0.00 | 0.00 | 4.86 | 2.25 | 8.90 |
| 15-18-10-27:01 | 9.83 | 3.12 | 3.76 | 1.62 | 51.52 | 30.12 | 0.00 | 0.00 | 0.00 | 0.00 | 8.00 |
| 15-12-11-27:05 | 7.79 | 0.00 | 3.72 | 1.99 | 39.65 | 34.52 | 0.00 | 5.78 | 6.51 | 0.00 | 4.87 |
| 02-21-07-28:05 | 0.88 | 2.90 | 10.25 | 1.14 | 27.43 | 33.70 | 0.00 | 0.00 | 0.00 | 3.66 | 5.58 |
| 02-21-07-28:06 | 9.78 | 0.00 | 7.94 | 6.95 | 14.50 | 35.10 | 6.34 | 5.52 | 9.72 | 4.12 | 6.88 |
| 14-04-08-28:05 | 5.74 | 0.00 | 4.60 | 0.00 | 78.75 | 10.89 | 0.00 | 0.00 | 0.00 | 0.00 | 5.66 |
| 14-04-08-28:06 | 4.50 | 0.00 | 2.39 | 1.29 | 75.19 | 14.15 | 0.00 | 0.00 | 0.00 | 2.46 | 6.58 |
| 13-14-09-28:12 | 8.30 | 0.00 | 4.25 | 0.00 | 53.87 | 28.71 | 0.00 | 0.00 | 0.00 | 4.85 | 6.30 |
| 08-14-10-28:04 | 5.40 | 2.05 | 2.89 | 0.00 | 71.50 | 16.53 | 0.00 | 0.00 | 0.00 | 1.60 | 3.68 |
| 04-29-10-28:03 | 8.73 | 2.06 | 3.20 | 1.53 | 59.95 | 14.68 | 7.21 | 0.00 | 0.00 | 2.60 | 2.23 |
| 10-29-10-28:08 | 6.43 | 2.32 | 5.42 | 1.78 | 49.08 | 26.24 | 0.00 | 0.00 | 6.57 | 2.12 | 5.50 |
| 09-05-11-28:01 | 7.40 | 0.00 | 5.11 | 2.19 | 55.97 | 24.72 | 0.00 | 0.00 | 0.00 | 4.59 | 5.00 |
| 14-16-10-29:08 | 2.44 | 3.46 | 9.60 | 3.31 | 25.55 | 31.28 | 0.00 | 3.87 | 7.90 | 2.55 | 6.46 |
| 11-21-10-29:09 | 0.47 | 0.00 | 8.38 | 3.69 | 16.73 | 33.29 | 0.00 | 5.13 | 9.57 | 12.71 | 7.79 |
| 05-28-10-29:09 | 0.92 | 0.00 | 9.86 | 4.14 | 15.18 | 40.92 | 5.91 | 0.00 | 8.49 | 4.53 | 6.66 |
| 01-29-10-29:10 | 2.17 | 7.75 | 11.74 | 0.00 | 23.04 | 42.18 | 0.00 | 0.00 | 0.00 | 3.09 | 7.13 |
| | Qtz | Plag | K-Spar | Cc | Dol | Clay | Pyr | Gyp | Anh | Hal | |
| MIN | 4.50 | 0.00 | 2.39 | 0.00 | 14.50 | 10.89 | 0.00 | 0.00 | 0.00 | 0.00 | |
| MAX | 20.88 | 7.75 | 11.74 | 6.95 | 78.75 | 42.18 | 7.21 | 5.78 | 9.72 | 12.71 | |
| AVG | 9.17 | 1.59 | 6.02 | 1.95 | 45.05 | 27.16 | 1.21 | 1.26 | 3.35 | 3.19 | |
| SD | 3.83 | 2.04 | 2.99 | 1.80 | 21.46 | 9.49 | 2.54 | 2.23 | 3.96 | 2.90 | |