A Preliminary Investigation of the Mineralogy of the Bakken Shales in Southern Saskatchewan

Ming Lei,[1] Hairuo Qing [1] and Ian M. Coulson [1]

Lei, M., Qing, H., and Coulson, I.M. (2014): A preliminary investigation of the mineralogy of the Bakken shales in southern Saskatchewan; *in* Summary of Investigations 2014, Volume 1, Saskatchewan Geological Survey, Sask. Ministry of the Economy, Misc. Rep. 2014-4.1, Paper A-5, 14p.

Abstract

Late Devonian and Early Mississippian Bakken shales are important source rocks for some of the oil accumulations in southern Saskatchewan. However, there is a significant lack of research into the mineralogy of the Bakken shales, which may prevent a comprehensive understanding of their quality as source rocks. This project investigates the mineralogy of the Bakken shales in southern Saskatchewan using results from electron probe X-ray microanalysis (EPMA) and X-ray diffraction analysis (XRD) of twenty-five selected samples from three wells in the northern part of the Williston Basin. The mineral assemblages identified in the Bakken shales are: a) a detrital assemblage that includes quartz and feldspar; b) a mixture of detrital and authigenic clays; and c) a mixture of detrital and authigenic carbonate minerals. Preliminary results indicate that the Bakken shales generally contain an abundance of quartz and feldspar, and variable amounts of carbonate minerals and clay minerals (mostly illite and chlorite). Detrital quartz and feldspar are inversely correlated with total organic carbon (TOC), while clay abundances are directly correlated with TOC. Of the three wells studied in this paper, the two wells at the margins of the Williston Basin are characterized by more abundant quartz and feldspar and lower TOC contents compared to the well closer to the basin centre.

Keywords: *Bakken shale, source rock, mineralogy, southern Saskatchewan, Williston Basin, Mississippian-Devonian.*

1. Introduction

The study area encompasses Ranges 31W1 to 4W3 and Townships 3 to 16 within southern Saskatchewan in the northern part of the Williston Basin (Figure 1). The Late Devonian-Early Mississippian Bakken Formation is present throughout the subsurface of the Williston Basin in southern Saskatchewan. It is conformably overlain by the Souris Valley (Lodgepole) Formation of Mississippian age, and unconformably overlies the Big Valley Formation (Figure 2) (Christopher, 1961; Smith and Bustin, 2000; Kohlruss and Stamatinos, 2014). The Big Valley Formation unconformably overlies the Torquay Formation, and is only present in a portion of southern Saskatchewan, as shown in Figure 1 (Christopher, 1961; Nickel, 2010). In areas where the Big Valley Formation is not present, the Torquay Formation unconformably underlies the Lower Bakken shale (Nickel, 2010). Together the Torquay, Big Valley and Bakken formations comprise the Three Forks Group (Christopher, 1961). The Bakken Formation ranges from zero to 30 m in thickness throughout the study area, with local anomalously thick sections (a result of discrete salt collapse features) reaching 70 m (Kreis *et al.*, 2006). The Bakken Formation is subdivided into three members (Figure 2): 1) the Lower Member is composed of black bituminous to carbonaceous shale; 2) the Middle Member consists of calcareous or dolomitic siltstone to sandstone; and 3) the Upper Member is composed of dark brown to black bituminous shale (LeFever *et al*., 1991; Smith and Bustin, 1995; Kreis *et al*., 2006). The Bakken Formation represents a petroleum system that can be tracked from source rock to trap within the same lithostratigraphic unit (Karasinski, 2006; Halabura *et al*., 2007). The black shales of the Upper and Lower Bakken members serve as source rocks, whereas the Middle Bakken Member contains tight reservoirs that have been a hot play in Saskatchewan, North Dakota, and Montana (Kreis *et al*., 2006; Pearson *et al*., 2013; Pollastro *et al*., 2013; U.S. Energy Information Administration, 2013; Yang, 2014). The quantity of oil produced from the Bakken Formation in Saskatchewan has increased from 760 barrels/day in 2004 to 66,000 barrels/day in 2013 (Yang, 2014). It is important to characterize such a formation from both the source rock and reservoir perspective, to guide exploration and production in the region.

[1] University of Regina, Department of Geology, 3737 Wascana Parkway, Regina, SK S4S 0A2.

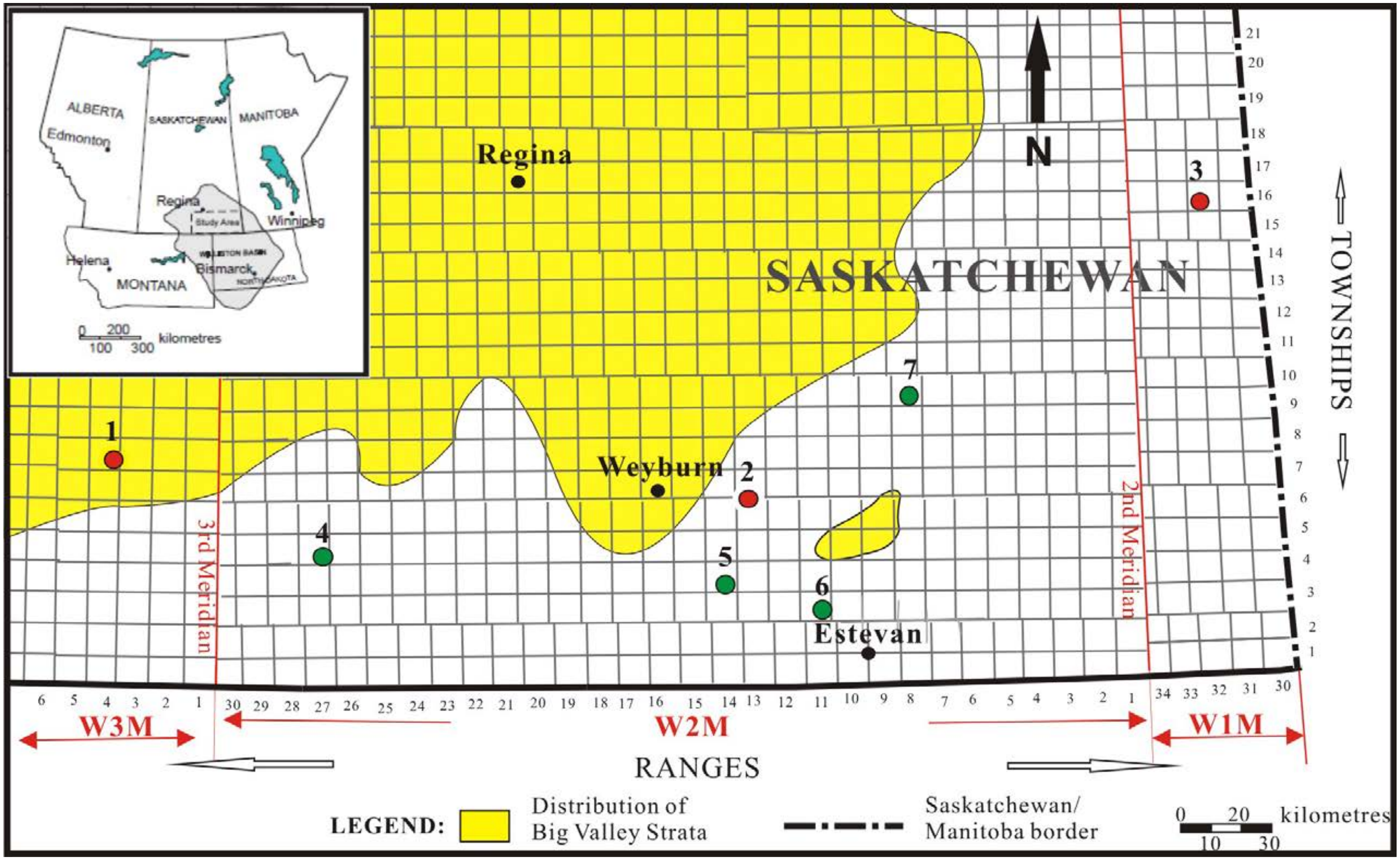

Figure 1 – Location of the study area relative to the province and to the Williston Basin (inset; outline of Williston Basin from Kohlruss and Nickel, 2009), and location of wells with core examined for this study (red dots): Well #1 (111/02-14-008-04W3/00; 51G001), Well #2 (101/06-09-007-13W2/00; 85A089), and Well #3 (101/05-04-016-31W1/00; 86H080). Green dots show the locations of the four wells that were selected for future study. The yellow-coloured area shows the subsurface distribution of Big Valley strata (Christopher, 1961; Nickel, 2010).

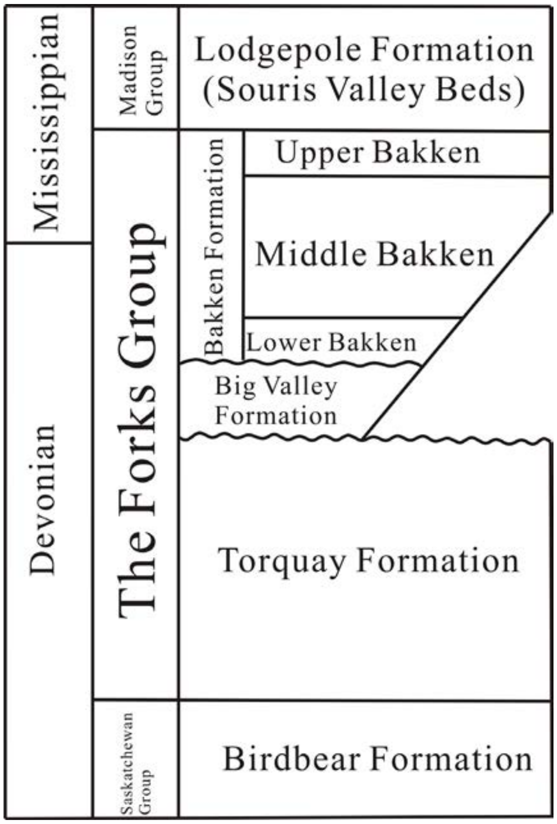

Figure 2 – Stratigraphic chart of Devonian/Mississippian units within the Bakken Formation in southern Saskatchewan, as well as the stratigraphy of overlying and underlying strata (modified from Kohlruss and Stamatinos, 2014).

The Bakken shales are effective source rocks in the Williston Basin petroleum system (Kreis *et al.*, 2006; Aderoju and Bend, 2012, 2014; Bend *et al*., 2013; Olajide and Bend, 2014). They are interpreted to be deposited in an offshore shelf environment, below storm wave base (Webster, 1984; LeFever *et al*., 1991; Pitman *et al*., 2001; Angulo and Buatois, 2012). The total organic carbon (TOC) content in the Upper and Lower Bakken members in North Dakota averages 11.3% (Webster, 1987; Sarg, 2012), but it has been demonstrated that there are considerable lateral and vertical variations in type and amount of organic matter (Aderoju and Bend, 2012, 2013, 2014; Wrolson and Bend, 2012, 2014; Bend *et al*., 2013). In contrast to the detailed studies of organic matter, there is a significant lack of understanding of the mineralogy of the Bakken shales and the effect of their mineralogy on the quality as source rocks. This project is designed to study the mineralogy of the Lower and Upper Bakken members across southern Saskatchewan in order to characterize spatial and temporal variations of the minerals, to relate them to their respective depositional environments, and to correlate these findings with matching samples from Wrolson and Bend (2012, 2014) and Aderoju and Bend (2014) to better understand the relationship of mineralogy to the nature and abundance of organic matter and how it relates to source effectiveness and heterogeneity of Bakken shales.

2. Methods

This study is based on examination of cores from three wells from across southern Saskatchewan. These cores were previously analyzed for organic geochemistry of both the Upper and Lower Bakken members (Wrolson and Bend, 2012, 2014; Bend *et al*., 2013; Aderoju and Bend, 2014). The three selected wells, from west to east (see Figure 1), are: Well #1 (111/02-14-008-04W3/00; 51G001), Well #2 (101/06-09-007-13W2/00; 85A089), and Well #3 (101/05-04-016-31W1/00; 86H080). Twenty-five core samples were collected from these three wells for detailed electron probe X-ray microanalysis (EPMA) and X-ray diffraction (XRD) analysis (Table 1) at intervals of around 50 cm. All 25 samples have corresponding total organic carbon (wt.% TOC) provided by Aderoju and Bend from Rock-Eval analysis (Wrolson and Bend, 2012; Aderoju and Bend, 2013, 2014).

Table 1 – Sample numbers, depths, and total organic carbon (TOC) contents for samples from the three wells included in this study. TOC values are from Wrolson and Bend (2012), and Aderoju and Bend (2013, 2014).

Well	Unit	Sample No.	Sample Depth (m)	TOC (wt.%)
#3: 101/05-04-016-31W1/00	Upper Bakken Member	1	682.4	6.69
		2	682.88	6.49
		3	683.37	8.83
		4	683.94	4.52
		5	684.76	13.4
	Lower Bakken Member	6	695.25	1.35
		7	695.68	1.75
#2: 101/06-09-007-13W2/00	Upper Bakken Member	8	1675.78	28.18
		9	1676.1	25.33
	Lower Bakken Member	10	1691.32	14.16
		11	1691.85	16.62
		12	1692.17	13.15
		13	1692.78	10.75
#1: 111/02-14-008-04W3/00	Upper Bakken Member	14	1685.63	6.96
		15	1686.47	6.23
		16	1687.02	5.42
	Lower Bakken Member	17	1697.62	6.81
		18	1698.12	4.41
		19	1698.45	3.9
		20	1699.06	3.33
		21	1699.38	3.35
		22	1699.86	3.18
		23	1700.16	4.04
		24	1700.81	3.67
		25	1701.16	5.57

Semi-quantitative XRD analysis is an effective method to study the mineral composition and content of shales (*e.g.*, Schieber and Zimmerle, 1998). Rock chips, roughly 2 grams in weight, from each core sample were ground into powder and mounted onto a glass slide for the XRD bulk powder analysis. XRD spectra were obtained by scanning in the 2-theta range of 6 to 80 degrees. The collected XRD spectral patterns were compared with synthetic diffraction patterns, generated using PANalytical's HighScore Plus software, and weight fractions of minerals were calculated. XRD methods provide a complete picture of the phase composition of the whole rock. Rock sample chips from another portion of each sample were mounted and polished for probe imaging and analyses. The electron microprobe is equipped with backscattered electron (BSE) detector and energy dispersive spectrometry (EDS) systems. The EDS was used to analyze the energy spectrum of emitted X-ray radiation in order to determine the abundance of specific elements in response to electron induced excitation. This method of analysis provides a rapid means of determining the chemical composition of phases present within the samples, as an aid to mineral identification. The combination of EDS compositional data with BSE imagery enabled mineral modes to be determined for every sample, as the BSE images are based on the average atomic number of the minerals' constituent elements. Each mineral phase has a unique relative grey level, allowing its area to be calculated and correlated with its abundance in the sample. These methods of modal mineral analysis can determine mineral proportions of less than 0.5% (Pye *et al.*, 2005).

Precise identification of clay minerals using XRD is complex, due to similarities in structural properties between muscovite, hydromuscovite, glauconite, and biotite. Reliable identification can only be achieved by a combination of chemical, XRD and differential thermal analyses (Smith, M.G., 1996; Smith, F., 1999; Adamis and Williams, 2005; Jackson and Murphy, 2011). Therefore, phyllosilicates such as micas and clay minerals are grouped together and reported as clay minerals in this study, although mica occurs only as a very small fraction (less than 10%) based on visual estimation from thin section and EPMA.

3. Results

Three mineral assemblages are identified in the Bakken Shale members: a) a detrital assemblage that includes quartz and feldspar; b) a mixture of detrital and authigenic assemblages of clays; and c) a mixture of detrital and authigenic assemblages of carbonate minerals. In addition, pyrite, apatite, and rutile are identified as minor components.

a) Electron Probe X-ray Microanalysis (EPMA) Backscattered Electron (BSE) Images

BSE images indicate that Bakken shales are dominated by very fine-grained (<3.9 µm) particles, within a groundmass of variable amounts of silt (Figures 3 and 4). Minor amounts of pyrite occur as bright white euhedral crystals, and as framboids filling pore spaces and replacing organic matter and other minerals (Figures 3 and 4). Organic matter occurs in bedding-parallel laminae (Figure 3) or fills pore spaces (Figure 4). Conodonts are present locally as tooth-like-shaped crystals of the mineral apatite (Figure 4); conodonts previously reported in the Bakken shales have been interpreted as Late Devonian and Early Mississippian in age (Christopher, 1961; Hayes, 1985; Karma, 1991).

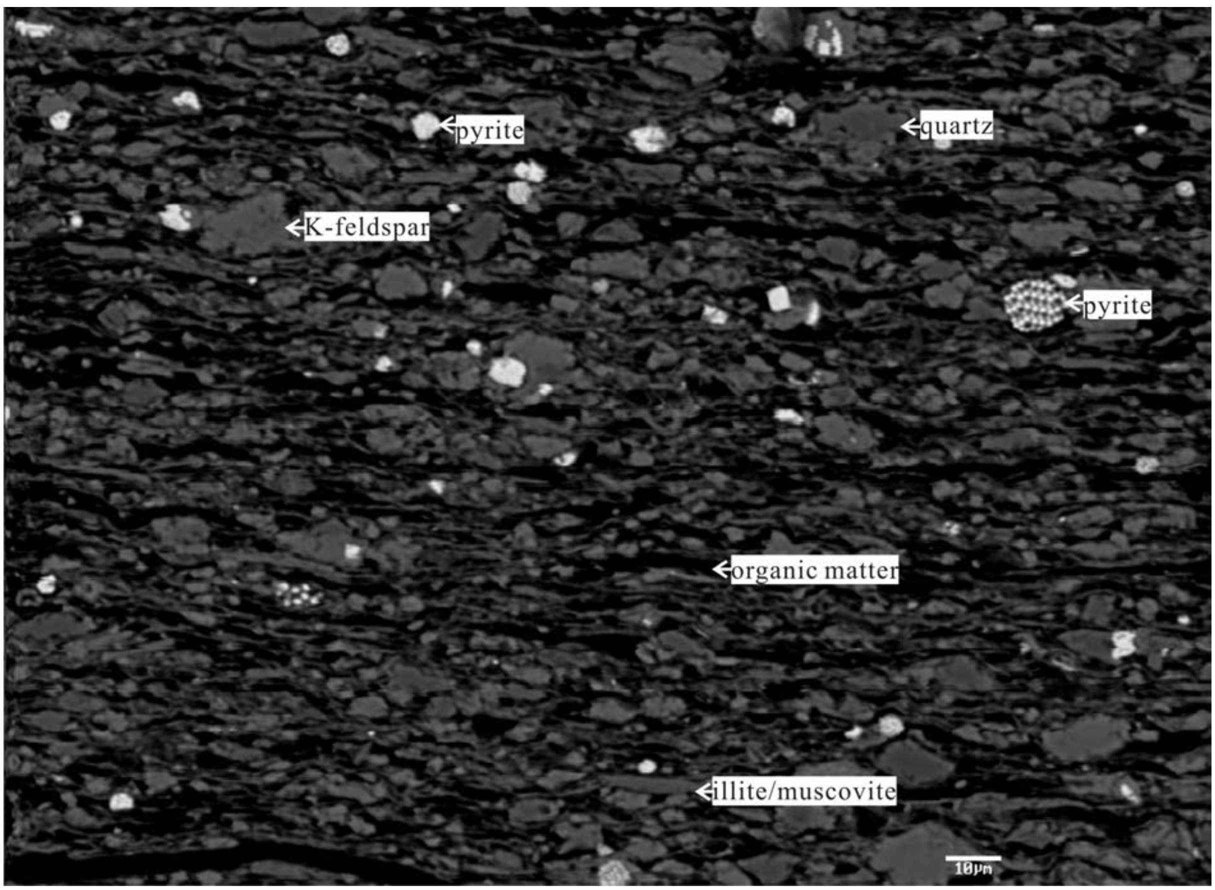

Figure 3 – EPMA backscattered electron (BSE) image of very fine-grained Lower Bakken shale from Well #1 (111/02-14-008-04W3/00; 51G001) at a depth of 1697.62 m (sample #17). Bright white features are euhedral and framboidal pyrite. Organic matter (black interstitial material) is present in bedding-parallel laminae.

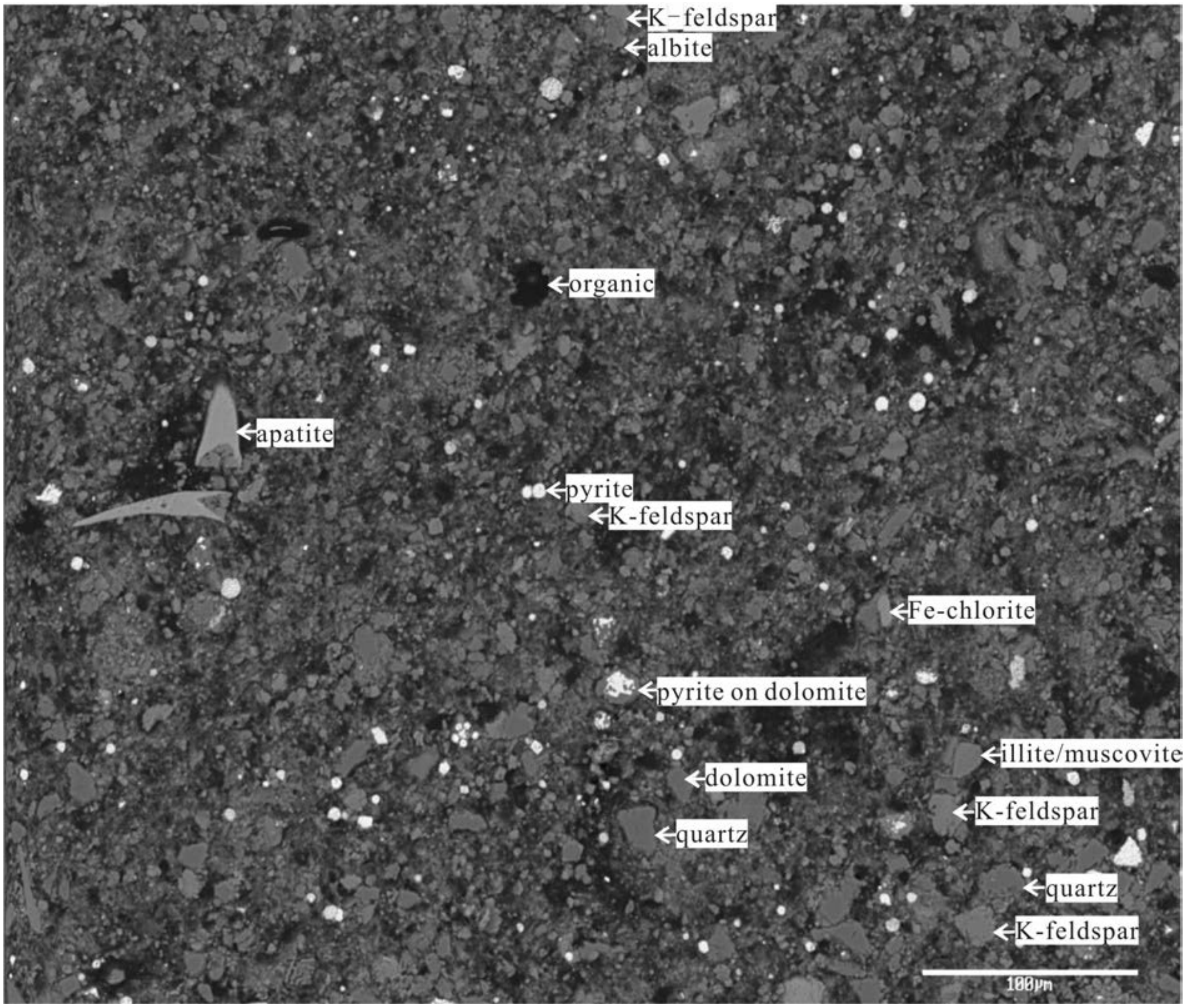

Figure 4 – EPMA backscattered electron (BSE) image of very fine-grained Upper Bakken shale from Well #3 (101/05-04-016-31W1/00; 86H080) at a depth of 683.37 m (sample #3). Bright white features are euhedral and framboidal pyrite. Organic matter fills the pore spaces. The tooth-like-shaped structures composed of apatite are conodonts.

b) Mineralogical Variation in the Well Cores Examined

The preliminary XRD results (Figure 5) indicate the Bakken shales contain a variable amount of clay and carbonate minerals and a high abundance of quartz and feldspar. Clay mineral content ranges from 5% to 62%, the quartz abundance ranges from 5% to 37%, the amount of feldspar varies from 10% to 42%, and the carbonate content ranges from 2% to 42% (Figure 5). This illustrates the basin-wide heterogeneity of the Bakken shales. Figure 5 also illustrates the variability of the mineral composition of the Upper Bakken Member relative to the Lower Bakken Member.

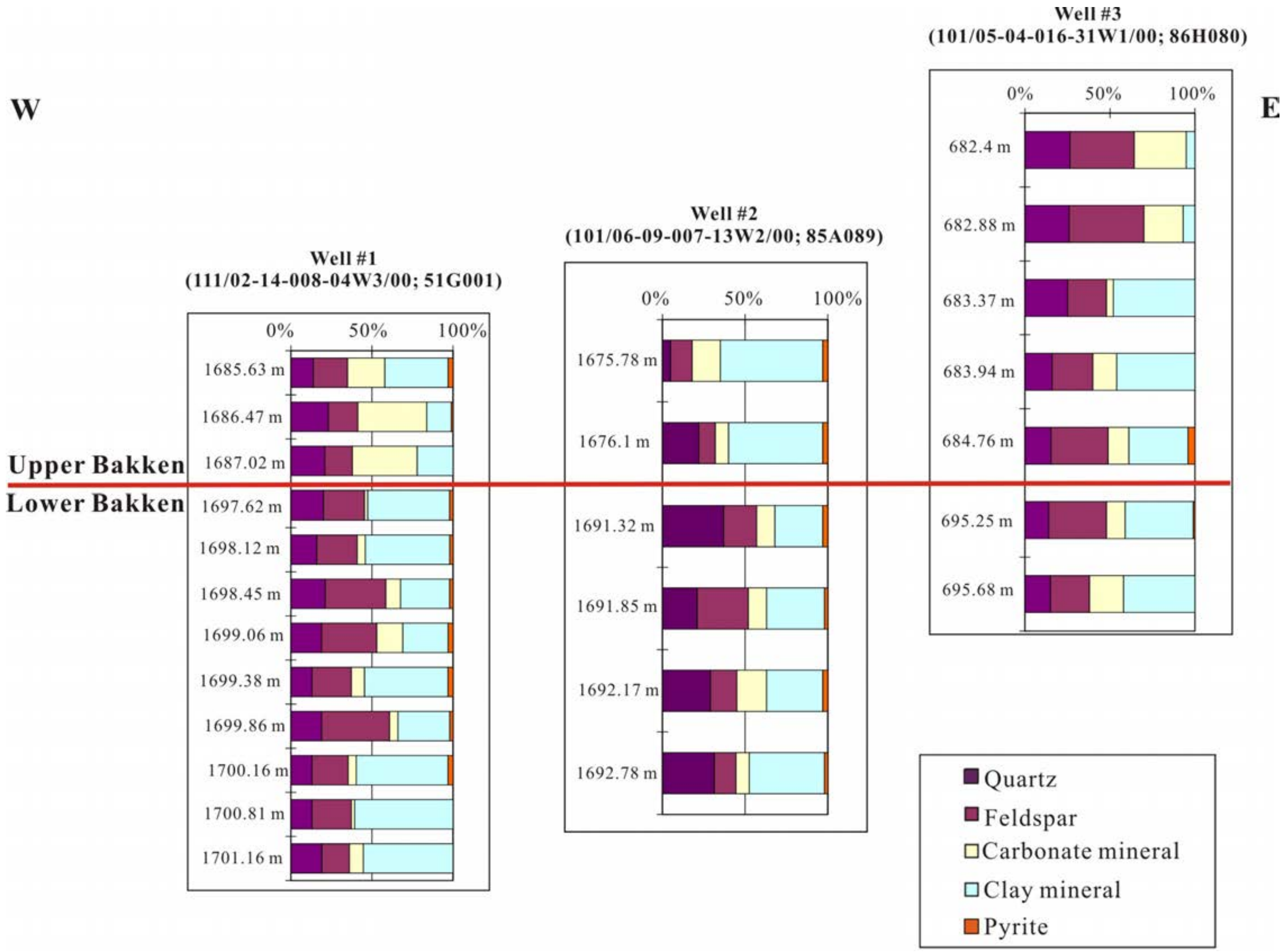

Figure 5 – Mineral content of Bakken shales from three wells (based on XRD analysis). Each bar represents an individual sample at the indicated depth analyzed for that well. The colour division within the bars represents different types of minerals. The red line divides samples from the Upper Bakken vs. samples from the Lower Bakken.

c) Variation in Mineralogy with Depth

Clay Minerals

The content of clay minerals from Bakken shales varies from 5% to 62%, with an average abundance of 39% (Figure 6). The Upper Member contains an average of 25%, 59%, and 28% clay minerals in wells 1, 2 and 3, respectively. Clay mineral content in the Lower Member averages 45% in Well #1, 36% in Well #2, and 41% in Well #3. In the Upper Bakken shale, there is a much higher abundance of clay minerals in Well #2 (59%; Figure 6). There is a slightly lower amount of clay minerals (36%) in the Lower Bakken shale in Well #2, which is in the central part of the Williston Basin, compared to that in the wells on the basin margins (45% in Well #1, and 41% in Well #3; Figure 6). The percentage of clay minerals also increases with increasing depth in the Lower Bakken member of Well #2 (Figure 6).

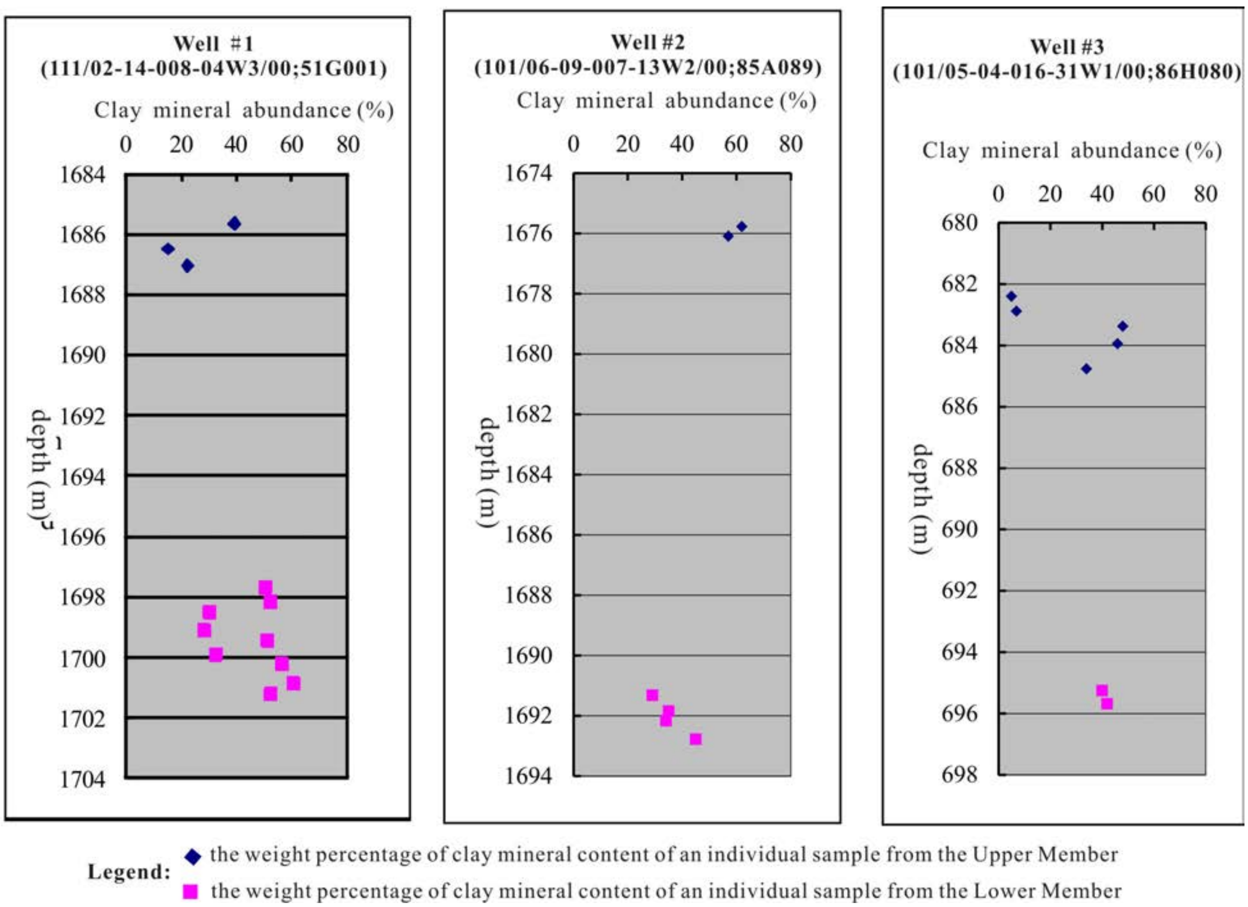

Figure 6 – Variations in clay mineral abundance with depth. Each point represents a weight percentage of clay mineral content of an individual sample at a certain depth in a well. Stratigraphic distribution of clay minerals from the Upper Member samples are marked in blue, and the Lower Member samples are in pink.

Quartz and Feldspar

The detrital quartz and feldspar content in the three wells studied varies from 18% to 70%, averaging 45% (Figure 7). In the Upper Member, there is a much lower amount of detrital quartz and feldspar (25%) in Well #2, which is in the central part of the Williston Basin, compared to that in the wells at the basin margins (38% in Well #1, and 54% in Well #3; Figure 7). The Lower Member contains an average of 45% of these minerals in Well #1, 50% in Well #2, and 43% in Well #3. The amount of quartz and feldspar also decreases with increasing depth in the Lower Member at Well #2 (Figure 7).

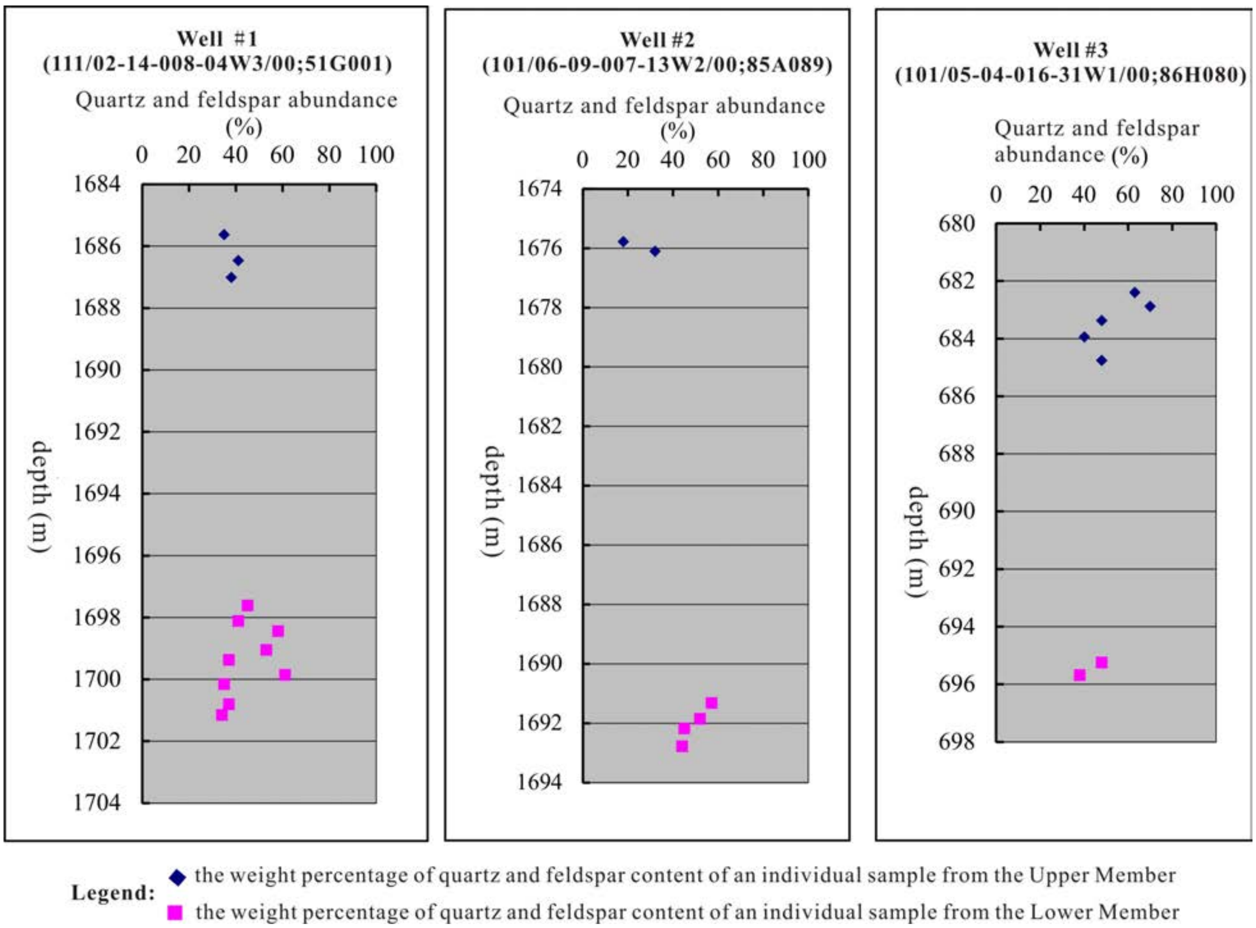

Figure 7 – Variations in detrital quartz and feldspar abundance with depth. Each point represents a weight percentage of these two minerals in an individual sample at a certain depth in a well. Stratigraphic distribution of quartz and feldspar from the Upper Member samples are marked in blue, and the Lower Member samples are in pink.

Carbonate Minerals (Calcite and Dolomite)

The percentage of carbonate minerals by weight ranges from 2% to 42%, averaging 14% (Figure 8). The Upper Member has an average of 35% carbonate minerals in Well #1, 12% in Well #2, and 16% in Well #3. The carbonate mineral content in the Lower Member averages 7%, 12%, and 16% in wells 1, 2 and 3, respectively. The carbonate mineral content decreases with increasing depth in the Upper Member of Well #3 (Figure 8), whereas it increases with increasing depth in the Upper Member of Well #1 (Figure 8).

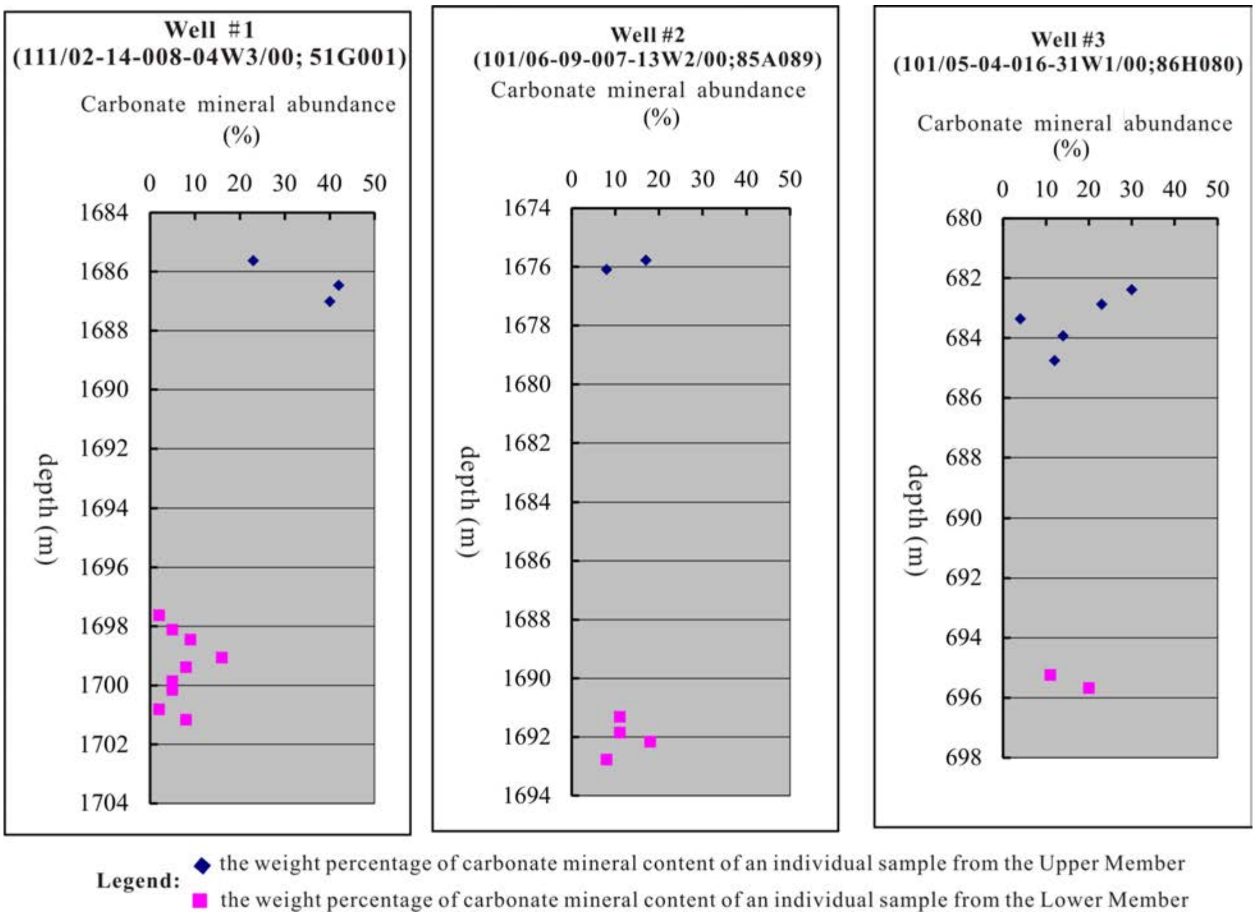

Figure 8 – Variations in carbonate mineral abundance with depth. Each point represents a weight percentage of carbonate minerals (calcite and dolomite) in an individual sample at a certain depth in a well. Stratigraphic distribution of carbonate minerals from the Upper Member samples are marked in blue, and the Lower Member samples are in pink.

d) Mineral Abundance vs. Total Organic Carbon Content (TOC)

Quartz and Feldspar Abundance vs. TOC

Figure 9 illustrates the quartz and feldspar content relative to the total organic carbon (TOC) content of the three wells studied. Well #1 and Well #3 have lower TOC contents and higher quartz and feldspar content compared to Well #2. A correlation line between the detrital mineral content and TOC was drawn based on all data. This correlation line shows that there is a generally negative relationship between the detrital minerals and TOC, with the correlation line having a slope of about -0.2. However, a relatively low value of R^2 (0.1069) indicates a poor correlation. This is likely a result of the limited data available.

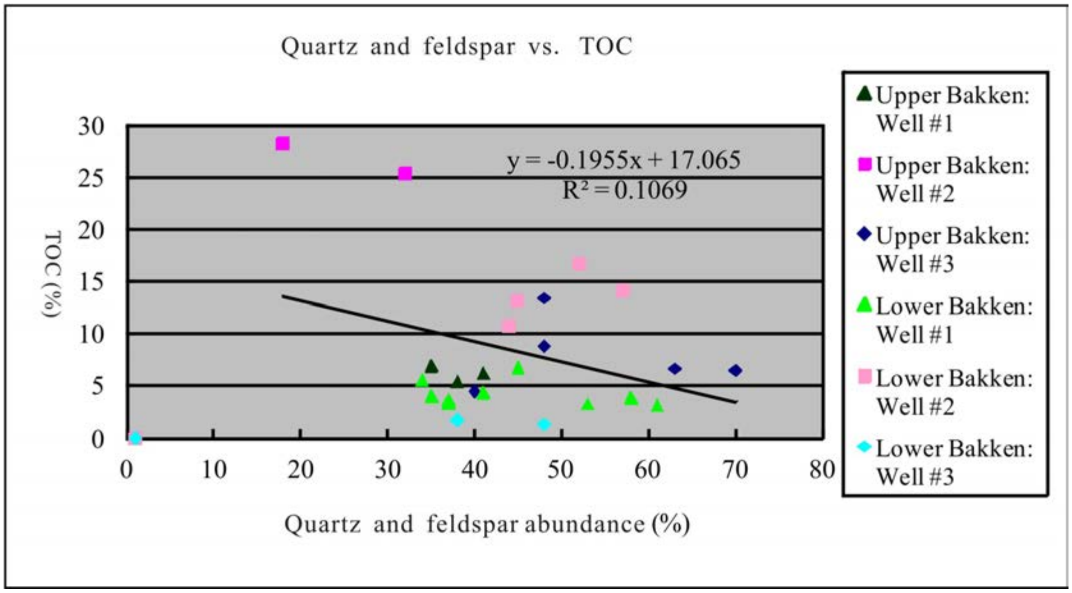

***Figure 9** – Detrital mineral (quartz and feldspar) content vs. total organic carbon (TOC) content. Each point represents a weighted percentage of quartz and feldspar content (x axis) and total organic carbon content (y axis) of an individual sample.*

Clay Mineral Abundance vs. TOC

Figure 10 illustrates the content of clay minerals relative to the TOC content of the three wells studied. Generally, the TOC content of the Upper Bakken Member is higher than that of the Lower Member. The Upper Member samples from Well #2 have the highest average TOC, with corresponding very high clay mineral contents (Figure 10). The TOC content in the Upper Member in wells #1 and #3 is lower than that of Well #2. Both these wells also have lower clay mineral contents compared to that of Well #2 (Figure 10). Among the samples analyzed from the Lower Member, samples from Well #2 have a higher TOC content than do samples from the other two wells, with a clay mineral content ranging from 29% to 45% in Well #2 (Figure 10).

The correlation between TOC and clay mineral content varies within the different wells (Figure 10). The Upper Member in Well #2 (which lies closer to the central part of the Williston Basin) has higher amounts of clay minerals with corresponding higher TOC contents than wells #1 and #3 (the two wells near the basin margins; Figure 10). In the study area, our samples from the three wells studied display a generally direct correlation between clay mineral content and TOC contents, with a correlation line drawn between all data points having a slope of 0.1 (Figure 10). However, a very low R^2 value (0.0545) indicates a poor correlation between the clay mineral content and TOC content, which may be due to the limited number of samples collected in this study, and local heterogeneity in the individual wells.

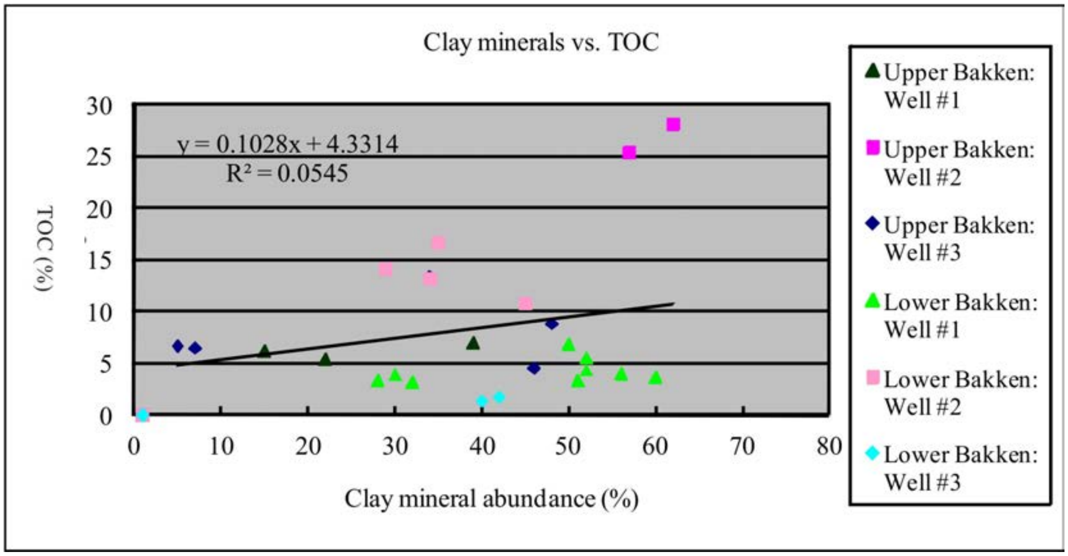

Figure 10 – Clay mineral content vs. total organic carbon (TOC) content. Each point represents a weighted percentage of clay mineral content (x axis) and total organic carbon content (y axis) of an individual sample.

4. Summary

The mineral assemblages identified in the Bakken shales in this study are: a) a detrital assemblage that includes quartz and feldspar; b) a mixture of detrital and authigenic assemblages of clays; and c) a mixture of detrital and authigenic assemblages of carbonate minerals. The Bakken shales generally contain a high abundance of quartz and feldspar, and variable amounts of carbonate and clay minerals (mostly illite and chlorite).

The preliminary data from the three wells analyzed indicate the mineralogical composition of shales in both the Upper and Lower Bakken members varies with depth and with location within the Williston Basin. Wells #1 and #3, which lie near the western and eastern margins of the basin, respectively, generally have a higher content of detrital quartz and feldspar and lower TOC content than the shales from Well #2, which lies closer to the basin centre. The data also indicate that the abundances of detrital quartz and feldspar are inversely correlated to TOC content, while clay mineral abundances are directly correlated to TOC content. However, the correlations of TOC content with clay mineral abundances show a very low linearity, which may be related to local heterogeneity and limited sampling. Such relationships will be further investigated by analyzing more samples from these three wells, and samples from four additional wells from different parts of the basin (see Figure 1) in order to accurately document the mineralogy of the Bakken shales and the correlation of this mineralogy with TOC in typical source rocks.

5. References

Adamis, Z. and Williams, R.B. (2005): Bentonite, Kaolin, and Selected Clay Minerals; Environmental Health Criteria 231, World Health Organization, Geneva, 196p.

Aderoju, T.E. and Bend, S.L. (2012): The Bakken Formation of Saskatchewan: a high resolution geochemical evaluation; GeoConvention 2012: Vision, May 14 to 18, 2012, Calgary, Alberta, poster abstract, 2p.

Aderoju, T.E. and Bend, S.L. (2013): Rock-Eval evaluation of the Bakken Formation in southern Saskatchewan; *in* Summary of Investigations 2013, Volume 1, Saskatchewan Geological Survey, Sask. Ministry of the Economy, Misc. Rep. 2013-4.1, Paper A-2, 14p.

Aderoju, T.E. and Bend, S.L. (2014): Organic matter variations within the Upper and Lower Bakken shales of Saskatchewan, with implications for origin and hydrocarbon generation; GeoConvention 2014: FOCUS, May 12 to 16, 2014, Calgary, Alberta, abstract, 5p.

Angulo, S. and Buatois, L. (2012): Integrating depositional models, ichnology, and sequence stratigraphy in reservoir characterization: the middle member of the Devonian–Carboniferous Bakken Formation of subsurface southeastern Saskatchewan revisited; AAPG Bulletin, v96, p1017-1043.

Bend, S.L., Aderoju, T.E., Olajide, O., Wrolson, B., and Yurkowski, M. (2013): New light through old windows: a geochemical and petrographic review of the Upper and Lower Bakken, southern Saskatchewan; 21st Williston Basin Petroleum Conference, April 30 to May 2, 2013, Regina, Saskatchewan, abstract.

Christopher, J.E. (1961): Transitional Devonian-Mississippian Formations of Southern Saskatchewan; Sask. Dept. Miner. Resour., Rep. 66, 103p.

Halabura, S., Buatois, L., Angulo, S., and Piché, L. (2007): From source to trap: a review of the Bakken petroleum system, Upper Devonian-Mississippian, southeastern Saskatchewan; *in* Summary of Investigations 2007, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2007-4.1, Paper A-4, 8p.

Hayes, M.D. (1985): Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota; Mountain Geologist, Rky. Mtn. Assoc. Geol., v22, p64-77.

Jackson, R. and Murphy, S. (2011): Mineralogical and Lithogeochemical Analyses of DGR-5 and DGR-6 Core; Technical Report TR-09-06, Geofirma Engineering Project 08-200 (11 April 2011).

Karasinski, D.R. (2006): Sedimentology and hydrocarbon potential of the Devonian Three Forks and Mississippian Bakken Formations, Sinclair area, southeast Saskatchewan - southwest Manitoba; unpubl. M.Sc thesis, Dept. of Geological Sciences, University of Manitoba, Winnipeg, 398p.

Karma, R. (1991): Conodonts of the Bakken Formation (Devonian-Mississippian) in Saskatchewan, northern Williston Basin; *in* Christopher, J.E. and Haidl, F. (eds.), Sixth International Williston Basin Symposium, Sask. Geol. Soc., Spec. Publ. No. 11, p70-73.

Kohlruss, D. and Nickel, E. (2009): Facies analysis of the Upper Devonian-Lower Mississippian Bakken Formation, southeastern Saskatchewan; *in* Summary of Investigations 2009, Volume 1, Saskatchewan Geological Survey, Sask. Energy and Mines, Misc. Rep. 2009-4.1, Paper A-6, 11p.

Kohlruss, D. and Stamatinos, K. (2014): Preliminary bulk density mapping of the Upper and Lower Bakken Member shales of southeastern Saskatchewan: a potential indicator for oil generation and expulsion; *in* Summary of Investigations 2014, Volume 1, Saskatchewan Geological Survey, Sask. Ministry of the Economy, Misc. Rep. 2014-4.1, Paper A-2, 7p.

Kreis, L.K., Costa, A.L., and Osadetz, K.G. (2006): Hydrocarbon potential of Bakken and Torquay formations, southeastern Saskatchewan; *in* Gilboy, C.F. and Whittaker, S.G. (eds.), Saskatchewan and Northern Plains Oil & Gas Symposium 2006, Saskatchewan Geological Society, Spec. Publ. No. 19, p118-137.

LeFever, J.A., Martiniuk, C.D., Dancsok, E.F.R., and Mahnic, P.A. (1991): Petroleum potential of the middle member, Bakken Formation, Williston Basin; *in* Christopher, J.E. and Haidl, F. (eds.), Sixth International Williston Basin Symposium, Saskatchewan Geological Society, Spec. Publ. No. 11, p74-95.

Nickel, E. (2010): A review of Three Forks Group stratigraphy in southeastern Saskatchewan; *in* Summary of Investigations 2010, Volume 1, Saskatchewan Geological Survey, Sask. Ministry of Energy and Resources, Misc. Rep. 2010-4.1, Paper A-5, 6p.

Olajide, O. and Bend, S.L. (2014): Paleozoic petroleum systems of the northern Williston Basin: a quantitative basin modeling assessment; GeoConvention 2014: FOCUS, May 12 to 16, 2014, Calgary, Alberta, abstract, 13p.

Pearson, C.M., Griffin, L., Wright, C.A., and Weijers, L. (2013): Breaking up is hard to do: creating hydraulic fracture complexity in the Bakken Central Basin; SPE (Society of Petroleum Engineers) Hydraulic Fracturing Technology Conference, February 4 to 6, 2013, The Woodlands, Texas, abstract, 15p.

Pitman, J.K., Price, L.C., and LeFever, J.A. (2001): Diagenesis and fracture development in the Bakken Formation, Williston Basin: implications for reservoir quality in the Middle Member; U.S. Geological Survey, Professional Paper 1653, 17p.

Pollastro, R.M., Roberts, L.N.R., and Cook, T.A. (2013): Geologic assessment of technically recoverable oil in the Devonian and Mississippian Bakken Formation; Chapter 5 *in* U.S. Geological Survey Williston Basin Province Assessment Team, Assessment of Undiscovered Oil and Gas Resources of the Williston Basin Province of North Dakota, Montana, and South Dakota, 2010 (ver. 1.1, November 2013), U.S. Geological Survey, Digital Data Series DDS–69–W, 34p.

Pye, K., Broggs Jr, S., and Tovey, N.K. (2005): Backscattered Scanning Electron Microscopy and Image Analysis of Sediments and Sedimentary Rocks; Cambridge University Press, 191p.

Sarg, J.F. (2012): The Bakken – An Unconventional Petroleum and Reservoir System; Project DE-NT0005672, National Energy Technology Laboratory (March 2012).

Schieber, J. and Zimmerle, W. (1998): Petrography of shales: a survey of techniques; *in* Scheiber, J. (ed.), Shales and Mudstones, Petrography, Petrophysics, Geochemistry, and Economic Geology, Volume 2, p3-12.

Smith, F. (ed.) (1999): Industrial Applications of X-ray Diffraction; CRC Press, 993p.

Smith, M.G. (1996): The Bakken Formation (Late Devonian-Early Mississippian): a black shale source rock in the Williston Basin; unpubl. Ph.D. thesis, the University of British Columbia, Vancouver, Canada, 785p.

Smith, M.G. and Bustin, R.M. (1995): Sedimentology of the Late Devonian and Early Mississippian Bakken Formation, Williston Basin; *in* Hunter, L.D.V. and Schalla, R.A. (eds.), 7th International Williston Basin Syposium, Montana Geol. Soc., Spec. Pub., p103-114.

Smith, M.G. and Bustin, R.M. (2000): Late Devonian and Early Mississippian Bakken and Exshaw black shale source rocks, Western Canada Sedimentary Basin: a sequence stratigraphic interpretation; AAPG Bulletin, v84, p940-960.

U.S. Energy Information Administration (2013): Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries outside the United States; U.S. Department of Energy, Washington, June 13, 2013, pI-46-I-49.

Webster, R.L. (1984): Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota; *in* Woodward, J., Meissner, F.F., and Clayton, J.C. (eds.), Hydrocarbon Source Rocks of the Greater Rocky Mountain Region, Rocky Mountain Association of Geologists, Denver, Colorado, p57-81.

Webster, R.L. (1987): Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota; *in* Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., and Longman, M.W. (eds.), Williston Basin: Anatomy of a Cratonic Oil Province, Rocky Mountain Association of Geologists, Denver, Colorado, p269-286.

Wrolson, B.M. and Bend, S.L. (2012): High resolution organic facies of the Bakken Formation, Williston Basin, Saskatchewan, Canada; GeoConvention 2012: Vision, May 14 to 18, 2012, Calgary, Alberta, poster abstract, 5p.

Wrolson, B.M. and Bend, S.L. (2014): Maceral variations and maceral assemblages within the Upper and Lower members of the Bakken Formation, Williston Basin, Saskatchewan, Canada; GeoConvention 2014: FOCUS, May 12 to 16, 2014, Calgary, Alberta, abstract, 6p.

Yang, C. (2014): Hydrocarbon play ranking and production trends in Saskatchewan to Year End 2013; Sask. Ministry of the Economy, Sask. Geological Survey, poster.