

Preliminary Bulk Density Mapping of the Upper and Lower Bakken Member Shales of Southeastern Saskatchewan: A Potential Indicator for Oil Generation and Expulsion

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Abstract

The use of bulk density coupled with formation resistivity of shale source rocks is a possible method of identifying the level of maturity of the rocks, and their potential for oil generation and oil expulsion.

The Late Devonian to Early Mississippian Bakken Formation shales of the Williston Basin are extremely rich source rocks and in some areas of the basin have been responsible for generating and expelling vast amounts of oil. Migration of this oil into suitable stratigraphic traps has resulted in unprecedented economic gain in parts of Saskatchewan, Manitoba, North Dakota and Montana.

Studies of the Bakken Formation in central Williston Basin in North Dakota have identified areas where its shales are, without question, thermally mature and have generated and expelled oil. However, Bakken Formation shales in northeastern Williston Basin in Saskatchewan have been examined and reported as being thermally immature, with no evidence of oil generation or expulsion.

This paper will illustrate how mapping bulk density and formation resistivity has identified anomalous areas in southeast Saskatchewan where Bakken Formation shale source rocks may indeed be thermally mature and may indeed have expelled oil, contrary to previous studies' findings.

Keywords: Bakken Formation, source rocks, tight oil, bulk density, formation resistivity, Late Devonian, Early Mississippian, southeast Saskatchewan.

1. Introduction

Southeastern Saskatchewan's tight oil (low permeability) Bakken oil play has become an astonishing success story. Favourable economic conditions have enabled the use of horizontal wells combined with multistage fracturing to liberate oil from the Bakken's extremely low permeability (<1 millidarcy (mD)) reservoir rocks in the Viewfield, Ryerson and Roche Percee oil pools (Figure 1).

As of November 30, 2014 there were 2591 producing Bakken Formation oil wells in southeast Saskatchewan. Since 1956, Bakken wells have cumulatively produced 25.8 million cubic metres (m³) of oil at a current rate of 9754 m³/day. The majority of this production has occurred since 2005 and has been from the Viewfield oil pool.

An emerging Bakken Formation and Torquay Formation (Bakken-sourced oil) oil play along the Saskatchewan–North Dakota–Montana border (Figure 1) has been of interest recently because it offers new opportunities for oil production from the Bakken. This emerging oil play is likely an extension of the Bakken shale oil play in North Dakota, in central Williston Basin, which is reliant on close vertical proximity of thermally mature Bakken shale source rocks and juxtaposed reservoir rocks, including Middle Bakken siltstones and sandstones as well as the Torquay's silty dolostones. The location of the new production in Saskatchewan supports a theory that mature Bakken source rocks may extend farther north than previously thought.

The purpose of this paper is to use non-standard techniques of bulk density and formation resistivity mapping to strengthen the theory that primary migration of oil from Upper and Lower Bakken shales into Middle Bakken siltstones and sandstones and Torquay Formation silty dolostones has occurred north of the Canada–US international border.

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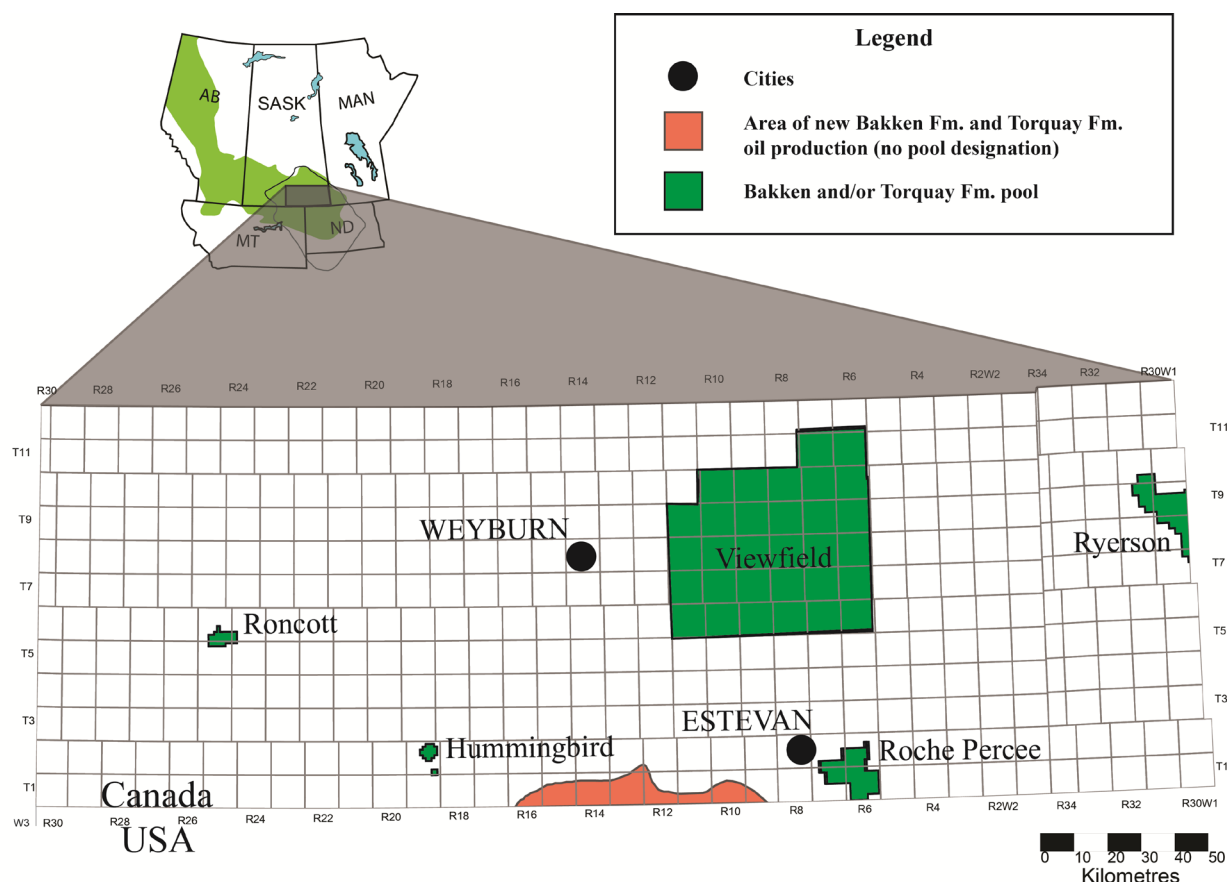


Figure 1 – General location of the study area. The green polygons represent existing Bakken shale oil pools, while the region in red represents new Bakken Formation and Torquay Formation tight oil production along the Canada–US international border. Oil produced from the Torquay Formation is Bakken-sourced oil. Inset shows study area in the context of the location of the Williston Basin (thin black outline) and the Bakken Formation (Exshaw Formation in Alberta; area coloured in green). Abbreviations on inset: AB = Alberta, SASK = Saskatchewan, MAN = Manitoba, MT = Montana, ND = North Dakota.

2. Study Area

The study area is bounded to the east by the Saskatchewan–Manitoba border, to the south by the Saskatchewan–US (North Dakota and Montana) international border, to the west by the Third Meridian (W3) and to the north by the northern boundary of Township 12 (Figure 1). The study area includes all Saskatchewan’s tight oil Bakken production. For the purposes of this paper, tight oil is defined as reservoirs with low permeability (<1 mD) that require horizontal drilling and multistage fracturing to stimulate production.

3. General Stratigraphy

The Three Forks Group Bakken Formation is comprised of siltstone and sandstone (Middle Bakken Member) between upper and lower black, organic-rich shales (Upper and Lower Bakken members; Figure 2). The Bakken Formation overlies argillaceous siltstones and silty dolostones of the Devonian Torquay and Big Valley formations. Where present, the underlying Big Valley Formation is unconformable with the Lower Bakken Member shale (Christopher, 1961). Where the Torquay underlies the Bakken, the contact at the base of the Lower Bakken is relatively sharp and also unconformable. In the eastern portion of the study area (approximately Ranges 30 to 33W1M), the Lower Bakken and lowermost portion of the Middle Bakken are absent and the Middle Bakken is in sharp contact with Torquay Formation silty dolostones (Nickel, 2010).

The Bakken Formation is overlain by organic-rich fossiliferous limestones of the Souris Valley Beds (Lodgepole Formation) of the Madison Group, which conformably overlie the Upper Bakken Member shale (Christopher, 1961).

Period	Group	Formation	
Mississippian	Madison Group	Lodgepole Formation (Souris Valley Beds)	
		Three Forks Group	Bakken Formation
	Middle Bakken		
	Lower Bakken		
	Big Valley Formation		
	Torquay Formation		
Devonian			
	Saskatchewan Group	Birdbear Formation	

Figure 2 – Stratigraphic chart of the Devonian–Mississippian units within the Saskatchewan, Three Forks and Madison groups in southeast Saskatchewan (modified from Nickel, 2010).

4. Source Rock, Thermal Maturity and Primary versus Secondary Oil Migration in the Bakken Formation of Saskatchewan

Oil in Saskatchewan’s Viewfield pool has been sourced from the Upper and Lower Bakken shales. The oil is not locally sourced, however (*i.e.*, not primary), but has migrated up-dip from central Williston Basin in North Dakota, where the shales are known to be thermally mature and the majority of oil pools are a result of primary oil migration. The oil travelled northward into Saskatchewan and was stratigraphically trapped where the Middle Bakken Member reservoir rocks pinch out.

The Bakken Upper and Lower shale members in Canada are comprised of highly organic, black, carbonaceous and pyritic shales with total organic carbon (TOC) contents averaging slightly less than 12% in the Lower Member and nearly 18% in the Upper Member (Kreis *et al.*, 2006). Although areas in North Dakota have been identified as having thermally mature source rocks, it has been reported that the Upper and Lower Bakken Member shales are not thermally mature anywhere in Canada (Osadetz *et al.*, 1992; Osadetz and Snowdon, 1995). The indicators of thermal maturity— $T_{\max}$ and hydrogen index—reported for the Bakken shale in Saskatchewan have been found to be too low and too high, respectively, suggesting that Bakken shales in Saskatchewan have not generated or expelled oil.

Drilling and production from the Bakken and Torquay formations along the Saskatchewan–US international border suggests otherwise, and perhaps unorthodox oil exploration techniques such as using shale resistivity and/or shale bulk density mapping could reveal possible thermal maturity in these rocks.

a) Shale Resistivity and Oil Generation

Several authors (*e.g.*, Meissner, 1978; Schmoker and Hester, 1990; Kreis *et al.*, 2006) have linked an increase in shale resistivity to either migrated (secondary) or generated (primary) oil within the Bakken Formation. In particular, the research undertaken by Schmoker and Hester (1990) found that resistivity values greater than 35 ohm-m in US Bakken shales correspond with the commencement of oil generation.

b) Shale Bulk Density and Oil Maturity

According to Jarvie *et al.* (2011) immature Bakken shales, like those found in Saskatchewan, are partially kerogen-supported, based on their high TOC, and subsequently have very low bulk density (< 2.00 to 2.10 grams per cubic centimetre (g/cc)). They state that, as the kerogen in the shale matures (that is, as increased burial depth results in increased temperature and pressure), it becomes pliable and loses strength. This will cause the kerogen to begin to convert to bitumen and oil. The development of pressure from this process can induce microfractures, and oil is expelled from the thermally weakened kerogen through these fractures. Eventually the kerogen compacts, resulting in

an increase in the shale's bulk density and an increase in oil content as the source rocks become progressively more mature.

Jarvie *et al.*'s (2011) work illustrates that low-thermal-maturity kerogen in Bakken shales that has not changed to bitumen or oil has double the volume of organic carbon for an equal mass. They noted the bulk density of immature Bakken shales could be as low as 2.00 g/cc. In the shales where kerogen has changed to bitumen and oil, the pore spaces have collapsed, leading to higher bulk densities.

In addition, the work by Jarvie *et al.* (2011) showed that Bakken shales with higher thermal maturities were thinner and their bulk densities had increased. When the bulk density for various samples of Bakken shale was plotted against Rock-Eval $T_{\max}$ measurements for the samples, they noted a correlation, in that increasing bulk density corresponded with increasing Rock-Eval $T_{\max}$ (an indication of thermal maturity). They also observed that the densities for fully mature Bakken shales stabilized around 2.32 g/cc.

5. Study Methods

To determine if Jarvie *et al.*'s (2011) research could be applied to the Bakken Formation in Saskatchewan, bulk densities of Saskatchewan's Upper and Lower Bakken Member shales were collected from 1156 geophysical well logs (drilled from 1980 to present) in an effort to identify areas of increased bulk density (>2.10 g/cc) and very high bulk density (>2.25 g/cc). The median, maximum and minimum bulk densities of the Upper and Lower Bakken shales were recorded (Figure 3), regardless of thickness. Contour maps were then generated using Golden Surfer® 12 software's kriging algorithm to illustrate the spatial distribution of the recorded bulk density values.

At the same time, given the findings of Schmoker and Hester (1990), deep-reading resistivity measurements (*i.e.*, measurement of the true formation fluid resistivity) from the same 1156 geophysical well logs mentioned above were recorded for Upper and Lower Bakken shales. This was done to map the spatial variability of the formation fluid resistivity for comparison with the bulk density, to establish areas where these two indicators of favourable maturity coincide. Formation fluid resistivity mapping for the purpose of identifying mature source rocks in Saskatchewan has been attempted previously by Kreis and Costa (2005) and Kreis *et al.* (2006), and the work for this study is meant as an update of their work.

Separate contour maps of the maximum and median bulk density were constructed for both the Lower and Upper Bakken Member shales, and the 35 ohm-m resistivity contour lines for the Lower and Upper Bakken shales were overlain onto the corresponding bulk density maps. Since, according to Jarvie *et al.* (2011), bulk density in immature Bakken shale ranges from <2.00 to 2.10 g/cc while the onset of oil generation can occur at bulk densities >2.10 g/cc and $T_{\max}$ of 425°C , a minimum cut-off of 2.10 g/cc for bulk density was used in these contour maps so that areas of potential shale compaction and related potential oil expulsion would be more obvious. It should be noted that, for this initial investigation, no attempt was made to generate isopach maps to calculate the volume of rock (and hence the volume of potential source rock) with bulk densities greater than 2.10 g/cc.

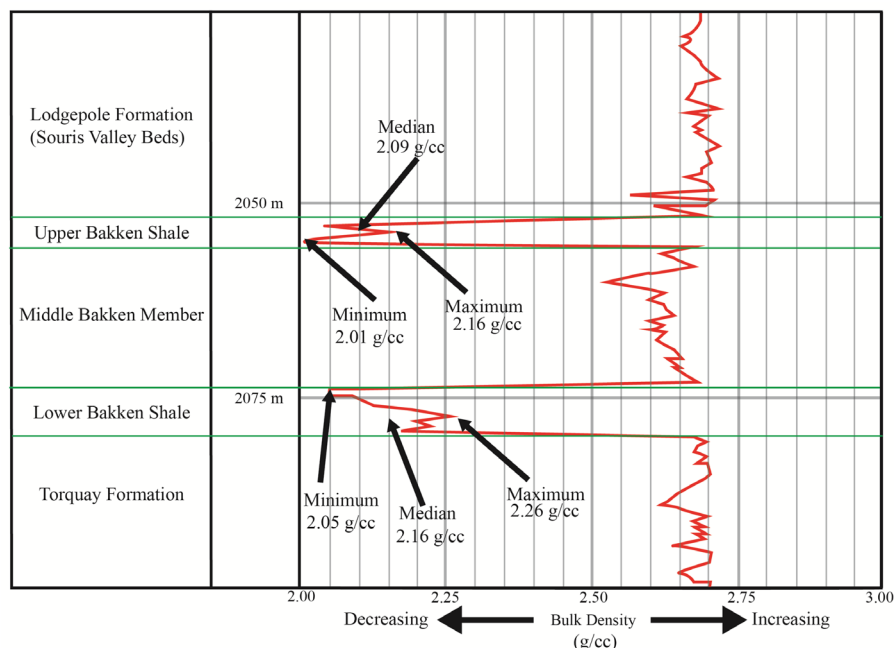


Figure 3 – Well log showing theoretical bulk density (formation density) of the Bakken Formation in the study area. Examples of bulk density “picks” are illustrated. (Second column from left gives depth below surface.)

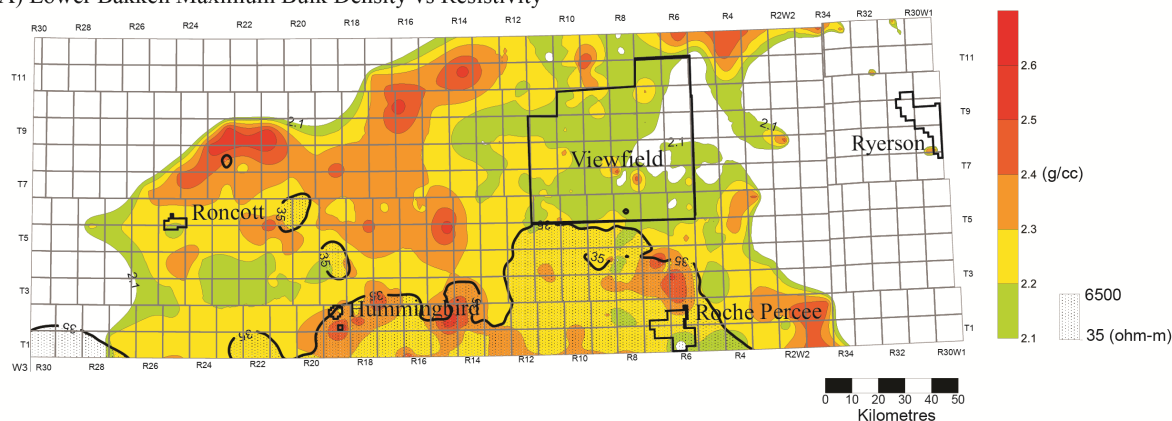
6. Bakken Shale Resistivity and Bulk Density Mapping Results

a) Lower Bakken Member Shale

Several observations can be made regarding the Lower Bakken shale maximum and median bulk density maps (Figures 4A and 4B, respectively). Both maps have areas of high and low bulk density values. Notably, several regions of high bulk density exist within the area outlined by the 35 ohm-m contour, in particular around Township 3 Range 6W2, Township 2 Range 15W2, and Township 2 Range 19W2. The 35 ohm-m contour line wraps around these areas of higher bulk density, suggesting the two variables are not completely independent of each other. Also of note is a large area north and slightly east of the 35 ohm-m contour line (Townships 6 to 12, Ranges 4 to 14 W2) that represents a region of relatively low bulk density (with exceptions) that coincides closely with the prolific Viewfield Bakken oil pool. The presence of low bulk density values in this area supports, or at least does not contradict, the theory that oil in the Viewfield pool was not locally sourced but has migrated to its present location from areas with more thermally mature, therefore higher bulk density, rocks.

Another area of interest is an east-trending bulk density high that lies between Townships 8, 9 and 10 on the west side of the study area, from approximately Range 13W2 to Range 26W2. This connects with a north-trending bulk density high that lies between Ranges 14 and 18W2 in Townships 9 to 11. The majority of this area does not coincide with deep-reading resistivity values greater than 35 ohm-m so alternate explanations for the origin of this region of high bulk density need to be explored.

A) Lower Bakken Maximum Bulk Density vs Resistivity



B) Lower Bakken Median Bulk Density vs Resistivity

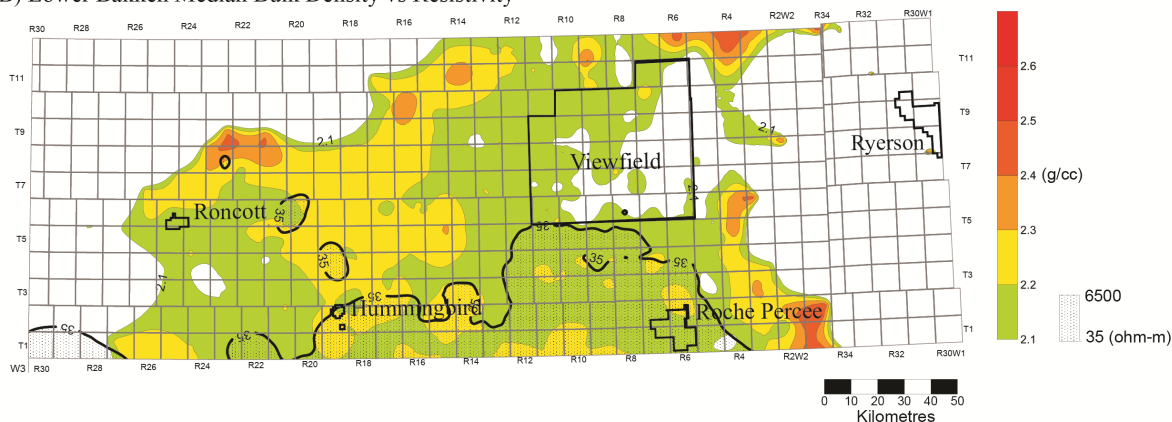


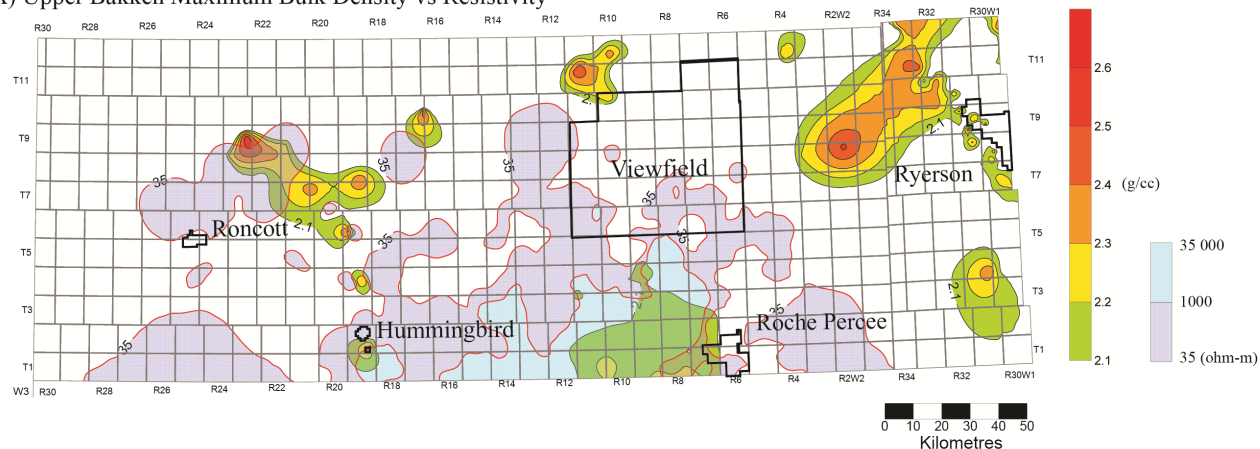
Figure 4 – A) Contour map of the maximum bulk density readings for the Lower Bakken Member shale. B) Contour map of the median bulk density readings for the Lower Bakken Member shale. Included on both maps is the 35 ohm-m resistivity contour line (thick black line) for the Lower Bakken Member shale. Bulk density values greater than 2.10 g/cc represent areas of potential shale compaction related to oil generation and expulsion. Areas with resistivity greater than 35 ohm-m represent anomalously high resistivity in Bakken shale, indicative of potential for either oil generation or a pathway for oil migration. Areas of high bulk density coincident with areas of resistivity equal to or greater than 35 ohm-m are of particular interest, since both source rock maturity indicators are corroborating. The 35 ohm-m contour line “coincidentally” separates anomalously high bulk density readings (>2.10 g/cc) from the low or typical Bakken shale bulk density readings (<2.10 g/cc) in the Viewfield pool area.

b) Upper Bakken Member Shale

The Upper Bakken 35 ohm-m contour line extends much farther north into the study area than that of the Lower Bakken, but far fewer of the higher maximum and higher median bulk density values in this member exceed the 2.10 g/cc threshold (Figures 5A, 5B). Two areas of note on the maximum bulk density map (Figure 5A) fall within the limits of the 35 ohm-m contour line. The first is an extensive area covering approximately 12 townships, from Ranges 7 to 11W2, starting at the Saskatchewan–US international border and extending northward to Township 4. The other area straddles Townships 1 and 2 of Range 19W2. These two areas also correspond with regions of resistivity values above the 1000 ohm-m threshold. Both these areas are smaller on the median bulk density map (Figure 5B), but still present.

Several other areas with bulk density highs in the Upper Bakken exist outside of the 35 ohm-m contour line (Figures 5A, 5B) and warrant further investigation. Of particular interest is the area along the Saskatchewan–Manitoba border between Townships 7 and 10 that coincides with the recently developed Ryerson Bakken–Torquay pool (Figures 1, 5A, 5B). Further research to determine the reason for these high bulk density values would be extremely useful, since the cause may simply be due to lithological variation rather than compaction due to oil expulsion.

A) Upper Bakken Maximum Bulk Density vs Resistivity



B) Upper Bakken Median Bulk Density vs Resistivity

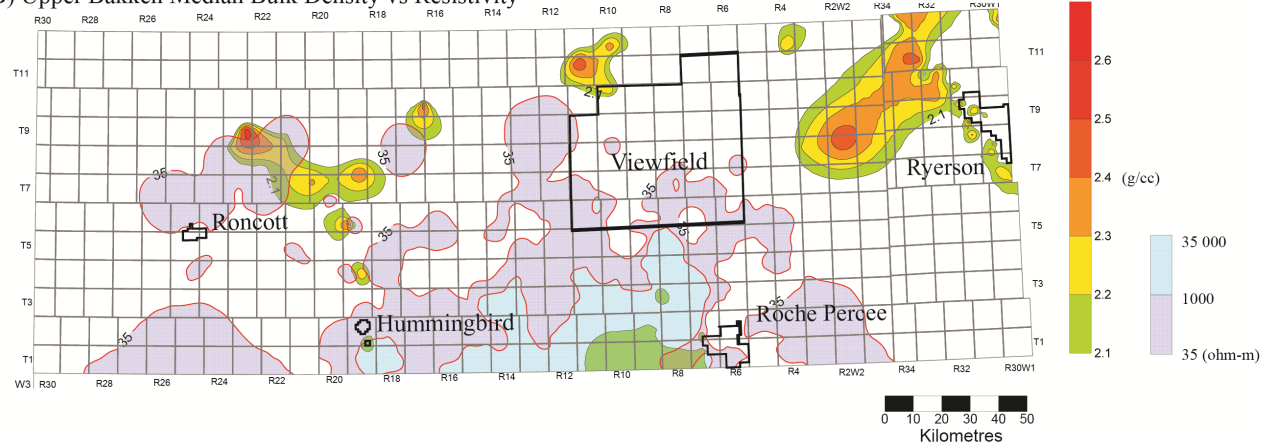


Figure 5 – A) Contour map of the maximum bulk density readings for the Upper Bakken Member shale. B) Contour map of the median bulk density readings for the Upper Bakken Member shale. Included on both maps is the 35 ohm-m (areas shaded in light purple) and 1000 ohm-m (areas shaded in light blue) contour lines for the Upper Bakken Member shale. As in Figure 4, areas of potential shale compaction related to oil generation and migration are those with bulk densities greater than 2.10 g/cc. Potential areas of oil generation or oil migration can be identified where resistivity values for Bakken shale exceed or equal 35 ohm-m (the 1000 ohm-m contour line was added to indicate areas of highest resistivity). As with the Lower Bakken shale maps in Figure 4, areas of high bulk density coincident with resistivity values greater than 35 ohm-m are of particular interest and are worth further research into the maturity level of the source rocks.

7. Discussion

Locations in the study area where anomalously high deep-reading resistivity (>35 ohm-m) and bulk densities (>2.3 g/cc) for Bakken shale coincide indicate areas with the potential for thermally mature Upper and/or Lower Bakken Member shales, if only in thin layers. This concordance of favourable indicators for oil generation and source rock maturity, respectively, makes these areas excellent candidates for further research into the nature of the bulk density anomalies and further investigation into the shales' potential as thermally mature source rocks.

It is difficult to determine the cause of the increased bulk densities of the Upper and Lower Bakken Member shales from well logs alone, so it is necessary to further investigate the reason for anomalous readings. Correlating the bulk density highs to detailed lithology by viewing available Upper and Lower Bakken Member cores is recommended, as well as correlating these highs to other thermal maturity indicators such as hydrogen index, Rock-Eval T_{max} , TOC and vitrinite reflectance. Favourable results may help to expand the areas of exploration for potential Bakken Formation oil-bearing shales. This is especially important for those areas outside of the 35 ohm-m contoured region and specifically the intervals within the shales that show the highest bulk density values. These areas may show higher bulk density values due to lithological variations rather than compaction, and this possibility should be ruled out before assumptions regarding compaction due to oil expulsion are made.

It would also be useful to perform additional research on areas with known Bakken oil production that coincide with the bulk density highs shown on Figures 4 and 5, since this would help confirm the validity of using bulk density versus formation resistivity mapping to identify areas of source rock maturity. Through further analysis, the nature of the relationships between lithology, bulk density and formation resistivity may reveal an additional technique for oil exploration.

8. References

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