

Williston Basin Petroleum Systems: Inferences from Oil Geochemistry and Geology¹

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1. Manuscript submitted February 9, 2000; Accepted July 2000

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ABSTRACT

The Williston Basin has often been used as a model for petroleum exploration and production in basins around the world, so it is appropriate to update and accurately describe its functional petroleum systems. The fact that carbonate source rocks in the Madison Group were overlooked for many years demonstrates the need for careful assessment of effective petroleum systems. Using geochemical data from 106 oil samples and extensive literature references, an up-to-date assessment of petroleum systems in the Williston Basin is provided by geochemical analysis of dead oils from 16 producing horizons. Oil and source rock extract fingerprinting and biomarkers have been used to type oils and correlate sources in the Williston Basin. This work combines these published results with light hydrocarbon data from whole oil gas chromatographic fingerprinting of oils. While light hydrocarbon yields are affected by sample handling and storage, this study demonstrates that these oils can be distinctly typed and correlated using light hydrocarbon data. Overall, these data further elucidate the dominant Madison Group petroleum system in the Williston Basin, while also elucidating secondary petroleum systems including the Duperow, Red River, and Bakken-Lodgepole systems as well as other minor systems.

Light hydrocarbons segregate the oils into distinct families and are a useful means of typing oils, evaluating maturity, calculating generation temperatures, and assessing oil mixes. Madison Group oils sourced by Madison carbonate source rocks are enriched in 6-carbon ring light hydrocarbons, toluene and methylcyclohexane. While this 6-ring preference is generally thought to be indicative of terrestrially sourced oils, these oils are definitively derived from carbonate or marly shale source rocks. Bakken oils are enriched in 5-carbon ring light hydrocarbons such as the alkylated cyclopentanes, which appears characteristic of a clay-rich, marine shale source. Red River oils are enriched in normal paraffins and exhibit characteristic Ordovician-sourced (*G. prisca*) oil fingerprints. Other unique petroleum systems revealed by these data include the Tyler, Duperow, Winnipegosis, and the Deadwood oils. Other oils in this study are related to the above oil types, e.g., the single Spearfish oil groups with Madison oils, Nisku oils are principally grouped with Bakken oils, and Interlake oils type primarily with Red River oils.

Mixing of oils does not occur extensively in the U.S. Williston Basin based on interpretation of oil fingerprints of oil samples and laboratory mixtures of Madison, Bakken, and Red River oils. Commingled production yields oils with hybrid characteristics that can be discerned by fingerprint and biomarker data.

INTRODUCTION

The Williston Basin is an intracratonic, sag type Paleozoic basin located primarily in north central United States and central Canada on the western shelf of the North American Craton (Fig. 1) (Gerhard et al., 1987; Peterson, 1988). Principal structural features include the Nesson Anticline in west central North Dakota, the Cedar Creek anticline in southeastern Montana, and the Richey, Weldon, Poplar Dome, and Brockton-Froid fault zones in eastern Montana (Meissner, 1978; Schmoker and Hester, 1983; Peterson, 1988; LeFever et al., 1995). This map also shows the temperature contours of the U. Devonian-L. Mississippian (Bakken) interval (Schmoker and

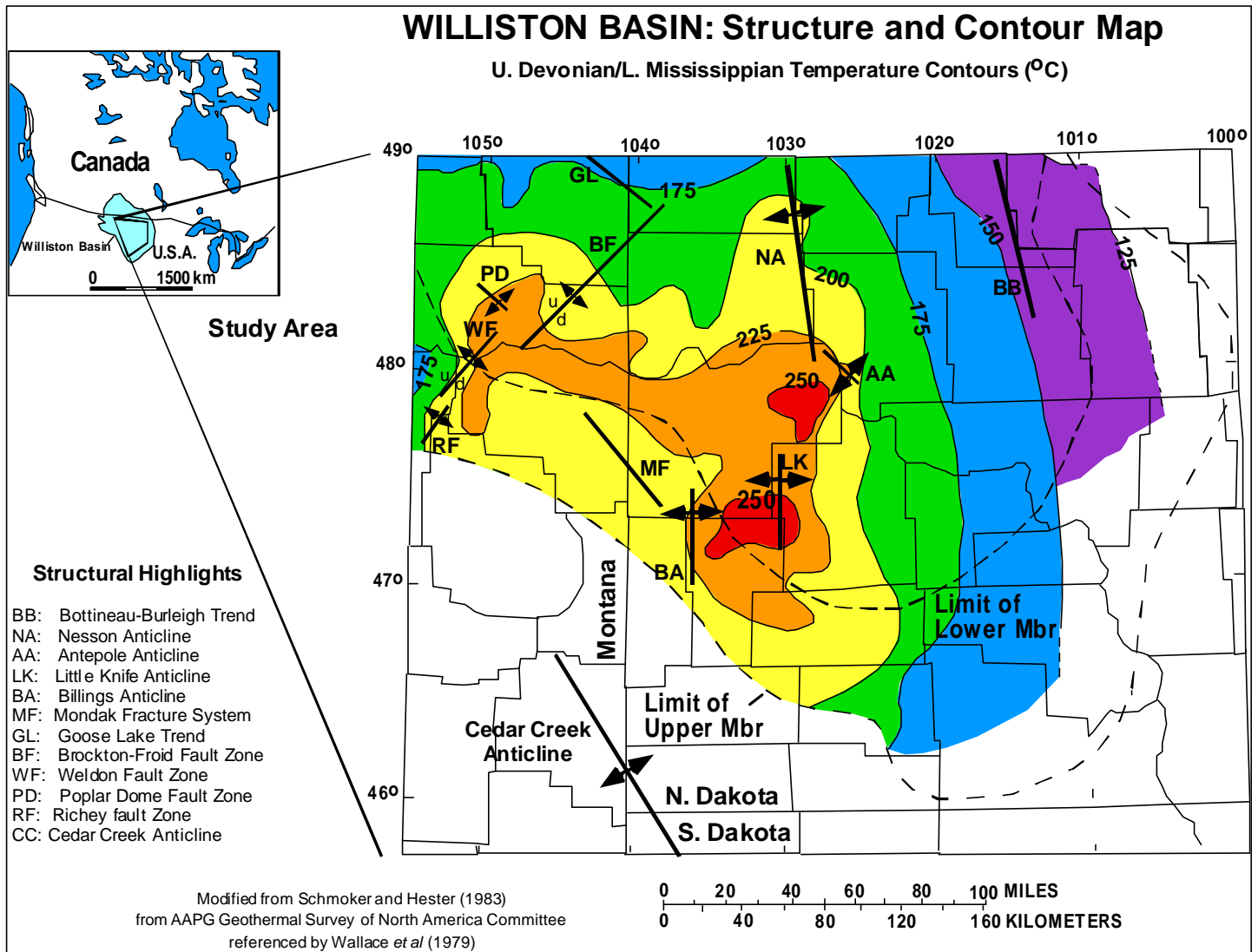
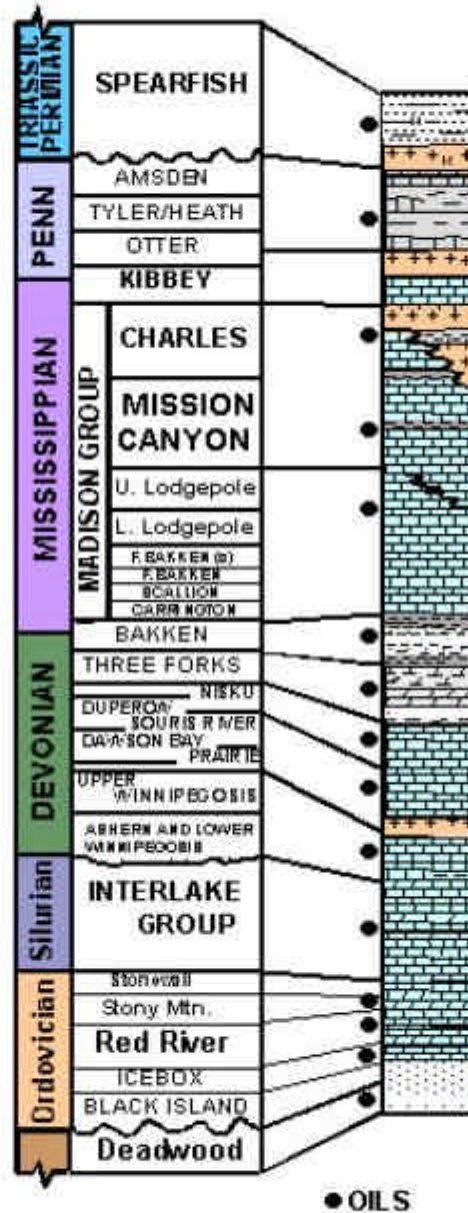


Figure 1. Diagrammatic structure map of study area showing structural highlights with U. Devonian-L. Mississippian temperature contours (in °C).

Hester, 1983). Maximum present-day temperatures in this interval are approximately 250°F (121°C) in the hottest parts of the basin. A stratigraphic column shows formations and ages as well as horizons from which oil data are reported (Fig. 2) (Meissner, 1978; Gerhard et al., 1987; Webster, 1984; Burrus et al., 1996).

A summary of the production history through 1996 by age of reservoirs from North Dakota only was compiled from production reports of the North Dakota Geological Survey (Table 1, Figure 3). Madison Group reservoirs account for 61% (750 million barrels of oil) of North Dakota's Williston Basin historical oil production. Little attention has been given the source of Duperow oils even though Duperow reservoirs are the second highest producing horizon, exceeding Red River Formation production by about a percentage point. Combined Madison Group, Duperow, and Red River reservoirs account for over 80% of North Dakota's oil production. Bakken reservoirs account for 3.2% of production. The impact of a new play can be dramatic; Bakken-sourced Lodgepole oils had one year production rates accounting for 10% of the production totals in 1996 alone. This play was described in LeFever and Anderson (1984) about 10 years prior to the major Lodgepole discovery in

Williston Basin Stratigraphic Column and Horizons Studied



Modified from Webster (1984), Meissner (1978), Gradetz and Snowden (1995)

Figure 2. Generalized stratigraphic column with oil samples noted.

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Oil typing and petroleum systems analysis in the Williston Basin were first published by Williams (1974) and Dow (1974) who detailed 3 petroleum systems as the Tyler, Bakken-Madison, and Winnipeg-Red River. Using sterane biomarkers Grantham and Wakefield (1988) suggested that an effective source rock was present in the Mission Canyon Formation. Osadetz et al. (1992) suggested and confirmed (Osadetz et al., 1994; Osadetz and Snowdon, 1995) a Lodgepole source for Madison oils. Price and LeFever (1995) described a "dysfunctionalism" in the hypothesized Bakken-Madison petroleum system based on quite different saturate and aromatic gas chromatographic data between the Bakken and Madison Group oils. Using C₇ light hydrocarbon data Madison, Bakken, and Red River oils were typed and characterized as separate oil families (Jarvie et al., 1997, Obermajer et al., 1999). Further correlation of an organic-rich Mission Canyon carbonate source rock to various Madison oils was achieved using light hydrocarbons and biomarkers (Jarvie and Walker, 1997). They also demonstrated the presence of organic-rich intervals throughout the Madison Group including 3 organic-rich Mission Canyon horizons (up to 14% TOC) in the Danielson #1 well in Sheridan County, Montana. On the other hand, based on same criteria, they correlated the Lodgepole mound oil in the Conoco Kuntz well in Stark

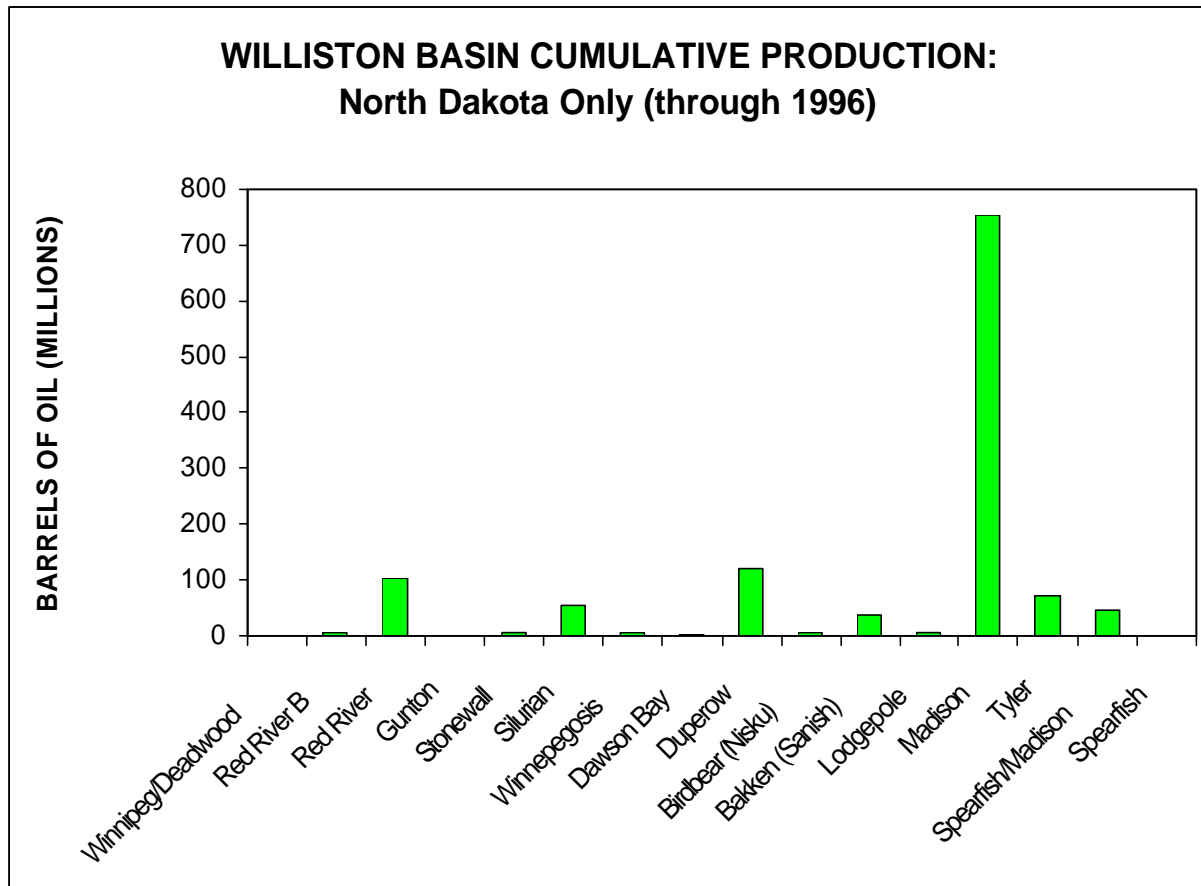


Figure 3. Williston Basin production totals through 1996 by reservoir (North Dakota only).

County, North Dakota to the underlying Bakken Formation, although organic rich False Bakken rocks have nearly identical fingerprints.

While Osadetz et al. (1992) suggest a Lodgepole source as opposed to Mission Canyon source (Jarvie and Walker, 1997) for Madison Group oils, there is, in part, some discrepancy over nomenclature. For example, in Osadetz and Snowdon (1995) the Tilston Member is shown to be in the Lodgepole Formation, whereas in the U.S., the Tilston Member is placed in the lower Mission Canyon Formation (Harris et al., 1966; Hansen, 1966; Gerhard, et al., 1987). In addition other intervals in the Mission Canyon Formation have high source potential such as the Richey Shale and other markers.

EXPERIMENTAL APPROACH FOR OIL TYPING

Chromatographic analysis of whole oil samples provides a “fingerprint” of hydrocarbons from C₁ to C₄₄, when present. An oil fingerprint is a histogram of the yield and distribution of resolvable compounds present in an oil. Quantitative results from these analyses were used to characterize and type these oils, infer source rock characteristics, determine thermal maturity, assess mixing or commingling of production, and predict oil expulsion temperatures. All oils were fingerprinted using whole oil, high resolution gas chromatography, while saturate and aromatic fraction biomarkers were assessed on selected samples from various key producing horizons. In addition, whenever sufficient sample was available, API gravities and sulfur contents were measured.

Light hydrocarbons are volatile compounds and will evaporate during sample handling and storage. There is no doubt that the yields of these compounds in dead oil samples is diminished when compared to live oils in reservoirs or live oils collected and stored under pressure. However, by using peak ratios or compound class comparisons these volatile compounds can be used to type oils quite effectively (Mango, 1987; Halpern, 1995; ten Haven, 1996). The effect of evaporation was reported by Jarvie and Walker (1997), who found that while the relative abundance of these compounds diminished, the assessment of oil type and maturation was not significantly affected except when the light hydrocarbons were nearly completely removed. Further, they devolatilized (“topped”) a Bakken oil and artificially matured the oil at 350°C for 24 hours and analyzed the formed oil. This newly formed oil was readily identified as a Bakken oil, so moderate to high level maturation will not adversely affect these interpretations.

Typically oil-to-oil and oil-to-source rock correlations are completed with biomarker data. Biomarkers are molecular fossils derived from biological precursors of oil. Molecular similarities are used to correlate oils-to-oils and oils-to-source rocks, whereas dissimilarities are used to demonstrate differences. However, light hydrocarbon composition is also indicative of homologous oil families, i.e., oils from the same source as shown by Mango (1987). Light hydrocarbon composition appears to be related to organic matter type, lithology, and maturity and perhaps other factors such as mineralogy and hydrogen partial pressure.

Both light hydrocarbons and biomarkers are needed for interpretation when oils are mixed, or when an oil system is secondarily charged with retrograde condensate. Biomarker data will only type the original oil and will provide no information on mixing of light hydrocarbons or secondary condensate charge. Thus, a combination of biomarker and light hydrocarbon data is a powerful typing, secondary charge, and alteration evaluation tool. Geochemical interpretations should be based on a variety of techniques over the entire compositional range of an oil.

OBJECTIVES OF STUDY

The objectives of this study were to:

- type and group the oils from the Paleozoic section including one Triassic oil
- infer source rock characteristics including kerogen type, depositional environments, and lithofacies
- assess the possibility of oil mixing
- assess thermal maturity, temperatures of oil generation, and GOR values
- delineate major and minor petroleum systems with data available to date

Samples

Oil samples were analyzed from across the Williston Basin and from a wide range of different fields and producing horizons (Table 2, Fig. 4). The majority of the oils, however, are from 3 horizons: Madison Group, Bakken Formation, and Red River Formation. Only single samples or smaller sample sets were available from the Spearfish, Tyler, Lodgepole, Nisku, Duperow, Winnipegosis, Interlake, Winnipeg, and Deadwood oils. The Lodgepole Formation is arbitrarily separated from the Madison Group in this study. Thus, the Madison Group oils consist only of Mission Canyon and Charles Formation oils, which are collectively referred to simply as Madison oils. The Lodgepole oils include three Stark County Waulsortian mound oils and a single Lodgepole oil from Divide Field in Sheridan County, Montana.

Results

Prospective Williston Basin Source Rocks

A variety of authors have published or presented data on various source rock horizons in the Williston Basin (Williams, 1974; Dow, 1974; Webster, 1984; Price et al., 1984; Osadetz and Snowdon, 1995; Jarvie et al., 1996; Jarvie and Inden, 1997; Jarvie and Walker, 1997). The data reported in these references are summarized by average total organic carbon (TOC) values and hydrogen indices (Table 3). On the other hand, Peterson (1988, 1995) noted the presence of possible source horizons by visual inspection of rock samples. Detailed oil-to-source correlations using biomarker data are reported in Osadetz and Snowdon (1995), whereas the intra-Madison oil-to-source correlation was documented by Jarvie and Walker (1997) using both biomarkers and light hydrocarbons from Madison oils and Madison source rocks.

The commercial potential of a source rock depends both on its hydrocarbon generation potential and the volume of source rock. As both the presence and volume of Madison source rocks has been questioned, organic richness, petroleum potential, source thickness and aerial extent of this prospective source rock must be considered. Based on the organic richness and petroleum potential of Madison source rocks in the #1 Danielson well (Table 3) and a contour map of the thickness of marine dark shales and shaly carbonates interbedded within the massive carbonates of the Madison Group (Peterson, 1996), Madison Group source horizons do have sufficient hydrocarbon generation capacity to account for the bulk of Madison Group oils. Peterson shows the thickness of these prospective source units to range from 50 ft thick on the fringe of the basin to 200-300 ft thick in the central part of the Williston Basin. However, a detailed study of Madison sources in the central part of the Williston Basin has not yet been completed.

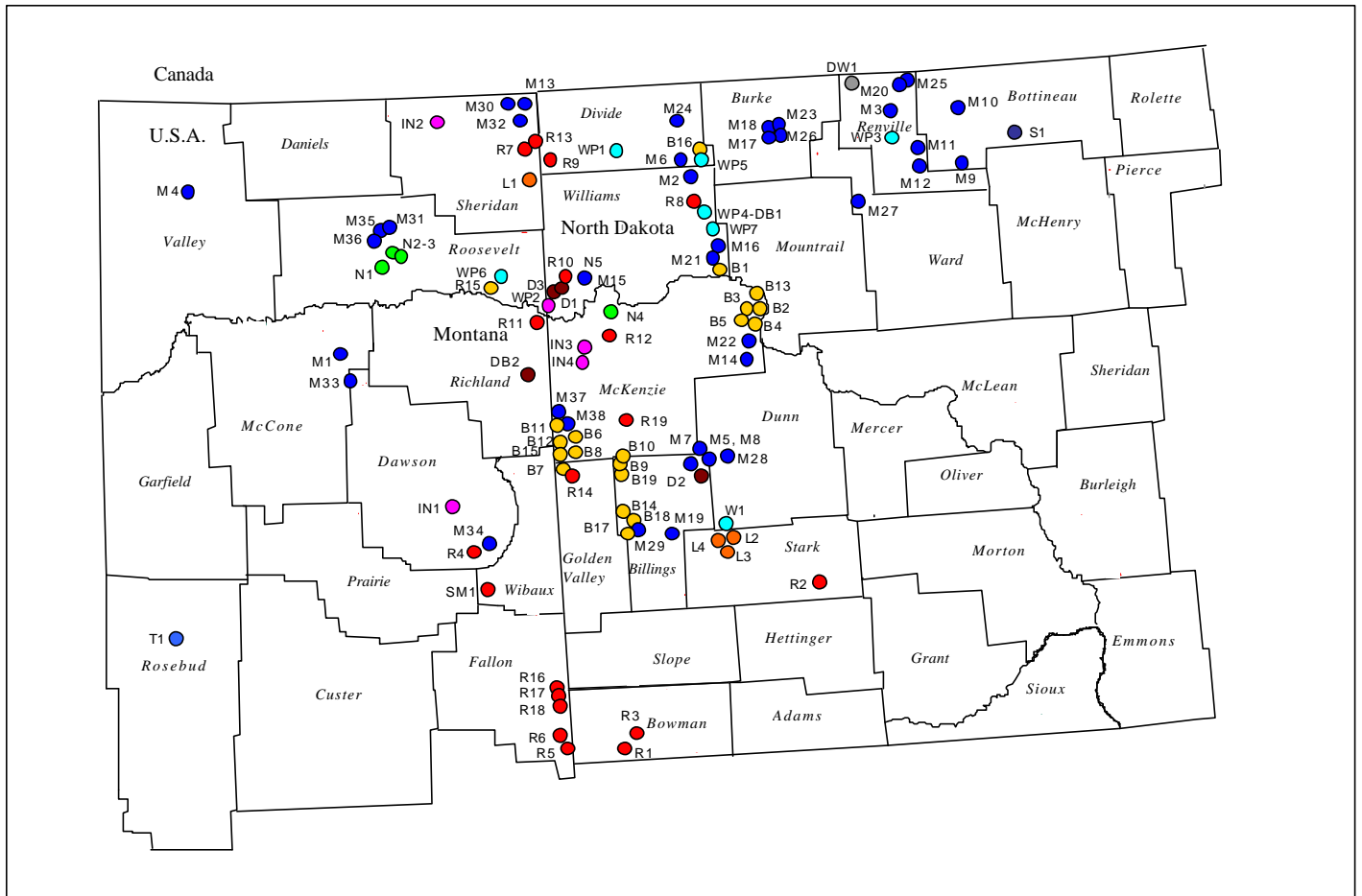


Figure 4. Sample location map (see Table 2 for well names).

Quantitative Gas Chromatographic Fingerprints, Yields, and Ratios

The gas chromatographic (GC) fingerprints of the 106 oils in this study show considerable variability in the yields and distribution of their principal hydrocarbon components. Fingerprints of selected samples from 7 horizons are shown with both the light (C_1 - C_8) and heavy (C_8 - C_{35+}) hydrocarbons (Fig. 5a-g). These oils are interpreted to represent primary oils, i.e., oils from unique source rocks that have no evidence of mixing or alteration. There are various subgroups within the Madison Group and Red River oil types based on minor compositional variations. Quantitative light hydrocarbon data on all the dead oil samples are shown in Table 4.

Higher Molecular Weight Hydrocarbons (C_8+)

The C_8+ hydrocarbons are typically used to type any differences in normal paraffin distribution in combination with isoprenoid hydrocarbons. Some oils such as the Ordovician Red River oils are readily recognizable from their C_8+ fingerprints by the characteristic odd carbon preference in the C_{13} - C_{20} paraffins as well as the decreased hydrocarbon yield in the C_{20+} range (Fig. 5.f.2) (Williams, 1974; Zumberge, 1983; Reed et al., 1986; Longman and Palmer, 1987; Jacobson et al., 1988). The facies differences noted by Jacobson et al. (1988)

Figure 5A. Tyler oil M8-77, Rosebud County, Montana: (1) light hydrocarbon fingerprint, and (2) C₈+

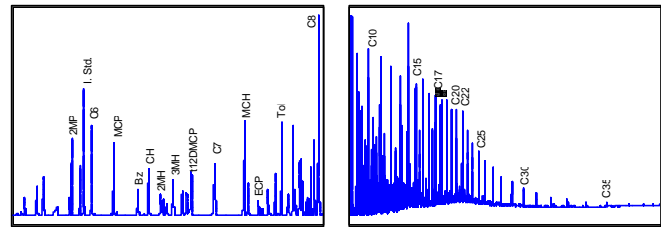


Figure 5B. Madison oil, Wiley #1, Wiley Field, Bottineau County, North Dakota: (1) light hydrocarbon fingerprint, and (2) C₈+ fingerprint.

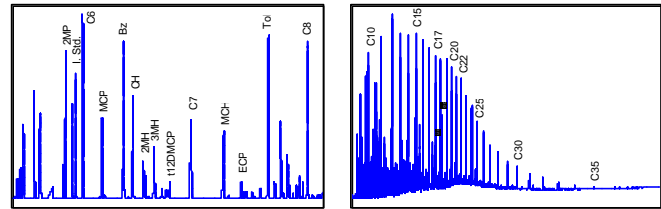


Figure 5C. Bakken oil, Federal #6-1, Elkhorn Ranch Field, Billings County, North Dakota: (1) light hydrocarbon fingerprint, and (2) C₈+ fingerprint.

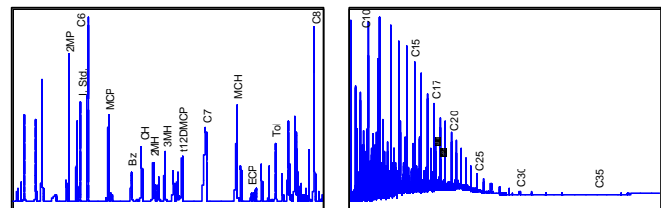


Figure 5D. Duperow oil, Erickson #4-25, Hardscrabble Field, Williams County, North Dakota: (1) light hydrocarbon fingerprint, and (2) C₈+ fingerprint.

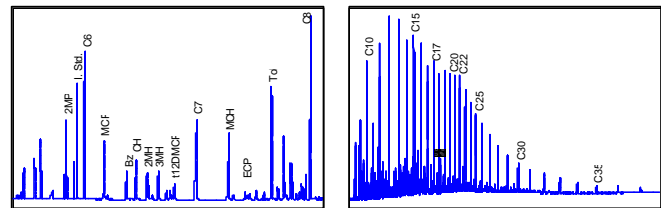


Figure 5E. Winnipegosis oil, Wildrose #36-11, Moraine Field, Divide County, North Dakota: (1) light hydrocarbon fingerprint, and (2) C₈+ fingerprint.

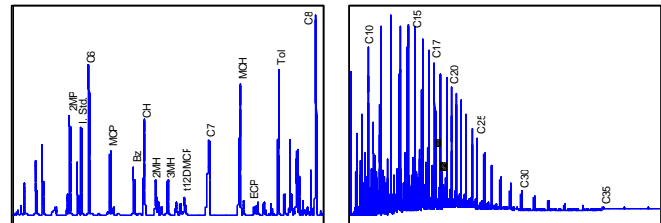


Figure 5F. Red River oil, #42-30, E. Little Beaver Field, Fallon County, Montana: (1) light hydrocarbon fingerprint, and (2) C₈+ fingerprint.

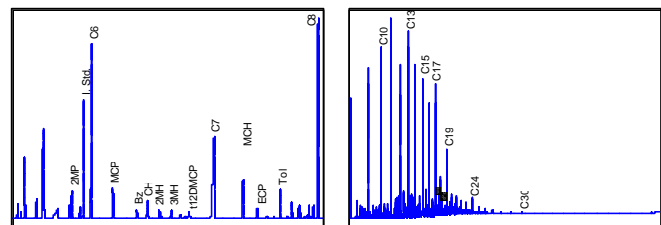


Figure 5G. Deadwood oil, Larsen #1, Newporte Field, Renville County, North Dakota: (1) light hydrocarbon fingerprint, and (2) C₈+ fingerprint.

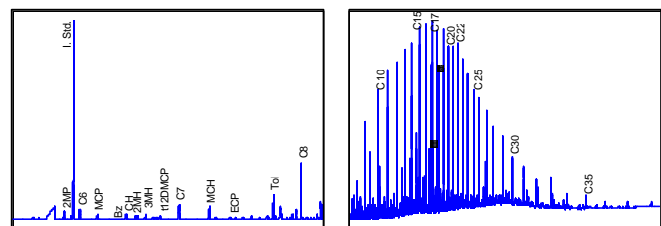


Figure 5 a-g. Light hydrocarbon and C₈+ gas chromatographic fingerprints of primary (unaltered or mixed) oils: (a) Tyler, (b) Madison Group, (c) Bakken, (d) Duperow, (e) Winnipegosis, (f) Red River, and (g) Deadwood.

resulting from differences in organic matter assemblages were observed in this Ordovician oil set. All have odd-carbon preference in the C₁₃-C₂₀ range, but some oils have extended paraffin (C₂₀₊) content with n-C₂₄ predominance.

Other distinctions among these oils are apparent from differences in the paraffins and isoprenoid biomarkers, particularly pristane and phytane. For example, the Madison Group oils have very low pristane-to-phytane ratios (typically less than 1) as has been previously noted (Zumberge, 1983; Osadetz and Snowdon, 1995; Price and LeFever, 1995), whereas typical Bakken oils have values greater than 1.00. A standard geochemical plot of the ratio of isoprenoid biomarkers, pristane and phytane, to the normal paraffins, C₁₇ and C₁₈, respectively, indicates variable source types for these oils that have been ascribed to varying depositional environments of the organic matter (Fig. 6) (Connan, 1974; Hunt, 1996).

These data indicate several segregated families of oils following distinctive maturation trends. For example, Madison, Bakken, and Red River oils are inferred to be derived from different source rocks. Certain oils group with these 3 main groups including the Spearfish with Madison oils, the 4 Lodgepole and 4 Nisku oils with Bakken oils, and Interlake and Winnipeg oils with Red River oils. The single Madison oil plotting with the

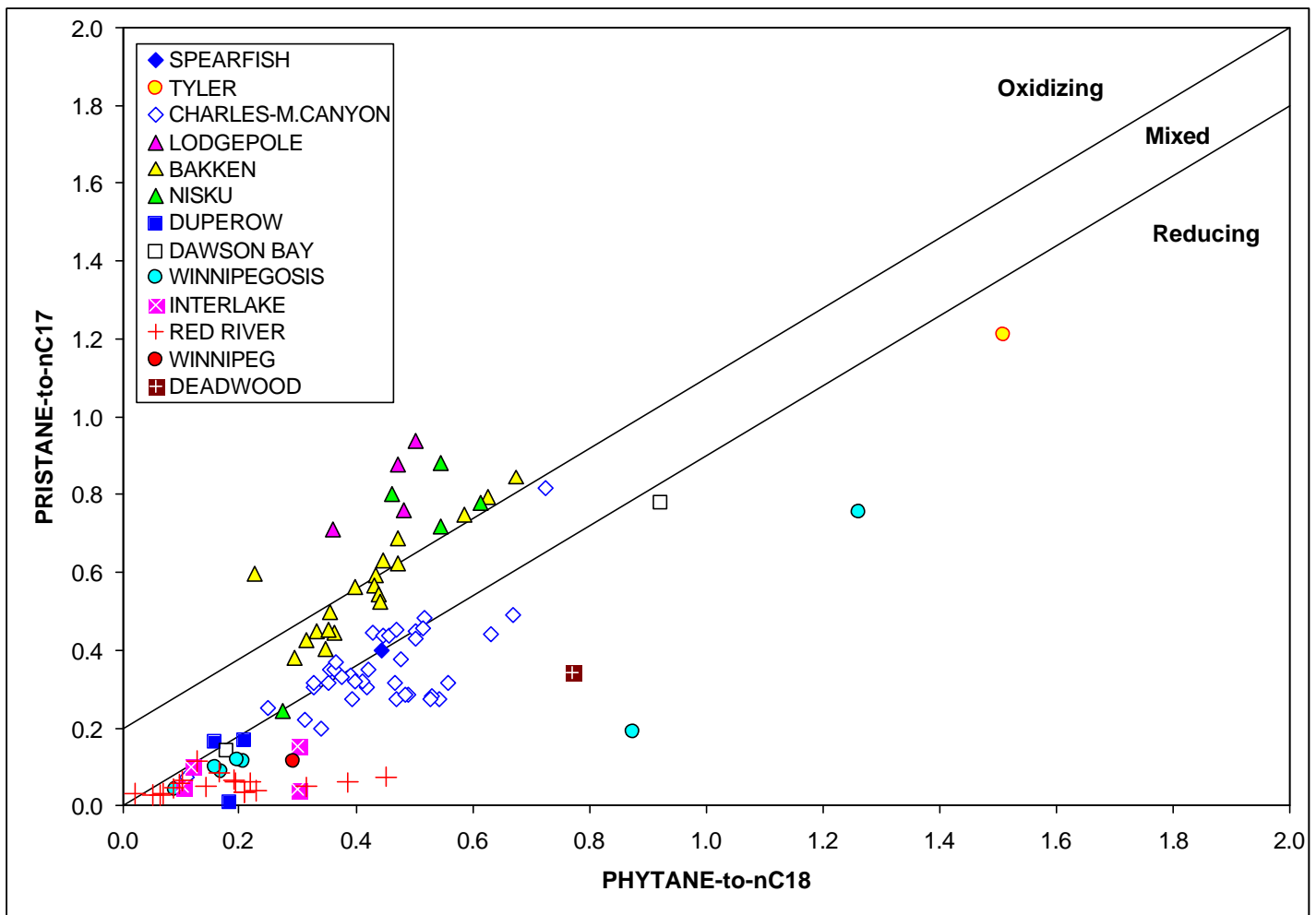


Figure 6. Inferred depositional environment based on GC data.

Bakken-Lodgepole oils is the Northlustrre Field oil (M4) in Valley County, MT and is likely a Bakken or mixed source oil. Other oils in western Montana are mixed or commingled oil types, which will be described. The single Nisku oil (N5) plotting apart from the other Nisku oils is actually commingled Nisku-Duperow oil suggesting a mixed Bakken-Duperow source for this oil. Winnipegosis oils largely group together as do 2 Duperow oils. Other oil groups are not obvious from these data.

These groupings are further elucidated using a common ratio of the isoprenoid biomarkers, pristane and phytane, to a ratio defined as the Ordovician carbon preference index (OCPI) based on paraffins in the C₁₂ to C₂₀ hydrocarbon range (Fig. 7). This plot was selected based on observed differences in pristane-to-phytane ratios among the Madison-Bakken-Red River oils and definitive odd carbon preference in the Red River oils in this paraffin range as noted by Williams (1974) (Fig. 5.f.2). The Madison Group oils are clearly segregated from the Lodgepole mound, Bakken, and Nisku oils as well as the Red River oils. All 4 Lodgepole oils have definitive odd carbon preference in their GC fingerprints indicative of mixing or commingled production from Bakken and Red River sources. The Richey Field Madison oil (M33) also has definitive odd carbon preference and is likely mixed or commingled Madison-Red River oil. These data also separate the Winnipegosis oils from other oil types, although there is considerable scatter among those oils. Note that some Red River and Winnipeg oils have OCPI values (>1.7) and are not shown on this plot.

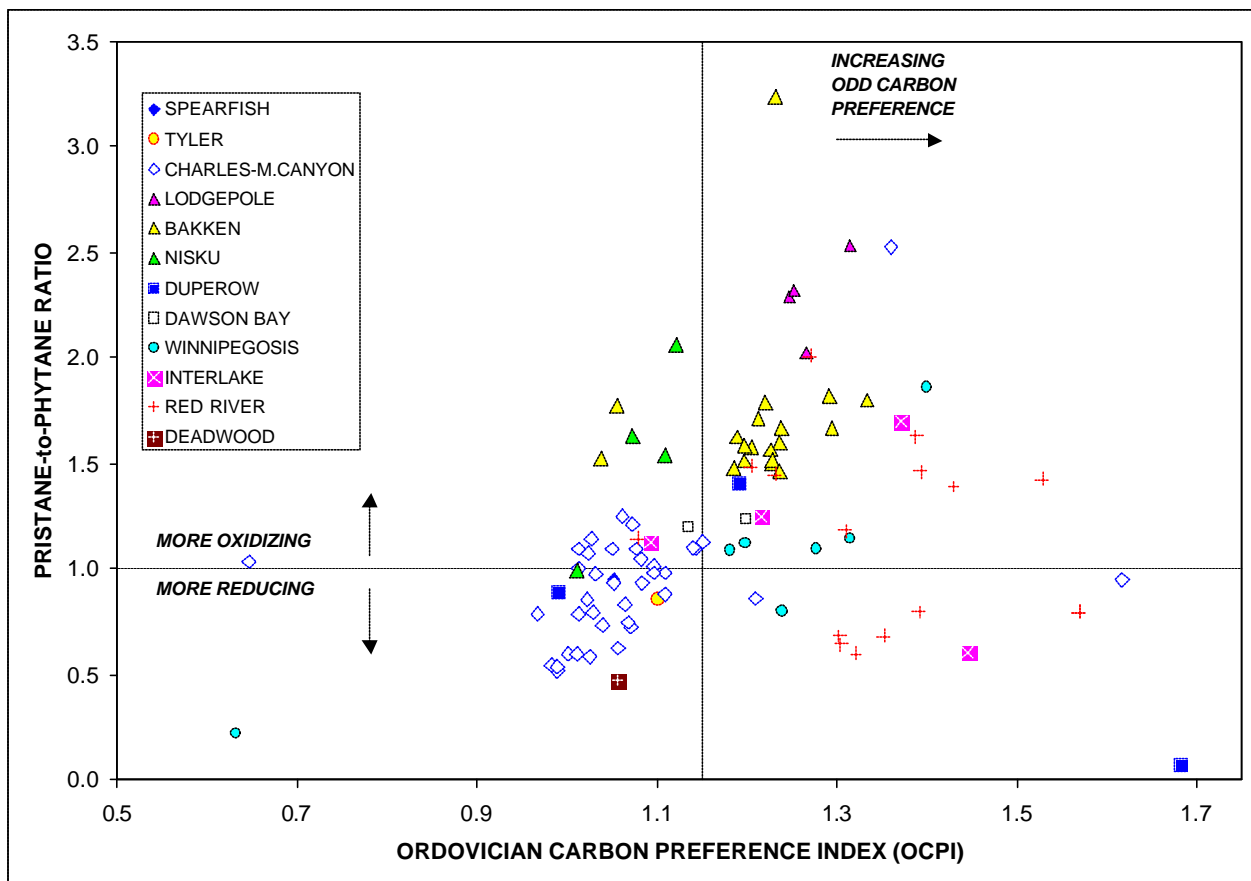


Figure 7. Depositional environment and odd carbon preference in n-C₁₃ to n-C₂₀.

Red River oils have variable sulfur contents with one group having sulfur contents in the 0.50 to 0.70 wt.% range, and the remainder with less than 0.40 wt. % sulfur. This is likely related to facies variations within the Red River as noted by Jacobson et al. (1988) and impacts oil quality. There does not appear to be geographic relationship of these differences in sulfur contents. High sulfur Red River oils (0.40-0.70%) occur in Fallon and Richland counties, MT, as well as in Stark and McKenzie counties, ND. Likewise, low pristane-to-phytane ratios and concentrations occur across the basin, as do very high values. Even in Fallon County, MT, the Cedar Creek Red River oils from horizontal production all have relatively high pristane-to-phytane ratios (ca. 2), whereas immediately to the southeast a few miles, the Little Beaver oils have values less than 1. It may be that some mixing or commingling of these oils has occurred where high sulfur Madison oils are mixed with Red River oils, thereby affecting the sulfur contents as well as pristane-to-phytane ratios.

There are also large differences in sulfur contents among the Madison oils with oils in the northeastern part of North Dakota (Burke, Renville, Ward, and Bottineau counties) having the highest values (Table 2). In general high sulfur oils have lower API gravities. This is consistent with kinetic assessment of the rates of kerogen decomposition where sulfur-rich kerogens decompose under lower thermal stress (Hunt et al., 1991; Jarvie and Lundell, 2000) yielding oil at lower maturity, but of lower quality.

The Newporte Field Deadwood oil also plots apart from other oil groups in both figures 5-6 suggestive of a different source unit. Zumberge (1983) suggested a unique source for the Deadwood oil based on tricyclic biomarkers and carbon isotopic data and Peterson (1988) indicated that dark shales in the Deadwood could be the source. However, Castaño et al. (1994) suggested a Winnipeg source for this oil.

In summary, C₈+ GC data show the following generalized groupings or mixes:

- ◆ Spearfish-Madison Group
- ◆ Lodgepole-Bakken-Nisku Group
- ◆ Red River Groups
- ◆ Madison-Bakken mixes (oils M2, 4, 31, 35-36)
- ◆ Madison-Red River mixes (oils M1, M33, R2)
- ◆ Bakken-Duperow mix (oil N5)

Light Hydrocarbon Gas Chromatographic Data

The differences among these oils are apparent from a plot of their aromaticity and paraffinicity ratios (toluene-to-heptane ratio and heptane-to-methylcyclohexane ratio as defined by Thompson, 1983) (Fig. 8). For example, the Madison oils all have higher amounts of toluene compared to other oils, especially Bakken and Red River oils. The 3 Lodgepole mound oils from Stark County, ND plot with Bakken oils as does the Divide Field Lodgepole oil (L1) and 4 Nisku oils. The Divide Field Lodgepole oil is far removed from the main play in Stark County, ND suggesting possible Lodgepole plays further to the northwest in the basin.

Four Madison oils from Poplar Dome and MacGregor field (M2, M31, and M35-36) group with the Bakken family of oils based on light hydrocarbon data only. However, biomarker data on these oils have characteristics of a carbonate sourced oil similar to other Madison oils, i.e., they have high C₂₄tetracyclic to C₂₆S tricyclic terpane ratios, which no Bakken oil or rock extract from the U.S. Williston Basin has been shown to have (e.g., see Figure 13a), and C₃₅ hopane predominance. It does have C₂₃ tricyclic terpane-to-C₃₀ hopane ratio greater

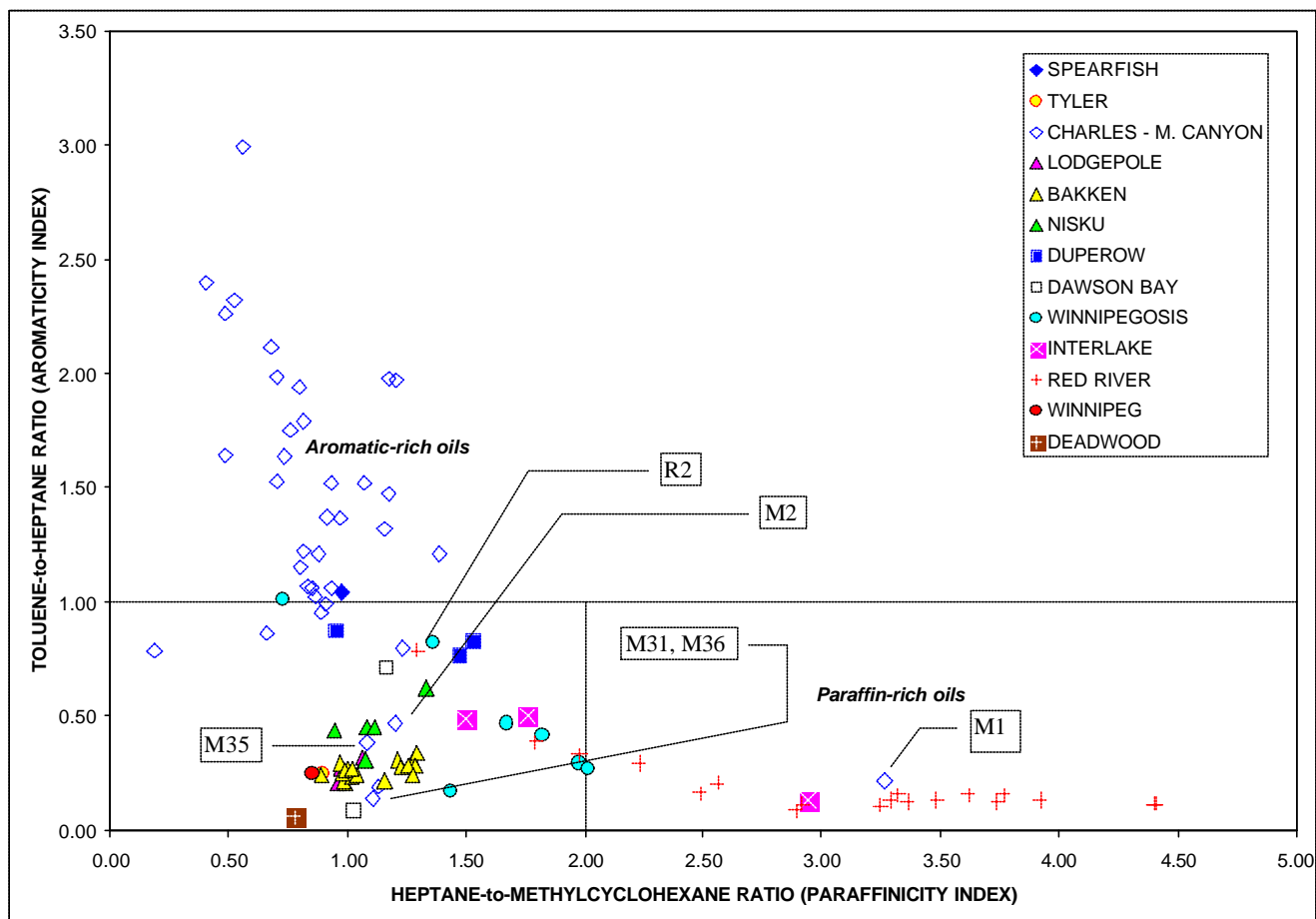


Figure 8. Comparison of the relative paraffinicity and aromaticity of C₇ hydrocarbons.

than 1, whereas most Madison oils have a value less than 1. The Poplar Dome field is located in a faulted zone (Fig. 1, PD) providing a migration pathway from the Bakken. It is likely that other fault blocks in this area, where the Cararett Coulee, Nielson Coulee, and Bredette fields are located, are likely mixed or commingled production oils sourced by Bakken and Madison source rocks. The Bakken light hydrocarbons predominate in these oils, whereas the biomarkers are predominately from the Madison. The Madison source rock may be either the Mission Canyon or the Ratcliffe Member of the Charles Formation. Both have organic rich intervals and carbonate biomarker signatures (D.M. Jarvie, unpublished data). The fact that these mixed oils are found in faulted fields adds credence to the lack of vertical migration pathways elsewhere in the basin and also demonstrates the ability to distinguish mixed or commingled oils. On the other hand, Madison oils in the Canadian Williston Basin have been shown to be mixed based on light hydrocarbon data (Jiang et al., 2000). Again, mixing is quite easily distinguished based on the comparison of the Canadian data to the data herein, where segregation of the U.S. Madison oils and the mixing of Canadian Madison oils are both clearly obvious. In fact the Canadian Madison oils appear to have a very high Bakken oil content based on light hydrocarbon data only. Horizontal migration of Bakken oil into these Madison reservoirs is the most likely explanation for the mixed Canadian Madison-Bakken oils. The geographic extent of this mixing in Canada is unknown. However, mixing does not appear to be occurring extensively in the U.S. Williston Basin based on the distinct segregation of Madison and Bakken oils by both light hydrocarbon and biomarker analysis except at certain fields such as Poplar Dome and MacGregor Fields.

One Madison oil, the Cow Creek field oil (M1), groups with Red River oils based on light hydrocarbon data. This oil is commingled production, but the bulk of the light hydrocarbons are correlated to Red River sources. The nearby Richey Field oil is a typical Madison oil in its light hydrocarbon content, but it has odd carbon preference in the C₁₅-C₁₉ paraffin range characteristic of Ordovician oils. Thus, this oil is likely a mixed or commingled Red River-Madison oil. This is in agreement with the assessment of Price and LeFever (1995) who suggested the possibility of a mixed oil in Richey Field. Both light hydrocarbons and C₈+ fingerprints are needed to assess mixing of oils with other horizons or commingled production.

The high aromatic content of nearly all Madison Group oils is paradoxical considering that these are carbonate-sourced oils, which is supported by biomarker data, high sulfur contents, and lithofacies characterization. Typically, decomposition of terrestrial source rocks is thought to be the primary source of the light aromatics in oils. Alternatively, high aromatic contents are often thought to be associated with fractionated oils, i.e., oils where gas exsolution selectively enhances light aromatic contents (Thompson, 1987), although Mango has contested this argument and provided an independent light hydrocarbon parameter to assess fractionation (Mango, 1990). Neither is the case in the Madison Group as there are no other terrestrial characteristics, no terrestrial source rocks, and no evidence of fractionation. If, for example, these oils were derived because of fractionation of a deeper oil pool, this should result in preferential changes in the ratio of light cycloalkanes, methylcyclopentane and t-12-dimethyl-cyclopentane (t12DMCP) (Mango, 1990; 1994). These compounds were chosen as they have similar physico-chemical characteristics that should be equally altered by fractionation. In fact, these data show type-specific differences among the oil types of the Madison, Bakken, and Red River oils (Fig. 9). Thus, Madison oils are neither terrestrial-sourced nor fractionated, yet all Madison sourced oils have relatively high aromatic contents. Based on the excellent correlation of light hydrocarbons from organic-rich Mission Canyon carbonate source rocks to the light hydrocarbons in Madison Group oils (Jarvie and Walker, 1997), high aromaticity is characteristic of the Madison Group oils and source rocks.

It has been shown experimentally that linear alkylbenzenes such as toluene are produced from aliphatic-rich macerals (Sinninghe Damste et al., 1991, 1993). These compounds are thought to be derived from straight-chain paraffins by cyclization followed by hydrogen abstraction to form hydrogen-poor aromatic hydrocarbons. This may be a role that sulfur plays in iron-poor sediments such as these Madison carbonates. In addition, hydrogen disproportionation from unsaturated paraffins (alkenes) during kerogen cracking would be enhanced by free sulfur availability thereby increasing aromatization reactions.

Madison source rocks have higher aromaticity values than the oils that they source (Jarvie and Walker, 1997). Thus, the aromatic hydrocarbons appear to be selectively stripped during migration in a process referred to as geochromatography based on their increased polarity and water solubility when migration through rocks of variable mineralogy. It would follow that Madison oils with extremely high aromatic contents likely have not migrated very far, otherwise these compounds would be present in lesser amounts.

Various light hydrocarbon data have been used to type oils (Williams, 1974; Dai Jinzing, 1992; Mango, 1994; ten Haven, 1996; Jarvie et al., 1997; Odden et al., 1998). Considering the C₇ light hydrocarbon characteristics of the major oil types in the Williston Basin, i.e., Madison sourced oils are enriched in 6-carbon ring compounds such as toluene and, to some extent, methylcyclohexane, Bakken oils are enriched in 5-carbon ring and branched hydrocarbons, and Red River oils are paraffin-rich, a ternary plot of these C₇ hydrocarbon groups that accounts for all C₇ hydrocarbons, segregates the oils quite distinctly (Fig. 10). These differences are obviously related to source differences both in organic matter composition and in depositional environments of the source rocks.

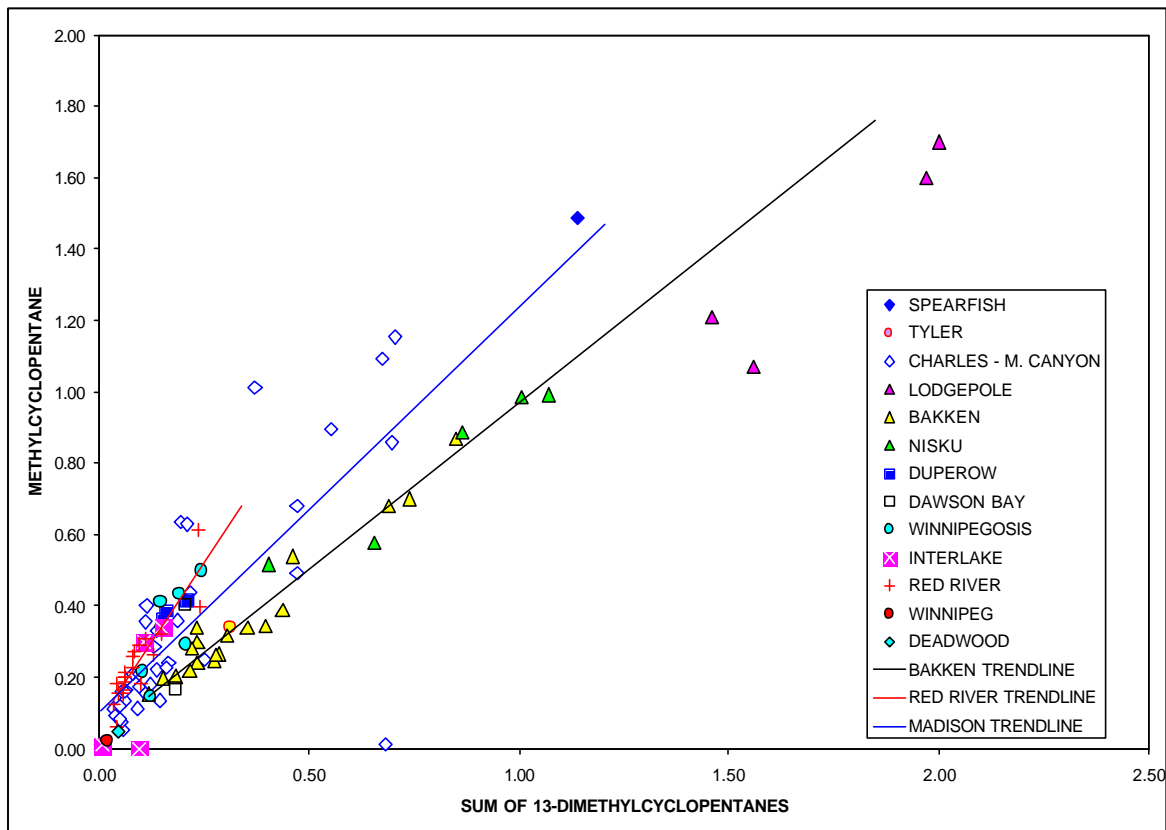


Figure 9. Assessment of fractionation by C₆ and C₇ light hydrocarbons.

In the Lodgepole-Bakken-Nisku oil family, the isoalkanes and dimethylcyclopentanes decrease quite linearly with increasing maturity. This confirms that ring-opening reactions are occurring during maturation. Thus, some C₇ light hydrocarbons are formed from ring opening reactions. For example, decomposition of trans-1,2-dimethylcyclopentane would lead to increased 2- and 3-methylhexanes, 2,3-dimethylpentane, and heptane concentrations, which impacts the yield of compounds used to calculate generation temperatures. Thus, generation temperatures could be affected by secondary oil decomposition reactions rather than strictly primary cracking of kerogen to oil. While there appear to be maturity trends among the Madison oils, differences along the trend are related to organic facies or migration differences, as the concentration of toluene decreases, the C₇ isoalkanes and dimethylcyclopentanes, and heptane increases. Likewise, differences in Red River oils appear to reflect organic facies differences where a decrease in paraffinicity coincides with a slight increase in C₇ isoalkanes and dimethylcyclopentane concentrations.

Again, the Madison Group oils plotting with the Bakken oils in many of these figures are mixed Madison-Bakken sourced oils. These oils are from Poplar Dome (M31, 35, and 36) and the McGregor (M2) field in the heart of the Nesson Anticline, Williams County, North Dakota.

The possibility of mixing of Bakken and Madison sourced oils was considered in this study particularly with recent reports of mixing in Canadian Williston Basin oils (Jiang et al., 2000) and mixing (or commingled production) is evident in the Poplar Dome oils. A fair number of the Madison oils have GC fingerprints with slightly elevated t12DMCP contents that could be indicative of some clay-rich, marine shale input to these oils.

These oils are characterized by pristane-to-phytane ratios slightly greater than 1 and slightly higher t12DMCP than expected in Madison carbonates. However, the toluene content is higher than typical Bakken oils. These oils are located in the central part of the basin, although some oils are from Burke County, ND. These oils likely represent a marly shale facies within the Mission Canyon Formation such as the organic rich Richey Shale or mixing of Madison and Bakken oils. However, mixing is not extensive given the distinct separation of these oils and lack of a continuum in Figures 8 and 10. However, the data of Obermajer et al. (1999) and Jiang et al. (2000) do suggest a continuum between Bakken and Madison oils in Canada. There may also be some Duperow input to some of these Madison oils (M2 - McGregor field, M4 - Northlustrre field, and M30 - Flat Lake field) that further complicates oil typing.

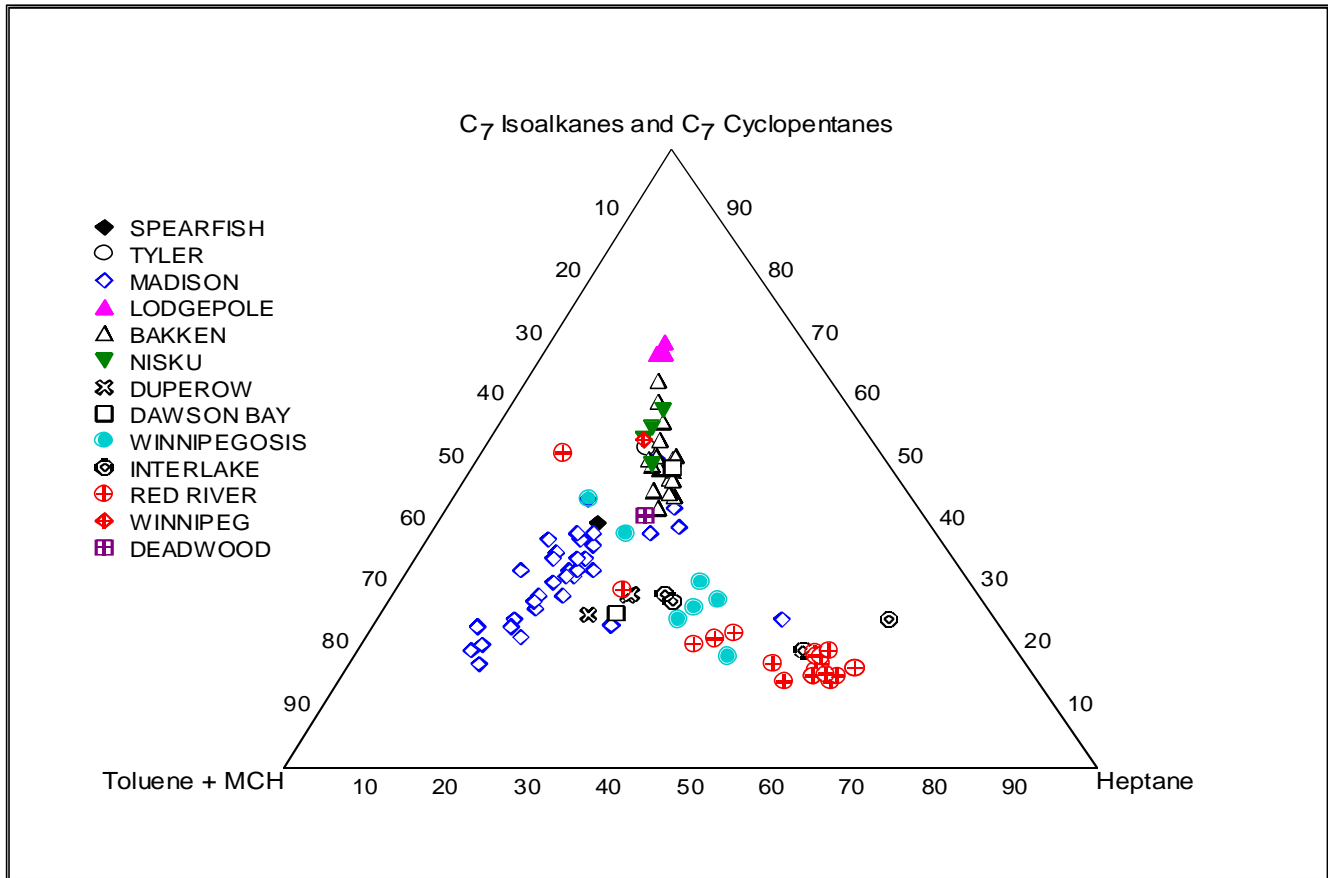


Figure 10. Ternary plot of C₇ hydrocarbons.

Oil mixing was further assessed by analyzing laboratory mixes of Madison, Bakken, and Red River oils. Immature and mature Bakken were taken as end member oils and were mixed with a carbonate Madison oil and Red River oil. This same end member Madison oil was mixed with the Red River oil. An end member oil is considered a pristine oil without any alteration or mixing of sources.

Two plots were constructed to illustrate the mixing lines from these experiments (Fig. 11a-b). The aromaticity-paraffinicity plot illustrates that if mixing did occur, it would mean that most Madison oils are less than 40% Bakken oil (Fig. 11a). If mixing was occurring extensively, there should be a continuum present between the two groups as seen in Canadian oils (Obermajer et al., 1999; Jiang et al., 2000). Instead there are no oils having between 40-85% Bakken oil in the U.S. Williston Basin. When the ternary plot of Figure 10 is evaluated with

these oil mixes, the mixing lines are inconsistent with the grouping of oils as the mixing line does not coincide with the trends among the 3 principal oil groups (Fig. 11b) nor is a continuum shown between Bakken and Madison oils (Fig. 10). Thus, oil mixing between Madison and Bakken does not appear to be occurring extensively in these oils from the U.S. Williston Basin, whereas it is evident in the Canadian Williston Basin.

Madison-Red River oil mixes show a nonlinear trend based on the ratios employed in Figure 11a. Two oils show commingled Madison – Red River oil characteristics: (a) the Buffalo Creek oil (R2), and (b) the Richey oil (M33). These oils either are mixed Madison-Red River oils or from commingled production. DST oils could be used to assess production allocation for commingled production by construction of mixing curves (Kaufman et al., 1987, 1990) using both light hydrocarbons and higher molecular weight hydrocarbons.

The ternary plot in Figure 10 shows that four of the five Nisku oils correlate to a Bakken source; the other correlates to mixed Bakken-Duperow sources. The Nisku oils in Roosevelt County, MT (N1-N3) and McKenzie County, ND (N4) are the Bakken sourced Nisku oils. Williams (1974) also related the underlying Nisku oils to a Bakken source. While overpressuring of the Bakken Formation has restricted upward expulsion of hydrocarbons except for the mound oils, expulsion downward is not constrained, but rather enhanced by these pressures.

The Duperow oils tend to have higher aromatic contents than Bakken, Winnipegosis, and Red River oils. They also have C₂₂ paraffin predominance and appear to represent a unique source rock unit likely within the Duperow itself (Fig. 5.d.1-2). This was suggested previously by Grantham and Wakefield (1988) based on sterane biomarkers. Peterson (1988) has also suggested dark marine shales and shaly carbonates interbedded in the Duperow and Nisku formations as possible source horizons. Organic-rich, oil-prone Duperow source rocks have been identified in the Western Williston Basin and outside its western boundaries (D. M. Jarvie and R. F. Inden, unpub. data). The Nisku oil (N5) from Hardscrabble field has a characteristic Duperow fingerprint with higher light aromatic content, slightly higher OCPI values, and C₂₂ predominance. This oil is reported as Nisku/Duperow oil by the operator (Table 2) and is either mixed or commingled production.

Interlake oils are variable, correlating with Red River oils, or in one case Winnipegosis or Duperow oils (Fig. 10). It has been substantiated by Osadetz and Snowdon (1995) that the Winnipegosis is a source interval, although Peterson (1988), without citing geochemical evidence, has suggested the Upper Ordovician Stony Mountain and the Middle Devonian Souris River Formations as possible sources of pre-Prairie Middle Devonian and Silurian oils. The Woodrow Field Interlake oil (IN1) in Dawson County, ND and the McCoy Creek (IN2) oils correlate to Red River oils showing low light hydrocarbon concentrations, high OCPI, and C₂₄ predominance. One Nameless Field oil (IN3) groups with Red River oils that show no C₂₄ predominance, but the second Nameless Field oil (IN4) is not Ordovician-like and is likely sourced from the Winnipegosis or the Duperow.

Some of the Red River oils have slightly higher aromatic, e.g., Round Prairie (R10), Kaiser Francis (R8), and Alexander (R12) field oils likely from mixing with aromatic-rich (Madison or Duperow) oil. The Kaiser and Alexander oils do have high OCPI values characteristic of Ordovician oils, but also with some mix or commingling from an aromatic-rich oil.

Pristine Ordovician *G. prisca* sourced oils have GC fingerprints with strong odd-carbon preference in the C₁₁ to C₁₉ paraffin range (Fig. 5.f.2), very low light hydrocarbon contents until high maturity, moderate to low aromatic contents, and often elevated n-C₂₄ paraffin content. This is exhibited by the Stony Mountain (SM1) oil

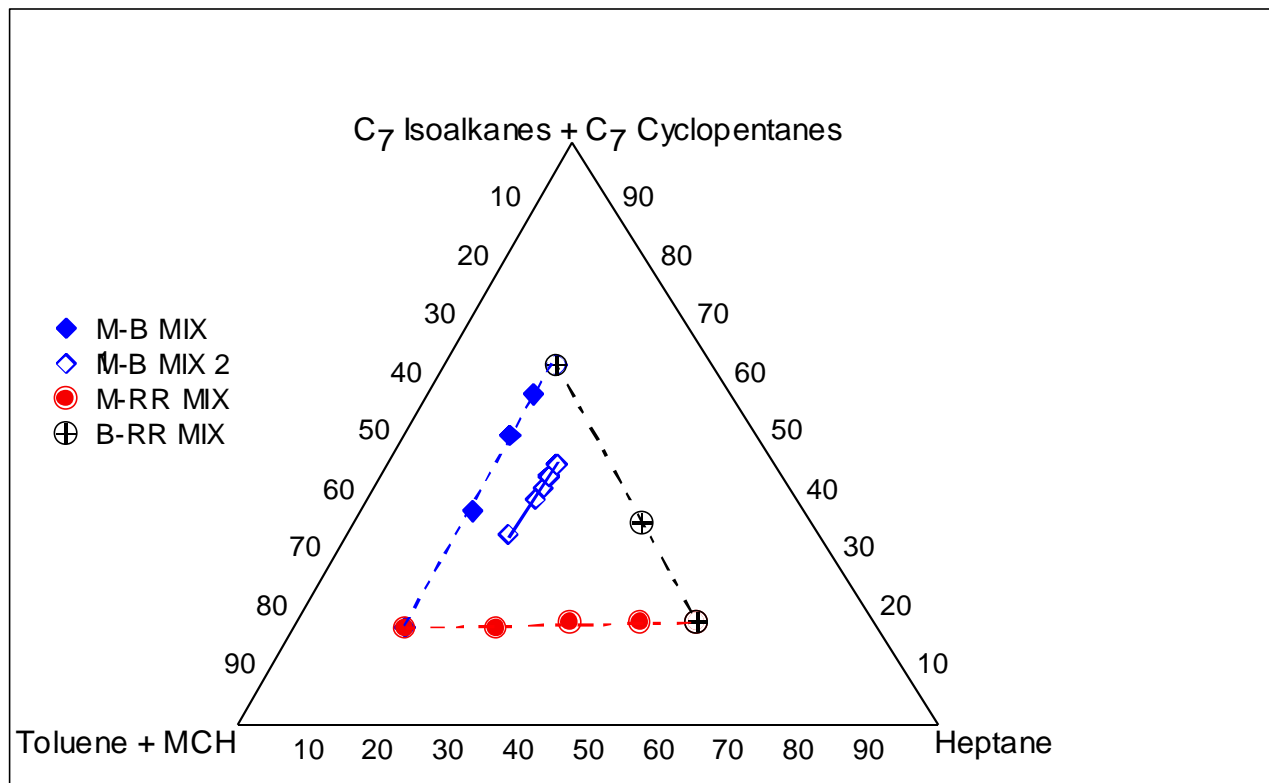
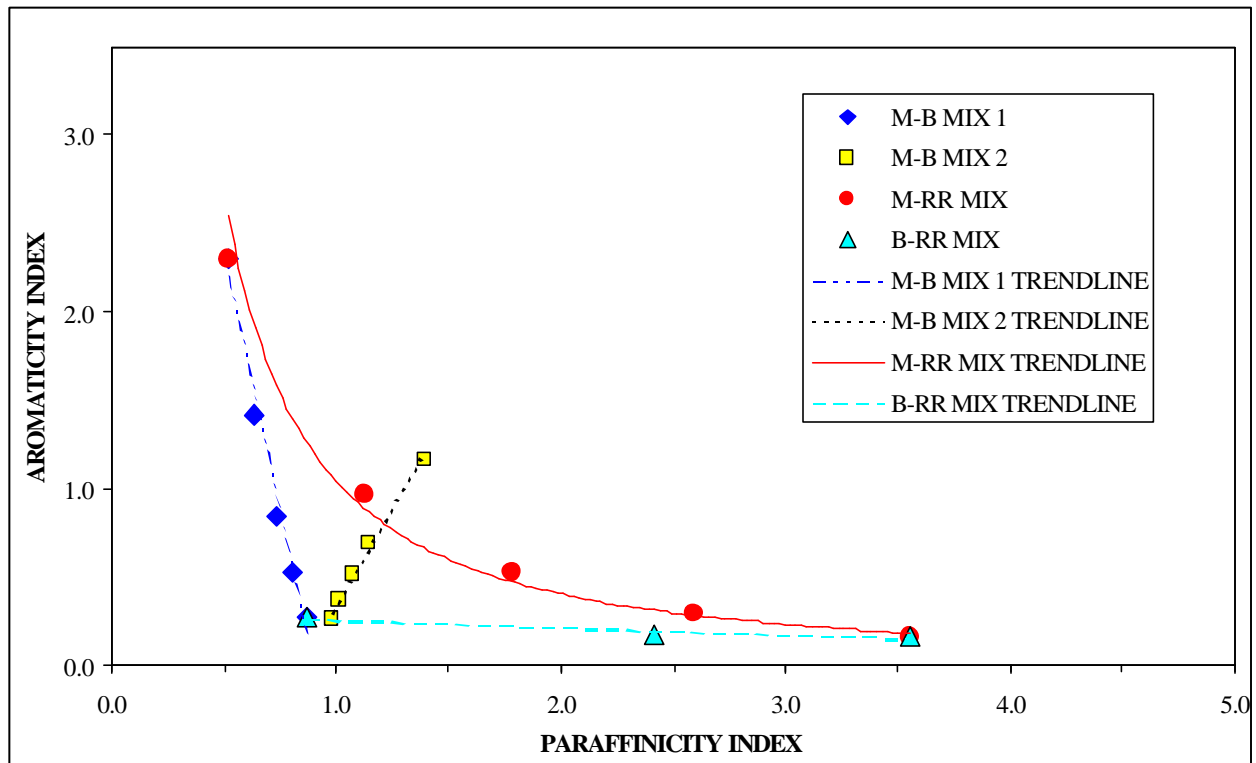


Figure 11. (a) C_7 aromaticity and paraffinicity plot with oil mixing trendlines for Madison-Bakken (M-B), and Bakken-Red River oils (BRR).

as well as the Medicine Pole Hills (R1), Coyote Creek (R3), Gas City (4), Little Beaver (R5-6), Brush Lake (R7), Daneville (R9), and Fairview (R11) Red River oils.

Pristine Ordovician *G. prisca* sourced oils have GC fingerprints with strong odd-carbon preference in the C₁₁ to C₁₉ paraffin range (Fig. 5.f.2), very low light hydrocarbon contents until high maturity, moderate to low aromatic contents, and often elevated n-C₂₄ paraffin content. This is exhibited by the Stony Mountain (SM1) oil as well as the Medicine Pole Hills (R1), Coyote Creek (R3), Gas City (4), Little Beaver (R5-6), Brush Lake (R7), Daneville (R9), and Fairview (R11) Red River oils.

While the Winnipeg was originally proposed as the source of Red River oils by Williams (1974) and Dow (1974), it has been shown more recently that there are Yeoman (Osadetz and Snowdon, 1995) or equivalent Red River sources (Jarvie and Inden, 1997). However, oil prone Winnipeg source rocks similar to Red River sources have been identified in Hettinger and Phillips counties, North Dakota and Montana, respectively (D. M. Jarvie and R. F. Inden, unpub. data). The single Winnipeg oil in this study from Dunn County, ND is correlates to Red River oils, having the classic Ordovician fingerprint with C₂₄ predominance characteristic of Assemblage B oils described by Jacobson et al. (1988).

The Newporte Field Deadwood oil also appears to be unique being highly enriched in paraffinic hydrocarbons. The Deadwood oil was analyzed by high temperature GC and contained high molecular weight paraffins above 65 carbon atoms (n-C₆₅₊) indicative of greater than 5% wax content and low cloud point. Its GC fingerprint and biomarker data suggest a unique source with no indication of the odd carbon preference of the Stony Mountain, Red River and Winnipeg oils and its very low pristane-to-phytane ratio (0.47) is quite different from those oil types. Summons et al. (1988a, b) have shown similar characteristics found in the Deadwood oil to be indicative of Cambrian-age source rocks.

Tyler oils were typed by Williams (1974) and Dow (1974) as intra-Tyler sourced; this has been substantiated by Osadetz and Snowdon (1995), although organic-rich Heath Formation also may also contribute to these oils. Peterson (1988) and Jarvie and Inden (1997) have suggested both Tyler and Heath formations as possible sources of Tyler oils depending on areas where these horizons are present. The Heath Formation does appear to have slightly higher oil potential than the Tyler Formation (Table 2). Tyler oils show considerable variability in both light hydrocarbons and biomarkers as shown by Aram (1985), who found at least 5 subgroups of Tyler oils in the Central Montana Trough.

Lithofacies Assessment of Selected Samples

Hughes et al. (1995) postulated and supported empirically a technique for inferring lithofacies of source rocks from oil chemistry. Using dibenzothiophene-to-phenanthrene and pristane-to-phytane ratios, they were successful in predicting marine carbonates, marls, and shales as well as lacustrine and terrestrial sourced oils, although the separation between marine shales and lacustrine sourced oils was not distinct.

Using this technique, the Madison oils that were analyzed are all inferred to be characteristic of marine carbonate or marly shale source rocks, as is the single Triassic Spearfish oil (Fig. 12). There are two distinct groupings of Madison Group oils based on pristane-to-phytane ratios, dibenzothiophene-to-phenanthrene ratios, and sulfur content. Madison oils farther to the north, either in northeastern or northwestern counties in the North Dakota and Montana, respectively, are derived from carbonate source rocks with high sulfur contents. Madison oils in the central portion of the Williston Basin are likely derived from a marly shale facies with

higher clay contents and lower sulfur contents. The Tolley Field oil (M3 on Fig. 4) is one such oil, suggesting a marly shale source within the Mission Canyon. Biomarker data are very similar for the 2 Madison oil types with the key difference being elevated C₂₃ tricyclic terpanes in one group.

The 4 Lodgepole oils and 2 Bakken oil plots in the marine shale region as does a Nisku oil (Zone 3) further substantiating their correlation.

A Duperow oil plots in Zone 2 apart from both the Winnipegosis and Red River oils suggesting a different source for these oils, i.e., likely in the Duperow itself. Likewise, the single Winnipegosis oil also plots in the marine shale region suggesting a unique source. A Silurian Interlake oil (IN1), which is *G. prisca* Red River type oil, plots in the sulfate-poor lacustrine zone. This is not entirely surprising as these oils have chemical characteristics similar to lacustrine oils, i.e., fairly uniform (polymeric) organic matter composition with higher amounts of carbon and hydrogen than found in more biologically diverse source rocks. The single Tyler oil plots in the mixed shale-carbonate lithofacies zone, although considerable variation has been noted among Tyler lithofacies assessments.

There is also good correlation between sulfur contents and pristane-to-phytane ratios in assessing these different lithofacies, although this does have limitations (Hughes et al., 1995). For example, the higher sulfur oils all have pristane-to-phytane ratios less than 1.00, and very high DBT-to-Phen. ratios indicative of marine carbonate sourced oils.

Marine shale and lacustrine oils or oils from kerogenites such as the Red River oils can be distinctly separated by combining the Hughes et al. (1995) plot with the light hydrocarbon data as shown in Figure 10. Highly paraffinic oils such as *G. prisca*, lacustrine, or those from evaporitic sources, contain high amounts of the normal paraffin, heptane, whereas marine shales have lower amounts of heptane and higher amounts of the dimethylcyclopentanes and isoalkanes due to differences in source material and clay content. Thus, lacustrine oils would plot among the Red River type oils in Figure 10, whereas marine shales would plot with Bakken oil types.

Other Biomarker Data

Biomarker data in combination with GC data was utilized to group Williston oils into 5 oil families (Osadetz and Snowdon, 1995). Madison Group oils all have C₃₅ hopane predominance and very high C₂₄ tetracyclic-to-C₂₆S tricyclic terpane ratios (Jarvie and Walker, 1997). On the other hand, Lodgepole, Bakken, and Nisku oils lack these characteristics, although the extended hopanes are generally weak in Bakken-sourced oils. Comparison of a low maturity Bakken-sourced Lodgepole mound oil to a Mission Canyon (Sherwood) oil in terms of terpane contents clearly illustrates these differences (Fig. 13a, b). Zumberge (1983) also noted differences in the tricyclic terpane biomarkers between Madison and Bakken oils. Osadetz and Snowdon (1995) classified Bakken oils with low sulfur and no C₃₅ hopane predominance as Type "B" oils, whereas the Madison Group oils were their Type "C" oils. They also showed a higher sulfur, Bakken oil type that showed C₃₅ hopane predominance, but without low pristane-to-phytane ratios of the Madison oils (their Type "E" Bakken oils). No Bakken oils were identified as Type "E" oils in this set of 19 Bakken oils. The only Bakken oil having slightly higher sulfur content in this data set was the Stoneview field oil (B16) in Divide County, ND with 0.79% sulfur. All the other Bakken oils were less than 0.50% sulfur and generally less than 0.10%. A single Bakken oil, not included in this data set from the Hummingbird field in Saskatchewan, does have slight C₃₅ hopane predominance indicative of a carbonate or marly shale source rock, but has pristane-to-phytane

greater than 1.00, a very high t12DMCP-to-C₇ ratio, and a toluene-to-C₇ ratios less than 1.00 typical of all the Bakken oils and atypical of any Madison oils in this data set.

Thermal Maturity

Using the C₇ ratio of BeMent et al. (1994) and the equation disclosed by Mango (1997), average generation/expulsion temperatures were calculated (Table 4). This ratio is considered an absolute temperature indicator, but must be considered an average based on being a mix of the same oil of variable maturities. However, when extensive secondary cracking or alteration of oil occurs such as thermo-chemical sulfate reduction, the calculation is invalid. Since no secondary cracking or alteration is evident, the calculated temperatures are valid. While biomarker maturity parameters such as sterane isomerization reactions (R to S), Ts/Tm, and C₂₉Ts/C₂₉Tm are correlated to vitrinite reflectance, they have not been correlated to temperature per se.

Based on the C₇ generation temperature calculation and biomarker maturity parameters, the Lodgepole mound oils were generated under lower thermal stress than other Bakken-sourced oils. The calculated average generation temperatures for Lodgepole oils are 113-115°C, whereas average Bakken oil generation temperatures are about 120°C. The present day Dickinson Lodgepole reservoir temperature is recorded as approximately 107°C (LeFever et al., 1995), which is consistent with the slighter higher temperatures that would be present in the underlying Bakken Formation. Paradoxically, despite the fact that these are referred to as low maturity Bakken oils, sourced from low maturity Bakken rocks, they are excellent quality (44°API). The Bakken rocks underlying the mound oils have low measured vitrinite reflectance values based on the maturity profile from this well, but have relatively high Tmax values (441-445°C). However, they retain relatively high remaining petroleum potentials (450-500 hydrogen indices) indicative of low level conversion of Bakken kerogen (15-30% estimated conversion). The False Bakken rocks in this area yield similar light hydrocarbon fingerprints as the Bakken and have been shown to be organic rich in various areas (D. M. Jarvie and R. F. Inden, unpub. data).

A plot of the average generation temperatures to the ratio of the C₆ hydrocarbons, 2-methylpentane and 3-methylpentane, illustrates the maturity trend among these oils and their increasing generation and expulsion temperatures (Fig. 14a). The oils generated under the lowest thermal stress, i.e., the lowest maturity, are high-sulfur, carbonate-sourced Madison Group oils, especially those oils from north central North Dakota (Burke, Renville, and Bottineau counties). For example, the Glenburn field oil (M9) has a low generation temperature of 108°C and has 2.87% sulfur content.

Prediction of gas-to-oil ratios (GOR) using light hydrocarbon data shows fair correlation (Fig. 14b) (Mango, personal communication). This suggests the possibility of mapping GOR values across the basin from dead oil fingerprints as a complement to PVT testing, particularly when these tests are not economically feasible. This would be applicable only to pristine oil samples, although oil mixes could likely be assessed using a combination of light hydrocarbon data and higher molecular weight GC or biomarker data.

Generation and Expulsion

Hydrocarbon generation is a function of thermal exposure, time, and chemical composition of the organic matter. Organic matter such as the *G. prisca* kukersites of the Ordovician Red River Formation decompose under relatively higher thermal stress than marine carbonates and shales. Typical discrete kinetic models tend to overestimate their decomposition temperatures by 7-10°C, so Gaussian or Nucleation models are preferred

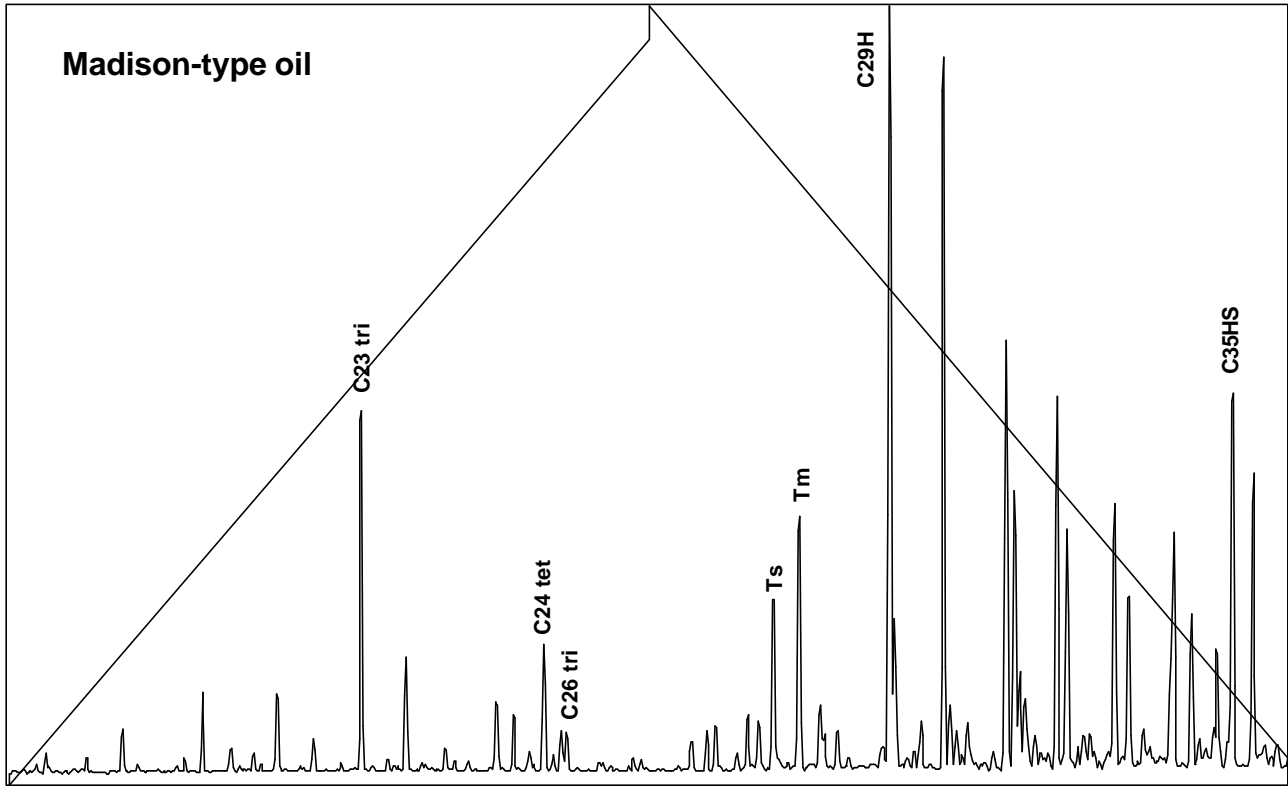
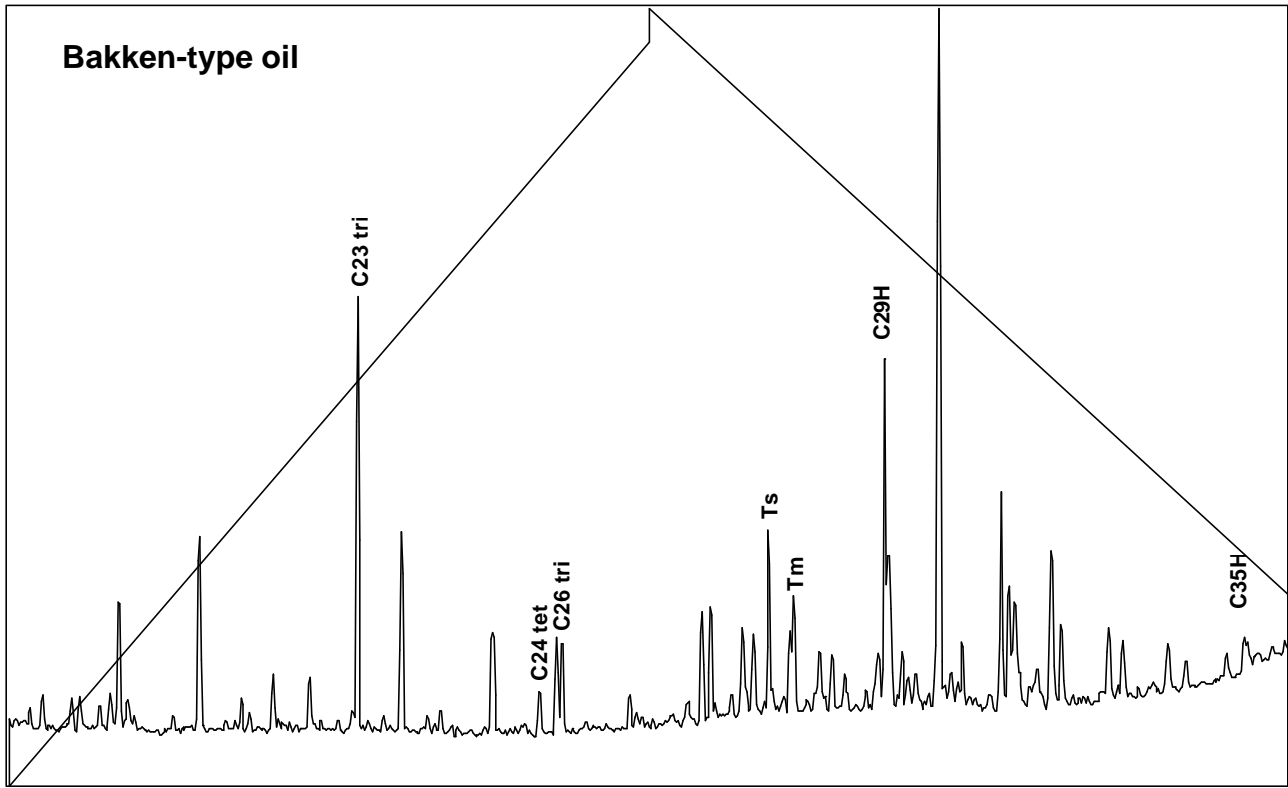


Figure 13. Comparison of saturate fraction terpane biomarker (m/z 191) ion chromatograms: (a) Bakken-sourced Lodgepole mound oil, and (b) Mission Canyon-sourced Sherwood Member oil.

for kinetic modeling of these types of kerogen (Burnham et al., 1996). Because of the polymer-like organic composition consisting almost exclusively of carbon and hydrogen, once it reaches a critical generation temperature, it is rapidly converted to hydrocarbons over a 10-15°C temperature range (Jarvie and Inden, 1997).

On the other hand, sulfur-rich, marine carbonates of the Mission Canyon decompose under much lower thermal stress than either the Bakken or Red River source rocks and have much broader temperature ranges for hydrocarbon generation (Jarvie and Inden, 1997). Thus, wherever Bakken resistivity is high, indicative of oil generation, the younger, shallower, and slightly cooler Madison Group carbonate source rocks are likely also in the oil window due to their more reactive kerogen. If Bakken source rocks are projected to generate at the temperatures reached at depths of 10,000 ft (Price et al., 1984), sulfur-rich, carbonate source rocks would generate at depths from 1000-2000 ft shallower.

The Bakken underlying the Lodgepole mounds has been shown to contain surprisingly high gas and light liquids potential with relatively high amounts of low maturity gas generation. Despite being classified as a highly oil prone kerogen based on its high hydrogen index, approximately 80% of the generated products from the Bakken underlying the Stark County mound oils are in the C₁-C₁₄ hydrocarbon range with of 53% being C₁-C₄ gases based on resolvable hydrocarbons only (Jarvie et al., 1998). This is also consistent with the relatively poor high molecular weight biomarker response from Bakken extracts and oils, and high quality Bakken oils. These results are consistent with the data of Muscio et al. (1994), who showed that Bakken rocks generate surprisingly high amounts of gas at low maturity and Price (oral commun.) and Jarvie et al. (1998), who measured high yields of carbon dioxide during hydrous pyrolysis experiments.

Prairie salt dissolution has been suggested to provide a means for thicker sedimentation of the Bakken Formation underlying these carbonate mounds (LeFever et al., 1995), although a gas seep vent community has been suggested also (Longman, 1996). LeFever et al.'s hypothesis is consistent with the more oxidized organic matter type seen in these rocks, whereas Longman's hypothesis concurs with the early methane and carbon dioxide generation identified in laboratory experiments.

It is obvious from these data that both hydrocarbon and nonhydrocarbon gases are contributing to increased pressures in Bakken Formation source rocks at relatively low thermal maturities. Overpressuring may be causing a retardation in the thermal maturation of Bakken organic matter, although this is highly controversial (Price and Wenger, 1991; Carr, 1999). Osadetz and Snowdon (1995) also suggested that expulsion is delayed from the Bakken until a maturity of ca. 0.90% vitrinite reflectance. In fact the Bakken Formation retains hydrocarbons very well as noted by the retention of high concentrations of light hydrocarbons in 3 year-old Bakken cores (Jarvie and Walker, 1997).

Where the Bakken is overpressured, it is not expelling hydrocarbons upward except where migration pathways by faulting are available or where the generation pressures exceed the fracture thresholds. Bakken expulsion is more likely to be downward because of pressure seal and gradient. Thus, Upper Bakken oil, in the absence of faulting, is likely retained in the Bakken or expelled into the middle Bakken Sanish sand except for the Lodgepole mound oils. The gas-rich Bakken underneath the mound oils has generated sufficient gas to fracture and expel hydrocarbons. Likewise, the lower Bakken is expelling downward into the Nisku based on the correlation to Nisku oils. Lateral migration within the Bakken is limited due to the poor porosity and permeability of Bakken shales, although lateral migration through the Sanish Sand and other permeable horizons, is quite likely.

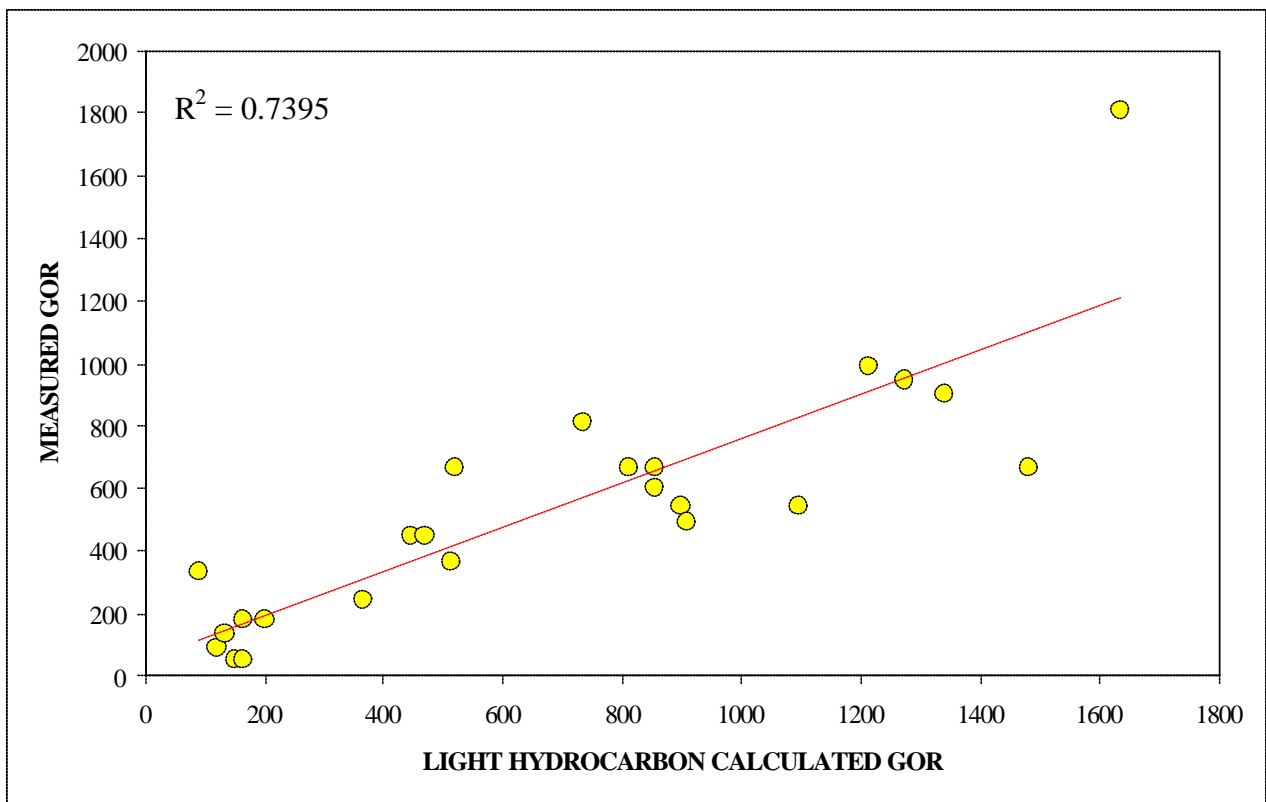
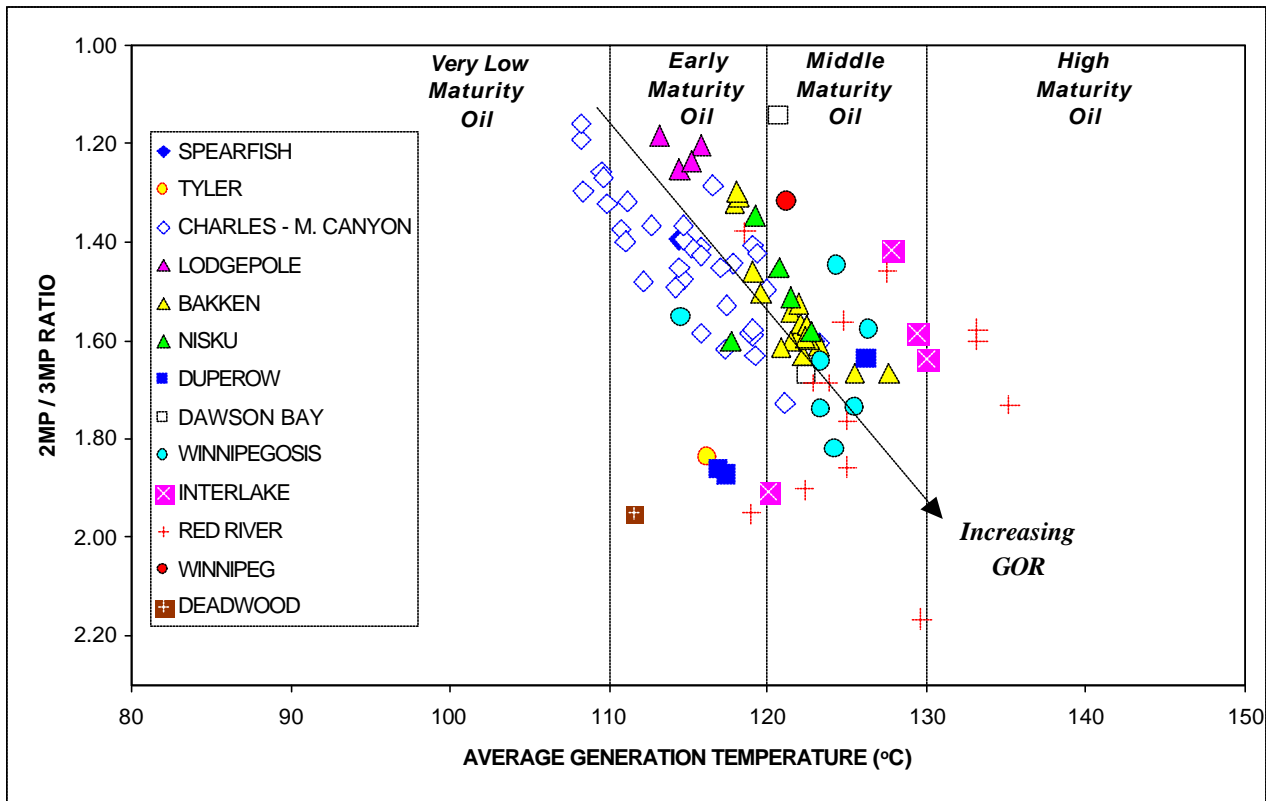


Figure 14. Maturity and GOR trends (a) Light hydrocarbon generation temperature (maturity) trend; (b) calculated GOR values from light hydrocarbon data.

Migration Pathways

There appears to be limited upward migration of hydrocarbons in the U.S. Williston Basin based on the correlation results of this study. There are obvious locations where vertical migration has occurred such as the mound oils and along major faults such as Poplar Dome. The near perfect correlation of Lodgepole mound oils to Bakken sources and the typing of oils at Poplar Dome to mixed Bakken-Madison sources suggests that vertical migration is not extensive based on the lack of correlation of between Madison and Bakken oils elsewhere across the U. S. Williston Basin.

Lateral migration of hydrocarbons from the U.S. to Canadian portion of the Williston Basin traps has been hypothesized because higher maturity source rocks are present in the U.S. Williston Basin. Several observations from this study are relevant to this discussion. First, Canadian Madison oils do appear to be mixes of Madison-Bakken or mostly Bakken oil which is indicative of lateral migration as the Bakken is immature in Canada (Osdatez and Snowdon, 1995). Second, if long distance migration has occurred, it would be expected that the aromatic contents of Madison oils in Canada should be lower as a result of geochromatographic fractionation during migration. This should also be noted in migration-related geochemical parameters such as the nitrogen-bearing carbazole compounds (Li et al., 1995; Larter et al., 1996). Third, the high-sulfur carbonate source rocks of the Madison Group generate under lower thermal stress, so local generation is feasible at temperatures of 90-110°C.

Seals

A key consideration in petroleum systems analysis is the presence and efficiency of seals to preserve hydrocarbons in traps. Dow (1974) and Peterson (1988) outlined the geographic extent of some of these seals and their relationship to oil pools. The lack of correlation of Madison oils with Bakken oils except in certain highly faulted locales demonstrates that seals are effective between the Bakken and Madison as well as other horizons. Peterson (1995) cited geologic problems with a Bakken source of Madison oils, which included the necessity of migration through very efficient seals located throughout the Madison Group. The presence of seals in the Madison also infers the necessity of multiple source horizons within the Madison Group to explain slight variations in Madison oils; this has been substantiated by the presence of 3 organic-rich zones in the Danielson #1 well (Jarvie and Walker, 1997). Further, wherever overpressuring occurs within the Bakken, it is effectively a pressure-sealed system. Benzing and Shook (1996) hypothesized that pressure seals form in the presence of interstitial gas and the Bakken has been shown to generate gas at low maturity. In addition, an overpressured system has significantly increased storage capacity (Holm, 1998) enabling such a system to retain more of its generated products, which will either be expelled in the presence of fractures or further cracked to light hydrocarbons.

Summary of Petroleum Systems

Based on the data compiled for this study, as well as the work of others as noted, the effective and hypothesized petroleum systems in the Williston Basin are summarized in Table 5.

CONCLUSIONS

Whole oil gas chromatographic analysis of dead oil samples clearly elucidates differences in composition among U.S. Williston Basin oils. These differences distinctly segregate oils from the same source rock into a

homologous oil family. Both the light hydrocarbons and C₈₊ hydrocarbons proved effective tools in typing these oils. These data, in conjunction with biomarker data, were particularly effective at evaluating mixed oil types. Using a combination of techniques is essential particularly to evaluate oil mixes, secondary condensate charge, and commingling of production as both the light and heavy compounds will vary depending on source(s) and maturity.

In addition the prediction of oil generation temperatures from light hydrocarbon data is consistent with source rock kinetic data, which shows that sulfur-rich, carbonate oils are generated under lower thermal stress than source rock lithofacies containing low amounts of sulfur. Further, the light hydrocarbon data predicted GOR values with reasonable accuracy given that the oils and GOR values were not from matched samples. This predictive tool will aid mapping of GOR values across a field or basin from fingerprinting of dead oil samples.

Based on the oil geochemistry reported here and extensive published data largely from the geological surveys in Canada and the U.S., the following specific observations on oil families are reported:

1. Madison oils are distinct from Bakken oils indicative of different sources. This is based on 6-ring preference in the C₇ hydrocarbons shown by Madison oils which is evident in Madison source rocks as well as biomarker data, the latter of which demonstrates that Madison Group oils are derived from carbonate or marly shale source rocks.
2. On the basis of laboratory oil mixes, mixing of Madison and Bakken oils does not appear to be extensive in the U.S. Williston Basin. This is supported by incompatible mixing lines between selected end-member oils and the distinct segregation of Madison and Bakken oil families demonstrated in this study. However, Madison and Bakken oils in the Canadian Williston Basin form a continuum suggesting high input of Bakken oil into Madison reservoirs (Jiang et al, 2000).
3. A single Spearfish oil from McHenry County, ND, correlates with Madison Group oils based on its very high aromatic content, low pristane-to-phytane ratio, and carbonate biomarker signature.
4. Lodgepole mound, Bakken, and most of the Nisku oils studied are Bakken-sourced oils with the Lodgepole oils being lower maturity oils than typical Bakken-produced oils. Of particular note is the Lodgepole oil from Divide Field in Sheridan County, Montana, which groups with the Stark County Lodgepole mound oils. One Nisku oil (Hardscrabble, N5) is mixed or commingled Bakken-Duperow sourced oil.
5. Some Madison Group oils in this study are mixed Bakken-Madison sourced oils. These oils are from E. Poplar (Roosevelt, MT) and McGregor Field (Williams, ND). The McGregor oil may have some Duperow input in lieu of, or in addition to, Madison input.
6. Duperow and Winnipegosis oils are different from each other and other oils, but show considerable variability perhaps due to mixing or commingling of production. It is likely that there are separate sources for these oils.
7. Red River oils are rich in normal paraffins. Subgroups of these oils are present and are distinguished by varying sulfur contents, pristane-to-phytane ratios, and C₂₄ predominance, although some of this variation could result from mixing or commingling of oils. The single Winnipeg oil from Dunn County, North Dakota types with the Red River oils having C₂₄ predominance.

8. The four Silurian Interlake oils show variable geochemical characteristics. Two oils (Woodrow and Sheridan oils (IN1-2)) group with Red River oils having strong OCPI values and n-C₂₄ predominance. One Nameless Field oil (IN3) has odd preference but no n-C₂₄ predominance and is similar to the Kaiser Francis Field Red River oil (R8). The other Nameless Field oil (IN4) is very waxy, shows little odd preference, and no n-C₂₄ predominance. It is more similar to Winniepegosis or Duperow oil types.

9. The Cambrian Deadwood oil has characteristics different from Red River and Winnipeg oils. It is a very waxy, low maturity oil with a pristane-to-phytane ratio less than 1. It may be derived from a yet unidentified Winnipeg source, but is more likely derived from a Deadwood source as suggested by Peterson (1995).

10. A single Tyler oil is likely derived from a marly shale source within the Tyler or Heath Formations. These oils have been shown to be quite variable, however (Aram, 1985).

Dedication

This paper is dedicated to Lois Maye Jarvie in celebration of her life (1912-1999) and in appreciation for the care and love extended to her by her brother, R. K. Hoover and his wife, Phyllis.

Acknowledgments

The author wishes to thank Richard F. Inden for involving me in his Williston Basin work and for the collection of “extra” samples when in the field. Gratitude is extended to Conoco Inc. for its release of Lodgepole mound oils and Bakken rock samples as well as the Geological Survey of Canada for supplying samples and data on oils from Canadian Madison reservoirs for comparison to oils in this study. Oil samples from Amoco, Chevron, Unocal, and the USGS/NDGS were greatly appreciated. The detailed reviews by Mark Longman, Frank Mango, C. W. Keighin, and an unidentified reviewer helped significantly in the improvement of the manuscript. Frank Mango’s help with the GOR research was greatly appreciated. A special thanks is extended to my Humble colleagues for their help and patience.

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TABLE 1

Cumulative Williston Basin Oil Production North Dakota Only (through 1996)		
Reservoir	Barrels of Oil	Percentage of Total
Winnipeg/Deadwood	300,000	0.02%
Red River B	5,300,000	0.43%
Red River	103,800,000	8.48%
Gunton	140,000	0.01%
Stonewall	8,700,000	0.71%
Silurian	54,100,000	4.42%
Winnepegosis	6,000,000	0.49%
Dawson Bay	3,400,000	0.28%
Duperow	120,500,000	9.84%
Birdbear (Nisku)	4,800,000	0.39%
Bakken (Sanish)	39,300,000	3.21%
Lodgepole	6,600,000	0.54%
Madison	752,800,000	61.47%
Tyler	72,000,000	5.88%
Spearfish/Madison	46,500,000	3.80%
Spearfish	400,000	0.03%
Total (through 1996)	1,224,640,000	100.00%

TABLE 2

Map No.	Formation	Member	Age	Well Name	Depth (feet)	Location	Field	County	State	API Gravity	Sulfur (wt.%)
S1	SPEARFISH		CRETACEOUS	N8-77	na	48-77208 x 100.78803	RUSSEL	BOTTINEAU	ND	na	0.59
T1	TYLER		PENNSLVANIAN	M8-77	na	46.61168 x 108.38045	na	na	MT	28.9	1.03
M1	MADISON	CHARLES	MISSISSIPPIAN	na	na	20-T22N-R47E	COW CREEK	MCCONE	MT	na	0.36
M2	MADISON		MISSISSIPPIAN	AL PEDERSON #1	9224-9249	20-T158N-R95W	MCGREGOR	WILLIAMS	ND	39	0.30
M3	MADISON	SHERWOOD	MISSISSIPPIAN	COLTVET #1	5222-5232	09-T161N-R86W	TOLLEY FIELD	RENVILLE	ND	na	1.03
M4	MADISON	RATCLIFFE	MISSISSIPPIAN	MARY SAUBAK #1-19	5384-5975	19-T32N-R453	NORTHLUSTRE	VALLEY	MT	na	1.06
M5	MADISON	MISSION CANYON BC	MISSISSIPPIAN	KLATT #1-19-2A	9786-9814	19-T145N-R97W	LITTLE KNIFE	DUNN	ND	45.2	0.32
M6	MADISON		MISSISSIPPIAN	OLSON #24-1	7800-7804	24-T160N-R96W	HAMLET	DIVIDE	ND	38.5	0.42
M7	MADISON	MISSION CANYON	MISSISSIPPIAN	LIND #1-13-3C	9734-9792	na	LITTLE KNIFE	MCKENZIE	ND	44.5	0.32
M8	MADISON	MISSION CANYON	MISSISSIPPIAN	SABROSKY #4-31-4C	9682-9758	31-T145N-R97W	LITTLE KNIFE	DUNN	ND	44.7	0.29
M9	MADISON	MISSION CANYON	MISSISSIPPIAN	A.E. OBERG #4	4514-4577	18-T158N-R81W	GLENBURN	RENVILLE	ND	25.1	2.87
M10	MADISON	MISSION CANYON	MISSISSIPPIAN	WILEY #1	4086-4097	19-T161N-R81W	WILEY	BOTTINEAU	ND	26.4	2.53
M11	MADISON	SHERWOOD	MISSISSIPPIAN	DAVIDSON #1	4907-4919	19-T160N-R84W	N. GRAND	RENVILLE	ND	na	2.58
M12	MADISON	SHERWOOD	MISSISSIPPIAN	OBERHOTZTER #1	4893-4914	04-T159N-R84W	CHOLA	RENVILLE	ND	na	1.90
M13	MADISON	L. RATCLIFFE	MISSISSIPPIAN	Haugen-Peal #1	na	18-T37N-R583	FLAT LAKE	SHERIDAN	MT	na	2.13
M14	MADISON	MISSION CANYON	MISSISSIPPIAN	ROUGH CREEK UNIT #1	na	13-T148N-R98W	ROUGH CREEK	MCKENZIE	ND	na	0.72
M15	MADISON		MISSISSIPPIAN	METZGER USA #1-19	na	24-T153N-R102W	HARDSCRABBLE	WILLIAMS	ND	35.8	0.45
M16	MADISON		MISSISSIPPIAN	#1 Authur Inversion	8350-8390	NENE2-155N-96W	BEAVER LODGE	WILLIAMS	ND	41	0.24
M17	MADISON		MISSISSIPPIAN	#1 Gilt Edge Realty Co.	7180-7212	NWSW25-161N-92W	FOOTHILLS	BURKE	ND	39	0.98
M18	MADISON		MISSISSIPPIAN	#1 Village of Lignite	6248-6259	NENW12-162N-92W	RIVAL	BURKE	ND	38.6	0.43
M19	MADISON		MISSISSIPPIAN	#1 Scoria Unit	9213-9258	NENE10-139N-101W	SCORIA	BILLINGS	ND	41.7	0.41
M20	MADISON		MISSISSIPPIAN	#2 Aubrey Harkness	957-3978	SWSE27-164N-84W	ELMORE	RENVILLE	ND	33.5	1.87
M21	MADISON		MISSISSIPPIAN	na	na	4-154N-96W	CAPA	WILLIAMS	ND	40.4	0.27
M22	MADISON		MISSISSIPPIAN	na	na	152N-95W	HAWKEYE	MCKENZIE	ND	38.6	0.47
M23	MADISON		MISSISSIPPIAN	#1 Mabel L. Doe	6420-6427	11-T161N-91W	N.E. FOOTHILLS	BURKE	ND	35.8	0.85
M24	MADISON		MISSISSIPPIAN	#1 Baukol-Noonan Inc.	na	10-T162-95W	BAUKOL WILDCAT	DIVIDE	ND	39	0.60
M25	MADISON		MISSISSIPPIAN	#1-A Clarence Lund	4890-4896	33-T162N-85W	MOUSE RIVER PARK	RENVILLE	ND	28.6	na
M26	MADISON		MISSISSIPPIAN	#1 Gehrke Heirs	5828-5851	T162N-90W	WOUBURN	BURKE	ND	35.2	1.19
M27	MADISON		MISSISSIPPIAN	#1 Leo E. Johnson	6776-7100	7-T157N-87W	S.W. AURELLA	BOTTINEAU	ND	28.9	na
M28	MADISON		MISSISSIPPIAN	#1-19-2A Klatt	9786-9814	19-T145N-97W	LITTLE AURELLA	DUNN	ND	43.4	0.39
M29	MADISON		MISSISSIPPIAN	#1-23 State	9278-9352	23-T141N-101W	T.R.	BILLINGS	ND	41.7	0.43
M30	MADISON		MISSISSIPPIAN	#1-A McKinnon	6555-6585	9-T37N-57E	FLAT LAKE	SHERIDAN	MT	31.9	0.99
M31	MADISON		MISSISSIPPIAN	#11 Unit	5721-5796	10-T28N-51E	E. POPLAR	ROOSEVELT	ND	40.4	0.30
M32	MADISON		MISSISSIPPIAN	na	6442-6541	18-T37N-58E	FLAT LAKE	SHERIDAN	MT	28.6	1.49
M33	MADISON		MISSISSIPPIAN	na	na	24-T23N-49E	RICHEY	MCCONE	MT	41.3	0.48
M34	MADISON	CHARLES	MISSISSIPPIAN	ELOEK #2	na	na	WOODROW	DAWSON	MT	na	na
M35	MADISON	CHARLES	MISSISSIPPIAN	EPU #112	na	na	E. POPLAR	ROOSEVELT	MT	na	na
M36	MADISON	CHARLES	MISSISSIPPIAN	EPU #105	na	na	E. POPLAR	ROOSEVELT	MT	na	na
M37	MADISON	MISSION CANYON	MISSISSIPPIAN	USA 23-22-41	9104-9180	33-T148N-104W	MONDAK	MCKENZIE	ND	na	na
M38	MADISON	MISSION CANYON	MISSISSIPPIAN	KLANDL 43-26	8812-9024	26-T148N-105W	MONDAK	MCKENZIE	ND	na	na
L1	LODGEPOLE		MISSISSIPPIAN	HAAVEN 12-24	8404-8444	24-T34N-58E	DIVIDE	SHERIDAN	MT	na	na
L2	LODGEPOLE		MISSISSIPPIAN	KNOPIK 1-11	na	11-T139-97W	ELAND	STARK	ND	na	na
L3	LODGEPOLE		MISSISSIPPIAN	KDRAMAS #75	na	31-T140N-96W	DICKINSON DEEP	STARK	ND	na	na
L4	LODGEPOLE		MISSISSIPPIAN	KUNTZ 2-1	na	2-T139N-97W	DUCK CREEK	STARK	ND	na	na
B1	BAKKEN		DEVONIAN	#1 B.E. Hove	9833-9925	2-T154N-95W	HOFFLUND	WILLIAMS	ND	43.8	0.40
B2	BAKKEN	SANISH	DEVONIAN	#1 Brenna-Lacey	10330-10435	1-T152N-95W	ANTELOPE	MCKENZIE	ND	45.4	0.48
B3	BAKKEN	SANISH	DEVONIAN	#1 F.E. Weedeman TR	10282-10445	32-T153N-94W	ANTELOPE	MCKENZIE	ND	45.7	0.03
B4	BAKKEN	SANISH	DEVONIAN	#1 Rose	10606-10615	33-T152N-94W	ANTELOPE	MCKENZIE	ND	45	0.04
B5	BAKKEN	SANISH	DEVONIAN	Gudbranso N-1	10650-10660	34-T152N-94W	ANTELOPE	MCKENZIE	ND	46	0.04
B6	BAKKEN		DEVONIAN	Federal 11-26H	11094-13145 HOR	26-T146N-104W	BICENTENNIAL	MCKENZIE	ND	39.6	0.06
B7	BAKKEN		DEVONIAN	MOI 41-19H	10868-12385 HOR	19-T144N-103W	BICENTENNIAL	MCKENZIE	ND	40	0.04
B8	BAKKEN		DEVONIAN	MOI 33-19	11200-12712 HOR	19-T145N-103W	BICENTENNIAL	MCKENZIE	ND	40.1	0.06
B9	BAKKEN		DEVONIAN	#3 Short COM.	10386-12696 HOR	26-T143N-102W	ELKHORN RANCH	BILLINGS	ND	42.8	0.05
B10	BAKKEN		DEVONIAN	MOI 44-25H	10660-13150 HOR	25-T142N-102W	ELKHORN RANCH	BILLINGS	ND	40	0.03
B11	BAKKEN		DEVONIAN	MOI 44-7H	11226-14330 HOR	7-T146N-102W	PIERRE CREEK	MCKENZIE	ND	41	0.04
B12	BAKKEN		DEVONIAN	MOI 13-1H	10977-12494 HOR	1-T146N-103W	PIERRE CREEK	MCKENZIE	ND	41	0.05
B13	BAKKEN-THREE FORKS		DEVONIAN	T.G. DOROUGH "C" NCT-1	10092-10164	3-T153N-95W	CHARISON	MCKENZIE	ND	45.6	0.03
B14	BAKKEN		DEVONIAN	MOI 41-17H	10400-12802	17-T144W-102W	BUCKHORN	BILLINGS	ND	40	0.04
B15	BAKKEN		DEVONIAN	MOI 34-21H	10839-13221 HOR	21-T146N-104W	SQUAW GAP	MCKENZIE	ND	39.7	0.06
B16	BAKKEN		DEVONIAN	U. DEV. / L. MISS. HOLTE BND #1	na	31-T161N-R94W	STONEVIEW	DIVIDE	ND	40.9	0.79
B17	BAKKEN		DEVONIAN	U. DEV. / L. MISS. FEDERAL #6-1	10419-10431	06-T143N-R101W	ELKHORN RANCH	BILLINGS	ND	45.7	0.14
B18	BAKKEN		DEVONIAN	MOI 41-5H	10775-12950 HOR	5-T141N-101W	DEMORES	BILLINGS	ND	na	na
B19	BAKKEN		DEVONIAN	MOI 24-35H	10543-14001 HOR	35-T143N-101W	ELKHORN RANCH	BILLINGS	ND	na	na
N1	NISKU		DEVONIAN	MCKEE #1	na	13-T30N-R47E	na	ROOSEVELT	MT	na	na
N2	NISKU		DEVONIAN	MULE CREEK #1	7620-7625	20-T31N-R48W	N. TULE CREEK	ROOSEVELT	MT	na	0.17
N3	NISKU		DEVONIAN	SLETVOLD #1	7660-7692	18-T30N-R48E	TULE CREEK	ROOSEVELT	MT	na	0.11
N4	NISKU		DEVONIAN	DEER PASS #20-2	na	20-T153N-R101W	INDIAN HILL	MCKENZIE	ND	38.7	0.09
N5	NISKU/DUPEROW		DEVONIAN	HABEMEYER #33-15	na	13-T153N-R102W	HARDSCRABBLE	WILLIAMS	ND	37.1	na
D1	DUPEROW		DEVONIAN	PEDERSON #5-24-4A	11032-11050	2-T153N-R102W	HARDSCRABBLE	WILLIAMS	ND	35.3	0.13
D2	DUPEROW		MISSISSIPPIAN	ZABOLOTYNY OBSERV #4-3-2D	na	03-T144N-R98W	LITTLE KNIFE	BILLINGS	ND	40.7	0.06
D3	DUPEROW		DEVONIAN	ERICKSON #4-25	na	25-T153N-R102W	HARDSCRABBLE	WILLIAMS	ND	39.7	0.18
DB1	DAWSON BAY		DEVONIAN	PEDERSON #1	na	18-T158N-R95W	TEMPLE	WILLIAMS	ND	42.9	0.13
DB2	DAWSON BAY		DEVONIAN	NEVINE #1	na	08-T23N-R553	LAMBERT	RICHLAND	MT	na	0.40
WP1	WINNIPEGOSIS		DEVONIAN	WILDROSE #36-11	10493-10505	36-T161N-R98W	MORAINES	DIVIDE	ND	na	0.11
WP2	WINNIPEGOSIS		DEVONIAN	OYLOE #1	11790-11824	07-T154N-R103W	ROUND PRAIRIE	WILLIAMS	ND	na	0.12
WP3	WINNIPEGOSIS		DEVONIAN	GOLDEN #34X-34	8310-8313	34-T161N-R87W	SHELL PINNACLE	RENVILLE	ND	29.1	0.45
WP4	WINNIPEGOSIS		DEVONIAN	PEDERSON #4	na	18-T158N-R95W	TEMPLE	WILLIAMS	ND	42.8	0.24
WP5	WINNIPEGOSIS		DEVONIAN	NYGUARD	10832-10840	35-T160N-R96W	HAMLET	DIVIDE	ND	45.2	0.85
WP6	WINNIPEGOSIS		DEVONIAN	BESSIE CRUSCH #1-10-2A	11430-11440	10-T28N-R58E	N. BAINVILLE	ROOSEVELT	ND	na	na
WP7	WINNIPEGOSIS		DEVONIAN	TOTAL STATE #22-36	11048-11058	36-T159N-R96E	TEMPLE	WILLIAMS	ND	na	0.10
IN1	INTERLAKE		SILURIAN	NPG-NCT #12	9179-9204	17-T16N-R54E	WOODROW	DAWSON	MT	na	na
IN2	INTERLAKE		SILURIAN	TANGE #1	na	20-T36N-R53E	MCCOY CREEK	SHERIDAN	MT	na	0.29
IN3	INTERLAKE		SILURIAN	LINDHECKER #1-35-4D	13150-13221	35-T151N-R102W	NAMELESS	MCKENZIE	ND	na	0.21
IN4	INTERLAKE		SILURIAN	MIRACHEK #1-34-1C	11094-11134	34-T151N-R102W	NAMELESS	MCKENZIE	ND	na	na
SM1	STONY MOUNTAIN		ORDOVICIAN	#43X-19	8958-8978	19-T12N-R57E	PINE	WIBAUX	MT	na	0.26
R1	RED RIVER		ORDOVICIAN	SUSOG WICK #1-X	9381-9481	15-T130N-R104W	MEDICINE POLE HILLS	BOWMAN	ND	na	0.24
R2	RED RIVER		ORDOVICIAN	SCHANK #1	10216-10226	15-T137N-R92E	BUFFALO CREEK	STARK	ND	na	0.49
R3	RED RIVER		ORDOVICIAN	MILLER #1-62	9776-9806	21-T13N-R104W	COYOTE	BOWMAN	ND	na	0.22
R4	RED RIVER		ORDOVICIAN	#44-34	8858-8860	34-T14N-R55E	GAS CITY	DAWSON	MT	na	0.22
R5	RED RIVER		ORDOVICIAN	#42-30	8459-8477	30-T04N-R62E	E. LITTLE BEAVER	FALLON	MT	na	0.66
R6	RED RIVER		ORDOVICIAN	#33-30	8312-14835	30-T04N-R62E	LITTLE BEAVER	FALLON	MT	na	0.67
R7	RED RIVER		ORDOVICIAN	MELBY #3-1	11407-11469	11-T33N-R55E	BRUSH LAKE	SHERIDAN	MT	na	0.31
R8	RED RIVER		ORDOVICIAN	AGRE #2-22	12792-12806	22-T158N-R95W	KAISER FRANCIS	WILLIAMS	ND	47.4	0.21
R9	RED RIVER		ORDOVICIAN	ANDERSON STATE #1-30	11158-11194	25-T161N-R103W	DANEVILLE	DIVIDE	ND	38.1	0.20
R10	RED RIVER		ORDOVICIAN	BND-OYLOE #1-A	13036-13046	07-T154N-R103W	ROUND PRAIRIE	WILLIAMS	ND	40.6	0.11
R11	RED RIVER		ORDOVICIAN	HUNTER #1	12613-12698	24-T25N-R58E	FAIRVIEW	RICHLAND	MT	na	0.53
R12	RED RIVER		MISSISSIPPIAN	FLB #24-1	13670-13755	24-T151N-R101W	ALEXANDER	MCKENZIE	ND	na	0.62
R13											

TABLE 3

Formation	Age	Average TOC (wt.%)	Average Hydrogen Index (mg HC/g TOC)	Reference
Winnipeg	L. Ordovician	1.68	420	This paper
Icebox (Winnipeg)	L. Ordovician	1.55	520	Osadetz and Snowdon, 1995
Yeoman	Ordovician	9.07	728	Osadetz and Snowdon, 1995
Red River	Ordovician	7.13	664	This paper
Brightholme (M. Winnipegosis)	L. Devonian	7.38	515	Osadetz and Snowdon, 1995
Winnipegosis	L. Devonian	0.59	120	Osadetz and Snowdon, 1995
Duperow	Devonian	3.02	342	This paper
Bakken	Dev.-Miss.	12.57	481	Price et al., 1984 (immature only)
Bakken	Dev.-Miss.	11.08	401	Muscio, 1994 (immature only)
Lower Bakken	Dev.-Miss.	17.63	410	Osadetz and Snowdon, 1995
Upper Bakken	Dev.-Miss.	11.77	399	Osadetz and Snowdon, 1995
Lodgepole	Mississippian	5.49	401	Osadetz and Snowdon, 1995
L. Mission Canyon	Mississippian	1.96	394	Jarvie and Walker, 1997
M. Mission Canyon	Mississippian	8.50	300	Jarvie and Walker, 1997
U. Mission Canyon	Mississippian	1.92	273	Jarvie and Walker, 1997
Ratcliffe	Mississippian	1.83	378	This paper
Tyler	Pennsylvanian	0.80	na	Williams, 1974
Tyler	Pennsylvanian	6.08	174	This paper
Heath	Pennsylvanian	2.68	na	Williams, 1974
Heath	Pennsylvanian	5.83	268	This paper
Heath	Pennsylvanian	6.99	518	Cole and Drozd, 1994 (Central Montana)

TABLE 4

Map No.	FORMATION	Pr / Ph	Pr / C17	Ph / C18	OCPI	DBT / Phen.	C7/MCH	TOL/C7	2MP/3MP	Ctemp (°C)	Sum of C7 Hydrocarbons		
											n-C7 (P1)	Tol. and MCH (N16)	MHs, DMHs, DMCPS (P2+M25+N15) (%)
S1	SPEARFISH	0.95	0.40	0.44	1.05	3.12	0.97	1.05	1.39	114	20%	41%	40%
T1	TYLER	0.95	1.21	1.51	1.10	0.37	0.90	2.25	1.30	116	20%	23%	52%
M1	MADISON	2.52	0.08	0.11	1.36	nd	3.26	0.22	1.73	121	50%	26%	24%
M2	MADISON	1.07	0.48	0.52	1.02	nd	1.20	0.47	1.44	118	22%	28%	50%
M3	MADISON	1.03	2.73	3.16	0.65	0.37	0.19	0.79	0.17	150	3%	18%	79%
M4	MADISON	1.25	0.82	0.73	1.06	nd	0.66	0.86	1.37	111	17%	40%	44%
M5	MADISON	1.14	0.35	0.35	1.03	nd	0.89	0.95	1.60	123	21%	43%	36%
M6	MADISON	1.00	0.45	0.50	1.01	nd	0.91	0.99	1.41	116	20%	42%	38%
M7	MADISON	1.09	0.35	0.36	1.01	nd	0.86	1.02	1.60	123	21%	45%	34%
M8	MADISON	0.97	0.34	0.39	1.03	nd	0.93	1.06	1.59	123	21%	45%	34%
M9	MADISON	0.52	0.28	0.54	0.99	nd	1.39	1.21	1.30	108	23%	45%	32%
M10	MADISON	0.55	0.28	0.53	0.98	nd	1.18	1.47	1.40	111	21%	48%	31%
M11	MADISON	0.54	0.27	0.53	0.99	nd	0.93	1.52	1.32	110	19%	51%	30%
M12	MADISON	0.60	0.29	0.47	1.00	nd	0.48	1.64	1.19	108	14%	54%	32%
M13	MADISON	0.79	0.49	0.67	1.03	nd	1.21	1.97	1.25	110	17%	48%	35%
M14	MADISON	1.21	0.25	0.25	1.07	nd	0.52	2.32	1.41	119	16%	67%	17%
M15	MADISON	0.78	0.31	0.42	1.01	nd	0.56	2.99	1.48	115	14%	67%	19%
M16	MADISON	1.01	0.30	0.33	1.10	2.63	0.84	1.07	1.50	120	21%	47%	32%
M17	MADISON	0.88	0.38	0.47	1.11	nd	0.88	1.21	1.41	115	19%	44%	37%
M18	MADISON	0.98	0.33	0.38	1.11	nd	0.82	1.22	1.45	117	20%	45%	32%
M19	MADISON	0.73	0.28	0.39	1.04	nd	0.70	1.98	1.59	119	17%	59%	24%
M20	MADISON	0.62	0.29	0.49	1.06	2.05	1.16	1.32	1.36	113	21%	47%	32%
M21	MADISON	1.05	0.32	0.33	1.08	nd	0.80	1.15	1.42	119	20%	49%	31%
M22	MADISON	0.98	0.32	0.35	1.10	7.05	0.73	1.64	1.28	117	19%	56%	26%
M23	MADISON	0.94	0.46	0.51	1.05	nd	0.91	1.37	1.39	115	18%	44%	38%
M24	MADISON	0.73	0.32	0.46	1.07	7.17	0.70	1.53	1.45	114	18%	54%	28%
M25	MADISON	0.58	0.32	0.56	1.03	nd	1.07	1.07	1.52	117	21%	51%	28%
M26	MADISON	0.93	0.43	0.50	1.08	nd	0.97	1.36	1.37	115	18%	44%	38%
M27	MADISON	0.60	0.29	0.48	1.01	nd	0.82	1.79	1.32	111	18%	55%	27%
M28	MADISON	1.09	0.37	0.36	1.08	nd	0.85	1.07	1.58	122	20%	46%	34%
M29	MADISON	0.84	0.32	0.41	1.06	nd	0.68	2.11	1.59	119	17%	60%	23%
M30	MADISON	1.10	0.45	0.43	1.05	nd	0.80	1.94	1.48	112	15%	48%	37%
M31	MADISON	1.13	0.44	0.45	1.13	nd	1.13	2.20	1.38	119	28%	30%	42%
M32	MADISON	0.74	0.44	0.63	1.07	nd	1.18	1.98	1.16	108	17%	49%	34%
M33	MADISON	0.95	0.20	0.34	1.62	nd	1.23	0.80	1.62	117	29%	47%	23%
M34	MADISON	0.86	0.22	0.31	1.21	nd	0.76	1.75	1.59	116	19%	59%	21%
M35	MADISON	1.09	0.44	0.46	1.14	nd	1.08	0.39	1.53	117	27%	35%	38%
M36	MADISON	1.10	0.45	0.47	1.14	nd	1.11	0.14	1.63	119	30%	31%	39%
M37	MADISON	0.85	0.35	0.42	1.02	nd	0.48	2.28	1.49	114	15%	65%	20%
M38	MADISON	0.78	0.32	0.40	0.97	nd	0.40	2.40	1.43	116	13%	64%	23%
L1	LODGEPOLE	2.02	0.76	0.48	1.27	0.12	1.06	0.32	1.18	113	15%	18%	67%
L2	LODGEPOLE	2.53	0.71	0.36	1.31	0.26	0.96	0.21	1.25	114	15%	18%	67%
L3	LODGEPOLE	2.29	0.94	0.50	1.25	0.33	1.00	0.24	1.20	116	14%	17%	68%
L4	LODGEPOLE	2.32	0.88	0.47	1.25	0.31	0.97	0.27	1.23	115	14%	19%	67%
B1	BAKKEN	1.80	0.45	0.33	1.23	nd	1.22	0.31	1.63	122	25%	29%	46%
B2	BAKKEN	1.82	0.50	0.35	1.29	nd	1.28	0.31	1.54	121	27%	29%	44%
B3	BAKKEN	1.60	0.38	0.29	1.24	nd	1.29	0.34	1.61	123	26%	29%	44%
B4	BAKKEN	1.50	0.44	0.36	1.23	0.04	1.22	0.28	1.59	122	26%	28%	47%
B5	BAKKEN	1.67	0.43	0.32	1.24	nd	1.28	0.28	1.57	122	25%	27%	48%
B6	BAKKEN	1.51	0.79	0.63	1.20	0.16	0.98	0.26	1.32	118	18%	23%	60%
B7	BAKKEN	1.71	0.63	0.45	1.21	nd	0.99	0.21	1.51	121	21%	26%	53%
B8	BAKKEN	1.56	0.75	0.58	1.23	nd	0.98	0.22	1.31	118	20%	24%	56%
B9	BAKKEN	1.63	0.59	0.43	1.19	nd	1.02	0.24	1.60	121	23%	28%	48%
B10	BAKKEN	1.58	0.57	0.43	1.20	nd	1.04	0.25	1.61	121	23%	28%	48%
B11	BAKKEN	1.52	0.54	0.44	1.23	0.11	1.00	0.27	1.57	123	22%	28%	51%
B12	BAKKEN	1.47	0.52	0.44	1.24	nd	1.16	0.22	1.57	123	24%	26%	50%
B13	BAKKEN	1.33	0.45	0.35	1.23	nd	1.26	0.28	1.60	123	26%	28%	47%
B14	BAKKEN	1.58	0.62	0.47	1.20	nd	0.97	0.25	1.52	122	22%	29%	49%
B15	BAKKEN	1.48	0.64	0.68	1.19	nd	0.97	0.29	1.29	118	16%	21%	62%
B16	BAKKEN	1.53	0.40	0.35	1.04	nd	1.28	0.25	1.46	119	24%	25%	50%
B17	BAKKEN	1.77	0.56	0.40	1.05	nd	0.99	0.27	1.67	126	24%	31%	45%
B18	BAKKEN	1.76	0.69	0.47	1.22	nd	0.89	0.24	1.59	122	21%	29%	50%
B19	BAKKEN	1.67	0.60	0.43	1.23	nd	1.02	0.27	1.67	128	26%	32%	42%
N1	NISKU	2.06	0.80	0.46	1.12	nd	0.95	0.44	1.45	121	19%	28%	53%
N2	NISKU	1.93	0.88	0.54	2.51	1.61	1.08	0.45	1.51	121	19%	26%	55%
N3	NISKU	1.63	0.72	0.54	1.07	nd	1.11	0.45	1.58	123	22%	29%	49%
N4	NISKU	1.54	0.78	0.61	1.11	nd	1.08	0.31	1.35	119	19%	23%	58%
N5	NISKU/DUPEROW	1.00	0.25	0.28	1.01	nd	1.33	0.63	1.60	118	25%	34%	41%
D1	DUPEROW	0.07	0.01	0.18	1.68	nd	1.53	0.83	1.86	117	29%	43%	28%
D2	DUPEROW	1.40	0.17	0.16	1.19	0.09	0.95	0.88	1.64	126	26%	50%	25%
D3	DUPEROW	0.90	0.17	0.21	0.99	nd	1.47	0.77	1.87	117	29%	42%	28%
DB1	DAWSON BAY	1.20	0.14	0.18	1.13	0.79	1.16	0.72	1.67	122	29%	46%	25%
DB2	DAWSON BAY	1.24	0.78	0.92	1.20	0.11	1.03	0.09	1.14	121	25%	27%	49%
WP1	WINNIPEGOSIS	0.22	0.19	0.87	0.63	nd	1.36	0.82	1.64	123	24%	38%	38%
WP2	WINNIPEGOSIS	1.14	0.09	0.17	1.31	nd	1.43	0.18	1.58	126	37%	33%	30%
WP3	WINNIPEGOSIS	0.85	0.76	1.26	1.24	nd	0.73	0.1	1.55	115	17%	40%	44%
WP4	WINNIPEGOSIS	1.09	0.12	0.21	1.28	nd	1.98	0.30	1.74	123	40%	32%	27%
WP5	WINNIPEGOSIS	1.09	0.10	0.16	1.18	0.57	1.67	0.47	1.45	124	37%	39%	24%
WP6	WINNIPEGOSIS	1.86	0.04	0.09	1.40	nd	2.01	0.27	1.82	124	46%	36%	18%
WP7	WINNIPEGOSIS	1.13	0.12	0.20	1.20	nd	1.82	0.42	1.74	126	38%	36%	26%
INT1	INTERLAKE	0.61	0.04	0.30	1.44	0.16	2.94	0.14	1.91	120	55%	26%	19%
IN2	INTERLAKE	1.70	0.05	0.10	1.34	nd	1.94	0.14	1.82	127	63%	13%	24%
IN3	INTERLAKE	1.25	0.15	0.30	1.22	nd	1.50	0.49	1.58	129	33%	38%	28%
IN4	INTERLAKE	1.13	0.10	0.12	1.09	nd	1.76	0.50	1.64	130	35%	38%	27%
SM1	STONY MOUNTAIN	0.79	0.05	0.32	1.57	nd	3.32	0.16	1.90	nd	58%	27%	15%
R1	RED RIVER	0.70	7.52	4.30	4.89	nd	3.23	0.14	1.73	135	10%	39%	51%
R2	RED RIVER	1.15	0.12	0.13	1.08	nd	1.29	0.79	1.60	133	28%	43%	29%
R3	RED RIVER	0.69	0.08	0.45	1.30	nd	3.25	0.11	1.86	125	60%	25%	14%
R4	RED RIVER	1.63	0.07	0.19	1.39	nd	3.48	0.14	1.95	119	58%	25%	17%
R5	RED RIVER	1.39	0.06	0.22	1.43	nd	4.41	0.11	1.96	nd	62%	21%	16%
R6	RED RIVER	0.80	0.06	0.38	1.39	nd	4.40	0.12	1.96	nd	62%	21%	16%
R7	RED RIVER	1.46	0.06	0.20	1.39	nd	3.74	0.13	1.94	nd	61%	24%	15%
R8	RED RIVER	1.49	0.07	0.10	1.20	nd	1.79	0.39	1.46	128	41%	39%	20%
R9	RED RIVER	0.60	0.03	0.21	1.32	nd	3.29	0.14	1.69	124	58%	26%	16%
R10	RED RIVER	1.18	0.09	0.17	1.31	nd	1.98	0.33	1.56	125	43%	36%	21%
R11	RED RIVER	0.65	0.04	0.21	1.30	nd	2.92	0.12	1.76	125	58%	27%	15%
R12	RED RIVER	1.44	0.04	0.09	1.23	nd	2.23	0.29	1.58	133	45%	33%	22%
R13	RED RIVER	0.68	0.04	0.23	1.35	nd	3.36	0.13	1.90	122	59%	25%	15%
R14	RED RIVER	1.43	0.05	0.14	1.53	nd	2.89	0.09	1.69	123	57%	25%	19%
R15	RED RIVER	2.01	0.06	0.10	1.27	nd	2.48	0.17	1.38	119	55%	31%	14%
R16	RED RIVER	1.97	0.03	0.06	1.64	nd	3.62	0.16	2.17	130	57%	25%	18%
R17	RED RIVER	2.32	0.03	0.05	4.49	nd	3.77	0.16	1.86	124	57%	24%	18%
R18	RED RIVER	1.99	0.03	0.07									

TABLE 5

Source Rock - Reservoir	Production	References
Mission Canyon-Spearfish (P)	> 0.4 MMBO	This study
Bakken-Spearfish (H)	(see above)	Osadetz, and Snowdon, 1995
Tyler-Tyler (P)	> 70 MMBO	Williams, 1974; Dow, 1974
Ratcliffe-Ratcliffe (H)	na	This study
Mission Canyon-Mission Canyon (P)	> 750 MMBO	This study; Jarvie and Walker, 1997
Bakken-Lodgepole (P)	> 6 MMBO	This study; Jarvie and Walker, 1997
Bakken-Bakken (P)	> 4 MMBO	Williams, 1974; Dow, 1974
Bakken-Nisku (P)	> 5 MMBO	Williams, 1974; this study
Duperow-Duperow (H)	> 120 MMBO	Zumberge, 1983
Duperow-Dawson Bay (H)	> 3 MMBO	This study
Winnipegosis-Winnipegosis (H)	> 6 MMBO	Osadetz and Snowdon, 1995
Winnipegosis-Interlake (H)	(see below)	This study
Red River – Interlake (P)	> 55 MMBO	This study
Red River - Red River (P)	> 100 MMBO	All post-1974 studies
Red River - Winnipeg (P)	> 0.03 MMBO	This study
Winnipeg - Winnipeg (H)	(see above)	This study
Ordo/Cambro-Deadwood (H)	na	Zumberge, 1983; Peterson, 1988

(P) = proven

(H) = hypothesized