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SIGNIFICANT PALEOZOIC PETROLEUM SOURCE ROCKS IN THE CANADIAN WILLISTON BASIN: THEIR DISTRIBUTION, RICHNESS AND THERMAL MATURITY (SOUTHEASTERN SASKATCHEWAN AND SOUTHWESTERN MANITOBA)

K.G. Osadetz and L.R. Snowdon

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PREFACE

The Williston Basin, which underlies much of Saskatchewan and Manitoba, is an important petroleum producing basin in Canada, second only to the Alberta Basin. Yet, the Canadian Williston Basin is only lightly explored when compared to the Alberta Basin. The great volume of Cambrian, Ordovician and Silurian rocks in particular has not been properly explored, despite the knowledge that these systems are the most significant producing intervals in the adjacent American part of Williston Basin. This Bulletin describes the Paleozoic source rocks from which Williston Basin oils originate as part of a comprehensive re-evaluation of the oil potential in the Canadian Williston Basin. It complements other works published in the Bulletin of Canadian Petroleum Geology and the Proceedings of the 5th and 6th Williston Basin Symposia which describe the petroleum produced in the Williston Basin. Together these reports characterize factors controlling petroleum occurrence in the Canadian Williston Basin. They also point qualitatively to a significant undiscovered petroleum potential in Cambrian, Ordovician, Silurian and Devonian rocks, none of which are major producing horizons in Saskatchewan or Manitoba. During the conduct of this study several new oil pools were discovered in Ordovician and Devonian strata, a clear indication that the qualitative potential indicated herein has a real significance.

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PRÉFACE

Le bassin de Williston, qui occupe une grande portion du sous-sol de la Saskatchewan et du Manitoba, est un important bassin producteur de pétrole, le second au Canada après le bassin de l'Alberta. Toutefois, la partie canadienne du bassin de Williston n'a été que faiblement explorée comparativement au bassin de l'Alberta. On a particulièrement peu tenu compte de l'important volume de roches du Cambrien, de l'Ordovicien et du Silurien, bien que l'on sache que ces systèmes constituent les intervalles productifs les plus significatifs de la portion américaine contiguë du bassin de Williston. Dans le présent bulletin, on décrit les roches mères paléozoïques dont proviennent le pétrole du bassin de Williston, dans le contexte d'une réévaluation détaillée du potentiel pétrolier de la partie canadienne du bassin. Le bulletin complète d'autres travaux publiés dans le Bulletin of Canadian Petroleum Geology et les actes des 5^{e} et 6^{e} symposiums sur le bassin de Williston, qui décrivent le pétrole produit dans le bassin. Tous ensemble, ces rapports caractérisent les facteurs régissant la présence du pétrole dans le secteur canadien du bassin de Williston. Ils suggèrent aussi qualitativement le potentiel pétrolier significatif des roches du Cambrien, de l'Ordovicien et du Dévonien, dont aucune ne constitue des horizons productifs majeurs en Saskatchewan ou au Manitoba. Au cours de l'étude, ont été découverts plusieurs nouveaux gisements de pétrole dans les strates de l'Ordovicien et du Dévonien, ce qui montre clairement que le potentiel qualitatif indiqué dans cet article a une réelle importance.

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Abstract

Four regionally important Paleozoic source rocks have been identified within the Canadian Williston Basin. These include Type I kukersites in the Upper Ordovician Bighorn Group, and marine, Type II source rocks in Middle Devonian Winnipegosis, Devonian to Mississippian Bakken and Mississippian Lodgepole formations. Kukersites are thin, organic-rich carbonate platform source rocks. Type II, source rocks occur in fondobeds settings and include rich sources. Type II source rock richness varies with depositional facies and diagenetic processes, especially microbial degradation which reduces Bakken and Winnipegosis hydrocarbon (HC) yields. Other platform sources in the Middle Ordovician Winnipeg Formation and Winnipegosis Formation lie on maximum flooding surfaces, and although thin, they may be laterally extensive.

Type I and Type II sources have distinctive main hydrocarbon generation stages beginning at not less than 0.77% and 0.70% Vitrinite Reflectance (VR), respectively. Only Bighorn and Winnipegosis sources are thermally mature in Canada, in an enhanced hydrocarbon generation region. This region has anomalous crustal structure, including the Nesson Anticline and the North American Central Plains conductivity anomaly. Oil windows occur between 750 and 1650 m shallower than elsewhere in the basin. Bighorn, Winnipegosis and Lodgepole expulsion thresholds coincide with the main hydrocarbon generation threshold appropriate to each source rock. Expulsion from Bakken sources is delayed and does not occur until 0.90% VR. Tectonic history and crustal structure impose geographic restrictions on patterns of source rock accumulation, diagenesis and maturation. These considerations restrict hydrocarbon potential and migration pathways of oils from each source rock.

Résumé

On a identifié quatre roches mères paléozoïques d'importance régionale dans la partie canadienne du bassin de Williston. Ce sont notamment les kukersites de type I dans le Groupe de Bighorn (Ordovicien supérieur) et les roches mères marines de type II dans les formations de Winnipegosis (Dévonien moyen), de Bakken (du Dévonien au Mississippien) et de Lodgepole (Mississippien). Les kukersites sont de minces roches mères de plate-forme carbonatée, riches en matière organique. Les roches mères de type II se rencontrent dans un milieu caractéristique de couches formées en eau profonde et comprennent des roches mères riches. La richesse des roches mères de type II varie selon les faciès sédimentaires et les processus diagénétiques, notamment la dégradation microbienne qui a réduit les rendements en hydrocarbures des formations de Bakken et de Winnipegosis. D'autres roches mères situées sur plate-forme, dans la Formation de Winnipeg (Ordovicien moyen) et la Formation de Winnipegosis, se situent sur des surfaces d'inondation maximale et, bien que minces, peuvent avoir une vaste étendue latérale.

Les sources de type I et les sources de type II présentent des stades principaux distinctifs de génération d'hydrocarbures, qui débutent au moins aux valeurs respectives de 0,77 % et 0,70 % de réflectance de la vitrinite (VR). Seules les roches mères des formations de Bighorn et de Winnipegosis présentent une maturité thermique au Canada, dans une région de génération accrue d'hydrocarbures. Cette région a une structure crustale anomale, notamment l'anticlinal de Nesson et l'anomalie de conductivité des plaines centrales nord-américaines. Les fenêtres de pétrole se situent à une profondeur entre 750 et 1 650 m de moins qu'ailleurs dans le bassin. Dans les formations de Bighorn, de Winnipegosis et de Lodgepole, les seuils d'expulsion coïncident avec le seuil principal de génération d'hydrocarbures propre à chaque roche mère. L'expulsion à partir des roches mères de Bakken est retardée et n'a lieu que lorsque la valeur de VR de 0,09 % est atteinte. L'évolution tectonique et la structure crustale imposent des restrictions géographiques quant aux schémas d'accumulation, de diagenèse et de maturation des roches mères. Ces considérations permettent de placer dans certaines limites le potentiel en hydrocarbures et les cheminements des pétroles à partir de chaque roche mère.

Summary

Four regionally significant, rich, Palaeozoic source rock intervals occur in the Canadian Williston Basin. Type I source rocks occur in several Upper Ordovician Bighorn Group formations. These thin carbonate source rocks occur in a tectonically controlled, geographically limited depression on the Yeoman Formation epeiric platform. They are generally immature in Canada and their main stage of hydrocarbon generation occurs at not less than 0.77% VR. Explusion from kukersitic sources appears to accompany significant hydrocarbon generation. Ordovician sources have an enormous petroleum potential, largely because a comparable or even greater source rock volume in the United States is thermally mature.

Middle Devonian Winnipegosis Formation contains several Type II sources with the thickest, richest developments occurring in Upper member-equivalent basinal facies where they too have an extraordinary petroleum potential. Hydrocarbon yields and petroleum potential are often reduced by microbial alteration during early diagenesis. Immense volume compensates for decreased source rock richness. Most Winnipegosis basinal sources are thermally immature. A significant volume of Winnipegosis source rock was deposited over the hydrocarbon generation anomaly, resulting in significant hydrocarbon generation in Canada. Other Winnipegosis Type II sources lie between the Upper and Lower members of Winnipegosis Formation in platform settings. These too occur at maximum flooding surfaces and are thin, but may be laterally extensive. Their distribution and maturity patterns are not well known.

Rich persistent Type II sources occur in the Upper and Lower Bakken shales. Variations in depositional facies and microbial degradation during diagenesis significantly depreciated Bakken Formation petroleum potential and large parts of the formation have only fair to good hydrocarbon yields. However, the richest sources tend to occur in the most mature regions. The main hydrocarbon generation stage window occurs consistently at expected maturities, 0.70% VR, but its depth commonly fluctuates between 2300 and 3050 m, following thermal history variations. The hydrocarbon generation anomaly helps thermal maturity locally, while maturities improve regionally with increasing maximum burial depths. Explusion is delayed until higher maturities, 0.9% VR, contrary to standard source rock models. Bakken maturities exceed this expulsion threshold south and west of the Missouri River severely restricting Bakken hydrocarbon potential and migration pathways.

Rich sources occur in geographically and stratigraphically restricted parts of the lower Lodgepole Formation, but most strata in the Mississippian Madison Group have no source potential. Episodic transgressions deposit each lenticular source rock body in a starved distal ramp environment. Compared with Winnipegosis and Bakken source rocks, Lodgepole Type II sources have consistently higher hydrocarbon yields and may have escaped serious diagenetic degradation. Cores are sparse but they suggest the oil window may occur sooner than that of other Type II sources, but below 2070 m.

Elevated heat flows associated with crustal structure along the Ancestral Nesson structure strongly affect thermal maturity. Enhanced maturation results in the Type I oil window occurring at approximatley 2450 m, and Type II oil windows occurring at approximatley 2300 m, much shallower than expected. The same crustal structure strongly influcences source rock distribution and forms a fundamental control on hydrocarbon potential in Williston Basin.

Sommaire

Il existe quatre intervalles de roches mères paléozoïques d'importance régionale dans la partie canadienne du bassin de Williston. Les roches mères de type I se rencontrent dans plusieurs formations du Groupe de Bighorn (Ordovicien supérieur). Ces minces roches mères carbonatées se situent dans une dépression à contrôle tectonique, géographiquement limitée, sur la plate-forme épicontinentale de la Formation de Yeoman. Elles sont généralement immatures au Canada et leur principal stade de génération d'hydrocarbures apparaît à une valeur VR d'au moins 0,77 %. L'expulsion à partir de roches mères kukersitiques semble accompagner une génération significative d'hydrocarbures. Les roches mères ordoviciennes ont un énorme potentiel pétrolier, largement parce qu'un volume comparable ou même supérieur de roches mères a atteint aux États-Unis la maturité thermique.

La Formation de Winnipegosis (Dévonien moyen) contient plusieurs roches mères de type II dont les niveaux les plus épais et les plus riches se trouvent dans la partie du faciès de bassin équivalent au membre supérieur, où leur potentiel pétrolier est également extraordinaire. Les rendements en hydrocarbures et le potentiel pétrolier sont souvent réduits par l'altération microbienne au cours des premières phases de diagenèse. L'immense volume compense la richesse réduite des roches mères. La plupart des roches mères de bassin dans la Formation de Winnipegosis sont thermiquement immatures. Un volume significatif de roches mères de la Formation de Winnipegosis s'est déposé au-dessus de l'anomalie de génération d'hydrocarbures. Il en résulte une formation significative d'hydrocarbures au Canada. D'autres roches mères de type II de la Formation de Winnipegosis se situent entre le membre supérieur et le membre inférieur de la Formation de Winnipegosis dans des contextes de plate-forme. Elles aussi se trouvent au niveau de surfaces d'inondation maximale et sont minces, mais peuvent avoir une vaste étendue latérale. On connaît mal leur distribution et leurs schémas de maturité.

On rencontre des roches mères riches et persistantes de type II dans les shales de la partie supérieure et de la partie inférieure de la Formation de Bakken. Les variations des faciès sédimentaires et la dégradation microbienne au cours de la diagenèse ont nettement réduit le potentiel pétrolier de la Formation de Bakken, et de vastes portions de cette formation n'ont que des rendements médiocres à bons en hydrocarbures. Toutefois, les roches mères les plus riches tendent à se trouver dans les régions les plus matures. La fenêtre de la principale étape de génération d'hydrocarbures apparaît constamment aux maturités prédites, soit lorsque VR atteint 0,70 %, mais sa profondeur oscille souvent entre 2 300 et 3 050 m, selon les variations de l'évolution thermique. L'anomalie de génération d'hydrocarbures favorise localement la maturité thermique, tandis que la maturité s'améliore à l'échelle régionale en fonction de l'accroissement de la profondeur maximale d'enfouissement. L'expulsion est retardée jusqu'à ce que soient atteintes des maturités plus élevées, ou une valeur VR de 0,9 %, contrairement aux modèles normalisés de roches mères. Dans la Formation de Bakken, les maturités dépassent ce seuil d'expulsion au sud et à l'ouest du fleuve Missouri, limitant ainsi considérablement le potentiel en hydrocarbures et les parcours de migration des hydrocarbures de la Formation de Bakken.

Des roches mères riches existent dans les portions géographiquement et stratigraphiquement restreintes de la partie inférieure de la Formation de Lodgepole, mais la plupart des strates du Groupe de Madison (Mississippien) n'ont pas de potentiel en tant que roches mères. Des transgressions épisodiques ont déposé chaque roche mère lenticulaire dans un milieu de rampe distale à faible remplissage sédimentaire. Comparativement aux roches mères des formations de Winnipegosis et de Bakken, les sources de type II de la Formation de Lodgepole ont des rendements constamment plus élevés en hydrocarbures et ont peut-être échappé à une sérieuse dégradation diagénétique. Les carottes de forage sont rares, mais les résultats suggèrent que la fenêtre de pétrole pourrait apparaître plus tôt que celle des autres sources de type II, mais au-dessous de 2 070 m.

Les flux thermiques élevés associés à la structure crustale le long de la protostructure de Nesson ont une forte influence sur la maturité thermique. La maturation accentuée crée la fenêtre de pétrole de type I qui se situe à environ 2 450 m de profondeur, et les fenêtres de type II qui se situent à approximativement 2 300 m, soit à une profondeur bien moindre que prévu. La même structure crustale influence fortement la distribution des roches mères et constitue un contrôle fondamental sur le potentiel en hydrocarbures du bassin de Williston.

INTRODUCTION

The Williston Basin (Fig. 1) dominates the central North American craton. Its major petroleum provinces (Fig. 2) represent a significant petroleum resource, especially for Canada. Oils in the Canadian and American parts of the Williston Basin occur in markedly different settings. Large anticlinal fields, like those of the Nesson and Cedar Creek Anticlines, dominate the American regions (Fig. 2; J. LeFever et al., 1987; Gerhard et al., 1987; Clement, 1987). Much American production comes from Paleozoic, particularly Silurian, formations. Canadian accumulations occur primarily in stratigraphic traps. In southeastern Saskatchewan and southwestern Manitoba, oils occur at or near the Mississippian subcrop. There are lesser petroleum resources in Ordovician, Middle Devonian, Upper Devonian and Mesozoic formations. In southwestern and west-central Saskatchewan, oils occur in stratigraphic traps in latest Devonian to Mississippian, Jurassic, and Lower Cretaceous formations. These contrasts suggest potential for further oil discoveries in the Canadian Williston Basin, particularly in Middle Devonian and older Paleozoic strata, which were, until recently, little explored.

This report is part of a comprehensive evaluation of petroleum origin and generation in the Williston Basin. It describes Paleozoic source rocks with a significant petroleum potential, their distribution, richness and thermal maturity. Rock-Eval/Total Organic Carbon (TOC) anhydrous pyrolysis and gross compositions of solvent extracted bitumen define critical thermal maturities. One of these, the expulsion threshold, matches oil pool minimum thermal maturity. Using these results we recognize significant potential in rocks lying below the Bakken Formation and recognize important new source rocks in the Mississippian Madison Group.

Geological setting

General setting

The Williston Basin has an intracratonic setting and low, episodic subsidence rates (Fowler and Nisbet,

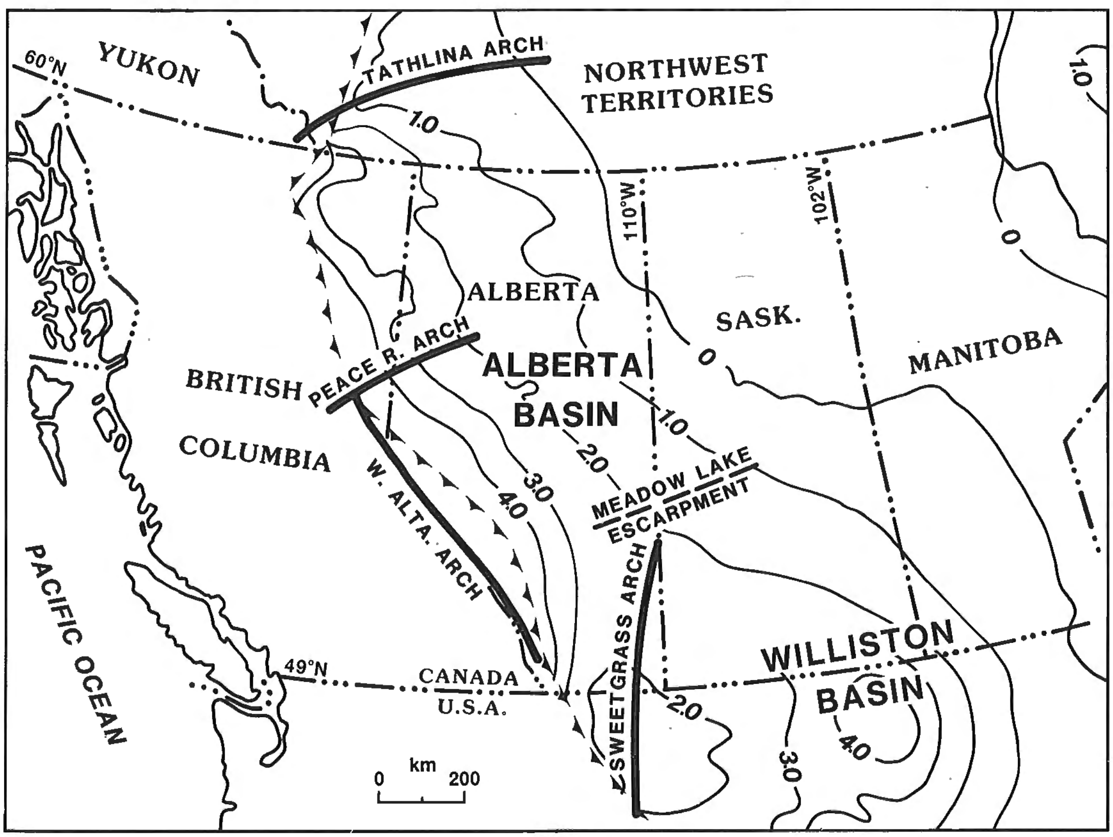

Figure 1. Sedimentary basins and major structural elements in the Western Interior Platform geological province south of 60°N. Sedimentary succession thickness is indicated by contours in kilometres.

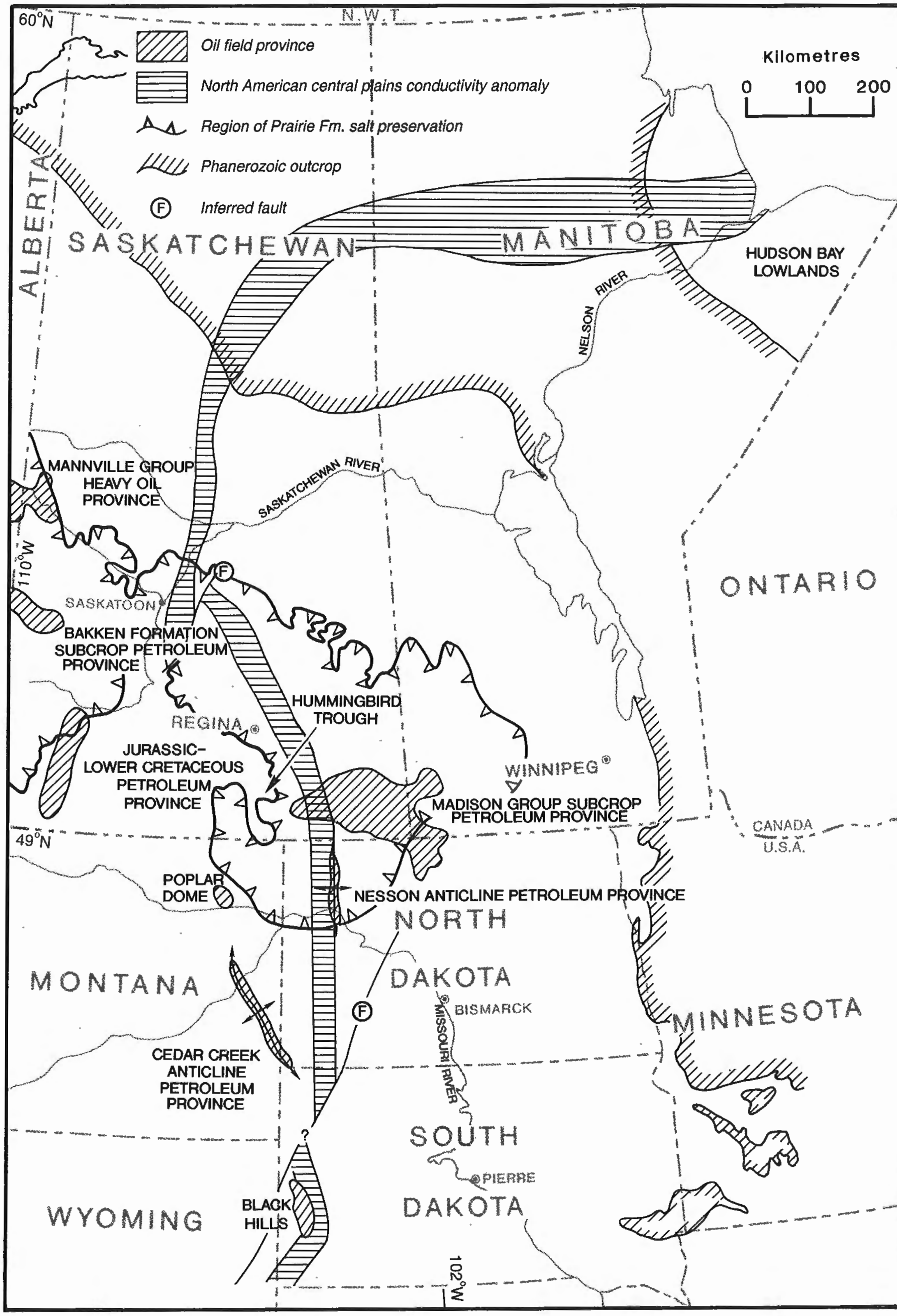

Figure 2. *Petroleum provinces and important tectonic elements in the Williston Basin and adjacent area. Only generalized outlines of the Mississippian Madison Group Subcrop Petroleum Province and other Williston Basin petroleum provinces are indicated. The position of the North American Central Plains Conductivity Anomaly and basement faults offsetting that feature is from Morel-a-l'Huissier et al. (1990). The Prairie Formation salt dissolution edge is from Christopher (1984b).*

1985; Ahern and Mrkvicka, 1984; Sloss, 1984; Gerhard et al., 1982). The sedimentary succession is approximately 5 km thick near the basin centre in North Dakota (Fig. 1). The Williston Basin is a dominantly preservational basin, commonly linked to larger tectonic features. Its well established petroleum provinces, clearly described rock succession, modest burial history and simple tectonics make this an uncomplicated area to study.

Stratigraphic succession

The succession includes six sequences bounded by unconformities (Figs. 3, 4). The Middle Cambrian to Lower Ordovician Sauk sequence (Ricketts, 1989; Sloss, 1963) was deposited on the early Paleozoic miogeocline of western North America (R. LeFever et al., 1987; Bond and Kominz, 1984). The Tippecanoe sequence, Middle Ordovician clastic rocks and Upper Ordovician and Silurian carbonates and evaporites which onlap from the east (Osadetz and Haidl, 1989; Kendall, 1976; Vigrass, 1971), were deposited in the eastern North American epeiric seaway. Upper Ordovician rocks of this sequence contain important petroleum sources.

The third sequence, Kaskaskia, includes Middle Devonian (Ehrets and Kissling, 1987; Rosenthal, 1987), Upper Devonian and Mississippian formations (Kent, 1987a, b). A major transgressive event in the Late Devonian (Bakken Formation) marks a change in Kaskaskia sequence depositional patterns and sedimentation style (Sandberg et al., 1983; Edie, 1958). This sequence is the most important interval for petroleum source rocks in the Williston Basin. Three regionally significant sources are present, the Middle Devonian Elk Point Group, the latest Devonian to earliest Mississippian Three Forks Group and the Mississippian Madison Group.

The next sequence is the Pennsylvanian, Permian and Triassic Absaroka. This sequence is generally absent from the Canadian Williston Basin. In the American Williston Basin, where this sequence contains effective petroleum source rocks (Williams, 1974; Dow, 1974), formations are thin and contain many unconformities. The fifth sequence, the Zuni, can be locally subdivided into two sequences. The first of these sequences includes the Jurassic, when Williston Basin changed from a large reentrant on the craton margin into an orogenic foreland (Poulton, 1984; Carlson, 1968). The lower sequence contains a time equivalent succession to the last cratonically derived miogeoclinal succession.

Latest Jurassic, Cretaceous and Tertiary successions of the Columbian and Laramide orogenic forelands (Stott, 1984) form the final significant depositional episode (Christopher, 1984a, b). Thick shales of this final sequence include significant potential source rocks, but they are all immature in the Canadian Williston Basin (Macauley et al., 1985).

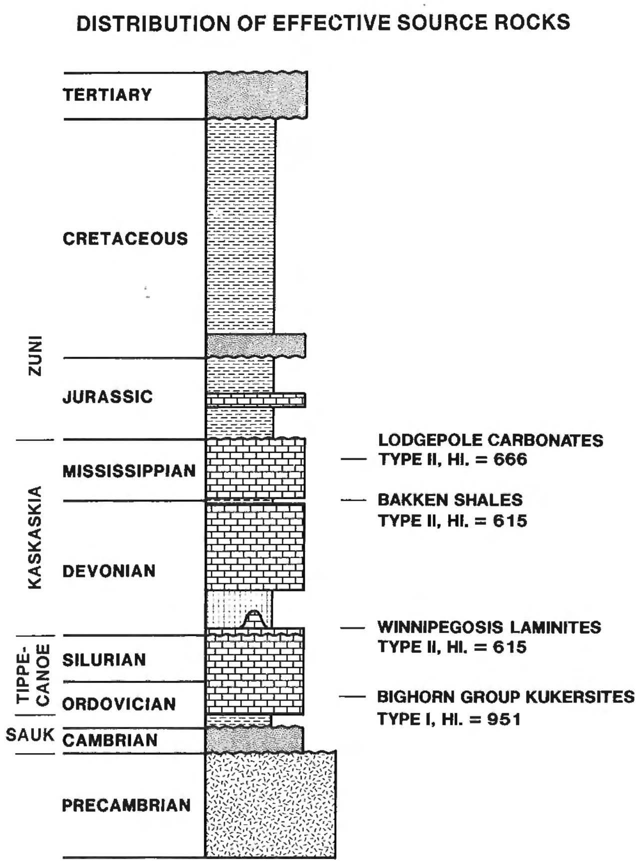

Figure 3. Generalized lithological succession in the Canadian Williston Basin. Only five unconformity bounded successions are present in Canada and the succession is significantly thinner than that found in the United States. Regionally significant potential petroleum source rock formations are indicated.

Tectonic setting

The Williston Basin lies within the Interior Platform structural province. Basin monoclines are interrupted by important epeirogenic basement folds (Fig. 2), such as the Nesson (J. LeFever et al., 1987; Gerhard et al., 1987) and Cedar Creek anticlines (Clement, 1987). These structures exert fundamental controls on hydrocarbon (HC) generation and petroleum occurrence in the Phanerozoic succession. An anomalous crustal

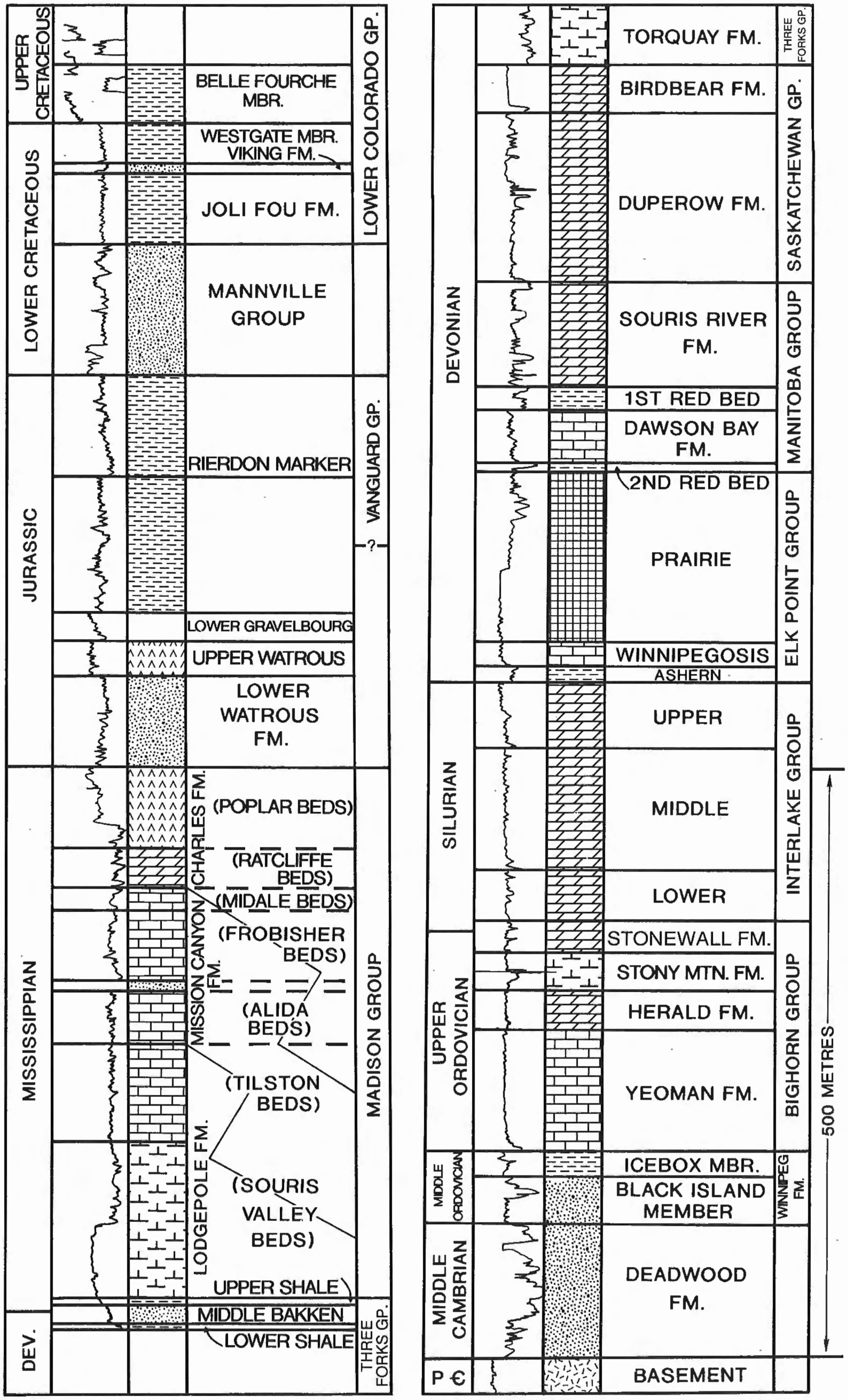

Figure 4. *Generalized Paleozoic succession in the northeastern Canadian Williston Basin, indicating the stratigraphic position and nomenclature referred to in the text.*

region lies along longitude 103°W, south of latitude 51°N (Fig. 2). It coincides with the North American Central Plains conductivity anomaly (Jones and Savage, 1986) and associated heat-flow anomalies (Majorowicz et al., 1988). The North American Central Plains conductivity anomaly (Fig. 2) is an intense, long (2000 km), wide (80 km) feature. It occurs between 10 and 20 km deep and is probably caused by crustal lithological variation (Jones and Craven, 1990). This region subsided anomalously throughout the Phanerozoic, the effects are recognizable in both sediment thickness (J. LeFever et al., 1987; Gerhard et al., 1987; Ahern and Mrkvicka, 1984) and lithofacies patterns (Osadetz et al., 1989, 1990; Osadetz and Haidl, 1989). The same region includes the Nesson Anticline, which shows enhanced hydrocarbon generation in Paleozoic rocks (Osadetz et al., 1989, 1990; Price et al., 1984) and elevated coal ranks in Tertiary strata (Cameron, 1991).

Previous work

The conclusions of this study differ significantly from those of previous studies (Leenheer and Zumberge, 1987; Williams, 1974; Dow, 1974). The difference results from variations in experimental design and improved analytical technique. Our comprehensive well profile survey and characterization of particular stratigraphic horizons resulted in the identification of new potential source rocks. These results, combined with new studies of petroleum composition, motivated an evaluation of oil-source correlations (Osadetz et al., 1992).

Initial oil-source correlations were made using solvent extracts from potential petroleum sources lying stratigraphically near the most common occurrence of compositionally defined oil families (Williams, 1974; Dow, 1974). Most subsequent studies elaborated particular aspects of these oil-source associations. Studies of molecular compositions from solvent extracts of Williston Basin Bakken and Alberta Basin Exshaw strata re-enforced suggested correlations to Type II oils (Williams, 1974; Leenheer and Zumberge, 1987; Leenheer, 1984; Zumberge, 1983). However, sulfur isotopic compositions from Upper Bakken solvent extract do not compare favorably with Type II oil compositions, suggesting only the Lower shale member of the Bakken Formation was an effective oil source (Thode, 1981). Arneth (1984) studied carbon isotopic variations in carbonate, Total Organic Carbon (TOC) and bitumen fractions throughout the succession.

Many other studies focused on the Bakken Formation because of its abundant organic carbon and its importance in earlier studies (Dembicki and Pirkle, 1985; Price et al., 1984; Leenheer, 1984; Schmoker and Hester, 1983; Meissner, 1978). Webster (1984) concluded that the Bakken Formation was a rich source with a single oil window beginning at 2740 m and an intense hydrocarbon generation zone at 3048 m. Vitrinite Reflectance data associated with critical thermal maturities are approximately 0.53% and 0.69% (Webster, 1984, fig. 26). Data from 46 solvent extracts suggest that hydrocarbon yield from unstained sources generally increases with depth and thermal maturity. When significant hydrocarbon generation begins, average hydrocarbon yields are approximately 20 mg/g TOC. The greatest hydrocarbon yields coincide with regions of lowest Hydrogen Index (HI = S2/TOC) and highest Production Index (PI) values, suggesting that this was evidence for hydrocarbon generation and expulsion (op. cit.).

A Bakken Formation study throughout the American Williston Basin reported 40 solvent extract compositions and used pyrolytic results to distinguish between two different shale facies, but suggested no significant differences between the two shale members (Price et al., 1984). Lithological variations in the two shale members follow distance from the formation's edge and reflect source rock quality variations controlled by the depositional environment. Preferring pyrolytic richness and maturity indicators to solvent extract criteria, the regionally comprehensive study identified two oil windows in different geographic regions. One occurred at approximately 2300 m and the other at approximately 3050 m current depth. Enhanced maturity follows a zone generally coincident with Nesson Anticline and was initially attributed to an aborted, Late Cretaceous–Paleocene rift (op. cit.). This region extends into Canada (Majorowicz et al., 1988; Osadetz et al., 1989, 1990) where elevated heat flows occur due to compositional differences in the Precambrian basement (Morel-a-l'Hussier et al., 1990), not crustal thinning.

Other studies attributed source potential to formations using lithology, TOC abundance and anhydrous pyrolysis (Rock-Eval; Osadetz and Snowdon, 1986a, b; Macauley et al., 1985; Thomas, 1968). Rock-Eval/TOC and extract data from Yeoman and Winnipeg formation samples confirmed significant source rock potential, particularly in kukersites (Osadetz et al., 1989), as suggested by sedimentological studies (Kohm and Louden, 1978, 1982; Kendall, 1976). High TOC suggested that rich potential source rocks occur in the Winnipegosis Formation (Wardlaw and Reinson, 1971) and this too has been confirmed (Osadetz et al., 1990).

Contemporary exploration developments

Dome Petroleum and partners made important wildcat discoveries at Tableland (11-14-2-9W2) and Minton (11-2-3-21W2) in 1976. These discoveries revived the prospect of commercial production from deeper Paleozoic horizons and showed a need for petroleum potential assessment of older horizons in Canada. During the late 1980s and early 1990s, successful exploitation of these discoveries coincided with the execution of this project. This new play concept motivated exploration and new hydrocarbon discoveries in Ordovician (Potter and St. Onge, 1991; Osadetz and Haidl, 1989) and Middle Devonian strata (Martindale et al., 1991; Martindale and MacDonald, 1989) were found. Innovative exploration techniques, particularly horizontal drilling, began the production of oil from Bakken Formation shale in North Dakota (LeFever et al., 1991; Fischer and Rygh, 1989). Together, these developments provided motivation for understanding Paleozoic petroleum sources in the Williston Basin.

Results of this study

Source rock distribution

Most Paleozoic rocks in the Williston Basin have little or no petroleum source rock potential, however, there are four regionally significant Paleozoic source rocks. These source rocks are Type I kukersite in the Upper Ordovician Bighorn Group, and marine, Type II source rocks in the Middle Devonian Winnipegosis, Devonian to Mississippian Bakken and Mississippian Lodgepole formations. Most significant source rocks are organic-rich, stratigraphically and geographically restricted, and form only a small part of the stratigraphic unit that hosts them. All four source rocks extend into the United States and they are the source for major petroleum accumulations in southwestern Saskatchewan (Osadetz et al., 1991a), southeastern Saskatchewan, southwestern Manitoba (Osadetz et al., 1992), and the United States (unpublished data).

Controls on source rock richness

Stratigraphic setting and depositional environment of the host formation constrains depositional and diagenetic controls on source rock accumulation and richness. Kukersite is a thin, organic-rich, Type I, carbonate source, which accumulated in distal ramp depositional settings. Type II source rocks accumulated in both distal ramp and fondobeds settings, and their richness varies with depositional facies and diagenetic processes. Microbial degradation, a process that significantly reduces Bakken and Winnipegosis hydrocarbon yields, is especially important.

Potential source rocks in the Middle Ordovician Winnipeg and Middle Devonian Winnipegosis formations are generally thin and are associated with maximum flooding surfaces in shallow marine shelf and platform settings, respectively. They may be laterally extensive and have significant petroleum potential, but core control is too sparse to clearly understand their distribution and significance.

Thermal maturity and hydrocarbon expulsion threshold

Tectonic history and crustal structure impose restrictions on source rock accumulation, diagenesis and maturation. Williston Basin Type I and Type II source rocks enter the main hydrocarbon generation stage at 0.77% and 0.70% Vitrinite Reflectance (VR), respectively. A region of enhanced hydrocarbon generation coincides with anomalous north–south trending crustal structure, the Nesson Anticline and the North American Central Plains conductivity anomaly. Oil windows occur between 750 and 1650 m shallower in this high heat-flow region than elsewhere in the basin. The expulsion threshold of Bighorn Group strata coincides with full maturity at 0.77% VR. The Bakken Formation is mature at 0.70% VR, but expulsion is delayed until 0.90% VR. Other Type II source rocks have expulsion thresholds that coincide with the main hydrocarbon generation stage (0.70% VR), restricting the hydrocarbon potential and migration pathway for each source rock. Only Bighorn Group and Winnipegosis Formation source rocks are thermally mature in Canada. Most hydrocarbon generation has occurred in western North Dakota and most oils have migrated a long distance before accumulation.

PROCEDURES

Anhydrous pyrolysis

Rock samples were pyrolyzed using Rock-Eval/TOC. This technique evaluates oil and gas shows, oil and gas generation potential, thermal maturity, and identifies organic matter type (Espitalie et al. 1985; Peters, 1986; Tissot and Welte, 1978, p. 443–447). It is a useful screen for recognizing source rocks and stained lithologies. The analysis gives five parameters: S1, S2, S3, TOC and T_{max}. The S1 parameter measures free or adsorbed hydrocarbons volatilized at moderate temperatures (300°C). S2 measures the hydrocarbons liberated during ramped heating (300–550°C at 25°C/min.). The S3 parameter measures organic CO_2 generated from the kerogen during rapid heating (300–390°C at 25°C/min.). The measure of all these parameters is milligrams of product/gram of rock sample (mg/g, equivalent to kg/t). TOC is measured in weight per cent (%). T_{max}, the temperature corresponding to the S2 peak maximum temperature, is measured in degrees Celsius (°C).

Rock-Eval results correlate to other techniques (Espitalie et al., 1985; Tissot and Welte, 1978). Source rock potential is sensitive to lithology, TOC and S2 values (Table 1). It is common practice to rate carbonate rocks with lower TOC values than richer siliciclastic rocks. Extractable hydrocarbon yields from leaner carbonate rocks are comparable to those from richer siliciclastic rocks (Tissot and Welte, 1978, p. 430; Gehman, 1962). The organic matter associated with carbonate rocks is commonly more hydrogen-rich and thermally labile than that in fine grained siliciclastic rocks. As a result, more organic carbon *may* be transformed into bitumen in carbonate rocks than in average siliciclastic source rocks of comparable maturity.

Rock-Eval/TOC parameters have significance only above threshold TOC, S1 and S2 values. If TOC is ≤0.3%, then all parameters have questionable significance and the experiment suggests no potential.

Table 1

Standard criteria for rating potential source rocks

Rating	%TOC in shales	%TOC in carbonates
Poor	0.00–0.50	0.00–0.12
Fair	0.50–1.00	0.12–0.25
Good	1.00–2.00	0.25–0.50
Very good	2.00–4.00	0.50–1.00
Excellent	>4.00	>1.00

S2 Value (mg of HC/g of rock)

Rating	S2 Value
Poor	<2.00
Fair	2.00–5.00
Good	>5.00

Oxygen Index (OI = S3/TOC) has questionable significance if TOC is ≤0.5%. Both T_{max} and Production Index (PI = S1/(S1 + S2)) have questionable significance if S1 and S2 are ≤0.2. Results can be affected by mineral matrix effects: these either retain generated compounds, generally lowering the S1 or S2 peaks while increasing T_{max}, or liberate inorganic CO_2 and increase S3 and OI. These effects are important if TOC, S1 and S2 are low, an effect not significant in this study because most of these samples have >5% TOC. OI values greater than 150 mg/g TOC suggest either low TOC or a mineral matrix CO_2 contribution during pyrolysis.

Solvent extract gross composition

The amount and composition of solvent extractable bitumen also characterizes source rocks. The bitumen was extracted using the Soxhlet technique. Extract fractionation used packed column chromatography following a method similar to that published by Snowdon (1981). The resulting gross composition characterizes source rock richness and maturity. Solvent extract hydrocarbon yield, quoted in milligrams of extract/gram of Total Organic Carbon (mg/g TOC), is a richness indicator. An hydrocarbon yield of less than 30 mg/g TOC suggests no potential, between 30 and 50 mg/g TOC suggests marginal potential, between 50 and 80 mg/g TOC suggests good potential, and greater than 80 mg/g TOC suggests excellent potential. Per cent of hydrocarbons (%HC) as an indicator of maturity is commonly thought to be independent of organic matter type and lithology, although this appears incorrect for this study. Less than 25% hydrocarbon characterizes thermally immature source rocks, 25% to 45% hydrocarbon characterizes marginally mature source rocks, 45% to 55% hydrocarbon characterizes the main hydrocarbon generation stage, and greater than 55% hydrocarbon characterizes stained samples.

RESULTS

Reconnaissance profiles

Initially we analysed 36 well profiles (Table 2; Fig. 5) totaling approximately 8500 cuttings samples (to be reported elsewhere). These data were used to identify regionally significant and persistent Paleozoic source rocks. Osadetz and Snowdon's (1986a) Parry Norcanols No. 1 well report illustrates one such profile. Most Paleozoic stratigraphic units had no potential, rich petroleum source rocks occur in a few

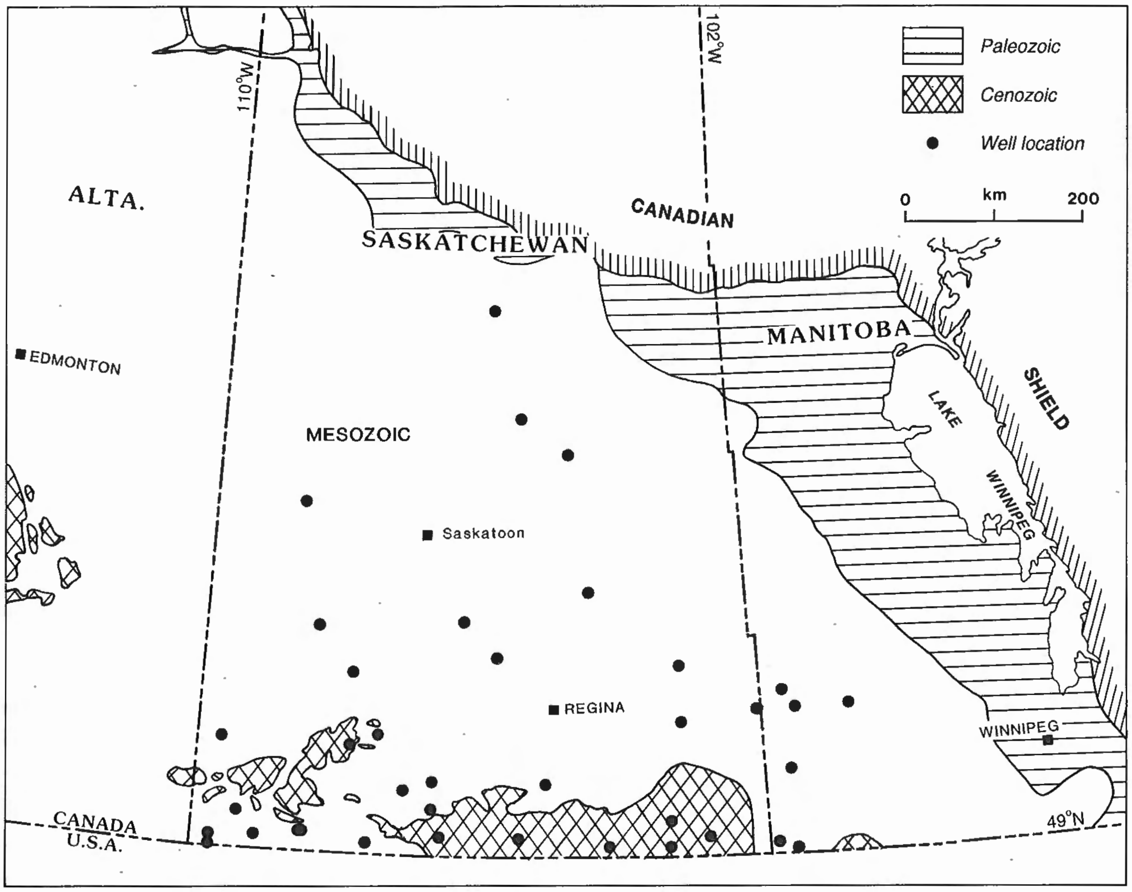

Figure 5. *Locations of wells sampled for reconnaissance Rock-Eval/TOC analysis. Well locations and analysed intervals are listed in Table 2.*

stratigraphic units in limited geographic areas. The reconnaissance study confirmed the presence of several regionally significant source rocks identified by previous studies and found at least one new one in the Mississippian Lodgepole Formation (Figs. 3, 5; Osadetz and Snowdon, 1986b). An additional ten partial profiles comprising about 620 samples were used to constrain Lodgepole source rock distribution (Table 2).

Detailed core studies

Several previously identified Paleozoic source rocks were either not identified or observed infrequently during the reconnaissance program. This resulted from the mixing of cuttings samples, thin source rock development, or restricted lateral distribution. We sampled cores from such source rocks. Two important source rocks not easily recognized in cuttings lie in the Ordovician Bighorn Group and Middle Devonian Winnipegosis Formation (Fig. 4).

We used core samples to further characterize intervals with good petroleum potential and analysed approximately 500 core samples from known source rocks, other prospective lithologies (subsequently proven to have no potential), and oil stained rocks. Experimental results from 298 samples characterize regionally significant Paleozoic sources (Appendix 1) and were used to calculate parameter averages for each stratigraphic unit (Table 3).

Significant petroleum source rocks

Persistent source rock intervals occur within the Mississippian Lodgepole Formation, Mississippian to Upper Devonian Bakken Formation (Lower and Upper shale members), Middle Devonian Winnipegosis Formation, and Upper Ordovician Bighorn Group (Fig. 4). Stratigraphically restricted, but possibly regionally significant, good source rocks occur in the Middle Ordovician Winnipeg Formation. We also document poor potential where others previously

Table 2

Rock-Eval/TOC reconnaissance well profiles

Well Name	Location	KB	Sample interval (ft.)
General Reconnaissance			
Landa Robert Moore #1	05-20-001-27W1	1491	10–5980
California Standard Pierson Province	02-29-002-29W1	1578	20–4360
California Standard Daly 15-18	15-18-010-27W1	1614	20–5370
Shell Newdale	12-23-017-20W1	2060	450–2750
Imperial Birtle #1	01-27-017-26W1	1791	18–4240
Riddle Tidewater St. Marthe Crown	01-04-017-30W1	1580	750–4770
Imperial Foxwarren #1	16-32-019-27W1	1821	40–4160
James P. Owen Kincaid #1	12-16-002-07W2	1888	20–6100
Shell Oungre #1	07-01-002-14W2	2206	720–6420
McBride et al. Frobisher	14-07-003-03W2	1893	690–4720
Imperial Garville	08-23-003-24W2	2524	2940–9340
Shell Minard A1-4	01-04-005-07W2	1958	710–5622
Norcanols Parry #1	16-08-009-21W2	2547	65–9042
Tidewater Broadview Crown 8-36	08-36-016-06W2	1947	1290–6290
Sohio Melville #1	11-14-022-06W2	1796	20–3520
California Standard Holdfast	14-12-023-26W2	1811	620–5900
Tidewater Krasne Crown #1	16-14-030-16W2	2163	1110–5170
British American Kuras 5-29	05-29-046-18W2	1432	240–2975
British American Halas 4-4	04-04-050-23W2	1517	900–2925
Great Plains et al. Montreal Lake	05-22-062-26W2	1937	20–1800
Shell Albercan Govenlock #1	02-07-001-28W3	2763	20–7280
Amerada Shell Crown S-A 5-31	05-31-002-11W3	2735	1620–8052
Shell Barclay Supreme	07-02-002-28W3	3044	2340–6620
Sohio Standard Regent Wood Mtn.	09-18-003-03W3	3259	650–4300
Imperial Tidewater Climax #1	06-10-003-18W3	3076	360–8470
Imperial Robsart	01-01-005-25W3	3157	650–820
British American Baciu 15-36	15-36-006-04W3	2531	20–7900
Sun Christie Meyronne 1-3	01-03-008-07W3	2495	650–5270
Sun Christie Gravelbourg 7-16	07-16-009-04W3	2560	650–7500
Imperial Swift Current #1	11-20-013-13W3	2893	40–7880
B.A. et al. Wilnichenko (Hatton)	02-12-013-27W3	2480	20–6300
Tidewater Braddock Crown #1	05-07-014-10W3	2654	20–6820
Tidewater Assoc. Kyle Crown #1	03-32-021-13W3	2665	40–6140
Sohio Wartime #1	02-14-026-17W3	2071	20–5540
Imperial Davidson #1	16-08-027-01W3	2054	25–5220
Calvin Charter Sapphire Wilkie #1	01-29-040-19W3	2216	520–5020
Lodgepole Special Study			
B.A. Canadian Dev. Walter	05-14-005-06W2	1949	4405–5695
Imperial Canadian Superior Stoughton	03-27-008-08W2	2058	4140–5140
Socony Weybern No. 1	08-11-008-14W2	1883	4310–5290
Imperial Tidwater Dumas	01-20-011-02W2	2265	3640–3990
California Standard Fillmore	06-03-011-09W2	2102	3830–4525
Tidewater Imperial Bender Creek	13-11-012-05W2	2498	3900–4390
Socony Sohio West Marquis No. 1	12-28-019-28W2	2006	3130–3570
Socony Owen Peepeekeesis	13-11-022-11W2	2126	2380–2640
Duval Yorkton	13-10-024-03W2	1688	1340–1540
B.A. et al. Pine Hill	08-29-027-07W2	1807	1450–1530

attributed good potential. Two such examples are green shale of the Winnipeg Formation (Dow, 1974; Williams, 1974) and dolomite–anhydrite laminite of the Lower member, Winnipegosis Formation (Wardlaw and Reinson, 1971). Other lesser, or poorly known, Paleozoic source rocks occur (unpublished data).

Solvent extracts

Solvent extractions characterize source rock potential and thermal maturity and indicate the presence of staining. We examined 264 samples that pyrolysis experiments suggested to have the potential to generate

Table 3

Mean values of Rock-Eval/TOC parameters for significant Paleozoic source rocks

Zone	S1	S2	S3	TOC	HI	OI
Icebox Member	0.21	11.66	0.42	1.55	519.5	44.7
Yeoman Formation	1.24	77.33	1.00	9.07	727.7	22.6
Brightholme member	2.49	40.30	2.00	7.38	514.6	33.1
Winnipegosis Mudstone	0.63	0.77	0.39	0.59	120.1	63.6
Bakken Lower shale	7.01	86.72	3.50	17.63	409.6	31.0
Bakken Upper shale	4.22	57.19	2.36	11.77	398.8	27.5
Lodgepole Formation	2.56	26.76	2.04	5.49	400.9	48.6

hydrocarbons. Most have Rock-Eval/TOC parameters equal to or exceeding formation averages (Table 3). Total extract yield and hydrocarbon yield vary with TOC. Samples with very low TOC and high yields result from analytical difficulties. We use caution interpreting results with TOC $<0.52\%$ and total hydrocarbon yields >500 mg/g TOC. Comparison with nearby similar lithologies often resolves ambiguities. Staining occurs in the Winnipegosis Formation: compare samples (Appendix 2) 6794 and 6796 with 6795 from the same well, and 6798 and 6799 in a nearby well. Staining also occurs in the Yeoman Formation: compare samples 6848 and 6883 with 6847 in the same well, or similarly mature samples. Other samples, such as 7184 from the Bakken Formation, have very low HI values for their maturity and hydrocarbon yield and are omitted from further discussion.

Solvent extract studies confirm potential in each Type II source rock identified by Rock-Eval/TOC experiments. Solvent extract richness evaluations commonly differ from pyrolytic evaluations, generally following organic matter type. Extract data underestimate the richness of Ordovician Type I organic matter, but most effectively describe the richness of Type II kerogen. HI and transformation ratio ($TR=(HI_0-HI)/HI$) variations are the only effective indicator of Type I source rock maturity, but extract and pyrolytic maturity parameters both show Type II source rock maturity.

SOURCE ROCK DISTRIBUTION AND LITHOLOGY

Winnipeg Formation

The Middle Ordovician Winnipeg Formation is a mudstone-sandstone dominant unit, up to 76 m thick in Canada and reaching approximately 100 m in the U.S. part of the basin. It unconformably overlies and onlaps both the Precambrian basement and the Upper Cambrian-Lower Ordovician Deadwood Formation (Paterson, 1971; Vigrass, 1971). It is compositionally and sedimentologically similar to the Inner Detrital Facies Belt of the lower Paleozoic succession in the upper Mississippi valley (Ostrom, 1964). It is an erosionally isolated element of the eastern North American cratonic platform succession deposited across the Transcontinental Arch (Osadetz and Haidl, 1989).

The Winnipeg Formation generally is a poor source rock in southeastern Saskatchewan and southwestern Manitoba. Lithologies like those found in Canada appear to be the source for some oils in the American Williston Basin. Rich source rock lithologies, like kukersites, may occur in the Winnipeg Formation in the United States and possibly even in Canada, although they have yet to be found. Characteristic lithologies are either sandstone and siltstone that dominate the Black Island Member, or green shale and silty shale in the overlying Icebox Member (Paterson, 1971). These lithologies have no petroleum potential. Thin, rich source rocks — rare lithologies restricted to the Icebox Member, and generally occurring near its top or base (Fig. 6) — occur in intervals interpreted as maximum flooding surface accumulations (Fig. 6, Appendices 1, 2). The lower horizon is richer and more persistent than the upper, it occurs primarily in the offshore mudstone facies belt and is less well developed in the transitional facies belt (Fig. 7; Vigrass, 1971). Upper Icebox Member source rocks have similar depositional settings.

Source rocks are black, papery shale and rusty black, lithic greywacke (rock fragments are limonitic oolites). They occur as thin beds, laminations, or partings in predominantly green shale deposited at shelf depths, below fair weather wave base but in contact with storm waves. These observations agree

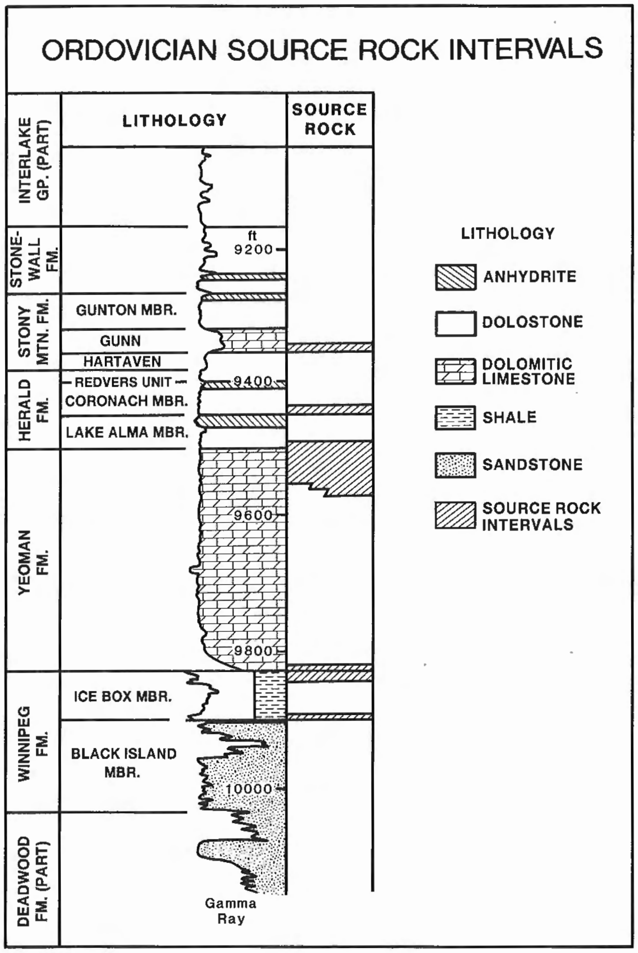

Figure 6. *Stratigraphic position of potential petroleum source rocks in the Middle and Upper Ordovician succession.*

with those of Dow (1974), who found most Winnipeg shale to be lean, generally <0.6% TOC. Dow (1974) suggested two geographic regions, without reference to stratigraphic position, where source rock potential improved. The first region, centered on longitude 104°W, underlies rich source rocks of the Bighorn Group (Fig. 8). The second region lies southeast of Minot, North Dakota, south of the Manitoba-Saskatchewan interprovincial boundary.

The maximum flooding surfaces associated with the richest Canadian source rocks should have more distal equivalents in North Dakota. In these areas, kukersite, the most important lower Paleozoic source rock, may have accumulated. Williams (1974) illustrated saturate fraction gas chromatograms (SFGCs), typical of kukersite, from solvent extracts of the North Dakota Winnipeg Formation. Coeval strata in the Decorah Formation also contain kukersite-like lithologies (Jacobson et al., 1988). Although no Winnipeg Formation kukersite occurs in the Canadian Williston Basin, *Gloeocapsomorpha prisca* alginite occurs in the Winnipeg Formation (Osadetz et al., 1989), and kukersite occurs in the basal Yeoman Formation (03-14-008-20W2, 2577 m; Appendix 1). Basal Yeoman kukersite occurs in regions where Winnipeg Formation source rock richness also improves (Dow, 1974).

Bighorn Group

The Cincinnatian and lower Niagaran Bighorn Group is a carbonate-evaporite dominant unit, up to approximately 230 m thick in Canada. It appears to conformably overlie and progressively onlap the Middle Ordovician Winnipeg Formation, and Upper Cambrian to Lower Ordovician Deadwood Formation (Osadetz and Haidl, 1989; Kendall, 1976). It is similar to the lower Paleozoic Middle Carbonate Facies Belt deposits in the upper Mississippi valley (Ostrom, 1964). The Bighorn Group is an onlapping, platform carbonate succession that crossed the Transcontinental Arch synchronous with the Taconic orogeny (Osadetz and Haidl, 1989).

Petroleum source rocks in Bighorn carbonates are kukersite. Kukersite is kerogenous lime mudrock composed predominantly of *Gloeocapsomorpha prisca* alginite. It occurs in the Yeoman, Herald, and Stony Mountain formations (Fig. 6; Table 3; Appendices 1, 2). The richest source rocks occur in the Yeoman Formation and are more than a metre thick. Other rich source rocks occur sporadically within the Coronach Member and Redvers Unit of the Herald Formation (Appendix 2). Kukersite is rare in the Gunn Member, Stony Mountain Formation and has an undetermined extent. A kukersite pictured by Kendall (1976, Plate XXIIIB), in the Lake Alma Member of the Bead Lake well (6-8-4-21W2), could not be found for analysis. Lake Alma Member, Herald Formation, and the Harthaven Member, Stony Mountain Formation, samples are stained rather than source rocks (Appendix 2). Other members and lithologies are lean. Thus Yeoman Formation kukersite is the sole documented, regionally significant source rock in the Bighorn Group.

Kukersite has a limited distribution and thickness in the Yeoman Formation. It is a small part of this formation, yet it persists across a large region. The most persistent source interval occurs in the upper Yeoman Formation, it extends across an area lying along longitude 104°W, including the first 23 townships between ranges 9 and 21, west of the second meridian. Within this region the average kukersite thickness in cored intervals is 23 cm (Fig. 8).

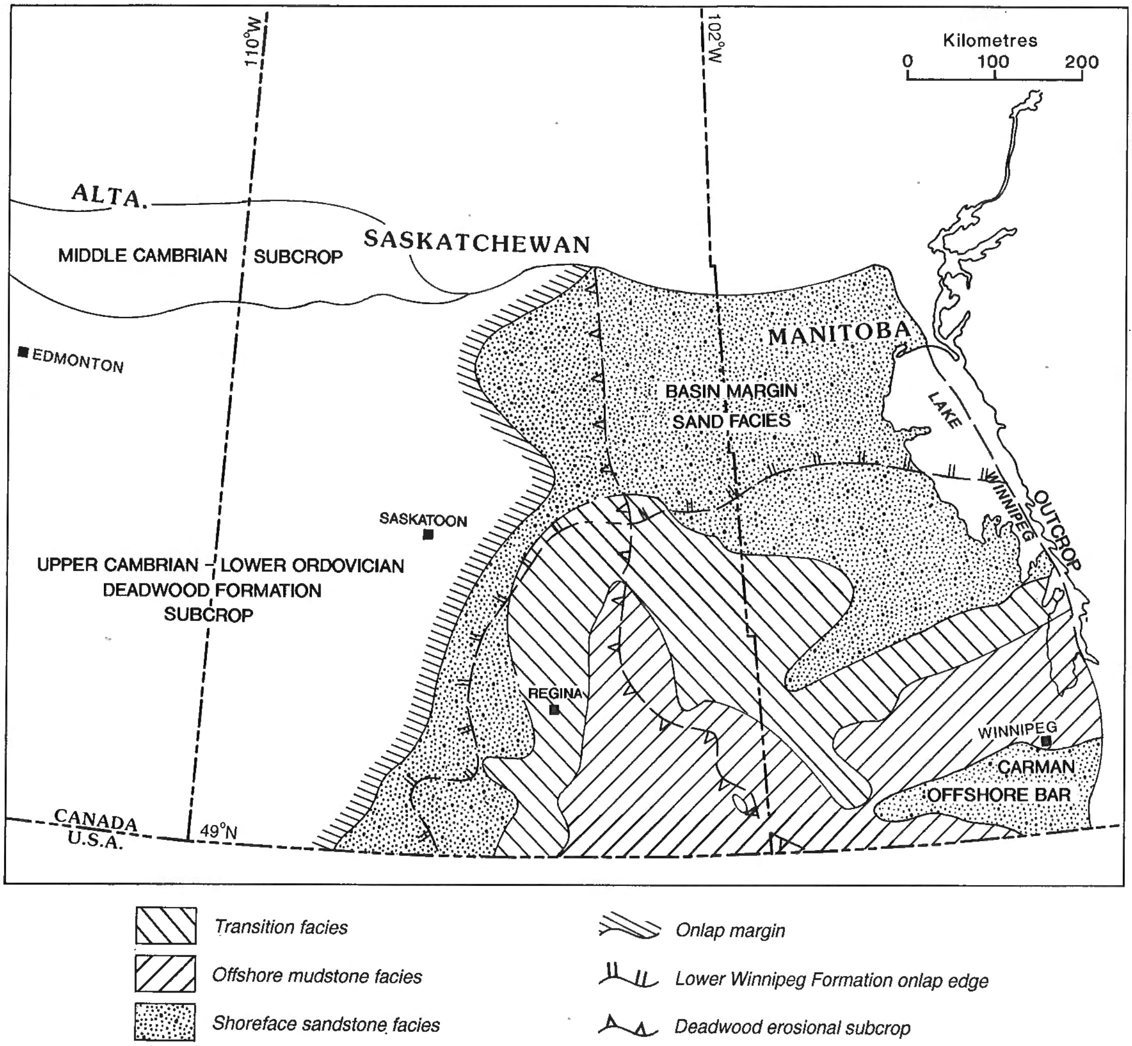

Figure 7. *Facies distribution of the Middle Ordovician Winnipeg Formation in the Canadian Williston Basin. Upper Winnipeg Formation lithofacies belts are after Vigrass (1971). Other important Cambrian and Ordovician stratigraphic contacts are also indicated.*

Kendall (1976) outlined the Upper Ordovician depositional facies in southeastern Saskatchewan, identifying north-south oriented lithofacies patterns within the upper Yeoman Formation. Kukersite distribution conforms to this trend. The region is also overlain by a thickened Lake Alma Member, Herald Formation (Stoakes et al., 1987), suggesting that the region formed a persistent depression in the Middle Carbonate Facies Belt. Such a feature would have been at a high angle to the magnafacies pattern. The depression follows the grain of underlying basement tectonic domains and geophysical features. The anomalously subsiding crustal block that contains the kukersite accumulations lies on the western margin of the North American Central Plains Conductivity Anomaly (longitude 104°W). The eastern margin of the upper Winnipegosis platform subsequently overlay this region due to a structural inversion between Late Ordovician and Middle Devonian time. This tectonic control largely excludes Canadian kukersite from elevated heat flows and enhanced hydrocarbon generation.

Kukersite, locally called kerogenite (Kendall, 1976), occurs as thin laminae, and thin beds of laminated pale yellowish brown to black, bituminous lime mudstone that has a resinous luster. Heterogeneous rocks form by mixing bioclastic material with kukersite or by bioturbation of kukersite. The bioclasts are commonly crinoid ossicles with lesser skeletal fragments, forming bioclastic floatstones with a kukersite matrix. Bioturbation is common but of variable intensity. Trace fossils are predominantly *Thalassinoides*-like Type II burrows described by Derby and Kilpatrick

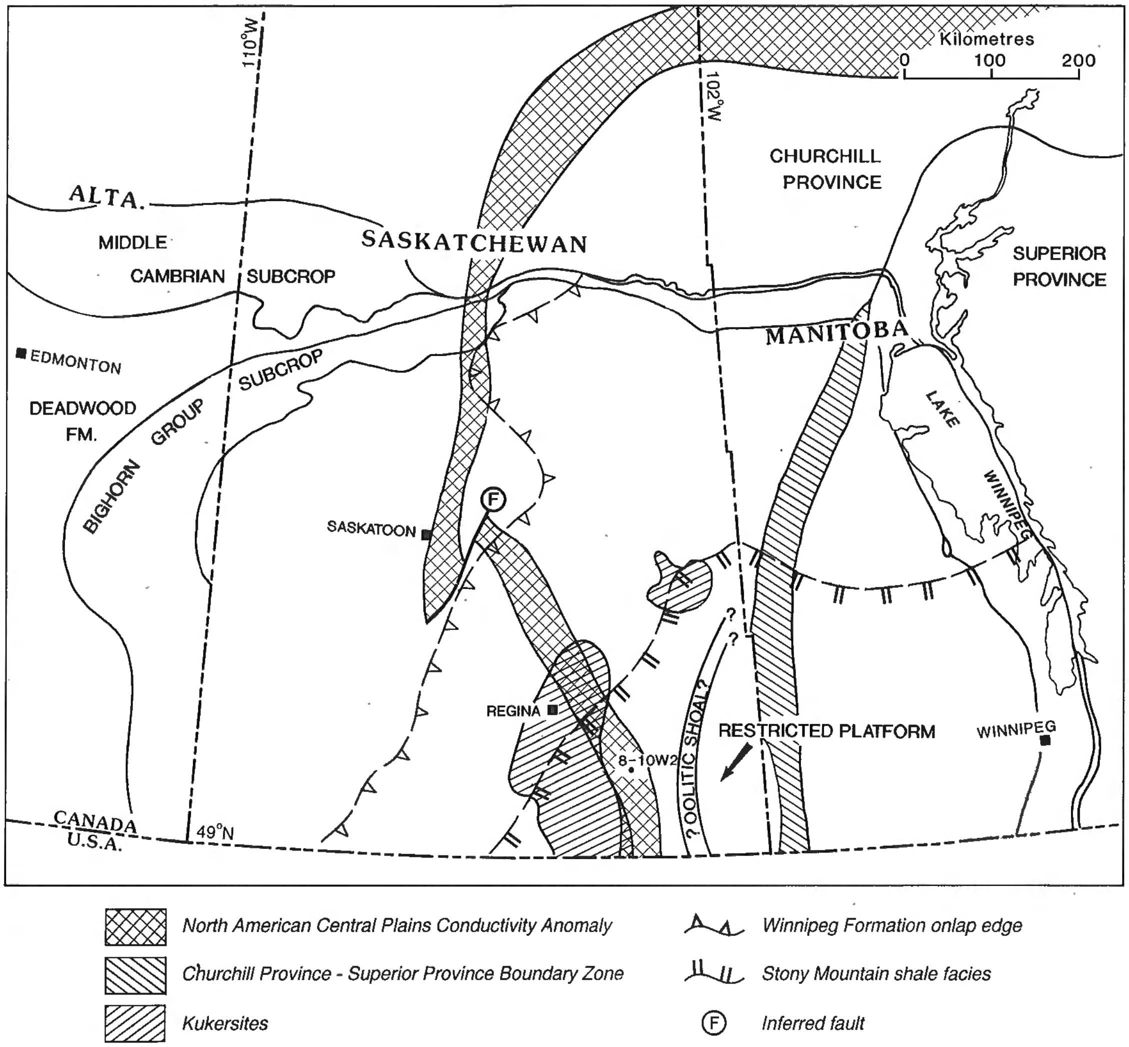

Figure 8. *Distribution of the Upper Ordovician Bighorn Group in the Canadian Williston Basin. Basement structural and geophysical features are from Morel-a-l'Huissier et al. (1990) and the Winnipeg Formation onlap limit is from Vigrass (1971) and Paterson (1971). Upper Yeoman Formation lithofacies distribution is after Osadetz and Haidl (1989) using elements suggested by Stoakes et al. (1987) and Kendall (1976). The interprovincial boundary follows Range 30W1 south of latitude 54°N. North of 54° the boundary follows longitude 102°W.*

(1985). Where bioturbation is complete, it destroys kukersite and the rock is identical to "Tyndall stone" of the mudrock dominated ramp facies. Where bioturbation is incomplete, rich kukersitic beds contain backfilled burrows with no source rock potential.

Petrography suggests kukersite is an accumulation of non-motile, palmelloid and subtidal stromatolitic mat phases of *G. prisca's* life cycle. The organism was common in the subtidal carbonate ramp setting of the Late Ordovician Middle Carbonate Facies Belt (Stasiuk and Osadetz, 1990). A ponded, mildly anoxic to strongly dysaerobic bottom layer protected this region from infaunal predation and degradation by inhibiting bioturbation.

Winnipegosis Formation

The Middle Devonian Winnipegosis Formation is a predominantly carbonate succession. It consist of a platformal Lower member, commonly 6 to 15.5 m thick (Wilson, 1984), but up to approximately 20 m thick, and a platformal and basinal succession of the Upper member. The Upper member thickens to more than 50 m toward the platform margin (Ehrets and Kissling, 1987). A persistent starved basin, the Prairie, with 70 m thick pinnacle reefs (Fig. 9), covered large areas. It lay northeast and east of the Winnipegosis platform margin (Wilson, 1984) and west and southwest of the Elm Point platform (Rosenthal, 1987).

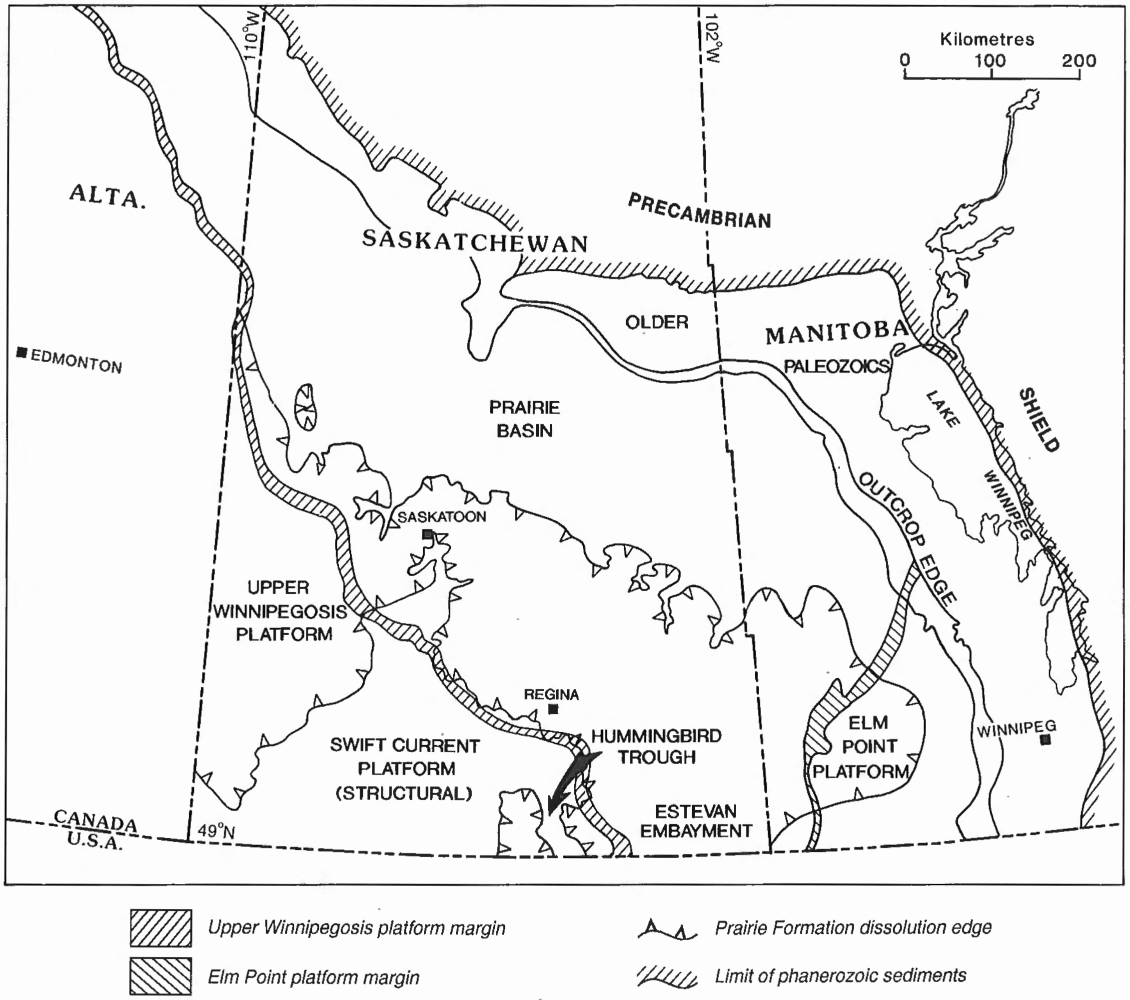

Figure 9. *Distribution of the Upper Elk Point Group in the study area. The carbonate platform of the Lower member, Winnipegosis Formation, underlies the entire Upper member distribution. The Upper Winnipegosis and Elk Point platforms (after Ehrets and Kissling, 1987, and Rosenthal, 1987) pass northward into the Prairie Basin where Brightholme source rocks and Upper Winnipegosis pinnacle reefs accumulated. Embayments in the Upper Winnipegosis/Elk Point platform of the Estevan area coincide with north–south trending basement structural features, including the North American Central Plains Conductivity Anomaly (NACPCA). The dissolution edge of Prairie Formation salts is after Christopher (1984b). Comparison with Figure 8 reveals a subtle structural inversion between Late Ordovician and Middle Devonian time. Most Yeoman Formation source rocks accumulated slightly west of the region of anomalous crustal structure and enhanced HC generation, whereas the Estevan Embayment, with its rich Brightholme source rocks and pinnacle reef reservoirs, was deposited directly over the enhanced HC generation region. The present day structure generally follows Ordovician trends.*

In ''off-reef'' settings, open marine, clean carbonates of the Lower member underlie bituminous lime mudstones intercalated with facies of the reef margin (Rosenthal, 1987). Basinal laminites are conformably and gradationally overlain by thinly laminated anhydrite and gypsum beds. Wardlaw and Reinson (1971) included both the bituminous and evaporitic laminites in the Lower member, Winnipegosis Formation. Subsequent work suggests that the bituminous laminites form a mappable, lithologically distinct unit, deposited during the interval of pinnacle reef growth. Stoakes et al. (1988) suggested the informal stratigraphic name Brightholme member to describe the starved basin bituminous laminites. Within this publication we use the name Brightholme member as defined by Stoakes et al. (1988), use of the Lower member (restricted) refers to a unit similar to the originally defined member, but without its basal bituminous laminites.

Winnipegosis potential source rocks occur in different stratigraphic and geographic positions. Different members have different dominant lithofacies, controlled primarily by depositional setting (Fig. 10). Platform deposits of the Upper and Lower members are undobeds. Upper member undobeds pass basinward into unnamed mudstone clinobeds, present primarily in North Dakota (Ehrets and Kissling, 1987). Clinobeds intertongue with starved basin, bituminous laminites of the Brightholme member. Basinal laminites are equivalent to the pinnacale reefs of the Upper member (Stoakes et al., 1988; Rosenthal, 1987; Edie, 1959).

Some source rocks occur near the base and top of the Lower member, generally coincident with maximum flooding surfaces (Fig. 10). Such source rocks occur sporadically and have poor to fair potential. The Upper member and its basinal equivalents include several lithofacies, representing distinct depositional environments and having specific characteristics. No source rocks occur within the Upper member platform facies.

Brightholme source rocks are the thickest and richest. The Brightholme member is identical to the laminated facies described by Rosenthal (1987). In Manitoba, a systematic core hole drilling program sampled the starved basinal facies and found the member to be 1 to 15 m thick (Rosenthal, 1987). In southeastern Saskatchewan, exploring for Winnipegosis pinnacle reefs has meant that wells miss the starved basin lithofacies. Consequently there are few cores in the Brightholme member. Those cores cut in the Brightholme are usually near carbonate build-ups where the member averages about 60 cm and is up to 1 m thick. This is probably a biased sample and it is likely that the Brightholme member thickens away from reefs, as observed in Manitoba. Brightholme member source rocks conformably overlie Lower Winnipegosis platform carbonates and occur as rare, thin beds or laminae intertonguing with equivalents of the Upper member pinnacle reef facies.

During the Middle Devonian, north–south oriented basement structural domains, centred at longitude 102°W, subsided more than adjacent areas (Fig. 9). This resulted in a large embayment (Estevan Embayment) of the Middle Devonian platform edge which separates the Elm Point and Upper Winnipegosis carbonate platforms. Brightholme member source rocks accumulated in this embayment, overlying an area of elevated crustal heat flow (Majorowicz et al., 1988) and enhanced hydrocarbon generation (Osadetz et al., 1989) related to the underlying North American Central Plains Conductivity Anomaly. This results in the occurrence of rich source rocks where oil windows are anomalously shallow. Other platform margin embayments occur on a smaller scale along subsidiary northwest–southeast trending linears (Ehrets and Kissling, 1987) (Fig. 9).

The Lower member (restricted) is generally a good to fair source although much leaner than the Brightholme member because its predominant

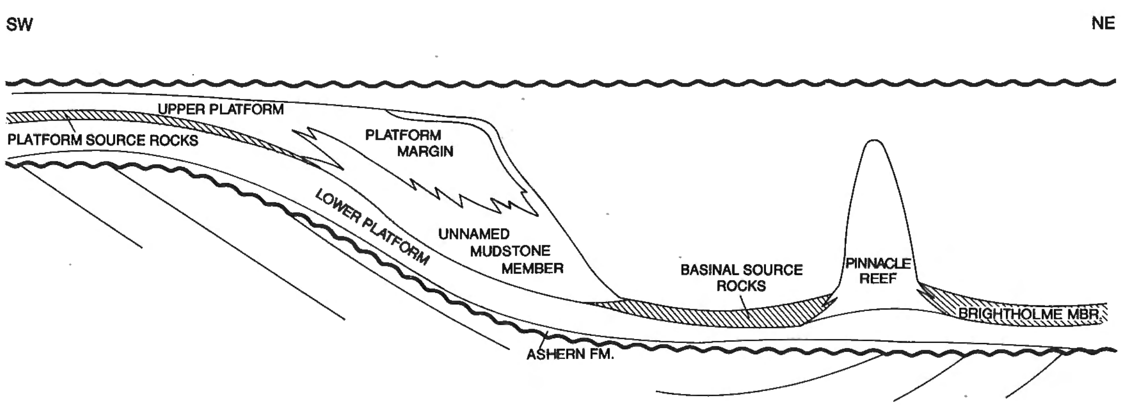

Figure 10. Winnipegosis Formation depositional settings. Potential petroleum source rocks are deposited at maximum flooding surfaces in both platformal and basinal settings. Brightholme member basinal source rocks are commonly sampled, particularly in Manitoba, where continuously cored mineral exploration boreholes have been drilled. Other sources are cored less frequently. Platformal source intervals have been encountered, but their extent and richness is poorly known because they are seldom cored. The unnamed mudstone clinobeds adjacent to the platform margin have poor source rock potential.

lithologies are clean carbonates and evaporites. A thick, unnamed mudstone member occurs as clinobeds between the starved basin and platform in North Dakota (Fig. 10). This member includes the informal Alpha and Beta "shales" (Ehrets and Kissling, 1987). At its distal edge it intertongues with the Brightholme member while to the west and south it passes into the Upper member platform strata. Although much thicker than other fine grained Winnipegosis lithofacies, this rock body has, at best, only fair source rock potential (Table 3; Appendices 1, 2).

Bakken Formation

The uppermost Devonian–lowermost Mississippian Bakken Formation has a middle sandstone–siltstone member between two shale members and is distributed widely across the Canadian and American Williston Basin (LeFever et al., 1991; Webster, 1984; Christopher, 1961) (Fig. 11). Throughout Saskatchewan, the Lower shale member is commonly less than 8 m thick, and the Upper shale member is less than 2 m thick. In North Dakota, the Lower shale member reaches a maximum of 17 m thick, the Middle member is up to 27 m thick, and the Uper shale member is 9 m thick.

The interpretation of Bakken depositional environments has caused much debate (see LeFever et al., 1991 for a review), yet the presence of normal marine planktonic fauna, an impoverished benthic fauna, and stratigraphic and sedimentological evidence suggest Bakken shales were deposited in an impoverished marine shelf environment. The abundance of organic carbon in these shales has

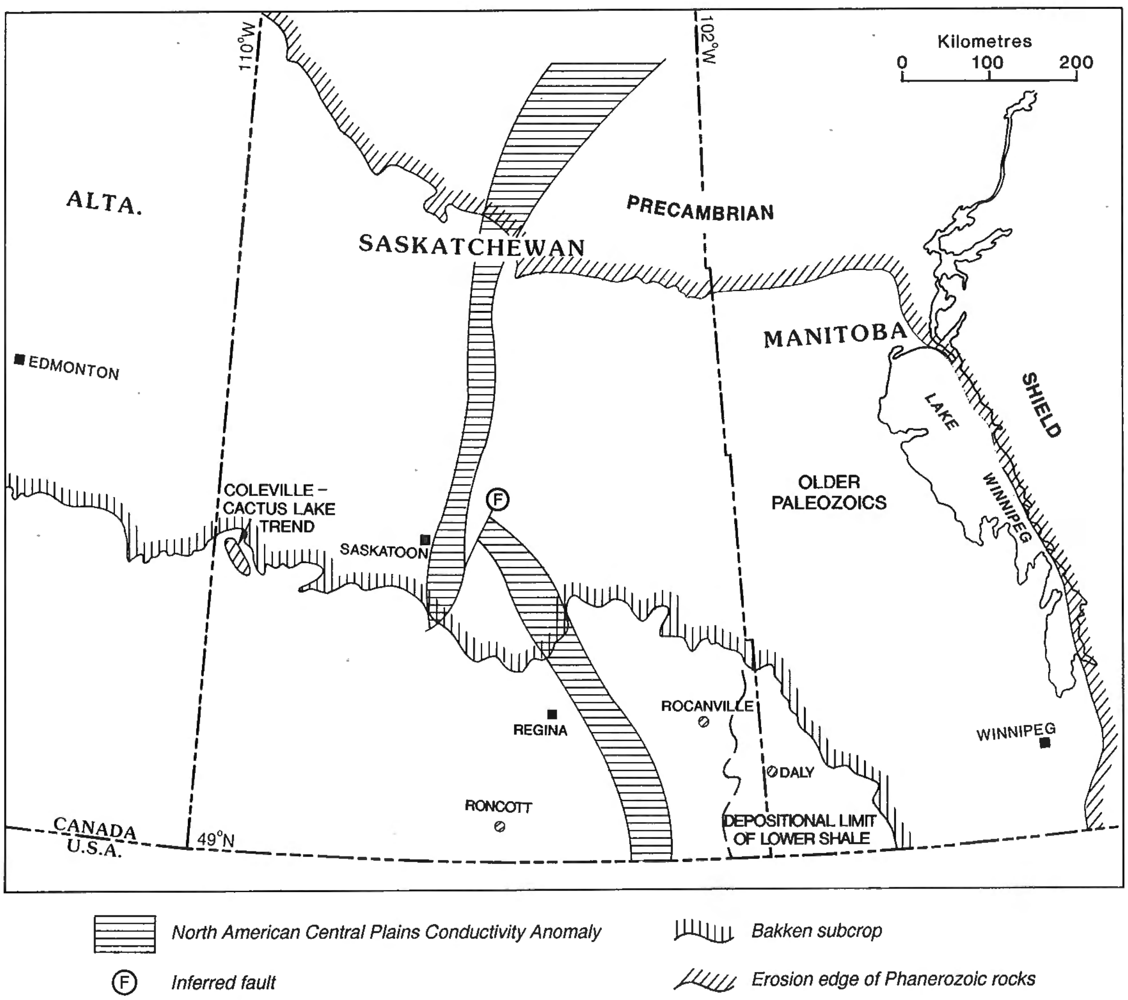

Figure 11. Bakken Formation distribution in the Canadian Williston Basin, showing the depositional limit of the Lower shale member (after Christopher, 1961) and the position of significant oil fields in the Middle sandstone member. The North American Central Plains Conductivity Anomaly and basement structures offsetting that feature are after Morel-a-l'Huissier et al. (1990).

commonly led to the suggestion of a layered water column and a strongly anoxic bottom layer. The composition of resulting oils and source rock solvent extracts does not suggest persistent anoxic bottom waters (Osadetz et al., 1992), although sedimentological indications of a layered water column are common. Some samples examined by Leenheer (1983) suggest that a persistent anoxic bottom layer may have occurred in Alberta.

Potential sources occur as black shales and mudrocks, the characteristic lithology of the shale members. Green, red and maroon lithologies in northern and eastern areas do not have significant hydrocarbon potential, neither do carbonaceous partings that occur within the coarser grained middle member. Comparison with the work of Christopher (1961) shows that lithological and colour variations generally coincide with richness variations.

Lodgepole Formation

Lime mudstones of the Lower Mississippian Lodgepole Formation (Madison Group) abruptly but conformably overlie the Bakken Formation. In Canada, the Madison Group has a complex internal stratigraphy but can be subdivided into three successions (Fig. 12). The use of informal marker units, defined using wireline logs, obscures these subdivisions in basinal settings. The lowest succession, consisting of onlapping–offlapping carbonate ramp cycles, persisted until Tilston-MC_2 deposition ended (Figs. 5, 12). Succeeding Alida strata onlap lower beds and are followed by regressive strata. These beds mark a change in depositional style from low-angle carbonate ramps to prograding rimmed platforms. When Frobisher deposition ended, the basin, largely filled, was again transgressed and the succeeding Midale Beds were deposited in a broad, shallow basin dominated by restricted carbonate and evaporite accumulation. This scenario continued until the end of Poplar accumulation (Figs. 5, 12). This depositional framework bears a resemblance to the carbonate ramp–rimmed platform–karst plain succession that characterizes correlative successions in the west-central American interior (Sandberg et al., 1983; Gutschick et al., 1980; Sandberg and Gutschick, 1980). However, regional correlations remain to be established and Williston Basin Mississippian stratigraphy requires further work.

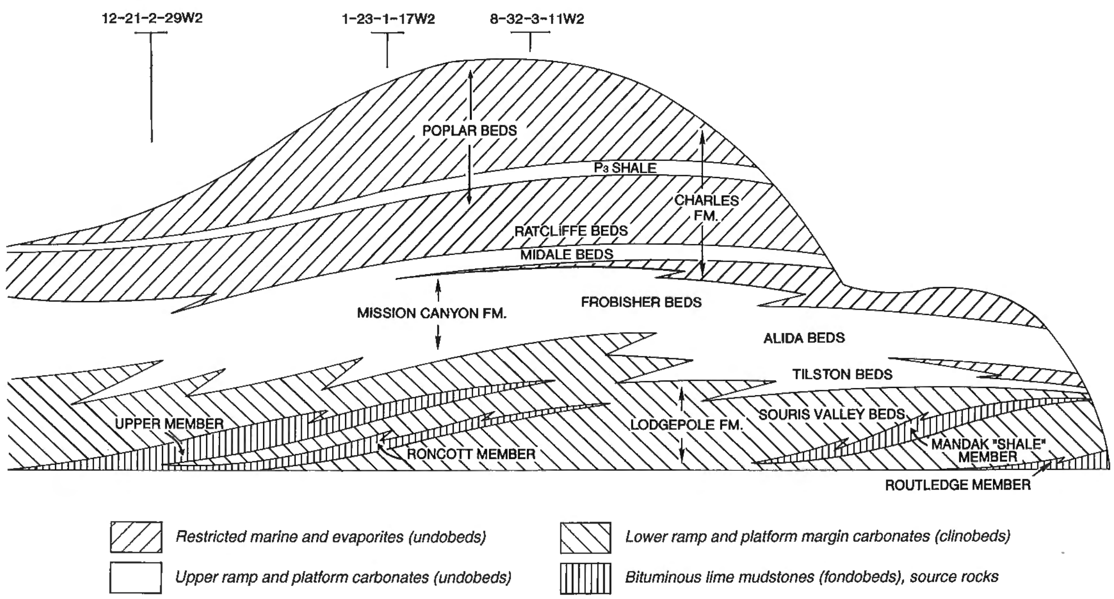

Figure 12. *Diagrammatic section showing generalized Madison Group lithostratigraphic relationships. The four generalized lithologies include distal ramp bituminous lime mudrocks, lower ramp and platform margin lime mudstones, wackestones and grainstones, and grainstone dominated upper ramp and platform lithofacies, generally succeeded by restricted marine and evaporitic lithofacies. Potential source rocks appear restricted to the initial Tilston–Souris Valley carbonate ramp succession, although Upper member source rock accumulation may have persisted into the early periods of rimmed platform progradation during Frobisher–Alida deposition.*

The bulk of the Lodgepole Formation has little or no source potential. Few recognize the formation as a regionally significant source (Osadetz and Snowdon, 1986b), yet it is the most important source of oils in the Madison subcrop (Osadetz et al., 1992) and the southwestern Saskatchewan Jurassic–Lower Cretaceous petroleum provinces. There are few cored intervals from potential source lithologies and the regional source rock distribution must be inferred from persistent wireline log markers.

Cyclical carbonate–evaporite platform sediments described by Edie (1958) have distal equivalents that contain rich source rocks. Rich, regionally significant, potential petroleum source rocks occur exclusively in the lowest depositional package. Lodgepole source rocks are successive, distal, starved, carbonate ramp accumulations that are generally equivalent to Tilston and Souris Valley beds (Lodgepole to MC_2 succession in Manitoba) in platformal settings.

Basal Lodgepole strata are comprised of glauconitic lime mudstones and sparse, fine grained crinoid floatstones with a glauconitic lime mudstone matrix. The overlying lithological succession is complex in Manitoba (McCabe, 1959, 1963) and southeastern Saskatchewan. East of Weyburn, a lime mudstone succession overlies basal Lodgepole beds. It contains thin "Marker Beds" (Fuller, 1956) of reddish brown and brownish black shales and argillaceous limestones. West of Weyburn, the Mission Canyon Formation thins abruptly (Edie, 1958, fig. 2) and the Lodgepole Formation includes several bituminous rock bodies. These bituminous, starved, distal ramp deposits are interbedded with regressive, offlapping, wackestones and mudstones.

LeFever and Anderson (1984) have mapped basinal Lodgepole cycles in the United States consisting of basinward thinning distal ramp deposits. There are at least three source rock bodies in the Lodgepole Formation. Several informal stratigraphic units, including the Upper and Roncott members (Osadetz and Snowdon, 1986), indicate that the bituminous lime mudstone source rocks in the Lodgepole Formation have been previously recognized (Figs. 12, 13; Appendix 1). These bituminous lime mudstone members were followed seismically (Reimer, 1989, p. 176) and referred to as a "deep Mississippian shale marker", in reality the Upper member, and an unnamed underlying reflection, in reality the Roncott Member. Both the Upper and Roncott members are identifiable in sections in the United States (LeFever and Anderson, 1984), where they form partly basinward thinning, distal ramp deposits. The "Mandak shale" of the Lodgepole Formation (McCabe, 1959) is another, older, bituminous lime mudstone that underlies strata correlative with the Upper and Roncott members. It too thins basinward (Lineback and Davidson, 1984, Fig. 3) and may correlate with the Lodgepole "Marker Beds" (Fuller, 1956; Table 2). Each source rock body is the distal portion of a series of eastwardly migrating carbonate ramps.

The basal Upper member and a thin bed in the Roncott well are vitreous to resinous, bituminous lime mudstone. The thinner and less persistent "marker beds" source rocks are commonly argillaceous lime mudstone and calcareous shale. At approximately the third meridian, the thinning Upper member merges with condensed underlying beds to overlie basal Lodgepole strata. Source rock bodies are lenticular but incompletely mapped. They are up to a few tens of metres thick and cover several tens of townships (Fig. 13). Prairie Formation evaporite dissolution did not affect Upper or Roncott member accumulation.

SOURCE ROCK RICHNESS

Source rock potential depends on TOC content and kerogen quality as characterized by hydrocarbon generation potential and conversion efficiency (per gram TOC). Increased source rock volume or high TOC content can compensate for poor quality. Kerogen and bitumen composition and quantity, or their pyrolyzates, are common richness indicators. Rock-Eval/TOC anhydrous pyrolysis, solvent extract yield, and atomic hydrogen, oxygen and carbon analyses provide parameters characterizing residual hydrocarbon potential and organic matter type. Source rock potential indicators are commonly normalized to TOC.

S1 and hydrocarbon extract yield indicate actual hydrocarbon generation, however they are not directly comparable. Solvent extractable hydrocarbon masses can be up to three times those measured in S1 pyrolyzates, an indication that much bituminous material may occur in the S2 peak (Snowdon, 1984). Both indicators are affected by thermal maturity and migration.

Winnipeg Formation

Petroleum potential of the Winnipeg Formation varies with lithology. Green shales have little TOC (Appendix 1). In other fine grained clastic rocks, concentrations up to 10.41% TOC occur, although the average is only 1.55% TOC (Table 3). Pyrolysis S2

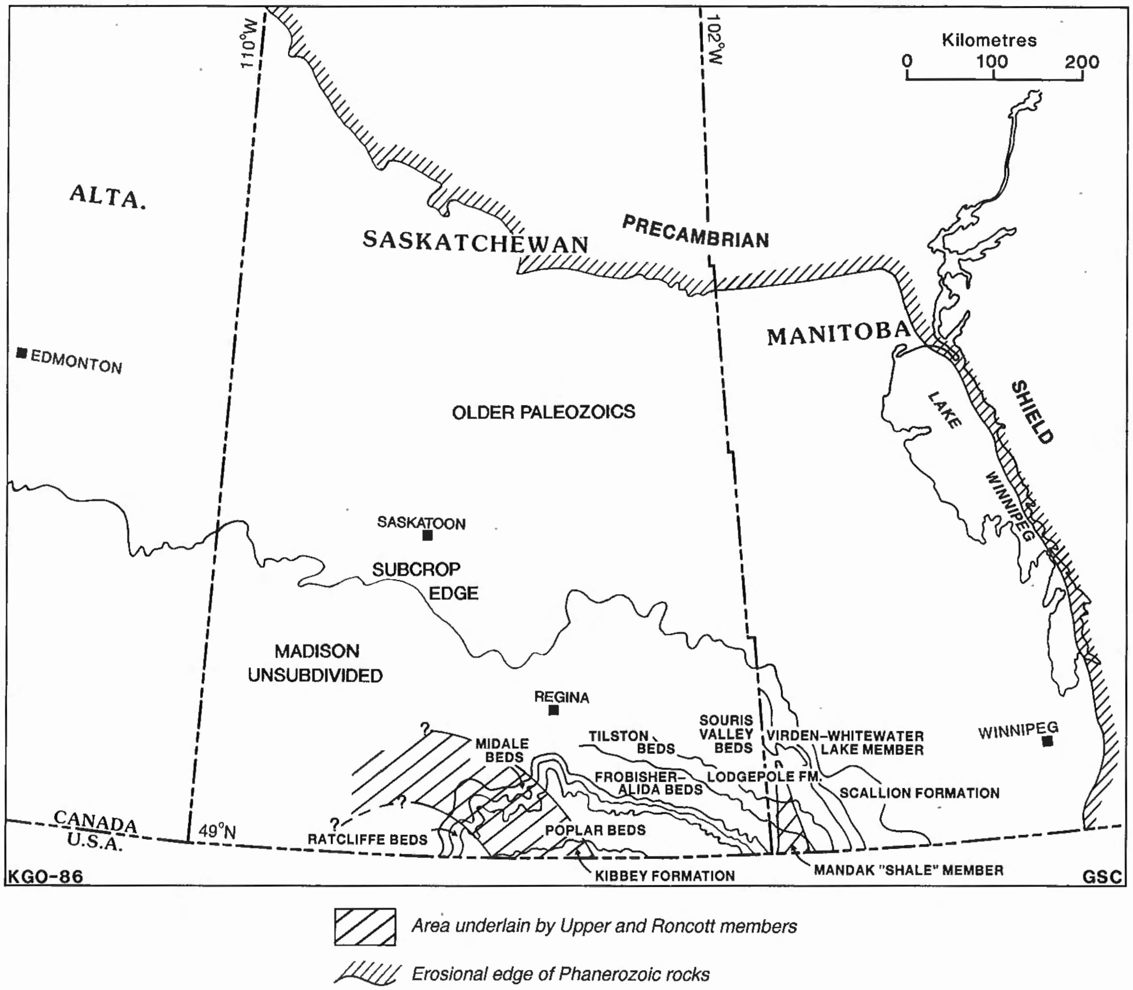

Figure 13. *Madison Group distribution in the Canadian Williston Basin showing the subcrop of stratigraphic units from the Madison Group (after Podruski et al., 1987) and the distribution of lime mudrock bodies from the Mandak, Roncott and Upper members. Mandak "shale" distribution is after McCabe (1959).*

yields up to 98.19 kg/t characterize the richest sample. Average yield from 10 samples is 11.66 kg/t. With the omission of the richest sample (not a common rock in this formation), the average S2 is 3.21 kg/t. There is a strong linear correlation between TOC and total petroleum potential (TPP = S1 + S2), such that TPP is 9.56x(TOC)-2.93. The negative intercept suggests an inert organic matter component. Average richness represents an aggregate value.

Starvation and reducing conditions, controlled by water depth and physical basin restriction, control organic richness in Winnipeg strata. The marked difference between the sample from the basal Icebox Member maximum flooding surface and other samples suggests improved potential controlled by depositional environment. Samples from transitional facies belt settings (Fig. 7), although the most numerous, are not the richest Winnipeg source rocks.

Organic material includes dispersed alginite associated with acritarchs, chitinozoa, and fragments of brachiopods and arthropods (Osadetz et al., 1989). Alginite is composed of dispersed *Gloeocapsomorpha prisca* Zalessky 1917 cup-like agglomerations. It is roughly equivalent to an organically lean microfacies found in Bighorn kukersites (Stasiuk and Osadetz, 1990; Osadetz et al., 1989). HI values ranging from 368 to 924 mg/g TOC suggest both Type II and Type I organic material. *G. prisca*, a Type I precursor organism, in samples with Type II HI values, suggests either mixed organic matter types or diagenetic alteration.

Hydrocarbon extract yields range from 6 to 19 mg/g TOC (Appendix 2) and indicate no potential. Variations in hydrocarbon yield are attributable to richness but not TOC. In one well (01-04-20-32W1), hydrocarbon yields appear to increase with increasing T_{max}, HI and %HC, yet the apparently more mature sample is at a shallower depth and only 16 m away from other samples. Samples such a short distance apart must have similar maturities. Both samples have Type I HI, organic matter with a maturity that cannot be adequately characterized by most Rock-Eval and extract maturity parameters (Espitalie et al., 1985). Comparison of Type I samples with deeper, although not significantly more mature, Type II samples from the 05-15-10-02W2 well show hydrocarbon yields that are similar. These also have poor potential.

Bighorn Group

Kukersite contains up to 34.9% TOC (Appendix 1) with an average of 9.07% TOC (Table 3). Hydrocarbon yield from pyrolysis is up to 339 kg/t (S2 peak), the average yield is 77.32 kg/t. There is a strong linear correlation between TOC and TPP [TPP = 9.56x(TOC)-8.15], suggesting an inert organic component. Thermally immature samples commonly have HI values greater than 800 (Fig. 14) and OI values below 20, suggesting a Type I source. Petrographic examination indicates that kukersite is *G. prisca* alginite occurring in a distinctive petrographic microfacies (Stasiuk and Osadetz, 1990).

Richness and organic matter type must be interpreted using immature, undepleted samples. We have estimated the initial Hydrogen Index (HI_0) from the slope of TOC versus TPP. This technique accounts for early catagenic products. Identification of immature samples is source specific because Type I source rocks do not exhibit systematic variations in T_{max}, PI or hydrocarbon yield with maturity (Fig. 15). By relying on compositional homogeneity in macerals it is possible to use HI variations with depth to identify immature samples. On plots of either HI (Fig. 14) or (S1 + S2)/TOC against depth, a strong linear trend occurs above 2950 m, defining an immature sample trend.

Below 2950 m there is a wide range of HI values at a given depth. The general restriction of staining to below 2800 m corroborates this interpretation. Immature samples from the TPP plot slope indicate that HI_0 is 956 ± 33. The small standard error and the HI_0 value of 1016 ± 82, comparable to that derived from the extrapolated (S1 + S2)/TOC value at zero

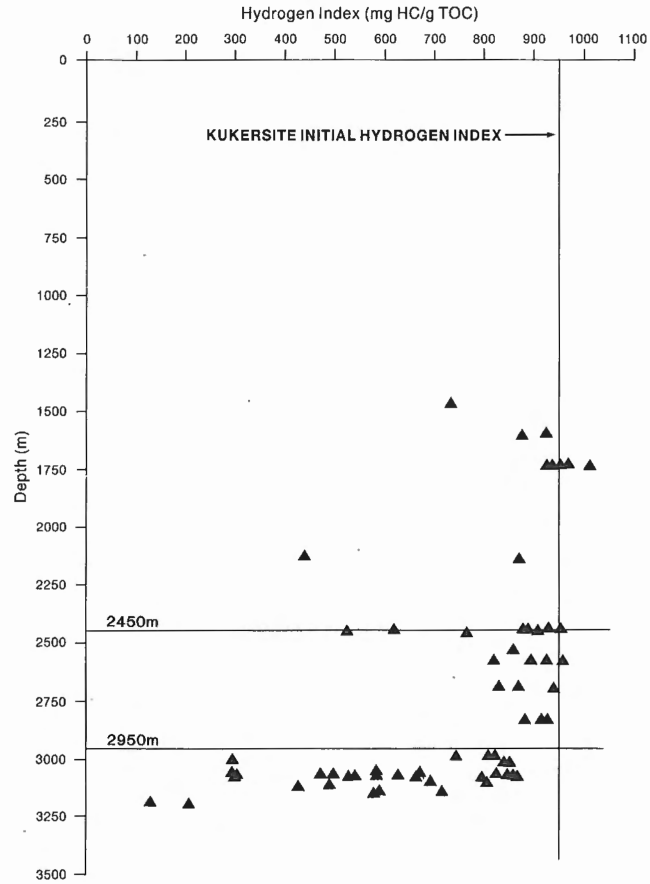

Figure 14. *Yeoman Formation: kukersite HI variations with depth. The HI_0 is 956 ± 33 and is inferred from the slope of the Total Petroleum Potential plot. Note the significantly lower HI values below 2450 m and 2950 m, in both cases the decrease in HI is interpreted to result from catagenic HC generation. Differences in the position of the top of the oil window reflect geographic variations in thermal history caused by lateral heat flow variations associated with changes in crustal structure. An enhanced HC generation region is associated with the North American Central Plains Conductivity Anomaly. Similar effects can be observed in other formations.*

depth, suggests great uniformity of organic matter type, consistent with petrographic observations. Kukersites are interpreted to be rich source rocks. These features also show that, unlike some Type II sources, there has been no significant reduction of petroleum potential due to degradation.

Solvent extract yields do not reflect source rock richness deduced from HI_0. Hydrocarbon yields vary greatly among comparably mature samples and

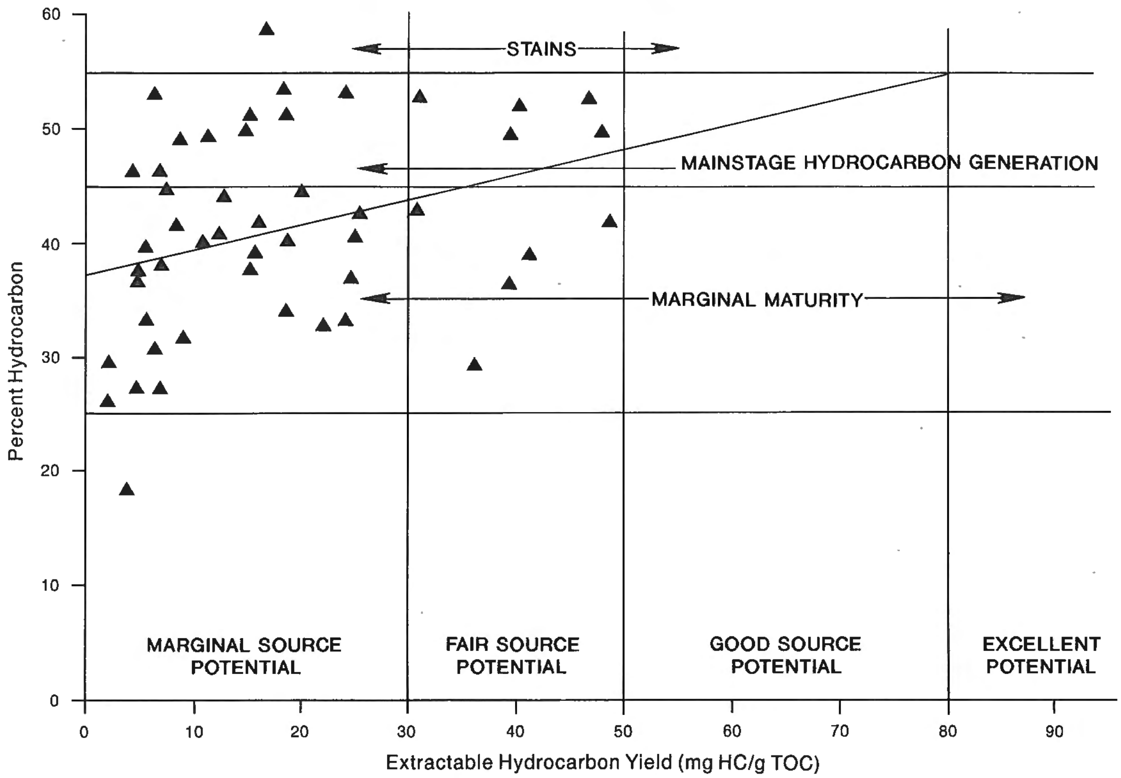

Figure 15. *Yeoman Formation: HC yield versus %HC from kukersite solvent extracts. A regression line to the data has been calculated, it suggests that HC yield increases with increasing %HC, although the correlation is poor. Standard HC yield richness and HC% thermal maturity thresholds are not applicable to this Type I source rock.*

hydrocarbon yields from the most mature samples, even some below the oil window, are similar to the least mature. There is a very weak positive correlation between extract hydrocarbon yield and %HC (Fig. 15). As hydrocarbon generation begins and the transformation ratio (TR) passes 10%, hydrocarbon yield increases to approximately 50 mg/g TOC. Thus, extract data suggest only marginal to good potential. We believe extract hydrocarbon yields underestimate the richness in kukersite because of organic matter type. Kinetic parameters for Type I source rocks (Ungerer and Pelet, 1987) suggest abrupt hydrocarbon generation due to their homogeneous and atypical kerogen structure. Thus increases in hydrocarbon yield lag until the main stage of oil generation. Yet even within the oil window, hydrocarbon yields do not match Rock-Eval/TOC source rock quality indications. We attribute this to expulsion, an interpretation supported by staining below 2800 m (Osadetz et al., 1989).

Yeoman kukersite rocks are persistent, thin, organic-rich platform carbonate source rocks. Their great petroleum potential appears clear, based on pyrolytic parameters of immature samples, but not from extract data. Kukersite also occurs in several other Bighorn Group units. Some of these, particularly the Stony Mountain Formation, may have significant potential in the United States.

Winnipegosis Formation

Average TOC in the Winnipegosis Formation is 7.38% (Table 3), from both starved basin and platform facies. Rich source rocks occur throughout the Brightholme member where TOC commonly exceeds 5% and reaches 45.92% (Appendix 1). There is a very strong linear correlation between TOC and Brightholme TPP [5.84x(TOC)-0.35], which averages 42.78 kg/t. TOC in unnamed mudstone clinobeds does not exceed 2.5% and averages 0.59% (Table 3). The positive correlation between TPP and TOC in the clinobeds is not strong but results in TPP=1.77x(TOC)+0.35. The average clinobed TPP is only 1.40 kg/t.

Immature samples in the Brightholme member can be identified using depth, T_{max} and PI criteria. The HI_0

is 615 ± 25, based on data from TPP plots of immature samples, suggesting Type II organic matter (Fig. 13). There is close similarity between HI_0 and (S1 + S2)/TOC extrapolated to zero depth (654 ± 27). Important HI variations remain despite this apparent homogeneity. Some Winnipegosis samples have higher HI values, up to 802, suggesting that a Type I organic matter (OM) component dominates in some intervals. Other lower HI values, below 600, reflect poor quality, immature sources with depositionally or diagenetically degraded potential.

Rich, but thin, source rocks occur in the Lower member (Appendix 1) where it conformably and gradationally overlies the Brightholme member. Both members have similar organic matter and solvent extracts (Appendix 2). Extracts were obtained from nine Lower member samples. Only three of these samples (6842, 7089, 7099) are unstained and have hydrocarbon yields that suggest marginal to good potential (Appendix 2). The thick mudstone clinobeds shows little potential, except at its distal limit where it interfingers with the Brightholme member (Appendices 1, 2). Most stained samples lie below the oil window. The richest unstained sample, 6909, has yields comparable to Brightholme samples.

Hydrocarbon yields confirm that the richest source rocks occur in the Brightholme member (informal), but they also suggest poorer and more variable richness than would be inferred from HI_0 (Appendix 2). Excepting sample 6741, hydrocarbon yields between 5 and 80 mg/g TOC in the Brightholme samples can be found at any depth. This represents a range of poor to excellent potential, with the greatest number of samples having poor and marginal potential (Appendix 2). There is a weak positive correlation between hydrocarbon yield and %HC, strongly influenced by sample 6741 (HC yield = 135.46 mg/g TOC, %HC = 50.91%). Hydrocarbon yield does not vary systematically with HI (Fig. 16), and reduced petroleum potential must be explained by combining pyrolytic, extract and petrographic data.

Basinal Winnipegosis source rocks are bituminite rich and contain Type II organic matter. They contain abundant unicellular, planktonic alginite dominated by *Tasmanites* and *Leiosphaeridia* (Type I OM). They also contain significant amounts of dasycladacean calcareous algae. Characteristically they form a laminated lithology rich in yellow-brown fluorescing bituminite and yellow fluorescing alginite bodies (Stasiuk et al., 1991). Hydrogen indices are generally intermediate, equal to or less than 650, suggesting Type II marine organic matter (Fig. 17). Some alginite rich samples have higher HI values, clearly indicating Type I organic matter. Toward the Winnipegosis platform margin, carbonate sources are in beds approximately equivalent to the unnamed mudstone clinobeds. These carbonates are interlaminated with organic-rich, micro-interlaminated, fluorescing bituminite and non-fluorescing bituminite, with lesser planktonic alginite (op. cit.).

Mechanisms proposed for bituminite origin include anaerobic microbial degradation by fermentation, sulphate reduction (Stasiuk and Goodarzi, 1988; Stach et al., 1982), or depositional oxidation (Teichmuller and Ottenjann, 1977). Low OI values and microtextures suggest that depositional oxidation is an unlikely mechanism for the production of Winnipegosis bituminites. Fermentation can also be excluded because heterotrophic bacteria appear unable to use higher molecular weight organic substrates (Boreham and Powell, 1987), and also because OI values are sufficiently low that oxidation must be insignificant. Stratigraphic associations with marine sulphate evaporites in the conformably overlying Lower member (restricted) suggest appropriate conditions for anaerobic sulphate reduction by methanogenic bacteria. This process could produce observed effects on HI (Rice and Claypool, 1981). The exact mechanism of microbial degradation has not been proven, yet immature samples, with HI and hydrocarbon yields lower than the formation average, provide clear evidence for petroleum potential degradation by this or other processes (Fig. 16).

Three sample subsets are identifiable on the HI and hydrocarbon yield variation diagram (Fig. 16). The first subset is generally immature and has Type I HI values greater than the formation average HI_0. These samples are enriched in Type I OM. Like Type I kukersite, their hydrocarbon yields do not vary systematically with maturity. Samples of the second subset plot within the region defining rich Type II maturation, only four samples lie within the intense hydrocarbon generation zone (%HC ≥ 45%). The third subset includes immature samples having low HI and hydrocarbon yields falling below the rich Type II thermal maturation pathway. These samples are degraded microbially, reducing their petroleum potential by removing hydrogen without increasing OI. This is consistent with microbial mechanisms required to produce observed bituminite textures, such reactions usually occur during early diagenesis. Our data suggest that the richest TOC samples have escaped degradation and dominate TPP-based HI_0 calculations.

Lower member source rocks have hydrocarbon yields that suggest poor to marginal potential (Appendix 2) and petrographic textures that match

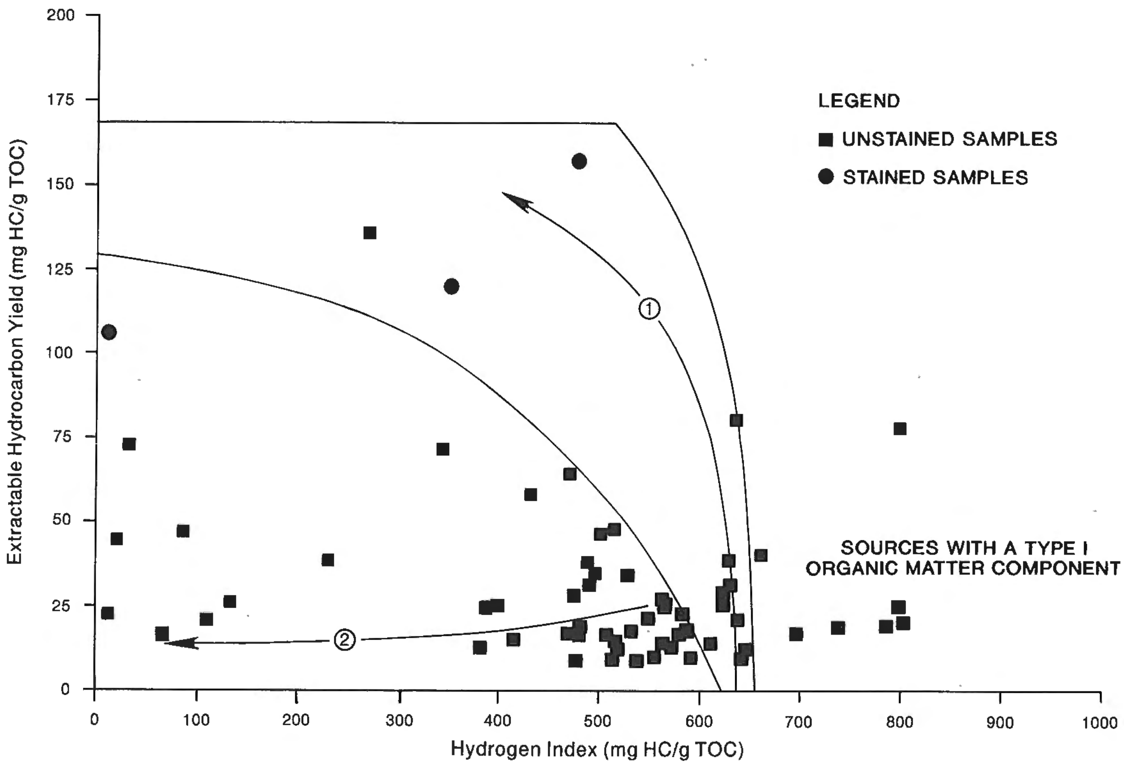

Figure 16. *Brightholme member, Winnipegosis Formation: HC yield plotted against HI for solvent extract. The indicated region of increasing HC yield with decreasing HI (line 1) is an inferred rich source rock maturation pathway. This pathway is constructed by first relating standard HC generation models (Powell and Snowdon, 1983) to HI, and then by relating HC yield to standard %HC criteria for comparable thermal maturities using the regression analysis in Figure 14. The central line reflects the evolution of rich source rocks with HI_0 of 654, while the envelope reflects other rich source rocks whose HI_0 lies within the standard error associated with the TOC versus Total Petroleum Potential regression line. Samples with much higher HI values probably indicate a Type I organic matter component, while samples whose HC yields are much lower than expected for their HI (line 2) are interpreted to indicate petroleum potential reduction because of microbial activity.*

extract richness indications. These source rocks exhibit degradation of, and borings in, morphologically intact lamalginite, reducing fluorescent intensity and shifting $lambda_{max}$ toward the red region (Stasiuk et al., 1990). Therefore, Winnipegosis platformal source rocks resemble Yeoman kukersites petrographically (Stasiuk et al., 1991), but do not have Type I HI values (Appendix 1).

Bakken Formation

Samples of shale with colours other than black and brown generally have little or no TOC and thus little or no potential (Appendix 1). Black shales of the Upper and Lower members are the richest, most widespread source rocks in Williston Basin. Thirty-one samples from the Lower member average 11.77% TOC (Table 3) and the average TPP is 61.4 kg/t. Twenty-nine samples from the Upper member average 17.63% TOC (Table 3) and the average TPP is 93.72 kg/t. There is a strong linear relationship between TPP and TOC in both members. For the Lower member TPP = 5.87x(TOC)-7.66, and for the Upper member TPP = 5.63x(TOC)-5.69. The 30 richest samples average 18.71% TOC and TPP = 6.15x (TOC) + 1.68. Considering the large volume of the Bakken Formation, its pyrolytically indicated petroleum potential is remarkable, consistent with other estimates (Dembicki and Pirkle, 1985; Price et al., 1984; Webster, 1984; Leenheer, 1983; Schmoker and Hester, 1983; Meissner, 1978).

Immature Bakken samples can be identified using T_{max}, PI and %HC. Contrary to expected maturity variations, HI (Fig. 18) and (S1 + S2)/TOC increase

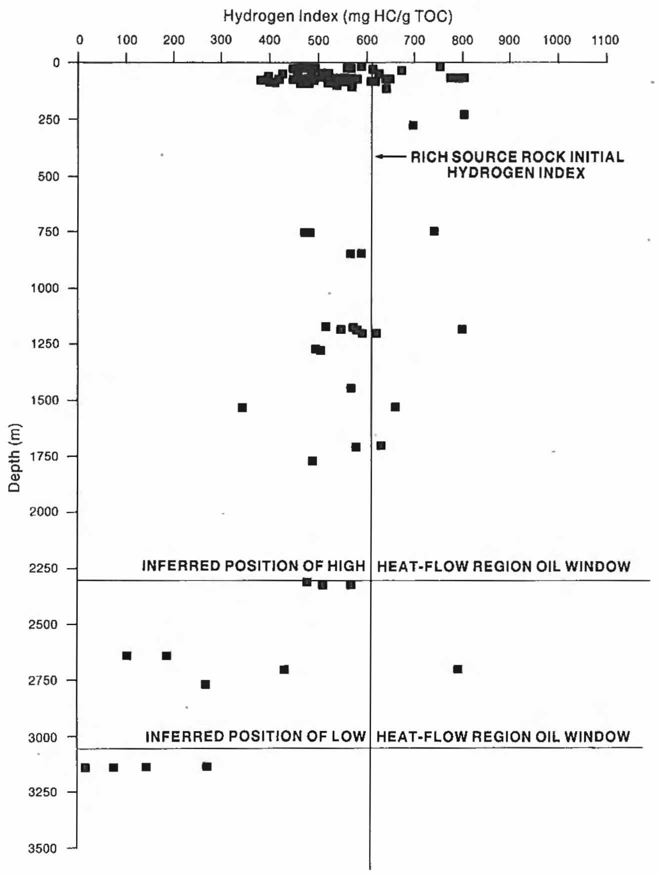

Figure 17. *Brightholme member, Winnipegosis Formation: HI variation with depth. The HI_0 is 654 ± 27, inferred from the slope of the Total Petroleum Potential plot. Note the significant gap in data between 1770 and 2330 m that prevents clear description of the top of the oil window. Lower HI values below 2330 m are interpreted to result from catagenic HC generation. Deeper appearance of oil windows in other geographic areas, reflecting lower effective heat flows, are lacking because the distribution of mature Brightholme source rocks occurs only in the enhanced HC generation region.*

with depth and (S1 + S2)/TOC increases with TOC. We interpret this to reflect depositional and diagenetic patterns now mimicked by depth contours. Current sample depth roughly reflects distance from paleoshoreline during deposition. Christopher (1961) clearly showed that changes in facies and shale colour follow changes in depositional setting. Rich source rocks that occur at depths greater than 1600 m and have HI values >400 apparently accumulated in deep water where oxidation was not effective. Lower Bakken samples with TOC values greater than 8.97% and (S1 + S2)/TOC > 500 now occur at depths below 1700 m (Fig. 18). Four of these samples have a TOC

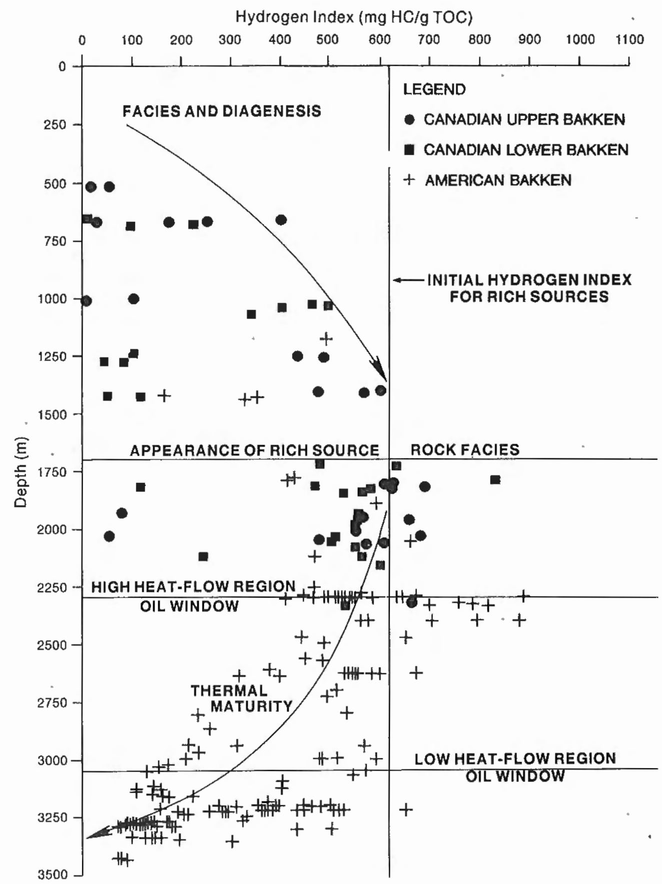

Figure 18. *Bakken Formation: HI variation with depth. Canadian data are from this study (Appendix 1) and American data are from Price et al. (1984) and Webster (1984). The HI_0 is 615 ± 60, inferred from Canadian data using the slope of the Total Petroleum Potential plot. It is applicable for all samples except some samples with Type I HI's. Note the significant increase in HI above 1700 m, which is attributed to both depositional facies and microbial processes. Decreasing HI values below 2300 m are interpreted to result from catagenic HC generation. Deeper immature samples and oil windows reflect lower effective heat flows in geographic regions away from the enhanced hydrocarbon generation region associated with the North American Central Plains Conductivity Anomaly. Although high and low heat-flow oil windows (following Price et al., 1984) are shown, it is more appropriate to consider that oil windows vary continuously with geographic variations in thermal history and that these two oil windows represent amongst the highest and lowest effective heat-flow environments. Note the general coincidence between the present depth of the high heat-flow oil window for both the Bakken and Winnipegosis (Fig. 13) formations, both Type II source rocks.*

range of 3.50% to 10.65%, occur between 1000 and 1100 m, have intermediate HI values, and (S1 + S2)/TOC values between 300 and 500 (Fig. 18). Nine other samples at variable depths have a considerable TOC range, from 0.47% to 21.60%, and HI and (S1 + S2)/TOC values less than 300. Similar variations occur in the American Williston Basin (Price et al., 1984; Webster, 1984) where burial patterns do not follow Bakken paleobathymetry, making relationships between HI and depositional facies less obvious (Fig. 18).

Using only samples from the Lower member collected below 1700 m, the HI_0 is 594 ± 79, suggesting a rich Type II source rock. Upper Bakken shales exhibit a similar relationship among depth, HI and (S1 + S2)/TOC values. Many very rich samples have reduced HI values, suggesting that organic matter type varies. Those with more than 13.25% TOC and from below 1750 m have consistently high HI values. Using these rich shale samples, HI_0 is 544 ± 102, also suggesting Type II OM. The greater uncertainty in this value reflects greater HI variation in the Upper member. The rich Type II samples in both shales have a combined HI_0 of 615 ± 60 (Fig. 18).

Not all Bakken sources are as rich as the geographically restricted subset used to characterize the HI_0, approximately half the samples have HI values less than 550. Such variations are not attributable to maturity and generally reflect degradation following depositional and diagenetic trends.. HI variations match pyrolytic carbon [PC = 0.82(S1 + S2)] variations. In the Canadian Williston Basin, PC values are approximately 50%, a characteristic of Type II OM. In the American Williston Basin some samples have PC values up to 72% and HI values greater than the HI_0 determined from Canadian samples (Price et al., 1984; Webster, 1984). This indicates the addition of Type I OM to the predominant Type II OM. Type I material is probably *Tasmanales* alginite, a common palynomorph in the Bakken Formation (Christopher, 1961). Some samples have HI values typical of Type III OM and PC values significantly less than half the TOC, also suggesting a component of Type III OM.

Solvent extract data reflect the less optimistic source rock potential rating suggested by both rich and degraded sources. All Canadian samples have hydrocarbon yields less than 50 mg/g TOC. There is a strong linear correlation between hydrocarbon yield and %HC. Extrapolation of this correlation line gives hydrocarbon yields between 46 and 86 mg/g TOC during main stage hydrocarbon generation (Fig. 19; Appendix 2). Adding extract data from American Williston Basin immature samples (Webster, 1984; Price et al., 1984; Fig. 19) to Canadian samples suggests that this correlation line overestimates Bakken richness. American samples with lower hydrocarbon yields (less than 46) generally have lower HI values, suggesting microbial degradation. We maintain that the more optimistic HI_0 better characterizes the effective source, although it represents only one half of the Canadian and American samples.

Upper Bakken samples have marginally higher hydrocarbon yields than Lower Bakken shales at similar maturity (Appendix 2). This is different from average Rock-Eval/TOC characteristics that suggest the lower shales are richer sources. This difference is due to the greater abundance of Type I OM, with higher HI values, in the Lower member. From Webster's (1984) data we infer TOC to be higher in the upper shale, although neither Webster (1984) nor Price et al. (1984) discussed differences between the two shales. We conclude that the Lower member has a greater petroleum potential due to its greater abundance of Type I OM and its larger volume.

Petrographic observations confirm a complex kerogen composition (Stasiuk et al., 1990). Much of the organic material is a degraded, amorphous, nonfluorescing bituminite Type III. Nondegraded materials are predominantly planktonic marine alginite with lesser acritarchs, terrestrial sporinite and minor amounts of vitrinitic and inertinitic material (op. cit.). The Lower member contains abundant *Tasmanites*-rich alginite.

Oxidation, microbial degradation and maturity influence Bakken hydrocarbon yields (Fig. 20). HI-HC yield variations tend to reflect only Type II source rocks because American samples with Type I HI values tend not to have been extracted in the immature zone. Some samples plot within the rich source region on the HI versus HC yield diagram. A few samples (6961, 7185 and 6911) trace out a clear trend of increasing hydrocarbon yield controlled primarily by maturity.

Approximately half the samples have reduced hydrocarbon potentials. Stasiuk et al. (1990) suggested that observed bituminite textures originate from either diagenetic microbial degradation or depositional oxidation. Oxidation clearly affects shale colour, TOC and OI among shallower samples. Other particularly deep samples, with higher TOC and HI, must be degraded microbially (Fig. 20). Reduced petroleum potential cannot be attributed to the addition of Type III OM because vitrinite is not an abundant maceral component, although Type III HI values are common.

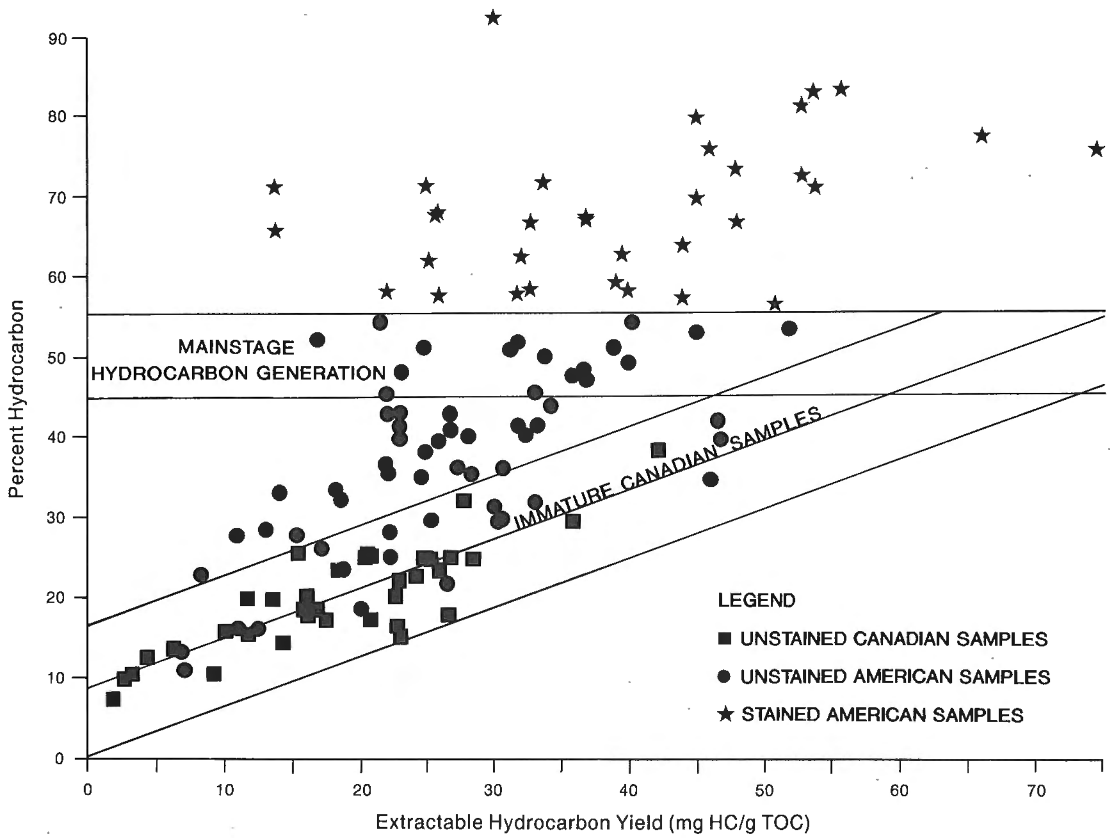

Figure 19. *Bakken Formation: solvent extract HC yield plotted against extract %HC. Sources of data include this study (Appendix 2) and studies in the American region by Price et al. (1984) and Webster (1984). Stained samples (%HC>55%) are distinguished from unstained samples. The regression line reflects unstained samples from Canadian data only and suggests that HC yield increases with increasing %HC, although the correlation is poor if American data are included. Note the absence of American samples along the regression line in the main HC generation stage (45%≤%HC≤55%). The standard HC yield richness and %HC thermal maturity thresholds indicated are applicable to most samples, although a few samples with Type I Hydrogen Indices (Fig. 17) may not follow conventional extract richness and maturity variations.*

Among the Canadian immature samples, hydrocarbon yield decreases with decreasing HI. Other parameters suggest that this variation does not reflect maturity (Fig. 20), but they do resemble Winnipegosis source rock degradation patterns and petrographic textures that were also inferred to be microbially degraded.

Lodgepole Formation

Most of the Lodgepole has little or no potential; potential source rocks occur both east and west of Weyburn (Appendix 1). In the eastern domain, source rocks in Fuller's "marker beds" (1956) are commonly poor, less than 7% TOC and less than 16 kg/t TPP (Appendix 1). Correlative intervals in Manitoba show improved thickness and better HI values. West of Weyburn, source rocks occur in both the Upper and Roncott members. Western region source rocks are rich, >15% TOC, with TPP up to 100 kg/t. Considered together, all three intervals have an average TOC of 5.49% (Table 3), an average TPP of 29.32 kg/t and a strong relationship between TOC and TPP [TPP = 7.08x(TOC)-9.56].

Lodgepole HI (Fig. 21) and (S1 + S2)/TOC increase with depth suggesting depositional and diagenetic controls on richness, similar to Bakken distal–proximal relationships that we infer to have persisted during Madison deposition. Therefore, increasing Lodgepole sample depths mimic increasing early Mississippian water depth.

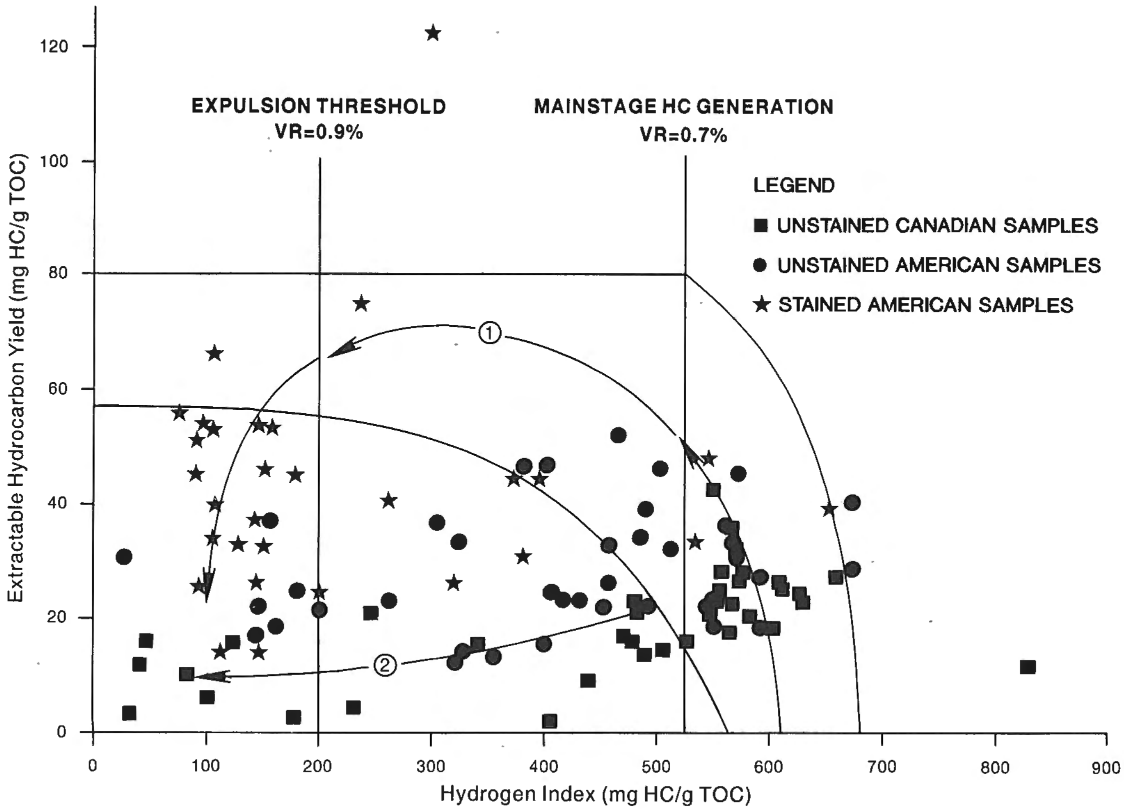

Figure 20. *Bakken Formation: solvent extract HC yield as a function of HI. The indicated region of increasing HC yield with decreasing HI is an inferred rich source rock maturation pathway constructed using the technique described for Figure 15. Line 1 reflects the evolution of rich source rocks with a* HI_0 *of 615, while the envelope reflects other rich source rocks with a* HI_0 *within the standard error associated with the TOC versus Total Petroleum Potential regression line (Fig. 18). Samples with much higher HI values probably indicate a Type I organic matter component. Unstained samples with HC yields below the rich source rock evolution envelope (line 2) are interpreted to be affected by microbial degradation. The HC yield of stained samples, with HI<200 and falling below the rich source rock evolution trend, is inferred to be depleted by expulsion. The expulsion threshold is interpreted to occur at 0.9% VR.*

Source rock richness indicators also follow TOC variations. Samples from the Upper member with less than 3.1% TOC have HI values less than 400 and slightly higher OI values, suggesting that oxidation reduces potential in some locations (Appendix 1). Deeper (>1750 m), richer samples, with a much wider range of TOC (3.57–15.6%), exhibit less HI variation. HI varies between approximately 500 and 725, suggesting a consistent organic matter type (Fig. 21). Using these rich Type II samples, $HI_0 = 666 \pm 41$. Organic material is primarily an orange-brown fluorescing, mesh-like matrix bituminite network and lesser marine alginite (L.D. Stasiuk, pers. comm., 1989). Amorphous kerogen dominates the organic material on slides prepared for palynomorph identifications (J. Utting, pers. comm., 1986).

Rich Lodgepole source rocks have Rock-Eval/TOC parameters significantly lower than those in the Bakken shales (Table 3; Appendix 1). However, solvent extract data (Appendix 2) suggest that the Lodgepole may have better quality source rocks. All seven Lodgepole solvent extracts come from two wells and have comparable gross compositions (Appendix 2). Total yields vary between 237 to 420 mg/g TOC and hydrocarbon yields range between 45.62 and 118.60 mg/g TOC. All have comparable HI values and maturities such that the variation of extract composition with maturity could not be determined. There is a good linear relationship between hydrocarbon yield and %HC (Fig. 22), but the samples exhibit very limited variation in thermal maturity. The hydrocarbon yield versus %HC regression line can be

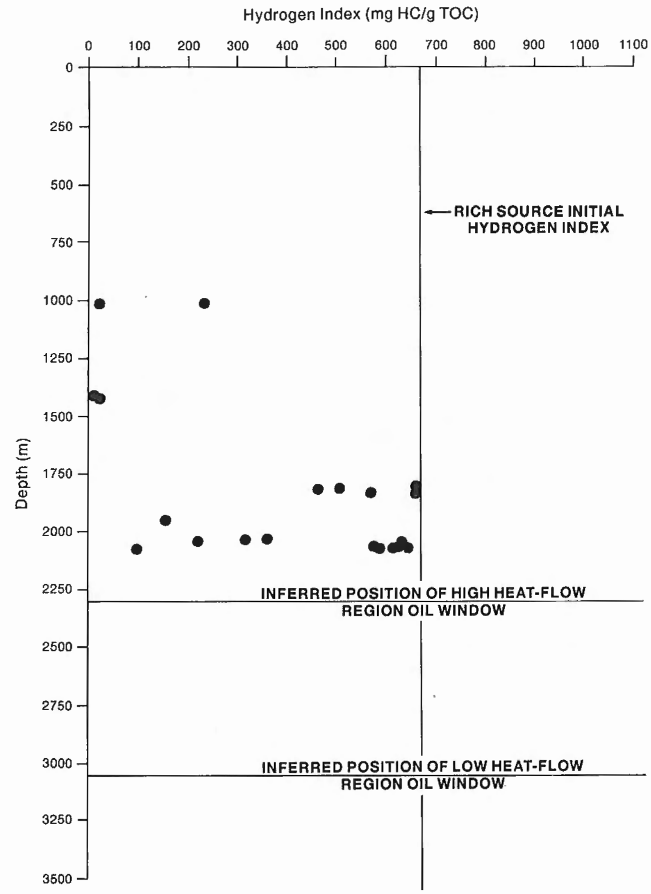

Figure 21. *Lodgepole Formation: HI variation with depth.* HI_0 *is* 666 ± 41*, a good Type II response, and is inferred from the slope of the Total Petroleum Potential plot. Note the progressive increase in HI with depth that is attributed to petroleum potential reduction by microbial processes like that observed among Bakken samples (Fig. 20, Line 2). Inferred position of high and low heat-flow oil windows are from Price et al. (1984). These also follow oil windows for both the Bakken (Fig. 17) and Winnipegosis (Fig. 13) formations, other Type II source rocks.*

extrapolated and used to plot a rich source rock evolution pathway on the HI versus HC yield diagram (Fig. 23).

With so few samples it is not possible to adequately analyse variations of Lodgepole HI with depth (Fig. 21). Other Type II source rocks in the basin are characterized by bituminite predominance and increasing HI with depth, accompanied by microbial degradation. High hydrocarbon yields and variations in the HI versus HC plot (Fig. 23) suggest that Lodgepole sources escaped pervasive microbial degradation. Contrasts between Lodgepole and other Type II sources are considerable. Although only a small number of samples were available, they have consistently higher hydrocarbon yields suggesting marginal to excellent potential, better than other sources at comparable maturities. Rich source rocks in Bakken shales yield no more than 42 mg/g TOC in the deepest well drilled in the Canadian Williston Basin and have hydrocarbon yields not exceeding 25.4 mg/g TOC. In the same well all Lodgepole yields exceed 45 mg/g TOC, yet both formations have comparable HI_0.

The Lodgepole Formation contains rich source rock bodies in its lower part which accumulated in starved, distal ramp depositional environments. These Type II bituminite-rich source rocks have higher hydrocarbon yields than Winnipegosis and Bakken source rocks with similar HI values and maturities. The apparent absence of microbial degradation might explain the apparently better quality of Lodgepole source rocks.

SOURCE ROCK THERMAL MATURITY

Critical levels of thermal maturity

Thermal maturity is determined from several pyrolytic, compositional and petrographic criteria, including staining and the appearance of petroleum accumulations. These various techniques provide four critical criteria for determining thermal maturity. Critical criteria from different indicators are not always coincidental or applicable to each source rock. The critical maturities are: top of the oil window, main hydrocarbon generation stage, expulsion threshold, and upper limit of oil generation. The top of the oil window occurs at a source rock transformation ratio of 10%, equivalent to 0.65% VR in Type II and Type I source rocks. The top of the oil window may be different from the main hydrocarbon generation stage. For example, the main hydrocarbon generation stage for Fe-rich Type II marine sources occurs at approximately 0.7% VR (Powell and Snowdon, 1983), equal to 20% TR (Espitalie et al., 1985).

The minimum maturity of free bitumen and migrated oils attributed to any source rock is a most important measure of thermal maturity, it characterizes the source rock expulsion threshold and is a true measure of economic potential. Expulsion threshold estimates require deduction of oil pool thermal maturities, the equivalent vitrinite reflectance of which must be inferred (van Graas, 1990). The expulsion threshold can also be defined using the

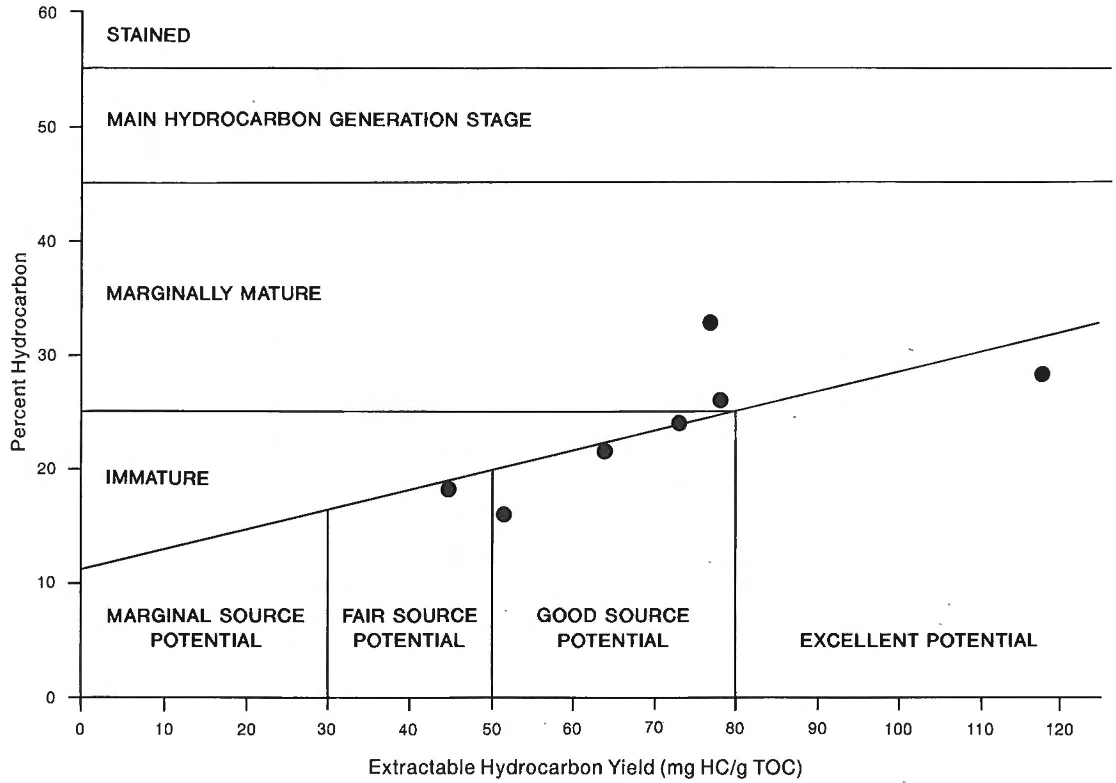

Figure 22. *Lodgepole Formation: solvent extract HC yield plotted against extract %HC. The regression line shows a good correlation, but it does not reflect maturity variations because of the limited range of sample maturities. Samples from the same well (Appendix 2) should have similar thermal maturities. Indicated standard HC yield richness and %HC thermal maturity thresholds are applicable to most samples.*

abrupt appearance of pervasive sample staining, both visually and in solvent extracts. Another critical thermal maturity is the upper limit of oil generation due to thermal cracking (Powell and Snowdon, 1983). The thermal cracking of C_{15+} HC becomes important at a reflectance of 1.2% VR and is largely completed by approximately 1.6% VR. The marked decline in wet gas production that signifies the onset of the dry gas zone does not occur until 1.8% VR. The end of peak liquid hydrocarbon generation occurs at 1.2% VR. The interval between 1.2% VR and 1.8% VR, the onset of the dry gas zone, defines the transition zone (op. cit.).

Hydrocarbon generation is a kinetic process that depends on kerogen composition. For reasons discussed above, %HC in Type I source rock solvent extracts do not indicate a main hydrocarbon generation stage (Tissot et al., 1987). Many standard maturity indicators, including T_{max} and solvent extract %HC, are insensitive to Type I OM maturation. Fortunately Type I kukersites have consistent HI_0 values making the transformation ratio (TR) an effective maturity indicator, and defining the top of the oil window. The expulsion threshold can be inferred from oil pool and petrographic data, the main hydrocarbon generation stage is inferred to coincide with the expulsion threshold.

Solvent extract %HC data are especially effective Type II source rock maturity indicators because of their direct relationship to hydrocarbon generation. Rock-Eval maturity criteria include T_{max}, PI and transformation rate [1200 (HI_0- HI)]/[HI_0(1200-HI)]. T_{max} and PI values are generally good indicators for Type II OM. Transformation ratio and rate can be employed only when HI_0 values are determined accurately. This is not the general case for Williston Basin Type II sources: kinetically based hydrocarbon generation models and maturity parameters characterize only those rich Type II source rocks whose HI_0 values are comparable to the samples from which kinetic parameters were derived. Maturation of microbially degraded and partially oxidized lithologies remains uncharacterized.

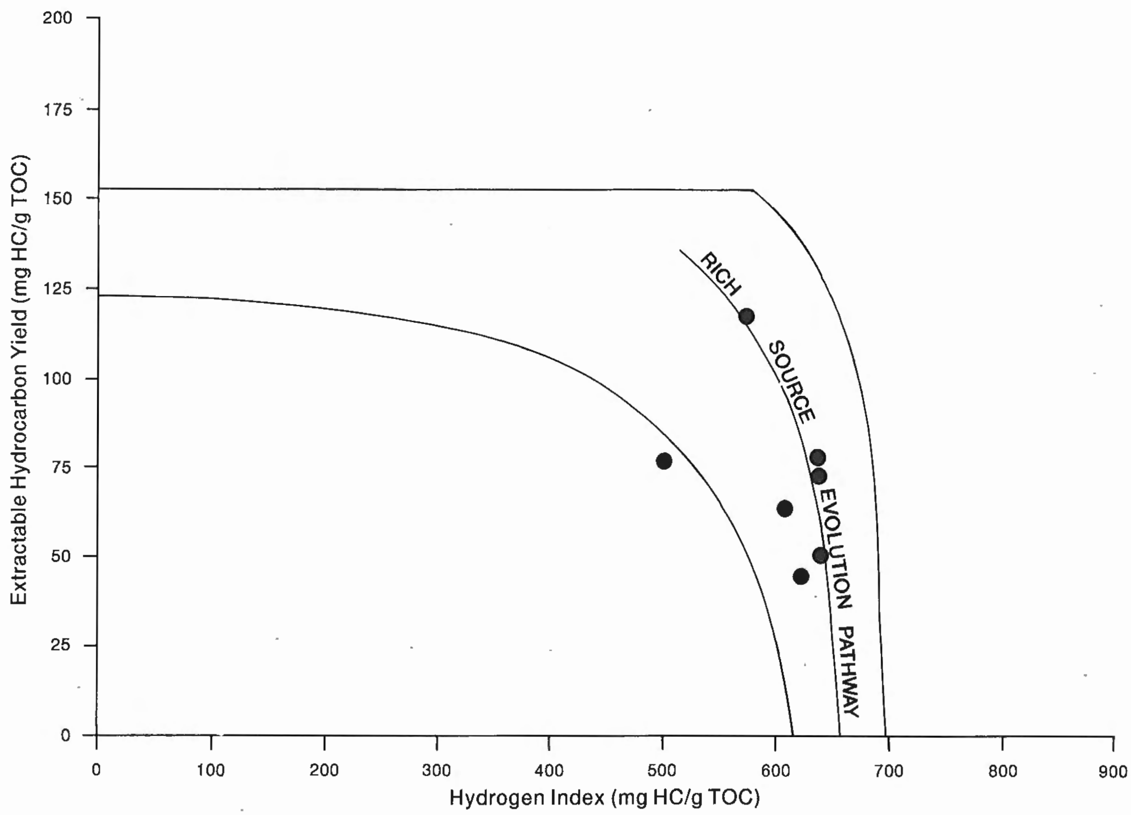

***Figure 23.** Lodgepole Formation: solvent extract HC yield as a function of HI. The indicated region of increasing HC yield with decreasing HI is an inferred rich source rock maturation pathway, constructed using the technique described for Figure 15. The central line reflects the evolution of rich source rocks with a HI_0 of 666, while the envelope reflects other rich source rocks with a HI_0 within the standard error associated with the TOC versus Total Petroleum Potential regression line (Fig. 18). Note the apparent absence of samples with HC yields far below the rich source rock evolution envelope, a trend that was interpreted as petroleum potential reduction by microbial activity in the Winnipegosis and Bakken formations. None of these source rocks are thermally mature.*

Kinetic hydrocarbon generation models are constrained by both depositional and erosional history. The latest epeirogenic interval is the least well constrained. Differential uplift and erosion post-dates deposition of the Paleocene Ravenscrag Formation, during an epeirogenic episode affecting much of the cratonic interior. Throughout this study region epeirogenic effects were minor and source rock maturity patterns still follow present depth. Many samples, particularly marginally mature and mature samples, are from south of Township 7, where an estimated 450 to 475 m of post-Paleocene erosion occurred. The amount of erosion decreases toward the American border where an estimated thickness of 250 to 275 m was eroded during the same time period. Therefore differential uplift is small and has been a minor influence on maturation thresholds. Consequently we discuss thermal maturity patterns by referring to present depths.

General patterns

At any location in the Williston Basin, maturation increases progressively with depth, consistent with coalification gradients in the Mesozoic succession (Stasiuk et al., 1993; Stasiuk, 1989; Price et al., 1984) and Hilt's Law. Maturities at similar depths but different places show variations not accounted for by differential uplift and erosion alone. Price et al. (1984) were the first to notice that the oil window for Bakken source rocks varied with geographic position in the basin. In particular, they identified an enhanced hydrocarbon generation region along the crest of

Nesson Anticline, approximately longitude 103°W. Osadetz et al. (1989) recognized the same feature in Canada, and associated enhanced hydrocarbon generation in Upper Ordovician rocks with this feature. Price et al. (1984) correctly attributed these effects to elevated crustal heat flows, but it was Majorowicz et al. (1988) who recognized the association of enhanced hydrocarbon generation and crustal structure. Crustal structures identified by magnetotelluric soundings (Jones and Savage, 1986) confirm that anomalous heat flows are due to lithological structure in the crust (Majorowicz et al., 1989). The North American Central Plains Conductivity Anomaly (NACPCA) is an intense, 2000 km long, 80 km wide feature situated between 10 and 20 km deep (Jones and Craven, 1990). Sedimentation, structure and hydrocarbon generation in Phanerozoic rocks overlying this zone reflect its presence.

The region of the NACPCA subsided anomalously throughout the Phanerozoic. Its effects are recognizable in both thickness (LeFever et al., 1987; Gerhard et al., 1987; Ahern and Mrkvicka, 1984) and lithofacies patterns (Osadetz et al., 1989, 1990; Osadetz and Haidl, 1989). The same region roughly coincides with Ancestral Nesson Structure, including the Nesson Anticline and a larger region of enhanced hydrocarbon generation in Paleozoic source rocks (Osadetz et al., 1990; Osadetz et al., 1989; Price et al., 1984). It also includes a region of elevated coal reflectances (Cameron, 1991).

During the Late Ordovician, this ancestral structure was a positive feature. The anomalously subsiding crustal block lay on the western margin of the western flank of the North American Central Plains Conductivity Anomaly, a region subsequently overlain by the Upper Winnipegosis platform's eastern margin. As a result, Upper Ordovician kukersitic source rocks generally occur in regions away from elevated heat flows and enhanced hydrocarbon generation. During the Middle Devonian, north–south oriented basement structural domains centered on longitude 102°W subsided more rapidly, deeply embaying the Middle Devonian platform edge, and separating the Elm Point and Upper Winnipegosis carbonate platforms. Brightholme member source rocks accumulated in this embayment characterized by elevated crustal heat flow and enhanced hydrocarbon generation related to the underlying North American Central Plains Conductivity Anomaly. This resulted in rich Middle Devonian sources being deposited directly on regions of enhanced hydrocarbon generation, in sharp contrast with Upper Ordovician source rock distribution. These differences suggest subtle structural inversion of north–south trending basement blocks important to both thermal maturation and hydrocarbon potential.

Specific source rock thermal maturity indicators

Bighorn Group kukersite

Several visual and pyrolytic parameters characterize Bighorn kukersite maturity, but other maturity indicators are not useful due to kerogen compositional peculiarities. Stains generally occur at depths below 2800 m (Appendix 2) (Osadetz et al., 1989). PI increases above 10% below 2950 m (Fig. 24), accompanied by decreased HI and (S1 + S2)/TOC values in the interval between 2950 and 3200 m.

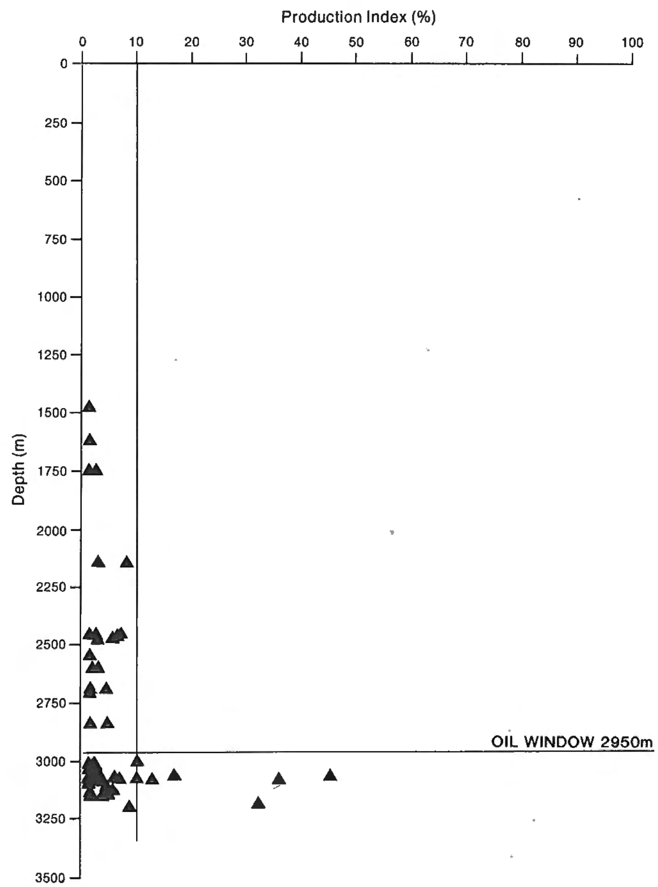

Figure 24. *Yeoman Formation: kukersite PI variation with depth. The 2950 m oil window, determined from HI variation with depth, coincides with an increase in PI beyond 10%. PI data gives no indication of the higher oil window, 2450 m. The oil window is inferred using HI data and is consistent with thermal histories associated with other formations along the crest of the maturation anomaly.*

Average kukersite TR around 3050 m is approximately 36%. Increased TR below 2950 m is accompanied by hydrocarbon generation (Fig. 14), while decreased (S1 + S2)/TOC values suggest expulsion into secondary migration pathways.

One well in the Froude area (16-20-008-10W2) (Appendices 1, 2), beyond the general eastern limit of kukersite accumulation and directly overlying the axis of most intense enhanced hydrocarbon generation, shows decreased HI and slight staining (sample 6988) at approximately 2450 m (Fig. 14), although S1 values are low. Petrographic observations confirm indigenous hydrocarbon generation is occurring (Stasiuk, pers. comm., 1993) and we infer that the Froude well (16-20-008-18W2) exhibits hydrocarbon generation due to much higher effective heat flows in that area.

T_{max} is insensitive to thermal maturity in Type I organic matter (Espitalie et al., 1985). Bighorn extracts show no systematic %HC variation with depth, a characteristic attributable to the compositional peculiarities of Type I kerogen. Most Bighorn samples fall within the expected region for normal maturation on the HI versus %HC crossplot (Fig. 25). This apparent conformity is deceiving, even the shallowest, most immature samples have %HC values suggesting marginal maturity, as do approximately two-thirds of the samples from below the oil window (2950 m).

Winnipegosis Formation

Winnipegosis Type II source rocks show that hydrocarbon generation occurs in Canada, although the lack of samples between 1771 and 2313 m introduces uncertainties into maturity characterizations. The large HI_0 variations of immature samples due to organic matter type and microbial degradation poses another difficulty. T_{max} and PI values provide the best maturity indications, they show that hydrocarbon generation has already begun below 2313 m. T_{max} varies with depth linearly and can be inferred to be 435°C at approximately 2100 m (Fig. 26). PI values exceed 10% below 2300 m (Fig. 27). These two depths define the top of the Winnipegosis oil window in the enhanced hydrocarbon generation zone. Winnipegosis samples from the United States in the zone of enhanced hydrocarbon generation, and from below 3000 m, also have high PI values and T_{max} values.

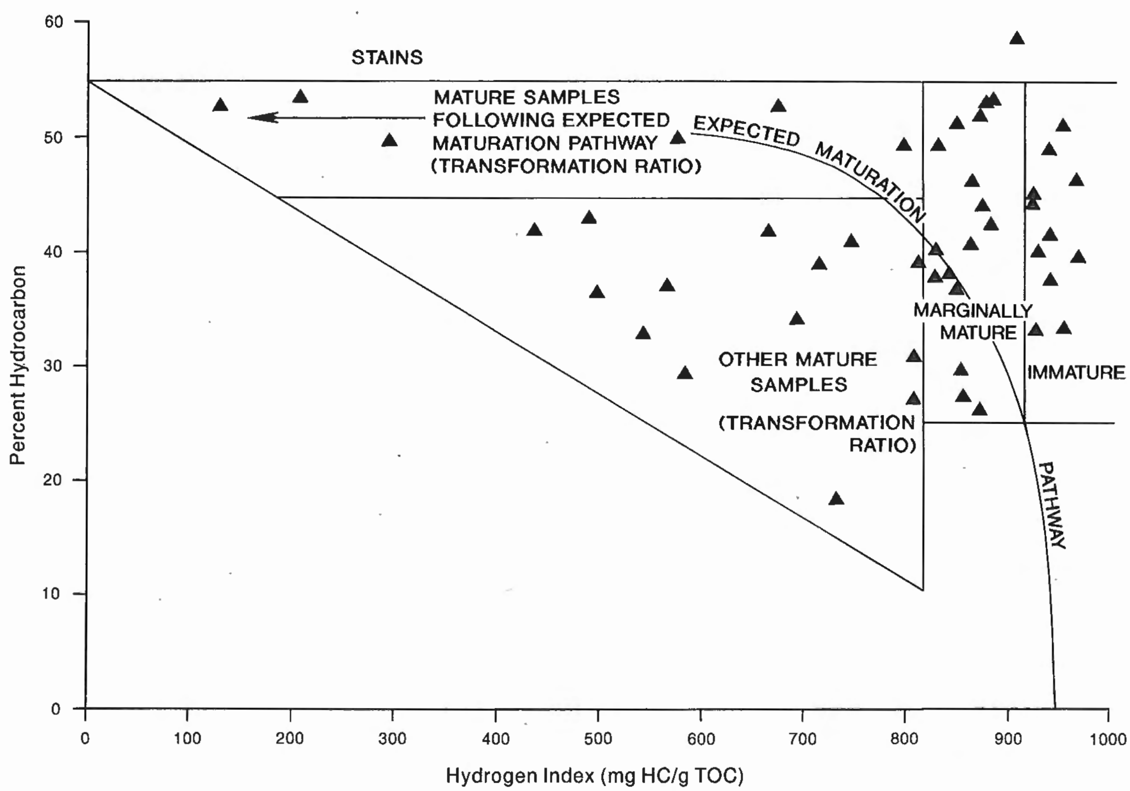

__Figure 25.__ Yeoman Formation: kukersite solvent extract %HC variation with HI. Standard %HC thermal maturity criteria do not apply because of organic matter type. Various fields of different thermal maturity levels constrained by TR are indicated.

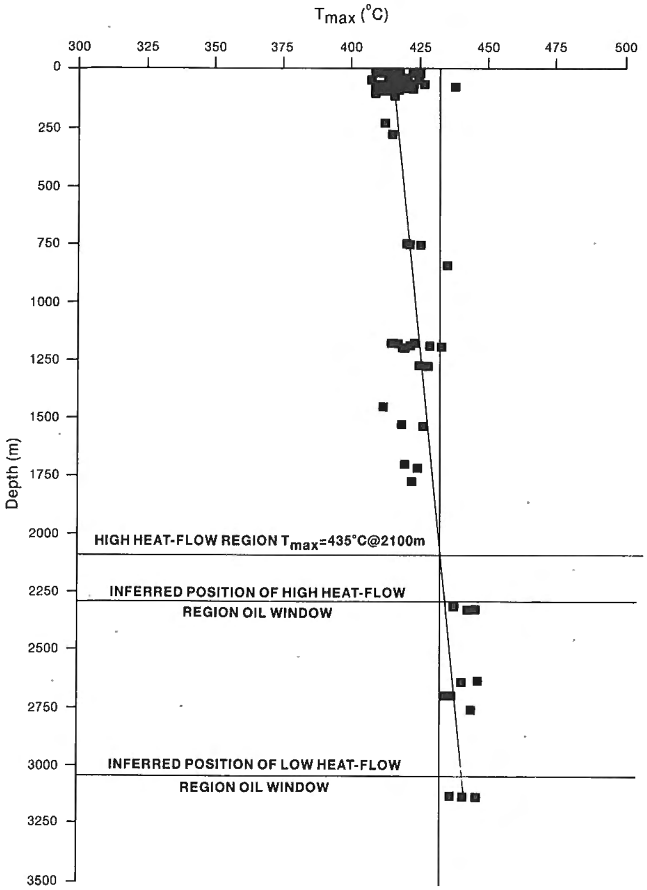

Figure 26. Brightholme member, Winnipegosis Formation: T_{max} variation with depth. The regression line indicates that T_{max} is 435°C at 2100 m. The positions of Type II source rock high and low heat-flow oil windows are consistent with Winnipegosis Formation PI and %HC data and observations for Bakken Type II source rocks as described by Price et al. (1984).

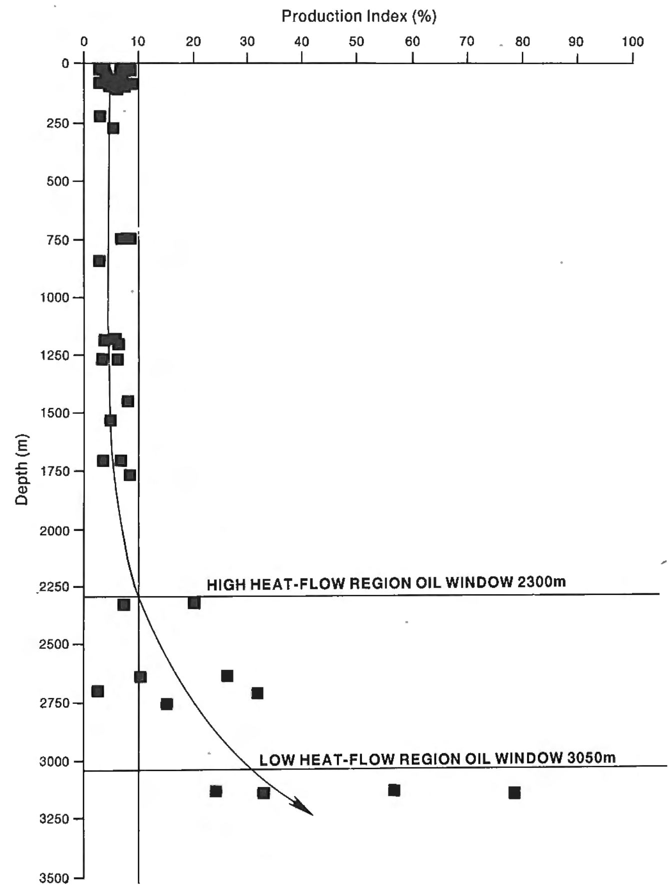

Figure 27. Brightholme member, Winnipegosis Formation: PI variation with depth. The positions of Type II source rock high and low heat-flow oil windows are consistent with Winnipegosis Formation %HC data and observations for Bakken Type II source rocks (Price et al., 1984).

HI and solvent extract data do not contribute to identification of the main hydrocarbon generation stage, primarily due to variations in kerogen composition reflected by large HI_0 variations (Fig. 16). It is harder to interpret %HC variations with depth (Fig. 28), most samples from above 1150 m have less than 25% hydrocarbon in the extract. Four Brightholme samples from above 500 m have marginally mature %HC values, probably due to Type I OM. Between 1150 and 1771 m, solvent extracts suggest immaturity and marginal maturity. Data from below 2313 m indicate predominantly marginally mature rocks, but there is a range from immature to stained %HC values.

Many Winnipegosis samples plot off the HI versus HC yield trend for rich, normally maturing sources, due to diagenetic and depositional degradation (Fig. 16). Some samples (6873, 6744, and 6806) have a Type I OM component material that would mature like Bighorn Type I sources. Other samples (e.g., 7100) (Appendix 2) suggest that the oil window of degraded material occurs at greater depths, even in the enhanced hydrocarbon generation zone. Few Winnipegosis samples (6828, 6872, 6871, 6741, 6795, 6799 and 7099) fall along the rich source maturation trend on the HI versus hydrocarbon yield diagram. These data can be interpreted as consistent with the %HC versus depth data, suggesting that marginal maturity also begins below 1150 m.

Bakken Formation

Examined Bakken sources are not thermally mature in Canada, the deepest samples have the highest HI

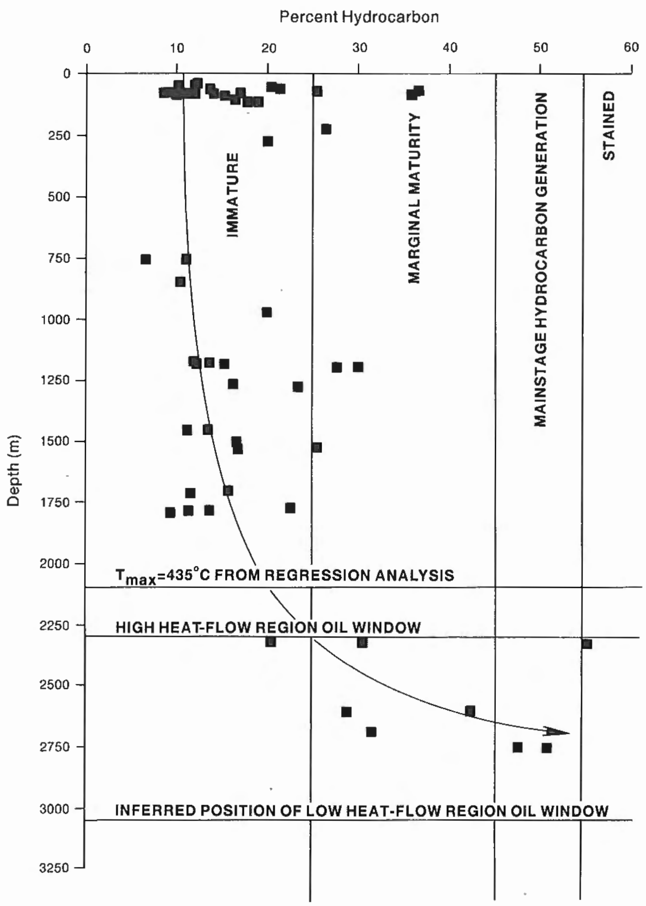

Figure 28. *Brightholme member, Winnipegosis Formation: solvent extract %HC variation with depth. The positions of Type II source rock high and low heat-flow oil windows are consistent with Winnipegosis Formation PI data and observations for Bakken Type II source rocks (Price et al., 1984).*

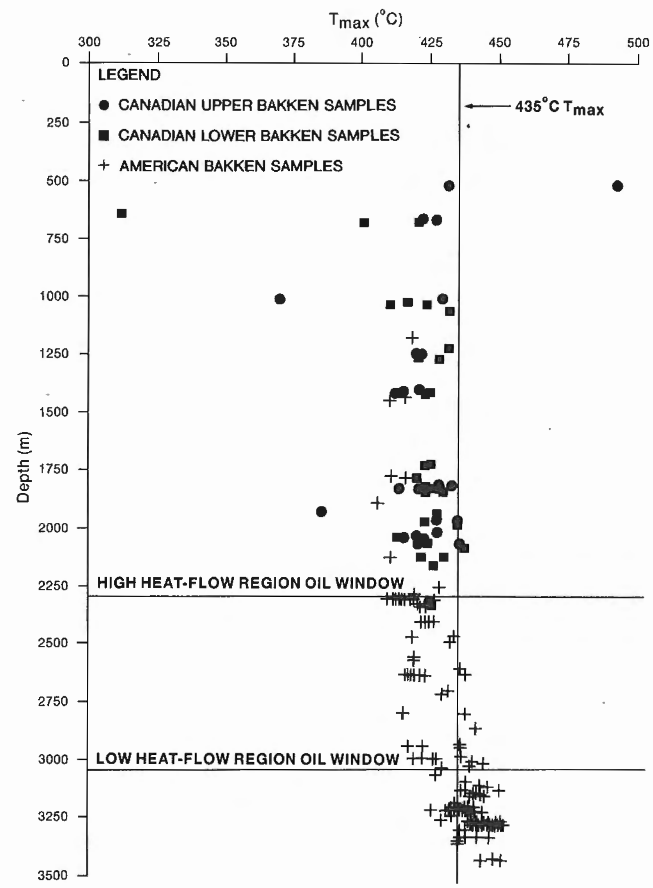

Figure 29. *Bakken Formation: T_{max} variation with depth. Sources of data include this study (Appendix 2) and studies in the American region by Price et al. (1984) and Webster (1984). Positions of Type II source rock high and low heat-flow oil windows are consistent with Winnipegosis Formation thermal maturity indicators and other Bakken indicators.*

values, in both shale members. Abnormally high %HC for given hydrocarbon yields are generally attributable to a Type I organic matter component that is common in the formation. Maturity indicators from Bakken strata in Canada are consistent with American studies.

Price et al. (1984) used T_{max} (Fig. 29) and PI (Fig. 30) to define an oil window between approximately 2330 and 2440 m in enhanced maturity regions. Similar maturities occur at approximately 3050 m in "normal" geothermal gradient areas. The main stage of oil generation, based on %HC values (45–55% HC), occurs at approximately 2300 m (Fig. 31), the same depth suggested by Rock-Eval, PI and T_{max} data. Most samples remain marginally mature (25–45% HC), suggesting a deeper oil window consistent with a lower effective heat-flow region. The depth to critical maturities of Bakken PI and T_{max} data compares closely with that inferred for Brightholme Type II source rocks.

Lodgepole Formation

Some Lodgepole Formation pyrolytic data, PI > 10% and T_{max} > 435°C, suggest that the Lodgepole Formation is mature in this sample set, however, none of the solvent extract samples suggest that the formation has entered the main stage of hydrocarbon generation. We conclude that an oil window cannot be accurately defined with the available samples, although it can be inferred to lie below the deepest sample, 2070 m. The oil window for Winnipegosis and Bakken Type II OM occurs at approximately 2300 m, the

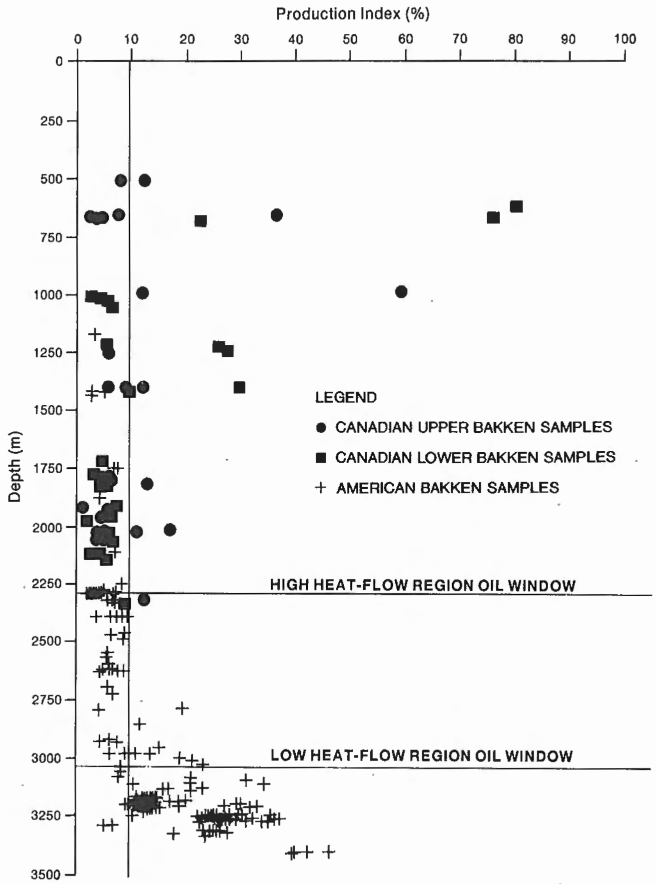

Figure 30. *Bakken Formation: PI variation with depth. Sources of data include this study (Appendix 2) and studies in the American region by Price et al. (1984) and Webster (1984). The positions of Type II source rock high and low heat-flow oil windows are consistent with other Type II source rock maturity indicators.*

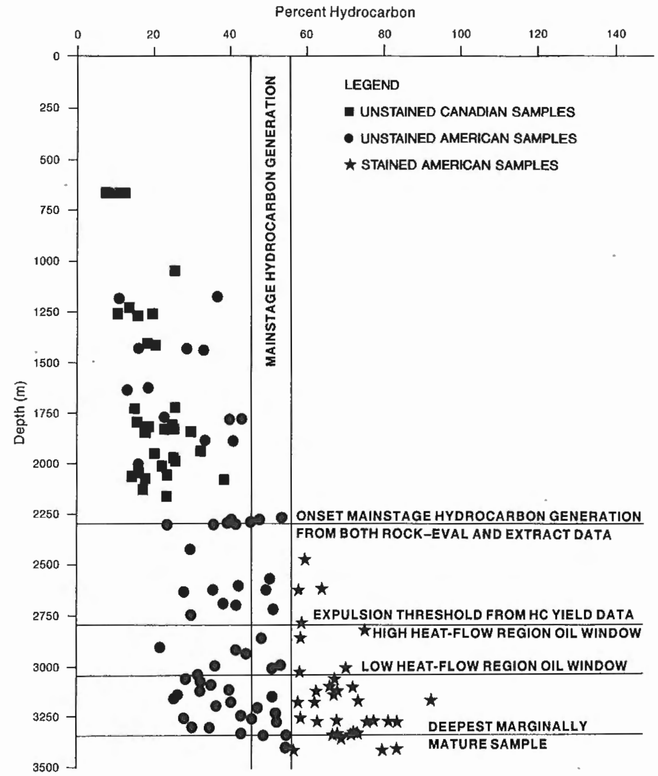

Figure 31. *Bakken Formation: solvent extract %HC variation with depth. Sources of data include this study (Appendix 2) and studies in the American region by Price et al. (1984) and Webster (1984). The positions of Type II source rock high and low heat-flow oil windows are consistent with other Type II source rock maturity indicators.*

Lodgepole oil window should also be expected near that depth. There are insufficient Lodgepole samples to illustrate %HC or maturity variations with depth, but comparing Bakken and Lodgepole hydrocarbon yields at comparable depths shows compositional differences, not discernible from pyrolytic experiments.

Lodgepole samples have consistently higher hydrocarbon yields than Bakken sources at comparable depths. Rich sources in Bakken shales yield no more than 42 mg/g TOC in the deepest parts of the Canadian Williston Basin and no more than 25.4 mg/g OC in the same well where all Lodgepole hydrocarbon yields exceed 45 mg/g TOC. Yet both formations have comparable HI_0 values. In two wells (14-15-002-23W2, samples 6394, 6378, 6379; 1A-02-006-25W2, samples 6377, 6376, 6375), samples from both formations and only a short distance apart must be of the same thermal maturity, yet T_{max} decreases from the Lodgepole Formation to the Bakken Formation. PI varies similarly. Lodgepole samples from the Paisley Brook well (6378 and 6379) have PI values of 9.3% and 11.2%. A Lower Bakken sample from the same well (6394) has a PI value of 6.1%. In the Roncott well, Lodgepole PI is 8.5%, compared to 6.5% and 5.6% in the Upper and Lower Bakken shales, respectively.

Summary

Bighorn Type I source rocks generally show few signs of hydrocarbon generation until approximately 2950 to 3200 m, where a wide TR range abruptly occurs. The TR average of 36% at approximately 3050 m defines the top of the oil window, although imprecisely, because the depth to an average 10% TR cannot be determined. At the same depths, some Bighorn Group samples show negligible TR. An exception to the general pattern of Ordovician thermal maturity occurs in a single well on the axis of an anomalous crustal structure where positive indications of hydrocarbon generation occur at 2450 m. Kerogen composition makes it impossible to define a main hydrocarbon generation stage using solvent extracts.

Rock-Eval/TOC maturity parameters suggest that most Type II source rocks enter the top of the oil window at present depths of approximately 2300 m in the region of enhanced hydrocarbon generation. Bakken Formation data from the United States suggest the presence of another Type II oil window at approximately 3050 m (Price et al., 1984). Solvent extract data suggest that the Bakken main hydrocarbon generation stage is roughly coincident with the top of the oil window defined by Price et al. (1984) using Rock-Eval/TOC data. Winnipegosis Formation samples are lacking through depth intervals critical to the identification of the top of the oil window. The top of the Winnipegosis oil window must be interpolated from maturity parameter profiles, coinciding generally with that of the Bakken Formation. The few Winnipegosis solvent extracts from suitable depths do not contradict the pyrolytically defined oil window, but they do not adequately define the main hydrocarbon generation stage.

Kinetic transformation ratio models

We correlate source rock thermal maturity indicators with kinetic transformation and vitrinite reflectance (VR) models to characterize thermal history and thermal maturation. Inferred VR can be compared to critical source rock and oil maturities. We use Williston Basin source rock OPTIKIN kinetic parameters (Ungerer and Pelet, 1988; Ducreux, 1988), determined for another activity (Burrus et al., 1991), as input for MATOIL maturation models. Model TR profiles use a deep well from the U.S. part of the basin (NW SW/SE Sec. 9 T150N R95W) and time invariant basal heat flows. Models of the deepest well in Saskatchewan (Halkett 15-7-3-8W2) are comparable for heat fluxes less than 80 mW/m^2.

Model and observed TR data were matched to VR values using Type IV OM kinetic parameters. This resulted in a series of correlations among TR, model VR, depth and constant basal heat flux (Fig. 26). By comparison to model curves, observed TR and vitrinite reflectance measurements can be used to constrain thermal history models. Critical thermal maturities can be compared to vitrinite reflectance models, associated oils and general hydrocarbon generation models as a function of thermal history.

Type I OM constraint on thermal history

Bighorn Group kukersites provide the easiest initial comparison between model and observed TR because of their homogeneous maceral composition and consistent HI_0. Observed and model TR suggest thermal histories vary systematically about the axis of the anomalous crustal structure and enhanced hydrocarbon generation. Data from the Froude well (16-20-8-10W2), which lies nearest the axis of this structure, show a wide range of TR. The highest values suggest a basal heat flux of approximately 70 mW/m^2. At a few townships to the west, approximately Range 11W2, more than 90% of the kukersite TR suggested heat fluxes are <65 mW/m^2. There the average kukersite TR is approximately 36% at 3050 m, suggesting a basal heat flux of approximately 62 mW/m^2. At these depths there are still samples, generally lying geographically further to the west, with low TR, suggesting effective heat flows as low as 55 mW/m^2.

Type II OM constraints on thermal history

Winnipegosis Formation samples have a very wide range of HI_0 values. Although some samples conform to predictions from kinetic models, they cannot confirm the thermal histories suggested by Yeoman samples. Bakken Formation HI values show considerable variation at shallow depths, but below 1700 m, rich Bakken source rocks with stable HI_0 make the comparison of observed and model TR possible. There is general agreement between the thermal histories suggested by Bakken and Bighorn models. Almost all samples below 2300 m suggest heat flux between 50 and 70 mW/m^2. Samples at a distance from the axis of enhanced hydrocarbon generation have lower thermal maturities at similar depths. Because Bakken shales occur over the axis of anomalous crustal structure, it is not surprising that they better represent higher heat-flow regions, 65 to 70 mW/m^2, than Ordovician samples. Heat flows as high as 70 mW/m^2 would result in T_{max} and PI oil windows much higher than suggested by Price et al. (1984). Although these models may be locally applicable, we suggest that the highest thermal histories are not generally representative of the enhanced hydrocarbon generation region. It is more likely for 60 to 65 mW/m^2 to be effective heat flows characteristic of the high heat-flow zone, as these are consistent with Bakken Rock-Eval data.

Petrographic constraints on thermal history

Data from Webster's study (1984) on Figure 32 vary with depth and geographic position, such as those reported by Price et al. (1984). Less than half the samples, generally occurring shallower than 2800 m, suggest anomalously low reflectances. These fall to the left of the 40 mW/m² model reflectance gradient. Other samples, generally from below 2800 m, fall primarily between 50 and 60 mW/m², and two samples plot near the 65 mW/m² model curve.

TR and solvent extract data all suggest higher heat flows than those required to match Bakken reflectance data from depths less than 3000 m. Those samples plotting above the 50 mW/m² curve are not from the region of enhanced hydrocarbon generation. Price and Barker (1985) recognized the anomalously low value of some Bakken reflectance measurements, however, they probably overestimated the degree of suppression. This we infer from their anomalously high reflectance gradients in Cenozoic and Mesozoic rocks (compare Cenozoic and Mesozoic gradients of Price et al., 1984, with those of Stasiuk, 1989, and Stasiuk et al., 1993). Price and Barker (1985) suggest that the suppression of reflectance was primarily due to maceral composition, particularly the high exinite content of Paleozoic marine source rocks. In contrast, logarithmic huminite reflectance gradients, constructed using only shale intervals in Cenozoic and Cretaceous rocks (Stasiuk et al., 1993; Stasiuk, 1988), generally agree with model reflectance gradients.

Summary

Bighorn and Bakken transformation data suggest that there is a continuous and gradual variation of heat flow throughout the basin. These results can be generalized. With exceptions, TR data suggest a high heat-flow region, 60 to 65 mW/m², in the vicinity of the anomalous crustal structure along longitude 103°W and a low heat-flow region, 50 to 55 mW/m², away from that axis. Model vitrinite reflectance curves are consistent with TR data from source rocks and extrapolated huminite logarithmic reflectance gradients measured in shaly portions of the Cenozoic and Cretaceous succession. They do not agree with observed Bakken reflectances, probably due to maceral composition.

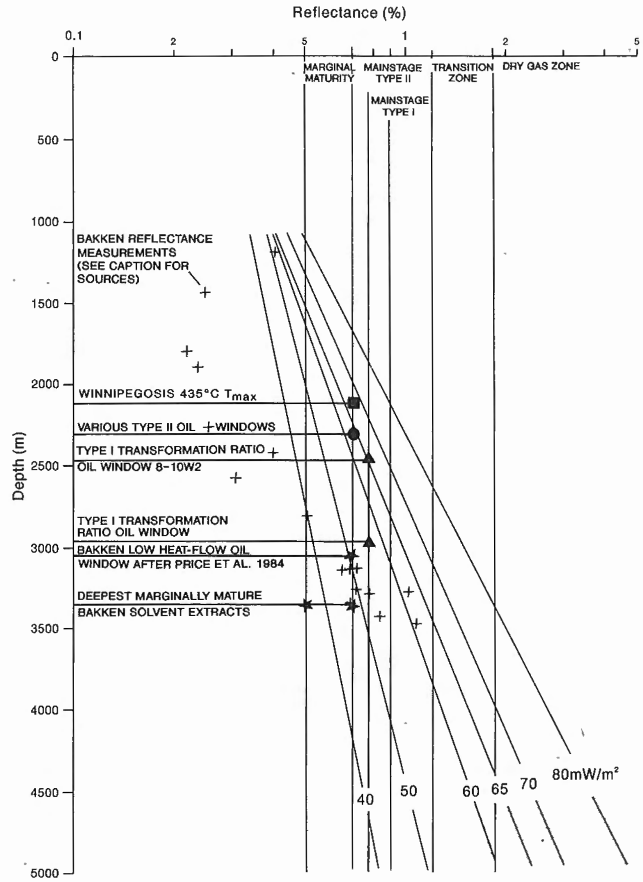

***Figure 32.** Modelled vitrinite reflectance profiles for the Williston Basin. Critical thermal maturity indicators for various Williston Basin source rocks suggest a range of effective heat flows between 40 and 67 mW/m², generally conforming to a relative distance from the enhanced HC generation zone overlying the North American Central Plains Conductivity Anomaly. Time-invariant basal heat-flow vitrinite reflectance profiles were modelled using a MATOIL computer program (c. B.É.C.É.I.P. and I.F.P.) and Type IV kinetic parameters constrained by a geological history compiled from well data in NW SW/SE Sec. 9 T150N R95W, near Blue Buttes field North Dakota, and the surrounding area. Best-fit log-linear vitrinite reflectance profiles for basal heat flows of 40, 50, 60, 65, 70 and 80 mW/m² are shown. Vitrinite reflectance thresholds for critical stages of HC generation from Powell and Snowdon (1983) are shown. Correlations among T_{max}, TR, and vitrinite reflectance are from MATOIL program documentation. Bakken Formation vitrinite reflectance data are from Webster (1984) and Price et al. (1984).*

Critical maturity thresholds

Top of the oil window

The top of the oil window (10% TR) for Bighorn kukersite, can be inferred from MATOIL models and compared to other indicators of hydrocarbon generation. In the region of enhanced hydrocarbon generation, a 65 mW/m^2 heat-flow model predicts the top of the oil window at approximately 2450 m (Fig. 32). A deeper oil window, 2800 m, is predicted using the 60 mW/m^2 model. It coincides with common, visually detected staining and is slightly shallower than Ordovician oil pools. In regions with the lowest effective heat flow, 50 to 55 mW/m^2, the kukersite oil window begins between 3100 and 3500 m. Although the low heat-flow model cannot be confirmed, it is consistent with Type II OM models.

The Winnipegosis, Bakken and Lodgepole, rich, unaltered, undegraded Type II source rocks all enter the oil window at similar depths. This can only be confirmed for Winnipegosis and Bakken sources in the region of enhanced hydrocarbon generation. The top of the oil window for the Winnipegosis Formation is between 2000 and 2200 m, in general agreement with observed T_{max} and PI data. Bakken samples in the enhanced hydrocarbon generation region also reach 10% TR between 2000 and 2300 m, matching the elevated oil window observed by Price et al. (1984). Kinetics of Lodgepole samples suggest that 10% TR would be reached in the enhanced hydrocarbon generation zone at approximately 2050 to 2300 m, although rich source rocks are not known in that region.

In regions away from the zone of enhanced hydrocarbon generation, all three sources reach 10% TR by 3000 m. Price et al. (1984) observed this for the Bakken and it is also expected for Lodgepole sources. The significance of the deeper, low heat-flow oil window for Winnipegosis source rocks is less certain. Platform lithofacies occur where the formation reaches suitable depths away from the enhanced hydrocarbon generation region. Source rocks there have different petrographic characteristics and possibly different kinetic parameters.

The depth to the top of the oil window, as defined by 10% TR, varies as a function of thermal history and source rock type. Type I kukersites have oil windows beginning at 2450, 2800, and 3100 to 3500 m, for effective heat flows of 65, 60 and 55 to 50 mW/m^2, respectively. The top of the oil window for the 60 mW/m^2 model coincides with the appearance of prominent stains in the formation, although they could be the result of migration. Oil windows for Type II source rocks are consistently shallower than the oil windows characteristic of kukersitic sources with similar thermal histories. In the high heat-flow region, all three source rocks would enter the oil window at depths between 2000 and 2300 m, consistent with available observations. In the low heat-flow region, all three enter the oil window at approximately 3000 m, only confirmed by Bakken source rocks.

Main hydrocarbon generation stage

Positive indicators of the main hydrocarbon generation stage include solvent extract data, particularly %HC values greater than 45% and hydrocarbon yield increases with %HC. Solvent extract data is not applicable to Type I source rocks, instead, pyrolytic indicators of hydrocarbon generation and depletion, including TR, must be used. The position and thermal maturity of the least mature oils attributable to any source rock provide an indication of its expulsion threshold. Expulsion does not necessarily coincide with the main hydrocarbon generation phase, but it will not precede it.

Expulsion thresholds from source rocks

Osadetz et al. (1989) used kukersite kerogen compositional consistency and the relationship between (S1 + S2)/TOC and depth to determine that approximately one quarter of the total hydrocarbon potential of mature Canadian kukersitic source rocks had been expelled. Minor changes result from using TR and the HI_0 values suggested above (Fig. 29), the average TR increases to approximately 36%. Expulsion can be estimated using the relationship: $\% \text{ expelled} = 100x(HI_0-(S1+S2)/TOC)/HI_0$. Samples below 2950 m suggest that, of the total petroleum potential, approximately 32% is expelled. This is about 4% less than the average TR, but consistent with the observed average PI of samples below the oil window (Fig. 24). Model VR values associated with the depth interval of source rock depletion and staining are between 0.80 and 0.85%.

The Bakken extract data set includes unstained samples that show increased hydrocarbon yield with increased maturity (Figs. 19, 20). However, many unstained American samples and some unstained Canadian samples have degraded hydrocarbon yields.

Degraded sources have a wide %HC variation bounded on its lower limit by the regression line through Canadian data (Fig. 19). American samples include a stained subset having low HI and high hydrocarbon yields, generally between 35 and 60 mg/gm TOC. Rich samples at comparable maturities should have hydrocarbon yields of approximately 60 to 76 mg/g TOC (Fig. 19). Uncertainty in initial hydrocarbon yield complicates the expulsion efficiency calculation.

It is probably correct to infer that expulsion depletes the hydrocarbon yields of these samples (Fig. 20). Depleted samples have HI values between approximately 75 and 200. A HI of 200 corresponds to approximately 0.9% VR (Fig. 32). Explusion is significantly delayed compared to the main stage of hydrocarbon generation (0.7% VR), as suggested by solvent extract data and commonly associated with standard Type II hydrocarbon generation (Powell and Snowdon, 1983). Thus delayed expulsion characterizes Bakken sources.

Much of the petroleum generated in the Bakken Formation, between 0.70 and 0.90% VR, will not be expelled. Bakken maturities exceed the expulsion threshold south and west of the Missouri River (Price et al., 1984; Webster, 1984), severely restricting hydrocarbon potential and migration pathways. This retention is consistent with the very high oil saturation in the formation (Meissner, 1978), and explains the current overpressuring of the formation below the oil window (Burrus et al., 1991; Meissner, 1978). Whether this resource is recoverable from the formation, and what role such a resource might play in production from horizontally drilled holes in the shale members (Fischer and Rygh, 1989), should be interesting topics for future study.

Expulsion thresholds for Winnipegosis and Lodgepole sources cannot be inferred from source rock data alone. However, the correlation of their oil pool compositions, specifically 18α(H)-trisnorneohopane/17α(H)-trisnorhopane thermal maturity (Ts/Tm), to VR suggests that they should conform to standard Type II OM models. These expulsion threshold differences should result in significantly different resource potential among different Type II sources. Oil pool compositions support this (Osadetz et al., 1992).

Expulsion thresholds from oil pools and stains

In the Canadian Williston Basin, oils attributed to Bighorn Group source rocks and produced from Bighorn Group reservoirs generally occur at depths between 2865.8 and 3061.5 m. In the same area, stains are prominent below 2800 m. The most thermally mature source rocks occur in the same region. One pool, Weirhill, lying close to the axis of anomalous crustal structure and near the Froude well, produces from a depth of 2470 m.

Oil pools in Winnipegosis pinnacle reefs occur over the depth interval 2282 to 2607 m, the least mature oil is produced from 2310 m. Some pools contain migrated oils, but many are locally sourced (Osadetz et al., 1992). Only a few Bakken oils occur in Canada, between 1824 and 654.3 m. All of them have migrated great distances and cannot constrain the position of hydrocarbon generation or expulsion thresholds.

Oil in Madison Group reservoirs has also commonly migrated. Most pools are in the Charles and Mission Canyon formations, whereas the source rocks are in the Lodgepole Formation, and commonly occur long lateral distances away from the top of the oil window.

Molecular composition of the oils provide additional indicators of expulsion thresholds. Especially effective are Ts/Tm ratios calculated from gas chromatography-mass spectrometry m/z 191 fragmentograms. Each oil family has a minimum value of this ratio that can be interpreted as the source rock expulsion threshold. Kukersite oils have a minimum Ts/Tm ratio of 0.60 for oils produced from approximately 2930 m, in the lower heat-flow zone (Osadetz et al., 1992). Ts/Tm is 0.61 for oils produced from 2470 m in the enhanced hydrocarbon generation zone. The least mature, densest oils from the Winnipegosis pinnacle reef, at Oxbow pool, are produced from approximately 2320 m. They have Ts/Tm ratios of approximately 0.3 to 0.4. Comparable Ts/Tm ratios are characteristic of the least mature oil pools attributed to Lodgepole source rocks. All pools attributed to Bakken source rocks are low density, very mature oils with Ts/Tm ratios equal to or exceeding 1.16 (op. cit.).

Winnipegosis pinnacle reef oil pool Ts/Tm ratios correlate positively with C_{29} S/R sterane thermal maturity ratios, although some sterane thermal maturity ratios are inexplicably higher than expected equilibrium values (Osadetz et al., 1992). Using a correlation between sterane thermal maturity and vitrinite reflectance, Osadetz et al. (1991b) proposed an empirical correlation between Ts/Tm and vitrinite reflectance. The least mature Winnipegosis and Lodgepole oils are approximately 0.70% VR and the least mature Bakken oils are 0.90% VR.

The applicability of the Ts/Tm to VR correlation to other types of organic matter is uncertain. Using the correlation, the thermal maturity of the least mature Ordovician oil is approximately 0.77% VR. The lowest associated bitumen reflectances, 0.60% (Stasiuk, pers. comm., 1993), also suggest a thermal maturity equivalent to 0.77% VR (cf. Jacob, 1985). The depths of Ordovician stains and production suggest that TR increases coincide with the expulsion thresholds.

At depths of 2450 to 2500 m and heat flows of 65 mW/m^2, model vitrinite reflectance profiles suggest VR values comparable to those inferred from bitumen and Ts/Tm measurements. This provides strong corroboration that 65 mW/m^2 effective heat flow characterizes the high heat-flow zone.

Higher reflectances result when model effective heat flows are higher. The model heat flow is 70 mW/m^2 if TR data in the Froude well is matched. This suggests reflectances equivalent to 0.80% VR. In the Oungre–Lake Alma area, staining is prominent below 2800 m and TR increases rapidly below 2950 m. Suggested effective heat flows there are 60 to 62 mW/m^2 and associated model VR values are approximately 0.80 to 0.85%, higher than those suggested by other methods. Regardless, VR models, oil pool data and bitumen reflectances all suggest that the kukersite expulsion threshold is higher than that for Lodgepole and Winnipegosis sources, but lower than that for Bakken source rocks. We infer that expulsion from kukersitic source rocks occurs at thermal maturities no lower than 0.77% VR.

The main hydrocarbon generation stage and expulsion threshold of all four source rock formations is distinctly different from the pyrolytically defined top of the oil window. Expulsion from Lodgepole and Winnipegosis source rocks occurs at the beginning of the main hydrocarbon generation stage, at thermal maturities of 0.7% VR. The main stage of Bakken hydrocarbon generation coincides with that of other Type II sources, but expulsion from Bakken sources occurs at much higher thermal maturities, approximately 0.9% VR. This is consistent with patterns of source rock solvent extract staining and other characteristics of that formation. Bitumen and oil associated with Type I kukersite have a main hydrocarbon generation stage and an expulsion threshold that are coincident, but higher than those of Type II source rocks. Evidence from oil pools and bitumen suggest that 0.77% VR is the critical maturation level for kukersite, but staining and production suggest thermal maturities of 0.80 to 0.85% VR. However, hydrocarbon generation and expulsion may have preceded present thermal maturities. We infer an expulsion threshold at not less than 0.77% VR.

CONCLUSIONS

Source rock potential depends on its richness and maturity. Richness depends on kerogen volume and quality. Depositional setting is the primary control on source rock volume but paleoecology and depositional environment affect kerogen quality. Diagenetic effects, especially microbial degradation, reduce the potential of some Type II sources.

Four regionally significant, rich, Paleozoic source intervals occur in the Canadian Williston Basin. Type I sources occur in several Upper Ordovician Bighorn Group formations. These thin carbonate sources occur primarily in a tectonically controlled, geographically limited depression on the Yeoman Formation epeiric platform. They are generally immature in Canada. Their kerogen composition delays main stage hydrocarbon generation until higher maturities, not less than 0.77% VR. Tectonic controls, so important for source rock accumulation, do not place kukersite within the enhanced hydrocarbon generation region. Expulsion from kukersitic sources appears to accompany significant hydrocarbon generation at not less than 0.77% VR.

The Middle Ordovician Winnipeg Formation contains source rocks in the Canadian Williston Basin. The richest source rocks occur at maximum flooding surfaces, and although thin, they are probably widespread. They contain organic matter like that in Bighorn Group kukersite but are commonly leaner and mixed with Type II marine organic material. Limited evidence from the American Williston Basin suggests that this formation may also contain kukersite, although not in Canada (Williams, 1974). The potential of similar sources in other Upper Ordovician strata, particularly the Stony Mountain Formation, requires additional study. Despite their thinness, restricted distribution, and exclusion from areas of enhanced thermal maturation, Ordovician source rocks have an enormous petroleum potential, largely because a comparable or even greater source rock volume in the United States is thermally mature.

The Middle Devonian Winnipegosis Formation contains several Type II source rocks with the thickest, richest developments occurring in Upper member-equivalent basinal facies, where they have an extraordinary petroleum potential. Some source rocks are rich, but most are generally only marginal or good quality. Hydrocarbon yields and petroleum potential are commonly reduced by microbial alteration during early diagenesis. Immense volume compensates for decreased source rock richness. Most Winnipegosis starved basin source rocks are thermally immature.

Winnipegosis kerogen is thermally more labile than Ordovician kerogen. Unlike Ordovician source rocks, a significant volume of Winnipegosis source rock was deposited atop the hydrocarbon generating thermal anomaly, resulting in a laterally restricted, shallow main hydrocarbon stage (0.7% VR at 2300 m), covering a large region in Canada. Unlike Ordovician source rocks, Middle Devonian starved basin source rocks do not extend south of the basin centre. However, thermally mature source rocks in the United States are at least comparable to those in Canada and the associated petroleum potential is great.

Other Type II source rocks, petrographically distinct from the Brightholme member, lie between the Upper and Lower members of the Winnipegosis Formation in platform settings. These source rocks occur at maximum flooding surfaces and are thin, but may be laterally extensive, their distribution and maturity patterns are not well known. Westwardly increasing burial beneath the foreland basin succession may compensate for decreased crustal heat flows if Winnipegosis platform source rocks occur in southwestern North Dakota, western Saskatchewan and Alberta.

Rich, persistent Type II sources occur in the Upper and Lower Bakken shales. Variations in depositional facies and microbial degradation during diagenesis significantly depreciate Bakken Formation petroleum potential and large parts of the formation have only fair to good hydrocarbon yields. However, the richest sources tend to occur in the most mature regions. The main hydrocarbon generation stage window occurs consistently at expected maturities, 0.7% VR, but its depth commonly fluctuates between 2300 and 3050 m, following thermal history variations. The hydrocarbon generating thermal anomaly enhances maturity locally while maturities improve regionally with increasing maximum burial depths. Expulsion is delayed until higher maturities (0.9% VR) are attained. Bakken maturities exceed this expulsion threshold south and west of the Missouri River, severely restricting Bakken hydrocarbon potential and migration pathways.

Most strata in the Mississippian Madison Group have no source rock potential. Rich source rocks occur in geographically and stratigraphically restricted parts of the lower Lodgepole Formation. Episodic transgressions deposited each lenticular source rock body in a starved, distal ramp environment. Compared with Winnipegosis and Bakken source rocks, Lodgepole Type II sources have consistently higher hydrocarbon yields and may have escaped serious diagenetic degradation. Cores are sparse but data from available cores suggest that the oil window may occur sooner than for other Type II sources, but below 2070 m.

Elevated heat flows associated with a crustal feature along the Ancestral Nesson structure strongly affect thermal maturity. Enhanced maturation results in the Type I oil window occurring at approximately 2450 m, and the Type II oil window occurring at approximately 2300 m, much shallower than expected. The same crustal structure strongly influences source rock distribution and forms a fundamental control on hydrocarbon potential in the Williston Basin.

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APPENDIX 1

Select Rock-Eval/TOC experiment results from core samples

Location	Depth	T_{max}	S1	S2	S3	TOC	HI	OI
Winnipeg Formation, Icebox Member (Middle Ordovician)								
01-04-020-32W1	1375	442	0.00	4.28	0.15	0.53	807	28
01-04-020-32W1	1391	435	1.08	96.19	1.76	10.41	924	16
03-14-008-20W2	2593	445	0.04	1.01	0.19	0.21	480	90
03-14-008-20W2	2595	446	0.04	1.59	0.04	0.38	418	10
03-14-008-20W2	2598	441	0.05	1.15	0.05	0.29	396	17
05-15-010-02W2	2282	440	0.17	4.72	0.33	1.07	441	30
05-15-010-02W2	2282	435	0.10	4.79	0.35	1.02	469	34
05-15-010-02W2	2282	438	0.33	4.91	1.16	1.03	476	112
05-15-010-02W2	2285	438	0.24	2.10	0.08	0.57	368	14
05-15-010-02W2	2285	431	0.00	1.15	0.35	0.27	425	129
05-15-010-02W2	2286	439	0.29	6.39	0.15	1.25	511	12
Yeoman Formation, kukersitic lithologies (Upper Ordovician)								
03-08-001-11W2	3186	459	0.61	1.30	0.42	0.99	131	42
03-08-001-11W2	3193	458	0.80	8.52	0.40	4.06	209	9
10-25-001-15W2	3115	449	0.19	3.22	0.51	0.75	429	68
10-25-001-15W2	3142	458	0.50	93.33	0.75	13.01	717	5
10-25-001-15W2	3142	456	0.93	27.54	2.91	4.63	594	62
10-25-001-15W2	3144	455	0.85	30.62	0.54	5.28	579	10
01-14-001-17W2	3094	449	0.19	11.07	0.63	1.59	696	39
01-14-001-17W2	3107	447	0.64	14.07	1.14	2.86	491	39
01-14-001-17W2	3109	448	0.50	62.91	0.60	7.78	808	7
07-23-001-17W2	3074	456	0.11	10.93	0.27	1.64	666	16
13-23-001-17W2	3062	441	0.40	3.75	0.50	0.79	474	63
13-23-001-17W2	3068	449	1.78	2.17	0.50	0.71	305	70
13-23-001-17W2	3074	455	0.07	8.80	0.59	1.62	543	36
13-23-001-17W2	3076	452	0.64	134.25	0.29	15.54	863	1
13-23-001-17W2	3076	458	0.56	171.61	0.64	19.87	863	3
13-23-001-17W2	3082	457	2.78	210.35	0.87	26.35	798	3
11-27-001-17W2	3072	454	0.92	12.74	0.52	2.41	528	21
16-36-001-18W2	3052	443	0.64	3.25	1.57	1.10	295	142
16-36-001-18W2	3062	451	4.37	158.39	0.85	19.12	828	4
16-36-001-18W2	3072	452	2.80	19.50	0.39	3.10	629	12
15-09-002-14W2	3065	448	1.84	26.56	1.74	5.33	498	32
15-09-002-14W2	3069	448	1.29	26.76	1.04	4.57	585	22
15-09-002-14W2	3070	446	2.72	4.89	1.41	1.63	300	86
08-16-002-14W2	3052	456	0.93	33.63	0.36	4.97	676	7
08-16-002-14W2	3053	453	0.15	4.92	0.30	0.84	585	35
03-20-002-16W2	3071	455	0.28	72.42	0.61	8.54	848	7
03-20-002-16W2	3076	456	0.44	121.60	0.64	13.95	871	4
06-13-002-19W2	3020	455	0.92	88.67	0.76	10.55	840	7
06-13-002-19W2	3021	455	0.96	57.92	0.40	6.83	848	5
07-23-003-17W2	2990	455	1.05	106.23	0.40	14.21	747	2
07-23-003-17W2	2990	456	1.57	128.26	2.56	15.64	820	16
07-23-003-17W2	2992	455	1.83	103.90	0.47	12.79	812	3
03-26-004-20W2	2830	453	0.68	90.99	0.49	9.91	918	4
06-11-004-21W2	2829	449	0.70	18.03	0.39	2.04	883	19
06-11-004-21W2	2830	451	0.56	61.44	0.48	6.61	929	7
08-02-006-16W2	2686	454	0.16	18.63	0.32	2.24	831	14
08-02-006-16W2	2689	449	0.88	27.52	0.40	3.16	870	12
08-02-006-16W2	2696	450	0.60	86.38	0.53	9.16	943	5
12-13-007-19W2	2993	442	0.62	5.58	0.58	1.89	295	30
16-20-008-10W2	2445	453	2.37	147.98	0.59	16.69	886	3
16-20-008-10W2	2446	451	1.12	113.73	0.52	12.94	878	4
16-20-008-10W2	2446	453	1.07	146.03	2.53	15.28	955	16
16-20-008-10W2	2446	455	3.21	158.69	3.37	17.07	929	19
16-20-008-10W2	2447	449	0.35	5.09	0.43	0.82	620	52
16-20-008-10W2	2455	450	0.36	5.46	0.40	1.04	525	38
06-32-008-16W2	2459	453	3.70	202.70	1.23	22.29	909	5

APPENDIX 1

Select Rock-Eval/TOC experiment results from core samples - Continued

Location	Depth	T_{max}	S1	S2	S3	TOC	HI	OI
06-32-008-16W2	2466	453	0.22	4.22	0.34	0.55	767	61
03-14-008-20W2	2576	432	0.93	47.68	0.83	5.33	894	15
03-14-008-20W2	2576	446	0.85	52.00	1.10	6.33	821	17
03-14-008-20W2	2577	446	2.72	116.03	0.14	12.12	957	1
03-14-008-20W2	2577	447	2.30	93.60	1.20	10.09	927	11
06-05-008-22W2	2532	450	0.20	14.81	0.40	1.72	861	23
14-11-014-16W2	2126	440	0.60	6.92	0.57	1.58	437	36
14-11-014-16W2	2136	449	0.87	33.33	0.63	3.82	872	16
02-04-022-15W2	1732	452	3.48	339.10	3.03	34.94	970	8
02-04-022-15W2	1732	450	2.86	291.05	2.91	30.47	955	9
02-04-022-15W2	1732	452	3.38	268.25	3.38	28.49	941	11
02-04-022-15W2	1733	448	3.42	203.98	1.07	22.05	925	4
02-04-022-15W2	1733	451	2.13	243.10	3.10	23.98	1013	12
01-25-023-16W2	1599	448	1.03	113.01	0.83	12.21	925	6
01-25-023-16W2	1603	447	0.52	57.09	0.64	6.52	875	9
04-10-033-01W3	1466	427	0.44	57.91	4.27	7.90	733	54
Herald Formation, Coronach Member (Upper Ordovician)								
13-23-001-17W2	3042	443	1.06	2.97	0.05	0.68	436	7
Herald Formation, Redvers Unit (Upper Ordovician)								
02-08-003-14W2	2930	449	0.11	5.62	0.38	0.76	739	50
02-11-010-09W2	2286	425	0.19	0.59	0.94	0.63	93	149
Stony Mountain Formation, Gunn Member (Upper Ordovician)								
02-11-010-09W2	2273	447	1.65	177.60	0.95	22.20	800	4
Winnipegosis Formation, Lower member (Middle Devonian)								
12-24-001-10W2	2766	447	0.33	2.24	0.47	0.73	306	64
09-31-004-08W2	2422	449	0.94	5.93	2.40	2.24	264	107
08-01-004-09W2	2560	454	0.25	0.41	0.75	0.86	47	87
Winnipegosis Formation, Brightholme member (Middle Devonian)								
NENE05161-95W0	3134	444	0.29	0.08	0.12	0.30	26	40
NENE05161-95W0	3134	439	0.45	0.35	0.19	0.41	85	46
NENE05161-95W0	3135	449	0.52	1.67	0.27	0.60	278	45
NENE05161-95W0	3135	449	0.49	1.00	0.32	0.65	153	49
11-29-001-25W1	1534	428	1.09	24.39	0.12	6.97	349	1
04-12-007-25W1	1198	421	8.00	122.46	0.73	20.65	593	3
04-12-007-25W1	1199	420	5.50	97.34	0.56	15.56	625	3
02-21-007-28W1	1447	413	4.97	62.69	1.63	10.97	571	14
10-22-030-16W1	69	427	0.54	25.44	0.38	3.23	787	11
10-22-030-16W1	70	415	1.04	23.16	0.80	2.89	801	27
10-22-030-16W1	71	418	0.32	11.83	0.45	1.53	773	29
10-22-030-16W1	72	421	0.11	2.69	0.35	0.49	548	71
00-00-030-17W1	118	416	6.29	120.48	3.68	18.78	641	19
03-29-036-25W1	230	412	0.83	24.00	0.04	2.99	802	1
13-10-036-26W1	276	415	3.51	66.25	1.22	9.49	698	12
00-00-041-24W1	106	408	2.02	29.19	1.71	5.12	570	33
05-13-044-24W1	76	414	0.57	16.39	0.65	3.93	417	16
08-14-044-25W1	67	414	1.63	28.68	1.43	5.95	482	24
08-14-044-25W1	74	410	5.77	96.72	3.56	18.01	537	19
08-14-044-25W1	77	422	0.35	8.32	0.35	2.08	400	16
08-14-044-25W1	79	417	2.04	44.97	1.72	8.68	518	19
08-14-044-25W1	80	419	0.25	10.00	0.37	2.55	392	14
08-14-044-25W1	62	419	1.32	17.69	0.96	3.68	480	26
08-14-044-25W1	71	421	0.14	5.10	0.55	1.09	467	50
08-14-044-25W1	72	413	5.86	78.16	3.07	13.78	567	22
08-14-044-25W1	73	420	0.76	12.24	0.82	2.23	548	36
08-14-044-25W1	73	408	2.08	30.58	1.24	6.32	483	19
08-14-044-25W1	75	411	1.17	20.76	1.04	5.11	406	20
08-14-044-25W1	75	413	3.99	50.38	2.52	10.34	487	24
08-14-044-25W1	77	412	1.34	22.30	1.07	5.00	446	21

APPENDIX 1

Select Rock-Eval/TOC experiment results from core samples - Continued

Location	Depth	T_{max}	S1	S2	S3	TOC	HI	OI
08-14-044-25W1	79	415	0.96	14.65	1.02	3.85	380	26
08-14-044-25W1	66	427	0.75	14.09	0.77	2.43	579	31
08-14-044-25W1	71	421	1.18	24.39	1.25	4.87	500	25
10-11-045-26W1	85	415	7.20	93.33	3.16	16.73	557	18
10-11-045-26W1	94	417	0.71	19.52	0.59	4.06	480	14
10-11-045-26W1	94	414	0.99	13.47	0.91	2.93	459	31
10-11-045-26W1	91	411	3.85	47.44	2.47	9.14	519	27
10-11-045-26W1	92	408	6.65	69.95	3.80	12.99	538	29
14-12-045-26W1	84	417	1.62	26.54	0.96	4.99	531	19
14-12-045-26W1	87	419	1.50	25.58	1.16	5.39	474	21
14-12-045-26W1	87	414	6.78	102.40	3.04	16.72	612	18
14-12-045-26W1	88	418	0.37	8.60	0.32	1.75	491	18
14-12-045-26W1	89	414	1.27	27.16	0.94	5.09	533	18
14-12-045-26W1	84	413	1.33	17.16	0.74	2.76	621	26
14-12-045-26W1	89	411	0.62	6.71	0.58	1.66	404	34
14-12-045-26W1	90	420	0.26	3.96	0.38	0.99	400	38
14-12-045-26W1	88	422	0.32	4.64	0.80	1.14	407	70
14-12-045-26W1	88	411	2.81	35.03	1.68	6.63	528	25
09-15-046-22W1	24	409	8.88	91.70	5.79	16.18	566	35
09-15-046-22W1	25	411	3.92	47.16	2.37	10.30	457	23
09-15-046-22W1	26	409	1.94	25.28	1.36	5.22	484	26
09-15-046-22W1	87	420	0.81	13.43	0.83	2.76	486	30
09-15-046-22W1	024	415	2.10	31.01	1.55	5.08	610	30
09-15-046-22W1	025	417	2.92	44.07	2.49	7.92	556	31
09-15-046-22W1	027	417	2.68	36.21	1.70	7.37	491	23
09-15-046-22W1	0021	425	0.07	3.24	0.51	0.55	589	92
09-15-046-22W1	0022	422	0.28	8.96	0.41	1.19	752	34
09-15-046-22W1	0024	412	4.29	56.70	4.39	12.16	466	36
09-15-046-22W1	0027	408	4.44	50.21	2.85	11.27	445	25
05-07-048-25W1	040	415	0.51	11.75	0.74	1.75	671	42
05-07-048-25W1	050	407	1.56	23.38	1.49	5.51	424	27
05-07-048-25W1	058	417	0.17	3.14	0.58	0.69	455	84
05-07-048-25W1	059	424	0.76	12.67	0.95	3.20	395	29
12-24-001-10W2	2764	447	0.71	4.02	0.45	1.45	277	31
04-18-001-21W2	2701	437	1.13	2.46	0.54	0.56	439	96
04-18-001-21W2	2701	440	0.89	37.38	0.47	4.68	798	10
16-15-002-09W2	2638	449	0.25	0.71	0.59	0.64	110	92
16-15-002-09W2	2639	443	0.52	4.63	0.76	2.36	196	32
10-33-006-13W2	2313	440	3.11	12.45	2.02	2.56	486	78
10-27-007-21W2	2323	445	2.38	30.61	1.93	5.35	572	36
10-27-007-21W2	2324	448	0.64	8.51	1.58	1.64	518	96
08-36-016-06W2	1528	420	1.01	22.99	0.20	3.46	664	5
06-29-018-16W2	1771	424	13.26	154.19	2.13	31.38	491	6
16-13-042-19W2	843	436	3.49	99.64	4.01	16.89	589	23
16-13-042-19W2	845	436	2.32	68.75	3.42	12.10	568	28
01-15-048-17W2	1703	421	1.83	49.40	3.12	7.78	634	40
01-15-048-17W2	1709	426	3.20	46.36	4.34	7.94	583	54
10-24-067-23W2	74	415	1.94	53.01	3.33	8.24	643	40
10-24-067-23W2	74	438	1.75	82.86	4.10	12.80	647	32
10-24-067-23W2	78	421	2.10	65.95	5.46	13.81	477	39
16-11-033-01W3	1268	426	1.13	19.75	3.13	3.96	498	79
16-11-033-01W3	1270	429	1.07	32.77	3.18	6.47	506	49
07-02-038-01W3	1185	430	3.36	82.08	5.29	10.21	803	51
07-02-038-01W3	1185	424	3.76	69.06	4.91	12.53	551	39
07-02-038-01W3	1186	434	5.15	111.64	5.47	19.20	581	28
06-16-038-01W3	1176	425	2.94	55.49	5.43	9.68	573	56
06-16-038-01W3	1177	416	8.66	141.93	8.54	27.44	517	31
06-16-038-01W3	1178	418	8.69	148.29	8.41	28.63	517	29
05-29-047-03W3	749	421	4.71	72.17	4.75	9.75	740	48
05-29-047-03W3	751	422	3.86	48.55	2.62	10.09	481	25
05-29-047-03W3	752	426	7.50	79.83	3.85	16.91	472	22
07-34-073-06W3	43	420	1.18	31.44	2.28	5.03	625	45

APPENDIX 1

Select Rock-Eval/TOC experiment results from core samples - Continued

Location	Depth	T_{max}	S1	S2	S3	TOC	HI	OI
07-34-073-06W3	47	418	1.63	37.72	3.26	7.40	509	44
07-34-073-06W3	49	413	1.97	44.51	3.62	8.58	518	42
Winnipegosis Formation, unnamed Mudstone member (Middle Devonian)								
SESE26156-93W	3668	452	0.76	0.56	0.16	0.54	103	29
SESE26156-93W	3671	445	0.70	0.73	0.31	0.49	148	63
SESE26156-93W	3672	449	0.27	0.17	0.23	0.28	60	82
SESE26156-93W	3674	449	0.38	0.49	0.28	0.39	125	71
SESE26156-93W	3679	455	0.43	0.63	0.27	0.39	161	69
SESE26156-93W	3682	449	0.42	0.51	0.30	0.44	115	68
NENW35156-93W	3674	454	1.47	2.91	0.27	2.49	116	10
NENW35156-93W	3690	447	0.30	0.40	0.44	0.41	97	107
NENW35156-93W	3696	449	1.36	0.59	0.38	0.49	120	77
NENW35156-93W	3700	449	0.65	0.61	0.42	0.53	115	79
NENW35156-93W	3703	448	0.50	0.76	0.59	0.59	128	100
NENW35156-93W	3707	456	0.55	0.79	0.14	0.89	88	15
NENW35156-93W	3718	448	0.05	0.01	0.13	0.15	6	86
NENW35156-93W	3722	456	0.38	0.63	0.32	0.76	82	42
NENW35156-93W	3728	448	0.14	0.07	0.25	0.25	28	100
NWSE02156-94W	3632	441	0.20	0.08	0.31	0.34	23	91
NWSE02156-94W	3633	445	0.44	0.35	0.39	0.46	76	84
NWSE02156-94W	3637	445	0.43	0.27	0.36	0.35	77	102
NWSW25158-95W	3406	443	0.54	0.89	0.34	0.54	164	62
NWSW25158-95W	3410	446	0.76	1.43	0.34	0.57	250	59
NWSW25158-95W	34O8	447	1.04	2.17	0.41	0.67	323	61
SENW28160-96W	3319	446	1.24	1.22	0.29	0.71	171	40
SENW28160-96W	3329	441	1.02	0.78	0.34	0.50	156	68
SENW28160-96W	3332	399	0.32	0.05	0.19	0.32	15	59
SWNW31163-97W	2966	448	0.36	1.00	0.32	0.69	144	46
SWNW31163-97W	2976	444	1.07	1.47	0.40	0.77	190	51
SWNW31163-97W	2983	446	1.29	1.53	0.25	0.66	231	37
SWNW31163-97W	2986	458	0.46	0.50	0.23	0.96	52	23
Winnipegosis Formation, "Brightholme-like" lithology in Upper member (Middle Devonian)								
08-20-004-14W2	2517	437	15.83	173.71	3.04	31.11	558	9
08-20-004-14W2	2518	436	18.36	218.77	2.29	45.92	476	4
Winnipegosis Formation, Upper member (Middle Devonian)								
02-21-007-28W1	1446	416	0.63	12.90	0.59	2.35	548	25
06-27-002-09W2	2614	439	0.44	2.67	0.51	1.96	136	26
06-27-002-09W2	2616	441	0.15	0.60	0.60	0.40	37	150
16-11-033-01W3	1267	429	3.38	29.67	2.07	3.41	870	60
Big Valley Formation (Upper Devonian)								
04-20-017-32W1	680	386	1.21	14.22	0.15	0.25	608	60
Bakken Formation, Lower shale member (Upper Devonian)								
15-06-016-30W1	0649	312	0.13	0.03	0.53	0.47	6	112
04-20-017-32W1	679	401	13.97	4.20	1.48	1.87	224	79
04-20-017-32W1	680	421	0.69	2.26	0.69	2.41	93	28
12-27-001-06W2	2082	439	8.55	103.26	1.15	18.80	549	6
02-14-001-16W2	2341	427	6.78	59.68	1.52	11.22	531	13
14-15-002-23W2	2161	427	10.27	157.27	4.35	26.13	601	16
03-34-002-27W2	2127	423	4.85	85.04	3.08	15.10	563	20
03-34-002-27W2	2127	431	1.35	29.36	4.50	11.95	245	37
15-31-003-11W2	1988	436	2.47	71.08	1.48	12.99	547	11
08-20-004-14W2	1971	424	13.14	164.81	3.05	29.75	553	10
09-13-005-13W2	1845	431	5.33	78.15	1.45	13.79	566	10
02-05-005-27W2	2066	425	4.41	78.73	3.06	15.61	504	19
11-15-005-28W2	2039	414	3.14	45.89	2.72	8.97	511	30
01-20-006-19W2	1939	428	8.96	104.64	1.20	18.85	555	6
05-04-006-24W2	1820	426	5.92	92.23	3.59	19.63	469	18
05-04-006-24W2	1821	424	1.57	26.14	4.82	21.60	121	22

APPENDIX 1

Select Rock-Eval/TOC experiment results from core samples - Continued

Location	Depth	T_{max}	S1	S2	S3	TOC	HI	OI
01-02-006-25W2	1827	427	7.01	126.16	3.28	20.33	620	16
01-02-006-25W2	1829	430	6.15	103.60	2.50	17.85	580	14
16-23-007-03W2	1414	425	0.39	0.89	0.59	1.90	46	31
16-10-007-15W2	1727	426	3.70	64.10	3.00	13.33	480	22
16-10-007-15W2	1728	424	3.33	60.09	2.59	9.55	629	27
13-30-007-23W2	1846	424	4.21	80.82	3.30	15.37	525	21
01-22-008-04W2	1421	424	0.57	4.97	0.74	4.35	114	17
14-27-008-26W2	1788	421	3.33	75.42	3.90	9.11	827	42
06-26-010-02W2	1266	421	0.29	0.79	0.43	1.95	40	22
11-36-013-11W2	1270	429	1.05	2.69	0.96	3.31	81	29
14-11-014-16W2	1226	432	0.29	4.36	1.84	4.40	99	41
13-29-016-08W2	1059	432	2.78	36.34	3.65	10.72	338	34
01-23-020-19W3	1024	417	2.25	43.47	2.73	9.47	459	28
01-23-020-19W3	1029	411	3.13	52.43	3.61	10.65	492	33
01-23-020-19W3	1035	424	0.94	13.87	1.41	3.50	396	40
Bakken Formation, Middle sandstone member (Upper Devonian and Mississippian)								
01-24-020-33W1	520	370	0.00	0.00	0.44	0.60	0	73
16-10-003-25W2	2088	423	5.04	86.12	2.79	15.89	541	17
06-07-005-18W2	2022	419	0.13	0.30	0.44	0.54	55	81
05-04-006-24W2	1810	425	0.54	8.07	0.31	1.67	483	18
16-10-007-15W2	1712	429	6.16	101.81	2.22	17.71	574	12
Bakken Formation, Upper shale member (Mississippian)								
16-30-009-30W1	1002	430	0.29	2.02	1.59	1.90	106	83
04-10-010-31W1	1009	370	0.03	0.02	1.10	1.31	1	83
04-20-017-32W1	667	428	1.84	61.30	7.50	15.18	403	49
04-20-017-32W1	669	423	4.48	52.04	9.18	20.55	253	44
04-20-017-32W1	670	427	1.63	45.45	8.72	25.82	176	33
04-20-017-32W1	667	427	1.75	35.97	5.87	15.63	230	37
04-20-017-32W1	669	422	3.80	6.38	7.42	20.40	31	36
01-24-020-33W1	519	493	0.03	0.31	1.14	1.69	18	67
01-24-020-33W1	519	432	0.08	0.54	0.73	0.96	56	76
12-27-001-06W2	2066	437	5.94	124.31	1.37	20.50	606	6
02-14-001-16W2	2324	426	13.38	87.96	2.39	13.25	663	18
04-31-001-27W2	2039	417	12.65	94.24	3.04	13.86	679	21
15-31-003-11W2	1970	436	8.84	154.61	1.34	23.47	658	5
16-10-003-25W2	2072	422	6.15	88.46	2.78	15.46	572	17
08-20-004-14W2	1954	428	14.11	180.56	2.52	31.89	566	7
09-13-005-13W2	1828	430	12.52	179.43	2.14	31.24	574	6
06-07-005-18W2	2019	429	8.50	134.40	2.60	24.37	551	10
09-33-005-25W2	1827	415	15.42	96.69	2.46	14.02	689	17
02-05-005-27W2	2053	424	5.04	85.98	3.92	17.95	478	21
11-15-005-28W2	2030	421	0.05	0.23	0.36	0.41	56	87
01-20-006-19W2	1928	387	0.02	3.39	1.98	4.08	83	48
01-02-006-25W2	1812	429	11.23	167.92	2.67	26.74	627	9
01-02-006-25W2	1812	434	12.20	173.60	2.95	28.58	607	10
16-23-007-03W2	1406	422	10.27	147.59	4.90	30.96	476	15
16-23-007-03W2	1407	416	15.93	108.36	4.06	18.00	602	22
13-30-007-23W2	1833	422	10.47	147.42	3.42	23.58	625	14
01-22-008-04W2	1413	413	8.78	79.84	3.59	14.08	567	25
06-26-010-02W2	1257	422	9.20	129.70	5.64	29.73	436	18
11-36-013-11W2	1259	421	8.64	126.01	4.07	25.79	488	15
Lodgepole Formation, Fuller's "Marker Beds" (Mississippian)								
16-30-009-30W1	1002	425	0.65	15.29	2.74	6.67	229	41
04-10-010-31W1	1004	427	0.11	0.91	2.51	5.12	17	49
16-23-007-03W2	1402	431	0.08	0.25	1.18	2.20	11	53
01-22-008-04W2	1408	430	0.21	1.13	2.29	6.27	18	36
01-22-008-04W2	1409	431	0.15	0.77	1.63	3.64	21	44

APPENDIX 1

Select Rock-Eval/TOC experiment results from core samples - Continued

Location	Depth	T_{max}	S1	S2	S3	TOC	HI	OI
Lodgepole Formation, Upper member (Mississippian)								
14-15-002-23W2	2062	438	4.07	23.98	1.13	4.16	576	27
14-15-002-23W2	2066	437	4.07	43.01	1.15	7.37	583	15
14-15-002-23W2	2066	439	3.39	33.00	2.01	5.16	639	38
14-15-002-23W2	2067	440	4.14	50.28	2.42	8.05	624	30
14-15-002-23W2	2070	441	3.82	37.14	2.39	6.09	609	39
14-15-002-23W2	2070	437	3.80	37.60	5.10	5.86	641	87
14-15-002-23W2	2071	439	4.97	39.40	2.51	6.15	640	40
15-12-003-21W2	2023	439	0.80	8.40	3.10	2.68	313	115
15-12-003-21W2	2026	436	1.05	11.15	1.50	3.10	359	48
15-12-003-21W2	2034	444	0.39	3.41	1.53	1.57	217	97
15-12-003-21W2	2044	433	4.82	91.37	4.16	14.46	631	28
15-12-003-21W2	2065	437	0.05	0.35	0.10	0.37	94	27
11-15-005-28W2	1938	415	0.06	0.67	0.56	0.44	152	127
Lodgepole Formation, Roncott Member (Mississippian)								
09-33-005-25W2	1825	423	4.94	60.61	1.16	9.19	659	12
09-33-005-25W2	1826	416	12.11	88.60	1.89	15.62	567	12
01-02-006-25W2	1808	427	1.75	16.43	0.95	3.57	460	26
01-02-006-25W2	1808	441	1.85	35.60	1.95	5.41	658	36
01-02-006-25W2	1808	440	1.50	16.15	2.90	3.21	503	90
Charles Formation (Mississippian)								
15-12-003-21W2	1679	438	1.01	6.81	1.36	1.85	368	73

APPENDIX 2

Solvent extracts from potential source rocks and stains, selected gross compositional data

No.	Location	Depth	TOC	Extract total	HC yield	HC percent	Saturate/ Aromatic HC
			Deadwood Formation (Upper Cambrian and Lower Ordovician)				
7055	04-10-033-01W3	1500	.13	202.43	18.40	9.1	.67
			Winnipeg Formation, Icebox Member (Middle Ordovician)				
6333	01-04-020-32W1	1375	.53	35.80	11.79	32.9	.65
6332	01-04-020-32W1	1391	10.41	10.97	2.91	26.6	1.27
6330	05-15-010-02W2	2282	1.03	23.33	10.61	45.4	.97
6331	05-15-010-02W2	2282	1.07	22.73	6.00	26.4	.65
7030	05-15-010-02W2	2282	10.41	2.97	.75	25.2	1.89
7011	05-15-010-02W2	2284	.40	80.81	8.14	10.1	1.80
7000	05-15-010-02W2	2285	.27	123.46	19.00	15.4	.20
6329	05-15-010-02W2	2286	1.15	23.80	7.30	30.7	.29
			Big Horn Group, Yeoman Formation (Upper Ordovician); kukersites				
6865	03-08-001-11W2	3186	.99	89.44	47.03	52.6	.85
6866	03-08-001-11W2	3193	4.06	35.25	18.83	53.4	.95
6864	10-25-001-15W2	3115	.75	220.79	113.26	51.3	.64
6627	10-25-001-15W2	3142	4.63	106.61	41.53	39.0	1.20
6862	10-25-001-15W2	3144	5.28	30.30	15.15	50.0	.86
7012	01-14-001-17W2	3094	1.59	55.42	18.87	34.0	.92
7003	01-14-001-17W2	3101	2.58	67.39	24.88	36.9	1.31
7007	01-14-001-17W2	3107	2.86	72.56	31.10	42.8	1.27
6388	01-14-001-17W2	3109	7.78	21.63	6.70	31.0	1.23
7017	01-14-001-17W2	3109	7.78	26.08	7.12	27.3	1.48
6880	07-23-001-17W2	3074	1.64	39.16	16.36	41.8	1.36
6917	13-23-001-17W2	3068	.71	780.79	394.37	50.5	1.05
6916	13-23-001-17W2	3074	1.62	68.01	22.29	32.8	.86
6623	13-23-001-17W2	3076	17.71	10.63	4.91	46.2	.97
6624	13-23-001-17W2	3082	12.18	23.99	11.85	49.4	1.44
6883	11-27-001-17W2	3072	2.41	146.82	73.41	50.0	.71
6393	16-36-001-18W2	3062	19.12	47.14	18.97	40.2	1.32
6991	16-36-001-18W2	3062	19.12	40.94	15.51	37.9	1.15
6998	15-09-002-14W2	3044	.18	802.00	375.94	46.9	1.19
7013	15-09-002-14W2	3065	.52	1123.37	337.33	30.0	1.08
7018	15-09-002-14W2	3065	5.53	108.86	39.57	36.3	1.15
6992	15-09-002-14W2	3069	4.57	123.84	36.31	29.3	.86
7014	15-09-002-14W2	3070	.16	321.56	76.99	24.0	.54
7031	15-09-002-14W2	3070	1.63	710.26	225.22	31.7	.79
6389	15-09-002-14W2	3076	35.58	8.29	2.47	29.8	.76
7006	15-09-002-14W2	3076	14.44	18.38	5.03	27.4	.74
6847	08-16-002-14W2	3052	4.97	59.47	31.36	52.7	3.41
6848	08-16-002-14W2	3053	.84	142.86	77.92	54.5	2.60
6933	03-20-002-16W2	3071	8.54	13.90	5.12	36.8	.75
6626	03-20-002-16W2	3076	15.49	8.64	2.27	26.3	.82
6934	06-13-002-19W2	3020	10.55	19.11	7.30	38.2	1.04
6935	06-13-002-19W2	3021	6.83	30.49	15.64	51.3	1.29
6632	07-23-003-17W2	2990	15.64	30.70	12.56	40.9	1.83
6977	07-23-003-17W2	2992	12.79	40.86	16.01	39.2	1.23
6974	03-26-004-20W2	2830	9.91	28.96	9.21	31.8	.87
6981	06-11-004-21W2	2829	2.04	60.63	25.80	42.5	1.50
6982	06-11-004-21W2	2830	6.61	28.23	11.32	40.1	.83
6984	08-02-006-16W2	2686	2.24	80.78	39.97	49.5	1.54
6985	08-02-006-16W2	2689	3.16	127.20	71.05	55.8	1.34
6986	08-02-006-16W2	2696	9.16	13.45	5.08	37.7	1.22
6918	12-13-007-19W2	2993	1.89	97.38	48.31	49.6	.91
6631	16-20-008-10W2	2445	17.07	46.00	24.52	53.3	1.48
6630	16-20-008-10W2	2446	15.28	12.82	6.82	53.2	1.17
6989	16-20-008-10W2	2447	.82	257.34	129.19	50.2	.92
6990	16-20-008-10W2	2455	1.04	154.77	55.32	35.7	.83

APPENDIX 2

Solvent extracts from potential source rocks and stains, selected gross compositional data - Continued

No.	Location	Depth	TOC	Extract total	HC yield	HC percent	Saturate/ Aromatic HC
6622	06-32-008-16W2	2459	16.27	29.53	17.35	58.8	1.57
6915	06-32-008-16W2	2466	.55	356.42	212.12	59.5	1.26
6387	03-14-008-20W2	2577	12.12	37.13	19.04	51.3	1.07
7010	03-14-008-20W2	2577	11.10	73.36	24.45	33.3	.73
6975	06-05-008-22W2	2532	1.72	62.19	25.32	40.7	1.19
6859	14-11-014-16W2	2126	1.58	116.99	48.91	41.8	.70
6858	14-11-014-16W2	2136	3.82	78.53	40.81	52.0	.66
7016	02-04-022-15W2	1731	.69	817.74	561.95	68.8	3.98
6380	02-04-022-15W2	1732	30.49	15.79	7.32	46.4	.60
6381	02-04-022-15W2	1732	28.49	18.75	9.21	49.1	.52
6993	02-04-022-15W2	1732	34.94	14.84	5.90	39.8	.64
6995	02-04-022-15W2	1732	30.47	17.96	6.02	33.5	.74
7015	02-04-022-15W2	1732	28.49	20.98	8.73	41.6	.83
6628	02-04-022-15W2	1733	23.98	17.78	7.96	44.7	.86
6861	01-25-023-16W2	1599	12.21	45.80	20.32	44.4	.47
6860	01-25-023-16W2	1603	6.52	29.85	13.15	44.0	.45
6994	04-10-033-01W3	1466	7.90	21.50	3.96	18.4	1.00
Big Horn Group, Yeoman Formation (Upper Ordovician); lithologies other than kukersites, not obviously stained							
6884	11-27-001-17W2	3066	1.06	1173.91	545.53	46.5	1.26
6885	11-14-002-09W2	2980	.43	417.51	278.34	66.7	1.05
6919	12-13-002-19W2	3016	.48	643.84	398.94	62.0	.63
Big Horn Group, Yeoman Formation (Upper Ordovician); obviously stained lithologies							
6863	10-25-001-15W2	3143	.79	1262.04	593.24	47.0	.97
6867	07-23-001-17W2	3063	.84	1204.00	787.34	65.4	1.14
6881	07-23-001-17W2	3075	.73	1153.14	509.10	44.1	.84
6882	11-27-001-17W2	3059	.38	1497.98	1015.04	67.8	1.11
6621	11-27-001-17W2	3071	1.17	1495.73	860.81	57.5	1.17
6857	08-16-002-14W2	3018	.22	1010.10	578.00	57.2	1.57
6844	08-16-002-14W2	3035	1.85	846.85	343.63	40.6	1.32
6845	08-16-002-14W2	3036	1.28	1185.43	386.64	32.6	1.68
6629	08-16-002-14W2	3038	.45	1733.02	1400.86	80.8	2.89
6846	08-16-002-14W2	3049	1.06	1062.38	384.16	36.2	.82
6856	08-16-002-14W2	3054	.76	1043.23	454.26	43.5	.69
6932	12-13-002-19W2	3018	1.42	66.65	30.18	45.3	1.09
6625	06-28-003-12W2	2876	1.44	1474.67	800.65	54.3	1.25
6972	02-08-003-14W2	2931	.56	1633.48	1286.35	78.7	1.74
6978	04-22-003-15W2	2937	.36	914.81	508.33	55.6	1.12
6633	07-23-003-17W2	2988	5.09	1027.95	470.24	45.7	1.22
6976	07-23-003-17W2	2989	.69	510.83	224.57	44.0	.99
6979	11-02-003-21W2	2864	.35	1834.48	1299.51	70.8	1.61
6980	06-11-004-21W2	2818	.75	1892.93	1057.58	55.9	1.13
6983	08-02-006-16W2	2678	.48	1188.45	442.71	37.2	1.10
6987	08-02-006-16W2	2698	.58	1173.74	549.07	46.8	.85
6988	16-20-008-10W2	2444	.54	173.67	68.12	39.2	.82
Big Horn Group, Herald Formation, Coronach Member (Upper Ordovician)							
7026	15-09-002-14W2	3037	0.06	823.24	322.84	39.2	1.16
7005	02-11-010-09W2	2289	.69	292.23	81.57	27.9	.84
7004	02-11-010-09W2	2293	.59	110.75	26.96	24.3	.75
7027	02-11-010-09W2	2296	.22	510.12	115.12	22.6	.93
Big Horn Group, Herald Formation, Lake Alma Member (Upper Ordovician)							
7008	01-14-001-17W2	3084	.71	1085.51	642.86	59.2	1.38
7002	01-14-001-17W2	3086	.82	432.70	243.90	56.4	1.21
6999	01-14-001-17W2	3087	1.00	856.15	422.31	49.3	1.33
Big Horn Group, Herald Formation, Redvers Unit (Upper Ordovician)							
7020	15-09-002-14W2	3028	.13	519.11	169.89	32.7	1.06
7029	15-09-002-14W2	3030	.38	1222.56	859.10	70.3	1.79
6973	02-08-003-14W2	2930	.76	55.34	20.49	37.0	.78
7019	02-11-010-09W2	2286	.63	360.68	90.17	25.0	.98

APPENDIX 2

Solvent extracts from potential source rocks and stains, selected gross compositional data - Continued

No.	Location	Depth	TOC	Extract total	HC yield	HC percent	Saturate/ Aromatic HC
	Big Horn Group, Stony Mountain Formation, Harthaven Member (Upper Ordovician)						
7001	15-09-002-14W2	3021	0.05	743.59	230.77	31.0	1.00
	Big Horn Group, Stony Mountain Formation, Gunn Member (Upper Ordovician)						
6392	02-11-010-09W2	2273	22.20	16.77	6.54	39.0	1.69
7009	02-11-010-09W2	2273	22.20	17.12	6.16	36.0	1.22
	Elk Point Group, Winnipegosis Formation, Lower member (Middle Devonian)						
6743	12-24-001-10W2	2766	.73	185.1	37.75	20.4	1.35
6785	09-31-004-08W2	2422	2.24	71.67	12.25	17.1	.31
	Elk Point Group, Winnipegosis Formation, Upper member (Middle Devonian)						
6786	08-01-004-09W2	2560	.86	197.82	58.29	29.5	.77
6787	08-20-004-14W2	2517	31.11	30.92	5.48	17.7	.64
6391	08-20-004-14W2	2518	45.92	110.52	20.69	18.7	.31
	Elk Point Group, Winnipegosis Formation, unnamed Mudstone member (Middle Devonian)						
6902	NENE05161-95W	3135	.60	333.33	245.88	73.8	3.05
6909	NENW35156-93W	3674	2.49	77.0	39.88	51.8	2.06
6903	NWNE29157-88W	3059	.26	114.81	26.41	23.0	.64
6901	SWNW07158-95W	3400	1.29	796.14	709.72	89.1	3.72
6899	SWSE34161-87W	2532	1.29	534.77	357.26	66.8	1.92
6900	NESE26161-95W	3277	1.79	383.61	327.75	85.4	3.12
	Elk Point Group, Winnipegosis Formation, Brightholme member (Middle Devonian)						
6868	11-29-001-25W1	1534	6.97	423.58	71.74	16.9	.10
6872	04-12-007-25W1	1198	20.65	32.89	9.89	30.1	.29
6871	04-12-007-25W1	1199	15.56	105.34	29.34	27.8	.44
6849	02-21-007-28W1	1447	10.97	99.64	13.57	13.6	.42
7189	10-22-030-16W1	69	3.23	92.88	19.30	20.8	.23
7188	10-22-030-16W1	73	2.01	64.47	14.01	21.7	1.00
6834	10-22-030-16W1	77	1.03	121.13	44.38	36.6	3.00
6835	10-22-030-16W1	78	1.45	82.25	20.88	25.4	2.30
6836	10-22-030-16W1	80	.94	62.71	22.40	35.7	1.86
6837	10-22-030-16W1	81	.28	262.28	106.03	40.4	1.37
7192	00-00-030-17W1	118	18.78	118.00	21.30	18.0	.31
6873	03-29-036-25W1	230	2.99	292.24	77.24	26.4	.22
6898	13-10-036-26W1	276	9.49	83.62	16.89	20.2	.42
7190	00-00-041-24W1	106	5.12	155.27	25.88	16.7	.39
7187	00-00-041-24W1	117	.72	204.68	38.99	19.0	.78
6851	05-13-044-24W1	76	3.93	133.19	15.39	11.5	.26
6841	08-14-044-25W1	67	5.95	188.06	18.54	9.9	.25
6840	08-14-044-25W1	74	18.01	63.06	8.72	13.8	.22
6850	08-14-044-25W1	77	2.08	272.78	25.08	9.2	.20
6838	08-14-044-25W1	79	8.68	124.21	12.96	10.4	.28
6839	08-14-044-25W1	80	2.55	276.92	23.53	8.5	.26
6870	10-11-045-26W1	85	16.73	71.27	10.11	14.2	.37
6869	10-11-045-26W1	94	4.06	167.72	25.80	15.4	.29
7191	14-12-045-26W1	84	4.99	200.40	34.42	17.2	.18
6852	14-12-045-26W1	87	5.39	569.20	64.19	11.3	.31
7186	14-12-045-26W1	87	16.72	114.76	13.99	12.2	.30
6854	14-12-045-26W1	88	1.75	346.94	37.75	10.9	.23
6853	14-12-045-26W1	89	5.09	174.01	17.24	9.9	.19
6741	12-24-001-10W2	2764	1.45	266.09	135.46	50.9	1.85
6808	12-24-001-10W2	2764	1.72	166.77	79.83	47.9	1.66
6742	12-24-001-10W2	2765	.25	457.80	253.18	55.3	2.45
6773	10-28-001-10W2	2744	.26	679.51	191.14	28.1	.72
6744	04-18-001-21W2	2701	4.68	78.62	24.89	31.7	.69
6774	04-30-001-23W2	2669	.18	657.17	139.88	21.3	.43
6772	04-30-001-23W2	2671	.10	756.60	169.81	22.4	1.0
7100	06-27-002-09W2	2614	1.96	90.38	26.24	29.0	.38
7099	06-27-002-09W2	2616	.40	172.17	73.11	42.5	.94

APPENDIX 2

Solvent extracts from potential source rocks and stains, selected gross compositional data - Continued

No.	Location	Depth	TOC	Extract total	HC yield	HC percent	Saturate/ Aromatic HC
6771	08-16-002-14W2	2708	.21	1455.33	491.88	33.8	1.49
6794	10-33-006-13W2	2309	.23	398.36	119.89	30.1	.86
6795	10-33-006-13W2	2310	.51	189.00	57.95	30.6	.89
6796	10-33-006-13W2	2313	2.56	443.81	157.55	35.5	.85
6798	10-27-007-21W2	2323	5.35	47.85	26.54	55.5	.48
6797	10-27-007-21W2	2324	.39	975.69	321.90	33.0	.63
6799	10-27-007-21W2	2324	1.64	230.15	47.82	20.8	.42
6828	08-36-016-06W2	1528	3.46	157.50	40.30	25.6	.81
6829	06-29-018-16W2	1771	31.38	138.99	31.50	22.7	.32
6833	03-13-019-09W2	1501	.48	280.24	47.01	16.8	.96
6831	07-22-021-11W2	1450	2.39	113.83	13.05	11.5	.45
6815	16-13-042-19W2	843	16.89	167.91	17.76	10.6	.21
6814	16-13-042-19W2	845	12.10	261.16	27.08	10.4	.24
6826	01-15-048-17W2	1703	7.78	193.64	31.02	16.0	.24
6827	01-15-048-17W2	1709	7.94	193.88	22.70	11.7	.24
6791	10-24-067-23W2	74	8.24	95.04	8.69	9.1	.28
6792	10-24-067-23W2	74	12.80	104.40	11.87	11.4	.30
6793	10-24-067-23W2	78	13.81	93.18	8.78	9.4	.51
6816	16-11-033-01W3	1262	.42	1453.87	250.42	17.2	.21
6824	16-11-033-01W3	1268	3.96	210.73	34.61	16.4	.20
6825	16-11-033-01W3	1270	6.47	197.59	46.58	23.6	.18
6805	07-02-038-01W3	1185	10.21	125.53	19.59	15.6	.35
6806	07-02-038-01W3	1185	12.53	176.12	21.68	12.3	.34
6807	07-02-038-01W3	1186	19.20	106.64	16.56	15.5	.29
6809	06-16-038-01W3	1176	9.68	105.76	12.67	12.0	.29
6810	06-16-038-01W3	1177	27.44	106.56	14.72	13.8	.20
6813	06-16-038-01W3	1178	28.63	64.73	10.04	15.5	.24
6749	05-29-047-03W3	749	9.75	279.24	18.78	6.7	.42
6748	05-29-047-03W3	751	10.09	143.28	16.24	11.3	.38
6750	05-29-047-03W3	752	16.91	151.22	16.82	11.1	.50
6788	07-34-073-06W3	43	5.03	202.69	24.97	12.3	.20
6789	07-34-073-06W3	47	7.40	137.46	16.52	12.0	.36
6790	07-34-073-06W3	49	8.58	110.01	11.42	10.4	.35
6775	12-21-077-25W3	1778	1.69	420.85	48.75	11.6	.46
6782	12-21-077-25W3	1781	8.07	339.81	46.95	13.8	.47
6783	12-21-077-25W3	1785	6.97	506.18	48.52	9.6	.37
6908	03-15-107-10W5	0974	17.53	189.18	38.18	20.2	.16
	Elk Point Group, Winnipegosis Formation, Upper member (restricted)						
6842	02-21-007-28W1	1446	2.35	186.14	24.98	13.4	.36
6739	12-24-001-10W2	2760	0.06	43.90	26.90	61.3	1.42
6740	12-24-001-10W2	2763	.15	234.57	164.02	69.9	2.58
6752	03-08-001-11W2	2814	.10	3267.66	1661.71	50.8	2.00
6751	03-08-001-11W2	2817	.12	1476.14	1077.28	73.0	2.58
7098	16-15-002-09W2	2638	.64	160.47	57.71	36.0	.64
7097	16-15-002-09W2	2639	2.36	125.08	25.42	20.3	.27
6784	07-24-004-05W2	2336	.13	602.71	151.78	25.2	1.06
6817	16-11-033-01W3	1267	3.41	1714.21	359.59	21.0	.14
	Elk Point Group, Winnipegosis Formation (Middle Devonian); obviously stained lithologies						
6770	08-16-002-14W2	2708	.15	4676.19	3328.57	71.2	2.05
6832	15-05-046-09W2	545	.13	8775.30	4663.46	53.1	5.27
6812	07-02-038-01W3	1172	.26	922.41	158.17	17.1	.27
	Manitoba Group, Dawson Bay Formation (Middle Devonian)						
6753	08-36-003-29W2	2396	1.27	450.08	62.67	13.9	.39
	Three Forks Group, Bakken Formation, Lower shale member (Upper Devonian)						
6928	15-06-016-30W1	0649	.47	413.54	122.86	29.7	1.73
6948	04-20-017-32W1	0680	.51	242.42	78.43	32.3	6.33
6911	12-27-001-06W2	2082	18.80	109.90	42.25	38.4	.61
6394	14-15-002-23W2	2161	26.13	76.92	18.24	23.7	.86
6395	14-15-002-23W2	2161	0.00	62.30	16.90	27.1	.58

APPENDIX 2

Solvent extracts from potential source rocks and stains, selected gross compositional data - Continued

No.	Location	Depth	TOC	Extract total	HC yield	HC percent	Saturate/ Aromatic HC
6944	03-34-002-27W2	2127	11.95	117.93	20.82	17.6	.61
6945	03-34-002-27W2	2127	15.10	101.05	17.35	17.2	.70
6930	15-31-003-11W2	1988	12.99	81.74	20.83	25.5	.30
6938	08-20-004-14W2	1971	29.75	98.07	24.75	25.2	.55
6961	09-13-005-13W2	1845	13.79	119.94	35.83	29.9	.70
6969	02-05-005-27W2	2066	15.61	98.02	14.23	14.5	.57
7185	01-20-006-19W2	1939	18.85	86.44	27.96	32.3	.67
6951	05-04-006-24W2	1820	19.63	90.85	16.73	18.4	.60
6953	05-04-006-24W2	1821	21.60	84.60	15.83	18.7	.64
6377	01-02-006-25W2	1829	17.85	80.71	20.31	25.2	.53
6926	16-23-007-03W2	1414	1.90	78.95	16.08	20.4	.83
6958	16-10-007-15W2	1727	13.33	80.09	20.56	25.7	.68
6959	16-10-007-15W2	1728	9.55	150.51	22.97	15.3	.63
6955	13-30-007-23W2	1846	15.37	88.69	15.96	18.0	.61
6956	14-27-008-26W2	1788	15.82	75.58	11.71	15.5	.64
6912	06-26-010-02W2	1266	1.95	58.86	11.65	19.8	1.00
6940	11-36-013-11W2	1270	3.31	62.70	9.97	15.9	1.19
6971	06-33-014-01W2	0904	0.06	1701.39	208.33	12.2	1.00
6970	06-33-014-01W2	0913	0.07	830.12	115.83	13.9	1.00
6962	14-11-014-16W2	1226	4.40	44.33	6.12	13.8	.65
6946	13-29-016-08W2	1059	10.72	59.93	15.40	25.7	1.50
	Three Forks Group, Bakken Formation, Middle sandstone member (Upper Devonian and Mississippian)						
6942	16-10-003-25W2	2088	15.89	111.22	15.50	13.9	.72
6966	06-07-005-18W2	2022	.54	141.46	28.29	20.0	.57
6952	05-04-006-24W2	1810	1.67	35.38	6.80	19.2	.87
6957	16-10-007-15W2	1712	17.71	116.94	31.11	26.6	.76
	Three Forks Group, Bakken Formation, Upper shale member (Mississippian)						
6929	15-06-016-30W1	0642	.29	174.99	56.61	32.3	.83
6328	04-20-017-32W1	667	19.13	25.94	1.90	7.3	.86
6334	04-20-017-32W1	670	25.82	26.41	2.58	9.8	.37
6949	04-20-017-32W1	0667	15.63	33.41	4.26	12.8	.93
6947	04-20-017-32W1	0669	20.40	30.92	3.17	10.2	.83
6910	12-27-001-06W2	2066	20.50	110.93	26.02	23.4	.33
6931	15-31-003-11W2	1970	23.47	106.77	26.94	25.2	.26
6943	16-10-003-25W2	2072	15.46	149.28	26.64	17.8	.66
6939	08-20-004-14W2	1954	31.89	110.65	22.59	20.4	.46
6960	09-13-005-13W2	1828	31.24	114.59	28.67	25.0	.45
6967	06-07-005-18W2	2019	24.37	103.10	22.99	22.3	.34
6968	02-05-005-27W2	2053	17.95	136.27	22.78	16.7	.58
7184	01-20-006-19W2	1928	4.08	460.59	160.89	34.9	.54
6376	01-02-006-25W2	1812	28.58	101.92	25.47	25.0	.38
6927	16-23-007-03W2	1406	30.96	87.21	16.15	18.5	.31
6954	13-30-007-23W2	1833	23.58	106.14	24.26	22.8	.51
6913	06-26-010-02W2	1257	29.73	87.45	9.17	10.5	.64
6941	11-36-013-11W2	1259	25.79	67.72	13.44	19.8	.12
	Madison Group, Lodgepole Formation (Mississippian)						
6382	14-15-002-23W2	2062	4.16	420.12	118.60	28.2	.21
6378	14-15-002-23W2	2066	5.16	303.66	79.01	26.0	1.00
6384	14-15-002-23W2	2067	8.05	247.59	45.62	18.4	.15
6385	14-15-002-23W2	2070	5.86	321.00	51.48	16.0	.18
6386	14-15-002-23W2	2070	6.09	299.14	64.97	21.7	.16
6379	14-15-002-23W2	2071	6.15	305.57	73.40	24.0	.17
6375	01-02-006-25W2	1808	3.21	237.07	77.88	32.8	.50