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PETROLEUM POTENTIAL OF THE MIDDLE MEMBER, BAKKEN FORMATION, WILLISTON BASIN

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ABSTRACT

The Bakken Formation is a widespread clastic unit between the Mississippian Madison Group and the Upper Devonian Big Valley, Torquay, or Three Forks formations. The formation typically consists of three members: a lower and upper organic-rich shale and a middle calcareous sandstone and siltstone.

The three members of the Bakken Formation exhibit an onlapping relationship, and converge and thin toward the margins or marginal shelf areas of the Williston Basin. In Manitoba, the lower member is absent, except for Waskada field.

Several correlative lithofacies have been recognized in the middle member. The lowermost unit of the middle member is a regressive deposit. The upper portions of the middle member

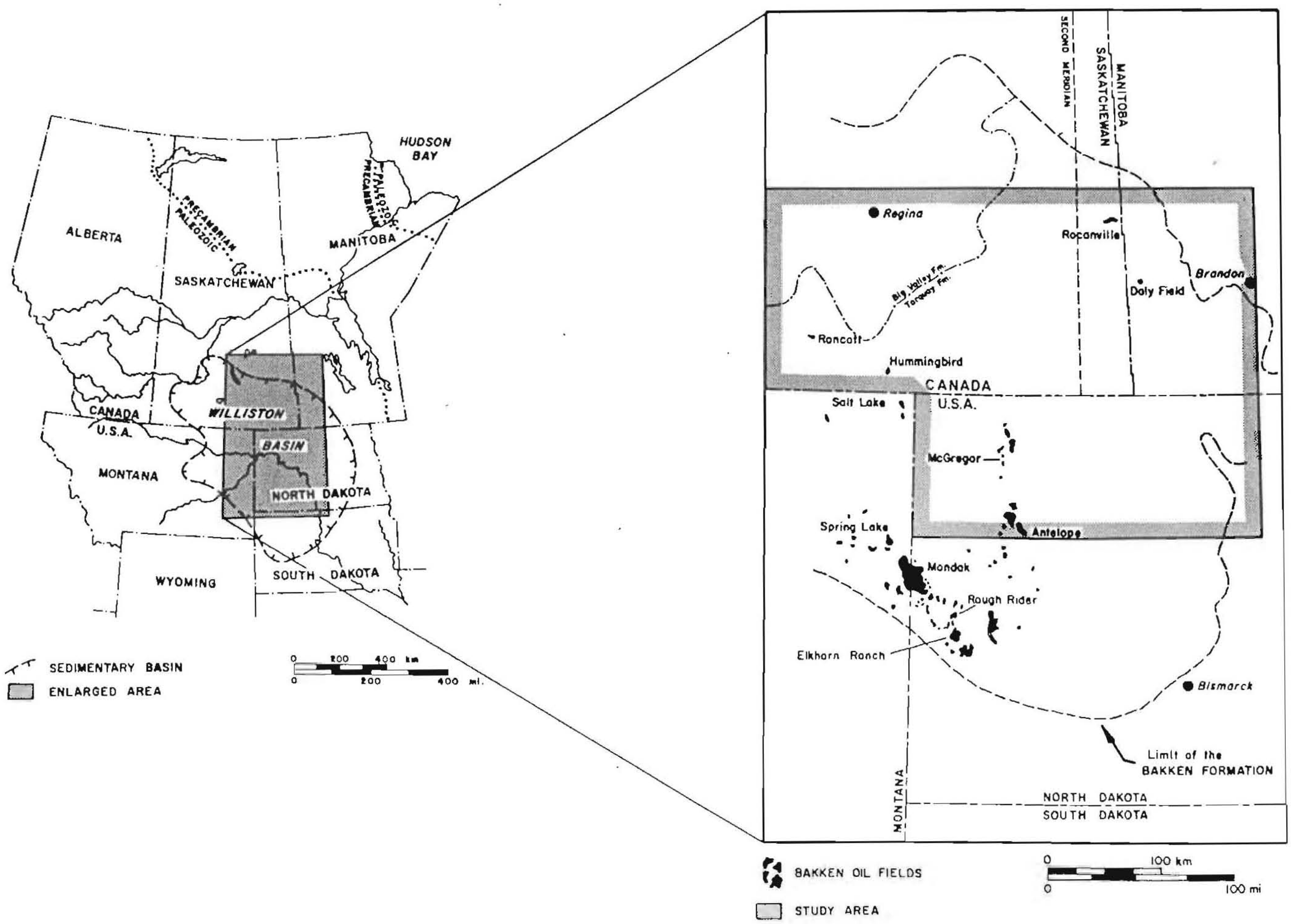

Figure 1: Index map showing the location of the study area within the Williston Basin. The approximate limit of the Bakken, Torquay, and Big Valley formations is indicated. Oil fields which are producing or have produced from the Bakken Formation are also shown.

show transgressive and regressive cycles, and intertidal deposits interfinger with their distal equivalents.

Conventional Bakken production is restricted to areas where it is a thermally mature source rock. The greater part of Bakken production in recent years has been taken from the shale of the upper and lower members, although there are outlying fields which produce from a sandstone within the middle member. This suggests that there has been a migration of Bakken oil from the central portion of the basin. The sandstone unit may provide a conduit for migration.

INTRODUCTION

The Bakken Formation has long been considered to be an important source rock for the oils of the Williston Basin. Numerous studies have examined the geochemistry and hydrocarbon potential of the Bakken shales (Dow, 1974; Williams, 1974; Webster, 1982; 1984; Schmoker and Hester, 1983; Price *et al.*, 1984). However, recent information indicates that a large amount of oil that has been produced and previously thought to have been sourced by the Bakken Formation was, in fact, generated within the Lodgepole Formation (Osadetz and Snowdon, in review; Osadetz *et al.*, in review).

The hydrocarbon potential of the Bakken Formation has been estimated to be at least 98 billion barrels (Webster, 1982; 1984). Based on the recent findings of the Geological Survey of Canada, a larger amount of undiscovered Bakken oil exists somewhere within the Williston Basin. Research indicates that this oil is probably stratigraphically trapped within a narrow zone that surrounds and includes the Bakken Formation.

Conventional Bakken production in North Dakota is restricted to areas where the Bakken is a thermally mature source rock. However, well beyond there are fields in Saskatchewan and Manitoba which produce from a sandstone within the middle member of the Bakken. This suggests that there has been an outward lateral migration of Bakken oil from the central portion of the Williston Basin. Recent focus on the Bakken Formation has been directed toward the development of and exploration for oil in the Bakken shales of North Dakota and Montana. This study will examine the overall stratigraphy and petroleum potential of the Bakken Formation in North Dakota, Manitoba, and Saskatchewan (Fig. 1).

GEOLOGICAL SETTING

The Williston Basin is an intracratonic, structural, and sedimentary basin located at the western edge of the Canadian Shield. It occupies portions of North Dakota, South Dakota, Montana, Saskatchewan, and Manitoba (Fig. 1). Gerhard *et al.* (1982) related the formation of the basin and other major structural features, including the Nesson, Cedar Creek, and Billings anticlines, to a major directional change in the structure of the Rocky Mountain belt.

Nearly continuous sedimentation has occurred in the North Dakota portion of the Williston Basin. This is represented by over 4,878 m (16,000 ft) of sediments representing Cambrian through Tertiary time. Basin sedimentation is characterized by cyclical transgressions and regressions with the repeated deposition of carbonates and clastics. Paleozoic strata are dominated by carbonates, whereas Mesozoic and Cenozoic strata consist mainly of clastic rocks.

Initial sedimentation occurred over an irregular Precambrian surface. Repeated clastic/carbonate sequences interrupted by major erosional events are evidenced by strata from Cambrian to Devonian time. The Devonian period marked a reorientation of the seaway to the north as a result of activity along the Transcontinental arch. Devonian sediments show the repeated transgressional-regressional cycles related to Elk Point basin deposition. A reorientation of the seaways occurred again during the Mississippian when the basin opened to the west through the central Montana trough. Terrestrial, marginal marine, and evaporite sediments are represented by Pennsylvanian through Triassic strata. The last sequence of marine strata was deposited during the Jurassic and Cretaceous periods.

A major angular unconformity separates the Paleozoic from the Mesozoic strata and probably represents one or more periods of erosion that occurred from Late Mississippian to Early Jurassic time. During this interval, Paleozoic strata in the northeastern part of the basin were uplifted and differentially eroded, while strata in the southern portion of the basin were relatively unaffected (McCabe, 1959). Successively older Paleozoic strata were progressively truncated toward the basin margin. Deposition resumed during Mesozoic time, when a thick sequence of Jurassic and Cretaceous strata was deposited on the eroded Paleozoic surface.

Within the Paleozoic itself, an unconformity separates Devonian and Mississippian strata and represents uplift and erosion which occurred from Late Devonian to Early Mississippian time. During that interval, Devonian strata were uplifted and exposed along the basin margins, while deposition continued in the deeper portions of the basin. Mississippian sediments were later deposited on the eroded Devonian surface (Sandberg, 1964).

In North Dakota, the Bakken Formation is a thin, clastic unit which straddles the Devonian-Mississippian boundary. It occurs solely in the subsurface and consists of three informal units, referred to as the lower, middle, and upper members in this report. The formation reaches a maximum thickness of 46 m (150 ft) in the central portion of the basin (Fig. 2).

The Bakken Formation subcrops in Manitoba along the northeastern portions of the study area, where it is unconformably overlain by the "Red Beds" of the Amaranth Formation (Jurassic).

Southeastern Saskatchewan is situated on the northern shelf adjacent to the Williston Basin (Christopher, 1961). Sediments associated with the margin form a southerly-dipping wedge that thins towards the northern erosional edge. The strong southerly tilt superimposed on these sediments occurred between Mississippian and Jurassic time and is probably related to basin subsidence.

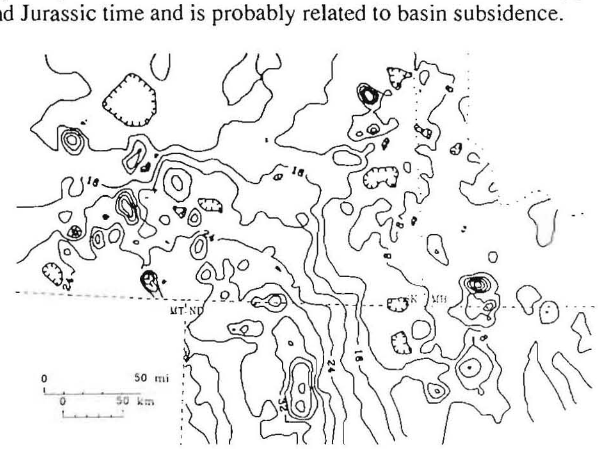

Figure 2: Isopach map of the Bakken Formation for the study area. Contour interval is 4 m (13 ft). Dashed line in northeastern Manitoba is the erosional limit of the Bakken Formation.

GENERAL STRATIGRAPHY

A persistent sequence of black shales and grey siltstones was recognized at the base of the Madison Group (Mississippian) limestones early in the exploration of the Williston Basin. These beds were referred to by a variety of names, including Kinderhook, Englewood, and Exshaw (Fuller, 1956). In an attempt to eliminate the confusion, a formal name, the Bakken, was introduced into the literature in 1953 by the Williston Basin Nomenclature Committee of the Saskatchewan Society of Petroleum Geologists and the Rocky Mountain Section of the American Association of Petroleum Geologists. No formal definition for the formation was presented at that time.

Nordquist (1953) formally defined and described the Bakken Formation for strata occurring at depths from 2,931 to 2,963 m (9,615 to 9,720 ft) in the Amerada Petroleum Corporation - H.O. Bakken #1 deep test (Fig. 3). The well is located in CSWNW Sec. 12, T.157N., R.95W. in Williams County, North Dakota. As based on samples, the formation is 32 m (105 ft) thick at its type section and consists of two black, organic-rich shales which are separated by a light grey to grey-brown, very fine-grained, calcareous sandstone.

Kume (1963) modified Nordquist's original description of the Bakken type section. He re-evaluated the thicknesses of the members, modified the sample descriptions for the lower and middle member, and designated a standard subsurface reference section. The standard reference section is located over the interval from 3,059 to 3,078 m (10,035 to 10,095 ft) in the Socony Vacuum Oil Company - C. Dvorak #1 well (SENE Sec. 6, T.141N., R.94.W, Dunn County, North Dakota). This well was selected because it was continuously cored from the lower portion of the Madison Group (Mississippian) into the Birdbear Formation (Devonian).

The Bakken Formation is formally recognized in southwestern Manitoba, southern Saskatchewan, and eastern Alberta (Fuller, 1956; MacDonald, 1956; McCabe, 1959; Christopher, 1961; 1962; Carlson and LeFever, 1987). In southwestern Alberta, the equivalent strata are divided into two formations: the basal black shale and middle siltstone member are included in the Exshaw Formation; and, the upper black shale is included with the basal shales of the Banff Formation (MacDonald, 1956). Usage of Exshaw and Banff formations is carried into northern Alberta and northern British Columbia. Correlations in northern Alberta and British Columbia become more difficult as the shale become lithologically similar to the underlying and overlying beds (Macauley *et al.*, 1961).

The Bakken Formation is an easily recognizable sequence on wireline logs in the subsurface of the Williston Basin. As previously stated, it comprises three members, a lower and an upper shale and a lithologically variable middle member. Readily apparent on wireline logs, the shales have abnormally high gamma-ray readings (>200 API), low resistivity (ohm-m) readings in the shallower portion of the basin, high resistivity readings in the deeper portion of the basin, and high transit times (80 to 120 microsec/ft) (Meissner, 1978; Webster, 1982; 1984). The middle member has normal wireline log characteristics for clastics and carbonates and becomes difficult to distinguish from the underlying Three Forks Formation when the lower shale is absent.

The three members of the Bakken Formation exhibit an onlapping relationship; each successively higher member has a greater areal distribution. The formation overlies the Three Forks Formation (Upper Devonian) in North Dakota and Manitoba, and the Upper Devonian Torquay and Big Valley formations in Saskatchewan. In turn, the formation is overlain by the Lodgepole Formation (Lower Mississippian) throughout North Dakota and Manitoba and by the Souris Valley Beds (Lower Mississippian) in Saskatchewan.

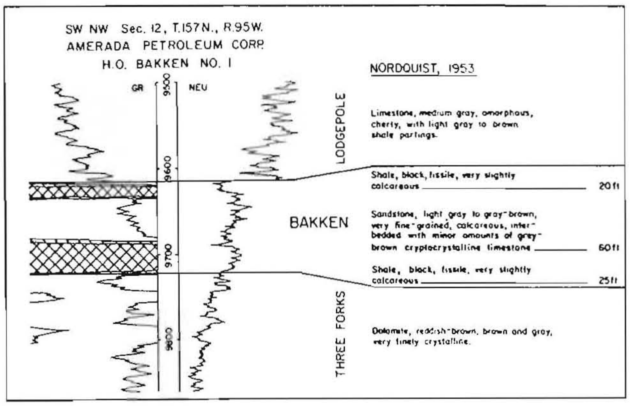

Figure 3: Type log for the Bakken Formation from Amerada Petroleum Corporation - H.O. Bakken #1 deep test. Lithologic description is from Nordquist (1953).

BAKKEN FORMATION

Lower Member

The lithology of the lower member of the Bakken Formation is uniform over the entire study area. It consists of a dark grey to brownish-black to black, non-calcareous, fissile, slightly to highly organic-rich shale. The colour of the shale varies depending on the amount of silt versus clay versus carbon present in the rock. Lesser amounts of siltstone, limestone, and sandstone occur within the lower member in North Dakota. The shale is finely laminated to massive and can be hard or soft ("wax-like").

In Saskatchewan, Fuller (1956) described a 2.5 cm (1 in) thick pebble bed at the base of the Bakken Formation. Constituents include dolostone fragments, occasional broken conodonts, and chert in a grey siltstone matrix. Phosphatic fragments are also occasionally present. Fuller suggested that the pebble bed represented the basal conglomerate of the Bakken Formation. Hayes (1984) described a thin, 2.5 cm (1 in), coarse, lag sandstone bed at the base of the lower member in North Dakota. The sandstone bed contains fragments of conodonts, pyritized clasts, phosphatic particles, fish bones, subangular quartz sand and silt, chert, carbonate debris, and rounded pebbles all floating in a shale matrix.

Fossils identified by Hayes (1984) in the lower member in North Dakota include algal plant spores (*Tasmanites*, sp.), conodonts, inarticulate brachiopods (*Lingula* sp., *Orbiculoidea* sp.), fish teeth, bones, and scales, conchostracans, rare ostracods, woody plant fragments, and sponge spicules. Fossils identified in Saskatchewan include *Lingula*, conodonts, spores or spore-like remains including *Tasmanites* (Fuller, 1956; Christopher, 1961).

The lower shale is organic-rich in the deeper portion of the basin and is considered to be a mature source rock. The organic material is distributed evenly throughout the member. Pyrite is also abundant, and occurs in thin, wispy laminae, in lenses or nodules, or disseminated throughout the interval. Fractures can also be present, can be irregular and blocky or smooth and conchoidal in the more siliceous sections. Occasionally, the fractures are healed with calcite or pyrite. Resinous or vitreous pods of carbonaceous material ("dead oil") are present along some of the fractures which occur parallel or subparallel to bedding.

The lower member reaches a maximum thickness of 17 m (55 ft) in North Dakota with a well-defined depocenter immediately east of the Nesson anticline. Thicknesses in Saskatchewan reported by Christopher (1961; 1962) for the lower Bakken shale member generally range from 6 to 8 m (20 to 25 ft). A local exception is the Sohio-Leakville #1 (4-11-14-26 W2M) where the lower Bakken shale member reaches a thickness of 13 m (43 ft). In Manitoba, the Lower Member is restricted to the Waskada area (Townships 1 and 2; Ranges 25 and 26 WPM) and is a maximum 13 m (43 ft) thick (McCabe, 1959; Martinuik, 1988).

Middle Member

The lithology of the middle member is highly variable in North Dakota. It consists of a light grey to medium dark grey interbedded sequence of siltstones and sandstones. Lesser amounts of shale, dolostones, and limestones rich in silt, sand, and oolites may also be present (Webster, 1982; Hayes, 1984; Thrasher, 1985). The siltstones and sandstones are massive or coarsely bedded with an occasional trough or planar cross-bed set. Much of the sequence is well sorted. Bioturbation commonly disturbs the bedding, especially in the more argillaceous portions. Features indicative of soft sediment deformation, including microfaults and flow structures, are also present. Cements include calcite, dolomite, silica, and pyrite. Insoluble residues comprise quartz silt and sand, feldspar, chert, glauconite, and silicified and pyritized fossils.

Fossils within the middle member include articulate and less common inarticulate brachiopods, pelmatozoan fragments, gastropods, and various trace fossils. Conodonts, plant spores, and ostracods were also observed but are considered to be rare (Hayes, 1984).

In Manitoba, the Middle Member consists primarily of a light greenish-grey to reddish- and purplish-grey siltstone to very fine- to medium-grained sandstone (Martiniuk, 1988). Much of the sequence is dolomitic and argillaceous. Mineralogically, the sandstones consist predominantly of quartz with minor amounts of feldspar. Coarser grain sizes are generally subrounded. The matrix is a dolomite or dolomitic shale, depending on the degree of sorting. Grain size increases in the northern and eastern portion of the study area.

McCabe (1959) reported that often the Middle Member is massive or finely laminated. Cross-bedding and contorted bedding were also noted. Several intraformational breccias and conglomeratic zones observed near the base of the unit probably represent diastemic and/or erosional breaks within the member.

In Saskatchewan, Christopher (1961; 1962) divided the middle sandstone member of the Bakken Formation into two units, A and B. Unit A, the lowermost unit, consists of a massive, calcareous, greenish-grey, pyritiferous, fossiliferous (primarily brachiopods), very fine-grained to silty sandstone that is present in the northwestern, western and southern portion of Saskatchewan. Unit B consists of an interfingering shale/sandstone sequence, designated B1 through B4. The shale units, B1 and B3, occur west of the second meridian. East of the second meridian, the two sandstone units, B2 and B4, come in contact to constitute the middle Bakken sandstone member. The uppermost unit, B4, represents a massive, fossiliferous, silty sandstone or coarse siltstone. This unit, in turn, is underlain by B2, a fine- to medium-grained, friable sandstone which changes westward into a well cemented, calcareous, medium-grained sandstone and oolitic calcarenite. Unit B2 exhibits well developed cross-bedding, ripple marks, current scour marks, and numerous diastems.

The middle member attains a maximum thickness of 27 m (87 ft) in North Dakota. Its depocenter, like the lower member, is well developed and is located just to the east of the Nesson anticline. In Manitoba, the Middle Member averages 4 m (13 ft) in thickness and reaches a maximum thickness of 16 m (52 ft) in the Waskada area. In the study area of Saskatchewan, the middle Bakken sandstone member reaches a maximum thickness of 18 m (60 ft) in the Herald and Torquay embayments (Christopher, 1961).

Upper Member

The upper member of the Bakken Formation is lithologically similar to the lower member and is also uniform throughout the study area (Fuller, 1956; McCabe, 1959; Christopher, 1961; 1962; Webster, 1982; Hayes, 1984; Martiniuk, 1988). It consists of dark grey to brownish-black to black, fissile, noncalcareous, carbonaceous and bituminous shale. It is more fossiliferous than the lower shale. Christopher (1961; 1962) reported abundant conodonts and chonetid brachiopods. Hayes (1984) noted the presence of other fossils including fish teeth, bones, and scales, rare woody plant fragments, inarticulate brachiopods, and spores in addition to conodonts. He also noted that one well had a well developed layer of reworked, pyritized, articulate brachiopods.

The upper member differs from the lower shale in North Dakota with the absence of crystalline limestones and greenish-grey shale beds and an increase in the organic content. Fractures are also present in the upper member. Thin, poorly defined laminae of silt-sized quartz and carbonate grains occur throughout. Small sandstone lag deposits were also described in the upper member by Hayes (1984). These deposits are rich in conodonts, fish bones and teeth, and phosphatic particles and occur at several zones within the shale.

The upper member reaches a maximum thickness of 9 m (28 ft) in North Dakota. The depocenter is poorly defined. In Saskatchewan, the shale is a maximum 4 m (12 ft) thick, averaging 1.2 m (4 ft). A uniform thickness of 2 m (7 ft) for Manitoba is reported by Martiniuk (1988). In the Waskada area of Manitoba, the Upper Member attains a maximum thickness of 18 m (59 ft).

Depositional Environments

A variety of environments have been suggested for the origin of the two black shales of the Bakken Formation. Workers agree that the environments of deposition were similar for the lower and upper shales and that conditions were uniform over the area. However, a wide range in ideas is possible when conditions conducive for shale deposition vary from open marine to terrestrial swamp.

Fuller (1956) suggested that the black shales were deposited in a vast swamp resulting from the retreat of Devonian seas. Iron oxides and sulfides reworked from Qu'Appelle Group sediments were reduced to form the iron sulfides of the Bakken muds. A transgression with the resulting incursion of seawater eroded the stable margins and formed the arenaceous beds of the middle member. A final seaward retreat of waters was followed with the return of conditions responsible for the formation of the black shales.

McCabe (1959) also suggested a marine swamp for the formation of the black shales. Restriction of circulation was due to prolific organic development. During the deposition of the Middle Member, the swamp was drowned or flooded by an influx of shallow marine clastics derived from older Paleozoic or Precambrian rocks. Stagnant, swamp conditions were reestablished for the deposition of the Upper Member. McCabe stated that the underlying Three Forks, the overlying Lodgepole, and the Middle Member were deposited in shallow marine conditions; therefore the shales were also probably deposited in shallow marine to terrestrial environment.

Christopher (1961; 1962) attributed the environment of deposition of the Bakken shales to a restriction of free flow water in a shallow sea due to sags and swells. Periodically fetid, the study area covering Saskatchewan converted to tidal flats and broad swamps. Thick black muds accumulated locally in sinkholes. Deposition of the middle Bakken sandstone member occurred in response to the southwesterly tilt of the Saskatchewan portion of the study area. Clastic sources of silt and clay were introduced into the area from the northeast and east and filled in basinal areas to the southeast, west, northwest and north. The initial transgression of the middle Bakken seas resulted in the rapid deposition of clays and silts and the burial and preservation of abundant brachiopods. After the initial deposition of Christopher's "A" unit, the eastern area began to subside and the sea spread over the platform area of Saskatchewan to the flat shelf area to the east and into Manitoba. This strandline and erosion of the Devonian extended into Manitoba. The deposition of the "B" unit followed with fine- to medium-grained sands intermittently laid down on a broad shelf in shallow water of variable current activity. Grey-black muds interfingered with the sands reflecting a "sea floor of flats, shoals, and broad hollows traversed by weak, shifting currents" (Christopher, 1962, p. 76). Sedimentation slowed and returned to swamp/lagoonal conditions, under which the upper Bakken shales were deposited. Bakken sedimentation was terminated by a major transgression under which the argillaceous limestones of the Madison Group were deposited.

Webster (1982) and Lineback and Davidson (1982) suggested a stratified water column for the deposition of the black shales. Evidence presented by Webster in support of this idea includes planar and thin laminations within the shale resulting from quiet water deposition below wave base; presence of planktonic algal spores (*Tasmanites* sp.), fish remains, cephalopods, ostracods, conodonts, and inarticulate brachiopods; high amounts of organic and pyritic material suggesting anaerobic conditions; uniformity over a large area; and the predominance of amorphous-sapropelic organic matter over terrestrial material. A temperate climate could account for the lack of mixing between the bottom and surface waters. The lithology and fossil content of the middle member suggests a return to aerobic marine conditions with moderate current activity.

Age

Early workers assigned a Mississippian age to the Bakken Formation based on lithology and limited paleontological data (Nordquist, 1953; Thomas, 1954; Fuller, 1956). McCabe (1959) included the Bakken as the basal formation of the Mississippian system. This assignment was based on the absence of the Lower Member of the Bakken over most of Manitoba and the evidence of erosion at the top of the Three Forks Formation, both indicating a possible time break. Martiniuk (1988) also placed the Bakken in Manitoba as the basal unit of the Mississippian sequence with the systemic boundary inferred at the unconformity between the Bakken and underlying Three Forks Formation.

Table 1: Composite lithofacies descriptions and correlations for the middle member of the Bakken Formation for the study area. Christopher (1961) divided the middle member into two units, A and B. Unit B was then further subdivided into B1, B2, B3, and B4. Thrasher (1985) and Karma and Parslow (1989) used macrofossils and lithology to subdivide the middle member into three units. This study incorporates both divisions of the middle member.

LITHOFACIES

	This Paper			Thrasher, 1985 Karma & Parslow, 1989	Christopher, 1961
UPPER MEMBER	SK	ND	MB	SK,ND	SK
SILTSTONE, massive, dense, mottled, dolomitic, argillaceous, grey-green, fossiliferous, disseminated pyrite, rhythmites up to 15 cm thick in lower half of section (occassionally fossil-rich), slightly bioturbated, contact with upper member sharp.	C	7	4 3	3	B4
PARALLEL INTERBEDS OF DARK GREY SHALE AND BUFF SILTY SANDSTONE, moderately bioturbated, vertical burrows, calcareous, disseminated pyrite, overall coarsening-upward, flame and load structures at base of coarse laminae, rhythmites up to 10 cm thick, upper half may display trough cross-bedded sandstone beds, gradational lower contact with underlying unit.	B3	6 5		2	B3
SANDSTONE, tripartite division with upper and lower third wavy and flaser bedded silty sandstone gradational to and from the middle coarse-grained sandstone which may be massive and/or bedded (trough and tabular cross-bedding, inclined and horizontal laminae, and swash cross-stratification) with pebble and fossil-rich lags (shale clasts up to 4 cm diameter where B2 overlies the lower member, and feldspar clasts). Mainly quartzose with minor feldspar and heavy minerals, disatems, rhythmites, few brachiopods, disseminated pyrite, buff to green, calcareous, slight to no bioturbation.	B2	4 3	2 1		B2
PARALLEL INTERBEDS OF DARK GREY SHALE AND BUFF SILTY SANDSTONE, moderate to very strong bioturbation disrupting laminae, dolomitic becoming calcareous with depth, disseminated pyrite, fossiliferous, lower contact gradational, upper contact gradational or erosive where channelling, grey-green.	B1	2			B1
SILTSTONE, massive, dense, mottled, very calcareous, argillaceous, grey-green, highly fossiliferous, random orientation of fossils, disseminated pyrite, lower contact may be either gradational over several centimeters or erosive.	A	1		1	A
LOWER MEMBER					

Christopher (1961; 1962) placed the systemic boundary at the base of the middle Bakken sandstone member in Saskatchewan. This decision was based on the lack of Kinderhookian age fossils in the lower Bakken shale member. Earliest recognizable Kinderhookian age fossils were described by Brindle (1960) in the middle sandstone member of the Bakken in Saskatchewan.

Detailed paleontological studies have been conducted on the Bakken Formation in North Dakota by Hayes (1984), Thrasher (1985), and Holland *et al.*, (1987). These studies suggest that the Bakken Formation is Devonian and Mississippian in age. Using conodont fauna from the shales, Hayes (1984) suggested that the systemic boundary occurred at or near the contact between the middle and upper members. The upper member has characteristically lower Mississippian conodonts that are not the earliest Kinderhookian. This suggests that there is a hiatus between the two that may coincide with a regionally extensive unconformity. Thrasher (1985) examined macrofossils of the middle member and concluded that the systemic boundary appears to be within the middle member.

DETAILED STRATIGRAPHY

The following is a detailed description of the lithofacies of the Bakken Formation based on data derived from the examination of core in North Dakota, Saskatchewan, and Manitoba. Composite lithofacies descriptions of the middle member, showing the correlations of the lithofacies identified, are shown in Table 1. The regional fence diagram (Fig. 4) shows the distribution of the various lithofacies over the study area.

NORTH DAKOTA

Bakken Formation: Lower Member

The lower member of the Bakken Formation overlies the greenish-grey, argillaceous burrowed siltstone of the Three Forks Formation. The lowermost contact was observed only in one core and was irregular and sharp. The contact was overlain by a bed containing small clasts of bitumen and fossil fragments.

The lower member consists of a dark brown-black to black, organic-rich shale. It can be massive and competent or fissile. Pyrite is generally disseminated throughout the shale; it also occurs in lenses, as nodules, or in laminations. In addition to pyrite grains, laminations formed by the alignment of silt-sized calcite grains are also present. Conodonts, ostracods, cephalopods, conchostracans, and brachiopods constitute the fossil assemblage of the shale.

A variety of fractures are associated with the lower member. Thin, hair-like, vertical fractures occur in the more massive zones. Conchoidal fractures are present when the lithology show an increase in silt content. Open bedding plane fractures with residual oil staining are also present. Closed vertical fractures are generally cemented with calcite or pyrite or both. A well

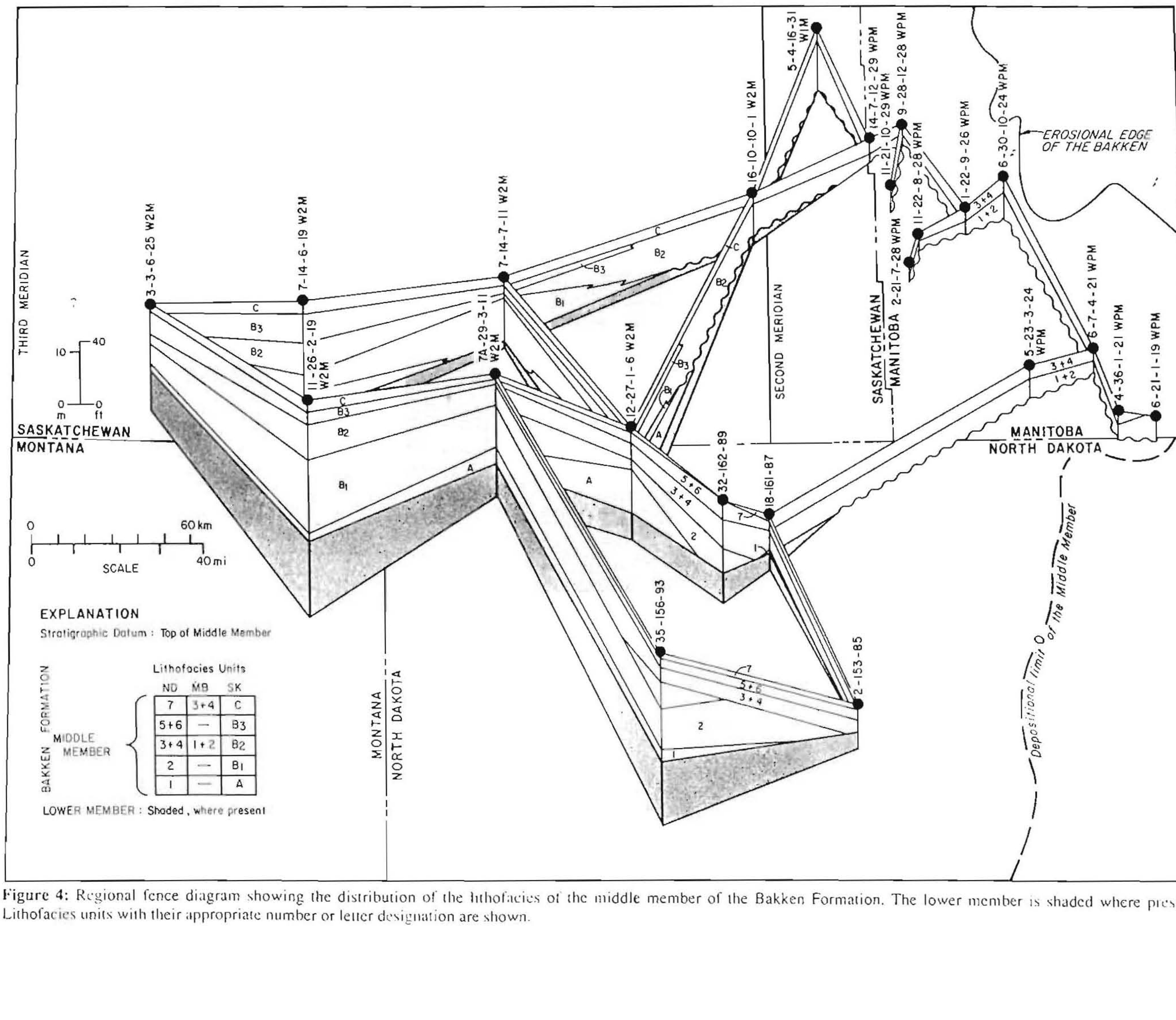

Figure 4: Regional fence diagram showing the distribution of the lithofacies of the middle member of the Bakken Formation. The lower member is shaded where present. Lithofacies units with their appropriate number or letter designation are shown.

developed breccia zone with calcite cement occurs in one well (SWNE Sec. 26, T.156N., R.91W.). Limestone interbeds are also present within this well. Many of the wells show small-scale deformed fractures, all of which are cemented with calcite or pyrite or both and are associated with laminations of silt-sized pyrite and calcite grains. Sizes range from 0.6 cm (.25 in) to several centimetres. Christopher (1961) suggested that these "vertical fissures" may have originated as mudcracks.

The contact between the lower member and the middle member is irregular and sharp or gradational. Beds containing small clasts and fossil fragments commonly overlie the sharp, irregular contacts. The gradational contacts show either a gradual decrease in argillaceous content to the siltstone/very fine- grained sandstone lithology of the middle member or a sequence of alternating shale and siltstone/sandstone beds that decrease in argillaceous content vertically. The gradational contacts are restricted to the northernmost wells in North Dakota.

Bakken Formation: Middle Member

Seven lithofacies were observed in the cores of the middle member in northern North Dakota. These facies are correlative with those recognized in cores in Manitoba and Saskatchewan (Table 1 and Fig. 4). Data are derived from Bakken core examined in 12 North Dakota wells. The seven lithofacies recognized in North Dakota, in ascending order, are as follows:

Lithofacies Unit 1 consists of a light grey, greenish-grey, or brownish-grey argillaceous siltstone. It is massive, cemented with calcite, and has scattered pyrite nodules, and fossils. Fossils generally include crinoids and brachiopods. One well shows abundant small brachiopods above the contact with the lower shale. Burrowing is locally present. The lithofacies range in thickness from 0.5 to 1.8 m (1.5 to 6 ft). Intergranular porosity and permeability for unit 1 in one well was determined to be 3.7 percent and 0.01 md, respectively.

Lithofacies Unit 2 is greenish-grey to brownish-grey, argillaceous siltstone or sandy siltstone to a brownish-grey, very fine-grained sandstone. The unit ranges up to 10 m (33 ft) in thickness. Small-scale clay drapes are present throughout, as well as burrows filled with pyrite. In one well (NENW Sec. 35, T.156N., R.93W.), where the unit is 8 m (27 ft) thick, burrowing is restricted to the upper 2 m (7 ft) and basal 1.5 m (5 ft). Scattered fossils, crinoids and brachiopods, are present throughout. Identifiable brachiopods include *Chonetes ornatus* and *Rhytiophora arcuatus*. Fossils are generally partially or completely replaced with pyrite.

Glauconite was noted in three wells over a restricted interval ranging from 0.6 to 1.2 m (2 to 4 ft). The glauconite is often associated with burrows. Hematite staining was also noted in the basal portion of one well. Cement, where present, consists of calcite and appears where the interval is coarser grained. Porosities range from 1.2 to 8.4 percent, averaging 5.5 percent. Permeabilities range from <0.01 to 0.41 md, averaging 0.22 md. Unit 2 was oil productive in one well with treatment.

One well, toward the central portion of the basin (NENW Sec. 35, T.156N., R.93W.), has an additional 5 m (16 ft) section between units 2 and 3 which is not present in the other wells (Fig. 5). The basal bed consists of a laminated, slightly argillaceous, oil stained, sandy siltstone, which grades upward into a medium brownish-grey, massive siltstone; an interbedded sequence of very fine-grained sandstone and claystone; and, a medium greyish-brown, uniformly laminated, oil-stained sequence of siltstone and very fine-grained sandstone. Individual sandstone beds are moderately well sorted and some are lensoidal.

Lithofacies unit 3 is the sandstone bed which is productive in Canada (Table 1). In North Dakota, the bed is prominent both in core and on wireline logs (Fig. 6) and easily mapped (Fig. 7). It is a medium grey, dark grey or greyish-tan, very fine- to fine-grained sandstone. Occasionally, the grain size increases into the upper medium range. The sandstone is moderately well sorted to well sorted and can be poorly sorted locally. Grains are generally well-rounded to rounded. Some of the finer grained material is subrounded to subangular. The sandstone consists predominantly of quartz with occasional feldspar and heavy minerals. Glauconite was observed in one well. Coarser grained material consists locally of rounded to subrounded ooid and crinoid fragments. In the wells where these sediments occur quartz is rare. Pyrite grains or nodules are scattered throughout. The sandstone is cemented generally by calcite and occasionally by pyrite.

Unit 3 consists commonly of an alternating sequence of massive, cross-bedded, and thinly laminated beds. The cross-bedded and massive beds are generally coarser grained. The upper portion may have multiple fining-upward sequences, whereas the lower portion may display reverse grading. Other features observed include load or channel forms grading upward into fine-grained material, and calcite-filled fractures. Soft-sediment deformation was observed in the middle of the unit in a few cores.

Unit 3 ranges in thickness from 0.2 to 4.6 m (0.5 to 15 ft), averaging 2 m (8 ft). The contacts between Unit 3 and the overlying and underlying units are sharp.

Measured porosities range from 0.09 to 12.1 percent, and average 7 percent. Permeabilities range from 0.02 to 5.8 md, and average 0.6 md. Oil staining appears to be restricted to the very fine-grained, thinly laminated quartz sandstone beds.

Lithofacies Unit 4 comprises interbedded light to medium grey, argillaceous to sandy siltstones and brownish-grey, very fine-grained sandstones and local claystone. The sequence is commonly laminated. Laminations are generally irregular or wavy bedded, or highly disturbed due to soft sediment deformation. Cross-ripple laminations and reverse grading are also present. There are occasional lenses of coarser-grained material in which the intergranular pores are filled with pyrite. Some sections also show extensive pyrite-infilled burrowing. A 0.3 m (1 ft) thick disturbed zone, due to soft-sediment deformation, is commonly present at the base of the unit.

Unit 4 reaches a maximum of 2 m (6.5 ft) in thickness. The unit is generally not cemented. Cement, where present, consists of dolomite.

Measured permeabilities are low (<0.01 to 0.15 md). Overall porosities are higher than the lower lithofacies, and range from 3.1 to 15.8 percent, averaging 8 percent.

Lithofacies Unit 5 consists of an alternating sequence of medium grey, argillaceous siltstones, light to medium grey, very fine-grained sandstones, and dark grey shale. It is thinly laminated. Laminations are either parallel or slightly undulatory and range in thickness from 1 to 5 mm (.04 to 0.2 in), with grain size increasing slightly in the thicker laminations. The unit is locally cemented with dolomite. Several of the wells exhibit soft-sediment deformation as contorted bedding either at the top or bottom of the interval or as small folds and faults (post-lithification) within.

Thicknesses of unit 5 ranges from 0.6 to 1.1 m (2 to 3.5 ft). Permeabilities range from <0.01 to 0.56 md, averaging 0.2 md. Porosities range from 3.8 to 12.4 percent, and average 7 percent.

Lithofacies Unit 6 consists of an alternating sequence of medium to light grey siltstone, dark grey claystone to brown/black shale; and, tan to light brownish-grey, very fine-grained sandstone, siltstone, and sandstone beds that commonly display planar or cross-ripple laminations. The sequence occurs as beds or lenses and is usually disrupted due to burrowing. The basal portion of the unit (0.3 to 0.9 m; 1 to 3 ft) consists predominantly of a thinly laminated, very fine-grained sandstone and siltstone with abundant burrows. Argillaceous content varies locally and generally increases upward within the section. The unit is locally cemented with dolomite.

Unit 6 varies in thickness from 0.9 to 3.2 m (3 to 10.5 ft), and averages 2 m (8 ft). Porosities range from 1.1 to 13.8 percent, averaging 5.5 percent. Permeabilities range from <0.01 to 97 md.

Lithofacies Unit 7 is a medium to light grey, massive to wispy laminated siltstone. Locally, the unit becomes greenish-grey where the argillaceous content increases and is generally

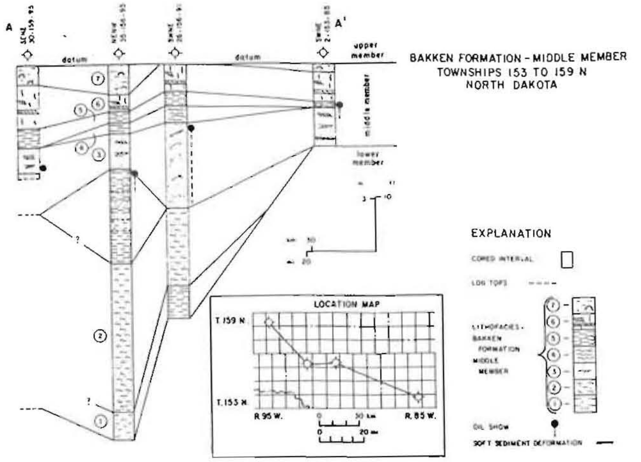

Figure 5: Fence diagram showing the correlation of lithofacies units of the middle member of the Bakken Formation from Townships 153 to 159 N, North Dakota. The lithofacies represented were described from cores. Oil shows are indicated over the interval where present.

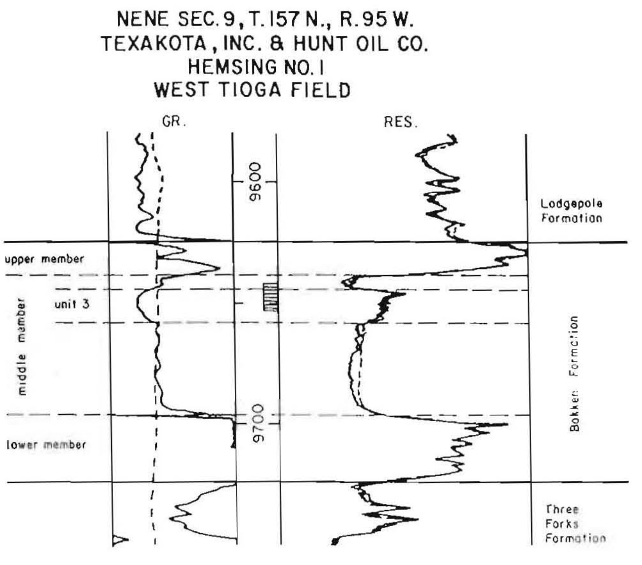

Figure 6: Typical log of the Bakken Formation in North Dakota. The three informal members of the formation are indicated. Unit 3 is the producing sandstone in the study area.

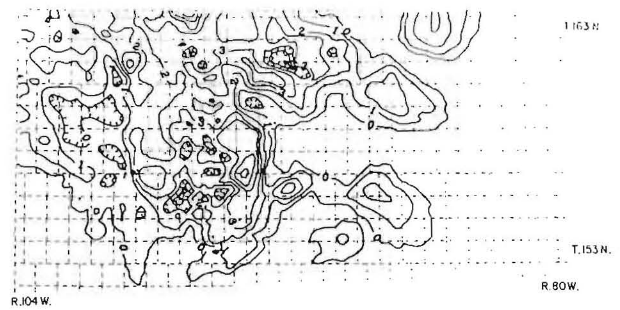

Figure 7: Isopach map showing the distribution of lithofacies unit 3, the producing sandstone, throughout northwestern North Dakota. Contour interval is 1 m (3 ft). Dashed lines are townships and are 10 km (6 mi) on a side.

cemented with calcite. Dolomite cement is present over a restricted interval in two cores. Brachiopods occur throughout and include *Chonetes gregarious*, *Chonetes ornatus*, and *Composita*. Cores from wells in the central portion of the basin also include bryozoan and crinoid fragments. Many of the fossils are partially or completely replaced with pyrite.

Thin beds of tan to light grey, very fine-grained sandstone occur toward the bottom of unit 7 and are commonly ripple cross-laminated. Beneath one of these cross-bed sets is an argillaceous layer, rich in brachiopods. This layer was observed in several wells.

Unit 7 ranges from 0.6 to 1.8 m (2 to 6 ft) in thickness. Permeabilities range from <0.01 to 109 md. Porosities range from 0.02 to 12.8 percent. Accumulations of pyrite occur near the upper contact with the upper member.

Bakken Formation: Upper Member

The upper member of the Bakken Formation consists of an organic-rich, slightly calcareous, massive to fissile, dark brown-black to black shale. The alignment of calcite and/or pyrite grains forms thin wispy laminations. Pyrite is disseminated throughout but also concentrated into lenses, nodules, and laminations. Small-scale fractures, observed in the lower member, are also present in the upper member. These fractures are filled with calcite and pyrite. Fossils observed within the shale include abundant conodonts and rare brachiopods.

The contact between the middle member and upper member appears to be sharp and irregular or gradational. In wells where the contact is sharp, a thin lag zone with pyrite and bitumen occurs along the surface. The gradational contacts exhibit a gradual upward increase in argillaceous content.

SOUTHWESTERN MANITOBA

Three Forks Formation

The Three Forks Formation is unconformably overlain by the Middle Member of the Bakken Formation throughout most of southwestern Manitoba. The Three Forks generally consists of light grey-green, blocky or massive, waxy, silty shale with disseminated pyrite. It may also occur at the Bakken contact as a buff, light grey-green or purple, silty, argillaceous dolostone; a purple, green and brown varicoloured or mottled, massive, dolomitic shale; or as a medium-grey, argillaceous, silty shale or interbedded siltstone and shale. It is difficult to distinguish Bakken from Three Forks lithologies in some areas.

Bakken Formation: Middle Member

Four lithofacies were identified within the Middle Member in southwestern Manitoba. These facies are correlative with those recognized in Saskatchewan and North Dakota (Table 1; Fig. 4). Data were derived from Bakken core examined in 32 southwestern Manitoba wells. The four lithofacies, in ascending order, are identified as follows:

Lithofacies Unit 1 is a buff to light grey or tan, very fine- to fine-grained sandstone. The unit may be massive to friable, slightly wavy bedded, or thinly laminated. Small-scale ripple cross-laminations are occasionally present near the top. Low-angle cross-bedding is also present in some cores. Wavy bedding occurs as 0.5 to 1 cm (0.2 to 0.4 in) thick lenses. Laminae generally consist of dark grey shale or green shale. Green shale laminae are often concentrated near the lower contact with the Three Forks Formation. The sandstone is wellsorted, subangular to subrounded, and consists predominantly of quartz. The facies exhibits some fair to good (10 to 15 percent), visible, intergranular porosity and is often oil stained (spotty, patchy, or an even light stain). It is considered to be a good reservoir facies.

In two wells in the Daly field (Townships 8 to 10; Ranges 27 to 29 WPM), unit 1 grades locally near its base to an interbedded sandstone and red, dolomitic, silty shale (Fig. 8). It grades entirely to a conglomerate in 4-29-10-29 WPM, and into an interbedded siltstone and shale north of Daly field in wells at 4-29-15-26 WPM, 8-8-16-27 WPM, 11-9-16-27 WPM and 14-35-16-27 WPM.

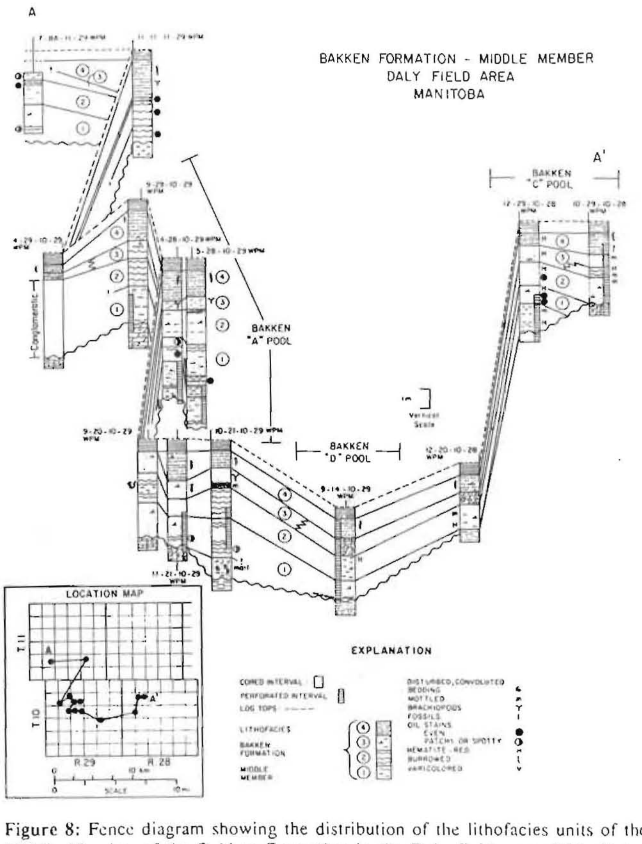

Figure 8: Fence diagram showing the distribution of the lithofacies units of the Middle Member of the Bakken Formation in the Daly field area of Manitoba. Lithofacies represented are described from cores. Sedimentary features, as well as oil staining are indicated.

Unit 1 is present where the Middle Member is thickest. It appears to have been deposited as massive beds in minor erosional or topographic lows on the underlying Devonian surface. Thickness ranges from 0.7 m to 4 m (2 to 13 ft) and averages 2 m (7 ft). The contact of unit 1 with the Three Forks Formation is erosional, as is evidenced by the erosional breccia or conglomerate at the base of unit 1 in several of the cores examined.

Lithofacies Unit 2 is an interbedded sequence of buff, light grey, tan or occasionally "salt and pepper", very fine- to fine-grained, silty sandstone and laminae of medium grey or green, silty shale. It is very thinly, parallel-laminated or thinly, wavy bedded or slightly undulatory. The laminations are 0.5 to 1 cm (0.2 to 0.4 in) in thickness. The sandstone is quartzose, slightly argillaceous, well sorted, angular to subrounded, and generally cemented with dolomite.

Patchy oil staining was noted in many cores. The facies exhibits fair to poor (5 to 10 percent), intergranular porosity. Burrowing is minor. The unit is mottled in places. Convoluted bedding (soft sediment deformation) is also locally present. One well, at 6-7-4-21 WPM, grades to an interbedded grey-green, mottled, dolomitic shale, and mottled, dolomitic, argillaceous siltstone.

Erosional contacts were noted within the unit in core at: 4-29-15-26 WPM and 14-35-16-27 WPM (Fig. 9). The 4-29-15-26 WPM well has a 10 cm (4 in) thick erosional contact near the middle of the unit that consists of brick red, very fine-grained sandstone intraclasts. This contact can be traced to the 14-35-16-27 WPM well, where it is present near the base of the unit. The contact is underlain by a 20 cm (8 in) thick, conglomeratic and brecciated zone characterized by desiccation cracks and sandstone intraclasts that range in size from 3 to 8 cm (1.2 to 3 in). Small-scale ripple cross-laminations were noted at the top of the unit in the well at 5-28-10-29 WPM. Unit 2 is entirely conglomeratic in 4-29-10-29 WPM and comprises green-grey shale intraclasts and silty, dolostone stringers.

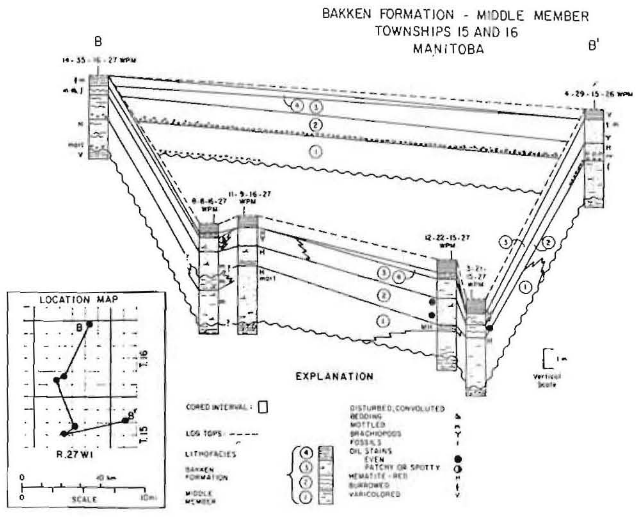

Figure 9: Fence diagram showing the distribution of the lithofacies units of the Middle Member of the Bakken Formation in Townships 15 and 16, Manitoba. Lithofacies represented are described from cores. Sedimentary features, as well, as oil staining are indicated.

Unit 2 is present in all cores examined and ranges in thickness from 0.6 to 1.8 m (2 to 6 ft) averaging 1.2 m (4 ft).

Lithofacies Unit 3 is a buff to light grey, or grey-green, very fine-grained to silty, argillaceous sandstone or siltstone, interbedded with medium grey, silty shale. The sandstone and siltstone occur as discontinuous lenses or faint wavy bedding. Grains are predominantly quartz and generally cemented by dolomite. The shale forms thin laminations or partings.

The unit may contain brachiopods throughout and is commonly burrowed. Pyrite is present in minor amounts. Mottled in places, the unit changes laterally to a silty, argillaceous dolostone or limestone in Township 8, Range 28 WPM and in the Daly field area. Unit 3 is present in all cores examined except 6-21-1-19 WPM and thickness ranges from 0.3 to 2.7 m (1 to 9 ft) and averages 0.8 m (3 ft).

Lithofacies Unit 4 is a massive, light to medium grey, dolomitic, shaly siltstone to silty shale. It is generally burrowed and present in all but seven of the cores examined. Brachiopods occur in distinctive zones or scattered throughout the unit in several cores. Fossil fragments are also a minor component. Thickness ranges from 0.3 to 2 m (1 to 7 ft) and averages 1 m (3 ft). The contact with the overlying shale of the Upper Member is generally sharp.

Bakken Formation: Upper Member

The contact between the Middle and Upper Member is generally sharp. The Upper Member is a black, massive, non-calcareous shale, occasionally fissile or finely banded in places. It may also have a basal, medium grey clay layer that reaches a maximum thickness of 15 cm (6 in). The Upper Member changes in colour from a black shale to a purple, brown, or brownish-red shale in the northern portion of the study area and the eastern half of Daly field. In these areas, the Middle Member is also oxidized, reflecting a period of post-Mississippian/pre-Jurassic subaerial exposure (McCabe, 1959).

SOUTHEASTERN SASKATCHEWAN

Five lithofacies were identified in southeastern Saskatchewan based on the examination and correlation of 35 cores. The subdivisions are based on Christopher (1961), who divided the middle Bakken sandstone member into two units, A and B. Unit B was further subdivided into B1, B2, B3, and B4. For the purpose of this study, Christopher's unit B4 has been renamed as unit C (Table 1). The fence diagram in figure 4 and the structural cross-sections of the Bakken pools (Figs. 10, 11, and 12) correlate these facies on a regional and local basis.

All three members of the Bakken Formation are present in the Saskatchewan portion of the study area; however only the middle Bakken sandstone member was examined in core. The lithofacies of this member are described, in ascending order, as follows:

Bakken Formation: Middle Sandstone Member

Lithofacies Unit A consists generally of a massive, dense, mottled, grey-green siltstone. It is locally argillaceous, highly fossiliferous, very calcareous, with pyrite disseminated throughout. The random orientation of the fossils suggests rapid burial. The basal contact with the lower Bakken shale member is either characterized by scours filled with fossil debris and pebble lags (shale clasts) or by contacts that appear to be gradational. The gradational contacts may be related to the reworking and incorporation of unconsolidated lower Bakken muds into the silts of the middle Bakken sandstone member (Christopher, 1961). Load and flame structures with associated cross-bedding and faint horizontal laminae have been identified in several cores. The upper contact with lithofacies B1 is gradational except in the eastern shelf area. In this area, erosion has progressively truncated unit A and the lower Bakken shale member (Fig. 4). The unit ranges in thickness from 0 to 8.3 m (0 to 27 ft).

Lithofacies Unit B1 consists of parallel interbeds of dark grey shale and buff, or occasionally grey-green, silty sandstone. The disruption of bedding due to very strong bioturbation results in wispy shale "drapes." This disturbed bedding distinguishes this unit from the underlying massive siltstone. The upper and lower contacts are gradational in the western portion of the study area. The upper contact is unconformable where B2 has channelled into B1. The unit is fossiliferous and dolomitic, becoming calcareous with depth. Disseminated pyrite is present. Unit B1 ranges from 1.6 to 14.5 m (5 to 48 ft) in thickness.

Lithofacies Unit B2 is a buff to cream, or greenish-tinted, calcareous sandstone which consists predominantly of quartz with minor feldspar and heavy minerals including disseminated pyrite. It may contain brachiopods and is slightly bioturbated. Numerous diastems are present.

Unit B2 displays a tripartite subdivision. The lower portion is a wavy and flaser bedded, silty sandstone and is transitional with the underlying unit B1. Shale clasts, up to 4 cm (2 in) in diameter, and felsic pebbles are found in channel lags where unit B2 overlies the lower Bakken shale member in the eastern portion of the study area. The middle portion is a coarse-grained, sometimes friable sandstone, and is transitional from the lower portion except where channelling occurs. This sandstone may be massive and/or bedded. Types of bedding include: trough and tabular cross-bedding; horizontal and inclined bedding (up to 25 degrees); and swash cross-stratification. The upper portion is a wavy- and flaser-bedded silty sandstone and is transitional with the middle portion. The upper contact with lithofacies unit B3 is gradational. The B2 unit varies in thickness from 0.4 to 15.6 m (1 to 51 ft).

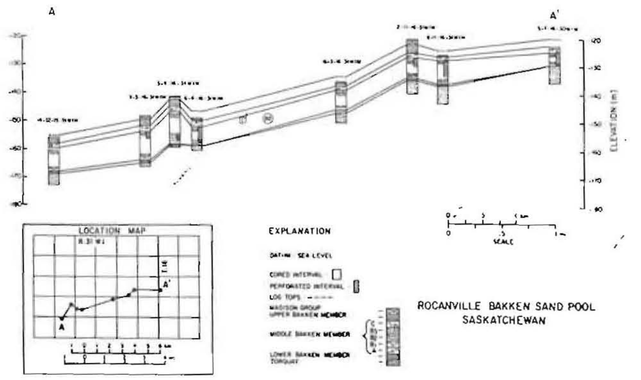

Figure 10: Structural cross-section showing the distribution of lithofacies units across Rocanville field, Saskatchewan. Lithologies represented were described from core.

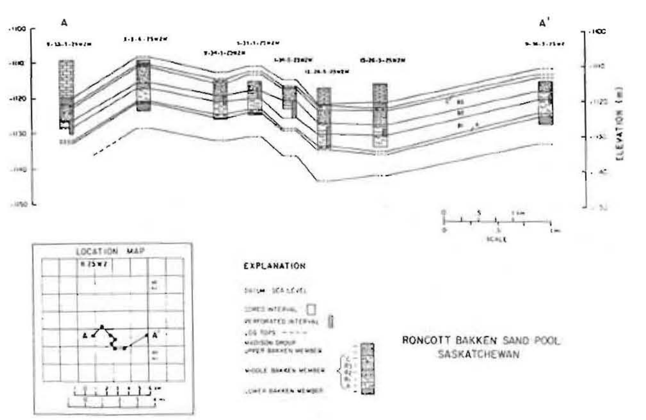

Figure 11: Structural cross-section showing the distribution of lithofacies units across Roncott field, Saskatchewan. Lithologies represented were described from core.

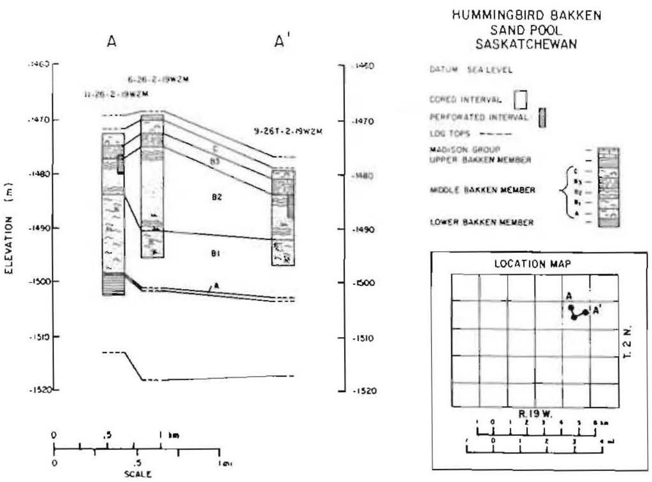

Figure 12: Structural cross-section showing the distribution of lithofacies units across Hummingbird field, Saskatchewan. Lithologies represented were described from core.

Lithofacies Unit B3 consists of parallel interbeds of dark grey shale and buff, slightly bioturbated, silty sandstone. The unit is calcareous. It contains disseminated pyrite and vertical burrows. Load and flame structures occur at the base of the sandy laminae. In the Roncott area (Townships 5 and 6; Range 25 W2M) unit B3 is punctuated by storm-generated density current deposits up to 10 cm thick with what are recognized as the BC(D)E structural divisions of the Bouma sequence. Thickness of B3 ranges from 1 to 4.5 m (3 to 15 ft).

Lithofacies Unit C is a grey-green, massive, dense, mottled, dolomitic, argillaceous siltstone. It is fossiliferous, slightly bioturbated and contains disseminated pyrite. The basal contact is selected either on a massive, mottled siltstone, or where silty rhythmites are encountered. The silty rhythmites range up to 15 cm (6 in) in thickness and are distinguished from B3 rhythmites by their finer grain size and the presence of scattered fossils. One core contained a 6 cm (2 in) thick band of fossil-debris. The upper contact with the upper Bakken shale member is generally sharp and conformable.

DEPOSITIONAL HISTORY OF THE BAKKEN FORMATION - MIDDLE MEMBER

Sandberg *et al.* (1983) developed a depositional model for the rocks of Middle Devonian through Late Mississippian age in the Western Interior. This model is based on eustatic sea level changes. Based on their model, initial sedimentation of the lower Bakken shales resulted from a rapid transgression in conjunction with tectonic activity of the Antler and Acadian orogenic belts. Evidence for this rapid transgression is the sharp disconformity of the Three Forks-Bakken contact along the basin margin. This indicates that the Three Forks was exposed to erosion before shale deposition. Further evidence from cores includes sharp contacts with rip-ups and other erosional features.

The initial phase of black shale deposition appears to have occurred in a shallow sea, based on the presence of benthic fauna in the basal portion of the lower shale member. Paleontological and geochemical data indicate a progressively deepening sea due to on-going transgression. Depth of the water column is still in debate. A stratified water column with anaerobic bottom conditions developed with this deepening event.

The middle member of the Bakken Formation is generally considered to be a transgressive deposit, based on its onlapping relationship with the underlying units (Webster, 1982; 1984; Hester and Schmoker, 1985). However, recent data indicates that the middle member is not entirely transgressive. Thrasher (1985) studied the macrofossils and biostratigraphy of the Bakken. In his study, the middle member was divided into three biostratigraphic units (Table 1). He suggested that unit 1, equivalent to Christopher's unit A, is a regressive deposit. It is the only portion of the middle member that is restricted to the central basin. It does not onlap onto the lower shale and therefore probably represents the low stand of the Bakken seas.

Deposition of the sediments of unit 1 occurred in a moderately well oxygenated, shallow water environment. Thrasher (1985, p. 106) suggested that the random orientation of disarticulated brachiopods probably resulted from "post-mortem current transport followed by rapid burial, and they may represent storm deposits." The environment was probably dysaerobic at times as evidenced by the greenish-grey colouring of the rocks and the presence of pyrite and sulfides in the matrix and on the fossils. Sandberg *et al.* (1983) reported that a long period of continental stability occurred into the Early Mississippian, when seas were at a low stand and the continent was generally flat.

Christopher (1961) interpreted the deposition of the massive siltstone, unit A, to result from a sudden marine transgression. Load structures, pebble and fossil-rich lags at the contact with the underlying shale, combined with randomly oriented fossils, suggest rapid burial as the shoreline advanced eastward, incorporating sediments and dispersing them deeper into the basin. The erosion of unit A in areas more proximal to the basin margin (Fig. 4), makes it difficult to determine the mechanism of deposition in the deeper basin, where unit A is preserved.

In Saskatchewan, subsequent shallowing of the water allowed the development of tidal flats and associated tidal channels, which, when factors such as structure, sedimentology and migration are favorable, form the reservoir. A regressive-transgressive pulse resulted in the deposition of units B1, B2, and B3. Figure 4 shows B2 as a wedge-shaped unit which interfingers with units B1 and B3, until it is no longer recognizable in the deeper parts of the basin. The regression allowed the shoreline to prograde into the basin, depositing the coarse clastic unit B2, in the nearshore environment. The finer-grained sediments of B1 represent the distal equivalent of B2. Subsequent transgression caused the shoreline to move towards the margin of the basin. Unit B3 represents the distal equivalent of B2 during this transgressive phase.

The interbedded laminae of B1 (see Table 1 for North Dakota and Manitoba equivalents) are generally highly bioturbated, suggesting slow sedimentation in a shallow siliciclastic sea (Johnson, 1978). These laminae are transitional to the sands of unit B2 (Table 1), which are typically flaser- to wavy-bedded, reflecting constantly fluctuating, but relatively low-energy conditions in an intertidal flat environment (Elliot, 1978). Elutriation may account for the massive sands of B2. Tidal channels intersecting the tidal flats are more prevalent in the Rocanville area of Saskatchewan, as is swash cross-stratification, which indicates a beach deposit (Harms *et al.*, 1982). In this area, the B2 sands rest unconformably on the lower Bakken shale member or the Torquay Formation.

The B2 sands in the Rocanville (Townships 15 and 16; Range 31 W1M) area of Saskatchewan, which are proximal to the margin of the basin, are very coarse and friable, with relatively good porosity and permeability. In contrast, the porosity and permeability of these sands in the Roncott (Townships 5 and 6; Range 25 W2M and Hummingbird (Township 2; Range 19 W2M) areas, which are much farther from the basin margin, are much less.

Unit B3 (Table 1) is similar in lithology to B1. The units merge in the western and southern portion of the basin (Fig. 4). The B3 unit is slightly to moderately bioturbated with vertical burrows, suggesting a slow rate of sedimentation, in contrast to the slightly faster rate of sedimentation represented by the lower portion of B1, which is intensely bioturbated. The density current deposits interbedded with the deeper water shales of the B3 unit in the Roncott area are probably storm-generated. Walker (1979, p. 94) stated: "The presence of rare "turbidites" would indicate the possibility of density current activity, and would not condemn the entire sequences to deposition in great depths of water."

Unit C (Table 1) is quite thin but widespread throughout the basin (Fig. 4). Currents active during the deposition of this unit were stronger than those occurring during the previous unit. Disarticulated brachiopods present are sorted by size and concentrated into thin, well-sorted beds of grey siltstones and very fine-grained sandstones.

A major eustatic rise in sea level related to further large-scale movement associated with the Antler and Acadian orogenic belt and onlap of the black shale sea followed deposition of the middle member (Sandberg *et al.*, 1983). This sea level rise represents the high stand of the Bakken seas.

The depositional history of the basin is further complicated by the dissolution of salt in the Devonian evaporites. This collapse and associated features can be documented in North Dakota, Manitoba, Saskatchewan, and Montana (McCabe,1959; Christopher, 1961; Anderson and Hunt, 1964; Webster, 1982; 1984; Martiniuk, 1988).

STRUCTURE

A structure map constructed on the Bakken Formation for the study area is shown on figure 13. In North Dakota the Nesson anticline is the most prominent structural feature. This anticline trends north for 176 km (110 mi) from the Killdeer Mountains, Dunn County, to just south of the Canadian border (Fig. 14). Associated with the Nesson anticline is the western Nesson fault, a feature that extends for the length of the fold, and the northwest-trending Antelope anticline. The northeast side of the Antelope structure is also faulted along its length. Episodic movement along the western Nesson fault and the development of the Nesson anticline has been related to basement tectonics (Gerhard *et al.*, 1982; 1987; LeFever *et al.*, 1987).

In the north-central portion of North Dakota, another basement feature that influenced the deposition of the overlying units is the fault that separates the Superior craton from the Trans-Hudson orogenic belt (previously referred to as the Churchill craton or Precambrian province) (Green *et al.*, 1985). Movement of fluids along this fault zone is apparently responsible for the dissolution of salt from the overlying Prairie Formation (Devonian). Evidence for this dissolution can be observed on structure and isopach maps of the formations overlying the Prairie.

Minor southwest-plunging folds are present in Burke County (Townships 161 to 164 N; Ranges 89 to 93 W) (Fig. 15). These folds probably result from basin subsidence, and have had an effect on the depositional patterns of the individual lithofacies, and as well porosity and permeability within the lithofacies.

In Manitoba, structure on the Upper Member is fairly regular and follows the regional Paleozoic tilt, dipping southwest at an average of 6 m/km (32 ft/mile) (Fig. 13). Several features depart from the regional pattern. The Virden (Townships 9 to 11; Ranges 25 to 27 WPM) and Daly (Townships 8 to 10; Ranges 27 to 29 WPM) fields are separated by a prominent north-south trending syncline which lies along the Birdtail-Waskada axis. The latter is a north-trending zone, approximately 32 km (20 mi) east of the Saskatchewan border, along which numerous local structure and isopach anomalies in the Devonian and later strata are concentrated. These anomalies may be a direct or indirect result of salt dissolution resulting from minor tectonic movement along the boundary zone between the Churchill and Superior provinces (Trans-Hudson orogenic belt) (McCabe, 1966; Green *et al.*, 1985). The axis coincides with the crustal boundary and the present solution edge of the Prairie Formation salt section (McCabe, 1966). The anomalies have been important in controlling the accumulation of oil in the Daly, Virden, and Waskada (Townships 1 and 2; Ranges 25 to 27 WPM) producing areas of southwestern Manitoba (McCabe, 1963).

Within the Daly field itself, several minor structural highs are coincident with areas of Bakken production. Within the Waskada field area a minor south-southwest plunging structural nose is coincident with anomalous Bakken and Three Forks thickening.

The Saskatchewan portion of the study area is divided by the Elbow-Hummingbird monoclinal flexure into two structural provinces (Christopher, 1961). These provinces are defined by the presence or absence of Middle Devonian evaporite beds (Fig. 14). The evaporites terminate along a northwesterly trend which approximately coincides with the Elbow-Hummingbird flexure. The eastern side forms an easterly striking monocline with associated subsidiary anticlinal and synclinal structures (including the syncline that underlies the Rocanville field). Devonian evaporites underlie the eastern portion. The western side has an irregular surface with easterly and northeasterly trends. The evaporites are absent from the western side. The Elbow-Hummingbird monoclinal flexure forms the eastern limb of the Hummingbird synclinorium in the southernmost portion of the study area.

Adjacent to the Hummingbird synclinorium is the Roncott anticlinorium. This is a broad, 48 km (30 mi) wide fold plunging in a south-southeasterly direction. The structure exists due to the presence of an outlier of Devonian evaporites. Overlying sediments are draped over the outlier, forming the feature.

Other notable features include the Rocanville-Torquay trend, the Regina- Melville platform, and the Herald and Torquay embayments (Christopher, 1961). The Rocanville-Torquay trend consists of a northeast-trending series of depressions outlined by producing wells (Fig. 14). The Regina-Melville platform represents "a broad undifferentiated sedimentary area between more basinal localities to the north and south" (Christopher, 1961.

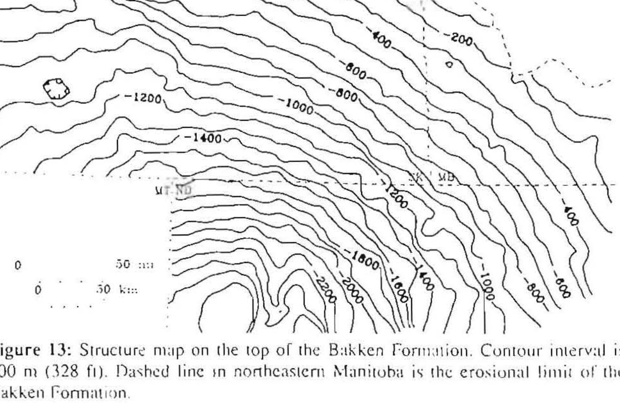

Figure 13: Structure map on the top of the Bakken Formation. Contour interval is 100 m (328 ft). Dashed line in northeastern Manitoba is the erosional limit of the Bakken Formation.

p. 59). The Herald and Torquay embayments represent the expression of the Williston Basin in southern Saskatchewan.

ISOPACHS

Distribution of the middle member of the Bakken Formation throughout the study area is shown in figure 16. In North Dakota the Bakken isopachs show depositional patterns related to the Elk Point Basin sedimentation. The depocenter of the middle member is elongated north-south and is located just to the east of the Nesson anticline. This is similar to isopach maps of the lower member. However, these trends are not apparent in the upper member, which has a poorly defined depocenter. The middle member, from its maximum thickness of 27 m (87 ft), thins gradually away from the depocenter towards its depositional limit.

Abrupt thickening and thinning of the middle member in the north-central portion of North Dakota are probably related to the dissolution of the underlying Devonian Prairie salt and subsequent collapse. Isopach maps of all three members, as well as underlying and overlying formations, display abrupt thickness changes. This is further supported by isolated occurrences of the lower member throughout north-central North Dakota.

Examination of an isopach map constructed for the middle member sandstone, unit 3, shows thinning over pre-existing structural features, such as the Nesson anticline and a series of folds in Burke County (Fig. 7). This is supported by the examination of available cores. The isopach of unit 3 also shows that its distribution is not as extensive as the distribution of the entire middle member which continues south of the study area.

In Manitoba, the isopach trends of the Bakken Formation are generally northwest-southeast, reflecting deposition related to the Elk Point Basin (Fig. 2). The most significant changes in thickness of the Bakken occur within the middle member, which

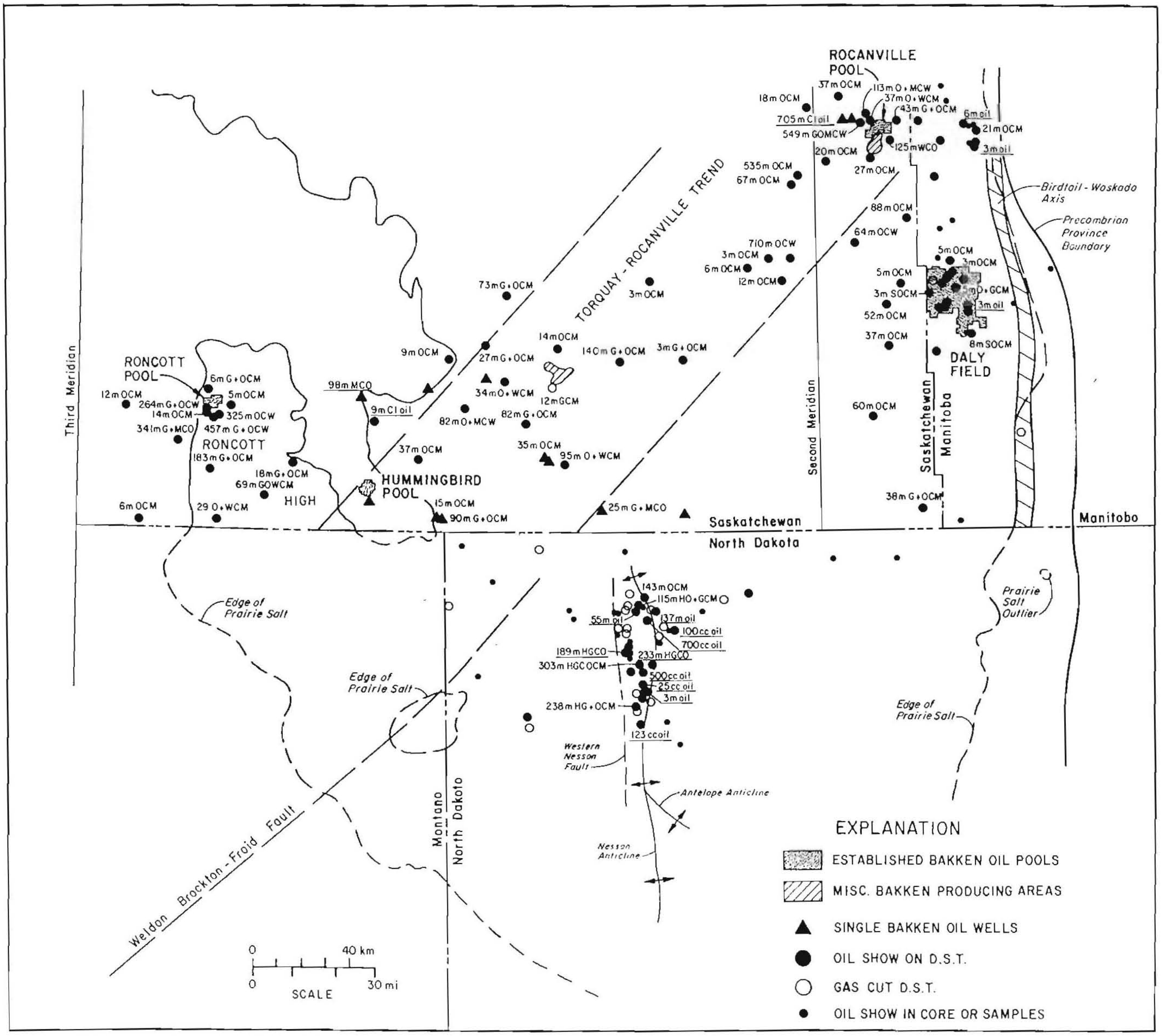

Figure 14: Diagram showing the relationship of structural features to oil shows and oil production within the study area. Major oilfields producing from the middle member of the Bakken Formation, oil shows from drill stem tests, cores or samples, and gas shows are indicated. Limit of the Prairie Formation salt is from Holter (1969), Anderson and Swinehart (1979), and McCabe (1980).

represents a major portion of total Bakken thickness (Fig. 16). The middle member averages 4 m (13 ft) in thickness; the upper member 2 m (7 ft). Sedimentation of the Bakken is controlled, in part, by the paleotopography of the underlying Devonian erosion surface. Minor thickening of the middle member may represent the infill of clastics into these erosional or paleotopographic lows.

Local variations in thickness in both the Bakken and Three Forks formations are evident throughout the study area in Manitoba. The greatest thickness variations occur in the Waskada field area where as much as 26 m (85 ft) has been added to the total Bakken and over 79 m (259 ft) added to the Three Forks. These anomalies are believed to be the result of the multiple-stage dissolution of the Devonian Prairie Formation salt section during the deposition of the Bakken and Three Forks formations. The local occurrence of the lower member in the Waskada area may also be accounted for by Prairie salt dissolution during early Bakken sedimentation (Martiniuk, 1988).

In Saskatchewan the isopach lines trend northwesterly (Figs. 2 and 16). In the eastern portion of the study area thicknesses gradually thin to the northeast. This changes abruptly west of the Elbow-Hummingbird monoclinal flexure. There are a series of thicks and thins that are possibly related to the dissolution of the Devonian Prairie Evaporite.

The Torquay-Rocanville trend is readily apparent on the isopach of the Bakken Formation (Fig. 2). This feature trends to the northeast from the Montana and North Dakota state lines. It is also present but not as well developed on the isopach of the middle member (Fig. 16).

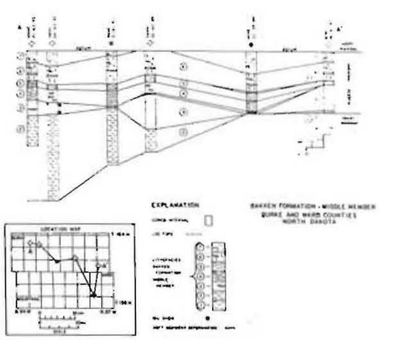

Figure 15: Fence diagram showing the distribution of lithofacies units across Burke and Ward counties, North Dakota. Lithologies represented are described from core.

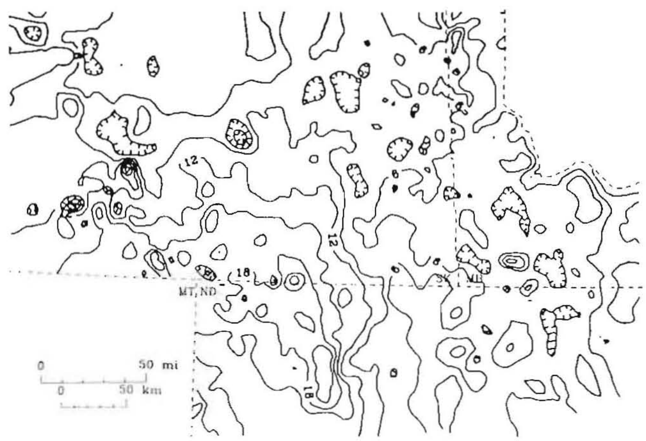

Figure 16: Isopach map of the middle member of the Bakken Formation for the study area. Contour interval is 3 m (10 ft). Dashed line in northeastern Manitoba is the erosional limit of the Bakken Formation.

PRODUCTION AND RESERVOIR CHARACTERISTICS

NORTH DAKOTA

The middle member of the Bakken Formation produces or has produced in nine fields situated along the northern portion of the Nesson anticline (Fig. 17). Fourteen wells scattered throughout these fields have a cumulative production through December 1990 of 85,334 m^3 (536,753 bbls).

Until recently, the Bakken Formation in North Dakota was generally considered not to be an economic venture as a primary target. Wells with associated Bakken production generally have multiple completions. Recompletions in the Bakken are common as wells reach their economic limit. Only one well (NESE Sec. 8, T.159N., R.95W.) in the study area completed in the middle member had the Bakken as its primary objective.

Three cycles of Bakken development can be seen in an examination of productive wells. The initial completion in the middle member occurred in 1963. Considered to be uneconomic, the well, a Duperow test, produced 118 m^3 (744 bbls) from the middle member before recompletion in the Madison. No further attempts occurred until the late 1970's when the price of oil increased significantly. This increased the profitability on marginal wells and encouraged exploration in the Bakken. The decline in oil prices resulted in another break in Bakken drilling. Attention has been redirected toward the Bakken once again, since the advent of the Bakken shale horizontal play.

Stoneview Field

Stoneview field (Townships 160 and 161 N; Ranges 94 and 95 W) is located along the northern tip of the Nesson anticline (Fig. 17). It is the most prolific of the Bakken pools, producing from the middle member in North Dakota with a cumulative production of 33,955 m^3 (213,580 bbls) of oil.

Three wells currently produce along the northern and western boundaries of the field. Perforated intervals include the upper shale to the base of the sandstone unit (unit 3). The best producer (SESW Sec. 30, T.161N., R.94W.) in the pool was perforated only in the sandstone unit and has attained a cumulative production of 11,454 m^3 (72,049 bbls).

All three wells were acidized during completion. Acid amounts range from 1,000 to 3,000 gallons of 15 percent HCl. One well (NENW Sec. 31, T.161N., R.94W.) also underwent a sand/oil fracture treatment (80,625 lbs of propant in 33,348 gallons of fluid). The best producer in the pool underwent the least amount of stimulation (1,000 gallons of acid). This may be explained by the restriction of the perforation to the sandstone unit. The other two wells also included perforations in the upper shale. Acidization of the upper shale results in the release of fines which may partially plug effective porosity.

Reservoir characteristics for Stoneview field are summarized in Table 2.

West Tioga

Production in West Tioga is from three wells situated in the central portion of the field (Townships 157 and 158 N; Range 95 W). The cumulative production from 1976 through December 1990 was 16,403 m^3 (103,175 bbls).

Reservoir characteristics for this field are limited. The perforated interval is restricted to the middle member sandstone, unit 3, with an average net pay of 3 m (10 ft). Gravity of the oil was reported as 42.0° API.

Only one well (NENE Sec. 9, T.157N., R.95W.) has a lengthy production history. Completed in February 1976, the well has a cumulative production of 11,669 m^3 (73,400 bbls). This well was stimulated with two acid treatments (4,000 gallons of 15 percent HCl) and a gelled water/sand fracture treatment. The next well was completed in 1987 and was acidized with 500 gallons of acid.

Other Fields

Production in the remaining fields is restricted to one or two wells. These wells are responsible for the remaining 34,976 m^3 (219,998 bbls) of oil produced from the middle member of the Bakken Formation.

The Bakken pool in North Tioga (Townships 159 and 160 N; Ranges 94 and 95 W) consists of two wells with a cumulative production of 6,929 m^3 (43,585 bbls). The earliest well, completed in 1987, perforated the entire Bakken interval. Perforations in the second well, completed in 1988, are restricted to unit 3. Both wells were stimulated with a sand-oil fracture treatment.

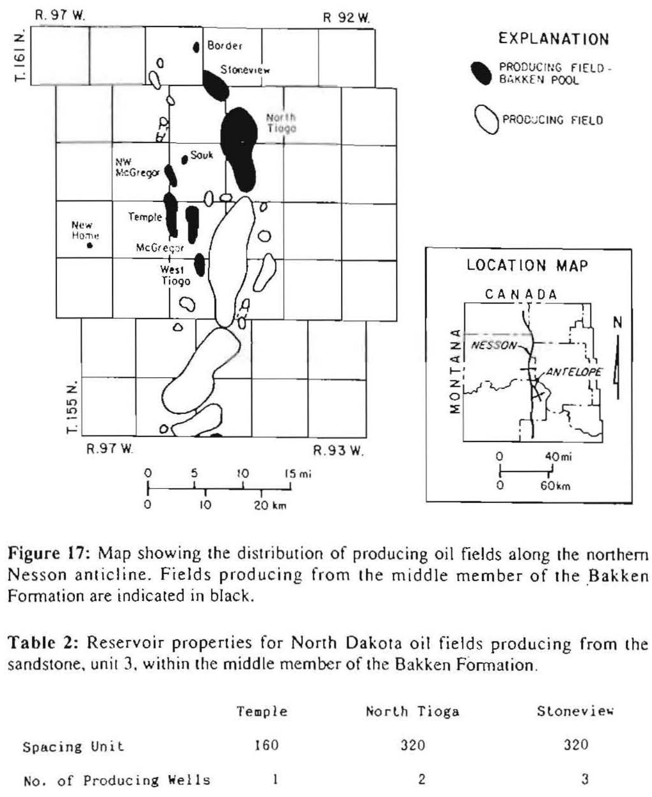

Figure 17: Map showing the distribution of producing oil fields along the northern Nesson anticline. Fields producing from the middle member of the Bakken Formation are indicated in black.

Table 2: Reservoir properties for North Dakota oil fields producing from the sandstone, unit 3, within the middle member of the Bakken Formation.

	Temple	North Tioga	Stoneview
Spacing Unit	160	320	320
No. of Producing Wells	1	2	3
Average Net Pay (ft)	12	12.5	6
Average Porosity (%)	7	2.3	12
Average Water Saturation (%)(S_w)	80	15	21
Oil Gravity, API @ 60°	40	39.7	44.0
Reservoir Drive Mechanism	Solution Gas	Solution Gas/ Fluid Drive	Solution Gas
Volumetrics, OOIP, bbls	139,000	472,798	1,765,000*
Recoverable Oil	14,000	47,279	264,765*
Recovery Factor (%)	10	10	15
Cumulative Production Oil (12/1990)	4,662	43,585	213,580
Water (12/1990)	1,704	5,770	12,198

*Volumetrics are calculated for a spacing unit of 160 acres, instead of the assigned 320 acre spacing.

Temple field Bakken pool (Township 158 N; Ranges 95 and 96 W) consists of two wells which were drilled in 1989. The initial recompletion was unsuccessful with low oil-high water production and was plugged and abandoned eight months later. This well was perforated in the lower Lodgepole Formation, not the Bakken. The second well was perforated in the upper shale to the base of the sandstone, unit 3. Reservoir data for this well are presented in Table 2.

The Bakken pools in the remaining fields consist of one well each. Perforated intervals cover the upper shale to the base of the sandstone or at least the middle member. All of the wells were stimulated with an acid and/or fracture treatment. Limited production was yielded by most of the pools with the exception of the wells in Sauk (Townships 159 N; Range 95 W) and McGregor (Townships 158 and 159 N; Range 95 W) fields.

SOUTHWESTERN MANITOBA

Daly Field

Production was first established in southwestern Manitoba in the Daly field in 1985, following the Newscope Resources Limited discovery at 13-21-10-29 WPM. The well was completed in the Middle Member with 2 m (7 ft) of net pay. Prior to the Bakken discovery, the Daly field was productive only in the Lodgepole Formation. Bakken and Lodgepole production is presently commingled in several wells.

Bakken oil in southwestern Manitoba is 824 g/m^3 (40.2° A.P.I.) and has a sulphur content of 1.30 g/kg. The shallow depth to production and high quality of oil make the prospect for Bakken in Manitoba attractive. Average depth to the producing zones of the Middle Member is 874 m (2,867 ft).

Seven Bakken pools have been established in the Daly field since the initial discovery: A, B, C, D, E, G and H (Fig. 18). In total, 35 wells were active Bakken producers as of January, 1991. As of December 31, 1990, the Bakken had produced 83,700 m^3 (526,473 bbls) of oil. Figures 19 and 20 summarize cumulative and average daily Bakken production for the Daly field.

Proven remaining established reserves for the Bakken in the Daly field as of December 31, 1990, were 43,200 m^3 (271,728 bbls)(1990 Manitoba Energy and Mines reserves estimates). Reservoir properties described for the three multi-well Bakken pools in the Daly field (A, B and D) are given in Table 3.

Bakken oil reservoirs within the Daly field appear to be controlled primarily by stratigraphic factors. They are localized within paleotopographic lows of the underlying Devonian erosional surface, where the sandstones are thickest.

Unit 1 is the primary reservoir facies of the middle member and the one in which there are the majority of completions. Based on core analyses, porosities range from approximately 15 - 20 percent within the unit. Oil shows have also been noted in unit 2, although, permeabilities are generally lower within this facies due to more silt and finely argillaceous laminae.

The distribution of unit 1 is related to the paleotopography of the underlying Three Forks Formation. It is present and a potential reservoir in the Daly Field where it has infilled minor erosional lows on the underlying Devonian erosional surface.

Stratigraphic trapping within the middle member in Daly field is created by the lateral pinchout and variation of unit 1 in combination with an upward fining to the very fine-grained, finely laminated sandstone of unit 2.

The fence diagram (Fig. 8) shows the productive facies within the middle member in the Daly Field. In the Bakken A Pool it is difficult to distinguish the lithology of unit 1 from that of the underlying Three Forks Formation. The lower contact is questionable in the wells at 10-21-10-29 WPM, 4-28-10-29 WPM and 5-28-10-29 WPM. However, unit 1 is interpreted in these wells to have changed laterally in its lower portion, into an interbedded, siltstone and blocky, green shale or marl. This has limited the eastern extent of the reservoir by creating vertical and lateral permeability barriers.

The western limit of the Bakken A pool is defined by the well at 4-29-10-29 WPM, where both units 1 and 2 are completely conglomeratic. The northwestern limit of the pool is undefined and offers potential for future development.

The Bakken D Pool, as represented by the well at 9-14-10-29 WPM, shows several lateral changes in units 1, 2 and 3 from the wells at the Bakken A Pool. Unit 1 has changed from a marly, interbedded, very fine-grained sandstone and shale to a very fine- to fine-grained, banded sandstone. Unit 2 has changed to a very fine-grained, mottled, hematite-red sandstone with green, shale laminations near the base, and unit 3 lithology from a very fine-grained, mottled sandstone to an argillaceous, silty dolostone.

The lithology of the Bakken B Pool is similar to the Bakken A Pool; however, all or most of the units in the middle member are hematite-red, which indicate that these units have undergone oxidation or exposure that appears to have occurred less extensively elsewhere in the Daly field area.

Structural factors are of secondary importance in the accumulation of Bakken oil in the Daly field. Minor structural closure is evident on highs on the upper member at the Bakken B Pool. Minor structural highs or noses on the upper member are also noted at the Bakken A, C and D Pools (Fig. 13).

It should be noted that a potential reservoir also exists below the Devonian erosional surface within a vuggy dolostone. The unit was perforated along with unit 1 in the productive Newscope Opinac Daly 11-21-10-29 WPM well.

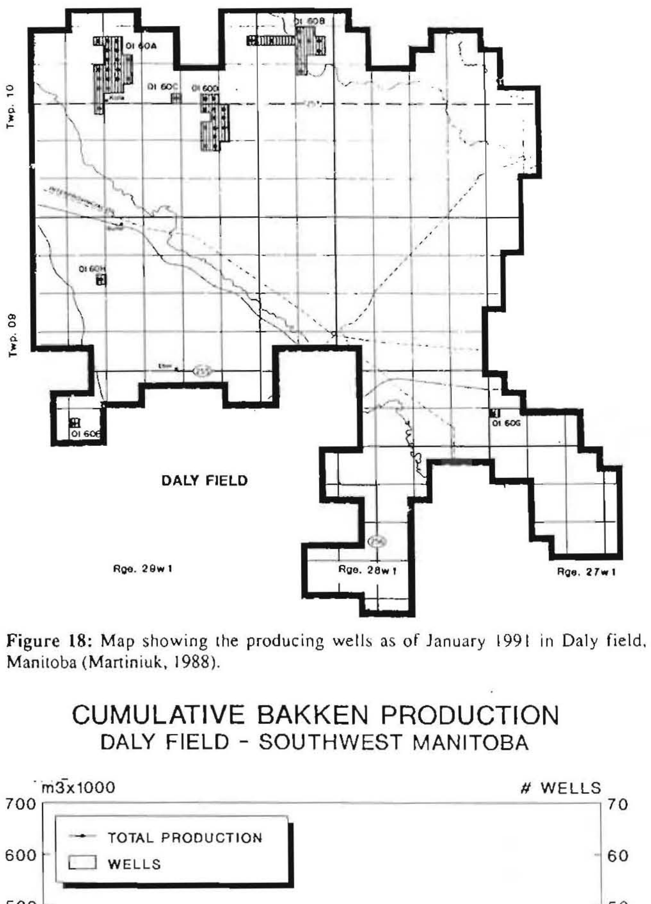

Figure 18: Map showing the producing wells as of January 1991 in Daly field, Manitoba (Martiniuk, 1988).

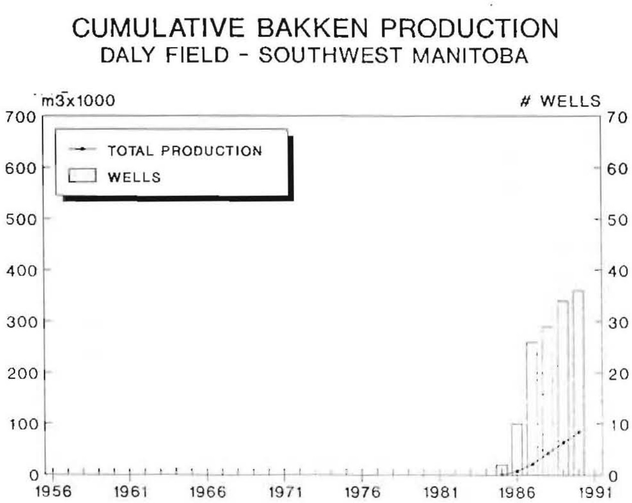

Figure 19: Cumulative production from the Bakken in Daly field in southwestern Manitoba.

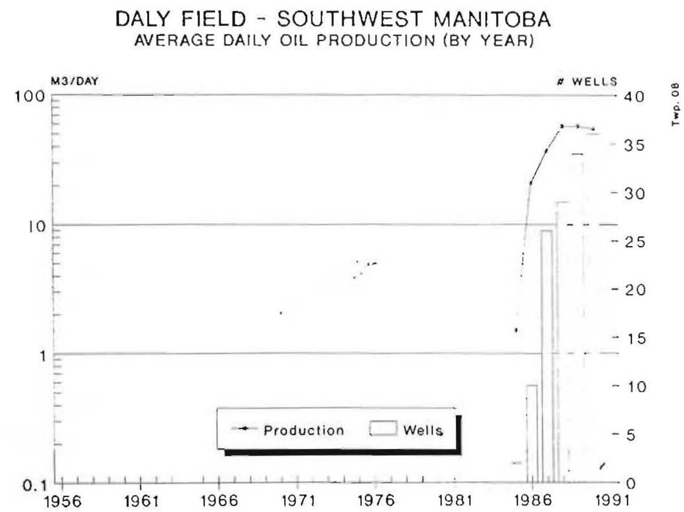

Figure 20: Average daily oil production by year for Daly field in southwestern Manitoba.

Table 3: Reservoir properties for the Bakken pools in Daly field, Manitoba.

	Daly Bakken A Pool	Daly Bakken B Pool	Daly Bakken D Pool
Area (ha)	336	240	240
No. of Producing Wells	15	7	12
Average Net Pay (m)	1.6	1.8	2.0
Average Porosity (%)	17	16	15
Average Water Saturation (%)	45	54	46
Shrinkage Factor (fr.)	0.89	0.89	0.89
Original Oil-in-Place (10^3m^3)	1125.2	492.0	336.4
Recoverable Reserves (10^3m^3)	62.8	11.7	51.4*
Primary Recovery Factor (%) (solution gas drive)	5.6	2.4	15.3
Cumulative Oil Production (10^3m^3)	46.6	8.3	[illegible]
Remaining Recoverable Reserves (10^3m^3)	16.2	3.4	[illegible]

* A pilot waterflood program has been recently initiated in the Bakken D Pool. Injection commenced on an inverted 7-spot injection pattern in July, 1990. Waterflood response was observed in early 1991. Between July, 1990 and February, 1991, daily production increased 16% from 15.4 m^3/d to 17.8 m^3/d. Cumulative voidage-replacement to March, 1991 is 0.22. Preliminary estimates for waterflood recovery are 27.5%, compared to a primary recovery for the pool of 15.3%.

SOUTHEASTERN SASKATCHEWAN

Cumulative Bakken oil production from southeast Saskatchewan totalled 601,232 m^3 (3.8 million bbls) at the end of 1989. Figure 21 indicates a sharp increase in yearly Bakken production beginning in 1985. A portion of this increase can be attributed to an infill program at Rocanville. However, the majority of the increase is due to the development of a new Bakken pool at Hummingbird as well as scattered Bakken discoveries throughout the area (Fig. 14). Economic production from the Bakken throughout southeastern Saskatchewan can now be found outside the traditional Bakken producing areas of Roncott and Rocanville

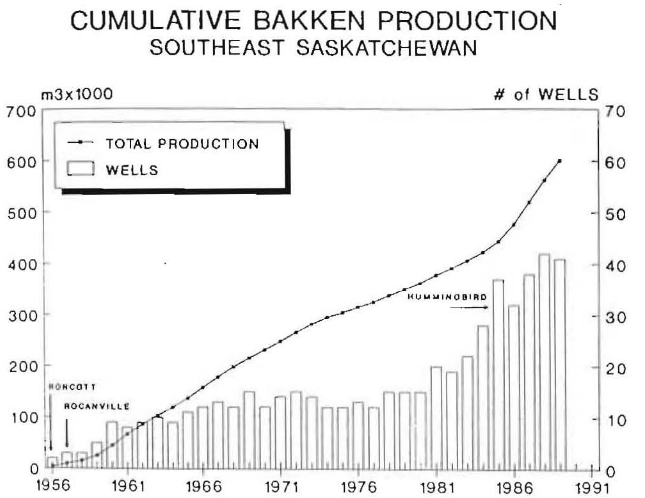

Figure 21: Cumulative production from the Bakken Formation in southeastern Saskatchewan.

The majority of production originates in the medial B2 sandstone unit where permeabilities and porosities are the greatest. However, oil staining has been noticed, and production has been attained, from silty intervals within the B1 and B3 units. This is possible due to the interfingering nature of these three units (Christopher, 1961). The future potential for Bakken production along this trend is enhanced by the occurrence of these stratigraphic traps and provides new possibilities for exploration beyond the areas of known structural traps.

Rocanville Pool

Rocanville is the most prolific Bakken reservoir within southeastern Saskatchewan (Fig. 22). Cumulative production as of October, 1990 reached 339,165 m^3 (2.1 million bbls). Remaining reserves are 102,000 m^3 (641,580 bbls) from initial reserves of 441,000 m^3 (2.8 million bbls) or 19 percent of original oil-in-place. The original oil-in-place as calculated by Saskatchewan Energy and Mines (1989) is 2.326 million m^3 (14.6 million bbls).

The Rocanville reservoir is located entirely within the B2 unit of the middle Bakken sandstone member where it exhibits typical channel cross-bedding, flaser bedding and/or rhythmites (Fig. 10). This lithology accounts for the excellent permeabilities in this reservoir which range from 30 md to as high as 1000 md with an average of 65 md. Permeability may have been enhanced by dolomitization of the original calcium carbonate cement (Kent, 1984). The average net pay is 5.6 m (18 ft). The average porosity is 20 percent (Saskatchewan Energy Mines, 1989).

Pressure history on this pool indicates that the reservoir oil was highly undersaturated at original conditions and that the pool is subject only to rock and liquid expansion along with a partial natural water influx drive mechanism (Gillard and Jordan, 1984). Excellent reservoir permeability would therefore account for the moderate oil recovery.

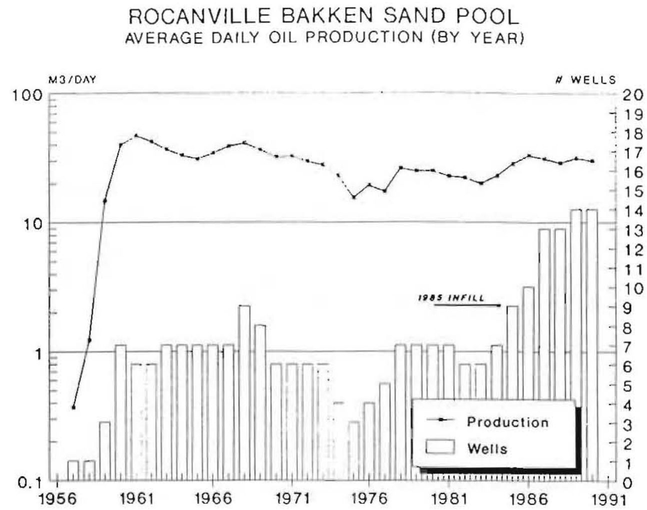

Figure 22: Average daily oil production by year for the Rocanville Bakken sand pool in Saskatchewan.

Roncott Pool

Roncott is the oldest producing Bakken reservoir in southeastern Saskatchewan, and has produced since 1956 (Fig. 23). It has a cumulative production of 104,843 m^3 (659,462 bbls). The pool may be near the end of its productive life with remaining reserves of only 11,000 m^3 (69,190 bbls) from initial reserves of 116,000 m^3 (729,640 bbls). Original oil-in-place is calculated at 1.037 million m^3 (6.5 million bbls) (Saskatchewan Energy and Mines, 1989) with estimated recoveries of 11 percent. The virtues of infill drilling should be reviewed to determine whether or not the capture of wedge and/or unswept oil is an economic option.

The majority of the wells in the Roncott reservoir are producing from the B2 unit, however, the perforated intervals of some wells have crossed over into either the B1 unit and/or the B3 unit (Fig. 11). Examination of core from these wells shows oil staining in coarser-grained beds within these units. Permeabilities range from 0.75 md to 75 md, averaging 6 md. These permeabilities are extremely low compared to an average of

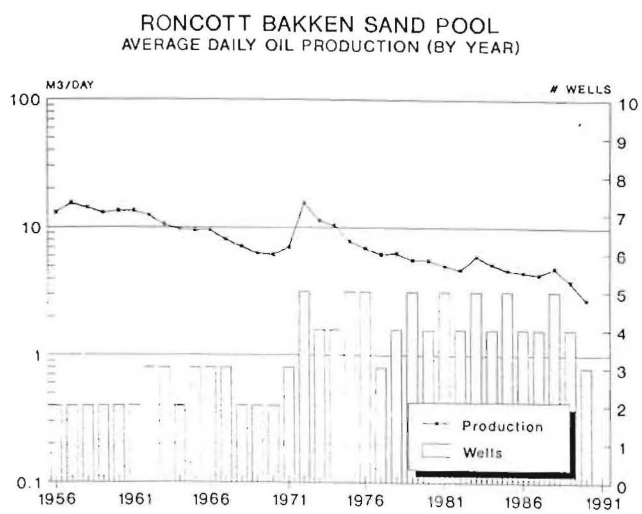

Figure 23: Average daily oil production by year for the Roncott Bakken sand pool in Saskatchewan.

65 md in the Rocanville reservoir. The difference reflects the interfingering of units B1, B2, and B3 along the distal margins of the clastic wedge, while the proximal reservoir at Rocanville is composed entirely of B2. Net pay averages 4.5 m (15 ft) and porosities average 14 percent. Porosity enhancement by dolomitization is more evident here than at Rocanville.

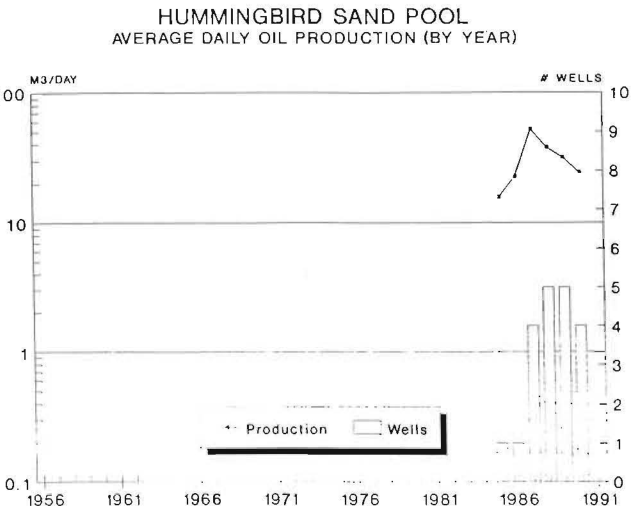

Figure 24: Average daily oil production by year for the Hummingbird Bakken sand pool in Saskatchewan.

Hummingbird Pool

The newest pool of established Bakken production is on the Hummingbird structure, where Birdbear and Ratcliffe production already exist. Bakken production at Hummingbird began in 1985 and rose dramatically over the next two years. Since 1987 a rather steep production decline has persisted (Fig. 24).

Cumulative production is 60,210 m^3 (378,720 bbls) to October, 1990. This represents well over half of the initial reserves of 98,000 m^3 (616,420 bbls) and leaves only 38,000 m^3 (239,020 bbls) remaining to be produced. Saskatchewan Energy and Mines (1989) has calculated original oil-in-place at 525,000 m^3 (3.3 million bbls) which places the recovery factor at 19 percent.

The majority of production is from the B2 unit (Fig. 12). There are also shows in the lowest portion of the B3 unit, where at least two wells have been completed. A distal equivalent of the producing channel sands at Rocanville, the Hummingbird reservoir has a higher argillaceous content. The sedimentary structures that dominate the Hummingbird reservoir include flaser-type bedding and wavy laminated sands and silts instead of the channel cross-bedding present at Rocanville. Porosities and permeabilities at Hummingbird are lower than the Rocanville reservoir. The average porosity and permeability at Hummingbird is 9 percent (Saskatchewan Energy and Mines, 1989) and 5 md, respectively. Average net pay is 4.9 m (16 ft).

Miscellaneous Production

Miscellaneous single well production and undesignated small pool production accounted for 114,335 m^3 (719,167 bbls) of the total Bakken production in southeastern Saskatchewan as of December, 1989. The most significant production is from a small cluster of 12 wells in the North Midale area (Townships 6 and 7, Range 11 W2M) that produced 56,599 m^3 (356,007 bbls).

The majority of this production is found within the Rocanville-Torquay structural trend (Fig. 14) (Christopher, 1961). The few exceptions to this rule are found on trend with the Brockton-Froid Fault zone and the Weldon Fault of northeastern Montana suggesting that these features may extend into southeastern Saskatchewan.

POTENTIAL

North Dakota

Potential exists for production from unit 3, within the middle member of the Bakken Formation in North Dakota. Core examination shows that the depositional pattern of the lower lithofacies, units 1 through 5, were affected by pre-existing structure and topography. Thinning of the sandstone, unit 3 over structural noses is evidenced by cores examined from Burke County (Fig. 15). This relationship strongly suggests a potential for updip stratigraphic pinch-out of the sandstone unit against impermeable rocks. When this situation is combined with a source rock, the Bakken shales, a potential for production is present. The sandstone unit is in contact with the upper Bakken shales of the study area. Fractures present locally also form other migration pathways. These factors can also be applied to other potentially productive lithofacies of the middle member.

A favorable property of the sandstone unit is its response to stimulation. The sandstone unit reacts well to stimulation by acid and/or sand-oil fracture treatments that can greatly increase the effective drainage area and enhance production.

Southwestern Manitoba

The Daly field has been developing continuously since Bakken oil was discovered in 1985. The area has been attractive due to the high quality of Bakken oil and the prospect for uphole completion in shallower zones within the overlying Lodgepole Formation.

Most of the Bakken pools presently established in the Daly field have been defined. Potential for future Bakken development remains however, in the northwestward extension of the Bakken A Pool into Township 11, Range 29 WPM (Fig. 8) where unit 1 is present.

Eastward, in the Virden field (Townships 9 to 11; Ranges 25 to 27 WPM), the Bakken remains largely untested. This is an area of Bakken thickening and of known salt collapse features within the shallower Lodgepole Formation. Possibility for a Bakken subcrop play may exist along the eastern edge of the field (Fig. 16).

Northward, toward the northeastern limit of the Bakken Formation, several free-oil recoveries have been made from drill stem tests in the middle member; specifically, from wells in Townships 15 and 16, Range 27 WPM (Fig. 14). The locality features a Bakken structural nose (Fig. 13). Minor erosional breaks within units 1 and 2 and lateral lithologic changes from fine grained sandstone to argillaceous, laminated siltstone, offer potential for a stratigraphic trapping eastward of this area. Several completions have been attempted but have not been successful due to high water recoveries.

Southeastern Saskatchewan

The potential for exploration and new discoveries in the Bakken is immense. Oil shows throughout the Saskatchewan portion of the Williston Basin as well as scattered single well production along the Bakken production trend (Fig. 14) suggest that significant amounts of undiscovered Bakken oil remain to be found.

Bakken sourced oils are characterized by very long migration pathways (Osadetz *et al.*, this volume), having been generated in the deepest portion of the basin, south of the Missouri River, and migrated radially as far away as Rocanville, over 200 km (124 mi). The length of migration may be a factor in determining API gravity of the oil. Rocanville oil has a gravity of 36° API whereas Roncott and Hummingbird produces 40° API oil. Even closer to the source, the previously mentioned North Midale wells produce 41° API oil and are situated directly north of the Bakken hydrocarbon generation region as described by Osadetz *et al.* (in review) (Fig. 25). Wells tested at Torquay and north of the international border at Roche Percee had 43° and 45° API oil, respectively.

Structural features that aid and control entrapment of Bakken oil include the linear depressions associated with the Rocanville-Torquay structural trend (Christopher, 1961), as well as the reversal of regional dip caused by flexure of the Bakken on the flanks of the Roncott high. These structures probably did not aid in the migration of oil from the center of the basin, but do provide favorable conditions for structural entrapment.

The interfingering of the medial B2 sandstone wedge along with the laminated shales and silts of the B1 and B3 units, provides another avenue of entrapment in areas where structural features may not exist.

SOURCE ROCK AND MIGRATION PATHS

The Bakken Formation has been documented as an excellent petroleum source rock within the Williston Basin (Dow, 1974; Williams, 1974; Meissner, 1978; Webster, 1984; Hester and Schmoker, 1985). The black shales are the richest and most widespread rocks in the Williston Basin (Osadetz and Snowdon, in review). The upper and lower shales of the Bakken Formation yield rich Type II sources (Dow, 1974; Webster, 1984; Osadetz and Snowdon, in review). The upper shale is generally richer than that of the lower shale.

Osadetz and Snowdon (*op. cit.*) concluded that thermal maturity of source rocks in the Williston Basin was strongly affected by elevated heat flows, notably along the Nesson crustal structure in North Dakota. Enhanced maturation resulted in Type II oil windows occurring at much shallower than expected depths, at 2,300 m (7,544 ft). The Nesson anticline is believed to have had an important control on hydrocarbon potential.

Production from the Bakken Formation occur at long distances from the regions of significant hydrocarbon generation (vitrinite reflectance = 0.7 percent) and expulsion threshold (vitrinite reflectance = 0.9 percent) (Osadetz *et al.*, in review). Osadetz *et al.* (in review, p. 84) noted that the "region sufficiently mature to expel hydrocarbons occurs in an area south of the Missouri River, a region unfavourably disposed to migrate oils into northeastern Williston Basin. Enhanced maturities are associated with high heat flows in the region of the North American Central Plains conductivity anomaly" (Fig. 25). This anomaly is a 2,000 km (3,220 mi) long, 80 km (129 mi) wide feature along which coincidental electrical conductivity and heat flow anomalies occur. The Nesson structure is associated with this feature. In Canada, Osadetz *et al.* (in review, p. 31) noted that ".... Family B oils occur exclusively in the Bakken Formation reservoirs at Roncott, Daly and Rocanville fields". Production from the Hummingbird pool are Family C oils. Osadetz *et al.* (in review) proposed a long distance migration path for oil to the Roncott, Rocanville and Daly fields (Fig. 25).

It is possible that until 1 (Manitoba) and its correlatives in Saskatchewan and North Dakota, as well as channel sands noted in these areas, provided the necessary conduit for oil migration and may represent the "lowstand system" proposed by Osadetz *et al.* (in review) (Fig. 25) These facies, where developed in erosional and paleotopographic lows on the underlying Devonian surface, are coincident with productive areas in Saskatchewan and Manitoba.

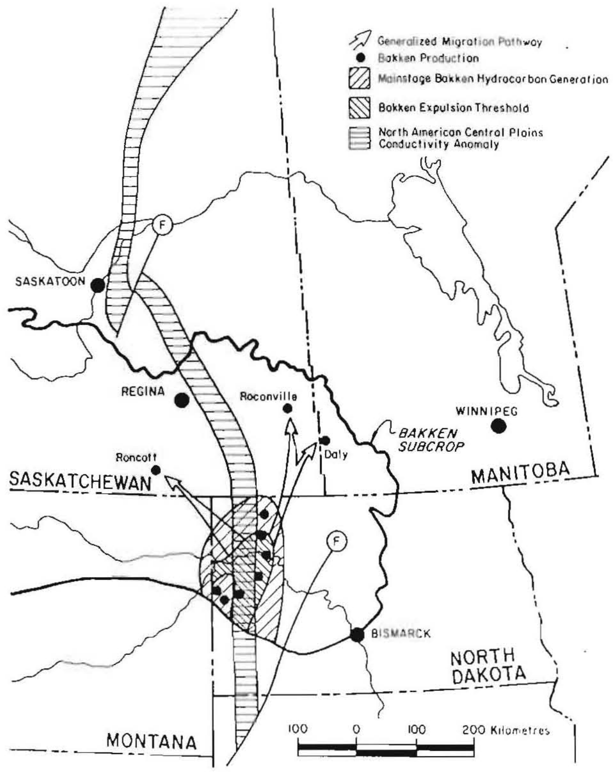

Figure 25: Diagram showing the area of mainstage hydrocarbon generation in the Bakken Formation. The area where the Bakken has exceeded its expulsion threshold is also indicated, as well as, the generalized migration pathway (from Osadetz *et al.*, 1991).

SUMMARY

1. The Bakken Formation consists of three members, a lower and an upper shale and a middle member. The middle member consists of multiple lithofacies which are correlative across the study area.
2. The middle member, overall, is considered to be a transgressive deposit, based on its onlapping relationship with the lower member. The lowermost unit of the middle member is probably regressive. It does not onlap the lower shale and therefore, probably represents the low stand of Bakken seas.
3. Smaller scale transgressive and regressive pulses are exhibited by the deposition of the upper portions of the middle member. The sandstone units represent intertidal deposits with associated tidal channels. Storm deposits are also present, locally.
4. The deposition of the middle member is further complicated by the dissolution of the Devonian evaporites.
5. Topography and structure of the underlying Devonian formations show a strong influence on the depositional patterns of portions of the middle member Bakken.
6. Significant oil shows scattered throughout the study area suggest a strong potential for successful future exploration.
7. The producing sandstone unit mapped in the study area may have provided the migration pathway for Bakken oils.

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