2008 Core Workshop
The Bakken Formation : Revisited

Julie A. LeFever and Stephan H. Nordeng
North Dakota Geological Survey

Introduction

The discovery of Elm Coulee Field in Richland County, Montana and Parshall Field in North Dakota has renewed the interest in the Bakken Formation. These wells were successful because of improvements in abilities of horizontal drilling technology to extract hydrocarbons from unconventional reservoirs. This was further fueled by a steady increase in oil prices. New wells have resulted in new information and cores and additional refinements to the interpretation of the Bakken.

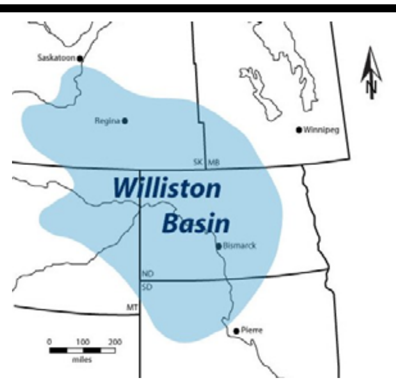

Figure 1 – Location of the Williston Basin

Geologic Framework

The Williston basin underlies portions North and South Dakota, Montana in the United States and portions of Saskatchewan and Manitoba in Canada (Figure 1). Although located currently in the central portion of the craton, the basin has

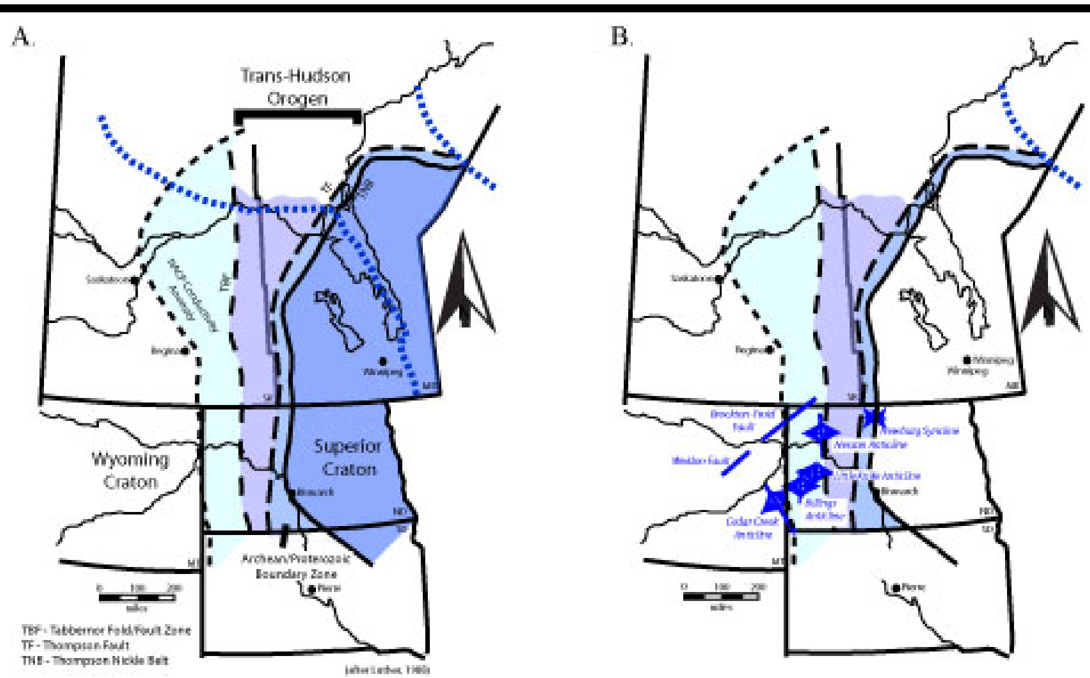

Figure 2 – (A) Underlying basement for the Williston basin (after Luther, 1988). (B) Structures present in the Williston basin and their relationship to the underlying structure.

had an active past. The central part of the basin is dominated by a north-south trend related to the underlying Precambrian bedrock (Figure 2).

Three distinct structural provinces can be identified and are as follows: the Superior Craton, the Trans-Hudson orogenic belt, and the Wyoming craton. The Trans-Hudson orogenic belt is comprised of a series of accreted terranes bounded by faults (Green et.al., 1985). These basement faults manifest themselves later along structures which include the Nesson, Billings and Little Knife anticlines. Additionally, the region referred to as the North American Central Plains (NACP) Conductivity Anomaly coincides with high heat flow that affects the generation of hydrocarbons from a variety of formations including the Bakken (Osadetz et.al., 1998).

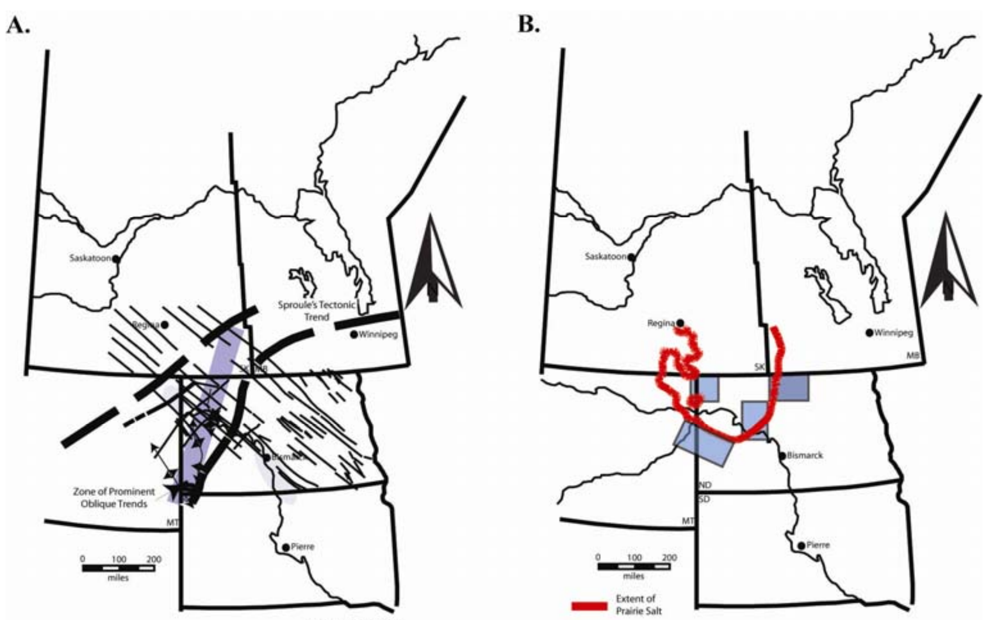

Figure 3 – (A) Diagram showing multiple lineaments that have been described in the literature for the Williston basin literature (Erickson, 1970). (B) Red line indicates the limit of the Devonian Prairie Salt with the northwest notch corresponding to the Hummingbird trough. Shaded areas indicate regions of potential salt collapse.

Multiple overprints of the existing basement structures have occurred through time with two prominent trends standing out (Figure 3; Erickson, 1970).

The existing structures and depositional environments are further affected by sediment loading and the dissolution of the various salts within the stratigraphic section (LeFever and LeFever, 2005). Reactived is common and well documented throughout the section. The principal salt affecting sedimentation in the basin is the Devonian Prairie salt (Figure 3).

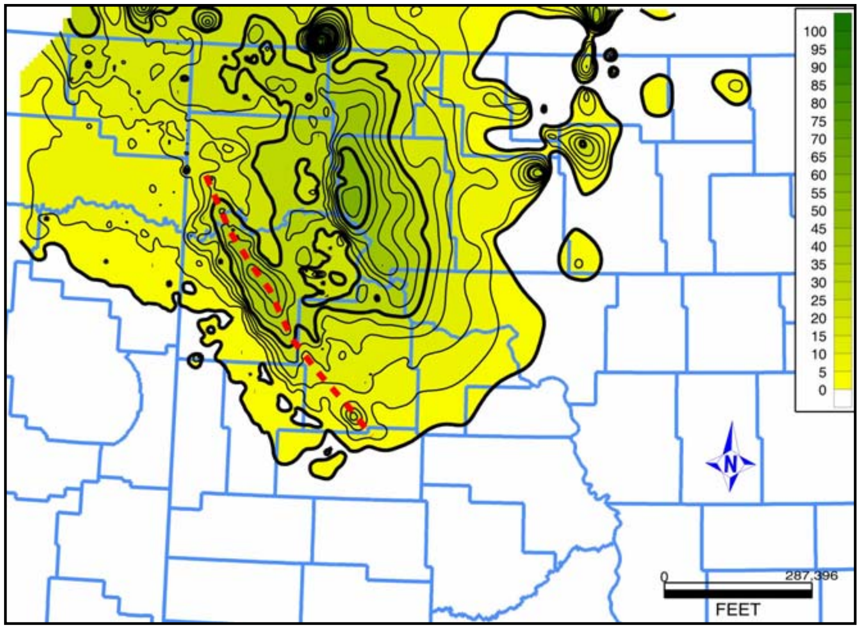

Figure 5 – Isopach map of the lower Bakken shale in North Dakota and Montana with a prominent northeast-southwest trend indicated by the red dashed line.

Bakken sedimentation was strongly influenced by basement tectonics and movements caused by partial or complete dissolution of the Prairie salt. A dissolution edge with thickness anomalies is present in north-central and southwestern North Dakota, and Richland County, Montana. Depending on location, the different members of the Bakken are affected at different times. Some of these features are subtle and localized on logs and cores whereas others are prominent on isopach maps (Figure 5). The Bakken is further affected by later dissolution that created additional fractures or reactivation existing fractures that enhance porosity and provide active pathways for diagenetic fluids. Also, dissolution features, such as the Hummingbird trough, may affect sediment transport in parts of the basin.

Three Forks Formation (Devonian)

The Three Forks Formation consists of an interbedded sequence of greenish grey and reddish brown shales, light brown to yellow grey dolostones, grey to brown siltstones, and quartzose sandstones with minor amounts of anhydrite (Figure 6). Local accumulations of a heavily burrowed coarse-grained siltstone to fine-grained quartz sandstone occur at the top of the Three Forks. These local accumulations are informally known as the "Sanish Sand".

The Three Forks Formation conformably underlies the Bakken in the central portion of the basin; an angular unconformity exists between the two formations along the margins of the basin. The Three Forks Formation reaches a maximum thickness of 250 ft. There are five lithofacies representing environments that range from subtidal to supratidal (Dumonceaux, 1984). The “Sanish sand” is thought to represent a beach or nearshore marine environment

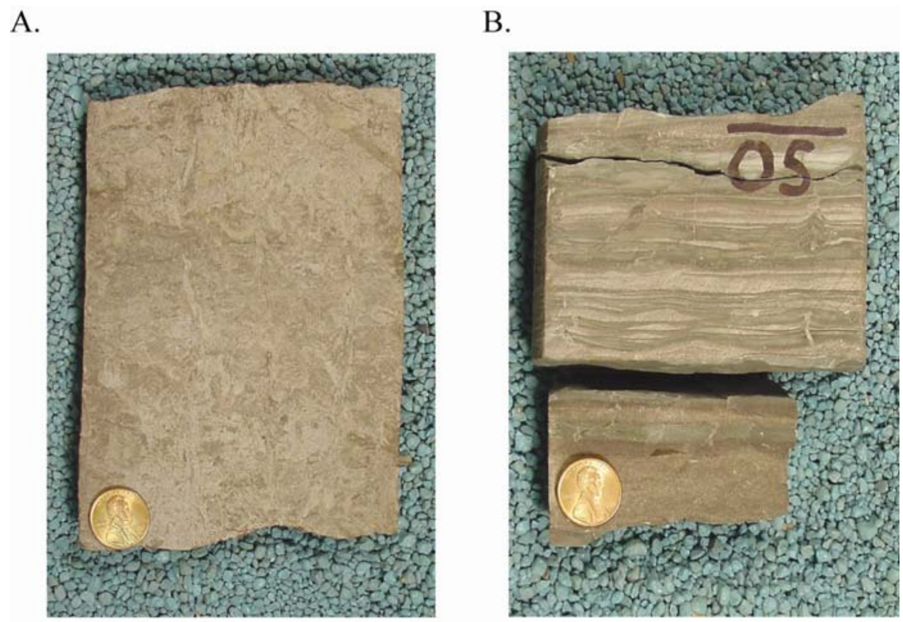

Figure 6 - Core photographs representative of the “Sanish” sandstone from the Raymond T. Duncan. - #1 Rose (SENE Sec. 2, T.153N., R.94W.). (A) Medium brown highly burrowed siltstone to very fine-grained sandstone characteristic of the “Sanish” sand (Depth – 10601.3 ft). (B) Characteristic apple green and tan interbedded sequence of the Three Forks Formation. (Depth – 10605 ft).

A significant amount of oil has been produced from the Three Forks Formation in Antelope Field, North Dakota and Sinclair Field, Manitoba (Nicholas, 2006). Its proximity to the source beds of the Bakken, suggests that Three Forks Formation is capable of storing significant volumes of Bakken sourced oil. This, in combination with well developed fracture and a high diagenetic porosity (up to 22 %), may provide additional targets for exploration (Karasinski, 2006).

Lodgepole Formation (Mississippian)

The Lodgepole Formation consists of a dense, dark grey to brownish grey limestone and calcareous shale with minor amounts of chert and anhydrite. A thin, black shale and black organic-rich limestone is present along the margin of the basin. This zone is informally known as the "False Bakken", and is readily apparent on wireline logs. It is separated from the Bakken by a thin, dense, medium grey pelmatozoan-rich limestone.

The Lodgepole Formation conformably overlies the Bakken and reaches a maximum thickness of 900 ft. It represents a marine transgression that restored normal circulation to the basin. Five major facies are represented by these rocks. These include: the central basin facies consisting of dark grey, irregularly laminated, crinoidal mudstone-wackestone; a basin slope facies containing medium to light grey argillaceous, crinoidoidal, brachiopod wackestones to packstones ; an open shelf facies with light colored, cherty, skeletal wackestones to packstonse a crinoidal mudstone facies formed at or near the shelf break; and a restricted environment grey shale (Heck, 1979). These facies tend to onlap along the basin margin throughout lower Lodgepole deposition.

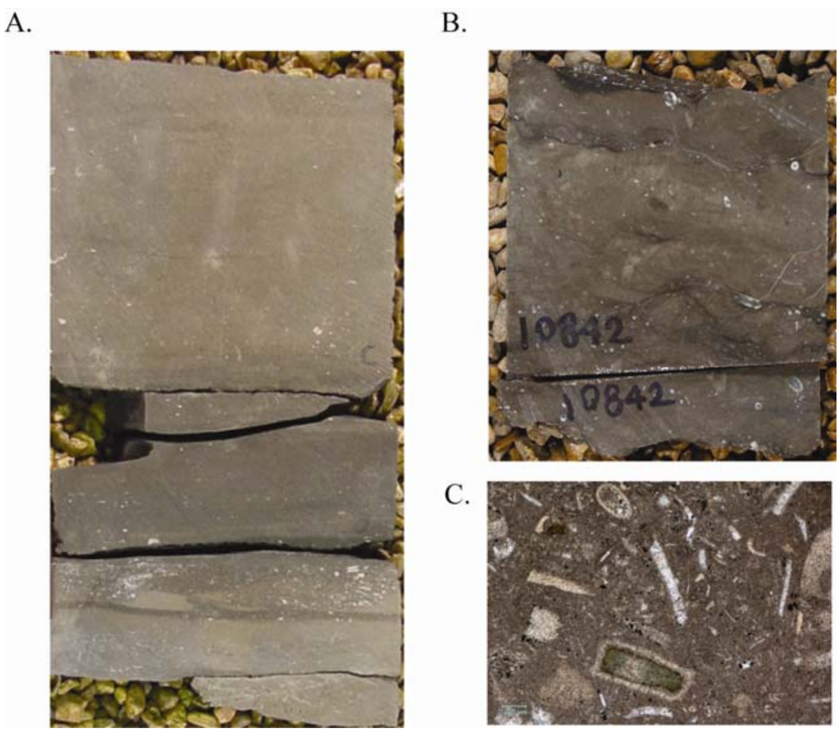

Figure 7 – (A) Core of the "False Bakken" organic-rich lime mudstone in the Conoco, Inc. – Federal 12 # 1 (SWSW Sec. 12, T.143N., R.102W). (B) Core of the pelmatozoan-bearing, burrowed, lime wackestone from the Marathon Oil Co. – Stohler #21-3H (NWNE Sec. 3, T.146N, R.94W.). (C) Photomicrograph of the pelmatozoan-bearing limestone wackestone to packstone (SESE Sec. 13, T.145N., R.104W.).

Bakken Formation (Mississippian-Devonian)

The Bakken is present in the subsurface Williston basin and extends over roughly two-thirds of the state of North Dakota. It attains a maximum thickness of 160 ft and has a well-defined depocenter just east of the Nesson Anticline (Figure 8).

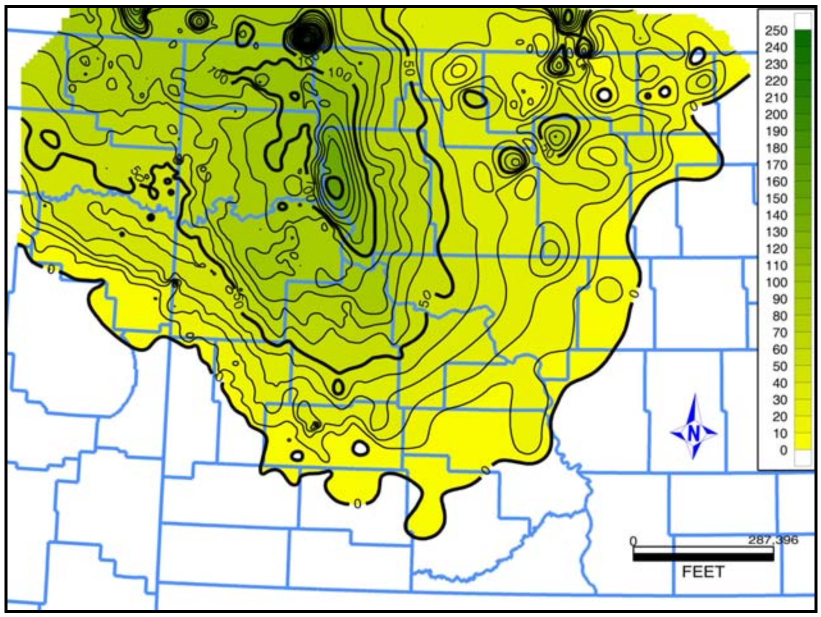

Figure 8 – Isopach map of the Bakken Formation in North Dakota and Montana. Note the depocenter along the eastern side of the Nesson anticline. Anomalous thicknesses on the eastern side of the map are related to collapse of the Devonian Prairie salt.

The overall stratigraphy of the Bakken is simple. The formation is defined as two black shales separated by a mixed sequence of siliciclastics and carbonates. Since the shales are highly radioactive, the formation is easily correlated on wireline logs. Although the shales are not the focus of this workshop they have a profound influence on the production and provide a source for the hydrocarbon as well as information about the depositional environments and basin development.

Lower Shale Member

The lower shale member lies unconformably on the Three Forks Formation along the margins of the basin but lies conformably with a gradational contact in the central portion of the basin. It reaches a maximum thickness of 50 ft in the depocenter to the east of the Nesson anticline. Other changes in thickness in north-central and McKenzie County North Dakota are probably related to dissolution of the Devonian Prairie Salt.

The shale is a dark brown to black, massive to fissile, non-calcareous, and organic-rich. Small amounts of siltstone, limestone, and sandstone are present towards the base. Quartz is the dominant mineral with minor amounts of muscovite, illite and other clays. Pyrite is present in lenses, laminations, or is finely disseminated throughout. Fossils within the shale member include foraminifera, conodonts, algal spores, brachiopods, fish teeth, bones and scales. These thin, coarser-grained deposits occur throughout the section as lags containing conodonts, bitumen and shell fragments. Others lags consist of thin layers of pyrite, foraminifera, and calcite grains.

Localized siltstone or limestone beds near the base of the formation (Figures 5 and 9) suggest that these shales were deposited in restricted water. The fossil assemblage present suggests a stratified water.

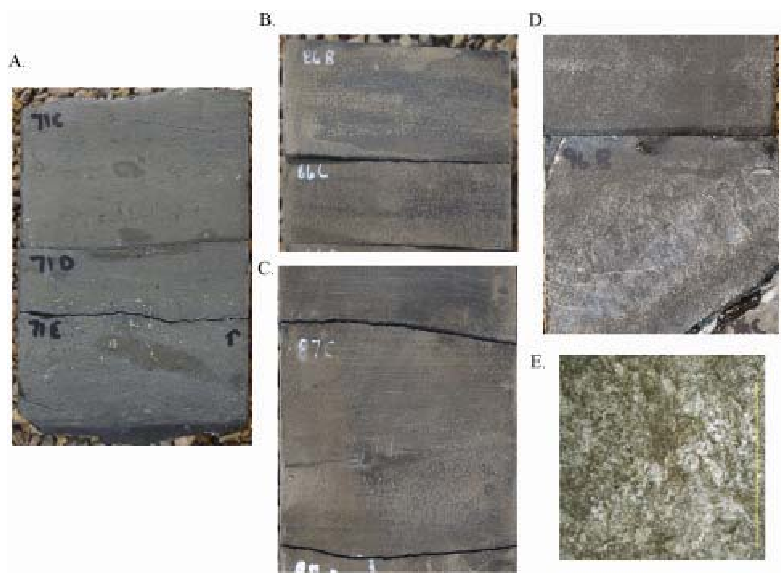

Figure 9 - Core photos from the EOG Resources, Inc. – Long #1-01H (Lot 4 Sec., 1, T.152N., R.90W.). (A) Core photograph showing the lime wackestone-packstone immediately above and including the contact with the underlying lower Bakken Shale. (B) Core of lower Bakken shale. (C) Small scale calcite filled explusion fractures from coarser grained layer within the lower shale. (D) Core photograph of the lower Bakken shale. (E) Photograph with close-up of a bryozoan build up within the lower Bakken shale with a late stage fracture and pyrite cementation.

Where the lower shale is mature and fractured, the fractures are smooth and conchoidal, but can be irregular or blocky. Fractures that are sub parallel to bedding are heavily oil stained. Smaller scaled expulsion related fractures occur in localized zones, these fractures are generally at an angle or parallel to bedding and form a straight edge with thin fracture planes when viewed from the top of the core (bedding plane view). The lower shale is generally less organic than the upper shale. The organic matter appears to be distributed evenly throughout the member.

Middle Member

Vertically variable, the middle member consists of five different lithofacies that can be traced laterally throughout the Williston basin. A brief description of the lithofacies is present in figure 10.

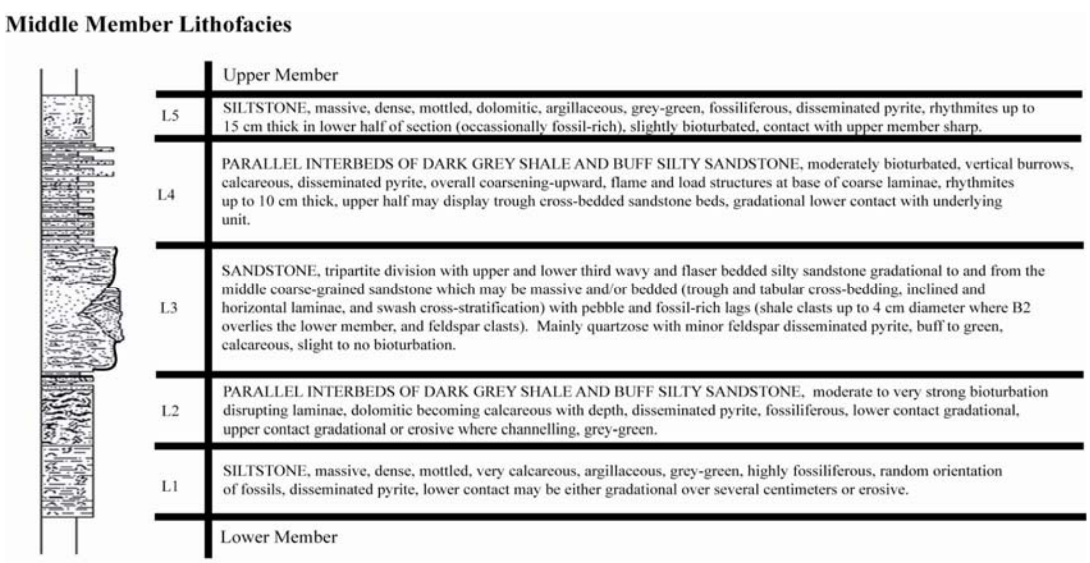

Figure 10 – Lithofacies present in the middle member of the Bakken Formation.

Lithofacies 1

Lithofacies 1 immediately overlies the lower Bakken shale. Where present this contact may be unconformable to conformable. Unconformable contacts have extensive lag deposits. It consists of light grey, greenish-grey, or brownish-grey argillaceous siltstone to dolomitic mudstone (Figure 11). It is generally massive, cemented with calcite, and has scattered pyrite nodules and fossils (crinoids and brachiopods). In rare instances glauconite grains are present. Locally the unit is burrowed. Porosity is generally intergranular.

Lithofacies 1 ranges from 1.5 to 6.5 feet and averages 3 feet in thickness. It represents the transitional facies from the anoxic shale deposition to the normal marine deposition of the middle member. It is difficult to identify on wireline logs due to the proximity of the lower shale and its thickness, but is easily identified in core.

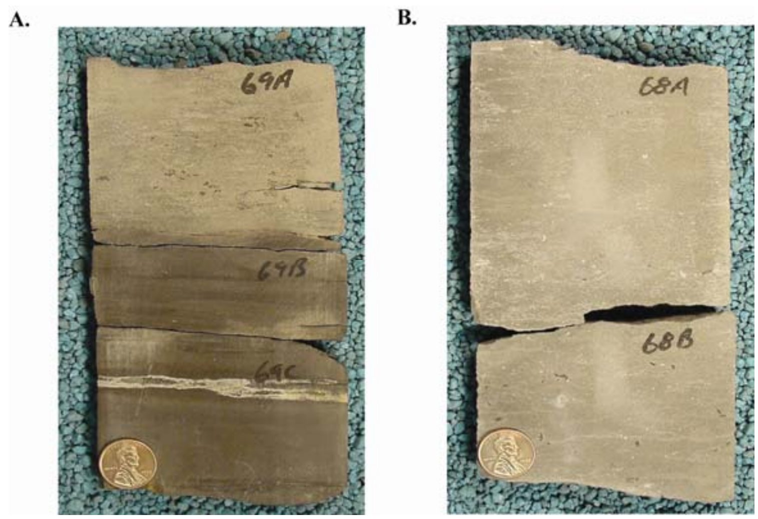

Figure 11 - Core photos from the Shell Oil Company - #32-4 Young Bear (SWNE Sec. 4, T.148N., R.92W.) A. Photograph shows the nature of the gradational contact between the lower Bakken shale and the overlying Lithofacies 1. The rock immediately above the contact consists of a silty, lime mudstone with small crinoid fragments. This grades upward into a massive calcareous siltstone. (Depth - 10469 ft) B. Slightly further away from the contact, the core becomes more typical of the lithofacies. It is generally massive, may have an occasional brachiopod or crinoid fragment. (Depth - 10468 ft).

Lithofacies 2

Lithofacies 2 consists of greenish-grey to brownish-grey, argillaceous siltstone or sandy siltstone to brownish-grey, very fine grained sandstone (Figure 12). Abundant *Helminthopsis* burrows are characteristic at the top of this facies. It decreases downward becoming rare in the lower half of the lithofacies marked by a distinctive change on the log character. There are scattered fossils throughout the section including crinoids and brachiopods. Many are replaced by pyrite. Also, nodular pyrite occurs occasionally. As the lithofacies coarsens, it may become well cemented. The rock is commonly cemented with calcite, but pyrite cement has been documented in some localities.

Local dolomitization of the calcite cement has resulted in an increase in porosity. Log porosities for this interval commonly range from 6 to 12% and appear to indicate dolomitization. Porosities also increase up-section as the rock becomes more heavily burrowed.

The interval reaches a maximum thickness of 33 ft and has a similar distribution to the previous lithofacies.

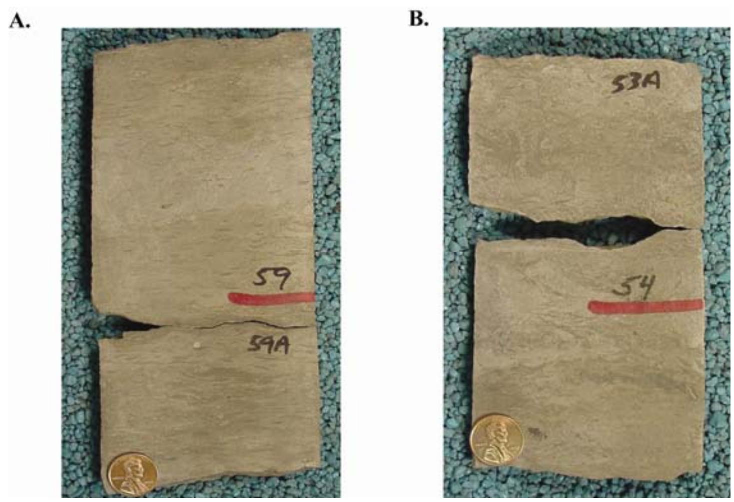

Figure 12 - Core photos from the Shell Oil Company - #32-4 Young Bear (SWNE Sec. 4, T.148N., R.92W.) (A) This photograph shows the characteristic clay draping associated with Lithofacies 2. Also displayed is the change from an argillaceous siltstone to a sandy siltstone to very fine-grained sandstone. Burrowing is present but not as abundant as in the adjacent photograph. (Depth – 10458.6 ft) (B) This sample is from the upper portion of the interval. Burrowing is pervasive and has destroyed any pre-existing fabric. Clay drapes are present but rare. The lithofacies is locally dolomitized. (Depth – 10453.6 ft)

Lithofacies 3

There are three parts to lithofacies 3 basinwide. The upper and lower third consists of wavy to flaser-bedded, light to medium grey, argillaceous to sandy siltstones and brownish-grey, very fine-grained sandstones with local claystones. The middle third consists of a medium grey, dark grey, or greyish-tan, fine- to medium-grained sandstone that may be massive, cross-bedded, or thinly laminated (Figure 13).

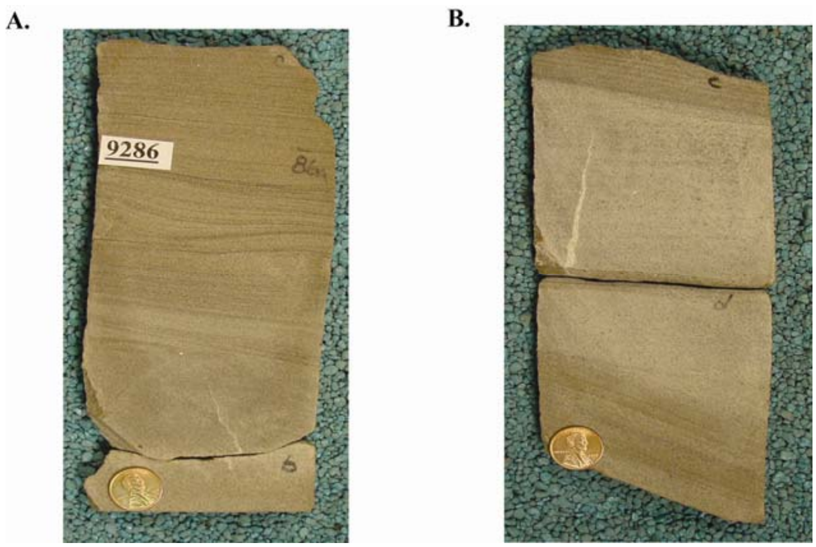

Figure 13 - Core photographs that are representative of Lithofacies 3. (A) Marathon Oil Company - #26-1 Laredo (SWNE Sec. 26, T.156N., R.91W.) Photograph shows an alternating sequence massive to thinly laminated fine-grained sandstone common to this interval. (Depth - 9284.8 ft) (B) From the same well, beds in this photograph are inclined. It is interesting to note that the lithofacies in this well represents a channel. (Depth – 9294.4).

In the North Dakota portion of the basin the lithofacies varies from a medium grey to dark grey to greyish-tan, very fine- to fine-grained sandstone to a medium grey limestone. Localized accumulations of coarser material exist in the northeastern portion of the map (Burke County). Limestone forms a series of bands along the southwestern extent of the Bakken, and along the top of localized highs. Towards the basin margin the limestone changes from a sand-algal packstone, to a sand-ooid packstone, ooid packstone, to an ooid-crinoid packstone-grainstone.

Away from the highs, the facies is predominantly sandstone and is moderately well-sorted to well-sorted and may be poorly sorted locally. Clasts consist predominantly of quartz with some feldspar and heavy minerals. They are rounded to well-rounded; the finer grained material is subrounded to subangular. Cement is generally calcite, and in some cases pyrite. Pyrite is disseminated throughout the interval. Quartz cement is present locally in coarser grained sections. The lower portion of the interval is locally reverse graded. The middle portion of the section consists of an alternating sequence of massive to cross-bedded to thinly laminated beds. These beds are generally coarser grained than the under and overlying lithologies. Overlying these beds is a series of multiple fining upward sequences. Other structures that have been noted in the core are rip-up clasts, load or channel structures, usually into the finer grained material, and calcite-filled fractures. Locally, soft-sediment deformation destroys the entire fabric. Oil staining may be present in the very fine-grained, laminated, predominantly quartz sandstone portion of the core. It appears that as the grain size increases in this lithofacies so does its ability to undergo cementation.

The thickness of Lithofacies 3 reaches a maximum of 17.5 ft, averaging 8 ft in the North Dakota portion of the Williston basin. This lithofacies is generally limited to the northern half of the state and thickens in a northward direction. Although it has a prominent, consistent, and easily mappable gamma-ray log response over the majority of its extent, the facies is difficult to determine on logs as the edge is approached. At least one well appears to have penetrated a channel sand characterized by a mixture of fragmented allochems and sand and higher angle bedding.

Contacts are conformable, but unconformities occur in localized areas along the Nesson anticline, along the southwestern margin, and along the Canadian border. The presence of an unconformity surface, soft-sediment deformation and the increase thickness in the area of Divide County suggests dissolution activity in the underlying Devonian Prairie salt by extending the Hummingbird trough into North Dakota. Available cores indicate that the northern and southern portion of the Nesson anticline was a positive feature throughout the deposition of this unit with a probable bypass channel through the lower central portion of the anticline. The structure is probably responsible for the distribution of clastics in this interval. Sand, sourced from the north, was routed around the eastern side of the Nesson anticline leading to the development of carbonates along the southwestern edge. It also starved the western side of the state of coarse clastics, producing a finer-grained facies.

Central Basin Facies

Central Basin Facies The initial study of the middle Bakken member by LeFever and others (1991) encountered four additional facies within the central portion of the North Dakota Williston basin. Grouped together they reach a maximum combined thickness of 24 ft.
The central basin facies consists of 4 distinctive lithologies that are limited to the central portion of the Williston basin. They are visible in core but are too small to be identified individually on wireline logs. As a group, the combined sequence on wireline logs with core control is mappable.

The basal 5 ft of this combined sequence consists of a laminated, slightly argillaceous sandy siltstone. There is a slight undulation to the laminations. This is overlain by 2 ft of medium brownish-grey massive siltstone. The third bed set consists of a 4.5 ft thick interbedded sequence of very fine-grained sandstones and wavy laminated claystones. The individual beds of this unit are moderately well-sorted. Some are lensoidal in shape and may be burrowed. A medium grayish-brown, laminated sequence of siltstones and very fine-grained sandstones rest on top. Laminations within this sequence are very uniform in thickness and range up to 5 cm in thickness. The thicker beds may be cross-bedded or massive. Although very fine-grained, cementation is limited to non-existent and the interval shows extensive oil staining.

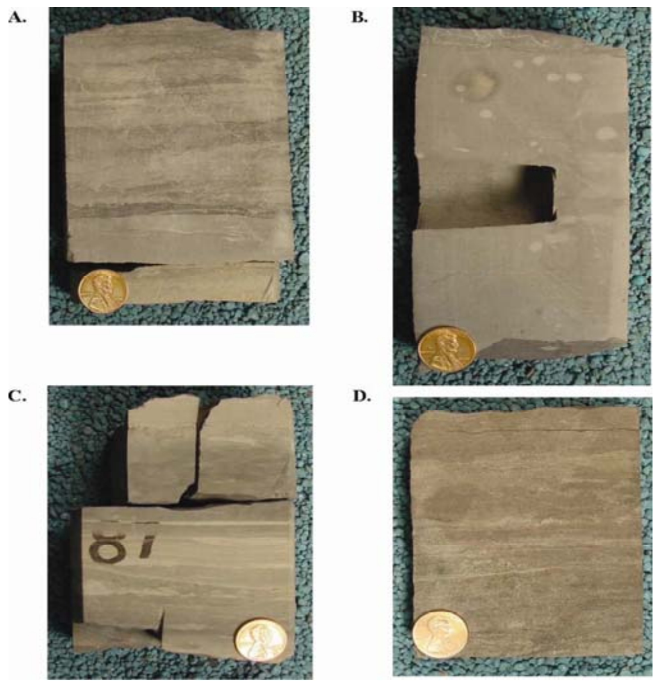

Figure 14 - (A) Brooks Exploration Company - #1-11 Rogstad (NESE Sec. 11, T.155N., R.91W.) Photograph shows wavy bedded argillaceous siltstone of this interval. (Depth - 9393 ft) (B) From the same well, the massive siltstone of the second interval (Depth – 9387.5). (C) Also from the same well, the third lithofacies is an interbedded fine-grained sandstone and claystone sequence with lensoidal shaped beds and some burrowing (Depth – 9387 ft) (D) Oryx Energy Company - #1-27 Stenejhem HD (NESE Sec. 27, T. 150N., R.97W) This core photograph is of a thicker bedded sequence of argillaceous siltstones and fine-grained sandstones. (Depth – 10938 ft)

Additional core data is expanding the areal extent of this lithofacies. As with the other middle member lithofacies, the contacts with the overlying and underlying beds vary from unconformable to gradational. Disconformities are abrupt and common with this interval and appear to be in response to local tectonics (probably related to salt dissolution). Cores on the western side of the state show finer grained sediment similar to the other middle member facies. The northern and southern end of the Nesson is structurally high noted by the thinner interval and unconformable contacts with the overlying lithofacies.

Lithofacies 4

Lithofacies 4 is represented by two distinct parts. The lower portion consists of an alternating sequence of medium grey, argillaceous siltstone to light to medium grey, very fine-grained sandstone, and dark grey shale laminae. The unit is thinly laminated, displays planar and cross-ripple laminations, moderately bioturbated in places, and locally cemented. The upper portion consists of an alternating sequence of medium to light grey siltstones, algal laminae, dark grey claystones to brown-black shales, and tan to light brownish grey, very fine-grained sandstones.

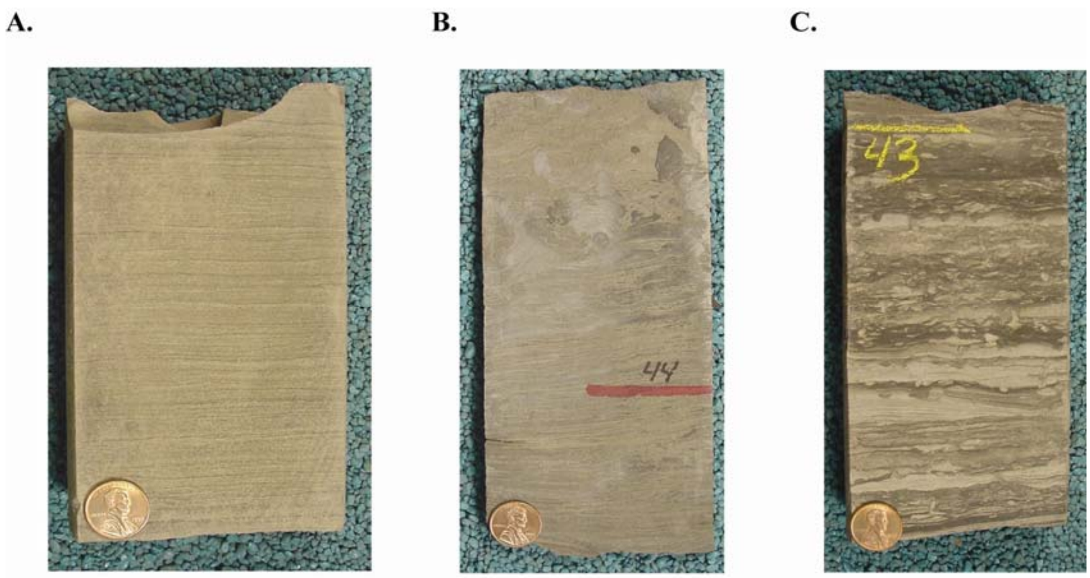

Figure 15 - Core photographs that are representative of Lithofacies 4. (A) Conoco Oil Company - #17 Watterud "A" (SESW Sec. 11, T.160N., R.95W.) Photograph shows the thin, slight wavy bedded argillaceous siltstone of this interval. (Depth – 8171.6 ft) (B) Shell Oil Company - #32-4 Young Bear (SWNE Sec. 4, T.148N., R.92W.) Photograph is an example of local variations encountered in some of these facies. Silty laminations are interbedded with algal mats. (Depth – 10443.5 ft) (C) Shell Oil Company - #32-4 Young Bear (SWNE Sec. 4, T. 148N., R.92W.) well shows the interbedded sequence of argillaceous siltstones with cleaner, discontinuous very fine-grained sandstones. Burrowing and brachiopods are present. (Depth – 10438.6 ft)

The lower siltstone to sandstone portion of the sequence shows thin parallel or slightly undulatory laminations. Laminations that are thicker are usually coarser grained. Locally, the rock is cemented with dolomite. Soft-sediment deformation is present locally. The basal beds to the upper sequence are thinly laminated, very fine-grained sandstones and siltstones with abundant burrows. Overlying sediments contain interbeds of thinly laminated to cross-bedded siltstones and very fine-grained sandstones. The sandstones occur also as discontinuous beds or lenses due to burrowing. Distribution of the argillaceous content within the interval varies locally, but generally increases towards the western side of the basin. Other features exhibited in core include dewatering structures and thin beds locally rich in organics. Cement, where present, is generally dolomite.

Lithofacies 4 ranges in thickness from 4 to 14 ft. The lower and upper portions of the facies reach a maximum thickness of 4 and 10 ft respectively. The lower contact of the facies is easily recognized on logs since it overlies the prominent clean gamma-ray bench created by lithofacies 3. Its upper contact with the overlying lithofacies 5 is easier to recognize on newer logs. The upper contact is generally gradational with the overlying lithofacies. The lower contact is conformable in the northern portion of the basin and unconformable in the southern portion of the basin. Environments change quickly in response to salt collapse. Sandy beds are still concentrated to the east of the Nesson anticline similar to the underlying lithofacies.

Lithofacies 5

Lithofacies 5 is a transitional facies that underlies the upper Bakken shale and consists of a medium to light grey or greenish-grey, massive to wispy laminated siltstone to a greenish grey massive carbonate (Figure 16). Thin beds of very fine-grained sandstone occur toward the bottom of the interval. These beds are tan to light grey and commonly have cross-ripple laminations. One fine-grained layer is underlain by and argillaceous layer rich in brachiopods. This brachiopod-rich layer is present in several of the wells. Brachiopods are present throughout the entire interval. In addition to the brachiopods, bryozoan and crinoid fragments are present in wells that are located towards the center of the basin. Many of the fossils are completely or partially replaced with pyrite. In addition to the brachiopods, bryozoan and crinoid fragments are present in wells associated with localized highs, such as the southern Nesson anticline and Burke County areas. In the shoaling areas the cement is commonly dolomite. The change from limestone to dolomite also occurs on the southern Nesson anticline as the localized zero edge is approached. Many of the fossils are completely or partially replaced with pyrite. Pyrite is disseminated through out the section increasing in concentration towards upper shale contact. The interval is massive immediately below the contact with the shale.

Thickness of the interval ranges from 2 to 6 ft, averaging 4.7 ft. The contact with the overlying Bakken shale may be gradational or abrupt depending on the location of the well in the basin. There is usually a well developed lag deposit of fossil fragments, bitumen grains, and pyrite, immediately overlying the contact where it is erosional. It is represented as a small clean spike on the newer gamma-ray logs (see wireline logs). However, it is commonly overshadowed by the high radioactivity of the overlying shale requiring close core control.

Upper Shale Member

The shale is similar to the lower shale. It is laminated to massive with poorly-sorted beds of silt-sized material. The upper shale has a higher organic content with lesser amounts of clay, silt, and dolomitic grains. Thin layers of pyrites grains, calcite and microfossils are locally common. Some of the microfossils are filled with quartz

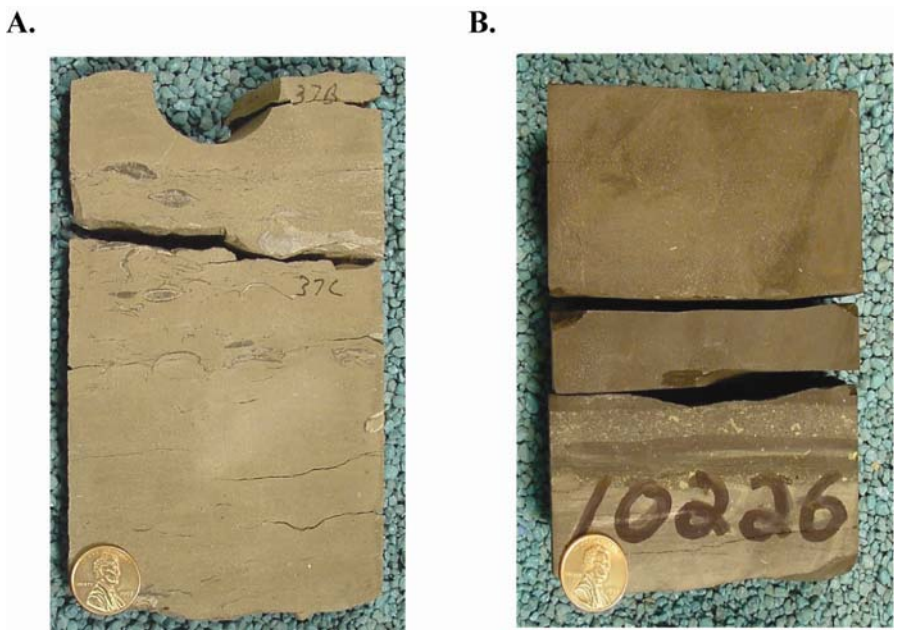

Figure 16 - Core photographs representative of Lithofacies 5. (A) Shell Oil Company - #32-4 Young Bear (SWNE Sec. 4, T. 148N., R.92W.) well shows the massive nature of the lithofacies. A traceable brachiopod bed is present in this photograph. (Depth – 10437.4 ft) (B) Meridian Oil Inc. - #44-27 MOI (SESE Sec. 27, T. 143N., R.102W.) This photograph shows the contact between Lithofacies 5 and the upper Bakken shale where it is unconformable. The contact is slightly irregular overlain by a well developed lag deposit consisting of fossil fragments, bitumen grains, and pyrite. (Depth – 10225.6 ft)

cement. Although the shale lacks the limestone and siltstone seen in the lower shale, it does have a gamma-ray log response in the central portion that represents a less kerogen-rich zone.

.

The upper shale represents the maximum extent of the Bakken Formation in the basin attaining a maximum thickness of 52 ft with a broader, less-defined depocenter (Figure 17). A lag sandstone rich in conodonts, fish bones, teeth and phosphatic particles may occur at the basal contact of the member.

As with the others, the upper shale appears conformable with the middle member in the central portion of the basin, although there is a faunal break between the two members. The break is thought to represent a disconformity or paraconformity that may coincide with a regionally extensive unconformity. It forms an angular unconformity with the Three Forks Formation along the margin of the basin and is conformably overlain by the Lodgepole Formation.

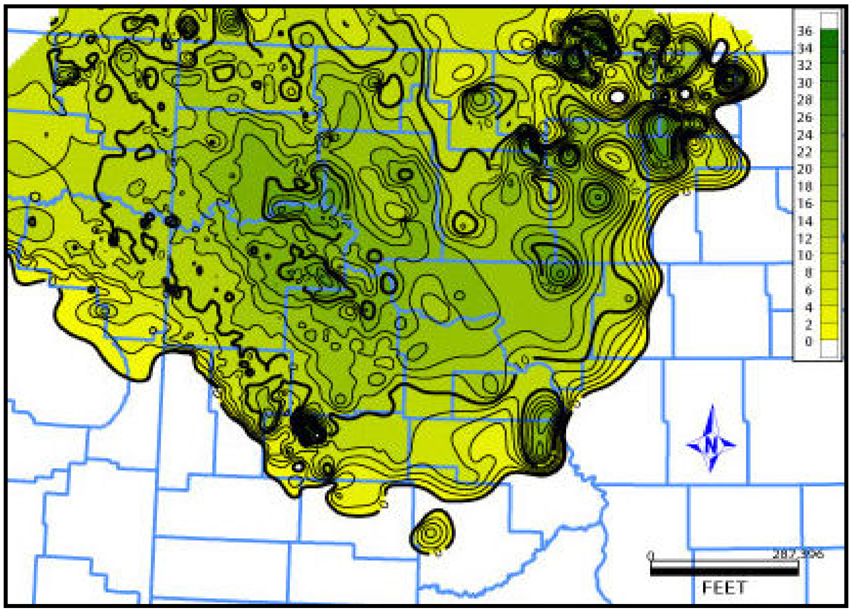

Figure 17– Isopach map of the upper Bakken shale in North Dakota and Montana. Irregular thicknesses along the shale margins are due to collapse of the Prairie salt.

Depositional History

The end of deposition of the Three Forks Formation was characterized by shallow marine to terrestrial sedimentation (Webster, 1984). The Devonian sea had withdrawn to the limit of the lower Bakken shale due to major uplift and erosion along the basin margin. Transgression began with the deposition of the lower Bakken shale and continued throughout Bakken time, as shown by the onlap nature of the Bakken members. Changes during the transgression, either in basin geometry, organic content, climate, or water conditions, resulted in anoxic conditions and the deposition of the uniform black, organic-rich shale. The anoxic conditions ended with the deposition of the middle member in normal, shallow marine waters. Strong current activity in addition to an influx of clastic material from the north or northwest occurred at this Deposition of the middle member and shale were interrupted for a time by a period of non-deposition or erosion (Hayes, 1984). This, in turn, was followed by the return of anoxic conditions and the deposition of the upper shale time. Continuous deposition resulted in a gradational contact between the Bakken Formation and the Lodgepole Formation. The Lodgepole marks the return of normal marine conditions to the basin. Transgression continued through the deposition of the lower Lodgepole Formation.

Throughout the depositional cycle of the Bakken, tectonic influences are readily apparent. Subtle charges in environment are present as the lithofacies adjust to localized uplift. Fractures on both the regional and local scale allow for fluid movement diagenetically change the rock. In addition the fractures assist in the development of the reservoir.

Depositional Model/Age

Several models have been proposed for the deposition of the black Bakken shales. The one that appears to be most widely accepted is a stratified water column in an offshore, marine environment (Lineback et al, 1987; Webster,1984; Karma, 1991). Anoxic conditions existed along the bottom of this water column for shale deposition. This is evidenced by the dark color, abundant pyrite, high organic content, and rare benthic fauna. The presence of conodonts and fish remains suggests an oxygenated zone above the bottom conditions. Minor modifications have been proposed by Hartwell (1998). His study suggests that higher energy environments periodically existed at the time of the deposition of the black shale, due to the presence of winnowed sulfide lags and micro cross-bedding. The presence of these features strongly suggests that the basin was shallower than previously thought, to allow for storms or currents to affect the base of the ocean floor. He suggested that extrabasinal influences, such as sea level change or climate, might be controlling the compositional variation measured within the shales.

The middle member is thought to have been deposited in aerobic marine to marginal marine conditions with moderate current activity. The light color, cross-bedding, trace fossils and abundant benthic fauna substantiate this hypothesis. The Bakken Formation was originally assigned a Mississippian age. However, faunal evidence now places the systemic Devonian/Mississippian boundary within the upper portion of the middle member.

Diagenesis

A number of important issues are outstanding with regard to the diagenesis of the Bakken. In part this results from the fairly complex mixture of lithologies that make up the middle member. However, a couple of points seem worth noting. The most obvious diagenetic feature present in the Bakken Formation is that diagenesis has reduced the original porosity of the Bakken to much less that 10 percent. Pore reducing diagenetic cements include calcite, dolomite, clays, minor amounts of chert and pyrite. In general, these diagenetic products tend to decrease reservoir quality to the point that economic production from the Bakken has not been technologically possible until recently . Most of the production from North Dakota, whether it be shale or mixed clastic/carbonate hosted, is apparently dependent upon fracturing. Horizontal and inclined fractures found in the middle member ,especially in the Parshall field, exhibit features that suggest that, at least for some fractures, there is a close association with fracturing and the either the generation or emplacement of oil or related fluids (Figure 18). Many of these fractures contain minor amounts of silica or calcite mineralization and tend to parallel micro-laminations of very finely crystalline dolomite. At this time the relationship between fracture orientation, fracture mineralization and matrix texture is poorly understood.

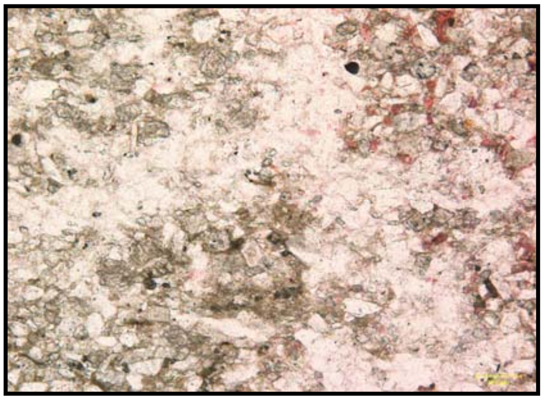

Figure 18 – Orthogonal fractures filled with silica cement within the middle member of the Marathon – Laredo 26-1 (SWNE Sec.26, T.156N., R.91W.).

Oil Generation

The Bakken Formation is a premier source rock, capable of generating enormous quantities of oil and gas. Early calculations of the source rock potential for this formation suggested the amount of oil generated ranged from 10 to 413 billion barrels (Dow, 1974; Schmoker and Hester, 1983; Webster 1982, 1984; Price, pers. com., 1998).

Migration of the Bakken oil has long been a topic of discussion. The Bakken Formation was thought to have sourced the large reservoirs within the Madison. The abnormally high fluid pressure from oil generation created its own set of vertical fractures, allowing for upward migration (Williams, 1974; Meissner, 1978). Geochemical examination of oils from the mid-Madison and Bakken reservoirs later ruled out the theory of vertical migration (Price and LeFever, 1994). Oils from the mid-Madison reservoirs did not show any affinity to the Bakken source rocks, and there was no evidence that mid-Madison reservoirs were either sourced by or mixed with oils derived from the Bakken source beds. Recently this topic has been revisited again (Li and Jiang, 2001; Jiang and others, 2001; Jiang and Li, 2003; 2002). Citing evidence from Canadian fields, the authors hypothesized oil migration out of the Bakken. It is interesting to note that the fields where Bakken oil exists in mid-Madison rocks are along the Hummingbird trough, an area where the Devonian Prairie salt is notably absent.

Regardless of the accepted migration theory, several items are apparent when dealing with the Bakken Formation. Lateral migration does occur. Large amounts of Bakken oil have been produced from areas where the source rocks are immature. Fields such as Rocanville, Roncott, and Hummingbird in Saskatchewan and Daly in

Manitoba, have produced significant quantities of oil. Vertical migration has been documented in Saskatchewan in the Hummingbird area. Vertical migration is much more difficult to prove in the United States side of the Williston basin. Overlying the Bakken through much of the area is a thick section of very dense and virtually impermeable carbonates of the Mississippian Lodgepole Formation. A similar situation occurs at the base of the Bakken Formation with a very tight sequence of siltstones, sandstones, and claystones of the Devonian Three Forks Formation. The result is that the Bakken Formation, an unconventional, highly overpressured oil and gas reservoir, cannot release its hydrocarbons to surrounding lithologies.

Another aspect of the Bakken that needs to be investigated concerns the production occurring at Parshall Field in an area that would normally be out of the T_{MAX} maturation window for the Bakken shales. Rock Eval ® analyses show the presence of Type II and Type III organic matter within the middle member of the Bakken. This may explain the earlier in-place generation of the oils in the field. The gas prone characteristics of Type III organic matter may have been the initial phase of generation. As pressure and temperature increased, the development of the micro-fracturing occurred. Added pressure from the middle member would, in turn, raise the pressure and temperature affecting the upper and lower shales. This increase would cause the conversion from smectite to illite and the kerogen-rich layers into hydrocarbons. Accommodation space is given by the clays present in the shales. Following the work of Lewan (1987), the hydrocarbon generating potential of the shales has not been exhausted. Portions of the shale still retain their immature characteristics while others, probably layers that are richer in kerogen, have actively undergone genereation.

Conclusions

The subtle facies relationships and diagenetic changes present in the middle member of the Bakken provide the framework when exploring for hydrocarbons in the unconventional reservoir. The interactions of this framework with the local and regional structure, as well as, the hydrocarbon generation processes complete the picture.

References Cited

Dumonceaux, G.M., 1984, Stratigraphy and depositional environments of the Three Forks Formation (Upper Devonian), Williston Basin, North Dakota, Master’s Thesis, University of North Dakota, Grand Forks, North Dakota, 189 p.

Dow, W.G., 1974, Application of oil-correlation and source-rock data to exploration in Williston Basin: AAPG Bulletin, vol. 58, no. 7, p. 1253-1262.

Green, A.G., Hajnal, Z., and Weber, W., 1985, An evolutionary model of the western Churchill province and western margin of the superior province in Canada and north-central United States: Tectonophysics, v. 116, p. 281-322.

Hartwell, J.W., 1998, Geochemical and petrographic analysis of the Upper Devonian-Lower Mississippian Bakken Black Shales from the Williston Basin, North Dakota: Master's Thesis, University of Cincinnati, Cincinnati, Ohio, 256p.

Hayes, M.D., 1984, Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota: Master's Thesis, University of North Dakota, Grand Forks, North Dakota, 178 p.

Heck, T., 1979, Depositional environments and diagenesis of the Bottineau interval (Lodgepole) in North Dakota, Master's Thesis, University of North Dakota, Grand Forks, North Dakota, 227 p.

Jiang, C, M. Li, Osadetz, K.G., Snowdon, L.R., Obermajer, M., and M.G. Fowler, 2001, Bakken/Madison petroleum systems in the Canadian Williston Basin. Part 2: molecular markers diagnostic of Bakken and Lodgepole source rocks: Organic Geochemistry, vol. 32, p. 1037-1054.

Jiang, C. and Maowen Li, 2002, Bakken/Madison petroleum systems in the Canadian Williston Basin. Part 3: geochemical evidence for significant Bakken-derived oils in Madison Group reservoirs: Organic Geochemistry, vol. 33, p. 761-787.

Jiang, C. and Maowen Li, 2002, Bakken/Madison petroleum systems in the Canadian Williston Basin. Part 4: diphenylmethanes and benzylcyclohexanes as indicators for oil derived from the Madison petroleum system: Organic Geochemistry, vol. 33, p. 855-860.

Karasinski, D.R., 2006, Sedimentology and Hydrocarbon Potential of the Devonian Three Forks and Mississippian Bakken Formations, Sinclair Area, Southeast Saskatchewan-Southwest Manitoba: Master's Thesis, University of Manitoba, 454p.

Karma, R., 1991, Geology and geochemisty of the Bakken Formation (Devonian and Mississippian) in Saskatchewan: Master's Thesis, University of Regina, Regina, Saskatchewan, 302 p.

LeFever, J.A. and R.D. LeFever, 2005, Salts of the Williston Basin, North Dakota, North Dakota Geological Survey Report of Investigation No. 103.

Lewan, M.D., 1987, Petrographic study of primary petroleum migration in the Woodford Shale and related rock units: *in* Migration of Hydrocarbons in Sedimentary Basins, Brigitte Doligez eds., p. 113-130.

Li, M., and C. Jiang, 2001, Bakken/Madison petroleum systems in the Canadian Williston Basin. Part 1: C20-C26 20-n-alkylpregnanes and their triaromatic analogs as indicators for Upper Devonian-Mississippian epicontinental black shale derived oils?: Organic Geochemistry, vol. 32, p. 667-675.

Luther, K.C., 1988, Proterozoic structures in north-central North Dakota: a gravity study: Master's Thesis, University of North Dakota, 116p.

Nicholas, M., 2006, Devonian Three Forks Formation, Sinclair and Surrounding Area, Southwestern Manitoba, *in* Saskatchewan and Northern Plains Oil and Gas Symposium Core Workshop Volume, Regina, Saskatchewan, p. 1-26.

Osadetz, K.G., B.P. Kohn, P. O'Sullivan, S. Feinstein, P.K. Hannigan, R.A. Everitt, C.F. Gilboy, R.K. Bezys, and L.D. Stasiuk, 1998, Williston Basin thermotectonics: variations in heat flow and hydrocarbon generation, in, J.E. Christopher, C.F. Gilboy, D.F Paterson, S.L. Bend, eds., Eight International Williston Basin Symposium, Saskatchewan Geological Society Special Publication No. 13, P. 147-165.

Price, L.C., and J.A. LeFever, 1994, Dysfunctionalism in the Williston Basin: the Bakken/mid-Madison petroleum system: Bulletin of Canadian Petroleum Geology, vol. 42, no. 2, p. 187-218.

Schmoker, J.W., and T.C. Hester, 1983, Organic carbon in the Bakken Formation, United States portion of Williston Basin: AAPG Bulletin, vol. 67, no. 12, p. 2165-2174

Webster, R.W., 1984, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota, *in* J. Woodward, F.F. Meissner, and J.L. Clayton, eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 57-82.

Williams, J.A., 1974, Characterization of oil types in Williston Basin: AAPG Bulletin, vol. 58, no. 7, p. 1243-1252.