

Stratigraphy and Sedimentology of the Bakken Formation of West-central Saskatchewan: A Preliminary Report

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The Devonian-Mississippian Bakken Formation is a dominantly siliciclastic unit in the subsurface of the Williston Basin (Figure 1). It produces oil and gas adjacent to the pre-Cretaceous unconformity in west-central Saskatchewan: the Cactus Lake, Hearts Hill, Luseland, Plover Lake, Court and North Court, Fusilier, Hoosier and North Hoosier, Buffalo Coulee and Buffalo Coulee North, and Coleville and Coleville South fields are located within the area of townships 30 to 36, ranges 23 to 29, west of the third meridian (Figure 2).

The Bakken Formation was divided informally by Nordquist (1953) into a lower black shale member, a middle siltstone-sandstone member, and an upper black shale member. The formation has long been recognized as a significant marker in the subsurface of the Williston Basin, identifiable by the high gamma-ray kick (over 200 api) and a low density reading for the upper and lower black shales (Figure 3).

Recently, the Bakken Formation has become important because of successful drilling of horizontal wells, the first of which was 1987 by Meridian Oil Inc. in North Dakota (LeFever, 1991).

The Bakken Formation and its lithologic and chronostratigraphic equivalents are found over two-

thirds of the North American continent. Conditions within the 'Bakken sea' were uniform over an extensive area, as demonstrated by the many lithologic equivalents of the formation. These include the Exshaw Formation of the Western Canadian Sedimentary Basin; the Antrim Formation of the Michigan Basin; the Ohio and Chattanooga shales of the Appalachian Basin; the New Albany Shale of the Illinois Basin; the Lower Mississippian Black Shale in the Permian Basin; the Woodford Formation in the Anadarko Basin (Arbuckle Mountains); the Sappington Member of the Three Forks Formation in Montana; the Cottonwood Canyon Member of the Lodgepole limestone of southern Montana and northern Wyoming; the Leatham Formation of Utah; and the Englewood Formation of South Dakota (Gutschick and Rodriguez, 1979; Sandberg *et al.*, 1980; Sandberg and

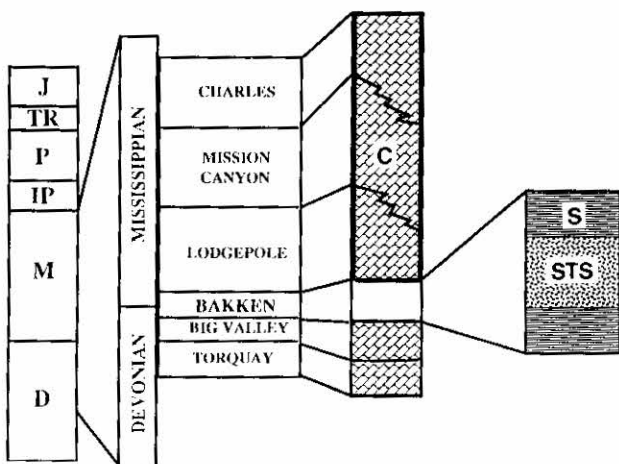


Figure 1 - Stratigraphic chart showing the Bakken Formation, and under- and overlying strata as found in west-central Saskatchewan. C=carbonate, S=shale, and STS=sandstone and siltstone.

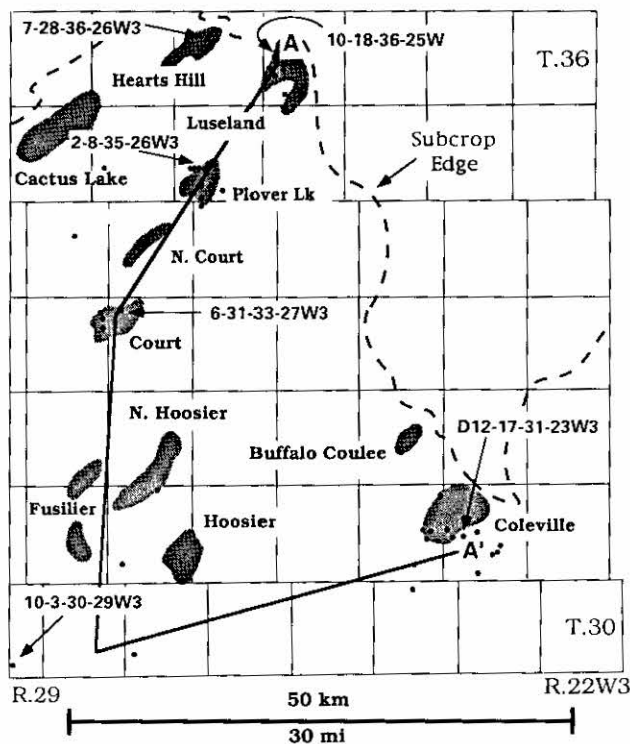


Figure 2 - Map of the study area showing cored wells used for this study, the oil and gas field outlines, and cross-section line A-A'.

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WELL 10-3-30-29W3

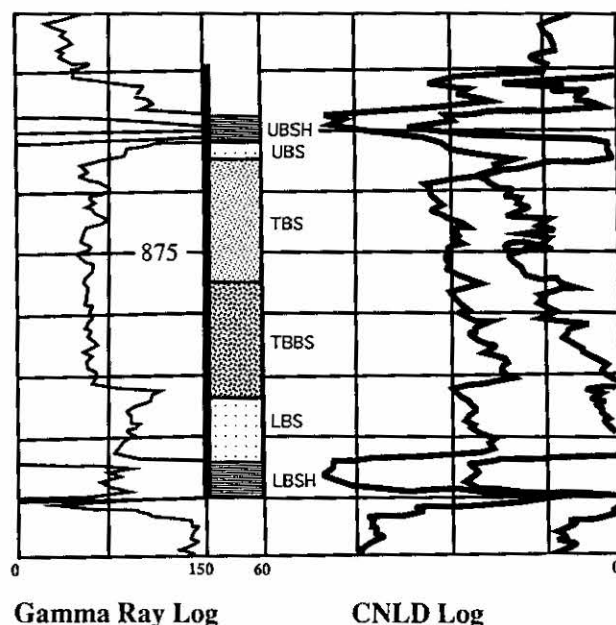


Figure 3 - Gamma Ray and Density log traces through the Bakken Formation from well 10-3-30-29W3; cored depths are from 860 to 894 m. Identified are the LBSh (lower member), LBS, TBBS, TBS, UBS (middle member), and the UBSh (upper member) that are described later in this paper.

Gutschick, 1969, 1979; Sandberg and Poole, 1977; Gutschick *et al.*, 1962; Sandberg, 1965; Sandberg and Klapper, 1967; Sando, 1967; Macqueen and Sandberg, 1970; Klapper and Furnish, 1962; Klapper, 1966; Hayes, 1985; Holland *et al.*, 1987; Meissner, 1978; Thrasher, 1987).

Few studies have been made of Bakken stratigraphy in southwestern Saskatchewan. Kents (1959) studied the Three Forks and Bakken formations and, more recently, Kent (1984) discussed the depositional history of Mississippian strata in southeastern Saskatchewan, including Bakken strata. Ducharme and Murray (1980) discussed the depositional environments and diagenesis of the Bakken Formation at Cactus Lake (Figure 2). The purpose of this paper is to summarize results from a preliminary investigation of the sedimentology and depositional environments of the Bakken Formation in west-central Saskatchewan.

In west-central Saskatchewan, the Bakken Formation unconformably overlies the Big Valley Formation, and is conformably overlain by the Souris Valley limestones of the Lodgepole Formation. A tripartite division of the formation is easily seen in geophysical logs and core (Figures 1 and 3).

All three members of the Bakken Formation are present in the study region, except where pre-Cretaceous erosion has removed some or all of the strata, or where the upper shale member is absent and Lodgepole rocks directly overlie middle Bakken sandstone (e.g. 7-28-36-

26W3 well). The lower shale member lies with a marked unconformity on green shales or grainstones of the Big Valley Formation. The lower shale member is, in turn, overlain by the middle sandstone member, which grades rather abruptly into the upper shale member or the transition beds that lie between the Souris Valley beds (Lodgepole Formation) and the Bakken Formation. These transition beds, which are calcareous sandstones, are included here as part of the upper member of the Bakken Formation because the base of the Lodgepole Formation is defined as the first carbonate bed above the Bakken Formation (Kents, 1959 p21).

1. Methods

Core and well data are abundant within the study area. A total of 55 cores were logged with detailed logging completed on 43 cores from localities within the study area (Figure 2) to define lithological units, and to infer depositional settings. Most were from post-1980 wells, because much of the older core is of poor quality, and provides little useful sedimentological information. About 120 core samples were taken from 16 wells for petrographic and microprobe analysis, and palynological preparation. Approximately 70 thin sections were stained for carbonates using the method of Dickson (1966).

2. Subdivisions of the Bakken Formation

Nine facies are identified from the Bakken Formation in west-central Saskatchewan, based on lithology, sedimentary structures, texture, colour, and fossil content. Figures 4 and 5 illustrate the stratigraphic succession and spatial distribution of the different facies of the Bakken Formation. Figure 4 highlights three types of contacts, three significant unconformities, and facies changes.

The upper and lower shale members of the Bakken Formation, although similar in appearance, are considered to represent different facies. They are referred to here as the upper black shale (UBSh) and the lower black shale (LBSh). The transitional calcareous sandstone (TRANS) is laterally equivalent to the UBSh (Figure 4 and Figure 5, column B) and is described separately.

The remaining facies described are from the middle member of the Bakken Formation. They are termed the lower bioturbated siltstone (LBS), oolitic-bioclastic grainstone (OBG), thinly bedded bioturbated sandstone (TBBS), thinly bedded sandstone (TBS), interbedded sandstone-siltstone-shale (ISSS), and upper bioturbated siltstone (UBS). For the remainder of this paper the facies will be referred to by their abbreviations.

a) Lower Black Shale Facies (LBSh)

The range of thickness for the LBSh in the study area is 1.8 to 7.7 m (Table 1 and Figures 4 and 5). Generally, the shales of the LBSh are black to very dark brown and, rarely, green. They are homogeneous, fissile to well indurated, waxy, non-calcareous to slightly calcareous, pyritiferous, and uraniferous. Amorphous or-

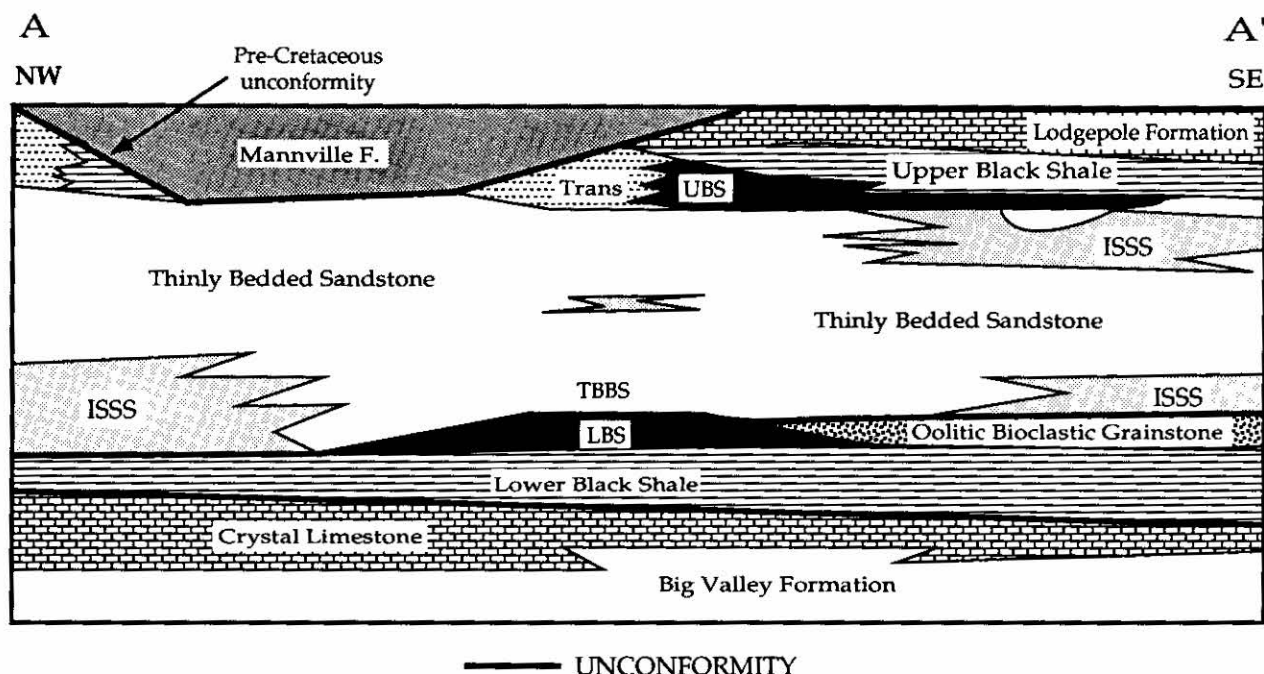


Figure 4 - Schematic diagram illustrating the general spatial relationships, distribution, and stratigraphic position of the Bakken facies.

ganic material is abundant, most commonly parallel to fine-grained clay laminae. Very fine laminations are the only sedimentary structures observed. Pyrite is common, found locally on bedding planes as spherules and nodules that range in size from microscopic to a few millimetres in diameter. The radioactivity detected on gamma-ray logs is caused by uranium, thorium, and potassium (Kents, 1959, p18).

Recognizable organic remains include flattened spore cases of *Tasmanites*, conodonts (Karma, 1991), *Foresia*, a pelagic alga, and conchostracans (Thrasher, 1987). Macrofossils include gastropods, *Lingula*, and other brachiopods (Fuller, 1956; Kents 1959; Macqueen and Sandberg, 1970). No macrofossils have been recognized in the black shales within the study area.

The trace fossil, *Terribellina*, although rarely observed, was found near the middle of a 4 m section of the lower shale, and showed slight to moderate compaction. *Terribellina* is included in the *Cruziana* ichnofacies (Pember-ton, 1985) which is associated with the neritic zone, and low energy. Subangular to subrounded, equant to elongate, silt-sized monocrystalline quartz grains occur in some thin laminae. Most are only one grain thick, or are scattered in the lower shale.

Parallel lamination, abundant organic matter, and the paucity of sedimentary structures suggest deposition below storm wave base (in excess of 30 m) in an anoxic environment. This may not be the case; however, because of the homogeneous nature of the LBSH, sedimentary structures, such as graded bedding, may not have developed, or may not be visible. Shale compaction to roughly 20 percent of the original depositional thickness is so great that sedimentary structures

would be obliterated or compressed, giving the sediment a parallel laminated appearance. Even if the LBSH were deposited in water depths where occasional waves, currents and storm surges could affect the sediment, the colloidal nature of clay-sized particles could keep the slurry in suspension until the disturbance passed. Then the suspended material would settle out uniformly (or so it would appear after compaction). Green 'patches' of shale in the LBSH indicate a decrease in organic carbon, which may be expected close to shoreline or at shallower depths, where increased turbulence would decrease anoxicity. Black shale deposition may have occurred in as little as a few tens of metres water depth.

b) Oolitic Bioclastic Grainstone Facies (OBG)

The OBG is composed of bioclasts (articulated, disarticulated, and fragmented), ooids and phosphatic particles, some of which are recognizable as fish detritus. The facies, which ranges in thickness from 0.4 to 3.5 m, is composed of fining-upward cycles up to 1 m thick. The basal part of each cycle is a lag deposit made up of coarse shell debris; the upper part is primarily ooid grainstone. No more than 2 cycles have been noted in any well in the study area. Rarely, lime mud lumps occur beneath shells (as seen in thin-sections).

Allochems are as large as 1 to 2 cm, but the average size is 4 to 5 mm. Skeletal allochems include whole and broken brachiopod shells, large branching bryozoans (fenestellids), foraminifera, crinoid plates and columnals, echinoid spines, ostracods, rare calcareous red algae, and phosphatic fish remains. Larger shells are oriented parallel to bedding, concave upward. Ooids are the

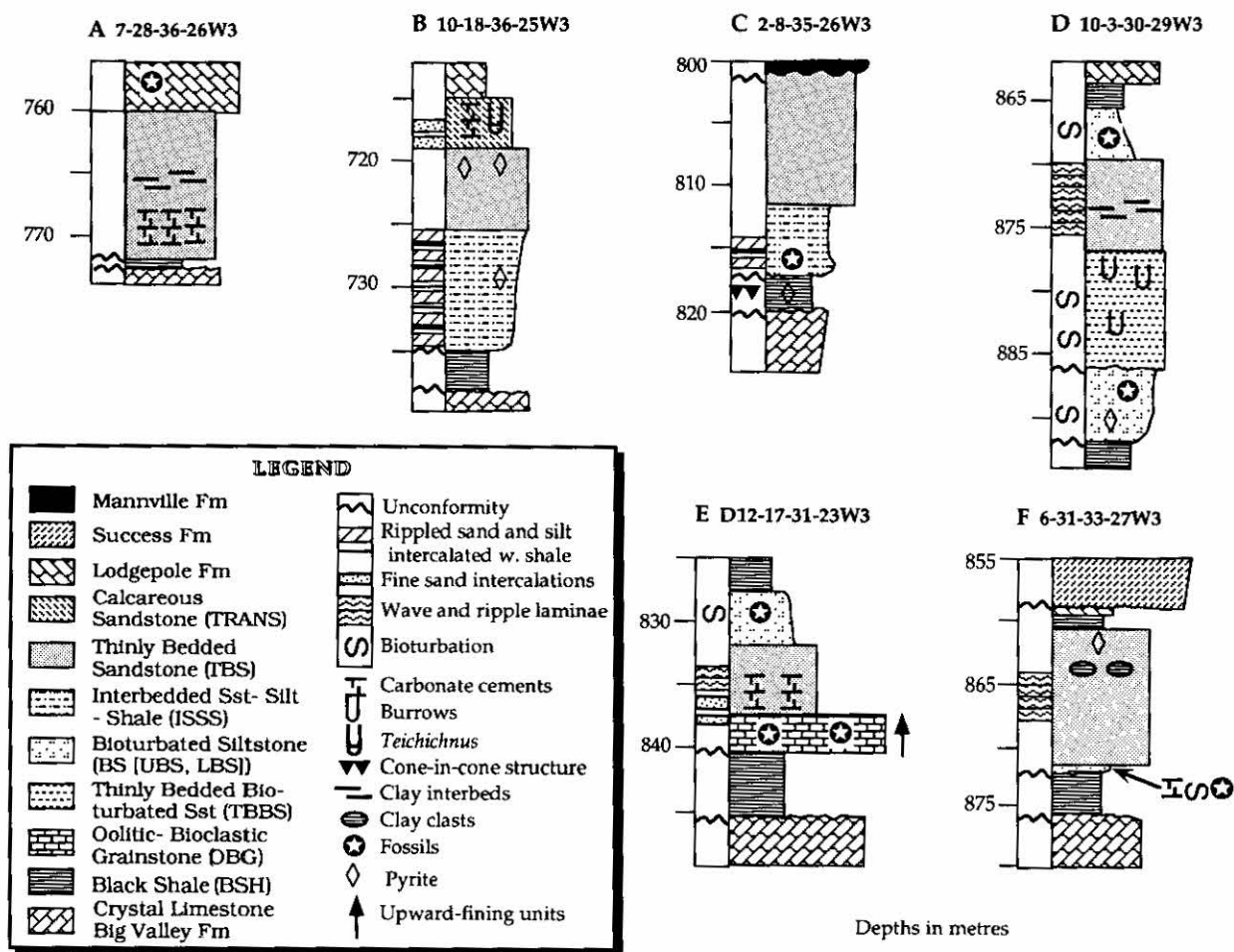


Figure 5 - Stratigraphic sections A to F are illustrations from cored wells 7-28-36-26W3, 10-18-36-25W3, 2-8-35-26W3, 10-3-30-29W3, D12-17-31-23W3, and 6-31-33-27W3 respectively. They show important contacts, facies distributions, sedimentary structures, and thicknesses.

most abundant component and make up 95 percent of the rock in the upper part of each cycle.

The presence of ooids, lack of fine-grained material (i.e. mud), and the breakage and orientation of shell debris suggest high energy levels, likely at or just below sea level, for the OBG. Cyclicity may indicate minor depth

Table 1 - Thickness ranges in metres for the entire Bakken, the lower, middle, and upper members at five different localities and the study area as a whole (total) are listed in order from most northerly to most southerly (see Figure 2). Only wells unaffected by pre-Cretaceous erosion (PKU) are used in thickness calculations. Five 'areas' are identified where wells are concentrated.

Areas	Bakken	Lower Member	Middle Member	Upper Member
Luseland	8.5-22.8*	1.8-4.0	5.7-18.8	0.4-1.0*
Plover Lake**	PKU	1.9-3.0	16.1-22.8	PKU
Court	11.0-17.8*	2.9-4.0	11.5-16.1	1.2-3.6*
Hoosier	21.6-31.1	2.9-4.3	16.9-26.1	1.3-2.7
Coleville	12.5-26.0	4.5-7.7	3.3-18.8	0.8-3.1
Total	12.5-31.1	1.8-7.7	3.3-26.1	0.4-3.6

Notes:

* Fewer wells than the total logged were used to calculate thicknesses; PKU affects the Bakken Formation in this area.

** The PKU has removed all of the upper and some middle Bakken at Plover Lake so that depositional thicknesses are unknown.

c) Lower Bioturbated Siltstone Facies (LBS)

Bioturbated siltstones are found in the lowermost stratigraphic position of the middle member of the Bakken Formation (Figure 5, columns D and F). Thicknesses range from 0.6 to 5.8 m. The LBS is a homogeneous, pyritiferous, intense-

ly bioturbated, grey to greenish grey silty claystone or clay-rich siltstone and sandstone. *Helminthopsis* (*Nerites* ichnofacies) and *Chondrites* (*Cruziana* ichnofacies) are the only identifiable trace fossils (Pemberton *et al.*, 1992). Allochems are abundant and include crinoid columnals and ossicles, brachiopods, and a few ostracods that are generally randomly oriented as a result of bioturbation.

Intense bioturbation, a normal marine ichnofossil assemblage and skeletal allochems are all commonly associated with open marine conditions, and indicate that the LBS was deposited under well-oxygenated, quiet water conditions. Sedimentary structures are completely obliterated; the fine-grained nature of the sediment suggests little coarse clastic input. The LBS is laterally equivalent to the OBG; it is likely that the LBS was deposited in a lagoon, or shoreward of the ooid shoals (OBG), the shoals protecting the lagoon from wave and current induced turbulence.

d) Thinly Bedded Bioturbated Sandstone Facies (TBBS)

The TBBS occurs only in the southwest corner of the study area (Hoosier area in Figure 2), where it ranges in thickness from 2.0 to 9.9 m. It is predominantly a muddy sandstone; silt and shale make up less than 30 percent of the unit. It is easily identified by abundant bioturbation and a well-developed shell lag at its base. Trace fossils include: *Helminthopsis*, *Terribellina*, *Asterasoma*, and *Planolites*. These forms are included in the *Cruziana* ichnofacies which is typically found in the sublittoral zone (Pemberton *et al.*, 1992). Brachiopods are abundant and are commonly found articulated and 'filled' with sand or authigenic pyrite. Shells are randomly oriented as a result of mixing caused by intense bioturbation. Remnants of original bedding are identifiable, and traces of fine-grained sand silt and clay interbeds are discernable. Bioturbation increases in intensity upward, but ends abruptly. The boundary between the TBS and the underlying TBBS is defined as the level above which bioturbation ceases.

Broken skeletal grains, peloids, and ooids are present, and resemble in size and appearance those found in the OBG. Quartz grains range from 0.06 to 0.2 mm, and are more variable in size than any other facies in the middle member.

The basal lag containing OBG-like material at the base of the TBBS indicates erosion into the OBG. Intense bioturbation suggests stable, well-oxygenated conditions allowing for abundant animal life. Localization of the TBBS (9 m thick in southwest; Figure 5, column D) may reflect minor topographic variance, or differences in sediment stability; the LBS might have been far more susceptible to erosion than the already partly cemented OBG.

e) Thinly Bedded Sandstone Facies (TBS)

The thinly bedded sandstone is the best reservoir rock in the study area. Thicknesses range from 0 to 15.8 m. The sandstone is composed of fine- to very fine-grained

quartz with an average grain size of 0.15 to 0.2 mm. Plagioclase and microcline make up less than 10 percent of the grains. Subangular to moderately well-rounded quartz grains exhibit overgrowths that were selectively to non-selectively replaced by calcite cement. There is little to no matrix in the TBS, and commonly the facies is uncemented and disintegrates into rubble in core. Oil gives the sandstone some cohesion. Attempts to make thin sections of the better reservoir rocks were unsuccessful.

Sedimentary structures include some wave, and abundant current ripples and herringbone cross-bedding. These are small scale, and average 1 to 2 cm in thickness. Normally graded bedding with slightly coarser grain size (0.25 mm) than the average (0.15 to 0.2 mm), and with erosional lower contacts, is present locally. Mudstone interbeds and mud rip-up clasts make up 10 percent or less of the facies, and are of the same composition as the finer grained interbeds of the ISSS (Figure 5, column F). Rare occurrences of *Chondrites* have been noted, and this may be an indication of a low level of bottom water oxygenation (Pemberton *et al.*, 1992).

The TBS is commonly found abruptly overlying the ISSS; it is difficult to tell because of oil staining, but many of the contacts between the TBS above and the ISSS below may be erosional. Mud rip-up clasts contained within the TBS that appear to be of the same composition as the finer (silt and mud) beds of the ISSS also indicate erosion. Herringbone cross-bedding, and wave cross laminae indicate bi-directional tidal currents and influence of waves. Stressed conditions related to tidal settings are reflected in the paucity of trace fossils in the TBS.

f) Interbedded Sandstone Siltstone Shale Facies (ISSS)

The ISSS consists of interbedded brown sand, brown grey silt and greenish grey shale in varying proportions. Sand to mud ratios vary from 80:20 to 50:50, and average 70:30. Bioturbation is slight, and where burrows (*Thalassinoides*?) are seen, they are horizontal, following bedding planes in the sandy beds. Where the sand to mud ratio is 50:50, abundant soft-sediment deformation features, such as flame and ball-and-pillow structures, are preserved, which may indicate rapid deposition. The presence of convolute bedding suggests that syndepositional slumping occurred. Brecciation in this facies suggests movement after the sediment was partly or wholly lithified, and may be related to earthquake activity, local collapse features associated with karstification in the Torquay Formation, or slumping of partly lithified tidal creek banks. Thicknesses within the ISSS range from 0 to 13.3 m.

Wavy, lenticular, flaser, and starved ripple bedding are abundant, and bedding types vary with the sand to mud ratio. The predominant sedimentary structures are current ripples. Bedsets are <1 to 5 cm thick, rarely exceed 5 cm, and average 1 to 2 cm. Clay drapes are found on both silt and sand interbeds. Rare graded bedding is seen in the sandstone beds and small-scale hummocky

cross-stratification has been observed in siltstone beds. Rare trace fossils are found parallel to bedding in the fine-grained interbeds and are filled with sand.

The TBS and ISSS are contiguous, and the two typically occupy the central part of the middle sandstone member within the Bakken Formation. Commonly, an upward succession of ISSS-TBS is found, but in places TBS-ISSS-TBS-ISSS, or ISSS-TBS-ISSS successions are observed. The TBS is interpreted to represent tidal creek migration over tidal flat (ISSS) deposits in the study area. The presence of mud, silt, and sand as discrete interbeds suggests that deposition took place under fluctuating energy levels. Flaser, lenticular, and wavy bedding are commonly associated with tidal deposits, but alone are not diagnostic of tidal sequences. However, the indicators of fluctuating energy levels, the presence of flaser, lenticular and wavy bedding, clay drapes, convolute bedding, and the spatial relationship of the ISSS to the TBS all suggest tidally-influenced sedimentation.

g) Upper Bioturbated Siltstone Facies (UBS)

The UBS shares many of the same characteristics as the LBS. Some differences are identified; the UBS is a mixture of finer grained carbonates and siliciclastic silt, and is pervasively dolomitized. Dolomitization may have increased the grain-size of the UBS; originally this facies may have been primarily shale. The UBS occupies the uppermost stratigraphic position within the middle member of the Bakken Formation and ranges in thickness from 0.4 to 3.4 m. Skeletal allochems characteristic of an open marine realm and intense bioturbation suggests that the UBS depositional environment was relatively unstressed.

A quiet water, well-oxygenated environment in the neritic zone is envisioned for the UBS. This is in accord with the slightly deeper water deposition of the upper black shale that occurred during late middle Bakken time. Gradually increasing water depth after the deposition of the TBS and ISSS resulted in UBS deposition that in turn, was followed by deposition of the TRANS and UBSH facies.

h) Transitional Calcareous Sandstone Facies (TRANS)

The TRANS consists of an intensely bioturbated, shaly, calcareous sandstone. The facies contains a shale and micrite matrix, very fine-grained quartz sand and phosphate nodules. It is dolomitized and patchy calcite cement is common; both the dolomite and calcite cements are ferroan. The shale is green and appears to be similar to the green UBSH; the quartz sand grains resemble those found in the middle member of the Bakken Formation. Burrows are abundant, but of low diversity; *Teichichnus* is the only trace fossil recognized. The ichnofossil assemblage may indicate harsh conditions, such as lack of oxygen. This facies is found locally in the Luseland, Plover Lake, and Court areas, and ranges in thickness from 1 to 4 m.

The TRANS is laterally equivalent to the UBSH (Figure 4). High density, low-diversity trace fossil assemblages indicate stressful conditions. *Teichichnus* belongs to the *Cruziana* ichnofacies (Pemberton *et al.*, 1992), and is commonly found at shallow subtidal depths. Anoxia is indicated by the small trace fossil community and the location of the TRANS laterally adjacent to the UBSH, which was surely affected by dysaerobic to anaerobic conditions. Shallow depths, or proximity to a shoreline (shallower or closer than the UBSH), would explain the less intense anoxia and coarser grain size of the TRANS.

i) Upper Black Shale Facies (UBSH)

The upper black shale shares many of the characteristics of the LBSH, although locally it is slightly coarser grained due to a higher content of silt-sized quartz grains. Thickness of the upper member of the Bakken Formation ranges from 0.8 to 3.6 m. The upper shale member also contains quartz silt laminae, visible in hand specimen. These laminae are commonly several grains thick and, in places, are graded. They may have resulted from storm activity or turbidity currents, and are locally abundant (e.g., the 1-7-31-23W3 well). Some of the coarser laminations form thin beds up to 2 cm thick; fine sand and silt within the beds are burrowed. In places, basal contacts are abrupt and/or erosive. Fish remains and rare plant fragments have been described by Thrasher (1987, p59), but were not observed in the study area.

The UBSH is commonly green, and grades laterally into the TRANS. This is a good indication that anoxia and black shale deposition occurred at shallower depths than previously thought (a minimum of 150 m depth according to Lineback and Davidson, 1982; Etensohn and Barron, 1981; Byers, 1977). At shallower depths, increased mixing of the water column would make more oxygen available. Green colouration is common in the UBSH in the study area and indicates slightly less reducing conditions and lower organic matter content than black coloration of the shales. Where the UBSH is green, it is in proximity to the TRANS which also indicates dysaerobic, rather than anaerobic conditions, that are typical of the black UBSH.

3. Depositional Environment and History

Previous studies on the Bakken Formation have focused on the interpretation of the black shales. To date, no one has been able to determine a maximum water depth for the basin that covered much of North America during late Devonian and early Mississippian time. Some models for black shale deposition (e.g., the Black Sea) require a deep, stratified water column with anoxic bottom conditions (Lineback and Davidson, 1982; Etensohn and Barron, 1981; Byers, 1977). While such models are satisfactory to explain black shale deposition in the Appalachian foreland basin, they do not account for the apparently shallow-water nature of the middle Bakken succession. The swamp theory (Christopher, 1961) has been obsolete since conodonts, unquestionably marine microfossils, were identified from many late Devonian—early Mississippian black shales. It

is proposed here that black shale deposition occurred in a few tens of metres of water. These depths would still permit pelagic fall out and would reduce the chances of organic matter being scavenged or oxidized on its way to, or on the bottom. Depths of a few tens of metres in a stratified water column make the shallow nature of the middle member easier to explain; far less sea level change is involved in this explanation.

The middle Bakken member in west-central Saskatchewan represents shallow water deposition relative to the LBSH and UBSH facies. The OBG was deposited under high energy conditions close to fair weather wave base. Bioturbation and the faunal content suggest open marine deposition for the LBS and UBS facies; trace fossil assemblages indicate shallow subtidal (neritic) conditions for the TBBS and LBS facies. The TBBS appears to cut into underlying facies (OBG and LBS) (Figure 4); a well developed basal lag deposit and the incorporation of OBG-like sediment at the base of the TBBS and the ISSS are good evidence for erosion prior to TBBS time.

The TBS and ISSS were deposited and reworked by tidal processes. The uniform grain size, sedimentary structures, and lack of ichnofossils within the TBS indicate moderate energy and restricted conditions, typical for tidally induced sedimentation in an environment affected both by waves and currents. The UBS is interpreted to represent deposition in the shallow subtidal realm.

The UBSH is green in some wells, especially in the northern part of the study area near wells that contain the TRANS at the same stratigraphic level. The TRANS is interpreted to be the result of deposition under dysaerobic conditions. A setting in shallower water where mixing of the water column would reduce anoxia would allow for dysaerobic conditions in close proximity to black shale deposition.

Many of the facies of the Bakken Formation show some evidence of stressed conditions suggesting that for most of Bakken time a harsh environment existed. Organic-rich black and green shales (LBSH and UBSH), and high density, low diversity faunas (TRANS), the paucity of trace fossils (TBS, ISSS) and an abundance of pyrite and ferroan cements all suggest restriction. A low oxygen content, elevated salinity, a high organic productivity and resultant oxygen depletion in the black shale, and/or periods of low nutrient status within the middle member (TBS), may have been some of the variables involved in creating the harsh environment that existed for most of Bakken time.

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