PETROLEUM GEOLOGY OF THE DEVONIAN THREE FORKS FORMATION, SINCLAIR FIELD AND SURROUNDING AREA, SOUTHWESTERN MANITOBA

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Abstract

The Sinclair Field (Townships 7 to 8, Ranges 28 to 29W1) is the newest oil field discovery in Manitoba and has greatly expanded in size and production since its discovery in 2004. The oil field had been previously explored in the 1960's, but the pay was missed by early exploration efforts. Proven and probable reserves are estimated at 3.8 million m^3.

The Devonian Three Forks Formation is a cyclical transgressive-regressive sequence of shaley, silty dolarenite, interbedded with shale and brecciated in many places. Deposition of the Three Forks was influenced by several weathering events due to transgressive and regressive cycles and basin tectonics. It is subdivided into four units. Unit 1 is the lowermost unit and the most widespread, and is the most oxidized and weathered of the units. Unit 2 is an interbedded siltstone and shale, massive shale and occasionally brecciated, and is productive as a secondary reservoir at the Sinclair Field and Daly Field (Townships 9 to 10, Ranges 27 to 29W1). Unit 3 is a red-brown highly oxidized silty shale. Unit 4, the uppermost unit represented in Manitoba, is an interbedded siltstone and silty shale with thick subunits of highly distorted and brecciated siltstone beds. Unit 4 is the primary and most productive reservoir at Sinclair Field. Thinning of the Three Forks and truncation of the best reservoir units towards the east suggest the eastern expansion of the Sinclair Field may be limited.

The sub-Paleozoic extension of the Precambrian Superior Boundary Zone (SBZ) runs north-south in the study area. The Birdtail-Waskada Axis (BWA; McCabe, 1967) runs roughly through the middle of the southern extent of the SBZ. Isopach, structural and siesmic evidence suggest the presence of faults running parallel to the SBZ eastern and western margins; these faults were active at the end of the Devonian. Movements along these faults caused the preservation of the primary reservoir (Unit 4) of the Three Forks Formation east and west of the SBZ margins, while secondary reservoir unit (Unit 2) was exposed as a plateau on the BWA. The preservation of Unit 4 in some wells east of the BWA margin, along the SBZ margin opens up the possibility that, under the right trapping conditions, there may be another Sinclair-type play yet to be discovered east of Range 24W1.

Introduction

The study area consists of the Sinclair Field (Townships 7 to 8 and Ranges 28-29W1) and the surrounding area, including Townships 3 to 10 and Ranges 24 to 29W1 (Figure 1). Sinclair Field is the most recent oil field in Manitoba. The Sinclair Field area had been previously explored in the 1960's, but the pay was missed by early exploration efforts. Since its discovery in 2004, and field designation in 2005, some 285 wells have been drilled at Sinclair Field by operators including Tundra Oil and Gas Limited, as well as Rideau Petroleum Ltd, Grand Banks Energy Corporation and Kiwi Resources Ltd. Of the 285 wells drilled in Manitoba in 2005, 201 were drilled at Sinclair Field. As of April 2006, proven and probable reserves are estimated at 3.8 million m^3 (John Fox, 2006, pers. comm.).

There are currently 9 commingled oil pools designated within Sinclair Field which produce from the Bakken/Three Forks Formations. The productive interval of the Sinclair Field is dominantly the Three Forks Formation, Qu'Appelle Group, with minor production from the overlying

Middle Member of the Mississippian Bakken Formation. The field has cumulatively produced approximately 197,000 m^3 oil (over 1 million barrels). In 2005, Sinclair Field represented approximately 20% of Manitoba's total oil production.

Located in the southwestern corner of Manitoba, the Three Forks Formation, Qu'Appelle Group represents the uppermost Devonian transgressive-regressive cycle prior to a major period of transgression and deposition of the overlying organic-rich sandstones and shales of the Mississippian Bakken Formation.

Geological Setting

Southwestern Manitoba is situated along the northeastern flank of the Williston Basin. Strata from the Paleozoic, Mesozoic and Cenozoic form a basinward thickening, southwestern sloping wedge. It reaches a total thickness of 2.3 km at its thickest point in the extreme southwestern corner of Manitoba, near the Saskatchewan interprovincial border and the North Dakota, U.S.A. international border.

The Paleozoic unconformity represents the largest time lapse in the history of the Phanerozoic, and most are due to tectonic uplift (McCabe, 1959). Several angular unconformities have been documented throughout the sedimentary section; the most major ones occurring at the end of the Paleozoic, Mesozoic and Cenozoic. Each Era was further affected within with unconformities, most of which occurred at the end of each Period. A progressive erosional truncation of the Paleozoic formations, from youngest in the west to oldest in the east, towards the basin margin, reflects the dynamic tectonic forces affecting the Williston Basin during this time. A widespread and significant erosional unconformity marking the end of the Devonian represents a period of uplift, and continued until early Mississippian time. It is this event that has most affected the deposition, reworking and erosion of the Three Forks Formation.

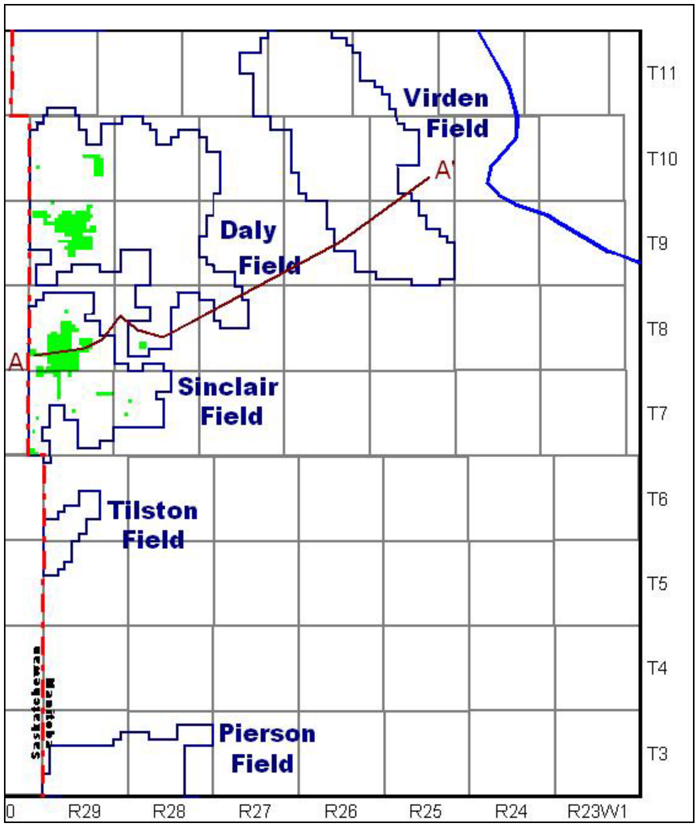

Figure 1: Map of the study area showing Manitoba oil field boundaries (as of January 1, 2006), commingled Bakken-Three Forks oil pools (green), and the Three Forks Formation subcrop edge (blue).

General Stratigraphy

The Three Forks Formation, Qu'Appelle Group is a Devonian silty, shaley dolarenite stratigraphically positioned between the overlying siltstones, sandstones and shales of the Mississippian Bakken Formation, and underlying carbonates and evaporites of the Devonian Birdbear Formation (Figure 2). The Three Forks Formation is subdivided into four units, similar to those recognized in southeastern Saskatchewan by Christopher (1961). In this study, units 2 and 4 are further subdivided into subunits or lithofacies (Figure 3).

Detailed Stratigraphy

Bakken Formation

The Upper Bakken Member is present throughout southwestern Manitoba, right up to its subcrop edge. It consists of black to brownish black to dark grey to purplish red, fissile to blocky, non-calcareous, conodont-bearing, radioactive shale. Its lower contact to the Middle Bakken Member is sharp and well defined. The maximum isopach is 13 m, occurring in localized areas in the Waskada Field associated with salt collapse. Within the study area, the isopach ranges from 2-4 m.

Era	Southeastern Saskatchewan			Manitoba			North Dakota	
Mississippian	Three Forks Group	Bakken Formation	Upper Bakken Member		Bakken Formation	Upper Bakken Member	Bakken Formation	Upper Member
			Middle Bakken Member			Middle Bakken Member		Middle Member
			Lower Bakken Member			ower Bakken Member		Lower Member
---?--								
		Big Valley Formation					Three Forks Formation	
		Torquay Formation	Unit 6					
			Unit 5					
			Unit 4	Qu'Appelle Group	Three Forks Formation	Unit 4		
			Unit 3			Unit 3		
			Unit 2			Unit 2		
			Unit 1			Unit 1		
Devonian	Saskatchewan Group	Birdbear Formation	Upper Birdbear	Saskatchewan Group	Birdbear Formation	Upper (biohermal facies)	Jefferson Group	Birdbear Formation
			Lower Birdbear			Lower (platform facies)		

Figure 2: Stratigraphic equivalencies chart.

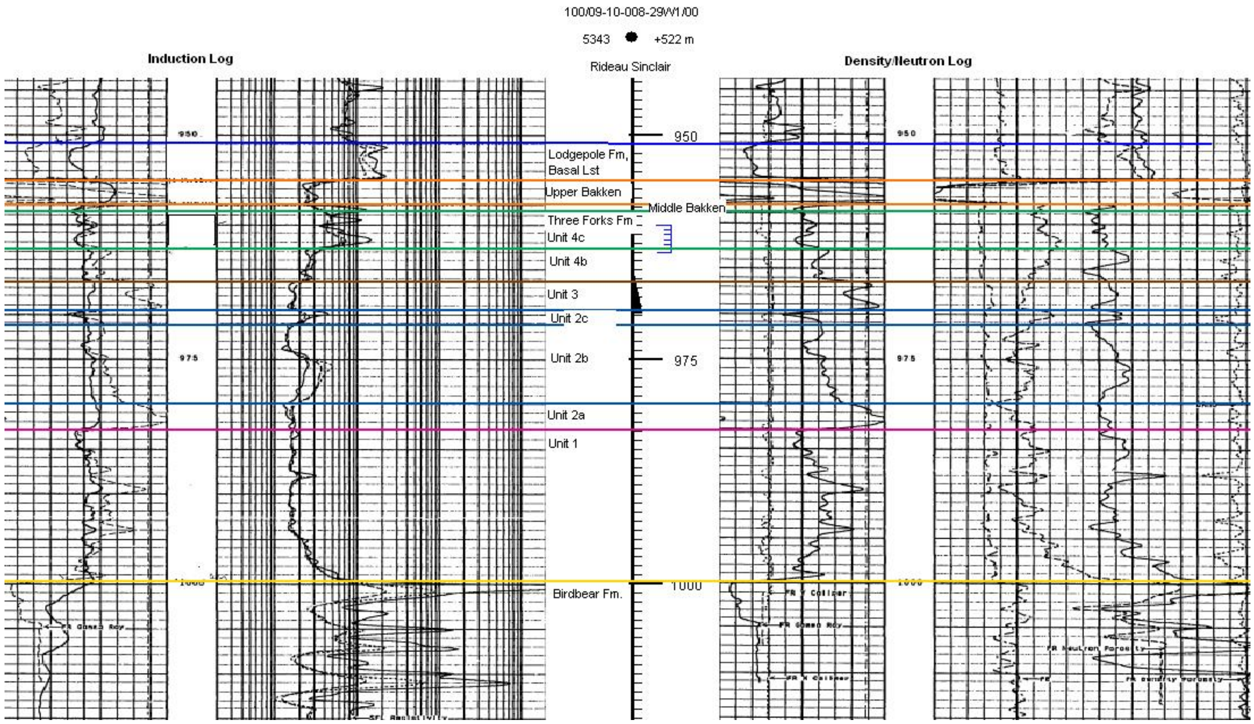

Figure 3: Reference log for the Three Forks Formation.

The Middle Bakken Member is present throughout southwestern Manitoba, right up to the subcrop edge. It consists of light to dark grey, mottled to laminated, siltstones and porous sandstones. Some cores from wells drilled at Sinclair Field, the Middle Member of the Bakken Formation is anomalously thick for the area. This additional section of the Middle Bakken may be caused by infilling lows at the Devonian Three Forks erosional surface and consists of repetitive fining upward planar laminations to wavy bedded, medium grey to light brown sandstone, grading to a coarse, porous sandstone in places. Martiniuk (1988) and LeFever *et al.* (1991) provide an indepth description of the Middle Bakken Member and its lithofacies.

The Lower Bakken Member is not present in the study area. Its occurrence in Manitoba is limited to a restricted area in the Waskada Field area where it is preserved in salt solution collapse structures (Martiniuk, 1988). The Lower Member consists of a black to brownish black, fissile, non-calcareous, radioactive shale. The lithology of this member is identical to that of the Upper Member.

Three Forks Formation

Unit 1

Unit 1 is the lowermost unit, lying conformably on the Birdbear Formation, and is correlative to Unit 1 of the Torquay Formation in southeastern Saskatchewan (Christopher, 1961). Core from the well at 14-34-10-24W1 was examined to describe Unit 1, as not complete core of this unit was available near the Sinclair Field. Unit 1 is the most weathered of all the units identified in the Three Forks in Manitoba. It is dominantly red-brown in colour. Oxidation has obliterated most of the original fabric of the unit. Occasional halos of reduced light brown dolarenitic siltstone and grey-green shales and silty shales provide a glimpse into the pre-weathered rock fabric of this unit. The lithology consists of light brown to tan brecciated dolarenite with a grey-green shale to silty shale matrix. The proportions of dolarenite to shale vary throughout, from 85% dolarenite and 15% shale in the least weathered zones, to 95% shale and 5% dolarenite in the most weathered zones at the base. Porosity within the oxidized portions is poor, while porosity in the remaining reduced halos is poor to moderate (estimated at 10-15% pinpoint porosity). Anhydrite occurs throughout this unit as white or resinous brown blebs and large nodules.

Log correlation of this unit from the core section at 14-34-10-24W1 to the Sinclair Field shows the thickness of this unit to be fairly uniform. Log signatures in the Sinclair Field show a cleaner signature with more porous zones (Figure 3) than that of the cored well, and may be similar to Units 2 and 4. In the eastern exposure of Unit 1 where it's exposed at the pre-Mississippian erosional surface (Township 10 Range 24W1), the Mississippian section is completely eroded, with the Lower Amaranth Red Beds directly overlying the Three Forks. The diagenetic evolution of the Three Forks would therefore be different in the east than in the Sinclair area, resulting in a more oxidized section due to exposure to weathering and downward percolating fluids from the Red Beds. The oxidation process in the Three Forks has had a negative effect on porosity and permeability.

Unit 2

Unit 2 generally consists of interbedded siltstone and shale, massive shale and is occasionally brecciated. It is correlative to Unit 2 of the Torquay Formation in southeastern Saskatchewan (Christopher, 1961). It is subdivided into four subunits or lithofacies based on available core data. Each subunit is described below in stratigraphic order from oldest to youngest.

<u>Subunit 2a</u>

Log interpretation suggests that the lower portions of the subunit is very similar to Unit 3 (Figure 3). Subunit 2a consists of a massive oxidized silty shale, as shown in core form the well at 2-8-8-29W1.

<u>Subunit 2b</u>

Subunit 2b is a variable unit consisting of randomly alternating cycles of brecciated dolarenitic siltstone in shale matrix, rhythmically alternating laminated siltstone and shale beds, and massive shale to silty shale (Figure 4). Halos of oxidized patches occur within the more reduced zones, and halos of reduced zones remain within the more oxidized zones. Siltstones within the reduced zones are commonly light brown to tan, and shales are grey-green. The oxidized zones are a uniform red-brown colour. Disseminated pyrite is common in the reduced zones, occurring mostly along preferential bedding planes and as blebs. Anhydrite is rare and occurs as very small blebs, best seen under UV light. Upper contact with Unit 2c is sharp.

The brecciated zones within Unit 2b consist of light brown to tan dolarenitic siltstone clasts within a grey-green shale to silty shale matrix. Original bedding is highly distorted and brecciated, while still partially preserving a faint bedding fabric with the orientation of the clasts. Porosity is tight in the shale and 10-15% in the siltstones, as pinpoint and intergranular porosity. Oil staining and UV fluorescence were noted in some cores.

The laminated zones within Unit 2b consist of rhythmically alternating thin beds of tan-coloured dolomitic siltstone and grey-green shale. Sedimentary structures present in this zone include ripple marks, lenticular bedding, trough cross-bedding, load structures and soft sediment deformation features. Hairline horizontal fractures along preferential bedding plans are common, some occurring early and in filled with silt, while others are late stage. Porosity is best developed in the siltstone beds as pinpoint, intergranular and small vugs, and ranges from 10-15%. No oil staining or UV fluorescence was observed in any of the cores.

The massive zones within Unit 2b consist of massive grey-green to rusty brown shale to silty shale with disseminated pyrite (reduced) or hematite (oxidized). This zone is often the most oxidized of the three zones, and commonly has the reduced halo effects. Occasional faint pseudo morphs of small subangular to subrounded red-brown siltstone clasts are visible scattered throughout the shale, or as accumulations in thin beds. This zone is tight and has no oil staining or UV fluorescence.

The most common sequence order of the brecciated/laminated/massive zones described above are, from top to bottom: brecciated zone, massive zone and laminated zone. Alternating massive and laminated zones occur frequently as well. On logs this unit appears as dirty siltstone with alternating gamma-ray and porosity signatures, responding to the variations in lithology and porosity over short distances (Figure 3).

Figure 4: Characteristic appearance of subunit 2b in core from 2-8-8-29W1 at a depth of 1007m.

Subunit 2c

Subunit 2c consists of a light brown to tan dolarenitic siltstone (~75%) with grey-green shale as laminae, interbeds and matrix (~25%) (Figure 5). Siltstone is massive and blocky in places, commonly laminated to wavy bedded; sedimentary structures include ripple marks, trough cross-bedding, load structures, gas or water escape structures (characteristic of this unit), and soft sediment deformation features. Disseminated pyrite occurs along preferential bedding planes and as blebs. Anhydrite occurs as rare pinpoint blebs. Hairline, infilled vertical fractures are common. Open vertical fractures occur occasionally. Hairline, infilled and open horizontal fractures occur throughout. Porosity is moderate (~15%) as pinpoint and intergranular. Oil staining and UV fluorescence is noted in several cores. Upper contact to Unit 2d is sharp and erosional. This unit is occasionally partially oxidized, giving the shale a rusty-brown colour and the pyrite altered to hematite. On logs, this unit shows up as a thin clean siltstone unit, with a low gamma-ray signature and corresponding decrease in resistivity, neutron and density, in contrast to the overlying high gamma-ray response typical of Unit 3 (Figure 3). Although not currently producing, this unit is a potential reservoir in the western part of the Sinclair Field.

Figure 5: Characteristic appearance of subunit 2c in core from 2-8-8-29W1 at a depth of 1003m.

<u>Subunit 2d</u>

Subunit 2d consists of a thin, massive, tight grey-green dolomitic shale to silty shale. Upper contact with Unit 3 is gradational. In core it is characteristically grey-green in colour, in contrast to the overlying rusty-brown shale of Unit 3. The unit is indistinguishable from Unit 3, where is has been oxidized. No oil staining or UV fluorescence has been noted in this unit.

Unit 3

Unit 3 consists of a characteristic rusty-brown dolomitic silty shale (~90%) with faint relict pseudo morphs of rotted angular fine-grained siltstone clasts (~10%) (Figure 6). It is correlative to Unit 4 of the Torquay Formation in southeastern Saskatchewan (Christopher, 1961). Shale is mostly massive, to faintly mottled or bedded in places. Small halos of grey-green shale occur occasionally. Anhydrite occurs as rare pinpoint blebs. This unit is tight, has no oil staining or UV fluorescence, and a sharp upper contact.

On logs, this unit can be identified by the sudden increase in gamma-ray in contrast to the overlying and underlying siltstone-rich zones (Figure 3). The gamma-ray signature decreases slightly in the middle portion of the unit, reflecting the increase in the occurrence of relict clasts.

Figure 6: Characteristic appearance of Unit 3 in core from 2-8-8-29W1 at a depth of 1001 m.

Unit 4

Unit 4 comprises generally of interbedded siltstone and silty shale with thick subunits of highly distorted and brecciated siltstone beds. It is correlative to Unit 4 of the Torquay Formation in southeastern Saskatchewan (Christopher, 1961). Unit 4 is subdivided into four subunits or lithofacies based on available core data. Forming the uppermost unit of the Three Forks Formation in Manitoba, it is the primary reservoir at Sinclair Field. This unit is present in the Sinclair Field, but quickly gets truncated to the east and north.

Subunit 4a

Subunit 4a consists of a thin, massive, tight grey-green dolomitic shale to silty shale (Figure 7) and is lithologically identical to subunit 2d. No oil staining or UV fluorescence has been noted in this unit. Difficult to distinguish on logs, it is recognized by a small gamma-ray deflection (Figure 3).

Figure 7: Characteristic appearance of subunit 4a in core from 2-8-8-29W1 at a depth of 1000m.

Subunit 4b

Subunit 4b consists of a light brown to tan dolarenitic siltstone clasts within a grey-green shale to silty shale matrix (Figure 8). Original bedding is highly distorted and brecciated, while still partially preserving a faint bedding fabric with the orientation of the clasts. Siltstone clasts are angular, vary in size from less than 5 mm to more than 7 cm, and commonly have preserved internal sedimentary structures. The overall unit is poorly sorted. The upper and lower third of the unit has a higher siltstone clast content than the middle third, which has a higher shale content. This shalier interval commonly has lenticular bedding. Pyrite is disseminated throughout. Anhydrite occurs as rare pinpoint blebs. Porosity is tight in the shale and 10-15% in the siltstones, as pinpoint, intergranular and as small vugs. Oil staining, a petroliferous odor, and bright yellow UV fluorescence is common in this unit, but is more concentrated in the zones with a higher siltstone clasts content. Unit 4b is part of the primary reservoir in the Sinclair Field. On logs, this unit shows up as an alternating shaley-silty zone with variable porosities and resistivities (Figure 3).

Figure 8: Characteristic appearance of subunit 4b in core from 2-8-8-29W1 at a depth of 997m, part of the primary reservoir at Sinclair Field.

Subunit 4c

Subunit 4c consists of a light brown to tan dolarenitic siltstone (~75%) with grey-green shale as laminae, interbeds and matrix (~25%) (Figure 9). Siltstone is massive and blocky in places, commonly laminated to wavy bedded; sedimentary structures include ripple marks, trough cross-bedding, load structures, and soft sediment deformation features. Disseminated pyrite occurs along preferential bedding planes and as blebs. Anhydrite occurs as rare pinpoint blebs. Hairline, infilled, and open vertical fractures occur occasionally. Hairline, infilled, and open horizontal fractures occur throughout. Porosity is moderate (~15%) and occurs as pinpoint, intergranular and small vugs. Oil staining, a petroliferous odor, and UV fluorescence is noted in all cores. This unit is almost identical to Unit 2c in lithology, but is much thicker and is not affected by oxidation. It has a sharp erosional upper contact with the Bakken Formation, commonly capped with a thin erosional lag deposit. Unit 4c is part of the primary reservoir unit in the Sinclair Field. On logs, this unit shows up as a relatively clean porous siltstone (Figure 3).

Figure 9: Characteristic appearance of subunit 4c in core from 2-8-8-29W1 at a depth of 995m, part of the primary reservoir at Sinclair Field.

Depositional Environment

During Three Forks time, there was a shift in the depositional environment that produced the carbonates and evaporites of the Devonian, to a more transitional clastics-dominated environment. Deposition occurred along a gentle, westerly sloping, coastal shelf, thereby forming a long clastic wedge thinning from west to east (Christopher, 1961). The depositional environment in Manitoba represents the eastern extend of that described in Christopher (1961), where oscillatory floodings of the sea and prolonged exposures to weathering affected the formation. During times of exposure, sea level dropped to the west, resulting in the Three Forks Formation being exposed for long periods of time; areas to the east had longer exposure and weathering than in the west. Intraformational weathering resulted in most of the original depositional fabric to be distorted, brecciated and corroded, leaving a rock with similarities to C-type soil horizons (Christopher, 1961). The highly oxidized units and subunits may have been exposed for longer periods of time, resulting in rocks with similarities to B-type soil horizons. The thickest, most uniform and widespread intraformational weathering event is represented by Unit 3. Massive shale units commonly occurring directly on top of oxidized regolithic units (herein referred to as subunits 2d and 4a) represent a transgression of the sea (Christopher, 1961) after a long period of exposure. This flooding was the beginning of another depositional, coarsing-upward cycle. Units 1, 2 and 4 of the Three Forks Formation in Manitoba represent coarsening upward cycles.

The majority of cores examined for this study display weathering, oxidation and/or reduction. The lack of any significant anhydrite observed in the cores of Units 2, 3 and 4 in Manitoba, in contrast to the quantities found in the Saskatchewan counterparts, indicate these units have been subject to longer periods of exposure. Unit 1, as observed in the core examined from the well at 14-34-10-24W1, contained large amounts of preserved white anhydrite, indicative of less weathered conditions, and is more typical of that seen in the units of the Torquay Formation in southeastern Saskatchewan.

Isopach, Structure and Tectonics

The isopach of the Bakken Formation in the Sinclair Field and southern part of the Daly Field shows a dramatic thinning of the Middle Bakken Member. Middle Bakken Member isopachs can vary from 9 m to less than 10 cm. In core, the Middle Bakken Member is often less than a meter thick, and in some cases its presence is questionable and may only remain as a very thin erosional lag deposit. Within the study area, the isopach ranges from 0.5 to 8 m, but averages around 1 to 2 m. The thickest isopachs are local occurrences suggestive of salt dissolution karsting during Bakken time (i.e.. 9-34-7-29W1 and 16-8-8-28W1). Recognition of the Middle Bakken of the Bakken Formation on wells logs is difficult to distinguish from the underlying units of the Three Forks Formation due to a dramatic thinning of the Middle Member in the Sinclair Area. The Upper Bakken Member isopach is fairly uniform, averaging 2 meters thick and exhibits no anomalous thicks or thins.

The regional isopach of the Three Forks generally thickens east to west, with its greatest thickness observed from Township 8 Range 29W1 south to the international United States boundary (Figure 10). The formation thins eastward with a rapid successive truncation of the units of the Three Forks towards the east (Figure 11). The units are truncated at the pre-Mississippian erosional surface. Units 3 and 4 are sharply truncated along a north-south trend between Ranges 28W1 and 29W1. East of this truncation, the isopach ranges between 18 to 22 m, forming a sort of "plateau" between Ranges 25 to 27W1, before gradually thinning eastward toward the subcrop edge, east of Range 25W1. The truncation of Units 3 and 4 is likely not due to depositional offlap, since these units are preserved in a few wells far to the east in Ranges 24W1 and 25W1 (i.e. 7-25-7-24W1 and 9-21-5-25W1). Therefore, there must be other factors causing the rapid thinning of the Three Forks Formation during the post-Mississippian erosional event. Anomalous thicknesses of the Three Forks Formation are also noted in wells located at Virden Field. These anomalies are related to the multiple-stage dissolution of the evaporite of the underlying Devonian Prairie Formation (Martiniuk, 1998) associated with the BWA.

The structure of the Three Forks shows a general northwest-southeast trend, with synclinal flextures at Sinclair, Daly and Virden Fields (Figure 12). Pronounced structural highs occur in the Daly Field, mimicking those seen in the Mississippian (Klassen, 1996). A prominent synclinal flexture of the contours is seen in the western half of Township 8, Range 28 W1.

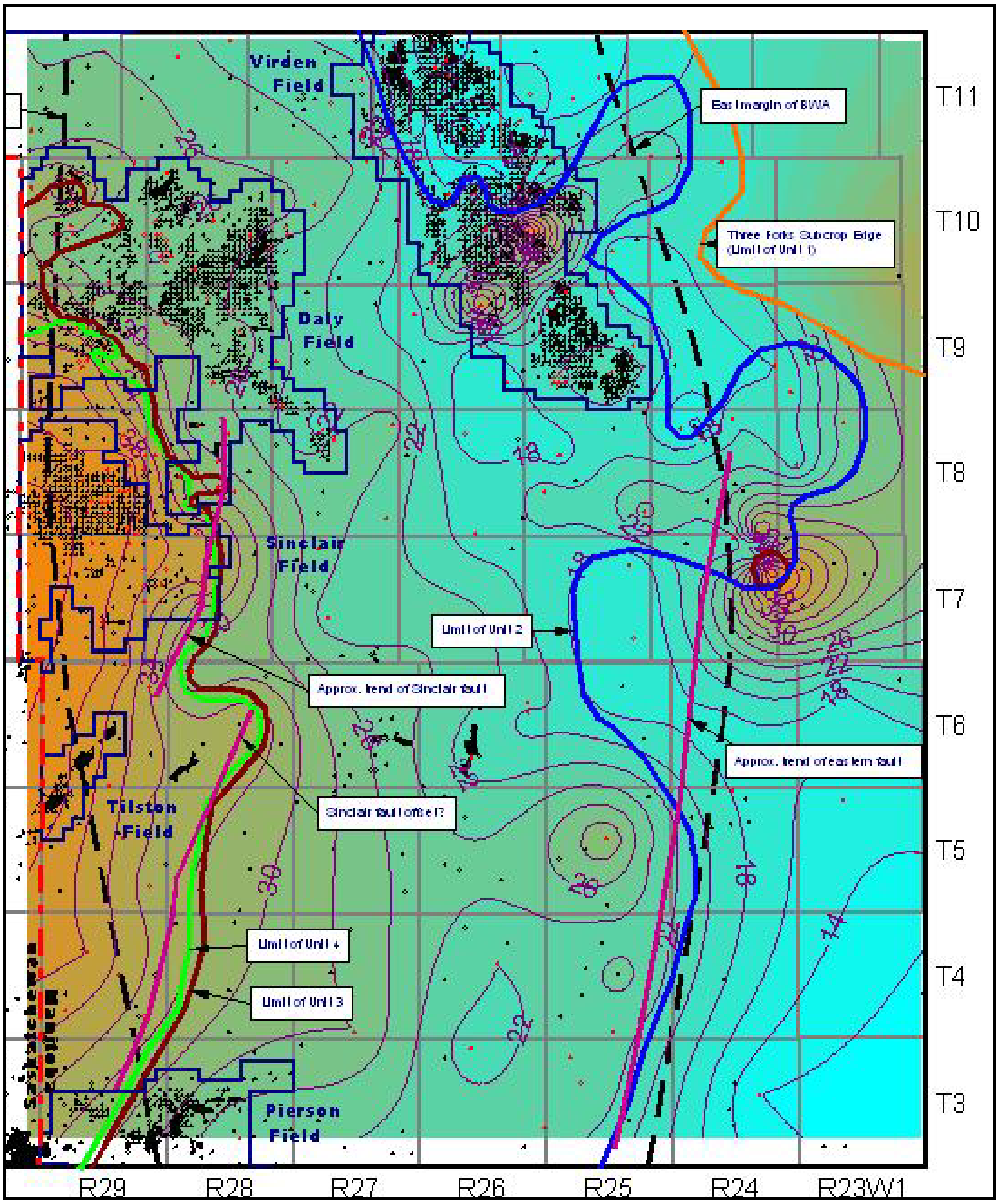

Figure 10: Isopach map of the Three Forks Formation showing the limits Units 1 to 4. Contour interval is 2 m. The BWA margins are shown as dashed lines. Select fault lines from Dietrich *et al.* (1998) have been extrapolated and extended to show their interpreted locations.

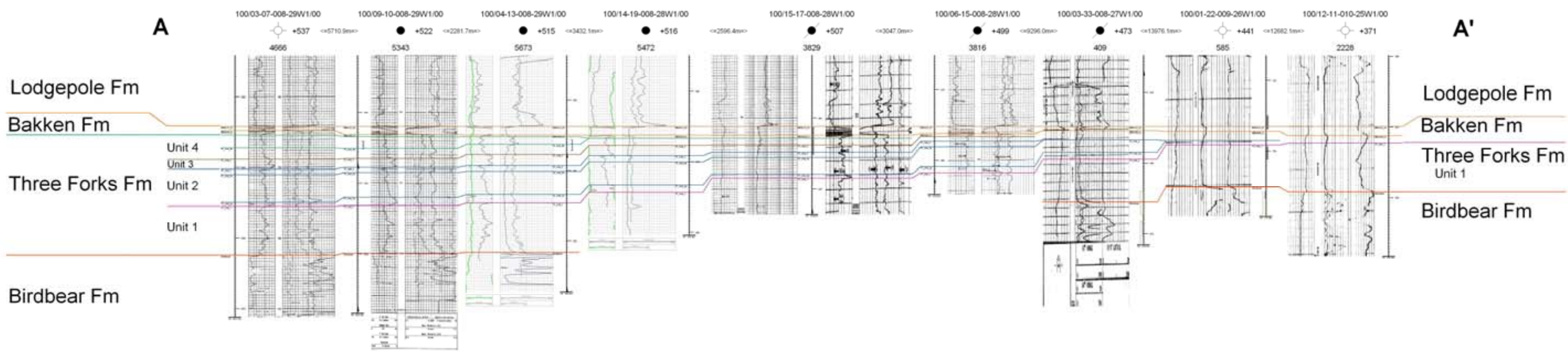

Figure 11: West to east stratigraphic cross-section AA' showing the truncation and erosion of the Three Forks Formation Units 1 to 4 through the study area. Cross-section line shown in Figure 1. Datum is top of Bakken Formation.

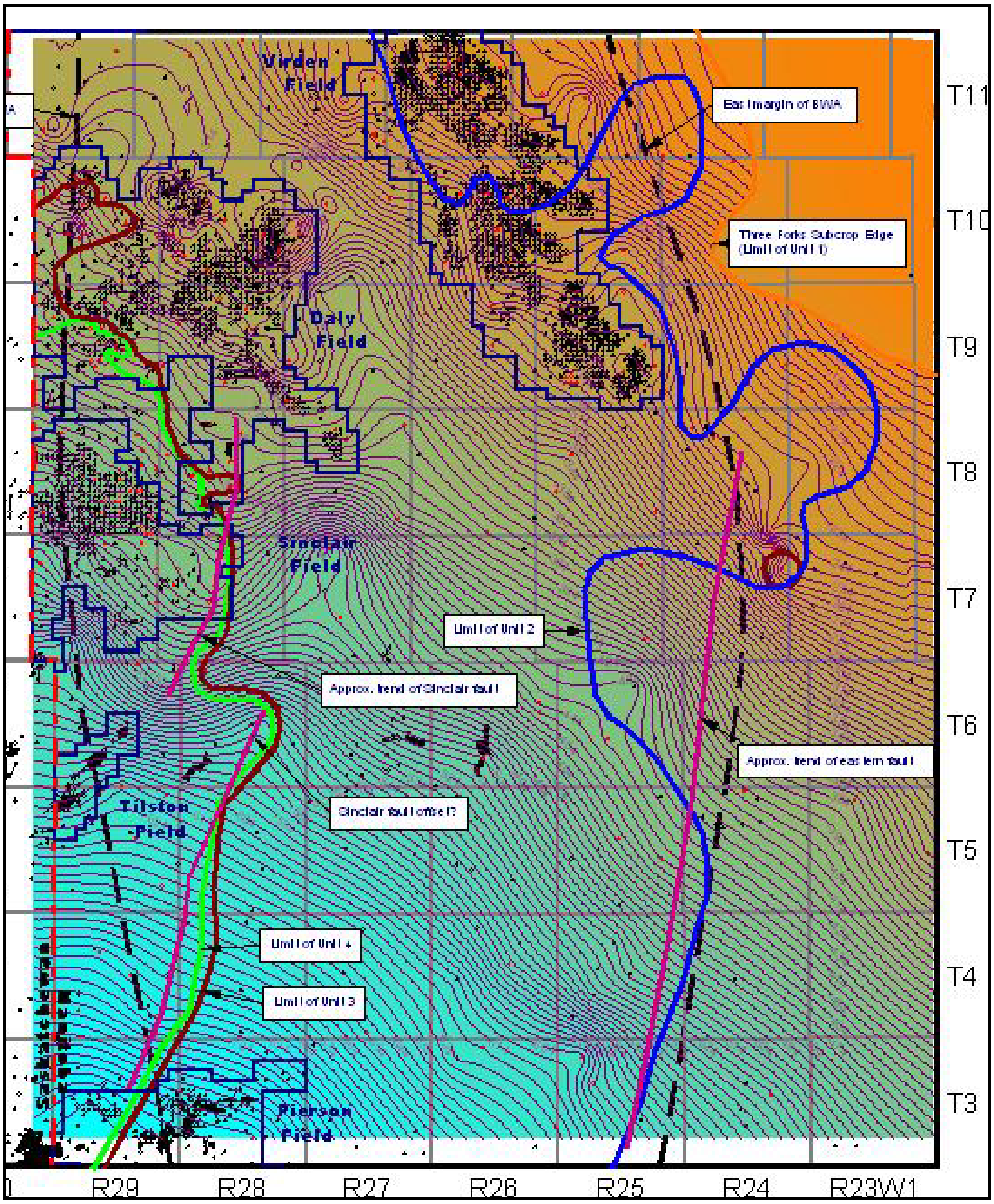

Figure 12: Structure map of the Three Forks Formation showing the limits of Units 1 to 4. Contour interval is 5 m. The BWA margins are shown as dashed lines. Select fault lines from Dietrich *et al.* (1998) have been extrapolated and extended to show their interpreted locations.

The area located between the rapid truncation of Unit 3 and 4 and the start of the isopach "plateau" of Unit 2 coincides with the western limit of the large Precambrian crustal suture called the Superior Boundary Zone (SBZ), and a smaller feature called the Birdtail-Waskada Axis (BWA; Figure 10; McCabe, 1967). The Birdtail-Waskada Axis (BWA) runs roughly through the middle of the southern extent of the SBZ. The BWA represents a zone that coincidences with structural and isopach anomalies observed in the structural contours on the Birdbear Formation, Three Forks Formation, Bakken Formation, Lodgepole Formation and Mississippian surface. These structural and stratigraphic features are attributed to large scale events, occurring from the end of the Devonian through to the Mississippian, and tapered off by the early Jurassic.

It appears that the Devonian may have had many tectonic effects superimposed on it, most of which are probably a result of the dissolution of the Prairie Evaporite and the tectonic effects of the SBZ. At the end of the Devonian, there was a major tectonic shift from the Elk Point Basin to the Williston Basin, being the dominant tectonic element affecting deposition of the Mississippian strata (McCabe, 1967). This tectonic shift would have had its effects exaggerated at the SBZ due to compositional and structural differences between the Precambrian Churchill Province and Superior Province crustal blocks. The Superior crustal block was more susceptible during these times, resulting in subsidence and uplift. Uplift of this crustal block was more common during times of erosion (McCabe, 1967), typical of that seen at the end of the Devonian. Such uplift would in turn affect the hydrodynamics of the basin, inviting more fresh water into the deeper parts of the basin, effectively dissolving the salts of the Prairie Evaporite. Early Bakken time, which straddles the Devonian-Mississippian boundary, is well known for having many salt collapse events throughout southwestern Manitoba. The effects this tectonic change would have had on pre-Birdbear strata is difficult to ascertain since there is currently not enough deep well control available in the area to determine the amount or even prove the existence of basement structural movement.

Dietrich *et al.* (1998) identified several faults using seismic data along a transect from southeastern Saskatchewan to southwestern Manitoba, one of which coincides precisely with the presence of Unit 4, which is truncated in Range 28W1, and is herein referred to as the Sinclair fault and its offset fault (Figure 10); the offset fault being a southern en echelon extension of the Sinclair fault, and also identified by Dietrich *et al.* (1998). This same transect identified a fault running roughly north-south around Range 25W1, which is the same trend and location as the wells identified in logs as having Unit 4 preserved. If preservation of Unit 4 in the east is more than just localized salt collapse structures, it may represent a large scale preservation of Unit 4 by block faulting, probably originating by deep basement events. Dietrich *et al.* (1998) extrapolated this eastern fault to the Precambrian basement. In contrast, Dietrich *et al.*(1998) interpreted the deepest penetration of the Sinclair fault and its offset fault to be just above the remnant salt of the Prairie Evaporite and does not reach the Precambrian basement. However, the coincidence of the location and trend of these faults with the eastern margin of the BWA suggest the re-activation of basement faults should not be dismissed.

Diagenetic Effects and Reservoir

The Three Forks Formation was strongly affected by weathering and subsequent diagenesis. The original siltstones and shales were weathered during times of regression which left the sea floor exposed to long periods of weathering and oxidation (Christopher, 1961), resulting in the distortion and brecciation of the beds. Different stages of weathering affected the units; Unit 3 shows the most significant effects of weathering, and bordering on a B-type soil horizon. With increased weathering, its effective porosity and permeability was lessened, with shales dominating and hematite clogging up pore spaces. Unit 3 is typically not a reservoir, but if located at the Devonian unconformity, may be slightly productive in combination with Unit 2. This is thought to be due to further weathering and diagenesis that would have increased porosity while exposed in lithified form at the unconformity.

Unit 4 and portions of Unit 2 were not affected by oxidation, but suffered only the effects of compaction and reduction. Reduction caused the growth of pyrite cubes and the effects of compaction caused horizontal stress fractures, both increasing effective porosity. While much of the siltstones have 10-15% porosity, porosity within the shales surrounding the siltstone breccia clasts was good too. Oil fluorescence was commonly seen within the shale matrix, but was most pronounced near large siltstone breccia clasts, giving a “bird’s eye” texture to the fluorescence, typical of pressure solution effects. This pressure effect resulted in lowered compaction pressures in the corners allowing for fracturing and increased pore space to develop in the shales.

Unit 4 and portions of Unit 2 are the dominant reservoir units. Where Unit 4 is truncated at the pre-Mississippian unconformity, production of the wells decrease. Unit 2 is more sporadically affected by oxidation-reduction reactions, as evidenced by the redox haloing effects common for this unit, effectively decreasing porosity and permeability. The unpredictability of the occurrence and the amount of redox effects in Unit 2 make development of the reservoir difficult. Unit 4 does not have redox halos and when present has proven to be a very predictable and consistent reservoir.

Three Forks Exploration

Exploration of the Three Forks Formation in Manitoba has been combined with the Bakken Formation exploration. The two formations are often considered a continuous, commingled reservoir and are pooled together. The Three Forks is currently productive in the Sinclair Field and in the southwest corner of the Daly Field. As a rather new exploration target, it has not been explored in other areas of the province.

Future development exists potentially along the north-south trend of the isopach thick of Unit 4. Unit 2 has development potential in areas where its best production where Subunit 2b is present and where Subunit 2c has been minimally affected by redox haloing.

New exploration efforts should be targeted northward and eastward of Sinclair Field within Unit 2, and possibly Unit 1. Log signatures of Unit 1 look promising west of the Unit 2 subcrop edge, but core of this unit is not available to correlate with the log signatures. Possible target zones may occur along the north-south trend parallel to the eastern limit of the BWA, from Range 24W1 and 25W1 (Figure 10) where local occurrences of Unit 4 have been preserved, based on log correlations. It is possible that another Sinclair is yet to be discovered along this eastern trend.

Sinclair Field Reservoir and Production History

The Sinclair Field was officially designated on January 1, 2005. The discovery well is located at 3-6-7-29W1, but the real growth of the field was due to the development of the 16 62B pool in Township 8 Range 29W1. Davidson and Gompf (2006) provided a development overview of the Sinclair Field up to September 2005. The field has grown in size dramatically since then. As of August 31, 2006, there were 476 wells licensed; 332 of which were cased for production. At the end of 2005, 210 wells were on production. As of December 31, 2005, Sinclair Field had a total cumulative production of 197 605 m^3 (1 million barrels), representing 20% of Manitoba's total production for 2005.

The 16 62B Bakken-Three Forks B pool is the largest of the pools in the Sinclair Field supplying 90% of the oil production (Figure 1). Development of the 16 62B pool is still ongoing, and its growth is further helped by its amalgamation with smaller pools on its periphery. Exploration and development beyond the 16 62B pool is active.

Davidson and Gompf (2006) reported reservoir pressures between 8261 to 10609 kPa, average reservoir temperature of 28.5°C, average core permeability of 1.8mD in the Bakken and 4.3 mD in the Three Forks, and average core porosities of 14.7% in the Bakken and 16.5% in the Three Forks. Davidson and Gompf (2006) reported OOIP estimates of 54,141 m^3/LSD to 119,514 m^3/LSD. As of April 2006, proven and probable reserves are estimated at 3.8 million m^3 (24 million barrels) (John Fox, 2006, pers. comm.).

Conclusions

The Three Forks Formation is a shaley, silty dolarenite, interbedded with shale and brecciated, which has been affected by several weathering events due to transgressive and regressive cycles and basin tectonics. It is is subdivided into four units. The uppermost of these units, Unit 4, is the primary and most productive reservoir at Sinclair Field. Production is also derived from Unit 2, a secondary reservoir at Sinclair and Daly Fields. Thinning of the Three Forks Formation and truncation of Unit 4 eastward suggests that the eastern expansion of the Sinclair Field may be limited. In contrast, the thick isopach trend running north-south along Range 29W1 south of Township 9, where Unit 4 is still present, suggest a southern expansion of the Sinclair Field may be more successful.

Isopach and structural evidence suggests block faulting may have occurred in the western sections of Range 28W1 south of the Township 9. This faulting would have resulted in uplift and the subsequent erosional truncation of Unit 3 and Unit 4 along eastern limits of Range 28W1. The fault trend may serve as a geological boundary in determining the eastern boundary of the Sinclair Field. The identification of a fault on the eastern edge of the SBZ along Ranges 24 and 25W1, coinciding with wells having preserved sections of Unit 4, may provide a similar reservoir in the west. Future potential for another Sinclair-type oil play may exist east of Range 24W1.

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APPENDIX A

Cores On Display

Tundra Sinclair Province
4-29-8-29 WPM
Licence # 5424
KB: 543.2 m
Total Depth: 1019.7 m
Core #1: 984.00-1002.00 m (Rec. 18.0 m)

DEPTH: (meters)	DESCRIPTION
	UPPER BAKKEN
984.00 – 985.43 (1.43 m)	Shale: Black; dense; fissile to blocky; conodonts; disseminated pyrite dolomitic; tight porosity; sharp lower contact.
	MIDDLE BAKKEN
985.43 – 985.49 (0.06 m)	Siltstone: medium grey; flaser bedding; mottled; upper contact has black shale clasts averaging 7.0 cm in diameter; disseminated pyrite; dolomitic; 10% intergranular porosity; sharp and erosional upper contact.
985.49 – 986.15 (0.66 m)	Siltstone: medium grey shaley siltstone with occasional light brown to grey green shale, grading to sandstone near the base of the unit; mottled in places; lenticular bedding; dolomitic; porosity increases with depth to 10% intergranular, pinpoint and vuggy porosity near the base of the unit, spotty oil staining; bright yellow UV florescence throughout more porous zones.
	THREE FORKS
986.15 – 988.05 (1.90 m)	**(Unit 4c)**
	Siltstone: 75% light brown to tan siltstone with 25% grey green shale laminae, occasionally grading to sandstone; soft sediment deformation; trough cross-bedding; minor interbeds of grey green shale matrix with siltstone clasts; hairline vertical fractures and hairline horizontal fractures along bedding planes, occasionally filled with anhydrite and pyrite; anhydrite blebs; disseminated pyrite throughout and along preferential bedding planes; dolomitic; 15% pinpoint, intergranular and occasional vuggy porosity grading to 20% in sandstone zones; light brown oil

DEPTH: (meters)	**DESCRIPTION**
	staining; bright yellow UV florescence in laminated and clastic zones; sharp and erosional upper contact.
988.05 – 991.37 (3.32 m)	**(Unit 4b)** Breccia: 60% grey green shale with 40% light brown to tan matrix supported siltstone clasts, clasts range in size from 0.5-6.0 cm and internal structure of the clasts is preserved; highly distorted bedding; disseminated pyrite throughout; anhydrite blebs; dolomitic; tight porosity in shale, 15% intergranular and pinpoint porosity in siltstone; rare small vugs are associated with siltstone; bright yellow florescence preferentially in shale matrix around siltstone clasts; gradational upper contact. Note: In middle third of unit, clasts are smaller, less defined, and almost unidentifiable because of "reworking"; internal structure of clasts are destroyed.
991.37 – 992.53 (1.16 m)	**(Unit 4a)** Shale: grey green shale, massive with very faint light brown to tan siltstone clasts and lenses; disseminated pyrite throughout and as blebs along preferential bedding planes; dolomitic; tight porosity; no UV florescence; sharp and erosional upper contact.
992.53 – 995.06 (2.53 m)	**(Unit 3)** Breccia: rusty brown massive shale with faint clastic zones with rotted siltstone clasts, clasts are less than 0.5 cm in size; grey green halos in places; green colour increases toward the base of unit; mottled; hairline horizontal fractures in filled with anhydrite in places; dolomitic; tight porosity; sharp upper contact.
995.06 – 996.83 (1.77 m)	**(Unit 2c)** Breccia: 75% light brown to tan siltstone with 25% grey green shale interbeds and matrix in more rubbly zones; grades to very fine sand in places; occasional zones of matrix supported siltstone clasts; clasts range in size from 0.5-6.0 cm and internal structure of the clasts is preserved; highly distorted bedding; hairline horizontal fractures along

DEPTH: (meters)	DESCRIPTION

preferential bedding planes; planar laminae to trough cross-bedding; load structures; soft sediment deformation; ripple marks; disseminated pyrite throughout; dolomitic; light patchy oil staining; no UV florescence; gradational upper contact.

Note:
995.65 m: escape structures

996.83 – 1001.29
(4.46 m)

(Unit 2b)

Siltstone/Shale Sequence: grey green shale with light brown to tan siltstone interbeds; rhythmic sequences of distorted bedding, laminated zones, and massive zones; sharp upper contact.

Distorted Bedding Zone:
60% grey green shale with 40% light brown to tan matrix supported siltstone clasts, clasts range in size from 0.5-6.0 cm and internal structure of the clasts is preserved; patchy rusty brown siltstone in places and along bedding planes; green halos within rusty brown zones; highly distorted bedding; anhydrite; dolomitic; tight porosity in shale, 15% intergranular and pinpoint porosity in siltstone; bright yellow florescence preferentially in shale matrix around siltstone clasts.

Laminated Zone:
50% grey green shale with 50% light brown to tan siltstone; rhythmites; ripple marks in siltstone; trough cross-bedding; soft sediment deformation; load structures; early stage vertical fractures in filled with siltstone and shale; mud (dessication?) cracks; hairline horizontal fractures along bedding planes; anhydrite; dolomitic; tight porosity in shale, 15% pinpoint, small vug and intergranular porosity in siltstone; no UV florescence.

Massive Zone: grey green shale, massive with very faint light brown to tan siltstone clasts and lenses; anhydrite; disseminated pyrite throughout and as blebs along preferential bedding planes; dolomitic; tight porosity; no UV florescence.

Tundra Sinclair
2-8-8-29 WPM
Licence # 5362
KB: 532.7 m
Total Depth: 1030.0 m
Core #1: 994.0-1012.0 m (Rec. 16.2)

DEPTH: (meters)	**DESCRIPTION**
994.00-996.53 (2.53 m)	**THREE FORKS** **(Unit 4c)** Siltstone: 75% light brown to tan siltstone with 25% grey green shale interbeds, laminae, and matrix; trough cross-bedding; ripple marks; planar lamination in places; soft sediment deformation; hairline vertical fractures, hairline horizontal fractures along preferential bedding planes; minor matrix supported and clast supported brecciation; disseminated pyrite throughout and along preferential bedding planes; dolomitic; 10-15% pinpoint, intergranular, and small vug porosity; light oil staining throughout; bright yellow UV florescence in shale laminae of the planar laminated zone, and in the shale of the breccia zones, UV florescence is minor in siltstone and is not present in areas that lack a shale matrix; sharp lower contact.
996.53-1000.00 (3.47 m)	**(Unit 4b)** Breccia: 75%grey green silty shale with 25% light brown to tan angular siltstone clasts; poorly sorted; highly distorted bedding; turbated; soft sediment deformation; clasts define a faint primary fabric; disseminated pyrite throughout, as blebs, and as euhedral crystals lining vugs; minor anhydrite; hematitic staining within shale, near the base of the unit; dolomitic; tight porosity in shale, 15% pinpoint, small vug and intergranular porosity in siltstone; spotty oil staining; yellow UV florescence as halos in the shale around siltstone clasts; sharp upper contact. Note: In middle of unit, clast abundance decreases and shale abundance increases; lenticular bedding is associated with higher shale content.
1000.00-1000.16 (0.16 m)	**(Unit 4a)**

DEPTH: (meters)	DESCRIPTION
	Shale: 90% grey green silty shale with 10% faint relict siltstone clasts; shale is massive and clasts are aligned to bedding fabric; dolomitic; tight porosity; no oil staining; no UV florescence; sharp upper contact.
1000.16-1003.26 (3.70 m)	**(Unit 3)** Shale: 90 % rusty brown silty shale with 10% faint relict rotted angular fine grained siltstone clasts; shale is faintly mottled; occasional zones where clast abundance increases up to 40%; clasts are orientated parallel to bedding fabric; occasional grey green halos; dolomitic; tight porosity; no visible oil staining; no UV florescence; sharp upper contact.
1003.26-1003.51 (0.25 m)	**(Unit 2a)** Shale: green grey shale; massive to mottled; dolomitic; tight porosity; no visible oil staining; gradational upper contact.
1003.51-1005.07 (1.56 m)	**(Unit 2b)** Siltstone: 85% light brown to tan siltstone with 15% grey green shale laminae, interbeds, and matrix; planar laminae; occasional turbated zones; load structures ripple marks; trough cross-bedding; soft sediment deformation; early stage hairline vertical fractures in filled with silt; hairline horizontal fractures along preferential bedding planes; occasional faint hematitic staining; disseminated pyrite throughout and along preferential bedding planes; occasional anhydrite; dolomitic; tight porosity in shale, 15% pinpoint and intergranular porosity in siltstone; erosional upper contact. Note: 1004.55 m:escape structures over a 33 cm zone.
1005.07-1010.39 (5.32 m)	**(Unit 2c)** Siltstone/Shale Sequence: rhythmic sequences of distorted bedding, laminated zones, and massive zones; sharp upper contact.

DEPTH: (meters)	**DESCRIPTION**
	Distorted Zone: 60% grey green silty shale with 40% fine grained angular siltstone clasts; bedding is highly distorted; in places clasts are smaller and oriented parallel to bedding fabric; occasional hematitic staining with halo effect; occasional anhydrite; dolomitic; tight porosity in shale, 10% pinpoint and intergranular porosity in siltstone; no visible oil staining; no UV florescence
	Laminated Zone: 50% light brown siltstone and 50% grey green shale; interbedded and laminated; occasional very think beds of fine grained angular siltstone clasts in shale matrix; planar laminae; ripple marks; lenticular bedding in places; trough cross-bedding; soft sediment deformation; hairline vertical fractures infilled with silt; hairline horizontal fractures along preferential bedding planes; load structures; occasional hemetitic staining; rare anhydrite; dolomitic; tight porosity in shale, 10-15% pinpoint and intergranular porosity in siltstone; no oil staining;
	Massive Zone: 90% grey green silty shale with 10% fine grained angular siltstone clasts; extreme hematitic staining in places causes colour gradation to rusty brown; occasional grey green halo effect; dolomitic; tight porosity; no visible oil staining
	Note: 1007.43-1008.54 m: extreme rusty zone, massive to distorted 1009.15-1010.39 m: extreme rusty zone, massive

APPENDIX B

Mosaic Core Photos of Cores on Display

Tundra Sinclair Province
4-29-8-29 WPM
Licence # 5424
Core #1: 984.00-1002.00 m

Tundra Sinclair
2-8-8-29 WPM
Licence # 5362
Core #1: 994.0-1012.0 m