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Williston Basin Project (Targeted Geoscience Initiative II): Summary report on Paleozoic stratigraphy, mapping and hydrocarbon assessment, southwestern Manitoba

By
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Cover photo: Localized folding in the Devonian Elm Point Formation (equivalent to Lower Member, Winnipegosis Formation), Lily Bay quarry. Photo credit: J. Bamburak.

Abstract

The Targeted Geoscience Initiative II (TGI II) Williston Basin Project developed a seamless geological model of Paleozoic- and Mesozoic-age rocks from basement to outcrop in an area that includes most of the Phanerozoic succession present in both eastern Saskatchewan and southwestern Manitoba. A series of structural and isopach maps was created using a database consisting of geological picks from 1) most of the drillholes penetrating Devonian and deeper horizons, and 2) selected wells, averaging five wells per township, that penetrate Mississippian- and Mesozoic-age rocks. This report discusses stratigraphic relationships, structural and isopach contour map trends, and major potential hydrocarbon reservoirs and play types for each Paleozoic formation in Manitoba. Also included are geochemistry results from select Mississippian units and a discussion on anomalous wells (i.e., those exhibiting an anomalous stratigraphic sequence that could not be correlated with the normal Paleozoic stratigraphy).

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Introduction

The primary objective of the Targeted Geoscience Initiative II (TGI II) Williston Basin Project was to develop a seamless geological model of Paleozoic- and Mesozoic-age rocks from basement to outcrop in an area that includes most of the Phanerozoic succession present in both eastern Saskatchewan and southwestern Manitoba. These strata represent the remnants of the Williston Basin and the Elk Point Basin (Figure 1). A database was built that comprises geological picks from 1) most of the drillholes penetrating Devonian and deeper horizons; and 2) selected wells, averaging five wells per township, that penetrate Mississippian- and Mesozoic-age rocks.

In the Manitoba portion of the project area, geophysical logs from 1405 subsurface wells and 1201 outcrop locations and stratigraphic test holes were used for this project; 1114 of those subsurface wells had Paleozoic formation picks made or verified in accordance with the stratigraphic framework established by the TGI Williston Basin Working Group (Figures 2–4). A total of 1201 wells from the Manitoba Stratigraphic Database (Bezys and Conley, 1998a) was used to map the outcrop portion of the Paleozoic sequence. This report summarizes some observations on the lithology, stratigraphy, and hydrocarbon and economic potential of the Manitoba Paleozoic sequence.

This report will discuss stratigraphic relationships, structural and isopach contour map trends, and major potential hydrocarbon reservoirs and play types for each Paleozoic formation in Manitoba.

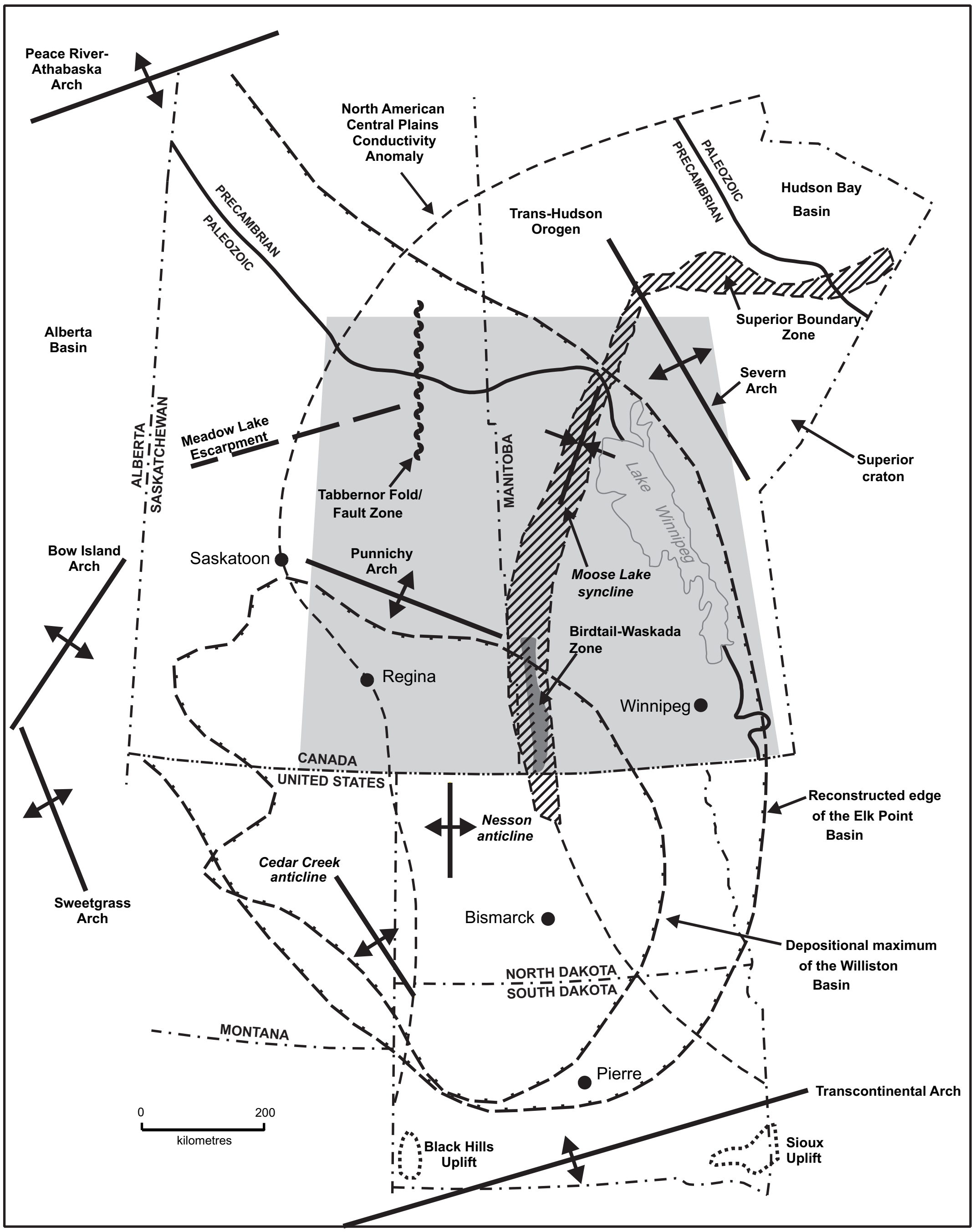

Figure 1: *Location of the Targeted Geoscience Initiative II (TGI II) Williston Basin Project area (shown in grey).*

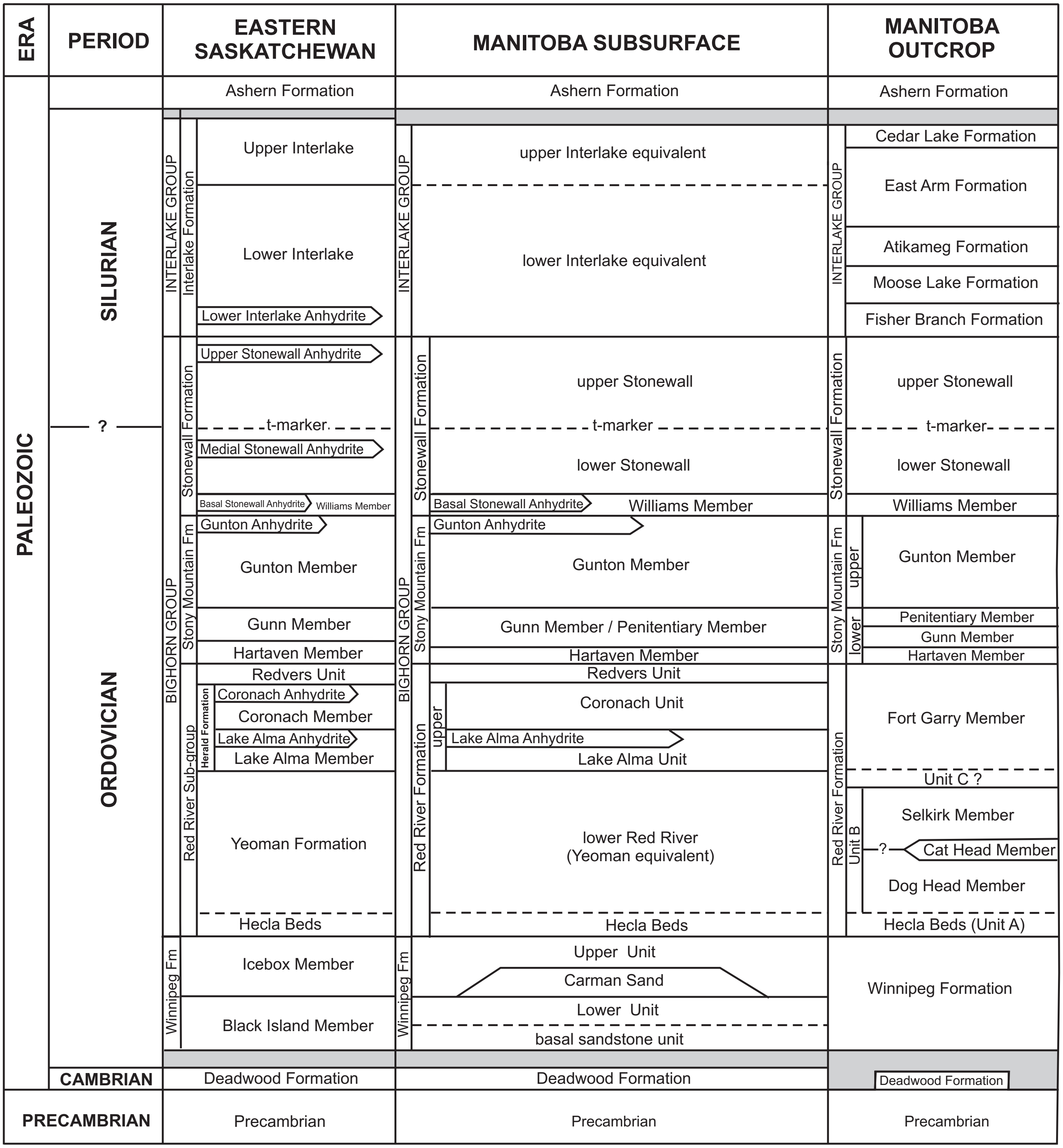

***Figure 2:** Lower Paleozoic (Silurian to Precambrian) portion of the Williston Basin Project stratigraphic column for eastern Saskatchewan and southwestern Manitoba.*

Geological setting

The TGI II project area is in the eastern extension of the Western Canada Sedimentary Basin (WCSB), and includes strata from the northeastern edge of the Williston Basin and the southeastern portion of the Elk Point Basin (Figure 1). The Cambrian and Ordovician clastic and carbonate sequence was part of a large cratonic depositional platform that extended from the Hudson Platform in the east and northeast to New Mexico in the south (Norford et al., 1994). The Middle Devonian carbonate and evaporitic sequences were deposited in the Elk Point Basin, a large intracratonic sub-basin. The clastic, carbonate and evaporitic sequences of Late Devonian to middle Cenozoic were deposited in the Williston Basin, also an intracratonic sub-basin. Although the Williston Basin dominated deposition after the Middle Devonian, deposition of all the pre–Late Devonian sequences was affected by it to some degree.

In Manitoba, Paleozoic-, Mesozoic- and Cenozoic-age

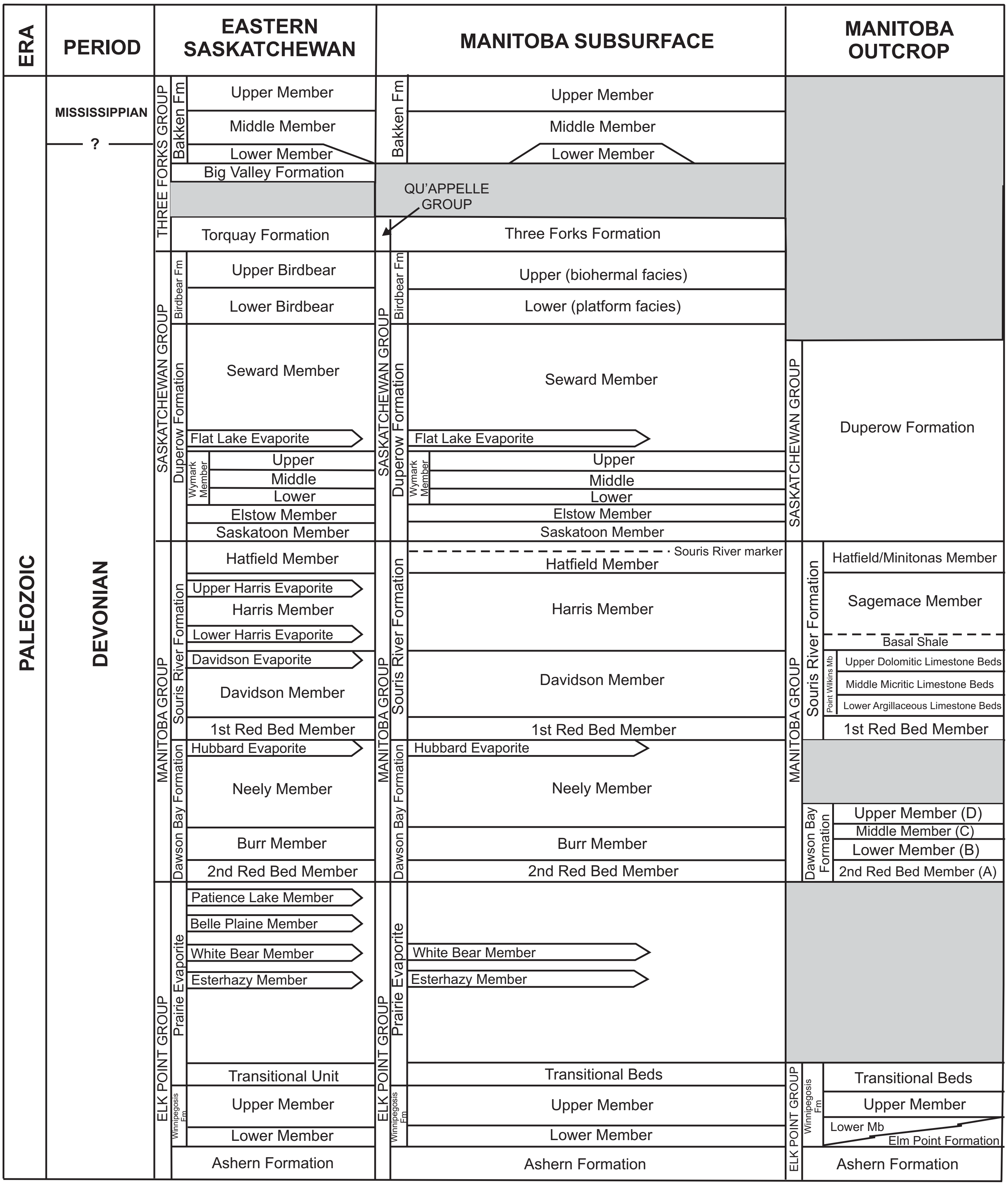

Figure 3: *Devonian portion of the Williston Basin Project stratigraphic column for eastern Saskatchewan and southwestern Manitoba.*

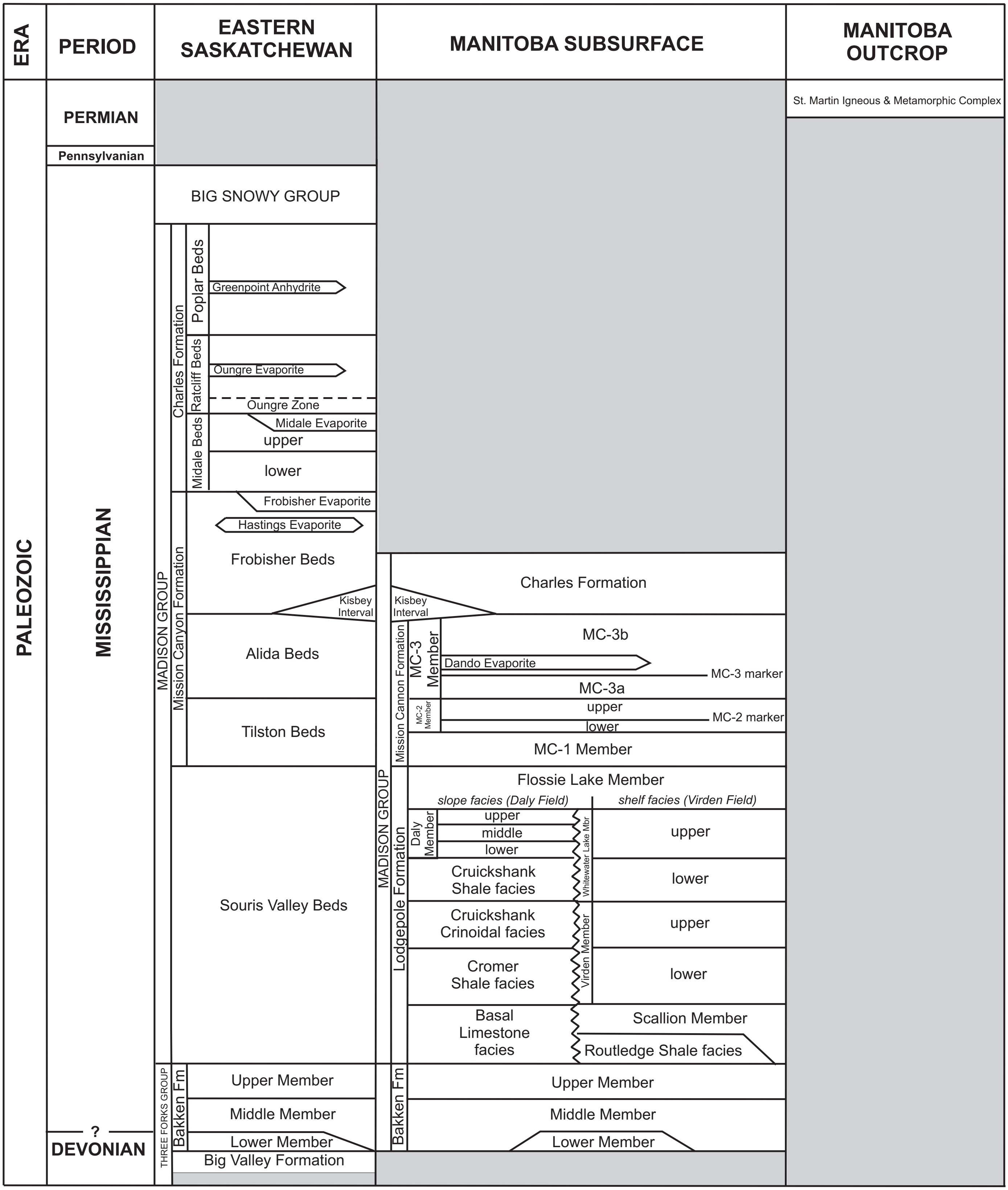

Figure 4: *Mississippian portion of the Williston Basin Project stratigraphic column for eastern Saskatchewan and southwestern Manitoba.*

strata form a basinward-thickening, southwesterly-sloping wedge, with the strata reaching a total thickness of 2.3 km in the extreme southwestern corner of Manitoba (Twp. 1, Rge. 29, W 1st Mer.).

The Paleozoic and Mesozoic strata are separated by a major angular unconformity. The Paleozoic unconformity represents the largest time lapse in the history of the Phanerozoic, and is mostly due to tectonic uplift (McCabe, 1959). Continental tectonic forces affected basinal changes through the Phanerozoic. Of particular importance is the southern extension of the Precambrian Superior Boundary Zone (SBZ) beneath the Phanerozoic cover in southwestern Manitoba. The SBZ imposed more localized effects through basement reactivation, having had several effects on the overlying strata, including control of depositional environments and imposition of preferential salt-dissolution zones.

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 WCSB during this time. Discordance between the current structural trend of the Ordovician strata and the regional depositional (isopach) trend is a result of higher rates of subsidence in the Manitoba portion of the basin (Bezys and Conley, 1998b; Bezys and Bamburak, 2004). By the Silurian, the tectonic setting had stabilized (Bezys and Conley, 1998d; Bezys and Bamburak, 2004). The early Devonian was a time of nondeposition and erosion on the Severn Arch (Figure 1), resulting in complete erosion of Ordovician and Silurian strata that had been continuous between the WCSB and the Hudson Basin (Norford et al., 1994). The Devonian marks the beginning of deposition in the Elk Point Basin and is characterized by a steady transgression with brief regressive pulses (Moore, 1988). A widespread and significant erosional unconformity marking the end of the Devonian represents a period of uplift, which continued until the early Mississippian. The Devonian–Mississippian boundary represents a change in basin dynamics and accompanying sea-level changes, characterized by the shallow-water carbonate sequences of the Mississippian, and marks the beginning of deposition within the Williston Basin.

Superior Boundary Zone

The Superior Boundary Zone (SBZ) is a 40–50 km wide crustal suture zone between Archean and Proterozoic crustal blocks (Figure 1; Dietrich and Magnusson, 1998). This zone has been defined "by gravity, magnetic and electromagnetic anomalies associated with crystalline basement features" by Dietrich and Magnusson (1998), as well as Rankin and Kao (1978), Green et al. (1979), Jones and Savage (1986) and Lyatsky et al. (1998). The geophysical expression of the SBZ and its relationship to other Precambrian crustal blocks within the TGI II project area were discussed in Li and Morosov (2007).

The SBZ extends beneath the Phanerozoic cover and has had a tremendous effect on the entire Phanerozoic section, through periods of basement reactivation. These episodes of reactivation manifest themselves mostly as faults, causing either stratigraphic-facies variations in sedimentary deposition or porosity variations and dissolution anomalies due to fluid movement through an extensive and deep fracture/fault system (Dietrich and Magnusson, 1998; Fedikow et al., 2004; Bamburak and Klyne, 2004; Bamburak, 2007). Dietrich et al. (1999) reported that basement-related structures are relatively small in amplitude, but these low-amplitude structures still have an important role in petroleum plays, particularly within the lower Paleozoic.

Effects of the SBZ occur from outcrop to subsurface; in the subsurface, its effects are most pronounced in the Birdtail-Waskada Zone (BWZ). The BWZ is a 20–35 km wide, north-trending zone in southwestern Manitoba. Originally defined as the Birdtail-Waskada Axis by McCabe (1967, 1971), the actual area that it covers is broader than initially thought, and has been renamed the Birdtail-Waskada Zone by Dietrich and Magnusson (1998). The authors are in agreement with the new, more appropriate designation. McCabe (1967, 1971) described this zone as having "numerous sharply defined structure and isopach anomalies, mostly related to post–Middle Devonian salt collapse." Dietrich and Magnusson (1998) described this zone as being "characterized by numerous structural and stratigraphic irregularities in Paleozoic strata, most of which are associated with Middle Devonian Prairie Formation salt." Although the zone is strongly influenced by salt dissolution in the Devonian Prairie Evaporite, its origins are deeper and effects greater than those caused by salt dissolution and collapse during the post–Middle Devonian. Dietrich and Magnusson (1998) reported several large, basement-originating fault systems in the BWZ, as seen on seismic records; they also identified a basement hinge line that runs the length of the BWZ and represents a flexing point between the two crustal blocks. Fault and fracture systems on either side of this hinge line are common. In response to the crustal blocks flexing with increased and decreased overburden load through geological time, the overlying strata are affected by periods of reactivation of these fault systems. Basinal fluids migrating through the stratigraphic package take advantage of the numerous fault and fracture systems, resulting in localized dolomitization, sulphide precipitation and porosity variations. The temperature and chemistry of these fluids are likely variable, affecting the hostrocks accordingly; however, these aspects of the basin are poorly understood.

Dietrich and Magnusson (1998) noted that the SBZ has affected the Phanerozoic section to varying degrees by faulting, and Dietrich and Bezys (1998) and Bamburak et al. (work in progress, 2008) have noted several outcrop- or near-surface–related features that are both direct and indirect evidence of faulting caused by basement reactivation. The evidence indicates that structural deformation and fluid movement have occurred and affected/created reservoir zones. It should be noted that closed structural traps related to induced structural deformation, either from the SBZ, the BWZ, salt collapse or even the suspected volcanic activity that caused the Hartney Structure (Twp. 5, Rge. 24, W 1st Mer.; Dietrich and Magnusson, 1998), offers potential in all reservoir zones subject to the sealing capacity of the overlying beds and the timing of the structure predating the migration and emplacement of the various hydrocarbon systems.

Cambrian stratigraphy

Deadwood Formation

The Deadwood Formation is a highly glauconitic argillaceous siltstone to fine sandstone (McCabe, 1978). This interbedded sand-silt-shale unit occurs as a thin wedge in the extreme southwestern corner of the province, and as small isolated outliers in the northeastern corner of the Paleozoic outcrop belt, where it was sheltered from erosion in basement graben structures (Manitoba Industry, Trade and Mines, 2002; TGI Williston Basin Working Group, 2008a). These outliers were found during mineral exploration drilling and are located in 12-34-54-16-W1 and 8-10-47-17-W1. The Deadwood is erosionally truncated at a major unconformity, underlain by the peneplaned Precambrian surface (TGI Williston Basin Working Group, 2008a) and overlain by high-permeability basal sandstone of the Winnipeg Formation (Figure 2). The presence of the Deadwood in the extreme southwestern corner of Manitoba and the thick preservation of this unit (85 m; Manitoba, Industry, Trade and Mines, 2002) in the northeastern corner of the Paleozoic outcrop belt indicate that it covered an area much larger than the current distribution of the lower Paleozoic sequence.

The Deadwood structure contours (TGI Williston Basin Working Group, 2008b) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopach trend (TGI Williston Basin Working Group, 2008c) shows an eastward thinning towards the erosional subcrop edge.

Due to the presence of the overlying basal sand of the Winnipeg Formation and the lack of a seal above the unconformity, the potential for a conventional unconformity truncation trap is limited. The possibility of Cambrian oil charging the basal Winnipeg sand where the porous Cambrian sand subcrops should not be overlooked. The interbedded sand-shale nature of the Deadwood would accommodate lateral migration within continuous sand from the basin centre to the erosional subcrop, and there is potential for structural trapping of this migrating oil within the sand. A possible trapping configuration could occur locally where Deadwood and basal Winnipeg strata onlap a Precambrian erosional high, as seen elsewhere in the basin. The seal in this case could be provided by the Winnipeg shale or lower Red River tight carbonate rocks if the feature is high enough.

Ordovician stratigraphy

Winnipeg Formation

The Winnipeg Formation is composed of Lower and Upper units (Figure 2). The Lower Unit is a continuous, poorly consolidated, quartz-rich sandstone sheet of varying thickness with excellent reservoir characteristics (McCabe, 1978). The Upper Unit consists mostly of shale with some interbedded sandstone. The Carman Sand is restricted to southwestern Manitoba (TGI Williston Basin Working Group, 2008d) and occurs as a localized, thick, highly permeable sand lens at the base of the Upper Unit that grades laterally into shale.

The Winnipeg structure contours (TGI Williston Basin Working Group, 2008e) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopachs (TGI Williston Basin Working Group, 2008d) show two thickening trends, one towards the Williston Basin depocentre in south-central Saskatchewan and a second towards the southeast with the deposition of the Carman Sand; a northward thinning is common to both trends. The rapid truncation of the thick Carman Sand at the Winnipeg edge indicates that the current WCSB edge is erosional and truncated, not depositional (Bezys and Bamburak, 2004). The WCSB during the Ordovician was the western remnant of a much larger depositional cratonic platform that extended from the Hudson Platform in the east and northeast to New Mexico in the south (Norford et al., 1994). Therefore, Ordovician sequences originally extended much farther to the east than their current distribution, and the Ordovician depositional edge has been eroded. The boundary between the two Winnipeg Formation thick isopachs corresponds to the location of the SBZ (TGI Williston Basin Working Group, 2008d). Bezys and McCabe (1996) stated that this boundary is not a coincidence and indicates that tectonic reactivation along that suture zone likely affected depositional patterns. Bamburak et al. (work in progress, 2008) have further explored this relationship towards the north. Refer to Bezys and Bamburak (2004) for a detailed discussion of the Ordovician tectonic and paleogeographic framework.

Oil shows in the Winnipeg have been documented in eight wells (Bezys and Conley, 1998b; Manitoba Industry, Economic Development and Mines, 2005). The overlying Upper Winnipeg shale could have good potential as a seal in a closed structural trap. Local onlap against a Precambrian erosional high, as discussed above, could provide a localized trapping configuration. Also, in areas where the top pick becomes indistinct due to the interbedding of sand and shale, updip pinchout of this sand sitting above the main sheet-like sand may provide for local trapping. Lithofacies variations within the Winnipeg are common within the BWZ and are likely caused directly from SBZ basement reactivation. Therefore, the BWZ provides the best location for exploring for stratigraphic traps in this formation. East of the BWZ, the updip edge of the Carman Sand's lenticular sand body provides a good opportunity for hydrocarbon trapping.

The sand of the Lower Unit has been quarried at Black Island in Lake Winnipeg for its high-quality silica sand, and is one of the purest deposits in North America (now abandoned). A similar sand is currently under investigation on the mainland, near Seymourville, by Gossan Resources Limited (Bamburak, pers. comm., 2008).

Red River Formation

The Red River Formation consists predominantly of dolostone beds with interbedded limestone, and anhydrite units near the top. It conformably overlies the Winnipeg Formation and underlies the Stony Mountain Formation (Figure 2).

Prior to the TGI II project, the Red River Formation in the Manitoba subsurface was informally subdivided into the Herald and Yeoman equivalents to the Saskatchewan formations of the same name (Martiniuk et al., 1998). The lower Red River in the Manitoba subsurface is equivalent to the Yeoman Formation–equivalent beds plus the Hecla Beds. In outcrop, the lower Red River is equivalent to the Hecla Beds; the Dog Head, Cat Head and Selkirk members; and Unit C. Through log correlations, it is possible to correlate the Redvers Unit, Coronach Member and Lake Alma Member of Saskatchewan's Herald Formation into Manitoba's subsurface, and the adoption of these names is recommended for these equivalent units in Manitoba. These all constitute the upper Red River in Manitoba, as shown in Figure 2. In outcrop, the upper Red River is equivalent to the Fort Garry Member. Bezys (pers. comm., 2007) successfully correlated the Redvers, Coronach and Lake Alma units in near-surface drillholes farther to the east and north, towards the outcrop belt, although these units are not discernible in actual outcrop.

The lower Red River is a burrow-mottled fossiliferous dolostone (Bezys and Bamburak, 2004). The upper Red River consists of cyclical beds of very fine, crystalline, nonfossiliferous dolostone (Martiniuk et al., 1998) and anhydrite. The Lake Alma and Coronach members each include either an anhydrite bed or argillaceous remnants of dissolved anhydrite. The Lake Alma and Coronach evaporite beds consist of anhydrite and have been affected by dissolution at their edges. The Lake Alma Evaporite is present in southwestern Manitoba and southern Saskatchewan, and the Coronach Evaporite is present only in south-central Saskatchewan (TGI Williston Basin Working Group, 2008f, g).

The Red River structure contours (TGI Williston Basin Working Group, 2008h) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopachs (TGI Williston Basin Working Group, 2008i) have a trend opposite to that of the structure contours, with the formation thickening towards the southeast and thinning towards the north. The formation's maximum thickness in the Canadian portion of the basin is located at the southern extent of the Manitoba outcrop belt. This truncation is in agreement with the erosional-edge theory discussed in Bezys and Bamburak (2004).

The Red River has several documented oil shows (Manitoba Industry, Economic Development and Mines, 2005) and has excellent hydrocarbon potential in Manitoba, as production is recorded from other parts of the Williston Basin. Basement-related structural closures are involved in most known Yeoman pools in the basin. The overlying Lake Alma Anhydrite makes for a competent seal in most places. However, variations in development of secondary porosity throughout the section are common and offer some interesting stratigraphic trapping possibilities; many of these are thought to be directly related to effects caused by the SBZ, particularly in the BWZ. Porous and permeable dolostone is consistently present near the top of the lower Red River, but seems to be only locally developed farther down in the section. There is a general trend towards a thicker package of porous dolostone when moving from the Saskatchewan border eastward towards the subcrop edge. The tight limestone in the lower part of the lower Red River passes laterally updip into porous dolostone. However, local variations in the porosity profile can be quite pronounced, as evidenced by wells in the area of Twp. 4, Rge. 25, W 1st Mer. This area is along the SBZ, suggesting that structural reactivation of the basement may have been involved in localized development of secondary porosity by fluid mobilization. Vertical fracturing in the Red River Formation has been documented along the northern extent of the SBZ beneath Phanerozoic cover and is associated with tectonic movement of the Precambrian basement (Bezys, 1996). This fracturing evidence suggests that the basement movement that has occurred in the southern extent of the SBZ would have created similar fracturing, thus providing conduits for fluid and oil migration. Dietrich and Magnusson (1998) reported the development of thicker porous zones in the Red River immediately updip from the main basement fault zone within the BWZ. This would create the potential for trapping in local updip porosity pinchouts throughout this area. These porosity variations are of sufficient magnitude that they might be resolved seismically.

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Stony Mountain Formation

The Stony Mountain Formation consists of the lower Hartaven and Gunn/Penitentiary members, and the upper Gunton Member (Figure 2). The Hartaven Member is present at the base of the Stony Mountain Formation in Saskatchewan and southwestern Manitoba, and consists of a fossiliferous, argillaceous, partly dolomitized high-purity limestone (Glass, 1990; Bezys and Conley, 1998c). The southern expression of the Gunn/Penitentiary Member is an interbedded, highly fossiliferous limestone-shale facies (referred to as the Gunn; Bezys and Bamburak, 2004), and the northern expression is an argillaceous dolostone facies (referred to as the Penitentiary; Bezys and Conley, 1998). In the subsurface, the Gunn and Penitentiary are indistinguishable from each other, and the term Gunn is more often used to represent this section. The Gunton Member consists of a sparsely fossiliferous, nodular bedded dolostone (Bezys and Conley, 1998b). North of the community of Gypsumville (Twp. 31, Rge. 9, W 1st Mer.), the entire Stony Mountain becomes Gunton-like.

The Stony Mountain structure contours (TGI Williston Basin Working Group, 2008j) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopachs (TGI Williston Basin Working Group, 2008k) have a similar trend to those of the Winnipeg Formation, with two areas of thick isopachs separated by a boundary of thinner Stony Mountain, corresponding with the location of the SBZ. Although the general isopach trend is a northward thinning of the sequence, the Stony Mountain is different from the other Ordovician formations in having a pronounced pockmarked character. The cause for this isopach irregularity stems from other tectonic controls, such as basin subsidence, that would have effected depositional patterns during this time, as evidenced by the cyclical fluctuations of depositional conditions resulting from eustatic effects (Bezys and Conley, 1999c). Differential compaction of the shaly components and facies changes within the northern and southern portions of the formation could also contribute to the isopach irregularities (Bezys and Conley, 1998c). The thickest areas of Stony Mountain occur in the southeast, at the southern extent of the Manitoba outcrop belt, and in the extreme south-central portion of Saskatchewan. The southeastern truncation at the Manitoba outcrop belt supports the erosional-edge theory.

The Stony Mountain has had only two documented oil shows (Bezys and Conley, 1998c; Manitoba Industry, Economic Development and Mines, 2005). The best prospects for hydrocarbon potential would be in the Gunton Member, where it is currently productive in southwestern Saskatchewan.

In the outcrop belt, the Gunton Member is used for crushed stone and occasionally as a building stone (Bezys and Conley, 1998c). More than 2 million tonnes of aggregate are quarried annually northeast of Stonewall and used mainly for road construction (Bezys and Bamburak, 2004).

Stonewall Formation

The Stonewall Formation is disconformably underlain by the Stony Mountain Formation and overlain by the Silurian Interlake Group. The formation is subdivided into two members, Upper and Lower, separated a thin, sandy argillaceous marker (t-marker; Porter and Fuller, 1959), a para–time-stratigraphic marker that represents the Ordovician–Silurian boundary (Figure 2). The formation consists of an argillaceous and sandy dolostone (Martiniuk, 1992). The Williams Member, a dense argillaceous dolostone (McCabe, 1979), occurs at the base of the Stonewall Formation and is capped in places by the Basal Stonewall Anhydrite–equivalent of Saskatchewan (TGI Williston Basin Working Group, 2008l).

The Stonewall Formation structure contours (TGI Williston Basin Working Group, 2008m) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopachs (TGI Williston Basin Working Group, 2008n) have a trend similar to that of the structure contours, with the formation thinning towards the outcrop belt in the north and east. The thickest isopach of the Stonewall in the Canadian portion of the basin is in southern Saskatchewan. The shift from Ordovician basinal deposition to Silurian stable-shelf deposition with a stabilization of the tectonic framework is recorded in the relatively uniform thickness and lithology of the Stonewall (Bezys and Conley, 1998d).

There has been only one documented oil show in the Stonewall Formation, in 3-9-4-11-W1 (Manitoba Industry, Economic Development and Mines, 2005). Little is known of the hydrocarbon potential of this formation, and it is not productive anywhere in the basin, likely due to its argillaceous character.

In the outcrop belt, the Stonewall Formation was used as a source of dolostone for high-magnesium lime and for construction of a few buildings in Stonewall (Bezys and Bamburak, 2004).

Silurian stratigraphy

Interlake Group

The Interlake Group is disconformably underlain by the Stonewall Formation and unconformably overlain by the Devonian Ashern Formation (Figure 2). This upper contact marks a major, basin-wide, pre-Devonian unconformity. The Interlake Group lithology is a finely crystalline dolostone with oolitic, fossiliferous, stromatolitic and biohermal interbeds (Glass, 1990). In the Manitoba subsurface, the Interlake is tentatively divided into lower and upper units (Figure 2); in outcrop, however, it is subdivided into the Fisher Branch, Moose Lake, Atikameg, East Arm and Cedar Lake formations. The boundary between the upper and lower units in the subsurface is equivalent to the v-marker, a para–time-stratigraphic marker (Porter and Fuller, 1959) within the East Arm Formation (Bezys, 1996).

The Interlake Group structure contours (TGI Williston Basin Working Group, 2008o) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopachs (TGI Williston Basin Working Group, 2008p) have a trend similar to that of the structure contours, with the formation thinning towards the outcrop belt in the north and east. The thickest isopach of the Interlake in the Canadian portion of the basin is in southern Saskatchewan. Bezys and Conley (1998e) suggested that the tectonic framework remained stable throughout deposition of the Interlake, as evidenced by the relative uniformity of the Interlake lithological assemblage. The end of the Silurian marks the beginning of changes in depositional patterns of the large cratonic platform to those characteristic of the Elk Point Basin. Regional uplift, including uplift along the Severn Arch (Figure 1), resulted in a significant depositional hiatus that is recorded as long periods of exposure and erosion (Norford et al., 1994).

There have been several oil shows documented in the Interlake (Manitoba Industry, Economic Development and Mines, 2005) and, given its production in the North Dakota and Saskatchewan portions of the basin, successful production from this unit in Manitoba is possible under the right conditions. The Interlake Group is also subject to the effects of the SBZ, which could give rise to the right trapping conditions. For example, Bezys (1990, 1996) reported extensive vertical fracturing in the East Arm and Moose Lake formations, and Bamburak (2007) has found evidence of potentially hydrothermally altered dolostone in the Interlake Group near Duck Bay (Twp. 36, Rge. 19, W 1st Mer.) on Lake Winnipegosis. Bamburak and Klyne (2004) have found sulphide-bearing dolomite near the northeastern end of Pemmican Island (Twp. 42, Rge. 18, W 1st Mer.) in Lake Winnipegosis. The presence of sulphides, as well as enhanced porosity, suggest that this altered dolostone may have been affected by fluids migrating upwards from the SBZ, whose eastern limit passes through the Duck Bay and Pemmican Island area in Lake Winnipegosis. Since the sub-Phanerozoic extension of the SBZ trends roughly south beneath the Phanerozoic cover towards the Canada–United States border, there is a possibility that enhanced porosity may occur elsewhere (and in older horizons), providing for excellent reservoir conditions with the benefit of the tight Ashern Formation acting as a top seal. The development of Mississippi Valley–type lead-zinc deposits in this horizon is also possible under these conditions (Gale et al., 1984; Gale and Conley, 2000).

A major angular unconformity occurs at the top of the Interlake Group, and this erosional surface shows evidence of extensive secondary-porosity development, including karst and solution-enlarged fracture systems. This secondary-porosity system can have excellent reservoir potential. Except along the main subcrop belt, the erosional surface is overlain by the shaly Devonian Ashern Formation, which has good sealing potential. The apparent continuity of this leached zone in the Interlake would provide a path for long distance migration of oil, with an opportunity for trapping in any closed structure or paleoerosional feature on the eroded Silurian surface.

The Interlake Group is widely used as crushed stone for highway projects (Bezys and Conley, 1998e). Gossan Resources Limited is currently evaluating the high-purity dolomite as a potential raw material to produce magnesium metal. Graymont Limited currently produces dolime from dolomite, quarried at Hilbre, in its Faulkner plant (Bamburak, pers. comm., 2008).

Devonian stratigraphy

Ashern Formation

The Ashern Formation consists of dolostone and shale that were deposited after a long period of nondeposition and significant erosion at the end of the Silurian, and marks the beginning of Devonian sedimentary deposition (Figure 3). It unconformably overlies the Silurian Interlake Group and conformably underlies the Winnipegosis Formation.

The Ashern Formation structure contours (TGI Williston Basin Working Group, 2008q) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition of the Ashern Formation in the Middle Devonian was in the Elk Point Basin. It was deposited on an eroded landscape during a transgression, and its isopach pattern partly represents the irregular infilling of topography (McCabe, 1967), with depositional controls from basin subsidence superimposed. This can be seen from the two different isopach trends in the formation, with thick isopachs occurring both in the south-central portion of Saskatchewan in the Canadian portion of the Williston Basin and in the north-central portion of Saskatchewan, where the formation thins towards the east (TGI Williston Basin Working Group, 2008r).

The argillaceous character of the Ashern succession makes it an unlikely hydrocarbon reservoir, but it acts as an excellent seal atop the carbonate rocks of the Interlake Group. There are no records of oil shows in this formation in Manitoba.

The Ashern Formation has occasionally been used in road construction and, because of its red colour, as a landscape material (Bamburak, pers. comm., 2008).

Winnipegosis Formation

The Winnipegosis Formation consists of fossiliferous dolostone and minor limestone, and is reefoid in places. It is subdivided into a lower member, representing platform-facies dolostone, and an upper member, representing a reefoid- or inter-reefoid–facies dolostone (Figure 3; Norris et al., 1982). At the top of the lower member, an anhydritic transition zone of limestone-shale breccia and crystalline limestone occurs locally (Martiniuk, 1992). Reef development in the Winnipegosis follows the BWZ trend, and reef growth is thought to be directly related to basement movement in the SBZ (Dietrich and Magnusson, 1998). The Winnipegosis conformably overlies the Ashern Formation, and underlies the Prairie Evaporite, where present, or the Second Red Beds Member of the Dawson Bay Formation where the Prairie Evaporite is absent.

The Winnipegosis Formation structure contours (TGI Williston Basin Working Group, 2008s) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition of the Winnipegosis Formation in the Middle Devonian was in the Elk Point Basin. Unlike other horizons, the structure contours of the Winnipegosis have a pronounced wavy character, with highs and lows related to the reef and inter-reef structures. The isopach map (TGI Williston Basin Working Group, 2008t) clearly shows the location of positive reef structures. Defined bull's-eye areas are related to thick isopachs (red and purple), inter-reef and ramp areas are represented by medium isopachs (yellow and orange), and basinal areas are represented by thinner isopachs (blue). The isopach patterns of reef/platform carbonate rocks and the basinal carbonate rocks mimics closely the Elk Point Basin paleogeographic map for the Winnipegosis Formation in McDonald (2007).

The Winnipegosis is productive in other parts of the basin. In Manitoba, there are several oil shows in this formation (Manitoba Industry, Economic Development and Mines, 2005) but no current production despite excellent reservoir development in the dolostone of the upper part of the formation. In the basinal setting, potential exists in pinnacle and patch reefs. Where salt or anhydrite of the Prairie Evaporite is present and encases the reef, there is potential for trapping of thick but aerially limited oil columns similar to those seen elsewhere in the basin. Potential for this type of play is limited to a small area along the Saskatchewan border, where both the reef–inter-reef topography is present and the Prairie Evaporite is preserved. In the shelf areas, trapping would be more dependent on the seal being provided by local structural closures with the Second Red Beds Member or Prairie transitional basal anhydrite. Where Mesozoic cover is present in the southern part of the main subcrop belt, subcrop truncation trapping associated with erosional topography may occur. Buried hills, similar to well-known Mississippian examples (e.g., Daly and Virden fields), may occur and be sealed by the Lower (Red Beds) and Upper (Evaporite) members of the Jurassic Amaranth Formation.

In outcrop, the Winnipegosis and the equivalent Elm Point Formation limestone is used as a crushed stone for road building (Bezys and Bamburak, 2004). In the past, the high-calcium Elm Point was used to produce cement. Currently, Graymont Limited produces high-calcium lime from its Faulkner plant, near Steeprock (Bamburak, pers. comm., 2008).

Prairie Evaporite

The Prairie Evaporite consists of thick halite beds with occasional potash zones near the top and minor anhydrite near the base (known as the Transitional Beds, formerly part of the Winnipegosis Formation; Figure 3). In Manitoba, the only potash zones present are the White Bear Member, which is very thin and only present in the extreme southwestern corner of the province, and the Esterhazy Member, a thicker economic potash bed present up to two ranges into Manitoba from the Saskatchewan border (Bannatyne, 1960, 1983). It conformably overlies the Winnipegosis Formation and underlies the Dawson Bay Formation (Figure 3).

The dissolution of the Prairie Evaporite is an ongoing process, starting from the late Middle Devonian. The current subcrop edge represents the edge of the Transitional Beds, as seen in subsurface logs. The basal transitional anhydrite is mixed with brecciated argillaceous remnants of the overlying dissolved salt units; since it is more resistant to dissolution, its presence indicates the approximate minimum of the depositional areal extent of this formation in the subsurface prior to dissolution. The salt edge of the Prairie Evaporite represents a dissolution front, where active dissolution is ongoing. In the outcrop belt, all evidence of the Prairie has been eroded/dissolved. The only suggestion that the true depositional edge of the Prairie Evaporite was equal to or greater than that of the Dawson Bay Formation is the postdepositional draping effect of the originally horizontal beds of the Dawson Bay over Winnipegosis reefs (Bezys and Bamburak, 2004), where early dissolution of the Prairie resulted in collapse of the overlying units. Collapse occurred both slowly and rapidly, resulting in gentle draping of overlying beds on top of the Winnipegosis (slow dissolution) and salt-collapse structures (rapid dissolution).

The Prairie Evaporite structure contours (TGI Williston Basin Working Group, 2008u) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition of the Prairie Evaporite in the Middle Devonian was in the Elk Point Basin. As with the Winnipegosis Formation, the structure contours of Prairie Evaporite have a slight wavy character, with highs corresponding to the positive reef structures of the underlying Winnipegosis Formation. The isopach map shows the pronounced variability in thickness of this formation, which is directly related to salt dissolution over time (TGI Williston Basin Working Group, 2008v). In Manitoba, the thinnest parts of the formation occur in a north-south band east of the BWZ. The rapid thickening in western Manitoba towards the Saskatchewan border corresponds to the active dissolution edge. Potash zones are best developed where the Prairie is at its thickest.

Preferential dissolution of the Prairie Evaporite has occurred along the BWZ (Figure 1) and is responsible for the formation of the trapping mechanisms of Manitoba's largest oil fields. Directly above the salt-front rollover, current production is limited to the Mississippian; however, the possibility of new and underexplored plays in the upper Paleozoic strata (Dietrich et al., 1999), particularly in the Devonian, still exists. Isolated dissolution patches of the Prairie within the current extent of the salt are the result of preferential dissolution of the salt above water-saturated Winnipegosis reefs and other fracture systems. The resulting salt-collapse structures have been documented to be as small as a single well in size (e.g., 5-13-5-29-W1) and as large as an oil field (e.g., the Waskada Field; Twp. 1–2, Rge. 24–26, W 1st Mer.). Multiple stages of salt collapse have been identified through time, with the most dominant salt-dissolution stages coinciding with the Devonian–Mississippian boundary and the Paleozoic–Mesozoic boundary. These two major unconformities represent times of significant change in the basinal tectonic setting through uplift and erosion, affecting the hydrodynamics in the basin and resulting in an increased rate of salt dissolution (McCabe, 1967).

The potash zones of the Prairie Evaporite are being mined in the Saskatchewan part of the basin. Thick accumulations of high-grade potash occur in Manitoba along the Saskatchewan border, in Twp. 16–22, Rge. 29, W 1st Mer. (Bannatyne, 1960, 1983), but Manitoba currently does not have any active underground mining. Solution mining of the salts of the Prairie Evaporite is currently occurring in brine wells at Hargrave, near the town of Virden (at 3-12-11-27-W1). Sodium chlorate, used by the paper industry, is produced in an adjacent plant, taking advantage of Manitoba's low-cost electrical energy (Bamburak, pers. comm., 2008).

Dawson Bay Formation

In the subsurface, the Dawson Bay Formation consists of the lower argillaceous beds of the Second Red Bed Member and the overlying Burr and Neely members (Figure 3). Prior to the TGI II project, the Burr and Neely members were not formally recognized in Manitoba's subsurface. The Burr Member is easily picked on logs, since it corresponds to the top of the Dawson Bay Formation. The Neely Member is difficult to pick on logs and therefore difficult to correlate using this method; however, it is reported to be visible in the Manitoba outcrop (Glass, 1990), indicating its continuous regional distribution. In outcrop, the Burr Member is correlative with the Middle (C) and Lower (B) members used in outcrop stratigraphy, and the Neely Member is correlative with the Upper (D) Member (Figure 3). The Dawson Bay conformably overlies the Prairie Evaporite when the latter is present, or disconformably overlies the Winnipegosis when the Prairie Evaporite is absent. Prior to this project, subdivision of the Dawson Bay into the above-mentioned members in the subsurface had not been attempted. Although stratigraphic correlations through core were not attempted, subsurface log correlation of these members from Saskatchewan into Manitoba was successful, suggesting the continuity of these units to the east.

The Dawson Bay structure contours (TGI Williston Basin Working Group, 2008w) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition of the Dawson Bay in the Middle Devonian was in the Elk Point Basin. As with the Winnipegosis and Prairie Evaporite formations, the Dawson Bay structure contours have a slight wavy character, with highs corresponding to the positive reef structures of the underlying Winnipegosis Formation, although this is less pronounced on the Dawson Bay structure surface than on the Prairie structure surface. Postdepositional structural effects would be related to the preferential dissolution of the Prairie above water-bearing Winnipegosis reefs, resulting in a draping effect of the Dawson Bay strata over the positive reef structures. The isopach map

(TGI Williston Basin Working Group, 2008x) shows that the formation is thickest in Manitoba towards the southeast (i.e., approaching the eastern outcrop belt, where it is truncated at the subcrop edge), similar to the Ordovician strata. The sudden thinning of the Dawson Bay in the east when approaching the formation edge is a result of pre-Jurassic erosion; this portion of the Dawson Bay is directly overlain by Jurassic strata. The westward thinning of the Dawson Bay is related to uplift, through faulting or tectonism, along the Peace River Arch (Figure 1; Moore, 1988); it is unclear if the uplift occurred during or after Dawson Bay deposition. The dissolution of the Prairie Evaporite during Dawson Bay deposition also affected the isopachs of the Dawson Bay, making it thicker in the east than in the west. The relative effects of the Prairie dissolution, versus the uplift along the Peace River Arch, on Dawson Bay deposition and thickness is difficult to determine.

There are several oil shows documented in the Dawson Bay in Manitoba (Manitoba Industry, Economic Development and Mines, 2005) and this formation does produce oil in the North Dakota portion of the basin. Its reservoir potential is further accentuated by the draping effect of this formation on buried Winnipegosis reefs in the areas where the Prairie Evaporite salt has been dissolved, providing for excellent potential traps. Karsting of the Dawson Bay would also play a roll in trapping and reservoir development.

The differentiation between the upper Neely and the lower Burr members is not always clear and may be reflective of highly variable porosity development. This lateral variation in porosity may provide potential for stratigraphic trapping, although it is not clear whether these variations reflect depositional facies or development of secondary porosity. The Hubbard Evaporite (TGI Williston Basin Working Group, 2008y), consisting of halite with thin partings of dolomite and anhydrite, is common at the top of the formation and acts as a cap. Along with the overlying First Red Beds of the Souris River Formation, it provides a seal for any local closed structure. Again, in the southern part of the subcrop belt, where the Mesozoic Amaranth cover is present, potential exists for trapping along the erosional topography of the subcrop surface.

In the outcrop belt, the Dawson Bay is host to modern-day brine springs, resulting in the development of large salt flats (Bezys and Bamburak, 2004; Fedikow et al., 2004). These salt springs indicate the presence of deep fractures and a plumbing system that is still active today. The SBZ occurs in this region and plays an important role in these systems (Fedikow et al., 2004).

In outcrop, the Dawson Bay has been used as crushed stone in road and causeway construction (Bamburak, pers. comm., 2008).

Souris River Formation

The Souris River Formation consists of cyclical shale, limestone, dolostone and anhydrite units. It is composed of four members in the subsurface in Saskatchewan, which are correlatable into Manitoba. From oldest to youngest, these are the First Red Beds, Davidson, Harris and Hatfield members. In outcrop, the Minitonas Member is equivalent to the Hatfield Member, the Sagemace Member to the Harris Member and the Point Wilkins Member to the Davidson Member; the First Red Beds has the same name in outcrop as in the subsurface (Figure 3). The Souris River marks the youngest Paleozoic formation exposed in the Manitoba outcrop belt. It conformably overlies the Dawson Bay Formation and underlies the Duperow Formation. Prior to this project, subdivision of the Souris River into the above-mentioned members in the subsurface had not been attempted. Although stratigraphic correlations through core were not attempted, subsurface log correlation of these members from Saskatchewan into Manitoba was successful, suggesting the continuity of these units to the east.

The Souris River structure contours (TGI Williston Basin Working Group, 2008z) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition of the Souris River at the end of the Middle Devonian was in the Elk Point Basin. As with the Dawson Bay Formation, the structure contours of the Souris River have a slight wavy character. The isopach trend (TGI Williston Basin Working Group, 2008aa) is the opposite from that of the Dawson Bay, in that it shows thinning towards the outcrop belt and pronounced thickening in central Saskatchewan. The rapid thinning of the Souris River approaching the eastern and northern edges is a result of pre-Jurassic erosion of the formation.

Several oil shows have been documented in the Souris River in Manitoba (Manitoba Industry, Economic Development and Mines, 2005) and this formation does produce oil in other parts of the basin. The cyclical interbedded nature of the formation, with discrete high-porosity/permeability dolostone interbedded with regionally persistent argillaceous beds often accompanied by thin anhydrite units, gives it good potential for closed structural trapping. The gas accumulations in this zone underlying the Daly structure in the Daly Field demonstrate the reservoir quality and trapping potential (Manitoba Industry, Economic Development and Mines, 2005). The best porosity development seems to be in the lower part of the Davidson Member. The Harris Member also has numerous cycles of thin reservoir-quality dolomites capped by thin argillaceous markers and/or anhydrite. As with the Dawson Bay, the southern part of the subcrop belt, where the Mesozoic Amaranth cover is present, offers potential for trapping along the erosional topography of the subcrop surface. The interbedded nature of this unit enhances the subcrop-trapping possibilities, as both top and seat seals are provided by the tight interbeds. Similar to the Dawson Bay, the Souris River is affected by the draping effects and karsting caused by Prairie Evaporite dissolution.

The Mafeking quarry has fossilized remnants of solution chimneys preserved in the Souris River Formation, which are a result of the same fracture and fluid-transport system that gives rise to the modern-day salt flats described in the Dawson Bay Formation section (Bezys and Bamburak, 2004; Fedikow et al., 2004).

In outcrop, the Souris River Formation has been used as a source of high-calcium limestone for cement-making in Regina, Saskatchewan and is currently being used as crushed stone for road construction (Bamburak, pers. comm., 2008).

Duperow Formation

The cyclical character of the Souris River Formation continues into the Duperow Formation but with limestone becoming more common. It consists of limestone and dolostone with occasional argillaceous and anhydritic units. It is composed of four members in the subsurface in Saskatchewan, which are correlatable into Manitoba. These are, from oldest to youngest, the Saskatoon, Elstow, Wymark and Seward members, with the Flat Lake Evaporite occurring near the base of the Seward Member (Figure 3). The subcrop of the Duperow is beneath Mesozoic cover over the entire trend. The Duperow conformably overlies the Souris River Formation and underlies the Birdbear Formation. Prior to this project, subdividing the Duperow into the above-mentioned members in the subsurface had not been attempted. Although stratigraphic correlations through core were not attempted, subsurface log correlation of these members from Saskatchewan into Manitoba was successful, suggesting the continuity of these units to the east.

The Duperow structure contours (TGI Williston Basin Working Group, 2008ab) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition of the Duperow in the Late Devonian was in the Elk Point Basin. As with the Souris River Formation, the structure contours of the Duperow have a slight wavy character. The isopach map (TGI Williston Basin Working Group, 2008ac) is similar to that of the Souris River, in that it shows thinning towards the subcrop edge, pronounced thickening in central Saskatchewan and localized thickening in the central portion of the project area. The rapid thinning of the Duperow approaching the eastern and northern edges is a result of pre-Jurassic erosion of the Duperow.

The Duperow Formation has several documented oil shows (Manitoba Industry, Economic Development and Mines, 2005) and is productive in parts of the basin. Its potential for structural trapping is similar to that of the Souris River, and is again demonstrated by the gas accumulation in the Daly structure (Manitoba Industry, Economic Development and Mines, 2005). Most zones with reservoir quality are in the Wymark Member and are interbedded with thin anhydrite beds and argillaceous markers. Potential also exists for lateral variations in both depositional and diagenetic facies within individual cycles that are known to play a role in trapping Duperow pools elsewhere in the basin. As with the Souris River, the interbedded nature of the unit enhances the trapping possibilities. Well control along the subcrop shows variations in the thickness of the overlying Lower Amaranth Formation, which suggests that relief on the underlying erosional topography could offer good potential for subcrop traps. Karsting of this formation from Prairie Evaporite dissolution can also play an important role in trapping and reservoir development.

Birdbear Formation

The Birdbear Formation consists of fossiliferous porous limestone and dolostone. The Lower Member represents a platform facies and the Upper Member represents a biohermal (reef) facies, capped by an anhydrite unit in places (Martiniuk et al., 1995). It conformably overlies the Duperow Formation and underlies the Three Forks Formation (Figure 3). The Birdbear subcrop trend is covered by Mesozoic rocks.

The Birdbear structure contours (TGI Williston Basin Working Group, 2008ad) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition of the Birdbear in the Late Devonian was in the Elk Point Basin. As with the Souris River Formation, the structure contours of the Birdbear have a slight wavy character, although less pronounced. The isopach map (TGI Williston Basin Working Group, 2008ae) shows that the formation thins towards the subcrop edge, thickens markedly in central Saskatchewan and displays localized thickening in the central portion of the project area. The rapid thinning of the Birdbear approaching the eastern and northern edges is due to pre-Jurassic erosion.

Oil shows have been documented in the Birdbear (Manitoba Industry, Economic Development and Mines, 2005) and it is productive in other parts of the basin. Well-developed dolomite porosity is generally present near the top of the Lower Member. It is capped by the interbedded anhydrite and argillaceous dolostone of the Upper Member. Again, this is favourable for structural trapping, as demonstrated by gas accumulation in this zone in the Daly structure (Manitoba Industry, Economic Development and Mines, 2005). There is some variation in thickness of the upper evaporite unit. This is most apparent in the Virden area, where the evaporite thins significantly and is replaced laterally by a high-permeability organic reef facies. This replacement, best shown by a core and DST at 6-6-12-24W1, suggests the possibility of trapping associated with reef–inter-reef differentiation at the top of the lower unit. Again, erosional truncation along the subcrop, which is overlain by Mesozoic units, offers potential for trapping. This is demonstrated by a well at 2-8-8-17W1, where the Jurassic Amaranth Upper (Evaporite) Member directly overlies the Lower Member at the subcrop. A completion attempt in the Birdbear yielded a flow of gas (nitrogen), indicating that the subcrop was in a trapping configuration.

Three Forks Formation (Torquay Formation)

The Three Forks Formation is equivalent to the Torquay Formation in Saskatchewan (Figure 3), and is a cyclical transgressive-regressive sequence of shaly, silty dolarenite with interbedded siltstone-shale and brecciated siltstone intervals. It conformably overlies the Birdbear Formation and disconformably underlies the Bakken Formation. The subcrop trend is covered by Mesozoic rocks.

The Three Forks structure contours (TGI Williston Basin Working Group, 2008af) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition of the Three Forks at the end of the Devonian was in the Elk Point Basin, but the tectonic sagging effect of the Williston Basin was starting to affect the depositional trends. The isopach map (TGI Williston Basin Working Group, 2008ag) shows that the formation thins towards the subcrop edge, thickens markedly in southeastern Saskatchewan and displays localized thickening towards the northern extent of the Torquay Formation in Saskatchewan. The rapid thinning of the Three Forks approaching the eastern and northern edges is due to significant amounts of pre-Mississippian and pre-Jurassic erosion. Along the Manitoba-Saskatchewan border, the Three Forks thins quickly to the east, corresponding to the western edge of the BWZ and SBZ. Differential uplift of the eastern block relative to the western block at the end of the Devonian resulted in rapid erosion, and therefore thinning, of the Three Forks surface towards the east. This erosion on the eastern block is seen as a broad thin plateau in most of the Manitoba portion of the project area.

The Three Forks Formation is productive in the Sinclair, Daly and Kirkella fields, and from small isolated pools in Twp. 4, Rge. 29, W 1st Mer. Its production is commingled with the siltstone and sandstone of the Middle Member of the Bakken Formation. The best reservoirs straddle the unconformity, with pay occurring both above and below the Three Forks–Bakken contact; however, occasional small isolated pools have been discovered in the lowest parts of the formation, immediately above the Birdbear.

In productive Three Forks wells, the pay occurs in the sandy or 'clean' parts of the well-defined Torquay cycles of Christopher (1961), or Three Forks cycles of Nicolas (2006), where these units subcrop (Nicolas, 2007) and are in communication with the permeable middle Bakken sandstone or siltstone above. It is not a conventional subcrop trap situation, in that the oil system resides in the younger strata above the unconformity. The subcropping permeable dolomitic sandstone and siltstone become part of the reservoir, which is controlled by a trapping mechanism in the overlying middle Bakken. The incorporation of Three Forks strata into the reservoir adds significantly to the storage volume and deliverability of this formation, and can make an otherwise thin and uneconomic middle Bakken accumulation economic to develop. In the Sinclair Field, trapping is related to block faulting that occurs in the eastern part of the field. The Sinclair Fault (Nicolas, 2006) is a dip-slip or oblique-slip fault that is represented by a rapid truncation of the reservoir beds on the hangingwall against tight beds on the footwall. The faulting is a direct result of Prairie Evaporite salt dissolution and collapse in the Sinclair Field area, and is seen as a synclinal flexure on all structure contour surfaces from the Dawson Bay to the Lodgepole, with most of the movement occurring during or shortly after Three Forks deposition. The cyclical nature of Three Forks deposition, combined with the progressive updip erosional truncation of the section, make it possible to map areas where this commingling of reservoir beds across the unconformity is likely to occur (Nicolas, 2007).

Mississippian stratigraphy

Bakken Formation

The Bakken Formation consists of the black shale of the Upper and Lower members separated by the siltstone and sandstone of the Middle Member (Figure 4). The Lower Member is only preserved locally in sinkholes that are salt-collapse structures resulting from dissolution of the Prairie Evaporite. The Middle Member sits disconformably on the Three Forks Formation when the Lower Member is absent. The Bakken is conformably overlain by the Mississippian Lodgepole Formation. The subcrop trend of this formation is covered by Mesozoic rocks.

The Bakken structure contours (TGI Williston Basin Working Group, 2008ah) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. Deposition occurred at the end of the Devonian and throughout the Mississippian in the Williston Basin. The isopach map (TGI Williston Basin Working Group, 2008ai) is similar to that of the Three Forks Formation, thinning over broad areas towards the eastern subcrop edge, thickening markedly in southeastern Saskatchewan and showing minor localized thickening towards the northern extent of the formation in Saskatchewan and in the Waskada Field area (Twp. 1–2, Rge. 24–26, W 1st Mer.) of Manitoba. The thickness in the Waskada Field is the result of preservation of thick sections of Bakken (particularly the Lower Bakken shale) in salt-collapse structures. Other localized minor isopach variations in Manitoba resulted from deposition of the Middle Bakken as infills on the paleotopography of the eroded Devonian surface (Martiniuk, 1988). The rapid thinning of the Bakken approaching the eastern and northern edges is due to proximity to the depositional edge, with minor amounts of pre-Jurassic erosion superimposed.

The Bakken is productive from the Daly, Kirkella and Sinclair fields, and from small isolated pools extending from the Sinclair Field to Twp. 4, Rge. 29, W 1st Mer. Bakken production is often commingled with that of the Three Forks. Oil production is from the Middle Member, while the Upper Member acts as a top seal in a large regional accumulation extending over the Sinclair and Daly fields. This accumulation straddles the unconformity and overlies the Three Forks beds, as discussed previously.

Rock-Eval®–TOC geochemical analysis of the Upper Member was conducted on a suite of samples. The results indicate that this member is organically immature, and that total organic content (TOC) can be variable (Appendix 1). Of interest are some localized thick and petrophysically 'hot' shales, which occur in the Kola area (Twp. 10, Rge. 29, W 1st Mer.) and are present throughout most of the productive Bakken fairway. The low-density, higher resistivity character, coincident with the elevated gamma-ray reading in 3-33-10-29W1, indicates a geochemical difference compared to the more 'normal' readings of the samples from 12-29-10-29W1. The 'hot' shale from 3-33-10-29W1 has TOC values ranging from 17.43% to 24.1% and temperatures at which maximum hydrocarbon generation occurs during the pyrolytic degradation of the kerogen (T_{max}) ranging from 408.0°C to 418.0°C. The 'normal' shale from 12-29-10-29W1 has TOC values ranging from 0.08% to 0.59% and a T_{max} value of 304.0°C. Although the samples from the 'hot' shale have a very high organic content, which is reflected by its very high gamma-ray reading on geophysical logs, the thermal maturity is below the oil-generation window, thus eliminating the possibility of local sourcing. This suggests that parts of the Upper Member with low-density, high-resistivity and elevated gamma-ray readings on geophysical logs have a much higher organic content than those with more 'normal' readings, but they still haven't reached organic maturity. The high gamma-ray responses over the shale are, in part, due to high uranium levels, as shown by the gamma-ray spectrometry log run at 12-29-10-28 over a normal Upper Member. In the

Sinclair Field, TOC values range from 16.86% to 25.93%, and T_{max} ranges from 408°C to 418°C.

In summary, Rock-Eval®–TOC results indicate that the Upper Member is not thermally mature enough to act as a source in this part of the basin. Within the regional accumulation discussed above, local variations in reservoir quality will determine whether the zone can be economically produced. These variations appear to relate to depositional controls, since the best reservoir development occurs in the higher energy, coarser sand facies. Productive areas with good sand development tend to trend in a northerly direction, likely reflecting a shoreline that trends parallel to regional depositional strike.

The Bakken Formation in Manitoba can thin to less than 1 m in places, as in the Sinclair Field and parts of the Daly Field, so future potential of the Bakken Formation relies heavily on the presence and character of the Three Forks Formation below. Isopach mapping of the sandy lenses within the Middle Member would help in locating and developing new and existing pools (*see* Martiniuk, 1988).

Lodgepole Formation

The Lodgepole Formation consists of a shelf to slope sequence of argillaceous, oolitic, crinoidal and cherty limestone. Figure 4 provides a detailed correlation breakdown between the shelf and slope terminology. This formation lies conformably on the Bakken Formation and conformably underlies the Mission Canyon Formation, or the Lower (Red Beds) Member of the Jurassic Amaranth Formation when beyond the Mission Canyon subcrop edge.

The Lodgepole structure contours (TGI Williston Basin Working Group, 2008aj) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopach map (TGI Williston Basin Working Group, 2008ak) shows a shift from the underlying strata. The trend is similar, in general, to the Devonian sequences, with thinning towards the eastern and northern subcrop edge, but the central area of pronounced thickening in the Canadian portion of the Williston Basin is in southeastern Saskatchewan and southwestern Manitoba. The rapid thinning of the Lodgepole towards the eastern and northern edges is due to pre-Jurassic erosion. In cross-section, the subcrop edge of the Lodgepole is an escarpment, with a rapid truncation of the formation by erosion at the end of the Mississippian. The isopach trend roughly follows the basin-slope-shelf facies differentiations of McCabe (1959) and Klassen (1996) with some room for facies gradations, where the thicker isopachs are related to the basin facies, medium isopachs to the slope facies and thinner isopachs to the shelf facies. The oolite shoals of the shelf facies (Klassen, 1996) indicate the proximity to the true depositional basin margin for the early part of the Early Carboniferous, reflective of the shrinking basin throughout the Paleozoic.

The Lodgepole Formation has been producing oil in Manitoba since 1951, when oil was first discovered in Manitoba. The reservoirs and traps of the Lodgepole have been well documented in previous reports (McCabe, 1963; Martiniuk and Arbez, 1986a, b; Klassen, 1996). In the Daly and Virden fields, the trapping mechanism is stratigraphic and structural, whereas the mechanism in the Souris Hartney, Regent, Whitewater, Mountainside and Lulu Lake fields is related to the porous Lodgepole facies subcrop trend and capped by the Amaranth Formation.

Of note, is the occurrence of reservoir facies within a Lodgepole 'mound' buildup in the Kirkella Field in 11-15-12-29W1, thought to be equivalent to the Cruickshank Crinoidal facies. These mounds form a profound lithological and stratigraphic anomaly within the Lodgepole, as the clinoform boundary at the Cruikshank Shale marker could not be carried through. This raises the question of the temporal relationship of the mound and the surrounding strata. Biostratigraphic analysis of the Daly Member and Cruickshank Crinoidal facies on and off these mounds suggests that the mounds predate normal Lodgepole deposition (Nicolas, 2008). Also of interest is the peculiar production performance of this mound well. The mound seems to be an anomalously high permeability body in hydraulic isolation from the reservoir in the offsetting wells. The mound wells seem to have no active pressure-support mechanism despite the active water drive seen elsewhere in the reservoir. This suggests that the mound itself is a stratigraphic trap rather than simply a lithological variation in a larger reservoir defined by other trapping mechanisms.

The Basal Limestone facies is a limy mudstone to wackestone with thin interbedded shale (Klassen, 1996). The shale interbeds are occasionally very dark, resembling the Upper Bakken. This facies has been suspected of being a possible source rock. Rock-Eval®–TOC geochemistry was run on a suite of samples to test this theory. The TOC values for these shale interbeds of 0.11–0.79% and T_{max} values of 342–427°C (Appendix 1) suggest that the Basal Limestone is no longer a source rock candidate.

The Routledge Shale facies is a dark, highly radioactive unit locally preserved between the Bakken Formation and the Scallion Member of the Lodgepole. Geochemical analyses were run on a suite of samples from this unit to ascertain source-rock potential. The TOC values ranged from 6.39 to 10.77, and T_{max} ranged from 413°C to 423°C (Appendix 1). Although the TOC contents are high, the T_{max} values indicate that the rocks are thermally immature. Conodont analysis on samples from this unit have a colouration index (CA) of 1, indicative of thermally immature sediments (Nicolas, 2008). Of note are the recent developments in gas production from immature shale in other basins with geochemical signatures similar to that of the Routledge Shale. Based on this information, the Routledge Shale is a good candidate for future exploration as a gas shale.

Future oil potential in the Lodgepole still exists, with subcrop plays providing the best prospects. In the highly salt-collapse–affected area of the Waskada and Pierson fields, there is low drilling density into the Lodgepole; however, oil shows indicate that oil has passed through the system in the Lodgepole in these areas.

Mission Canyon Formation (Alida and Tilston formations)

The Mission Canyon Formation consists of sequences of oolitic, fossiliferous, cherty and fragmental limestone with occasional bands of shale and anhydrite. It conformably overlies the Lodgepole Formation and underlies the Charles

Formation, or Amaranth Formation when past the subcrop edge of the Charles (Figure 4). The Mission Canyon Formation in Manitoba includes the equivalent Tilston Beds (TGI Williston Basin Working Group, 2008al, am), Alida Beds (TGI Williston Basin Working Group, 2008an, ao) and Kisbey Sandstone of Saskatchewan. In Manitoba, the Tilston Beds are equivalent to the MC-1 and MC-2 members, and the Alida Beds is equivalent to the MC-3 Member. The Kisbey had not been identified in Manitoba prior to TGI II. The Kisbey Interval in Manitoba was identified in Twp 1, Rge 28 and 29, W 1st Mer. (TGI Williston Basin Working Group, 2008ap, aq) through cross-border mapping of this unit using geophysical-log analysis; no core is yet available through this interval in Manitoba to further verify these correlations.

The Mission Canyon Formation structure contours (TGI Williston Basin Working Group, 2008an, ao) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopach map (TGI Williston Basin Working Group, 2008ap, aq) shows thinning of the formation towards the eastern and northern subcrop edge but pronounced thickening in the Canadian portion of the basin in south-central Saskatchewan. The rapid thinning of the Mission Canyon towards the eastern and northern edges is due to pre-Jurassic erosion. The irregular nature of the subcrop edge in Manitoba is a direct result of pre-Jurassic erosion, with localized erosional highs and occasional remnant islands of Mission Canyon dotting the edge.

The reservoirs and traps of the Mission Canyon have been well documented in previous reports (McCabe, 1963; Rodgers, 1986; Martiniuk et al., 2000). The pools in the Waskada Field are related to structural trapping due to salt-collapse structures, while the pools in the Pierson Field are stratigraphically trapped. The isolated MC-1 Member pools are related to subcrop traps along the MC-1 subcrop edge, where undiscovered oil potential still exists.

Charles Formation (Frobisher Beds)

The Charles Formation consists of massive anhydrite and minor dolostone that cap the Mississippian sequence. It overlies the Mission Canyon Formation and underlies the Amaranth Formation (Figure 4). This formation is not productive and acts as a seal on the Mission Canyon Formation MC-3 Member pools. In Manitoba, the Charles Formation is stratigraphically equivalent to the Frobisher Beds of Saskatchewan. The identification of the Kisbey Interval in Twp. 1, Rge. 28 and 29, W 1st Mer. (TGI Williston Basin Working Group, 2008ap, aq), as well as cross-border mapping of this unit, further supports the idea of Manitoba's Charles Formation being the shoreward anhydrite facies of the Frobisher Beds in Saskatchewan.

Confusion often occurs when discussing the Charles Formation of Saskatchewan and the Charles Formation of Manitoba. Despite their names, these two formations are not stratigraphically correlative (Figure 4). Comparison of the structure and subcrop edge on the Charles Formation, Midale Beds structure map (TGI Williston Basin Working Group, 2008ar) with the structure and subcrop edge on the Mission Canyon Formation, Frobisher Beds structure map (TGI Williston Basin Working Group, 2008as) shows that the edge of the former terminates in Rge. 30, W 1st Mer., before reaching the Manitoba border. McCabe (1959) applied the name 'Charles Formation' to the uppermost evaporitic succession of the Mississippian in Manitoba, in accordance with lithological or formational unit assigning methods. In contrast, Thomas (1954) referred to the current Manitoba Charles Formation as the MC-5 Member and the Kisbey Interval as the MC-4 Member of the Mission Canyon Formation. The cross-border correlations done during the course of this project suggest that the MC-4 and MC-5 terminology may be more appropriate than the currently accepted terminology of Charles Formation for Manitoba; this practice would minimize confusion and improve communication, while maintaining the Mission Canyon nomenclature sequence. It would mean that the Charles Formation of Manitoba would be the uppermost unit of the Mission Canyon Formation (MC-5 Member) and therefore be demoted to member status; the Kisbey Interval would become the MC-4 Member of the Mission Canyon Formation.

The Charles Formation (Frobisher Beds) structure contours (TGI Williston Basin Working Group, 2008as) trend southeast in Manitoba and then change to east in south-central Saskatchewan as they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopach map (TGI Williston Basin Working Group, 2008at) shows a thinning of the formation towards the eastern and northern subcrop edge, but a central area of pronounced thickening in the Canadian portion of the basin in southeastern Saskatchewan. The rapid thinning of the Charles towards the eastern and northern edges is due to pre-Jurassic erosion. The irregular nature of the subcrop edge is a direct result of pre-Jurassic erosion, with localized erosional highs and occasional remnant islands of the formation dotting the edge. The anhydritic nature of the Charles/Frobisher in Manitoba is again reflective of the shrinking basin throughout the Paleozoic, with the basin margin moving inwards towards the centre of the Williston Basin in North Dakota.

Anomalous wells

During the course of verifying and picking the stratigraphic tops for the TGI II project in Manitoba, a few wells were encountered that were anomalous compared to wells around them. This section discusses wells exhibiting an anomalous stratigraphic sequence that could not be correlated with the normal Paleozoic stratigraphy. This list only includes anomalous wells noted during the picking/verification of tops stage for the TGI II project, and is not meant as a comprehensive listing of anomalous wells in Manitoba.

100/08-31-002-23W1/00

This well is a Precambrian test that exhibits an anomalous section from the upper part of the Lodgepole Formation to the Second Red Beds of the Dawson Bay Formation. The section is entirely dolomitized and only tentative picks for the Dawson Bay Formation, Souris River Formation First Red Beds, Duperow Formation, Birdbear Formation, Three Forks Formation, and Cruikshank Shale facies of the Lodgepole Formation could be made. These picks suggest that the Lodgepole thickens by about 30 m, the First Red Beds to Birdbear interval thins by about 20 m, the First Red Beds thickens by about 30 m and the Dawson Bay thins by about 15 m. This feature is east of the current salt edge but may be related to differential salt solution of a completely removed Prairie Evaporite. Thinning of the Ashern Formation to t-marker interval by about 15 m suggests that basement faulting may also be involved. It is interesting to note that an offsetting well, also drilled to Precambrian, is situated on the same legal subdivision (L.S.) only about 125 m away and exhibits a normal Paleozoic section. This suggests that the observed anomaly is localized to the vicinity of the wellbore.

100/02-35-002-26W1/00, 100/05-03-004-25W1/00 and 100/07-25-007-24W1

These wells all have anonymously thick sections of Three Forks Formation compared to the regional trend. All of the Three Forks cycles as described by Nicolas (2006) are present in these wells, despite the distance from the subcrop edge for Units 3 and 4 (Nicolas, 2007). Local preservation of these upper units may be related to collapse structures resulting from Prairie Evaporite dissolution, and may also be related to the large-scale basement reactivation along the SBZ. All these wells fall along the eastern boundary of the SBZ (Nicolas, 2007).

100/04-32-003-25W1/00

In this well, the interval between the lower member of the Birdbear Formation and the Lower Wymark Member of the Duperow Formation thins by about 15 m and includes an anomalous shaly unit, about 20 m thick, that does not correlate with the regular section. No picks can be made within this interval with any certainty. The anomaly may be related to differential salt solution and is proximal to the eastern Prairie Evaporite salt edge.

100/01-19-005-24W1/00, 100/01-28-005-24W1/00, 100/01-29-005-24W1/00, 100/09-30-005-24W1/00 and 100/16-33-005-24W1/00

These wells exhibit extreme stratigraphic anomalies, including sections that are difficult to correlate, missing intervals, repeating intervals and steep structural gradients. They fall within the ‘Hartney Structure’, which has been described as an astrobleme (Sawatzky, 1975). Because of this, these wells should probably not be used for the construction of regional maps.

100/08-13-005-29W1/00

This well exhibits an anomalous section from the Paleozoic unconformity to the Lower Wymark Member of the Duperow Formation. No picks could be made within this interval. The section is about 60 m thicker than what would be expected regionally. The interval from the Lower Wymark to the Second Red Beds of the Dawson Bay Formation thins by about 20 m. The Prairie Evaporite salt is absent, even though the well is located west of the regional salt edge. Winnipegosis Formation thickness suggests a reef development. The reef may have been important in initiating local salt removal and subsequent collapse of overlying strata. The anomalous section may represent chaotic fill over a localized sink hole.

100/09-17-010-29W1/00

This well exhibits an anomalous section from the top of Lodgepole Formation to the top of Duperow Formation. Picks were made for the Cruikshank Shale facies of the Lodgepole Formation, the Three Forks Formation and the Birdbear Formation, but they are tentative at best. The Bakken Formation appears to be missing and the Birdbear is anomalously shaly. The Lodgepole to Three Forks interval is about 35 m thicker than in the offsets. The interval from the Duperow to the top of the Prairie Evaporite is about 55 m thicker than regional average. The well is in an area of salt preservation, yet only about 2 m of salt remains. Localized salt removal is likely the cause of the anomaly in the overlying section. The thickening of the overlying intervals suggests a localized gradual salt removal process with compensatory thickening of overlying beds. The local absence of the Bakken (in a productive pool) is difficult to explain.

Economic considerations

The primary objective of the TGI II Williston Basin Project was to develop a seamless geological model of Paleozoic- and Mesozoic-age rocks from basement to outcrop in an area that includes most of the Phanerozoic succession present in both eastern Saskatchewan and southwestern Manitoba. Prior to this project, such maps and correlations did not exist, making it difficult for industry and researchers to do regional studies. The results of this project have helped in understanding the stratigraphic similarities and differences between the two provinces and seeing the regional structural and isopach trends, thus making cross-border exploration easier and opening opportunities for western companies and investors to move east and explore Manitoba. This new exploration includes not only petroleum but also potash, brines, industrial minerals and Mississippi Valley–type lead-zinc deposits.

Conclusions

The Paleozoic sequence in Manitoba consists dominantly of dolostone and limestone, with minor evaporite, sandstone and siltstone units. These rocks have yielded abundant oil and gas, but are also an important source of industrial minerals.

Multi-jurisdictional mapping of the Paleozoic strata through the TGI II Williston Basin Project has required a careful investigation of stratigraphic correlations over long distances. Many of the correlations had been previously investigated, while others were in need of further examination. Of particular importance was the correlation of the members of the Red River Formation from Saskatchewan to the Manitoba subcrop and outcrop, since exact correlations of the detailed units were uncertain prior to this project. Stratigraphic correlation of members of the Dawson Bay, Souris River and Duperow formations from Saskatchewan to Manitoba were established through geophysical-log correlations over long distances, a feat not previously attempted at this scale. Stratigraphic correlation of these Devonian members through core examination is recommended to further strengthen confidence in these correlations.

Most of the Paleozoic hydrocarbon resources in the basin come from the Mississippian section, but the Devonian to Cambrian section is attracting more interest as exploration technology and stratigraphic understanding evolve. In Manitoba, the Three Forks Formation still has considerable hidden potential (Nicolas, 2007), since it is still a young play.

The Birdbear, Duperow, Souris River and Dawson Bay formations, the Interlake Group, and the Red River and Winnipeg formations all have good economic potential. The ratio of oil shows versus low drilling densities for deep wells lean favourably towards there being both large and small oil pools still awaiting discovery. The tectonic setting of Manitoba's seemingly stable craton indicates that the sub-Phanerozoic extension of the SBZ likely plays an important role in deep hydrocarbon trapping and reservoir development. A better understanding of the effects over time of the SBZ on the entire stratigraphic package is needed.

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TGI Williston Basin Working Group 2008f: Ordovician Red River Formation, Lake Alma Anhydrite: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-OLAA-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008g: Ordovician Red River Formation, Coronach Anhydrite: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-OCA-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008h: Ordovician Red River Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-ORR-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008i: Ordovician Red River Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-ORR-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008j: Ordovician Stony Mountain Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-OSM-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008k: Ordovician Stony Mountain Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-OSM-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008l: Silurian Stonewall Formation, Upper Stonewall Anhydrite: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-SUSA-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008m: Silurian Stonewall Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-SS-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008n: Silurian Stonewall Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-SS-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008o: Silurian Interlake Group: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-SI-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008p: Silurian Interlake Group: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-SI-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008q: Devonian Ashern Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DA-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008r: Devonian Ashern Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DA-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008s: Devonian Winnipegosis Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DW-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008t: Devonian Winnipegosis Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DW-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008u: Devonian Prairie Evaporite: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DPE-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008v: Devonian Prairie Evaporite: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DPE-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008w: Devonian Dawson Bay Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DDB-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008x: Devonian Dawson Bay Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DDB-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008y: Devonian Dawson Bay Formation, Hubbard Salt: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DHS-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008z: Devonian Souris River Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DSR-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008aa: Devonian Souris River Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DSR-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ab: Devonian Duperow Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DD-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ac: Devonian Duperow Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DD-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ad: Devonian Birdbear Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DB-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ae: Devonian Birdbear Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DB-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008af: Devonian Torquay Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DT-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ag: Devonian Torquay Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-DT-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ah: Mississippian Bakken Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MB-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ai: Mississippian Bakken Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MB-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008aj: Mississippian Lodgepole Formation: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-ML-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ak: Mississippian Lodgepole Formation: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-ML-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008al: Mississippian Mission Canyon Formation, Tilston Beds: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MT-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008am: Mississippian Mission Canyon Formation, Alida Beds: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MAB-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008an: Mississippian Mission Canyon Formation, Tilston Beds: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MT-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ao: Mississippian Mission Canyon Formation, Alida Beds: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MAB-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ap: Mississippian Mission Canyon Formation, Kisbey Sandstone: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MKS-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008aq: Mississippian Mission Canyon Formation, Kisbey Sandstone: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MKS-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008ar: Mississippian Charles Formation, Midale Beds: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MMB-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008as: Mississippian Mission Canyon Formation, Frobisher Beds: structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MFB-S, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

TGI Williston Basin Working Group 2008at: Mississippian Mission Canyon Formation, Frobisher Beds: isopach contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-MFB-I, scale 1:1 000 000, http://www.gov.mb.ca/stem/mrd/geo/willistontgi/maps.html#list [August 11, 2008].

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Appendix 1 — Rock-Eval®–TOC results

UWI	Well or location name	Licence no.	Formation	Member	TVD (m)	TOC (%)	T_{max}	S_1	S_2	S_3	PI	$\frac{S_2}{S_3}$	PC (%)	HI	OI	Data source (lab and year)
100/01-30-009-28W1/00	Chevron Daly 1-30-9-28 WPM	490	Lodgepole	Basal Limestone facies	860.68	0.11	420	0.02	0.03	0.29	0.42	0.10	0.02	27	264	GSC Lab 2007
100/03-13-014-29W1/00	CDCOG et al Willen 3-13-14-29 WPM	2557	Lodgepole	Basal Limestone facies	631.54	0.21	427	0.02	0.04	0.38	0.36	0.11	0.02	19	181	GSC Lab 2007
100/03-13-014-29W1/00	CDCOG et al Willen 3-13-14-29 WPM	2557	Lodgepole	Basal Limestone facies	637.03	0.35	342	0.02	0.03	0.46	0.37	0.07	0.03	9	131	GSC Lab 2007
100/11-33-003-26W1/00	Northrock South Ebor 11-33-3-26 WPM	4094	Lodgepole	Basal Limestone facies	1044.46	0.79	427	0.09	2.29	0.48	0.04	4.77	0.22	290	61	GSC Lab 2007
100/11-33-003-26W1/00	Northrock South Ebor 11-33-3-26 WPM	4094	Lodgepole	Basal Limestone facies	1054.61	0.52	429	0.07	0.85	0.45	0.08	1.89	0.10	163	87	GSC Lab 2007
100/11-33-003-26W1/00	Northrock South Ebor 11-33-3-26 WPM	4094	Lodgepole	Basal Limestone facies	1057.20	0.33	425	0.07	0.12	0.48	0.35	0.25	0.04	36	145	GSC Lab 2007
100/06-21-001-19W1/00	T.L. Cleary Turtle Mtn. Prov. 6-21-1-19 WPM	1149	Lodgepole	Routledge Shale facies	978.18	6.39	413	1.01	27.70	2.81	0.04	9.86	2.57	433	44	GSC Lab 2007
100/06-21-001-19W1/00	T.L. Cleary Turtle Mtn. Prov. 6-21-1-19 WPM	1149	Lodgepole	Routledge Shale facies	974.34	7.33	423	1.46	32.17	-	0.04	-	-	439	-	Petro-Canada 2006
100/06-21-001-19W1/00	T.L. Cleary Turtle Mtn. Prov. 6-21-1-19 WPM	1149	Lodgepole	Routledge Shale facies	975.77	6.59	419	0.86	25.82	-	0.03	-	-	392	-	Petro-Canada 2006
100/11-08-009-25W1/00	Enerplus Virden 11-08-9-25 WPM	4011	Lodgepole	Routledge Shale facies	721.00	10.77	-	1.91	47.50	-	-	-	-	-	-	Petro-Canada 2006
100/11-08-009-25W1/00	Enerplus Virden 11-08-9-25 WPM	4011	Lodgepole	Routledge Shale facies	722.37	9.52	-	1.86	46.63	-	-	-	-	-	-	Petro-Canada 2006
100/12-29-010-28W1/00	Tundra Daly Prov. COM 12-29-10-28 WPM	3869	Bakken	Upper Member	809.70	0.08	-	0.04	0.18	-	-	-	-	-	-	Petro-Canada 2006
100/12-29-010-28W1/00	Tundra Daly Prov. COM 12-29-10-28 WPM	3869	Bakken	Upper Member	809.92	0.34	-	0.04	0.11	-	-	-	-	-	-	Petro-Canada 2006
100/12-29-010-28W1/00	Tundra Daly Prov. COM 12-29-10-28 WPM	3869	Bakken	Upper Member	810.77	0.49	-	0.03	0.20	-	-	-	-	-	-	Petro-Canada 2006
100/12-29-010-28W1/00	Tundra Daly Prov. COM 12-29-10-28 WPM	3869	Bakken	Upper Member	810.88	0.59	304	0.04	0.13	0.58	0.25	0.22	0.07	22	98	GSC Lab 2007
100/03-33-010-29W1/00	Tundra Kola Unit No. 2 3-33-10-29 WPM	4489	Bakken	Upper Member	853.70	17.43	418	4.38	67.29	-	0.06	-	-	386	-	Petro-Canada 2006
100/03-33-010-29W1/00	Tundra Kola Unit No. 2 3-33-10-29 WPM	4489	Bakken	Upper Member	855.58	24.10	415	7.66	86.03	-	0.08	-	-	357	-	Petro-Canada 2006
100/03-33-010-29W1/00	Tundra Kola Unit No. 2 3-33-10-29 WPM	4489	Bakken	Upper Member	855.48	19.16	408	4.36	85.41	7.33	0.05	11.65	7.93	446	38	GSC Lab 2007
102/03-07-008-29W1/00	Tundra Sinclair A3-07-008-29 WPM	5144	Bakken	Upper Member	1010.78	20.08	417	4.28	72.99	-	0.06	-	-	363	-	Petro-Canada 2006
102/03-07-008-29W1/00	Tundra Sinclair A3-07-008-29 WPM	5144	Bakken	Upper Member	1012.42	25.93	412	9.38	98.50	-	0.09	-	-	380	-	Petro-Canada 2006
102/03-07-008-29W1/00	Tundra Sinclair A3-07-008-29 WPM	5144	Bakken	Upper Member	1011.35	16.86	408	4.53	79.49	4.52	0.05	17.59	7.33	471	27	GSC Lab 2007

Abbreviations: UWI, unique well identifier; TVD, total vertical depth; TOC, total organic content; T_{max}, temperature at which the maximum hydrocarbon generation occurs during pyrolytic degradation of the kerogen; S_1, milligrams of hydrocarbons that can be thermally distilled from 1 g of rock (mg/g); S_2, milligrams of hydrocarbons generated by pyrolytic degradation of the kerogen from 1 g of rock (mg/g); S_3, milligrams of CO_2 generated from 1 g of rock when heated to 390°C (mg/g); PC, pyrolyzed carbon; HI, hydrogen index (mg hydrocarbons/g C_{org}); OI, oxygen index (mg CO_2/g C_{org}).