GP2009-1

GEOSCIENTIFIC PAPER

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

By
M.P.B. Nicolas

Manitoba

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

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Nicolas, M.P.B. 2009: Williston Basin Project (Targeted Geoscience Initiative II): Summary report on Mesozoic stratigraphy, mapping and hydrocarbon assessment, southwestern Manitoba; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Paper GP2009-1, 19 p.

NTS grid: 62F, 62G, 62H, 62J, 62K, 62N, 62O, 63C, 63F

Keywords: Manitoba; Williston Basin; Western Canada Sedimentary Basin; Elk Point Basin; stratigraphy; oil and gas prospects; petroleum exploration; Mesozoic; Amaranth Formation; Reston Formation; Melita Formation; Waskada Formation; Success Formation; Swan River Formation; Pense Formation; Ashville Formation; Favel Formation; Second White Specks; Carlile Formation; Morden Shale; Morden Member; Boyne Member; Niobrara Formation; Pierre Shale; Boissevain Formation; Turtle Mountain Formation; hydrocarbons.

Published by:
Manitoba Science, Technology, Energy and Mines
Manitoba Geological Survey
360-1395 Ellice Avenue
Winnipeg, Manitoba
R3G 3P2 Canada
Telephone: (800) 223-5215 (General Enquiry)
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Cover photo: Fossil ripple marks in the Swan River Formation at the Roaring River outcrop (Bamburak and Christopher, 2004, Stop 8). Photo credit: M.P.B. Nicolas.

Abstract

The Targeted Geoscience Initiative 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. Using a database consisting of geological picks from more than 9000 drillholes, most of them penetrating the entire Mesozoic strata, selected wells (averaging five wells per township) were used to create a series of structural and isopach maps. This report discusses stratigraphic relationships, structural and isopach contour-map trends, and major potential hydrocarbon reservoirs and play types for the Mesozoic formations in Manitoba. Rock-Eval® geochemistry results for selected Cretaceous units are included.

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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, including strata from the Williston Basin and the Elk Point Basin (Figure 1). A database was built of geological picks from most of the drillholes penetrating Devonian and deeper horizons, and from selected wells (averaging five wells per township) penetrating 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 testholes were used for this project; 1114 of the subsurface wells penetrated the Paleozoic to some degree. All formation picks were made or verified in accordance with the stratigraphic framework established by the TGI Working Group. Figure 2 shows the stratigraphic correlations used in the project, and Figure 3 (in back pocket) shows a reference well with the geophysical log picks in southwestern Manitoba. Only subsurface oil and gas wells were used for mapping the Mesozoic sequence.

This report will discuss lithology, stratigraphic relationships, structural and isopach contour-map trends, and major potential hydrocarbon reservoirs and play types for the Mesozoic formations in Manitoba.

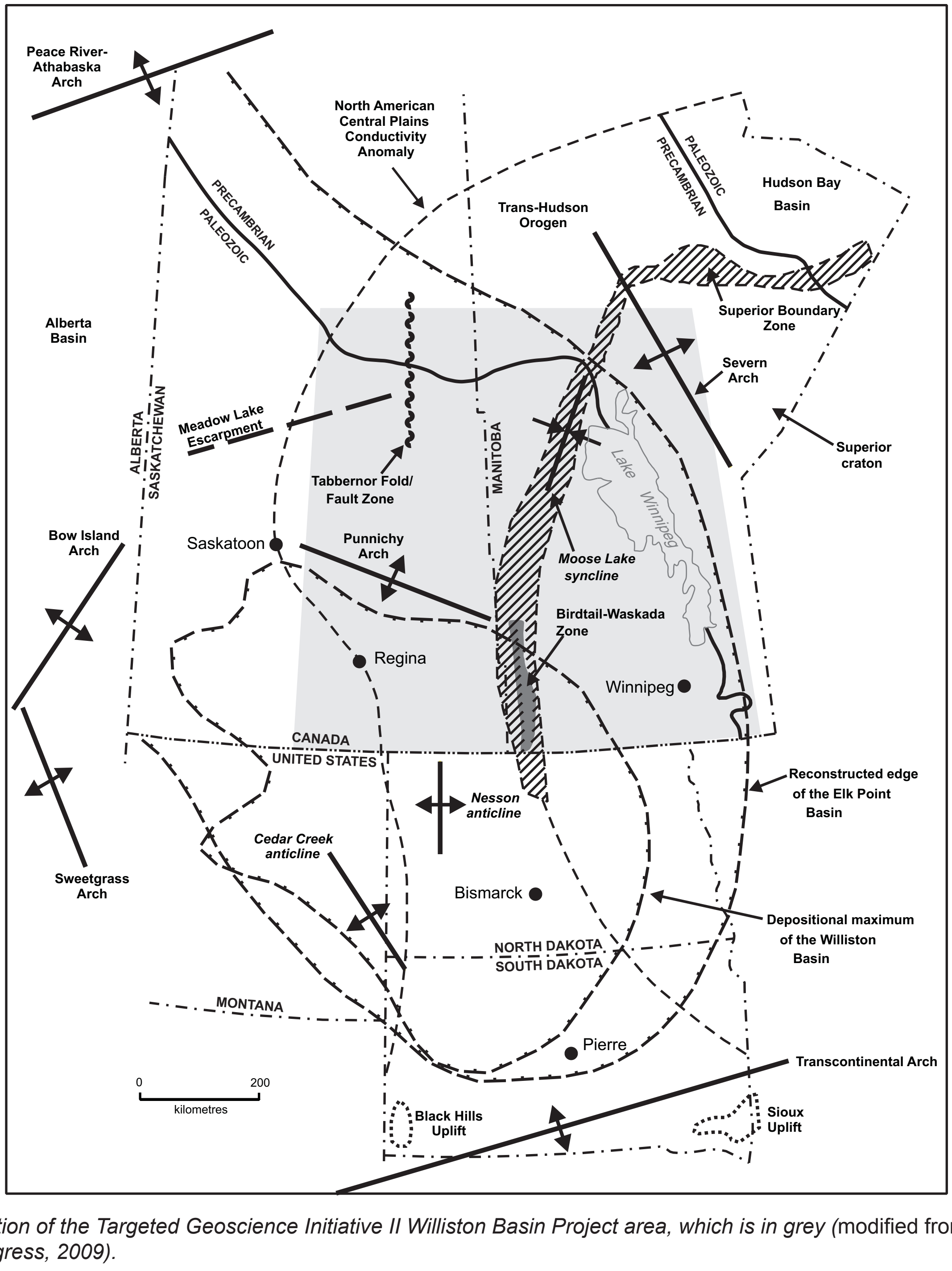

*Figure 1: Location of the Targeted Geoscience Initiative II Williston Basin Project area, which is in grey (*modified from *Bamburak et al., work in progress, 2009).*

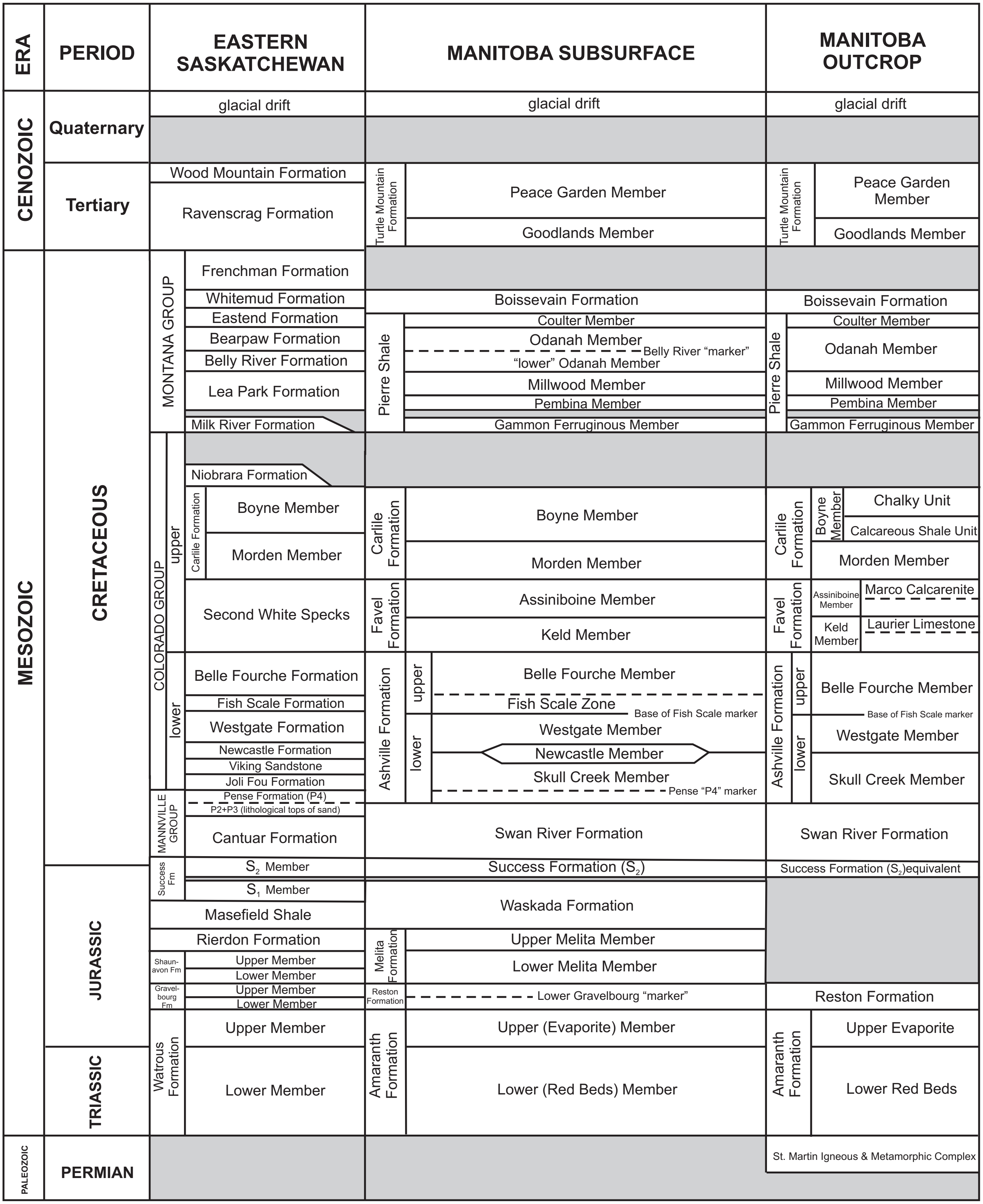

***Figure 2:** Mesozoic and Cenozoic portion of the Targeted Geoscience Initiative II stratigraphic column for eastern Saskatchewan and southwestern Manitoba.*

Geological setting

The TGI II project area is in the eastern part 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 to Silurian clastic and carbonate sequence was part of a large cratonic depositional platform that extended from the Hudson Basin 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 the Late Devonian to Middle Cenozoic were deposited in the Williston Basin, also an intracratonic sub-basin.

In Manitoba, Paleozoic-, Mesozoic- and Cenozoic-age 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 gap in the history of the Phanerozoic, and is mostly due to tectonic uplift (McCabe, 1959). Continental tectonic forces affected changes to the basin 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 period. 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, 1998a; Bezys and Bamburak, 2004). By the Silurian, the tectonic setting had stabilized (Bezys and Conley, 1998b; 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 originally been continuous between the WCSB and 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 a return to deposition within the Williston Basin.

During the late Paleozoic to early Mesozoic, the Williston Basin underwent a significant shift in dynamics, characterized by a period of differential uplift and erosion (Bamburak and Christopher, 2004). The Mesozoic formations in Manitoba were deposited within the east-median hinge and eastern platform zones of a major epicontinental sea (Bamburak and Christopher, 2004) and are characterized by sandstone and shale sequences. Dissolution of the Devonian Prairie Evaporite was ongoing during this period, with major salt collapses affecting depositional trends of the Mesozoic strata. Differential compaction of the Paleozoic strata and basement sagging from the large sediment load compounded the effects on the depositional trends of the Mesozoic units. Effects from these influences are visible in the isopach trends of the Mesozoic strata. Unlike the Paleozoic strata that have fairly uniform isopach trends from one formation to another (Nicolas, 2008a), each Mesozoic formation has a slightly different isopach trend, which, over time and with the culmination of differential compaction of the older Mesozoic units, affects the depositional patterns of the younger strata. These affects are noticeable on the isopach maps of the Stratigraphic Map Series for the TGI II Williston Basin Project, and are discussed in detail below.

Superior Boundary Zone

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

The SBZ extends below the Phanerozoic section 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 caused by fluid movement through an extensive and deep fracture and fault system (Dietrich and Magnusson, 1998; Bamburak and Klyne, 2004; Fedikow et al., 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 for 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 to 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 was renamed the Birdtail–Waskada Zone by Dietrich and Magnusson (1998). The author is 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 this 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, which represents a flexing point between the two crustal blocks. Fault and fracture systems on either side of this hinge line are common. The overlying strata were affected by periods of reactivation of these fault systems throughout the Phanerozoic. Basinal fluids migrating through the stratigraphic package took advantage of the numerous fault and fracture systems, resulting in localized dolomitization, sulphide precipitation and porosity variations. The temperature and chemistry of these fluids were likely variable, affecting the host rocks accordingly, however, these aspects of the basin are poorly understood.

Dietrich and Magnusson (1998) noted that faulting within the SBZ affected the Phanerozoic section to varying degrees and Dietrich and Bezys (1998) and Bamburak et al. (work in progress, 2009) 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 has occurred and affected and/or created reservoir zones. It should be noted that there are closed structural traps related to induced structural deformation, either from the SBZ, BWZ, salt collapse or even suspected volcanic activity giving rise to the Hartney Structure (Twp. 5, Rge. 24, W 1st Mer.; Dietrich and Magnusson, 1998). These traps offer hydrocarbon potential in all reservoir zones subject to the sealing capacity of the overlying beds and the presence of the structural traps before the migration and emplacement of the various hydrocarbon systems.

Mesozoic–Cenozoic

Three orogenic events occurred in North America during the Mesozoic: the mid-Late Jurassic to Early Cretaceous Nevadan orogeny; the Early to Late Cretaceous Sevier orogeny; and the Late Cretaceous to Tertiary Laramide orogeny. The sedimentary rocks making up the Mesozoic sequence were derived largely from these mountain-building events. The tectonic stresses afflicting the continent at this time, in combination with dramatic changes in sea level throughout the Mesozoic, are recorded in the Mesozoic strata by variations in depositional environments, lithology and thickness due to basin subsidence and differential uplift of structural features (e.g., BWZ).

Following the regression of the Paleozoic sea, the Williston Basin was subject to a long depositional hiatus along with a period of erosion. The Lake St. Martin structural disturbance occurred at this time (St. Martin Igneous and Metamorphic Complex in Figure 2); theories of its origin include meteor impact, volcanic eruption or a combination of both processes (McCabe and Bannatyne, 1970). The first Triassic and Middle Jurassic formation (Amaranth Formation) filled in the erosional irregularities of the Paleozoic and Precambrian surface. During this time, the BWZ was a paleotopographic high, and separated the northeastern portion of the Williston Basin in Manitoba from the main part of the northern Williston Basin in Saskatchewan (Poulton et al., 1994). The end of the Jurassic was marked by a multistage regional erosive event resulting in peneplanation of the surface and the formation of incised valleys that continued into the Early Cretaceous (Swan River Formation; Poulton et al., 1994). The Cretaceous is characterized by variations in eustatic effects, with both transgressive and regressive events. The events culminated in a maximum flooding surface in the Late Cretaceous, represented by the deposition of the Favel Formation. A final regression followed at the end of the Cretaceous and into the Tertiary, with the deposition of terrestrial and lacustrine sediments punctuated by numerous periods of erosion. The modern-day Quaternary landscape is characterized by glacial and interglacial erosion and deposition, subaerial exposure and variable terrestrial and lacustrine environments.

Triassic–Jurassic stratigraphy

Amaranth Formation

The Amaranth Formation consists of two members: the Upper (Evaporite) Member and the Lower (Red Beds) Member. This formation sits unconformably on the Paleozoic carbonate rocks. It is correlative to the Watrous Formation in Saskatchewan (Figure 2).

The Lower (Red Beds) Member consists dominantly of red argillaceous dolomitic siltstone and sandstone. Present in the southwest corner of Manitoba, this member outlines the eastern limit of erosion of the Triassic–Jurassic strata. In areas where it is at its thickest, the Lower Member is informally subdivided into an upper shaly unit and a lower sandy unit (Figure 3) with three distinguishable sandy zones (Barchyn, 1982).

The deposition of the Lower Member was on the starved shelf (Poulton et al., 1994) of the Paleozoic erosional surface, thickening where infilling erosional lows and thinning where draping over paleotopographic highs. The Upper (Evaporite) Member consists of a widespread, thick, anhydrite-gypsum evaporite that represents a restricted basin margin deposit, capping off the Red Beds below.

The Lower Member structure contours (TGI Williston Basin Working Group, 2008a) trend southeast in Manitoba and then change to east in south-central Saskatchewan, where they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The Lower Member isopach contours (TGI Williston Basin Working Group, 2008b) show the member thins to the north and east, and is absent in isolated patches; it is thickest in the extreme southwestern corner of Manitoba in the Pierson and Waskada field areas. The variability of the isopach closely reflects the highs and lows of the Paleozoic erosional surface (TGI Williston Basin Working Group, 2008c). The abrupt thinning of the member towards the subcrop edge is due to mid-Jurassic, pre-Cretaceous and pre-Quaternary erosion.

In Manitoba, the trend of the Upper Member structure contours (TGI Williston Basin Working Group, 2008d) follows the same trend as the Lower Member. The Upper Member isopach contours are similar to the Lower Member in the east, but the Upper Member thickens significantly south of the Daly and Virden fields and north of the Canada–U.S.A. international boundary. Westward into Saskatchewan, the trend of the isopach contours (TGI Williston Basin Working Group, 2008e) differs significantly from those of the underlying Lower Member and overlying Reston Formation. The abrupt thinning of the Upper Member towards the subcrop edge is due to pre-Cretaceous and pre-Quaternary erosion.

Current Mesozoic oil production in Manitoba is restricted to the Lower (Red Beds) Member of the Amaranth Formation and the Lower Melita Member of the Melita Formation. Known oil pools in the Lower (Red Beds) Member were restricted to the lower sandy unit by stratigraphic trapping related to an up-dip porosity-permeability pinchout (Barchyn, 1982). Recent, new-development drilling of the Amaranth Formation in the Waskada and Pierson fields has proven successful and suggests that new pool discoveries in this unit are still possible. Past development of the Amaranth Formation was mostly limited to south of Twp. 4 and west of Rge. 22, W 1st Mer.; however, recent exploration in Twp. 8, Rge. 24, W 1st Mer. has proven the Lower (Red Beds) Member to be economical when combined with Lodgepole Formation production, thereby expanding the possible exploration targets for Amaranth Formation reserves. Mapping the thickness, distribution and sand content of the lower sandy unit of the Lower (Red Beds) Member is the most prospective way to layout possible targets for future exploration. In Manitoba, the Lower (Red Beds) Member is ranked third for total cumulative oil and total remaining proven reserves as of 2007, after the Mississippian–Devonian Bakken–Three Forks and Lodgepole formations.

The Upper (Evaporite) Member has no hydrocarbon potential but, where present, it is an important subsurface top seal to the underlying Red Beds and Paleozoic limestone. It is also an important source of gypsum in Manitoba. This evaporite is currently quarried as an industrial mineral at Harcus, Manitoba; mined from underground near Amaranth and Silver Plains; and has been quarried in the past from an anomalous outlier, outcropping in the Lake St. Martin structural disturbance area (McCabe and Bannatyne, 1970). Gypsum has several uses in the construction industry, including wallboard, plaster of Paris, and its use in the production of Portland cement.

Reston Formation

The Reston Formation consists of a lower unit of greyish green and grey shale, a middle unit of dense, argillaceous, light-coloured limestone, and is topped by an oolitic to sandy zone (Stott, 1955). It unconformably overlies the Amaranth Formation and the Paleozoic carbonate rocks in areas where the Amaranth Formation is locally absent. Small areas occur where the Reston Formation is absent, often in areas where the Amaranth Formation is also absent.

The Reston Formation is correlative to the Gravelbourg Formation in Saskatchewan (Figure 2). The Upper Gravelbourg Member is represented in Manitoba by the middle limestone beds and upper oolitic to sandy zone (informal units Gbg 4 and Gbg 5, respectively; Figure 3). The Lower Gravelbourg Member is represented in Manitoba by the lower shale (informal unit Gbg 3; Figure 3); a unit that is informally referred to as the lower Reston unit. Any of these three units may or may not be present in a given area, making correlations difficult.

After the restricted evaporitic environment of the Upper (Evaporite) Member of the Amaranth Formation, renewed transgression resulted in the deposition of the Reston Formation in a shallow-marine environment with periodic shoaling and tidal and storm events. The shoaling was caused by the BWZ in Manitoba, which was a topographic high during this period (Poulton et al., 1994).

The Reston Formation structure contours (TGI Williston Basin Working Group, 2008f) trend southeast in Manitoba and east in south-central Saskatchewan, where they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. This is a similar trend to that of the Amaranth Formation. The isopach contours (TGI Williston Basin Working Group, 2008g) show an overall thinning of the Reston Formation towards the east, with the thickest isopach in Manitoba representing a thick belt that extends from Twp. 1 to 6, Rge. 8 to 29, W 1st Mer. The rapid thinning of the formation near the subcrop edge is due to pre-Cretaceous and pre-Quaternary erosion.

The Reston Formation currently does not produce any hydrocarbons in Manitoba. Formation tests have shown it to be water wet, except in the Waskada Field area where an oil show was recorded (Manitoba Industry, Economic Development and Mines, 2005). Complex salt collapse features in the Waskada Field may indicate opportunities for structural trapping mechanisms conducive to hydrocarbon trapping.

Melita Formation

The Melita Formation is composed mainly of shale with interbedded sandstone and occasional thin limestone. It is subdivided into two units: the lower Melita and upper Melita. The lower Melita unit disconformably overlies the Reston Formation and the Paleozoic carbonate in some areas. The upper Melita unit is conformable on the lower Melita unit. The regional correlations achieved during this project between the Melita units and the formations in Saskatchewan suggest that the lower Melita unit and the upper Melita unit are sufficiently distinct to be classified as individual members rather than units. The author suggests the official designation of Lower Melita Member and Upper Melita Member, and they will be referred to as such below.

The Melita Formation is correlative to the Rierdon and Shaunavon formations in Saskatchewan (Figure 2). The Lower Melita Member correlates to the Shaunavon Formation and the Upper Melita Member correlates to the Rierdon Formation.

Further transgression followed the deposition of the Reston Formation and lead to the deposition of the Melita Formation during a high sea-level phase with effects from periodic shoaling events and renewed subsidence of the Williston Basin due to the Nevadan orogeny in the west (Poulton et al., 1994). The BWZ remained a topographic high during the deposition of the Lower Melita Member but less so by the end of deposition of the Upper Melita Member, as seen by the depositional patterns of these members.

The Lower Melita Member consists of varicoloured shale with interbeds of calcareous sandstone. The shale beds show a wide range of colour, including orange-red and light yellowish brown, which distinguishes them from the Upper Melita Member shale beds. A thin band of medium to dark grey, fossiliferous shale commonly separates the Lower Melita Member from the nonfossiliferous Reston Formation. Crushed clam shells (*Ostea*) litter several zones in this shale (Stott, 1955). Sandstone layers are usually thin but do occur as thick packages in places north of Twp. 15; these are interpreted to represent sinuous channel sand.

The Upper Melita Member consists of greenish grey to brownish grey, slightly calcareous shale with thin beds of coquina and dense limestone (Stott, 1955; Bannatyne, 1970). Where preserved, the upper contact of this unit consists of a light-coloured, fossiliferous, mottled dense limestone (Stott, 1955); below, is dark greenish grey to brownish grey, calcareous shale with occasional interbeds of calcareous sandstone.

The Lower Melita and Upper Melita members have structure contours (TGI Williston Basin Working Group, 2008h, i) that are similar. They follow the same trends as the Reston and Amaranth formations but their isopach contour trends are slightly different. The Lower Melita Member isopach contour (TGI Williston Basin Working Group, 2008j) shows a thickening of the member south of the Daly Field up to the international boundary, and westward from Rge. 25, W 1st Mer. into Saskatchewan. The Upper Melita Member isopach contour (TGI Williston Basin Working Group, 2008k) shows a thickening of this member over the Daly and Virden fields, and then it thins away from this area. The thinning that occurs towards the subcrop edge is due to pre-Cretaceous and pre-Quaternary erosion, with extensive erosion towards the north (evidenced by an abrupt thinning).

The Melita Formation has heavy oil production in the St-Lazare area in Twp. 16, Rge. 29, W 1st Mer. The reservoir consists of thick sandstone, which represents a sinuous channel sand, overlying the Paleozoic carbonate rocks. The oil is thought to have migrated from the underlying Paleozoic carbonate rocks and become stratigraphically trapped in the porous channel sand that is capped by shale. The pool currently producing from the Melita Formation is small and its production low. Further exploration of the potential of the Melita Formation is difficult since trapping conditions within this unit are complex, and identification of possible reservoirs rely on the location of the sinuous channel sand beds. Detailed mapping of the Melita Formation sand beds, facies changes and their relationship to underlying units would be necessary to find more oil targets.

As an industrial mineral use, the Lower Melita Member has been quarried for brick clay south of Ste. Rose du Lac (Bannatyne, 1970).

Waskada Formation

The Waskada Formation is the least extensive of the Jurassic units, present only in the subsurface of southwestern Manitoba, south of Twp. 12 and west of Rge. 6, W 1st Mer. It conformably overlies the Melita Formation, and disconformably underlies the Swan River Formation, or Skull Creek Member of the Ashville Formation when the former is absent. The Waskada Formation correlates to the Masefield Shale, and possibly to the Success Formation (S_1) in Saskatchewan (Figure 2).

The Waskada Formation lithology is variable, including green bentonitic shale, with minor beds of carbonaceous shale, red shale and calcareous cemented sandstone (Stott, 1955; Bannatyne, 1970). Distinguishing this formation from some Cretaceous units above can be difficult where the thick basal channel sand units of the Swan River Formation are absent. Where the Skull Creek Member of the Ashville Formation is present directly above the Waskada Formation, the contact from the dark noncalcareous shale of the Skull Creek Member to the calcareous shale and sandstone of the Waskada Formation is suggested by only a slight change in the geophysical log, with a lower gamma-ray response and resistivity reading from the Waskada Formation.

The Waskada and Melita formations were deposited in a similar environment but the Waskada Formation was deposited during a time of higher subsidence rates, resulting in a thicker succession. The formation was then subjected to extensive erosion as the region was uplifted prior to the deposition of the Swan River Formation (Poulton et al., 1994).

The thickness and distribution of the Waskada Formation was affected by pre-Cretaceous uplift and erosion, which cut channels into the Waskada Formation and into the upper portion of the Upper Melita Member. Despite being highly eroded and cut by channels, the Waskada Formation structure contours (TGI Williston Basin Working Group, 2008l) follow the same general pattern as those of the underlying Jurassic units, and dip towards the southwest. The isopach contour map (TGI Williston Basin Working Group, 2008m) shows the dramatic effects of erosion on the thickness of the Waskada Formation, with rapid thinning towards the subcrop edge and the channel walls. Erosion is less of a factor towards the basin centre in North Dakota, where sediments were derived from the Columbian orogeny in the west and deposited in the Williston Basin, adding to the sediment load of this basin (Poulton et al., 1994).

Knowledge of the Waskada Formation in Manitoba is based only on drill cuttings, since it does not outcrop and has no formation tests (e.g., drill stem tests) or cores. Its variable lithology of shale and cemented sandstone suggests that it is not likely to be a good reservoir.

Success Formation

The Success Formation consists of two members, the S_1 and S_2. The S_1 Member is currently not recognized in Manitoba, but if it was present, it might be correlatable to the Waskada Formation (Figure 2). The S_2 Member has just recently been recognized in Manitoba. Previous work in Manitoba had interpreted this unit as the Waskada or Melita formation due to its stratigraphic position. However, mapping during this project has suggested it is possible to distinguish between the Waskada and Success formations within the area of Twp. 17 to 32, Rge. 27 to 29, W 1st Mer. A field trip stop at a former brick shale quarry during this project (Bamburak and Christopher, 2004, Stop 19) suggested that the Success Formation is present beneath the Cretaceous Swan River Formation, south of Ste. Rose du Lac and east of the Manitoba Escarpment. Previously, these beds were interpreted to be the Lower Melita Member, according to Bannatyne (1970) and Bamburak and Christopher (2004).

No formal description of the S_2 Member exists for Manitoba. A stockpile at the Ste. Rose du Lac quarry indicates the unit consists of weathered red shale with sphaerosiderite concretions throughout and sandy beds with a white kaolinitic matrix. This description is very similar to core descriptions for the S_2 Member in Saskatchewan at L.S. 1, Sec. 24, Twp. 20, Rge. 33, W 1st Mer. (abbreviated 1-24-20-33-W1; Christopher, 2003). In Manitoba, the S_2 Member is an unconformity-bound unit, overlying the Melita Formation and underlying the Swan River Formation, and its extent can be extrapolated into Manitoba from Christopher's (2003) mapping of the S_2 Member in Saskatchewan.

On the structure contour map (TGI Williston Basin Working Group, 2008n), the S_2 Member structural trend dips towards the southwest, towards the basin centre, but it was only deposited on the northern flank of the basin, suggesting a different and independent depositional system from the dominating marine environment of the Williston Basin. The Late Jurassic and Early Cretaceous are marked by uplift and a period of minimal erosion in a nonmarine environment, which influenced the deposition of the units during that time (Kent and Christopher, 1994). As a result, S_2 was limited to the northern side of the Punnichy Arch (Figure 1) in this tectonically active environment. The isopach contour map (TGI Williston Basin Working Group, 2008o) shows the unit in isolated sub-basins, where the unconformity-bound S_2 Member was deposited on an eroded landscape, filling in lows on the Jurassic surface, with overprinting effects from pre–Swan River Formation erosion. The depositional environment was similar to that of the Waskada Formation.

The S_2 Member in Manitoba is not considered to be a possible reservoir in Manitoba due to its weathered shaly and kaolinitic lithology. Its use as an industrial mineral is uncertain. If the unit interpreted to be part of the Lower Melita Member at the Ste. Rose du Lac quarry (Bamburak and Christopher, 2004) is in fact the S_2 Member, then the unit has uses for brick clay.

Cretaceous stratigraphy

Swan River Formation

The Swan River Formation in Manitoba is a consolidated and unconsolidated, fine-grained, silica-rich sandstone and sand, with silt and light to dark grey clay and shale. This unit lies unconformably on the erosional surface of Jurassic and Paleozoic rocks, and is conformably overlain by the shale of the Ashville Formation.

The sediments that form the Swan River Formation clastic wedge were derived from the west during the Nevadan and Sevier orogenies (Hayes et al., 1994) and were deposited in both marine and terrestrial environments. The lowermost sandstone, sand and silt were terrestrial and deposited in a complex and deeply incised drainage system; and the uppermost sand and silt with glauconitic interbeds was deposited in a mostly marine depositional environment (Leckie et al., 1994; Bamburak and Christopher, 2004).

The Swan River Formation occurs in two areas, separated by a broad irregular belt (where no Swan River Formation sand deposits occur) that extends eastward from the Saskatchewan interprovincial boundary to the base of the Manitoba Escarpment.

The Swan River Formation correlates to the middle and lower part of the Pense Formation and entirely to the Cantuar Formation, both part of the Mannville Group in Saskatchewan (Figure 2). The uppermost Pense shale, unofficially referred to as the P4 unit in Saskatchewan, had not been previously recognized and mapped in Manitoba. This study, however, has identified the P4 unit in Manitoba on geophysical logs (Figure 3) and in core. The P4 unit oversteps the Swan River Formation sand into the broad belt described above, but disappears near the edge of the Manitoba Escarpment and is not observed in outcrop. In Manitoba, the top of the Swan River Formation is a lithological pick in coreholes and geophysical well logs as it marks the first appearance of thick sand beds (Figure 3). In contrast, in Saskatchewan the top of the Pense Formation (equivalent to the lower part of the Skull Creek Member of the Ashville Formation in Manitoba) is defined stratigraphically by the uppermost extent of a transgressive shale before the appearance of the regressive marine shale of the Joli Fou Formation and therefore the Pense Formation includes the transgressive shale that lies above the sand deposits. The Pense Formation represents a flooding event and does not reflect the effects of the incised drainage pattern characteristic of the Cantuar Formation and lower part of the Swan River Formation. For the purpose of this project, a P4 unit equivalent was picked (Figure 3) in Manitoba to allow for proper cross-border mapping of the Mannville Group (TGI Williston Basin Working Group, 2008p). To verify this questionable stratigraphic relationship, paleontological analysis (foraminifera, palynology and dinocyst) was conducted (Nicolas, 2008b). The foraminifera results provided enough resolution over the sampling interval to question the presence of the Pense Formation P4 unit in many parts of Manitoba. Furthermore, the samples labelled as P4 during sampling may actually be lower Skull Creek Member (Nicolas, 2008b). Since the P4 unit represents a flooding surface, as does the lower Skull Creek Member, for the purpose of the maps generated from this project the P4 unit equivalent occurring in the lower Skull Creek Formation in Manitoba was maintained as originally picked.

The Cantuar Formation in Saskatchewan is separated into a number of members that, when mapped out, outline a complex drainage pattern with varying degrees of valley incisions, as described by Christopher (2003). The Swan River Formation in Manitoba has never been subdivided into individual members but geophysical log analysis indicates that similar subdivisions in Manitoba are possible (Figure 3). Preliminary identification of equivalents to the McCloud and Lloydminster members of the Cantuar Formation was accomplished through geophysical log analysis. Further geophysical log and core and drill cuttings analysis in Manitoba is required to better define the subdivisions.

The Swan River Formation structure contours (TGI Williston Basin Working Group, 2008p) trend southeast in Manitoba, and then change to east in south-central Saskatchewan, where they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The Swan River Formation subcrop/outcrop edge is strongly undulated due to erosion.

The isopach contour (TGI Williston Basin Working Group, 2008q) trends are more variable and not as predictable as the trends of the lower strata of the Williston Basin. Thick deposition is centred on two regions separated by the Punnichy Arch, with deposition on top of the Punnichy Arch occurring closer to the end of the deposition of the Mannville Group. In Manitoba, the Swan River Formation is thickest along the interprovincial boundary and north of Twp. 20. Thin remnants of the Swan River Formation, mapped in this project as the top of the Pense Formation P4 unit, drape over the Daly and Virden fields' structural highs and then towards the east up to the subcrop edge, forming a broad east-striking belt. In contrast to TGI Williston Basin Working Group (2008q) map, Nicolas (2000a, b) mapped the Swan River Formation based on the lithological pick at the top of the sand, and did not include the Pense Formation P4 unit pick commonly used in Saskatchewan.

The Swan River Formation has good potential for oil and gas. The Swan River Formation has been formation tested repeatedly over the years, with all results supporting its interpretation as a prominent freshwater aquifer. The Mannville Group and its equivalents in the west, to northeastern British Columbia, have proven hydrocarbon reserves in the sandy units (B. Hayes, pers. comm., 2005). Detailed mapping of the drainage pattern and the incised valleys of this system helps to pinpoint possible gas fields. The first step to best showcase the possibilities of the Swan River Formation in Manitoba is detailed mapping of the deeply incised channels and the sand units of the Swan River Formation, especially the lower Cantuar Formation equivalent members that are restricted to the western part of the province. The channel sand that infilled the valley potentially provides good reservoirs, with vertical trapping from the Jurassic shale units at the valley walls.

Ashville Formation

The Ashville Formation consists of four members: Skull Creek, Newcastle, Westgate and Belle Fourche. The Skull Creek, Newcastle and Westgate members, sometimes grouped and referred to as the lower Ashville Formation in Manitoba, form the section from the base of the Fish Scale Zone to the top of the Swan River Formation, or Jurassic sedimentary rocks where the Swan River Formation is absent, depending on the location. The Ashville Formation correlates to the lower Colorado Group of Saskatchewan, which includes the Joli Fou, Viking, Newcastle, Westgate and Belle Fourche formations (Figure 2). The lower Ashville Formation sits conformably on the Swan River Formation, but disconformably on Jurassic sedimentary rocks when the Swan River Formation is absent. The upper Ashville Formation is made up of the Belle Fourche Member, and includes the Fish Scale Zone. The Belle Fourche Member sits conformably on the Westgate Member.

After the marine deposition of the Swan River Formation, further transgression lead to the deposition of the Ashville Formation. It represents the first sedimentary deposition on a marine continental platform, which was part of a large epicontinental seaway that extended from the Gulf of Mexico to the Arctic sea (Leckie et al., 1994) at the beginning of a period of global sea-level rise. Sedimentation occurred on the foreland, adjacent to the tectonically active hinterland of the Laramide orogeny (Leckie et al., 1994).

The Skull Creek Member consists predominantly of dark grey shale with occasional sandy lenses and siltstone beds (McNeil and Caldwell, 1981). The lower part of the Skull Creek Member, as defined in Manitoba, includes the transgressive glauconitic marine shale of the Pense Formation P4 unit. This member also correlates with the Joli Fou Formation in Saskatchewan.

The Newcastle Member consists of fine-grained sand with interbeds of silt and clay (McNeil and Caldwell, 1981). This member correlates with the Newcastle and Viking formations in Saskatchewan. Its distribution is irregular, occurring in a southeast-trending belt in the eastern portion of North America's Mesozoic cover. Belts of sand deposits extend towards the Saskatchewan boundary in the areas of the communities of Virden, Kirkella and Binscarth. When the Newcastle Member is absent, it is difficult to separate the Skull Creek and Westgate members on geophysical logs (Figure 3). On geophysical logs, the Newcastle Member is identified by a blocky low gamma-ray response that occurs between the high gamma-ray responses of the overlying and underlying shale. Where this blocky sandy signature is absent, a high gamma-ray response, representing a unit approximately 3 m thick, is present on top of the Skull Creek Member and is used as the marker to distinguish Skull Creek Member shale from the Westgate Member shale. In the extreme southwest corner of the province, the break is more pronounced and is marked by a low gamma-ray response to a shaly marker. The Skull Creek Member is picked at the base of the shale. This shale may represent a lateral facies change of the Newcastle Member into the basinal shelf deposits of Reinson et al. (1994), but is not officially recognized as such.

The Newcastle Member represents a large clastic influx in a shallow marine environment (Leckie et al., 1994), the result of tectonic uplift in the west combined with a drop in sea level. A subsequent rise in sea level ended the deposition of the Newcastle Member clastic sequence and lead to the deposition of the overlying Westgate Member.

The Westgate Member consists of a dark grey noncalcareous shale with occasional lenses and burrows filled with silt to fine-grained sand, with rare bentonite seams (McNeil and Caldwell, 1981). This member correlates with the Westgate Formation in Saskatchewan. A clean sand package, correlatable to the Okla Sand in Saskatchewan (Simpson, 1979), occasionally occurs in the middle of this member; its distribution is clustered in belts, generally trending southeast, suggesting it may represent barrier sandbars. Its upper contact is sharp with the Belle Fourche Member. The lower contact of the Westgate Member with the Newcastle Member is sharp, but when the Newcastle Member is absent, the contact can be sharp to gradational with the Skull Creek Member.

The Belle Fourche Member consists of grey-black to black, carbonaceous, organic-rich shale with abundant fish fragments near the base, a prominent fish-scale marker bed known as the Fish Scale Zone (Figure 2), and a prominent bentonite bed near the top, referred to as the X bentonite (Figure 3; McNeil and Caldwell, 1981). The base of the Fish Scale Zone is a basinwide marker that separates the Upper and Lower Cretaceous (Leckie et al., 1994). The upper part of the Belle Fourche Member also contains a distinctive marker bed called the *Ostrea beloiti* beds (McNeil and Caldwell, 1974). It consists of fine- to medium-grained shell prisms and fragments of bivalves (McNeil and Caldwell, 1981). The Belle Fourche Member sits conformably on the Westgate Member, and disconformably underlies the Favel Formation. The top of the Belle Fourche Member correlates with the top of the Belle Fourche Formation in Saskatchewan, and the Fish Scale Zone correlates with the Fish Scale Formation in Saskatchewan, as shown in Figure 2.

The structure contour trends for the Skull Creek Member (TGI Williston Basin Working Group, 2008r), Newcastle Member (TGI Williston Basin Working Group, 2008s), Westgate Member (TGI Williston Basin Working Group, 2008t) and Belle Fourche Member (TGI Williston Basin Working Group, 2008u) are all similar. They all have a southeast trend that changes to east in south-central Saskatchewan towards the Williston Basin depositional centre, in the northwestern corner of North Dakota.

In contrast to the structure, the isopach contour trends for the different members of the Ashville Formation vary from one to the other, showing the effect of sea-level changes, salt dissolution, differential compaction and a shift away from Williston Basin–controlled deposition. The isopach contour of the Skull Creek Member (TGI Williston Basin Working Group, 2008v) is somewhat irregular, but generally shows the member thins to the north and east away from east-central Saskatchewan, where it is at its thickest, with another thick area in the north-central part of the TGI II Williston Basin Project area in Saskatchewan. The abrupt thinning towards the outcrop edge is related to erosion; the outcrop edge of the Skull Creek Member outlines the eastern limit of the strata making up the Manitoba Escarpment. The isopach trend of the Newcastle Member (TGI Williston Basin Working Group, 2008w) shows a major thickening of the member in Saskatchewan, related to thick shoreface deposits but in Manitoba and southeastern Saskatchewan, basinal deposits dominate with the exception of a moderately thick curvilinear sand, with irregular, lobate sandbodies and abrupt thinning at the southern edge. The northeastern edge of the sandbelt in Manitoba, which is represented by a thin isopach that tapers towards the northeast, represents a sandy shelf. The isopach contour of the Westgate Member (TGI Williston Basin Working Group, 2008x) shows a thinning of the member from west-central Saskatchewan, where it is at its thickest in the TGI II Williston Basin Project area, towards the north, and east to the outcrop edge at the Manitoba Escarpment. A localized thickening is present in Manitoba over the Kirkella and Virden fields (Twp. 12, Rge. 29, W 1st Mer. and Twp. 9–11, Rge. 25–26, W 1st Mer., respectively). The isopach contour of the Belle Fourche Member (TGI Williston Basin Working Group, 2008y) shows the member attains a maximum thickness farther to the east than the isopach trends of the underlying strata. Within the TGI II Williston Basin Project area, the Belle Fourche Member is at its thickest around the junction of the interprovincial and the international boundaries. The member thickness then decreases outward from that area. The abrupt thinning towards the outcrop edge is due to erosion, and closely follows the toe of the Manitoba Escarpment slope.

The sandstone in the Ashville Formation is a good prospect for both oil and gas, despite unsuccessful formation tests to date. Rock-Eval® analysis was conducted on a small suite of samples from the Ashville Formation. Total organic carbon (TOC) and T_{max} values were 0 to 7.41% and 411 to 420°C, respectively (*see* Appendix 1 for a full listing of the geochemistry results). These low TOC and T_{max} values indicate that the members are thermally immature. In outcrop, this formation was tested as an oil shale but was uneconomical, generating only 59.5 litres/tonne (L/t; Bamburak and Christopher, 2004). The Newcastle Member has the greatest hydrocarbon prospects due to its porous sand units and the possibility of stratigraphic trapping due to the pinching in and out of sand that is surrounded by the shale of the Westgate and Skull Creek members. The Okla Sand–equivalent within the Westgate Member may also prove to be a worthwhile exploration target, although formations tests of this sand have been unsuccessful to date (Manitoba Industry, Economic Development and Mines, 2005). The best reservoirs in the Belle Fourche Member would occur in the Fish Scale Zone, in thin siltstone and sandstone beds and lenses surrounded by the organic-rich shale.

Favel Formation

The Favel Formation is a calcareous, white-speckled, olive-black shale with two clearly defined limestone beds and some thin bentonite layers. On geophysical logs, the Favel Formation has a high gamma-ray response due to the presence of uranium related to the high organic content. The Favel Formation is subdivided, from oldest to youngest, into the Keld and Assiniboine members. Both the upper and lower contacts of the Favel Formation are conformable with the Carlile and Ashville formations, respectively. The Keld Member is characterized by the presence of the Laurier Limestone Beds at the top, and the Assiniboine Member is characterized by the presence of the Marco Calcarenite beds at the top. These two limestone units have characteristic geophysical log signatures (Figure 3), allowing for easy identification of the two members in the subsurface. Both members have similar lithology, but the Assiniboine Member generally has a lower calcareous content and weathers in outcrop more readily than the more resistant underlying Keld Member (McNeil and Caldwell, 1981).

The Favel Formation represents the maximum flooding surface of the Late Cretaceous transgression, with sea-level rise being dominantly eustatic in nature (Caldwell, 1984).

The Favel Formation correlates to the Second White Specks in Saskatchewan (Figure 2). No member-scale subdivision of this formation is officially recognized in Saskatchewan. However, subsurface cross-border correlations of both members are possible into eastern Saskatchewan but correlations become difficult farther to the west.

The southeast-trending Favel Formation structure contours (TGI Williston Basin Working Group, 2008z) are typical of the Williston Basin trends, changing to east-trending in south-central Saskatchewan, where they approach the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopach contour (TGI Williston Basin Working Group, 2008aa) trends of the Favel Formation show two areas of thickening, one in southern Saskatchewan at the international boundary, and one in Manitoba, trending southeast. The Favel Formation then thins gradually towards the northwest and abruptly as it approaches the outcrop edge at the Manitoba Escarpment.

Rock-Eval® analysis was conducted on a suite of samples from the Favel Formation, with TOC and T_{max} values ranging from 0 to 10.8% and 401 to 428°C, respectively. These low TOC and T_{max} values indicate that the members are thermally immature. The Favel Formation has been tested as an oil shale in outcrop but was considered uneconomical, generating only 60.0 L/t (Bamburak and Christopher, 2004). In contrast, the Favel Formation has very good gas potential in the subsurface. Modern exploration for shallow shale gas in the Favel Formation has been going on since 2003. In particular, EOG Resources Canada Inc. drilled three shallow wells (10-17-1-24-W1, 3-27-1-25-W1, 1-3-2-25-W1) in the Waskada Field, perforating them in the Assiniboine Member; the wells produced only water and were subsequently abandoned. The drilling techniques used to drill the EOG wells have been known to cause extensive formation damage in the boreholes during drilling, explaining the lack of gas production. Drilling technology specialized for shale-gas exploration has improved significantly since 2003, suggesting that production from this zone and in this area may still be possible, as long as the proper drilling techniques are used (Nicolas, 2008c). Formation tests of the Favel Formation in several parts of Manitoba returned significant gas shows (Manitoba Industry, Economic Development and Mines, 2005), suggesting shallow, unconventional, shale-gas plays may be present. The high organic content of the Favel Formation makes it a good candidate for biogenic gas generation. Since shallow, unconventional, shale gas generally has no horizontal trapping, and the gas is sourced *in situ*, the size of the pool is driven mostly by economics, making the prospects of large shallow gasfields in Manitoba possible. The viability of these large areal expanses of potential resources hinges on the proper economic climate and availability of advanced drilling technologies. The best reservoirs in the Favel Formation would occur in thin siltstone and sandstone beds and lenses surrounded by the organic-rich shale. This type of play is gaining momentum in the western part of the basin and interest is moving eastward. Discoveries and development of unconventional shale gas in the Favel Formation of Saskatchewan support the probability of such reserves in Manitoba.

Carlile Formation

The Carlile Formation consists of two members, the lower Morden Member and the upper Boyne Member (Figure 2). Prior to the TGI II Williston Basin Project, the Morden Member, formerly of formation status as the Morden Shale, had no official equivalent in Saskatchewan, but extensive cross-border correlations and stratigraphic study found it to be equivalent to the lower shale of the Carlile Formation (Christopher et al., 2006). The Morden Member can be correlated into eastern Saskatchewan but cannot be traced into central Saskatchewan. The Boyne Member, formerly known as the Niobrara Formation and previous to that as the Boyne Member of the Vermilion River Formation, was once thought to extend into Saskatchewan and correlate with the First White Specks and Govenlock members of the Niobrara Formation in the west. However, new cross-border correlations by Christopher et al. (2006) show this not to be the case. The Niobrara Formation is now thought to be eroded and truncated by the Milk River Formation long before it reaches Manitoba. The Niobrara Formation is now mapped as being present in Saskatchewan only towards the western limit of the TGI II Williston Basin Project area (TGI Williston Basin Working Group, 2008ab).

The Carlile Formation was deposited during a second major transgression with open-marine conditions (Leckie et al., 1994).

The Morden Member consists of a dark grey to black carbonaceous, organic-rich noncalcareous shale with occasional thin bentonite beds and calcareous iron-sulphide concretions. This formation is sharply and unconformably overlain by the Boyne Member, and is conformable with the underlying Favel Formation (Bamburak and Christopher, 2004).

The Boyne Member is a medium grey and buff, white-speckled, calcareous or chalky shale with several thin bentonite beds. In Manitoba, the member can be subdivided into a lower calcareous unit and an upper chalky unit (McNeil and Caldwell, 1981). The Boyne Member conformably overlies the Morden Member and is disconformably overlain by the Gammon Ferruginous or Pembina members of the Pierre Shale (Bamburak and Christopher, 2004).

The trend of the Carlile Formation structure contours (TGI Williston Basin Working Group, 2008ac) is typical of the Williston Basin trends, with a southeast trend changing to easterly in south-central Saskatchewan, where the formation approaches the Williston Basin depositional centre in the northwestern corner of North Dakota. The isopach contours (TGI Williston Basin Working Group, 2008ad) for the Carlile Formation show two distinct areas of thickening. The thickest section in the east in Manitoba is due the thickening of the Morden Member in this region, and the thickest section in the west in Saskatchewan is due to thickening of the Boyne Member (Christopher et al., 2006). Christopher et al. (2006) provided a full detailed description of the correlations and stratigraphy of the Carlile Formation.

Hydrocarbon prospects in the Morden Member are mostly for shallow unconventional shale gas. Only one formation test has been done on the Morden Member and its results were unfavourable; however, a gas show was recorded in the far eastern extent of the formation during the drilling of a water well (Manitoba Industry, Economic Development and Mines, 2005). In outcrop, this unit was tested as an oil shale but was uneconomical, generating only 24.0 L/t (Bamburak and Christopher, 2004).

The Boyne Member is another potential target for shallow, unconventional shale gas. Gas production from the Boyne Member was attempted in 4-29-W1 but production has not yet been reported (Nicolas, 2008c). Despite its good prospects, only one gas show was documented from the Boyne Member, in a water well in the east, near the Boyne Member's outcrop edge (Manitoba Industry, Economic Development and Mines, 2005). In outcrop, this unit was tested as an oil shale but was uneconomical, generating only 65.0 L/t (Bamburak and Christopher, 2004)., The subsurface characterization and evaluation of this unit is difficult in Manitoba as there are only two poor quality cores with poor recovery of this unit. Successful gas wells in this unit in other parts of the basin suggest that the Boyne Member in Manitoba may also be a possible target for unconventional, shale-gas exploration under the right economic conditions and using new drilling techniques. Similar to the Favel Formation, reservoirs in the Boyne Member would likely occur in thin siltstone and sandstone beds and lenses surrounded by organic-rich shale, as reported by Nicolas (2008c).

In 2006 to 2007, Tundra Oil and Gas Partnership drilled two wells (32-11-4-29-W1, 8-29-4-29-W1) to test the Carlile Formation. The wells were terminated in the Fish Scale Zone of the Belle Fourche Member of the Ashville Formation; both these wells were cored in the Boyne Member but no production has been reported yet.

Rock-Eval® analysis was conducted on a small suite of samples from the Morden and Boyne members. TOC and T_{max} values were 0.7 to 11.69% and 396 to 423°C, respectively for the Morden Member. The Boyne Member had TOC and T_{max} values of 7.34 to 7.57% and 416 to 417°C, respectively. TOC values for both members were low and T_{max} values indicate that the members are thermally immature. While little is known about the subsurface character of these members, they can be labelled as possible unconventional shale-gas exploration targets considering their high organic content, vertical and horizontal fracturing observed in core, and stratigraphic location between the gas-bearing Favel Formation and Pierre Shale.

As an industrial mineral, the Morden Member has been used in the past in brick-making plants located near Roseisle and Lockport, and the Boyne Member was used in the early 1900s as a natural cement-rock near the former community of Babcock (Bamburak and Christopher, 2004).

Pierre Shale

The Pierre Shale consists of, from oldest to youngest, the Gammon Ferruginous, Pembina, Millwood, Odanah and Coulter members (Figure 2). The formation sits disconformably on top of the Carlile Formation and is disconformably overlain by the Boissevain Formation. The Pierre Shale forms the bedrock for most of the Second Prairie Level in Manitoba, west of the Manitoba Escarpment, and is covered in most places by Quaternary deposits (Bamburak and Christopher, 2004).

The deposition of the Pierre Shale occurred during the culmination phases of the Laramide orogeny in a marine seaway (Dawson et al., 1994) at the beginning of a final regression of the sea (Leckie et al., 1994).

The Gammon Ferruginous Member is a uniform dark grey to brown mudstone or silty shale, with numerous red-weathering ferruginous or sideritic concretions (Bamburak and Christopher, 2004). This unit is not always present over the entire extent of the Pierre Shale, leaving the Pembina Member to sit directly over the Carlile Formation in places. This member is unconformably bound by the Carlile Formation below and the Pembina Member above, and represents an erosional remnant of the Milk River Formation in the west (Christopher et al., 2006).

Saskatchewan does not officially recognize the presence of the Gammon Ferruginous Member in the east near the Manitoba boundary, because it is difficult to distinguish between the Saskatchewan Carlile Formation top (sub–Pierre Shale unconformity) and the top of the Gammon Ferruginous Member in Manitoba on geophysical logs. It may also be possible that the unconformity surface between the Gammon Ferruginous Member and the Carlile Formation rises abruptly, moving westward just over the Saskatchewan boundary. Without definitive core or reliable cuttings available to test these theories, the uncertainty remains.

The Pembina Member is a distinctive sequence of interlayered, thin, buff, bentonite seams and thin, greyish black, noncalcareous marine shale (Bamburak and Christopher, 2004). The highest concentration of bentonite beds occurs near the top of the member, making it easily distinguishable from the overlying conformable Millwood Member on geophysical logs by its high gamma-ray response. This member sits unconformably on the Gammon Ferruginous Member, where present, or on the Carlile Formation. Although the Pembina Member is not officially recognized in Saskatchewan, it is correlatable to the lower part of the Lea Park Formation (Figure 2).

The Millwood Member is an olive-grey, silty, montmorillonite clay with abundant clay-ironstone concretions that weathers with a distinctive 'popcorn'- or 'cauliflower'-like textural appearance (Bamburak and Christopher, 2004). This member grades conformably upwards to the Odanah Member, and sits conformably on the Pembina Member. It correlates to the upper portion of the Lea Park Formation in Saskatchewan.

The Odanah Member is a grey to greenish grey, hard, siliceous shale with ironstone concretions and septarian structures, and thin interbeds of bentonite and bentonitic shale (Bamburak and Christopher, 2004). This member caps the Manitoba Escarpment. The lower contact with the Millwood Member is a stratigraphic marker consisting of green to olive, waxy bentonite that can be traced for several hundred kilometres in outcrop and further in the subsurface on geophysical logs (Bamburak and Christopher, 2004). Towards the west, in east-central Saskatchewan, the Odanah Member loses its hard siliceous character and the lower portion of the Odanah Member grades into the calcareous shale of the Belly River Formation (Figures 2, 3); this is the uppermost horizon mapped in the TGI II Williston Basin Project area. The upper portion of the Odanah Member correlates with the middle to lower section of the Bearpaw Formation in Saskatchewan (Figures 2, 3).

The Coulter Member is a bentonitic, soft, silty clay that conformably sits on the Odanah Member, and is capped gradationally by the Boissevain Formation where present (Bamburak and Christopher, 2004). This member correlates to the upper portion of the Bear Paw Formation in Saskatchewan (Figure 2).

The structure contours of the Gammon Ferruginous Member (TGI Williston Basin Working Group, 2008ae), Millwood and Pembina members together (TGI Williston Basin Working Group, 2008af) and lower Odanah Member (TGI Williston Basin Working Group, 2008ag) are typical of the Williston Basin trends, with a southeast trend, changing to east in south-central Saskatchewan, where they approach the Williston

Basin depositional centre in the northwestern corner of North Dakota. The isopach trends for each of these units are variable. All the members of the Pierre Shale have been affected by erosion, particularly at the edges of the outcrops on the Manitoba Escarpment. The Gammon Ferruginous Member isopach contours (TGI Williston Basin Working Group, 2008ah) show a southwestern thickening trend, with the thickest section of the unit preserved in the southwest corner of the TGI II Williston Basin Project area. The Millwood and Pembina members (Lea Park Formation) isopach contours (TGI Williston Basin Working Group, 2008ai) have a distinct northwest trend in Saskatchewan, showing a thickening of the unit towards the middle of the contours. The lower Odanah Member was the most affected by erosion; however, isopach contours (TGI Williston Basin Working Group, 2008aj) show an underlying westward thickening of the unit.

The Pierre Shale is another potential target for shallow, unconventional shale gas. Formation tests in the Pierre Shale are rare but shallow drillholes have shown low-grade gas shows in the vicinity of the Waskada Field (Twp. 1–2, Rge. 24–26, W 1st Mer.) and eastward towards Notre Dame de Lourdes (Manitoba Industry, Economic Development and Mines, 2005). Shallow, unconventional shale gas has been identified in the Belly River Formation in Saskatchewan, suggesting that such reserves may be present in Manitoba, but the formation remains largely unexplored. In 2006 to 2007, Tundra Oil and Gas Partnership drilled one well at 4-6-4-29-W1 to test the shallow Cretaceous shale units. The well was abandoned after a short distance of 348.0 m, terminating in the Millwood Member.

Bamburak and Christopher (2004) reported that nonswelling calcium bentonite from the Pembina Member was quarried for over 40 years in the Morden–Miami area, for use, after acid activation, as an adsorbent of impurities and decolourizer of vegetable and engine crankcase oils. The Odanah Member is currently being used as a road-building material in southwestern Manitoba, where sand and gravel deposits are scarce.

Boissevain Formation

The Boissevain Formation is a greenish grey, crossbedded sand with ovoid sandstone concretions; it becomes more kaolinitic upwards in the section (Bamburak and Christopher, 2004). Only locally preserved in the Turtle Mountain area of Manitoba, it is conformably underlain by the Coulter Member of the Pierre Shale and disconformably overlain by the Tertiary Turtle Mountain Formation. This formation correlates to the Whitemud and Eastend formations in Saskatchewan (Figure 2). Due to its discontinuity, limited areal extent and correlation uncertainties, this formation was not mapped for the TGI II Williston Basin Project.

The Boissevain Formation was deposited in a subaerial to lacustrine environment (Dawson et al., 1994) at the end of the culmination phases of the Laramide orogeny, after the regression of the sea.

The Boissevain Formation is not considered to be a prospect for oil and gas because of its shallow depth. In the early 1900s, sandstone concretions from the Boissevain Formation were cut into facing stone blocks and used, with fieldstone, in the construction of local buildings in the Boissevain–Deloraine area (Bamburak, 1978; Bamburak and Christopher, 2004).

Tertiary stratigraphy

Turtle Mountain Formation

The Turtle Mountain Formation consists of two members, the lower Goodlands Member and the upper Peace Garden Member. The Goodlands Member consists of soft, nonmarine bentonitic carbonaceous sand, silt and clay with occasional thin lignite seams (Bamburak, 1978). The Peace Garden Member consists of marine silty clay with thin very fine grained sand beds (Bamburak, 1978). This formation is locally preserved only in Turtle Mountain Provincial Park, Manitoba, but is likely correlatable to the Ravenscrag and Wood Mountain formations of Saskatchewan (Figure 2). Due to its discontinuity, limited areal extent and correlation uncertainties, this formation was not mapped for the TGI II Williston Basin Project.

The deposition of the Turtle Mountain Formation occurred during the tectonic relaxation phase after the Laramide orogeny in a nonmarine swampy coastal plain and fluvial environment (Dawson et al., 1994).

The Turtle Mountain Formation is not considered a prospect for gas because of its proximity to the surface. Lignite was produced on a small scale for local use in the past, with 28 000 t removed from shallow mines and open pits (Bamburak, 1978). The lignite in this area is of low quality and uneconomic and is not furthermore exploitable due to its probable location in an ecologically sensitive provincial park.

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 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. The regional structure and isopach trends make cross-border exploration easier, opening up opportunities for companies and investors to explore in Manitoba. These new economic opportunities are not limited to petroleum exploration but also include exploration for oil shale, coal and many industrial minerals.

Conclusions

The Mesozoic sequence in Manitoba consists mainly of sand, silt and shale, with occasional limestone units. This relatively flat-lying, unaltered sequence is marked by large-scale erosive events that indicate a dynamic history related to both major tectonic and eustatic events, making some stratigraphic correlations challenging.

Multijurisdictional mapping of the Mesozoic strata through the TGI II Williston Basin Project has required a careful investigation of stratigraphic correlations over long distances. Very few of the correlations had been previously investigated in detail. The Carlile Formation and Pierre Shale correlations were particularly challenging due to the numerous unconformity surfaces present within the section (Christopher et al., 2006). The correlation of the Morden and Boyne members into the Carlile Formation in Saskatchewan, as well as deciphering the Niobrara Formation and Milk River Formation relationship (Christopher et al., 2006), were two of the most significant discoveries in the Mesozoic stratigraphy for the TGI II Williston Basin Project. The Swan River Formation–Mannville Group relationship was another correlation that became better understood as a result of the project.

The Mesozoic succession has excellent economic potential. The Lower (Red Beds) Member of the Amaranth Formation and the Lower Melita Member of the Melita Formation currently provide all of the Mesozoic oil production in Manitoba. Recent development of the Lower (Red Beds) Member of the Amaranth Formation has proven successful and suggests that new pool discoveries in this unit are still possible, particularly when commingled with Mississippian Lodgepole Formation production. No other Mesozoic units have oil or gas production in Manitoba, but many formations show good potential. The Cretaceous Swan River Formation and Newcastle Member of the Ashville Formation are the best targets for oil, and the upper Ashville, Favel and Carlile formations and the Pierre Shale are the best targets for shallow, unconventional shale gas.

Acknowledgments

The author would like to thank J. Christopher and M. Yurkowski from the Saskatchewan TGI team for their expertise throughout the correlation and formation-tops picking phase of this project, as well as for the help understanding the Mesozoic strata of the Williston Basin, the lengthy discussions on Mesozoic geological evolution and stratigraphy, and their patience with endless questions. The author would like to thank J. Bamburak for sharing his extensive knowledge on Manitoba's Mesozoic outcrop stratigraphy and for peer reviewing this paper. The author would like to thank R. Bezys for her guidance, motivation and support throughout the TGI II Williston Basin Project. The author would also like to thank R. Syme for his constructive review of this paper.

The author would also like to acknowledge D. Karasinski of Petro-Canada, and the Geochemistry Laboratory of the Geo logical Survey of Canada in Calgary for the Rock-Eval® results.

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APPENDIX 1

Appendix 1 — Rock-Eval®–Total Organic Carbon Results

UWI /location	Well or location name	Sample type	Licence no.	Formation	Member	TVD (m)	TOC (%)	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC (%)	HI	OI	Data source or lab (year)
100/04-31-037-28W1/00	TGI Mesozoic Field Trip Stop 7: Lambert Hill	outcrop	NA	Ashville	-	0	5.46	417	1.62	19.63	-	0.08	-	-	360	-	Petro-Canada (2006)
100/13-35-025-21W1/00	TGI Mesozoic Field Trip Stop 13: Valley River	outcrop	NA	Ashville	-	0	1	-	0.01	0.11	-	-	-	-	11	-	Petro-Canada (2006)
100/13-35-025-21W1/00	TGI Mesozoic Field Trip Stop 13: Valley River	outcrop	NA	Ashville	-	0	0	-	0	0	-	-	-	-	-	-	Petro-Canada (2006)
100/13-35-025-21W1/00	TGI Mesozoic Field Trip Stop 13: Valley River	outcrop	NA	Ashville	-	0	0	-	0	0	-	-	-	-	-	-	Petro-Canada (2006)
100/04-27-013-23W1/00	Imperial Norman 4-27-13-23 WPM	core	642	Ashville	Belle Fourche	368.51	2.27	411	0.19	1.16	-	-	-	-	51	-	Petro-Canada (2006)
100/01-14-004-06W1/00	M-12-77, Miami SE	core	NA	Ashville	Belle Fourche	44.2	7.41	419	1.19	30.75	-	0.04	-	-	415	-	Petro-Canada (2006)
100/01-27-017-26W1/00	Imperial Birtle 1-27-17-26 WPM	core	17	Ashville	Belle Fourche, Fish Scale Zone	331.63	3.57	420	0.49	7.81	-	0.06	-	-	219	-	Petro-Canada (2006)
100/04-27-013-23W1/00	Imperial Norman 4-27-13-23 WPM	core	642	Ashville	Belle Fourche, Fish Scale Zone	350.83	3.36	413	0.43	3.97	-	0.1	-	-	118	-	Petro-Canada (2006)
100/04-27-013-23W1/00	Imperial Norman 4-27-13-23 WPM	core	642	Ashville	Belle Fourche, Fish Scale Zone	357.84	3.02	414	0.3	2.69	-	0.1	-	-	89	-	Petro-Canada (2006)
100/16-10-006-08W1/00	TGI Mesozoic Field Trip Stop 23: Roseisle	outcrop	NA	Carlile	Boyne	0	7.34	416	1.07	25.75	-	0.04	-	-	351	-	Petro-Canada (2006)
100/16-10-006-08W1/00	TGI Mesozoic Field Trip Stop 23: Roseisle	outcrop	NA	Carlile	Boyne	0	7.57	417	1.25	23.91	-	0.05	-	-	316	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Carlile	Morden	473.36	2.81	420	0.21	3.14	-	0.06	-	-	112	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Carlile	Morden	476.26	2.14	412	0.19	1.44	-	-	-	-	67	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Carlile	Morden	475.5	2.1	409	0.07	1.28	1.6	0.06	0.8	0.22	61	76	GSC Geochemistry Lab, Calgary (2007)
100/03-30-035-25W1/00	TGI Mesozoic Field Trip Stop 10: East Favel River	outcrop	NA	Carlile	Morden	0	11.69	396	3.13	29.37	-	0.1	-	-	251	-	Petro-Canada (2006)
100/04-01-033-23W1/00	TGI Mesozoic Field Trip Stop 12: Pine River	outcrop	NA	Carlile	Morden	0	10.05	422	2.87	37.41	-	0.07	-	-	372	-	Petro-Canada (2006)
100/06-13-006-08W1/00	TGI Mesozoic Field Trip Stop 24: Leary's Brick Plant?	outcrop	NA	Carlile	Morden	0	0.7	-	0	0	-	-	-	-	-	-	Petro-Canada (2006)
100/05-35-023-20W1/00	TGI Mesozoic Field Trip Stop 16: Vermilion River Upstream outcrop?	outcrop	NA	Carlile	Morden	0	1.94	423	0.18	1.73	-	-	-	-	89	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Favel	Assiniboine	483.97	10.8	418	1.37	52.37	-	0.03	-	-	485	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Favel	Assiniboine	484.79	8.43	416	1.27	46.48	-	0.03	-	-	551	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Favel	Assiniboine	491.75	8.08	415	1.42	38.93	-	0.04	-	-	482	-	Petro-Canada (2006)
100/01-14-004-06W1/00	M-12-77, Miami SE	core	NA	Favel	Assiniboine	11.28	8.02	410	3.25	36.64	-	0.08	-	-	457	-	Petro-Canada (2006)
100/02-03-039-27W1/00	TGI Mesozoic Field Trip Stop 6: Digger Dan	outcrop	NA	Favel	Assiniboine	0	0	-	0.02	0.05	-		-	-	-	-	Petro-Canada (2006)
100/14-15-034-23W1/00	TGI Mesozoic Field Trip Stop 11: Sclater Creek	outcrop	NA	Favel	Assiniboine	0	7.02	409	0.64	35.91	-	0.02	-	-	512	-	Petro-Canada (2006)
100/14-15-034-23W1/00	TGI Mesozoic Field Trip Stop 11: Sclater Creek	outcrop	NA	Favel	Assiniboine	0	9.26	402	1.64	46.84	-	0.03	-	-	506	-	Petro-Canada (2006)
100/14-15-034-23W1/00	TGI Mesozoic Field Trip Stop 11: Sclater Creek #2	outcrop	NA	Favel	Assiniboine	0	10.51	401	2.8	60.42	-	0.04	-	-	575	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Favel	Assiniboine, Marco Calcarenite	482.75	0.7	428	0.11	1.4	-	-	-	-	200	-	Petro-Canada (2006)
100/08-27-035-26W1/00	TGI Mesozoic Field Trip Stop 9: Minitonas	outcrop	NA	Favel	-	0	2.64	-	0.18	0.69	-		-	-	26	-	Petro-Canada (2006)
100/03-30-035-25W1/00	TGI Mesozoic Field Trip Stop 10: East Favel River	outcrop	NA	Favel	-	0	8.46	417	0.89	30	-	0.03	-	-	355	-	Petro-Canada (2006)
100/01-27-017-26W1/00	Imperial Birtle 1-27-17-26 WPM	core	17	Favel	Keld	297.69	8.36	414	1.76	37.1	-	0.05	-	-	444	-	Petro-Canada (2006)
100/01-27-017-26W1/00	Imperial Birtle 1-27-17-26 WPM	core	17	Favel	Keld	299.01	5.83	410	1.64	23.43	-	0.07	-	-	402	-	Petro-Canada (2006)
100/01-27-017-26W1/00	Imperial Birtle 1-27-17-26 WPM	core	17	Favel	Keld	299.47	5.85	413	1.78	23.94	-	0.07	-	-	409	-	Petro-Canada (2006)
100/01-27-017-26W1/00	Imperial Birtle 1-27-17-26 WPM	core	17	Favel	Keld	300	6.14	417	0.9	25.65	-	0.03	-	-	418	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Favel	Keld	498.05	9.99	412	1.58	47.23	-	0.03	-	-	473	-	Petro-Canada (2006)
100/11-29-001-25W1/00	NCE PET Waskada Prov. WSW 11-29-1-25 WPM	core	2543	Favel	Keld	504.75	4.84	417	0.58	22.21	-	0.03	-	-	459	-	Petro-Canada (2006)

Appendix 1 — Rock-Eval®–Total Organic Carbon Results *(continued)*

UWI /location	Well or location name	Sample type	Licence no.	Formation	Member	TVD (m)	TOC (%)	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC (%)	HI	OI	Data source or lab (year)
100/05-35-003-28W1/00	Morgan Pierson 5-35-3-28 WPM	core	4062	Favel	Keld	496.58	5.96	409	1.89	25.04	-	0.07	-	-	420	-	Petro-Canada (2006)
100/05-35-003-28W1/00	Morgan Pierson 5-35-3-28 WPM	core	4062	Favel	Keld	503	6.08	416	0.94	25.63	-	0.04	-	-	422	-	Petro-Canada (2006)
100/01-14-004-06W1/00	M-12-77, Miami SE	core	NA	Favel	Keld	26.52	7.4	410	2.5	30.77	-	0.08	-	-	416	-	Petro-Canada (2006)
100/02-30-022-17W1/00	TGI Mesozoic Field Trip Stop 17: Ochre River	outcrop	NA	Favel	Keld	0	9.91	413	1.53	49.52	-	0.03	-	-	500	-	Petro-Canada (2006)
100/02-30-022-17W1/00	TGI Mesozoic Field Trip Stop 17: Ochre River	outcrop	NA	Favel	Keld	0	6.24	409	0.86	30.61	-	0.03	-	-	491	-	Petro-Canada (2006)

Abbreviations: UWI, unique well identifier; TVD, total vertical depth; TOC, total organic content; T_{max}, maximum temperature; S_1, milligrams of hydrocarbons that can be thermally distilled from one gram of rock (mg/g); S_2, milligrams of hydrocarbons generated by pyrolytic degradation of the kerogen from one gram of rock (mg/g); S_3, milligrams of CO_2 generated from a gram of rock when heated up to 390°C (mg/g); PI, production index; PC, pyrolized carbon; HI, hydrogen index (mg hydrocarbons/g C_{org}); OI, oxygen index (mg CO_2/g C_{org}); GSC, Geological Survey of Canada.

TGI Mesozoic Field Trip stops are from Bamburak and Christopher (2004).