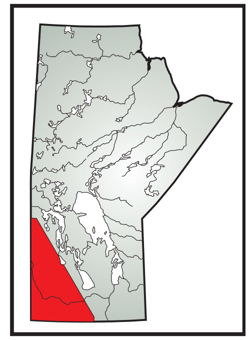
GS-17 Geochemistry and mineralogy of Cretaceous shale, Manitoba (parts of NTS 62C, F, G, H, J, K, N): preliminary results

by M.P.B. Nicolas and J.D. Bamburak



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Summary

The Shallow Unconventional Shale Gas Project is a four-year investigation of the shale gas potential of Manitoba's Mesozoic stratigraphy. The formations being evaluated for shale gas are the Ashville, Favel, Carlile and Pierre Shale. The preliminary organic geochemistry and mineralogical results of the samples collected in 2008, the first year of the project, are reported herein and are indicative of significant shale gas potential in the southern part of the study area, namely in the Pembina Hills and Pembina Valley regions. The 2009 field season focused on collecting samples from the northern part of the study area, particularly in the Riding Mountain, Swan River Valley, Duck Mountain and Porcupine Hills regions.

Introduction

The Shallow Unconventional Shale Gas Project is a four-year investigation of the shale gas potential of select Mesozoic shale sequences in southwest Manitoba. The formations studied are the Ashville, Favel, Carlile and Pierre Shale (Figure GS-17-1). As described by Nicolas (2008), the goal of the project is to summarize the shallow shale gas prospects for Manitoba by characterizing the known shale gas occurrences and their distribution, identifying intervals within prospective formations that have the greatest potential to contain natural gas, and identify new areas that have potential for shale gas accumulations. A historical discussion of shallow gas exploration in Manitoba is provided by Nicolas (2008) and Bamburak (2008); Manitoba's Cretaceous stratigraphic nomenclature is briefly reviewed by Bamburak and Nicolas (GS-19, this volume). Figure GS-17-2 shows the study area subdivided into the different phases of the project as further described in Nicolas (2008); to date, phase 1 of the project is nearly complete and phase 2 is in progress. The study area follows the Ashville Formation outcrop edge to the east and north (just beyond the Manitoba Escarpment edge on the First Prairie Level, from the Pembina Hills northwest to the Porcupine Hills) and the international and provincial boundaries to the south and west, respectively. Preliminary organic geochemistry and mineralogy results from phase 1, and the fieldwork for phase 2, are presented here.

The first year of the project was focused on collecting rock, water and gas samples from locations in the southern portion of the study area (phase 1). A discussion of water and gas results is in Nicolas and Grasby (GS-18, this volume). The outcrop sampling was limited to the Pembina Hills and Pembina Valley region (between Treherne and the international border), and the core sampling was limited to wells south of Twp. 13.

The second and third years of the project are focused on collecting shale samples from locations in the northern portion of the study area (phase 2), and will include data collection (petrophysical data from logs, unit tops, gas readings, etc.) from petroleum exploration wells from the entire project area. Outcrop sampling in the summer of 2009 was focused on the Riding Mountain, Swan River Valley, Duck Mountain and Porcupine Hills regions. Data collection from new samples in the phase 1 area will continue as required.

Several different analytical techniques have been employed on samples collected in the first year, and analytical work is ongoing. Rock Eval™ and total organic carbon (TOC) analyses were conducted on 87 new outcrop and core samples collected in 2008. X-ray diffraction (XRD) was conducted on 47 of the new samples. Major and trace element geochemistry by inductively coupled plasma–mass spectrometry (ICP-MS) and instrumental neutron activation analysis (INAA) are in process for the outcrop samples.

Phase 2 fieldwork

During the 2008 field season (phase 1), a total of 37 field stations were visited and 87 samples were collected; the preliminary findings from this fieldwork are discussed in Nicolas (2008). A second visit in 2009 to a key outcrop of the Boyne Member of the Carlile Formation added an additional three samples to the Pembina Hills sample set.

The majority of the 2009 fieldwork was conducted in the phase 2 region of the study area (Figure GS-17-2). Initial plans for the field season were to sample outcrop in the Riding Mountain, Swan River Valley, Duck Mountain and Porcupine Hills regions. High water levels and local flooding in creeks and rivers in the Porcupine Hills and Duck Mountain areas, and erosion and slumping of many previously known outcrops in the Swan River Valley and Riding Mountain areas, however, resulted in only 14 (of the approximately 40 planned) individual Cretaceous outcrop sites being examined and sampled over a two-week period in August. A total of 30 new Cretaceous samples were collected and represent various stratigraphic positions

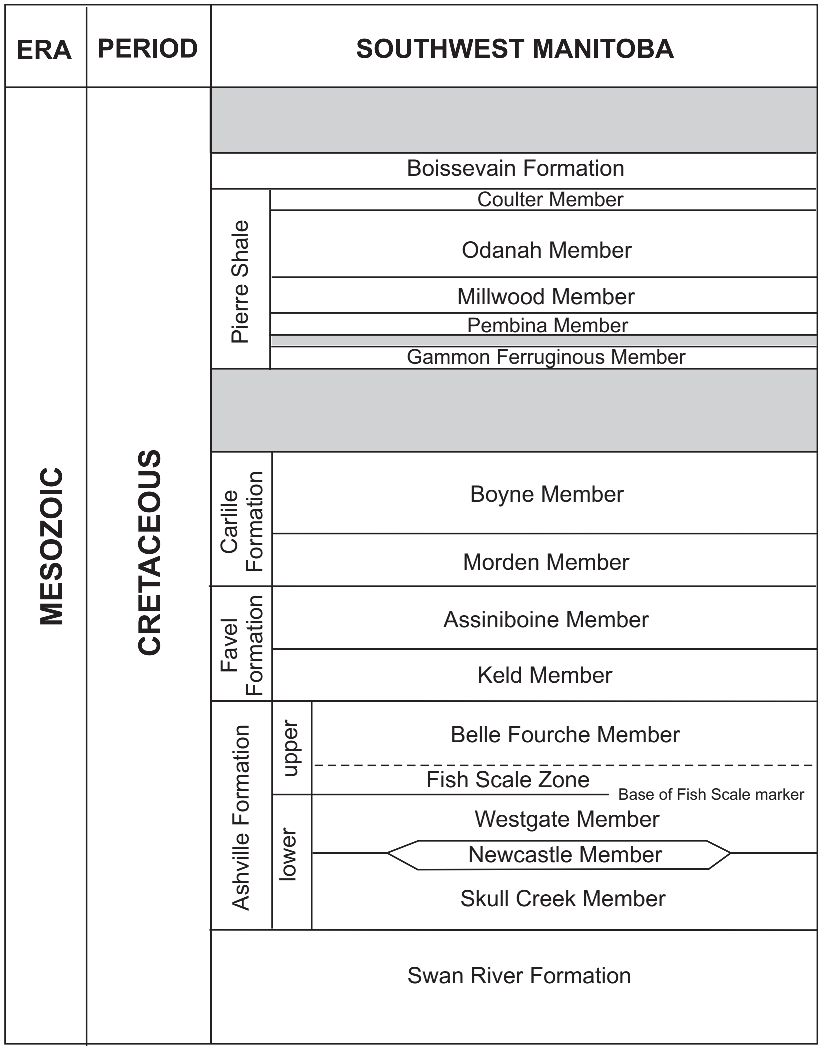

Figure GS-17-1: *Cretaceous stratigraphy of southwest Manitoba.*

within the Belle Fourche Member of the Ashville Formation, and the Assiniboine and Keld members of the Favel Formation. To compensate for the limited access to outcrop and lack of sampling opportunities, archived samples collected for the Cretaceous black shale investigations discussed in Bamburak (1999) will be included in this study to ensure wide stratigraphic coverage. Based on sample quality and stratigraphic position, suitable samples will be selected for organic geochemical and mineralogical analyses.

In contrast to the samples from the Pembina Hills region discussed in Nicolas (2008), there is very little lithological variation in the sections of the Belle Fourche Member (Ashville Formation) and the Favel Formation examined in the phase 2 area. The Belle Fourche Member sections consist of noncalcareous, blocky to fissile, dark grey shale with occasional bentonite seams and thin calcarenite beds. One outcrop visited on the north bank of the Wilson River (UTM Zone 14U, 408242E, 5669334N, NAD 83) displayed a 0.5 m thick bentonite seam; the stratigraphic location and thickness of this seam indicates that it is likely the X bentonite, a thick, widely distributed bentonite that is correlative in geophysical logs throughout parts of North America. The Assiniboine and Keld members of the Favel Formation consist of calcareous, blocky to fissile, dark grey, white-speckled shale with thick calcarenite beds and occasional thin bentonite seams.

Phase 1 results

Organic geochemistry

Introduction

Rock Eval 6/TOC analysis was conducted on most of the outcrop samples collected in 2008 and, to create a larger working dataset, the results were compiled with historical Rock Eval/TOC databases from Obermajer et al. (2005) and Nicolas (2009). The Rock Eval/TOC analytical method measures hydrocarbons, carbon dioxide and carbon monoxide released during heating of a sample. Parameters measured are S_1, S_2, S_3, T_{max}, and TOC. The S_1

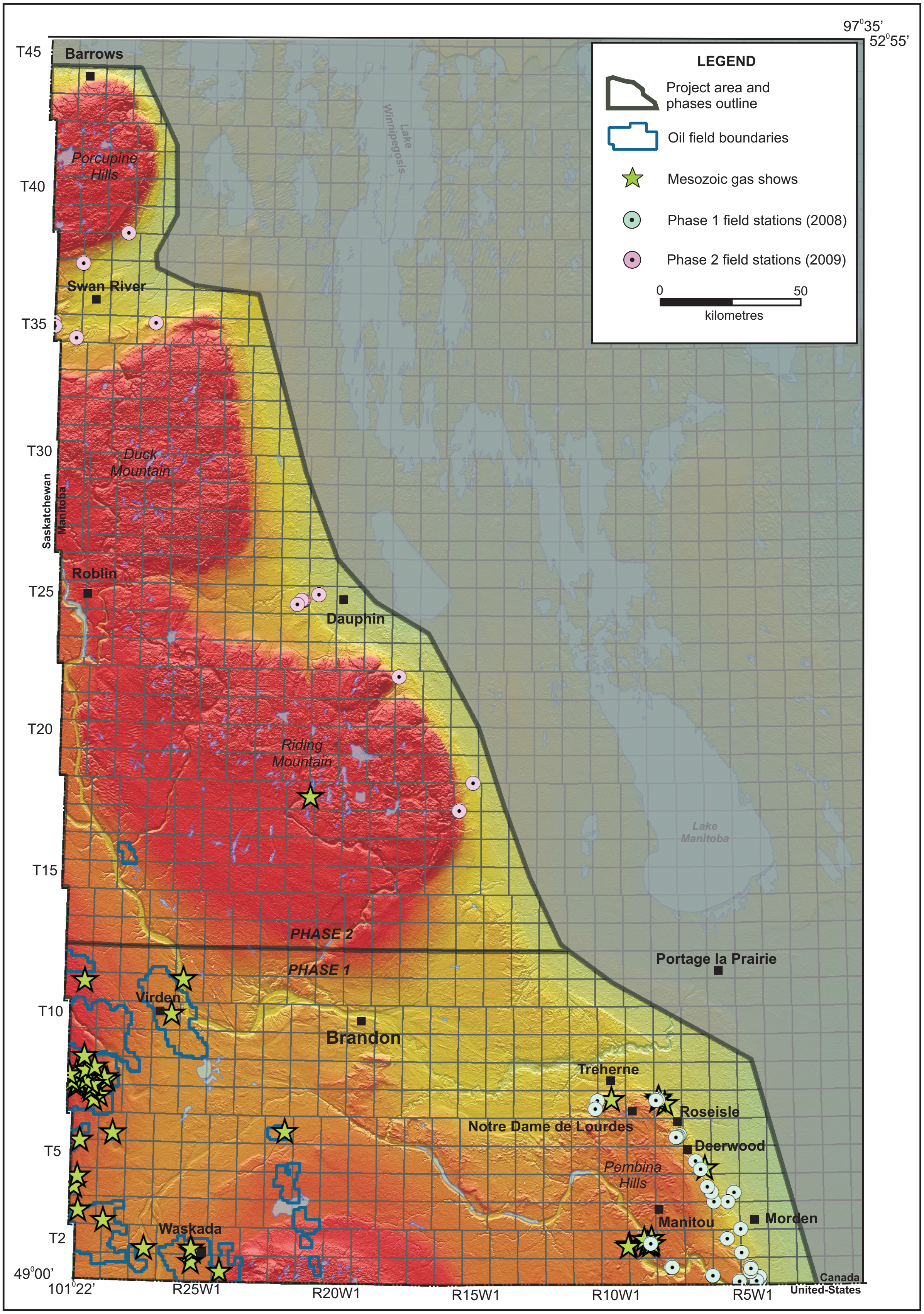

Figure GS-17-2: Digital elevation model map of the study area for the Shallow Unconventional Shale Gas Project, southwest Manitoba. Shown are the locations of phases 1 and 2 of the project, Mesozoic gas shows in relation to existing oilfields, and field station sites of the 2008 and 2009 sampling programs.

parameter is a measure of free or adsorbed hydrocarbons volatilized during heating of the sample up to 300°C. The S_2 parameter is a measure of the hydrocarbons released during gradual heating from 300° to 550°C at increments of 25°C/min. The S_3 parameter is a measure of the organic CO_2 and CO generated from the kerogen remaining during heating of the sample. T_{max} is the temperature at which the S_2 peak is reached, and correlates with the maximum temperature a rock has been subjected to during its burial history. TOC is the total organic carbon content of the rock sample. Mineral carbon (MinC) is also measured, giving the amount of carbon tied up in minerals, such as carbonate minerals. The S_1, S_2 and S_3 parameters are measured in milligrams of produced hydrocarbons per gram of rock sample (equivalent to kg/t), where the products are hydrocarbons for the S_1 and S_2 parameters, and CO_2 and CO for the S_3 parameter. TOC is reported in weight percent (wt. %) and T_{max} is measured in degrees Celsius. From the results of the tests, production index (PI; ratio of $S_1/(S_1+S_2)$), hydrogen index (HI; ratio of S_2/TOC) and oxygen index (OI; ratio of S_3/TOC) were calculated and, along with the ratio of S_2/S_3, are used to assess the shale gas potential of the sampled formations.

Interpretation and application of Rock Eval/TOC results is subject to filtering of the data to eliminate false readings and unreliable results. The results were filtered according to the guidelines of Osadetz (pers. comm., 2009), as follows. If TOC was <0.3 wt. %, the sample results were removed from further analysis. If TOC was <0.5 wt.%, the OI was considered unreliable, and was not used in computing OI for that sample and subsequently not plotted in diagrams containing OI. If S_1 and S_2 values were <0.2, the T_{max} and PI were considered unreliable, and those samples were eliminated from plots containing T_{max} and PI. The character of the flame ionization detector (FID) pyrogram for each sample, which is a graph showing the response of the sample to heating during sample analysis, was also taken into account to further eliminate samples with questionable results. Filtering the data reduced the number of samples available for interpretation for some stratigraphic members, and completely eliminated the Odanah and Millwood members due to the extreme immaturity of its sediments and low organic content. Rock Eval/TOC results for the samples collected in the 2008 field season are presented in MGS Data Repository Item DRI2009003[1].

The minimum temperature for a rock to reach thermal maturity is 100°C and referred to as the oil window for mature oils; the major phase of oil generation occurs between 100 and 150°C (Killops and Killops, 2005). Temperatures greater than 150°C result in thermally cracked hydrocarbons. Immature sediments are sediments that have not been subjected to temperatures above the oil window. If hydrocarbons are present in such sediments, they are gases that may have formed by in situ natural degassing processes or methanogenesis, the biogenic metabolic processes of methane-producing bacteria (methanogens). These gases are composed of hydrocarbons with one to four carbon atoms, such as methane, ethane, propane and butane and their related derivatives; pentane in gaseous form can be present on occasion (Killops and Killops, 2005). On the Rock Eval instrumentation, T_{max} corresponds to the maximum temperature a sample has been subjected to during its burial history. T_{max} can be used to indicate if a sample is immature (thermal maturity due to burial at <100°C corresponds to T_{max} <435°C on the Rock Eval instrumentation), mature (thermal maturity due to burial at 100–150°C corresponds to T_{max} between 435 and 465°C) or overmature (thermal maturity due to burial at >150°C corresponds to T_{max} >465°C). The oil window is the temperature at which oil and gas are expelled from the kerogen in the rock and are thus able to migrate away from the source. For conventional oil and gas systems, a source rock needs to reach the minimum temperature of 100°C (equivalent to T_{max} of 435°C as measured on the Rock Eval instrument). In unconventional biogenic systems, this temperature is not a requirement for gas accumulations.

Results

Rock Eval/TOC data interpretations are most reliable for large datasets, therefore the Rock Eval/TOC results for samples from the 2008 field season are combined with results from Obermajer et al. (2005) and Nicolas (2009) in order to provide a larger database and thus increase the reliability of the data interpretations. Figures GS-17-3 and -4 show the results of this geochemical compilation, subdivided by member.

Figure GS-17-3a is a plot of TOC for each member in stratigraphic order; after data filtering, this graph represents 328 samples. The green dashed line indicates the minimum TOC required for a fertile source rock. A general guideline followed in industry is that if the TOC is ≥2 wt. %, then the sample is classified as a good source rock, and if it's >10 wt. %, the sample is classified as an excellent source rock. If a sample has a TOC <2 wt. %, the sample is generally not an economical source rock candidate. The highest TOC values were obtained from the Boyne and Morden members of the Carlile Formation, the Assiniboine and Keld members of the Favel Formation, and the Belle Fourche Member of the Ashville Formation. The Boyne Member shows the highest TOC value at 15 wt. %. With the exception of the Millwood Member,

[1] MGS Data Repository Item DRI2009003, containing the data or other information sources used to compile this report is available online to download free of charge at http://www2.gov.mb.ca/itm-cat/web/freedownloads.html or on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Innovation, Energy and Mines, 360–1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

all of the sampled intervals show some results indicative of good or excellent source rock potential on the basis of their TOC values.

Figure GS-17-3b is a plot of T_{max} for each member in stratigraphic order; after data filtering, this graph represents 131 samples. The green dashed line indicates the Rock Eval oil generation window for mature oils, which corresponds to 435–465°C as measured on the Rock Eval instrumentation. Most of the samples plot below the oil window, indicating that most of the sediments are immature and have not been subject to high burial temperatures. The few samples that plot higher than the oil window were collected in deeper sections and may have some degree of downhole contamination, particularly in the case of drill-cutting samples used in the analyses reported in Obermajer et al. (2005). A weak trend of increasing T_{max}

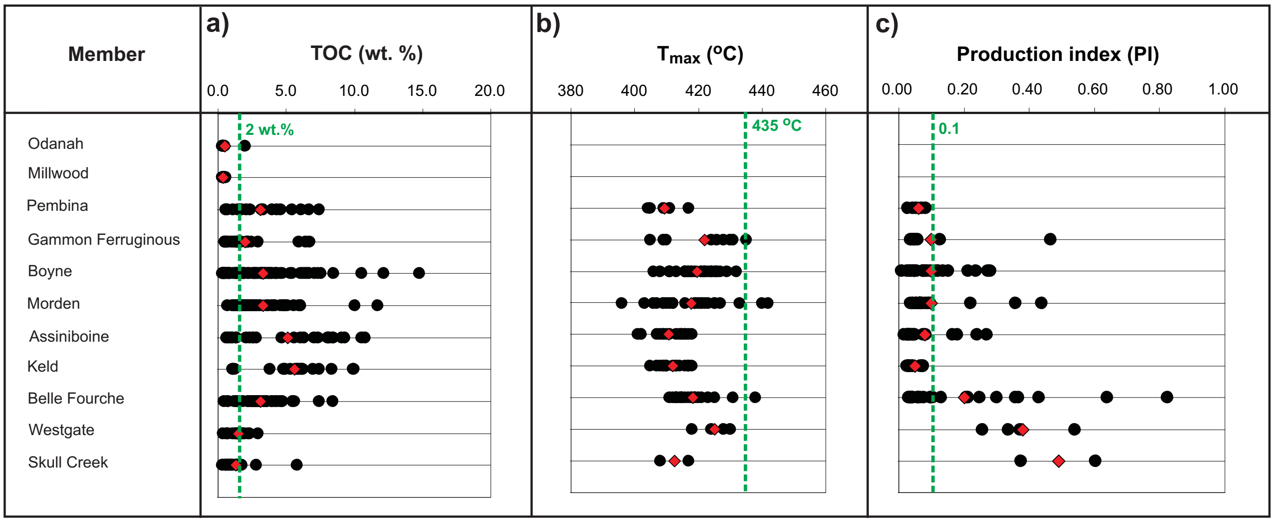

Figure GS-17-3: *New and archival (Obermajer et al., 2005; Nicolas, 2009) Rock Eval/TOC data grouped by member (Cretaceous shale, Manitoba) and placed in order of increasing stratigraphic depth; an average value for each member is shown in red;* ***a)*** *green dashed line indicates where total organic carbon (TOC) = 2 wt. %;* ***b)*** *green dashed line is equal to 435°C; and* ***c)*** *green dashed line indicates where production index (PI) = 0.1.*

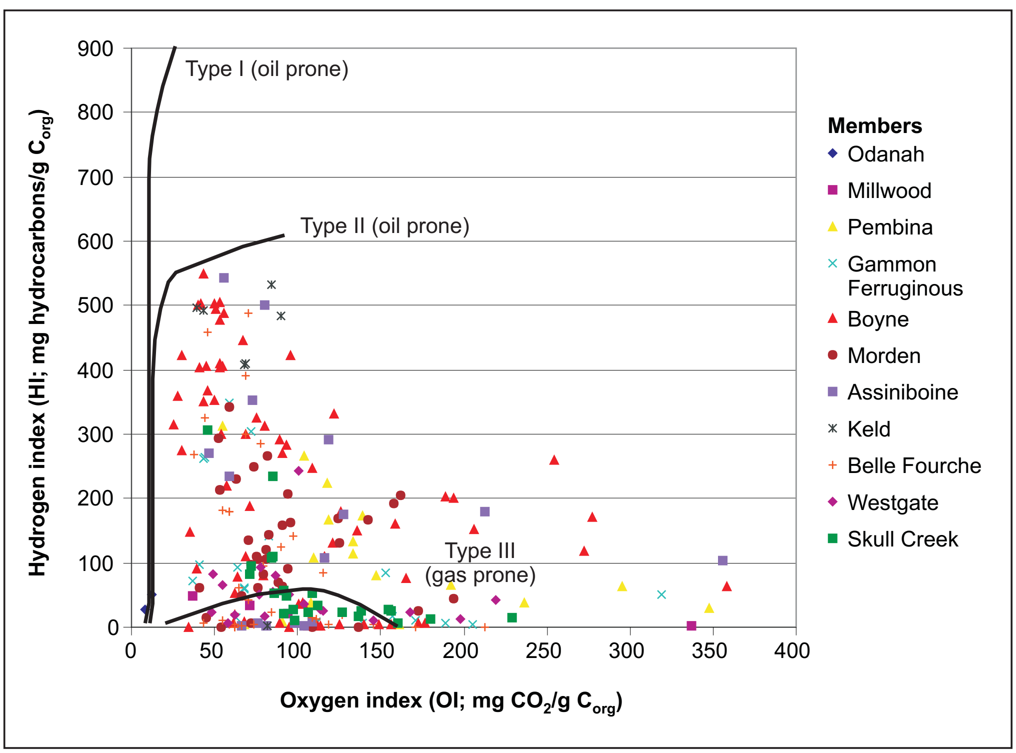

Figure GS-17-4: *Modified van Krevelen diagram of new and archival (Obermajer et al., 2005; Nicolas, 2009) Rock Eval data grouped by member (Cretaceous shale, Manitoba).*

with stratigraphic depth, as seen in Figure GS-17-3b, is expected, but is not well established due to the increased geothermal gradient. These results agree with the location of the samples along the margins of the Williston Basin, where shallower burial depths are to be expected.

Figure GS-17-3c is a plot of the PI, where PI is the ratio of $S_1/(S_1+S_2)$; after data filtering, this graph represents 131 samples. The PI is a measure of the hydrocarbon generation potential of a source rock. In a thermogenic system, PI should be between 0.1 and 1.0 (Zhang, 2008). This plot shows that, on average, most samples plot below the thermogenic minimum of 0.1 (green dashed line on Figure GS-17-3c). However, several samples plot above the minimum. Thermally immature samples plot above the thermogenic minimum, which suggests that the hydrocarbons released during the early heating of the samples were very light hydrocarbon compounds (Lafargue et al., 1998), and that there is a significant amount of free and/or adsorbed hydrocarbons in the samples.

The T_{max} and TOC results indicate that although the shale formations have not reached thermal maturity, these rocks are good to excellent source rocks. Despite the thermal immaturity of the rocks, several shale members plot in the thermogenic window on the PI diagram. Although it is clear that these shale formations have not been subjected to intensive heating, the high PI values are likely due to the high concentration of free or adsorbed gas in the system, suggesting a biogenic origin as identified in Nicolas and Grasby (GS-18, this volume).

A modified van Krevelan diagram (Figure GS-17-4) uses HI versus OI to distinguish kerogen types in the sediment samples. On Figure GS-17-4, samples that plot as a type I and type II kerogen are found in variably oil-prone sediments, whereas type III kerogen is found in gas-prone sediments, and type IV kerogen (not shown on diagram) is found in immature, gas-prone sediments. Samples collected for this study plot between the type II and type III kerogen lines, and below the type III kerogen line. This distribution is to be expected, particularly the abundance of points below the type III kerogen line, due to the overall immaturity of these sediments.

Mineralogy

Introduction

The mineralogy of shale gas reservoirs can help determine if a shale bed is a potential gas source and reservoir. For example, the presence and abundance of quartz and swelling clay minerals can not only indicate a unit's potential as an economic gas reservoir, but can provide important information for planning a drilling program since these minerals are sensitive to drilling fluids and drilling techniques. High quartz concentrations in combination with high TOC values are key requirements for excellent shale gas reservoirs. High TOC values indicate that the unit is a potentially good source rock (i.e., more gas production in situ) and the abundance of quartz grains within these fine-grained reservoirs make the rock brittle, therefore increasing the effectiveness of reservoir fracturing techniques, and thus increasing gas production. The presence of swelling clay minerals can damage potential reservoirs by destroying porosity and permeability during drilling, reservoir stimulation and gas production.

Results

X-ray diffraction (XRD) was conducted on a select suite of 47 samples collected from outcrop and core. Samples were selected on the basis of their TOC content and analyzed only if they had a TOC >2 wt. %, since these samples have the best source rock potential. In addition to those with high TOC values, samples from the Odanah Member were analyzed due to its siliceous character and enhanced potential reservoir qualities. After this sample filtering process, only samples from the Odanah, Pembina, Boyne, Morden and Assiniboine members were analyzed by XRD, whereas the Millwood and Gammon Ferruginous members of the Pierre Shale were not analyzed.

The average mineral abundance percentage for each member is shown Table GS-17-1 to provide a general overview of the variability in the Cretaceous sequence. Of particular interest is the high quartz content of the shale sequences. High variability of quartz content is particularly apparent in the Boyne Member, where individual results (MGS Data Repository Item DRI2009004[2]) show quartz contents ranging from 8 to 89%. This exemplifies the variability that exists at different stratigraphic intervals within the individual members.

The mineralogy results from Bannatyne (1970), although more detailed and accurate due to bulk geochemistry data, XRD results and microscopic examination of all shale horizons in Manitoba (Table GS-17-2), compare well with the samples collected for this study.

Snow Valley outcrop, Boyne Member, Carlile Formation

The discovery of siltstone beds within the Boyne Member of the Carlile Formation in 2008 is significant because it provides evidence for potentially porous siltstone and sandstone beds in the Cretaceous of Manitoba (Nicolas, 2008). These siltstone beds are the same as the cement-rock beds, here informally referred to as the

[2] MGS Data Repository Item DRI2009004, containing the data or other information sources used to compile this report is available online to download free of charge at http://www2.gov.mb.ca/itm-cat/web/freedownloads.html on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Innovation, Energy and Mines, 360–1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

Table GS-17-1: Averaged mineral abundances, grouped by member, for Cretaceous shale samples from Manitoba, as determined by XRD of 47 samples.

Formation	Pierre Shale	Pierre Shale	Carlile	Carlile	Favel
Member	Odanah	Pembina	Boyne	Morden	Assiniboine
Mineralogical abundance (%)	46.50% quartz	66.12% quartz	49.92% calcite	89.00% quartz	86.67% calcite
	40.88% opal	10.50% calcite	35.44% quartz	3.00% K-feldspar	10.34% quartz
	7.88% smectite	9.50% K-feldspar	4.88% illite	2.67% illite	1.00% kaolinite
	2.25% Na-feldspar	7.75% smectite	2.64% kaolinite	2.33% kaolinite	1.00% ankerite
	1.25% illite	1.50% Na-feldspar	1.84% pyrite	2.00% Na-feldspar	0.67% Exp.M.L.C.
	1.00% K-feldspar	1.38% gyspum	1.60% K-feldspar	1.00% Exp.M.L.C	0.33% illite
	0.25% kaolinite	1.38% jarosite	1.36% Exp.M.L.C	0.003% chlorite	
	0.12% gypsum	1.13% illite	1.08% gyspum		
		0.62% kaolinite	0.44% Na-feldspar		
		0.12% pyrite	0.36% chlorite		
			0.32% ankerite		
			0.08% cristobalite		
			0.04% unknown minerals		

Abbreviation: Exp.M.L.C.: expendable mixed layers clays (2 to 1 silicates).

Table GS-17-2: Mineralogy of select horizons in Manitoba, summarized from Bannatyne (1970).

Member/Formation	Mineralogy (in approximate order of abundance) according to Bannatyne (1970)
Odanah Member, Pierre Shale	dominantly composed of silicate; main clay mineral is illite (with Ca and Mg exchangeable ions) with some montmorillonite; trace amounts of quartz and cristobalite
Millwood Member, Pierre Shale	partly swelling montmorillonite (free of collapsed illitic layers); minor quartz and cristobalite; traces of opaline microfossils, goethite, carbonate minerals, mica, zeolite and gypsum
Pembina Member, Pierre Shale	montmorillonite (free of collapsed illitic layers); quartz; minerals from the kaolin and/or chlorite group; minor dolomite, goethite, quartz, mica, apatite and a zeolite mineral
Gammon Ferriginous Member, Pierre Shale	NA
Boyne Member, Carlile Formation	buff-weathering, highly calcareous shale (upper beds): mainly calcite; some illite; minor constituents include gypsum, limonite and quartz
Boyne Member, Carlile Formation	grey, calcareous shale (natural cement rock, middle beds): mainly illite; some calcite; some gypsum; small amounts of quartz; traces of siderite and pyrite
Boyne Member, Carlile Formation	dark grey, carbonaceous, calcareous shale (lower beds): mainly illite; some kaolinite and chlorite; small amounts of siderite, dolomite and calcite; minor constituents include quartz and pyrite; traces of gypsum
Morden Member, Carlile Formation	mainly illite (with Mg and Na as exchangeable ions); small amounts of quartz; traces of pyrite, siderite and gypsum
Favel Formation	mainly illite; some dolomite; minor consituents include gypsum, pyrite; small amounts of limonite, siderite and quartz
Belle Fourche Member, Ashville Formation	mainly illite (with Ca as exchangeable ions); minor consituents of pyrite, siderite, gypsum; small amounts of quartz; traces of dolomite
Westgate and Skull Creek members, Ashville Formation	mainly illite (with Ca and Mg exchangeable ions); kaolinite; minor amounts of gypsum, quartz and pyrite

Babcock beds, that were mined and quarried in the early 1900s in Babcock and near Deerwood.

The Babcock beds were only known to outcrop at one location; most of the outcrop, discussed in older references, has been obscured by erosion and overgrowth since it was exploited years ago. The new outcrop location of the Babcock beds, studied and sampled in 2008, is located in the Snow Valley along Roseisle Creek southwest of Roseisle, Manitoba. The lithological description of these beds is available in Nicolas (2008).

Figure GS-17-5 is a photograph of the Snow Valley outcrop, with the Babcock beds standing out as the more resistant beds. Figure GS-17-6 is a close-up of the Babcock beds showing their interbedded and coarse-grained

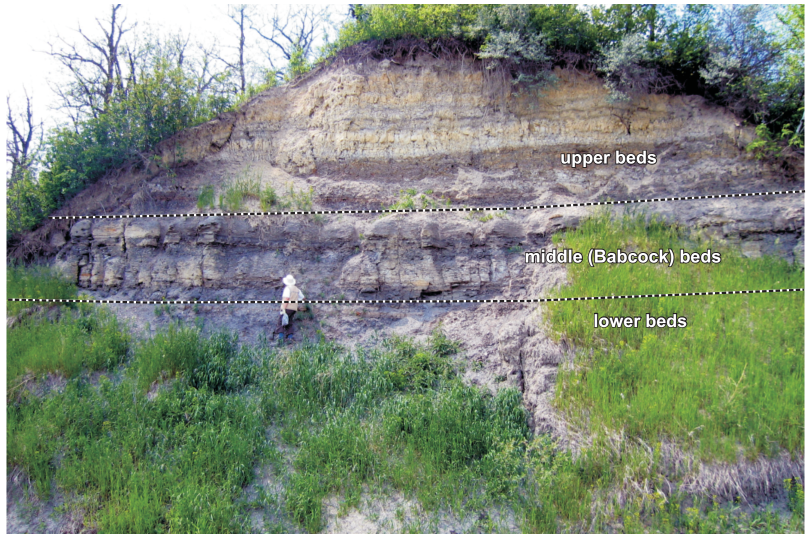

Figure GS-17-5: *Outcrop of the Boyne Member of the Carlile Formation in Snow Valley along Roseisle Creek, southwest of Roseisle, Manitoba. Subdivisions show the upper beds, middle (Babcock) beds and the lower beds.*

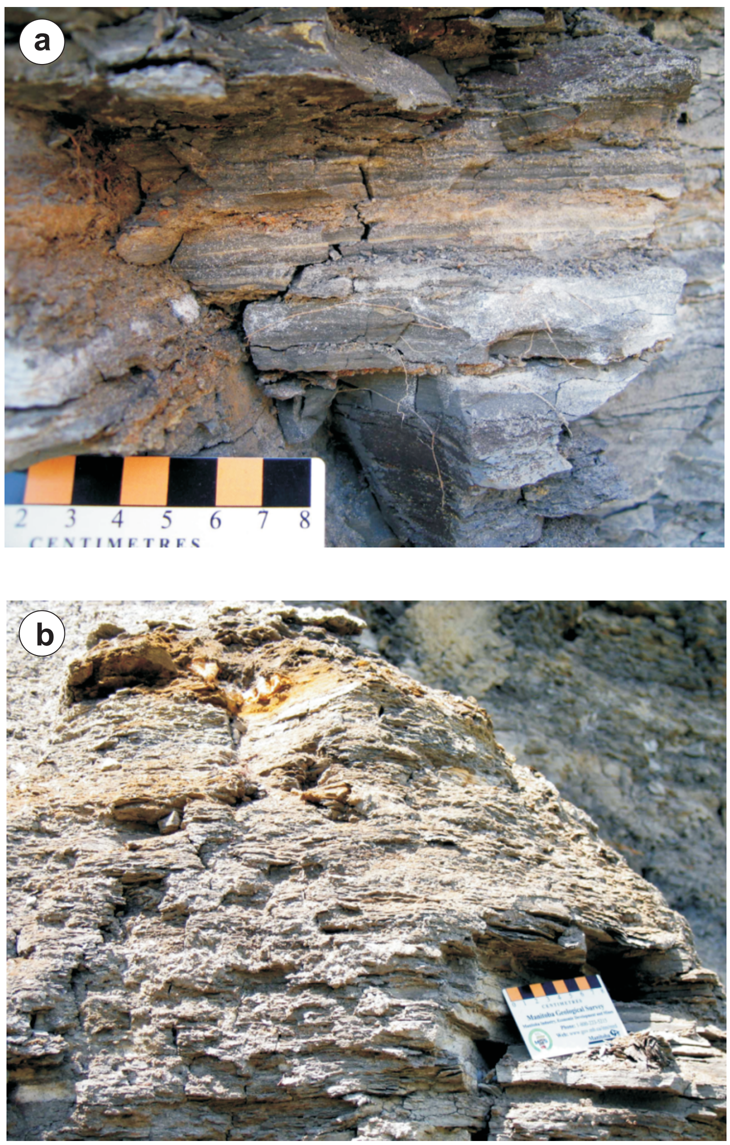

Figure GS-17-6: *Close-up of a portion of the Babcock beds, Roseisle, Manitoba, showing:* ***a)*** *shaly siltstone and sandstone interbedded with shale from the middle section of the Babcock beds; and* ***b)*** *interbedded sandstone and shale from the top of the Babcock beds near the contact with the upper beds.*

nature. The outcrop is subdivided into three parts: 1) upper beds, 2) middle beds (Babcock beds) and 3) lower beds. This subdivision correlates well with the Boyne Member units discussed in Bannatyne (1970), where the upper beds are the "buff-weathering, highly calcareous shale", the middle beds correlate to the "grey calcareous shale", and the lower beds are the "dark grey carbonaceous shale (southern area)".

The Roseisle outcrop returned some of the highest TOC results from the 2008 sample suite, with average TOC values of 3.11 wt. %, 10.55 wt. % and 6.51 wt. % for samples from the lower, middle and upper Babcock beds, respectively. All these values indicate that the Boyne Member is a good to excellent source rock. Evaluation of a core (Nicolas, unpublished data, 2009) from L.S. 8, Sec. 29, Twp. 4, Rge. 29, W 1st Mer. (abbreviated 8-29-4-29-W1) intersecting the same interval in the Boyne Member as that exposed at Snow Valley shows the same three-fold unit distribution, although the middle unit in the core lacks well-developed, siltstone beds. In core, the middle unit better resembles the description for the Boyne Sand (Glass, 1997). TOC values for the lower and upper beds from the core average 3.79 wt. % and 6.34 wt. %, respectively, similar to the values obtained from the same units in the outcrop section. The middle beds in the core returned a TOC value of 3.48 wt. %, significantly lower than the TOC values for the Babcock beds. It is possible that the core samples submitted for evaluation from this interval were not truly representative of the middle unit, and further sampling and analysis are planned.

The mineralogical results from the Roseisle outcrop are equally interesting with respect to quartz content. The lower beds contain 89% quartz, the middle Babcock beds average 56% quartz, and the upper beds average 45% quartz. Preliminary thin section examination of the Babcock beds indicates that quartz grains dominate the silt- and sand-size grain fraction. The quartz content of samples from the lower beds appears to be unusually high, and may not be representative. To compare, an outcrop near Notre Dame de Lourdes displays the same stratigraphy as the Roseisle outcrop, but lacks the well-defined interbedded siltstone and sandstone characteristic of the Babcock beds. The middle unit at the Notre Dame de Lourdes site resembles closely the description of the Boyne Sand of Glass (1997), but is siltier; somewhat of a cross between the Roseisle outcrop and the 8-29-4-29-W1 core. Samples from the lower beds at Notre Dame de Lourdes yielded relatively lower quartz values around 10%, with TOC values of 4.60 wt. %. The quartz contents of samples from the core at 8-29-4-29-W1 are 82% and 81% for the lower and middle beds, respectively, and highly variable between 8 and 82% in the upper beds.

The lithological character, high TOC values and high quartz content in the Babcock beds (middle beds) of the Boyne Member suggest that this target is worth exploring further into the subsurface, where these beds may potentially serve as a gas reservoir. Yurkowski (pers. comm., 2009) noted the presence of these beds in northeast Saskatchewan, suggesting their subsurface distribution is likely very extensive and may cover an area of over 50 000 km^2 in Manitoba. Stratigraphic positioning, geochemistry and lithological descriptions of the Babcock beds, the middle unit of the 8-29-4-29-W1 core and the Notre Dames de Lourdes site suggest that these units are correlative, and may be related to the Boyne Sand, which is the gas-bearing reservoir unit of the historical Kamsack gas discovery in Saskatchewan. Log analysis and drill cutting evaluation are needed to further verify the correlations, areal extent and continuity.

Discussion

Manitoba hosts a potential shale gas resource that has not been adequately explored with modern technology. Results from phase 1 of this study are encouraging. The combination of shale with thick siltstone and sandstone beds, documented gas shows, low T_{max} values, high TOC contents and high quartz fractions within the Boyne Member of the Carlile Formation indicate that Manitoba has the right geological conditions for the generation of unconventional shallow shale gas of biogenic origin.

The best Cretaceous shale gas targets in Manitoba are the Carlile Formation, particularly the Boyne Member, the Favel Formation and the Belle Fourche Member of the Ashville Formation. Geochemical and mineralogical analyses of the samples collected in phase 2 will provide more information on the prospects in the northern part of the study area, where documented gas shows are rare in these shallow shale sequences.

Economic considerations

The recognition of silty and sandy beds within the Boyne Member of the Carlile Formation in the Pembina Hills is critical for Manitoba to be considered as a potential player in the business of unconventional shallow shale gas exploration. Aside from having the right lithological characteristics, the use of a combination of organic geochemistry and mineralogical investigations on these beds may result in the discovery of a large natural gas resource in the province. Searching for other units in the Cretaceous shale sequence that have the right geochemical and mineralogical characteristics is important in order to expand the potential pay zone thickness at any given location, making exploratory drilling more attractive. The historical success of the Kamsack gasfield in Saskatchewan, which produced from the same stratigraphic unit, suggest that even as a single pay zone, the Babcock beds in Manitoba could potentially be produced economically without the need for commingling with other gas zones.

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