GS2018-11

Stratigraphy, lithology and petroleum potential of the Upper Devonian Duperow Formation in the Manitoba Potash Corporation core at 3-29-20-29W1, southwestern Manitoba (part of NTS 65K1)

by M.P.B. Nicolas and N. Chow[1]

In Brief:

- The continuous 153.36 m core showed stratigraphic basin continuity of the Saskatoon, Wymark and Seward members
- The cyclical carbonate-evaporite sequence recorded subtidal, intertidal and supratidal lithofacies
- Oil shows have been documented, supporting conventional reservoir models
- Organic-rich mudstone beds indicate good source rock generative potential, supporting unconventional reservoir models through self-sourcing

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Summary

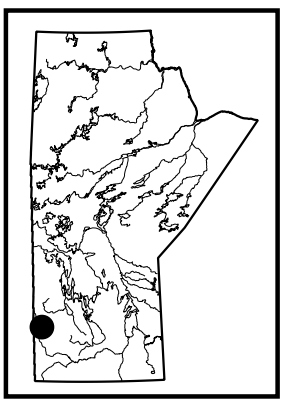
The Upper Devonian Duperow Formation is a cyclical carbonate-evaporite sequence within the Elk Point Basin. The Manitoba Potash Corporation (MPC) core from L.S. 3, Sec. 29, Twp. 20, Rge. 29, W 1st Mer. has a full section of the Duperow Formation, which is 153.36 m thick (502.90–656.26 m true vertical depth) with 99% of core recovered during drilling. The members preserved in this core are the Saskatoon, Wymark and Seward members, from bottom to top. Preliminary lithofacies analysis indicates that the subtidal, intertidal and supratidal lithofacies associations recognized in other studies of the Duperow Formation in Manitoba are also present in the MPC core.

Drill-stem tests of the Duperow Formation in the MPC well have returned muddy water, but oil shows have been documented throughout this formation in this core, which is supportive of a conventional reservoir model. Rock-Eval 6 analyses of thin, organic-rich lime mudstone beds indicate fair to very good source rock generative potential, supportive of an unconventional reservoir model through self-sourcing.

Introduction

The Upper Devonian (Frasnian) Duperow Formation is a cyclical carbonate-evaporite sequence that is present in the eastern side of the Elk Point Basin. In Manitoba, the Duperow Formation has a maximum thickness of 220 m in the extreme southwestern corner, where it occurs at maximum depths greater than 1500 m (Bates et al., 2016). It gradually shallows and thins to an erosional edge in the northeastern direction (TGI Williston Basin Working Group, 2008a, b). As the Duperow Formation has only been observed in the subsurface, core and downhole geophysical logs must be used for detailed study of this formation.

During the early mineral and oil exploration years in Manitoba, Duperow Formation cores were occasionally recovered (Figure GS2018-11-1), but all were short intervals and telescopic in nature. In 1986, Canamax Resources Inc. drilled a potash testhole as a pilot hole for the construction of a mine shaft for an underground potash mine in L.S. 3, Sec. 29, Twp. 20, Rge. 29, W 1st Mer. (abbreviated 3-29-20-29W1) located at UTM Zone 14, 325102.38W, 5624312.3N (NAD84). A continuous core was acquired at this location, from 14.0 to 900.0 m true vertical depth (TVD). With a total core recovery average of 96%, this core represents the first continuous look at the subsurface units in southwestern Manitoba, from the uppermost Cretaceous units to the base of the Devonian Winnipegosis Formation. This stratigraphic core was previously owned by Manitoba Potash Corporation (MPC). In 2014, the Manitoba Geological Survey (MGS) acquired this core from MPC and has stored it at the MGS Midland Sample and Core Library in Winnipeg (Nicolas, 2016). To maintain the integrity of this valuable core and provide MGS geologists the opportunity to fully and properly catalogue the core, access to it is currently limited.



In this core, the Devonian Duperow Formation is preserved from 502.90 to 656.26 m TVD, and has a total thickness of 153.36 m and 99% core recovery. The formation is covered from core 106, box 368 to core 129, box 487. This is the only core in Manitoba currently in archival storage that fully preserves the Duperow Formation, providing a

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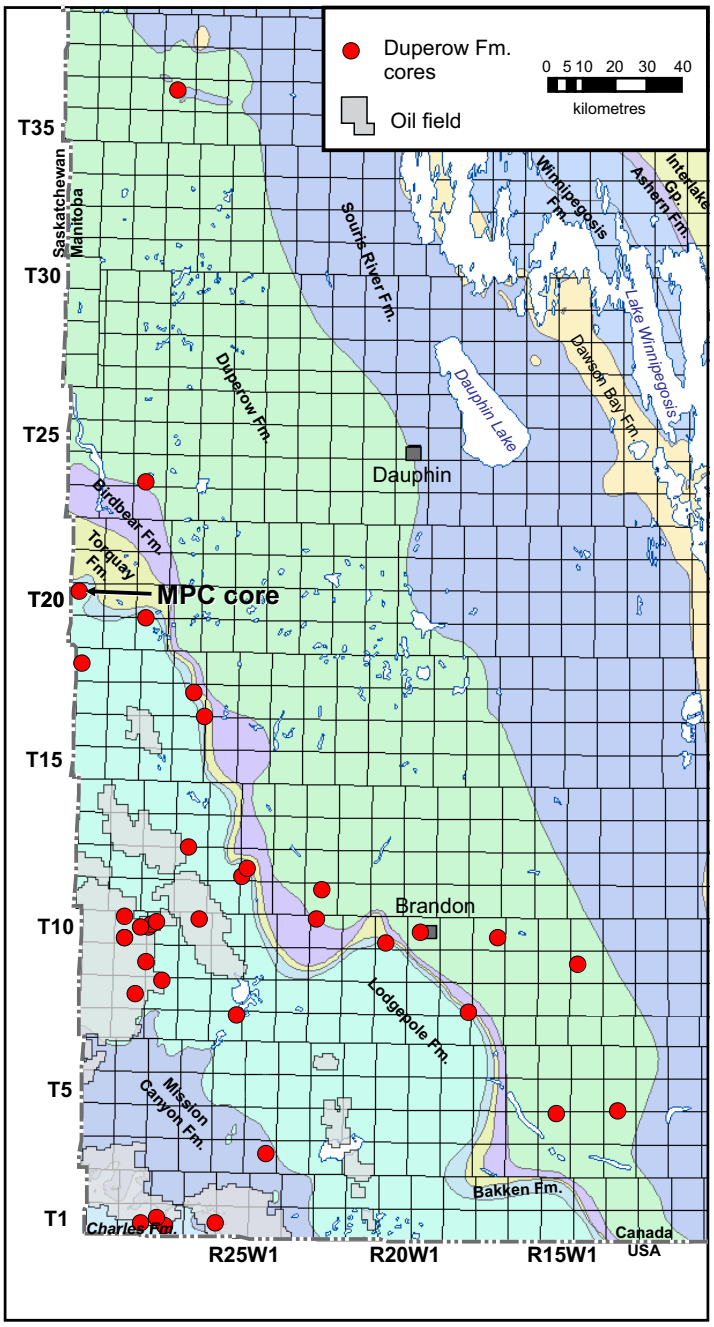

Figure GS2018-11-1: *Geological map of southwestern Manitoba showing the location of the Manitoba Potash Corporation (MPC) core and other Duperow Formation cores. Stratigraphic information is from Nicolas et al. (2010). Abbreviations: Fm., Formation; Gp., Group.*

complete and rare glimpse into the lithology and stratigraphy of the formation.

Previous work

The Duperow Formation was identified by the MGS as a formation that was poorly documented and understood in southwestern Manitoba, in comparison to other parts of the Elk Point Basin (e.g.,Wilson, 1967; Wilson and Pilatzke, 1987; Cen and Salad Hersi, 2006a, b). Through a regional cross-border study between Saskatchewan and Manitoba during the Targeted Geoscience Initiative II, Nicolas and Barchyn (2008) suggested that the stratigraphy for the Duperow Formation, including the Saskatoon, Elstow, Wymark and Seward members, in southeastern Saskatchewan is directly correlative with that in southwestern Manitoba. This was based on long-range correlations using geophysical wireline logs. For Manitoba to formally adopt the stratigraphic framework for this

formation, further study, which included core logging, would be required. From this need, a collaborative study of the Duperow Formation in Manitoba was initiated in 2011 between the MGS and the University of Manitoba. At the University of Manitoba, a B.Sc. thesis on the middle unit of the Wymark Member was completed by L. Eggie in 2012 (Eggie, 2012; Eggie et al., 2012). As an outgrowth of this work, a collaborative research and development agreement was set up between the University of Manitoba, ARC Resources Ltd. (Calgary), Natural Sciences and Engineering Research Council, and the MGS to support an M.Sc. thesis on the entire formation, which was completed by K. Bates in 2016 (Bates, 2016; Bates et al., 2016). The purpose of the project was to better understand the stratigraphy, lithofacies, diagenesis and petroleum potential of the formation throughout southwestern Manitoba. Through detailed core logging and subsurface correlations, Bates (2016) concluded that the Elstow Member could not be differentiated from the Saskatoon Member in Manitoba, hence only the Saskatoon, Wymark and Seward members are present, supporting previous studies by Kent (1983) and Cen and Salad Hersi (2006a). These earlier studies did not include the MPC core due to the confidentiality and inaccessibility of the core at that time.

Stratigraphy

The Duperow Formation is part of the Saskatchewan Group, which occurs throughout the Elk Point Basin. In Manitoba and in the MPC core, the Duperow Formation consists of, from oldest to youngest, the Saskatoon, Wymark and Seward members. Figure GS2018-11-2 shows the stratigraphic column and core log for the MPC core; the stratigraphic picks are provided in Table GS2018-11-1. The formation conformably overlies the Souris River Formation and conformably underlies the Birdbear Formation (Figure GS2018-11-4).

Saskatoon Member

The Saskatoon Member in the MPC core is 15.26 m thick and conformably overlies the Hatfield Member of the Souris River Formation. The lower contact is a hardground surface developed on mottled-nodular fossiliferous wackestone that is overlain by burrow-mottled lime mudstone (Figure GS2018-11-4).

The Saskatoon Member consists of fossiliferous wackestone-packstone to floatstone-framestone, commonly with large stromatoporoid fragments and articulated brachiopods; burrow-mottled dolomudstone, with recognizable *Planolites* and *Thalassinoides* burrows; and laminated, anhydritic argillaceous dolomudstone.

Wymark Member

The Wymark Member in the MPC core is 97.78 m thick and conformably overlies the Saskatoon Member. The lower contact is at the base of a nodular argillaceous lime mudstone identified as the C2 marker bed (cf. Wilson, 1967; Figure GS2018-11-5a). This member can be subdivided informally into three distinct conformable units:

1) the lower unit is 20.98 m thick and has an upper contact defined by the C1 marker bed;
2) the middle unit is 46.75 m thick with an upper contact defined by the B marker bed; and
3) the upper unit is 30.05 m thick with an upper contact at the A marker bed.

The marker beds can be correlated basin-wide (Wilson, 1967) and are characterized by high gamma-ray spikes that correspond to argillaceous beds (Figure GS2018-11-2).

The lower unit consists of alternating thick intervals of 1) mottled fossiliferous packstone, locally grading to fossiliferous floatstone-rudstone and framestone, with large stromatoporoids, corals, crinoid ossicles and articulated brachiopods, and argillaceous laminae throughout; and 2) nodular to burrow-mottled, slightly argillaceous, lime mudstone to dolomudstone and fossiliferous wackestone, with *Planolites* and rare stromatoporoid fragments and disarticulated brachiopods. The C1 marker bed appears to be massive to mottled, silty dolostone to siltstone (Figure GS2018-11-5b).

The middle unit is composed of thick intervals of 1) mottled fossiliferous packstone to floatstone with fragments of stromatoporoids, corals, crinoid ossicles and brachiopods; 2) wavy-laminated argillaceous lime mudstone to dominantly fossiliferous wackestone, with *Chondrites*, *Planolites* and rare *Skolithos* burrows, and scattered crinoid ossicles; and 3) planar-laminated argillaceous dolomudstone to lime mudstone with local dolopackstone interbeds and nodular anhydrite. Brecciated beds and convolute lamination occur locally. Two intermediate marker beds, P1 and P2, as well as the B marker bed, are well developed on the gamma-ray log, and consist of in situ brecciated, lime mudstone clasts within a shale to argillaceous lime mudstone matrix (Figure GS2018-11-5c).

The upper unit is composed of thick intervals of 1) fossiliferous floatstone, grading to packstone in places, with stromatoporoids, articulated brachiopods and corals; 2) wavy-laminated argillaceous lime mudstone to fossiliferous wackestone; and 3) shale and argillaceous dolomudstone/mudstone, with minor anhydrite nodules.

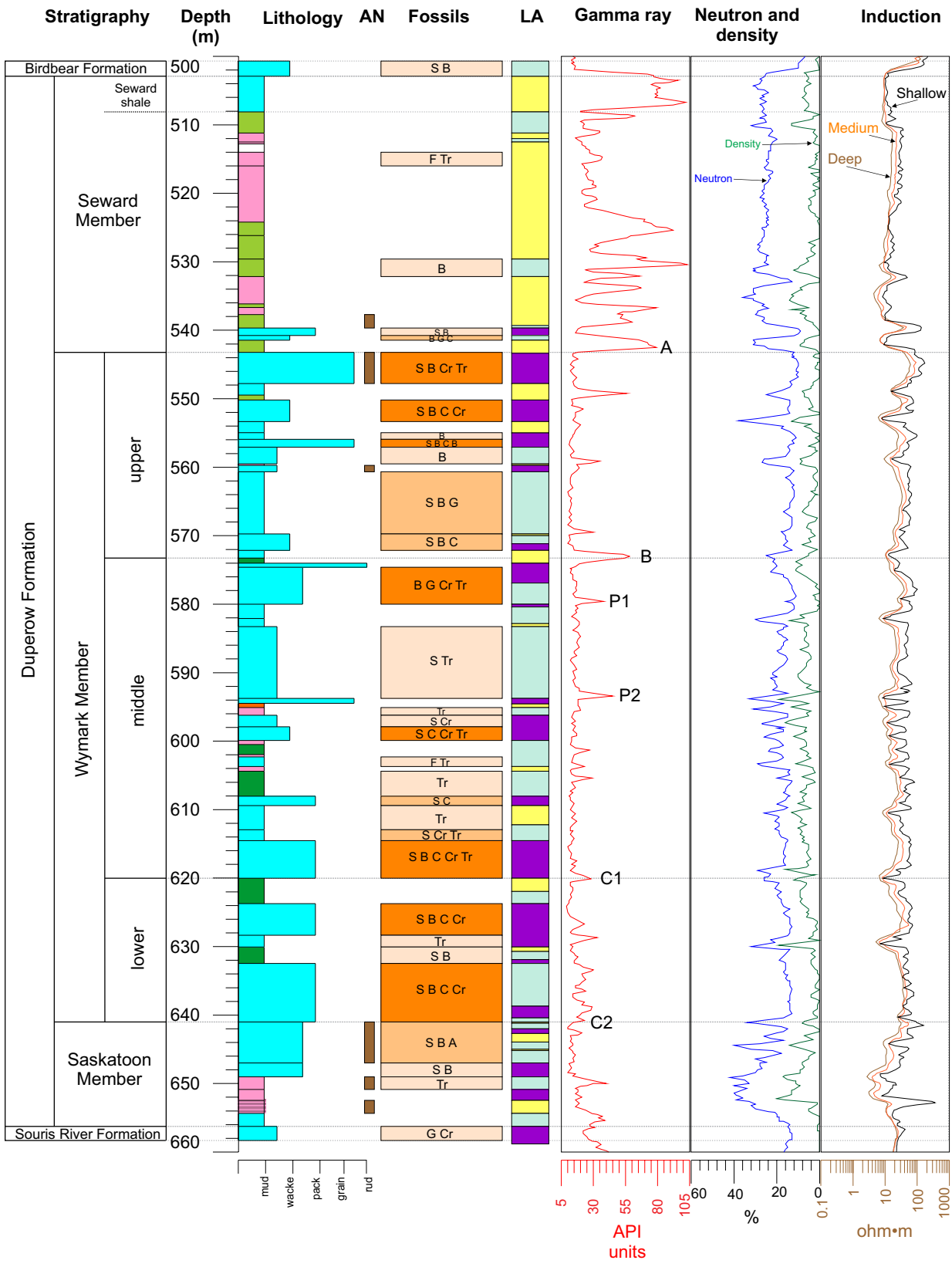

Figure GS2018-11-2: *Core log for the Duperow Formation in the Manitoba Potash Corporation (MPC) core at 3-29-20-29W1 with tracks for the stratigraphy, lithology, anhydrite occurrence (AN), fossils, lithofacies associations (LA), and gamma-ray, density and neutron, and induction downhole wireline geophysical logs. Prominent marker beds are labelled on the gamma-ray track. The core log legend is provided in Figure GS2018-11-3. Abbreviations: grain, grainstone; mud, mudstone; pack, packstone; rud, rudstone; wacke, wackestone.*

Table GS2018-11-1: Stratigraphic tops and thicknesses of the Duperow Formation and its members in the Manitoba Potash Corporation (MPC) core at 3-29-20-29W1.

Stratigraphic unit	Core depth (m)	Thickness (m)
Duperow Formation	502.90	153.36
Seward Member	502.90	40.32
Seward shale	502.90	5.22
base of Seward shale	508.12	-
Wymark Member	543.22	97.78
upper	543.22	30.05
middle	573.27	46.75
lower	620.02	20.98
Saskatoon Member	641.00	15.26
Souris River Formation	656.26	-

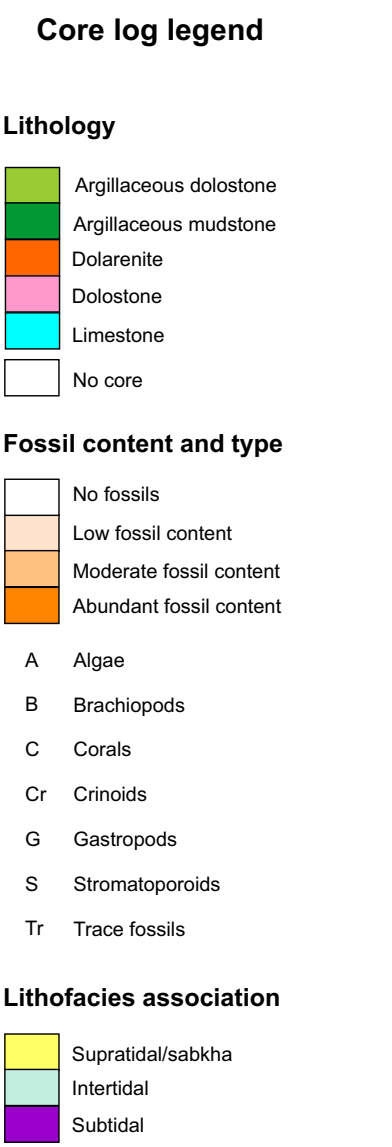

Figure GS2018-11-3: *Core log legend for Figure GS2018-11-2.*

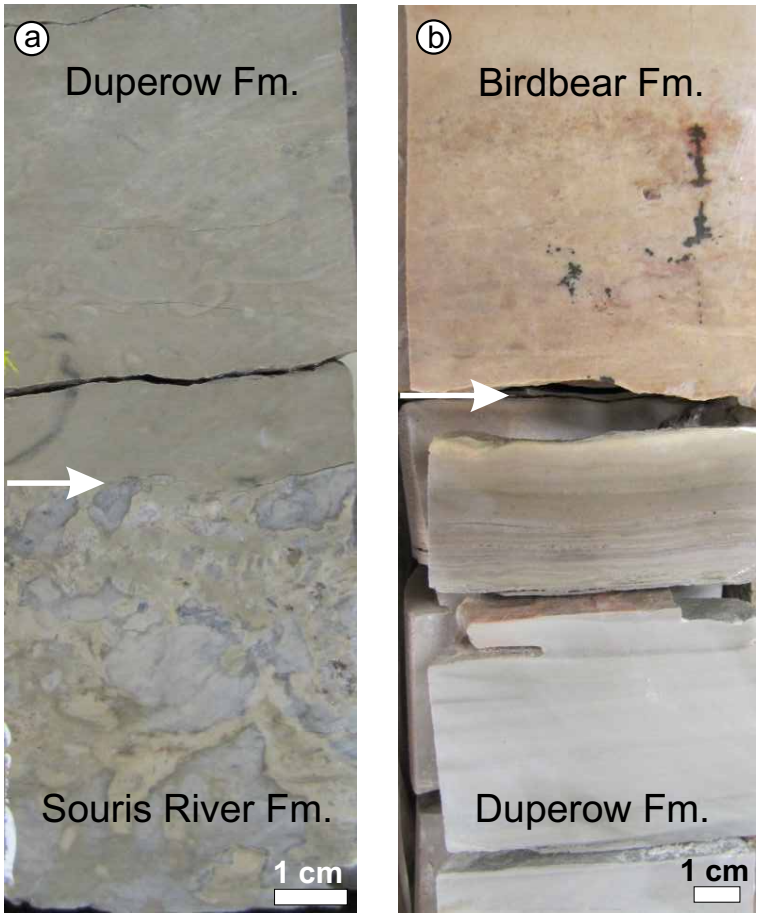

Figure GS2018-11-4: *Core photograph of lower and upper contacts of the Duperow Formation:* ***a)*** *at a depth of 656.26 m between the Souris River and Duperow formations, and* ***b)*** *at a depth of 502.90 m between the Birdbear and the Duperow formations, in the Manitoba Potash Corporation (MPC) core at 3-29-20-29W1; arrows mark contacts. Abbreviation: Fm., Formation.*

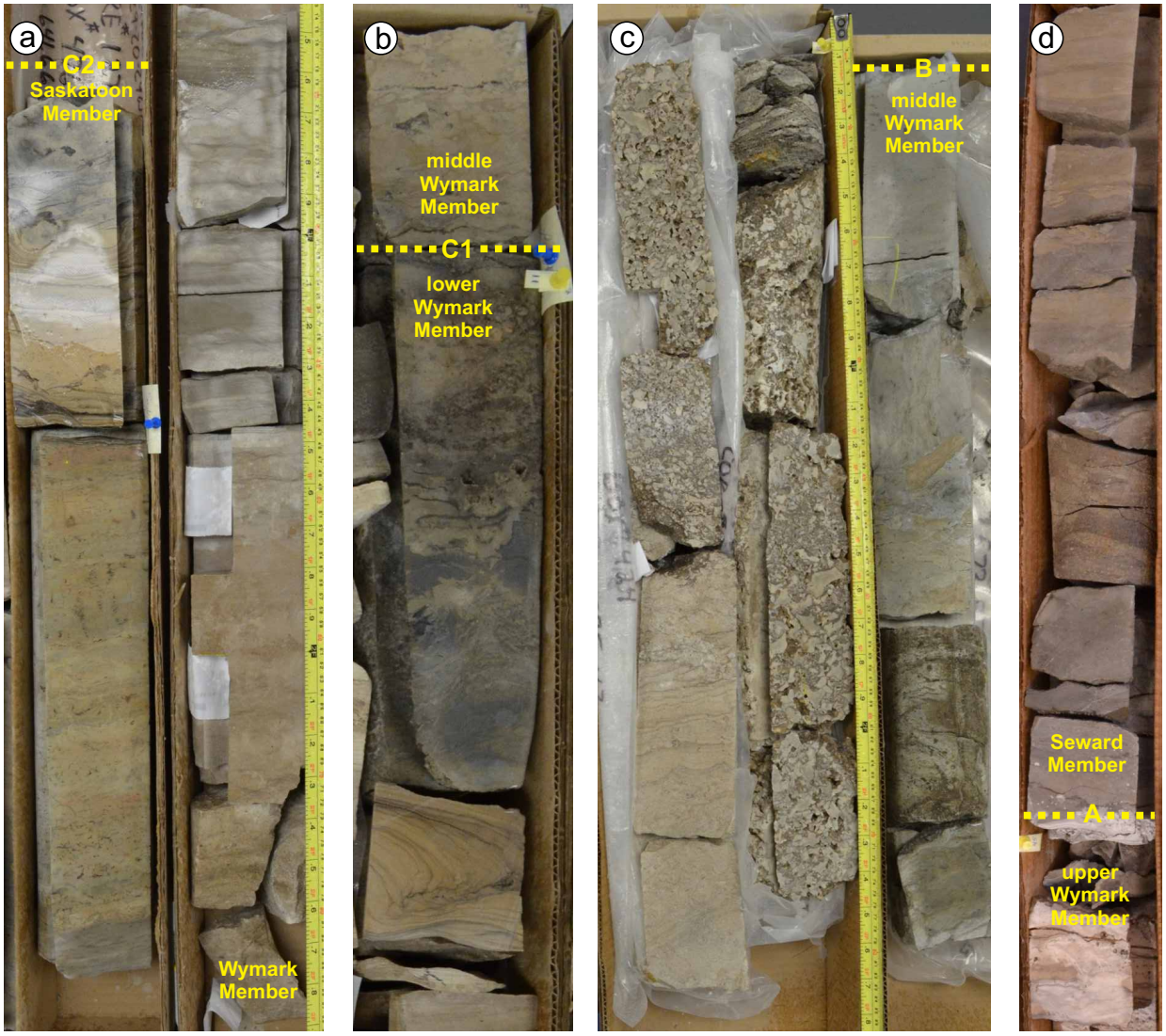

Figure GS2018-11-5: *Core photographs of key marker beds and contacts within the Manitoba Potash Corporation (MPC) core at 3-29-20-29W1:* ***a)*** *contact between Saskatoon and Wymark members, the C2 marker bed is within the lower Wymark Member;* ***b)*** *contact between lower and middle units of the Wymark Member, C1 marker bed is within the lower unit;* ***c)*** *B marker bed marking the top of the middle Wymark Member;* ***d)*** *contact between the Wymark and Seward members, A marker bed is at the base of the Seward Member. Core is 8 cm wide.*

The A marker bed is shale to argillaceous lime mudstone to dolomudstone (Figure GS2018-11-5d).

Seward Member

In the MPC core, the Seward Member is 40.32 m thick, with a lower contact at the base of the A marker bed and a conformable upper contact with limestones of the lower member of the Birdbear Formation. The Flat Lake Evaporite is not present in this core. The Seward Member is dominated by alternating intervals of 1) burrow-mottled to wavy-laminated, argillaceous lime mudstone to fossiliferous wackestone, with fragments of brachiopods, gastropods and corals; and 2) red-brown to green-grey, laminated to mottled, argillaceous dolomudstone to shale, which is locally brecciated. Fossiliferous floatstone, oncoid rudstone-floatstone and microbial laminite occur in the lower 2 m of the member. The upper 5.22 m is the Seward shale, a red-brown argillaceous dolomudstone with a characteristic high gamma-ray log signature (Figure GS2018-11-2).

Lithofacies associations

Previous sedimentological studies of the Duperow Formation in southwestern Manitoba have recognized a variety of carbonate and evaporite lithofacies that are interpreted to have been deposited in peritidal environments in an arid, interior platform (Eggie, 2012; Eggie et al., 2012; Bates, 2016; Bates et al., 2016). These litho-

facies are grouped into 1) subtidal, 2) intertidal and 3) supratidal/sabkha lithofacies associations. They form metre- to decametre-scale, shallowing-upward cycles.

Preliminary lithofacies analysis of the Duperow Formation in the MPC core indicates that the lithofacies framework developed by previous studies can also be applied to this core (Figure GS2018-11-2). The subtidal lithofacies association in the MPC core is dominated by fossiliferous wackestone-packstone to floatstone-framestone, with abundant stromatoporoids and corals and nodular packstone (Figure GS2018-11-6a–c). The intertidal lithofacies association consists mainly of wavy-laminated to burrow-mottled lime mudstone-dolomudstone to wackestone (Figure GS2018-11-6d). The supratidal/sabkha lithofacies association is composed mainly of planar-laminated dolomudstone and shale (Figure GS2018-11-6e, f). Anhydrite laminae and beds are rare, which is in contrast to the supratidal/sabkha lithofacies association present in other Duperow Formation cores, as described by Eggie (2012) and Bates (2016). Metre-scale, shallowing-upward cycles are recognized in all members of the Duperow Formation. Full cycles have the basal, subtidal lithofacies association that is overlain by the intertidal lithofacies association and the supratidal/sabkha lithofacies association, but many cycles are incomplete.

Oil shows

The Duperow Formation, which is stratigraphically equivalent to the prolific oil-producing Leduc Formation in Alberta, has oil production throughout the Elk Point Basin, including Saskatchewan, North Dakota and Montana. Live oil staining was observed in all three members of the Duperow Formation in Manitoba, as documented in Bates (2016). In the MPC core, the best oil shows occur in the upper beds of the lower Wymark Member and throughout the middle Wymark Member, and minor oil shows were observed in the upper Wymark Member and the lowermost beds of the Seward Member (Figure GS2018-11-7). While no oil staining was observed in the Saskatoon Member, the medium brown colouration of the rocks may have masked the staining, and no ultraviolet (UV) fluorescent tests were conducted on this member. The oil shows in the other members in the MPC core vary from brown spotty staining that fluoresces under UV light; to bituminous blebs and fracture coatings that produce a streaming white cut when dissolved in acetone and viewed under UV light; to mudstone laminae that commonly produce a streaming milky white cut in acetone under UV light.

Much of the core, particularly the limestone intervals, glow light yellow when viewed under UV light, which made identification of distinct oil staining challenging. It is uncertain if this UV fluorescence is due to mineralogy or petroleum, given the extent and consistency of UV fluorescence commonly observed on the core, particularly in the Wymark Member. Fresh samples were taken for UV testing in order to mitigate possible drilling mud contamination. Drilling records indicate no petroleum-based drilling muds were used during the drilling of the upper 700 m of this well (which includes the Duperow Formation); diesel was added to the drilling mud only below 700 m in anticipation of the salt sections expected at deeper depths.

Rock-Eval 6 results

Laminae and thin beds of dark brown, argillaceous lime mudstone are present throughout the Duperow Formation in the MPC core. Select samples from the Saskatoon and Wymark members (depths between 587.18 and 647.05 m) were collected for Rock-Eval 6 analysis to help characterize the organic matter and source rock potential of these laminae and beds; the results are listed in Table GS2018-11-2. Most of the samples have total organic carbon (TOC) values between 0.5 and 1.0 wt. %, which indicate good source rock generative potential. However, one sample (106-16-3884-587.18) from the middle Wymark Member has a TOC of 4.23 wt. %, indicating excellent source rock potential. The maximum temperature (Tmax) values for all the samples fall just below the oil window threshold of 435°C, indicating the rocks are slightly thermally immature. Kerogen type was determined by comparing the hydrogen index (HI) and oxygen index (OI) values, with most samples falling between type 2 (oil prone) and type 3 (gas prone) kerogens. However, two samples (106-16-3384-587.18 and 106-16-3384-608.09), both from the middle Wymark Member, have low OI and high HI values typical of type 2 kerogens (Peters, 1986).

Despite the thermal immaturity of the samples, some of these organic-rich beds have a halo of oil staining in the adjacent fossiliferous wackestone-packstone. This suggests localized hydrocarbon migration out of the argillaceous lime mudstones and the potential for an unconventional resource, where the source and the reservoir beds occur together.

Fractures and fluid flow

Fractures were common and prominent through the MPC core. The Wymark and Seward members have abundant long vertical fractures (Figure GS2018-11-7), which are commonly open and rarely completely or partially sealed with calcite or a bituminous residue. In addition,

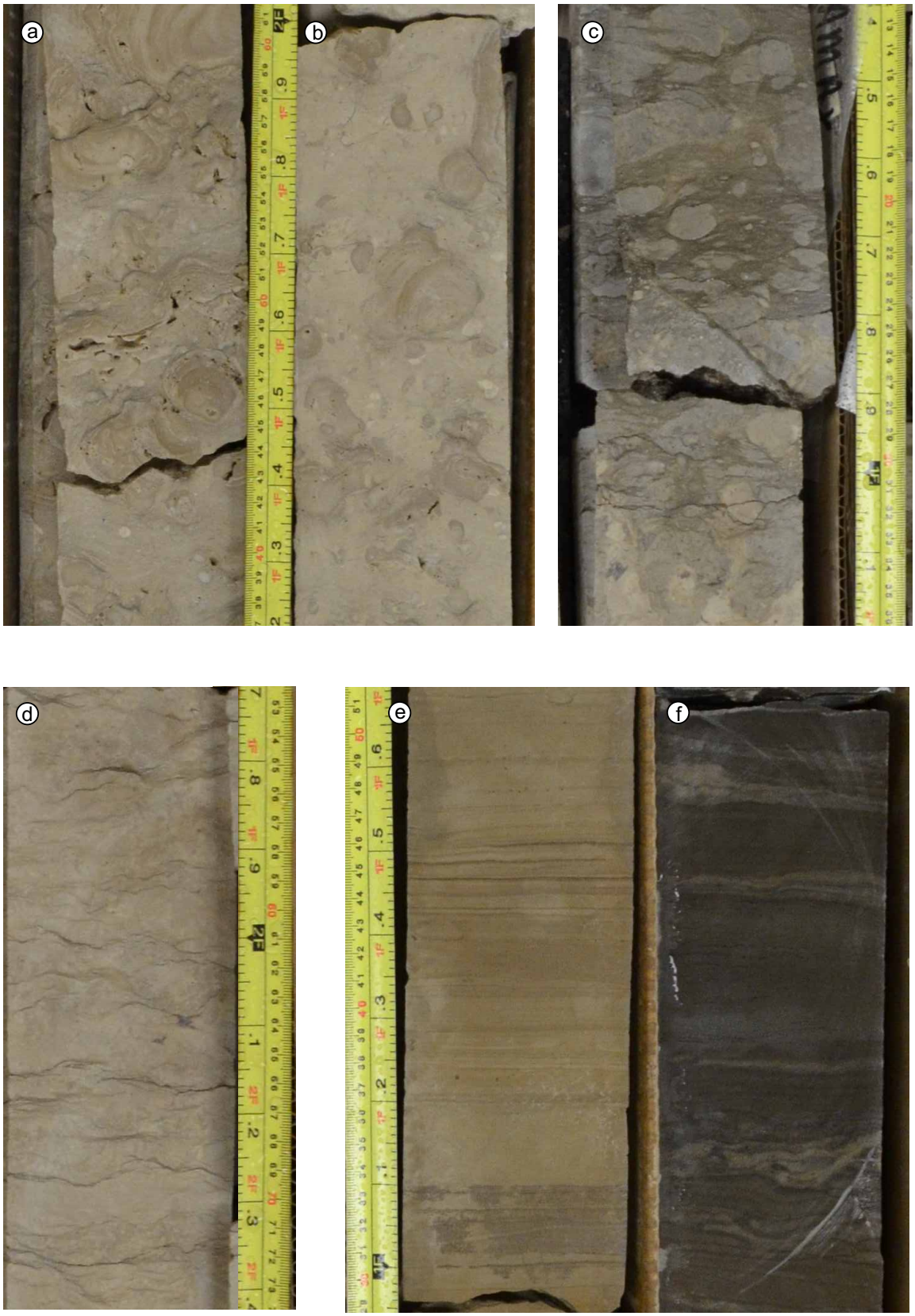

Figure GS2018-11-6: *Core photographs from the Manitoba Potash Corporation (MPC) core at 3-29-20-29W1 showing examples of the most dominant lithofacies within each lithofacies association:* ***a, b)*** *subtidal stromatoporoid floatstone at 624.79 and 624.09 m, respectively;* ***c)*** *subtidal nodular packstone at 635.40 m;* ***d)*** *intertidal, wavy-laminated to burrow-mottled mudstone to wackestone at 583.97 m;* ***e)*** *supratidal/sabkha planar-laminated dolomudstone at 652.94 m; and* ***f)*** *supratidal/sabkha interbedded dolomudstone and anhydrite at 653.64 m.*

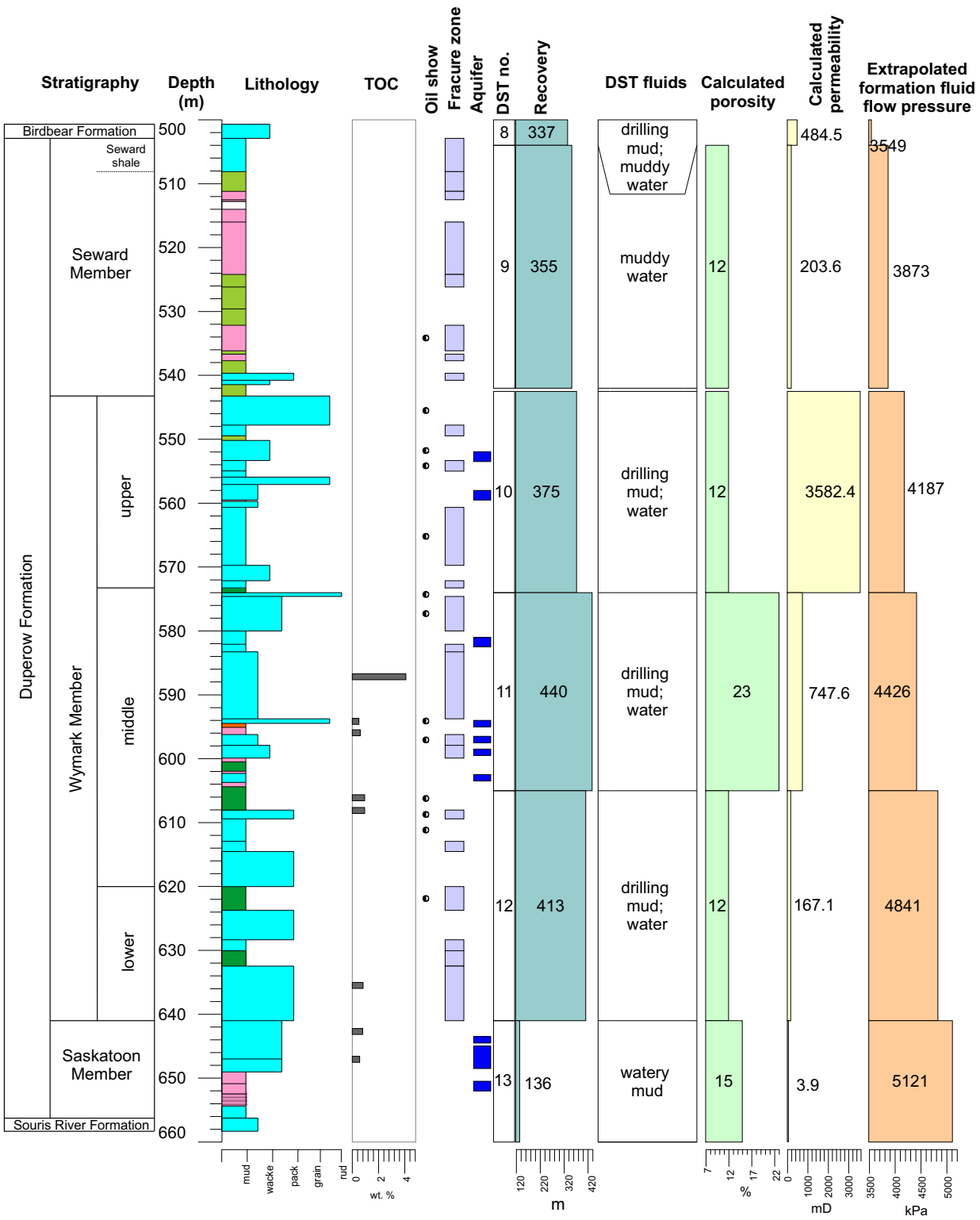

Figure GS2018-11-7: *Core log for the Duperow Formation in the Manitoba Potash Corporation (MPC) core at 3-29-20-29W1 with tracks for the stratigraphy, lithology, total organic carbon, oil shows, fracture zones, aquifer zones and drill-stem test (DST) results, including DST number, recovery, fluids, calculated porosity, calculated permeability and extrapolated formation fluid flow pressure. See Figure GS2018-11-3 for lithology legend. Abbreviations: grain, grainstone; kPa, kilopascal; mD, millidarcy; mud, mudstone; pack, packstone; rud, rudstone; TOC, total organic carbon; wacke, wackestone.*

Table GS2018-11-2: Rock-Eval 6 results for samples from the Manitoba Potash Corporation (MPC) core at 3-29-20-29W1. Abbreviations: HI, hydrogen index (mg hydrocarbons/g C_{org}; ratio of S2/TOC); MinC, mineral carbon; OI, oxygen index (mg CO_2/g C_{org}; ratio of S3/TOC); PC, pyrolyzed carbon; PI, production index (S1/(S1+S2); RC, residual carbon; S1, hydrocarbons thermally distilled from 1 g of rock; S2, hydrocarbons generated by pyrolytic degradation of kerogen from 1 g of rock; S3, milligrams of CO_2 generated from organic source in 1 g of rock; S3CO, milligrams of CO generated from organic source from 1 g of rock; Tmax, maximum temperature; TOC, total organic carbon.

Sample number	Depth (m)	TOC (wt. %)	Tmax (°C)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	S3CO (mg/g)	MinC (wt. %)	PC (wt. %)	RC (wt. %)	HI	OI	PI
106-16-3884-587.18	587.18	4.23	422	0.22	9.54	1.38	0.30	7.6	0.89	3.34	226	33	0.02
106-16-3884-594.15	594.15	0.52	414	0.01	0.38	0.35	0.05	7.3	0.05	0.47	73	67	0.04
106-16-3884-595.94	595.94	0.63	418	0.03	2.09	0.38	0.07	8.1	0.20	0.43	332	60	0.01
106-16-3884-606.12	606.12	0.98	428	0.04	1.74	0.62	0.11	1.4	0.18	0.80	178	63	0.02
106-16-3884-608.09	608.09	0.97	422	0.06	4.07	0.34	0.03	10.8	0.37	0.60	420	35	0.02
106-16-3884-635.50	635.50	0.84	426	0.04	1.38	0.66	0.11	8.7	0.15	0.69	164	79	0.03
106-16-3884-642.70	642.70	0.82	431	0.07	1.13	0.81	0.05	7.3	0.13	0.69	138	99	0.06
106-16-3884-647.05	647.05	0.58	431	0.05	1.47	0.44	0.09	10.3	0.15	0.43	253	76	0.03

zones of rubbly core are common and suggestive of intervals with extreme fracturing. No fractures were observed in the Saskatoon Member.

Six drill-stem tests (DSTs) were conducted in the Duperow Formation in this well. The DSTs had very good fluid recovery, although it consisted mostly of muddy water, indicating that this formation has very high fluid flows, as well as moderate to good porosity and variable permeability, and as expected, increased formation fluid flow pressure with depth (Figure GS2018-11-7). During drilling, there were 10 separate aquifers with large and steady fluid flows encountered, occurring mainly in vuggy and fractured packstone to floatstone beds, and locally in porous wackestone beds. In the Saskatoon Member, aquifer zones occurred in limestones between anhydrite-rich beds. The highest fluid recovery was in the middle Wymark Member, which has five high flow aquifers, whereas the lowest was in the Saskatoon Member despite it having three high flow aquifer zones. The DST results in the Saskatoon Member indicate moderate to good porosity but low permeability, suggesting that high formation pressure is likely the driver for higher fluid flow. Given the occurrence of three aquifers in this member, it is possible that the member contains fractures and that the MPC core simply did not intersect the fractures.

Conclusions

The Duperow Formation members preserved in this core, from bottom to top, are the Saskatoon, Wymark and Seward members. Preliminary lithofacies analysis indicates that the subtidal, intertidal and supratidal/sabkha lithofacies associations recognized in other studies of the Duperow Formation in Manitoba are also present in the MPC core.

The preliminary findings of this study indicate that oil has migrated through the formation (conventional reservoir model), but also supports the potential for a self-sourcing capacity (unconventional reservoir model). High fluid flows measured throughout the formation provide the hydrokinetic energy required for fluid migration and trapping. The Rock-Eval results for samples of organic-rich lime mudstones indicate good oil generative potential but fall just below the oil generation window. These results are in agreement with those of Bates et al. (2016) and support the idea that the Duperow Formation may be within the oil window in southwestern Manitoba, closer to the Pierson and Waskada oil fields, and could be both a source and reservoir rock.

Future work

Future work is expected to address stratigraphic correlation of the Duperow Formation in the MPC core with other cores in the Elk Point Basin. Detailed petrographic and geochemical studies are ongoing at the University of Manitoba.

Economic considerations

The Duperow Formation is an oil-producing horizon in Saskatchewan, North Dakota and Montana, and recent studies suggest there is moderate potential in southwestern Manitoba as well. The ability to view the entire Duperow Formation in the continuous MPC core provides much needed clarity on its stratigraphy, lithofacies architecture and oil potential. Preliminary findings from this study support that the Duperow Formation in Manitoba does have oil potential, both as a conventional and unconventional oil target.

Acknowledgments

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