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PETROLEUM CONFERENCE
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Dr. Don Kent Core Workshop Volume

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Special Publication Number 29

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[1] Saskatchewan Geological Survey; [2] Hummingbird Energy; [3] Lake Geological Consulting Inc.; [4] North Dakota Geological Survey; [5] University of Regina

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Lithofacies Characterization and Depositional Model of the Ordovician Red River Formation, Williston Basin, Southeastern Saskatchewan: New Ideas for Petroleum Exploration

Ashlee Thomas [1,2] and Hairuo Qing [2]*

[1] Saskatchewan Geological Survey, [2] University of Regina
* Corresponding author: Ashlee.Thomas@gov.sk.ca

The carbonate reservoirs of the Ordovician Red River Formation in the Williston Basin of southeastern Saskatchewan first produced oil in 1958, with the height of exploration and development spanning from the mid-1990s to 2000. Oil has been produced almost exclusively from structural traps (Potter and St. Onge, 1991; Kreis and Kent, 2000; Pu and Qing, 2003; Potter, 2006), and, since the early 2000s, the petroleum targets have been primarily shallower (*e.g.*, Mississippian Frobisher Beds). The theoretical oil generated from Red River source rocks is calculated at 95.4 x 10^6 m³ (600 x 10^6 barrels (bbls); Winnipeg Formation; Dow, 1974) or 31.8 x 10^6 m³ (200 x 10^5 bbls; Red River Formation kukersites; Osadetz and Haidl, 1989; Osadetz *et al.*, 1989); the amount of oil produced from the Red River in Saskatchewan's subsurface has been calculated at 4.87 x 10^6 m³ (30.6 x 10^6 bbls; calculated in geoSCOUT from the Ministry of Energy and Resources' Integrated Resource Information System (IRIS) data). These data suggest that there are significant volumes of oil remaining in the subsurface. That, coupled with the hiatus of Red River exploration and Saskatchewan's goal of increasing oil production to 600 000 bbls per day by 2030, has warranted a re-investigation into the Red River Formation.

The study area encompasses an area southeast of Regina and northeast of Weyburn, and extends from Township 8, Range 5 west of the Second Meridian (Tp. 8, Rge. 5W2M) to Tp. 16, Rge. 15W2M, covering approximately 99 townships and 9229 km². Wireline log analysis (143 wells), description of 63 cored intervals, petrography (50 thin sections) and mapping facilitated the identification of nine lithofacies and four facies associations. Collectively, these facies are interpreted to have been deposited as part of a low-energy muddy tidal flat system. Evaluation of reservoir characteristics (*e.g.*, porosity, permeability, oil saturations) suggests that lithofacies 3, 4, 8 and 9 have the greatest potential as oil reservoirs.

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Insights into the Tight Oil Plays of the Upper Devonian Torquay Formation in Southeastern Saskatchewan, Canada

Chao Yang [1]*

[1] Saskatchewan Geological Survey
* Chao.Yang@gov.sk.ca

This paper summarizes the stratigraphy, lithofacies, oil reservoir and production characteristics of the Upper Devonian Torquay Formation in southeastern Saskatchewan, gleaned from examination of geophysical well logs from over 2000 wells, cores from 18 wells, 30 thin sections from 9 wells and 11 X-ray diffraction (XRD) analyses from 2 wells. The study area encompasses Townships 1 to 15, Ranges 30 west of the First Meridian to 30 west of the Second Meridian.

Stratigraphically, the Torquay Formation overlies the Birdbear Formation and unconformably underlies the Big Valley and Bakken formations (Appendix 1). The Torquay Formation is subdivided into six units, unit 1 to unit 6 in ascending order, which can be correlated across much of the Williston Basin. These subdivisions, defined by examination of geophysical well logs and cores, provide the stratigraphic framework for mapping all units in this study. All six units can be traced throughout much of the study area, except on the eastern side, where units 5 and 6 are absent (Yang, 2018).

Seven distinct recurring lithofacies were identified in this study. Lithofacies 2 (F2) is the major reservoir rock for the Torquay oil play. Intercrystalline and intergranular porosities were created during early-stage dolomite recrystallization impacted by the eolian grain sizes. These porosities were reduced by late-stage dolomite recrystallization and overgrowth of quartz.

The Torquay Formation in southeastern Saskatchewan is interpreted as a lacustrine, mixed carbonate-siliciclastic, fine-grained deposit. This interpretation is based on the lack of fauna; presence of massive, oxidized red-brown deposits; reported nonmarine isotopic signatures; and type III kerogen. The Torquay Formation is dominated by evaporitic dolomite with no petrographic evidence of replacement of a precursor carbonate sediment, with lesser amounts of fine-grained siliciclastic sediments and even less abundant anhydrite. The study suggests a depositional model of storm-influenced saline lake deposits (Yang, 2020).

In Saskatchewan, the average oil production from the Torquay Formation, which is a tight oil play, has increased sharply, from 110 m^3/day (700 barrels/day (bbl/d)) in 2006 to nearly 1667 m^3/day (10 486 bbl/d) in 2018. This increase is ascribed to the application of horizontal drilling techniques, coupled with multistage hydraulic fracturing. Productive wells show a predominant horizontal leg length of 1200 to 1600 m. The current oil wells are concentrated in two producing areas: the Torquay and North Portal areas, along the U.S. border; and the Ryerson area, near the Saskatchewan–Manitoba border.

In the area along the U.S. border, a total of 450 oil wells in the Torquay Formation produced about 3 x 10^6 m^3 (18.6 million barrels (MMbbl)) of oil up to the end of 2018, from depths of 2200 to 2400 m. Of these, 405 are fracked horizontal wells. The reservoir rocks are dominantly silty dolostone, with porosities mostly ranging from 3 to 10% and very low permeabilities, ranging from 0.01 to 1 millidarcies (mD). Here, the Big Valley Formation is absent, placing the Torquay tight reservoirs directly beneath and in contact with Lower Bakken shales that, in this area, are mature, based on reported T_{max} and vitrinite reflectance (%Ro) values up to 435°C and 0.68, respectively. Oil generated from the Lower Bakken source rocks has most likely migrated vertically down from the shales into the top of the Torquay Formation.

In the area near the Manitoba border, a total of 270 oil wells produce from the Torquay, of which 130 are fracked horizontal wells producing from depths of 1000 to 1200 m. These wells have produced a total of 1.4 x 10^6 m^3 (8.7 MMbbl) of oil up to the end of 2018. Absent from this area are most of the Middle Bakken, all of the Lower Bakken shale, the Big Valley Formation and units 5 and 6 of the Torquay Formation, so that strata of Unit 4 of the Torquay are directly overlain by the upper Middle Bakken. Oil is produced from the dolomitic siltstone to very fine sandstone interbedded with dolostone. The reservoirs have good porosities, mostly from 10 to 18%, and low permeabilities, from 0.1 to 10 mD. Because the Bakken shale is not mature in this area, lateral, updip oil migration from the south and southwest was necessary to accumulate oil at the Torquay subcrop, where long-term exposure improved porosity. The subcrop was sealed by the Upper Bakken shale in an updip direction.

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New Rules: Recognizing Sea Level Drops on Highstand Carbonate Platform Shorelines

John H. Lake [1]*

[1] Lake Geological Services Inc.
* lakegeol@sasktel.net

The popular *Real Time with Bill Maher* HBO TV show has a segment at the end which he calls "New Rules" where he presents new viewpoints on old topics. A random collection of laws/editorials which define the new norms of our society. New Rules also apply to the way we interpret sedimentary structures at the end of depositional cycles in carbonate rocks. In my career of logging core I have realized that deviation from normal facies distributions through progressive sea level rise/fall or stillstand are recorded in the rock record. These deviations often result in hydrocarbons being trapped. Examples are chosen from the tectonically very stable Upper Devonian Birdbear, Duperow and Dawson Bay formations in southeast Saskatchewan.

New Rules applies to any sequence of rocks in which there is exposure or erosion before all of the facies of the Highstand Shoreline are deposited. The inspiration for this core presentation came from work by Ed Mathison on the Cretaceous Viking Formation in southwest Saskatchewan in which only a portion of the Lowstand Tidal Delta is preserved in stacked deltaic deposits (Mathison, 2014) combined with a Dr. Murray Gingras' Modern Willipa Bay Clastics Field Trip for the Saskatchewan Geological Society (Gingras, August 18-22, 2012). Murray emphasized the lateral facies changes in ichnology across the modern tidal flat.

An ideal tidal flat on a highstand shoreline should include an outer sequence of sediments dominated by shelter burrows being buried by lower energy sediments dominated by grazing burrows. Any deviation from this sequence of events is subject to the "New Rules" model and is likely to create exposure, porosity in carbonates and result in hydrocarbon-trapping potential. The Upper Devonian Duperow Formation from 13-22-17-30W1M Sylvite Ste. Marthe preserves inner tidal flat over outer tidal flat and what happens in response to a constant sea level. In contrast, the Ordovician Red River Formation example on Ashlee Thomas' core display shows tidal flat sediments are susceptible to erosion and exposure in response to a sea level drop following deposition. Turns out the preservation of the entire tidal flat sequence is the exception rather than the norm. Dubois *et al.* (2006) demonstrated that the inner tidal flat facies has lower permeability than the marine or land environments and is the mechanism for trapping hydrocarbons.

Marine transgressions over sediments deposited at sea level are usually destructive and tend to distribute the older sediments both landward and seaward in response to wave and tidal action (*i.e.*, Chandelier Island barrier bar east of the Mississippi River Delta, modern Gulf of Mexico). The Upper Devonian examples were chosen because of the stable nature of the basin during deposition with minimal effects of sea level change from glaciation and tectonic influences.

Conclusions

1) New Rules lets you see how extreme the sea level has fluctuated at the end of the Highstand Systems Tract by interpreting the extent of erosion along the shoreline
2) Fluctuations in sea level are controlled by glaciations and basin tectonics. The significance of Sequence Stratigraphy is to identify the erosional unconformities and shifts in facies deposition to identify new drilling targets. (Oil is trapped along shorelines and if the shoreline moves you have to know where it went in geographical terms). The inner tidal flat acts as the trap for hydrocarbons. The models for deposition are critical for understanding these lateral shifts. The present is not necessarily the key to the past as we do not have any good epeiric sea analogues because the water depths were an order of magnitude shallower than modern examples. Carbonates are deposited in transgressive environments of deposition (Sven Egenhoff, personal communication).

Paleozoic Reef Development

My ideas of Paleozoic Reef development changed after studying the sedimentology of the Middle Devonian Sierra Reef (Collins and Lake, 1988). Growth of reef-building organisms was limited to the fringes of the reef and the interior is a tidal flat setting. The actual living reef is a narrow fringe along the margin of the buildup and extends to the limit of the photic zone. The extent of this reef growth is dependent upon the angle of the slope. The Sierra Reef grew to a height of 700 ft/230 m.

Previous models have been interpreted from subsurface correlations of cores but the modern is the key to the past. Various carbonate invertebrates have been proposed as forereef and backreef indicators based on these hypothetical models. The problem is in interpreting the reef interior as a shallow tidal flat facies. The Mosaic Esterhazy 4-1-19-1W2M core example has robust bulbous stromatoporoid growth and is capped by tidal flat facies muds and calcareous algae-filled tidal channel (also part of the reef). Solitary rugose corals and amphipora sponges existed in these reef-top tidal channels. The John Pennekamp State Marine Park south of Miami, Florida, is a good modern analogue. A boat takes you out to the reef along a tidal channel lined with mangroves. The inner reef grows in one metre of water at low tide. The colonial corals are impressive but most of the sediment is supplied by calcareous blue-green algae platelets (Halimeda and Penicillis). The post-Devonian mass extinction makes it very difficult to recognize reef development as we rely on corals and stromatoporoids to recognize reef development. Only the calcareous algae facies survived the mass extinction. Syringopora colonial corals survived into the lower Mississippian but did not build wave-resistant reefs and were restricted to growing in tidal channels.

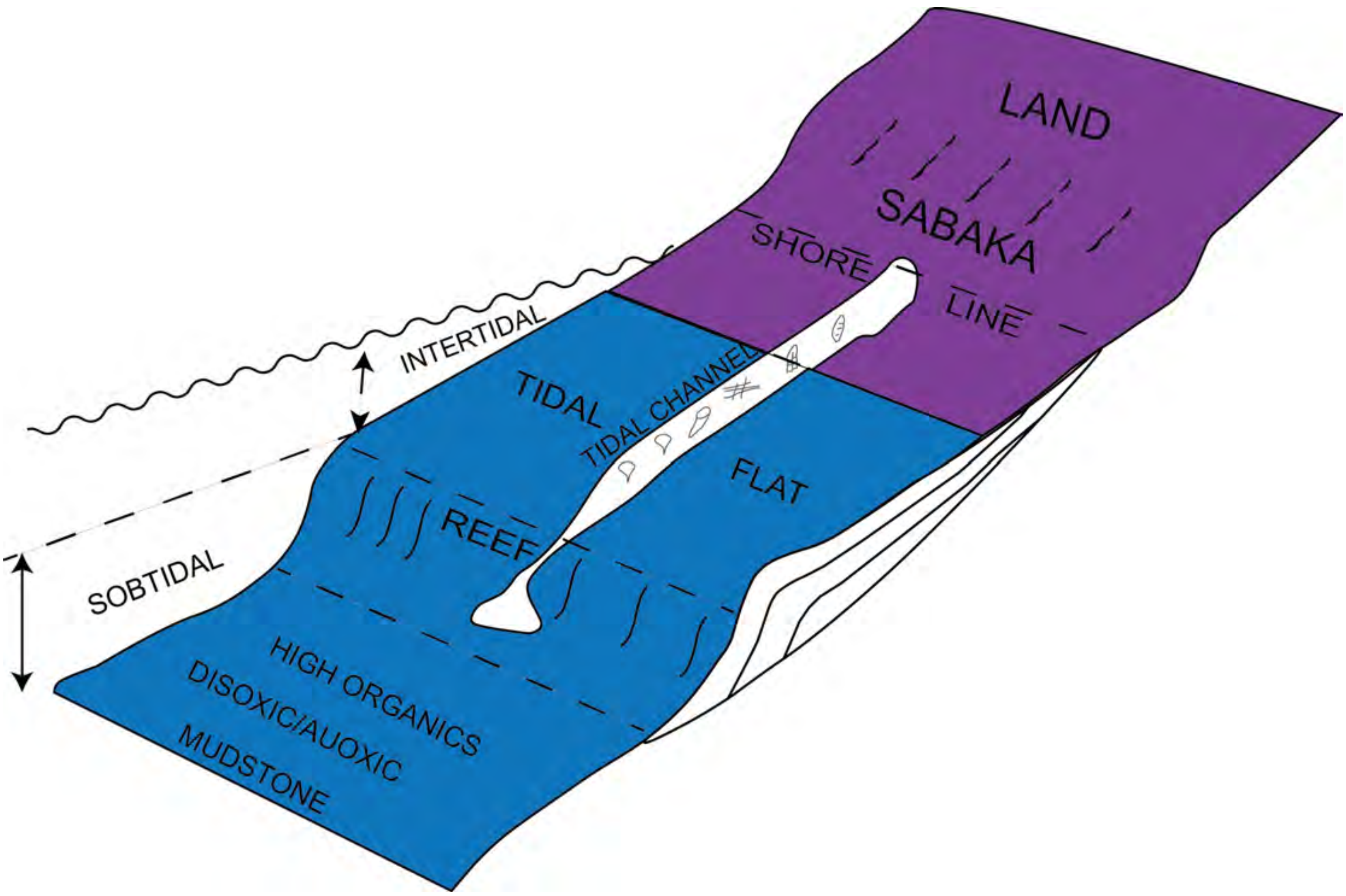
LAND
SABAKA
SHORE LINE
INTERTIDAL
TIDAL
TIDAL CHANNEL
FLAT
REEF
SOBTIDAL
HIGH ORGANICS
DISOXIC/AUOXIC
MUDSTONE

Figure 1.

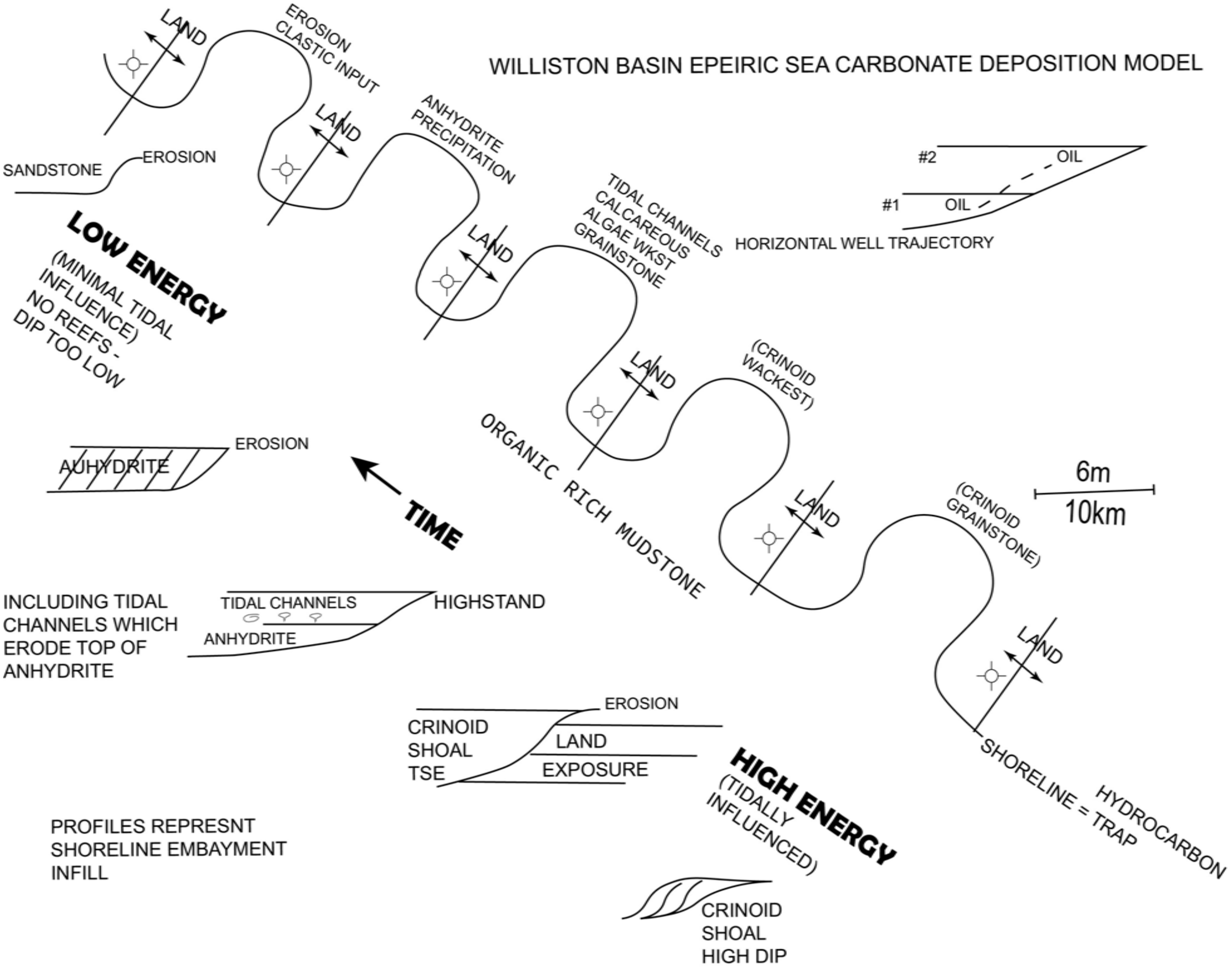
WILLISTON BASIN EPEIRIC SEA CARBONATE DEPOSITION MODEL
LAND
EROSION CLASTIC INPUT
SANDSTONE
EROSION
LAND
ANHYDRITE PRECIPITATION
LAND
TIDAL CHANNELS CALCAREOUS ALGAE WKST GRAINSTONE
#2
OIL
#1
OIL
HORIZONTAL WELL TRAJECTORY
LOW ENERGY
(MINIMAL TIDAL INFLUENCE)
NO REEFS - DIP TOO LOW
LAND
(CRINOID WACKEST)
ORGANIC RICH MUDSTONE
AUHYDRITE
EROSION
TIME
LAND
(CRINOID GRAINSTONE)
6m
10km
INCLUDING TIDAL CHANNELS WHICH ERODE TOP OF ANHYDRITE
TIDAL CHANNELS
ANHYDRITE
HIGHSTAND
LAND
EROSION
CRINOID SHOAL TSE
LAND
EXPOSURE
HIGH ENERGY
(TIDALLY INFLUENCED)
SHORELINE = TRAP
HYDROCARBON
PROFILES REPRESNT SHORELINE EMBAYMENT INFILL
CRINOID SHOAL HIGH DIP

Figure 2.

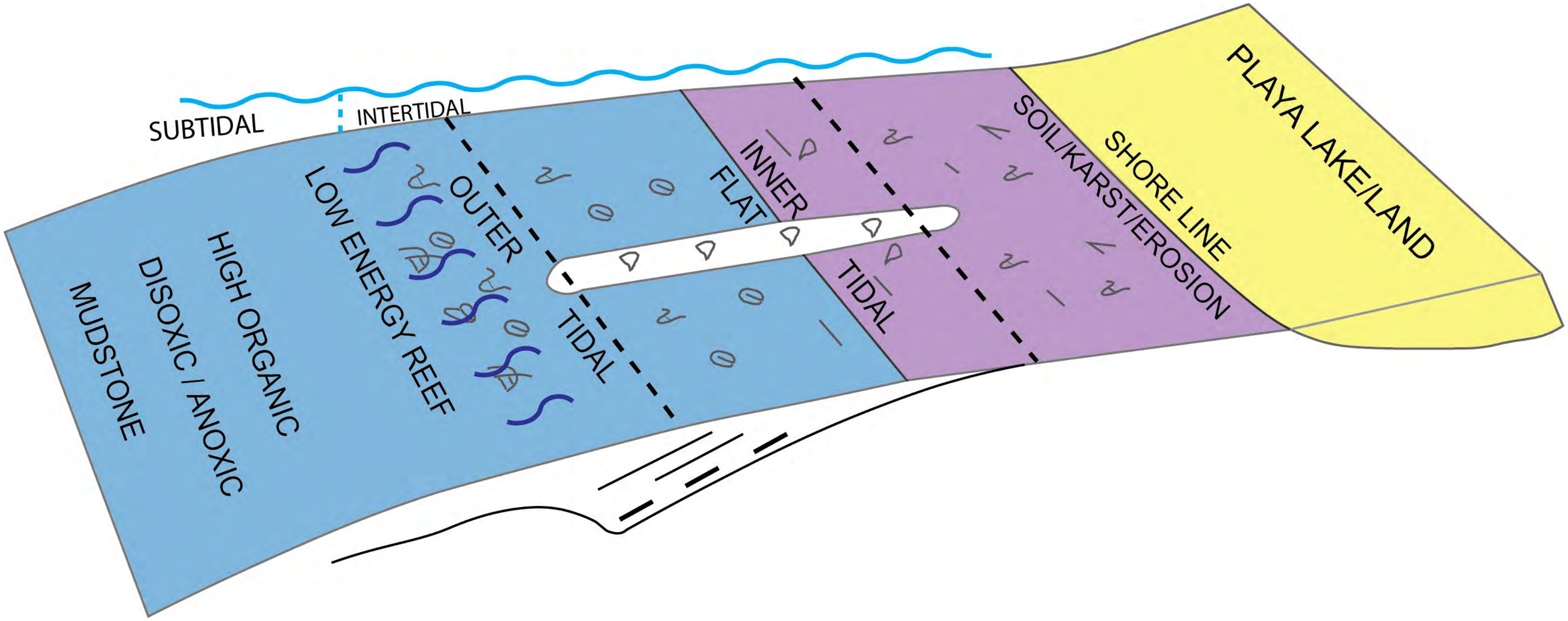
SUBTIDAL
INTERTIDAL
MUDSTONE
DISOXIC / ANOXIC
HIGH ORGANIC
LOW ENERGY REEF
OUTER
TIDAL
FLAT
INNER
TIDAL
SOIL/KARST/EROSION
SHORE LINE
PLAYA LAKE/LAND

Figure 3.

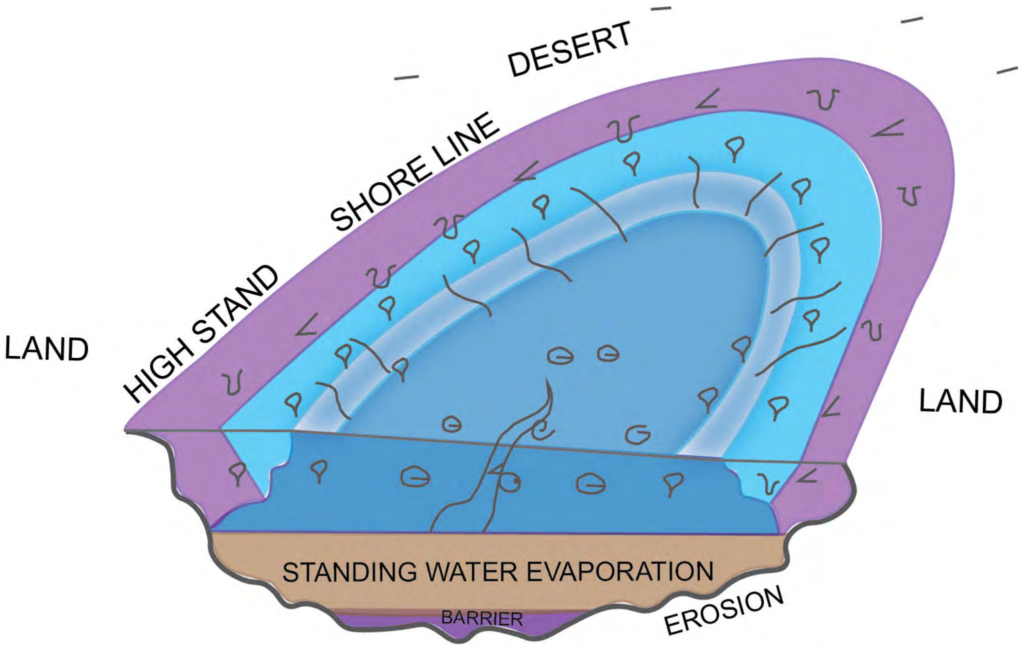

Figure 4.

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Stratigraphy, Sedimentology and Reservoir Characterization of the Upper Devonian–Lower Mississippian Bakken Formation, Southeastern Saskatchewan

Dan Kohlruss [1] and Holly Shoulak [1]*

[1] Saskatchewan Geological Survey
* Corresponding author: Dan.Kohlruss@gov.sk.ca

During the 2000s, southeastern Saskatchewan saw unprecedented land sale and drilling activity associated with the Upper Devonian–Lower Mississippian Bakken Formation oil play, with the Viewfield region being the most intensely developed, mainly using horizontal well technology and multistage fracturing completions. Recently, multi-lateral well technology has been implemented to help extend the life of the Viewfield pool, especially in areas where the main reservoir is thin and multistage fracturing is less effective.

The internal architecture of the Bakken Formation's Middle Member has been mapped and sedimentologically analyzed, resulting in a depositional history and sequence-stratigraphic account. The zone of most interest is the siltstone to fine sandstone, unit A, which represents a shallowing-upward succession deposited as part of a highstand systems tract. Unit A was later eroded and reworked during a falling-stage systems tract and overlain by unit B, which was deposited during both the falling-stage and the following lowstand systems tracts. Unit B sediments were then onlapped by unit C deposits during a subsequent transgression.

In the Viewfield area, oil is primarily trapped within unit A reservoir rocks, just below a regressive surface of marine erosion, and it is also constrained stratigraphically updip, to the northeast, by non-reservoir unit A rocks. The stratigraphic trap has been extensively detailed with a quantitative characterization using critical well-log parameters of the Middle Bakken Member.

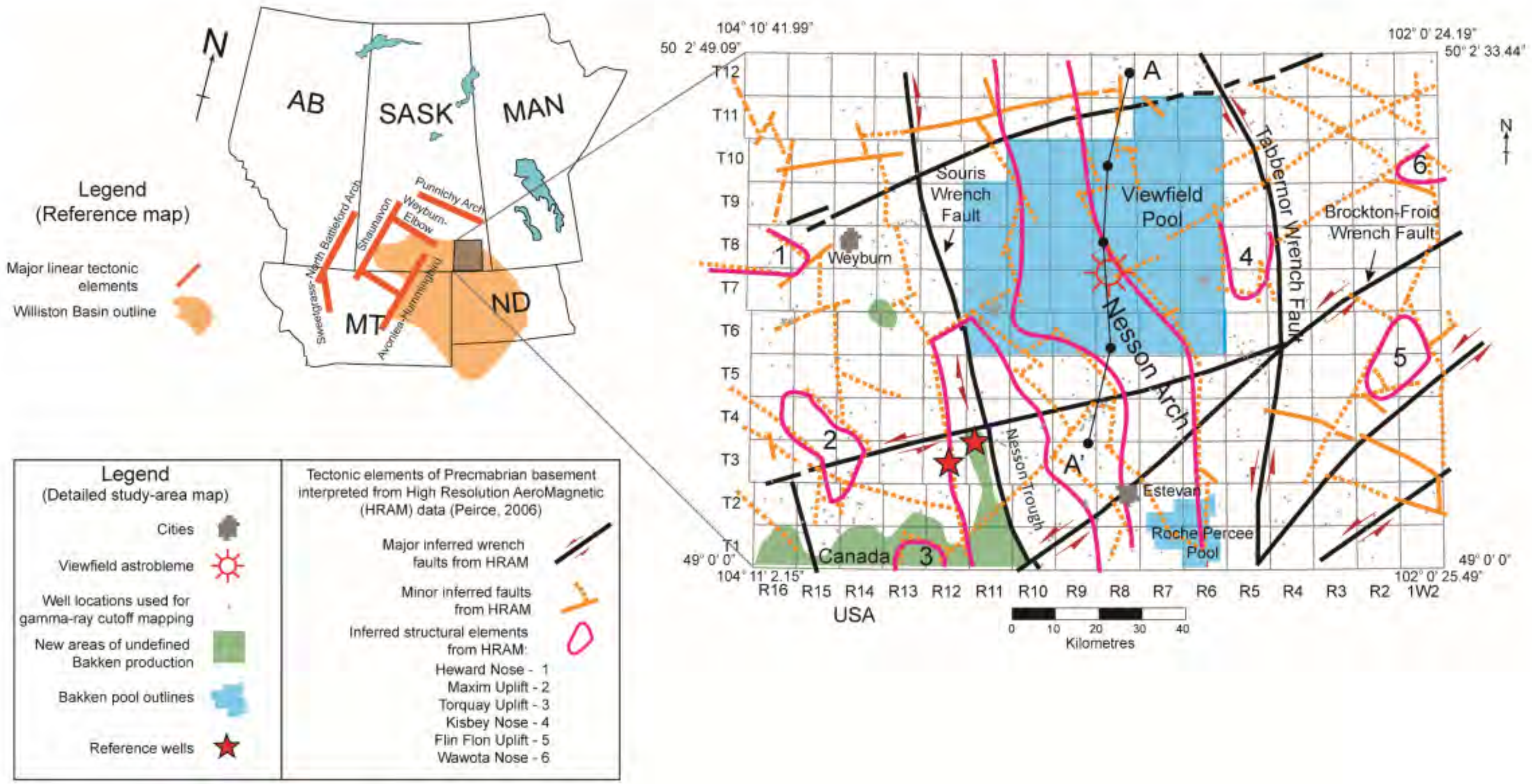

Figure 1 – The location of the study area in southeastern Saskatchewan. The inset reference map (top left) of the prairie provinces and northern United States highlights the location of the study area, the location of the Williston Basin and the major linear tectonic elements constraining the western portion of the basin (Kent and Christopher, 1994). As defined by Peirce (2006), interpretations from high-resolution aeromagnetics (HRAM) represent locations of tectonic elements of the Precambrian basement. The northernmost red star denotes the location of reference well 141/15-31-003-11W2/00; 81D003 used in Figure 3. A–A' delineates the line of the cross-section in Figure 5. Abbreviations on the inset map: AB – Alberta; SASK – Saskatchewan; MAN – Manitoba; MT – Montana; ND – North Dakota. Abbreviations on the study area map: T – Township; R – Range; W2 – west of the Second Meridian. The figure is from Kohlruss (2022).

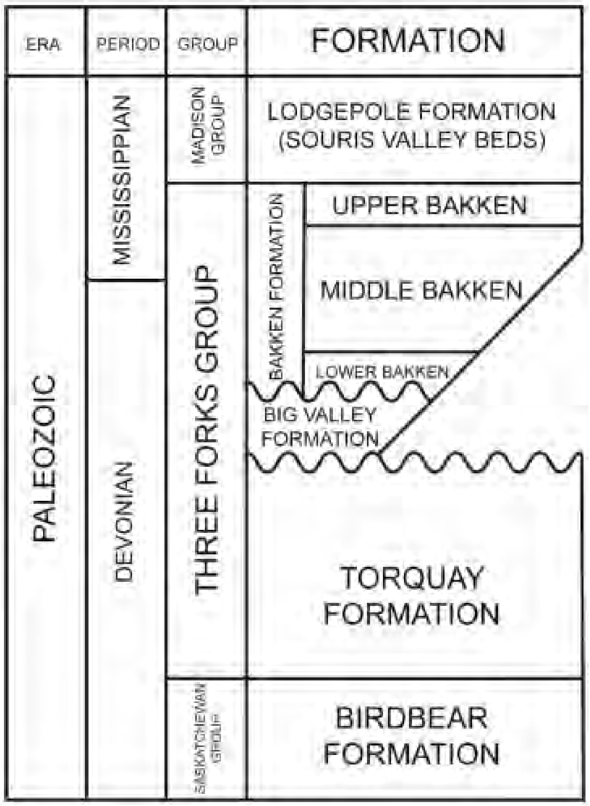

Figure 2 *– A Paleozoic stratigraphic chart for Saskatchewan showing the location of the Bakken Formation (*modified from *Saskatchewan Ministry of Energy and Resources, 2022). Wavy lines separating the Bakken Formation, the Big Valley Formation and the Torquay Formation indicate an unconformity surface. The figure is modified from Kohlruss* et al*. (2021).*

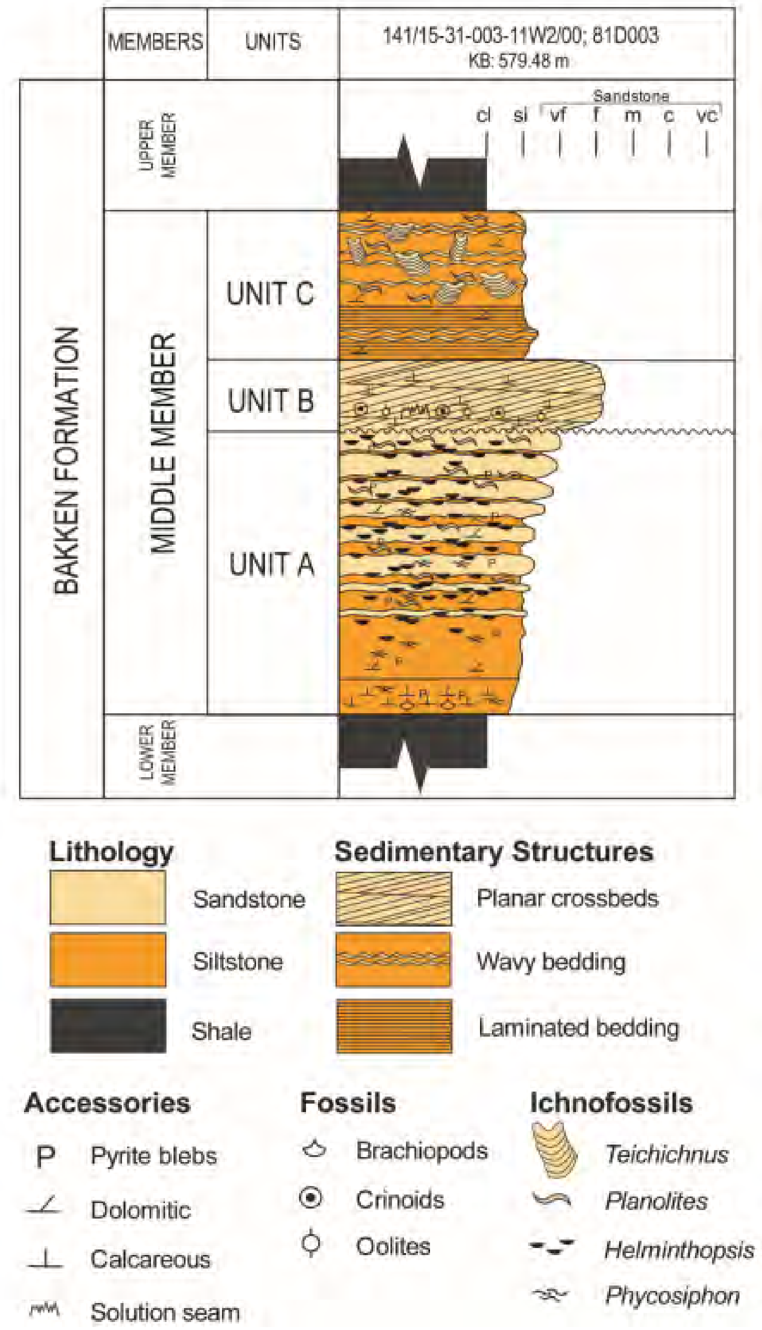

***Figure 3** – An internal stratigraphic chart of the Bakken Formation in well 141/15-31-003-11W2/00; 81D003 (*modified from *Kohlruss and Nickel, 2013). The wavy line separating the lithologies of units A and B represents an erosional surface; unit B was reported to down-cut on this surface, eroding the sandier upper part of unit A. The straight, black lines indicate that unit A's lower contact with the lower member shale is sharp, like unit B's upper contact. KB – kelly bushing; cl – clay; si – silt; vf – very fine; f – fine; m – medium; c – coarse; vc – very coarse.*

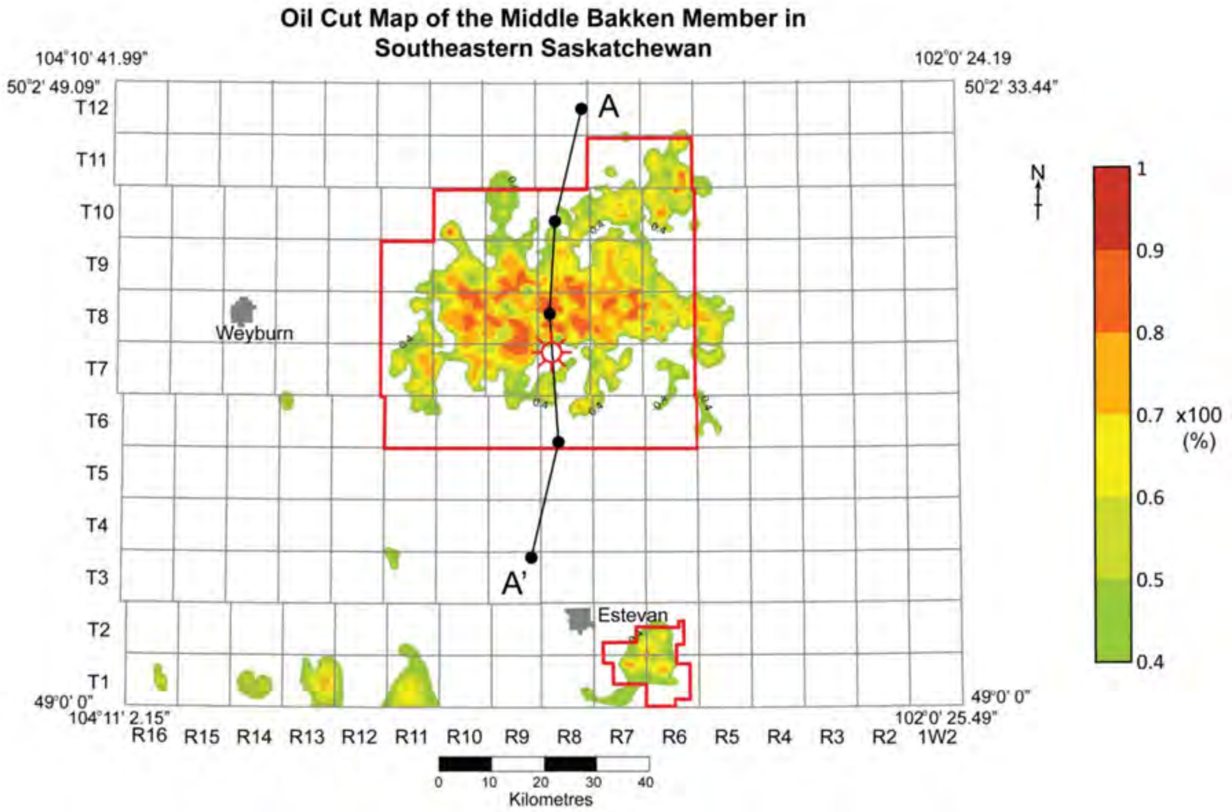

***Figure 4** – An oil-cut map where the* first 90 days of oil production / (first 90 days of oil production + first 90 days of water production) = oil cut*. This ratio was chosen to negate the effects of variations in well length and fracking techniques that would cause variations in production volume. Contours are the* first 90 days of oil / (oil + water) *in 0.10 intervals (10%) from 0.4 to 1 (40% to 100%), as indicated on the scale. Red outlines indicate the Bakken oil-pool boundaries (Rae McClintock, personal communication, 2019). The map is from Kohlruss (2022). T – Township; R – Range; W – west; A–A' – line of cross-section in Figure 5.*

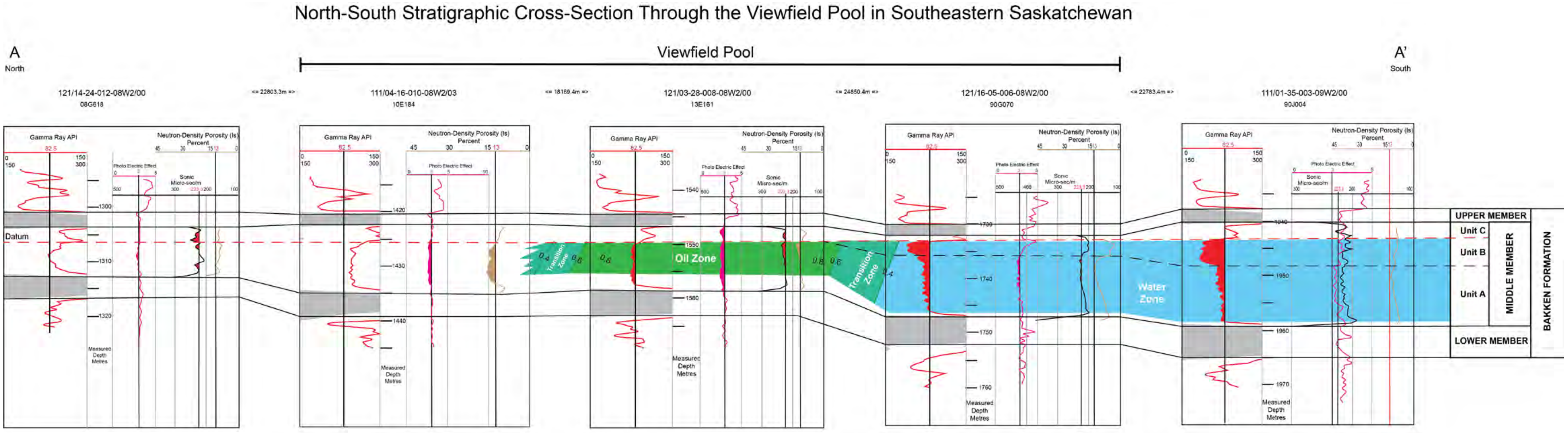

Figure 5 – A north-south stratigraphic cross-section through the Viewfield pool (datum = base of unit C). This cross-section illustrates the increasing thickness of the middle member from north to south and the increase in middle member rocks meeting a ≤82.5 API cutoff criteria as outlined in Kohlruss et al. *(2021), located left of the vertical 82.5 cutoff line and highlighted by red shading. The sonic log is represented in black, and Middle member rocks meeting ≥10% cutoff criteria are also highlighted in red shading. Correspondingly, the cross-section illustrates the decrease in reservoir quality to the north especially in wells 111/04-16-010-08W2/03; 10E184 and 121/14-24-012-08W2/00; 08G618. The stratigraphic trap created by Middle Member rocks is a result of the rocks that read higher than the 82.5 API cutoff. The gradual reduction in reservoir quality to the north also results in a gradual reduction in oil cut, creating a production transition zone as opposed to an abrupt trap. In contrast, the reservoir quality meets the gamma-ray cutoff south and downdip of the Viewfield pool but has low porosity (sonic and neutron-density) and high photoelectric values as well as part of the water zone of the oil column (wells 111/01-35-003-09W2/00; 90J004 and 121/16-05-006-08W2/00; 90G070). Well 121/03-28-008-08W2/00; 13E161 represents the ideal Viewfield reservoir location, located updip of the water-leg and oil-water transition zone and downdip of the stratigraphic trap created by the gradual reservoir pinch out and centred in the oil column. Within the Viewfield pool, all the key elements meeting the outlined cutoffs for a successful Bakken reservoir converge to create an ideal, conventional, tight oil trap. Here the sonic and photoelectric cutoffs are all exceeded, and an ideal Bakken reservoir exists. The oil-cut contours in the oil zone are schematic to approximate the location of the contours depicted in Figure 4. The light green colour represents a transition zone from 60% to 40% oil cut (0.6 to 0.4), the dark green colour represents the best oil-cut values from 60% to >80% (0.6 to >0.8) and the blue colour represents the downdip water zone of the oil column of <40% oil cut (<0.4). ls – limestone scale; sec – second; m – metre; API – American Petroleum Institute. The figure is from Kohlruss (2022).*

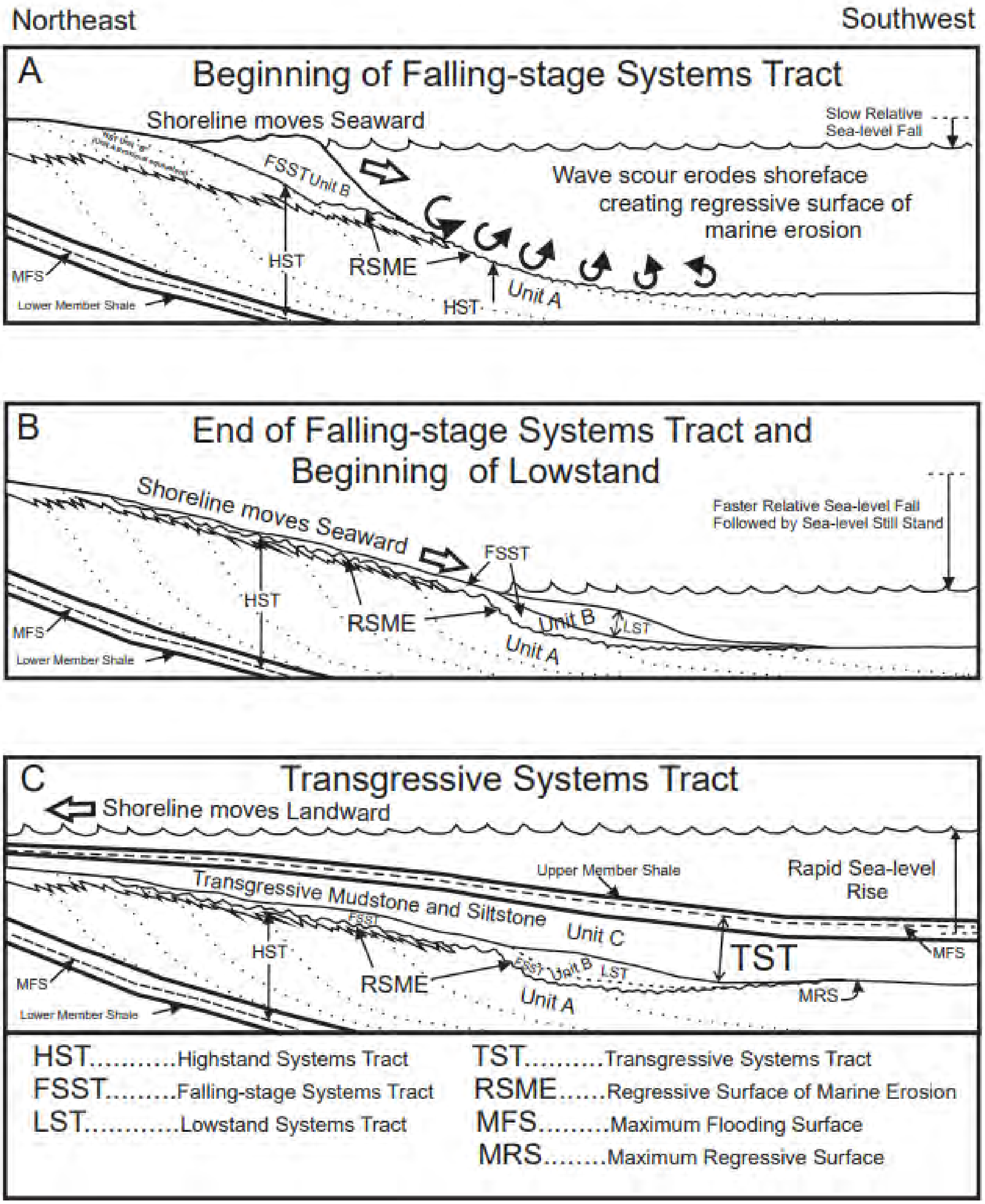

Figure 6 *– A generalized schematic cross-section showing geometric relationships of the Bakken Formation Middle Member units A, B and C, and depictions of events leading to deposition of these units:* ***A)*** *development of a regressive surface of marine erosion (RSME) during early falling-stage systems tract (FSST);* ***B)*** *the low basin gradient during Middle Member deposition resulting in rapid seaward movement of the shoreline during relative sea-level fall; when sea level stabilizes, a lowstand (LST) shoreface sand body begins to aggrade; and* ***C)*** *relative sea-level rise resulting in truncation of falling-stage and lowstand sediments by muds and silts. The figure is from Kohlruss and Nickel (2009).*

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Overview of the Diagenetic and Structural History of the Mississippian Frobisher Beds in the Steelman Pool in Southeastern Saskatchewan

*Arden Marsh [1]**

[1] Saskatchewan Geological Survey
* Arden.Marsh@gov.sk.ca

The Mississippian strata in the Williston Basin have a complex depositional and diagenetic history that has been extensively documented over the years. These strata are also of substantial economic interest to the oil industry having produced large quantities of hydrocarbons. Oil was first produced in the Steelman pool from the Frobisher Beds in southeastern Saskatchewan in 1954. Since then, the Steelman pool has produced 56.5 million m^3 (355.4 million barrels (MMbbl)) of oil from 2020 wells, not only from the Frobisher Beds (7.7 million m^3 (48.3 MMbbl) from 647 wells) but also the Ordovician Winnipegosis Formation (0.8 million m^3 (5 MMbbl) from 29 wells) and more impressively from the Mississippian Midale Beds (48 million m^3 (302.1 MMbbl) from 1344 wells).

From the study of core and well log data, the Frobisher Beds in the Steelman pool are interpreted to have been deposited in a peritidal environment as a complex succession of onlapping progradational parasequences during five transgressive and regressive cycles. During and following deposition, these strata were affected by many types and phases of diagenetic alteration, including cementation, dolomitization, micritization, karsting, chertification and anhydritization. There is also evidence of structural controls on sedimentation, diagenetic features and the accumulation of hydrocarbons in the Frobisher Beds, related to the reactivation of faults within the Precambrian crystalline rocks underlying southeastern Saskatchewan.

The purpose of this presentation is to show how the diagenetic and structural history of the Frobisher Beds in the Steelman pool has influenced porosity and migration pathways both positively and negatively. This information could then be used to help enhance known plays, as well as model and predict future potential plays.

Facies Analysis and Distribution of the Mississippian Frobisher Beds in Southeastern Saskatchewan

Holly Shoulak [1,2] and Hairuo Qing [2]*

[1] Saskatchewan Geological Survey; [2] University of Regina
* Corresponding author: Holly.Shoulak@gov.sk.ca

Introduction

Mississippian strata in southeastern Saskatchewan are located on the northeastern flank of the Williston Basin. The Frobisher Beds are a prolific oil producer; they have been in production since 1954, and, as of October 2024, have produced 58 million m^3 of oil. The Frobisher Beds are a succession of carbonate and evaporitic rocks. The carbonate sequences have been informally separated and named by industry based on marker beds that correspond with a spike on the gamma curve. The evaporite sequences have been formally named the Hastings and Winlaw evaporites.

The study area for this project encompasses Township 1, Range 30 west of the First Meridian (Tp. 1, Rge. 30W1M) in the southeast to Tp. 2, Rge. 32W1M in the northwest. Data were collected using detailed core examination, thin sections and petrophysical logs. Cores from 78 wells and 54 thin sections from 10 different wells were analyzed for this study. As part of the facies analysis for this study, 19 facies were identified. This presentation will discuss the analysis and interpretation of different facies and facies associations within the Frobisher Beds as well as their distribution in the study area.

Facies

The Frobisher Beds in the study area comprise 19 facies and five facies associations (FA). These facies can be categorized into three different reoccurring beds based on their depositional environments: marker beds, evaporites and carbonate sequences. The facies and facies associations are listed below in Table 1, in reverse stratigraphic order.

***Table 1** – Facies and facies associations (FA) of the Mississippian Frobisher Beds in southeastern Saskatchewan, in reverse stratigraphic order; colours highlight different bed types.*

Facies Association	Facies	Name	Bed Type
FA1	1	stromatolitic lime-boundstone	Marker
	2	laminated-massive dolomitic lime mudstone	
	3	massive, laminated to nodular anhydrite	Evaporite (Hastings Evaporite)
	4	silty mudstone	Marker
FA2	5	calcimicrobial wackestone	Carbonate
	6	microbial mudstone	
	7	moldic oolitic mudstone	
	8	peloidal-oncoidal mudstone-wackestone	
	9	grainstone	
FA3	10	siltstone	Marker
	11	mudstone	
	3	massive, laminated to nodular anhydrite	Evaporite (second Hastings Evaporite)
FA4	4	silty mudstone	Marker
	11	mudstone	
FA5	12	ooid grainstone	Carbonate
	13	ooid to oncoidal wacke-packstone	
	14	oncoidal packstone	
	15	peloidal packstone	
	16	fossilized wackestone-packstone	
	17	lime peloidal mudstone-wackestone	
	18	lime mudstone	
	19	ooid packstone	
	3	massive, laminated to nodular anhydrite	Evaporite (Winlaw Evaporite)

Discussion

In the study area, the Frobisher Beds were deposited as part of a shallow marine, intertidal and supratidal environment. During times of highstand systems tract, the study area was a low-energy homoclinal ramp. This allowed for two carbonate sequences to form (FA2 and FA5). Facies association 5, which represents the first appearance of carbonates, formed in a low-energy environment based on the number of microbes present but in a high enough energy environment to form ooids. Facies association 2 contains significantly more microbes, peloids and oncoids, which indicate a lower energy setting that could have been a homoclinal back ramp.

The marker beds consist of muds, siltstones, silty mudstones and boundstone. These beds can occasionally be oxidized, which could be an indicator of exposure; the equant clastic input indicates a proximity to land. The depositional environment of the marker beds has been interpreted as subtidal to supratidal.

Based on the size and thickness of the evaporites, they have been interpretated to have formed in a salina environment.

After deposition, these beds were subjected to subsidence, which caused tilting towards the southwest and the centre of the Williston Basin. These evaporites were then subjected to intense erosion, which caused older strata to be truncated outward from the centre of the basin. Lastly, the Frobisher Beds were unconformably overlain by the Watrous Red Beds.

Sask, Eh! Follow-up Analysis of the Mississippian Frobisher State A Marker in the Steelman Region of Southeast Saskatchewan for Open-hole, Multi-lateral Well Development

Kelsey Glennie [1]*

[1] Hummingbird Energy
* inlandcountry@gmail.com

In the Steelman region, the State A Marker, or simply "State A," underlies the Midale (Charles) limestone and/or the Frobisher Evaporite (Charles). Additionally, it overlies various subintervals of Mission Canyon packstones and mudstones. Due to State A's distinct log characteristics, it serves as a reliable petrophysical marker delineating the transition from the Mission Canyon to the Charles Formation.

In the Williston Basin, State A is commonly a microcrystalline dolomite facies with poor reservoir characteristics. Although occasionally targeted for standalone horizontal drilling, such efforts have generally yielded limited economic success, restricting broader development. More frequently, State A was exploited as a secondary zone and completed in conjunction with either Midale or Frobisher units.

Cores from the Steelman region highlight significant variability in State A reservoir quality. Within this region, State A includes multiple clastic and carbonate facies that can compartmentalize oil-saturated dolomite reservoirs. These facies likely contribute to the formation of isolated, stacked, permeable and hydrocarbon-bearing intervals.

With advancements in multi-lateral drilling techniques, this study suggests that down-spaced, open-hole, multi-lateral development may offer a viable method for unlocking and producing economic wells from a bypassed reservoir.

Stratigraphy and Hydrocarbon Reservoirs of the Ratcliffe Interval (Mississippian Madison Group) of Western North Dakota

Timothy O. Nesheim [1]*

[1] North Dakota Geological Survey
* tonesheim@nd.gov

Stratigraphy

The Ratcliffe Interval forms the uppermost section of petroleum reservoirs within the hydrocarbon prolific Mississippian Madison Group. The Ratcliffe has been partially divided into four formal to semi-formal subintervals within the central portions of the Williston Basin of western North Dakota, which include in ascending stratigraphic order: Midale, Berentson, Alexander and Flat Lake (Figure 1) (Hendricks, 1987; Nordeng, 2007). These four formal/semi-formal units have been described and interpreted as shallowing upward subintervals that transition from sabkha environments in the east to open marine carbonate environments in the central, western portions of the basin (Hendricks, 1987). Further north, within the Flaxton Field area, the Midale is interpreted to record an initial transgression followed by a regression (Lindsay, 1985). The regressive portion of the Midale consists of burrowed dolomitic limestone beds deposited within a low-energy restricted nearshore marine setting, laminated to thinly bedded dolostone deposited within a peritidal setting, and nodular to laminated/bedded dolomitic anhydrite (Lindsay, 1985).

Hydrocarbon Plays and Reservoirs

A horizontal Ratcliffe play emerged during the mid-2000s with the discovery of the Foreman Butte Field in northeastern McKenzie County (proximal to core #15715 on Figure 2). This play involved open-hole horizontal wells targeting oolitic-peloidal lime packstone-grainstone beds of the Flat Lake subinterval (Figure 1) (Nordeng, 2007). Vertical Ratcliffe productive wells in the area had previously produced from bioturbated dolostones of the Alexander subinterval as well as from the Flat Lake packstone-grainstone beds (Hendricks, 1987). The underlying Midale subinterval is primarily comprised of non-reservoir, argillaceous fossil lime wackestone to packstone across most of McKenzie County (Figures 2 and 3a).

An unconventional style (horizontal drilling with multi-stage hydraulic fracturing) Ratcliffe play developed in northern Burke County during 2012 to 2019 (proximal to core #9797 on Figure 2). A total of 43 horizontal Madison wells drilled in the upper Rival subinterval Interval were completed/restimulated with multi-stage hydraulic fracturing (Figure 1) (Starns and Nesheim, 2023). These unconventional wells stimulated into the Midale subinterval, which is largely comprised of bioturbated, micro-sucrosic dolostones (Figures 1 and 3b), similar to the dolostone reservoir facies of the Alexander subinterval in McKenzie County.

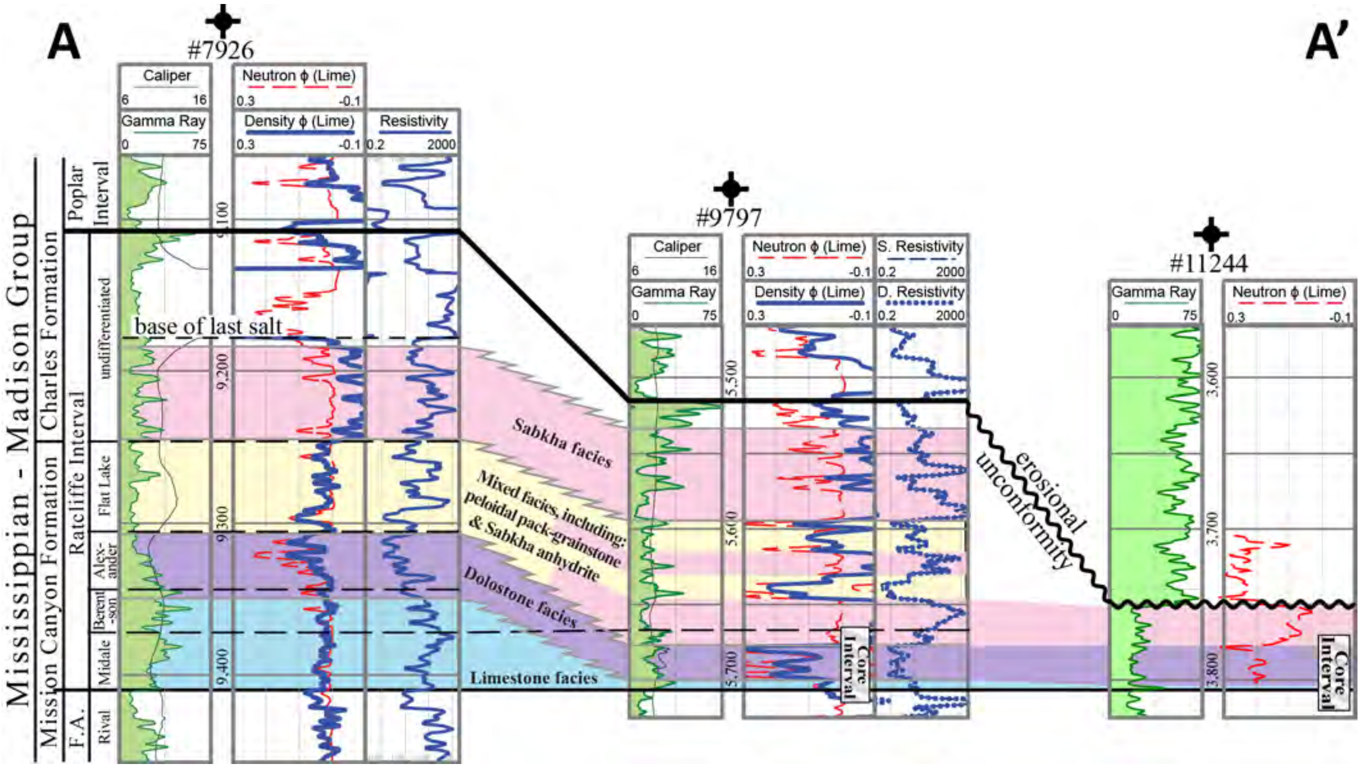

Figure 1 *– Cross-section of the Ratcliffe Interval depicting schematic facies correlations/changes. Stratigraphic subdivisions are primarily based upon Hendricks (1987).*

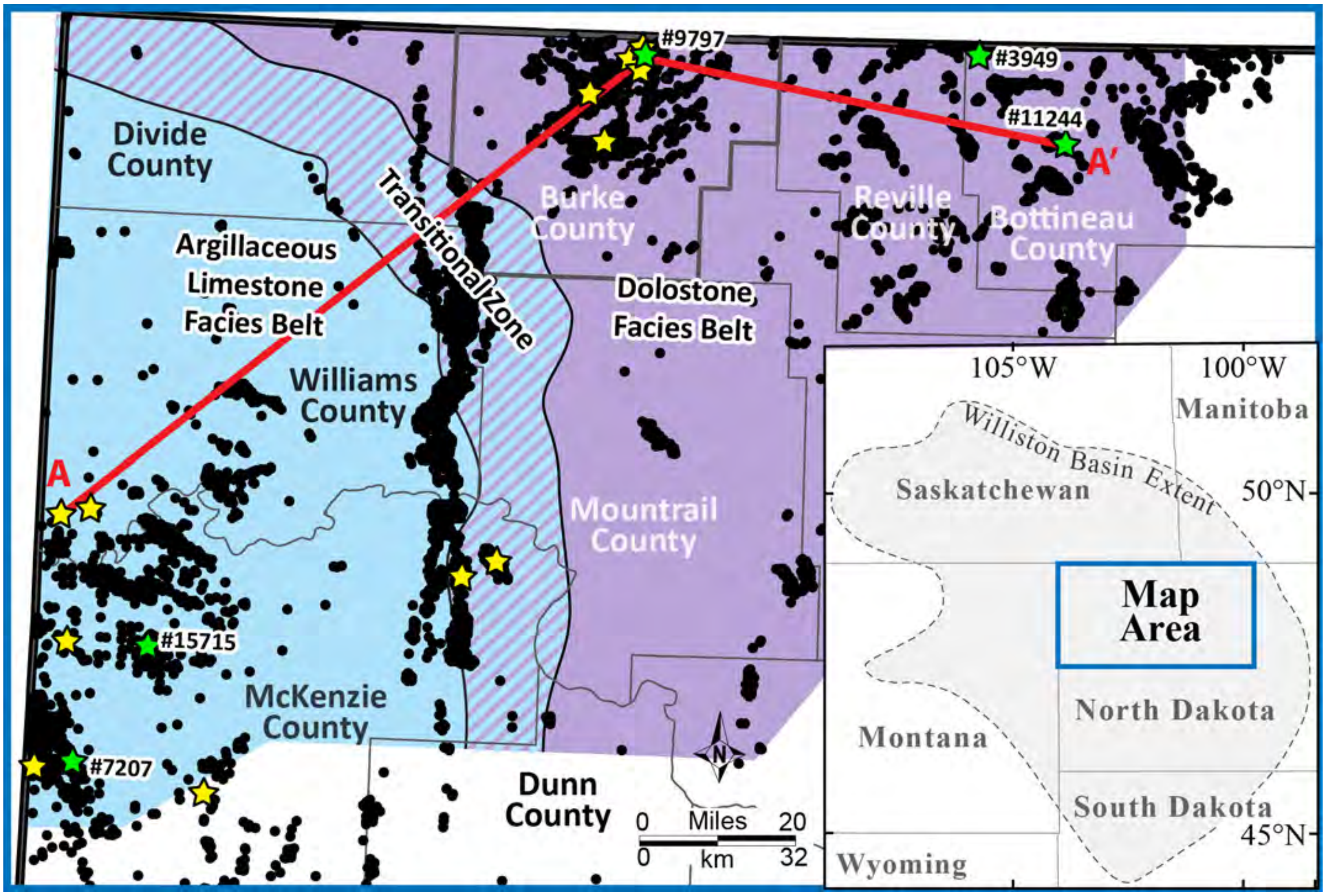

***Figure 2** – Generalized facies map for the Midale subinterval. Black circles represent oil and gas productive Madison wells. The "Limestone Facies" area (blue) represents where the Midale is composed primarily of the dark grey lime wackestone to packstone with abundant marine fossils, which does not appear to constitute hydrocarbon reservoir rock. The "Dolostone Facies" area (purple) depicts where the Midale section contains significant amounts of bioturbated micro-sucrosic dolostone fossil grainstone, which serves are reservoir rock for oil and gas productive Midale wells. The "Transitional Zone" area (blue and purple diagonal lines) contains an interbedding of the Limestone and Dolostone facies in relatively comparable proportions. Green stars depict the cores included in the workshop review with North Dakota Industrial Commission well numbers. The yellow stars depict locations of additional Ratcliffe cores examined to date by the author. A-A' represents the Figure 1 cross-section wells.*

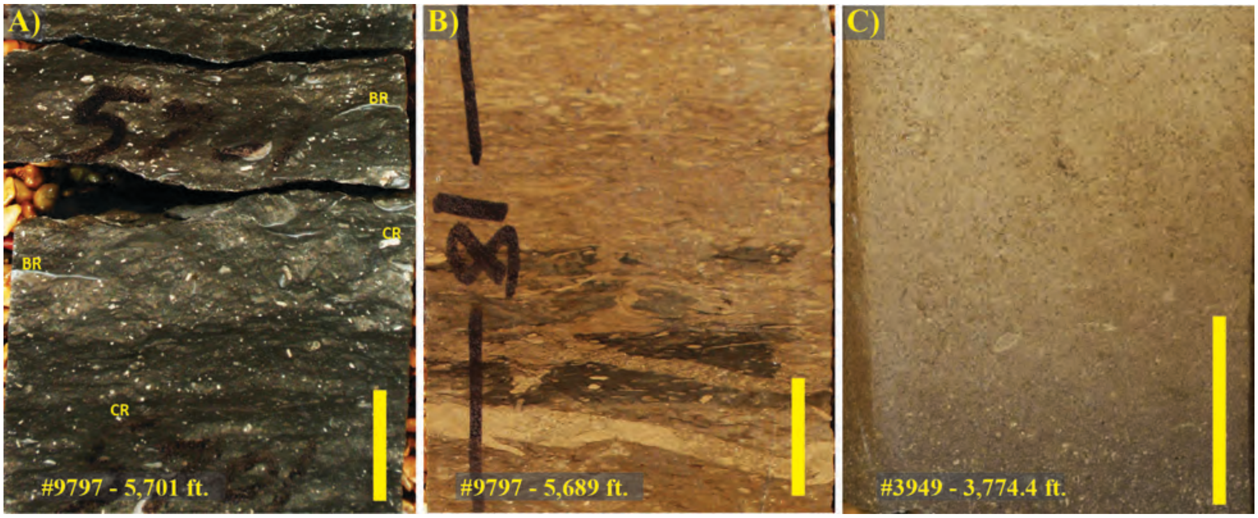

***Figure 3** – Core photographs from the Midale subinterval, including **A)** argillaceous fossil lime wackestone with crinoids (CR) and brachiopods (BR) (Midale); **B)** bioturbated fossil-peloidal dolomitic lime wackestone; and **C)** oil-stained, calcareous, dolo grainstone. North Dakota Industrial Commission well numbers and core depths in the bottom left corner of each photograph. Yellow lines depict one-inch scale bars.*

Vertical and open-hole (non-frac'd) horizontal oil wells have also produced from the Midale subinterval within north-central North Dakota (proximal to cores #3949 and #11244 on Figure 2). In this third productive area, most of the Ratcliffe Interval overlying the Midale subinterval has been eroded away (Figure 1). The Midale subinterval is primarily comprised of slightly to moderately calcareous dolo mudstone to grainstone in which the dolo grainstone beds comprise the petroleum reservoir facies (*e.g.*, Figure 3c).

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Paleokarst Reservoirs of the Lower Carboniferous (Mississippian) Madison Group and Jura-Cretaceous Success Formation, West-central Saskatchewan

Dan Kohlruss [1] and Tyler Music [1]*

[1] Saskatchewan Geological Survey
* Dan.Kohlruss@gov.sk.ca

The Lower Carboniferous (Mississippian) Madison Group and the Jura-Cretaceous Success Formation in west-central Saskatchewan combine to form a significant paleokarst terrain. The marine Madison limestones were subjected to a long period of exposure, weathering and erosion resulting in substantial structural irregularity at their upper surface and abundant decomposition of the limestones both at surface and below. The resulting karst byproduct is the primary method by which the Success Formation formed within the study area. Previous work recognized that the Success Formation was a result of karst processes but did not delve into detailed facies or facies associations descriptions nor provide any detailed mapping. This study has produced maps of the internal stratigraphy of the Success Formation's karst facies and facies associations for the first time.

Analysis of drillcores, drill cutting samples and geophysical well logs resulted in the identification of six distinct recurring karst facies as well as four karst facies associations. The karst facies encountered are the following:

- Facies 1: mudstone grading to matrix-supported chert-pebble conglomerate;
- Facies 2: matrix-rich, clast-supported chaotic chert and sandstone breccia;
- Facies 3: crackle breccia;
- Facies 4: mudstone;
- Facies 5: chaotic mud and chert rubble breccia/conglomerate; and
- Facies 6: matrix-supported chaotic breccia.

The karst facies associations (FA) represented are the following:

- Facies association 1: collapsed cave;
- Facies association 2: preserved cave roof;
- Facies association 3: epikarst; and
- Facies association 4: soil breccia-karst paleosol.

The Success Formation produces heavy oil and natural gas from two paleokarst reservoirs. These correspond with the collapsed cave (FA1) and epikarst facies associations (FA3). This was determined through analysis of cross-sections, structure and isopach maps and three-dimensional modelling of the facies associations. These were compared to oil cut and gas production maps that identified discrete oil and gas traps within the two reservoirs. The traps include 1) structural four-way closure (domes) related to the underlying Madison's paleotopography; and 2) lateral pinch-outs of the two paleokarst reservoir facies associations.

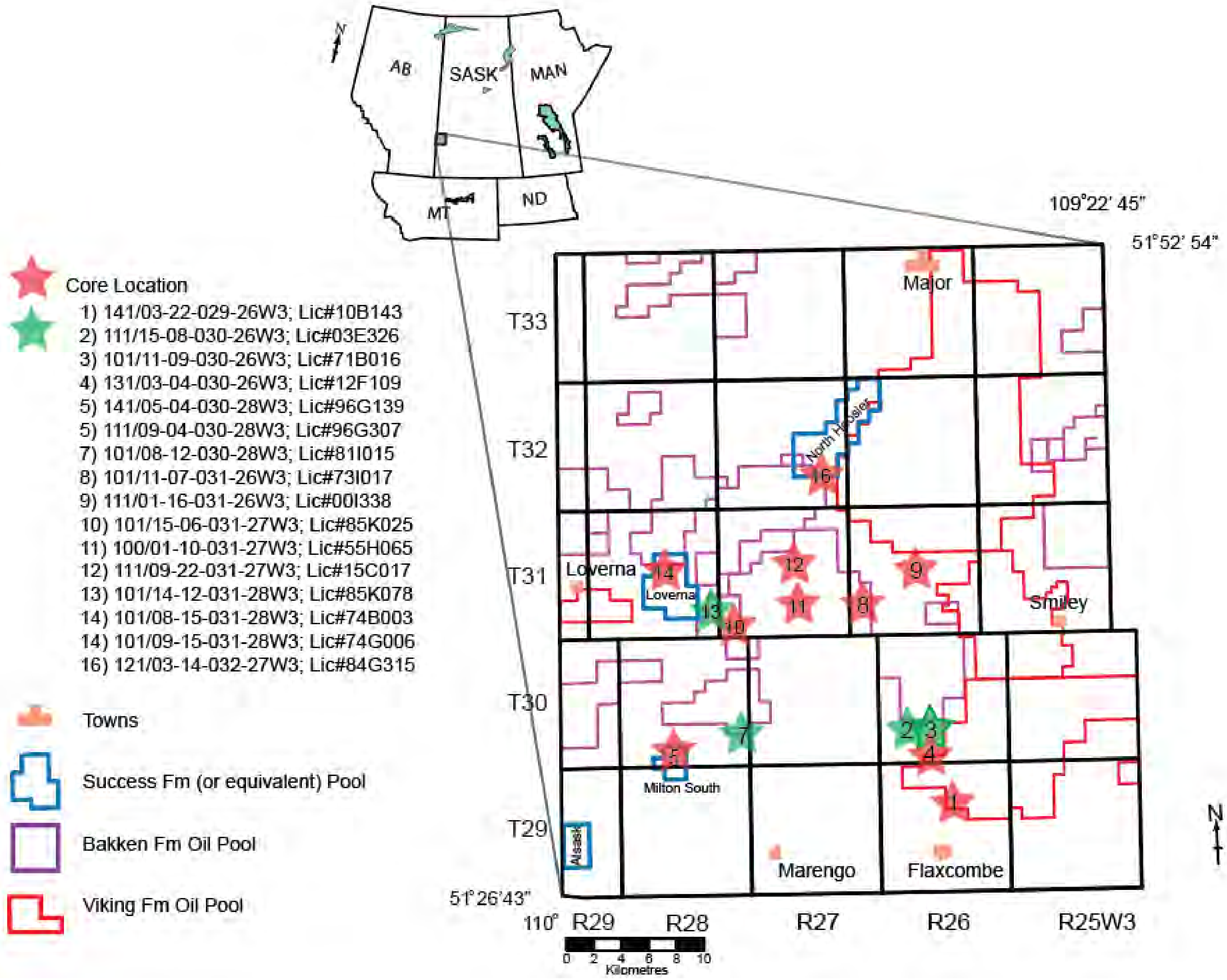

Figure 1 *– Location of the study area in west-central Saskatchewan. The orange stars represent the locations of cores used for the study, and the green stars represent locations of core displayed at the workshop. Abbreviations on map: T – Township; R – Range; W – West; Fm – Formation. Abbreviations on inset map: AB – Alberta; SASK – Saskatchewan; MAN – Manitoba; MT – Montana; ND – North Dakota.*

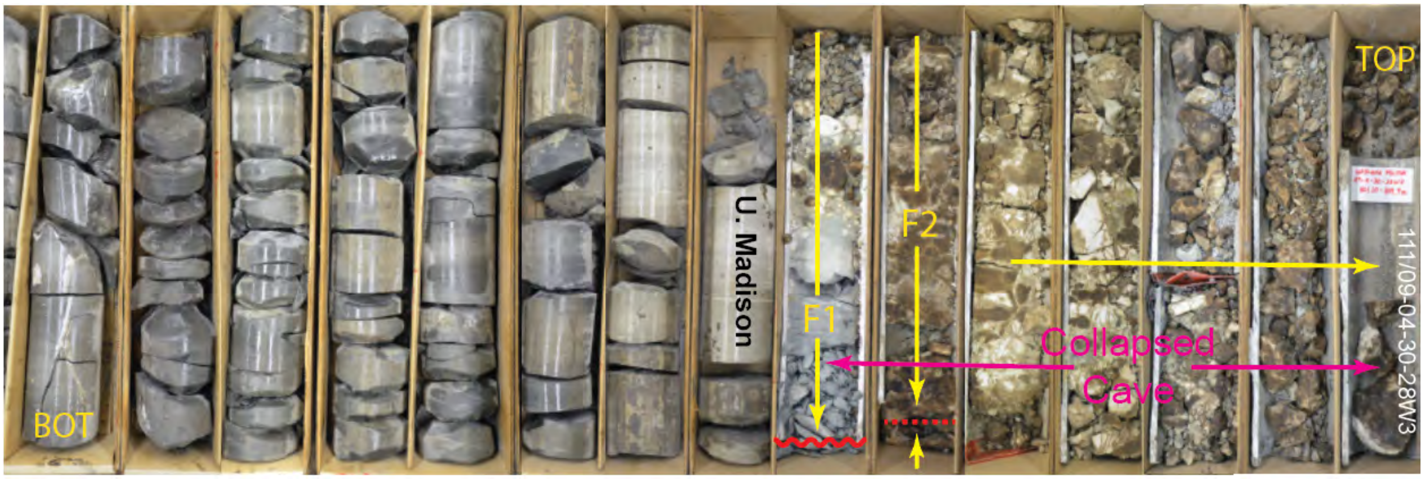

Figure 2 *– Core 1 from well 111/09-04-030-28W3; 96G307 illustrates the contact between the upper (U) Madison unit and the collapsed cave facies association, which includes facies 1 (F1) and 2 (F2).*

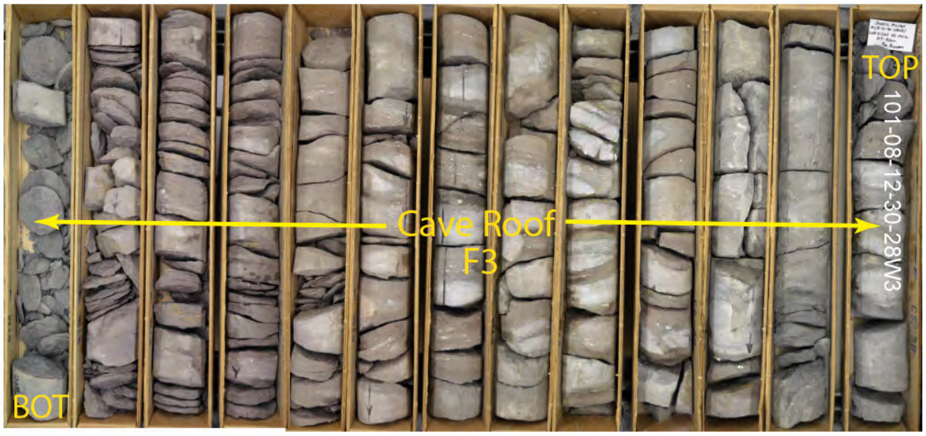

Figure 3 *– Core 2 from well 101/08-12-030-28W3; 81I015 illustrates facies 3 (F3) and the cave roof facies association.*

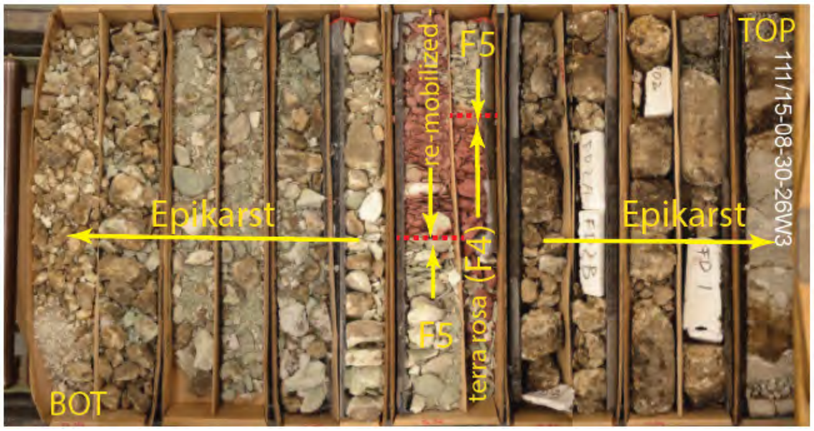

Figure 4 *– Core 3 from well 111/15-08-030-26W3; 03E326 illustrates the epikarst facies association, which includes facies 4 (F4) and 5 (F5). The relationship of facies 5 and the terra rosa (soil) mudstones of facies 4 is also illustrated.*

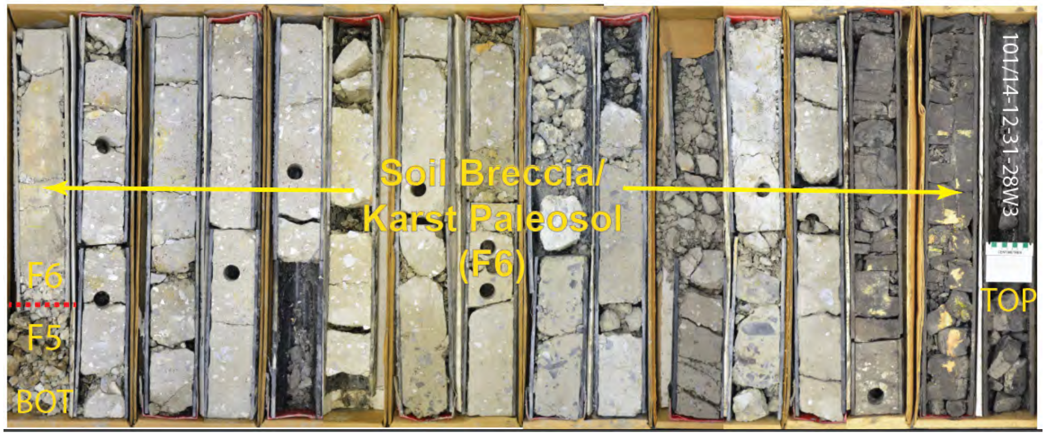

Figure 5 *– Core 4 from well 101/14-12-031-28W3: 85K078 illustrates the contact between facies 5 (F5) and 6 (F6). Core 4 shows the soil breccia/karst paleosol facies association (FA4) and the stacking relationship with facies 5 (epikarst facies association (FA3)). Notably, the chert clasts within FA4 change from white to dark grey and black towards the top of the unit. Facies association 4 is commonly capped with a coal.*

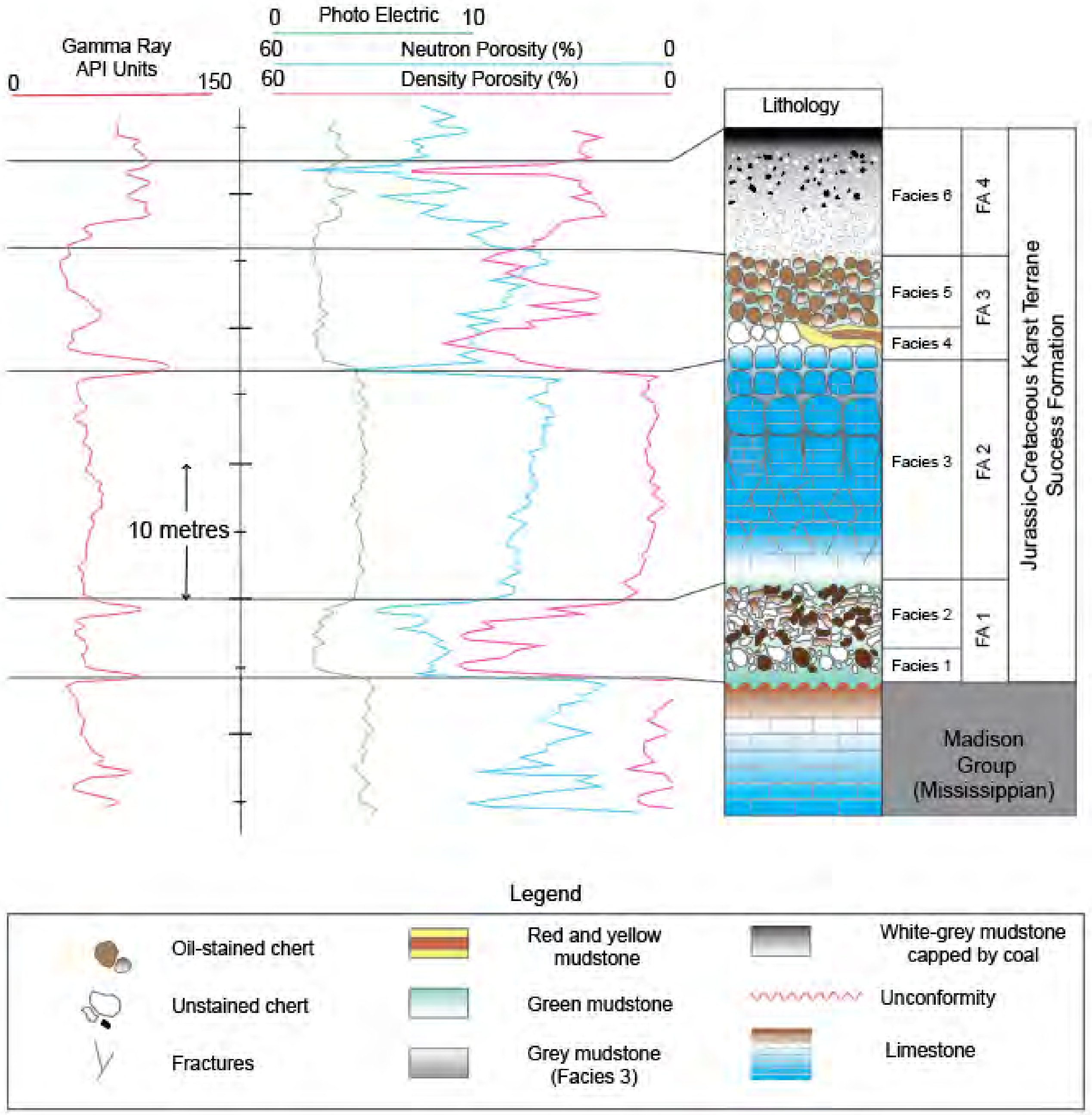

Figure 6 – *A schematic litholog illustrating the various facies and facies associations (FA) identified in the study area, as well as the idealized stacking pattern and corresponding composite geophysical well-log signatures. API – American Petroleum Institute.*

Multi-lateral Oil Well Production from the Mannville Group Heavy Oil Region in West-central Saskatchewan

Peter Hill [1]*

[1] Saskatchewan Geological Survey
* Peter.Hill@gov.sk.ca

Introduction

In 2024, Saskatchewan introduced the *Multi-lateral Oil Well Program (MLWP)*, which offers additional volumetric drilling incentives for multi-lateral horizontal oil wells drilled between April 1, 2024, and March 31, 2028. This program is designed to help the province achieve its goal of increasing oil production to 600 000 barrels per day by 2030. The program has resulted in the increased drilling of several multi-lateral horizontal wells targeting Mannville Group heavy oil reservoirs in west-central Saskatchewan. Multi-lateral wells are drilled in different configurations to drastically increase reservoir production by increasing the well recovery factor while limiting increased drilling costs. This study focuses on core from the Mannville Group heavy oil district close to multi-lateral wells. This presentation will highlight the geology and production from several multi-lateral projects targeting different members throughout the Mannville Group.

Geology

The Mannville Group is Aptian to Albian in age and, in west-central Saskatchewan, overlies the sub-Cretaceous erosional surface and is overlain by shales from the Joli Fou Formation (Figure 1). The Mannville Group is separated into nine members comprising quartz-rich sandstones, siltstones, mudstones and coals that typically coarsen upward (Christopher, 2003). Depositional settings are typically characteristic of a shallow marine, wave-influenced deltaic environment.

Drilling

Multi-lateral projects throughout west-central Saskatchewan have targeted several Mannville Group members and have been typically drilled in either a pitchfork or fishbone configuration (Figure 2).

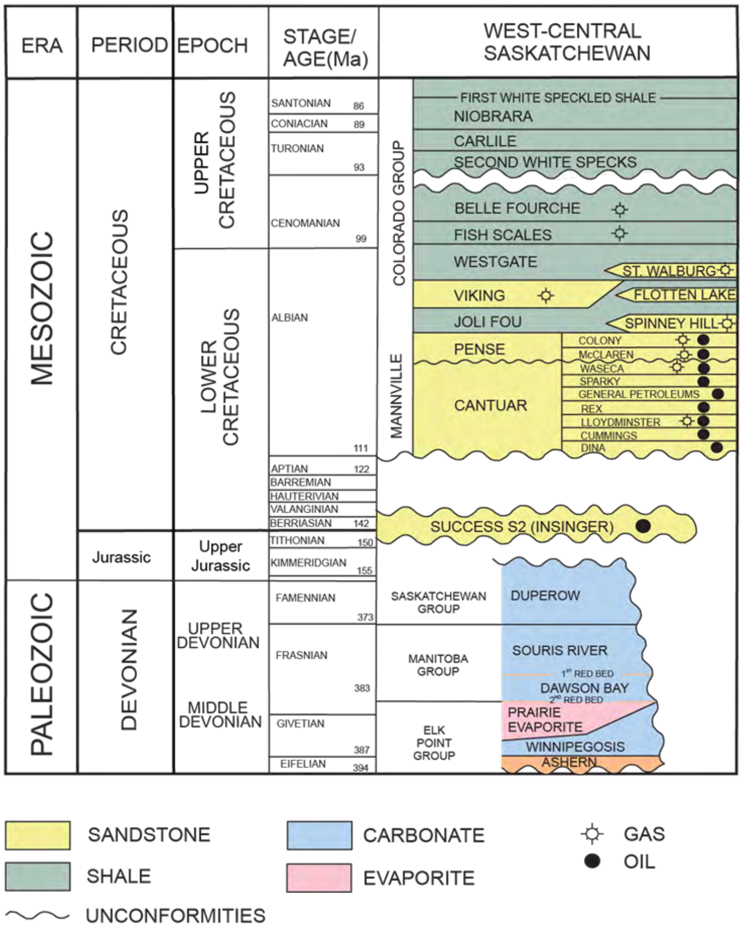

Figure 1 *– Stratigraphic correlation chart for west-central Saskatchewan showing the Mannville Group separated into nine members (*modified from *Saskatchewan Ministry of Energy and Resources, 2022).*

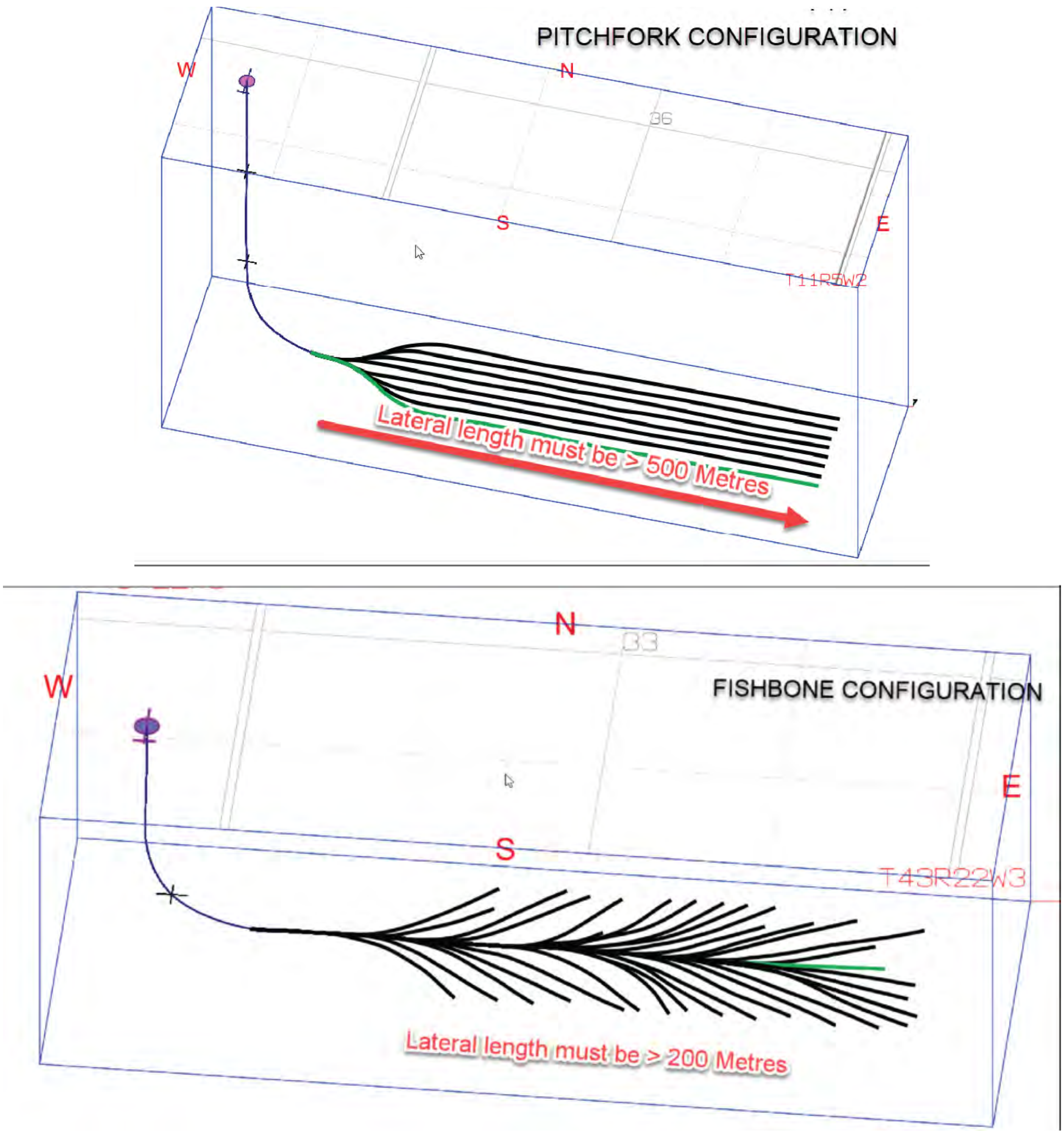

Figure 2 *– Schematics showing the typical drilling (pitchfork and fishbone) configurations for multi-lateral oil wells drilled in the Mannville Group in west-central Saskatchewan (Saskatchewan Ministry of Energy and Resources, 2024).*

This study will showcase and compare cores from nearby vertical wells for three of the following multi-lateral projects:

1) multi-lateral oil wells near the Sparky Member Baldwinton pool that were drilled in both a fishbone and pitchfork/fan configuration;
2) multi-lateral oil wells that were primarily drilled in a pitchfork configuration in the Lloydminster Member Tangleflags pool; and
3) extensive fishbone drilling in the Cummings Member Soda Lake pool.

Discussion

Initial investigation indicates that well performance is related to reservoir quality and thickness and is independent of drill configuration or the number of wellbores drilled. The overall best-producing multi-lateral wells have thicker continuous sandstone reservoirs, with low clay content and high porosity.

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Investigating the Critical Mineral Potential of Upper Cretaceous to Paleogene Coals and Carbonaceous Shales in Southwestern Saskatchewan, Canada

Meagan M. Gilbert [1] and Arden Marsh [1]*

[1] Saskatchewan Geological Survey
* Corresponding author: Meagan.Gilbert@gov.sk.ca

Late Cretaceous to earliest Neogene rocks are well exposed in the Frenchman River valley of southwestern Saskatchewan (Figure 1). Five latest Campanian to Maastrichtian formations are recognized. In ascending order, these are the Bearpaw, Eastend, Whitemud, Battle and Frenchman formations, which are overlain by the Paleogene Ravenscrag Formation (Figure 2). The Bearpaw to Ravenscrag formations were deposited primarily in the northern parts of the Williston Basin and in the Alberta foreland basin. These formations record a near-continuous depositional sequence of overall regressive clastic marine and marginal marine deposits (Bearpaw and Eastend formations) to nonmarine lacustrine, paleosol and fluvial successions (Battle to Ravenscrag formations).

The Eastend to Battle formations sequence records deltaic to coastal plain deposition during the final, second-order transgressive-regressive Bearpaw Cycle of the Western Interior Seaway. Regression is interpreted to have resulted from orogenic unloading of the Laramide orogeny to the west (Figure 3). A complete wave-dominated sequence is preserved and capped by meandering fluvial deposits and their associated floodplains.

The former Whitemud Formation has been demoted to member status within the Eastend Formation and was reinterpreted as a highly leached paleosol profile overprinting upper Eastend Formation facies (Gilbert and Marsh, 2025). This was due to subaerial exposure resulting from tectonic loading, which caused uplift in southwestern Saskatchewan (Figure 3). Feldspars within the upper Eastend Formation were kaolinized, resulting in the distinctive white colouration of the Whitemud Member. The overlying Battle Formation was deposited due to increased subsidence in the proximal foreland, resulting in deposition of lacustrine and wetland facies (Figure 3), further exacerbating leaching of the Whitemud Member.

Coal is a known source of critical mineral concentrations, such as germanium (Ge), gallium (Ga), uranium (U), vanadium (V), selenium (Se) and rare earth elements (REEs). Several mechanisms have been proposed to explain critical mineral enrichment in coals, which vary according to local depositional history and the minerals with which the coal is enriched. Due to the increasing demand for, and trade barriers facing, several critical minerals, investigating coal-hosted ore deposits for enrichment is increasingly important for economic growth and security. Coals within the Eastend Formation were sampled in the summer of 2024 for prospective critical mineral enrichment, with 136 total samples assayed. Enrichment of Eastend Formation coal seams is believed to be due to pedogenic kaolinization resulting from leaching of the feldspar-rich sediments of the overlying lignite beds.

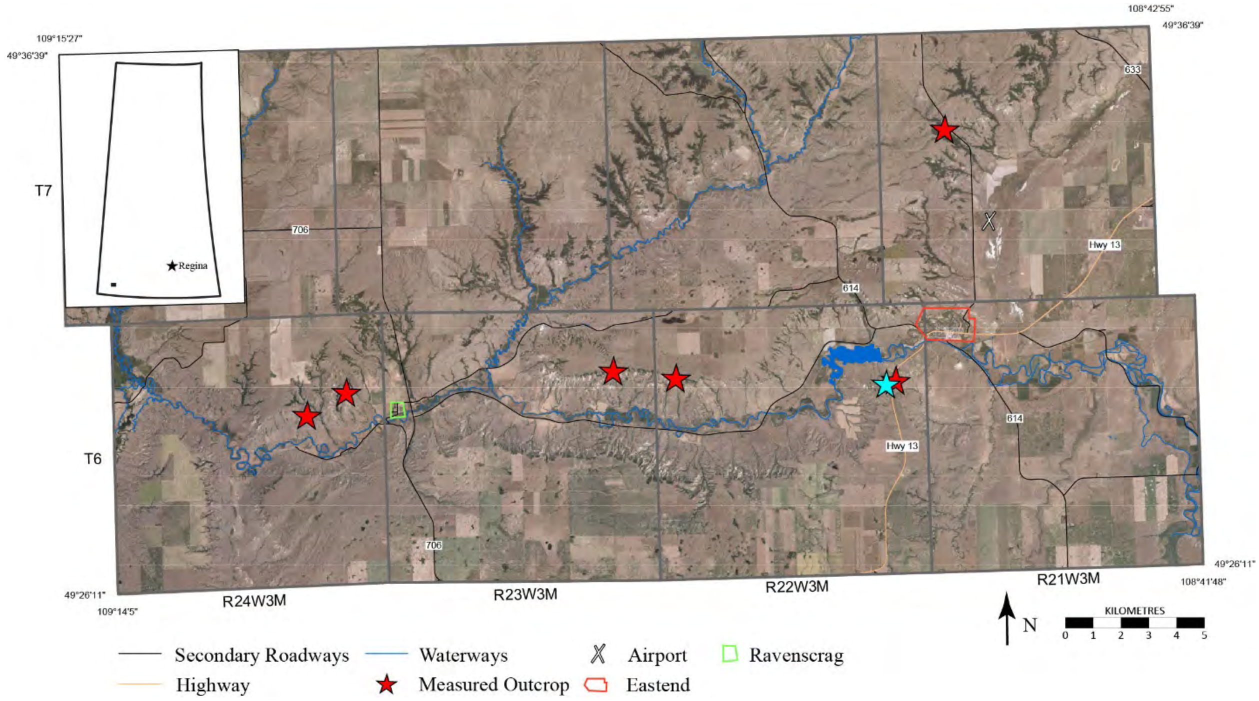

Figure 1 – *Orthophotographs (Saskatchewan Geospatial Imagery Collaborative) of the study area in southwestern Saskatchewan, showing outcrop localities (stars), with reference to regional landmarks and the Dominion Land Survey system. The Frenchman River valley and the Frenchman River trend west to east through the centre of the figure. Conglomerate Creek, draining the Conglomerate Creek Highlands, merges with the Frenchman River near the community of Ravenscrag (green outline). M – meridian; R – range; T – township; W – west. The figure is from Gilbert and Marsh (2025).*

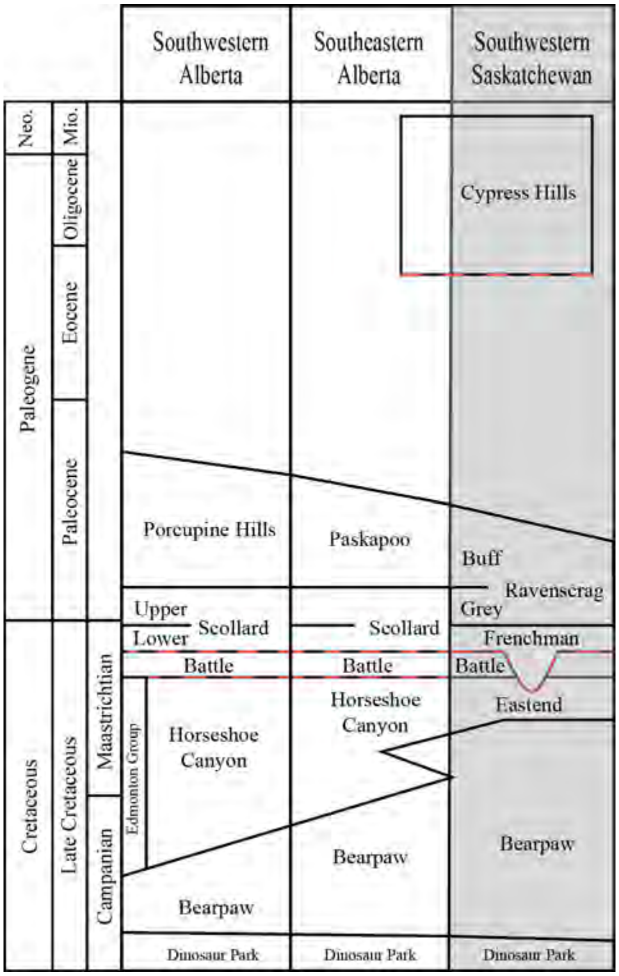

*Figure 2 – Stratigraphic nomenclature utilized in this study (*modified from *Saskatchewan Ministry of Energy and Resources, 2022), displayed beside the stratigraphy of Alberta for regional reference (Hamblin, 2004). All names represent formational status except for Upper and Lower Scollard (formal members) and Buff and Grey Ravenscrag (informal members). The dashed red lines indicate recognized disconformities. Mio. – Miocene; Neo. – Neogene. The figure is from Gilbert and Marsh (2025).*

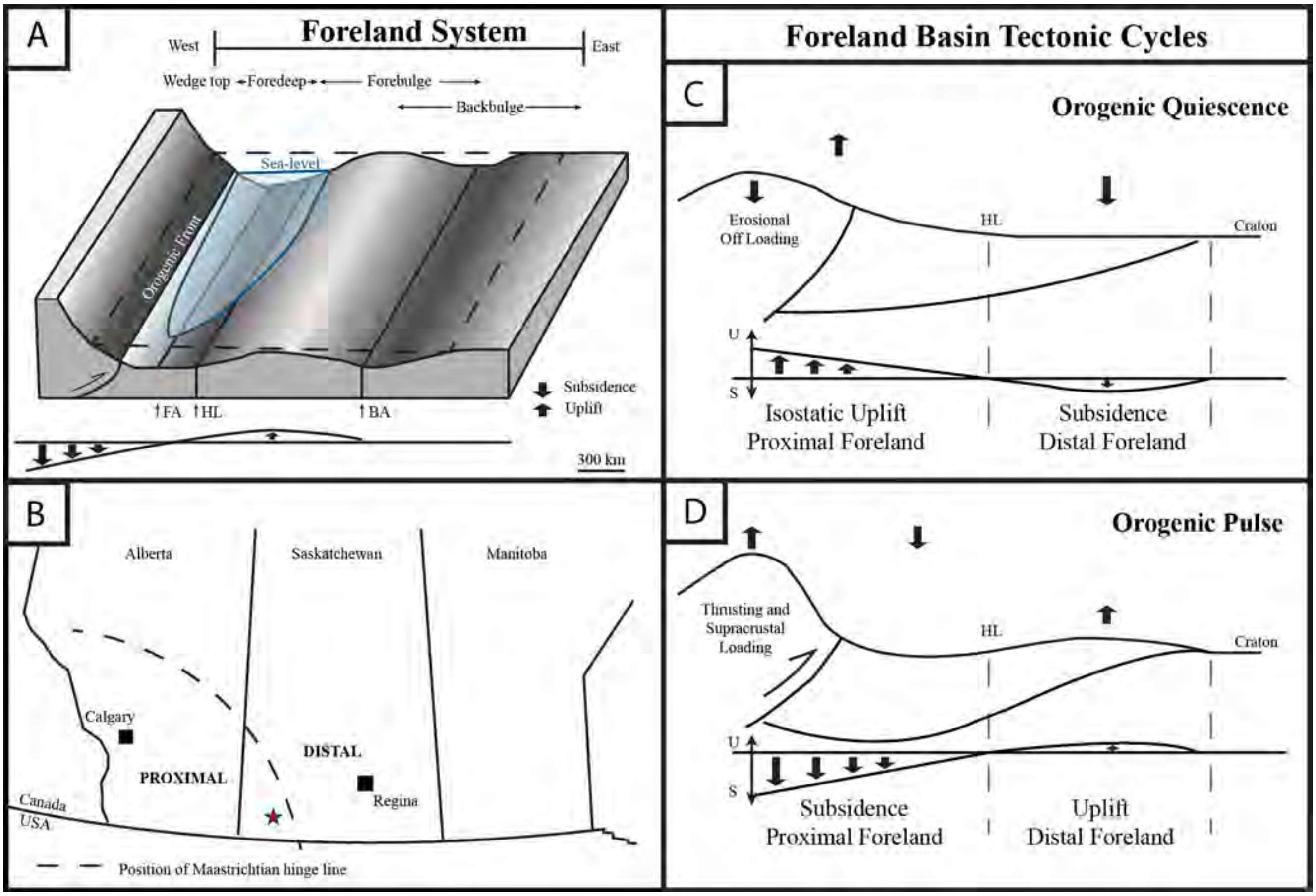

***Figure 3** – **A)** Configuration of a typical foreland basin system and its various depozones (wedge top, foredeep, forebulge and backbulge). The proximal and distal regions are separated by a hinge line (HL).* Modified from *Catuneanu* et al*. (2000). FA – foredeep axis; BA – backbulge axis. **B)** A map indicating the average position of the hinge line during Late Cretaceous–Paleocene times. Note that a hinge line can migrate depending on tectonic factors.* Modified from *Catuneanu and Sweet (1999). The red star indicates the position of the study area. **C)** A flexural model explaining the relationships between tectonic cycles within the foreland basin. During orogenic quiescence, the proximal foreland will experience isostatic uplift (U) and the distal foreland will undergo subsidence (S). The Eastend Formation was deposited in the distal foreland during such times. HL – hinge line. **D)** A flexural model explaining the relationships between tectonic cycles within the foreland basin. During orogenic pulse, the proximal foreland will experience subsidence (S), and the distal foreland will experience uplift (U). Pedogenesis during hinge line and distal foreland uplift resulted in the development of the Whitemud Member. Movement of the hinge line (HL) and continued subsidence led to deposition of lakes and wetlands of the Battle Formation approaching the hinge line. The figure is from Gilbert and Marsh (2025).*

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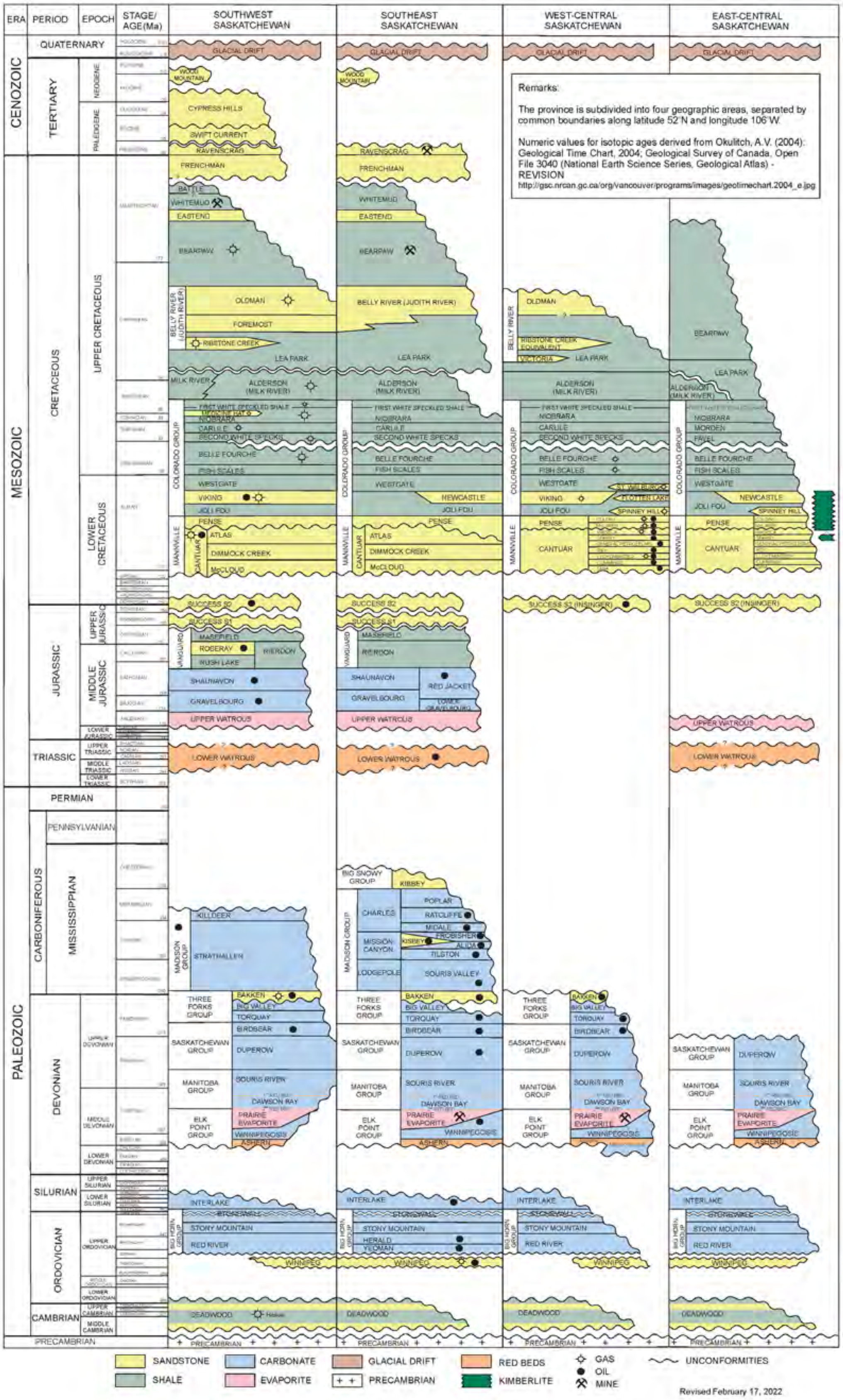
Gilbert, M.M. and Marsh, A. (2025): Depositional environments and regional stratigraphy of the Eastend to Battle formations in the Frenchman River valley near Eastend, Saskatchewan; Saskatchewan Geological Survey, Saskatchewan Ministry of Energy and Resources, Geoscience Report GR2025-6, 16p. https://publications.saskatchewan.ca/#/products/125913

Hamblin, A.P. (2004): The Horseshoe Canyon Formation in southern Alberta: surface and subsurface stratigraphic architecture, sedimentology, and resource potential; Geological Survey of Canada, Bulletin 578, 180p.

Saskatchewan Ministry of Energy and Resources (2022): Stratigraphic Correlation Chart; Saskatchewan Ministry Energy and Resources, URL <https://publications.saskatchewan.ca/#/products/81737>.

Appendix 1 – Saskatchewan Stratigraphic Correlation Chart (Saskatchewan Ministry of Energy and Resources, 2022)

https://publications.saskatchewan.ca/#/products/81737



Remarks:

The province is subdivided into four geographic areas, separated by common boundaries along latitude 52°N and longitude 106°W.

Numeric values for isotopic ages derived from Okulitch, A.V. (2004): Geological Time Chart, 2004; Geological Survey of Canada, Open File 3040 (National Earth Science Series, Geological Atlas) - REVISION
http://gsc.nrcan.gc.ca/org/vancouver/programs/images/geotimechart.2004_e.jpg

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