

# Lithofacies Characterization of the Middle Jurassic Upper Shaunavon Member in Southwestern Saskatchewan: Preliminary Results

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## Abstract

*The mixed clastic-carbonate sediments of the Upper Shaunavon Member were deposited unconformably on the homogeneous carbonates of the Lower Shaunavon Member. Examination of core from 65 wells has revealed seven reoccurring sedimentary facies within the Upper Shaunavon Member. These are: 1) very fine- to medium-grained peloidal sandstone; 2) bioclastic, oolitic packstone to grainstone; 3) bioturbated bioclastic sandstone and mudstone; 4) well-cemented sandstone; 5) calcareous shale; 6) mixed sandstone and dolomitic shale; and 7) shale, sandstone and coquina interbeds. Analysis of the facies association of the studied sections indicates a marginal-marine to shallow-marine, tidally influenced depositional environment. Oil is primarily found in tidal inlet channel deposits of the sandstone and limestone lithofacies (Facies 1 and Facies 2, respectively).*

*Future work includes mapping of the Lower Shaunavon Member and Mississippian Madison Group to determine possible controls on deposition of the Upper Shaunavon Member. Detailed analysis of porosity and permeability will help characterize Upper Shaunavon Member reservoirs and assist with further exploration in the area.*

**Keywords:** Upper Shaunavon Member, Shaunavon Formation, Middle Jurassic, tidal channel, tidal flat, bioturbation

## 1. Introduction

The Middle Jurassic Upper Shaunavon Member of the Shaunavon Formation in southwestern Saskatchewan has been a well-known oil producer since the 1950s. Although the Shaunavon Formation has two members, the Upper Member accounts for 97% of total production from the formation. A classic conventional oil play, as of January 2017, the total cumulative production from the Upper Shaunavon is  $64.1 \times 10^6 \text{ m}^3$  (403 million barrels (MMBbl)). Oil in the Upper Shaunavon Member is hosted within thin, sheet-like heterogeneous carbonate-clastic sediments. These mixed sediments form several stacked reservoirs that have been identified in the study area.

The Shaunavon Formation ranges from 40 to 55 m in thickness within the study area and consists of a Lower Member dominated by muddy lime facies (lithographic limestone of Brooke and Braun, 1972) and an Upper Member of mixed clastic-carbonate succession (Figure 1). The two members are separated by a disconformable contact (Christopher, 1964; Brooke and Braun, 1972). These previous publications mainly dealt with the subdivision of the stratigraphy and determination of the formation's age. The Lower Member is typically composed of oolitic beds (6 to 7 m thick) at the top, overlying tan microcrystalline mudstone. Fossils include corals, gastropods, echinoids and foraminifera.

Christopher (1964) subdivided the Upper Shaunavon Member into three informal units (U1, U2 and U3) that are separated by sedimentologic breaks and lithologic changes across these diastems. More recent biostratigraphic work

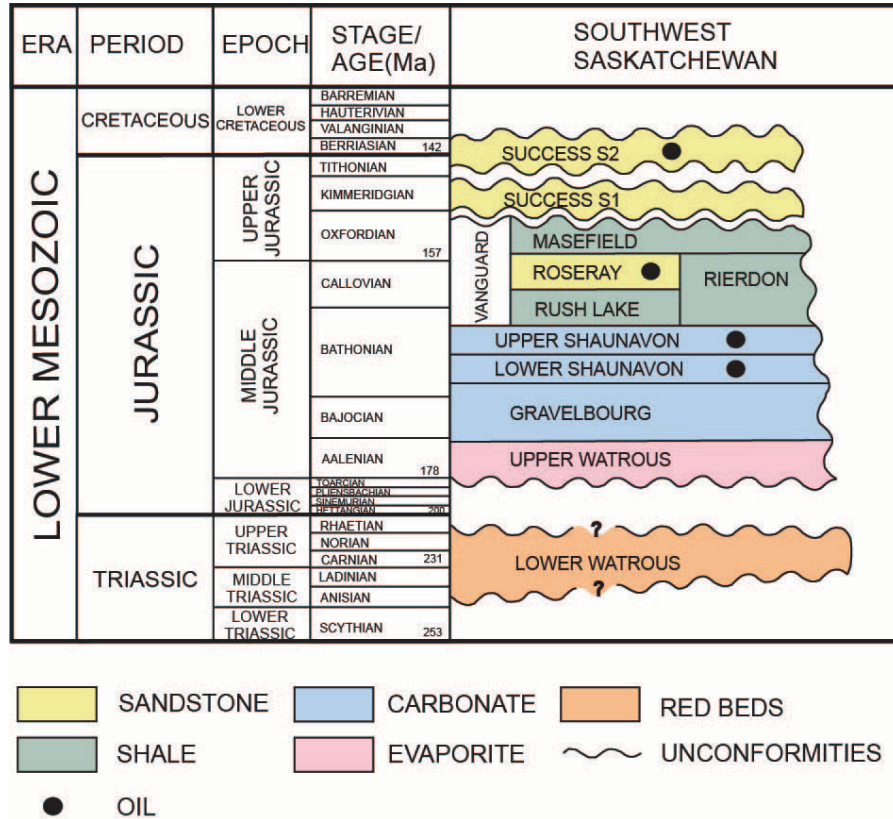
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by Georgescu and Braun (2006) used Charophyta organisms to date the formation as upper Bajocian to lower Bathonian in age.



**Figure 1** – Stratigraphic chart showing the relationship of the Shaunavon Formation to other formations in the Lower Mesozoic in southwestern Saskatchewan (modified from Saskatchewan Ministry of the Economy, 2014).

The purpose of this study was to analyze detailed sedimentological characteristics, which has led to the identification of several facies within the Upper Shaunavon Member. Facies descriptions were then used to determine preliminary interpretations of the depositional environment. Another objective of this study was to endeavour to decipher the vertical and lateral stratigraphic pattern of the reservoir and non-reservoir units of the formation within the study area. The depositional interpretations and stratigraphic architecture will assist in developing a geologic model to predict the distribution of oil and help characterize reservoirs.

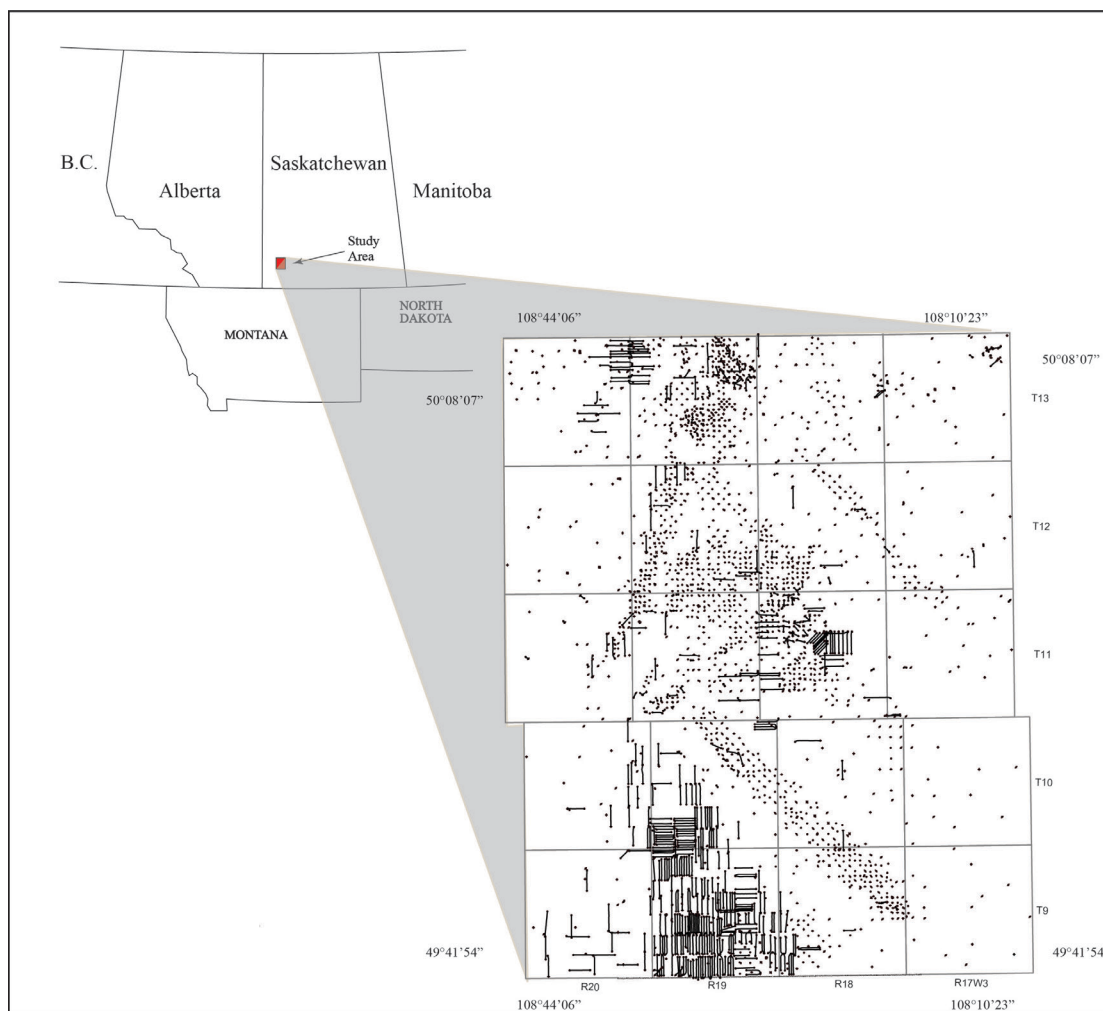
## 2. Geologic Setting

The Mesozoic Era was a time of intermittent tectonic activity in the western part of Canada. Convergent tectonics resulted in orogenic uplift and the rise of the Rocky Mountains. This uplifting was accompanied by the establishment of a foreland basin on the eastern side of the cordillera of western Canada. Southwestern Saskatchewan was part of this foreland basin (Poulton *et al.*, 1994).

The most important structural features in southwestern Saskatchewan during the Jurassic Period were the Sweetgrass Arch, the Alberta trough on the western side of the arch, and the Williston Basin to the east of the arch. The uplifting of the arch was prominent in Early to mid-Jurassic time (Brooke and Braun, 1972) and was a major sediment source for the Upper Shaunavon Member. This uplift stage was followed by subsidence during the late Middle to early Late Jurassic; this was accompanied by sea level rise and widespread transgression that led to deposition of the Shaunavon Formation.

### 3. Study Area and Methods

The main Shaunavon Formation oil pool trend in Saskatchewan extends from Townships 3 to 19 and Ranges 16 to 21 west of the Third Meridian in southwestern Saskatchewan. This oil pool trend is found along the Shaunavon syncline, which is part of the western flank on the northernmost extension of the Coburg syncline from Montana (Milner and Blakslee, 1958). For purposes of this study, the main area of interest is from Township 9, Range 17 west of the Third Meridian to Township 13, Range 20 west of the Third Meridian (Figure 2).



**Figure 2 – Top left:** Location of the study area within southwestern Saskatchewan. **Bottom right:** Detailed depiction of the study area, showing all of the wells drilled within the area. (T - Township; R - Range.)

There has been extensive drilling within the study area, with 2531 wells penetrating the Upper Shaunavon Member. To date, core from 65 wells has been examined in detail, to analyze stratigraphy, lithology, sedimentary structures and biogenic structures. Approximately 400 geophysical well logs have also been examined, to help supplement the drill core data. Facies and facies associations have been determined based on observations of lithology and sedimentary structures, and this will assist with explaining the depositional environment.

### 4. Facies Descriptions and Depositional Interpretations

The Middle Jurassic Upper Shaunavon Member has been divided into seven distinct facies based on lithology, physical sedimentary structures and biogenic structures. These are listed in descending stratigraphic order below.

### **a) Facies 1: Very Fine- to Medium-grained Peloidal Sandstone**

Facies 1 (F1) is composed of subangular to rounded, moderately sorted, very fine- to medium-grained quartz sandstone (Figure 3A). Thin planar laminations and climbing ripples are very common sedimentary structures within this facies. There are no visible trace fossils. Facies 1 sandstones are commonly highly oil stained, display good to excellent intergranular porosity, and are in close association with Facies 2. Peloids are very common and are generally 1 mm in size.

The structures in Facies 1 would suggest lower-energy conditions associated with tidal depositional systems. Permeable oil-stained sandstone represents the flanks of tidal channels (Christopher, 1964). The absence of trace fossils is indicative of the brackish-water conditions commonly found in tidal systems.

### **b) Facies 2: Bioclastic Oolitic Packstone to Grainstone**

Facies 2 (F2) is mainly composed of millimetre- to centimetre-sized carbonate shell fragments, ooids, pellets and peloids (Figure 3B). Pelecypods are the most common type of skeletal debris. Very fine, subangular to rounded quartz sandstone clasts are disseminated within the limestone. There are no visible biogenic structures. Facies 2 is in very close association with Facies 1 and displays excellent oil staining. Facies 1 and 2 are often interbedded and form the best reservoirs in the study area.

Planar bedding in Facies 2 would suggest low-energy unidirectional flow; however, thick, centimetre-sized shell fragments and rip-up clasts suggest high-energy conditions. Peloids and fine-grained ooids are not locally sourced and are likely the result of high-energy storms. Christopher (1964) suggests that F1 and F2 are closely associated, as the bioclastic coquinas that mark the base of tidal channels in F1 are also interbedded with F2 sandstones higher up within the channels.

### **c) Facies 3: Bioturbated Bioclastic Sandstone and Mudstone**

Facies 3 (F3) is composed of well-cemented, subangular to subrounded, well-sorted, very fine quartz sandstone with grey mudstone interbeds. Ooids and thin-walled pelecypod shell fragments occur locally. Facies 3 is present throughout the study area except where it has been eroded by Facies 1 and Facies 2 tidal inlet channels. Primary physical sedimentary structures within Facies 3 have been completely obliterated by intense bioturbation (Figure 3C). *Chondrites* and *Teichichnus* (Figure 3D) are very common trace fossils in this facies, while *Planolites*, *Skolithos*, *Rosselia* and *Thalassinoides* are rare. Facies 3 has very little oil staining, likely as a result of strong calcite cementation.

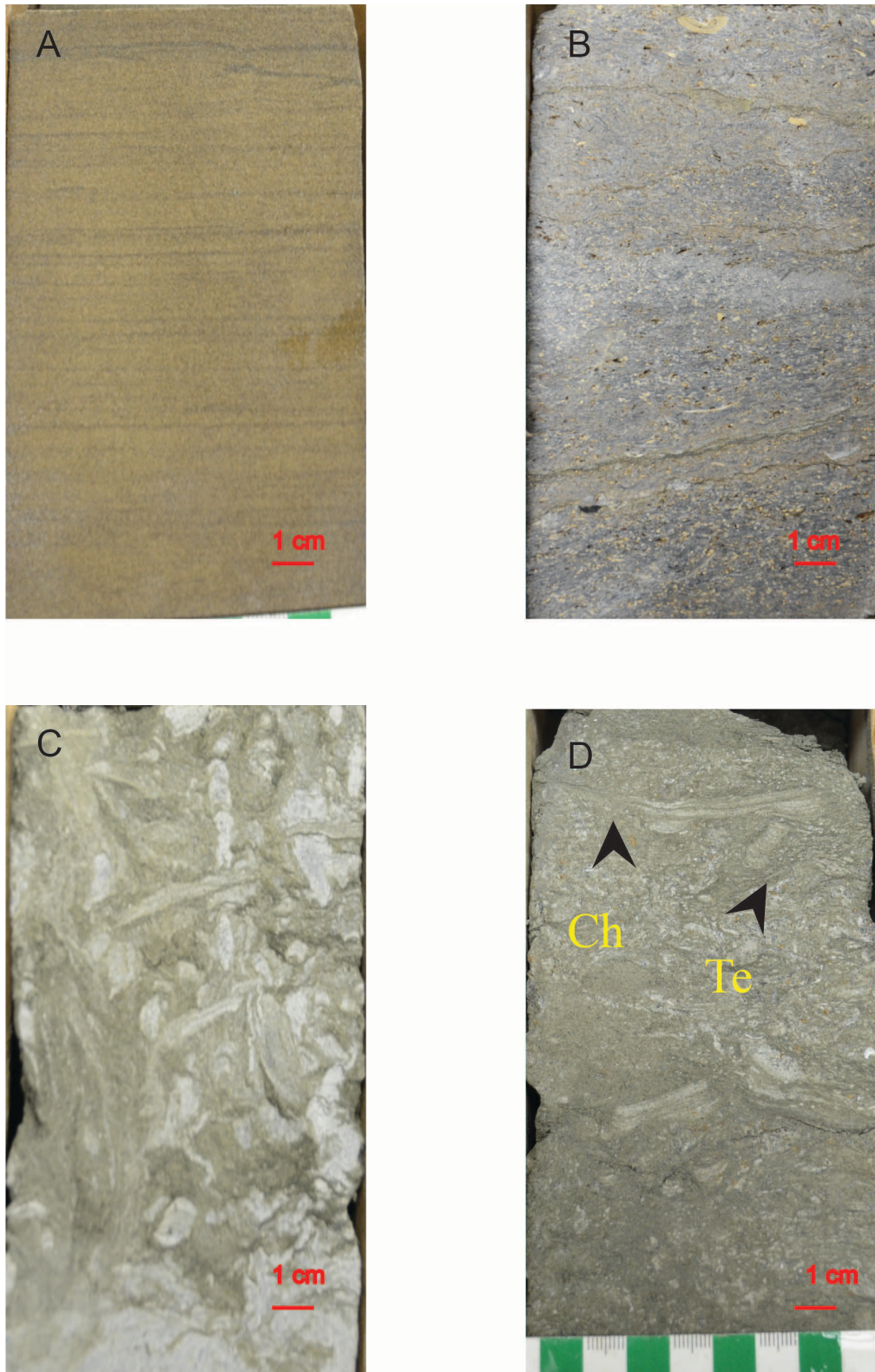
Facies 3 is interpreted to have been deposited under relatively low- to moderate-energy conditions. Variable energy conditions allowed for the deposition of mud and sandstone. The diverse assemblage of trace fossils belongs to the Cruziana ichnofacies, which is characteristic of a shoreface to subtidal wave-dominated ramp depositional environment. The wide ranges of sedimentary textures found within Facies 3 are also characteristic of the Cruziana ichnofacies (MacEachern *et al.*, 2010).

### **d) Facies 4: Well-Cemented Sandstone**

Facies 4 (F4) is composed of well-indurated, calcite-cemented, subangular to subrounded, very fine-grained sandstone. This facies has almost no oil staining throughout the entire study area. Facies 4 has been subdivided into two sub-facies based on differences in their sedimentary structures.

#### **Facies 4a: Massive Sandstone**

Facies 4a (F4a) is composed of very fine-grained, angular to subrounded quartz sandstone and is well cemented with light green calcite. Facies 4a is typically less than 75 cm and is the thinnest facies within the study area. The facies is described as massive, as there are no visible physical sedimentary or biogenic structures (Figure 4A).



**Figure 3** – Core photographs of facies 1, 2 and 3, identified in this study. **A)** Facies 1: oil-stained sandstone, from well 121/01-06-012-19W3/00, at a depth of 1363 m. **B)** Facies 2: bioclastic oolitic limestone, from well 102/09-29-013-18W3/00, at a depth of 1382 m. **C)** Facies 3: intensely bioturbated bioclastic sandstone and mudstone, from well 111/07-10-011-19W3/00, at a depth of 1354 m. **D)** Teichichnus (Te) and Chondrites (Ch), typical trace fossils in Facies 3, from well 131/11-24-011-20W3/00, at a depth of 1373 m.

#### **Facies 4b: Planar-laminated Sandstone**

Facies 4b (F4b) is distinguished from Facies 4a by being slightly coarser in grain size and containing thin (on a scale of millimetres), tabular bedding having internal planar laminations with poorly defined, low-angle cross-laminations that are arranged in repetitive successions (Figure 4B). Facies 4b sandstone is very fine- to fine-grained and better sorted than Facies 4a.

Both facies 4a and 4b were deposited in an agitated environment. The massive nature of Facies 4a may indicate a high rate of sedimentation within a tidal channel, whereas the laminated Facies 4b may indicate the normal deposition of a tidally influenced, low- to moderate-energy subtidal environment. The repeating successions in Facies 4b possibly represent tidal bundles (Dalrymple, 2010).

#### **e) Facies 5: Calcareous Shale**

Facies 5 (F5) is composed of fissile greenish grey calcareous shale mixed with minor amounts of very fine-grained, subangular quartz. Disseminated and euhedral pyrite are common within Facies 5. Thin planar laminations (Figure 4C) are very common in this facies throughout the study area. Syneresis cracks, although present, are not a common sedimentary feature. Plant and coal debris are common biogenic features.

Facies 5 is interpreted as having been deposited in relatively low-energy conditions, such as those found on a tidal mud flat or in a brackish lagoon. Plant debris, coal and laminated mudstones are common features found on tidal mud flats and associated supratidal marshes (Dalrymple, 2010). A lack of trace fossils, along with the presence of syneresis cracks, indicates highly variable salinities typical of alternating brackish and hypersaline depositional environments.

#### **f) Facies 6: Mixed Sandstone and Dolomitic Shale**

Facies 6 (F6) is composed dominantly of green dolomitic shale admixed with very fine-grained, rounded to well-rounded, well-sorted quartz sandstone (Figure 4D). Sandstone infilling of burrows is the result of moderate to intense bioturbation, which caused retexturing of the original sediments. Trace fossils are a monospecific assemblage, diminutive in size, and include common *Planolites* and rare *Skolithos* and *Teichichnus* ichnofossils. Oil staining is very common within the burrow-filling sandstone portions of the lithofacies; however, reservoir potential is low to moderate. Facies 6 is limited to the Leitchville pool in the southern part of the study area.

Facies 6 is interpreted as having been deposited in similar low-energy brackish conditions as Facies 5. Pemberton *et al.* (2009) suggest that the diminutive size and low diversity of the trace fossils are indicative of brackish-water conditions; however, salinities did not fluctuate enough to completely stop bioturbation.

#### **g) Facies 7: Interbedded Shale, Sandstone and Coquina**

Facies 7 (F7) is composed primarily of dark shale, interbedded with very fine-grained sandstone and coquina. The sandstone interbeds are very similar to Facies 1, and interbedded coquina portions are similar to Facies 2. Thin laminations are very common within the shales of Facies 7 (Figure 4E). Wavy and lenticular bedding are common features within this lithofacies. *Paleophycus* and *Thalassinoides* trace fossils are present but not common. The base of Facies 7 marks the contact between the Upper Shaunavon Member and the Lower Shaunavon Member. The contact is sharp and unconformable. Beds of sandstone and coquina, from half a metre to a metre thick, locally have excellent oil staining, but the overall reservoir quality is moderate.

Facies 7 was deposited in highly variable energy conditions on an exposed tidal flat environment. During periods of lower energy, laminated muds were deposited. These exposed tidal flats were often subject to high-energy storms and/or tidal currents, causing wave action that resulted in wavy and lenticular bedding within the sandstone. These storms would also transport carbonate grains such as ooids and shell fragments. *Paleophycus* trace fossils are characteristic of brackish-water conditions and periodic storms found on tidal flats (Pemberton *et al.*, 2009).

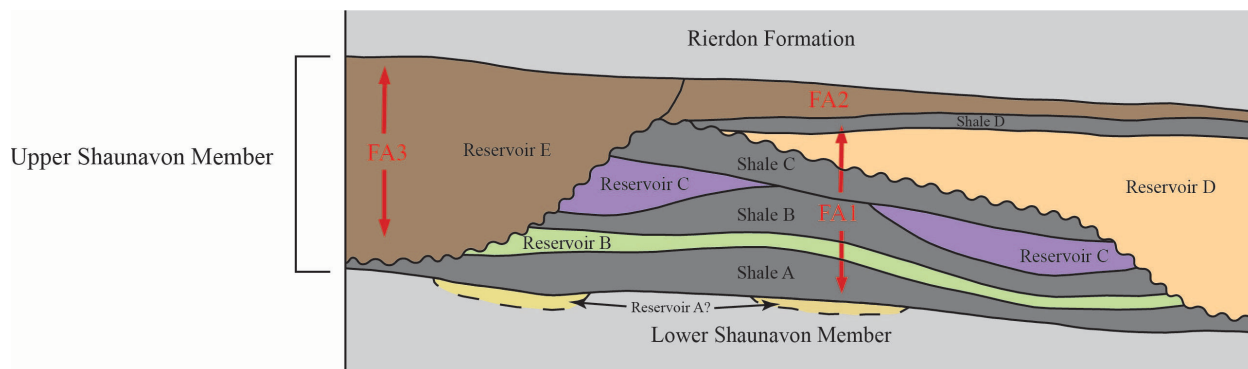


**Figure 4** – Core photographs of facies 4 to 7, identified in this study. **A)** Facies 4a: very fine-grained, well-cemented quartz sandstone, from well 101/16-09-009-18W3/00, at a depth of 1390.5 m. **B)** Facies 4b: slightly coarser-grained, planar-laminated sandstone, from well 101/07-15-009-19W3/00, at a depth of 1351.5 m. **C)** Facies 5: fissile greenish grey calcareous shale, from well 111/01-05-012-19W3/00, at a depth of 1328 m. **D)** Facies 6: intermixed sandstone and dolomitic shale, from well 150/08-18-009-18W3/00, at a depth of 1390.5 m. The sandstone infills burrows. **E)** Facies 7: interbedded shale, sandstone and coquina, from well 102/09-29-013-18W3/00, at a depth of 1188 m.

## 5. Facies Associations

The seven distinct reoccurring facies found within the Upper Shaunavon Member are very difficult to correlate across the study area. These facies are organized into three distinct facies associations, based on stacking patterns and depositional environment. A schematic model (Figure 5) of stacked reservoirs within the Upper Shaunavon Member

was documented by Marsh and Hill (2013) and will be compared to inferred facies associations identified in the present study, to assist in determining reservoir distribution and their controls.



**Figure 5** – Schematic of stacked reservoirs found within the Upper Shaunavon Member (modified from Marsh and Hill, 2013). Note the facies associations determined during the present study, labeled in red. FA1 = Facies Association 1, FA2 = Facies Association 2, FA3 = Facies Association 3.

### a) Facies Association 1: Tidal Flats

Facies Association 1 (FA1) is composed of facies F1, F2, F4a, F4b, F5, F6 and F7, and occurs at the base of the Upper Shaunavon Member. FA1 is dominated by calcareous and dolomitic muddy tidal flats consisting of facies F5, F6 and F7. Thin laminations and wavy ripples are common bedding features on the tidal flats. Coal and plant material are commonly observed within the muds of FA1, and amount of bioturbation is low to moderate.

The muddy tidal flats in FA1 are separated by coalescing, migrating tidal gullies made up of facies F1 and F2 sandstone and coquinas that range from 0.5 to 4 metres in thickness. These gullies offer the best potential reservoirs within FA1; however, they are very difficult to correlate across a large distance. These channels could be classified as Reservoirs A, B and C when compared to the schematic of Marsh and Hill (2013) (Figure 5). Interbedded F1 sands and F5 muds form beds of inclined heterolithic stratification (IHS), characteristic of tidal flats (Dalrymple, 2010). The lack of bioturbation, along with the erosive lags commonly found at the base of F1 and F2, are all indicative of smaller tidal channels (Dalrymple, 2010).

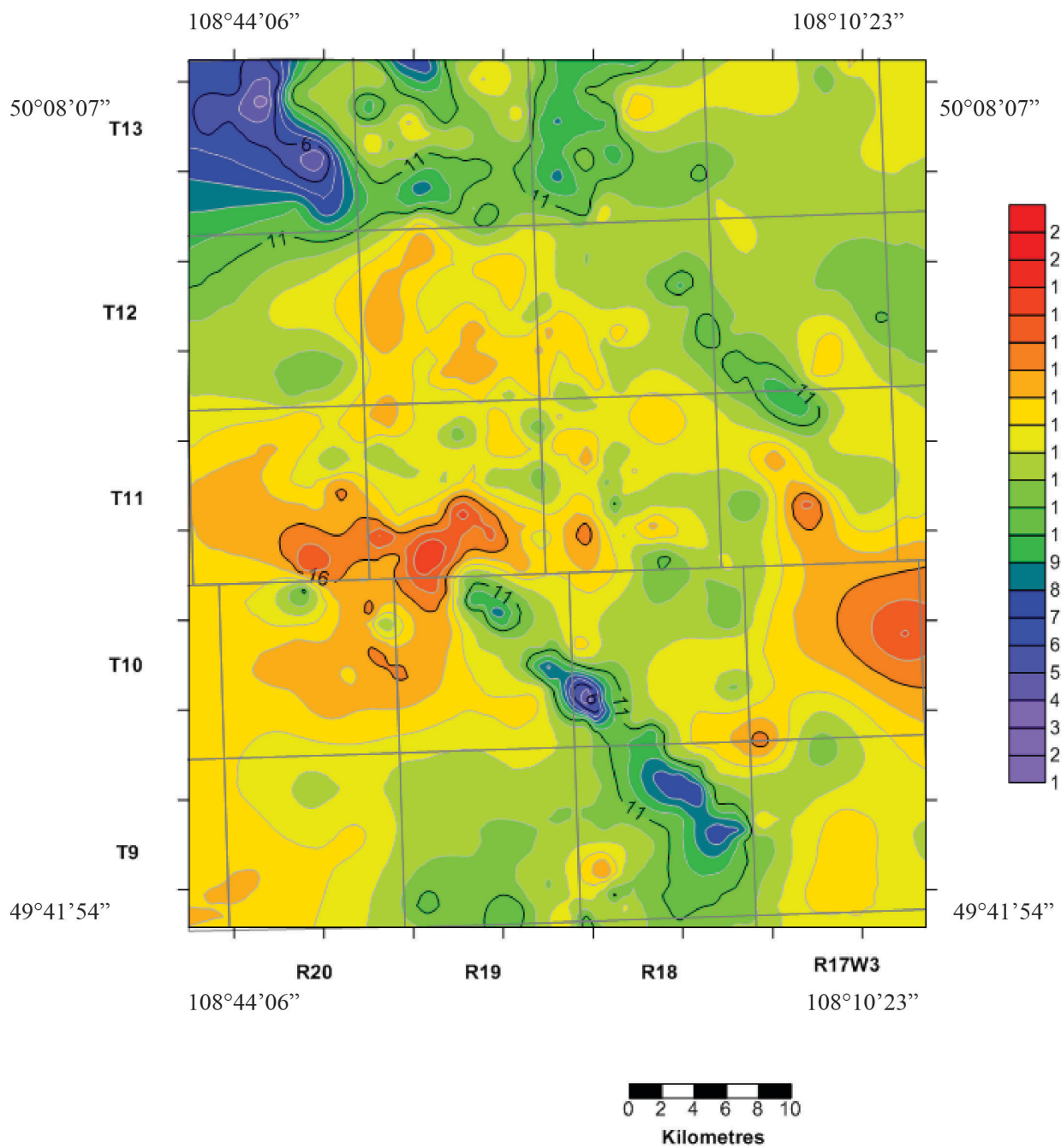
FA1 is present throughout the study area and has an average thickness of 12.6 metres (Figure 6). FA1 is less than 1 metre thick where it is eroded by Facies Association 3, which developed in larger tidal inlet channels in structural lows.

### b) Facies Association 2: Subtidal to Shoreface Wave-dominated Ramp

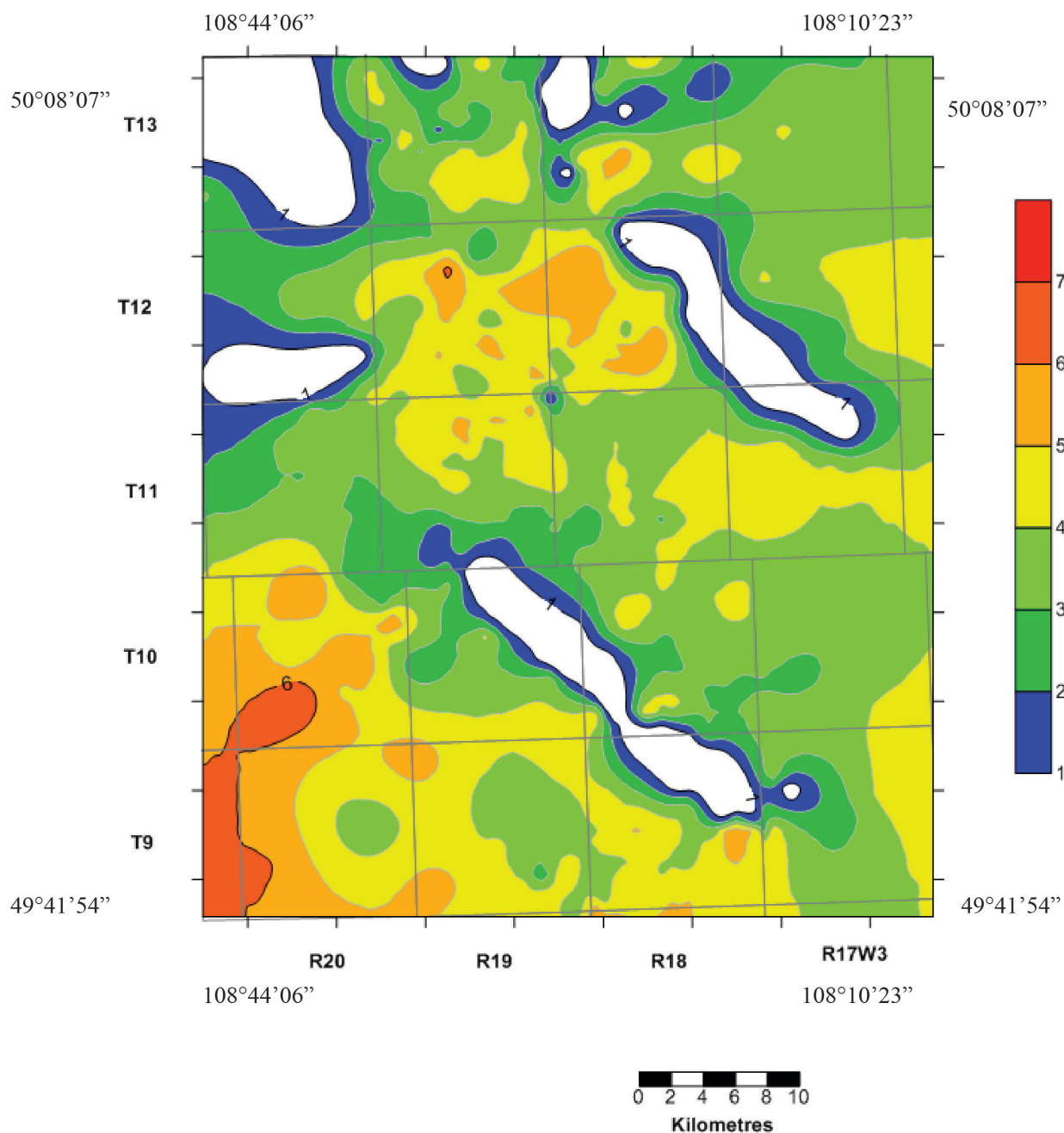
Facies Association 2 (FA2) is composed entirely of Facies 3 and occurs at the top of the Upper Shaunavon Member, overlying FA1 tidal flats. FA2 is an intensely bioturbated, well-cemented, very fine-grained sandstone interbedded with bioclastics and mudstone at the base. Physical sedimentary structures are absent due to intense bioturbation. Trace fossils belong to the *Cruziana* ichnofacies and include *Chondrites*, *Teichichnus*, *Planolites*, *Skolithos*, *Thalassinoides* and *Rosselia*.

The preservation of *Chondrites*, *Teichichnus* and *Rosselia* suggests that conditions were fully marine at time of deposition (Pemberton *et al.*, 2009). Bioclastic fragments and carbonate grains mixed with shale suggests shallow ramp settings (Tucker and Wright, 1990). There is almost no oil production from FA2.

FA2 has an average thickness of 3.1 metres in the study area and is only absent where eroded by FA3 (Figure 7).



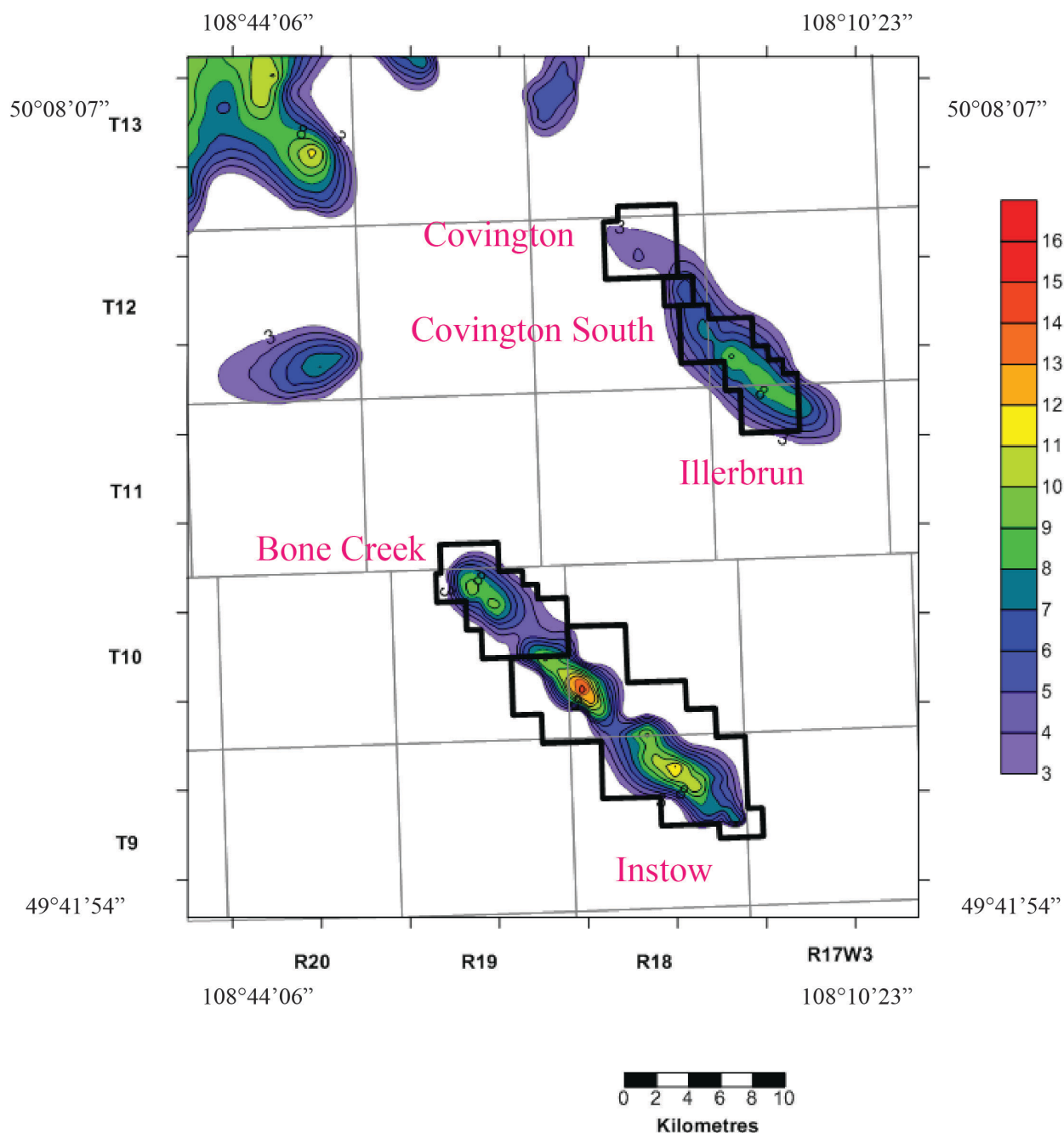
**Figure 6** – Isopach map of Facies Association 1. T - Township; R - Range. Contour interval is 1 m.



**Figure 7** – Isopach map of Facies Association 2. T - Township; R - Range. Contour interval is 1 m.

### c) Facies Association 3: Tidal Inlet Channels

Facies Association 3 (FA3) is composed of F1 and F2 sandstone and coquina. FA3 deposits located in the Bone Creek, Instow, Illerbrun, Covington and Covington South pools (Figure 8) represent the thickest (up to 16 m) and best-producing reservoirs in the study area. The Bone Creek and Instow pools have produced  $14.3 \times 10^6 \text{ m}^3$  (90 MMBbl) to date. Planar laminations and climbing ripples occur within FA3; however, these sedimentary features are usually obscured by extensive oil staining. Inclined planar bedding is locally observed in the coquina. Bioturbation is absent from FA3.



**Figure 8** – Isopach map of Facies Association 3. T - Township; R - Range. Contour interval is 1 m.

Tidal inlet channels from FA3 are distinguished from tidal channels in FA1 based on thickness and areal extent. Tidal inlet channels are typically greater than 5 metres in thickness. Hayes and FitzGerald (2013) suggest that tidal inlets are major tidal channels that provide tidal connections between marshes, bays and lagoons. Tidal inlets are also characterized by vertical stacking of individual facies and erosive lags at the base. The pebble lag found at the base of FA3 is part of a regional unconformity identified by Christopher in 1964. FA3 is equivalent to Reservoir E identified by Marsh and Hill (2013) and to the informal unit U3 defined by Christopher (1964).

FA3 is restricted to sub-Mesozoic structural lows that generally trend from northwest to southeast within the study area. FA3 ranges in thickness from 3 to 16 metres, with an average thickness of 7.7 metres (Figure 8).

## 6. Summary

Core examination, supported by geophysical well data, has identified seven reoccurring facies within the Middle Jurassic Upper Shaunavon Member in southwestern Saskatchewan. These facies include 1) very fine- to medium-grained peloidal sandstone; 2) bioclastic, oolitic packstone to grainstone; 3) bioturbated bioclastic sandstone and mudstone; 4) well-cemented sandstone; 5) calcareous shale; 6) mixed sandstone and dolostone; and 7) shale, sandstone and coquina interbeds. The seven facies have a complex stacking pattern and are divided into three facies associations based on their depositional environment. Integration of interpreted depositional system and stratigraphic architecture assisted in determining oil reservoir distribution. Sedimentary structures are mostly indicative of unidirectional flows. Thin, millimetre- to centimetre-sized laminations and planar beds are interpreted as having formed in a low- to moderate-energy depositional environment. Climbing ripples and pebble lags are interpreted as indicative of slightly higher-energy conditions.

Bioturbation in F3 is intense, displaying a high diversity and a wide range of scales. Ichnofossils are absent within F1 and F2 channel sandstones and coquinas. Within the shales, ichnofossils are generally very small and display a trace fossil assemblage of low diversity.

Initial interpretation of lithology, sedimentary structures and facies associations suggests mostly a marginal-marine, tidally influenced depositional setting throughout most of the Upper Shaunavon Member, which transitions to a shoreface setting at the top of the member. The presence of low intensity, diminutive and low diversity ichnofossils along with syneresis cracks suggests a stressed, variable salinity, brackish environment. Overall deposition occurred on tidal flats separated by numerous coalescing sandstone and coquina channels. Thick tidal inlet channel deposits accumulated in structural lows that trend from northwest to southeast.

The most prolific oil production in the study area occurs in the thick tidal inlet deposits in the Instow, Bone Creek, Covington and Illerbrun pools, which are equivalent to Reservoir E identified by Marsh and Hill (2013). Oil production, although not as prolific, also occurs in tidal bars and coalescing channels equivalent to Reservoirs A, B, C and D of Marsh and Hill (2013).

## 7. Future Work

Mapping the Lower Shaunavon Member and the Madison Group is crucial to understanding depositional controls and oil entrapment within the Upper Shaunavon Member. Future research will also include a detailed examination of porosity and permeability values from core analyses. Mapping of porosity and permeability, combined with production maps, should help identify optimal areas of production within Upper Shaunavon Member reservoirs.

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