Facies Analysis and Reservoir Characterization of the Middle Jurassic Upper Shaunavon Member, Southwestern Saskatchewan

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Abstract

In southwestern Saskatchewan, the mixed carbonate-clastic Middle Jurassic Upper Shaunavon Member has been a hydrocarbon-rich producer for decades. Detailed examination of 65 cores has identified five re-occurring sedimentary facies: 1) peloidal sandstone; 2) strongly bioturbated calcareous sandstone; 3) laminated, calcareous silty shale; 4) bioclastic sandy packstone to grainstone; and 5) interbedded silty fossiliferous mudstone. Oil is primarily found in facies 1 and 4.

A series of maps illustrating the distribution and thickness of two distinct reservoirs (lower and upper) within the Upper Shaunavon Member have been created from detailed core examination and facies analysis coupled with geophysical well-log analysis. Facies analysis and mapping of current producing reservoirs assisted in the creation of a predictive model for hydrocarbons within the Upper Shaunavon Member's main producing oil field trend in southwestern Saskatchewan. This investigation determined that there is excellent potential to further expand the play to the north and west; however, there is very little potential to the east of the current producing oil field.

Keywords*: Upper Shaunavon Member, Shaunavon Formation, Middle Jurassic, reservoir facies, carbonate-clastic mixing, reservoir characterization, geophysical well-log analysis, predictive model of hydrocarbons, medium oil producer*

1. Introduction

The Middle Jurassic Upper Shaunavon Member in southwestern Saskatchewan has been a prolific medium oil producer since the early 1950s. The Upper Shaunavon Member is one half of the Shaunavon Formation and comprises heterogenous mixed carbonate-clastic sediments. The Lower Shaunavon Member comprises purely carbonate sediments. Typically, the Upper Shaunavon Member has been produced conventionally from vertical wells, and, as of September 2023, it has produced approximately 73.1 million m^3 (459.8 million barrels) of oil throughout Saskatchewan.

The study area encompasses an area from Township 14, Range 17 west of the Third Meridian (Tp. 14, Rge. 17W3M) in the southeast to Tp. 16, Rge. 29W3M in the northwest (Figure 1). This area includes eight Upper Shaunavon Member producing pools: Delta West, Delta, North Premier, Antelope Lake, Antelope Lake West, Antelope Lake South, Suffield and Gull Lake North.

The purpose of this study was to examine sedimentological characteristics in order to identify individual facies within the Upper Shaunavon Member and to use this analysis to create a predictive model for the distribution of hydrocarbons. Analysis determined that, in the study area, there are three main reservoir facies within the Upper

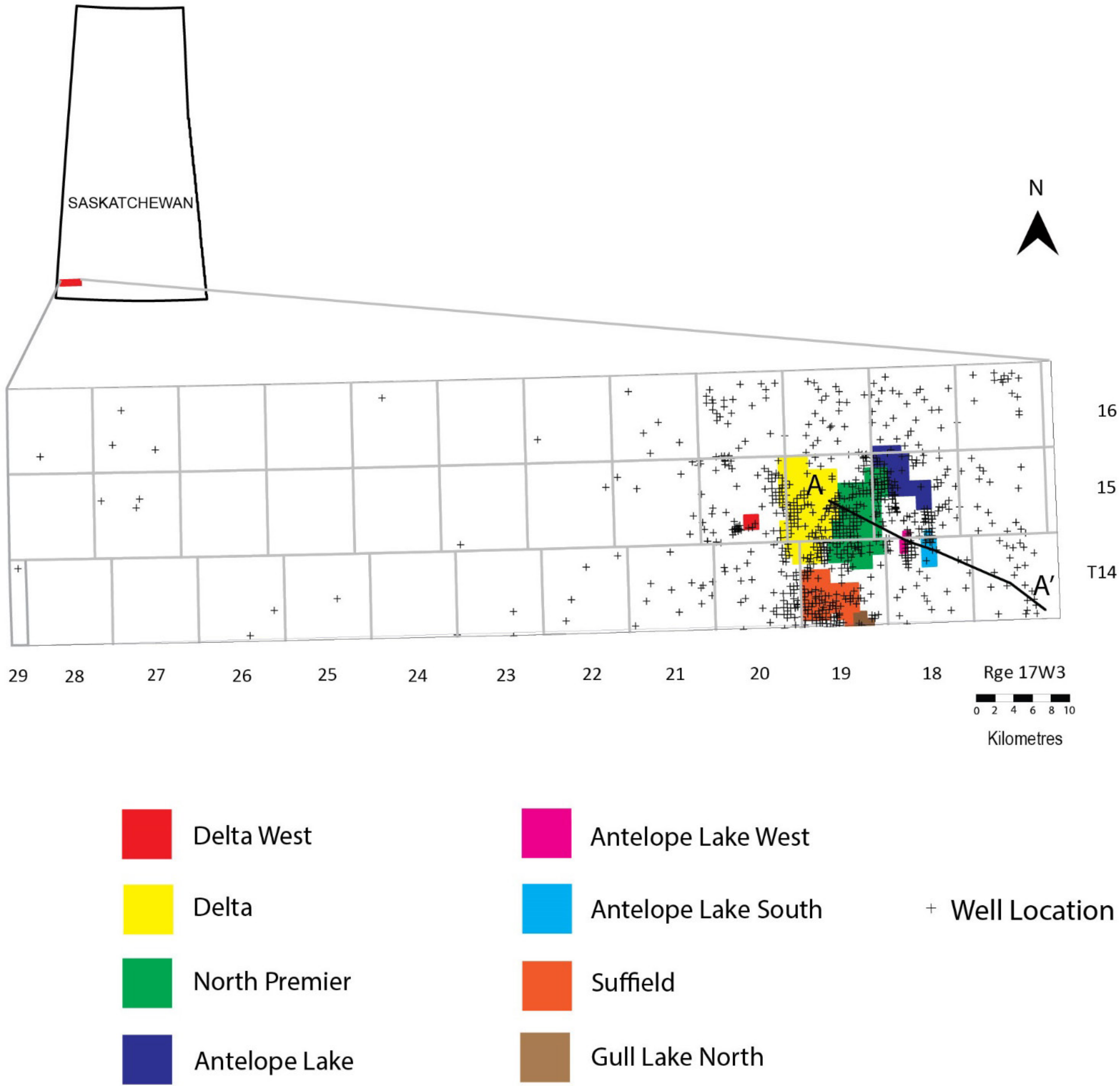

Figure 1 – *Location of the study area in southwestern Saskatchewan (upper map) and the outline of the eight oil pools that produce from the Upper Shaunavon Member (main part of the figure). Note that core locations are not shown on the map, and only wells used for this study are shown. Also shown is the location of cross-section A–A′ (Figure 14). Abbreviations: T – Township; Rge – Range; W – west.*

Shaunavon Member: peloidal sandstone, strongly bioturbated calcareous sandstone and bioclastic sandy grainstone to packstone. There are also two main reservoirs: a lower reservoir and an upper reservoir.

2. Previous Work

Initial stratigraphic work on the Upper Shaunavon Member was undertaken by Milner and Thomas (1954) and Milner and Blakslee (1958). Subsequently, Wall (1960), Pocock (1970,1972) and Kreis (1989) focused on palynology, and Paterson (1968) identified megafossils. One of the oldest comprehensive studies of the Upper Shaunavon Member was undertaken by Christopher (1964) and focused on stratigraphy, facies analysis, structural influences and depositional environments. More recent studies, such as Lincoln's (1990) thesis on the Bone Creek pool, have focused on local hydrocarbon distribution and controls. Additionally, Marsh and Hill (2013) characterized Upper Shaunavon Member reservoirs in the southern half of the oil pool trend; Hill and Salad Hersi (2016) and Hill (2018) focused on facies analysis and reservoir characterization in the middle region of the oil pool trend.

3. Upper Shaunavon Member Geology

The Middle Jurassic Upper Shaunavon Member is Bathonian in age and comprises one stratigraphic half of the Shaunavon Formation (Figure 2). In the study area, the Upper Shaunavon Member is overlain by the Rierdon Formation of the Vanguard Group and unconformably overlies the Lower Shaunavon Member. The Upper Shaunavon Member consists of mixed carbonate-clastic, thin sheet-like sediments, whereas the Lower Shaunavon Member comprises relatively homogenous carbonate sediments (Christopher, 1964).

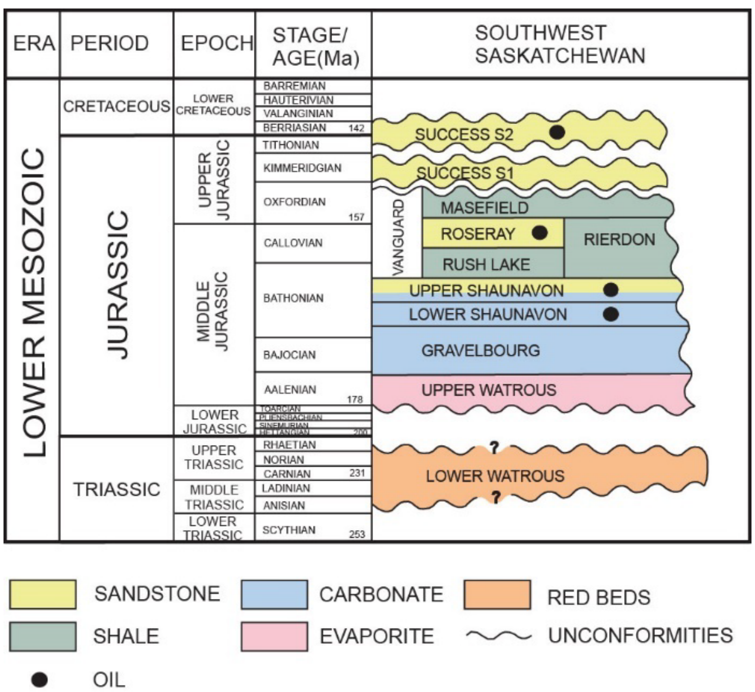

***Figure 2 –** Stratigraphic correlation chart for southwestern Saskatchewan (*modified from *Saskatchewan Ministry of Energy and Resources, 2022).*

4. Methods

Detailed sedimentological analysis of 65 cores was complemented with a suite of over 880 geophysical well logs (Figure 1). Facies analysis was primarily derived from the examination of the cores. This dataset was used to create a series of reservoir isopach maps, a structure map and cross-section. All of the maps for this study were created with Golden Software's Surfer 24 using a kriging algorithm.

5. Facies Analysis

The Upper Shaunavon Member has been divided into five distinct facies based on lithology and sedimentary structures. Although these facies may appear throughout the Upper Shaunavon Member, generally, they were observed, and are listed herein, in descending stratigraphic order. Facies 1, 2 and 4 comprise the reservoirs that are discussed in detail in the next section; facies 3 and 5 are not found within the reservoirs.

a) Facies 1: Very Fine- to Fine-Grained Peloidal Sandstone

Facies 1 (F1) is composed of moderately to well-sorted sandstone with subrounded to rounded, very fine to fine grains (Figure 3A). Climbing ripples are a very common sedimentary structure (Figure 3B). Trace fossils include *Cruziana* isp. and *Rosselia* isp. (Figures 3C and 3D, respectively). Facies 1 sandstones are generally very well oil stained. Peloids are present and are generally 1 mm in size.

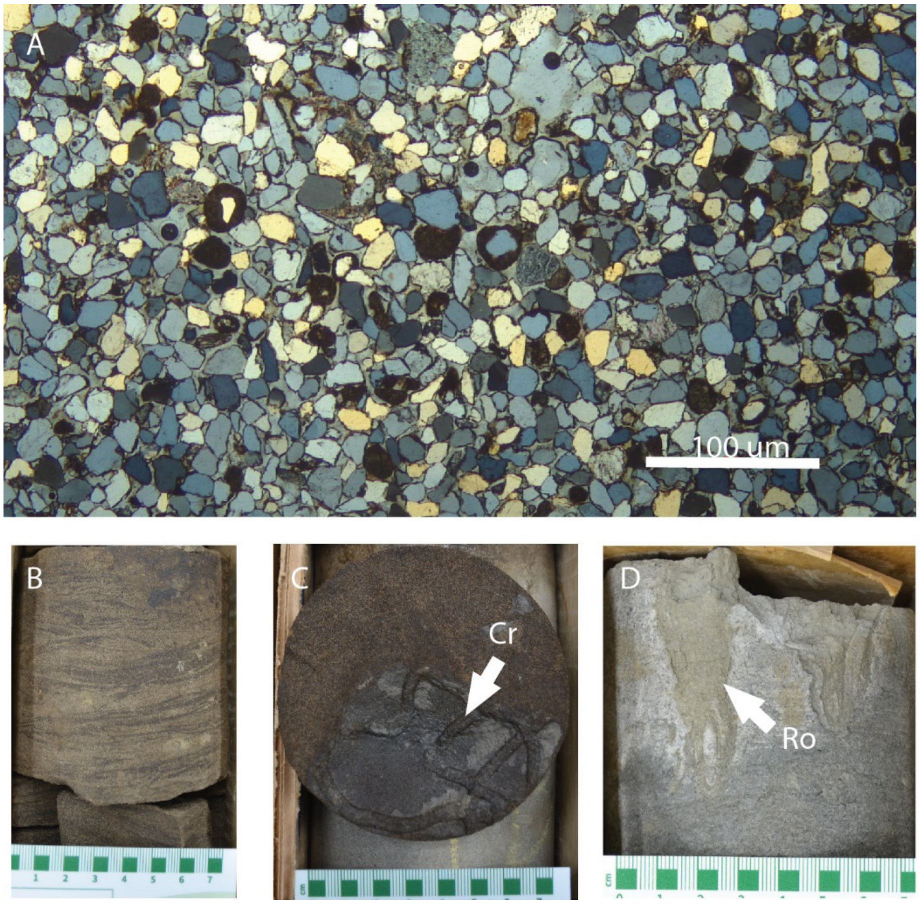

Figure 3 – A) *A thin section photograph from a sandstone in well 101/04-31-014-19W3/00; 94G156 at a depth of 1068.5 m displaying subrounded to rounded, very fine to fine grains.* ***B)*** *Climbing ripples from well 111/15-03-014-19W3/00; 67E065 at a depth of 1136.0 m.* ***C)*** *A* Cruziana *isp. (Cr) trace fossil from well 101/16-16-015-19W3/00; 65G172 at a depth of 1058.0 m.* ***D)*** *A* Rosselia *isp. (Ro) trace fossil from well 101/11-21-016-20W3/00; 66I004 at a depth of 1023.0 m.*

b) Facies 2: Strongly Bioturbated Calcareous Sandstone

Facies 2 (F2) is a well-cemented quartz sandstone with subangular to rounded very fine grains. Primary sedimentary structures have typically been obliterated by intense bioturbation; the most common trace fossils are *Teichichnus* isp., *Chondrites* isp. and *Rosselia* isp. (Figure 4). Shell fragments and peloids are present but uncommon. Oil staining in F2 is often patchy, weak and typically concentrated in the trace fossils.

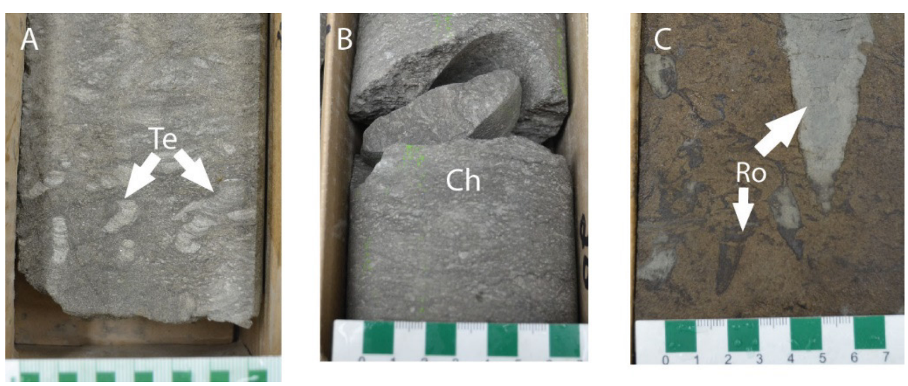

Figure 4 – *Core photographs showing* ***A)*** Teichichnus *isp. (Te) trace fossils from well 111/05-03-014-19W3/00; 97D098 at a depth of 1124.0 m;* ***B)*** Chondrites *isp. (Ch) trace fossils from well 121/05-06-015-18W3/00; 88G001 at a depth of 1095.0 m; and* ***C)*** Rosselia *isp. (Ro) trace fossils from well 101/13-11-013-23W3/00; 66F082 at a depth of 1018.4 m.*

c) Facies 3: Laminated Calcareous Silty Shale

Facies 3 (F3) is predominantly composed of calcareous shale with minor amounts of very fine sand-sized or silt-sized quartz. Planar laminations are a very common sedimentary structure (Figure 5A). Syneresis cracks are also present but not common. There is a significant amount of carbonate-clastic mixing within this facies (Figure 5B). There is no oil staining in this facies.

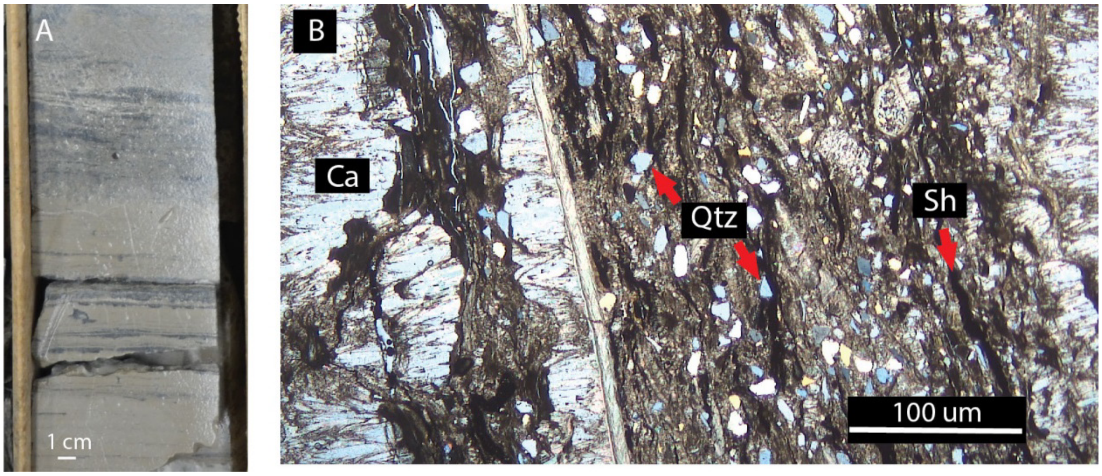

Figure 5 – A) *A core photograph showing thinly laminated shale from well 121/03-09-014-19W3/00; 95I155 at a depth of 1135.8 m.* ***B)*** *A thin section photograph showing carbonate-clastic mixing from well 121/11-02-015-19W3/00; 66C011 at a depth of 1085.5 m. Abbreviations: Ca – calcite; Qtz – quartz; Sh – shale.*

d) Facies 4: Bioclastic Sandy Packstone to Grainstone

Facies 4 (F4) is mainly composed of centimetre-sized carbonate shell fragments, peloids and sandstone comprising very fine– to fine-grained quartz (Figure 6B). Planar laminations are present but rare. Facies 4 packstone and grainstone typically have vuggy and moldic porosity, and they often have excellent oil staining (Figure 6A). Cementation of pores is the main factor preventing oil saturation.

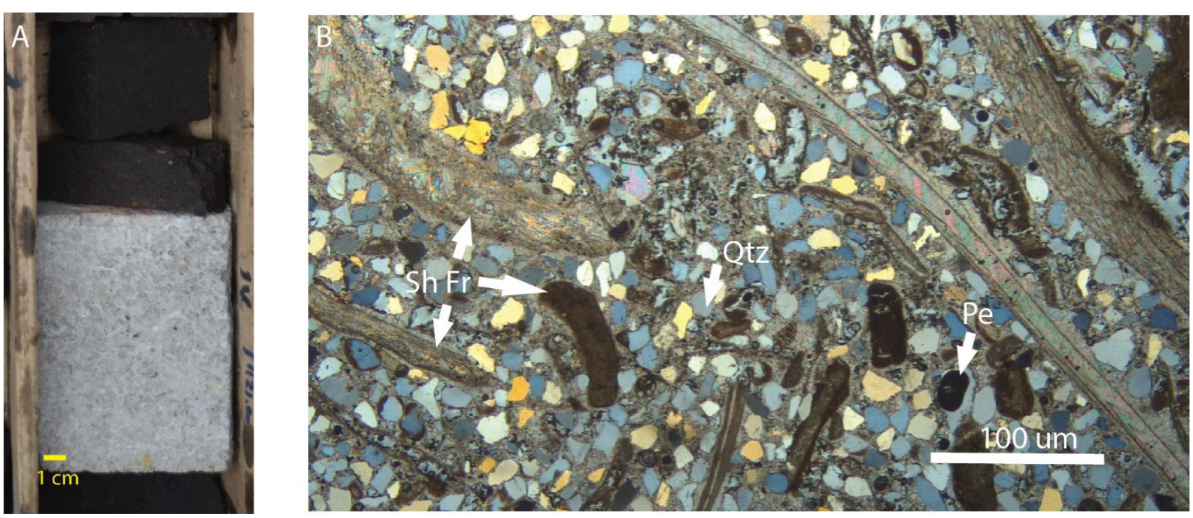

Figure 6 – A) *A core photograph from well 131/11-10-014-19W3/00; 96G067 at a depth of 1120.8 m showing moldic porosity and pervasive oil staining. The non–oil-stained interval is due to core analysis testing.* ***B)*** *A thin section photograph from well 131/11-10-014-19W3/00; 96G067 at a depth of 1126.0 m showing carbonate shell fragments (Sh Fr), peloids (Pe), quartz (Qtz) and the vast amount of carbonate-clastic mixing that occurred within this facies.*

e) Facies 5: Interbedded Silty Fossiliferous Mudstone

Facies 5 (F5) is composed of calcareous mudstone interbedded with sandstone that is comprised of silty to very fine–grained quartz (Figures 7A and 7B). Shell fragments also occur within this facies. Thin, planar laminations are common. Mudstone, silt and fossil content within this facies are highly variable throughout the study area illustrating the vast amount of carbonate-clastic mixing that occurred. There is no oil staining in this facies.

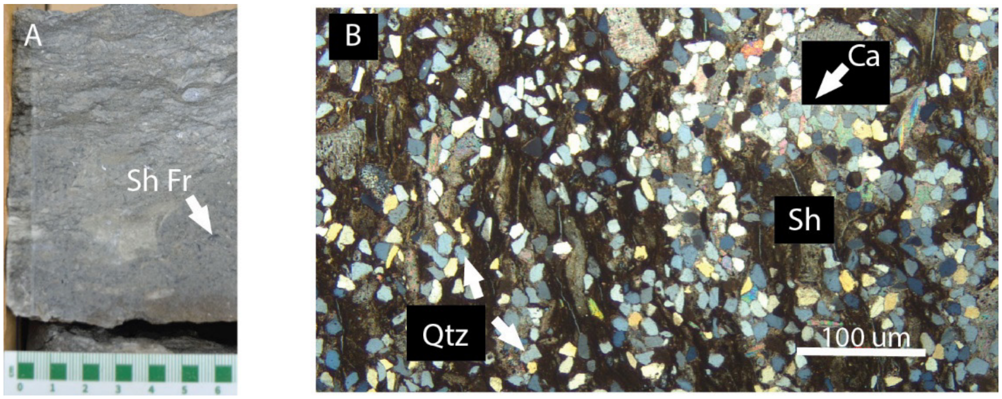

Figure 7 – A) *A core photograph from well 101/12-29-015-19W3/00; 67E071 at a depth of 1139.0 m showing mudstone with thin shell fragments (Sh Fr).* ***B)*** *A thin section photograph from well 131/04-32-015-18W3/00; 93J261 at a depth of 1040.8 m showing calcareous silty mudstone. Abbreviations: Qtz – quartz; Ca – calcite; Sh – shale.*

6. Reservoir Characteristics and Distribution

In this study, two reservoirs were identified within the Upper Shaunavon Member: a lower reservoir and an upper reservoir. Each reservoir comprises mixed carbonate-clastic sediments; however, their sedimentary features and depositional environments are distinct. Each reservoir also varies greatly in thickness and lateral distribution throughout the study area. Carbonate-clastic mixing plays a significant role in reservoir quality and hydrocarbon distribution.

a) Lower Reservoir

Description

The lower reservoir is composed of both a moderately sorted sandstone with subrounded to rounded, fine-grained quartz (F1) and millimetre- to centimetre-sized carbonate shell fragments comprised primarily of brachiopod shells (F4). Carbonate sediments occur as both packstone to grainstone beds and randomly within clastic beds. Vuggy and moldic porosity are common in the carbonate beds. The reservoir often has pervasive medium to heavy oil staining.

Distribution

The lower reservoir F4 sediments vary from 1 to 4.5 m in thickness and pinch out towards the southeast and the northwest (Figure 8). This reservoir is the thickest and best-producing reservoir in the Suffield pool. The lower reservoir F1 clastic sediments vary from 1 to 13 m in thickness and are absent towards the east (Figure 9). This reservoir is the thickest in the Delta West pool.

Geophysical Log Response

Figure 10 displays an example of ideal reservoir conditions from well 131/11-10-014-19W3/00; 96G067 within the Suffield pool.[1] Low gamma-ray signatures indicate very low clay content; this is the case for the lower reservoir. Resistivity log responses are typically very high due to excellent oil saturation, which is also easily visible in core; lower resistivity log responses may be due to a lack of oil saturation caused by cementation and loss of porosity and permeability. Porosity log responses are consistently high due to excellent moldic and vuggy porosity in the carbonate rocks and excellent intergranular porosity in the sandstone, which are both easily visible in core.

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[1] Note that spontaneous potential is on the figure but is not discussed here.

Photoelectric log responses are highly variable due to the amount of carbonate-clastic mixing and often have a serrated profile.

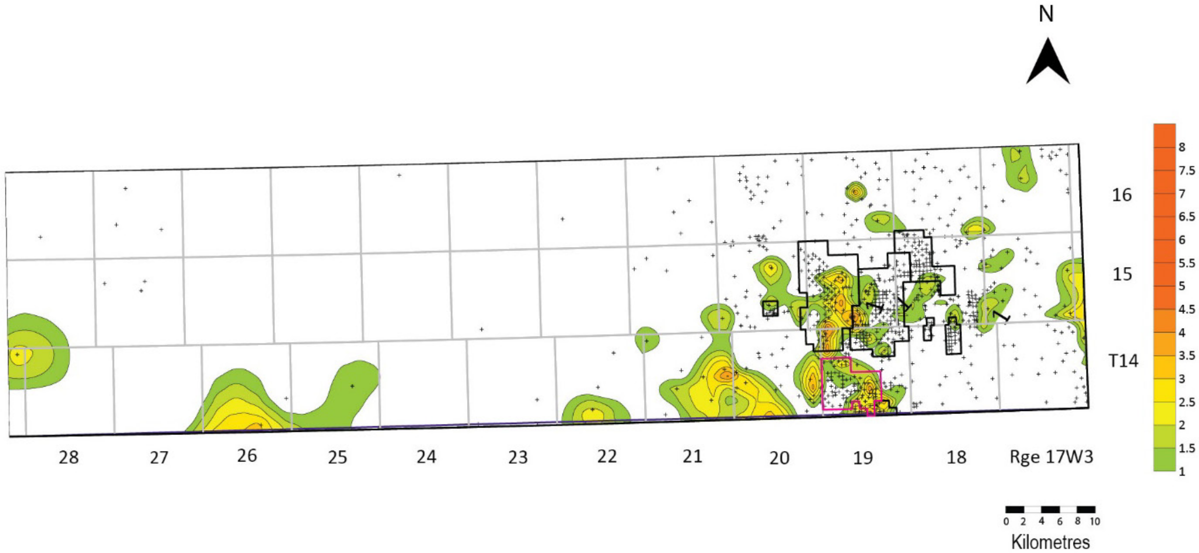

***Figure 8 –** An isopach contour map of the lower reservoir F4 packstone to grainstone. Oil and gas pool boundaries are outlined in black; the Suffield pool is outlined in pink. Facies 4 is the dominant facies within this reservoir although clastic sediments are still present. Abbreviations: T – Township; Rge – Range; W – west.*

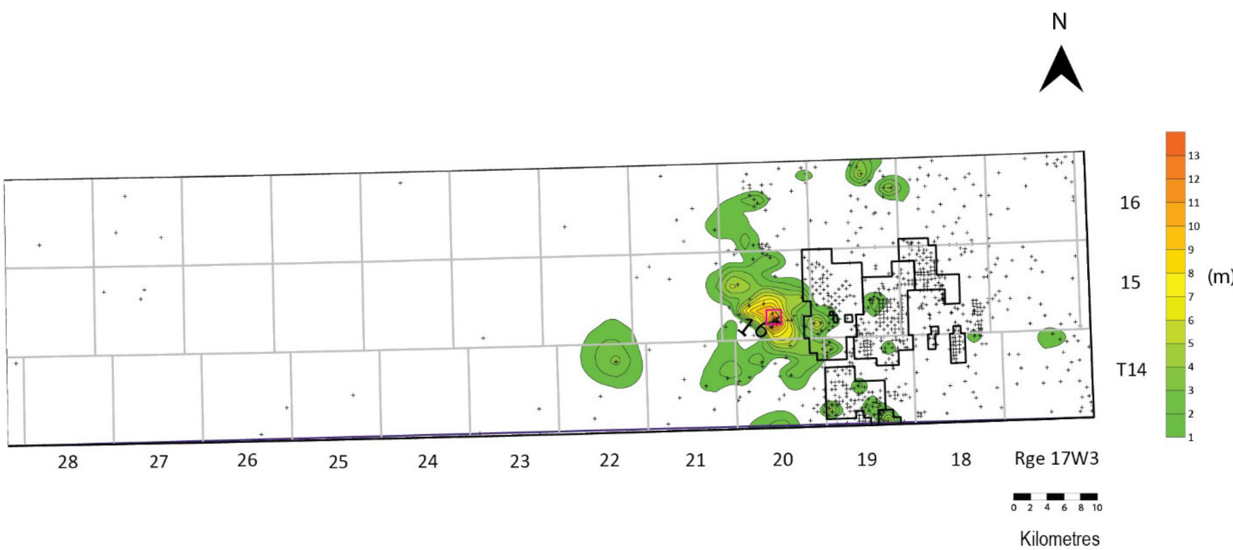

***Figure 9 –** An isopach contour map of the lower reservoir F1 peloidal sandstone. Oil and gas pool boundaries are outlined in black; the Delta West pool is highlighted in pink (Tp. 15, Rge. 20W3). Abbreviations: T – Township; Rge – Range; W – west.*

b) Upper Reservoir

Description

The upper reservoir is primarily composed of well-sorted peloidal quartz sandstones that are very fine to fine grained (F1) and strongly bioturbated calcareous sandstone (F2). Although F2 is present within this reservoir, it is often thin and not areally extensive, therefore, a separate isopach was not created. Where the upper reservoir consists primarily of F1 peloidal sandstones, oil staining is often pervasive; oil staining within F2 is often patchy and weak. Facies 4 packstones to grainstones are also present. Carbonate-clastic mixing in this reservoir is not as common as it is in the lower reservoir particularly to the north and northwest of the study area.

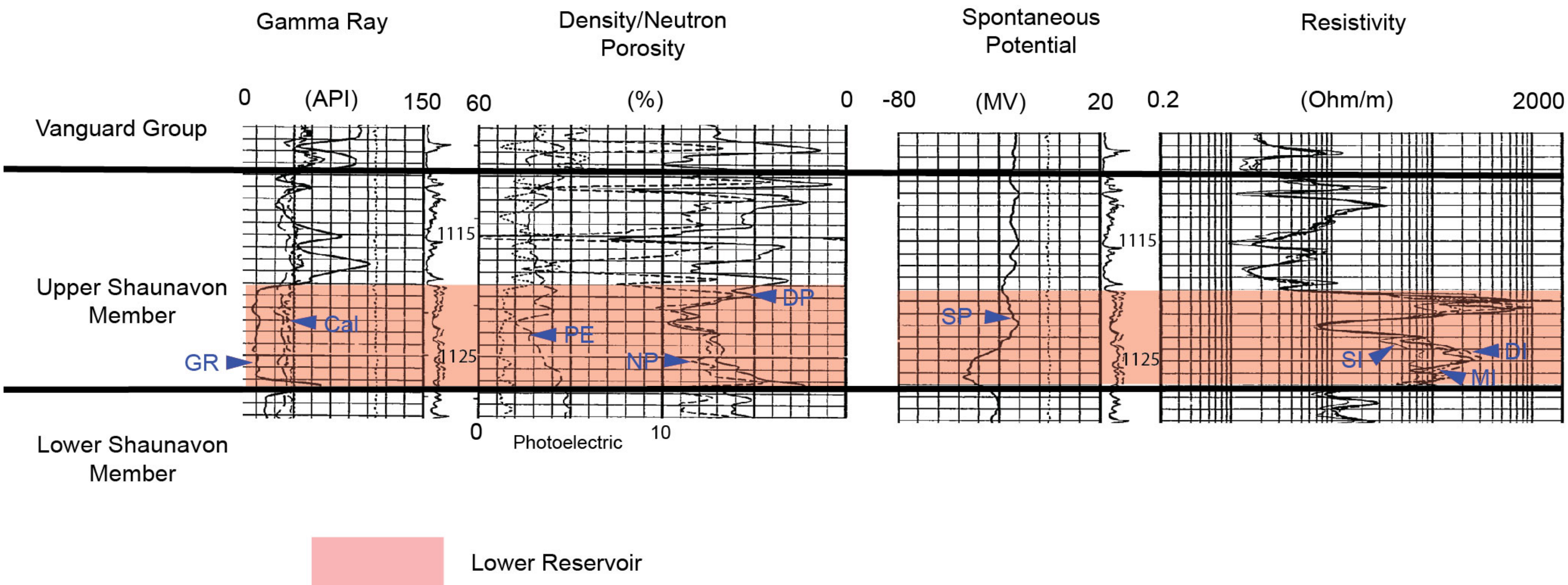

Figure 10 *– Gamma-ray, photoelectric, density/neutron porosity, spontaneous potential and resistivity logs from well 131/11-10-014-19W3/00; 96G067 within the Suffield pool. These logs demonstrate typical Upper Shaunavon Member lower reservoir well-log signatures for the study area. The photoelectric curve at 1122.0 m has a value of 2.0 barns/electron indicating F1 sandstones; photoelectric values from 1122.0 to 1127.0 m are between 2.0 and 4.5 barns/electron highlighting F4 carbonate sediments. High resistivity reading for the entirety of the lower reservoir indicates excellent oil saturation, which is also easily visible in core. The caliper log indicates the wellbore is generally the same size throughout this interval. The decrease in spontaneous potential at 1124.0 m indicates a facies shift from shale to a reservoir facies. Abbreviations: API – American Petroleum Institute; GR – gamma ray; Cal – caliper; PE – photoelectric; NP – neutron porosity; DP – density porosity; MV – millivolts; SP – spontaneous potential; SI – shallow induction; MI – medium induction; DI – deep induction.*

Distribution

The upper reservoir varies from 2 to 18 m in thickness with the thickest accumulation of sediments to the north in Tp. 16, Rge. 19 and 20W3 (Figure 11). The upper reservoir is the best-producing reservoir within the Delta pool.

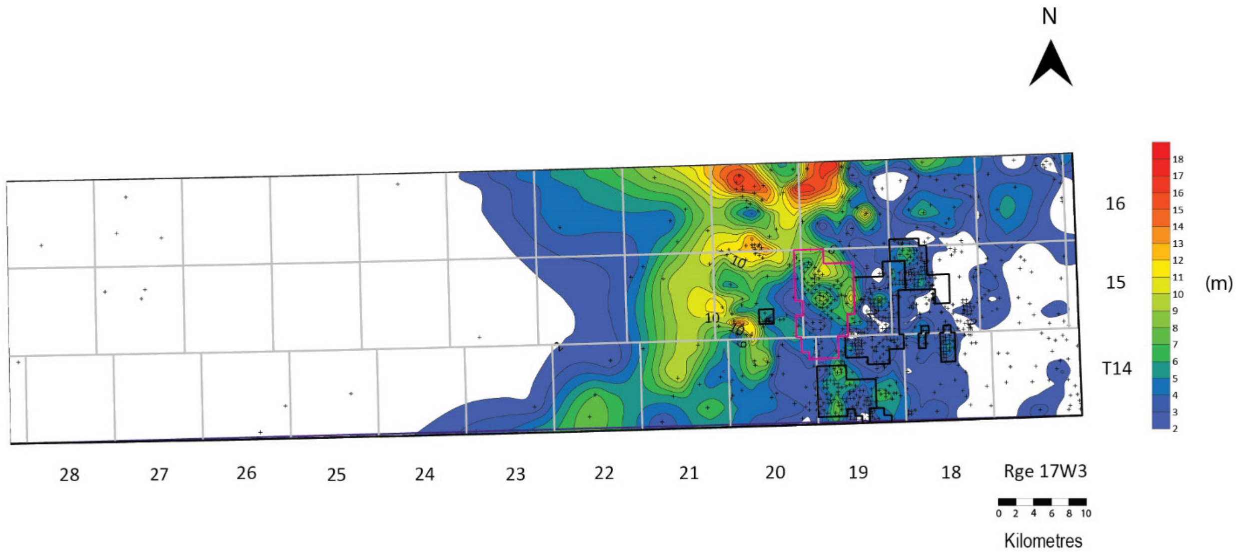

***Figure 11 –** An isopach contour map of the upper reservoir F1 peloidal shoreface sandstone and the F2 bioturbated calcareous sandstone. Oil and gas pool boundaries are outlined in black; the Delta pool is highlighted in pink. Abbreviations: T – Township; Rge – Range; W – west.*

Geophysical Log Response

Figure 12 displays an example of ideal reservoir conditions from well 131/11-10-014-19W3/00; 96G067 within the Suffield pool. Low gamma-ray signatures indicate a very low clay content within the upper reservoir. Where excellent oil saturation is visible in core, resistivity log responses are consistently high. Sonic porosity log responses are also consistently high within the F1 peloidal sandstones. Porosity log responses are significantly lower if F2 cemented sandstones and F4 carbonate packstones to grainstones are present. Photoelectric values (not shown) are somewhat variable if carbonate-clastic mixing is prominent; however, photoelectric values are typically around 2.0 barns/electron indicative of sandstone lithologies.

7. Structural Map and Cross-Section

Mapping of the top of the Upper Shaunavon Member illustrates a discernible structural low extending from Tp. 14, Rge. 17W3 to the eastern half of Tp. 14, Rge. 19W3 (Figure 13). This low has been identified as the Shaunavon Syncline (Christopher, 1984, 2003), which extends along the length of the Shaunavon Formation oil pool trend. The rest of the study area is covered by an extensive structural high extending from Rge. 19W3 westward to Rge. 28W3, which is highest in the northwest region of the study area.

A structural cross-section from northwest to southeast was constructed (Figure 14) and then compared to reservoir isopach maps (Figures 8, 9 and 11) and the structure map (Figure 13) to explain where current Upper Shaunavon Member production is located and where the potential exists to further expand the play. This dataset illustrates how the reservoir quality decreases due to increased mudstone content and how thickness of both the lower and upper reservoirs decreases and pinches out towards the eastern part of the study area (Figures 8, 9, 11 and 14). This coincides with the low observed on the structure map (Figure 13).

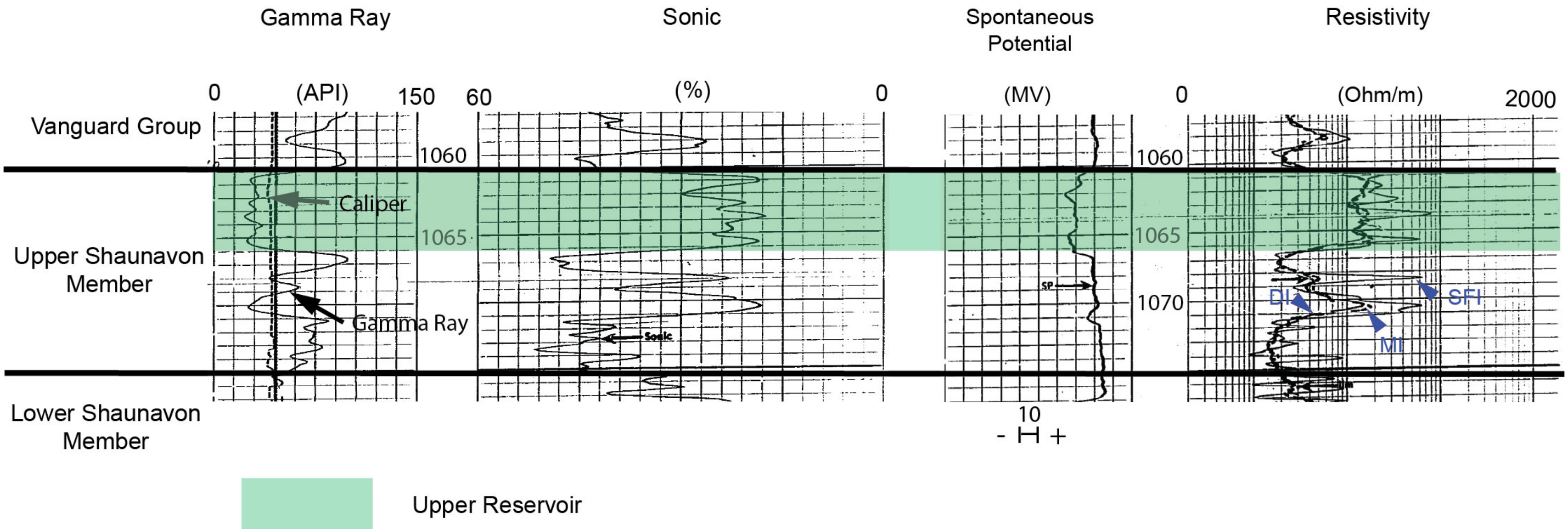

__Figure 12 –__ Gamma-ray, sonic porosity, spontaneous potential and resistivity logs from well 101/08-18-015-19W3/00; 80D067 within the Delta pool. These logs display typical Upper Shaunavon Member upper reservoir well-log signatures present in the study area. Note the high resistivity reading from 1060.5 to 1066.0 m indicating excellent oil saturation, which is easily visible in core. Abbreviations: API – American Petroleum Institute; SP – spontaneous potential; MV – millivolts; DI – deep induction; MI – medium induction; SFI – spherically focused log.

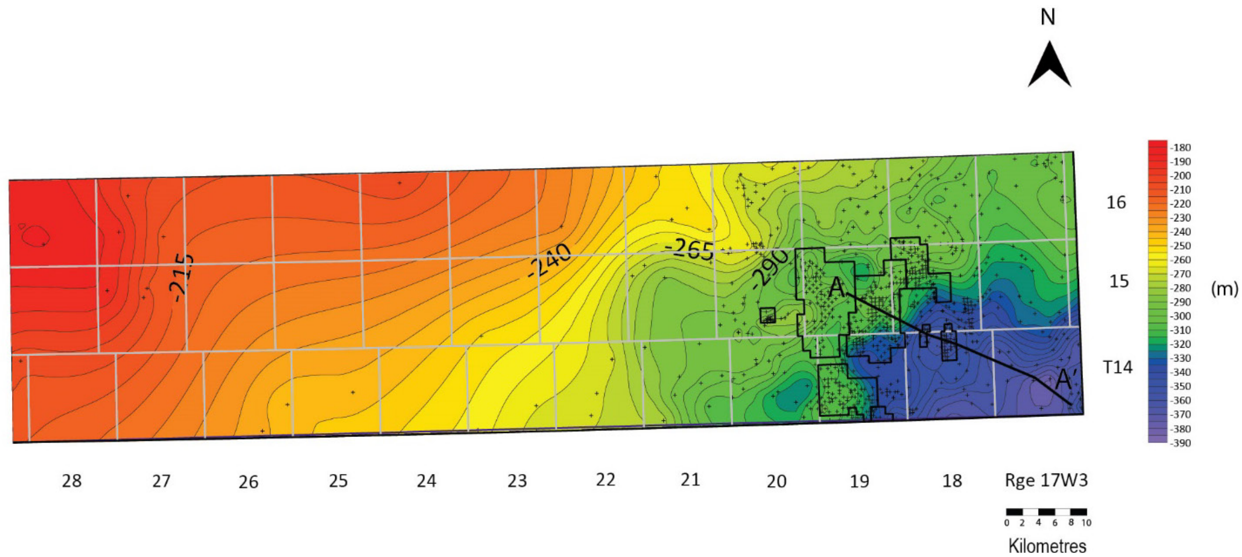

Figure 13 – *A structural contour map of the top of the Upper Shaunavon Member. Note the discernible structural low in the southeastern part of the study area. Oil and gas pool boundaries are outlined in black. Also shown is the location of cross-section A–A' (Figure 14). Abbreviations: T – Township; Rge – Range; W – west.*

8. Discussion

Two main reservoirs have been identified in the study area. Both reservoirs vary in distribution, composition and thickness, which play significant roles in hydrocarbon distribution. Paleogeographic mapping highlighting the west to east facies transition from mixed marine carbonates and clastic reservoirs to offshore mudstones suggests that Williston Basin water depth increased towards the southeast during the Middle Jurassic (Christopher, 1984). Upper Shaunavon Member sediments become much finer and muddier towards the east and southeast moving deeper into the basin. Further evidence of reservoir quality and thickness decreasing towards the east was observed by Christopher (1964) who mapped the sediments east of the main oil pool trend as marlstones and shales. Upper reservoir sandstone is absent in the southeastern part of the study area and is thickest in Tp. 16, Rge. 19 and 20W3 (Figure 11). These thicker accumulations are typically associated with structural highs to the north and west of the main oil pool trend. Uplift of the Sweetgrass Arch that extended as far west as south-central Alberta during the Bajocian age is likely a major source of clastic sediments resulting in thicker accumulations of sandstone proximal to this clastic source (Brooke and Braun, 1972). Upper reservoir isopach mapping (Figure 11) along with excellent oil saturations observed in core (Figure 15) highlight the potential for oil production to the west and northwest of the current producing Upper Shaunavon Member pools.

9. Summary

This paper identifies five recognizable lithofacies and two distinct reservoirs within the Upper Shaunavon Member of the Shaunavon Formation. Peloidal sandstone, strongly bioturbated calcareous sandstone and bioclastic packstone to grainstone comprise the two reservoirs. Thick accumulations of upper reservoir peloidal sandstone mapped to the west and northwest of current oil production coupled with oil saturations observed in core, accentuate the potential to expand the play. Reservoir quality and thickness decrease towards the east of current oil production.

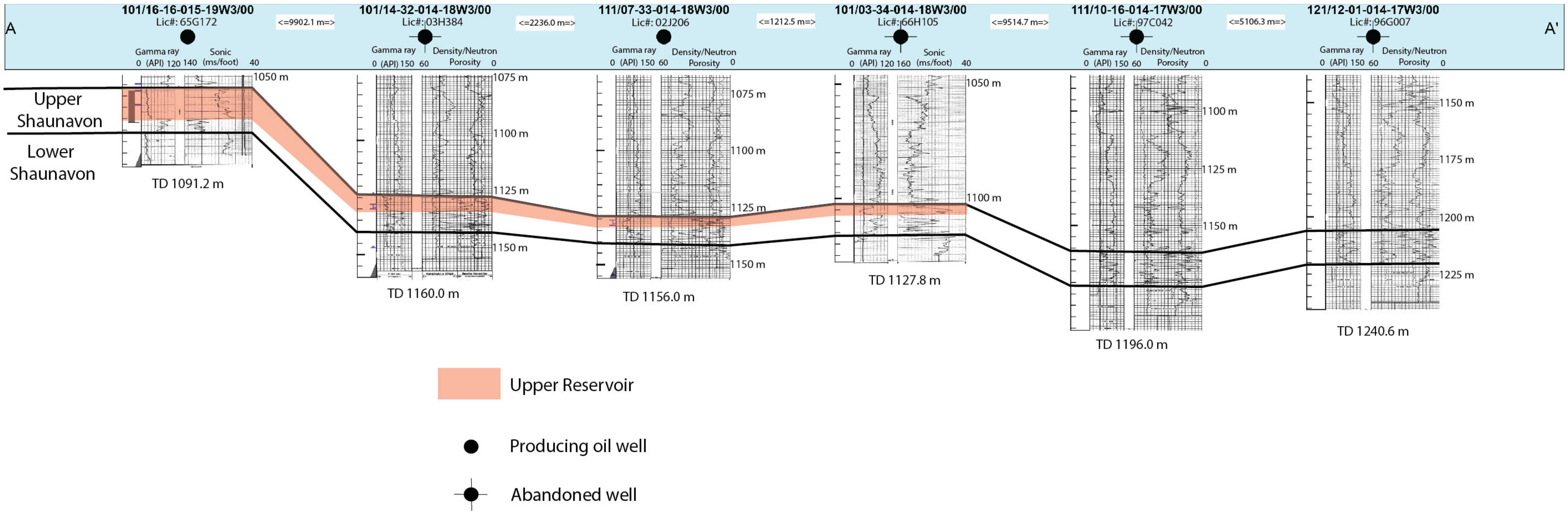

Figure 14 – Northwest to southeast structural cross-section A-A' (see Figures 1 or 13 for location) illustrating how upper reservoir sediments thin and decrease in quality due to increasing clay content (shown by higher gamma ray readings) moving from the structural high in the northwest to the structural low in the southeast. Abbreviations: Lic# – license number; TD – total depth; API – American Petroleum Institute; ms – microseconds.

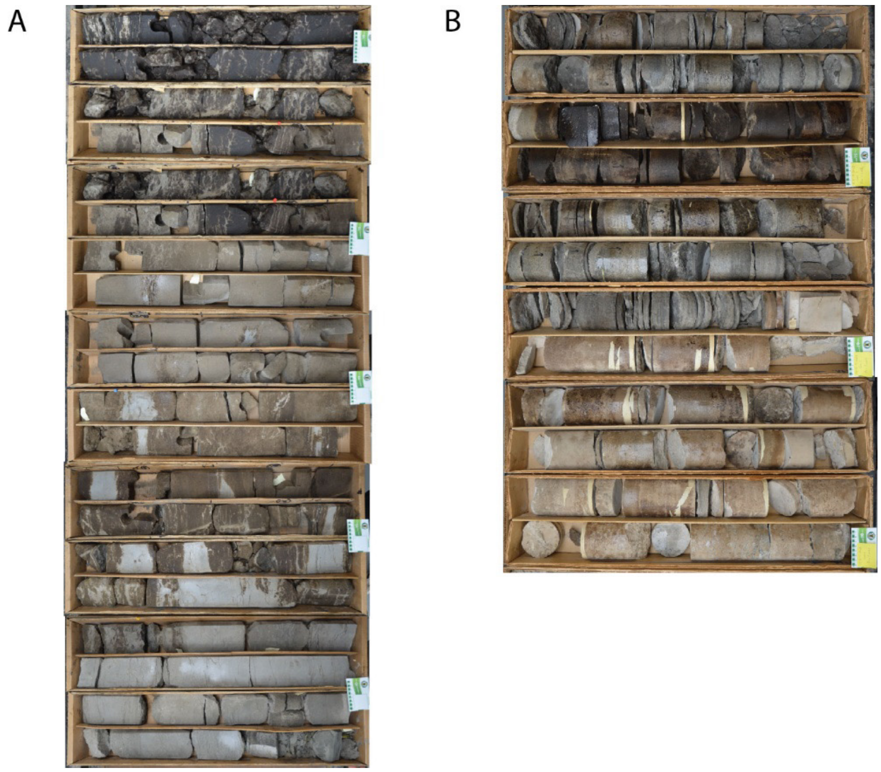

Figure 15 – *Core photographs showing oil-stained upper reservoir sandstones in* ***A)*** *well 121/03-33-016-20W3/00; 91G041 at a depth of 1025.0 to 1041.5 m and* ***B)*** *well 101/12-18-014-24W3/00; 66E082 at a depth of 963.2 to 971.2 m.*

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