

Structural Influences on Hydrocarbon Accumulation in the Viking Formation, West-central Saskatchewan

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Abstract

The Viking Formation has become one of the most important oil-producing reservoirs in Saskatchewan. It has been shown to be very resilient to fluctuations in oil price, since it is found at a relatively shallow depth and has a high API gravity, ranging from 30 to 36° (specific gravity 876 to 845 kg/m³).

The distribution of the Viking Formation's hydrocarbons in Saskatchewan is largely controlled by structural trapping and, to a lesser degree, by stratigraphic pinch-out of the reservoir facies. Topographic features created by the sub-Cretaceous erosional surface have significant control on Viking structural traps. The structural surface of the top of the Viking mimics the sub-Cretaceous erosional surface, draping over its erosional highs, in particular, the structural surface of the Madison Group and its subcrop edge.

Viking oil plays are generally found either differentially trapped up-dip from natural gas pools within a series of successive traps along the Viking's hydrocarbon migration pathway, or within structural lows below trapped natural gas.

Using a cross-section and a series of production, structure and isopach contour maps, this paper will illustrate the nature of Viking Formation hydrocarbon trapping and distribution.

Keywords: *Viking Formation, Cretaceous, Lower Colorado, Albian, tight oil, light oil, differential trapping, structural trapping, stratigraphic trapping, west-central Saskatchewan*

1. Introduction

This study was initiated to better understand the spatial distribution of the Viking Formation's oil and gas production in west-central Saskatchewan, identify production 'sweet spots', and determine the controls on the oil and gas distribution. It will also provide a much needed update to some valuable, but out-of-date reports on government research.

The study area is located within an area bounded on the southeast corner by Township 28, Range 17 west of the third meridian (17W3) and on the northwest corner by Township 34, Range 29W3. This area includes 29 Viking Formation oil and gas pools (Figure 1).

The area of study was chosen based on recent drilling activity that successfully uses horizontal drilling technology combined with multistage fracturing to extract oil from shallow, tight reservoirs. As of November 2014, the use of these technologies has created a renewed interest in the Viking Formation oil reservoirs, resulting in over 3880 new horizontal wells drilled since 2007, which produced 7.0 million cubic metres (m³; 44 million barrels) of oil and 1274 million m³ of natural gas (45.2 billion cubic feet).

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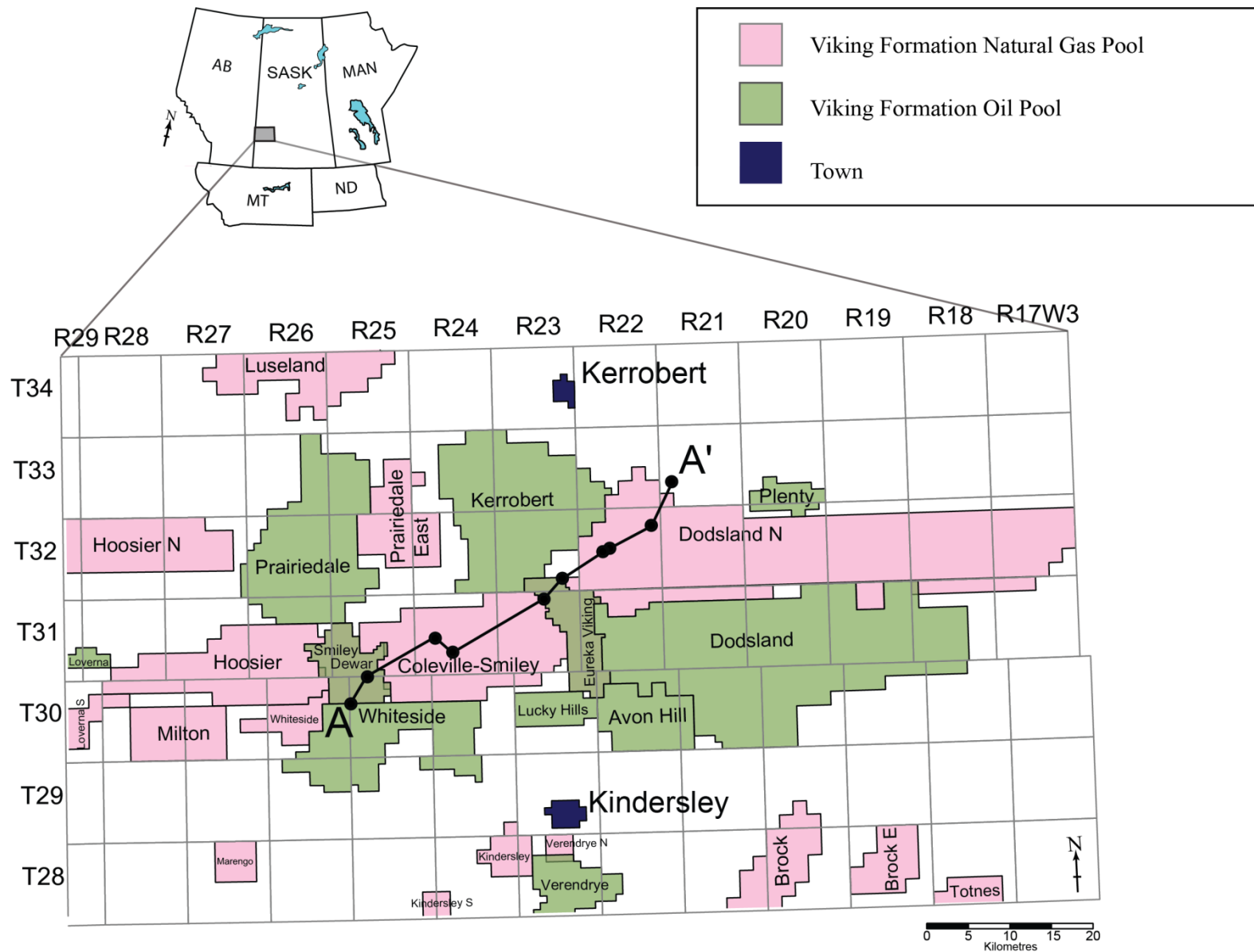


Figure 1 – Location of the study area in west-central Saskatchewan. The pink polygons represent Viking Formation gas pools while the green polygons represent Viking Formation oil pools (Smiley-Dewar and Eureka Viking are both natural gas and oil pools). Note the location of the towns of Kindersley and Kerrobert. Abbreviations on inset map: AB = Alberta, SASK = Saskatchewan, MAN = Manitoba, MT = Montana, ND = North Dakota. Line of cross-section shown in Figure 3 (A–A') is also delineated.

2. Previous Work

There have been recent studies performed on Saskatchewan's Viking Formation that have focused primarily on facies analysis, stratigraphy and depositional models, but which contain little data regarding controls on oil and gas emplacement (Tong *et al.*, 2005; Walz *et al.*, 2005; Ferdous *et al.*, 2006; Thomas, 2007a, 2007b; Walz, 2007; Tong, 2009; Mathison, 2013; Michaud, 2013). There has also been older, yet valuable, pioneering research conducted by Reasoner and Hunt (1954), who recognized the structural controls on oil and gas emplacement in the Bakken Coleville-Buffalo Coulee pool (overlapping area with Viking Coleville-Smilely pool); Jones (1961), who provided isopach and structure maps of areas south of this paper's research area; and Evans (1970), who identified and mapped clinofold beds within the internal stratigraphy of the Viking Formation in the Hoosier–Doddsland areas. White (1969) provided a detailed study of the North Hoosier area (identified in government records as Hoosier N.; Figure 1), which included the Viking pool, and detailed the structure of the Viking Formation and the elements that controlled its structure. Later, Christopher *et al.* (1971) further mapped the structural features of the Viking Formation and controls on its topography in the area between the towns of Kindersley and Kerrobert. Simpson (1982) reiterated many of the same observations as Evans (1970) and Christopher *et al.* (1971). Pozzobon and Walker (1990) described the facies and depositional environment within the Eureka Viking pool, while Christopher (1999) briefly summarized the findings of Christopher *et al.* (1971) and Simpson (1982).

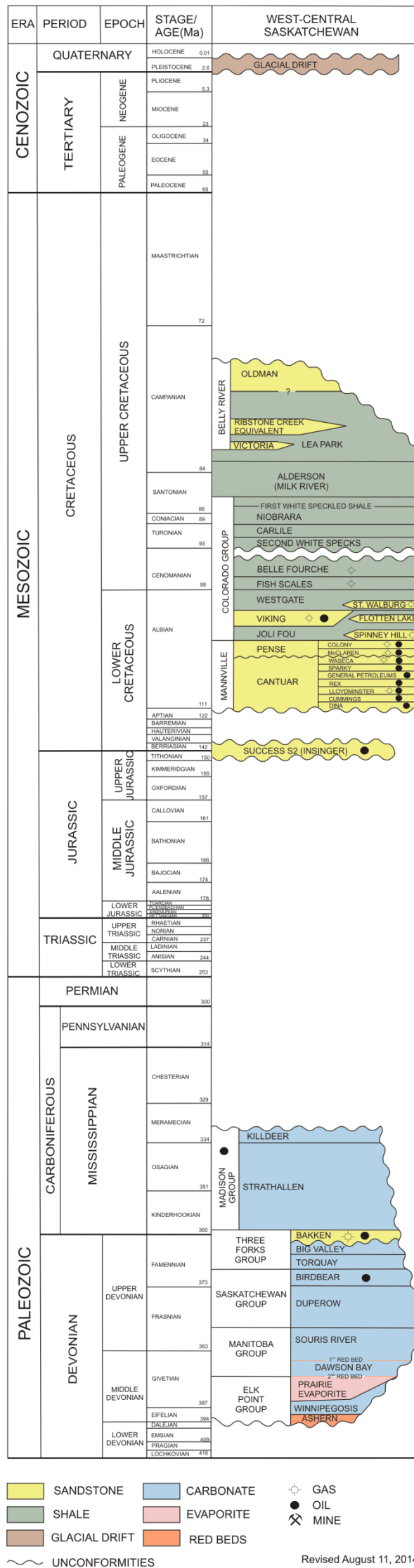
3. Geological Setting

The study area offers many exploration opportunities, including oil from the Devonian Birdbear Formation, oil and gas from the Devonian–Carboniferous Bakken Formation, oil from the Jurassic–Cretaceous Success Formation, oil and gas from the Cretaceous Mannville Group, and oil and gas from the Cretaceous Viking Formation (Figure 2).

The Viking Formation is Albian in age and is part of the Lower Colorado Group of the Lower Cretaceous Period (Figure 2). In general, the Viking Formation in the study area is made up of a fining-upward succession followed by a coarsening-upward succession of interbedded mudstones, silty mudstones, siltstones, and very fine-grained sandstones commonly comprised of granules of grey quartz and black chert. The sandier portions of the Viking Formation are regularly bioturbated. Common centimetre-scale siderite beds are also present.

The Viking Formation is slotted between two marine shales: the overlying Lower Cretaceous Westgate Formation, and the underlying Lower Cretaceous Joli Fou Formation (Figure 3). The Westgate Formation is overlain by the Upper Cretaceous Fish Scales Formation, a very distinct regional marker bed that is easily recognized on geophysical well logs. Underlying the Joli Fou Formation throughout the study area is the Lower Cretaceous Mannville Group. The Mannville Group is thickest where it corresponds with structural lows on the sub-Cretaceous erosional surface, which, when mapped regionally, is an angular unconformity (Jackson, 1984; Cant and Abrahamson, 1996). The age of the subcropping strata below the erosional surface progressively changes from Carboniferous to Devonian from south to north through the study area. A veneer of Jurassic–Cretaceous Success Formation is also locally preserved underneath the unconformity. Depending on the degree of erosion in the paleo-valleys, older formations can be found subcropping under the unconformity within the paleo-drainage systems. In particular, where the lows are deepest, Christopher (2003) mapped paleo-drainage systems overlying Carboniferous- or Devonian-aged rocks. The drainage patterns were interpreted from Mannville Group isopach mapping (Christopher, 2003).

It has been documented that Viking oils in the study area have API gravities in the range of 30 to 36° (specific gravity 876 to 845 kg/m³) and are predominantly paraffinic with low sulphur contents (Christopher *et al.*, 1971). This is unique for the area, since the underlying formations (Birdbear, Bakken, Success and Mannville Group) contain heavy crude oils in the range of 12 to 18° API (specific gravity 986 to 946 kg/m³). Since the Viking Formation is the shallowest producing unit in the area, the combination of a relatively shallow reservoir and oil that is very light has made the Viking an extremely appealing exploration and development target, and in times of fluctuating economic conditions, relatively resilient.



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Figure 2 – Stratigraphic correlation chart of west-central Saskatchewan (modified from Saskatchewan Ministry of the Economy, 2014). Note the number of potential reservoirs throughout the stratigraphic column.

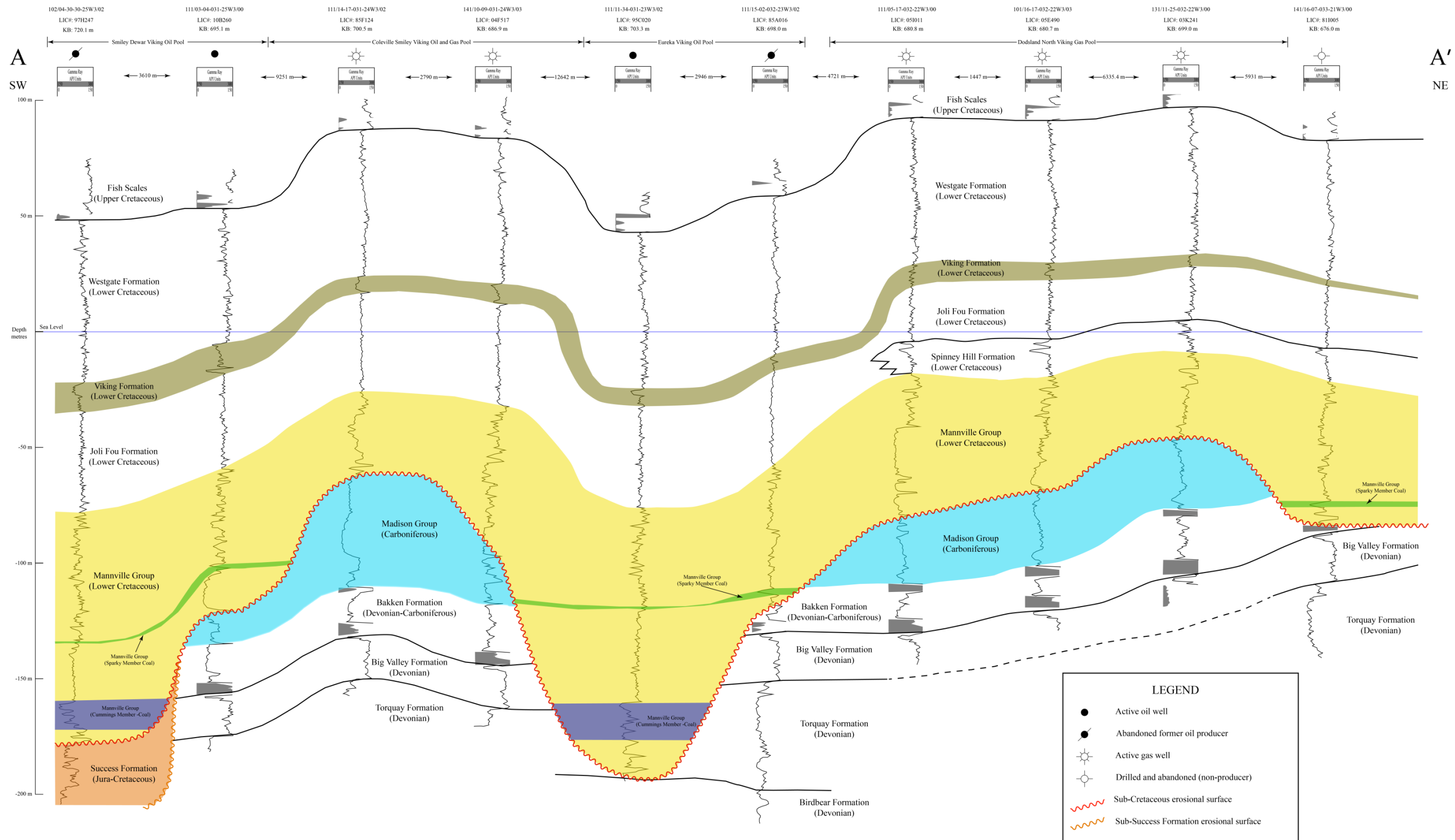


Figure 3 – Southwest-to-northeast structural cross-section through the study area. The cross-section illustrates the relationship of the Viking Formation to the underlying stratigraphy, in particular, the sub-Cretaceous erosional surface. Note how the Viking Formation somewhat mimics the structural topography of the underlying sub-Cretaceous erosional surface. Note the highest Viking structural elevations correspond with wells producing Viking natural gas, while the Viking structural lows are where the wells producing Viking oil are found. Hydrocarbons are not found in the most northeastern well since the Viking Formation has draped over the Madison Group subcrop edge and the hydrocarbons did not migrate beyond this edge at this location. NOTE: There are two different scales for the gamma-ray logs: the dark grey intervals represent values ranging from 150 to 300 API, all other values range from 0 to 150 API.

4. Methods

All contour maps in this study were produced using Ministry of the Economy data. In particular, over 15 000 Viking Formation tops were used to generate the isopach and structure contour maps. Oil and natural gas production rates and 'oil cut' values were also calculated and contoured, to illustrate the spatial distribution of the Viking Formation's oil and gas production and to identify production 'sweet spots', areas where the highest oil cuts and gas production exist. A combination of all the maps (structure, isopach, production, cross-section) was then used to illustrate the controls influencing the distribution of the hydrocarbons.

The gas production map (Figure 4) was developed by identifying Viking wells with natural gas production (associated and non-associated) and then contouring the initial 90 days of gas production from each individual well. Since Viking natural gas production is primarily non-associated and drilled as a vertical well (conventionally), there was no need to use methods to negate variances related to horizontal well length or mechanical fracture methods.

The oil cut map (oil-to-water ratio; Figure 5) was developed by identifying Viking oil production and contouring the initial 90 days of oil production (oil) from each individual well, divided by the initial 90 days of oil production (oil) plus the initial 90 days of water production (water) from each individual well. The following equation represents oil cut for each well:

$$\text{Oil Cut} = \frac{\text{oil}}{\text{oil} + \text{water}}$$

This method was used to negate the variances caused by the length of horizontal wells, the number of mechanical fractures per well and the variances in mechanical fracture size.

The values for gas production and oil cut were entered into a Microsoft® Excel® 2007 spreadsheet and were then mapped using Golden Software's Surfer® 12 mapping program. The contours generated for the gas production map used a minimum curvature algorithm while the oil cut map contours used a Kriging algorithm.

The structure and isopach maps in Figures 6, 7, 8 and 9 were generated from the Ministry of the Economy's formation top database (unpublished) and if any formation tops were incorrect they were edited as required. These values were entered into a Microsoft® Excel® 2007 spreadsheet and mapped using Golden Software's Surfer® 12 mapping program. The contours generated for these maps used Golden Software's Kriging algorithm. Subcrop edges plotted on the maps were derived and modified from Marsh *et al.* (2011).

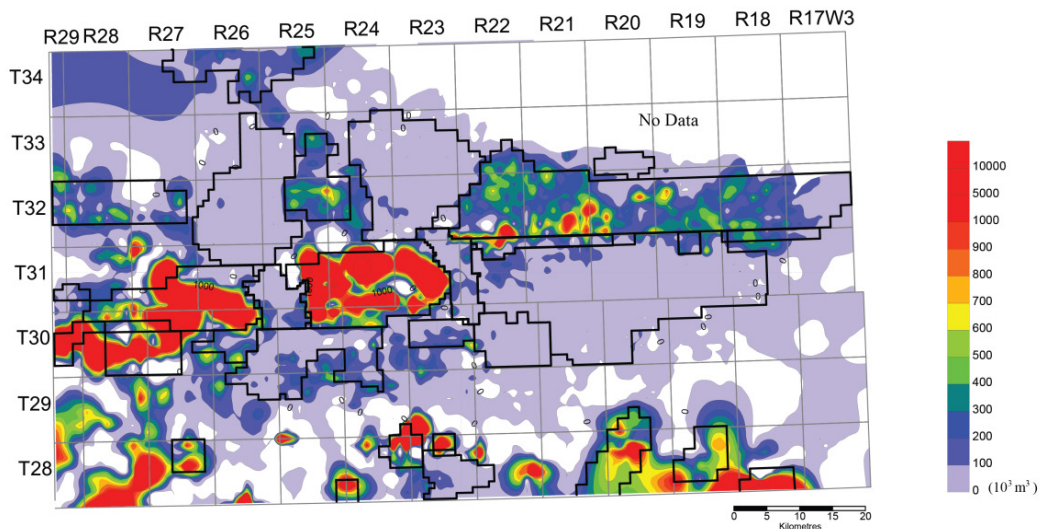


Figure 4 – Initial 90 days of Viking Formation natural gas production. Due to the wide variance in natural gas production, the contour intervals are variable to best illustrate the natural gas accumulations. The contours between 0 to 1000 $\times 10^3$ m^3 are at an interval of 100 $\times 10^3$ m^3 , while the contours between 1000 to 10 000 $\times 10^3$ m^3 are at an interval of 5000 $\times 10^3$ m^3 . Viking oil and gas pool boundaries are shown in black.

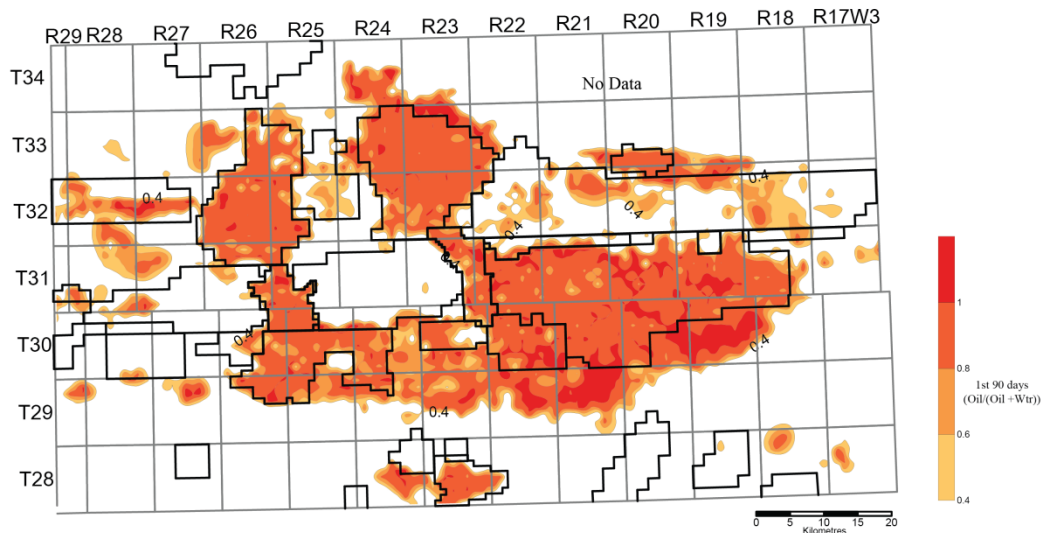


Figure 5 – Initial 90 days of oil production / (first 90 days oil production + first 90 days water production) = oil cut. This ratio was chosen to negate the effects of variations in well length and fracking techniques that would cause variations in production volume. Contours are first 90 days oil/(oil + water) in 0.20 intervals. Viking oil and gas pool boundaries are shown in black.

5. Viking Formation Characteristics in the Study Area

The isopach map constructed for the Viking Formation (Figure 6) shows that the formation is thickest through the study area in the south and thins to the north. The isopach trends are oriented east-west and formation thickness varies from slightly more than 20 metres thick to as little as 2 metres thick.

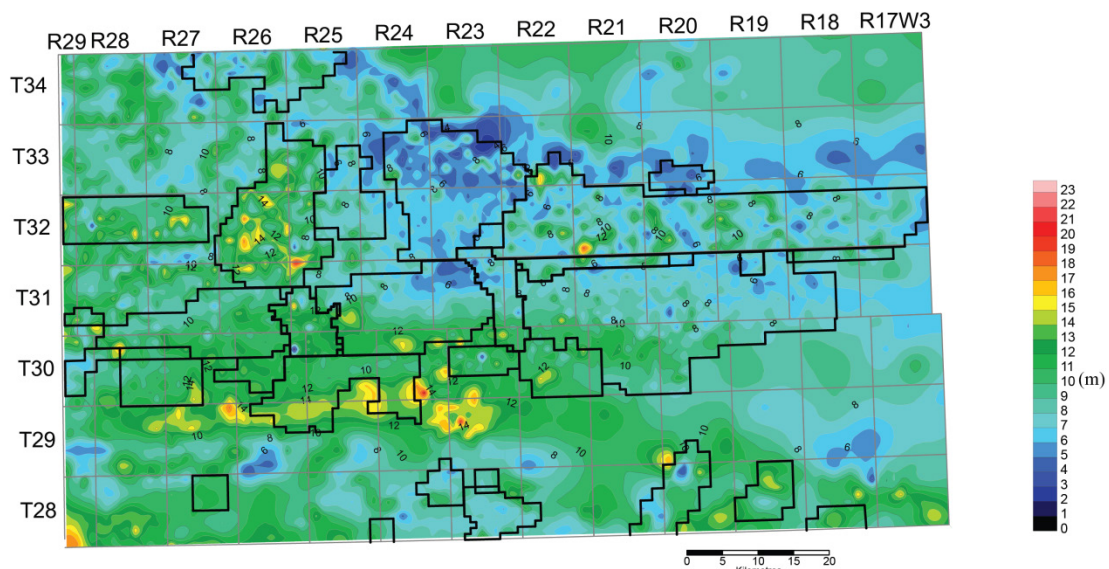


Figure 6 – Isopach contour map of the Viking Formation. Contour interval for thickness of Viking Formation is 1 metre. Viking oil and gas pool boundaries are shown in black.

Structure contour maps created using the top of the Viking Formation (Figure 7) reflect the sub-Cretaceous erosional surface due to compaction of the underlying Mannville Group within erosional lows and draping over the erosional highs, resulting in the Viking structure surface mimicking the topography of the sub-Cretaceous erosional surface, although moderately subdued (Figure 3). Throughout the study area, the top of the Viking is found at relatively shallow depth, ranging from 560 to 840 metres below surface (or 70 m above sea level to 45 m below sea level; Figure 7).

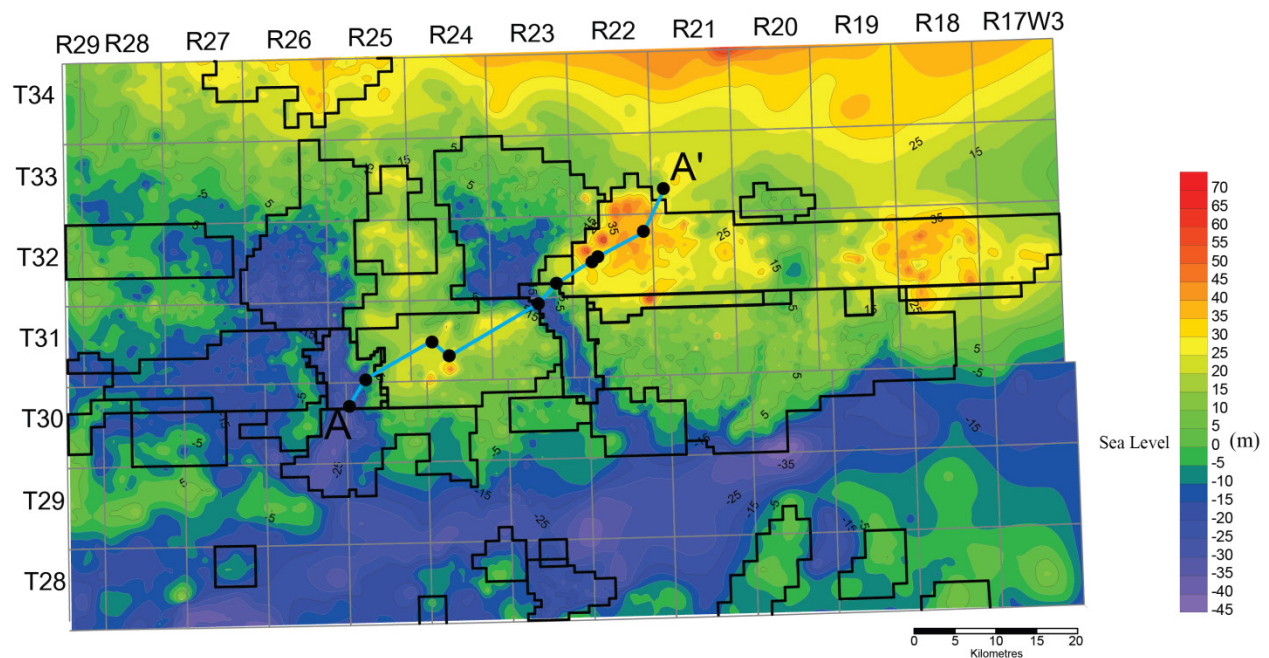


Figure 7 – Structure contour map of the Viking Formation. Contour interval for depth of Viking Formation is 5 metres; depths are relative to sea level. Viking oil and gas pool boundaries are shown in black. Blue line A-A' is the cross-section in Figure 3.

6. Viking Formation Hydrocarbon Trapping

Two styles of hydrocarbon trapping in the Viking Formation are observed in the study area: hydrocarbons are either trapped structurally, or through stratigraphic pinch-out of the Viking sandstone reservoirs.

a) Structural Traps

The structural traps are a result of the Viking Formation's mimicking of the underlying sub-Cretaceous erosional surface, which created roll-over (anticline) style traps on paleo-topographic highs. These structural traps can be observed in several places, and are easily identifiable on the Viking structure map (Figure 7) when compared to the cross-section A-A' in Figure 3. These roll-over (anticline) features visibly coincide with areas of Viking oil and gas production (Figures 1, 4 and 5). The Prairiedale, Smiley Dewar, Whiteside, Eureka Viking, Lucky Hills and Doddsland oil pools, along with the Hoosier North, Coleville-Smiley and Doddsland North gas pools are examples of this style of trap (Figures 1 and 3).

There is an overall regional dip of the formation tops through the study area, where the elevation progressively becomes higher from southwest to northeast (Figure 7). Viking Formation oil is originally derived from Colorado Group shales that are found down-dip and to the west (Creaney *et al.*, 1994); that natural gas and oil moved up-dip through buoyancy drive from southwest to northeast in the study area until the strata locally dipped downward and lost elevation, creating closure to the buoyancy drive. Where the Viking Formation rolled over the closure structure, a trap was created.

Natural gas can be found in structural traps at the highest elevations, while oil can be found trapped below, within structural lows and along the flanks of the elevated highs (Figures 4, 5 and 7).

The same relationship is present in the pools in the southern part of the study area. Marengo, Kindersley South, Kindersley, Verendrye North, Brock, Brock East and Totnes natural gas pools and the Verendrye oil pool are located along an erosional-anticlinal edge of the Madison Group. Here, the Viking drapes over this edge and natural gas is located structurally above the oil trapped along this margin. Christopher *et al.* (1971) and Christopher (1999) also observed these phenomena and reported similar observations in their research.

When comparing the structural map (Figure 7) with the isopach map (Figure 6), it is evident that the structural lows and highs seen in the Viking Formation are largely independent of isopach thickening and thinning, and therefore compaction is assumed to have occurred after Viking deposition, as a result of the loading of hundreds of metres of sediment on top of the Viking Formation and Mannville Group. Oil emplacement followed after compaction, since it is compaction that created the structures that control hydrocarbon distribution throughout the study area.

Cross-section A-A' (Figure 3) illustrates the relationship of the Viking Formation to the underlying strata. The cross-section highlights two paleo-valleys formed at the sub-Cretaceous erosional surface and how, through compaction of the Mannville Group and draping of the Viking Formation, the Viking structure mimics the sub-Cretaceous erosional surface (Figure 3). The cross-section also illustrates how the northern subcrop edge of the Madison Group created a roll-over trap that limited northward oil and natural gas migration (Figures 3 and 8). A second roll-over trap exists where the Viking Formation drapes over the remnant Madison Group between the two paleo-valleys.

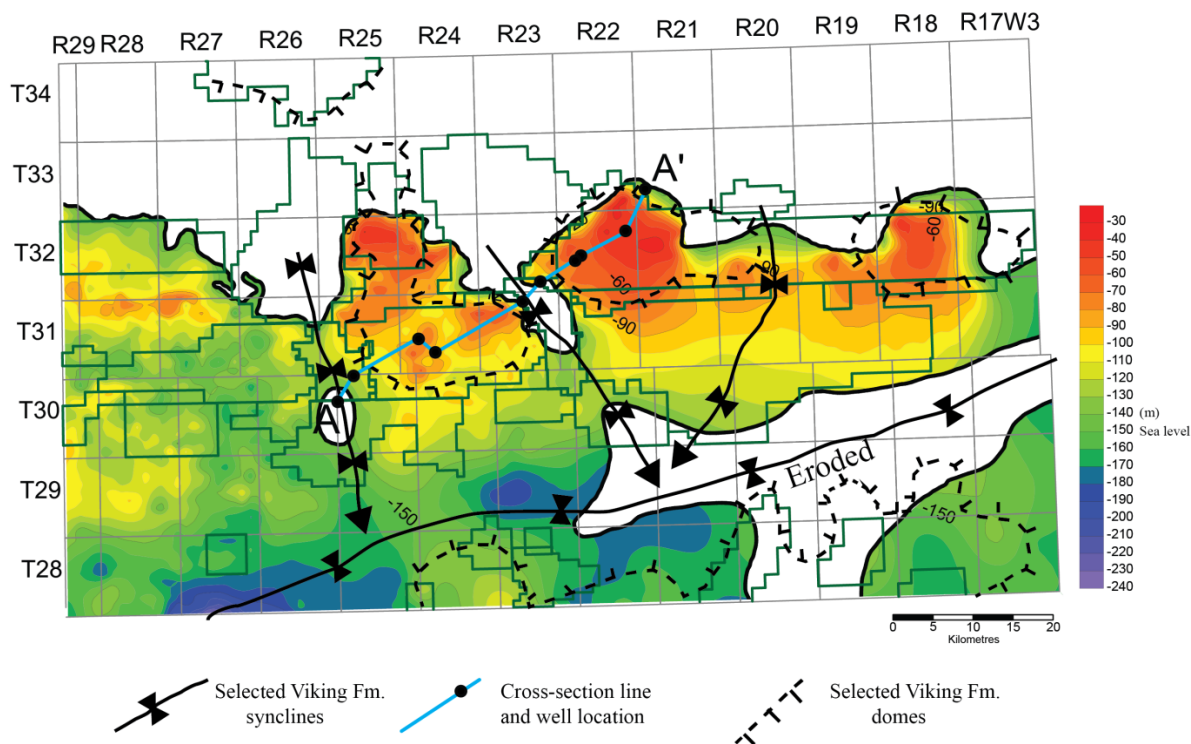


Figure 8 – Structure contour and subcrop map of the Madison Group. Note the areas of low relief (sub-Cretaceous erosion), completely eroded Madison, and the subcrop edge (thick, solid black line). A schematic representation of Viking synclines and domes has been overlain, to illustrate the structural relationship of the Viking and Madison: Viking synclines coincide with Madison lows, domes with Madison highs. Contour interval is 10 metres; depths are relative to sea level. Viking oil and gas pool boundaries are shown as dark green outlines. Arrowheads at the ends of the syncline symbols indicate direction of plunge.

b) Stratigraphic Pinch-out Traps

The Kerrobert and Plenty Viking oil pools (Figure 1) are examples of attenuation of the Viking Formation sandstone reservoir to the north, which resulted in oil trapped at a stratigraphic pinch-out. In both pools, the oil portion of the hydrocarbon column bypassed the structural roll-over trap created by the Madison Group subcrop edge by following two north-south paleo-valleys identifiable as narrow Viking structural lows (synclines; Figures 7 and 8, wells 102/04-30-30-25W3/02 and 111/11-34-031-23W3/02 in Figure 3). Because the subcrop edge of the Madison has been altered by erosion, the oil continued to migrate northward and leaked beyond the Madison subcrop edge to become trapped by the pinch-out of the Viking sandstone reservoir rather than by structural roll-over, as is seen along the majority of the northern edge of the Dodsland North gas pool (Figures 3 and 4).

The Prairiedale Viking oil pool is somewhat similar in that the oil bypassed the Madison subcrop edge through an erosional low, but the trap for this pool is slightly different. The trap at this location is both structural and stratigraphic in nature. Viking oil was trapped against the rising paleo-structure of the sub-Cretaceous unconformity (structural), below the Viking Luseland pool gas cap on the northeast margin of the pool (Figures 1, 5 and 8), and was prevented from further up-dip migration by the pinch-out of the Viking sandstone reservoir (stratigraphic) in the northwest portion of the pool (Figure 7).

These Viking oil pools (Kerrobert, Plenty and Prairiedale) are examples of differentially trapped oil up-dip of gas pools. Throughout the study area, natural gas filled the lowest traps first until the structures were full to the spill-point. The oil then spilled up-dip, finally filling the traps in Prairiedale, Kerrobert and Plenty. This likely occurred successive times along the migration pathway and included the pools in the south portion of the study area, such as Marengo, Kindersley South, Kindersley, Brock, Brock East and Totnes, and explains why the structural lows up-dip of gas pools are charged with oil. The nature of the Dodsland North Viking gas pool also supports this interpretation, due to its lower natural gas production rates compared to those seen further down-dip (Figure 4). The majority of the natural gas was trapped south and west of the Dodsland North pool. By the time the natural gas migrated to this pool, there were not sufficient amounts of natural gas to completely fill the trap, resulting in oil and gas existing in the same trap in different phases.

Figure 9 combines many of the elements from the previous figures and illustrates the various trapping mechanisms in play within the study area.

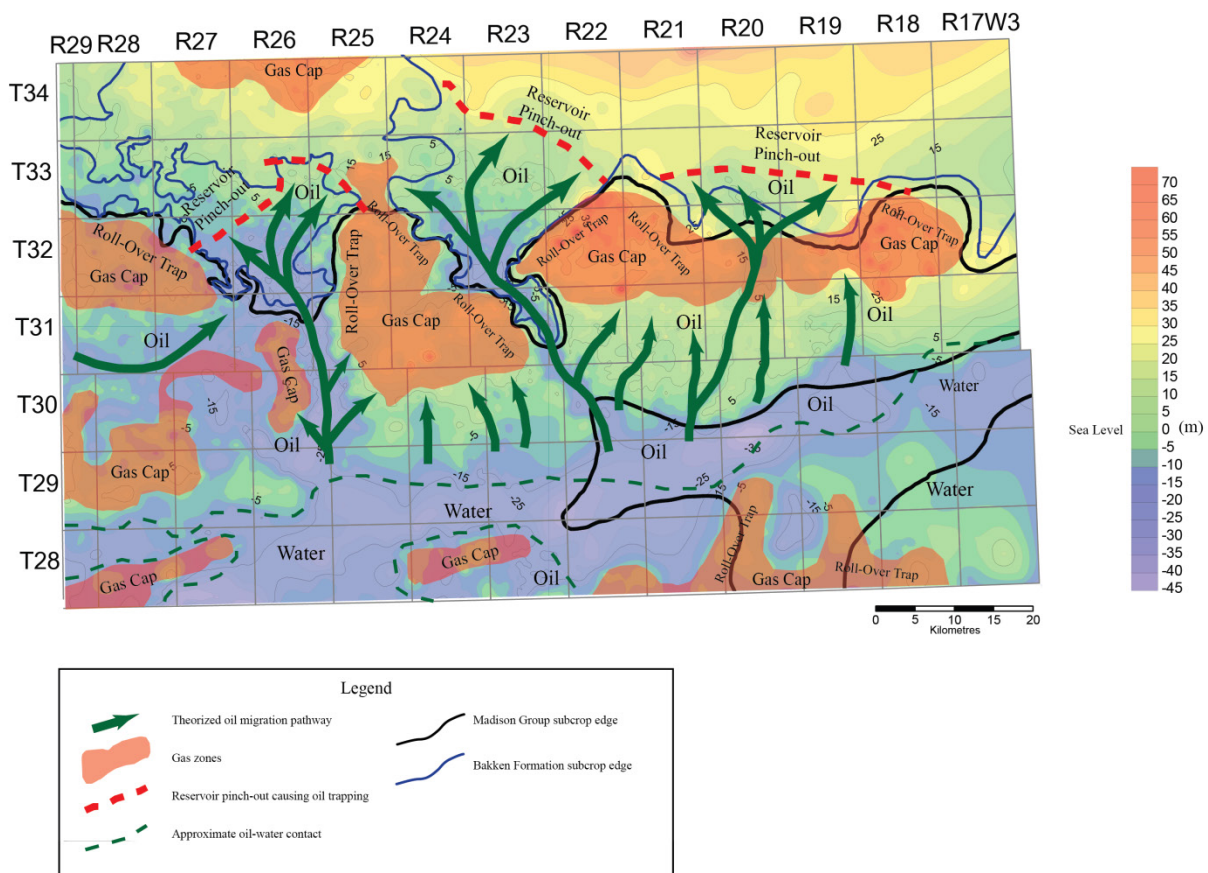


Figure 9 – Composite illustration showing the Bakken Formation and Madison Group subcrop edges along with the Viking Formation structure contours. Interpreted hydrocarbon migration pathways are indicated, and the interpreted contacts for natural gas, oil and water are marked. Interpreted method or nature of natural gas and oil trapping is also shown. Contour interval for Viking Formation depth is 5 metres; depths are relative to sea level.

7. Summary

- Viking Formation oil has a higher than average API gravity than is typically found in the west-central area of Saskatchewan. The API gravity ranges from 30 to 36° (specific gravity 876 to 845 kg/m³), which is very light compared to the low API gravity oils found in the Mannville Group, Success, Bakken and Birdbear formations, which average between 12 to 18° (specific gravity 986 to 946 kg/m³).
- Viking Formation reservoirs are very appealing since they are found at a relatively shallow depth, ranging from 560 to 840 metres below surface within the study area.
- The Viking structural surface somewhat mimics the sub-Cretaceous erosional surface, draping over remnant erosional highs, in particular the structural surface of the Madison Group and its subcrop edge.
- Oil and natural gas distribution is largely controlled by the structural features created by the sub-Cretaceous erosional surface, where the hydrocarbons are trapped in structural roll-overs (anticlines), and/or by reservoir facies pinch-outs.
- Many small structures control the distribution of the Viking Formation's hydrocarbons. Oil can be found differentially trapped up-dip from natural gas pools within successive traps along the hydrocarbon migration pathway. Oil can also be found trapped in structural lows below trapped natural gas.

8. Further Research

Recognizing the importance of the sub-Cretaceous erosional surface to oil entrapment in the Viking Formation, plans to further define this surface are under way. The Madison Group subcrop edge will also be further refined, using the Viking structure contour map as a guide since, despite fewer well penetrations intersecting the Madison Group or deeper, it is apparent that this edge is reflected in the Viking structure contours. Future research will also include more detailed mapping of the Success Formation, since it is also a poorly understood reservoir for which it is difficult to predict and correlate the reservoir facies. Viking structure maps may also be a useful tool for predicting Success Formation reservoir targets.

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