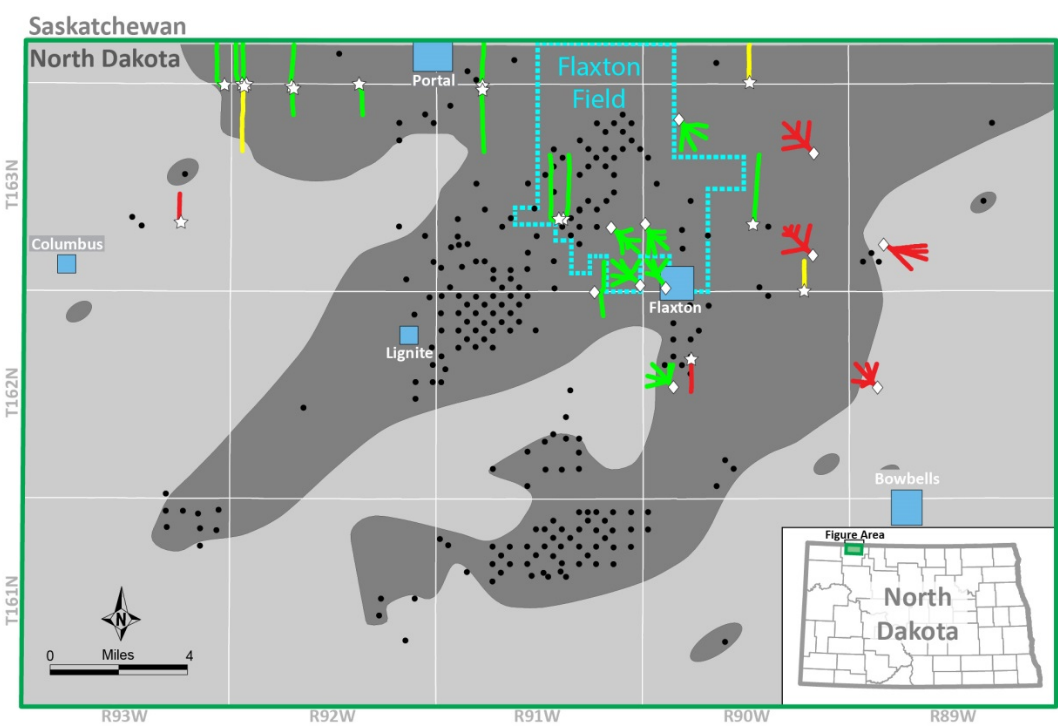
Spatial distribution of elevated oil saturations within the Midale subinterval (Mississippian Madison Group), Burke County – North Dakota

By

Timothy O. Nesheim



Geological Investigation No. 213
North Dakota Geological Survey
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
2018

Introduction

More than two dozen horizontal wells targeting the Midale-Rival subintervals of northern Burke County, North Dakota have been completed with multi-stage hydraulic fracturing over the past few years (Nesheim, 2019). Overall, production results and reported economics from these wells have been encouraging, with initial monthly average production rates of 200+ barrels of oil per day (BOPD) (Table 1). Future development may lead to the drilling and completion of dozens to hundreds of additional wells (Nesheim, 2019). Conventional (vertical) oil and gas production from the Midale-Rival subintervals in northern Burke County began in the 1950's while horizontal drilling with open-hole completions targeting the upper Rival began to emerge in the 1990's (Voldseth, 1987; Nesheim, 2019). The successful augmentation of horizontal drilling and hydraulic fracturing is merely the reemergence of an older petroleum play that has been revitalized by technological advances. Understanding the distribution of elevated oil saturations is one key piece to assessing the potential of the Midale-Rival unconventional-style play.

Stratigraphy/Geologic Background

The Midale is the basal subinterval of the Mississippian Ratcliffe interval, and ranges from being part of the Mission Canyon (basin center) to being part of the Charles Formation (basin margins) depending on the stratigraphic positioning of the deepest evaporite bed (Fig. 1) (Cook, 1976; LeFever and Anderson, 1986). The Midale has been previously interpreted to record an initial transgression followed by a regression within the Flaxton Field area of northern Burke County (Lindsay, 1985) (Fig. 2). The regressive portion of the Midale includes: burrowed dolomitic limestone 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). The greater Ratcliffe interval is comprised of several formal to informal subintervals that have been described and interpreted as shallowing upward sedimentation cycles that grade from open marine deposits in the basin center to sabkha anhydrite-dominated sediments to the east (Hendricks, 1987).

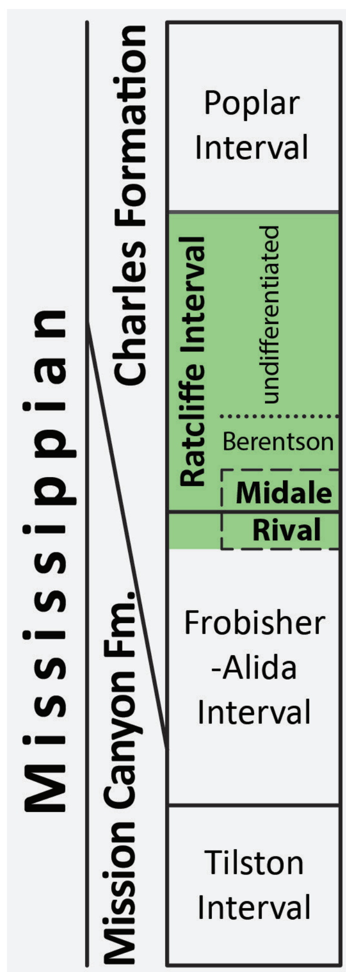


Figure 1. Stratigraphic nomenclature chart for the Mission Canyon and Charles Formations. Based upon work by Cook (1976).

Table 1. Information on Midale-upper Rival horizontal wells with multi-stage hydraulic fracture completions

NDIC #	API Well Number	Well Name	Current Operator	Original Operator	Surface Location Information					Peak	Lateral	Note:
					Section	Township	Range	Latitude	Longitude	BOPD*	Length (ft)	
16049	33013013460000	PARADOX 43-36-163-9	CORNERSTONE NATURAL	PRIMA EXPLORATION, I	36	163N	91W	48.898052	-102.417401	124	**	1
16220	33013013530000	NELSON UNIT 1	WINDRIDGE OPERATING,	DENALI OIL & GAS MAN	2	162N	91W	48.893555	-102.445252	147	**	1
16297	33013013570000	POUDRE 44-18H	THURSTON ENERGY INVE	PRIMA EXPLORATION, I	18	162N	90W	48.854056	-102.394878	102	**	1
16653	33013013720000	PARADOX 11-30H	THURSTON ENERGY INVE	PRIMA EXPLORATION, I	30	163N	90W	48.922592	-102.41224	165	**	1
16742	33013013800000	LEON UNIT 1	CORNERSTONE NATURAL	CORNERSTONE NATURAL	8	163N	90W	48.965883	-102.390938	166	**	1
16867	33013013860000	MESA 13-29H	THURSTON ENERGY INVE	PRIMA EXPLORATION, I	29	163N	89W	48.913629	-102.259969	22	**	1
16956	33013013870000	CRYSTAL 44-18H	THURSTON ENERGY INVE	PRIMA EXPLORATION, I	18	162N	89W	48.853946	-102.265578	16	**	1
17524	33013014360000	PARADOX 34-31H	THURSTON ENERGY INVE	PRIMA EXPLORATION, I	31	163N	90W	48.895928	-102.399604	149	**	1
19042	33013015010000	SCHWARTZ 4-11H	CORNERSTONE NATURAL	CORNERSTONE NATURAL	11	163N	90W	48.95263	-102.305941	18	**	1
19177	33013015070000	RAWN 4-26H	CORNERSTONE NATURAL	CORNERSTONE NATURAL	26	163N	90W	48.909307	-102.306035	21	**	1
19551	33013015230000	OLNEY 2-25H	CORNERSTONE NATURAL	CORNERSTONE NATURAL	25	163N	91W	48.921825	-102.43486	134	**	1
19947	33013015340000	MATTER STATE 3-17H	WINDRIDGE OPERATING,	CORNERSTONE NATURAL	17	162N	90W	48.864677	-102.383907	41	4,882	2
24958	33013017020000	SWENSON 4H	PETRO HARVESTER OPER	PETRO HARVESTER OPER	23	163N	93W	48.923652	-102.709943	58	3,810	3
27104	33013017530000	BRATLAND 3-1H	PETRO HARVESTER OPER	PETRO HARVESTER OPER	3	163N	92W	48.980426	-102.595078	253	4,159	3
27959	33013017800000	TAFELMEYER MA-3427	CORNERSTONE NATURAL	CORNERSTONE NATURAL	34	164N	90W	48.982064	-102.3464	116	4,982	3
28199	33013017910000	BUSCH 5-1H	PETRO HARVESTER OPER	PETRO HARVESTER OPER	5	163N	92W	48.979612	-102.639048	230	3,779	3
28214	33013017920000	BUSCH 32-1H	PETRO HARVESTER OPER	PETRO HARVESTER OPER	5	163N	92W	48.979614	-102.638631	535	5,439	3
29096	33013018020000	HUFF MC-35-6390	CORNERSTONE NATURAL	CORNERSTONE NATURAL	35	163N	90W	48.895365	-102.310935	113	3,709	3
31719	33013018180000	BUSCH TRUST 31-30 1	PETRO HARVESTER OPER	PETRO HARVESTER OPER	31	164N	92W	48.981954	-102.66738	290	5,593	3
31720	33013018190000	BUSCH TRUST 31-30 1	PETRO HARVESTER OPER	PETRO HARVESTER OPER	31	164N	92W	48.981954	-102.667297	291	5,650	3
31721	33013018200000	BUSCH TRUST 06-07 1	PETRO HARVESTER OPER	PETRO HARVESTER OPER	31	164N	92W	48.981954	-102.667213	119	9,041	3
32423	33013018240000	FLX1 22-15 163-91 B	PETRO HARVESTER OPER	PETRO HARVESTER OPER	22	163N	91W	48.924143	-102.467296	293	9,136	3
32424	33013018250000	FLX1 22-15 163-91 D	PETRO HARVESTER OPER	PETRO HARVESTER OPER	22	163N	91W	48.924143	-102.467212	252	8,978	3
32992	33013018290000	PTL1 32-29 164-91 B	PETRO HARVESTER OPER	PETRO HARVESTER OPER	5	163N	91W	48.980178	-102.517021	182	5,932	3
32993	33013018300000	PTL1 05-08 163-91 B	PETRO HARVESTER OPER	PETRO HARVESTER OPER	5	163N	91W	48.980178	-102.516938	184	9,179	3
33148	33013018310000	STR1 22-15 163-90 B	PETRO HARVESTER OPERAT	PETRO HARVESTER OPER	27	163N	90W	48.922231	-102.343398	223	9,767	3
34171	33013018530000	KESTREL STATE 36-2	WINDRIDGE OPERATING,	WINDRIDGE OPERATING,	1	163N	93W	48.980355	-102.682498	219	5,865	3

1 = Horizontal upper Rival well with an initial open-hole completion. Horizontal well was later re-stimulated using multi-stage hydraulic fracture completion.
2 = Initially drilled and competed as a horizontal Bakken well in 2011-12. Horizontally re-drilled and completed in the upper Rival-Midale in 2017.
3 = Horizontal upper Rival-Midale well with initial multi-stage hydraulic fracture completion.
*Barrels of oil per day (BOPD) during month of highest average daily oil production following multi-stage hydraulic fracture completion
**Limited information on multi-stage hydraulic fracture restimulation

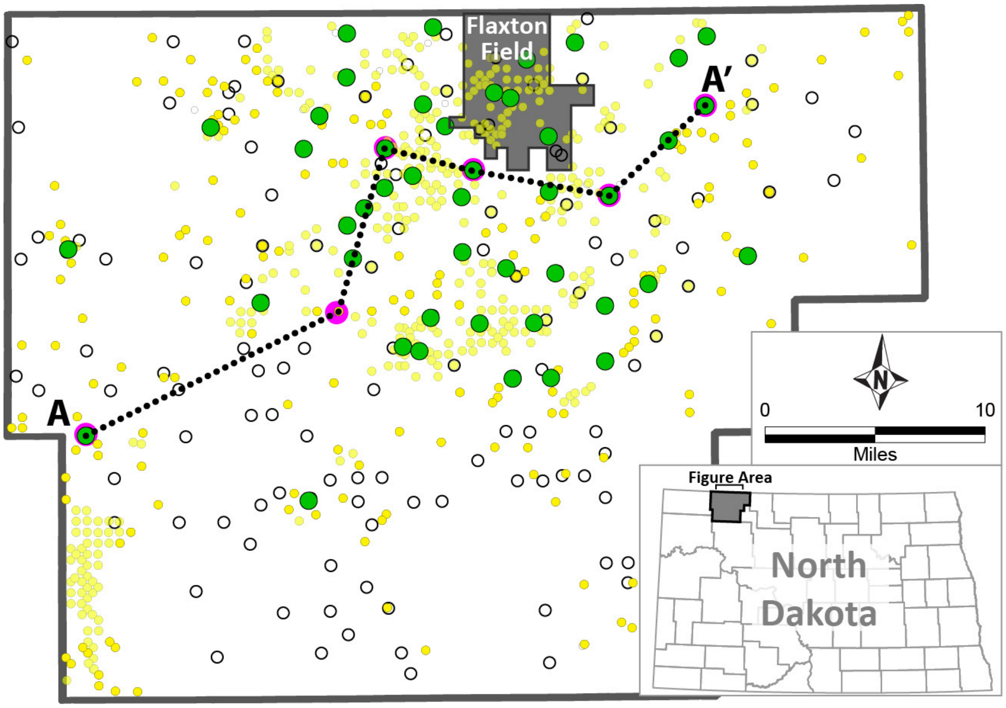


Figure 2. Map of study area (Burke County) displaying well locations with Midale drill stem tests (yellow circles), core-plug data (green circles), and digital wireline logs for fluid saturation calculatons (black-lined white circles). A-A' shows the location of the Figure 3 cross-section.

The Rival subinterval, also referred to informally as the "Nesson," forms the upper portions of the Frobisher-Alida interval and directly underlies the Ratcliffe (Fig. 1) (Cook, 1976). Across western North Dakota, the Rival subinterval forms part of the Mission Canyon Formation which has been described as regressive-shoaling upward carbonate to anhydrite sequences (Lindsay, 1985), similar to the overlying Ratcliffe interval. Lindsay (1985) described the upper several feet of the Rival subinterval within the Flaxton Field area as oolitic/peloidal lime packstone-grainstone that overlies nodular anhydrite, which he interpreted as a minor transgressive event.

Purpose of Study

The primary goal of this study was to deduce the spatial extent of elevated, producible oil saturations within the Midale subinterval across Burke County in effort to better understand the potential future extent of the unconventional-style development of the play. While the underlying upper Rival subinterval is also part of the targeted reservoir interval, the upper Rival is typically only several feet thick across the play area while the Midale subinterval pay zone is tens of feet thick and therefore may contain the majority of in-place hydrocarbon resource.

Methods

Several sets of data were compiled and generated for this study, including: 1) perforation and production data from legacy vertical wells, 2) fluid saturations measured from standard core-plug analysis, 3) drill stem test (DST) fluid and gas recoveries, and 4) oil saturations and original oil in place (OOIP) calculated from wireline logs (Fig. 2). Within each step, wireline logs were examined to determine the stratigraphic unit/s tested and/or perforated (Fig. 3). After examining each individual data set, all four data sets were examined together to delineate an area of relatively continuous elevated oil saturations for the Midale

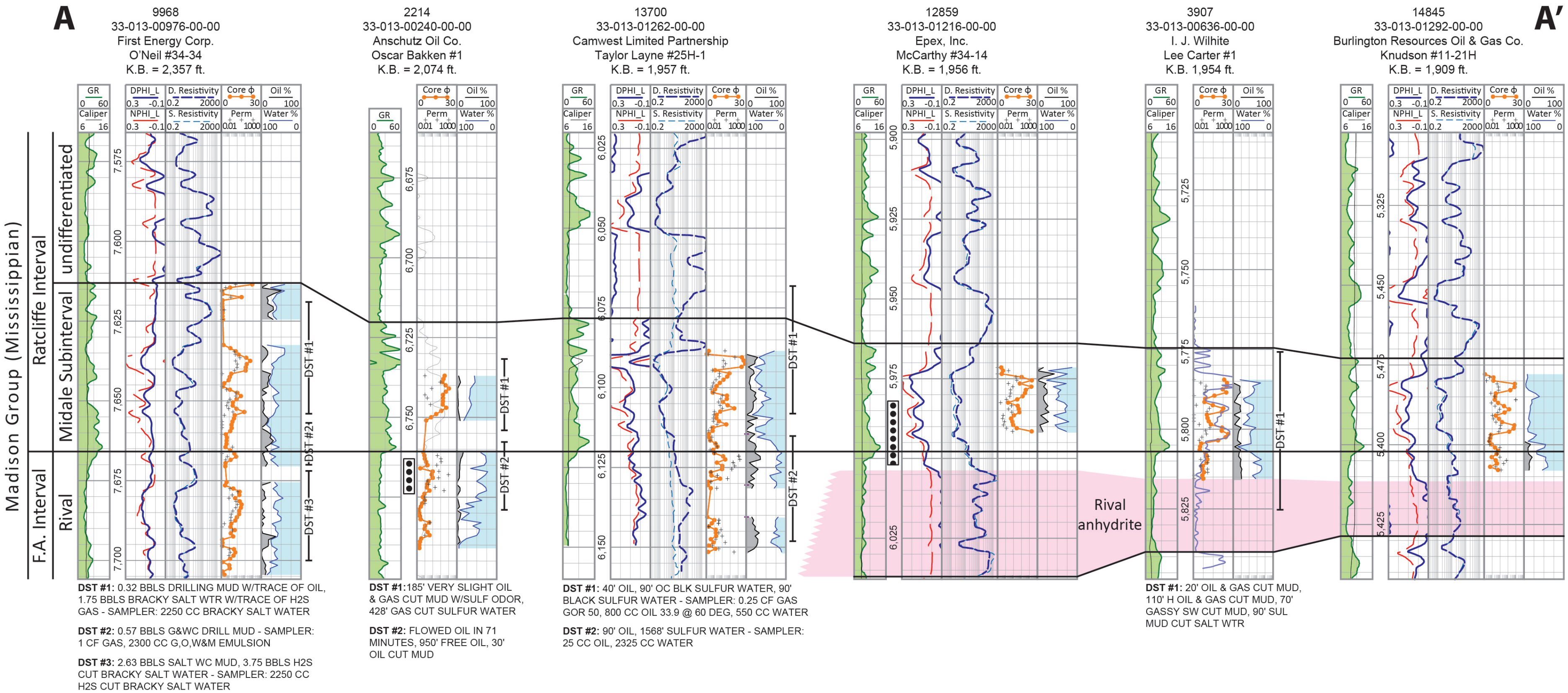


Figure 3. Stratigraphic cross-section (datum = Rival top) of the Midale-upper Rival subintervals showing example wireline logs, standard core-plug analysis data, drill stem test (DST) information, and perforations (large black dots in depth column). Depths (right of GR, gamma ray log) are in measured depth (feet below K.B.). ϕ = porosity (core-plug); DPHI_L = density porosity (limestone matrix); D. Resistivity = deep resistivity; DST = drill stem test; F.A. = Frobisher-Alida; ft. = feet; GR = gamma ray; K.B. = Kelly bushing elevation; NPHI_L = neutron porosity (limestone matrix); Oil % = core-plug oil saturation; Perm = permeability (milli-darcies); S. Resistivity = shallow resistivity; Water % = core-plug water saturation

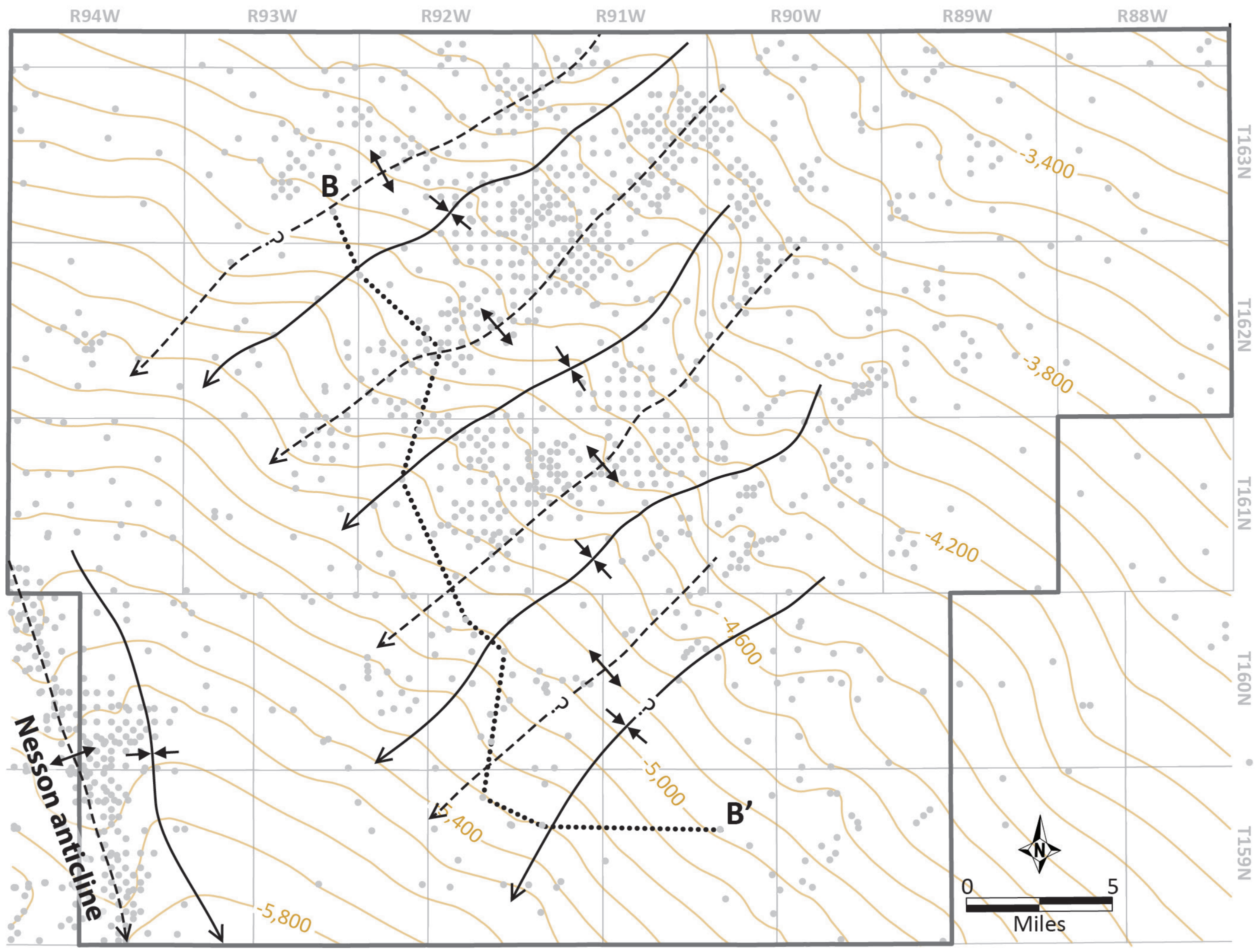


Figure 4. Structure contour map on the Rival subinterval top (Midale base) showing axial traces with plunge of interpreted subtle synclines (solid black lines) and anticlines (dashed black lines). Contours are in feet below sub-sea level with 100 foot intervals. B-B' shows the location of the Figure 6 cross-section.

subinterval. Secondarily, wireline log tops were utilized for isopach and structure contour mapping to evaluate the potential influence of structural feature/s on Midale oil accumulations.

Results

Structure

The Midale-Rival play in northern Burke County has previously been described as a combination structure-stratigraphic play (Lindsay, 1985; Voldseth, 1987). While examination of stratigraphic trapping was beyond the scope of this study, the structural component was evaluated using formation tops from wireline logs to create isopach and structure contour maps. A series of three subtle southwest-northeast trending synclines were identified on the structure contour map of the Frobisher-Alida/Rival subinterval top, which is also the base of the Midale subinterval (Fig. 4). All three synclinal axial traces directly overlie pronounced thickening trends of the Ratcliffe interval, which includes the Midale subinterval (Figs. 5 and 6). A possible fourth southwest-northeast trending syncline is speculated to exist southwards of the other three based on the Ratcliffe interval isopach (Figs. 5 and 6). The structure contour map does not clearly display this fourth syncline (Fig. 4), but this may be due to more limited well control along the prospective synclinal

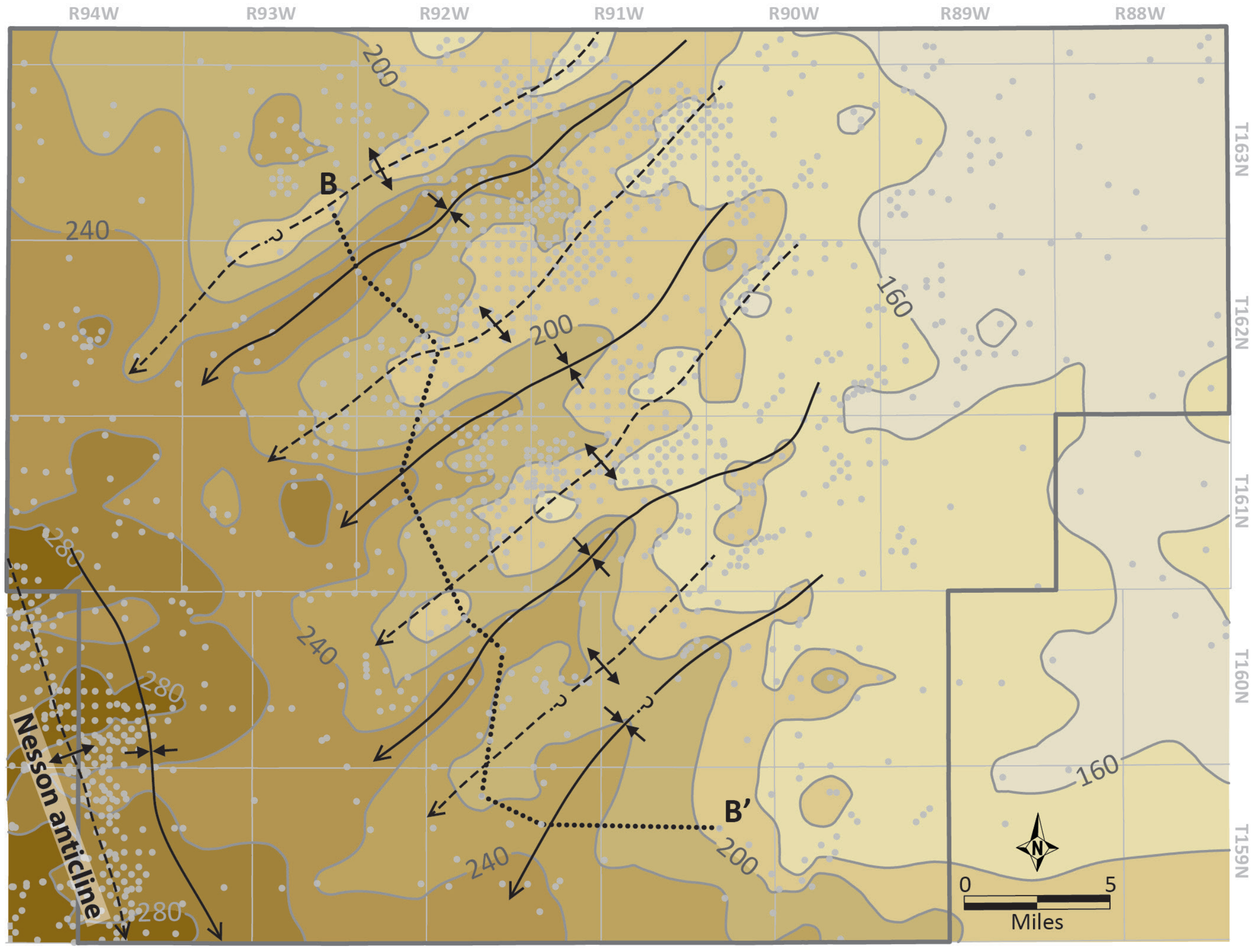


Figure 5. Isopach map of the Ratcliffe interval showing axial traces with plunge of interpreted subtle synclines (solid black lines) and anticlines (dashed black lines). Contour interval is 20 feet. B-B’ shows the location of the Figure 6 cross-section.

axis. Three subtle anticlinal trends interlay these synclines, as well as a fourth potential anticline towards the northwest, which correspond with thickening of the Ratcliffe interval (Figs. 4 and 5). Lindsay (1985) previously noted “three subtle anticlinal noses” trending through northern Burke County that coincide with many of the Midale and Rival oil fields.

While the origin and history of these structures is beyond the scope of this study, one notable observation can be made. The Ratcliffe interval and Last Salt section share a thickness relationship where thicker Last Salt sections correspond with thickening of the Ratcliffe interval and thin to absent Last Salt sections correlate with thinning of the Ratcliffe interval (Fig. 6).

<u>Legacy Vertical Well Production</u>

Perforation depth intervals and hydrocarbon production records were examined in relation to wireline logs and 285 wells were identified with oil and gas productive perforations across the Midale section (Fig. 7). Of those wells, 119 produced exclusively from the Midale. The remaining 166 wells were commingled producers with perforations extending into over- and/or underlying Madison sub-units, primarily the underlying Rival subinterval.

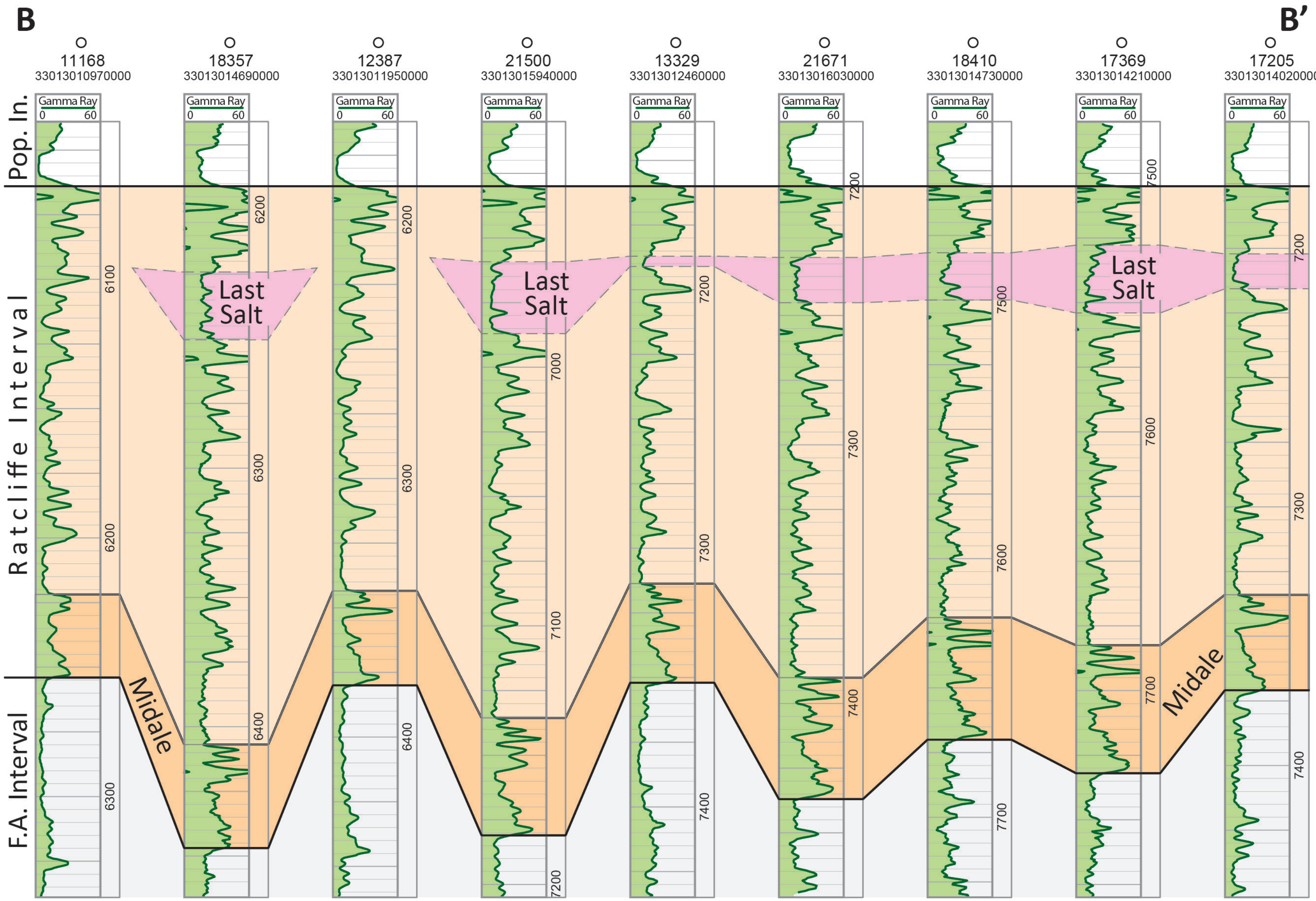


Figure 6. Northwest-southeast cross-section of the Ratcliffe interval showing thickness variations that coincide with subtle syncline and anticline structures.

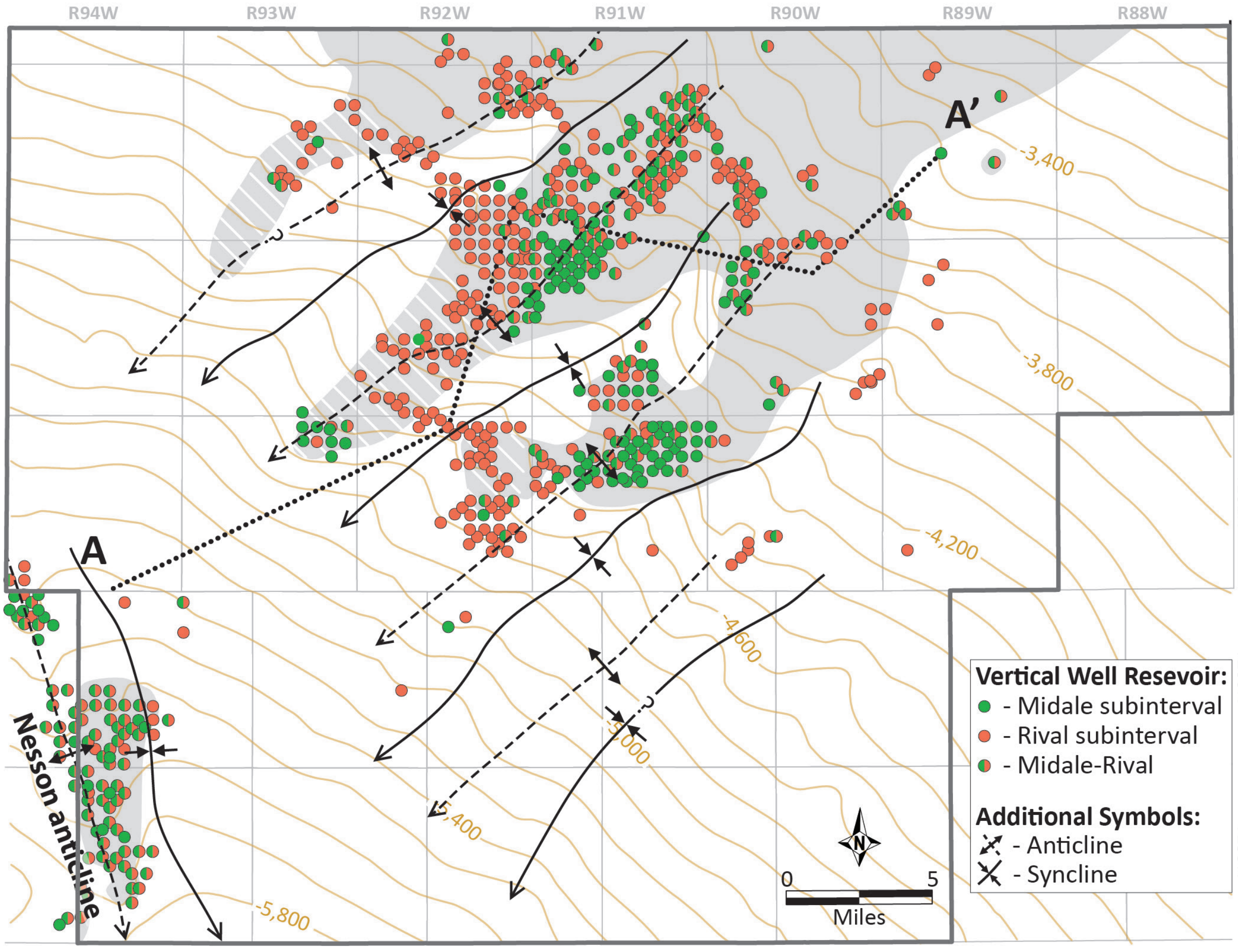


Figure 7. Map showing the distribution of vertical wells that have produced out of the Midale and/or Rival subintervals. Light brown lines are structure contours of the Frobisher-Alida interval/Rival subinterval stratigraphic top, in feet below sea level. A-A' shows the location of the Figure 3 cross-section.

Two main areas of vertical Midale production occur in central (T161N, R90W) to north-central (T163N, R91W to NW corner of T162N, R91W) Burke County with a third area in the southwestern corner (T160-161N, R94W) which corresponds with the Nesson anticline (Fig. 7). Beyond those three areas, smaller clusters to isolated, singular productive wells extend sporadically throughout the central to north-central portions of the county. Many of the vertical Midale-Rival wells loosely form southwest-northeast linear trends that are parallel to and positioned along the anticlines. The Midale-Rival production in northern Burke County is up dip from the Nesson anticline.

Core-Plug Fluid Saturations

Standard core-plug analysis data was available for 94 partial to complete Midale cores across the study area, which was used to examine fluid saturations (oil and water) (Fig. 8). Core-plug data from 56 of the cores, selected based on spatial distribution, were converted into digital format (Excel spreadsheets), imported into Petra©, depth adjusted to fit wireline logs, and evaluated for lateral oil saturation trends (Fig. 3). The nondigital, hardcopy data of the remaining 39 cores were visually examined in comparison to the converted digital data.

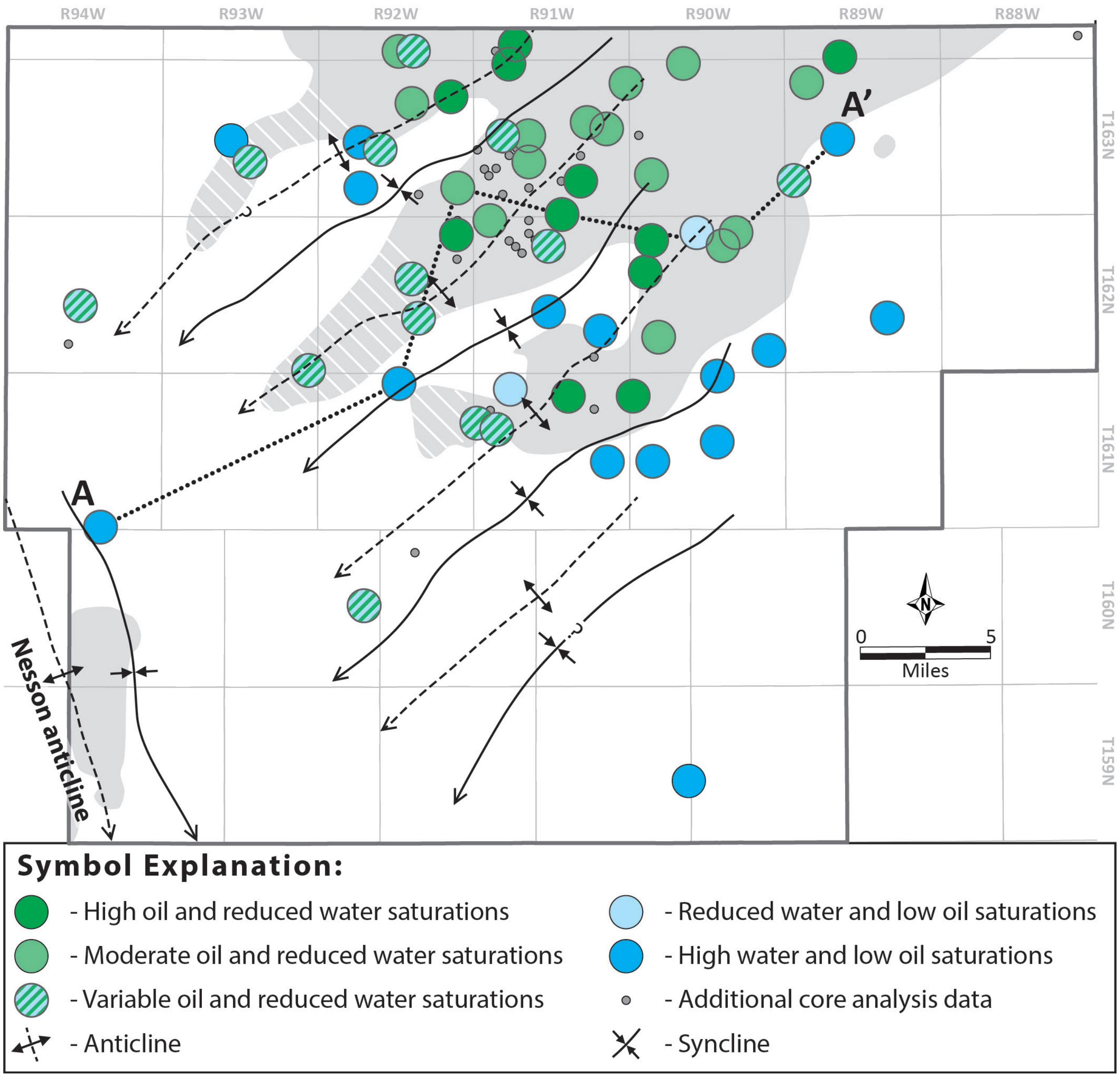


Figure 8. Map depicting qualitative evaluation of standard core-plug fluid (oil versus water) saturation data. The light grey fill shows the approximate extent of semi-continuously elevated Midale oil saturations. A-A' shows the location of the Figure 3 cross-section.

Semi-qualitative evaluation of the core-plug data was conducted due to the inconsistencies described below. Upon extraction, fluids and/or gases will begin escaping the pores of a given core sample. Therefore, by the time a core sample is analyzed for pore fluids, some of the original fluids are missing. Also, drilling fluids may penetrate some of the pores of a cored interval during extraction, particularly in more permeable rock. Several variables may affect the fluid saturation measurements of a core sample, including: drilling techniques during core extraction, core handling after extraction prior to analysis, atmospheric conditions, and the duration of time between extraction and core-plug analysis.

Most of the available Midale core-plug data extends across the northern portions of Burke County. Core-plug fluid saturations in the Midale range from up to 20-30% oil with corresponding water saturations of

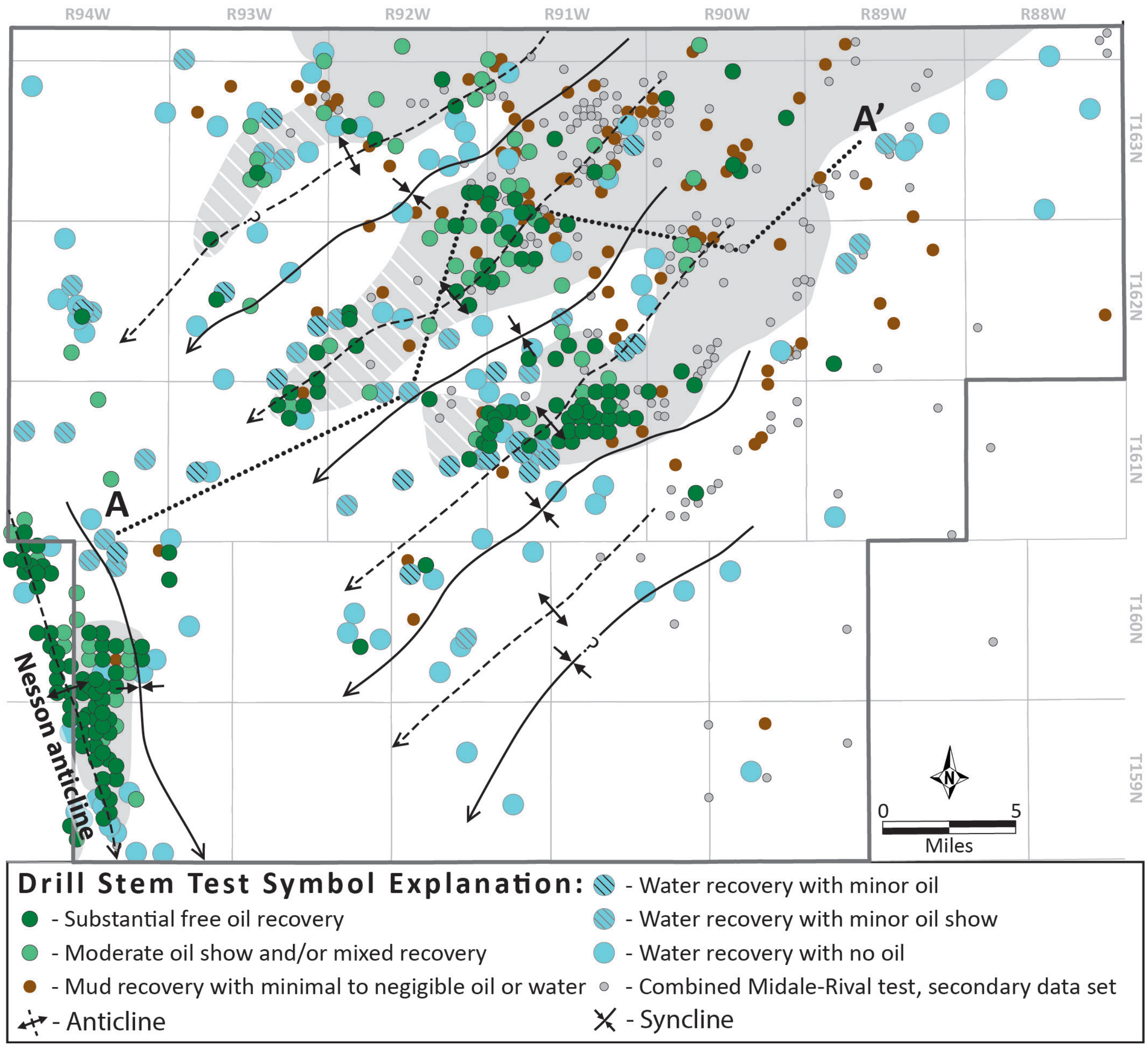


Figure 9. Distribution of Midale drill stem tests with qualitative rankings. Substantial free oil recovery equals free oil in the pipe and/or sampler with moderate to limited water. A moderate oil show and/or mixed recovery represents moderate to heavily oil cut mud and/or water with moderate to limited water. The light grey fill shows the approximate extent of semicontinuously elevated Midale oil saturations. A-A' shows the location of the Figure 3 cross-section.

around 50% or less (e.g. well #12859 – Fig. 3), to negligible oil saturations coupled with 80-90% or more water saturations (e.g. well #14845 – Fig. 3). High oil saturations within the Midale are distributed across the central to northcentral portions of the county, with high water saturations more common to the east and west (Fig. 8).

Drill Stem Test Recovery Data

DST data was reviewed for the Burke County area to examine the spatial distribution of oil recoveries from the Midale subinterval. Through the examination of wireline logs and reported DST depth intervals, 625 wells were found to contain one or more DST's run on the Midale, 584 from within Burke County, and an additional 41 that were proximally located to the county border (Fig. 9). DST's from 465 of the wells were run exclusively on the Midale section while the additional 175 were run simultaneously on both the Midale and underlying Rival subintervals. The exclusive Midale DST's were utilized as a primary data set while the commingled Midale-Rival DST's were a secondary data set.

DST's were qualitatively ranked based on reported pipe and/or sample recovery volumes. Qualitative analysis was completed due to DST variables such as: 1) duration (time) of test and 2) the stratigraphic-vertical extent of the test (some DST's spanned the entire Midale section while others tested only part of the subinterval). Some of the tests recovered minimal fluid other than a small amount of drilling mud, likely due to the short duration of the test and/or low permeability of the tested interval. Such tests provide minimal insight into fluid saturation content, but do indicate that the tested Midale interval contains relatively low permeability. Elsewise, some amount of formational fluid or gas would have flown from the tested reservoir interval, even for a test of short duration.

The remainder of the DST's ranged from recovering abundant water with negligible oil to recovering almost exclusively oil and gas. These tests are indicative of the type(s) of producible fluids and/or gases within the tested intervals. Midale DST's were found to consistently recover primarily water within the northeastern and northwestern corners as well as across most of the southern half of the study area. Midale DST oil recoveries were found distributed throughout the central to north-central portions of the study area and in the southwestern corner (Fig. 9), which is similar to the vertical well distribution and the higher core-plug oil saturations positioned along the subtle anticlines (Figs. 7 and 8).

Wireline Log Calculations

Digital wireline logs from 170 wells, spatially dispersed across Burke County, were combined with formation water chemistry and temperature (to determine water resistivity) to calculate fluid (oil and water) saturations across the Midale section. A total of 93 wells had pre-existing digital logs available for usage while wireline logs from older, non-digital, raster formats were digitized from 77 additional wells within Petra©. Calculated oil saturations were then used to estimate OOIP and utilized to delineate the extent of elevated Midale oil saturations.

In order to calculate Midale water saturations, the following parameters needed to be determined: 1) the wireline log porosity that best matches the core-plugs porosity values, and 2) resistivity of the interstitial water (naturally occurring formational water). Overall, the density log porosity calculated with a limestone matrix was found to trend closely with the core-plug porosity for the Midale. The two main components to determine interstitial water resistivity include: 1) salinity of the water, sodium chloride (NaCl) content), and 2) temperature. Midale water chemistry data was examined from over 30 wells (Fig. 10). Based on available information, most (possibly all) of these analyses were completed on water samples recovered from DST's. Such water recoveries may range from consisting almost entirely of natural formation water that flowed from the reservoir during the test, to a mixture of drilling fluid(s) and/or natural formation water. The majority of the water analyses reveal that the Midale formation water generally appears supersaturated with respect to NaCl, often containing 250,000-300,000+ ppm (parts per million) of NaCl. Water tests with significantly lower NaCl content do not form any obvious spatial trend and are thought to be a function of the intermixing of drilling fluids with interstitial water of the Midale.

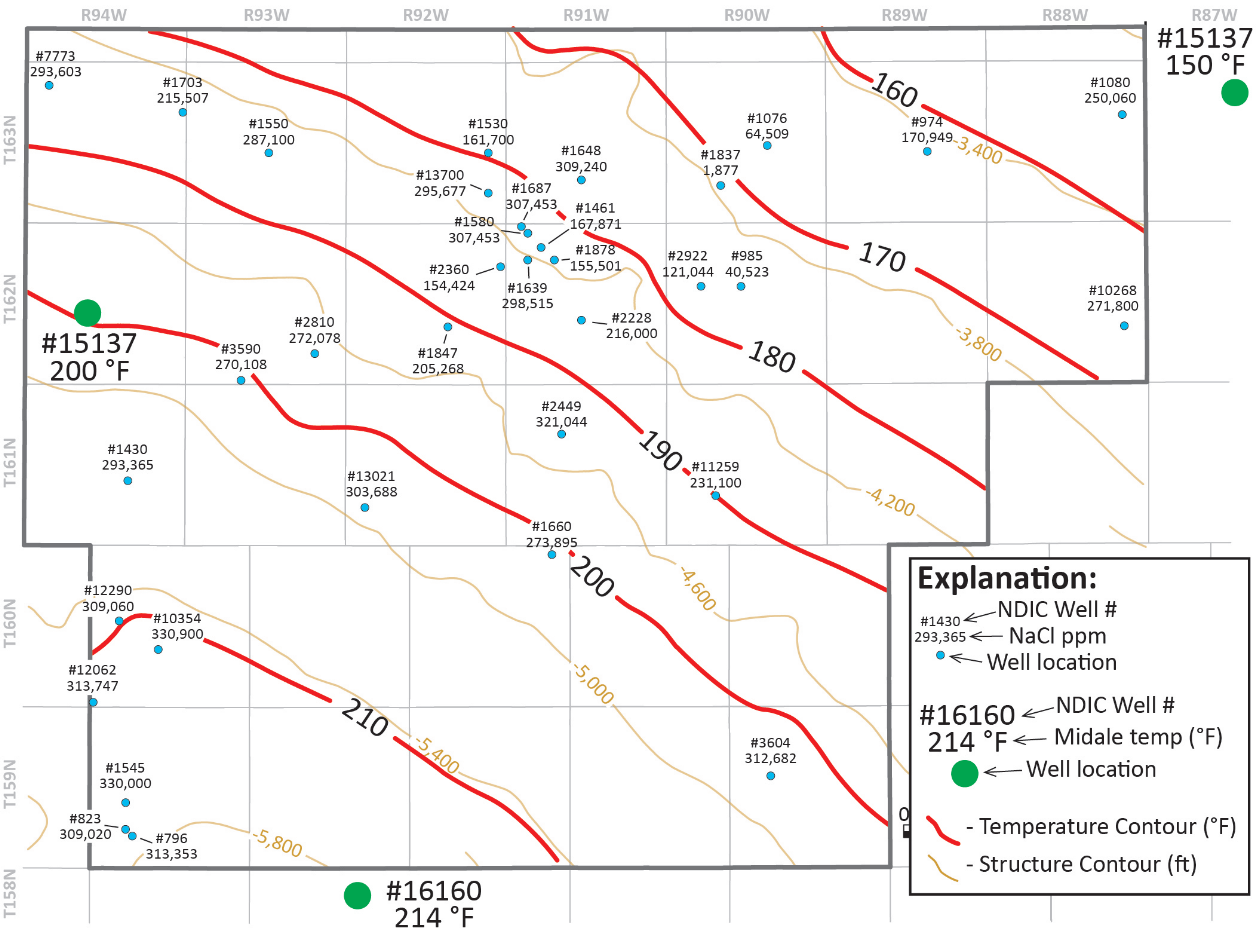


Table of Midale Formation Water Resistivity Values:

150-160 °F = 0.0205 Ohms	170-180 °F = 0.0180 Ohms	190-200 °F = 0.0150 Ohms	210-220 °F = 0.0140 Ohms
160-170 °F = 0.0195 Ohms	180-190 °F = 0.0160 Ohms	200-210 °F = 0.0145 Ohms	

Figure 10. Water chemistry and formation temperature data for the Midale subinterval. Structure contours are on the Rival/Frobisher-Alida top (base of the Midale). Temperature data is from McDonald (2015). Water chemistry data was compiled from the North Dakota Oil and Gas Division database.

Subsurface temperatures for the Midale subinterval were extracted from three wells in the Burke County area (Fig. 10), which were recently temperature logged by the North Dakota Geological Survey (McDonald, 2015). While bottom-hole temperatures from Midale DST's were examined, the NDGS well temperatures are more representative of actual, equilibrated subsurface temperatures (Stolldorf, 2018). Midale formation temperatures were created using the NDGS temperatures combined with the Rival top structure contours (Fig. 10).

Finally, the Archie equation (Eq. 1) was applied to the 167 digital logs to calculate oil and water saturations across the Midale porosity interval (Figs. 3 and 11). Midale water resistivity values were determined across the study area using the temperature contours of Figure 10 and the Midale interstitial water resistivity values of Table 1. OOIP, in barrels per acre units, was next calculated by combining the density porosity with the calculated oil saturations (Eq. 2).

Equation 1

$$S_W = (R_W/(R_T(\phi^m)))^{(1.0/n)}$$

ϕ = density porosity with limestone matrix
n = saturation component
m = cementation component
R_W = resistivity of formation water
R_T = true resistivity of formation (deep resistivity)
S_W = water saturation

Equation 2

$$OOIP = 7758*A*h*\phi*(1-S_W)/1$$

ϕ = density porosity with limestone matrix
A = area (acres)
h = height (feet)
OOIP = original oil in place
S_W = water saturation

Steps to creating OOIP Contour map:

1) Clipped density porosity (limestone matrix, DPHIL) to span only the Midale porosity zone.
2) Adjusted the DPHIL log by changing all negative porosity values to zero. This was done to avoid negative porosity values combining in the OOIP calculation to create false positive oil in place.
3) Calculated water saturation (SW) across the Midale porosity interval assuming n=2 and m=2, and R_W = 0.017 ohms (estimated average value for across study area).
4) Adjusted calculated SW by changing all values >100% to 100% (this step was not a normalization as values between 0% and 100% were left unchanged).
5) Calculated OOIP across Midale porosity interval in 0.2 ft. increments of barrels of oil per acre-foot.
6) Calculated an arithmetic sum of OOIP for the Midale porosity interval.
7) Created preliminary OOIP contour map with the map module of Petra©.
8) Made manual adjusted to OOIP contours.

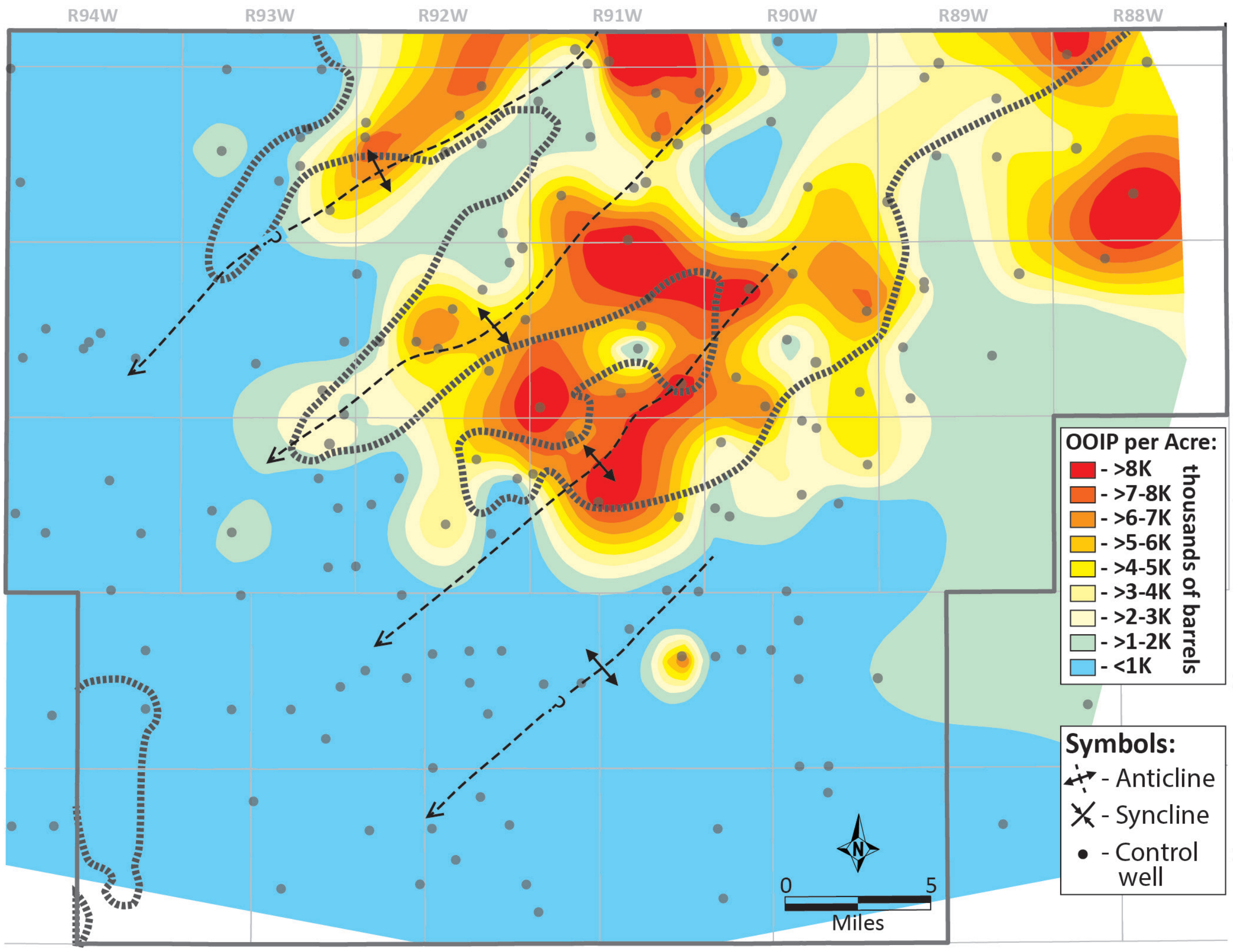


Figure 11. Original oil in place within the Midale subinterval calculated from wireline logs. The thick grey dashed linesshow the approximate extent of semi-continuously elevated Midale oil saturations. A-A' shows the location of the Figure 3 cross-section.

Similar to the core-plug and DST data, the highest OOIP values extend across the north-central portion of the study area while the lower OOIP values span the southern half and northwestern corner (Fig. 11). One difference, however, is high OOIP values extend into the northeastern corner of the study area where core-plug analysis data shows high water with negligible oil saturations and DST recoveries are primarily water (Figs. 8, 9, and 11). If the Midale is non-hydrocarbon productive in the northeastern corner, then this difference could be the result of a substantial lithological change to the Midale that diminishes the accuracy of the Archie equation (which could affect one or more of the equation variables), and/or the Midale contains non-producible (residual) oil. Alternatively, the Midale could contain hydrocarbon resource potential eastward of the elevated oil saturated area delineated through this study.

<u>*Composite Map*</u>

The area of elevated Midale oil saturation depicted on the majority of maps in this publication was delineated by combining the four data sets described above: 1) vertical well production, 2) core-plug fluid saturations, 3) DST recoveries, and 4) wireline log calculations. Vertical well production and core-plug fluid saturation data sets are thought to be the most reliable indicators of elevated, producible oil saturations. The core-plug data were measured directly off of extracted Midale core samples while the exclusive (non-commingled) vertical Midale well production shows long-term fluid production. The DST's provide a less

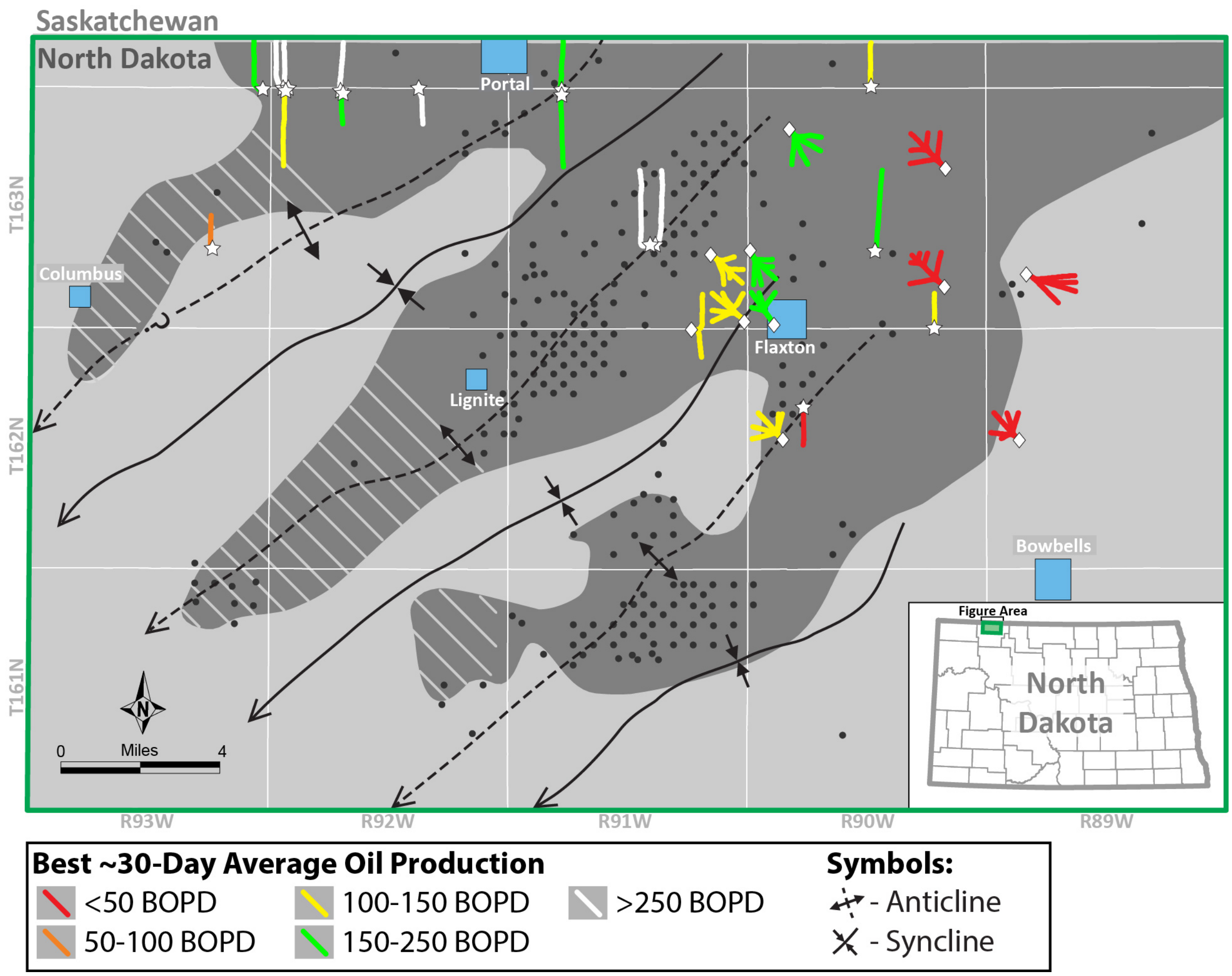


Figure 12. Map of interpreted area with elevated, producible Midale oil saturations (dark grey) with unconventional-style wells color coated based on average daily oil production (BOPD = barrels of oil per day) during the month of peak production. White stars indicate horizontal Midale-upper Rival wells that were initially completed with multi-stage hydraulic fracturing. White diamonds indicate horizontal wells that were initially open-hole completions and recently restimulated using multi-stage hydraulic fracturing. Small grey circles are vertical Midale wells. The diagonal lines indicate where the elevated Midale oil saturations are less certain and/or more variable.

reliable, short-term look at reservoir production. The wireline log calculations have limitations, such as not accounting for Midale lithological changes both laterally and vertically, which will alter the calculation accuracy but still provide a useful secondary dataset.

The area of elevated Midale oil saturations shown on Figure 12 represents where all four data sets are in overall agreement and, therefore, likely depicts where the Midale subinterval contains relatively continuous elevated saturations of producible oil (in addition to hydrocarbon gas). Away from this area, the Midale is primarily water productive with smaller, discontinuous zones of elevated oil saturations. Most of the best producing unconventional-style wells, with 30-day average initial production rates >150 BOPD, have been located towards the northwestern portion of the oil-saturated Midale area (Fig. 12). Many of the less productive wells (<50 BOPD) have been re-stimulations of pre-existing horizontal open-hole wells located towards the eastern side of the oil saturated area (Fig. 12).

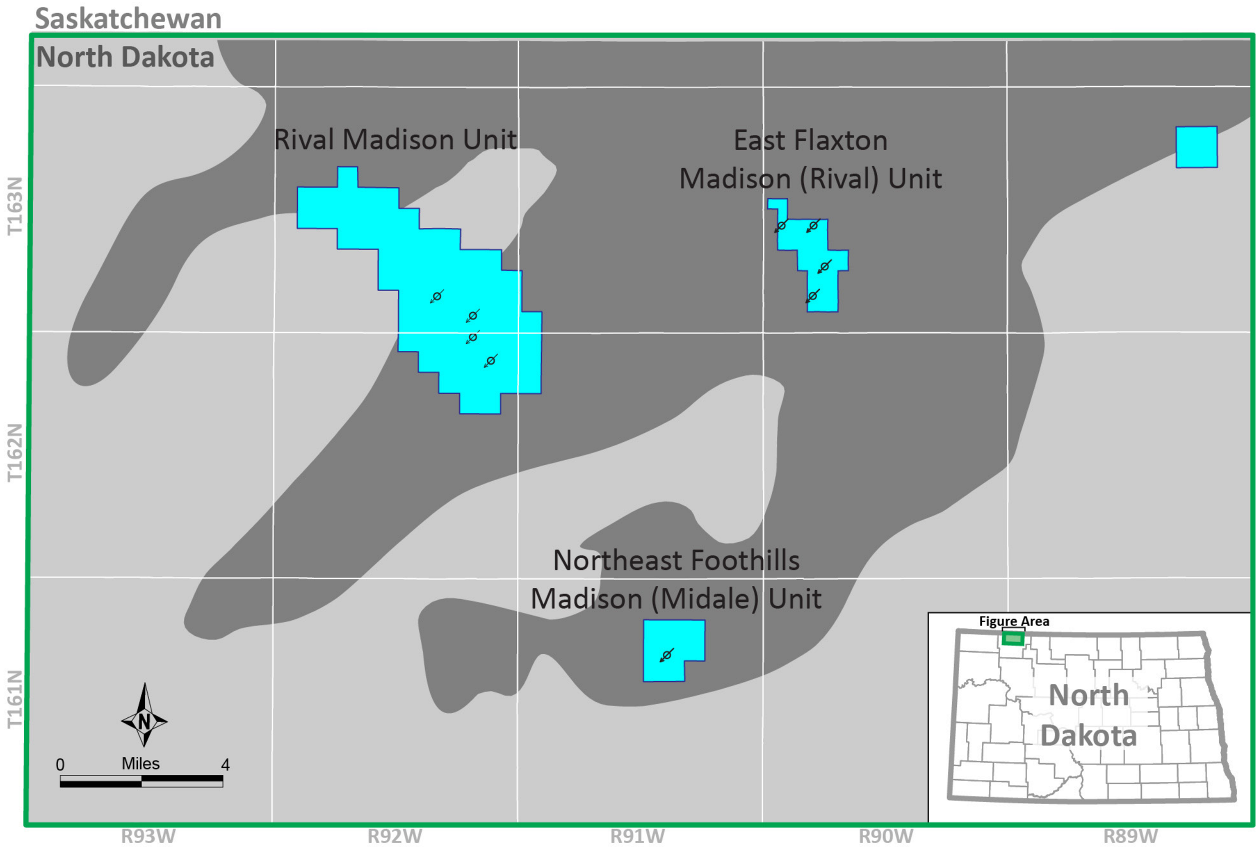


Figure 13. Map with unitized Midale-Rival fields (blue) and injection wells (circles with diagonal arrows) in relation to interpreted area with elevated, producible Midale oil saturations (darker grey fill).

The oil saturated area forms a relatively irregular shape with three southwest-northeast trending "fingers" that appear to merge towards the northeast. These three oil saturation "fingers" parallel the subtle, interpreted synclinal and anticlinal trends (Fig. 12). They fall in between the synclines while approximately overlying the anticlinal axes. This relationship supports previous interpretations that the Midale-Rival play is at least partly controlled by structure (Lindsay, 1985; Voldseth, 1987). Along the southwestern portions of these three oil saturation "fingers," the four data sets show inconsistent indications of elevated, producible oil saturations.

The total Midale oil saturation area spans approximately 160,000 acres. While unconventional-style wells are spaced across most of that area, additional acreage has yet to be tested towards the northeast as well as further to the south. This delineated area shows where the Midale subinterval may be most conducive to productive unconventional-style wells. Production results across this area have and will continue to vary due many factors, several of which are reviewed below.

Additional Considerations

Three separate areas in northern Burke County have been unitized and water flooded for enhanced oil recovery efforts (Fig. 13). Within two of these unitized areas, the upper Rival has been water flooded while the third area the Midale has been flooded. Unconventional-style well development proximal to the injection well sites may be limited as a portion of the targeted reservoir has been flooded, displacing the original in-place hydrocarbons with injected water.

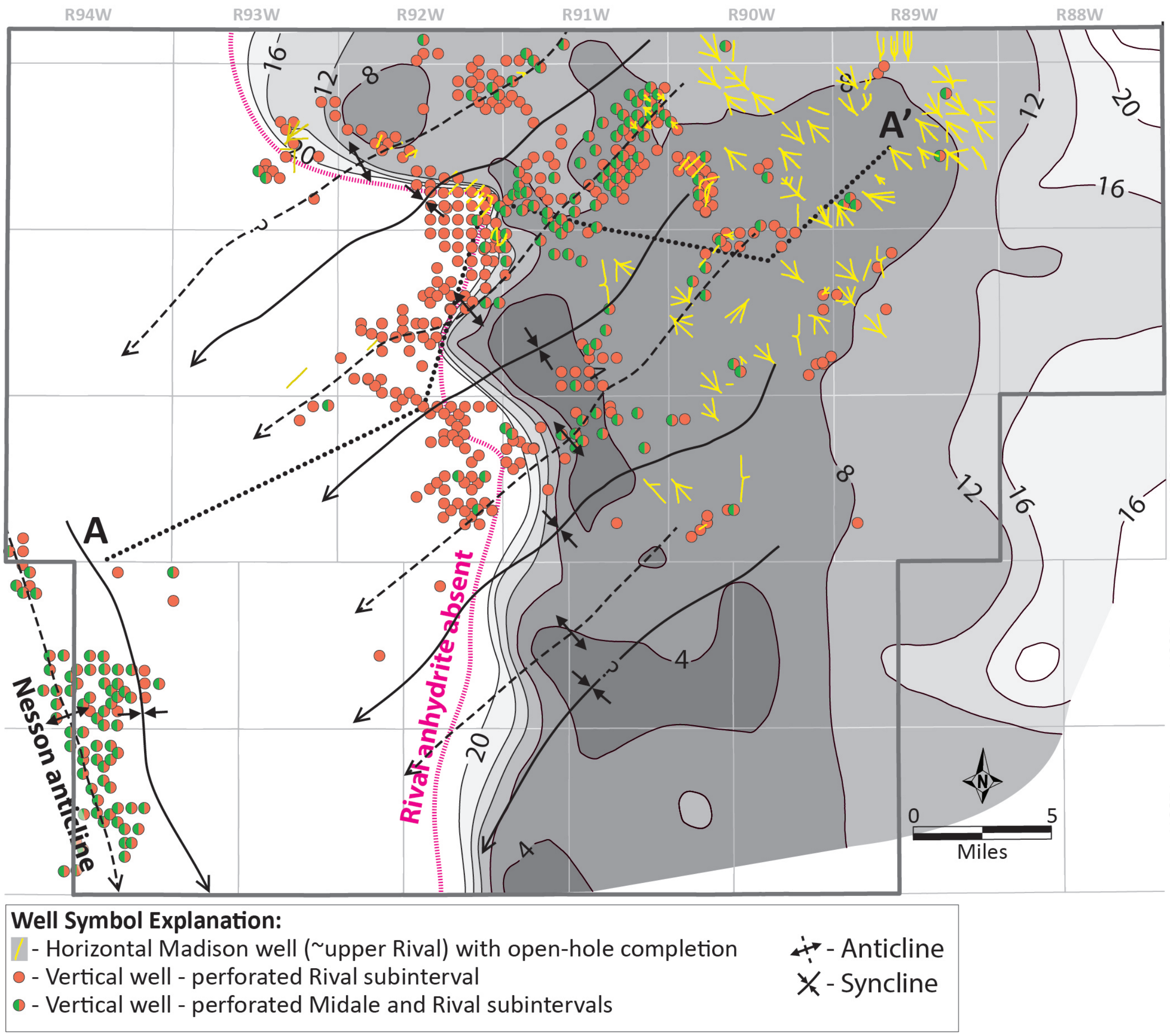


Figure 14. Rival production map for Burke County. Colored filled contours depict the net thickness of the moderately porous upper Rival overlying anhydrite. A-A' shows the location of the Figure 3 cross-section.

Another item of consideration is resource depletion from vertical wells. Many of the vertical Midale-Rival wells have only cumulatively produced 10'000's of barrels of oil at very low but steady production rates, likely due to low reservoir permeability. In such locations there is still likely plenty of resource left in place for unconventional-style development. However, in other locations, vertical Midale-Rival wells have cumulatively produced 100,000's BBLS oil, which may constitute a significant amount of removed/ produced resource.

While the Midale constitutes the majority of resource for the unconventional-style wells, the underlying upper Rival has been the horizontal landing target and also contains several feet of moderately porous and potential oil-charged reservoir. Based on the semi-continuous and extensive distribution of vertical and horizontal (openhole completions) upper Rival oil wells (Fig. 14), elevated Rival oil saturations are speculated to be more extensive laterally than those of the overlying Midale section. Still, oil saturation levels, reservoir properties, and thickness of the upper Rival pay zone also likely play a notable role in the production success of the unconventional-style Midale-Rival wells.

References

Cook, C.W., 1976, A mechanical well log study of the Poplar interval of the Mississippian Formation in North Dakota: North Dakota Geological Survey, Report of Investigation No. 52, 20 p.

Hendricks, M.L., 1987, The lower Ratcliffe interval (Mississippian) in Williams and McKenzie Counties, North Dakota: Fifth International Williston Basin Symposium Core Work Shop Volume, Saskatchewan Geological Society, edited by D. W Fischer, p. 33-58.

LeFever, J.A., and Anderson, S.B., 1986, Structure and stratigraphy of the Frobisher-Alida and Ratcliffe intervals, Mississippian Madison Group, north-central North Dakota: North Dakota Geological Survey, Report of Investigations No. 84, 17 p., 14 pl.

Lindsay, R.F., 1985, Rival, North and South Black Slough, Foothills and Lignite Oil Fields: their depositional facies, diagenesis, and reservoir character, Burke County, North Dakota: The Society of Economic Paleontologists and Mineralogists (SEPM), Rocky Mountain Carbonate Reservoirs, p. 217-263.

McDonald, M.R., 2015, Preliminary Results of Temperature Logging in the Williston Basin to determine Heat Flow: North Dakota Geological Survey, Report of Investigations No. 115, 170 p.

Nesheim, T.O., 2019, Review of the Emerging Midale-Upper Rival (Mississippian Madison Group (Unconventional-Style Play, Northern Burke County: North Dakota Department of Mineral Resources, Geo News, v. 46 no. 1, p. 4-6.

Stolldorf, T.D., 2019, Williston Basin Static Temperature Logging Program Continues to Yield Results: North Dakota Department of Mineral Resources, Geo News, v. 46 no. 1, p. 14-16.

Voldseth, N.E., 1987, Coteau and Dale intervals of the Mississippian Mission Canyon Formation; Flaxton Field, Burke County, North Dakota: Fifth International Williston Basin Symposium Core Work Shop Volume, Saskatchewan Geological Society, edited by D. W Fischer, p. 89-109.