Redevelopment of Madison Fields in Burke County Demonstrates Fracture Stimulation is Effective

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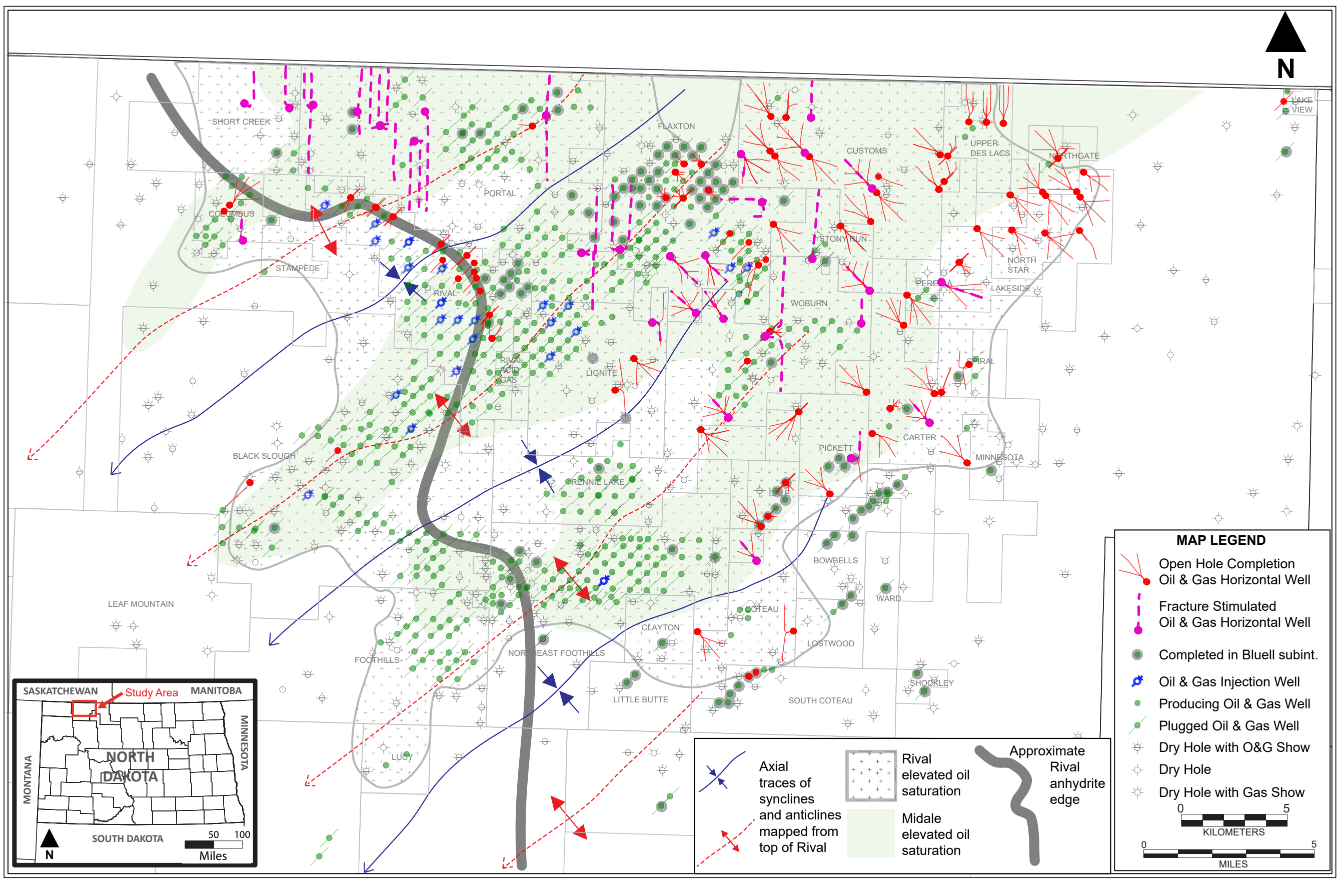

GEOLOGIC INVESTIGATION NO. 272
NORTH DAKOTA GEOLOGICAL SURVEY
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INTRODUCTION

The Mississippian Madison Group is a composite of three formations and multiple intervals and subintervals which compose a carbonate package with upwards of 2,400 feet of thickness and an areal extent that covers the Williston Basin (Nesheim and Onwumelu, 2022 and Murphy et al., 2009) (figs. 1 and 2). This core-based study focuses on the Midale and Rival subintervals at the base of the Ratcliffe and the top of the Frobisher Alida Intervals, respectively, in Northern Burke County, North Dakota (figs. 1 and 2). This study presents a review of the carbonate facies and stratigraphy as observed from core and open hole log evaluation, the three main development styles that have been used in oil and gas production in the region, and evidence that points to hydraulic fracture stimulation of dedicated laterals as the most effective development method employed in the region to date. Also included in the results is a review of development opportunities in the region.

Development of oil and gas in the Rival and Midale subintervals (Madison Group) in Burke County has seen nearly continuous drilling and production activity since shortly after the discovery of oil and gas in North Dakota and can serve as a case study for future redevelopment in other Madison fields. Over the long and diverse history of oil and gas development in Burke County, activity progressed from conventional vertical development to localized water flooding, to exploring and developing downhole potential in the Bluell subinterval in the early 1980s, evolving into an open hole horizontal play in the late 1990s. In 2012, the implementation of unconventional-style, multi-stage hydraulic fracture stimulation rounded out this play as a microcosm of the last 70 years of technological advances in the oil and gas industry. The success of the recent development implementing fracture stimulation bodes well for the remaining resource potential of the immediate area and other Madison fields across the state.

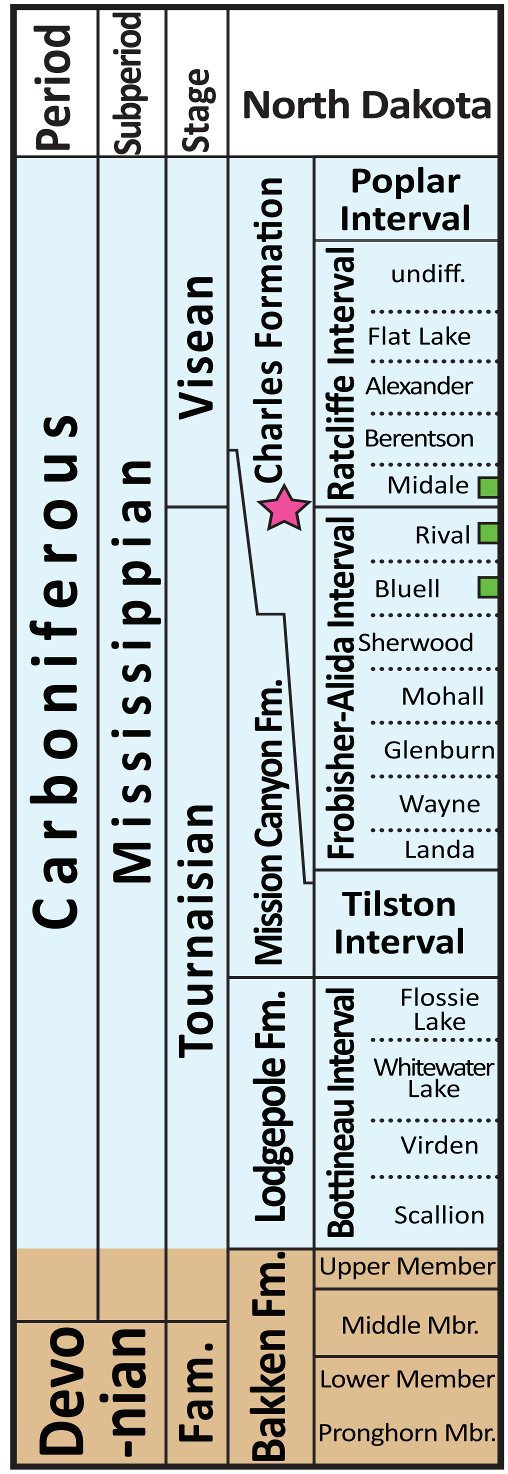

FIGURE 1. Simplified stratigraphic column of the lower Mississippian and upper Devonian section in the Williston Basin, North Dakota, highlighting the location of the Midale, Rival, and Bluell subintervals of the Madison Group with green squares. The pink star highlights the Midale and Rival subintervals, the primary producing intervals discussed here. Modified from Nesheim and Onwumelu, 2022.

METHODS

Core analysis data was obtained from historical reports in PDF or digital form and depth shifted to match wireline logs. Forty wells were added to the core analysis data set used in Nesheim (2018) for a total of 96 wells. Twenty-one cores

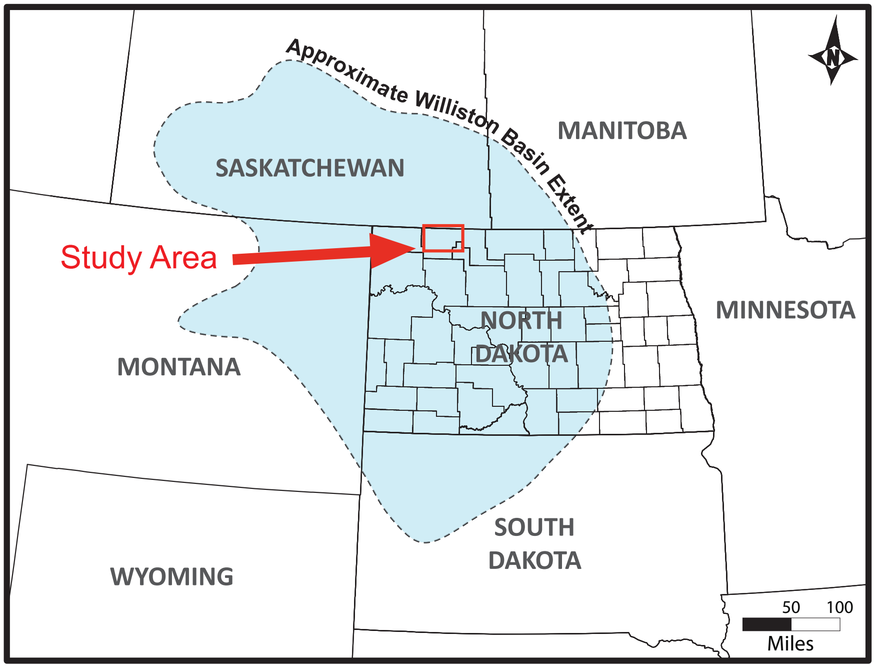

FIGURE 2. Location of study area in North Dakota, illustrating the approximate extent of the Williston Basin. The Madison Group is present throughout the Williston Basin and extends into neighboring states to the south and west, and into Canada.

from the Midale and Rival subintervals were described across the study area to define and document facies, and nine cores were selected to observe core chip fluorescence. Core descriptions were used to correlate log responses so that facies could be picked on wireline logs when descriptions were unavailable.

Core fluorescence was observed using a porcelain spot plate and petroleum distillate (lighter fluid) as a solvent. Samples were chipped off cores at one-foot intervals, crushed, and soaked in solvent for three hours before final observations were made. A section of the spot plate with no sample added (solvent only) was used as a control for zero fluorescence, and a sample from the Fines 24-19 (NDIC #27319) was used as a standard for strong fluorescence. The standard utilized from the Fines 24-19 well is from a depth of 4,436.9′ MD in the Wayne Subinterval of the Madison Group in Bottineau County, with core analysis plug properties illustrated in Table 1.

TABLE 1. Core plug analysis properties of fluorescence standard.

Depth	Air Permeability (Maximum) md	Porosity (Helium) %	Bulk Density gm/cc	Grain Density gm/cc	Oil Saturation %
4436.5 - 4437.5	86.9	34.2	1.85	2.81	48.1

Production data was gathered from the North Dakota Department of Mineral Resources databases for all wells in the study area and segmented into categories to analyze and display the results of development efforts in the region over the last 65+ years. In the following sections, a series of maps are presented which display cumulative oil production, cumulative gas production, and initial water cut from the three main categories of wells: 1) vertical producers, 2) open hole horizontal multi-lateral projects, and 3) single lateral fracture stimulated wells (grassroots and recompletions). Data was often manually segmented into the first twelve months of production to arrive at statistics for initial production to characterize reservoir productivity. The locations of wells used for these three methods are indicated in Figure 3 below, and the results of the interpretations of these data follow in this report. Raw data utilized to produce maps and figures herein can be found in the appendices that accompany this report.

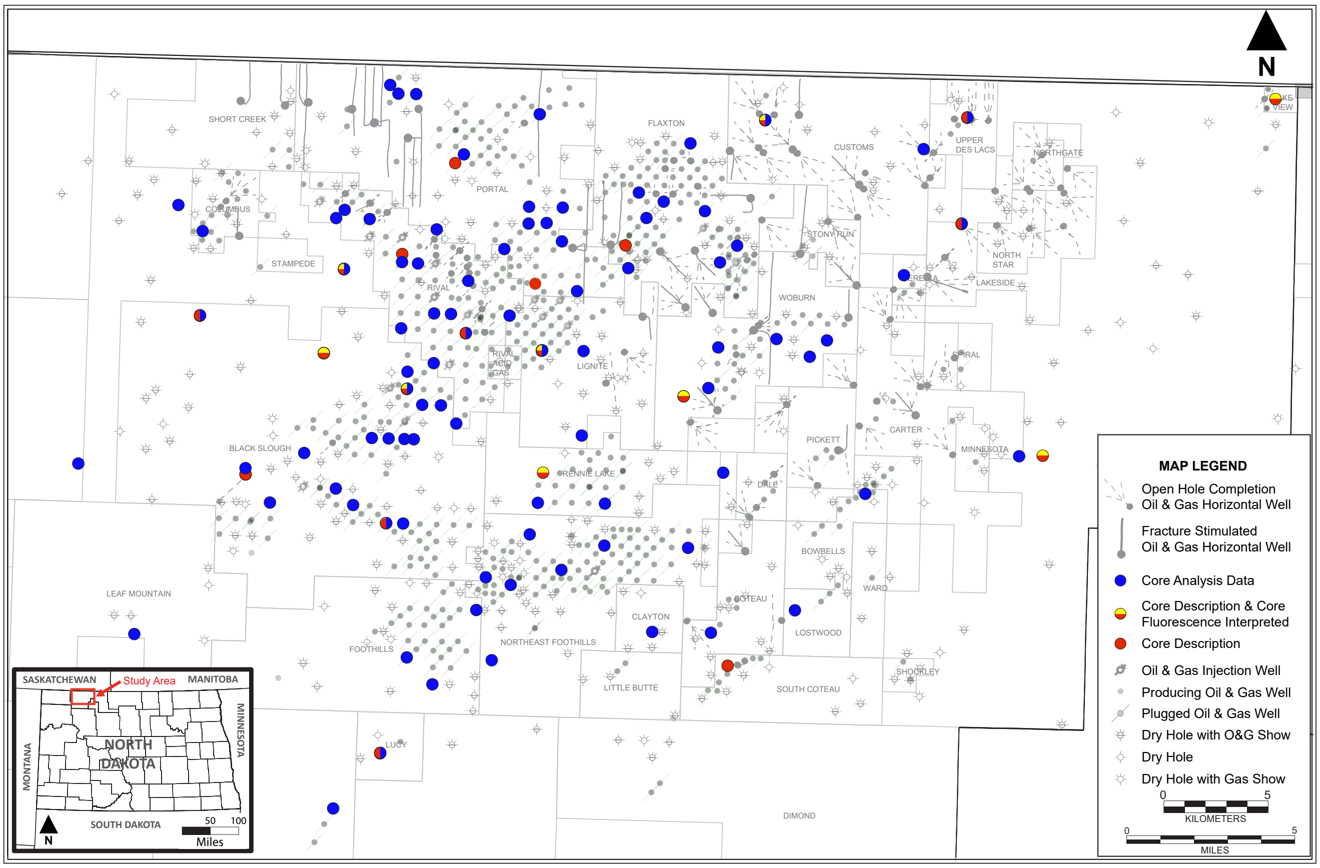

FIGURE 3. Locations of wells and well data investigated for this report.

FACIES DESCRIPTIONS

The following section provides a review of the primary rock types (facies) that comprise the Rival, Midale, and the lower portion of the Midale anhydrite subintervals within the study area (fig. 1), and an overview of the stratigraphic framework. In this study, these units have been subdivided into five facies that are described below. These five facies are presented using the Taylor Layne #25H-1 as a type log for reference. The Taylor Lane #25H-1 well was cored and then sidetracked in the Rival Field as the first example of open-hole horizontal development. It has produced 331,000 barrels of oil since 1994.

FACIES 1

The light-medium gray anhydrite of the Rival, upper Midale, and Midale anhydrite subintervals (facies 1) are observed in massive, mosaic, and bedded morphologies, and in nodular form. In most occurrences, anhydrites are interbedded with other lithologies.

Midale anhydrites were rarely cored, but where observed are anhydrites with chicken wire, massive, mosaic, and bedded morphologies with interbedded calcareous shales and dolostone. The Sorum SWD 1 well in the Flaxton Field (NDIC #32618) has available core photographs on the North Dakota Department of Mineral Resources website and is a good reference because it contains 15′ of anhydrite cored in the Midale anhydrite.

In the Rival subinterval, anhydrite commonly occurs in nodular form when associated with grainstone, and in massive form when associated with algal mats which are common in the lower Rival. These massive anhydrites in the lower Rival are what has been commonly interpreted as the ‘Rival shoreline’ (e.g., Lindsay, 1985), with the depositional environment interpreted to be a coastal lagoon/sabkha type in a carbonate ramp model (Lindsay, 1985). Massive anhydrites of the lower Rival increase in thickness to the northeast and form the stratigraphic baffle/trap for many of the fields in the study area. The general boundary of increasing anhydrite is noted in later figures as the ‘approximate anhydrite edge’.

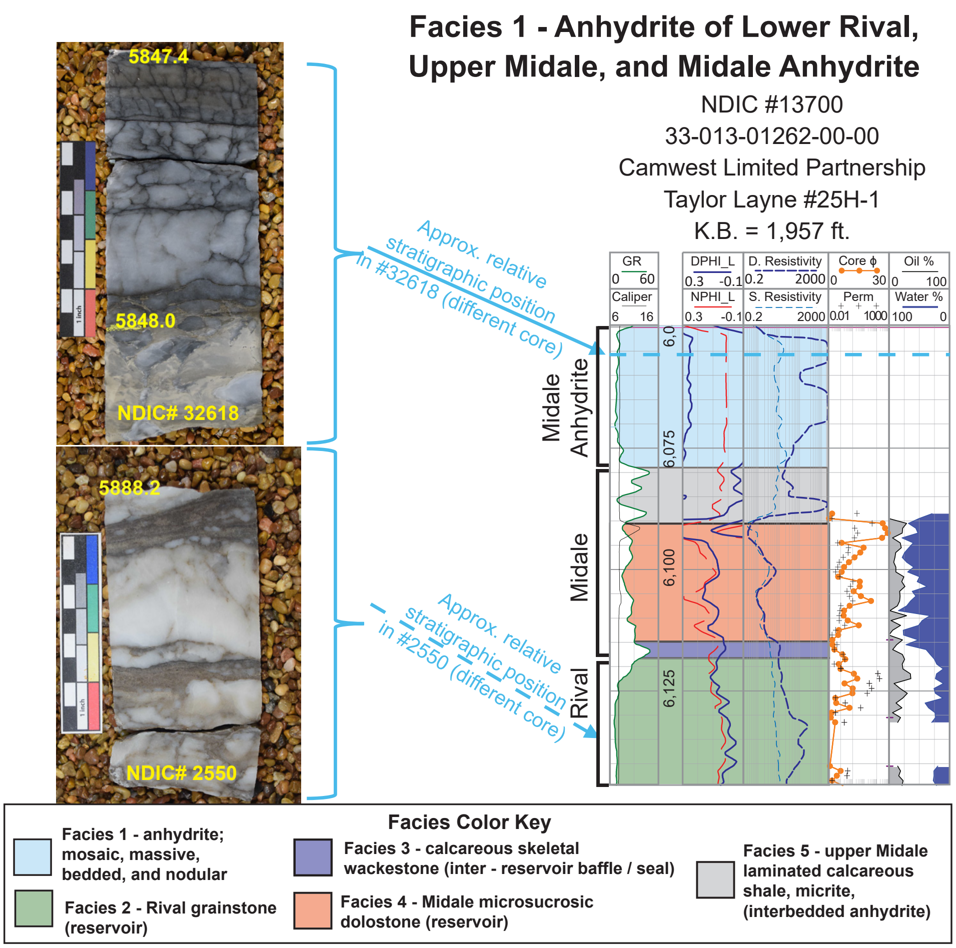

FIGURE 4. The stratigraphic position of facies 1-5 on the Taylor Layne #25H-1 type log and facies 1 representative photographs and relative location. Note that there is no abundant anhydrite in the Rival in the type log, as it is in the Rival Field outboard of the thick anhydrite concentrations. Representative photographs from NDIC #2550 in the Portal Field and NDIC #32618 in the Flaxton Field are presented along with relative stratigraphic positions.

FACIES 2

Massive gray to brown calcareous grainstone (facies 2) commonly exhibits abundant peloids, and oncoids and oolitic zones can also be found throughout the section. Occasional zones of sucrosic limestone have been observed. The upper contact with facies 3 (described below) is occasionally burrowed and fossiliferous, with the fossil assemblage dominated by half brachiopod shells and crinoidal stem fragments, corals are rare. Within the grainstone portions, vuggy and pinpoint porosity is common and is variably occluded by calcite. In several of the cores described, the upper 1 – 5 feet is a peloidal packstone. Lower in the section, algal mats are often observed, sometimes in association with massive anhydrite. The dominant depositional environment for the grainstone facies is interpreted to be high energy, near-shore deposition due to the abundance of peloids and observation of oncoids and ooids. Grainstone is an oil reservoir that has been the focus of development and is present across the study area at the top of the Rival subinterval (the uppermost subinterval of the Frobisher-Alida Interval).

Facies 2 - Peloidal / Oncolithic / Oolitic Grainstone of Upper Rival

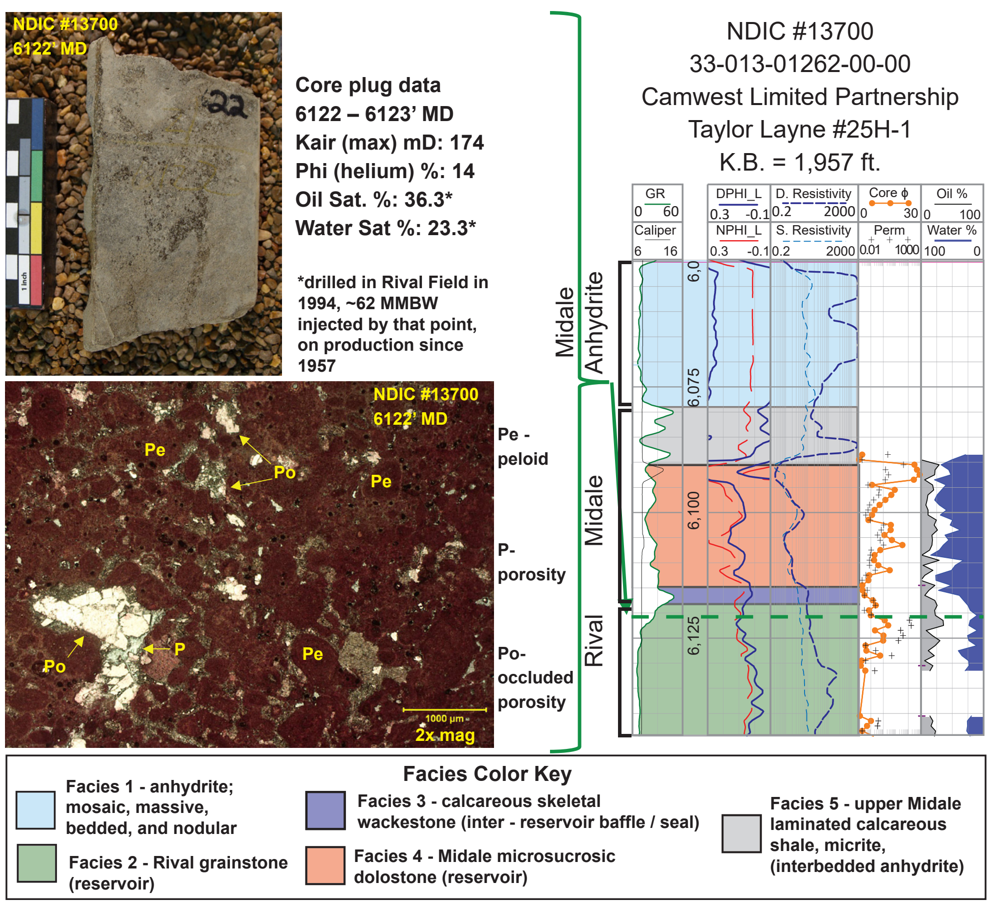

FIGURE 5. Representative photograph, thin section photomicrograph, and log of the Rival grainstone (facies 2) in the Rival Field, showing key features including occluded porosity, peloids, and grain-supported fabric with low carbonate mud content.

FACIES 3

Calcareous skeletal mudstone – wackestone (facies 3) is lightly to moderately bioturbated with abundant fossil fragments. Facies 3 is uniformly dark gray, with the exception that to the northeast of the study area, it grades into an oil-stained calcareous mudstone in NDIC #13384. Fossil fragments are commonly half brachiopod shells and crinoid stem fragments. The abundance of carbonate mud points to low energy deposition, and the faunal assemblage suggests normal marine conditions. In most of the fields of Burke County, this facies is present in thicknesses of 3′ – ~10′, and is interpreted to be a vertical permeability barrier to the dual reservoir system (i.e., facies 2 & facies 4). Facies 3 is consistently found at the base of the Midale and is remarkably uniform in character. In the study area it is a reliable marker bed for descriptions, geosteering, and log correlations.

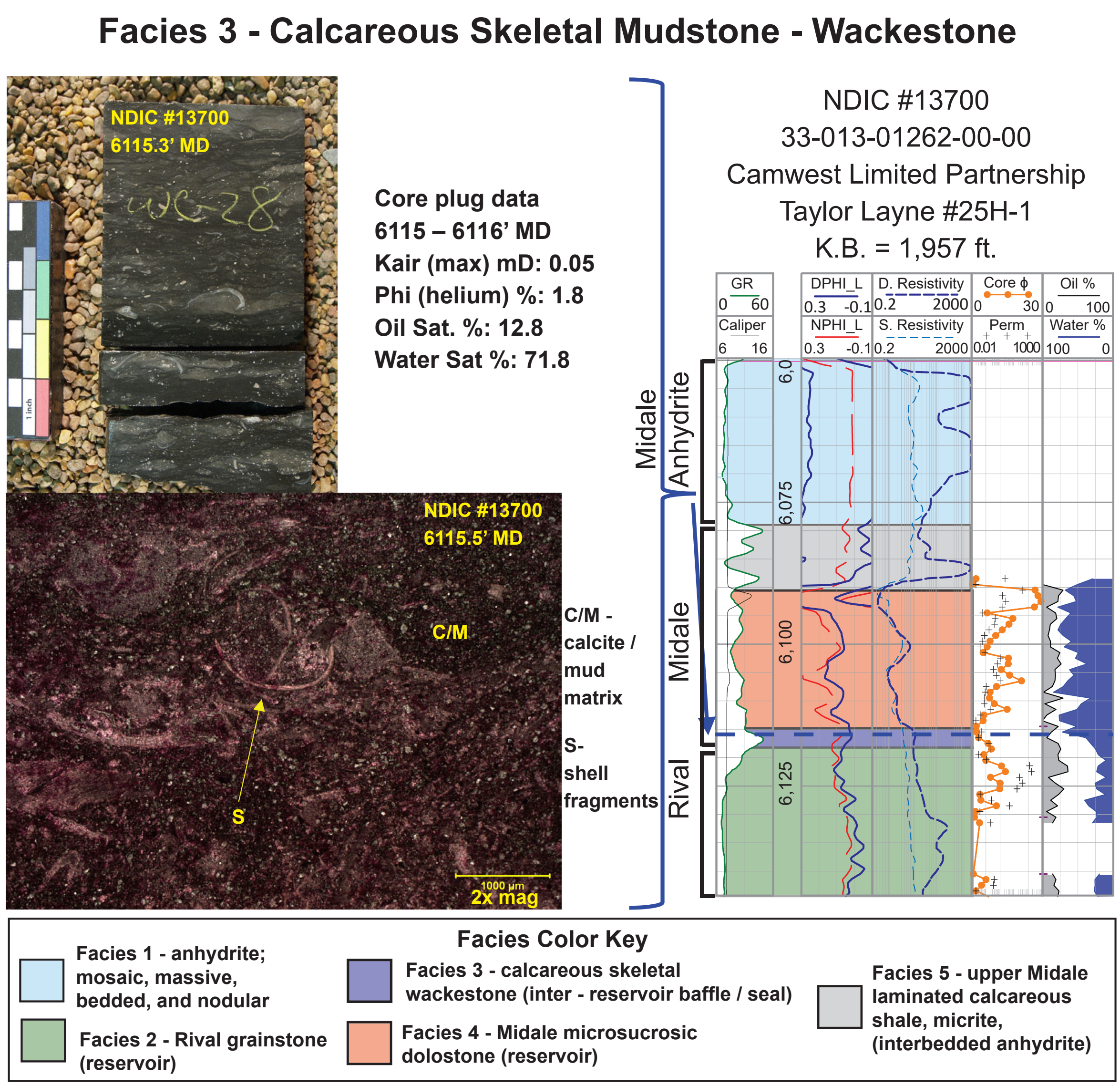

FIGURE 6. Representative photograph, thin section photomicrograph, and log showing the location of the lower Midale skeletal wackestone (facies 3) vertical permeability barrier.

FACIES 4

A light brown, poorly laminated to massive microsucrosic dolostone (facies 4) is usually found to be bioturbated with occasional increases in calcite content. Bioturbation is variable vertically, generally decreasing towards the base with a corresponding increase in mud content. Occasionally, shell fragments and rare peloidal packstone beds are present. Rare occurrences of graded beds and cross-bedded carbonate grainstone were observed. Microsucrosic dolostone has a consistent light brown oil staining across the area; where not dolomitized, oil staining is noticeably lower. The abundance of carbonate muds and burrowing points to a low energy, restricted marine setting as noted by Lindsay (1985). Microsucrosic dolostone forms the upper reservoir in the study area within the Midale subinterval and is consistent in thickness and continuous across the study area, where it exhibits only subtle variations. Reserves in the Midale have been developed with vertical wells and are almost certainly being exploited with the implementation of fracture stimulation in the study area. These reserves are the likely source of some of the increased production and potentially the increased water production from recent horizontal wells.

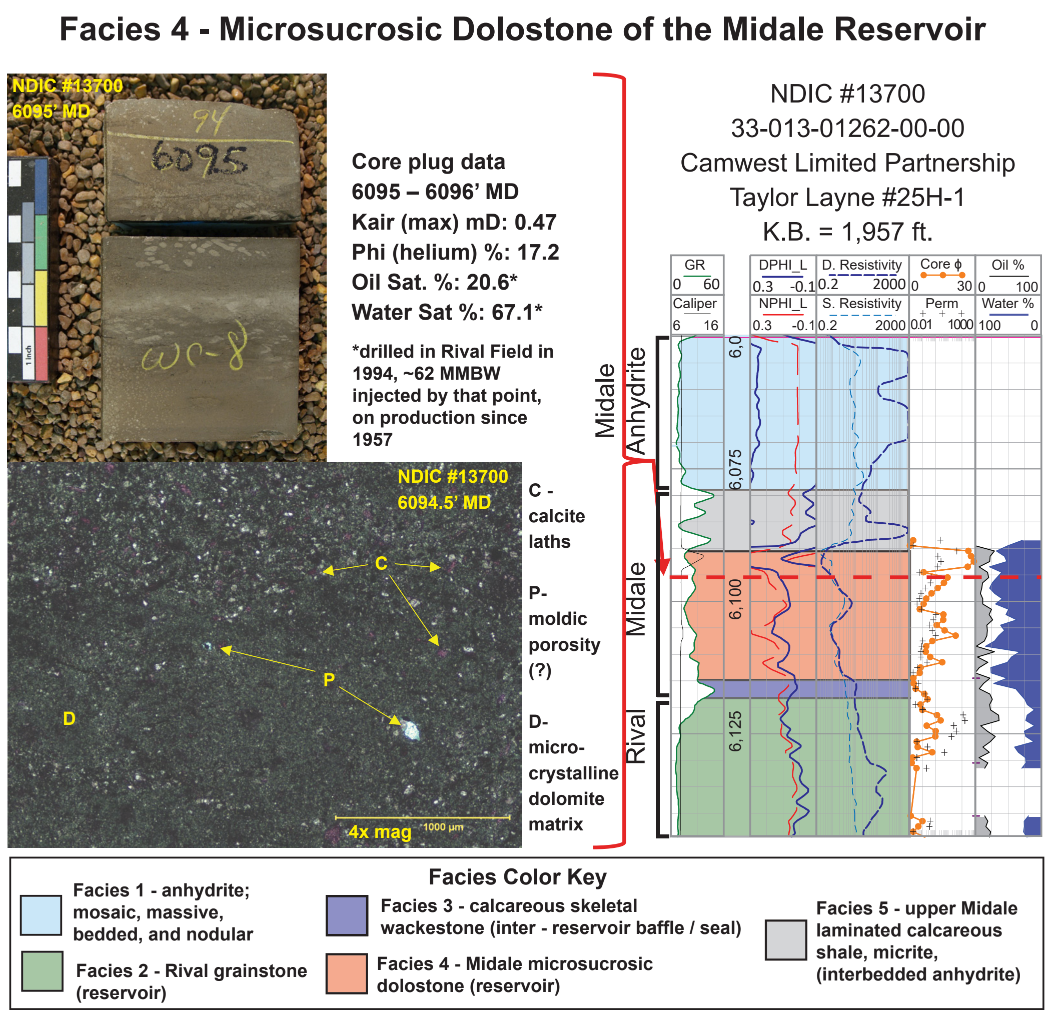

FIGURE 7. Representative photograph, thin section photomicrograph, and log showing the location of the Midale microsucrosic dolostone reservoir (facies 4).

FACIES 5

Laminated calcareous shales and micrite (facies 5) are dark grey to light brown with a noteworthy lack of bioturbation. Massive and bedded anhydrite interbedded with the laminated calcareous shales and micrite has been lumped in with facies 5 in later figures (e.g., Figure 9) for simplicity. While this approach may not be the proper technique concerning facies methodology, it simplifies the picture for communication and is noted here so that the reader is aware. The base is a sharp contact with the microsucrosic dolostone (facies 4) below, indicating an abrupt transition to low energy deposition and a decrease in bioturbation. The laminated, low permeability calcareous shales, in combination with interbedded anhydrites, are interpreted to be an effective vertical seal.

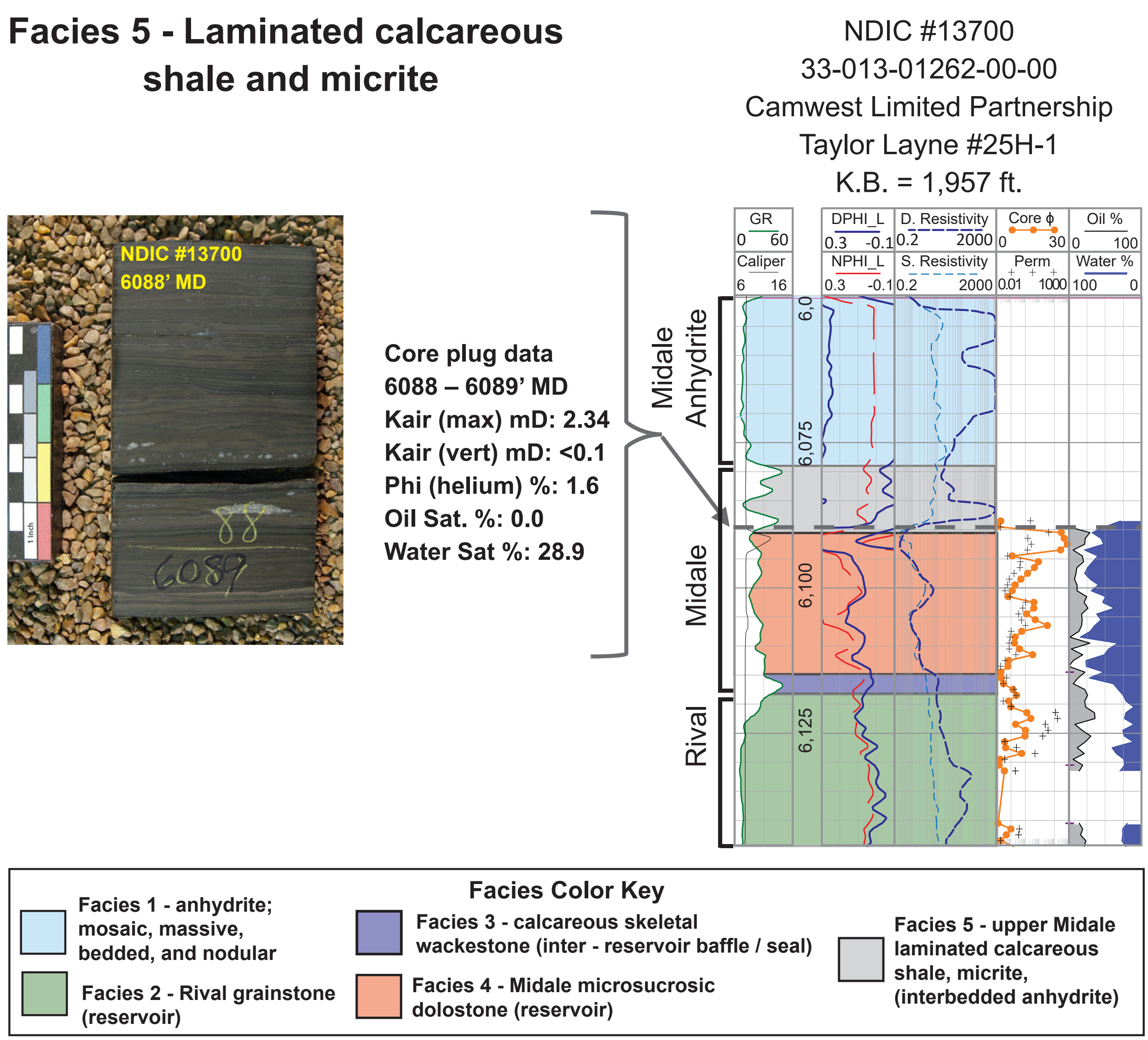

FIGURE 8. Representative photograph, thin section photomicrograph, and log showing the location of the Midale laminated calcareous shale (facies 5).

STRATIGRAPHY

Figure 9 is a stratigraphic cross-section hung on the top of the Rival subinterval (top Frobisher-Alida), illustrating the stratigraphic and facies relationships of the major lithologies of the study area. The five facies are present across the area with limited exceptions and the only significant thickness variation occurs in the Rival grainstone (facies 2) due to a lateral facies change from grainstone to anhydrite in the lower Rival to the northeast. This transition to a thinner grainstone sequence with underlying thick anhydrite composing most of the Rival subinterval is what has been referred to as the 'Rival shoreline' and what is denoted on subsequent maps and figures as the 'approximate Rival anhydrite edge'.

ROCK PROPERTIES

Core analysis data from 96 wells were gathered and porosity and permeability measurements were cross-plotted and color-coded according to facies type. Figure 10 illustrates the dual reservoir system composed of the upper Rival grainstone (facies 2) and the Midale microsucrosic dolostone (facies 4) reservoirs. These two reservoirs, separated by an areally consistent vertical permeability barrier (facies 3) exhibit different permeability vs porosity trends as a direct result of their respective sedimentological and diagenetic characteristics. Table 2 illustrates the ranges and averages for porosity and permeability measurements for the four facies of interest. In the compilation of this data, fractured core plugs were not excluded from the dataset and are the likely source of extraneous values that are apparent in Figure 10 and Table 2. Not all core datasets indicated fractured plugs. Appendices 1 and 2 contain the data and additional comparison tables.

Variability exists in reservoir quality across the study area and helps to explain the range of development results discussed in later sections of this report. Core plug measurements from the Rival grainstone, in green, illustrate that permeabilities can be higher in the Rival compared to the Midale. The Midale can exhibit significantly higher porosities, likely due to the effects of dolomitization and the development of intercrystalline porosity (Linsday, 1985).

TABLE 2. Ranges and averages of porosity and permeability measurements for the four facies for which core data was compiled. Facies 2 (Rival) and facies 4 (Midale) are the main reservoir intervals.

Facies 2 - Rival Reservoir			Facies 3 - Skeletal Wackestone			Facies 4 - Midale Reservoir			Facies 5 - Laminated Shale		
Porosity	Min	0.10	Porosity	Min	0.20	Porosity	Min	0.10	Porosity	Min	0.20
	Max	31.90		Max	24.90		Max	38.40		Max	30.50
	Avg	6.79		Avg	6.35		Avg	14.64		Avg	9.97
Perm.	Min	0.00	Perm.	Min	0.00	Perm.	Min	0.01	Perm.	Min	0.01
	Max	795.00		Max	9.50		Max	100.00		Max	7.30
	Avg	3.90		Avg	0.29		Avg	1.15		Avg	0.58

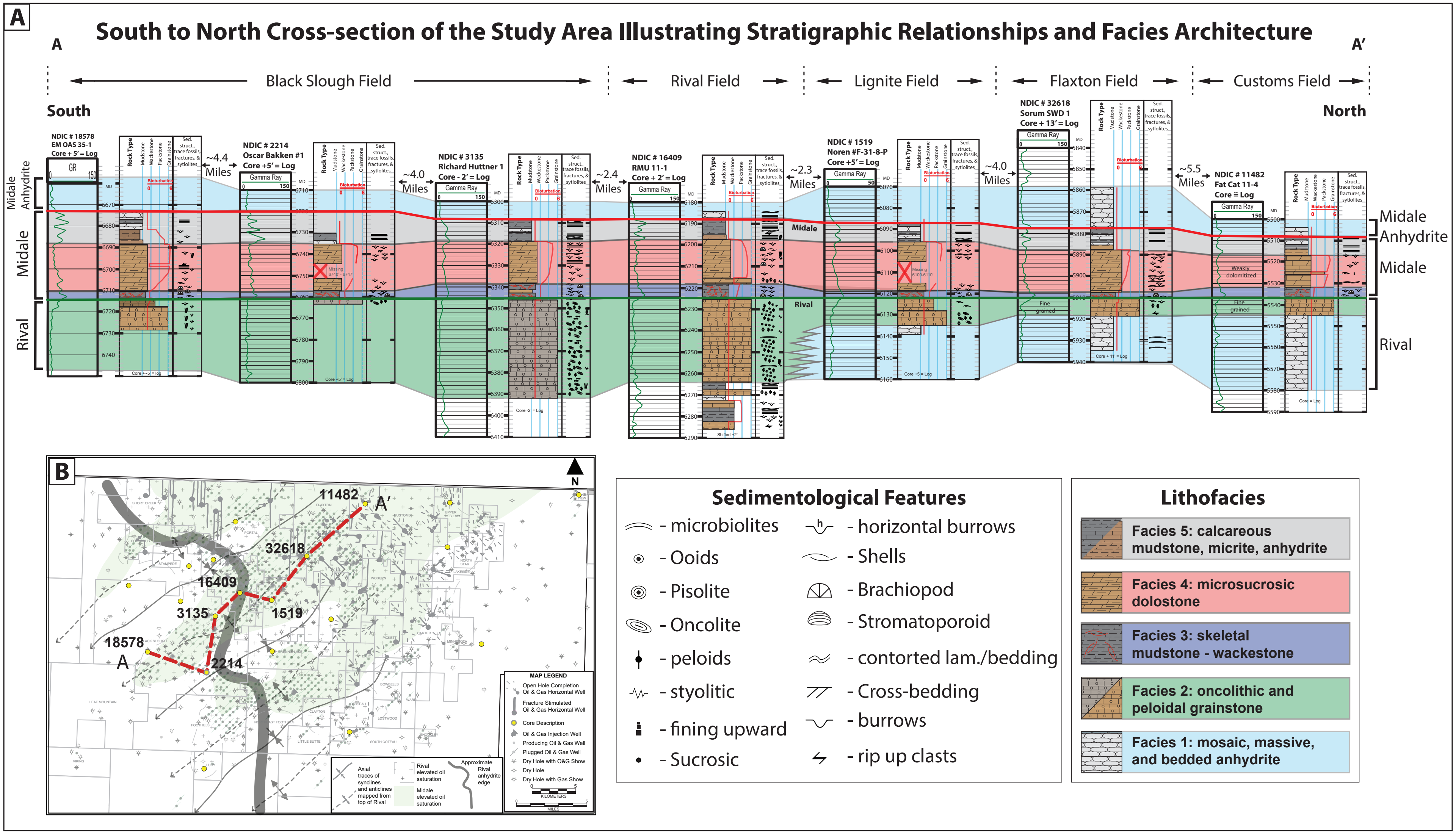

FIGURE 9. (A) Stratigraphic cross-section of the Rival and Midale subintervals in the study area, hung on the Rival top (top Frobisher-Alida). Core illustrations accompany gamma-ray logs, and facies are indicated by colors which correspond to the other figures in this report. Note the increase in anhydrite thickness to the north; the edge of this increased thickness has been commonly referred to as the 'Rival shoreline', and is indicated on the index map (B) with a thick gray line. The thickened anhydrite concentrations in the Rival are a likely baffle to migration pathways in the region and a key driver of oil accumulations in Burke County in the Rival subinterval.

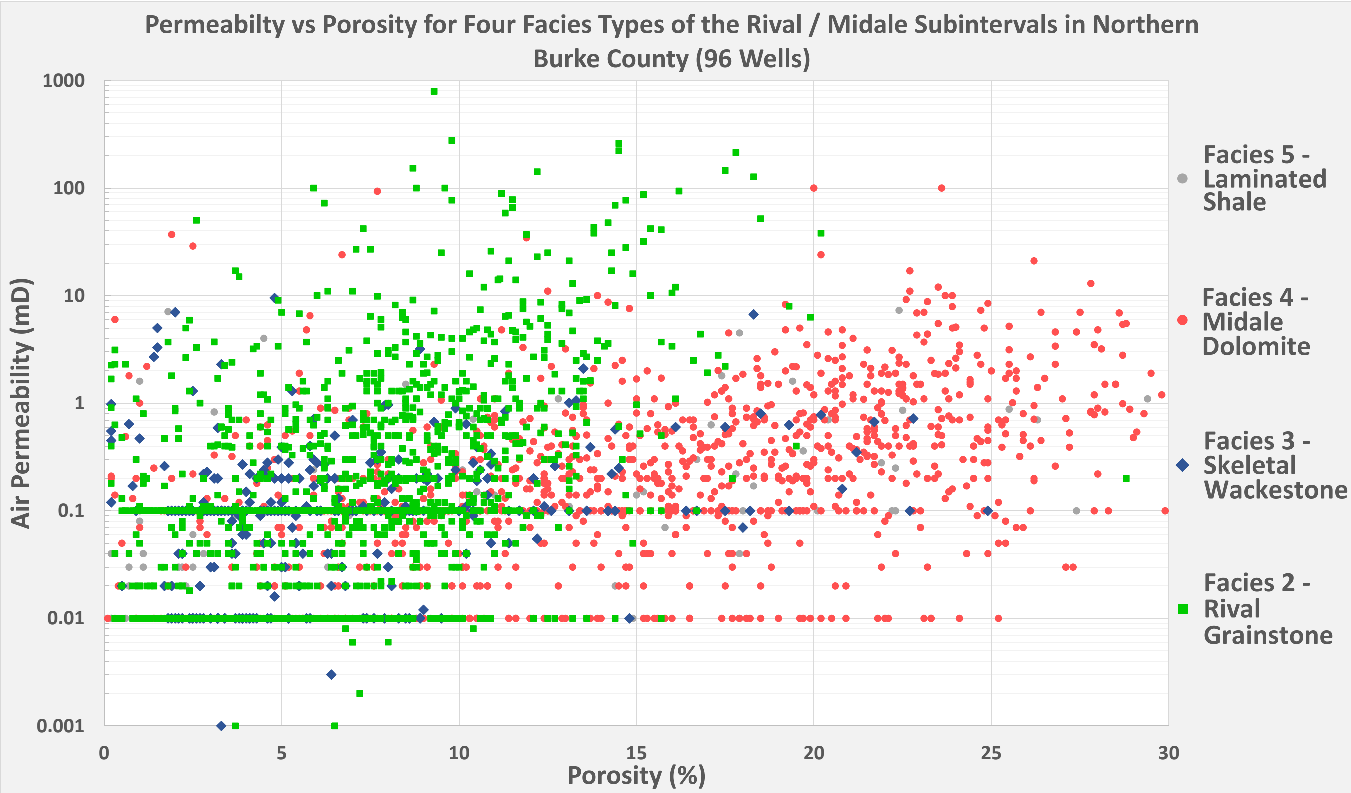

FIGURE 10. Permeability vs. porosity for the five facies of the upper Rival and Midale subintervals as defined in this study. Note the higher permeability of the Rival at lower porosity, and the high porosity and low permeability values that exist in the Midale. The Midale is likely a significant contributor to production from fracture stimulated wells in the region. Older permeability measurements are often reported as less than a certain value (e.g., <0.1 mD), presumably due to instrumentation. This resulted in the numerous values of the same lower permeabilities at various porosities on this chart.

GEOLOGICAL DRIVERS

Previous studies (i.e., Nesheim, 2018 and Lindsay, 1985) have discussed at length and in detail the sedimentology, stratigraphy, and contributing factors to the productivity of the Midale and Rival subintervals in the region. This study builds upon the previous work to provide an assessment of the prospectivity of the Rival grainstone (facies 2) reservoir in the region, coupling this additional work with the work of others to provide a regional assessment of geological drivers in this dual-reservoir oil accumulation. A key contribution of this study is an assessment of the regional potential of the Rival grainstone which was developed by comparing average core plug water saturations to initial production results of various wells in the region. In the sections that follow, production results from the three development well types are presented, underlain by a simplified view of the primary drivers of oil production in the area.

The primary drivers of oil production in the study area are 1) reservoir quality and oil saturation of the Rival grainstone, 2) oil saturation of the Midale (Nesheim, 2018), 3) proximity to subtle regional anticlines and inferred natural fracture systems (Nesheim, 2018), and 4) location relative to the edge of thick anhydrite accumulations in the Rival. The 'Rival shoreline' likely is a regional stratigraphic baffle to probable migration pathways (Nesheim 2018, Lindsay, 1985, and this study). These four main controls on oil production in the region are interpreted in this and previous studies (Nesheim, 2018, Lindsay, 1985) and presented in Figure 11 in a regional view.

The reservoir quality of the Rival grainstone was interpreted by use of water saturation measurements from core plug data from 96 wells across the area (Figure 3). Production results were incorporated to extend the area of potential or existing development to account for historical results. The reader should note that this interpretation was done using core plug water saturations and the correlation of productive wells to ~50% average core plug water saturations. Cumulative production of vertical wells, in addition to initial water cuts and water saturation from core plug analysis, were used to guide the interpretation of the areal extent of elevated oil saturation. A map of average core plug water saturation (Plate 1), and its derivative (fig. 11) should be considered an optimistic assessment of potential.

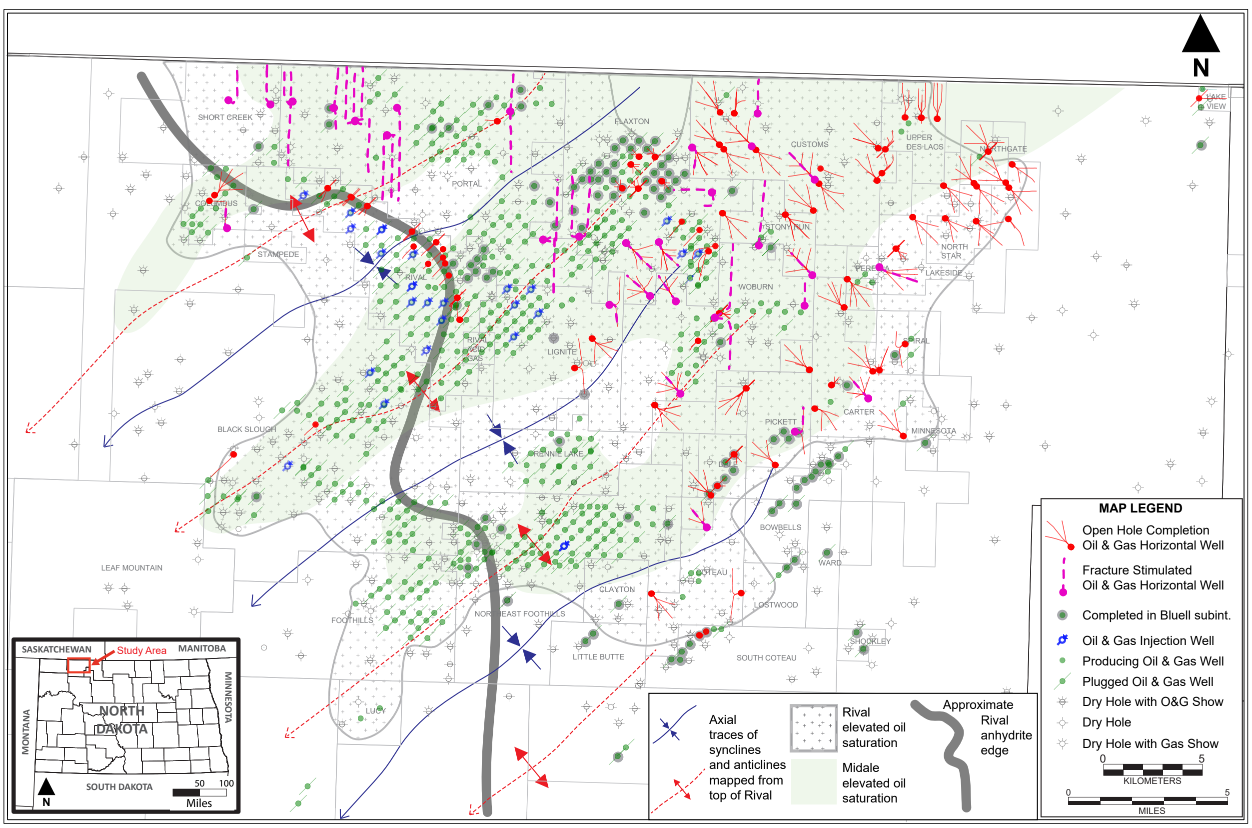

FIGURE 11. Key geologic drivers of reservoir performance in northern Burke County with development well type. Modified from Nesheim (2018). The gray stippled region is the area of potentially productive Rival grainstone as delineated by the comparison of the core plug water saturations to well productivity (this study).

VERTICAL WELL DEVELOPMENT HISTORY & PRODUCTION RESULTS

In 1955, four years after the discovery of oil in North Dakota, the Gunnar Opseth 1 discovery well (NDIC # 945) of northern Burke County was producing ~800 barrels of oil per month from the Midale and upper Rival carbonate reservoirs in what would become the Coteau Field in east-central Burke County. The following decade of development in northern Burke County saw a flurry of activity (fig. 12), with nearly half of the total number of vertical wells drilled and completed in the first stage of development (484 producers - 194 dry holes). By 1960, there were 15 named fields in the region and unitization efforts were undertaken in the early to late 1960s (Anderson et al., 1960; Lindsay, 1985).

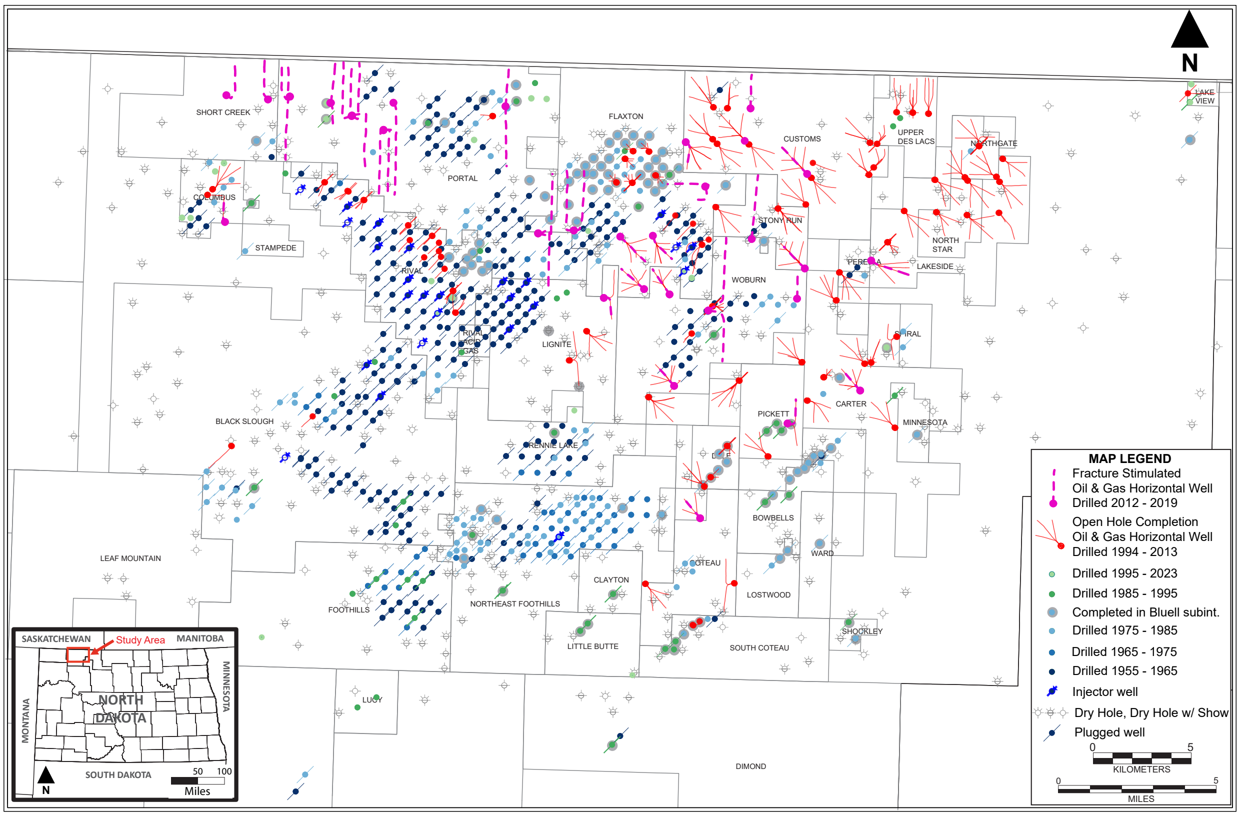

FIGURE 12. Drilling activity in northern Burke County by decade. Most vertical and horizontal wells target the Rival and/or Midale subinterval.

Through the late 1960s and 1970s, drilling activity and production declined in Burke County. However, a period of increased drilling occurred in the early 1980s, which saw an increase in production primarily due to the development of the underlying Bluell subinterval in the Flaxton Field (Voldseth, 1986, fig. 1), and some other peripheral Rival – Midale development (figs 12 and 13). In total, 36 fields were discovered in the area. The cumulative production and the four distinct development strategies that were applied to these conventional carbonate reservoirs are shown in Figures 12 and 13. Monthly field production data can be found in Appendix 3 of this report.

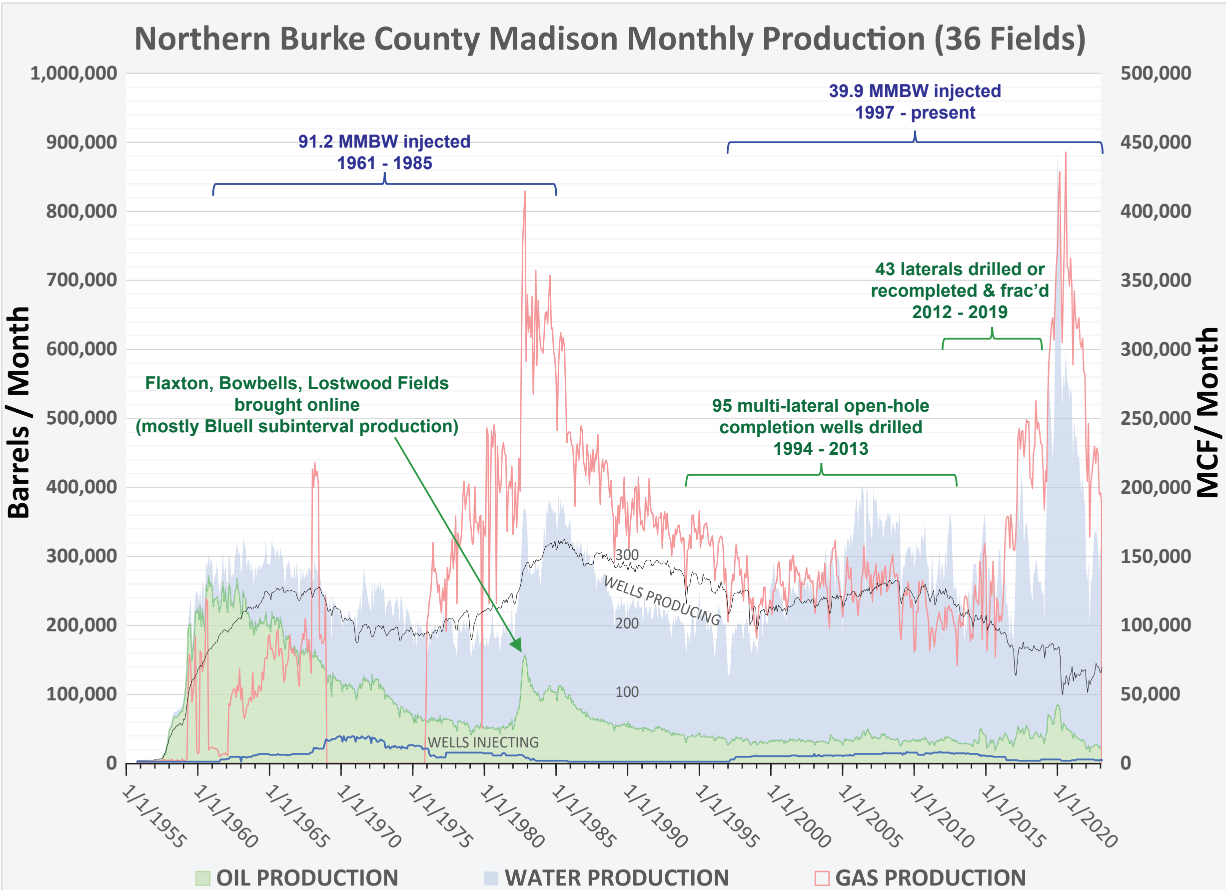

FIGURE 13. The historical monthly production of oil, water, and gas for 36 Madison fields in northern Burke County highlights the impact of the four different development styles over time.

Vertical well production values from North Dakota Department of Mineral Resources databases are presented in Figures 14 – 16. Cumulative oil production, first twelve months' average water cut, and cumulative gas production are plotted below well symbols colored by age for comparison. Gas production reporting is limited before ~1976, and as a result, cumulative gas values likely underrepresent actual totals. Also noted in Figures 14 – 16 are those wells in the region that were perforated in the Bluell subinterval (AKA Dale or Coteau after Voldseth, 1986). As discussed later in this report, the Bluell subinterval has been explored and produced in the region and may represent an underdeveloped resource in northern Burke County. Vertical well monthly production data can be found in Appendix 4 of this report.

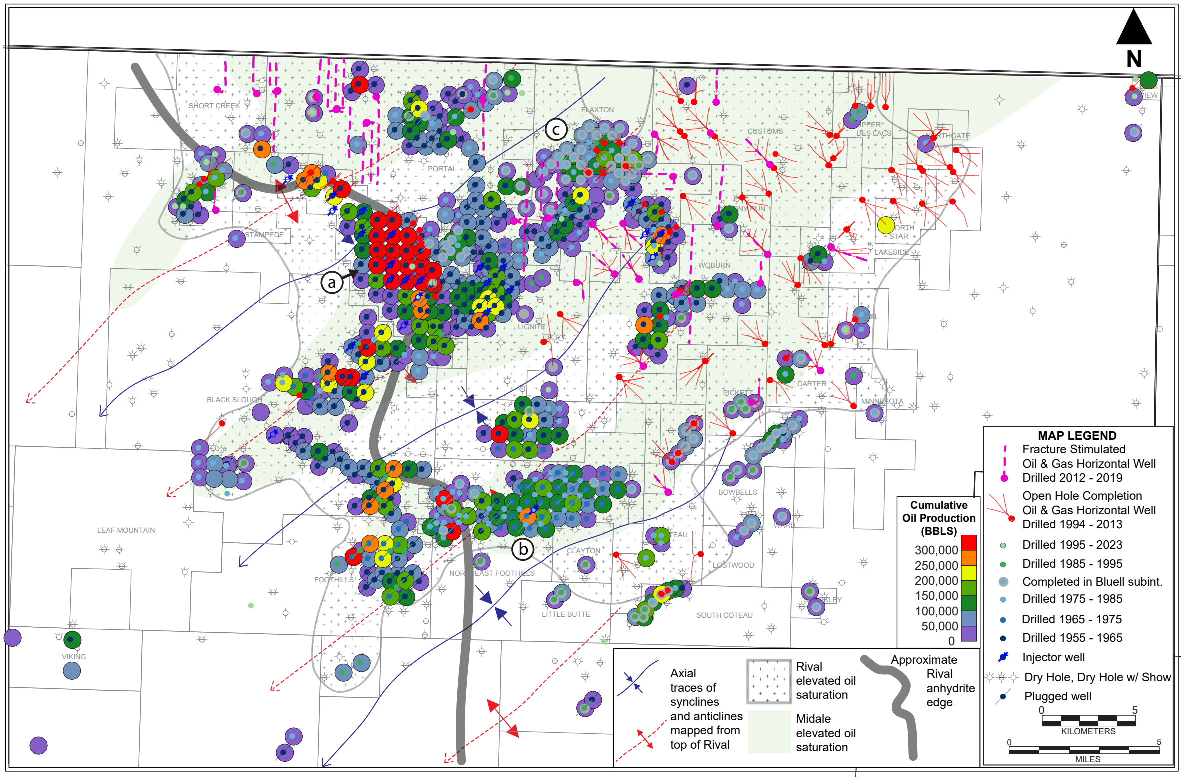

FIGURE 14. Vertical well cumulative oil production for Madison Group wells in northern Burke County, with letters indicating fields mentioned in text: a) Rival Field, b) Northeast Foothills Field, c) Flaxton Field.

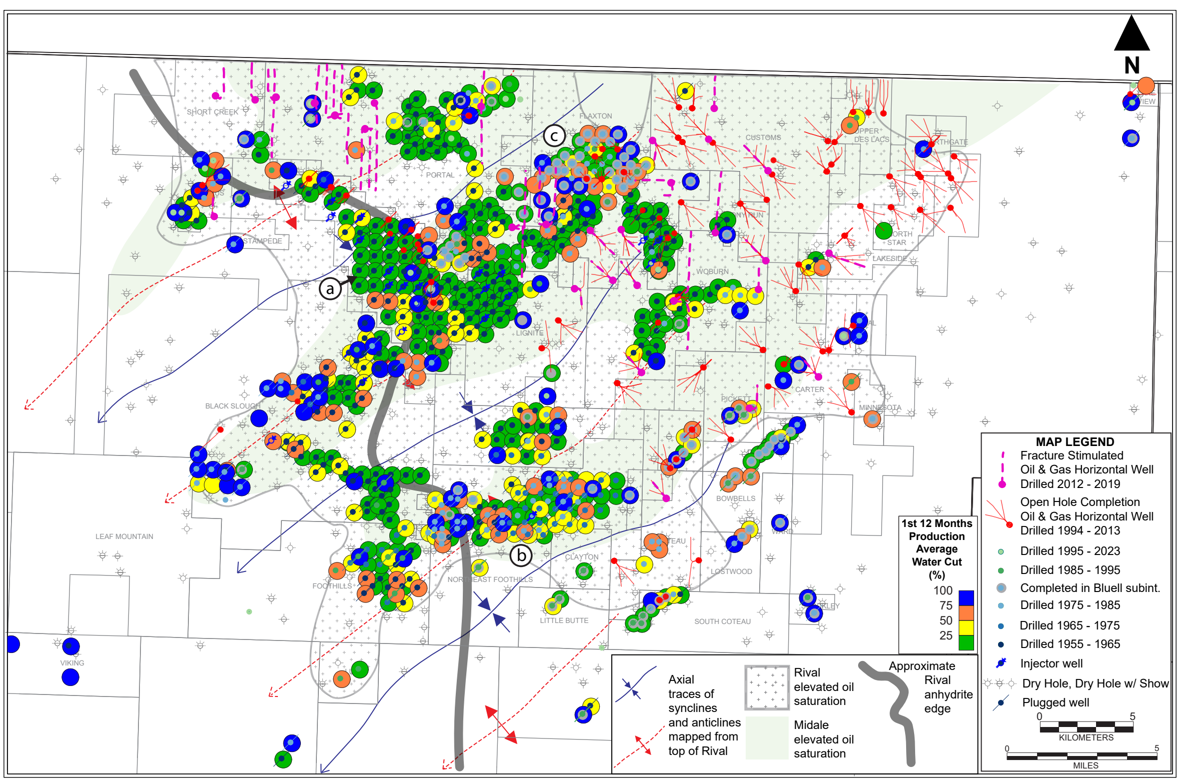

FIGURE 15. Vertical well first 12 months' production average water cut for Madison Group wells in northern Burke County, with letters indicating fields mentioned in text: a) Rival Field, b) Northeast Foothills Field, c) Flaxton Field.

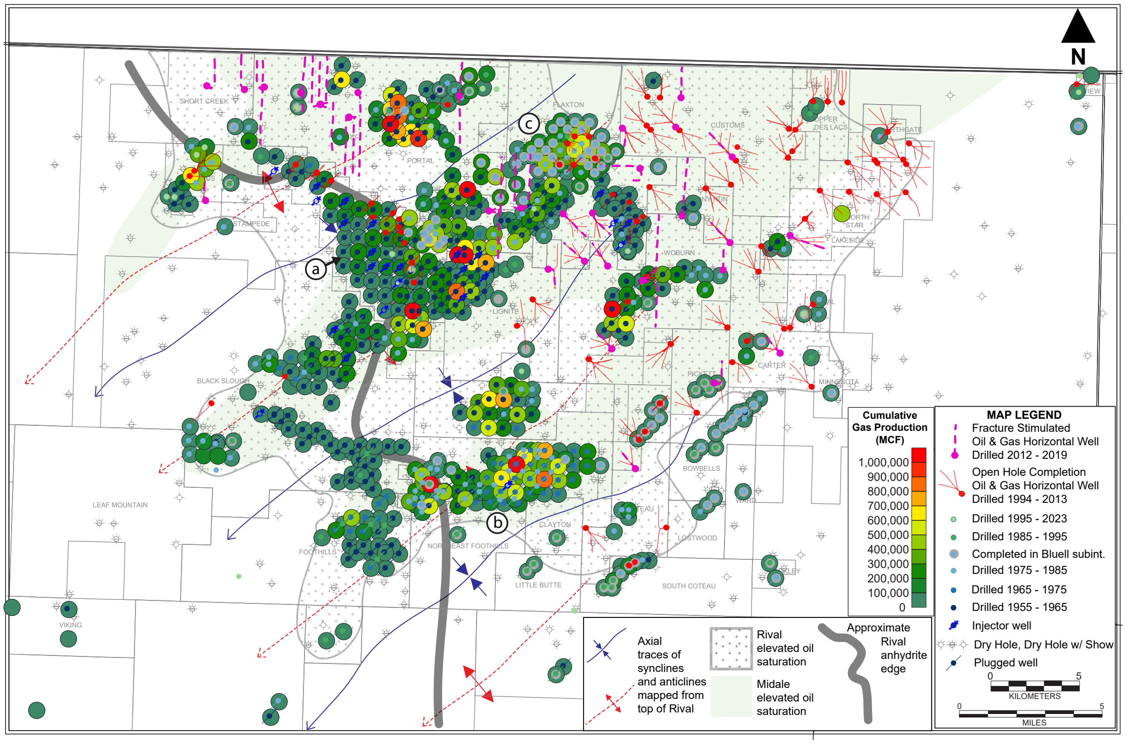

FIGURE 16. Vertical well cumulative gas production for Madison Group wells in northern Burke County, with letters indicating fields mentioned in text: a) Rival Field, b) Northeast Foothills Field, c) Flaxton Field.

DISCUSSION: VERTICAL WELL PRODUCTION

Vertical wells are of the greatest abundance and have the highest cumulative production values, predominantly due to the long production periods. Note the dramatically increased cumulative oil production values for a cluster of producers in the center of Figure 14. These wells are located in the core of the Rival Field, which is in the best reservoir location, and near the anhydrite edge, but are also surrounded by injectors that injected ~62 MMBW, suggesting that water flooding has been an effective secondary recovery mechanism in the Rival Field. Also of interest in reviewing cumulative oil production from vertical wells is the relatively low cumulative production from areas that were later developed with open-hole and fracture stimulated horizontal wells. These areas were likely seen as uneconomic under conditions at the time but were later developed with new methods to produce, in some cases, significant quantities of oil and gas per well.

Investigation of the initial water cuts of vertical wells (fig. 15) reveals a range of values that suggests that some field boundaries are bounded by higher water cut wells and an inferred oil-water contact, while other fields are not. Areas with a combination of lower cumulative oil production and lower water cuts were often developed later with horizontal wells. Higher water cut wells have been used in addition to wells with average core plug water saturations over 50% to refine the boundaries of potentially productive Rival reservoir. The interpretation of the area of 'Rival elevated oil saturation' in Figures 11 – 23 is meant to serve as a guideline for more detailed, local assessments. These data suggest that potential exists in the region, as has been observed with recent horizontal well development.

Gas production data is limited before 1976 in many cases, but available data suggests that vertical wells have produced smaller amounts of gas, and those with significant cumulative gas production are the result of a longer duration of production (fig. 16). From the onset of development of the fields of Burke County, it has been noted that the reservoirs are a solution gas drive system and vertical wells likely manage reservoir pressure more gradually to diminish rapid drawdown. However, there was a noteworthy increase in gas production in 1982 (fig. 13); much of this gas production is sourced from the Flaxton and Northeast Foothills fields, which produced predominantly from the Bluell and Midale subintervals, respectively. This data, in addition to later discussion, suggests that the Midale subinterval may have a higher gas content than the Rival subinterval. The Bluell subinterval may also have higher-end gas-to-oil ratios.

OPEN HOLE HORIZONTAL WELL DEVELOPMENT HISTORY & PRODUCTION RESULTS

In 1994, the Taylor Layne 25H-1 (NDIC #13700) was drilled in the Rival Field as the first open-hole lateral completion within the study area. Following the Taylor Lane, 95 wells with 258 laterals, commonly multi-lateral projects, have used this development technique to date. This development effort had the upper Rival as its primary target, with the Midale a secondary target that in some projects was drilled with a dedicated lateral. These wells helped to stem the production decline of the area but had variable results. Six single or multi-lateral projects were identified which targeted only the Midale. These wells are detailed in Table 3 and indicated in Figs. 17 – 19 with black arrows and labels. Figures 17 – 19 illustrate cumulative oil production, the first twelve months' average water cut, and cumulative gas production. Barrels of oil per day values were gathered by taking an average of the first twelve months' monthly reported production values and dividing that value by 30.

TABLE 3. Midale only open-hole horizontal development wells.

API	NDIC #	First 12 Months Production Avg Oil / Month	First 12 Months Production Avg Water / Month	First 12 Months Production Avg Gas / Month	First 12 Months Production Avg Water Cut	Field	Drill or Re-drill Date	Number of Laterals	Values through December 2022		
									CUM OIL (BBLS)	CUM WATER (BBLS)	CUM GAS (MCF)
33013007260000	5202	26*	34*	189*	100%	RIVAL	1995	2	26	9,180	1,909
33013009100000	9469	426	1,653	3,531	80%	FLAXTON	2000	4	23,276	99,855	293,987
33013012690000	13913	318	1,542	759	83%	BLACK SLOUGH	1995	1	59,087	281,095	190,176
33013013320000	15721	164	1,455	1,462	90%	RIVAL	2007	1	3,822	40,630	30,024
33013013640000	16500	126	968	1,045	89%	RIVAL	2007	1	5,470	59,606	61,997
33013014810000	18578	888	4,445	5,428	83%	BLACK SLOUGH	2010	1	78,380	429,203	711,740

*1 month of production after drilling

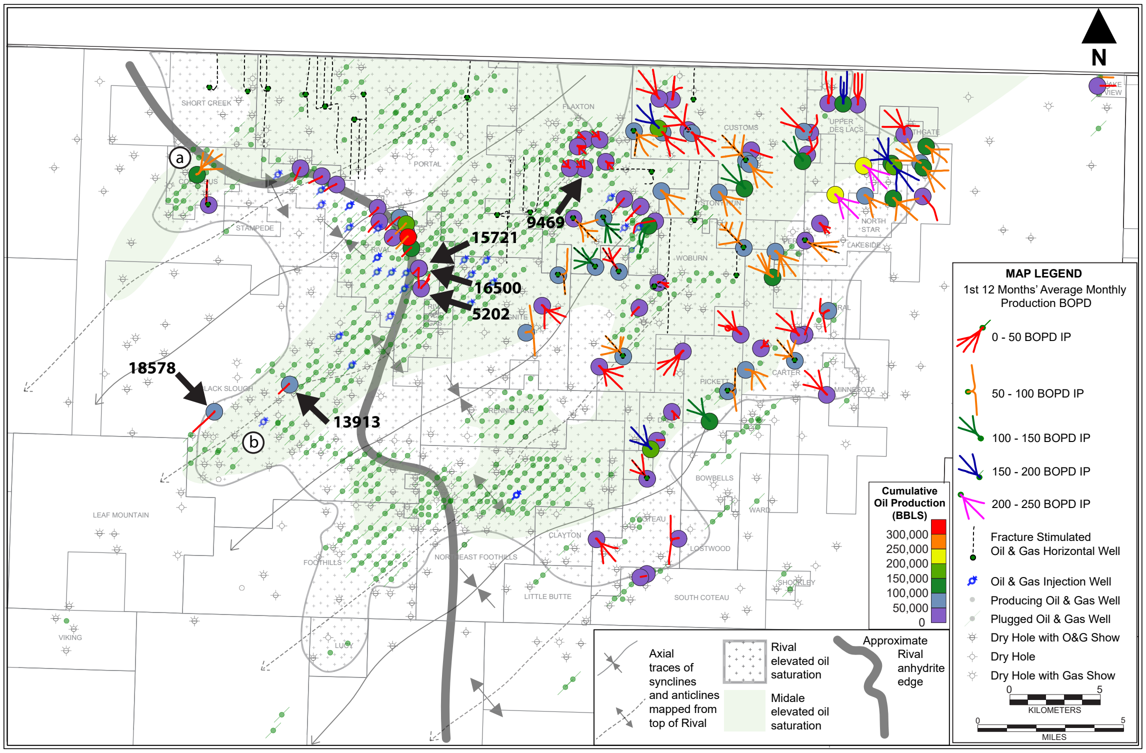

FIGURE 17. Open-hole horizontal cumulative oil production and first 12 months' average barrels of oil per day plotted on well paths, with letters indicating fields mentioned in text: a) Columbus Field, b) Black Slough Field.

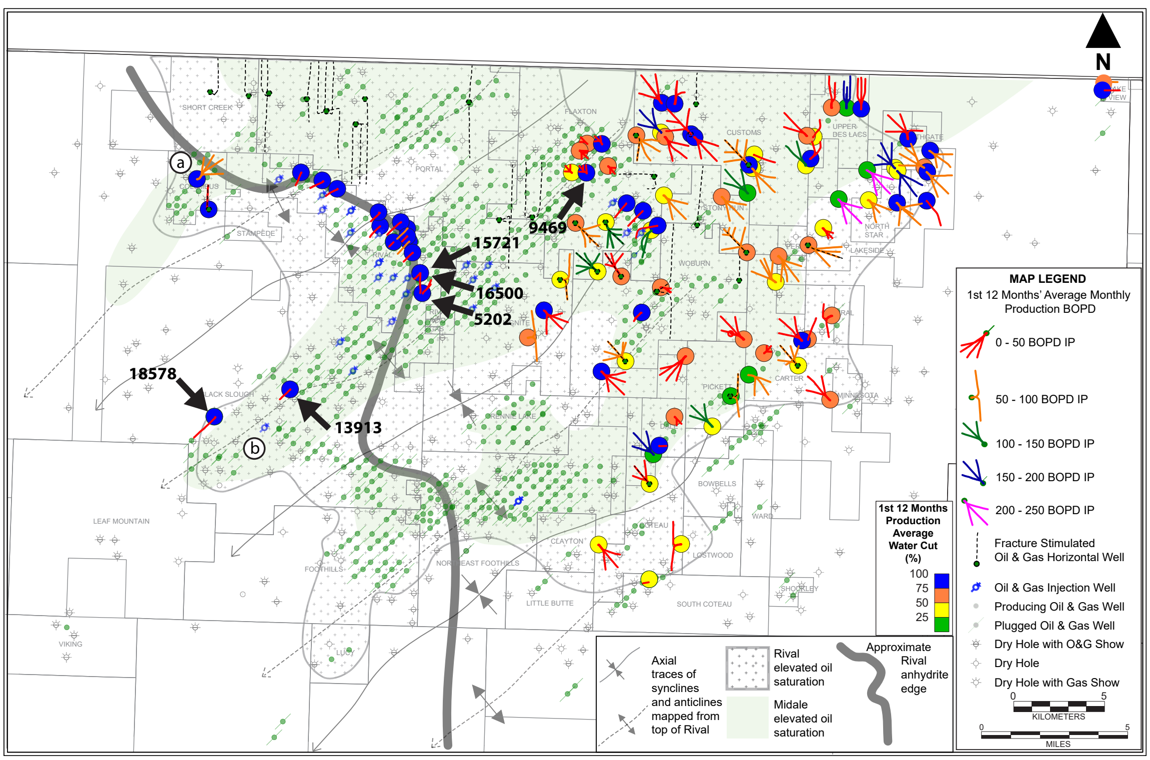

FIGURE 18. Open-hole horizontal projects' first 12 months' production average water and first 12 months' average barrels of oil per day plotted on well paths, with letters indicating fields mentioned in text: a) Columbus Field, b) Black Slough Field.

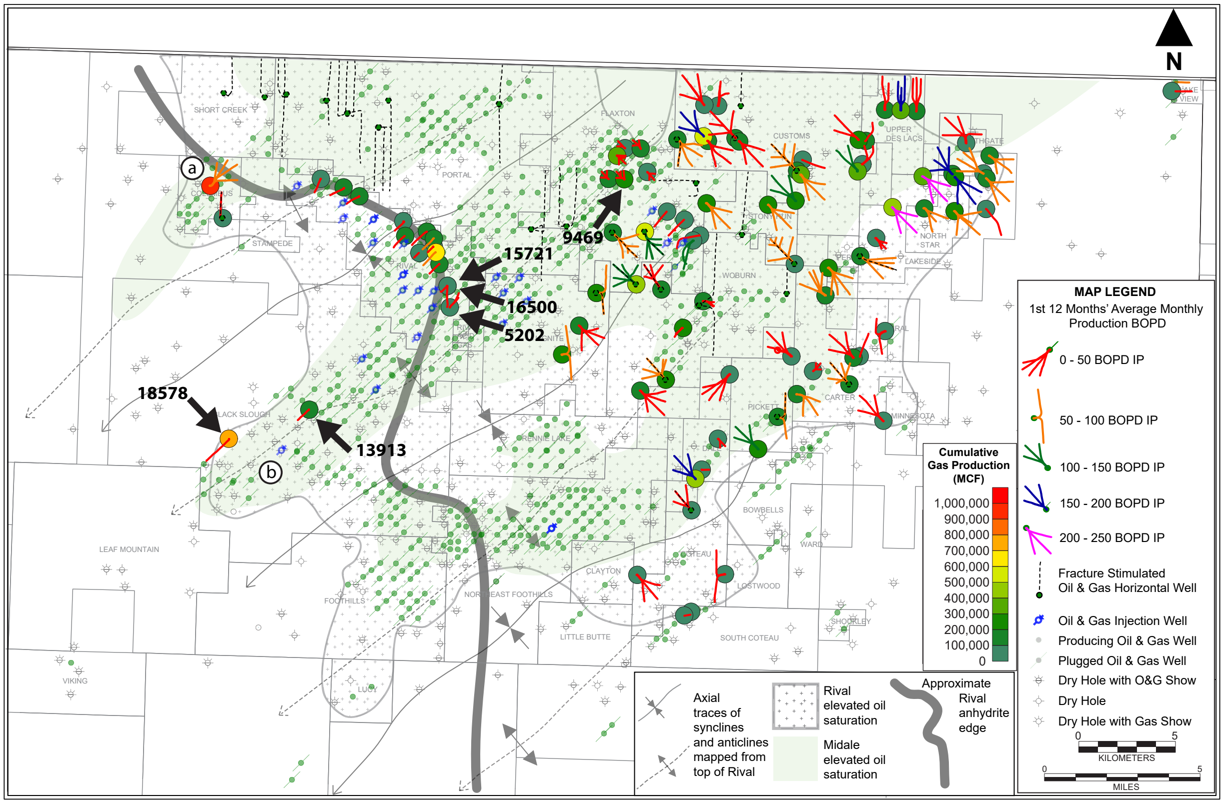

FIGURE 19. Open-hole horizontal well cumulative gas production and first 12 months' average barrels of oil per day plotted on well paths, with letters indicating fields mentioned in text: a) Columbus Field, b) Black Slough Field.

DISCUSSION: OPEN-HOLE HORIZONTAL WELL PRODUCTION

Open-hole multi-lateral projects often focused on areas peripheral to existing production that had seen little or no vertical development and a thin (generally less than 10') Rival grainstone. Note the spatial variability of results and lack of a clear production trend (fig. 17). These data, in conjunction with porosity and permeability data (fig. 10) suggest that the reservoir quality of the Rival is variable, and sweet spot behavior related to grain size variability or porosity occlusion could be a driving factor in well performance. Open-hole horizontal projects in new development areas (i.e., not in the Rival Field) exhibited a range of initial water cuts (fig. 18). No direct relationship was observed between multi-lateral open-hole projects with a dedicated Midale lateral and those without. One interpretation of these data is that variability in production is a direct reflection of variable reservoir quality in the Rival subinterval, the primary target of most of these projects.

Open-hole multi-lateral projects have produced small quantities of gas with some noteworthy exceptions (e.g., NDIC #22083 in the Columbus Field and NDIC # 18578 in the Black Slough Field – a cored, Midale only test). These data suggest two likely potential scenarios: 1) open hole horizontals do not rapidly decrease reservoir pressures, and/or 2) the Midale is a source of the high gas production seen in fracture stimulated wells; these are not mutually exclusive.

FRACTURE STIMULATED WELL DEVELOPMENT HISTORY & RESULTS

The introduction of hydraulic fracture stimulation (fracture stimulation) to the area saw a staged approach where some existing open-hole laterals were recompleted as single laterals and fracture stimulated, beginning with the Ormiston Unit 1. Originally drilled as a dual lateral open hole completion in 2006, it was recompleted and fracture stimulated in 2012, resulting in a promising bump in production from ~12 BOPD for the 12 months prior to ~32 BOPD for the 12 months after the recompletion, and significant associated increases in gas and water (Figure 20). Monthly production data for the Ormiston Unit 1 and the other horizontal wells in this report can be found in Appendix 5.

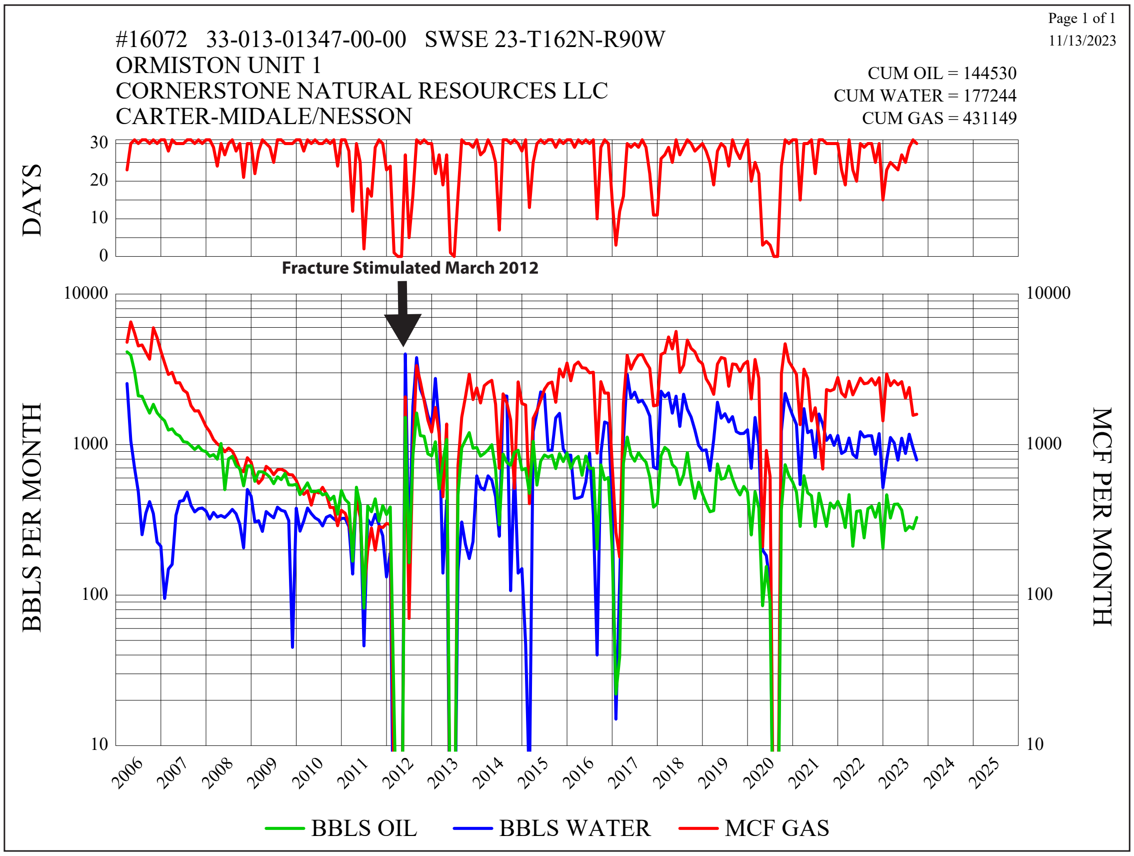

FIGURE 20. The production history of the Ormiston Unit 1, the first well in the study area to be recompleted and fracture stimulated in 2012, illustrates the associated increase in production.

Within two years, fracture stimulation was the dominant development strategy in the region, and 43 single lateral wells (including recompletions) were fracture stimulated through 2020. Recompletions and dedicated laterals drilled from the surface and fracture stimulated, often referred to as 'grassroots wells', were implemented in tandem during this period. A campaign of recompletions in 2017 yielded variable but promising results. Dedicated laterals with fracture stimulations averaged 15 stages, 1.5 million pounds of proppant, ~30,000 barrels of fluid, and ~7,000' in lateral length – on the smaller end of other unconventional development strategies in the Williston Basin. Data can be found in Appendix 6 of this report.

Figures 21 – 23 illustrate cumulative oil production, the first twelve months' average water cut, cumulative gas production of fracture stimulated wells, and the first twelve months' production average barrels of oil per day. For wells that were initially open-hole completions and later recompleted and fracture stimulated, the data presented is from after the fracture stimulation only. The projects which were recompleted and fracture stimulated were accessing reservoir that had already been produced with open hole multi-lateral projects for 7 – 10 years in some cases. As grassroots horizontal wells were often drilled from multi-well pads, production data colored circles are posted at bottom hole locations.

DISCUSSION: FRACTURE STIMULATED HORIZONTAL WELL PRODUCTION

Grassroots fracture stimulated horizontal wells have yielded the most consistent, highest oil production of recent redevelopment efforts, with the best results in the Portal Field and Flaxton Fields. Recompletions, shown where well paths are colored with underlain adjacent black well paths (figs. 21 – 23), had varied success and limited reporting data restrains the ability to interpret if fracture treatment variability is a cause. However, it is important to note that recompletions produced reservoir that had already been developed for several years in some cases. When taken independently, dedicated fracture stimulated horizontals are the highest performers. One interpretation of these data is that fracture stimulation homogenizes the complexities of the Rival grainstone and Midale dolostone to produce more consistent production results.

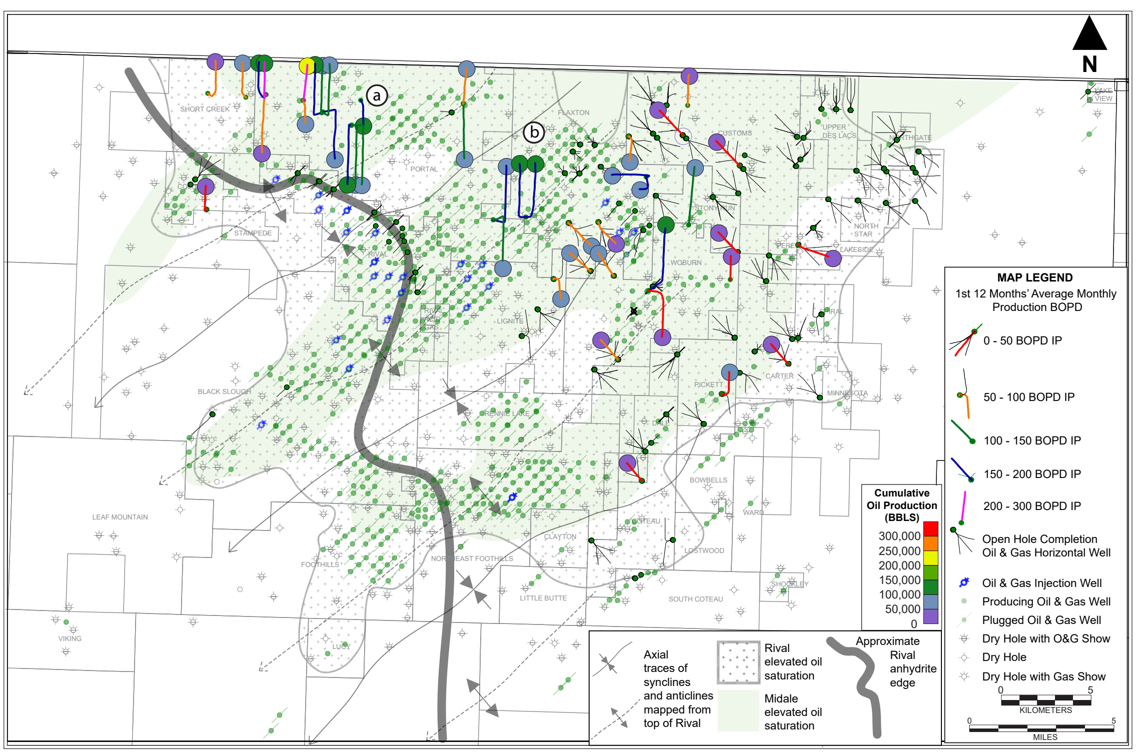

FIGURE 21. Fracture stimulated horizontal well cumulative oil production (grassroots and recompletions), with letters indicating fields mentioned in text: a) Portal Field, b) Flaxton Field.

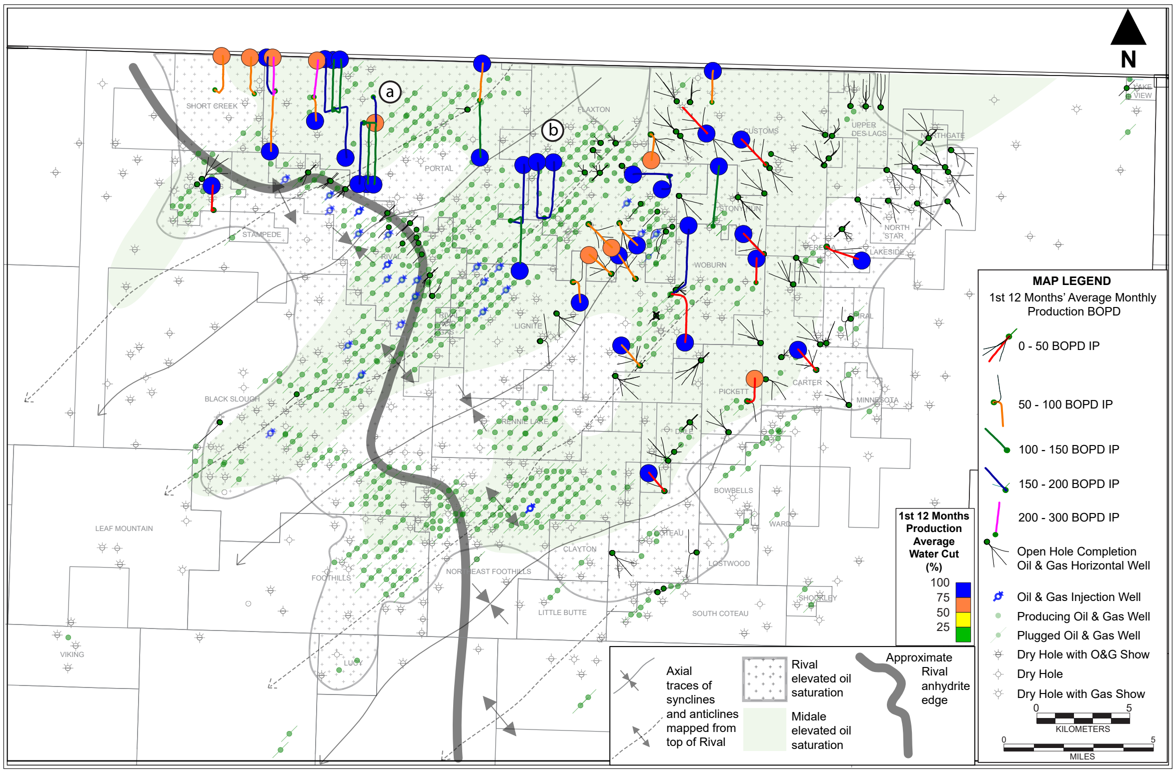

FIGURE 22. Fracture stimulated horizontal well first 12 months' production average water cut, with letters indicating fields mentioned in text: a) Portal Field, b) Flaxton Field.

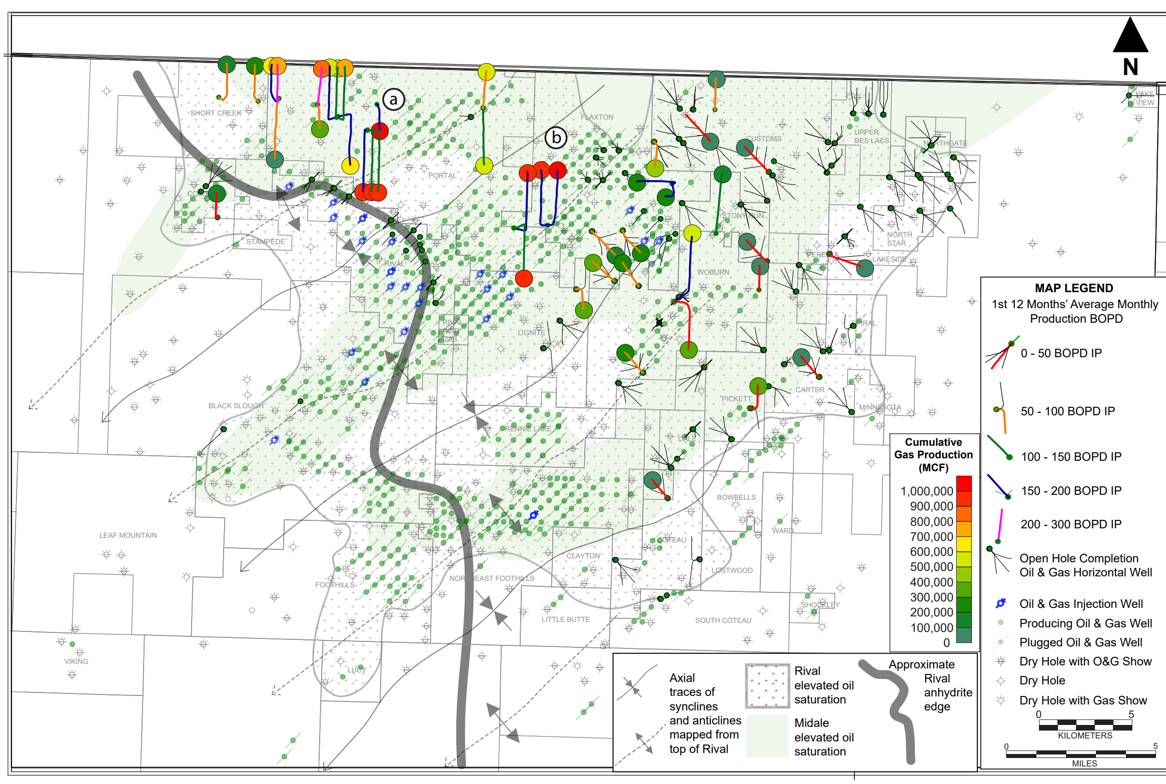

FIGURE 23. Cumulative gas production of fracture stimulated wells, with letters indicating fields mentioned in text: a) Portal Field, b) Flaxton Field.

Fracture stimulated horizontals consistently resulted in higher-end water cuts during initial production. Some of the highest rate, highest cumulative production wells in the Portal Field exhibited the highest water cuts of observed data. Future projects that seek to employ fracture stimulation as a development style should expect to see water as a significant portion of production streams and plan accordingly for disposal requirements.

Fracture stimulated horizontals have produced large amounts of gas, with some examples in the Portal Field producing nearly a billion cubic feet at the time production data were gathered. These wells are also some of the largest fracture stimulation treatments in the region and produce among the highest amounts of associated oil and water. See Appendix 6 for fracture stimulation data and production data for specific well values. These larger production values from fracture stimulation treatments suggest that fracture stimulation is effectively accessing the resources of the region and accelerating production.

DISCUSSION: PRODUCTION COMPARISON BETWEEN WELL TYPES

A noteworthy finding of this study is the improved cumulative oil production seen in the fracture stimulated wells. Figure 24 illustrates cumulative oil production by well type, binned in 50 MBO increments. Note the logarithmic scale due to the significant differences in quantity between well types. Fracture stimulated wells have more consistent, higher cumulative oil production, a less positive skew, and shorter production periods. When recompletions are excluded or separated, the increased productivity is even more apparent (fig. 24). These data suggest that fracture stimulation is the most effective method to develop the resource of the study area over a shorter period, often referred to as rate acceleration.

Fracture stimulated wells exhibit a uniform distribution of gas production, compared to the strongly positive skew in both vertical and open-hole horizontal well projects (fig. 25). Note that several fracture stimulated wells have produced nearly 1 BCF or more of gas per well. These data suggest that fracture stimulation is rapidly depleting this solution gas drive reservoir, increasing rates and producing resources in a shorter timeframe, but the implications of this for reservoir engineering should be considered. A more detailed assessment by reservoir engineering experts is warranted.

While fracture stimulated wells usually produce oil at higher rates than all other categories, they also produce more water. Fracture stimulated wells have significantly higher initial water cuts than vertical wells, and also higher water cuts than most open-hole horizontal well projects. An assessment of the higher water cuts of the Midale only open hole horizontals suggests that a potential source of the high water production in fracture stimulated horizontal wells is the Midale reservoir.

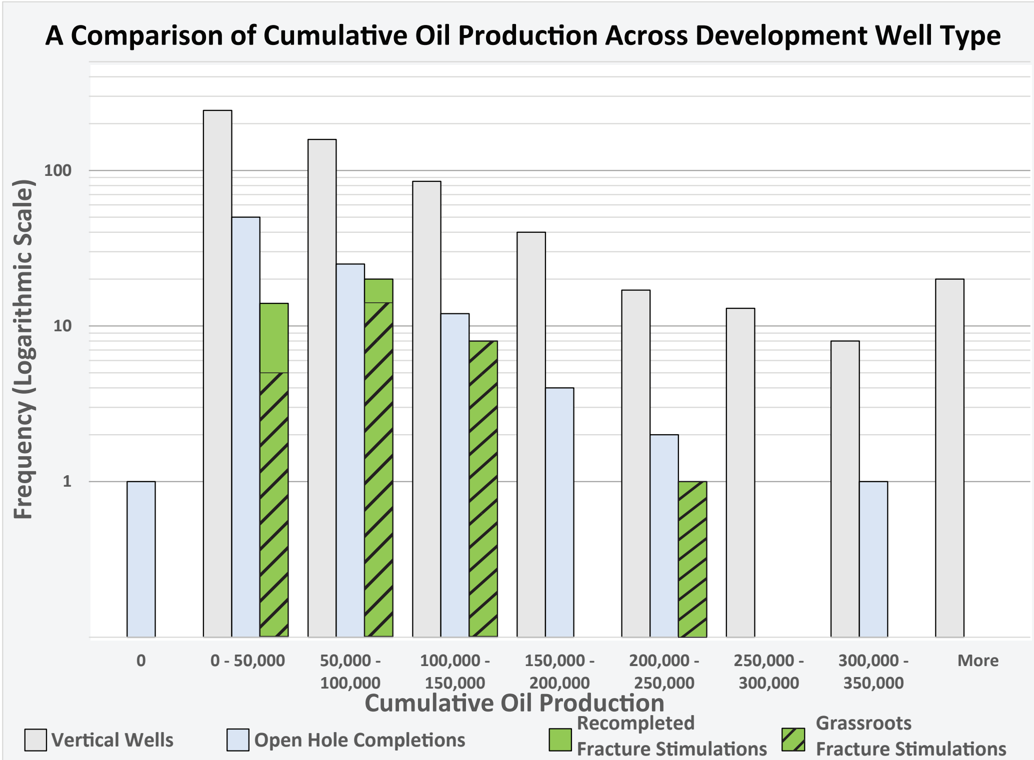

FIGURE 24. Comparison of cumulative oil production between categories in northern Burke County. Note the logarithmic scale. Cumulative oil production in recompleted fracture stimulated wells in green, grassroots fracture stimulated wells in black cross-hatching.

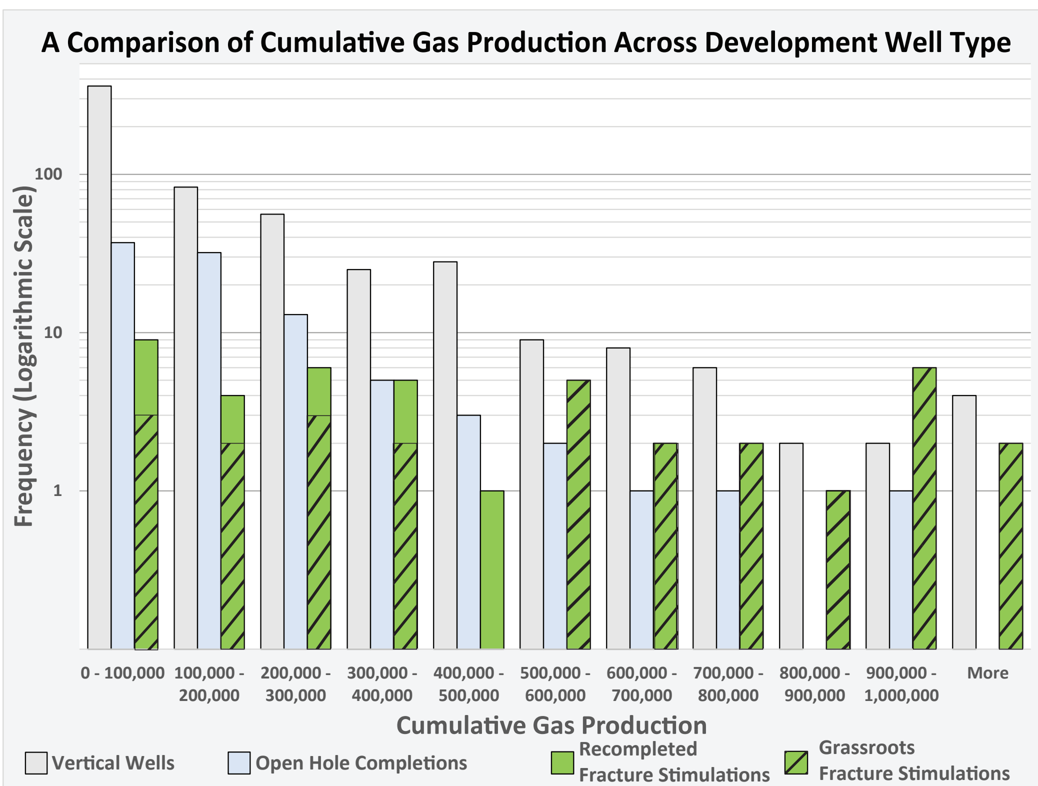

FIGURE 25. Comparison of cumulative gas production between categories. Note logarithmic scale. Cumulative gas production of recompleted fracture stimulated wells in green. Grassroots fracture stimulated wells are indicated by those areas overlain with black cross-hatching.

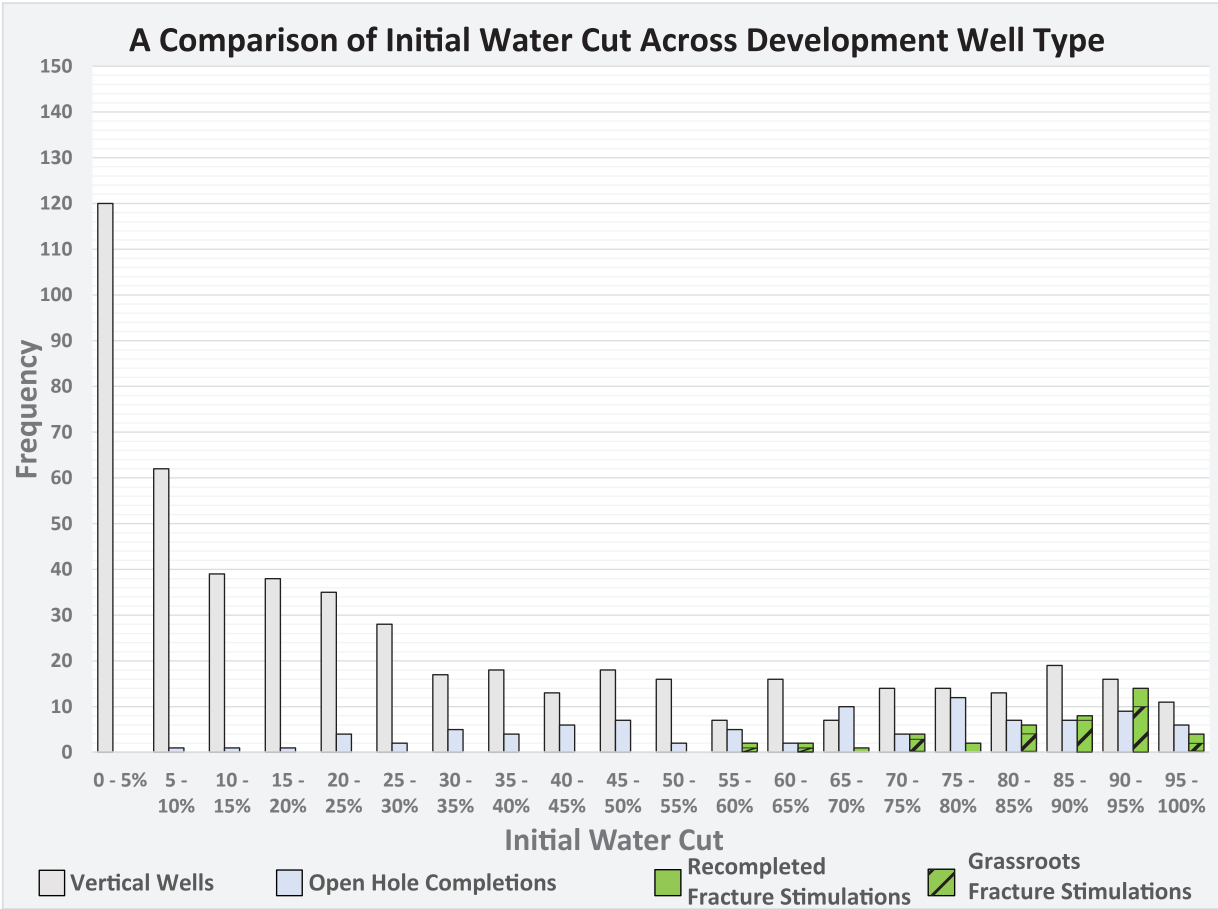

FIGURE 26. Comparison of the first 12 months' average production water cut between categories in northern Burke County. Grassroots fracture stimulated wells are indicated by those areas overlain with black cross-hatching.

As of December 2022, Burke County Madison fields have produced 60.4 MMBO, 146.3 MMBW, and 107.8 BCF of gas – a long-lived development of an established resource that has provided returns for close to three-quarters of a century (Table 4). The development of the Rival - Midale Formations in northern Burke County can serve as a case study for the scale and scope of other Madison Group redevelopment. The success of fracture stimulation treatments in Burke County oil fields suggests it is an effective method to increase oil recovery in legacy fields and their surroundings, with significant room for future development in the immediate area and beyond.

Fracture stimulation has been the most effective development technique applied to the region from the stance of consistency and expediency of production (i.e., rate acceleration). Cumulative production and production rates increased primarily due to fracture stimulation of undeveloped resources adjacent to existing production, notably in the Portal Field. The

TABLE 4. Cumulative production through December 2022 for the Madison Group from the 36 oil fields of northern Burke County.

Well Type	Dates	Count	Oil Production MMBO	Water Production / Injection MMBW	Gas Production BCF
Vertical Producers	1955 - 2011	607 (435 dry)	51.4	79.5	73.7
Vertical Injectors	1961 - 1985 1997 - present	28	N/A	131.2	N/A
Open-hole Multi-lateral Horizontal Producers	1994 - 2013	95 (258 laterals)	5.9	40.4	15.4
Fracture Stimulated Single-lateral Horizontal Producers	2012 - 2019	43 (15 recompletions)	3.1	26.4	18.7
Totals		**1371**	**60.4**	**146.3**	**107.8**

total oil production from 2015 – 2019 (fig. 13) and cumulative production values from 2012 – 2019 (Table 4) demonstrate that fracture stimulated wells made a significant contribution to the production of oil and gas with fewer wells over a shorter period.

DISCUSSION: FRACTURE STIMULATION AND ITS IMPACT ON PRODUCTION

To determine the effectiveness of fracture stimulation in the development area, the details of the fracture stimulation treatments were gathered from Department of Mineral Resources well files where available and summarized in Table 5. Appendix 6 contains the data and selected cross-plots.

Recompletions were generally smaller fracture stimulations with three exceptions, and these three recompletions of increased size had a negligible impact on production. In contrast, dedicated fracture stimulated laterals were subjected to larger treatments, but results varied spatially with the strongest initial rates and cumulative production in the north-central portion of the study area in the Portal and Flaxton fields. The areas of the Portal and Flaxton fields which had the best results of the fracture stimulated horizontal wells had low cumulative production and low initial water cuts in the neighboring vertical wells (figs. 14 and 15). Future development efforts utilizing fracture stimulation could use these areas as an analog for prospectivity.

TABLE 5. A summary of fracture stimulation treatments applied in Burke County.

Recompletions - 15 wells		Lateral Length (Feet)	Stages	Volume (BBLS)	LBS of Proppant	LBS of Proppant / Lateral Foot	Max Pressure (PSI)	Max Treatment Rate (BBLS/Min)
	Range	2,300' - 6,100'	6 - 13*	4,800 - 38,300**	94,500 - 1,300,000**	17 - 282**	3,977***	15 - 43.3****
	Average	4,600'	N/A	16,400**	538,800**	120**	N/A	N/A
	* Note - two reports of number of stages ** Note - three recompletions with volume over 14,000 BBL & weight over 400,000 LBS *** Note - one value reported **** Note - two values reported							

Dedicated Fracture Stimulated Laterals - 28 wells		Lateral Length (Feet)	Stages	Volume (BBLS)	LBS of Proppant	LBS of Proppant / Lateral Foot	Max Pressure (PSI)	Max Treatment Rate (BBLS/Min)
	Range	3,300' - 9,900'	8 - 26*	10,100 - 52,800*	426,100 - 2,446,700*	120 - 328*	4,000 - 8,900*	18 - 52*
	Average	7,300'	15*	29,700*	1,449,000*	193*	7,300*	40*
	* Note - two acid fracs excluded							

Fracture stimulation data was compared to production results to discern any key drivers. Upon comparison, correlations between various variables were moderate at best. The most productive wells are in Portal and Flaxton fields, and their spatial concentration is evident from the previous maps in this report. While the performance of larger fracture stimulation points to its advantage as a development method in the Portal and Flaxton fields, the range of results emphasizes the heterogeneity of oil charge and reservoir quality across the study area. There is a moderate correlation between the first 12 months' average BOPD and pounds of proppant applied per foot of lateral (fig. 27). These data suggest that larger, 'unconventional style' fracture stimulation treatments of dedicated laterals can yield promising rate acceleration.

CORE FLUORESCENCE AND IDENTIFICATION OF LOCAL POTENTIAL

Core fluorescence was observed for nine wells in the study area to qualitatively characterize a low – moderate – high fluorescence response for the Midale and Rival reservoir intervals (facies 2 & facies 4). Figure 28 illustrates the summary of results for the wells observed. In an undeveloped area at the southwest periphery of the Rival Field (figs. 28 and 29), core fluorescence observations were employed to corroborate core plug water saturation data

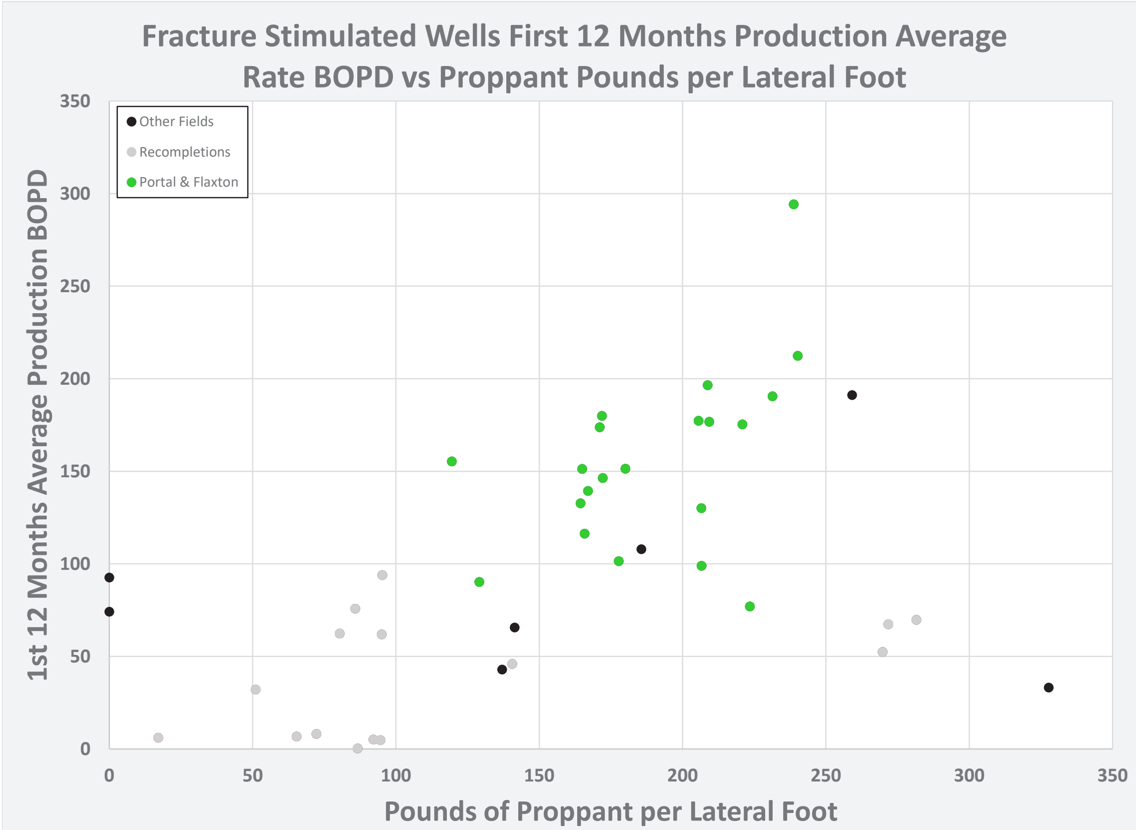

FIGURE 27. Average barrels of oil per day initial production vs pounds of proppant per lateral foot for fracture stimulated wells in northern Burke County.

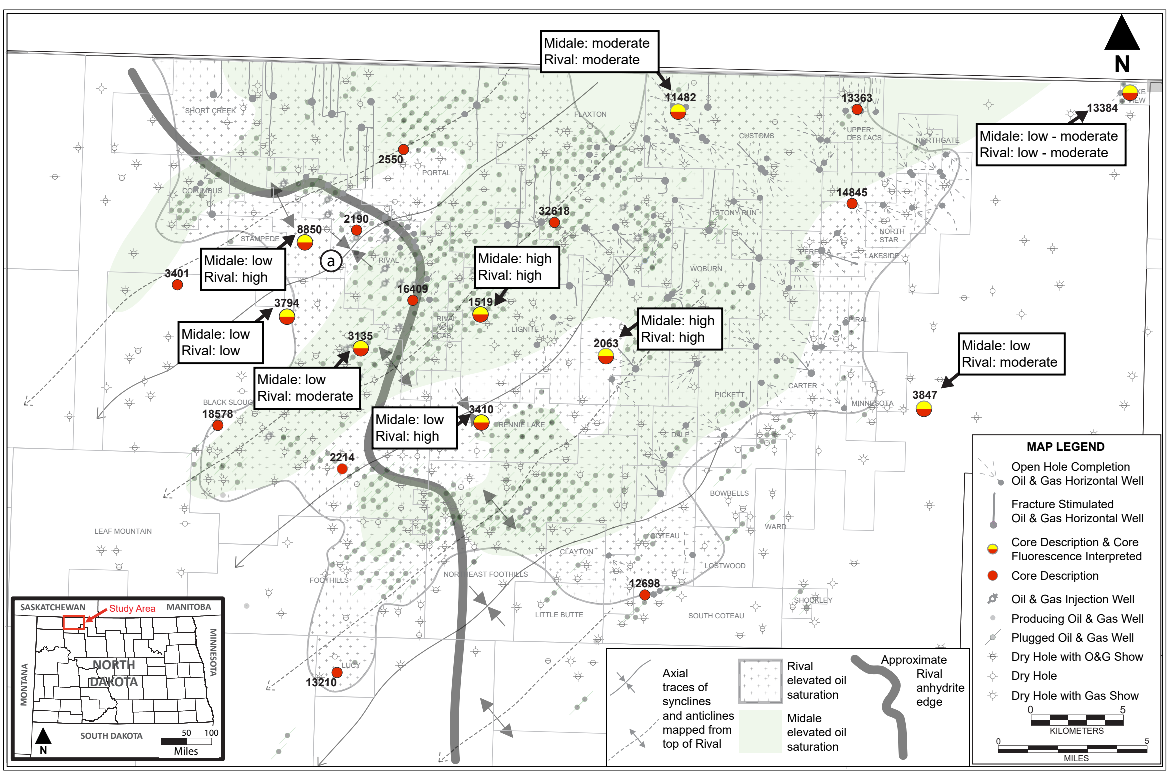

FIGURE 28. Core fluorescence observations for the study area with letter a) indicating area mentioned in text: outboard Rival Field.

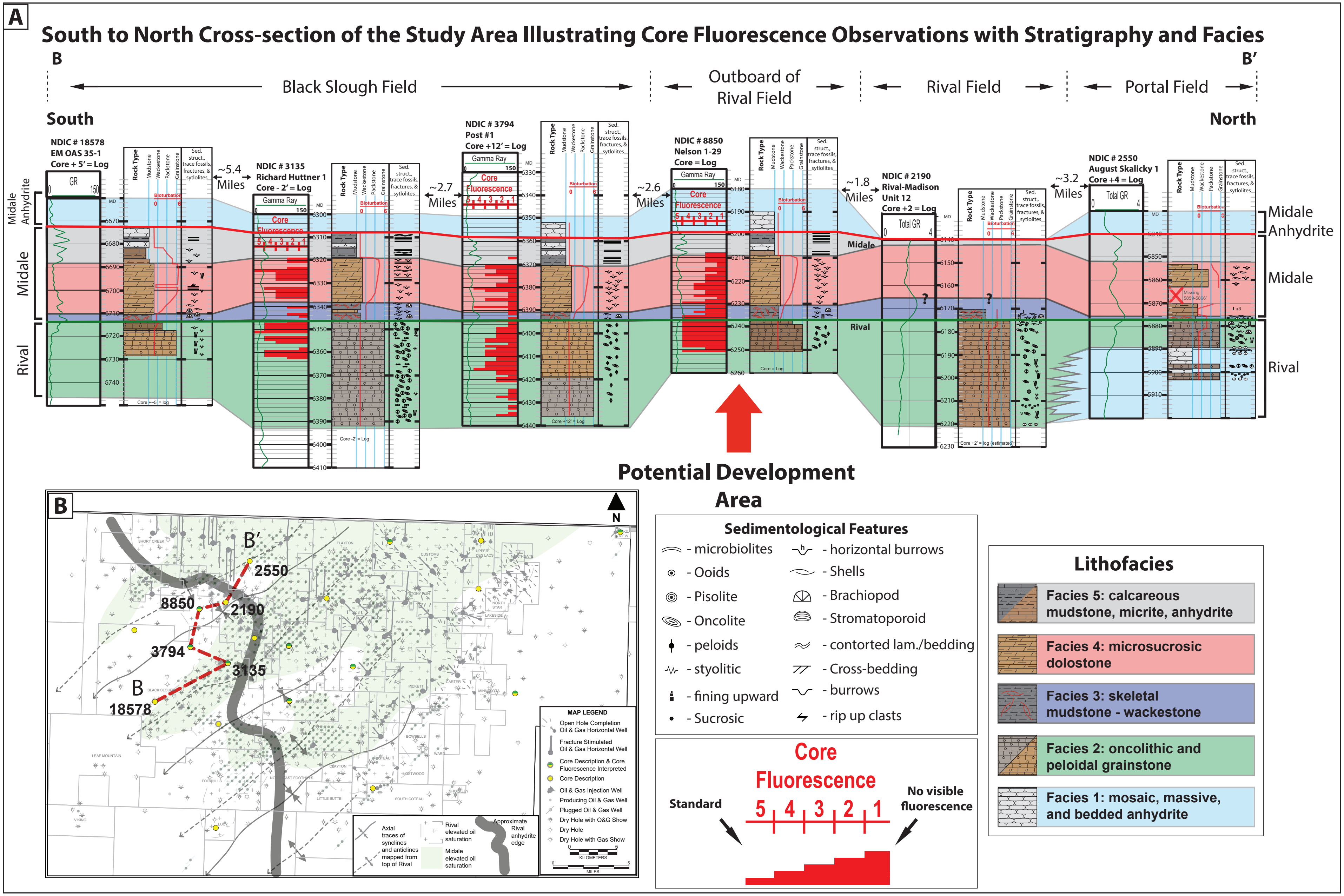

FIGURE 29. (A) South to north cross-section from the Black Slough Field to the Portal Field illustrating core fluorescence observations with core descriptions of selected wells, highlighting the increased core fluorescence in NDIC #8850 on the southwest periphery of the Rival Field on the index map (B).

that indicates promising oil saturation. While no quantitative assessment was undertaken, core fluorescence was observed to be a rough proxy for oil saturations in the study area. The results of the observation of fluorescence in NDIC #8850 suggest development potential in the area.

Figure 29 is a cross-section across the western portion of the study area, which displays core descriptions in addition to core fluorescence observations. Note the elevated fluorescence in the Rival subinterval in NDIC #8850 (fig. 29). This well is outboard of the Rival Field in an area of low development well density, likely due to low porosity/permeability in some of the local wells. However, core plug data in addition to core fluorescence measurements suggest this as an area for detailed investigation into the viability of future development. This is particularly prospective when considered along with core and log data from adjacent well NDIC #11929 (fig. 30). Elevated oil saturations such as are found in #8850 and ~10% porosity zones, as are indicated in #11929, could be present in the immediate area. These criteria represent a potential development target that could benefit from fracture stimulation (fig. 30).

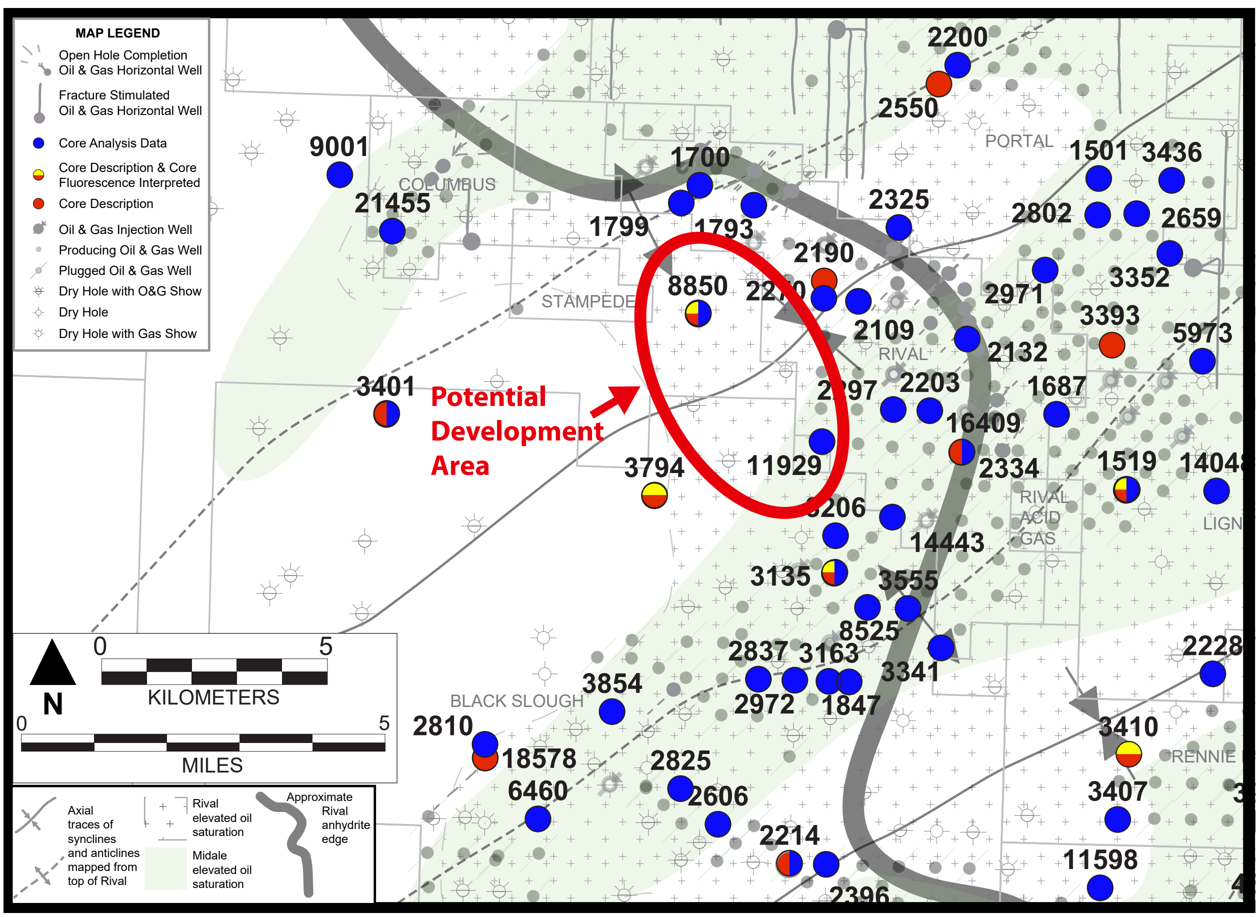

FIGURE 30. An area of interest for future development potential on the southwest periphery of the Rival Field.

REGIONAL OPPORTUNITIES – OTHER TARGETS:

The Bluell subinterval of the Frobisher-Alida Interval, also known locally as the Dale or Coteau (Voldseth, 1986), is an oil-producing interval in the region that has been explored, tested, and cored. Forty-four wells were encountered in this study which cored the Bluell subinterval and/or the underlying Sherwood subinterval; multiple others likely exist in the region. One hundred and seven wells were identified with perforations in the Bluell or Sherwood subintervals. These wells were predominantly in the Flaxton Field which primarily produced from the Bluell subinterval (Voldseth, 1986). Figure 31 presents the locations of wells that have cores or perforations in the intervals below the Rival and highlights three horizontal wells (Table 6) that targeted the Bluell or Coteau subintervals in the study area.

Future development efforts in the area should consider the downhole potential in the Bluell and subjacent units as potential exploration targets. No attempt was made in this study to deconvolve co-mingled production from wells with Bluell, Rival, and/or Midale production. However, a detailed assessment could yield the identification of the areal location of productive zones in the Bluell and the potential extension thereof utilizing available data.

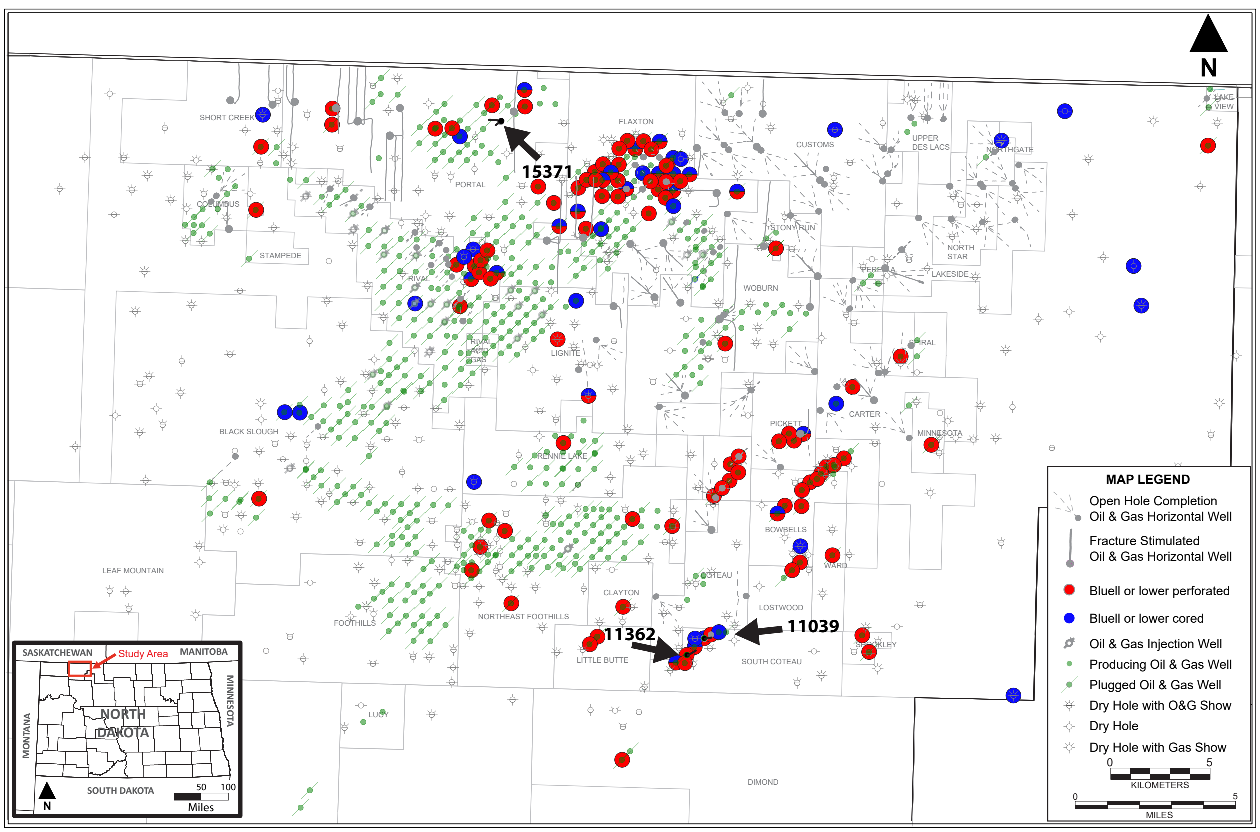

FIGURE 31. Wells with cored intervals and/or perforations in the subintervals underlying the Rival (e.g., Bluell, Sherwood) encountered in this study. Note the three horizontal wells that targeted either the Bluell subinterval or the Coteau, highlighted with black arrows.

TABLE 6. Horizontal tests of the Bluell / Coteau subinterval

API#	NDIC #	Well Name	Field	Spud Date	Lateral Target Interval	Cumulative Oil Production (BBLS)	Cumulative Gas Production (MCF)	Cumulative Water Production (BBLS)
33013010830000	11039	OPSETH 29-7	South Coteau	12/12/2011	Bluell	46,679	20,563	55,091
33013011140000	11362	ALBIN 29-13	South Coteau	12/21/2011	Bluell	1,471	240	129,742
33013013240000	15371	BALLANTYNE 6-8	Portal	3/15/2003	Coteau	57,095	701,192	84,032

CURRENT WELL PRODUCTION

In August 2023, 145 active wells in the 36 fields in the study area were producing on a monthly basis ~28 thousand barrels of oil, ~324 thousand barrels of water, and ~228 million cubic feet of gas. Thirteen fields had no production, and six fields accounted for greater than 80% of the total: Columbus, Short Creek, Lignite, Woburn, Flaxton, and Portal. More than half of the total production was from the Portal and Flaxton Fields, which contained nearly half of the producing wells. Two injection wells were active in the Flaxton Field.

CONCLUSIONS:

The preceding maps and figures illustrate several encouraging observations for the remaining resource potential of the region. These findings can be applied to the immediate area, with the extension of these principles to other redevelopment opportunities in the many Madison Group fields of North Dakota. This study suggests that:

1) In areas of variable reservoir quality, the implementation of fracture stimulation can help to produce more repeatable results but may quickly depressurize the reservoir.

2) In areas of stacked reservoirs with indirect or limited communication, fracture stimulation is likely to increase recovery.

3) Fracture stimulation appears to be an effective rate acceleration method in the study area and could yield similar results in the immediate area and in other Madison Group fields.

4) Core chip fluorescence can be utilized as a proxy for core plug measurements where data is unavailable.

5) The Bluell subinterval in Burke County warrants further exploration.

The southwest periphery of the Rival Field warrants a closer look for further resource development potential, as the reservoir quality is expected to be high, historical production indicates potential, and core chip fluorescence observations presented herein suggest a strong oil charge. While the porosity in the subject well (#8850) is low, this study suggests that grain size distribution and reservoir quality in the upper Rival can vary significantly, and development opportunities may exist in the immediate area.

This look back speaks to a promising future for the continued development of the Madison Group in North Dakota – the second-largest producing formation by volume in the history of North Dakota's journey of oil and gas development (Nesheim, 2022). By developing around existing fields in Burke County, operators have demonstrated that areas where Madison Group reservoirs had been uneconomic as conventional developments due to low permeability can have development potential with new technologies (i.e., fracture stimulation and/or horizontal drilling). Examples such as the Portal Field show that fracture stimulation in and around known oil accumulations can serve as an effective method for continued development opportunities in Burke County and across North Dakota.

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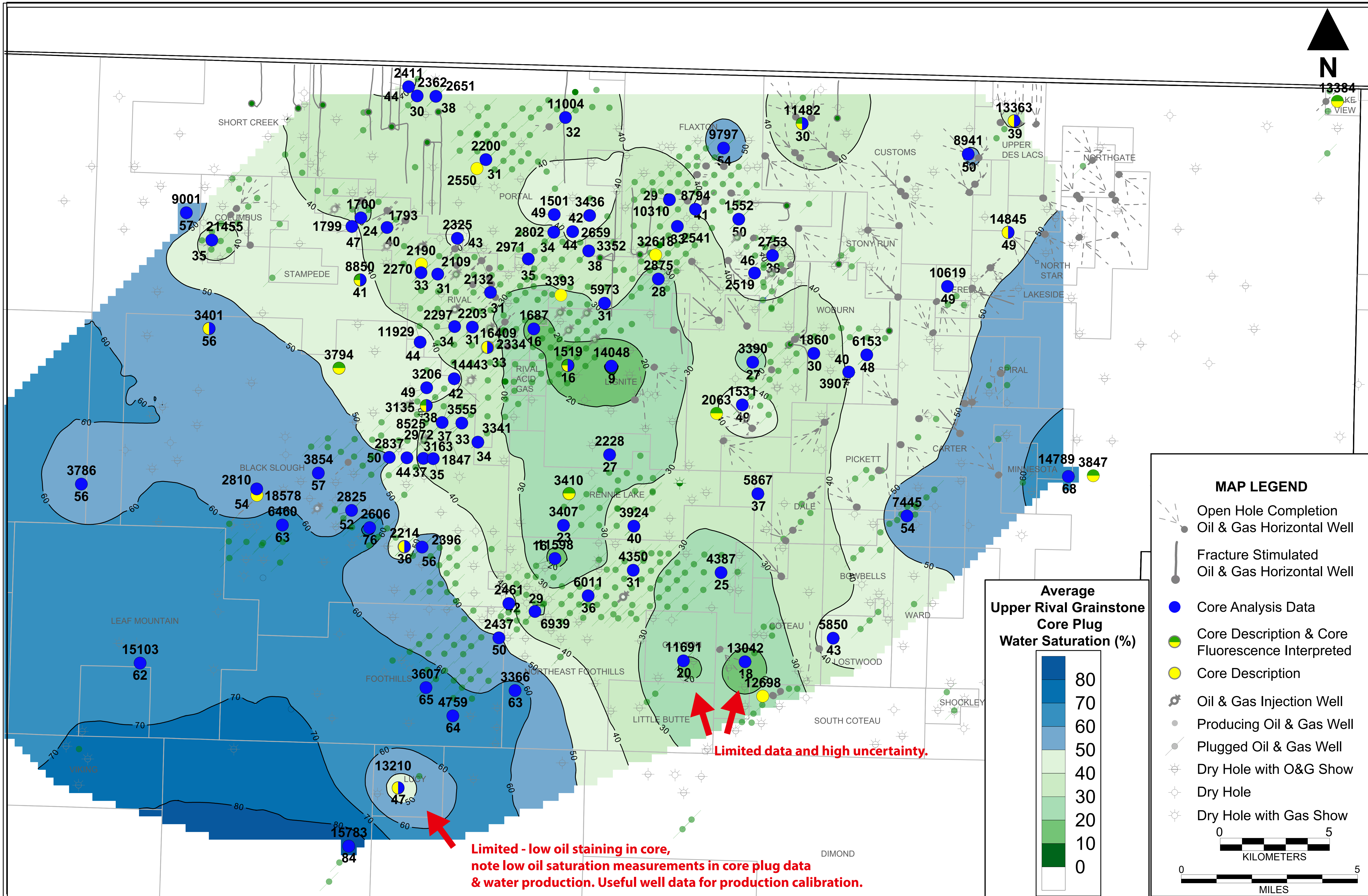

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MAP LEGEND
Open Hole Completion Oil & Gas Horizontal Well
Fracture Stimulated Oil & Gas Horizontal Well
Core Analysis Data
Core Description & Core Fluorescence Interpreted
Core Description
Oil & Gas Injection Well
Producing Oil & Gas Well
Plugged Oil & Gas Well
Dry Hole with O&G Show
Dry Hole
Dry Hole with Gas Show
0 5 KILOMETERS
0 5 MILES
Average Upper Rival Grainstone Core Plug Water Saturation (%)
80
70
60
50
40
30
20
10
0
Limited data and high uncertainty.
Limited - low oil staining in core, note low oil saturation measurements in core plug data & water production. Useful well data for production calibration.
SHORT CREEK
COLUMBUS
STAMPEDE
PORTAL
FLAXTON
CUSTOMS
UPPER DES LACS
NORTHGATE
STONY RUN
NORTH STAR
LAKESIDE
WOBURN
RIVAL
RIVAL ACID GAS
LIGNITE
SPIRAL
CARTER
PICKETT
MINNESOTA
BLACK SLOUGH
RENNIE LAKE
DALE
BOWBELLS
WARD
COTEAU
LOSTWOOD
LEAF MOUNTAIN
FOOTHILLS
NORTHEAST FOOTHILLS
LITTLE BUTTE
SOUTH COTEAU
SHOCKLEY
VIRDEN
LUCY
DIMOND