MIDDLE THREE FORKS DEVELOPMENT IN THE BAKKEN-THREE FORKS PETROLEUM SYSTEM, RATE ACCELERATION OR RESOURCE ADDITION?

by

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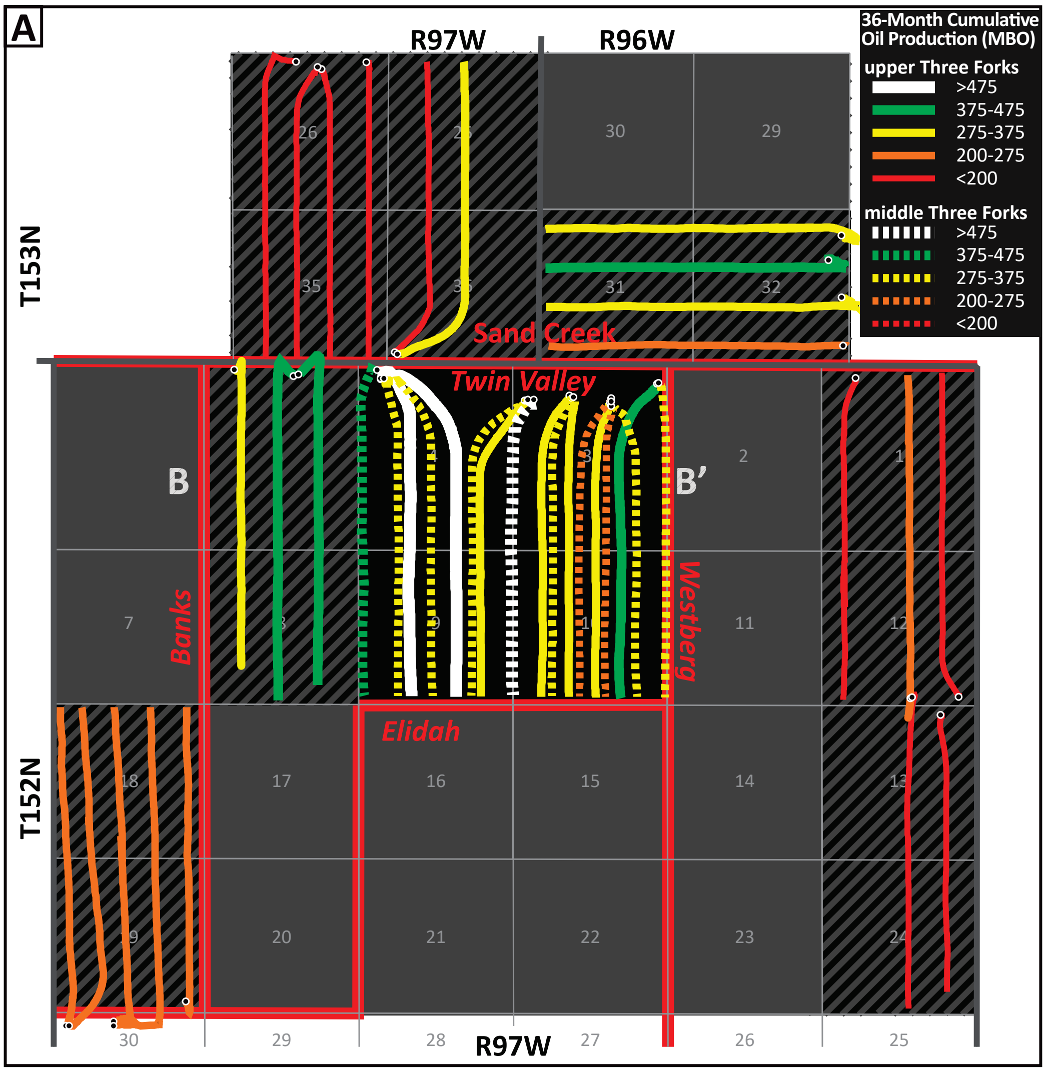

REPORT OF INVESTIGATION NO. 135
NORTH DAKOTA GEOLOGICAL SURVEY
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On the cover: Lateral map of upper Three Forks and middle Three Forks horizontal wells within the Twin Valley field area color-coded by initial 36-month cumulative oil production totals. The solid black fill indicates spacing units with Middle Bakken, upper Three, and middle Three Forks reservoir development. The black fill with diagonal grey lines indicates spacing units with development in only the Middle Bakken and upper Three Forks.

EXECUTIVE SUMMARY

The following study was completed in 2023 which examined the production of nine 1280-acre spacing units in the Bakken-Three Forks petroleum system to evaluate whether developing the middle Three Forks reservoir adds to long-term volumetric oil production. Two of the spacing units evaluated included stacked laterals in the Middle Bakken, upper Three Forks, and middle Three Forks, which were projected to produce approximately 7 million barrels of oil per spacing unit. Meanwhile, the other seven spacing units had well development in only the Middle Bakken and upper Three Forks, and were projected to produce 3 to 5 million barrels of oil per spacing unit. These results indicate drilling and developing the middle Three Forks reservoir, in addition to the Middle Bakken and upper Three Forks reservoirs, will increase the estimated ultimate recovery of oil for each spacing unit on the order of two million barrels.

This study represented a small but first step towards understanding the resource potential of the middle Three Forks reservoir within the Bakken-Three Forks petroleum system. Starns and Nesheim (2024) was subsequently completed as a phase II of the middle Three Forks resource evaluation project. The two reports were published separately due to the difference in timing of their completions as well as slight variations in methodologies. The two papers were published simultaneously because of their overlapping topic.

INTRODUCTION

The Bakken and Three Forks Formations emerged during 2000-2010 as the first unconventional tight oil resource play within the global oil and gas industry. As the first unconventional tight oil play, the Bakken-Three Forks serves as a case study for exploring and developing current and future unconventional resource plays. Early resource assessments of the Bakken-Three Forks petroleum system varied but generally concluded that billions of barrels of oil, in addition to hydrocarbon gas resources, would eventually be recovered through exploration and development (Nordeng and Helms, 2010; Gaswirth et al., 2013). More than 18,000 Bakken-Three Forks wells have been drilled and completed within North Dakota, the core acreage of the Bakken-Three Forks play, which have combined to produce approximately 4.8 billion barrels of oil and 37 TCF of gas to date (NDOGD, 2023). Additional wells continue to be drilled in the play and production extends into both the Montana and Canadian portions of the basin (Fig. 1).

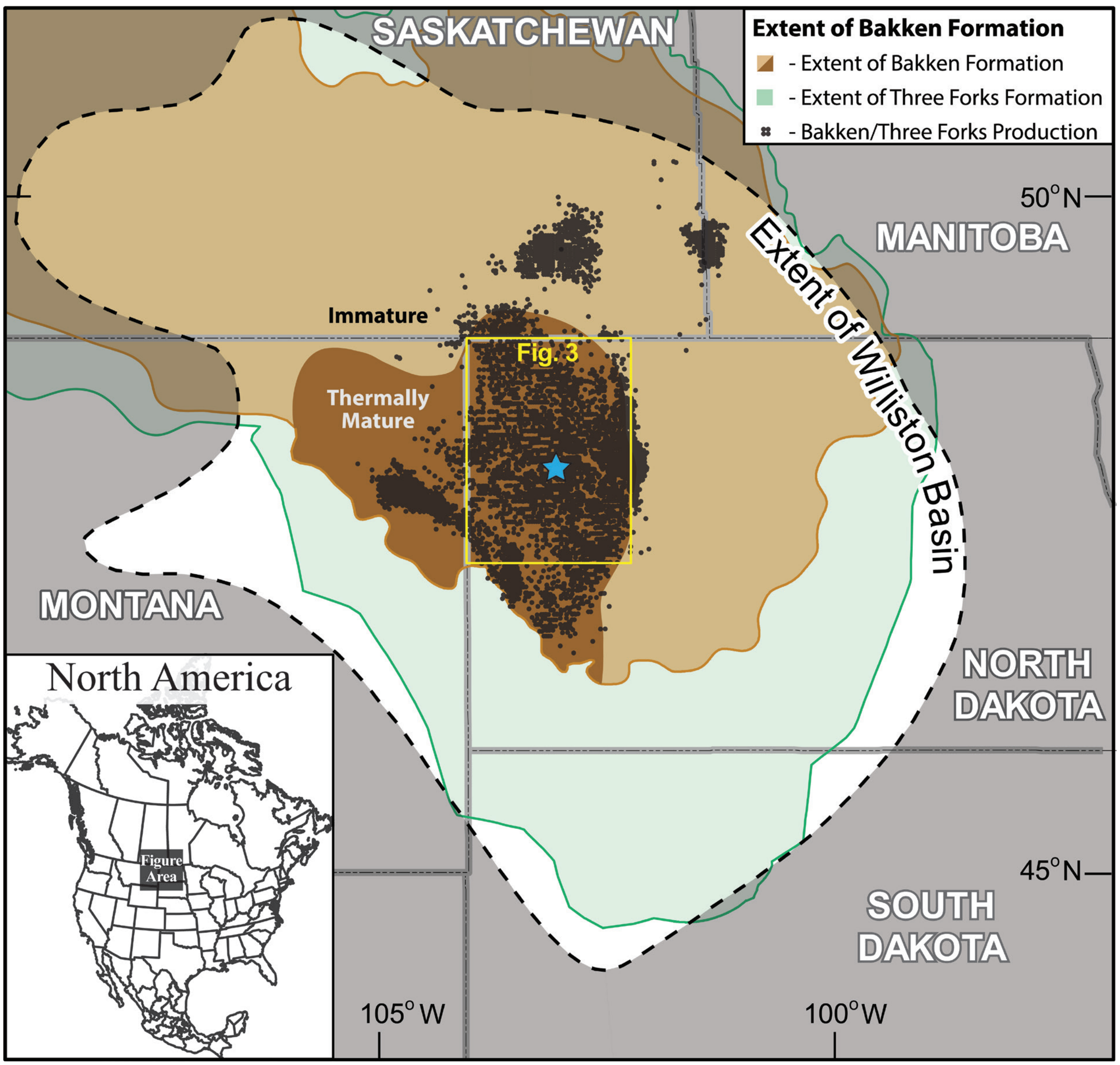

FIGURE 1. Regional extent of the Bakken and Three Forks Formations with the distribution of productive wells within both formations. The blue star indicates the location of the case study area.

As the Bakken-Three Forks play evolved, both the lateral and vertical extent of the play has expanded over the past 20+ years. Oil production from the Bakken began in the 1950s with vertical wells targeting natural fracture systems, and a short-lived horizontal play targeting naturally fractured shale occurred in the late 1980s to early 1990s (Murray, 1968; Nordeng et al., 2010). Horizontal drilling targeting the Middle Bakken, coupled with hydraulic fracturing, led to the discoveries of Elm Coulee Field in eastern Montana during 2000, the Parshall Field in western North Dakota during 2006, culminating in the initial Bakken oil boom in the Williston Basin (Fig. 2) (Nordeng et al., 2010). Operators later began targeting the upper Three Forks Formation in 2008, which is positioned directly beneath the Bakken and developed into an additional reservoir target for exploration and development (Fig. 2) (Nordeng et al., 2010; Bottjer et al., 2011). In the early 2010s, the Pronghorn Member was identified and defined as a basal unit of the Bakken Formation, emerging as a more localized reservoir along the southernmost margins of the Bakken's extent (LeFever et al., 2011; Skinner et al., 2015).

Exploration testing continued to expand downwards into the middle and lower portions of the Three Forks beginning in 2012-13 (Fig. 2) (Petroleum News, 2012; Gaswirth and Marra, 2015). A combined 400+ horizontal wells were drilled, most of which have been completed, between the middle and lower Three Forks from late 2012 through mid-2023 (Nesheim, 2020b). After an initial, more

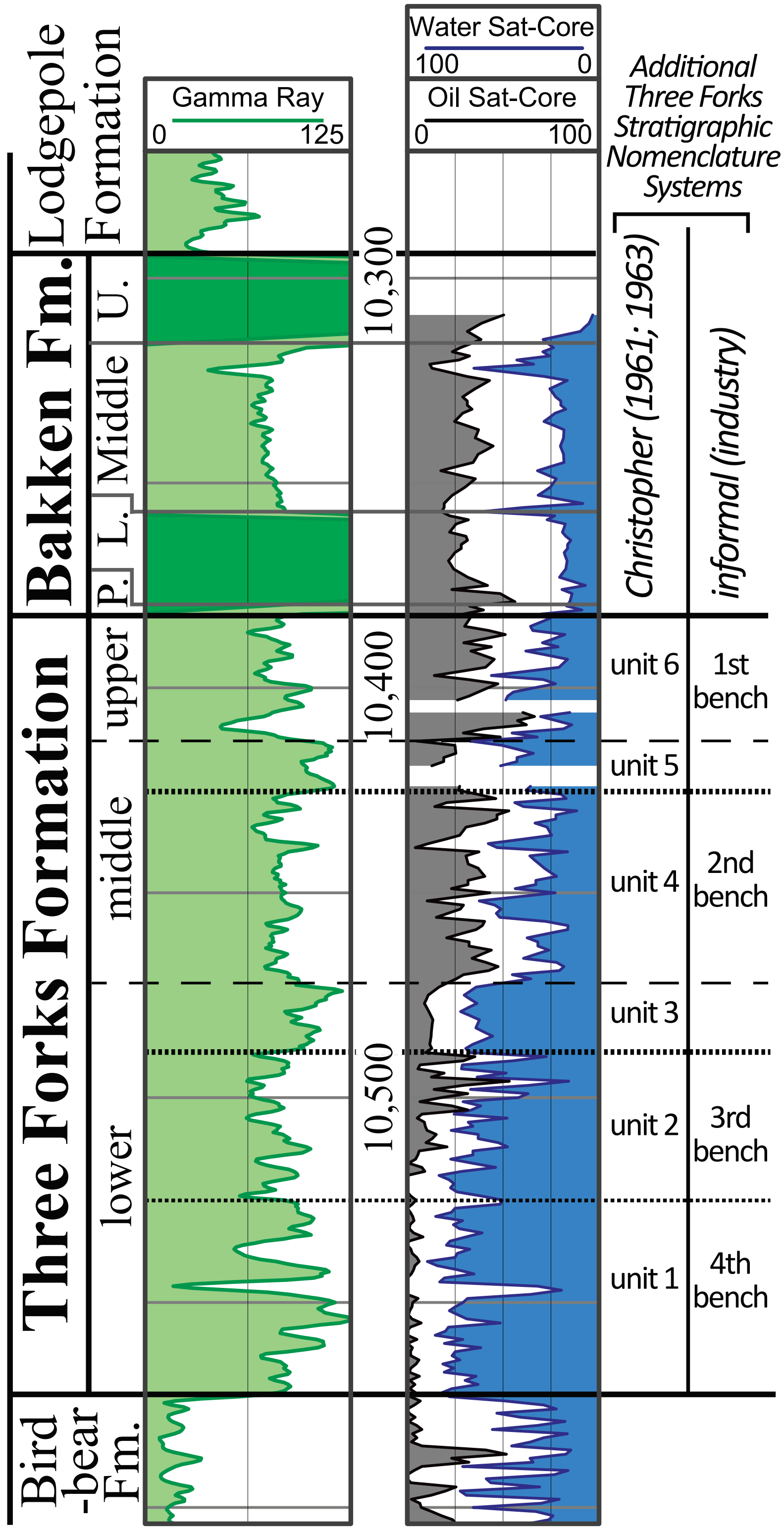

FIGURE 2. Gamma-ray wireline log example of the Bakken-Three Forks section with core-plug oil and water saturation data from Enerplus Resource's Hognose 152-94-18B-19H-TF (NDIC: 26990; API: 33-053-05475-00-00).

regional phase of drilling and completions during 2013-14, developmental drilling of the middle Three Forks followed focusing on the more productive acreage in and around northeastern McKenzie County (Fig. 3) (Nesheim, 2020a). This is approximately the same acreage where middle Three Forks core-plug oil saturations reach their highest levels (Nesheim, 2019), water-cuts of middle Three Forks wells routinely drop below 50%, and 700-day cumulative oil production totals commonly range from 200 to 300+ MBO (Nesheim, 2020c). To date, more than 340 horizontal wells had been drilled and completed in the middle Three Forks through August 2023, producing more than 91 million barrels of oil, 106 million BBLS water, and 234 BCF gas. Overall, the middle Three Forks has become an additional developmental reservoir within the area of northeastern McKenzie County, near the central, deepest portions of the Williston Basin.

Only 43 horizontal wells have been drilled and completed in the lower Three Forks (Nesheim, 2021a) that have combined to produce approximately 6.7 million barrels of oil, 11.0 million barrels of water, and 14.0 BCF of gas through August 2023. Only six lower Three Forks horizontal wells have been drilled following 2014, and there have been no new wells in the unit since mid-2017 (Nesheim, 2021a), likely due to variable and overall low well production results. Therefore, while resource potential in the unit may be present, the lower Three Forks has yet to become a regular developmental reservoir within the Bakken-Three Forks Petroleum System.

The initial USGS assessment of the Bakken Petroleum System in 2008 accounted for development within only the Bakken because minimal drilling and production data existed at the time for the Three Forks. A follow up USGS assessment in 2013 reassessed the Bakken Formation and also included the Three Forks for the first time as more than 1,600 horizontal wells had been drilled and completed in the upper Three Forks at that time (Gaswirth and Marra, 2015). The 2013 assessment noted that operating companies had begun to drill and complete wells in the middle and lower Three Forks (Gaswirth and Marra, 2015), but, due to limited production results and geologic information, were not substantially factored into the assessment results.

Another assessment of the Bakken-Three Forks was completed by the USGS in 2021 (Marra et al., 2021). Compared to the 2013 assessment, the 2021 assessment included a more detailed subdivision of the Three Forks into multiple assessment units based upon regional geologic components and well performance. However, this latest Three Forks assessment did not include any separate assessment of the middle (or lower) Three Forks. Additionally, each 2021 Three Forks assessment unit accounted for only four Three Forks wells per 1280-acre spacing unit, which is the standard drilling density of the upper Three Forks reservoir. Therefore, the 2021 USGS assessment of the Three Forks Formation appears to have accounted for minimal to negligible development in the formation beyond the upper Three Forks reservoir.

An important question arises given that multiple operating companies are continuing to develop the middle Three Forks reservoir, but the most recent USGS assessment factored in negligible middle Three Forks development. Does direct drilling and development of the middle Three Forks reservoir provide additional resource recovery, or does middle Three Forks co-development simply accelerate recovery rates of resources that would have otherwise been recovered by standalone upper Three Forks reservoir development? The purpose of this paper is to examine a case study area with upper Three Forks well development that includes spacing units both with and without middle Three Forks co-development. If middle Three Forks co-development simply accelerates oil and gas recovery rates, but does not add any long-term resource, then

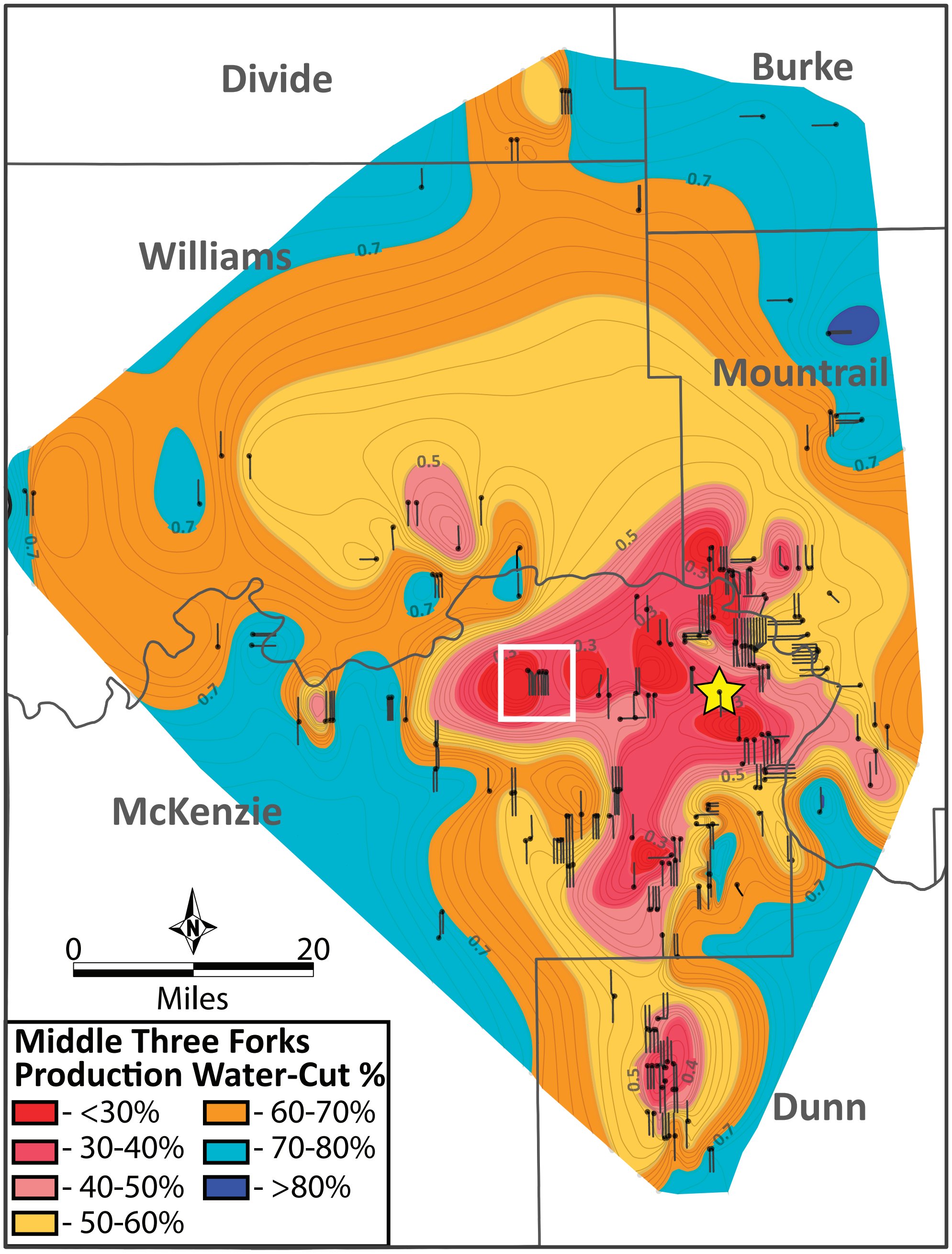

FIGURE 3. Water-cut map of middle Three Forks horizontal wells based upon productive wells drilled and completed through the end of 2019. Middle Three Forks horizontal wells are displayed by small, black lines. The white outline indicates the main study area, which corresponds with Figures 4, 10, and 16. The yellow star indicates the location of the Figure 2 well, Enerplus Resource's Hognose 152-94-18B-19H-TF (NDIC: 26990; API: 33-053-005475-00-00).

upper Three Forks wells should be less productive in the middle Three Forks co-development area versus upper Three Forks well performance where the middle Three Forks was not co-developed.

GEOLOGIC BACKGROUND

The Three Forks Formation is a mixed carbonate-siliciclastic unit that was deposited during the Late Devonian (Murphy et al., 2009; Droege, 2014; Franklin and Sarg, 2018) (Fig. 2). Two competing models for deposition include a storm dominated intrashelf, restricted marine setting (Franklin and Sarg, 2018) versus an arid, hypersaline, lacustrine environment (Garcia-Fresca et al. 2018). The Three Forks mineral assemblage is comprised primarily of fine-grained dolomite with moderate amounts of clay (mostly illite) and silt-to sand-sized quartz with variable amounts of anhydrite primarily in the lower portions of the section (Ashu, 2014; Murphy, 2014). The Three Forks has been sub-divided into different nomenclature systems, including: 1) six sub-units ranging from unit 1 to unit 6 in ascending stratigraphic order (Christopher, 1961; 1963); and 2) an upper, middle, and lower member distinction (Bottjer et al., 2011), which is utilized herein (Fig. 2). Additionally, an informal "bench" terminology system has also been developed by industry, where four reservoir target horizons are referred to as benches one to four in descending stratigraphic order (Fig. 2).

The upper Three Forks reservoir (also referred to as the "1st bench") is composed mostly of tan silty dolostone that is, in part, intercalated with grey to green claystone (Bottjer et al., 2011; Franklin and Sarg, 2018). The middle Three Forks reservoir (2nd bench) also contains some laminated to intercalated silty tan-brown dolostone but contains conglomeratic facies associations with re-worked dolostone clasts (Nesheim, 2021b). Both reservoir intervals are typically on the order of 30-40 ft (9-12 m) thick and are separated by a 12-14 ft (3-4 m thick) interval primarily composed of poorly laminated silty mudstone that is comprised of relatively equal proportions of quartz-dolomite-clay (Nesheim, 2021b).

The Three Forks is disconformably overlain by the Bakken Formation (Mississippian-Devonian), which is comprised of four members, in descending order: Upper, Middle, Lower, and Pronghorn Members (Fig. 2) (LeFever et al., 2011). The basal Pronghorn Member ranges from siltstone to sandstone (proximal deposits) and silty to sandy mudstone (distal deposits) (LeFever et al., 2011). The proximal deposits of the Pronghorn can serve as hydrocarbon reservoirs and currently represent the southernmost reservoir of the petroleum system as previously mentioned (Skinner et al., 2015). Meanwhile, the distal Pronghorn is overall clay-rich (poor reservoir quality), and, when present and substantially thick, has been interpreted to form a barrier to hydrocarbon charge from the lower Bakken shale to the upper Three Forks (Millard and Brinkerhoff, 2016). Both the distal and proximal deposits of the Pronghorn are discontinuous across western North Dakota and range from being absent to reaching combined thicknesses of over 40 feet (12 m) (LeFever et al., 2011). The Upper and Lower Members consist of black, slightly calcareous, organic-rich shale (LeFever et al., 2011). The Middle Member consists primarily of siltstones that record a history of progradational and retrogradational basin filling parasequences with very low angle geometries (Egenhoff et al., 2011; Egenhoff and Fishman, 2020).

Overall, the Three Forks forms a non-self-sourced, tight oil reservoir. The Three Forks contains minimal petroleum source rock based upon visual examination and sampling/analysis (Ashu, 2014). The overlying lower Bakken shale is an excellent quality source rock (TOC values commonly > 10%), originally contained abundant Type II (oil-prone) kerogen, reaches a maximum thickness of 60 ft (18 m), ranges from immature to peak-mature with respect to oil generation in the Williston Basin, and is understood to be the primary source of Three Forks hydrocarbons (Nordeng et al., 2010; Abarghani et al., 2018; Nesheim, 2019). Three Forks reservoir quality in western North Dakota is low porosity (< 6%) with small pore diameters (1–100 nm) and very low permeability (< 1 millidarcy, mD) (Nordeng et al., 2010; Bottjer et al., 2011; Saidian and Prasad, 2015; Liu et al., 2017). Three Forks reservoir quality increases northwards into Canada with increased average porosity and permeability values of 11–17% and 1–8 millidarcies respectively in southwestern Manitoba (Nicolas, 2012), and 5–15% porosity with 1–20 millidarcies permeability within southern Saskatchewan (Kreis and Costa, 2005). At a minimum, the increase in porosity and permeability likely allows for some lateral hydrocarbon migration within the Bakken-Three Forks along the northern margins of the Williston Basin, where the Bakken shales are thermally immature to hydrocarbon generation, but the reservoirs still hold hydrocarbons (Nicolas, 2012).

METHODS

The Twin Valley Field area was selected for several reasons: 1) the field area is positioned near the central, deepest portions of the Williston Basin where the middle Three Forks exhibits elevated core-plug oil saturations, low productive well water cuts (<50%) (Fig. 3), and high 700-day cumulative oil production totals (200-300+ MBO) (Nesheim, 2019, 2021c). Additionally, the Twin Valley Field has two adjacent 1280-acre spacing units with co-development of the Middle Bakken, upper Three Forks, and middle Three Forks reservoirs through drilling ~two-mile horizontal wells that were completed with multi-stage hydraulic fracturing (Fig. 4). Multiple surrounding spacing units have experienced developmental drilling in only Middle Bakken and upper Three Forks reservoirs to date, which allows for the comparison of upper Three Forks well performance both with and without middle Three Forks co-development. Lastly, natural fracturing due to basement-induced structural movement is thought to be relatively minimal as the field location is located several miles away from the western flank of the Nesson anticline, the most pronounced structural feature in the central basin area (Fig. 3).

Drilling records were reviewed and geo-steering was completed for horizontal wells to determine the reservoir target of each lateral drilled. Gamma Ray Measured While Drilling and other drilling records provided direct evidence if one or both Bakken shales had been drilled through by each horizontal well, which provided a preliminary distinction of Middle Bakken versus Three Forks wells. For geo-steering, isopach maps using vertical well control within and around the study area were completed on the Upper, Middle, Lower, and Pronghorn Members of the Bakken Formation as well as the middle and upper units of the Three Forks Formation. Structure contour mapping was completed on Bakken and Three Forks Formation tops using both vertical and horizontal well control. Well control included 72 total wells: 16 vertical, 30 horizontal Three Forks, and 26 horizontal Middle Bakken wells. Additional control points were added to the structure contour mapping through Upper and Lower Bakken shale strikes noted in horizontal well drilling records as well as through geo-steering (i.e. if geo-steering indicated Upper and/or Lower Bakken shale penetration by lateral, but drilling records indicated no shale penetration, structure contour control point/s were added accordingly). Structure contour and isopach maps were then combined with directional drilling surveys to geo-steer all Three Forks wells (and select Middle Bakken wells) and confirm upper versus middle Three Forks horizontal wells.

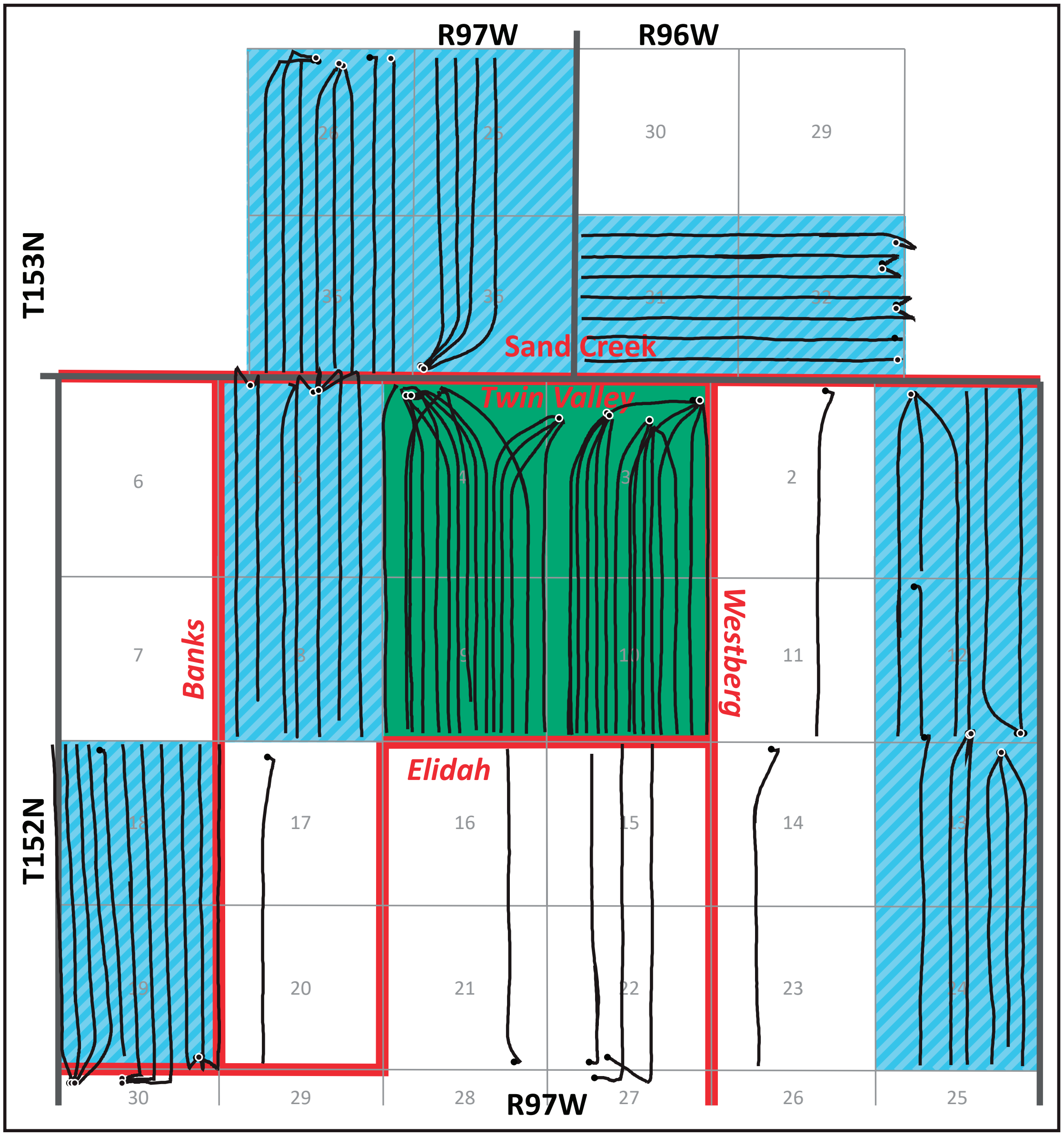

FIGURE 4. Field map of the Twin Valley Field area showing field names and outlines in red and horizontal laterals drilled in the Bakken and Three Forks Formations. The green-shaded 1280-acre spacing units in the middle of the map represent where the operators drilled and completed horizontal wells in the Middle Bakken, upper Three Forks, and middle Three Forks reservoirs. The blue-shaded 1280-acre spacing units depict where operators have drilled and completed wells in only the Middle Bakken and upper Three Forks reservoirs to date.

Petrophysical logs, structure contour, and isopach mapping were examined to characterize geologic variations across the study area in reservoirs, source rocks, and immediately adjacent stratigraphic units. Petrophysical logs from vertical wells were compiled and digitized for older wells. Petrophysical log cross-sections were built, primarily to qualitatively evaluate changes in lithology and/or reservoir quality of the upper Three Forks across the study area.

Monthly production records were compiled for Three Forks and Middle Bakken wells within the study area and utilized to tabulate 12-month, 24-month, and 36-month cumulative oil production totals. Additionally, decline curve analyses were completed to generate estimated ultimate recovery (EUR) oil volumes within the Decline Curve Analysis Module of Petra© set to a minimum of 10 barrels of oil per day cut off. Hydraulic fracture stimulation information was compiled from well completion reports available through the North Dakota Industrial Commission (NDIC, 2023). Completion data was compared with well production results to evaluate potential trends between completion methodology and well performance. Field maps plotting Three Forks well laterals with 36-month oil cumulative totals were created to examine the effects of well density on production results as well as production distribution trends.

RESULTS

Review of geologic variations of the study area showed that most of the subunits comprising the Bakken and Three Forks Formations thicken slightly towards the east-northeast while dipping westwards (Figs. 5-7). Most of the members/subunits comprising the Bakken and middle to upper Three Forks Formations vary in thickness across the study area by only a few feet, which is generally a <20% thickness variation (Figs. 6 and 7). The upper Three Forks reservoir yields a normalized gamma-ray signature consisting of alternating low (≤50 API) to moderate (≥100 API) intervals that show good overall lateral continuity across the study area (Fig. 8). Structure contour mapping reveals the Three Forks Formation top dips westward overall from less than -8,200 feet in the northeast to around -9,000 feet subsea level along the western border (Fig 7).

A total of 40 Three Forks horizontal wells (30 upper Three Forks and 10 middle Three Forks) were identified across nine different 1280-acre spacing units within the study area that were drilled with ~two-mile laterals and had reached 36 months of production or more (Figs. 9b, c and 10a, b). Additionally, 42 total Middle Bakken wells were identified and confirmed within the study area, consisting of 40 wells drilled and completed with ~two-mile laterals and 2 wells with only ~one-mile laterals (Figs. 9a and 10c). Two spacing units within the middle of the study area were confirmed to include upper Three Forks and middle Three Forks co-development, with 7 upper Three Forks wells and 10 middle Three Forks wells overlain by 11 Middle Bakken wells (Figs. 10 and 11). Seven surrounding spacing units were identified with a total of 23 upper Three Forks wells, overlain by Middle Bakken wells, and no co-development of the middle Three Forks. Six additional 1280-acre spacing units are present in the study area, but at the time of the study did not include any Three Forks development wells which were off confidential status.

The 36-month cumulative oil production totals and EURs of both the Bakken and various sets of Three Forks wells are summarized in Table 1 (expanded in Tables S1 and S2). Figures 12 and 13 display cumulative monthly oil production plots and a comparison of 36-month cumulative oil production totals versus EUR volumes for Three Forks wells within the study area.

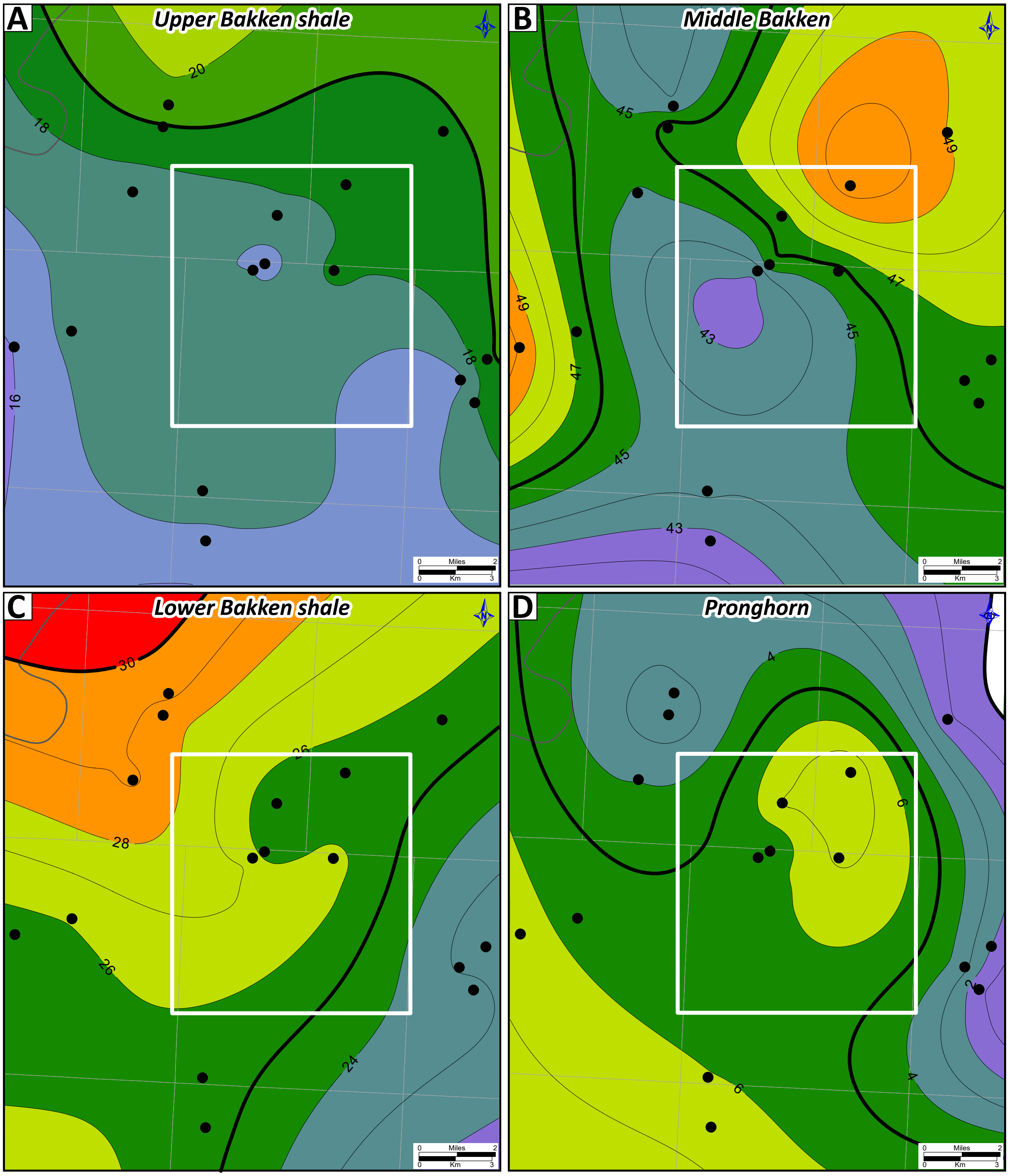

FIGURE 5. Isopach maps of the members comprising the Bakken Formation: **A**) Upper Bakken Member, **B**) Middle Bakken Member, **C**) Lower Bakken Member, and **D**) Pronghorn Member. Contours are in two-foot intervals and the white outline depicts the Twin Valley field area of Figures 4 and 10.

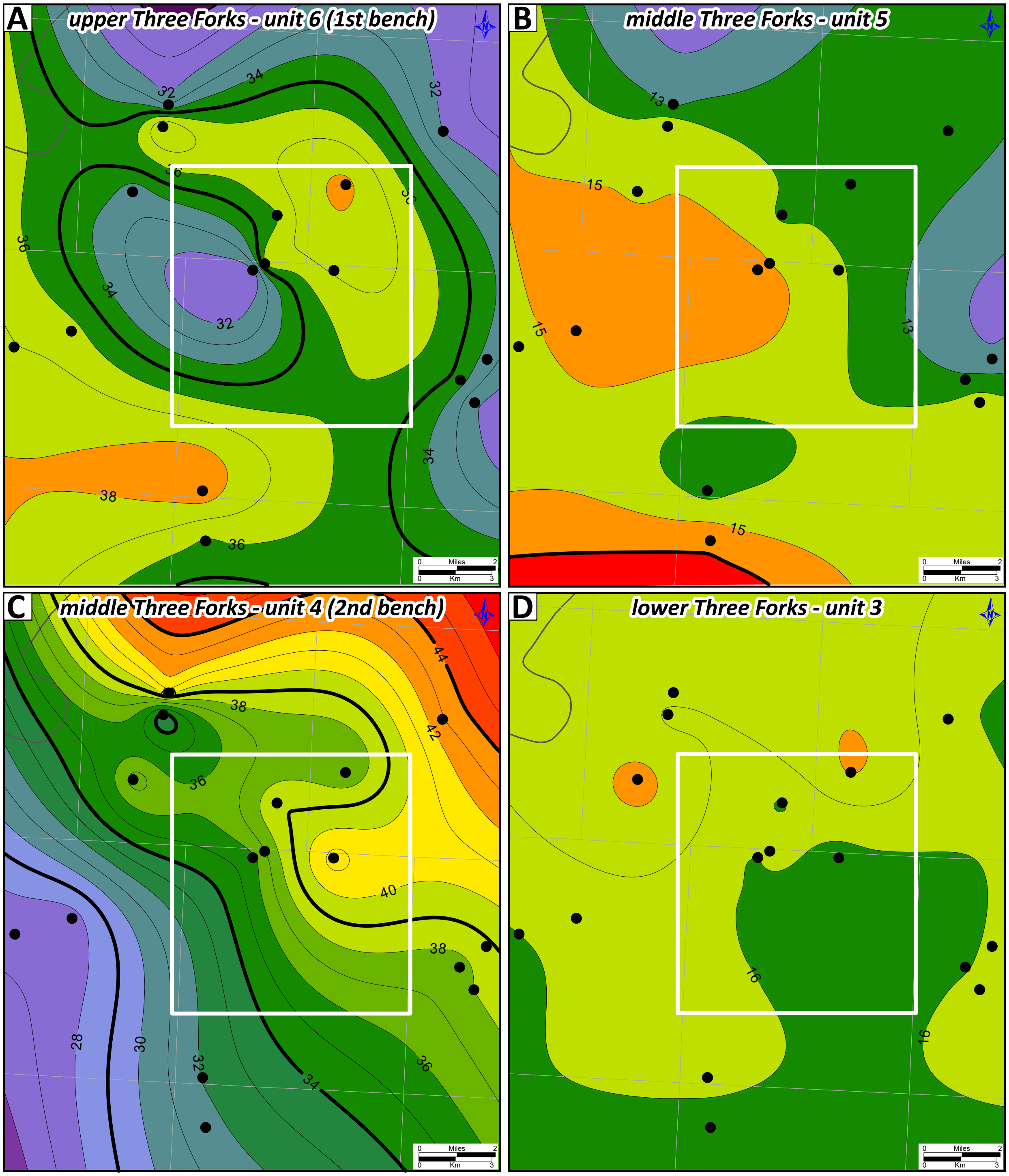

FIGURE 6. Isopach maps of the informal subunits comprising the middle and upper portions of the Three Forks Formation: **A**) unit 6, **B**) unit 5, **C**) unit 4, and **D**) unit 3 (Christopher 1961; 1963). Contours are in two-foot intervals and the white outline depicts the Twin Valley field area of Figures 4 and 10.

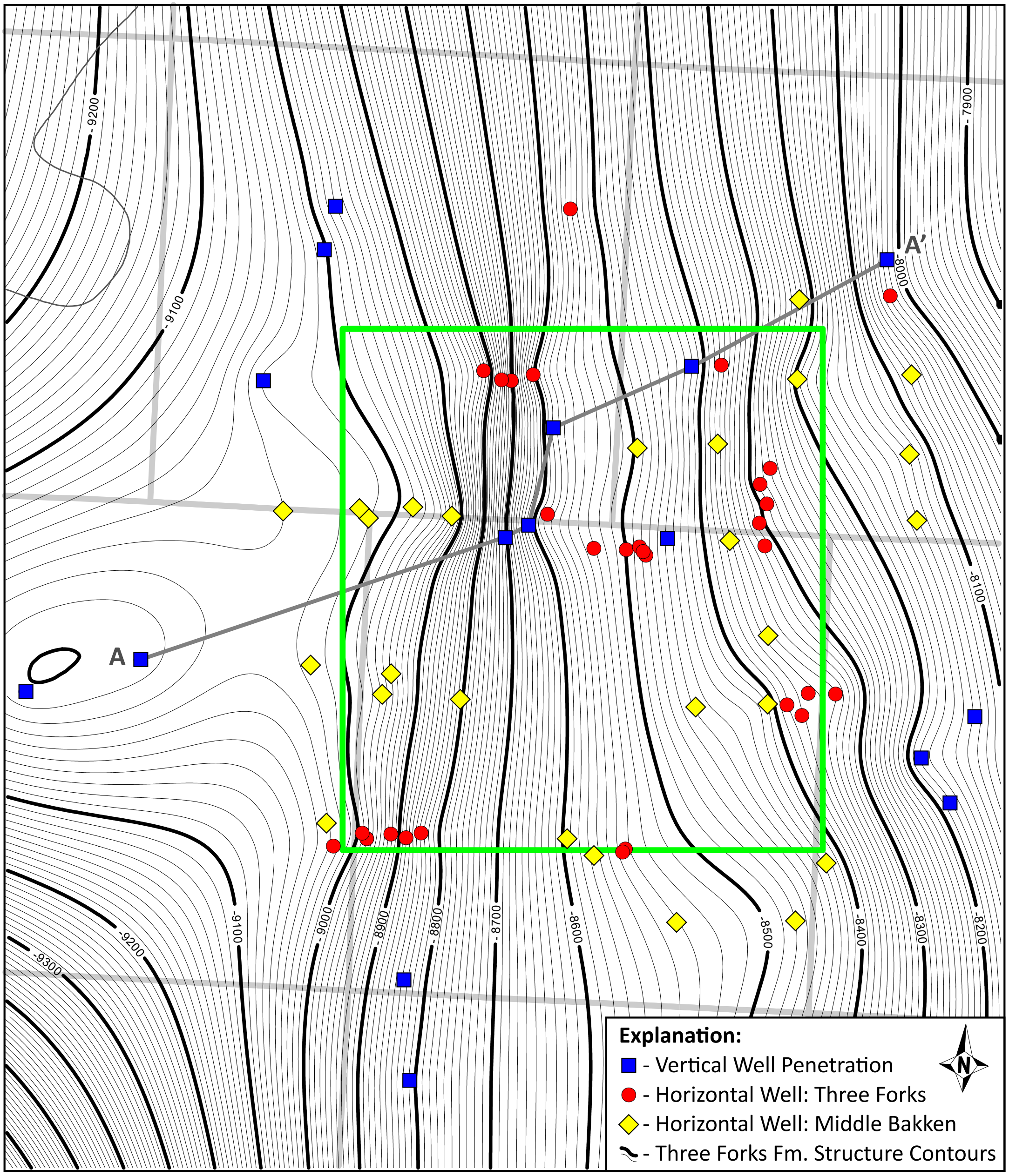

FIGURE 7. Structure contour map of the Three Forks Formation top. Contours are in 10-foot intervals. The Twin Valley field area of Figures 4 and 10 is indicated by the green outlined area. Figure 8 cross-section displayed by A-A′.

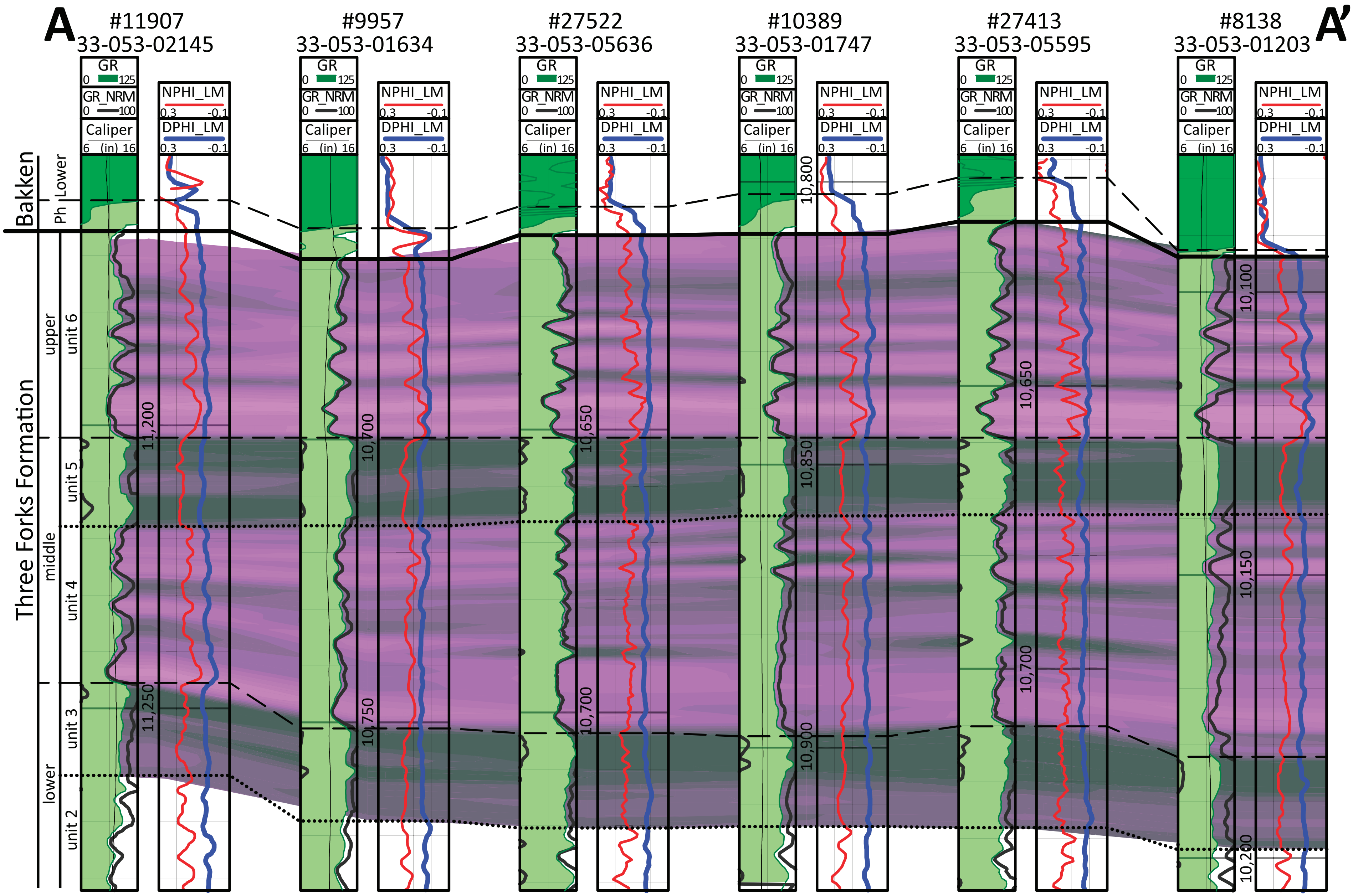

FIGURE 8. Stratigraphic cross-section of the middle and upper Three Forks Formation with petrophysical logs. Above each well listed in descending order are the North Dakota Industrial Commission and API well numbers. The interpretive color fill is based upon the normalized gamma ray of the Three Forks section. GR = gamma ray; GR_NRM = normalized gamma ray; in = inch; NPHI_LM = neutron porosity calculated using limestone matrix; DPHI_LIM = density porosity calculated using limestone matrix

The current development pattern for the Middle Bakken and upper Three Forks reservoirs within the study area appears to range from three to six, approximately evenly spaced horizontal wells per reservoir horizon within each 1280-acre spacing unit (Fig. 10). Meanwhile, the middle Three Forks reservoir in the co-development area includes a total of ten wells between both spacing units, averaging five wells per 1280-acres (Fig. 10a), which is on the high end of Middle Bakken/ upper Three Forks well spacing.

The amount of proppant injected as well as the number of stimulation stages of hydraulic fracture completions of upper Three Forks wells have varied substantially within the study area. Hydraulic fracture stimulations on the 30 upper Three Forks wells ranged from injecting <1 million to approximately 15 million pounds of proppant through 5 to 97 total stages (Table S3, Fig. 14). Most upper Three Forks wells within the study area were completed with between 3 and 7.5 million pounds of proppant and 25-40 hydraulic fracture stimulation stages, including almost all the upper Three Forks wells within spacing units with middle Three Forks co-development (Fig. 14).

Examining the composite production of individual spacing units both with and without middle Three Forks co-development, the two spacing units that have had co-development of the Middle Bakken, upper Three Forks, and middle Three Forks reservoirs (S3/S10-T152N-R97W and S4/S9-T152N-R97W) have combined 36-month cumulative oil production per well totals of 4.75 and 5.15 MMBO along with composite EURs of 6.72 and 7.16 MMBO (Fig. 15, Table S4). Meanwhile, spacing units that have only had co-development

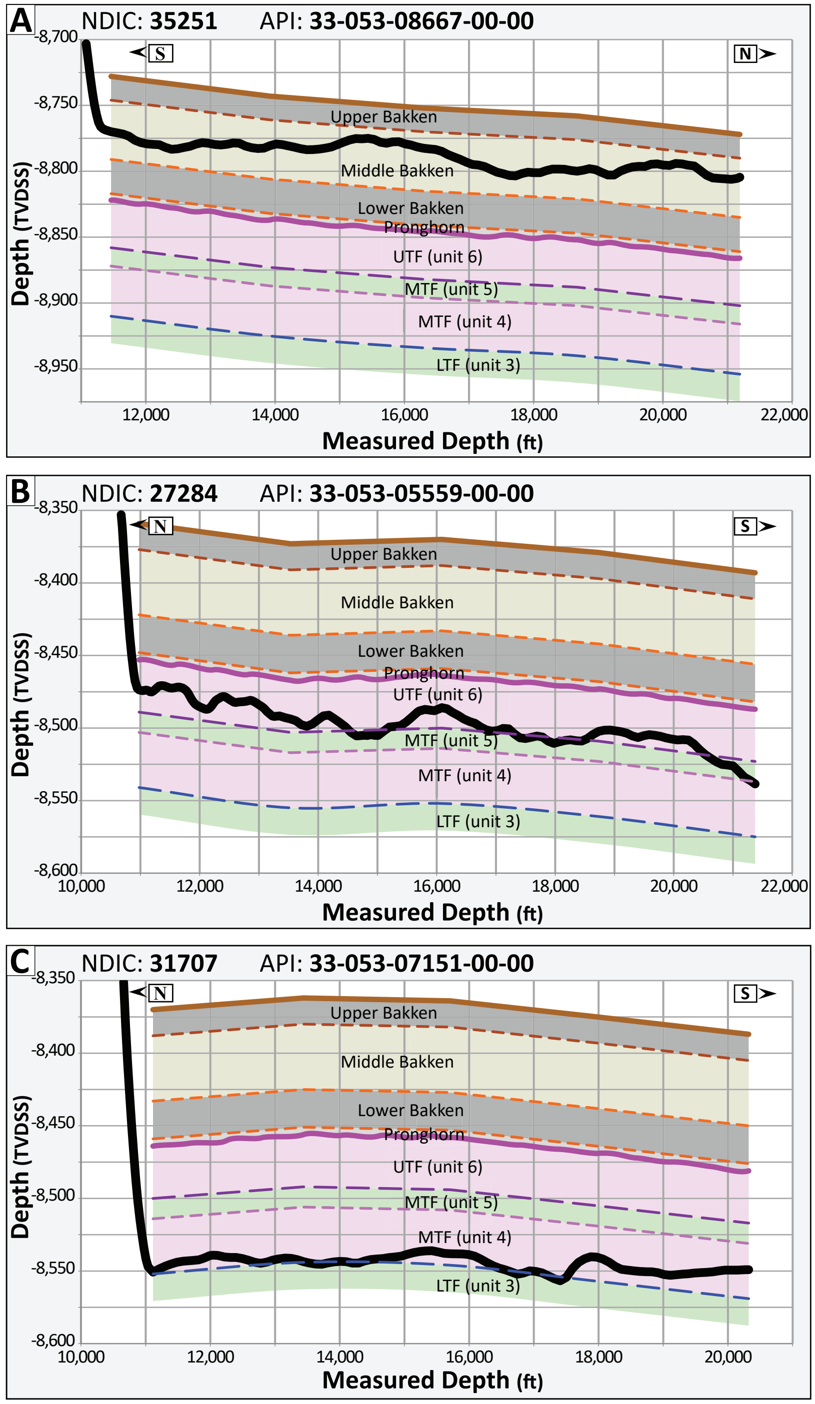

FIGURE 9. Example geo-steering plots generated through this study of the **A**) Middle Bakken, **B**) upper Three Forks, and **C**) middle Three Forks horizontal wells.

of the Middle Bakken and upper Three Forks (S18/S19-T152N-R97W, S26S/35-T153N-R97W, S5/S8-T152N-R97W, and S31/32-T153N-R96W) have combined 36-month cumulative oil production totals of 1.56 to 2.72 MMBO and composite EURs ranging from 3.50 to 5.05 MMBO (Fig. 15, Table S4).

INTERPRETATIONS

Upper Three Forks well performance varies substantially across the study area with 36-month cumulative production totals ranging from 105 to 650 MBO per well with EUR volumes of 226 to 820 MBO (Table 1 and S2). Before interpreting the influence of middle Three Forks co-development, geologic as well as drilling and completion controls are first reviewed and interpreted with regards to upper Three Forks well performance. The Lower Bakken shale, the source rock for Three Forks hydrocarbons (Nesheim, 2019), thins slightly eastward across the study area (Fig. 16a). A decrease in source rock and generated hydrocarbons per unit area could decrease hydrocarbon charge into the upper Three Forks reservoir and negatively impact upper Three Forks well performance. However, decreased Lower Bakken shale thickness does not consistently correspond with decreased upper Three Forks well performance (Fig. 16a). Additionally, if enough hydrocarbons have been generated and expelled to charge the underlying middle Three Forks reservoir, then the intermediate upper Three Forks reservoir should be adequately charged as hydrocarbons would have to pass downward through the upper Three Forks to charge the middle Three Forks. The Pronghorn Member has been documented to be comprised in part of

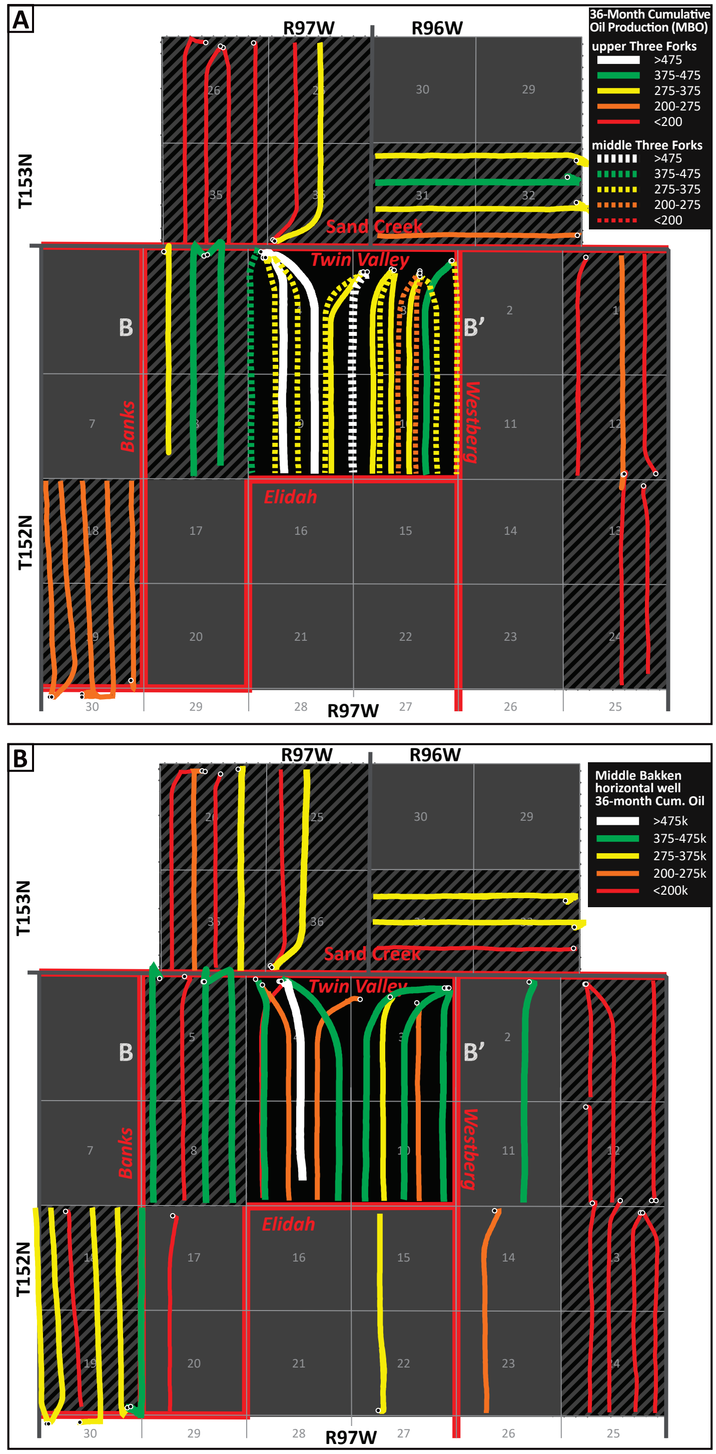

FIGURE 10. Bakken and Three Forks Formation lateral maps within the Twin Valley field area color-coded by initial 36-month cumulative oil production totals. **A**) Lateral map of upper Three Forks and middle Three Forks horizontal wells, and **B**) lateral map of the Middle Bakken horizontal wells. The solid black fill indicates spacing units with Middle Bakken, upper Three Forks, and middle Three Forks reservoir development. The black fill with diagonal grey lines indicates spacing units with development in only the Middle Bakken and upper Three Forks. Figure 11 cross-section position indicated by B-B′.

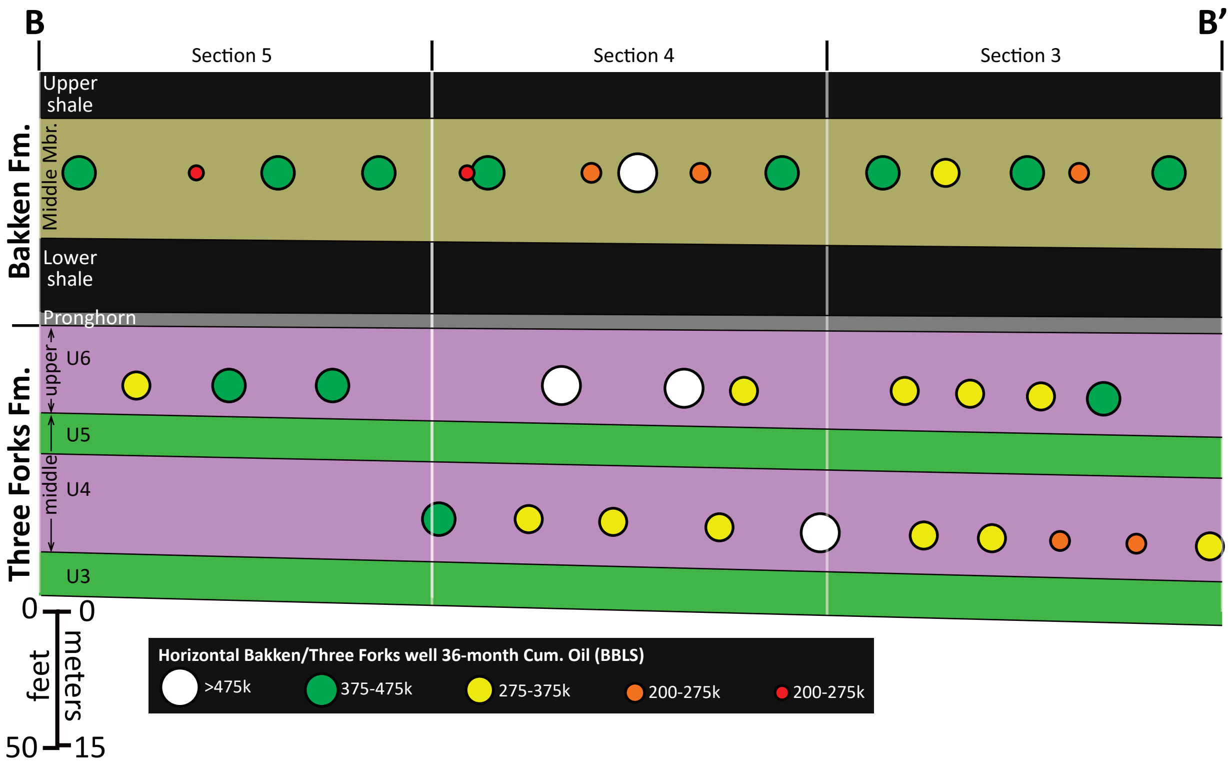

FIGURE 11. West to east semi-schematic stratigraphic cross-section of the Bakken and middle to upper Three Forks formations. Vertical and lateral distribution of horizontal well boreholes are displayed by circles that are color-coded to each well's initial 36-month cumulative oil production.

TABLE 1. Summary of 36-month cumulative oil production totals and estimated ultimate recovery of Middle Bakken (MB), upper Three Forks (UTF), and middle Three Forks (MTF) within the study area. Avg. = average; Min. = Minimum; Max. = maximum; MBO = thousands of barrels of oil

Well Target/Type	# Wells	36-Month Cum. Oil (MBO)			EUR (MBO)		
		Min.	Max.	Avg.	Min.	Max.	Avg.
MB	40	96	514	282	237	1385	569
UTF w/o MTF	23	105	449	235	226	798	449
UTF w/ MTF	7	295	650	424	383	820	569
MTF	10	269	539	341	342	795	526

a clay-rich distal mudstone facies in the central basin area that impedes downward hydrocarbon migration from the Lower Bakken shale source rock to the upper Three Forks reservoir (Millard and Brinkerhoff, 2016). However, the Pronghorn Member is on the order of only a few feet thick in the study area and the slight thickening of the unit toward the northeastern portions of the study area does not correspond with decreased upper Three Forks well performance (Fig. 16b). Lastly, changes in reservoir thickness could correspond to changes in the original oil in place, which again could influence upper Three Forks well performance. However, neither the thinning of the upper Three Forks toward the west-central portion of the study area, nor the thickening of the reservoir towards the east, correspond with any clear changes in upper Three Forks well production (Fig. 16c). Overall, thicknesses in the Lower Bakken source rock, upper Three Forks reservoir, and the intermediate Pronghorn do not appear to account for substantial changes in upper Three Forks well production within the study area.

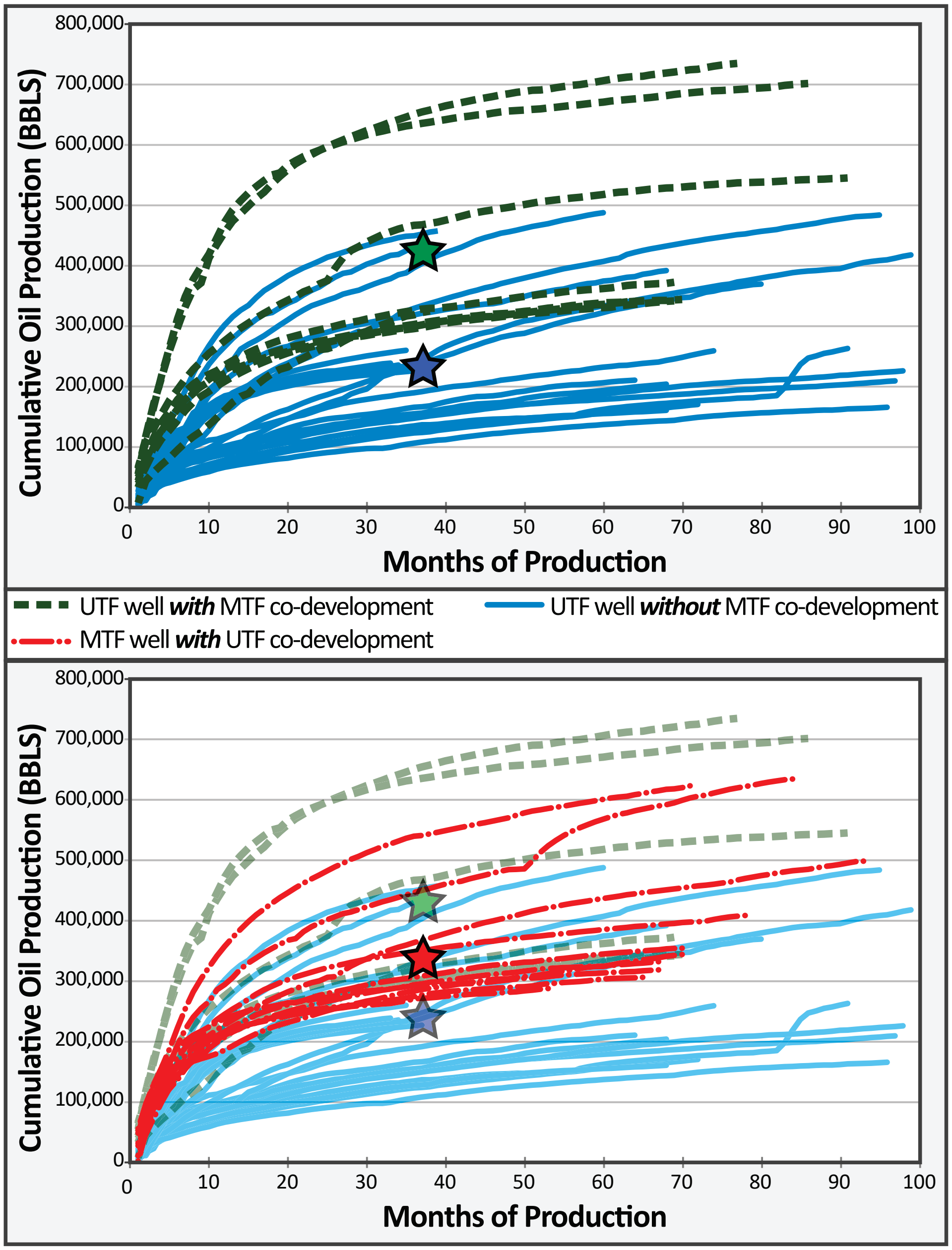

FIGURE 12. Monthly cumulative oil production plots of Three Forks wells within the study area. **A**) Displays production of upper Three Forks wells both with and without middle Three Forks co-development. **B**) Displays upper Three Forks wells overlain by middle Three Forks wells. Colored stars depict the 36-month cumulative oil production totals of upper Three Forks wells with middle Three Forks co-development (green), upper Three Forks without middle Three Forks co-development (blue), and middle Three Forks horizontal wells in the co-development case study area (red).

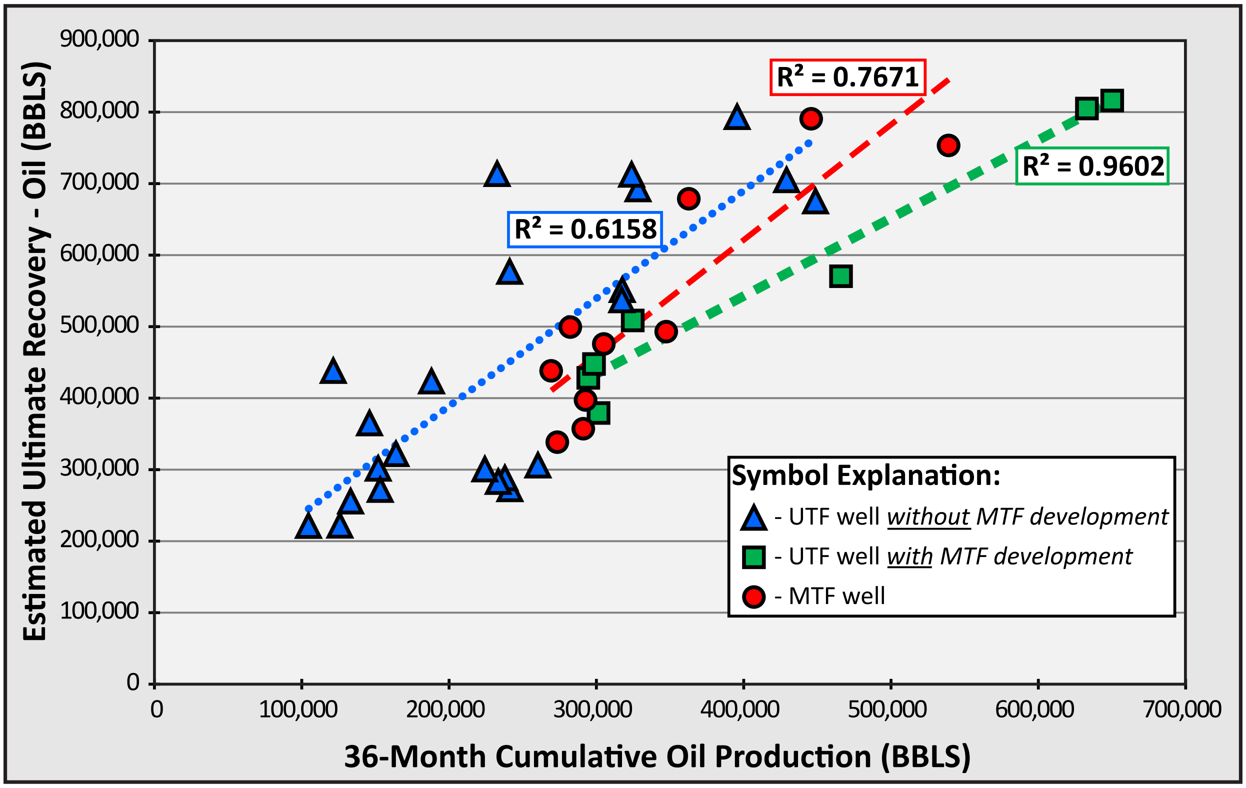

FIGURE 13. Diagrams plotting 36-month cumulative oil production totals versus estimated ultimate recovery of horizontal wells drilled in the Three Forks Formation. MTF = middle Three Forks; UTF = upper Three Forks

Structure contour mapping does not reveal any major structural features within the study area (Figs. 7 and 16d). However, the structure contours do become more closely spaced along the western half of the study area, which marks an abrupt increase in the subsurface dip of the Three Forks Formation top that may be associated with natural fracturing (Fig. 16d). Natural fracturing may increase both the storage capacity and/or reservoir quality (increased permeability). Upper Three Forks wells in the middle to western portions of the Twin Valley Field are located along the most closely spaced structure contours and are some of the most productive upper Three Forks wells in the study area, both with and without middle Three Forks co-development (Fig. 16d). However, wells in sections 26-35 and 25-36 of T153N-R97W of Sand Creek Field to the north are along the more closely spaced structure contours and are some of the poorest producing upper Three Forks wells in the study area (Fig. 16d). Structure may play a role with some upper Three Forks well performance but has no consistent influence across the study area based upon available geologic information.

Qualitative examination of petrophysical logs across the study area does not reveal any substantial changes in the upper Three Forks reservoir. The gamma ray signature is generally a good proxy of clay content, and decreased clay content typically correlates with improved reservoir quality for the Three Forks (Peterson, 2013; Adedolyin, 2022; Nesheim, 2021). The gamma ray signature of the middle and lower portions of the upper Three Forks does not display any substantial variation in wells logged within and around the study area (Fig. 8). The uppermost several feet of the upper Three Forks appears to vary moderately, but as previously reviewed, upper Three Forks thickness changes do not appear to correlate to upper Three Forks well production results. Based upon qualitive log review, there does not appear to be substantial variation in upper Three Forks reservoir quality in the study area.

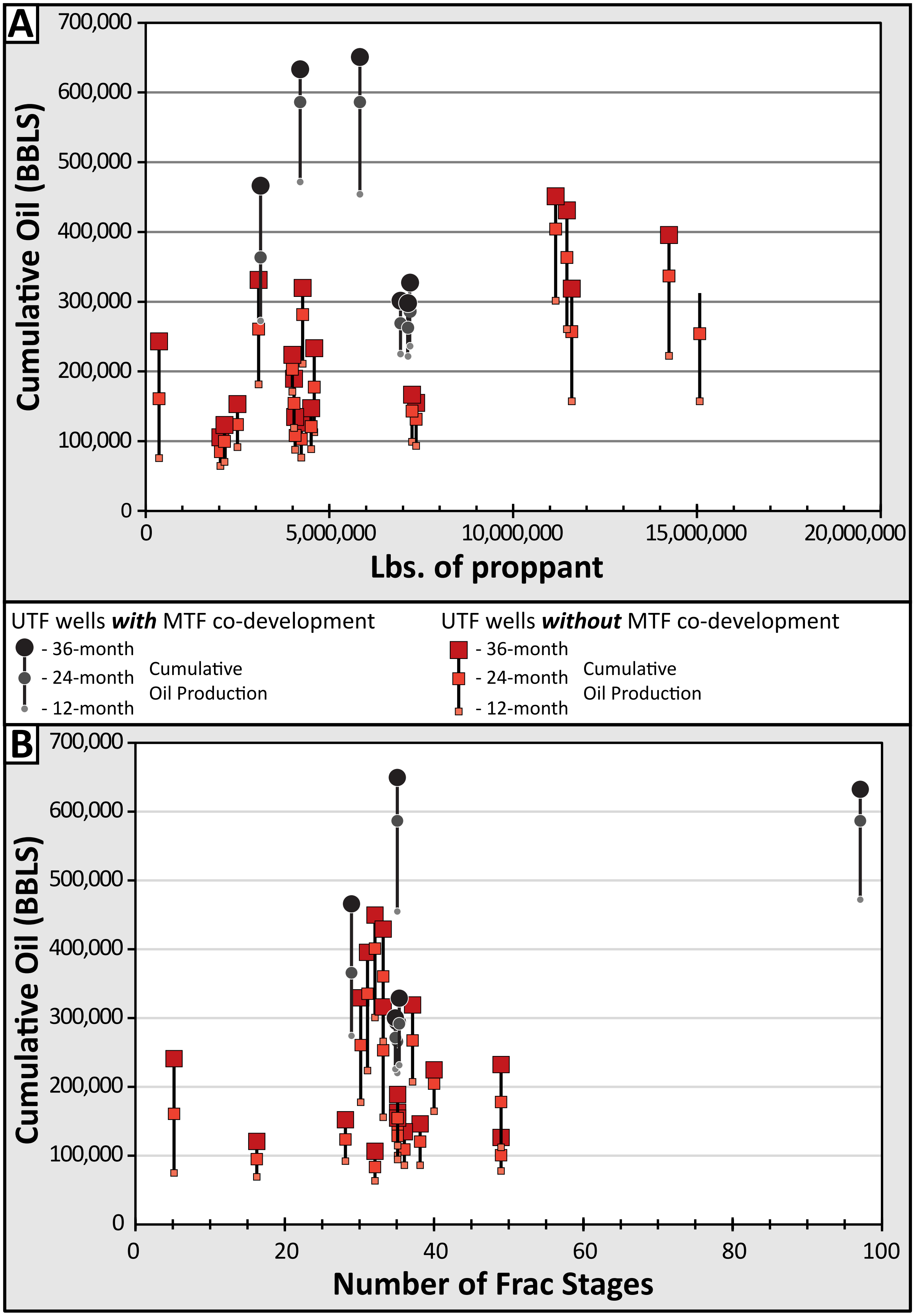

FIGURE 14. Cumulative oil production per well in 12-, 14-, and 36-month time increments versus **A**) pounds (lbs.) of proppant and **B**) number of stages during each well's hydraulic fracture simulation during initial completion.

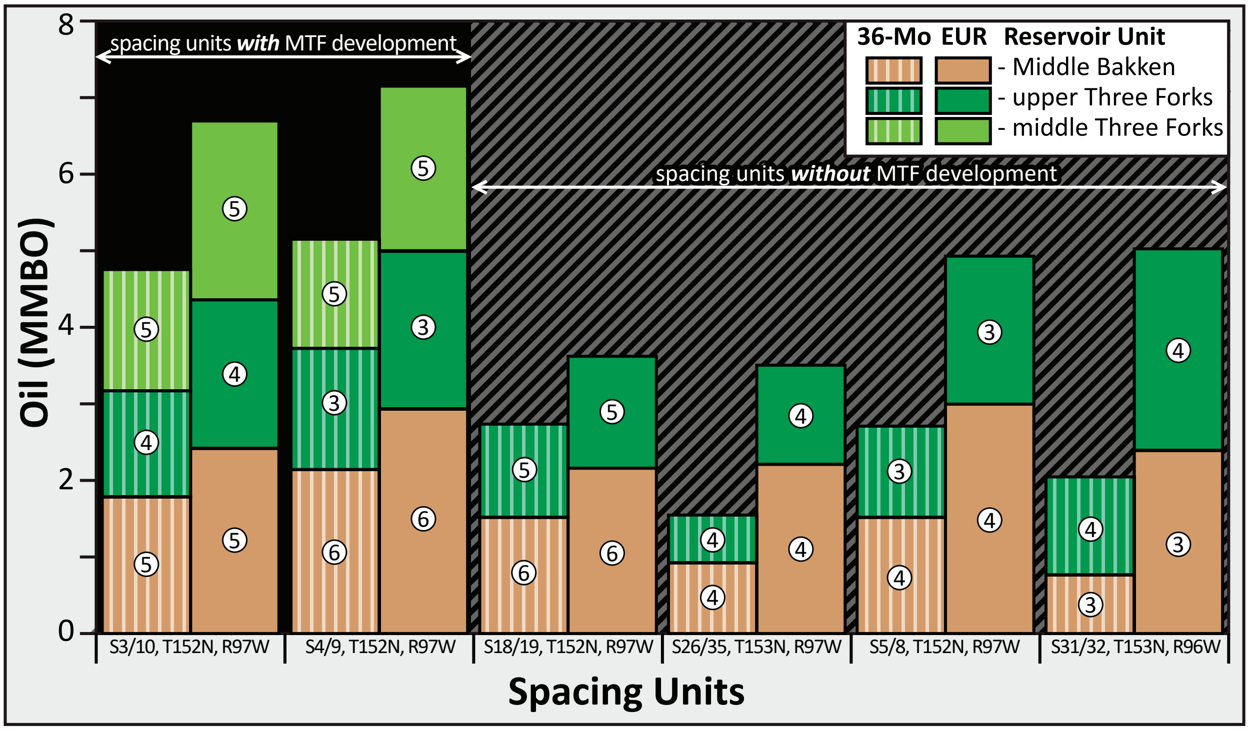

FIGURE 15. Diagram displaying the 36-month cumulative oil production per well and estimated ultimate recovery (EUR) volumes by composite 1280-acre spacing unit in the study area when the Middle Bakken, upper Three Forks, and, where developed, middle Three Forks reservoirs have been fully developed (fully developed = 3+ approximately evenly spaced wells drilled and completed with ~two-mile laterals per reservoir).

Well density and/or multi-stage hydraulic fracture completions could be non-geologic controls on upper Three Forks well performance. Increased well density could lead to adjacent wells competing for overlapping reservoir rock volumes (fluid/reservoir communication) that in turn could decrease well performance. However, other than one spacing unit in the SW corner of the study area with five upper Three Forks wells, the rest of the spacing units include upwards of three to four approximately evenly spaced upper Three Forks wells both within and outside the middle Three Forks co-development area (Figs. 10a and 15), meaning well density variations cannot account for the increased upper Three Forks well performance in the middle Three Forks co-development units. More injected proppant and/or frac stages could lead to faster and/or increased resource recovery by tapping into more hydrocarbon-charged, low-permeability reservoir rock. While a weak correlation between increased proppant and oil production can be observed within the upper Three Forks wells outside of the middle Three Forks co-development, the amount of proppant and number of frac stages of upper Three Forks wells completed in the co-development area is comparable to most of the surrounding upper Three Forks wells (Fig. 14), which indicates the well completions alone cannot account for the increased upper Three Forks well production in the co-development area. Therefore, neither well density nor available reviewed completion data can account for the better upper Three Forks well performance within the middle Three Forks co-development area.

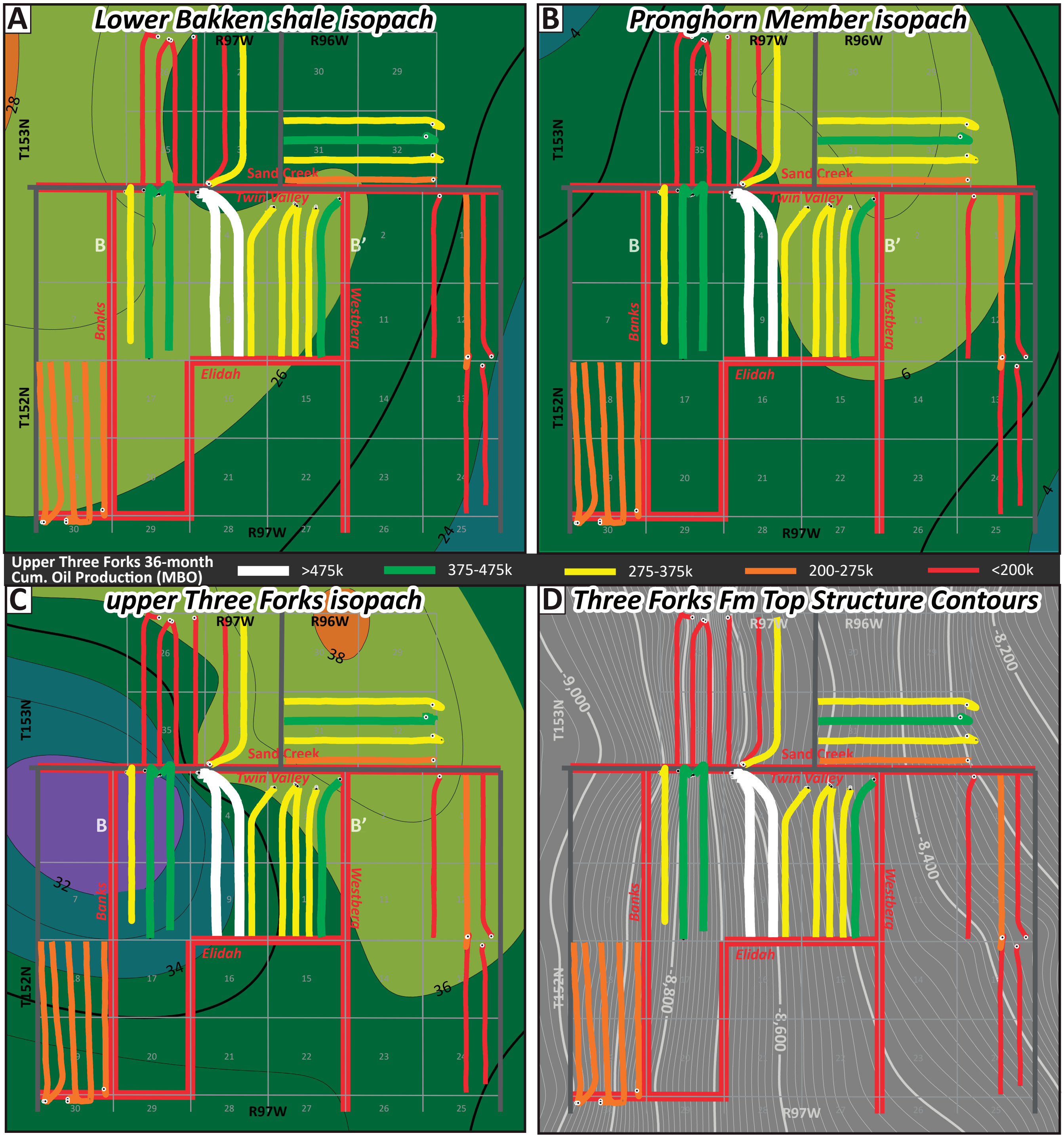

FIGURE 16. Geologic maps of Bakken-Three Forks subunits overlain by upper Three Forks horizontal laterals. Maps include **A**) Lower Bakken shale isopach, **B**) Pronghorn Member isopach, **C**) upper Three Forks (unit 6) isopach, and **D**) structure contours of the Three Forks Formation top. Isopach contours are in two-foot intervals (A-C) and structure contours are in 10-foot intervals.

DISCUSSION

If the middle Three Forks wells were simply pulling oil downwards from the upper Three Forks reservoir and/or producing oil that would otherwise have been recovered with standalone upper Three Forks development, then the upper Three Forks wells within the co-development area should be less productive than the surrounding upper Three Forks wells. Also, the spacing units with middle Three Forks co-development should not be any more productive than spacing units without co-development. The results of this study show the opposite. The upper Three Forks wells in the middle Three Forks co-development area are more productive with 36-month cumulative oil production totals and EUR averages that are 198 MBO and ~120 MBO higher than the averages of the surrounding upper Three Forks wells in spacing units without middle Three Forks development (Tables 1 and S1). Furthermore, the middle Three Forks well EURs range from 342 MBO to 757 MBO with an average of 526 MBO oil per well (Fig. 13 and Tables 1 and S1), which are overall comparable to the upper Three Forks well performances across the study area. Overall, the combined 36-month oil production totals per well and the composite EUR volumes of the spacing units with middle Three Forks co-development are on the order of 2-3 MMBO higher than the spacing units that only developed the Middle Bakken and upper Three Forks reservoirs (Figure 15 and Table S4). Given that upper Three Forks and middle Three Forks wells within the co-development area are, on average, outperforming upper Three Forks wells from the surrounding spacing units, and the co-development spacing units are outproducing the surrounding spacing units by 2-3 MMBO, middle Three Forks co-development is not negatively impacting upper Three Forks well performance, but instead appears to be adding to total resource recovery. Additional factors that could impact the performance of upper Three Forks wells are further discussed below.

While the injected proppant volumes and number of hydraulic fracture stimulation stages do not fully explain variations in upper Three Forks well performance, there may be other related factors not examined through this study. Five different operators have drilled and completed wells within the study area to date, one operator co-developed the middle Three Forks reservoir while the other four operators have opted not to co-develop the middle Three Forks to date. Additional drilling components that could vary from one operator to another that could influence well production include: geo-steering/lateral placement, quality of proppant injected into the reservoir (ceramic beads versus low-quality natural sand), or other completion methodology not reported within the publicly available completion reports (e.g. sliding sleeve versus plug and perf for multi-stage hydraulic fracture completions).

The results of this study indicate that the middle Three Forks is a 3rd reservoir to develop, in addition to the Middle Bakken and upper Three Forks, within at least portions of the Williston Basin of western North Dakota. The area with intermittent middle Three Forks development and water-cut below 60%, positioned in northeastern McKenzie to southwestern Mountrail counties, spans over one million acres (Fig. 3). Assuming a drilling density of 3-4 wells per 1280-acre spacing unit, which is the standard developmental drilling density of the upper Three Forks, there is the potential for on the order of thousands of future middle Three Forks development wells. The development potential within this prospective low water cut area is likely variable and may not be continuous. Further study, particularly on a more regional scale, is needed to better understand the middle Three Forks full resource potential (e.g. Starns and Nesheim, 2024).

CONCLUSIONS

Upper Three Forks well performance varies substantially across the relatively small study area, with 36-month cumulative production totals ranging from 105 to 650 MBO per well with EUR volumes of 226 to 820 MBO. Within the middle Three Forks co-development area, the upper Three Forks wells are overall more productive than the surrounding upper Three Forks wells without overlapping middle Three Forks co-development based upon both 36-month cumulative oil production totals and calculated EURs. Additionally, the middle Three Forks wells reviewed have yielded comparable production results to overlapping and adjacent upper Three Forks wells. The two spacing units with middle Three Forks development are both projected to eventually produce approximately 7 million barrels of oil while the surrounding spacing units without middle Three Forks development are each projected to only produce 3 to 5 million barrels. Factors such as structure, source rock and reservoir thickness, preliminary petrophysical reservoir quality, and hydraulic fracture completion methods do not appear to account for the variations in upper Three Forks well performance. While these factors may play secondary roles in upper Three Forks well performance, none of them appear to be a main control on production results within the study area. Therefore, the middle Three Forks co-development does not negatively impact upper Three Forks well performance, but instead represents a significant additional reservoir to develop within at least portions of the Bakken-Three Forks Petroleum System.

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TABLE S1. Three Forks horizontal well production summary.
BBLS = barrels; Cum. = cumulative; EUR = estimated ultimate recovery

NDIC	API Number	36-Month Oil Cum. (BBLS)	EUR (BBLS)
Middle Three Forks Horizontal Wells			
27283	33053055580000	362,688	682,608
27522	33053056360000	445,786	794,533
30688	33053067130000	292,566	401,344
30776	33053067490000	347,479	496,753
31704	33053071480000	273,407	342,379
31706	33053071500000	269,322	441,940
31707	33053071510000	282,289	503,111
31711	33053071540000	291,061	361,013
32327	33053074180000	304,955	479,693
32329	33053074200000	539,139	757,200
	Averages	***340,869***	***526,057***
Upper Three Forks Wells ***with*** *MTF Development*			
27284	33053055590000	466,050	574,486
27520	33053056340000	633,101	809,044
30774	33053067470000	650,275	820,011
31705	33053071490000	301,402	383,199
31710	33053071530000	324,721	512,565
31715	33053071580000	294,543	432,332
32328	33053074190000	298,305	451,657
	Averages	***424,057***	***569,042***
Upper Three Forks Wells ***without*** *MTF Development*			
22914	33053041300000	241,141	581,425
23276	33053042270000	104,544	225,915
24452	33053046090000	121,360	442,652
25416	33053049430000	151,885	306,086
25417	33053049440000	328,296	696,818
26490	33053052870000	145,934	369,279
28779	33053060720000	163,951	326,387
28781	33053060740000	133,188	260,155
28783	33053060760000	153,182	276,205
28784	33053060770000	188,079	427,994
30227	33053065720000	395,501	797,722
30234	33053065780000	317,586	555,719
30325	33053066130000	323,873	717,087
31011	33053068460000	125,882	226,388
31012	33053068470000	232,586	717,943
34248	33053082800000	317,232	541,610
34250	33053082820000	429,176	709,374
34252	33053082840000	448,831	679,706
35098	33053086080000	260,283	310,435
35100	33053086100000	241,228	277,379
35115	33053086170000	237,797	292,524
35117	33053086190000	233,437	287,394
35252	33053086680000	224,291	305,140
	Averages	***239,968***	***449,189***

TABLE S2. Middle Bakken horizontal well production summary.
BBLS = barrels; Cum. = cumulative; EUR = estimated ultimate recovery

NDIC	API Number	36-Month Oil Cum. (BBLS)	EUR (BBLS)
17925	33053029990000	106,766	322,258
19102	33053031740000	285,389	1,384,686
19280	33053032030000	304,012	615,815
19750	33053033130000	213,569	750,789
20048	33053033840000	174,747	988,862
20277	33053034280000	154,417	392,679
20336	33053034510000	95,846	939,890
20589	33053035270000	514,227	692,136
20595	33053035310000	197,894	582,244
20710	33053035640000	196,551	510,200
20812	33053035980000	359,993	509,584
22360	33053039660000	234,444	282,103
22361	33053039700000	456,466	691,528
22386	33053039770000	445,564	630,304
22387	33053039780000	389,374	529,918
22388	33053039790000	425,700	609,376
22598	33053040430000	425,700	591,225
23275	33053042260000	139,433	362,144
23277	33053042280000	149,267	534,838
24453	33053046100000	96,210	237,156
24454	33053046110000	174,442	592,528
25415	33053049420000	198,086	485,798
26491	33053052880000	168,112	367,289
27521	33053056350000	445,154	576,428
28778	33053060710000	163,512	570,857
28780	33053060730000	216,735	808,245
28782	33053060750000	181,309	325,346
30225	33053065700000	312,366	843,703
30232	33053065760000	359,870	611,695
30687	33053067120000	214,599	281,381
31013	33053068480000	184,258	413,104
31708	33053071520000	253,871	289,523
31712	33053071550000	279,128	389,291
32326	33053074170000	261,887	399,431
34249	33053082810000	404,150	810,977
34251	33053082830000	470,508	926,536
34253	33053082850000	449,862	755,292
35099	33053086090000	341,530	412,277
35116	33053086180000	319,648	421,205
35118	33053086200000	342,630	495,634
35251	33053086670000	439,433	643,135
35253	33053086690000	301,355	338,607
		282,096	*569,429*

TABLE S3. Compiled completion information for horizontal Three Forks wells.

NDIC Well #	API Well Number	Completion Date	Well Target	Top	Bottom	# Frac Stages	Injected Fluid (BBLS)	Injected Proppant (Lbs.)	Max Pressure (PSI)	Max Trtmt. Rate (BBLS/min)
31715	3305307158	9/18/2016	**UTF**	11,060	20,393	35	115,397	7,129,606	9,028	51.9
31705	3305307149	9/26/2016	**UTF**	11,110	20,459	35	113,334	6,957,370	9,338	56.7
31710	3305307153	9/14/2016	**UTF**	11,118	20,721	35	115,844	7,128,400	9,127	52
32328	3305307419	9/22/2016	**UTF**	11,604	20,248	35	112,476	7,122,800	9,174	53.3
27284	3305305559	6/7/2014	**UTF**	11,020	21,121	29	52,263	3,131,295	9,396	41.2
27520	3305305634	10/11/2014	**UTF**	11,158	21,573	97	88,532	4,215,200	9,456	40.7
30774	3305306747	10/6/2015	**UTF**	11,110	22,062	35	79,669	5,819,284	8,991	52
34248	3305308280	1/15/2019	**UTF**	11,165	22,031	33	191,165	11,658,460	9,328	91.7
34250	3305308282	1/26/2019	**UTF**	11,215	22,009	33	190,310	11,544,000	9,731	91.5
34252	3305308284	2/2/2019	**UTF**	11,135	21,583	32	189,812	11,219,300	9,692	91
30817	3305306772	2/25/2022	**UTF**	11,140	21,304	52	271,440	11,929,500	9,344	57.9
31003	3305306840	2/27/2022	**UTF**	11,160	21,307	52	260,651	11,794,881	9,351	54.9
25416	3305304943	2/17/2014	**UTF**	10,921	19,536	28	67,298	2,539,089	8,619	46
25417	3305304944	3/19/2014	**UTF**	11,036	21,466	30	82,753	3,104,439	8,332	42
28779	3305306072	6/17/2015	**UTF**	11,426	20,709	35	139,380	7,340,480	8,604	55.5
28781	3305306074	4/29/2015	**UTF**	11,163	20,070	36	67,562	4,074,100	8,245	40.7
28783	3305306076	5/12/2015	**UTF**	11,488	20,159	35	115,543	7,346,000	8,537	45.4
28784	3305306077	3/31/2015	**UTF**	11,083	20,287	35	60,000	4,072,300	8,436	40.8
30325	3305306613	12/10/2016	**UTF**	11,025	21,075	33	195,347	15,143,030	8,574	77.8
22914	3305304130	5/15/2013	**UTF**	19,258	20,463	5	9,957	401,740	7,621	30
30234	3305306578	11/7/2015	**UTF**	11,200	20,922	37	66,189	4,308,460	8,482	41
30227	3305306572	10/13/2016	**UTF**	11,110	20,516	31	186,686	14,299,550	8,733	71
24452	3305304609	5/29/2013	**UTF**	11,146	21,462	16	44,297	2,177,420	9,480	42
26490	3305305287	5/1/2014	**UTF**	11,144	21,650	38	86,839	4,541,660	10,292	40.8
31011	3305306846	9/21/2015	**UTF**	11,117	21,171	49	102,471	4,282,180	9,564	45.7
31012	3305306847	9/20/2015	**UTF**	11,226	22,340	49	94,477	4,616,520	9,251	40.6
23276	3305304227	1/7/2013	**UTF**	11,058	19,920	32	47,051	2,106,640	9,239	42.4
35252	3305308668	8/28/2019	**UTF**	11,455	21,206	40	210,546	4,019,478	9,260	87
35115	3305308617	7/30/2019	**UTF**	11,882	22,105	40	213,302	3,974,253	9,331	86
35117	3305308619	7/14/2019	**UTF**	11,605	21,577	40	235,825	3,996,378	9,294	87
35098	3305308608	9/3/2019	**UTF**	11,523	21,483	40	216,161	3,997,515	9,171	87
35100	3305308610	9/7/2019	**UTF**	11,682	21,764	40	216,346	4,013,782	9,208	86
31704	3305307148	9/7/2016	**MTF**	11,335	20,806	35	112,687	6,962,370	9,193	7769(?)
31706	3305307150	9/20/2016	**MTF**	11,220	20,269	35	111,065	6,748,846	9,515	60.4
31707	3305307151	9/14/2016	**MTF**	11,150	20,182	35	111,682	7,231,873	9,468	54.4
31711	3305307154	9/17/2016	**MTF**	11,170	20,370	35	112,982	7,140,000	9,210	51.6
32327	3305307418	9/6/2016	**MTF**	11,430	20,803	35	103,229	7,140,000	9,098	53.2
32329	3305307420	9/14/2016	**MTF**	11,245	20,381	35	135,033	10,029,000	9,181	55.3
27283	3305305558	6/7/2014	**MTF**	11,226	20,936	30	45,688	2,521,845	8,972	40.6
27522	3305305636	10/7/2014	**MTF**	10,930	21,419	30	54,871	3,665,680	9,685	41.1
30775	3305306748	10/6/2015	**MTF**	11,140	21,746	31	72,431	4,502,096	808	52
30776	3305306749	10/8/2015	**MTF**	10,113	21,351	31	63,221	4,203,000	8,722	53
30688	3305306713	10/6/2015	**MTF**	10,010	21,021	35	66,683	4,204,965	8,753	56

*MTF = middle Three Forks; UTF = upper Three Forks

TABLE S4. 3-Year Cumulative Oil Production Totals and Estimated Ultimate Recoveries of Bakken-Three Forks wells within the Twin Valley Field area by spacing unit.

Well #	API Number	Lateral Target	3-YR Oil Cum	EUR (BBLS)	
S3/10, T152N, R97W					
22386	33053039770000	Middle Bakken	445,564	630,304	
22387	33053039780000	Middle Bakken	389,374	529,918	
22388	33053039790000	Middle Bakken	425,700	609,376	
31708	33053071520000	Middle Bakken	253,871	289,523	
31712	33053071550000	Middle Bakken	279,128	389,291	
31710	33053071530000	Upper Three Forks	324,721	512,565	
31715	33053071580000	Upper Three Forks	294,543	432,332	
31705	33053071490000	Upper Three Forks	301,402	383,199	
27284	33053055590000	Upper Three Forks	466,050	574,486	
32329	33053074200000	Middle Three Forks	269,570	378,600	*
31711	33053071540000	Middle Three Forks	291,061	361,013	
31704	33053071480000	Middle Three Forks	273,407	342,379	
31706	33053071500000	Middle Three Forks	269,322	441,940	
31707	33053071510000	Middle Three Forks	282,289	503,111	
27283	33053055580000	Middle Three Forks	181,344	341,304	*
		Totals	***4,747,346***	***6,719,341***	
S4/9, T152N, R97W					
20589	33053035270000	Middle Bakken	514,227	692,136	
22360	33053039660000	Middle Bakken	234,444	282,103	
22361	33053039700000	Middle Bakken	456,466	691,528	
27521	33053056350000	Middle Bakken	445,154	576,428	
30687	33053067120000	Middle Bakken	214,599	281,381	
32326	33053074170000	Middle Bakken	261,887	399,431	
27520	33053056340000	Upper Three Forks	633,101	809,044	
30774	33053067470000	Upper Three Forks	650,275	820,011	
32328	33053074190000	Upper Three Forks	298,305	451,657	
27522	33053056360000	Middle Three Forks	222,893	397,267	*
30688	33053067130000	Middle Three Forks	292,566	401,344	
30776	33053067490000	Middle Three Forks	347,479	496,753	
32327	33053074180000	Middle Three Forks	304,955	479,693	
32329	33053074200000	Middle Three Forks	269,570	378,600	*
		Totals	***5,145,921***	***7,157,376***	

TABLE S4. continued.

S18 & 19, T152N, R97W

20277	33053034280000	Middle Bakken	154,417	392,679	
35099	33053086090000	Middle Bakken	341,530	412,277	
35116	33053086180000	Middle Bakken	319,648	421,205	
35118	33053086200000	Middle Bakken	171,315	247,817	*
35251	33053086670000	Middle Bakken	219,717	321,568	*
35253	33053086690000	Middle Bakken	301,355	338,607	
35117	33053086190000	Upper Three Forks	233,437	287,394	
35115	33053086170000	Upper Three Forks	237,797	292,524	
35098	33053086080000	Upper Three Forks	260,283	310,435	
35100	33053086100000	Upper Three Forks	241,228	277,379	
35252	33053086680000	Upper Three Forks	224,291	305,140	
		Totals	***2,705,018***	***3,607,025***	

S26 & 35, T153N, R97W

20812	33053035980000	Middle Bakken	359,993	509,584
28778	33053060710000	Middle Bakken	163,512	570,857
28780	33053060730000	Middle Bakken	216,735	808,245
28782	33053060750000	Middle Bakken	181,309	325,346
28779	33053060720000	Upper Three Forks	163,951	326,387
28783	33053060760000	Upper Three Forks	153,182	276,205
28781	33053060740000	Upper Three Forks	133,188	260,155
28784	33053060770000	Upper Three Forks	188,079	427,994
		Totals	***1,559,949***	***3,504,773***

S5 & 8, T152N, R97W

34249	33053082810000	Middle Bakken	404,150	810,977
34251	33053082830000	Middle Bakken	470,508	926,536
34253	33053082850000	Middle Bakken	449,862	755,292
20710	33053035640000	Middle Bakken	196,551	510,200
34248	33053082800000	Upper Three Forks	317,232	541,610
34250	33053082820000	Upper Three Forks	429,176	709,374
34252	33053082840000	Upper Three Forks	448,831	679,706
		Totals	***2,716,310***	***4,933,695***

TABLE S4. continued.

S31 & 32, T153N, R96W

20336	33053034510000	Middle Bakken	95,846	939,890
30225	33053065700000	Middle Bakken	312,366	843,703
30232	33053065760000	Middle Bakken	359,870	611,695
30325	33053066130000	Upper Three Forks	323,873	717,087
30227	33053065720000	Upper Three Forks	395,501	797,722
30234	33053065780000	Upper Three Forks	317,586	555,719
22914	33053041300000	Upper Three Forks	241,141	581,425
		Totals	***2,046,183***	***5,047,241***

S1 & 12, T152N, R97W

24454	33053046110000	Middle Bakken	174,442	592,528
26491	33053052880000	Middle Bakken	168,112	367,289
17925	33053029990000	Middle Bakken**	106,766	322,258
24453	33053046100000	Middle Bakken**	96,210	237,156
24452	33053046090000	Upper Three Forks	121,360	442,652
31012	33053068470000	Upper Three Forks	232,586	717,943
26490	33053052870000	Upper Three Forks	145,934	369,279
		Totals	***1,045,410***	***3,049,105***

S13 & 24, T152N, R97W

20595	33053035310000	Newfield (4-well)	197,894	582,244
23275	33053042260000	Newfield (4-well)	139,433	362,144
23277	33053042280000	Newfield (4-well)	149,267	534,838
31013	33053068480000	Newfield (4-well)	184,258	413,104
31011	33053068460000	Upper Three Forks	125,882	226,388
23276	33053042270000	Upper Three Forks	104,544	225,915
		Totals	***901,278***	***2,344,633***

*Section line well, production split 50/50 with adjacent spacing unit

**Horizontal well with ~1 mile lateral