Examination of Oil Saturations and Horizontal Well Production for the Middle and Lower Three Forks Formation

By

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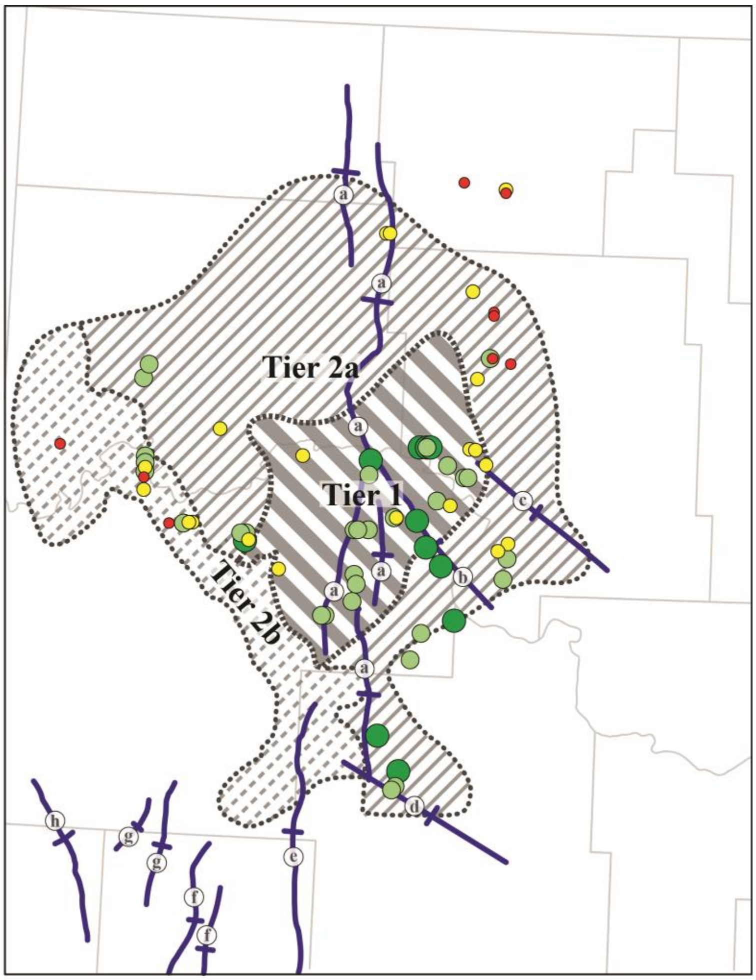

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INTRODUCTION

Beginning in 2012, operating companies within the Bakken-Three Forks play began examining and testing the middle to lower portions of the Three Forks Formation (Three Forks) (Fig. 1) as a prospective unconventional reservoir (Petroleum News, 2012; Gaswirth and Marra, 2015). During that time, informal nomenclature was adopted that subdivided the Three Forks into four benches, referred to as the 1st through 4th benches in descending order (Fig. 1). Prior to 2012, drilling and production within the Bakken Petroleum System was primarily focused on the Middle Bakken and upper Three Forks (1st bench).

Beginning in early 2015, approximately three years after commencement of initial drilling and testing of the middle to lower Three Forks, the North Dakota Oil and Gas Division began tracking the specific target interval of horizontal Three Forks wells. Since that time, over 180 horizontal wells have been drilled and completed in the middle to lower Three Forks Formation, which have combined to cumulatively produce nearly 20 million barrels of oil to date (Fig. 2). The majority (~80%) of those wells targeted the middle Three Forks (2nd bench). A significant number of additional, pre-2015 middle to lower Three Forks wells are also present, but the number of those earlier wells and their cumulative production volumes have yet to be determined.

There is currently limited geological information available regarding the petroleum geology and economic importance of the middle to lower Three Forks. Resource assessments of the Three Forks Formation have ranged from approximately 2 to 4 billion barrels of recoverable oil (Nordeng and Helms, 2010; Gaswirth et al., 2013), but these assessments have been limited to the upper Three Forks (1st bench). This report represents a continuation of a recently initiated study by the North Dakota Geological Survey on the origin and distribution of oil saturations within the middle and lower Three Forks. The present production footprint of middle Three Forks (2nd bench) and lower Three Forks (3rd bench) horizontal oil wells drilled since 2015 is also examined with discussion on future well distribution.

GEOLOGY

The Three Forks Formation is a mixed carbonate-siliciclastic unit that was deposited during the Late Devonian (Franklin and Sarg, 2017, Droege, 2014; Murphy et al., 2009). 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 which becomes more common towards the lower portions of the section (Ashu, 2014; Murphy, 2014). Previous studies have sub-divided the Three Forks into different nomenclature systems, including: 1) six sub-units ranging from unit 1 to unit 6 in ascending stratigraphic order (Christopher, 1961); and 2) an upper, middle, and lower member distinction (e.g., Bottjer et al., 2011), which is utilized in this report. The informal “bench” terminology is secondarily referred to herein due to its apparent common usage within the oil and gas industry (e.g. Fig. 1).

The upper, middle, and lower sub-units of the Three Forks Formation share similar mineralogical compositions (dolomite, quartz, clay), but texturally vary from one another. The lower Three Forks ranges from oxidized (red) to reduced (green) massive dolomitic mudstone with anhydrite nodules interbedded with matrix-supported breccias and occasional thin nodular anhydrite beds (Franklin and Sarg, 2017). Based at least in part on the presence of nodular anhydrite, a Sabkha-like setting has been speculated for the lower Three Forks depositional setting (Ashu, 2014). The basal portions of the middle Three Forks is largely comprised of siltstone to mudstone beds containing variable amounts of pebble-sized dolostone clasts interpreted as debris flows (Droege, 2014). The middle Three Forks transitions upwards into tan silty dolostone interlaminated to interbedded with grey to green claystone, which is capped by an interval of red to green dolomitic claystone (Droege, 2014; Franklin and Sarg, 2017). The upper Three Forks is composed mostly of tan silty dolostone that is interlaminated to interbedded with grey to green claystone, similar to portions of the middle Three Forks (Bottjer et al., 2011; Franklin and Sarg, 2017). Depositional interpretations for the upper Three Forks have ranged from tidal flat (e.g. Berwick and Hendricks, 2011) to a storm dominated intrashelf setting (Franklin and Sarg, 2017).

Overall, the Three Forks appears to contain minimal petroleum source rock (Ashu, 2014). Hydrocarbons present within the Three Forks are believed to be sourced from the overlying lower Bakken shale, which is the source rock in closest known stratigraphic proximity to the Three Forks and is considered to be a world class petroleum source rock (Fig. 1) (Nordeng and Helms, 2010). The low porosity (<6%) and permeability (<1 millidarcy, md) throughout the Bakken-Three Forks section in western North Dakota leads to the interpretation that most of the oil in place has been locally generated and minimal lateral migration has taken place. However, hydrocarbons are produced from the Bakken and Three Forks Formations in the northern, shallower portions of the Williston Basin (Saskatchewan and Manitoba, Canada – e.g., Nicolas, 2012), where the Bakken shales appear to be thermally immature with respect to oil generation. Bakken-Three Fork reservoirs within southwestern Manitoba display increased average porosity and permeability values of 11-17% and 1-8 millidarcies (Nicolas, 2012). The increase in porosity and permeability likely allows for some lateral hydrocarbon migration within the Bakken-Three Forks in portions of the Williston Basin.

The lower Bakken shale ranges from disconformably overlying the upper Three Forks to being stratigraphically separated by the Pronghorn Member (Pronghorn) of the Bakken Formation (LeFever et al., 2011). When present, the Pronghorn conformably underlays the lower Bakken shale within the central basin area and disconformably along the basin margins, and the lower contact is disconformable with the underlying Three Forks (LeFever et al., 2011). There are two general facies that comprise the Pronghorn; proximal and distal deposits. The proximal deposits contain beds of siltstone to sandstone which constitute hydrocarbon-charged reservoir that has been the focus of horizontal drilling within the southern margins of the Bakken play (LeFever et al., 2011). The distal deposits are composed primarily of silty to sandy shale/mudstone, which extend northwards of the proximal deposits (LeFever et al., 2011). 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 thicknesses of over 40 feet (LeFever et al., 2011).

METHODS

Oil and water saturation data measured from core samples were compiled to examine the vertical and lateral distribution of oil saturations within the middle to lower Three Forks. A total of 48 complete to near-complete (>90% of section) cores with standard core plug oil and water saturation data where compiled for the middle Three Forks (2^{nd} bench). Twenty-six complete to near-complete (>90% of section) and six partial cores with core plug oil and water saturation data where compiled for the lower Three Forks (3^{rd} and 4^{th} benches). Average oil and water saturations for the middle and lower Three Forks were spatially plotted to delineate possible fluid saturation trends and to compare the saturation data with the other geologic components.

Lower Bakken shale thickness and thermal maturity were examined to qualitatively evaluate hydrocarbon generation proximal to the Three Forks Formation. Pre-existing geochemical data was compiled from the North Dakota Industrial Commission database, which totaled 439 lower shale core samples from 48 wells. Average T_{max} and hydrogen index (HI) were used to examine thermal maturity of the lower shale. Average values were utilized to balance out instrumentation variation (error) for T_{max} and source bed heterogeneity for HI.

T_{max} represents the temperature in °C that corresponds with the maximum generation of hydrocarbon vapor during the programmed heating portion of Rock-Eval pyrolysis. The heating portion of Rock-Eval pyrolysis is when a given source rock sample is heated from 300°C to 650°C at a rate of 25°C per minute. The higher the T_{max}, the more thermally mature a sample is with respect to hydrocarbon generation and the greater the percentage of original kerogen that has been converted into hydrocarbons. A T_{max} of 435°C has been interpreted to represent the point where Bakken shales have reached the intense oil generation window and have generated enough hydrocarbon volume to charge stratigraphically adjacent units, such as the Middle Bakken and upper Three Forks (Nordeng et al., 2009).

HI is a measurement of milligrams of hydrocarbons (mg HC) per gram of total organic carbon (TOC) generated and measured during Rock-Eval pyrolysis. On a scale of 0 to 1200, HI essentially represents the ratio of organic carbon capable of converting to hydrocarbons (kerogen) to that of TOC. TOC represents the sum of kerogen plus live hydrocarbons (oil and gas) and inert organic carbon. The HI of a given source rock will gradually decrease during thermal maturation as kerogen is converted into hydrocarbons and some of the generated hydrocarbons are expelled from the source rock interval.

Isopach (thickness) mapping was conducted on the lower Bakken shale using wireline logs from 240 wells. A three step process was utilized to create the isopach map: 1) the top and base of the lower shale were picked using primarily the gamma ray log in conjunction with resistivity and porosity logs, 2) the lower shale thickness was calculated by subtracting the top from the base, and 3) the calculated thickness values were contoured in Petra© with minor manual contour editing.

Isopach and thermal maturity maps were compared with oil saturation data to qualitatively examine the distribution of oil saturations within the middle and lower Three Forks. Cumulative oil production totals through the first 700 days were compiled and tallied for 70 middle Three Forks (2^{nd}

bench) and 24 lower Three Forks (3^{rd} bench) producing wells. These wells were spatially plotted to compare well production with oil saturation trends and various Williston Basin structures.

RESULTS

Middle and Lower Three Forks Oil Saturations

Fluid saturations can be used to subdivide the middle Three Forks into three areas based primarily on oil saturations and secondarily on water saturations. The highest average oil saturations and overall lowest water saturations extend through the central portions of the study area, which is referred to herein as the tier 1 middle Three Forks area (Fig. 3). Fluid saturations were found to be nearly indistinguishable between the upper and middle Three Forks within this tier 1 area (e.g., Fig. 1). There is also a larger, tier 2 area where water saturations are higher in the middle Three Forks, but notable oil saturations are still present (Fig. 3). In the tier 2 area, oil saturations are generally higher in the upper Three Forks than the in middle Three Forks. Moving laterally outward from beyond the tier 1 and 2 oil saturation areas, the tier 3 area merely represents where core plug water saturations overall continue to increase while oil saturations decrease (Fig. 3).

Oil and water saturations within the lower Three Forks appear to be less systematic across the study area. Oil saturations within individual lower Three Forks core plugs do occasionally reach upwards of 50-70% (e.g., Figs. 1 and 4). However, oil saturation averages across the lower Three Forks section are most commonly 10-20% on the high end (Fig. 4). Within some cores, oil saturations are notably higher within the upper portions of the lower Three Forks (~3^{rd} bench) (e.g., Fig. 1), but typically are relatively consistent across the entire section (e.g., well #21706, Fig. 5).

Lower Bakken Shale Thickness and Thermal Maturity

The lower Bakken shale ranges from being absent within the southern corners of the study area to reaching thicknesses of over 50 feet in western Mountrail County (Fig. 6). The thinning of the lower shale towards the southwest corner of the study area corresponds with where the Pronghorn Member thickens to upwards of 30+ feet thick along a northwest-southeast trend (Fig. 7). A similarly oriented lower shale thickening trend is located towards the northeast, where the lower shale ranges from 30 to 60+ feet thick east of the Nesson anticline (Fig. 6).

The average T_{max} of the lower shale from individual core data sets was found to range from 431° to 459°C (Figs. 8 and 9). Meanwhile, the average HI of the lower shale ranged from 616 mg HC/g TOC towards the northeast corner of the study area, to <100 mg HC/g TOC within central portions of the study area, where the lower shale reaches its greatest burial depths (Fig. 10). The average T_{max} and average HI of lower shale core sample sets generally trend together, where T_{max} increases and HI decreases (Fig. 8). A few notable exceptions occur primarily with samples that were collected and analyzed from older, pre-1970's wells (Fig. 8).

Middle and Lower Three Forks Oil Production

A total of 70 horizontal wells have been drilled and completed within the middle Three Forks since 2015 which have reached 700 days or more of cumulative production. The 700-day cumulative oil production totals of those wells include: 9 (13%) with less than 50,000 barrels, 21 (30%) with between 50,000 and 100,000 barrels, 29 (41%) with between 100,000 and 200,000 barrels, and 11 (16%) with greater than 200,000 barrels (Fig. 11). The average 700-day cumulative oil production for these 70 middle Three Forks wells is approximately 128,000 barrels of oil.

A total of 24 horizontal wells have been drilled and completed within the lower Three Forks since 2015 which have reached 700 days or more of cumulative production. The 700-day cumulative oil production totals of those wells include: 6 (25%) with less than 50,000 barrels, 6 (25%) with between 50,000 and 100,000 barrels, 10 (42%) with between 100,000 and 200,000 barrels, and 2 (8%) with greater than 200,000 barrels (Fig. 12). The average 700-day cumulative oil production for these 24 middle Three Forks wells is approximately 111,000 barrels of oil.

INTERPRETATIONS

Middle Three Forks Oil Saturations and Well Production

Three geologic factors appear to control the distribution of oil saturations within the middle Three Forks: 1) the thickness of the lower Bakken shale; 2) the thermal maturity of the lower Bakken shale; and 3) the thickness of the Pronghorn Member. The area of highest oil saturations within the middle Three Forks appears to correlate with where the lower Bakken shale has generated the greatest volume of hydrocarbons, based upon the lower shale's thickness and the thermal maturity. A thickness of ≥20 feet for the lower shale appears to substantiate a sufficient volume of original kerogen or, in other words, an adequate amount of hydrocarbon generation potential (Figs. 6, 13). The area where the average lower Bakken shale HI drops below 150 mg HC/g TOC and average T_{max} climbs above 450 °C correlates with where enough of the original kerogen (where the lower shale is ≥20 feet thick) has been thermally converted into hydrocarbons to generate the necessary hydrocarbon volume to substantially charge both the upper and middle Three Forks (Figs. 8-10, 13). High oil saturations within the middle Three Forks extend slightly northeast of the high maturity area where the lower shale thickens to over 40 feet (Fig. 13). The lower maturity decreases the percentage of original kerogen converted into hydrocarbons, but the volume of original kerogen (lower shale thickness) increased enough to partially offset the lower maturity.

The distal deposits of the Pronghorn Member have previously been described as a barrier to the downward charge of hydrocarbons from the lower Bakken shale into the underlying Three Forks (Millard and Brinkerhoff, 2016). Generally, wherever the Pronghorn Member is less than five feet thick, it does not appear to have impeded the downward hydrocarbon charge from the lower Bakken shale into the underlying Three Forks (Figs. 5, 7, 13). Three Forks core oil saturations tend to be low to absent where the distal Pronghorn facies (moderately high gamma ray wireline log signature) is present and greater than five feet thick (e.g., well #22096 – Fig. 5). However, intermediate oil saturation averages (10-30%) for the middle Three Forks were observed in 4 of 9 cores along a northwest-southeast Pronghorn Member (distal deposits) thickness trend extending through the western portion of the study area (Fig. 13). Therefore, the presence of the Pronghorn Member greater than five feet thick only decreases the likelihood of notable oil saturations within the middle Three Forks.

Middle Three Forks horizontal well production appears to be a function of at least two factors: 1) oil saturations, and 2) structure. Most of the better producing middle Three Forks wells drilled and completed since 2015 are located in proximity to structure and/or the area of highest oil saturation (Fig. 11). The intermediate to poor producing middle Three Forks wells are commonly located within areas of intermediate to low oil saturations and/or away from known structures (Fig. 11). Structures (e.g., Nesson anticline) may create natural fracture systems that locally enhance the downward migration of hydrocarbons from the lower shale into the Three Forks and/or allow for better hydrocarbon drainage from horizontal well completions.

Lower Three Forks Oil Saturations and Well Production

Oil saturation averages in the lower Three Forks rarely reach the same levels as the higher oil saturation averages (≥30%) of the tier 1 middle Three Forks area. The lower Three Forks cores containing higher average oil saturations are spatially separated from one another by cores with lower average oil saturations and appear anomalous (Fig. 4). Instead, the lower Three Forks typically only reaches intermediate levels (10-30%) for average oil saturation, comparable to the tier 2 oil saturation area for the middle Three Forks. This may be due to the lower Three Forks being more spatially removed from the lower Bakken shale than the middle and upper Three Forks, and hydrocarbon charge is simply reduced due to the stratigraphic separation of source rock and reservoir. In addition, the lower Three Forks may also be an overall lower quality reservoir that is less capable of taking in hydrocarbon charge. The lower Three Forks is typically marked by the presence of variable amounts and forms (nodules versus beds) of anhydrite (Ashu, 2014; Franklin and Sarg, 2017), a mineral known for partially to completely plugging pore throats and reducing reservoir quality in other petroleum reservoirs. The concentration and distribution of anhydrite within the lower Three Forks may vary across the basin, which could spatially change the reservoir quality.

The majority of lower Three Forks wells (20 out of 24) with 700-day cumulative production totals are located within the area of intermediate oil saturation averages (10-30%), and the other four wells are in proximity (Fig. 12). Half of these lower Three Forks wells have 700-day cumulative production totals less than 100,000 barrels of oil while only two have eclipsed 200,000 barrels (Fig. 12). Lower Three Forks production is speculated to be similarly controlled by oil saturations and structure, but well control with adequate production histories is currently limited.

DISCUSSION

Pronghorn Member Impact

The discontinuous oil saturations within the middle Three Forks along the distal Pronghorn thick trend (tier 2b – Fig. 11) could be the result of a one of more features. Lateral oil migration through the Three Forks Formation from the basin center towards the southwest could be one way to emplace hydrocarbons in the middle Three Forks below the Pronghorn thick trend. Such migration could either be from increased reservoir quality and/or the presence of natural fracture-fault systems. Another possibility could be facies changes within the Pronghorn Member where either the Pronghorn becomes more organic-rich and serves as a discontinuous source rock that discontinuously charges the underlying Three Forks and/or the Pronghorn becomes less clay-rich and is less impeding to the downward charge of hydrocarbons from the lower shale.

Study Limitations

Previous work by Brinkerhoff et al. (2016) examined and concluded that the lithofacies comprising the upper Three Forks have variable reservoir quality characteristics (e.g., effective porosity) and that higher clay content correlated with higher water saturations. Core-based reservoir analysis of the middle and lower Three Forks may reveal similar results and could be used to evaluate local to regional reservoir quality variations useful in further delineating middle to lower Three Forks production trends.

This study assumed that the greater thickness and/or thermal maturity for the lower Bakken shale equates to greater volumes of generated hydrocarbons. This assumption would only hold true if the lower Bakken shale was relatively homogenous in terms of original average organic-richness and kerogen type. Differences in kerogen would equate to different rates of oil generation in relation to thermal conditions for a source rock. Differences in original organic-richness would in turn translate to variations in oil generation potential per unit volume of source rock. All petroleum source rocks likely display some vertical and lateral variation in their average original kerogen composition and organic-richness.

Fluid saturations evaluated in this study were limited to core analysis data. Most wells that penetrate the middle and lower Three Forks are generally not cored but instead only have wireline logs. Wireline logs can be calibrated and used to calculate hydrocarbon and waters saturations which could expand the number of control points used to map fluid saturation trends from dozens to hundreds of wells.

Future Exploration and Development

The majority of middle Three Forks wells permitted and/or drilled and completed since early 2015 have been proximal to the area of highest core plug oil saturation (Fig. 7). As reviewed above, higher oil saturations appear to be a main component that correlates with better well production along with structure and associated natural fracture systems. The middle Three Forks tier 1 area (Fig. 11) may be poised for near continuous developmental drilling simply because of the apparent presence of adequate resource volumes. Production within the tier 1 area will likely vary, in part, due to variations in structure and potentially reservoir quality. Production and development across the tier 2a area (Fig. 11) may be discontinuous in part due to the apparent lower concentrations of in-place resource. Economic conditions (oil prices) may also play a role, at least in the pace in which the middle Three Forks is explored and developed across the tier 2a area. The author hypothesizes that structure (natural fracture systems) and/or better quality reservoir for the middle Three Forks is necessary within the tier 2a area to allow for higher hydrocarbon recovery.

Exploratory drilling and testing of the lower Three Forks (e.g., one well per spacing unit or field area) will likely expand across, to slightly beyond, the area with higher average oil saturations (Figure 4 and Figure 12). However, economic conditions may play a substantial role in the amount and continuity of infill development drilling (e.g., multiple wells per spacing unit). Some of the lower Three Forks producing wells examined in this study are comparable to middle and upper Three Forks producing wells, but overall the lower Three Forks appears less productive.

CONCLUSIONS

- Oil saturations in the middle Three Forks appear to be controlled by the thickness and thermal maturity of the lower Bakken shale, where thicker and/or more thermally mature lower shale has generated enough hydrocarbons to substantially charge both the underlying upper and middle Three Forks.

- The middle Three Forks can be separated into two tiers of acreage based on saturation data: <u>tier 1 area</u>: oil saturations typically average >30% and water saturations average <50% (nearly indistinguishable from the upper Three Forks), and <u>tier 2 area</u>: oil saturations average 10-30% and water saturations average 50-80%.

- The previously documented northwest-southeast Pronghorn Member (distal deposits) thickness trend along west central North Dakota appears to inhibit, but not negate hydrocarbon charge into the middle Three Forks.

- Oil saturation averages of 10-30% within the lower Three Forks extend across a similar, albeit smaller area compared to oil saturations of the middle Three Forks. The lower Three Forks oil saturation averages also never reach the same levels as the middle Three Forks tier 1 area.

- Horizontal well production from the middle and lower Three Forks appear to correlate with both hydrocarbon (oil) saturation levels and the presence or absence of structural features.

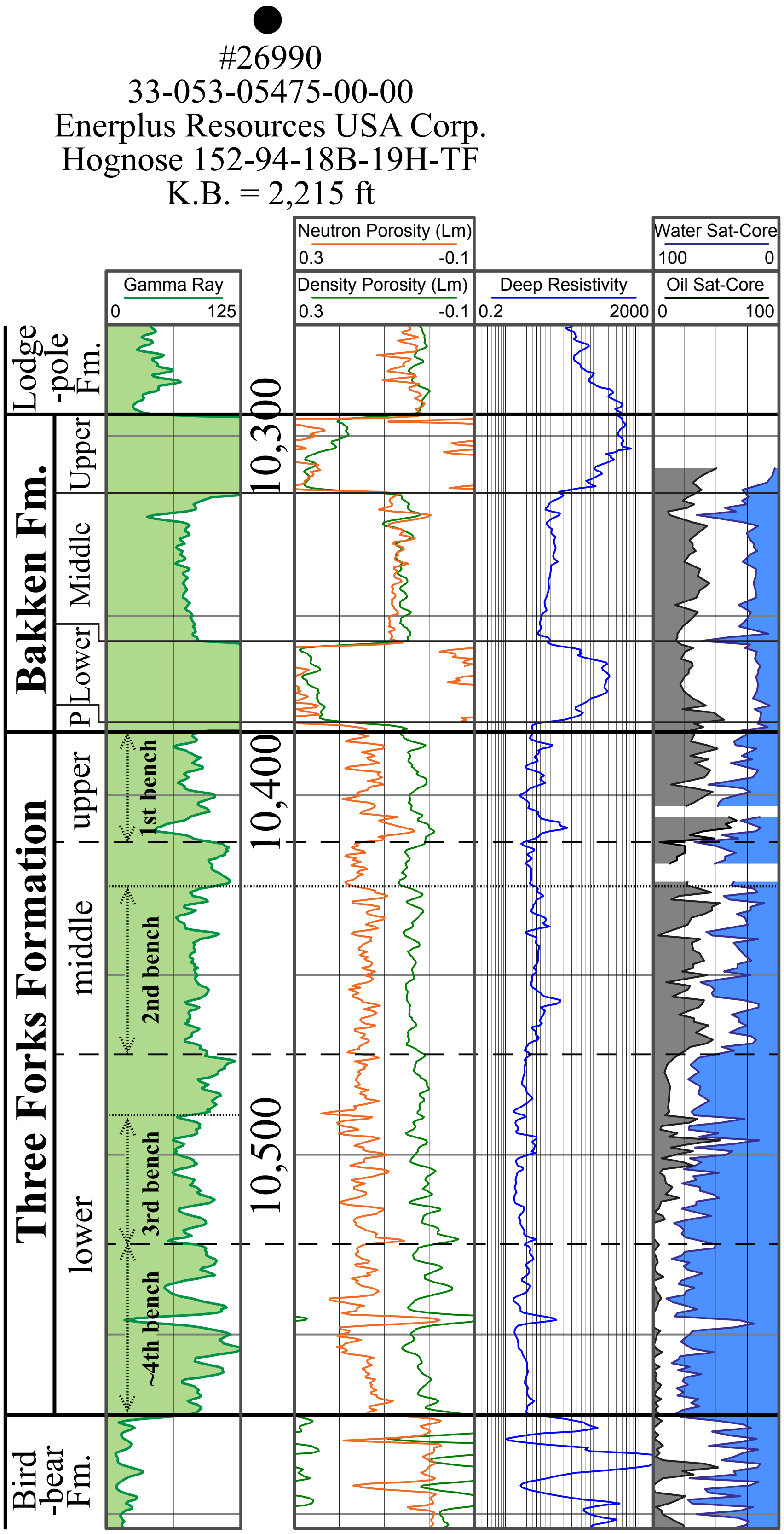

Figure 1. Wireline log example of the Bakken and Three Forks Formations with core plug oil and water saturation data (right side). Note the consistent oil saturations (typically 25-50%) that extend from the Bakken down through the base of the middle Three Forks (2nd bench) and some notable oil saturations (mostly 10-30%) present within the upper portions of the lower Three Forks (3rd bench). K.B. = Kelly Bushing; Lm = Limestone; P = Pronghorn; sat = saturation. Depths are in feet below surface (Kelly bushing).

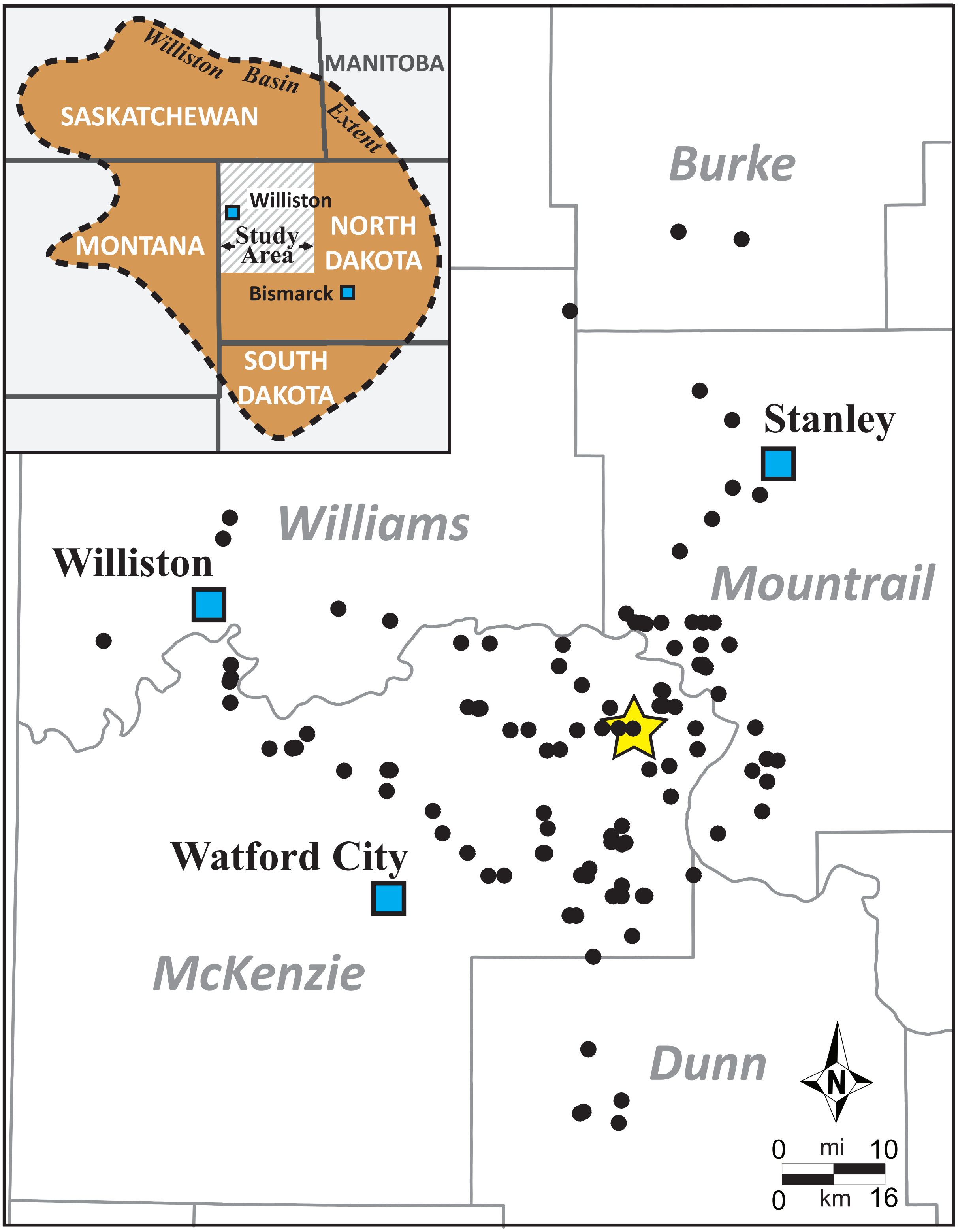

Figure 2. Map of the distribution of productive horizontal oil wells (black circles) that have been drilled and completed within the middle Three Forks (2nd bench). A basin-scale reference map is provided in the top left corner.

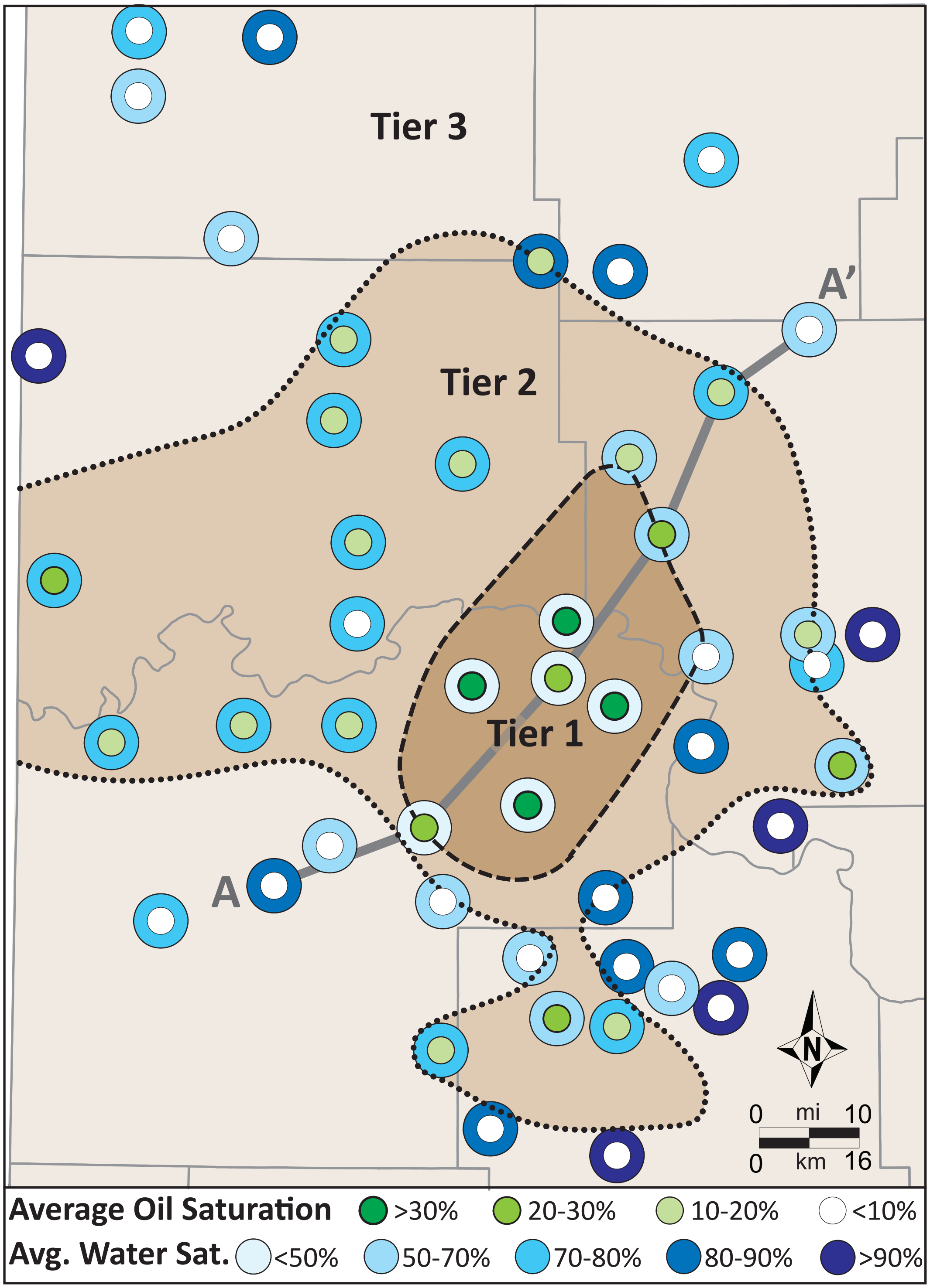

Figure 3. Fluid saturation map showing the average oil (white-green dots) and water (blue circles) saturations of the middle Three Forks from standard core plug analysis data. The thick dashed outline depicts where the middle Three Forks averages the highest oil (20-40%) and lowest water (<50%) saturations. The dotted outline depicts where the middle Three Forks typically contains intermediate oil (10-30%) and water (50-80%) saturations. Beyond the intermediate oil saturation area, core plugs from the middle Three Forks commonly average 70-90% water saturation with <10% oil saturation. A-A' shows the location of the Figure 5 cross-section.

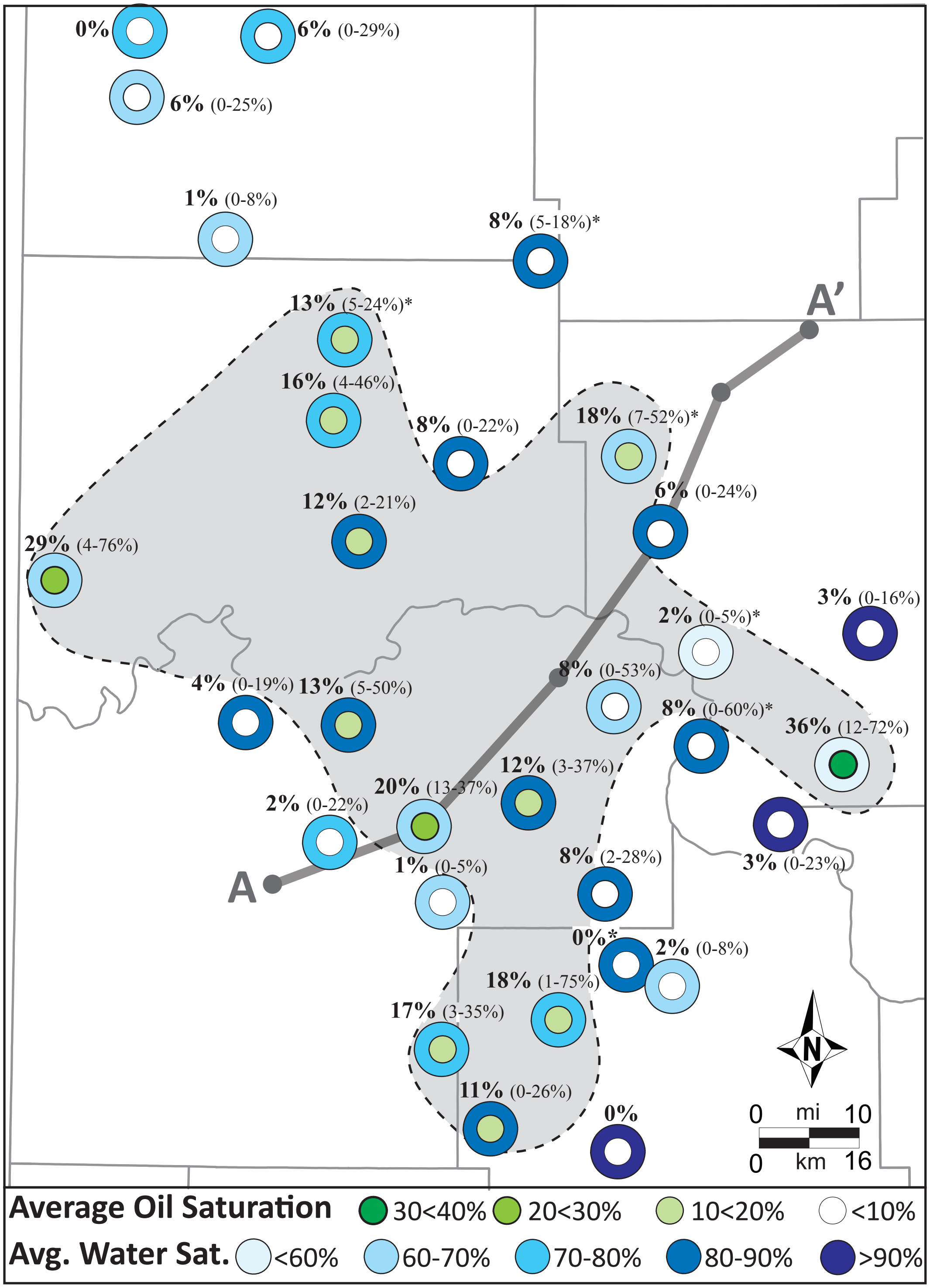

Figure 4. Fluid saturation map for the lower Three Forks (3rd and 4th benches). The circles depict the well locations while the coloring represents the average oil (white-green) and water (blue) saturations from compiled standard core analysis data. The average oil saturation for the lower Three Forks is listed in larger bold font while the minimum and maximum oil saturations are listed in parentheses in smaller, non-bold font. * = core and/or saturation data extends only partway down through the lower Three Forks. The grey area depicts where the lower Three Forks core saturations commonly average 10-20% oil and ≤80% water. A-A' is the location of the Figure 5 cross-section.

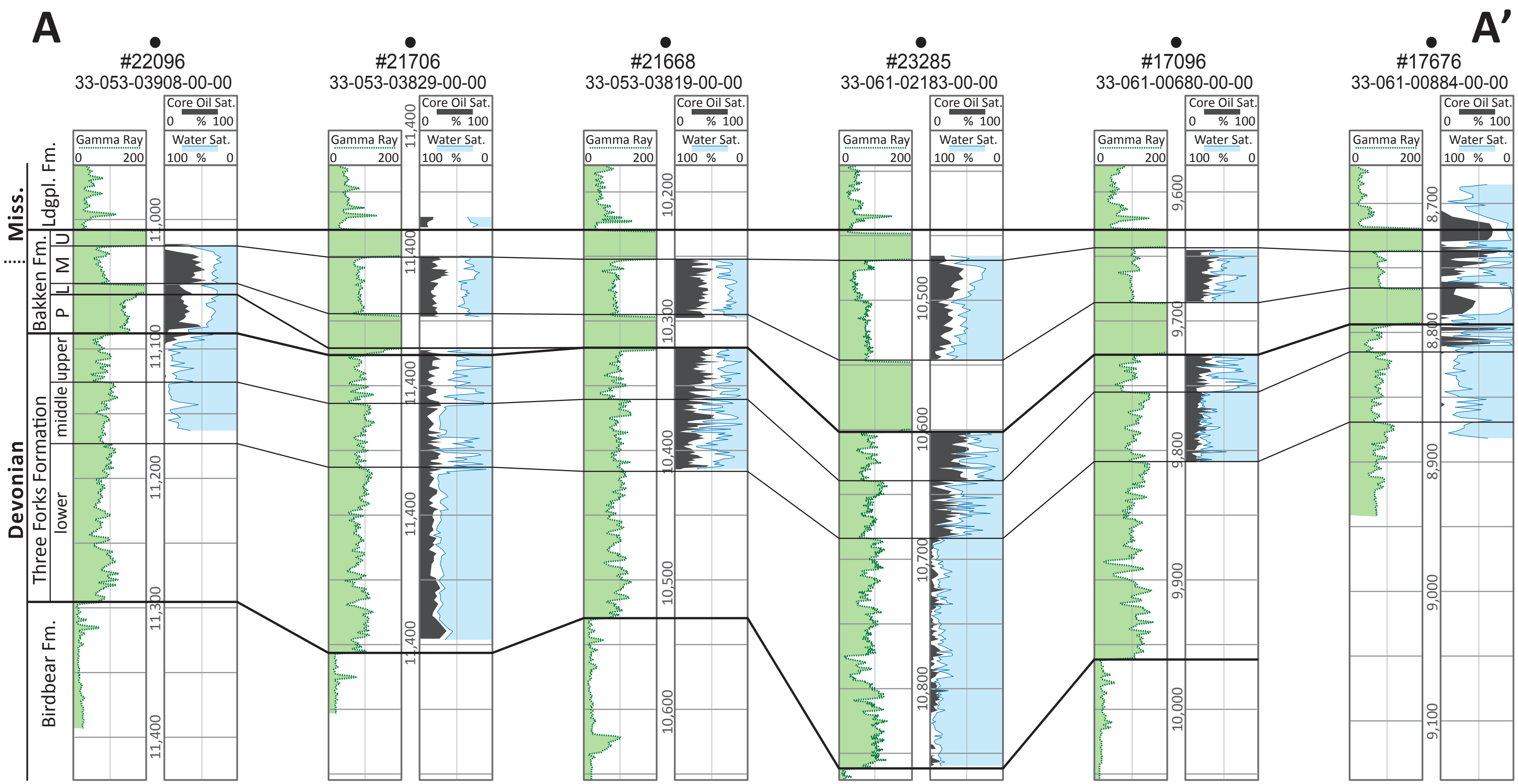

Figure 5. Cross-section of the Bakken and Three Forks Formations displaying gamma ray and oil-water saturation data from core plugs. The North Dakota Industrial Commission and API well numbers are listed above each well. True vertical depth (feet below Kelly bushing) is displayed within the space between the gamma ray and fluid saturations. Miss. = Mississippian; Ldgpl. Fm. = Lodgepole Formation; P = Pronghorn Member; L = Lower Member; M = Middle Member; U = Upper Member

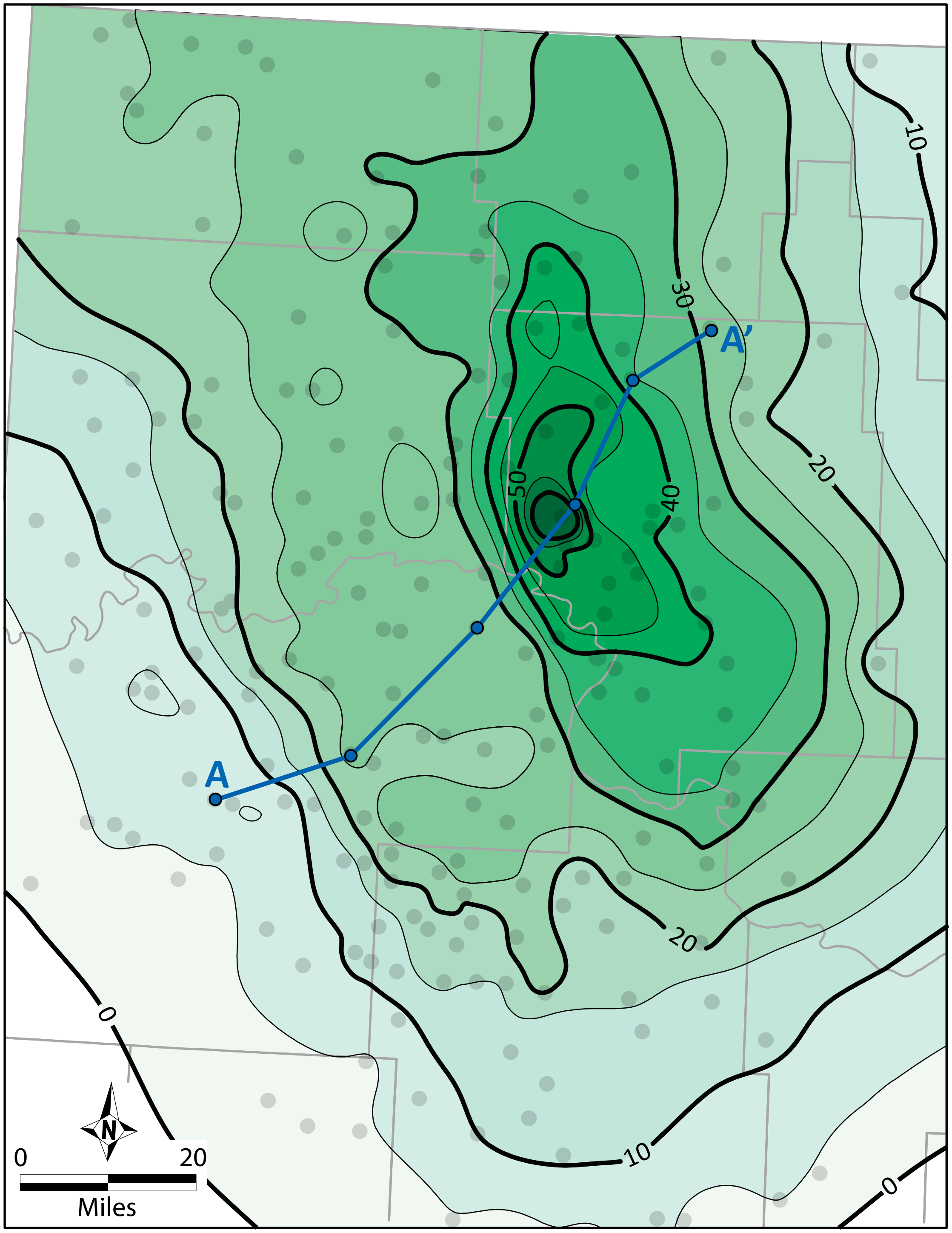

Figure 6. Isopach map of the lower Bakken shale. Contours are in 5 foot intervals. The light grey circles depict the control wells used to create the map. A-A' is the location of the Figure 5 cross-section.

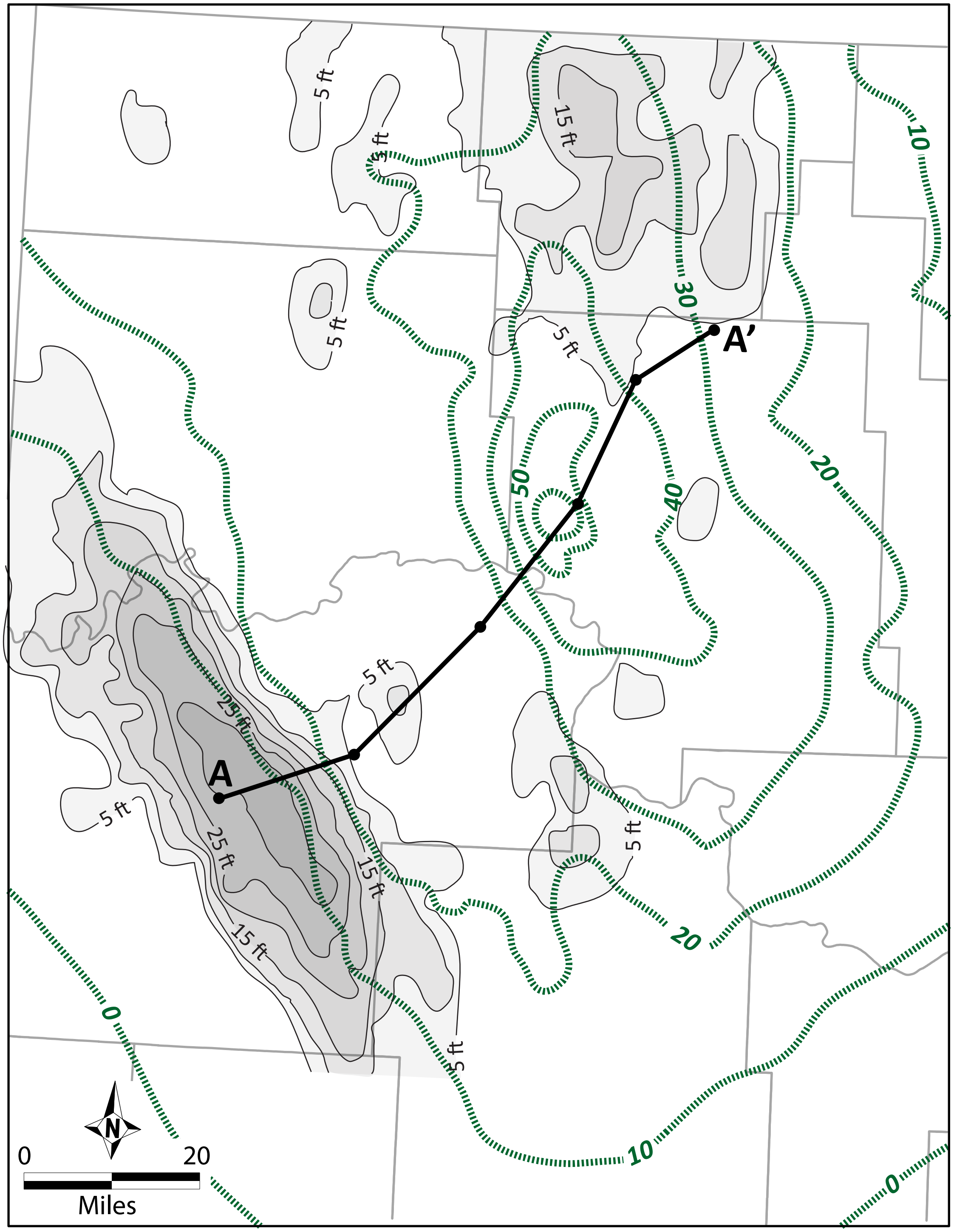

Figure 7. Isopach map of the lower Bakken shale (thick green lines) and distal deposits of the Pronghorn Member (grey shading and thin black lines). Pronghorn contours are from LeFever et al. (2012). A-A' shows the location of the Figure 5 cross-section.

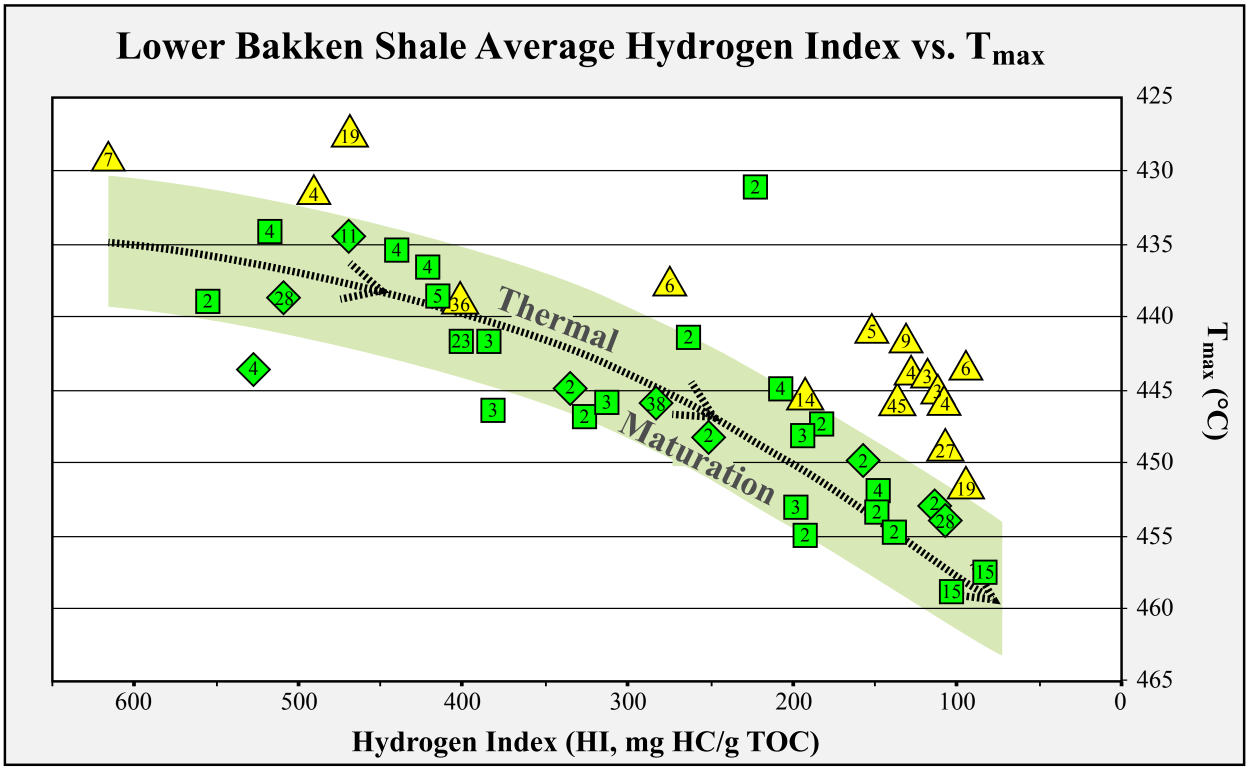

Figure 8. Diagram depicting the average hydrogen index and average T_{max} by core for lower Bakken shale samples. Yellow triangles represent data from core samples collected before 1970 and green symbols are data from core samples cut after 1970. The green squares represent core data submitted by the original operator that cut the given core while the green diamonds and yellow triangles denote data the North Dakota Geological Survey had on file with more limited information on the data collection. The number within each symbol depicts the number of samples analyzed from that given core. The data from pre-1970's core samples display notably lower T_{max} values in relation to HI when compared to the data for post-1970 core samples. This variance is similar to that observed in Red River source rock samples by Nesheim (2017) and is suspected to be a function of difference in instrumentation.

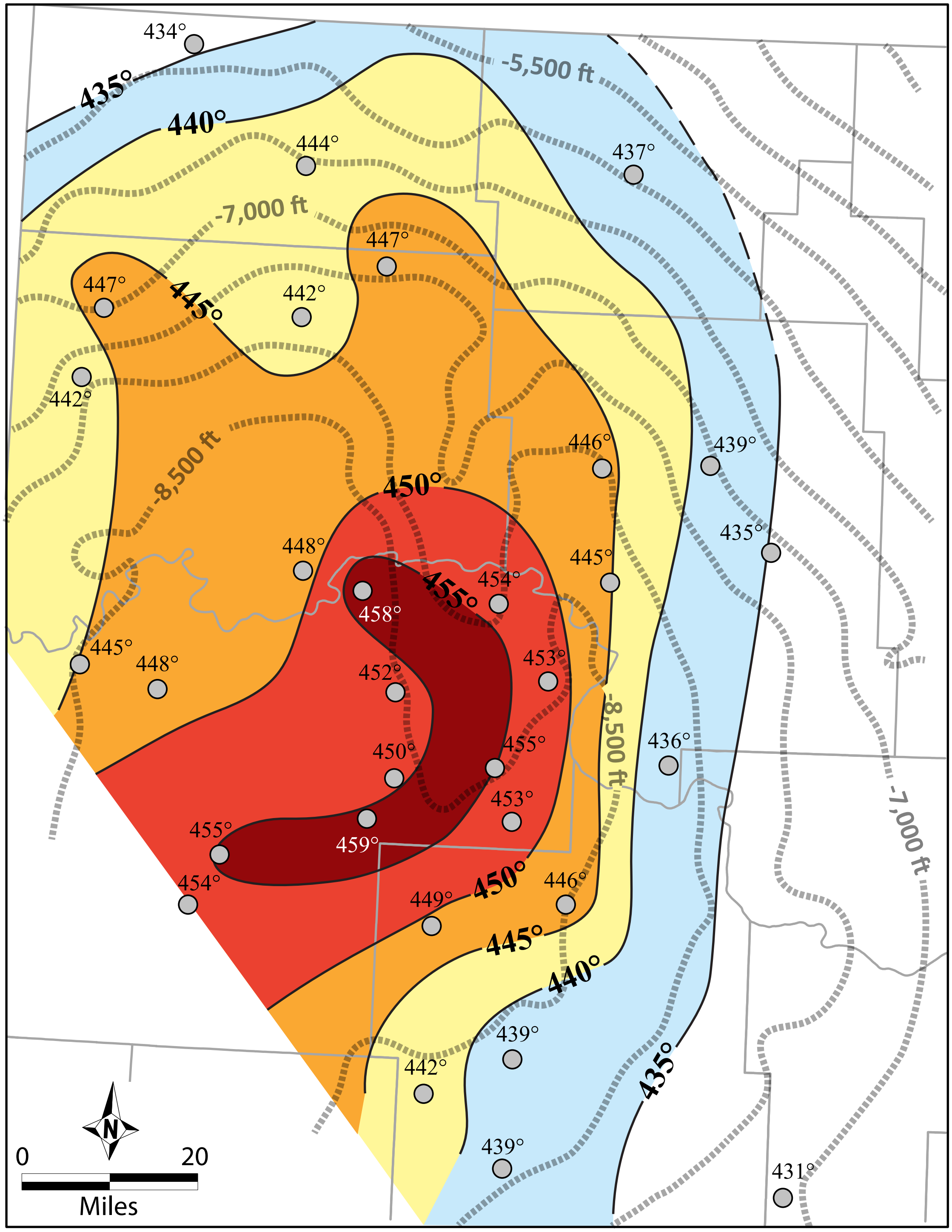

Figure 9. Contour map of the average T_{max} measured from two or more lower Bakken shale core chip samples. Grey circles represent core control wells and the values near each symbol represent the average lower Bakken shale T_{max}. The semi-transparent dotted grey lines depict structure contours (feet below sea level) on the lower Bakken shale top.

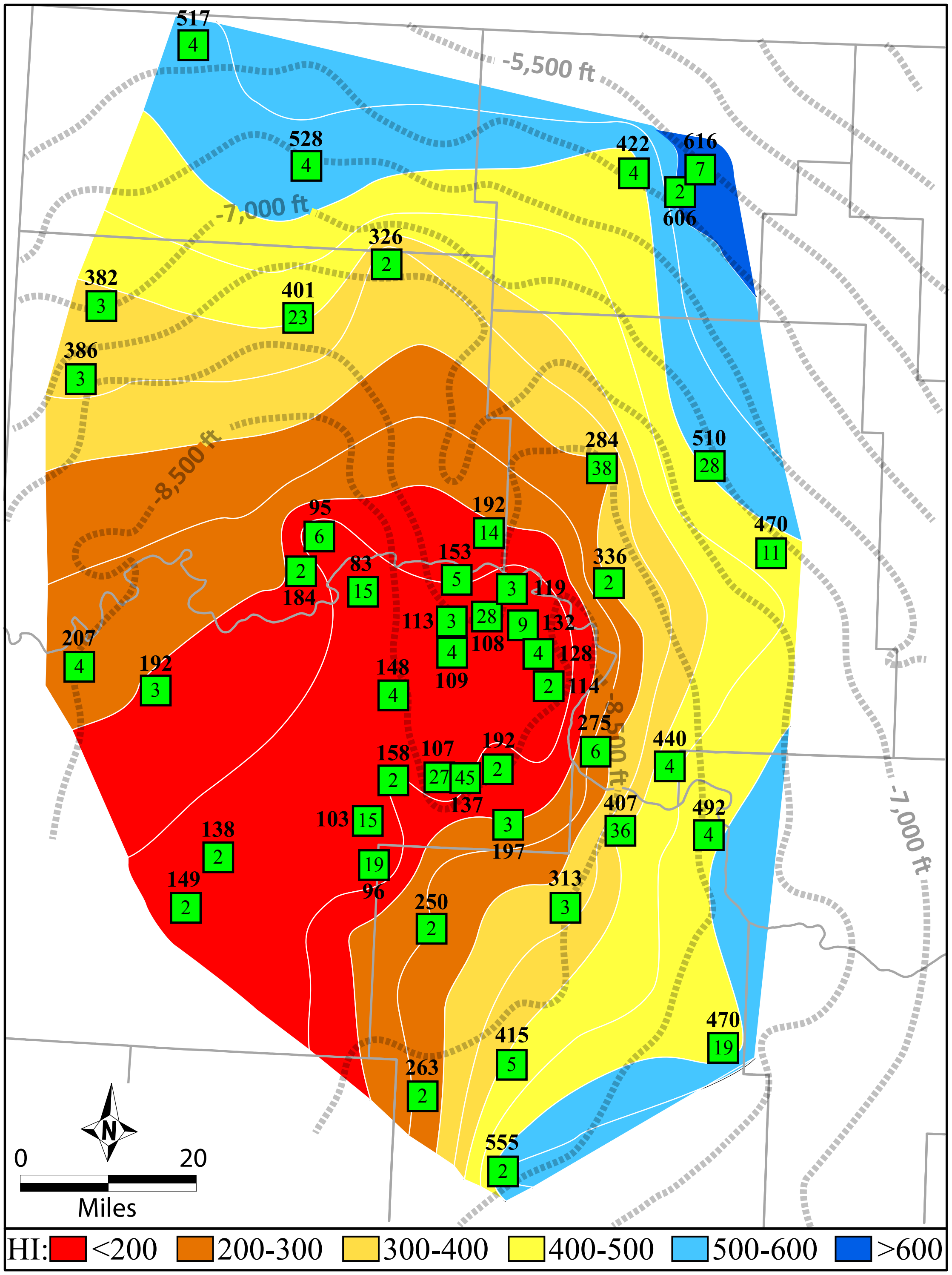

Figure 10. Contour map displaying the average hydrogen index (HI) of lower Bakken shale samples by core. Green square symbols represent core locations. The number within each symbol is the number of analyzed samples and the number above each symbol is the average HI. The light grey lines are county boundaries. The semi-transparent dotted grey lines depict structure contours (feet below sea level) on the lower Bakken shale top.

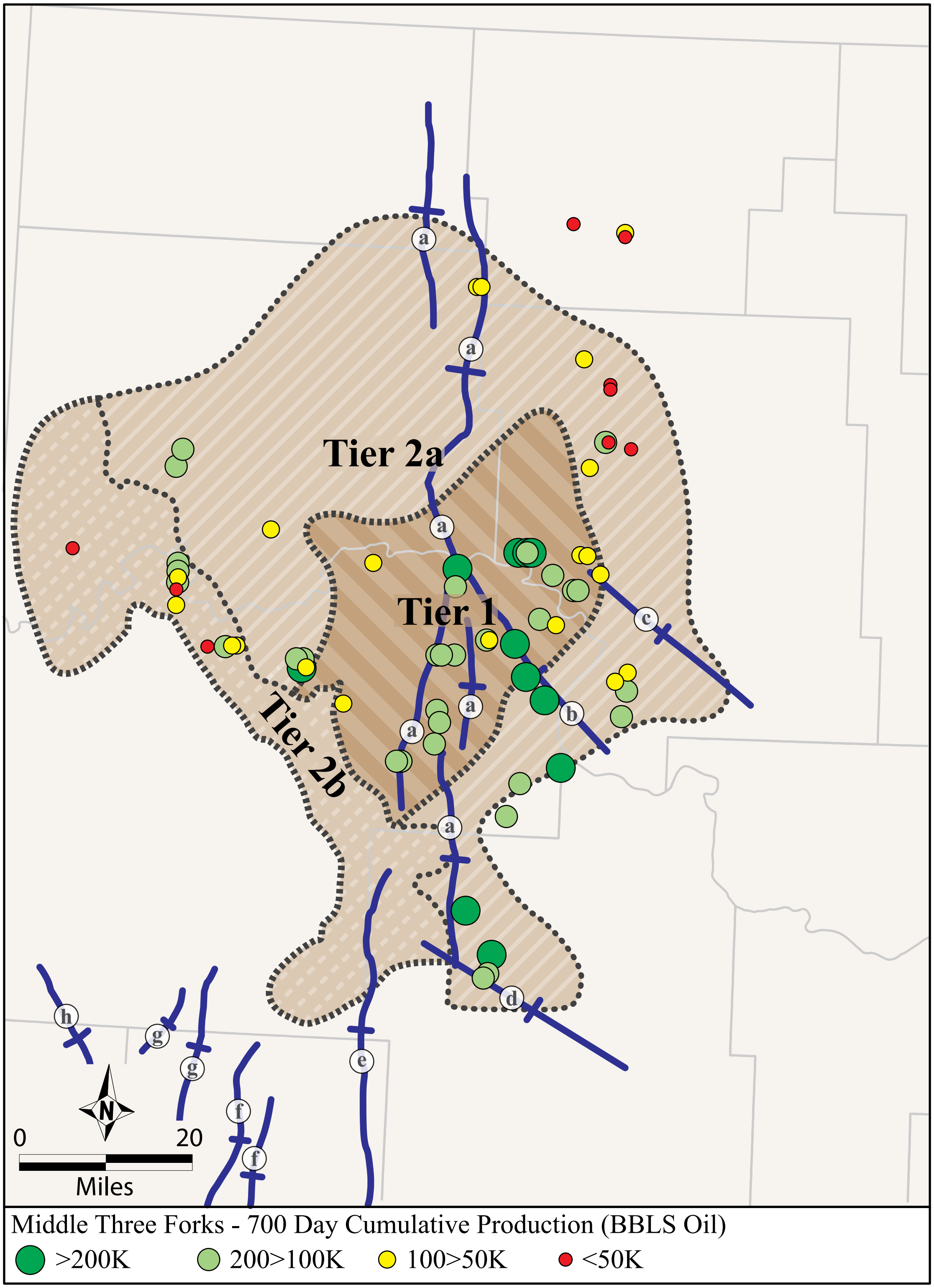

Figure 11. Comparison of middle Three Forks horizontal well 700-day cumulative oil production with various oil saturation tiers (tan-brown color fill and diagonal lines) and Williston Basin structures (blue lines). a = Nesson anticline; b = Antelope anticline; c = unnamed anticline from Nordeng et al. (2009); d = unnamed anticline from Sorensen et al., (2010); e = Little Knife anticline; f = Billings Nose anticline; g = Roughrider anticline; h = Beaver Creek anticline

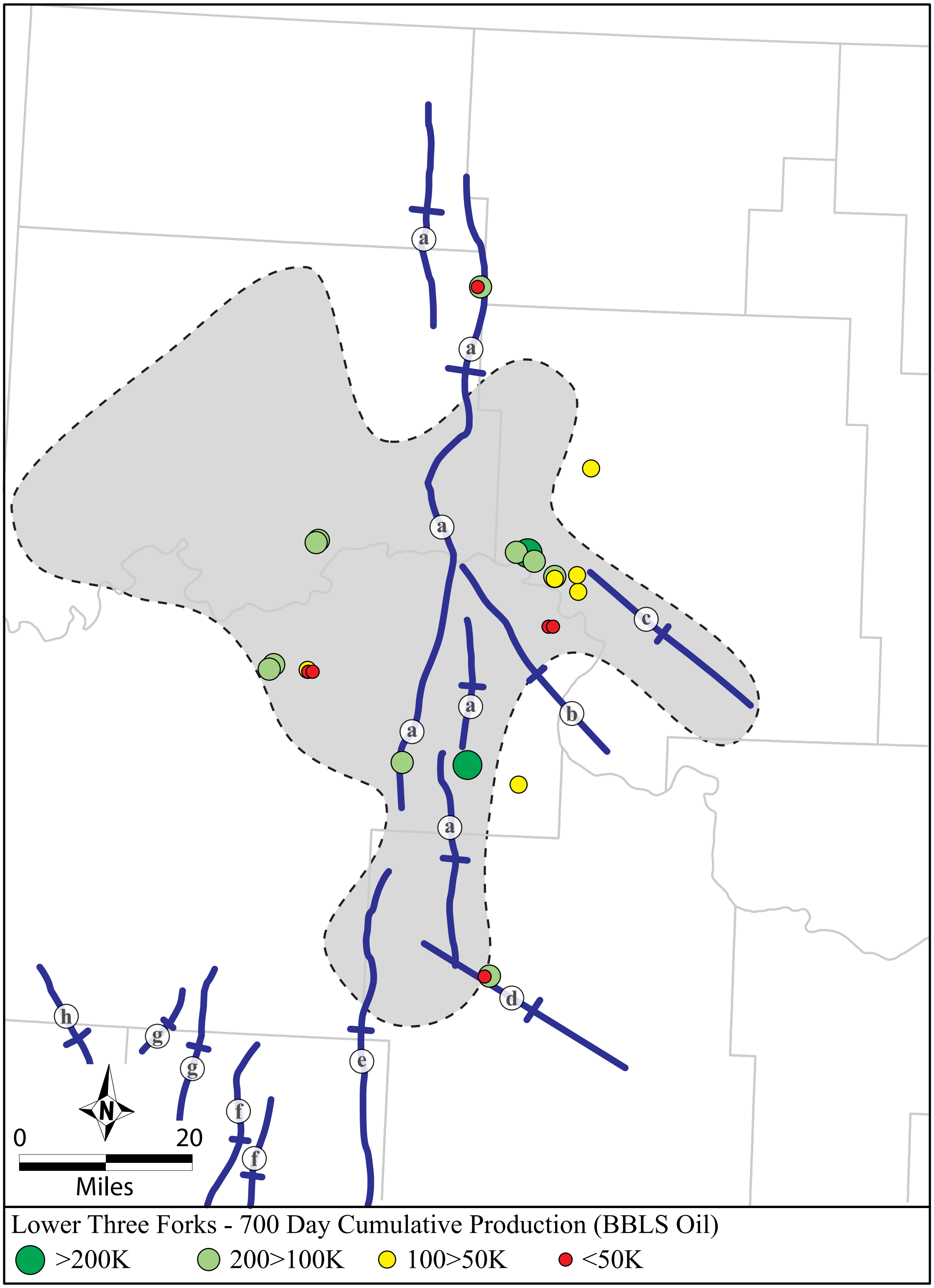

Figure 12. Comparison of lower Three Forks (~3rd bench) horizontal well 700-day cumulative oil production with the area of higher average lower Three Forks oil saturations (diagonal lines) and various Williston Basin structures (blue lines). a = Nesson anticline; b = Antelope anticline; c = unnamed anticline from Nordeng et al. (2009); d = unnamed anticline from (Sorensen et al., 2010); e = Little Knife anticline; f = Billings Nose anticline; g = Roughrider anticline; h = Beaver Creek anticline

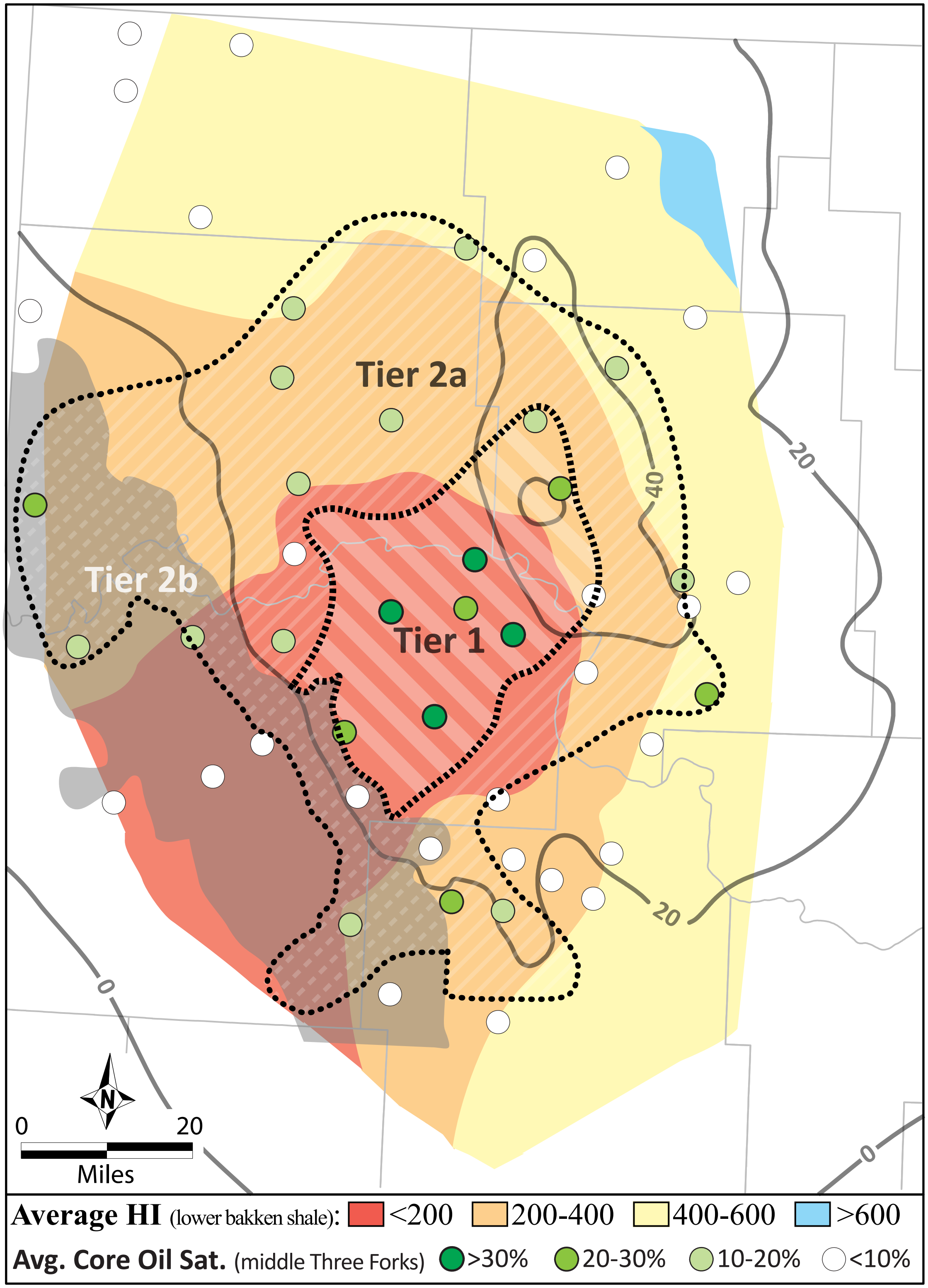

Figure 13. Map comparing the average core plug oil saturations of the middle Three Forks with the lower Bakken shale thickness (thick dark grey contour lines) and thermal maturity (average HI = yellow-green-red colors), and the distal Pronghorn Member thickness trend from LeFever et al. (2012) and Millard and Brinkerhoff (2016) (transparent grey). The adjusted areas of highest (tier 1) and intermediate (tier 2) core plug oil saturations for the middle Three Forks are displays by the dotted outlined areas.

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