Stratigraphic Correlation and Thermal Maturity of Kukersite Petroleum Source Beds within the Ordovician Red River Formation

By

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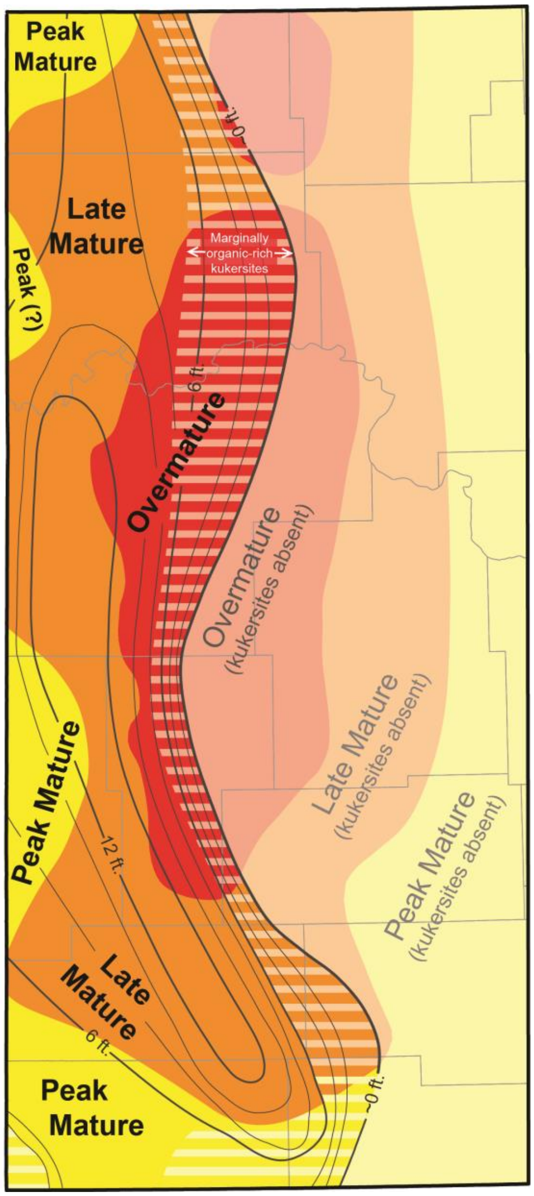

REPORT OF INVESTIGATION NO. 118
NORTH DAKOTA GEOLOGICAL SURVEY

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2017

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ABSTRACT

The Upper Ordovician Red River Formation contains a number of relatively thin petroleum source beds, referred to as kukersites. Previous studies have mentioned these prospective source beds, but did not quantitatively examine their extent or significance in western North Dakota. Examination and analysis of 28 cores and over 300 wireline logs have revealed that up to ten distinct kukersites can be recognized in the Red River D interval. These kukersites can be correlated individually for 10's to 100's of miles across the western quarter of the state where they span approximately 9,800 square miles. Each kukersite is typically thin (1-2 ft thick) and contains highly variable total organic carbon (TOC) content, ranging from <1 to >30 wt. %. However, they combine to commonly reach net thicknesses of 6-12 ft (3.7 m) with average present day TOC values of typically 3-6 wt %. The interpreted thermal maturity with respect to oil generation of the kukersites ranges from peak mature to overmature based on geochemical data and produced hydrocarbon characteristics, indicating the Red River petroleum system may be self-sourced. Trends in produced hydrocarbon characteristics suggest there is limited lateral hydrocarbon migration through the Red River C and D intervals where the kukersite beds are present. Better recondition and understanding of the kukersites as significant petroleum source beds should enhance future Red River exploration and development in the Williston Basin.

INTRODUCTION

The Ordovician Red River Formation (Red River) has been a substantial hydrocarbon productive interval in western North Dakota and the surrounding portions of the Williston Basin. Over 2,700 oil and gas wells, consisting of both horizontal and vertical completions, have produced more than 600 million barrels of oil from the Red River Formation across the Williston Basin (Fig. 1). In western North Dakota, approximately 1,400 Red River wells have produced over 300 million barrels of oil and 750 billion cubic feet of gas* to date, making the Red River the third most productive stratigraphic horizon behind Bakken-Three Forks Formations and the Madison Group (North Dakota Oil and Gas Division, 2017a,b). Dow (1974) and Williams (1974) initially proposed that Red River hydrocarbons were externally sourced from the underlying Icebox Formation. However, numerous publications since have described and examined intra-formational Red River source beds referred to as both kerogenites (Kendall, 1976; Carroll, 1979; Longman et al., 1983) and kukersites within more recent studies due to high concentrations of the algal microfossil *Gloeocapsomorpha Prisca* (Osadetz and Snowdon, 1995; Stasiuk and Osadetz, 1990; Fowler et al., 1998). Winnipeg oils have also been found to be geochemically distinct from Red River Formation oils throughout the northern portions of the Williston Basin, which indicates hydrocarbon sources from separate, unique source beds (Smith and Bend, 2004).

Red River (upper Yeoman Fm.) kukersites have been mapped within southern Saskatchewan and reportedly have over 5 billion barrels of petroleum generation potential, but thermal maturity work indicates the Saskatchewan Red River kukersites are largely immature with respect to oil generation and have only generated approximately 200 million barrels (Osadetz et al., 1989; Osadetz and Haidl, 1989; Osadetz and Snowden, 1995). Kukersites have been briefly described in Red River studies of eastern Montana and western North Dakota (Kohm and Louden, 1978; Carroll, 1979; Longman et al., 1983; Nesheim et al., 2015), which contains the central, deepest portions of the Williston Basin. Beyond southern Saskatchewan, the extent of Red River kukersites and their hyrdrocarbon generation significance in the Williston Basin is poorly understood.

More recently, Nesheim (2017) provided a preliminary examination of the distribution, thermal maturity, and hydrocarbon generation significance of kukersite beds within the Red River D interval (upper Yeoman) of western North Dakota. This document provides additional material (e.g. additional maps, cross-sections, appendix diagrams) related to the extent and thermal maturity of Red River D interval kukersites within western North Dakota.

**Cumulative gas production numbers are only reported from 1998 to present for North Dakota. Pre-1998 production was estimated based on post-1998 production records.*

GEOLOGICAL BACKGROUND

Deposition of the Red River Formation occurred during the Late Ordovician and began within a subtidal, normal-salinity marine setting that transitioned into cyclic, normal marine to hypersaline sedimentation sequences. The Red River Formation reaches more than 700 ft thick within central North

Dakota and can be divided into upper and lower subunits, equivalent to the Herald, Yeoman, and lower portions of the Stony Mountain Formations of Saskatchewan (Kendall, 1976) (Fig. 2).

The lower Red River (Yeoman Formation) comprises approximately two-thirds of the formation and conformably overlies the Roughlock Formation of the Winnipeg Group (Fig. 2). The lower Red River consists predominantly of gray and brown, dolomitic, burrow-mottled, lime mudstone to fossil wackestone across the central portions of the basin, and grades into dense dolomite towards the margins of the basin where it becomes less fossiliferous and loses the burrow-mottled texture (Carroll, 1979). Fossil assemblages in the lower Red River include brachiopods, crinoids, and gastropods, which indicate normal marine salinity conditions (Kohm and Louden, 1978). The mottled texture of the lower Red River is thought to be primarily the result of *Thalassinoides* burrows that are typically several centimeters in diameter, or, alternatively, sediment dolomitization around smaller, causative burrows (Pak and Pemberton, 2003). Fossil packstone-grainstone beds, interpreted as storm deposits, are occasionally present throughout the lower Red River and are most common within the upper 100-150 ft of the unit (Kendall, 1976). Discontinuous dolomitization occurs in the upper 150 ft of the lower Red River, which is informally referred to as the D interval, D porosity, D zone, and/or C burrowed member (Kohm and Louden, 1978; Longman et al., 1983; Montgomery, 1997).

The upper Red River is composed of three subunits referred to informally as intervals A through C in descending order, where each interval contains a cyclic sedimentation sequence (Fig. 2). Alternatively, these intervals have been referred to as the A through C zones in descending order (e.g., Longman et al., 1983). Three general lithofacies comprise each interval in the ascending order: 1) bioturbated dolomitic to lime mudstone to fossil wackestone; 2) laminated microcrystalline dolomite; and 3) nodular to laminated anhydrite which is sometimes overlain by a thin argillaceous-dolomitic mudstone (Kendall, 1976; Kohm and Louden, 1978; Longman et al., 1983). The bioturbated wacke-mudstone facies of each cycle has been interpreted as subtidal in origin, deposited in normal marine salinity conditions, while the laminated facies have been interpreted as intertidal and/or subtidal (Carroll, 1979; Longman et al., 1983). The anhydrite beds are basin centered, disappearing towards the basin margins, and commonly display a laminated to bedded texture. These two distinct features led to the interpretation that Red River anhydrites are subtidal in origin (Longman et al., 1983) and/or intercontinental playa deposits (Kendall, 1976; 1984). The cyclic sequences, intervals A through C, have been interpreted as shallowing, brining upward cycles in which open marine, normal salinity conditions (bioturbated wacke-mudstone facies) transitioned to restricted, hypersaline conditions (anhydrite facies) within a primarily subtidal setting (Longman et al., 1983; Fox, 1993). Recent work by Husinec (2016) applied sequence stratigraphy to the upper Red River and similarly interpreted three complete long-term sequences (cycles) of deposition. Husinec (2016) interpreted the anhydrite beds to be largely low stand deposits that represent the beginning of each sequence instead of the final stage. Husinec further described various types of parasequences present within the three longer-term (3^{rd} order) sequences. Above the uppermost A-cycle is an additional interval of bioturbated lime wacke-mudstone, similar to the basal facies described above of each interval A through C. The Red River Formation conformably grades upwards into argillaceous limestone to calcareous shale of the overlying Stoughton Member of the Stony Mountain Formation (Fig. 2) (Longman et al., 1983).

Red River hydrocarbon reservoirs consist of laminated dolomite within the A, B, and C intervals and burrow-mottled dolomitic mudstone in the D interval. Dolomite is thought to have replaced original lime mudstone to packstone for all the Red River reservoirs (Kohm and Louden, 1978; Longman et al., 1983; Montgomery, 1997). The B, C, and D interval reservoirs have accounted for the vast majority of Red River hydrocarbon production to date, with limited production from the A interval. Investigations of the C and D interval reservoirs have revealed that dolomite porosity development in both intervals is highly variable, and that porous dolomite grades between low porosity limestone as well as low porosity cryptocrystalline dolomite in the C laminated member (Kohm and Louden, 1978; Longman et al., 1983; Fox, 1993). Longman et al. (1983) described and modeled porous dolomite within the C and D intervals (C burrowed member) as highly localized across eastern Montana. Wireline log mapping by Fox (1993) in northwestern North Dakota revealed comparable results of highly localized porous dolomite development. However, porous dolomite in the laminated member of the B interval has been described as continuous across long distances (100+ miles) in southwestern North Dakota (Montgomery, 1997). The B interval laminated member is also believed to have acted as a conduit for long-distance oil migration to source the Lantry Field of central South Dakota (Longman et al., 1998).

Early studies of the Red River Formation noted the presence of organic-rich mudstones within the D interval (also referred to as the C burrowed member and equivalent to the upper Yeoman Formation) that were initially referred to as kerogenites (Kendall, 1976; Kohm and Louden, 1978; Carroll, 1979; Longman et al., 1983). More recent studies have adopted the name kukersite for the prospective Red River source beds due to the presence of the algae microfossil *Gloeocapsomorpha Prisca* (*G. Prisca*) (e.g., Osadetz et al., 1989; Stasiuk and Osadetz, 1990; Osadetz and Snowdon, 1995; Fowler et al., 1998; Pak et al., 2010). Most studies have concluded that Red River kukersites formed within a subtidal marine setting, possibly during periods of basin restriction where euxinic bottom water conditions developed (Kendall, 1976; Kohm and Louden, 1978). Contrasting accumulation models have been proposed which include: benthic algal mats that grew on the sea floor (Stasiuk and Osadetz, 1990), and suspension settling of algae out of the water column during periodic algal bloom events (Pak et al., 2010). Kukersites have been reported as relatively thin (<2 ft thick), but have been described to correlate on a local, field scale (Kendall, 1976; Kohm and Louden, 1978) to a regional-scale (Longman et al., 1983). Osadetz and Snowdon (1995) reported a 9.07% total organic carbon (TOC) average for kukersite samples from southern Saskatchewan with an inferred original average hydrogen index (HI) of 956 based on marginally mature to immature kukersite samples.

Kukersite Kerogen Type and Organic-Microfacies

Kukersites consist of kerogenous lime mudrock that contains abundant concentrations of *G. Prisca* alginate (Stasiuk and Osadetz, 1990; Osadetz and Snowdon, 1995). Thermally immature kukersite samples are noted to have very high HI values (>800) and very low OI values (<20) (Osadetz and Snowdon, 1995). These geochemical characteristics indicate the organic carbon consists primarily of Type I kerogen which is very prone to generate oil under sufficient thermal stress. Stasiuk and Osadetz (1990) described two microfacies; 1) a disseminated *G. Prisca* that was planktonic, and 2) a non-disseminated stage where *G. Prisca* grew as subtidal algal mats on the sea floor. These two microfacies were interpreted to represent two separate life cycles of the same organism.

Fowler et al. (1998) described the same two *G. Prisca* microfacies within Red River kukersites in southern Saskatchewan and reported that the two microfacies had reached different levels of thermal maturity within the same core. Fowler described a stromatolitic layered, more organic-rich (>10% TOC) kukersite microfacies (non-disseminated *G. Prisca*) and a less organic-rich (3-5% TOC), non-layered microfacies (disseminated *G. Prisca*). Fowler interpreted the non-layered organic microfacies to be more thermally mature (Early Mature) with respect to oil generation than the layered organic microfacies (Immature) within the same core based primarily on fluorescence observations.

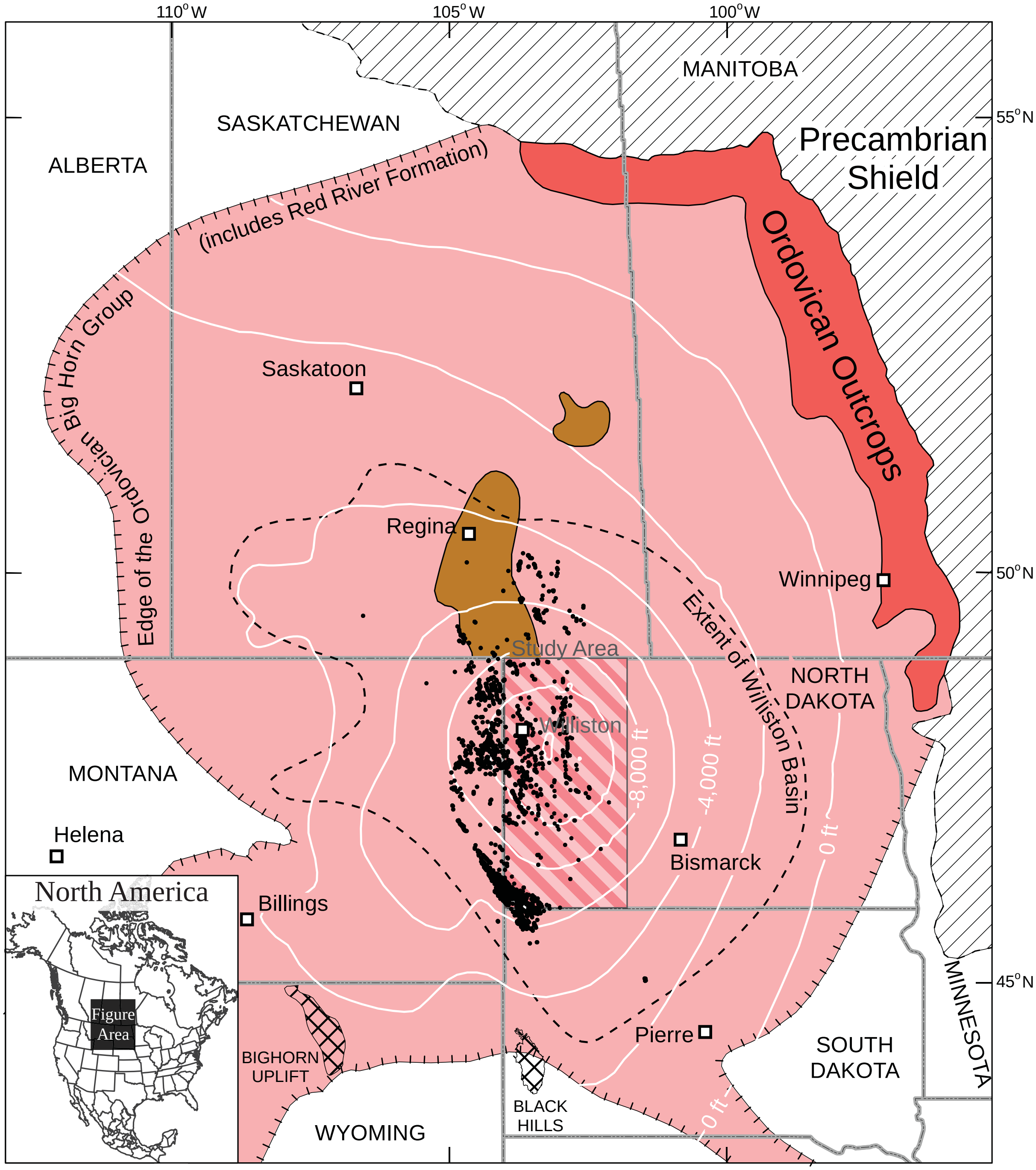

Figure 1. Regional extent map of the Ordovician Bighorn Group which includes the Red River Formation and equivalent units, modified from Kendall (1976). The black dots represent oil and gas wells that have produced from the Red River Formation while the brown colored areas represent the extent of Red River D interval (upper Yeoman) kukersites in southern Saskatchewan (Osadetz and Haidl, 1989). White lines represent structure contours on the Red River Formation top (depth below sea level), which have been combined and modified from Bezys and Conley (1998), Khan et al. (2006), Kreis and Haidl (1996), and Nesheim et al. (2015). Contour interval = 2000 ft (610 m).

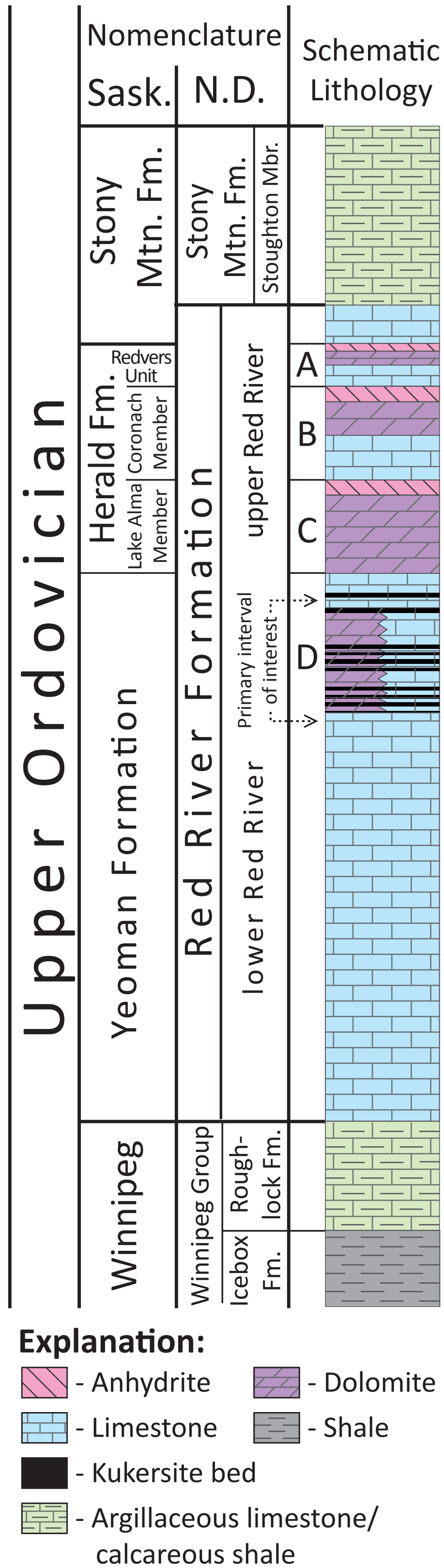

Figure 2. Stratigraphic column of the Red River Formation and surrounding units with approximate nomenclature correlations between Saskatchewan (Sask.) and North Dakota (N.D.).

Section I:

Kukersite Core Identification, Correlation, and Mapping

METHODS

Thirty-five Red River Formation cores were visually examined, 18 of which were sampled for geochemical analysis, in order to identify and evaluate kukersites in the Red River D interval (Fig. 3). All of the cores examined and/or sampled extended partially to completely through the D interval. Most of the cores also extended 10's to 100's feet above and/or below the D interval which aided in delineating the stratigraphic (vertical) extent of the kukersites. Core chip samples were collected from 18 cores and analyzed using LECO TOC and Rock-Eval pyrolysis to examine organic richness. While sampling focused on kukersites, samples were also collected from lighter colored, presumably more organic-lean lithologies. Cores containing kukersites were correlated to their respective wireline logs to determine kukersite wireline log signatures. Wireline logs from several hundred wells that penetrated the Red River section were then utilized to correlate individual kukersites and further delineate their lateral extent within the program Petra©. Net kukersite thicknesses were calculated on a well-by-well basis using primarily core measurements. Wireline logs were used as a secondary dataset because individual kukersites were often found to be too thin (<2 ft) for accurate wireline log resolution with respect to thickness calculations.

RESULTS AND OBSERVATIONS

Red River kukersites from western North Dakota cores are dark grey to black, range from moderately bioturbated and poorly laminated to non-bioturbated and thinly laminated, and are typically one- to two-feet thick (Figs. 4-6). Additionally, kukersites vary from being fossil-bearing to containing irregular intervals of fossil packstone to grainstone (Figs. 4-5). Fossil assemblages often include crinoids and brachiopods as well as ostracods and occasional coral fragments. Kukersite intervals typically display sharp lower contacts with gradational upper contacts, but sometimes share gradational lower and/or sharp upper contacts. The burrows present are typically millimeter-scale in diameter which contrasts with the centimeter-scale *Thalassenoides* style burrowing observed in the interbedded burrow-mottled fossil lime to dolomitic mudstone to fossil wackestone of the Red River D interval.

Kukersites are most commonly distinguishable on wireline logs by their elevated resistivity signatures which generally reach 20-200 ohms when surrounded by porous (2-20%) dolomite and ≥200 ohms when surrounded by low porosity (<2%) limestone (Fig. 6). The thicker, more organic-rich kukersites (K2 and K6 as described below) often display subtle elevated log porosity (neutron and density) and decreased sonic velocity travel time signatures (Fig. 6), a common log quality of organic-rich source beds (Passey et al., 1990). This porosity and sonic log signature is more pronounced when a given kukersite is interbedded with low-porosity limestone and less obvious when interbedded with porous dolomite (Fig. 6 – K6). The gamma-ray log response is both very low (<20 API) and indistinguishable across the burrow-mottled wacke-mudstone and interbedded kukersites (e.g., Fig. 6), even when an individual kukersite was observed to reach thicknesses of over 6 ft.

Ten kukersites, K1 to K10 in ascending order, were identified and correlated across western North Dakota using cores and wireline logs. Most of these kukersites (K2-K6, K8) extend relatively continuously in the subsurface for 10's to 100's of miles (Plate I). Each of these kukersite beds has unique lateral variations in extent, thickness, and organic richness as reviewed below in ascending stratigraphic order:

K1

The K1 kukersite is often the thinnest kukersite and only reaches a maximum thickness of 6 inches in core, which makes it difficult to identify and correlate on wireline logs. The K1 kukersite typically consists of only 1-3 inches of organic-rich mudstone (e.g., Fig. 4A). Even though it is very thin, the K1 kukersite was regularly observed in many of the D interval cores across the kukersite extent area. An elevated resistivity signature is intermittently present on wireline logs for the K1 kukersite, but this log signature often makes the K1 bed look thicker than it actually is. TOC values measured from K1 samples ranged from 1.3% to 6.6%.

K2

The K2 kukersite is the most regionally extensive, laterally consistent, and often most organic-rich of the D interval kukersites. The K2 kukersite is commonly 1.5- to 2-feet thick and averages 10-16% TOC, with individual core chip samples that reach up to 30% TOC. The higher TOC samples (>5%) were often from a faintly laminated to massive, very darkly colored facies with low levels of bioturbation which comprise upwards of 40% of the K2 kukersite (e.g., Fig. 4B). The lower TOC samples (<5%) were often from a more bioturbated to massive kukersite facies. Between the relatively consistent approximate 2 foot thickness and elevated TOC content, the K2 kukersite appears on wireline logs with both elevated resistivity and porosity (density, neutron, and sonic) log signatures. The K2 kukersite can be correlated very consistently with logs and cores across the entire western portion of the study area. The K2 kukersite could be used to mark the base of the D interval, as there is often negligible dolomitized burrow-mottled wacke-mudstone found below the K2 bed.

K3-K5

The K3, K4, and K5 kukersites are fairly comparable to one another when present. These kukersites tend to be only marginally to moderately organic-rich (~0.5<4.0% TOC) and individually range from several inches to upwards of 2 feet in thickness. These kukersites also tend to be composed primarily of the more massive to poorly laminated, moderately bioturbated kukersite facies (e.g., Figs. 4C, 4D, and 5E). Higher concentrations of fossil grains and thin irregular fossil packstone to grainstone beds are present within the K3-K5 kukersites than the more organic-rich underlying K2 and overlying K6 kukersites. The K4 and K5 beds appear to be present within the central to northern portions of the kukersite extent area, and absent towards the south. Meanwhile, the K3 kukersite appears to extend further southwards.

K6

The K6 kukersite is typically the 2nd most organic-rich kukersite (2nd to the K2). The K6 kukersite tends to be more organic-rich (6-12% TOC average) within the central to southern portions of the kukersite extent area. Within the northwest corner of the study area, the K6 kukersite tends to be more marginally organic rich (1-2% TOC). Similar to the K2 kukersite, the K6 is comprised of 20-40% of the more darkly colored, laminated facies when the K6 is more organic rich (e.g. Fig. 5B). The K6 kukersite tends to be 1-2 feet thick when present except within southwestern North Dakota, where northeast of the Cedar Creek Anticline it locally reaches 7-8 feet in thickness (C-C' – Plate I). The K6 thickening trend is oriented approximately northwest to southeast, which parallels the Cedar Creek Anticline to the south and Beaver Creek Anticline to the north.

K7

The K7 kukersite appears to be the most discontinuously present kukersite of the K1-K8 beds, and when present is only marginally to moderately organic rich (0.5-2.3% TOC average – e.g., Fig. 5C). Similar to the K4 and K5 kukersites, the K7 appears to be present within the central portions of the kukersite extent area and absent towards the south. Texturally, the K7 kukersite is comparable to the K3-K5 kukersites, containing moderate to high amounts of bioturbation and fossil grains

K8

The K8 kukersite ranges from being marginally organic rich (1-2% TOC average) to more highly organic rich (4-5% TOC average – e.g., Fig. 5D) where it also picks up an elevated porosity wireline log signature, similar to the K2 and K6 kukersites. The K8 kukersite can also be correlated fairly consistently across the study area, stretching from the Saskatchewan to the South Dakota border.

K9 & K10

The K9 and K10 kukersites appear to be commonly thicker than many of the other kukersites (> 2 ft), but are often composed of marginally organic-rich (~0.5-1.0% TOC) to organic-lean (<0.5% TOC) mudrock. Also, the K9-K10 stratigraphic section was not cored as often as the K1-K8 interval, which in turn makes correlating those two intervals more difficult and less certain.

The Red River D interval contains one or more organic-rich (≥1% TOC) kukersites, with individual bed thicknesses of ≥1 foot, within 23 of the cores examined along the western portions of the study area (Fig. 7). Compositely, these kukersites underlie approximately 9,800 square miles (~25,000 km^2) of western North Dakota, where they extend from the Saskatchewan to South Dakota and roughly 20-30 miles east of the Montana border (Fig. 7). While individual kukersites commonly range from only a few inches to a couple feet in thickness, their combined net thicknesses commonly reaches 6-12 feet across the western quarter of North Dakota (Fig. 7). Kukersites appear to grade laterally into tan-brown dense, organic-lean (<0.5% TOC) carbonate mudstone (Fig. 8A-B) and/or burrow-mottled mudstone, which were utilized in cross-section correlations, but not included in net kukersite thicknesses. This lateral transition to dense, organic-lean limestone occurs to many of the kukersites along their eastern margins as well as to some towards the southern portion of the study area. Furthermore, the Red River Formation contains thin (≤1 inch), organic-rich (≥0.5 wt % TOC) laminations in the eastern portions of the study area, beyond the mapped extent of the D interval kukersites (Fig. 8C-D). These organic-rich laminations are useful for thermal maturity mapping, but likely do not represent a sufficient quantity of petroleum source rock for significant hydrocarbon generation.

DISCUSSION AND IMPLICATIONS

The net thickness mapping of kukersites across the study area represents the first effort at delineating the quantitative amount of petroleum source rock in the Red River of North Dakota. Previous Red River studies in the US portion of the Williston Basin have only noted the presence of kukersites and speculated on their petroleum generation significance (e.g., Kohm and Louden, 1978; Longman et al., 1983). Discovering that the D interval consistently contains several feet of organic-rich carbonate mudrock across thousands of square miles is a key step in evaluating whether the Red River is potentially internally sourced for its hydrocarbon resources.

The K1-K10 stratigraphic correlations are based on hundreds of cross-section correlations made during this study using dozens of cores and hundreds of wireline logs (e.g., Plate I). The regional scale of these correlations had not formerly been recognized, likely due to the subtle wireline log signatures of the kukersites and their limited bed thicknesses. Red River kukersites have previously been described to correlate on a smaller, field scale (Kendall, 1976; Kohm and Louden, 1978; Longman et al., 1983). The ability to correlate these relatively thin horizons on a more regional, basin scale has important stratigraphic implications. Whether the kukersites are time-stratigraphic or time-transgressive, they will be useful in further study as marker beds when examining the sedimentology and stratigraphy of the Red River D interval.

While the complete depositional origin of the kukersites was beyond the scope of this study, a few useful insights may be drawn. First, structures such as the Nesson, Billings Nose, Cedar Creek, and Little Knife anticlines bound the lateral extent of the kukersites (Fig. 7), suggesting a structural component to the deposition and preservation of these petroleum source beds. The orogenic histories of each of these structures have been found to be complicated such that at different points in geologic time they may have been topographic highs, lows, or non-active (Clement, 1987; LeFever et al., 1987; LeFever and Crashell, 1991). Therefore, while the present day expression of these structures is one of positive relief, one or more of the structures may have been paleo-topographic lows and/or highs during deposition of the Red River D interval kukersites. Smaller structures across the basin, as well as structures not named above, may also play roles in the distribution, thickness, and organic richness of the kukersites on a local scale.

Second, the repetitive bed alternation between the thin kukersite beds and the burrow-mottled wacke-mudstone facies may be indicative of cyclic deposition. The kukersite intervals typically contain higher amounts of fossil packstone-grainstone than the burrow-mottled facies, which could be interpreted as evidence of a higher energy setting where water depth shallowed during kukersite deposition and deepened during the burrow-mottled facies.

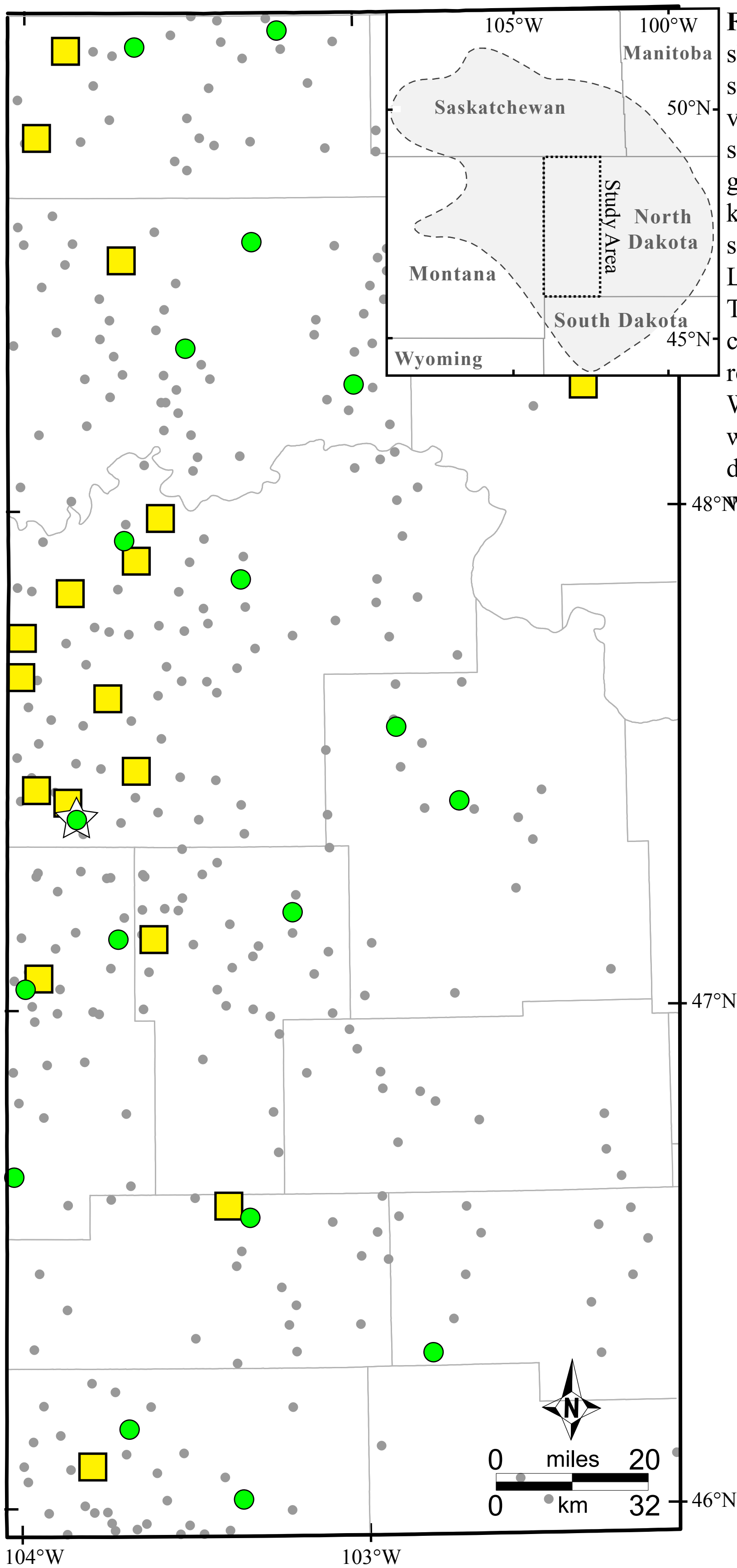

Figure 3. Map of the study area showing visually examined and sampled cores (green circles), visually examined cores (yellow squares), and wireline logs (small grey circles utilized primarily for kukersite correlations and secondarily for mapping purposes). Light grey lines are county outlines. The inset map on the top right corner shows the study area in relation to the extent of the Williston Basin (dashed outline with grey fill). The star symbol depicts the location of the Figure 6 well, NDIC #7218.

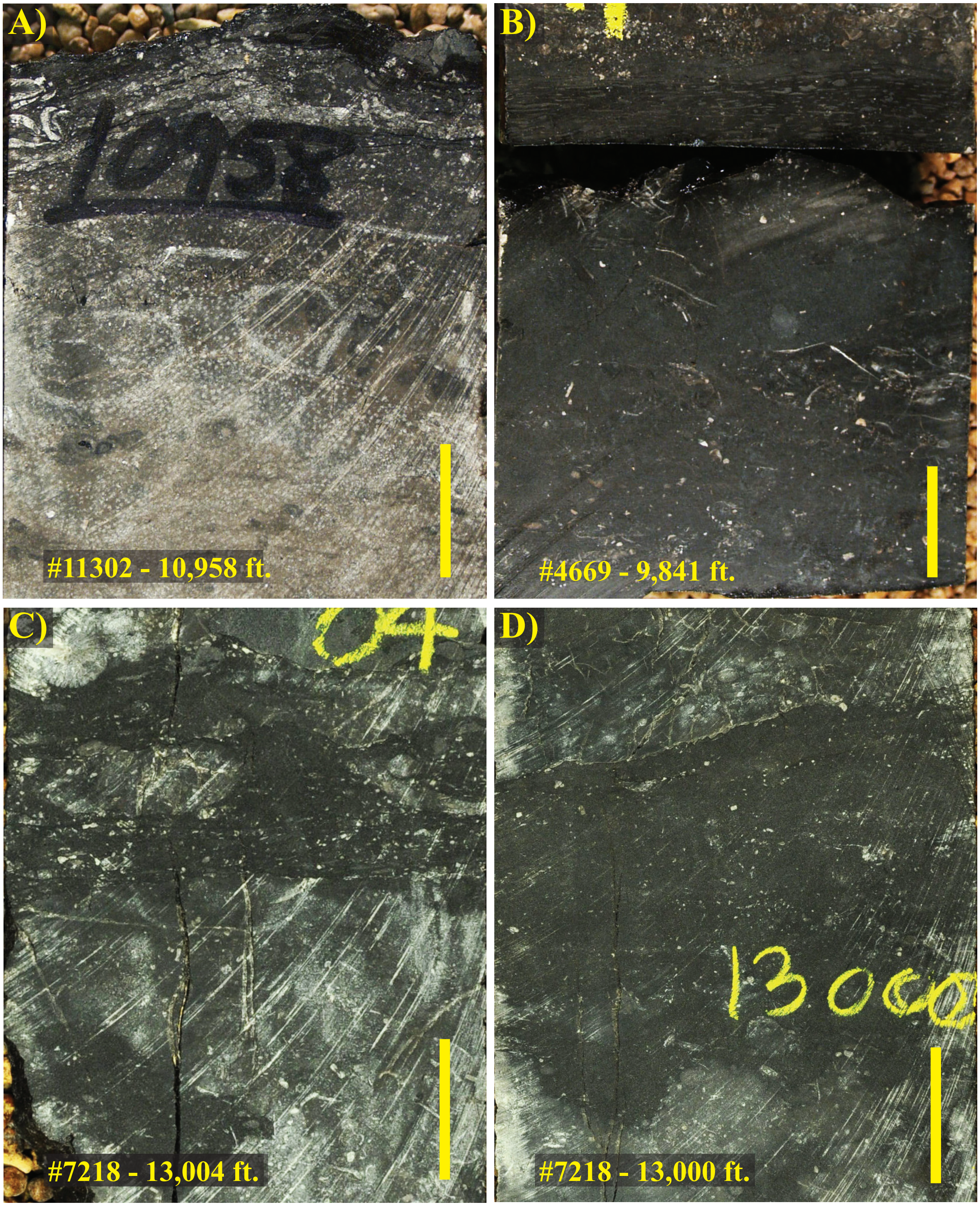

Figure 4. Core photograph examples of kukersites K1-K4 from the Red River D interval. A) K1 kukersite (top of image) overlying organic-lean (<<0.5% TOC) carbonate mudstone (bottom of image) with a gradational contact. B) K2 kukersite containing 6.9 to 20.5 wt. % TOC (4 samples, 12.4% average), C) K3 kukersite containing 0.4 to 0.8 wt. % TOC (2 samples, 0.6% average), and D) K7 kukersite containing 0.53 wt. % TOC (one sample). One-inch scale bar in the bottom right corner and NDIC well number with approximate core depth in the bottom left corner of each photograph.

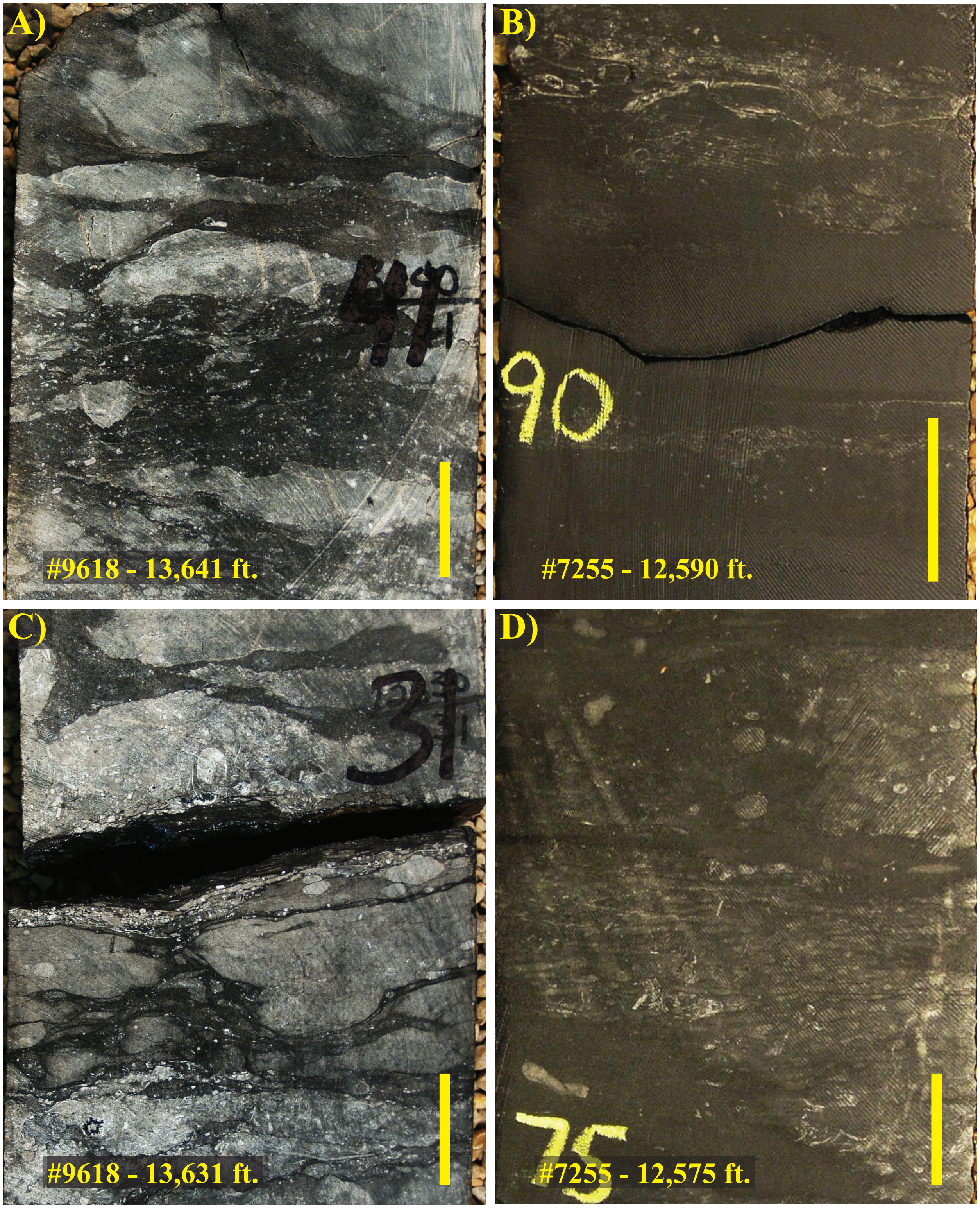

Figure 5. Core photograph examples of kukersites K5-K8 from the Red River D interval. A) K5 kukersite containing 0.2 to 3.2 wt. % TOC (4 samples, 1.1% averages). B) K6 kukersite containing 2.0 to 12.6 wt. % TOC (4 samples, 8.5% average), C) K7 kukersite containing 0.2 to 0.6 wt. % TOC (2 samples, 0.4% average), and D) K8 kukersite containing 2.9 to 7.9 wt. % TOC (3 samples, 5.1% average). One-inch scale bar in the bottom right corner and NDIC well number with approximate core depth in the bottom left corner of each photograph.

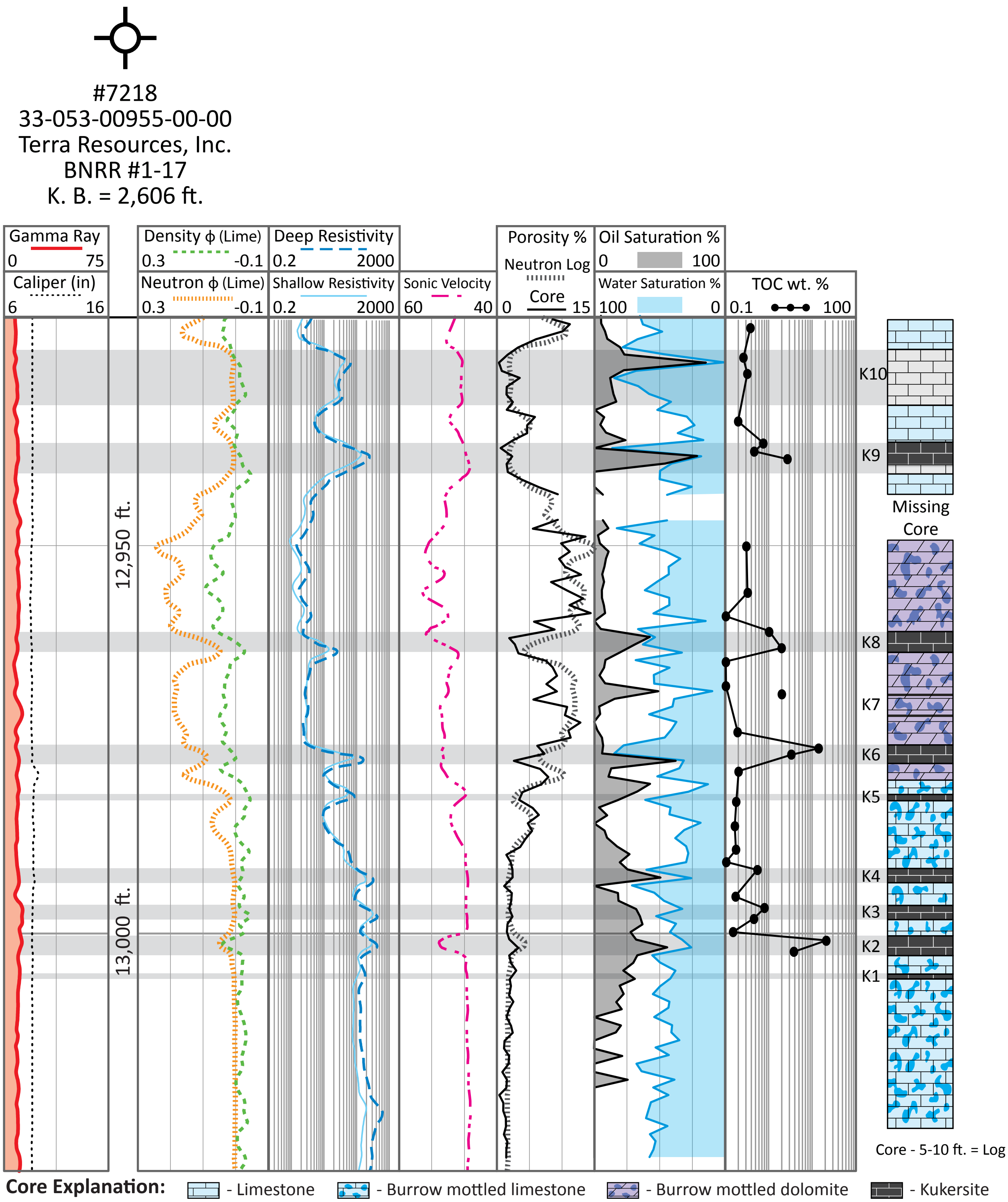

Figure 6. Wireline log suite (left) example of the Red River D interval with kukersites with standard core plug porosity and oil-water saturation data, core chip LECO TOC data, and illustrated core lithology profile (right). The K10 kukersite horizon and the lower portion of the K9 consist of the non-kukersite, organic-lean dense limestone facies within this core-log example. The K7 kukersite is largely absent, other than two moderately organic-rich (~2%TOC) thin beds/laminae (<1 inch).

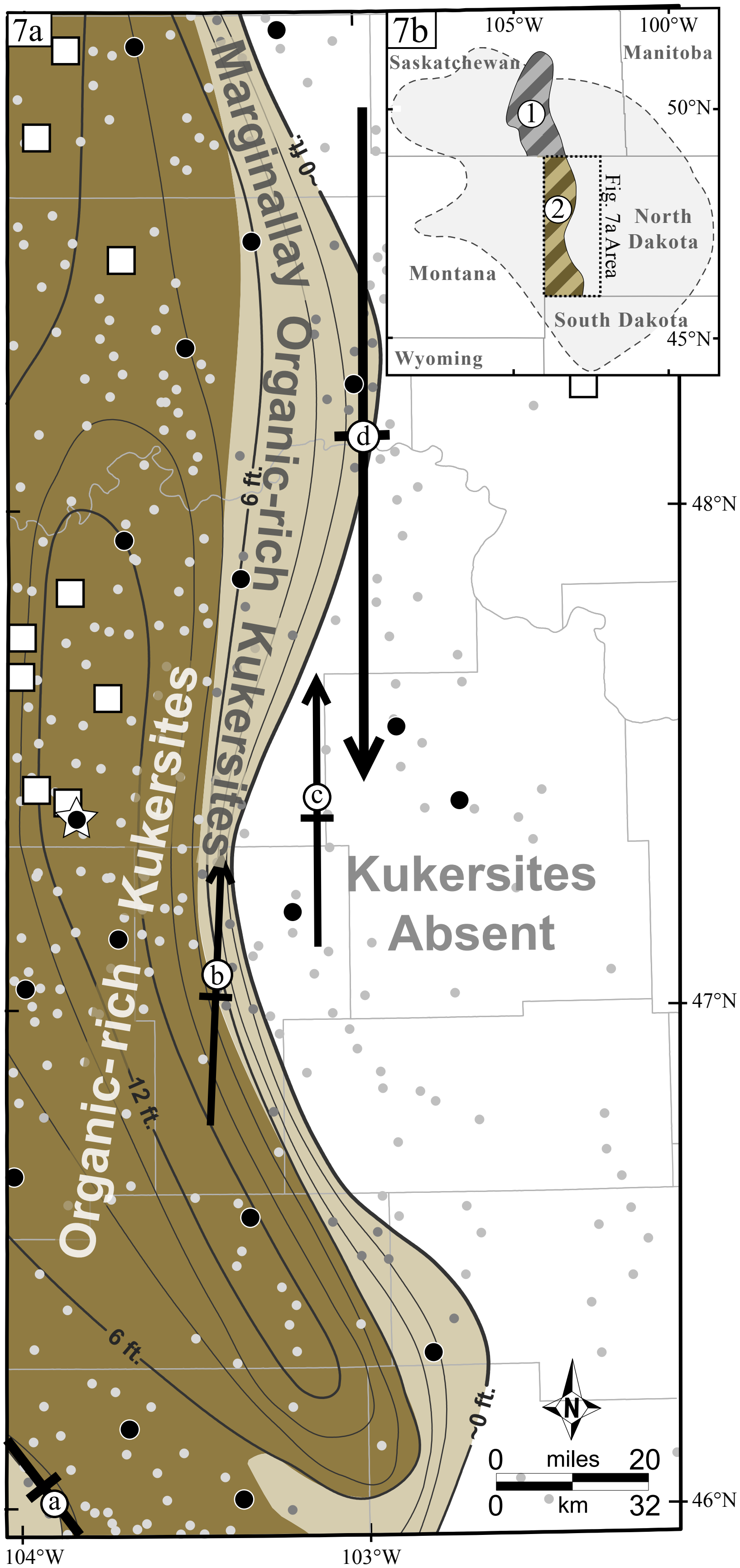

Figure 7. Kukersite extent maps for study area (7a) and Williston Basin (7b). 7a) Study area with kukersite extent in brown and kukersite net thickness contours (black lines = 2 ft (0.6 m) contour intervals). Kukersites combine to average 2% to 6% TOC within the "Organic-rich Kukersites" area (dark brown), and <2% TOC in the "Marginally Organic-rich Kukersites" area (light grey). Black circles represent partial Red River cores that were visually examined and sampled for TOC/Rock-Eval analysis. White squares represent cores that were visually examined but not sampled. Small white grey circles represent wells examined for kukersites using only wireline logs. The white star represents the location of the Figure 6 well. Thick black lines depict significant Williston Basin structures (anticlines) that appear to coincide with the boundaries of kukersite extent: a) Cedar Creek, b) Billing Nose, c) Little Knife, and d) Nesson anticlines. 7b) Williston Basin area showing kukersite extent, where area 1 for southern Saskatchewan was mapped by Osadetz and Haidl (1989) and area 2 was mapped for this study.

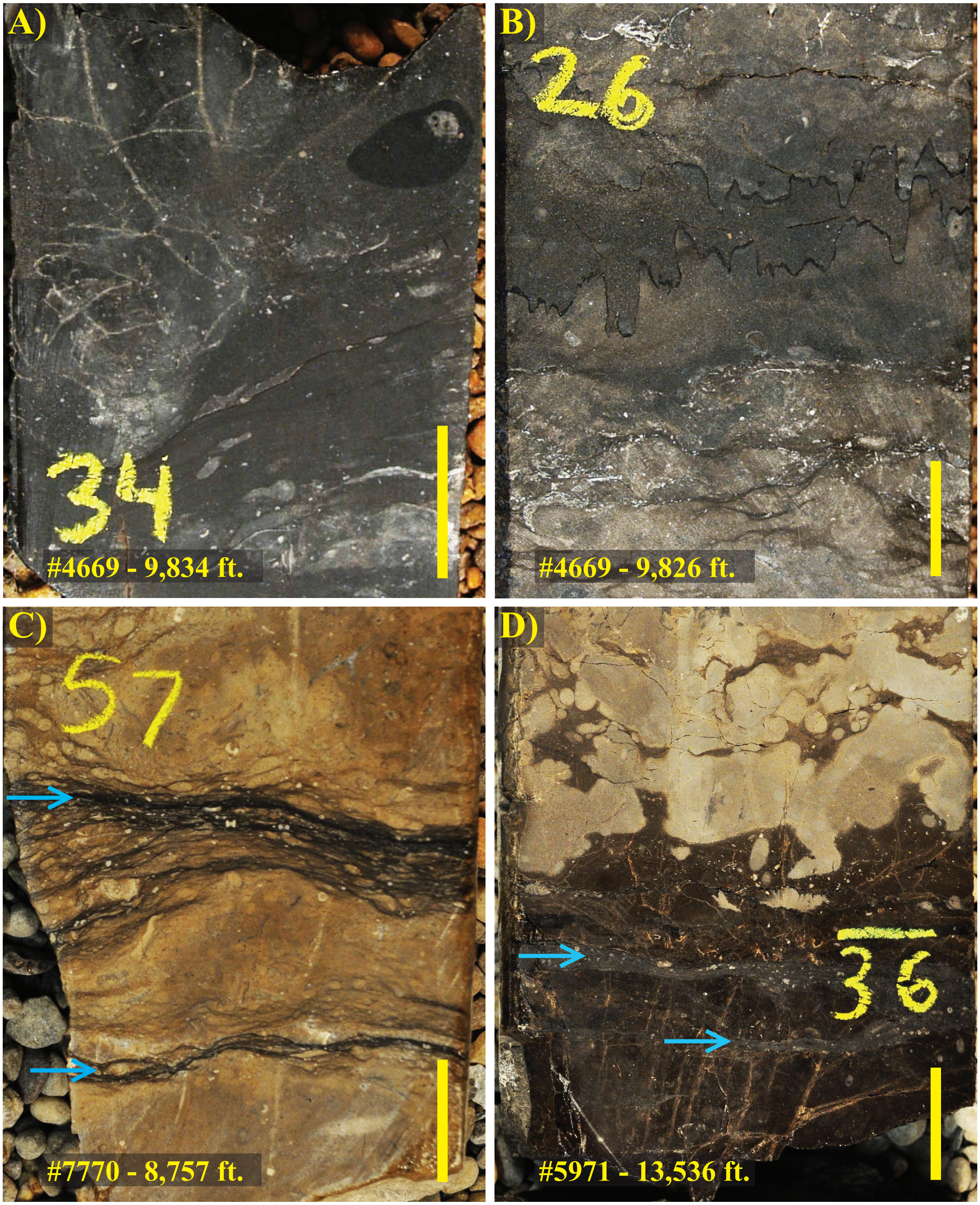

Figure 8. Core photographs from the Red River D interval. A) Dark grey, moderately organic-rich kukersite, K3 which contains 0.9 to 1.3 wt.% TOC, B) organic-lean (<0.5 wt. %), lateral equivalent of the K4 kukersite, C) limestone containing thin, organic-rich (~0.6 to 2.2% TOC) "wispy" laminations (blue arrows), and D) subtle but thin, organic-rich laminations (blue arrows) within a dark brown, organic-rich bed. As the kukersite beds thin and/or dissappear moving laterally, they grade into marginally organic-rich kukersites (e.g., 8A), organic-lean limestone beds (e.g. 8B), and/or thin, organic-rich laminae (e.g., 8C and 8D). NDIC well number with core depth and one-inch scale bar in the bottom left and right corners.

Section II:

Thermal Maturity of Kukersite Petroleum Source Beds and Thermally Generated, In-Place Hydrocarbons

METHODS

Kukersite thermal maturity was evaluated using geochemical data produced from core chips in conjunction with produced hydrocarbon characteristics. A total of 417 core chip samples were collected from 18 Red River cores and analyzed using the LECO TOC method (Fig. 9). Most of the samples were collected preferentially from the darker colored, and presumably more organic-rich, kukersite intervals. A few samples from each core were also collected from the lighter colored, presumably more organic-lean intervals (e.g., burrow-mottled facies) to develop a baseline of organic content throughout the upper half of the Red River. Samples that yielded 0.5 wt. % TOC or greater (and a few with <0.5% TOC) were analyzed using Rock-Eval 6 pyrolysis in order to evaluate the kerogen type, quality, and thermal maturity. All of the LECO TOC and Rock-Eval pyrolysis analytical work was completed by Weatherford Labs. Previously reported TOC and Rock-Eval pyrolysis data from Red River (upper Yeoman Fm.) kukersites of southern Saskatchewan (Osadetz and Snowdon, 1995) were reviewed and incorporated into this study to develop a more complete, regional understanding of kukersite kerogen type and thermal maturity.

Kukersite thermal maturity with respect to oil generation was evaluated using Tmax and hydrogen index (HI) values from LECO TOC and Rock-Eval pyrolysis analysis. HI represents the ratio of kerogen, organic carbon capable of converting into hydrocarbons, to total organic carbon, which includes kerogen along with inert (non-generative) carbon and hydrocarbons. Tmax represents the temperature at which the maximum rate of hydrocarbons released occurs during Rock-Eval pyrolysis. The Tmax data generated through Rock-Eval pyrolysis were screened to sort out unreliable and questionable values. Tmax values, used to examine thermal maturity, were measured from samples that contained >0.5 mg/g S2 (most contained >2.0 mg/g S2), which is above the 0.2 mg/g S2 cutoff recommended by Peters (1986). The reliability of Tmax values measured from kukersite cores samples was further assessed by examining the signal strength and shape of the S2 peaks on the Rock-Eval pyrolysis pyrograms (Fig. 10). Tmax values that were found to correlate with well-defined S2 peaks and strong signal strengths were rated as good to excellent and utilized for thermal maturity mapping (e.g., Figs. 10A and 10C). Tmax values found to correlate with S2 peaks that were poorly defined, irregularly shaped, and/or displayed very weak signals were rated as questionable to unreliable and were mostly not incorporated into thermal maturity investigation and mapping (e.g. Figs. 10B and 10D). Questionable pyrograms were utilized from a few, higher maturity cores, where more reliable (good to excellent quality) Tmax values were unavailable.

Produced hydrocarbon thermal maturity was further examined using available well information data to augment source bed geochemical data and evaluate lateral migration of generated hydrocarbons. Gas to oil ratios (GOR), oil properties (e.g., API oil gravity), and gas compositions of Red River C and D interval production was compiled to evaluate hydrocarbons produced from reservoirs proximal to kukersites. Production and perforation records compiled from well files were reviewed from over 450 wells that have produced from the Red River oil and gas pool according to the North Dakota Industrial Commission database. The following criteria was used to distinguish reliable data: greater than 3 months of production from perforations restricted to the C and/or D interval/s where monthly oil, gas, and water production volumes were all consistently reported in the North Dakota Industrial Commission database. API gravity of produced oil was compiled from lab analysis reports and well completion reports.

RESULTS AND OBSERVATIONS

Kukersite Tmax values are moderately to highly variable within a single core, but overall increase towards the basin center. Kukersite samples from a single Red River core yielded reliable Tmax values that sometimes varied by up to 10°C between the lowest and highest measured Tmax values (e.g. well #11139 – Fig. 11). Even within a single kukersite interval, from samples spanning less than 1 ft. of vertical core section, reliable Tmax values were found to vary by up to 6°C, a notable difference in thermal maturity evaluation. However, the average Tmax of kukersite samples by core increases from 446°C to ≥460°C towards the central, deepest portions of the basin (Figs. 11 and 12).

Kukersite HI values can be similarly variable within a single core, but overall decrease towards the central basin. Core sample sets that yielded relatively high HI values (>400) often displayed moderate to very high variability in kukersite HI, sometimes ranging from 240 to 901 mg HC/g TOC (e.g., well #11302 – Fig. 11). Within cores that yielded low HI kukersite values (<200), HI variability was much more limited (e.g., well #9618 – Fig. 11). The average kukersite HI of individual core data sets decreases from >500 mg HC/g TOC to <100 mg HC/g TOC towards the central, deepest portions of the basin (Fig. 13), an expected inverse trend to the average kukersite Tmax (Fig. 12). Plotting reliable Tmax and HI values of individual kukersite samples, HI values overall decrease while Tmax values increase for individual core chip samples, but there is a moderate amount of scatter in the data (Fig. 11A – HI vs. Tmax plot). Examining the average Tmax and HI values of kukersite samples by individual core data sets, the inverse relationship between Tmax and HI occurs with minimal scatter (Fig. 11B).

When examining the characteristics of produced hydrocarbons from the C and D intervals, reservoirs proximal to the kukersites, similar trends to kukersite thermal maturity emerge. Exclusive and reliable C and/or D interval production data from 216 wells were identified that met study-defined requirements (Figs. 14 and 15). Overall, API oil gravity and GOR of produced hydrocarbons from C and D reservoirs increase simultaneously with one another with a moderate amount of data scatter when plotted together (Fig. 16). Furthermore, compiled maps of GOR and API oil gravity data show that both produced hydrocarbon characteristics vary to some degree with one another, but overall increase towards the central, deepest portions of the basin (Figs. 14 and 15). Comparing produced hydrocarbon characteristics with kukersite geochemical data, the average HI decreases while the average Tmax, API oil gravity, and GOR all increase (Fig. 16).

INTERPRETATIONS AND DISCUSSION

Lateral Hydrocarbon Migration in the C and D Intervals

Lateral hydrocarbon migration within the C and D intervals appears to be minimal in the western half of the study area, where the kukersites are present. The relatively systematic increase in GOR and API oil gravity of producible C and D interval hydrocarbons is a function of thermal alteration of previously generated hydrocarbons as well as changes in the types of hydrocarbons being generated from the kukersites through continued, increasing thermal stress over time. The systematic increase in API oil gravity and GOR of hydrocarbons produced from the C and D interval reservoirs suggests lateral migration of generated hydrocarbons from the kukersites in those two intervals is minimal (<10 miles). If there was significant (>10 miles) lateral hydrocarbcon migration in these intervals, changes in produced hydrocarbon characteristics would likely be more variable spatially and would not change as systematically towards basin center. For example, oil produced from Red River wells in southern Saskatchewan display a wide range of API oil gravity (26-42°) where laterally hydrocarbon migration and a mixing of low and high maturity oils has been interpreted (Fowler et al., 1998; Pu et al., 2003).

The proposed limited lateral hydrocarbon migration in the C and D intervals is speculated to be a function of discontinuous reservoir quality which may be related to the presence of kukersites. Kohm and Louden (1978) previously suggested that kukersites (i.e. kerogenites) form hydrocarbon seals within the D interval (i.e. C burrowed member) reservoirs. One qualitative observation from this study is that the overall amount of porous dolomite within the D interval increases away from the central, deepest portions of the basin as well as east of the area of kukersite extent. The author speculates that the kukersite beds may also have formed partial barriers, or more so inhibitive layers to dolomitizing fluids that created the porosity and permeability within the D interval. Towards the central portions of the basin, where the kukersite beds are present in more abundance, D interval dolomite reservoir development is less prevalent where the downward flow of dolomitizing fluids into the burrow-mottled D interval was inhibited by the kukersite beds. As the kukersites disappear in the subsurface towards the margins of the basin, the dolomitizing fluids flowed into and through the D interval with less restriction resulting in more prevalent reservoir development within the D interval. Eventually, in the near absence of kukersites, dolomite reservoir development is continuous enough to form pathways for lateral fluid migration.

Hydrocarbon production from the D interval occurs eastward of the kukersite extent area both in southwestern North Dakota and southern Saskatchewan (Nesheim, 2017). Given the lack of thermally mature source rock in those areas, lateral hydrocarbon migration must have occurred within the D interval beyond the kukersite extent area. Dolomite porosity development in the Red River D interval of southern Saskatchewan is still variable, but displays enough lateral continuity for lateral migration (e.g. Figure 8 *in* Pu et al., 2003).

Kukersite Thermal Maturity

The thermal maturity of kukersite source beds and in-place, producible hydrocarbons increase in conjuncture with one another towards basin center due to the limited lateral migration of generated hydrocarbons in the C and D intervals. Produced hydrocarbon characteristics (API oil gravity and GOR) from the C and D interval reservoirs can therefore be used to approximate the level of thermal maturity for the D interval kukersites when source rock geochemistry (HI and TOC) is limited or absent from a given location or area. The preliminary HI map (Fig. 13) was re-contoured by incorporating the produced C and D interval hydrocarbon characteristics (Fig. 17).

Significant variations in HI between kukersite samples from a single core are speculated to be a function of kerogen variation, where the ratio of disseminated versus non-disseminated *G. Prisca* vary from one sample to another. Tmax variations are similarly thought to be a function of kerogen variation as well as some level of instrumentation error. Averaging Tmax and HI values from kukersite samples within a single core is thought to partially even out kerogen variation (disseminated versus non-disseminated *G. Prisca*) as well as instrumentation error. Therefore, average values for Tmax and HI by core were used to contour thermal maturity maps for both the study area (Figs. 12, 13, and 17) and larger Williston Basin area (Fig. 18).

Examining the Red River D interval kukersites from southern Saskatchewan through western North Dakota, average HI decreases from >900 to <100 mg HC/g TOC moving from shallower depths to basin center (Fig. 18). This decrease in average kukersite HI also corresponds to an increase in average Tmax across the basin (Fig. 19). The decrease in average HI and increase in average Tmax is interpreted to represent increasing kukersite thermal maturity, where the percentage of original kerogen decreases as it is converted into hydrocarbons.

A rapid decline in average HI occurs along the south-central Saskatchewan and northwestern North Dakota borders, where there is a high data population, and appears to occur along the southwestern corner and portions of the western side of the study area based on more limited data (Fig. 18). The rapid decline in average HI is interpreted to represent where the kukersite beds have reached the peak mature oil generation window, where kerogen has or is being converted to hydrocarbons at the peak conversion rate. The interpreted peak oil generation window corresponds to an average Tmax value range of 446° to 451° for the North Dakota data set, and 453° to 458° for the pre-existing data set for southern Saskatchewan from Osadetz and Snowdon (1995) (Fig. 19). The 7° Tmax difference is speculated to be a function of variation in the instruments used to create the two data sets.

The late mature stage of oil generation is defined as the interval where the majority of the original kerogen in source beds has been converted into hydrocarbons, and hydrocarbon generation continues with increasing thermal stress but at a slower rate than the peak mature window due to depleted kerogen quantities. The late mature stage of oil generation is interpreted where the average kukersite HI has dropped below 300 mg HC/g TOC, which is less than a third of the values of the assumed original HI of 956 mg HC/g TOC, and the rate of decreasing HI versus Tmax is more gradual (Fig 19b). The interpreted late mature window is also where the GOR of producible hydrocarbon in the reservoirs (C and D intervals) adjacent to the source beds continues to increase with greater depth and higher thermal stress as the remaining kerogen begins to generate more hydrocarbon gas versus oil (Figs. 15, 16, and 20).

The overmature stage of oil generation is defined as the point where limited hydrocarbon generation potential remains in the petroleum source beds. The remaining hydrocarbons being generated consist primarily of dry gas (methane). Further, the previously generated oil begins to thermally convert into dry gas (Fig. 20). The overmature stage of oil generation is interpreted based on two observations: 1) the gas to oil ratio (GOR) of producible hydrocarbons in the reservoirs (C and D intervals) adjacent to the source beds begins to rapidly increase with depth and thermal stress (Figs. 15 and 16), and 2) there is limited remaining hydrocarbon generation potential remaining in the kukersite source beds indicated by HI values of <100 mg HC/g TOC (Figs. 13, 16-18). The rapid increase in GOR of producible hydrocarbons is thought to be primarily a function of thermal conversion of previously generated oil into dry gas and secondarily the generation of hydrocarbon gas from remaining kerogen in the kukersite source beds. The low HI values are a function of hydrocarbon generation depleting the kukersite source beds.

While kukersite thermal maturity tends to increase overall with depth, the correlation is far from linear (Figs. 19A and 21). Heat flow from the underlying crystalline basement appears to vary substantially across western North Dakota, resulting in variable subsurface temperature gradients (Fig. 22) (McDonald, 2016). This leads to thermal maturity levels that may appear anomalously low for a given depth in one area (e.g., well #20043 – Fig. 18), while anomalously high in another (e.g., well #4241 – Fig. 18). An area of relative high heat flow appears to extend along the north-south synclinal axis of the Williston Basin, which parallels such structures as the Nesson, Little Knife, and Billings Nose anticlines (Fig. 22). Along this north-south oriented high heat flow trend, petroleum source beds in any given formation will likely reach higher levels of thermal maturity at shallower depths as compared to surrounding areas.

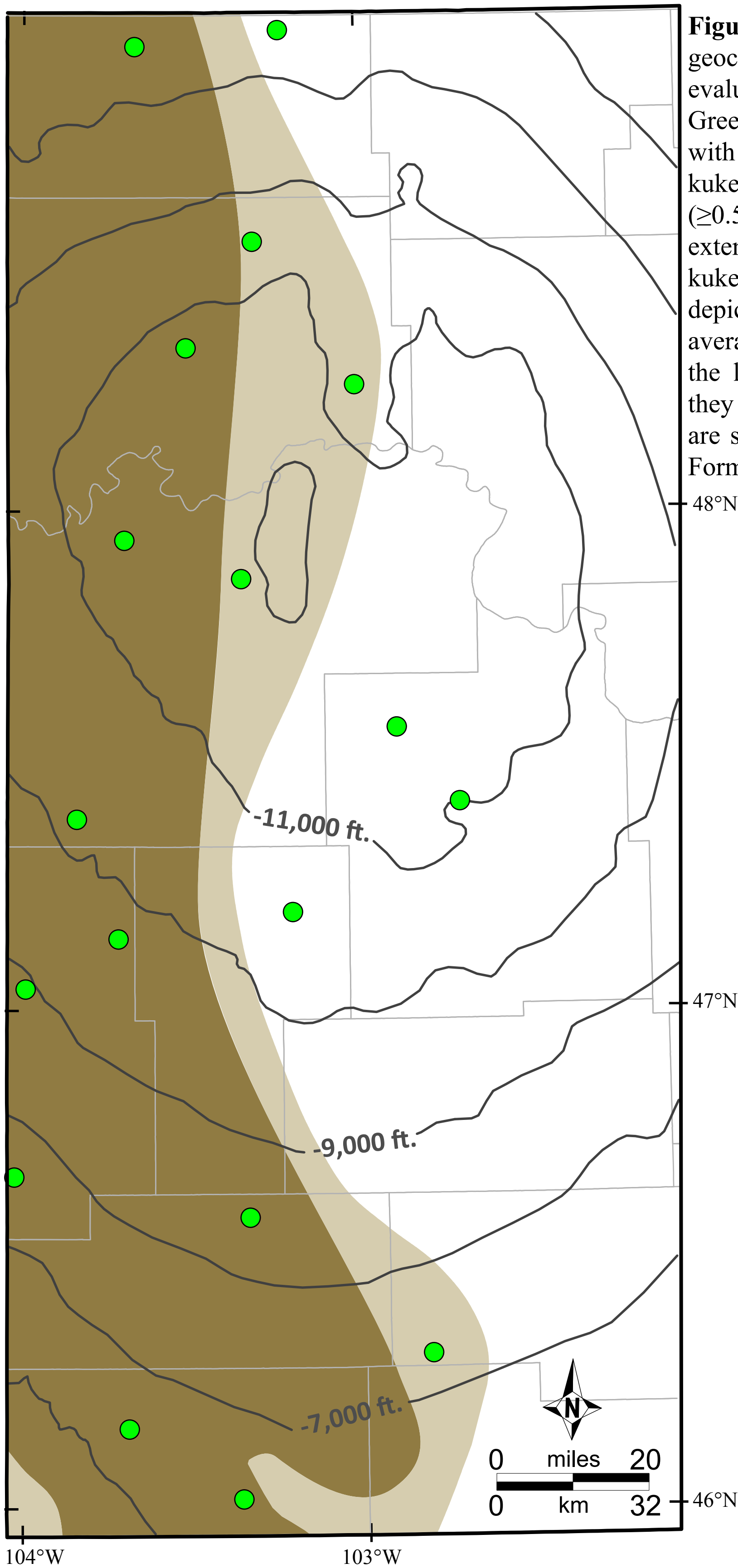

Figure 9. Study area showing the geochemical control wells used to evaluate kukersite thermal maturity. Green circles represent core locations with geochemical control data from kukersites and/or organic-rich laminae (≥0.5% TOC). Brown fill represents the extent of Red River D interval kukersites. The darker brown fill depicts were the kukersites combine to average 2% to 6% TOC (by weight), and the lighter brown fill represents where they average <2% TOC. The black lines are structure contours on the Red River Formation top.

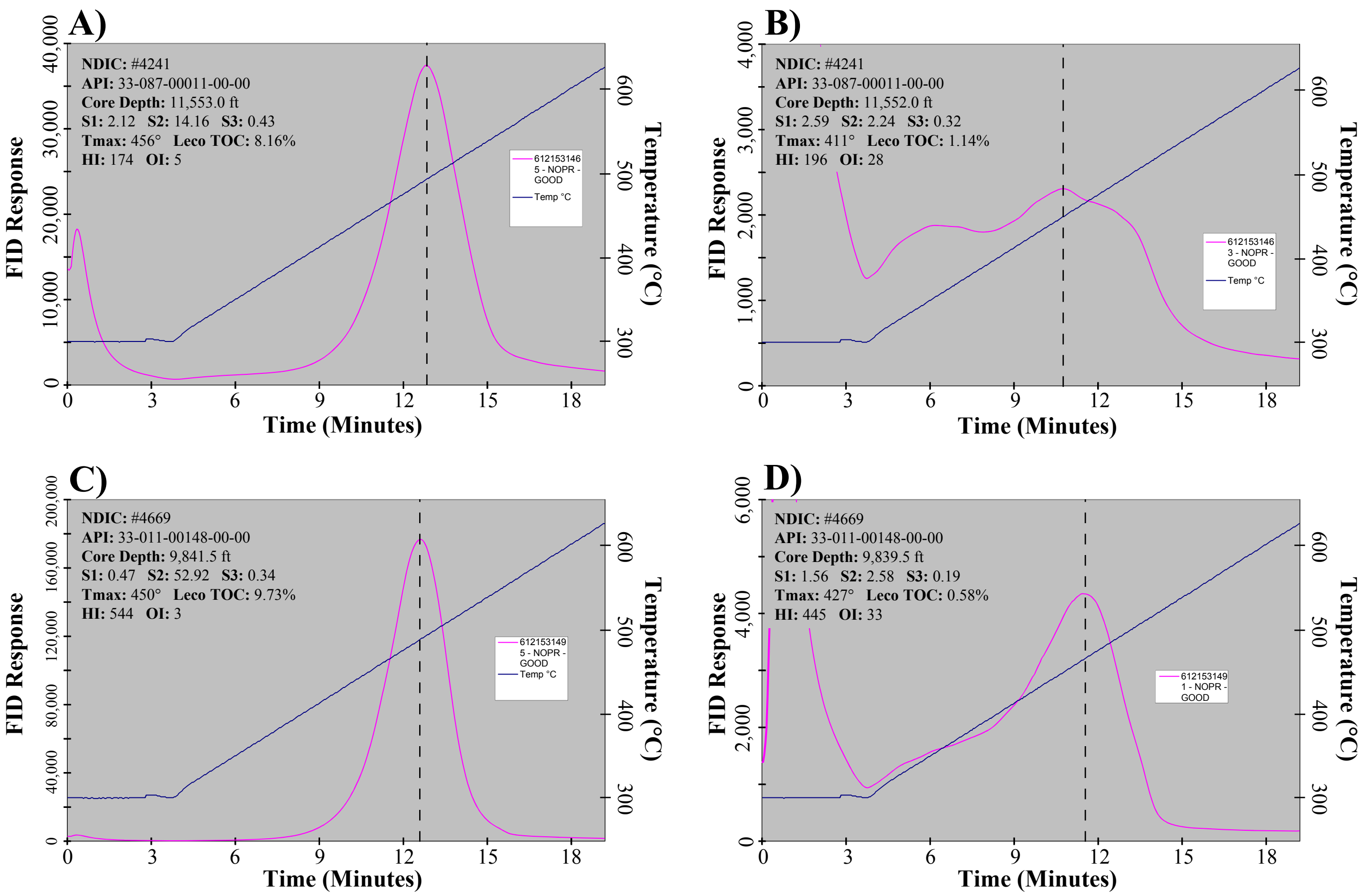

Figure 10. Example pyrograms from Rockeval pyrolysis for Red River kukersite samples. A) Excellent quality S2 peak from NDIC #4241 that corresponds with a reliable Tmax value, B) irregular S2 peak from NDIC #4241 that corresponds with an unreliable Tmax value, C) excellent quality S2 peak from NDIC #4669 that corresponds with a reliable Tmax value, and D) moderately irregular S2 peak from NDIC #4669 that corresponds with a questionable Tmax value. The pink line in each pyrogram corresponds with the FID (Flame Ionization Detector) response and the blue line represents the temperature. The dashed lines indicate the S2 peak used to calculate the Tmax value for each corresponding sample.

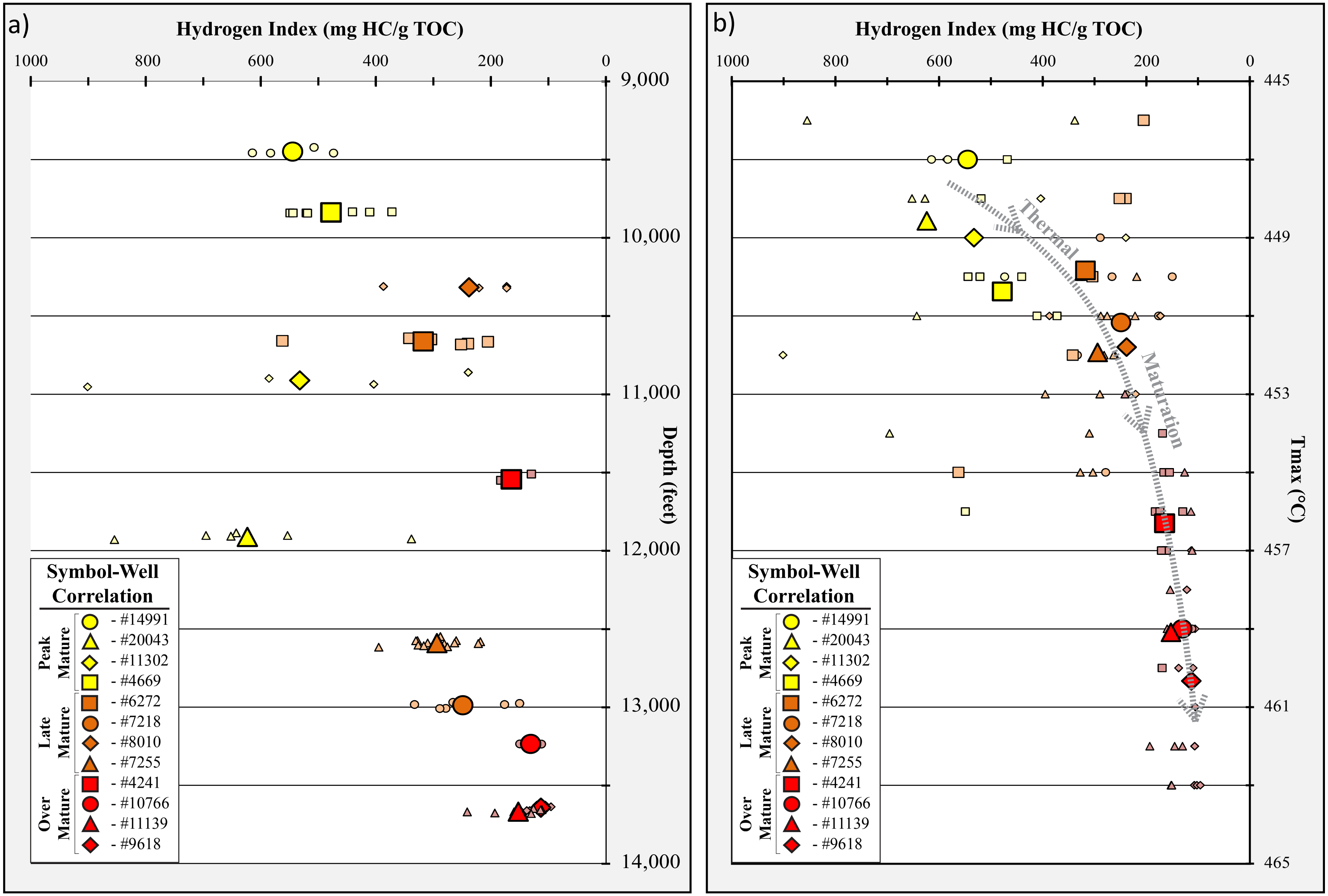

Figure 11. Hydrogen Index (HI) versus depth (11a) and Tmax (11b) of kukersite core samples from western North Dakota. Corresponding NDIC well number is listed in the explanation. The small symbols represent individual core chip samples that correlate to the large symbols, which represent the average values of kukersite samples within a given core.

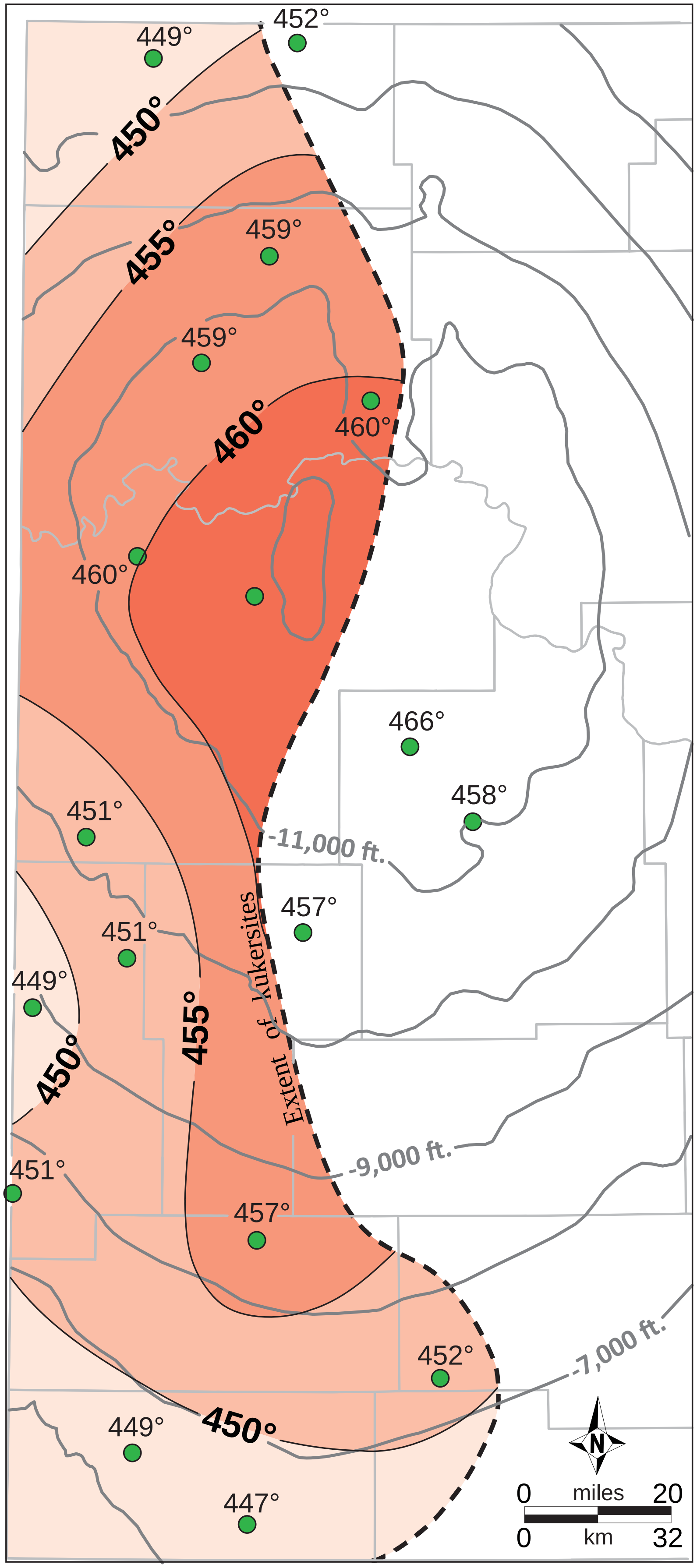

Figure 12. Map displaying the average Tmax of organic-rich (≥0.5% TOC) D interval core samples. Pyrograms were screened to remove questionable or unreliable Tmax values. The structure contours (grey lines) represent the top of the Red River Formation.

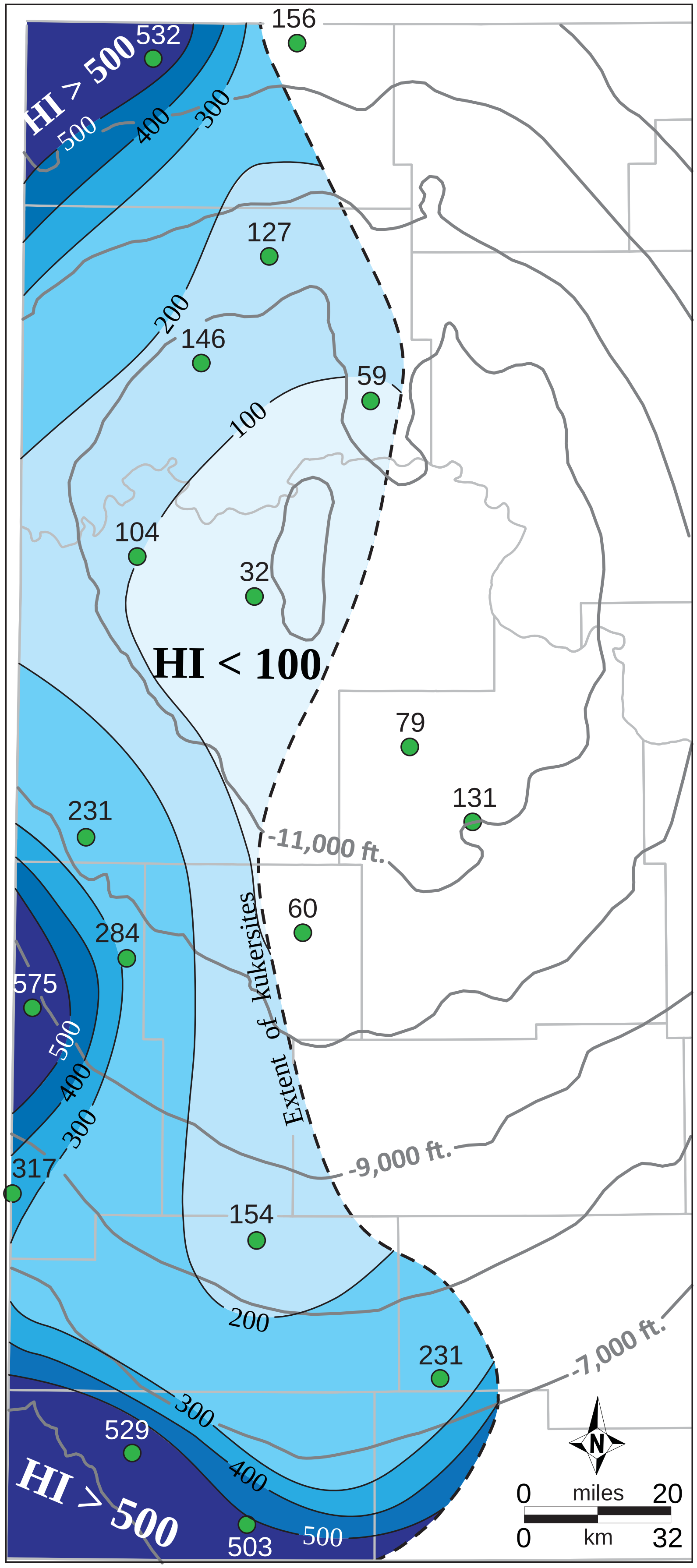

Figure 13. Preliminary map of the average Hydrogen Index (HI) of kukersite and other organic-rich (≥0.5% TOC) D interval core samples created utilizing only the geochemical core data. The structure contours (grey lines) represent the top of the Red River Formation.

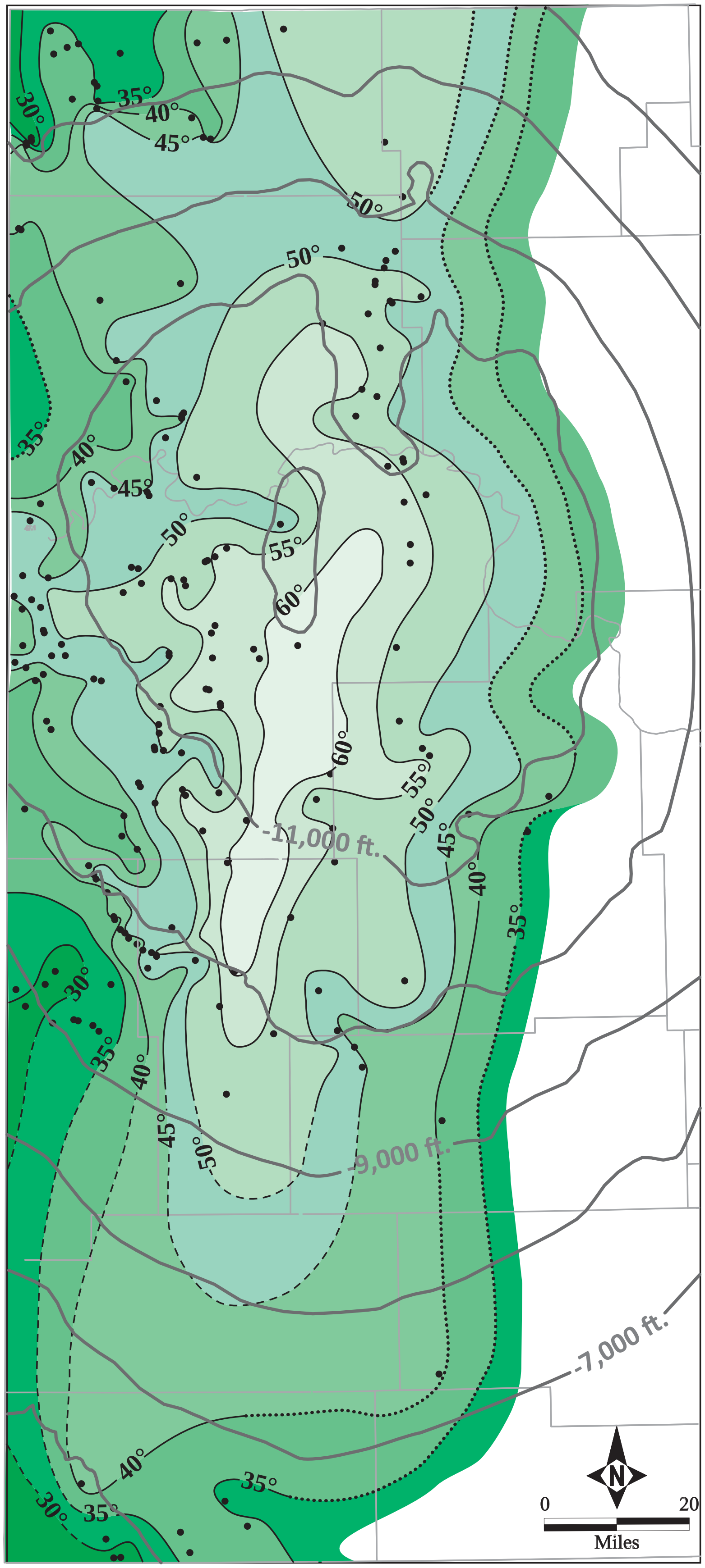

Figure 14. API oil gravity map for hydrocarbons produced from Red River Formation C and D interval reservoirs. The black solid, dashed (estimated), and dotted (inferred) lines are the contours for C and D interval API oil gravity (°C). Black dots represent control wells. The thick darker grey lines represent structure contours in 1,000 ft. increments on the Red River Formation top. Thin light grey line represent county borders.

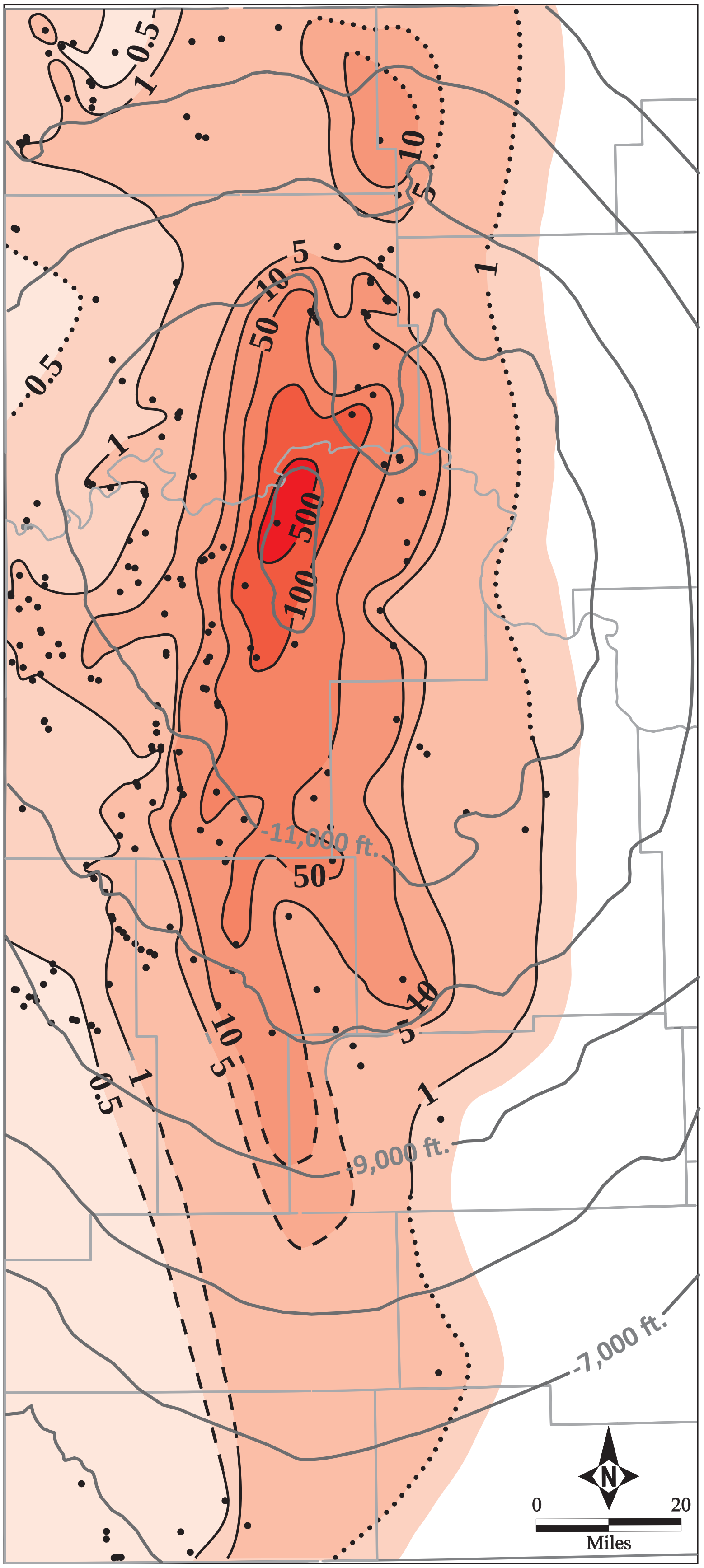

Figure 15. Gas to oil (GOR) ratio map for hydrocarbons produced from Red River Formation C and D interval reservoirs. The black solid, dashed (estimated), and dotted (inferred) lines are the contours for C and D interval hydrocarbon GOR. GOR units are in MCF (thousand cubic feet) gas per barrel of oil. Black dots represent control wells. The thick darker grey lines represent structure contours in 1,000 ft. increments on the Red River Formation top. Thin light grey line represent county borders.

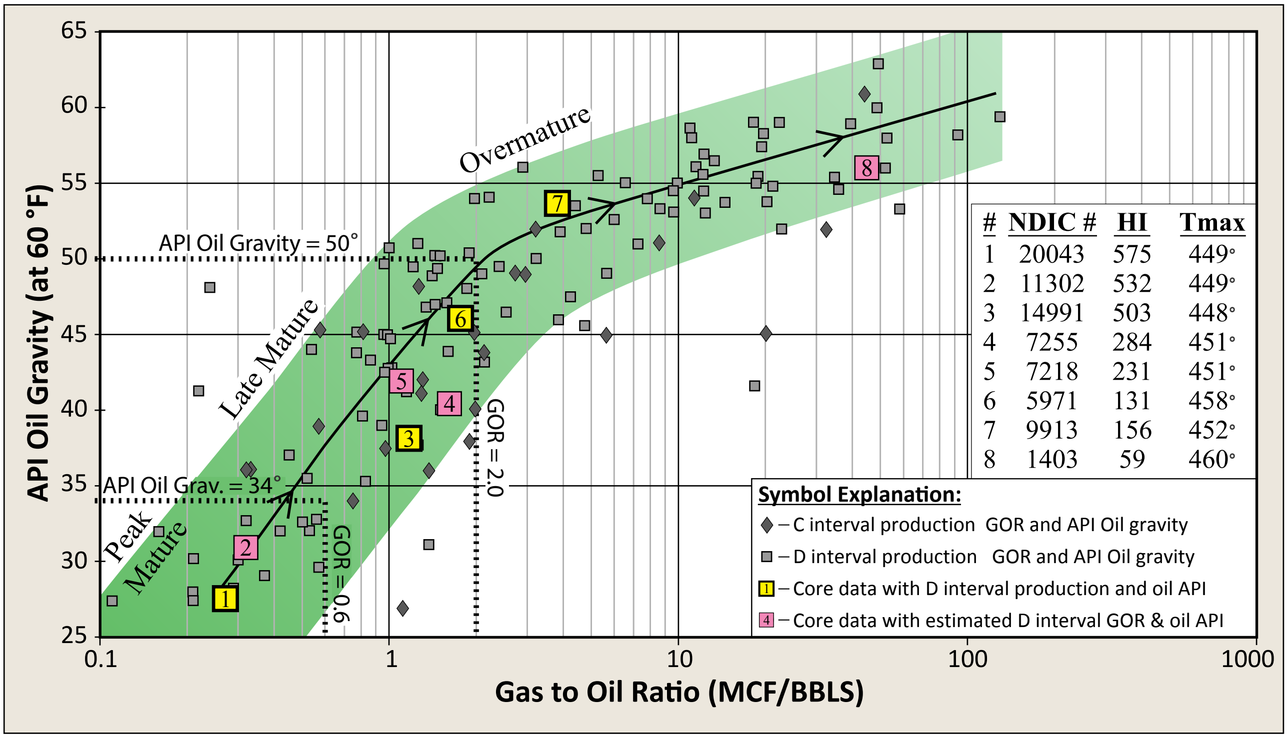

Figure 16. Produced hydrocarbon maturity diagram plotting API oil gravity versus gas to oil ratios for hydrocarbons produced from Red River C and D interval reservoirs. The average kukersite HI and Tmax values from corresponding cores with produced hydrocarbon data are given for eight wells. Four of those cores are from wells with reliable D interval production GOR and API oil gravity. GOR and API oil gravity was estimated for the additional four wells with core data sets using nearby and/or surrounding production data. While there is some scatter of the data, kukersite (source bed) thermal maturity increases (HI and Tmax) in conjuncture with the thermal maturity of hydrocarbons in adjacent reservoir beds, which presumably was sourced by local kukersites.

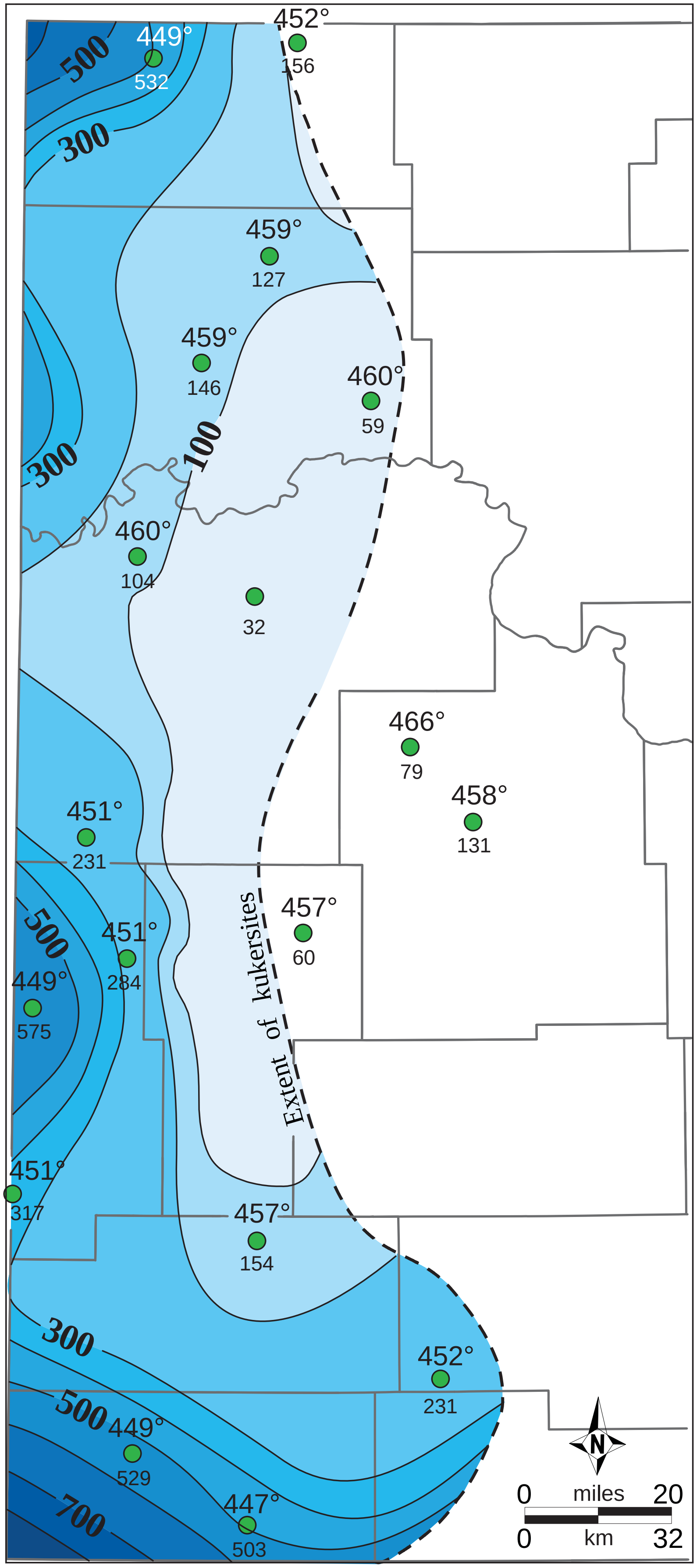

Figure 17. Revised average Hydrogen Index (HI) map for Red River D interval kukersites for western North Dakota created using geochemical core data augmented by produced hydrocarbon characteristics. Geochemical core data (TOC and RockEval pyrolysis) are the primary data set (Fig. 13), while API oil gravity and GOR of hydrocarbons produced from C and D interval reservoirs were utilized as a secondary data set (Figs. 14 and 15).

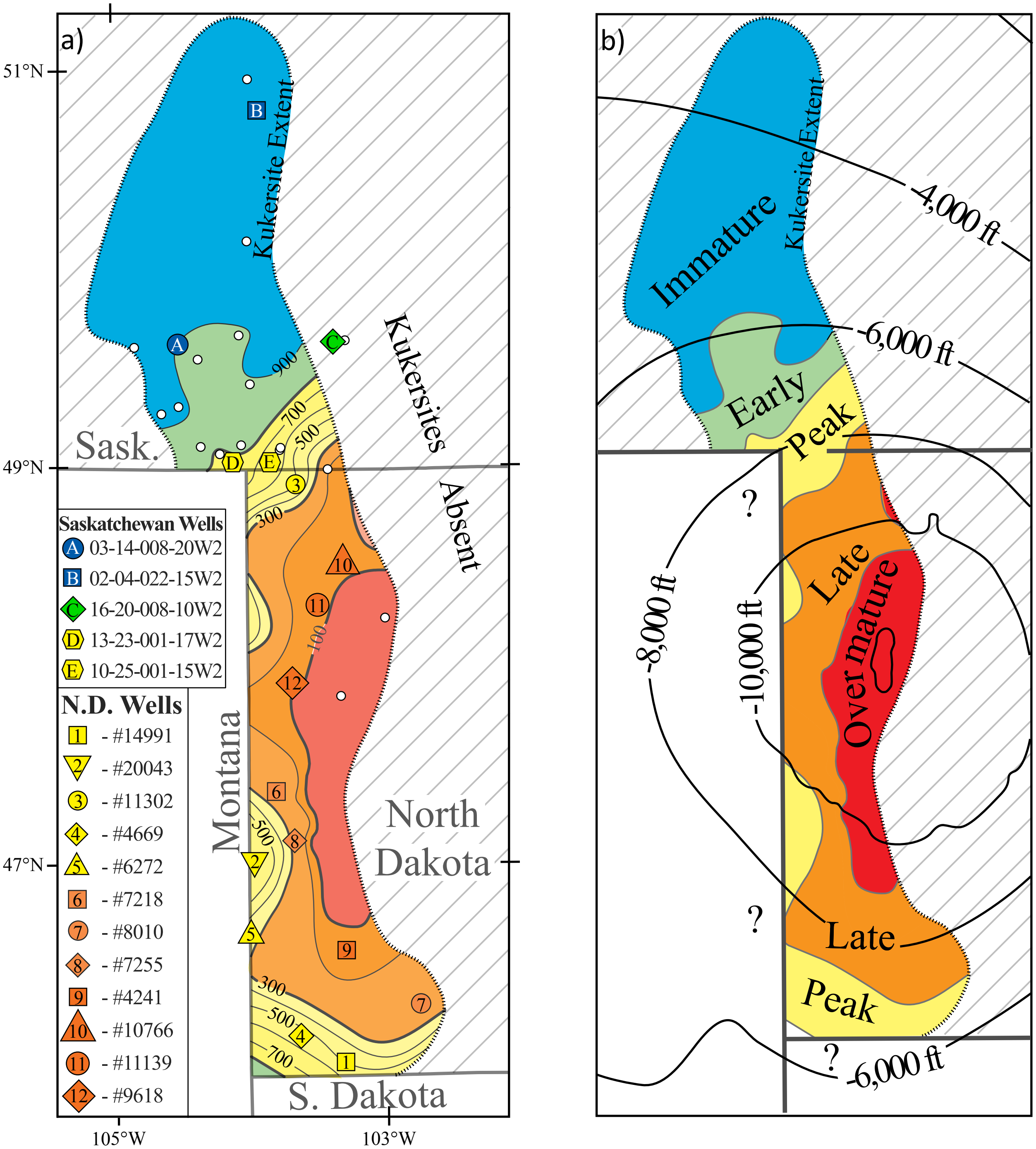

Figure 18. Red River kukersite extent map for southern Saskatchewan and western North Dakota displaying; 18a) average kukersite HI with well control, and 18b) interpreted stages of oil generation for kukersites with structure contours (black lines) on the Red River Formation top. Large symbols with corresponding numbers and letters represent wells with four or more analyzed kukersite samples that were used as the primary dataset to contour average kukersite HI. Small white circles represent additional core locations with three or less kukersite core chip samples analyzed for TOC and Rock-Eval (Saskatchewan) or with unreliable Tmax values due to very low S2 content and questionable to unreliable pyrograms (North Dakota). The extent of Red River kukersites in southern Saskatchewan is from Osadetz and Haidl (1989).

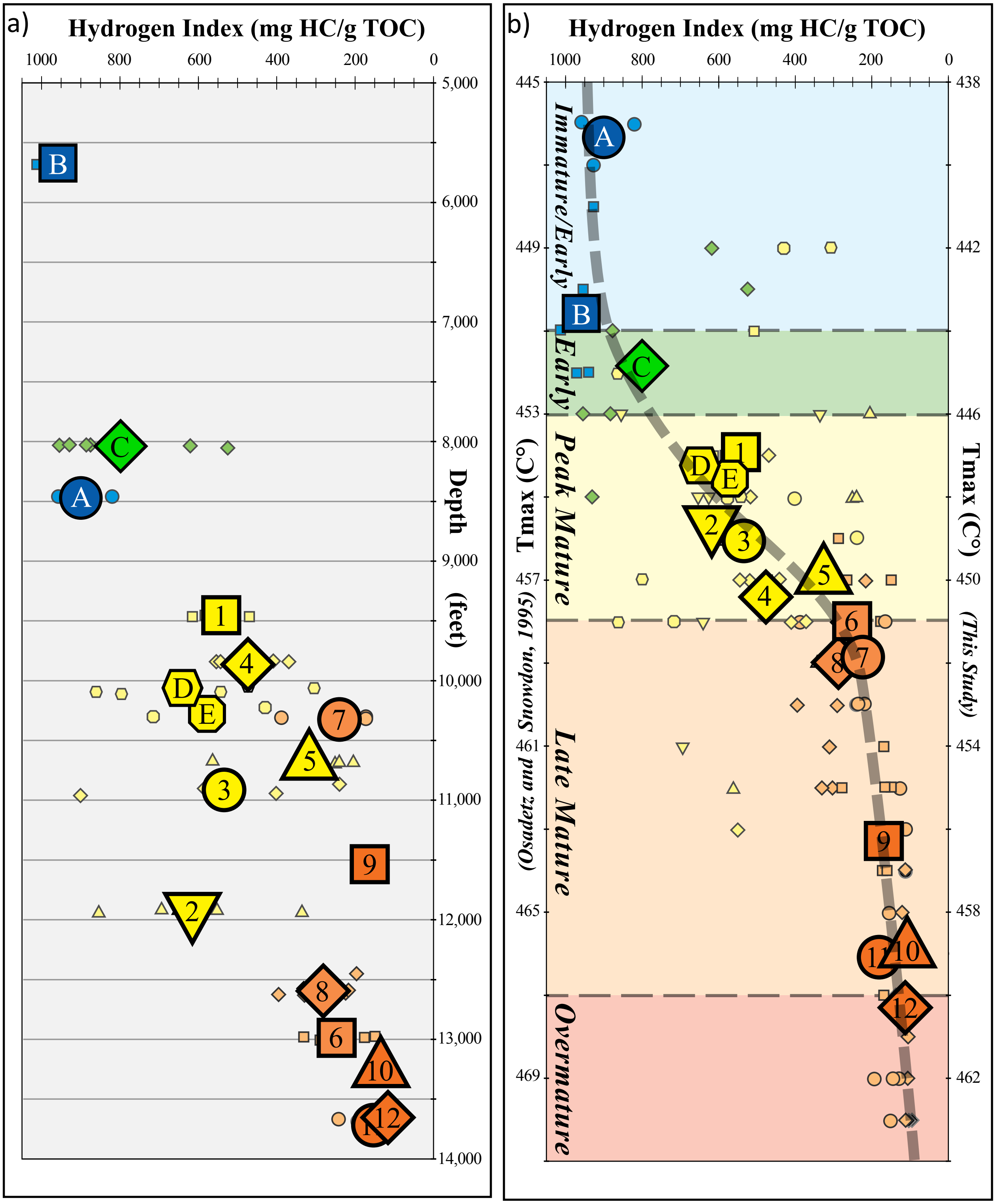

Figure 19. Kukersite HI versus depth (19a) and versus Tmax (19b). Large numbered (ND samples) and lettered (Sask. samples) symbols represent average kukersite HI by core. The small symbols represent individual core chip samples that correlate to the large symbols. Numbers and letters correspond to Figure 18.

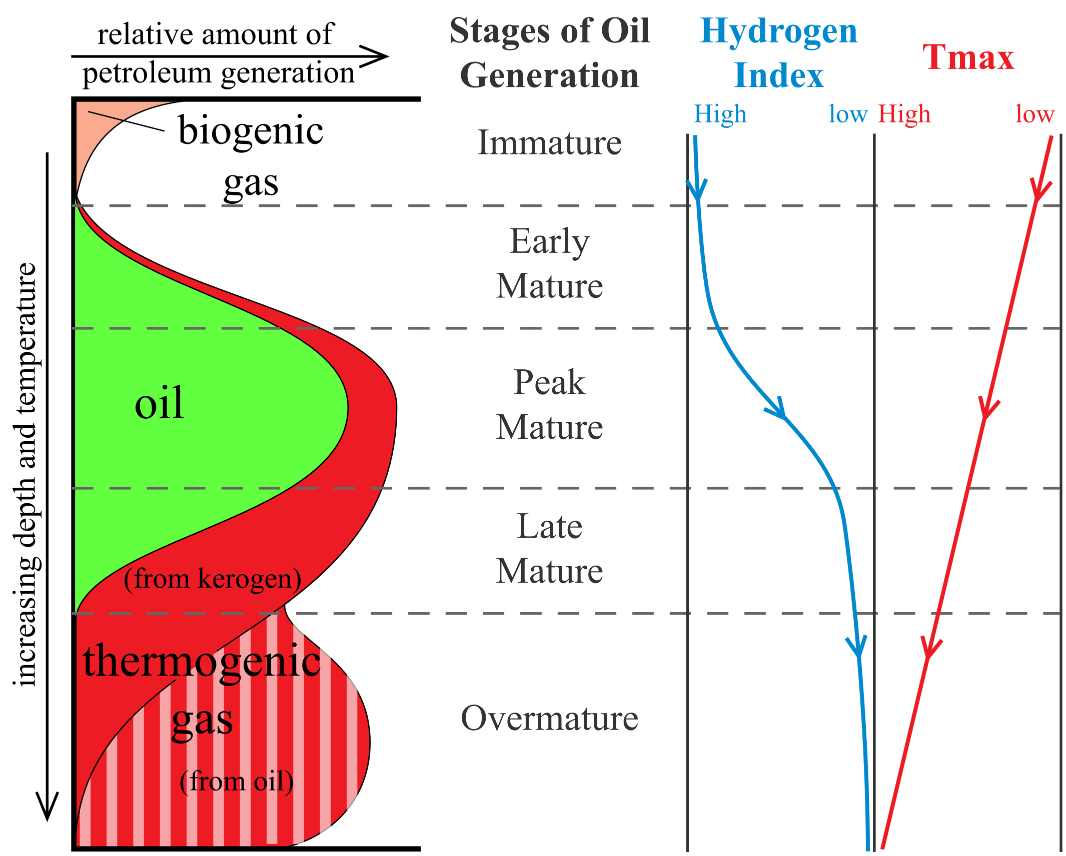

Figure 20. Stages of oil generation in relation to the general type of and quantity of generated hydrocarbons, increasing depth and temperature, and corresponding changes in source bed hydrogen index and Tmax values.

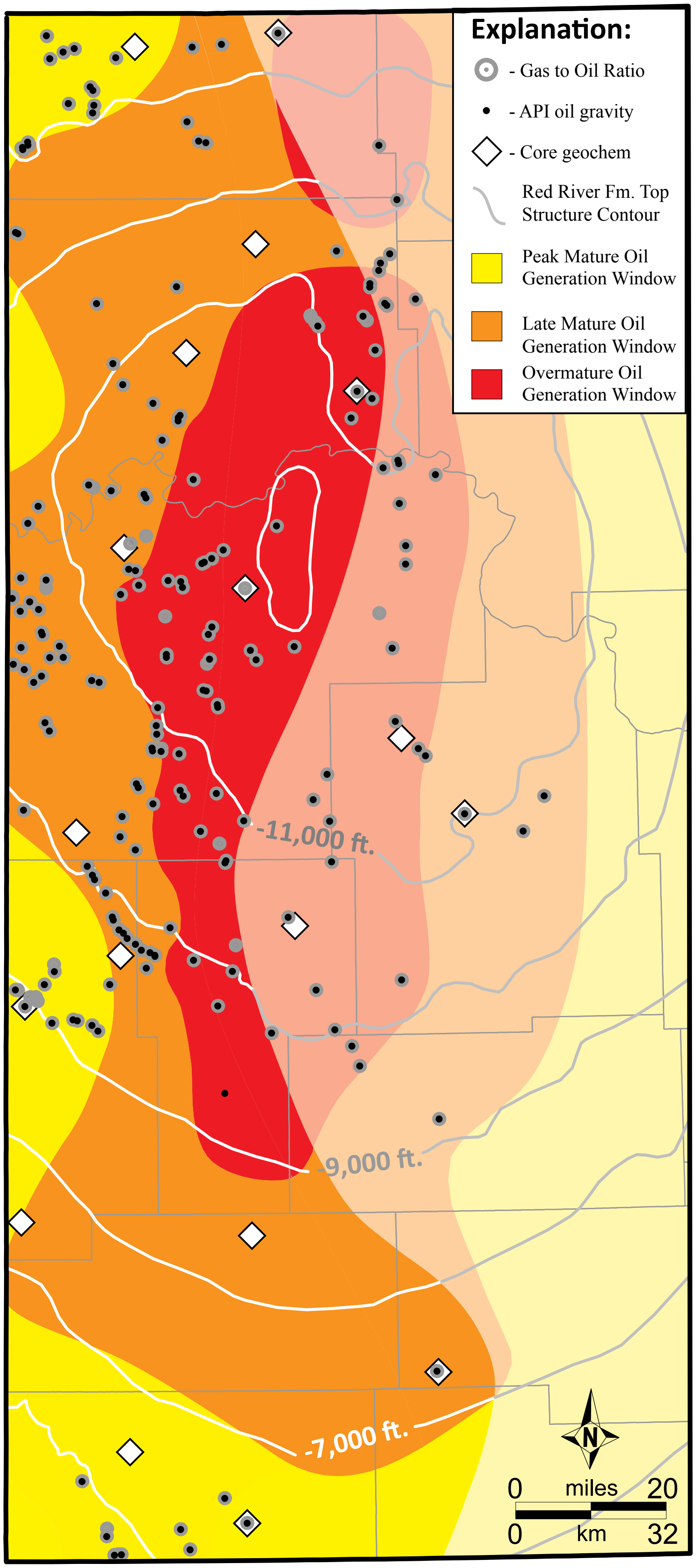

Figure 21. Map depicting the extent of D interval kukersites (bold colors = kukersites present, light colors = kukersites absent) versus interpreted thermal maturity and structural depth (feet below sea level). Note that the API oil gravity and GOR values for wells east of the area of kukersite extent very likely represent migrated hydrocarbons. Migrated hydrocarbons would likely have moved from deeper (higher thermal maturity conditions) to shallower depths (lower thermal maturity conditions) and therefore should be considered to depict a maximum level of thermal maturity.

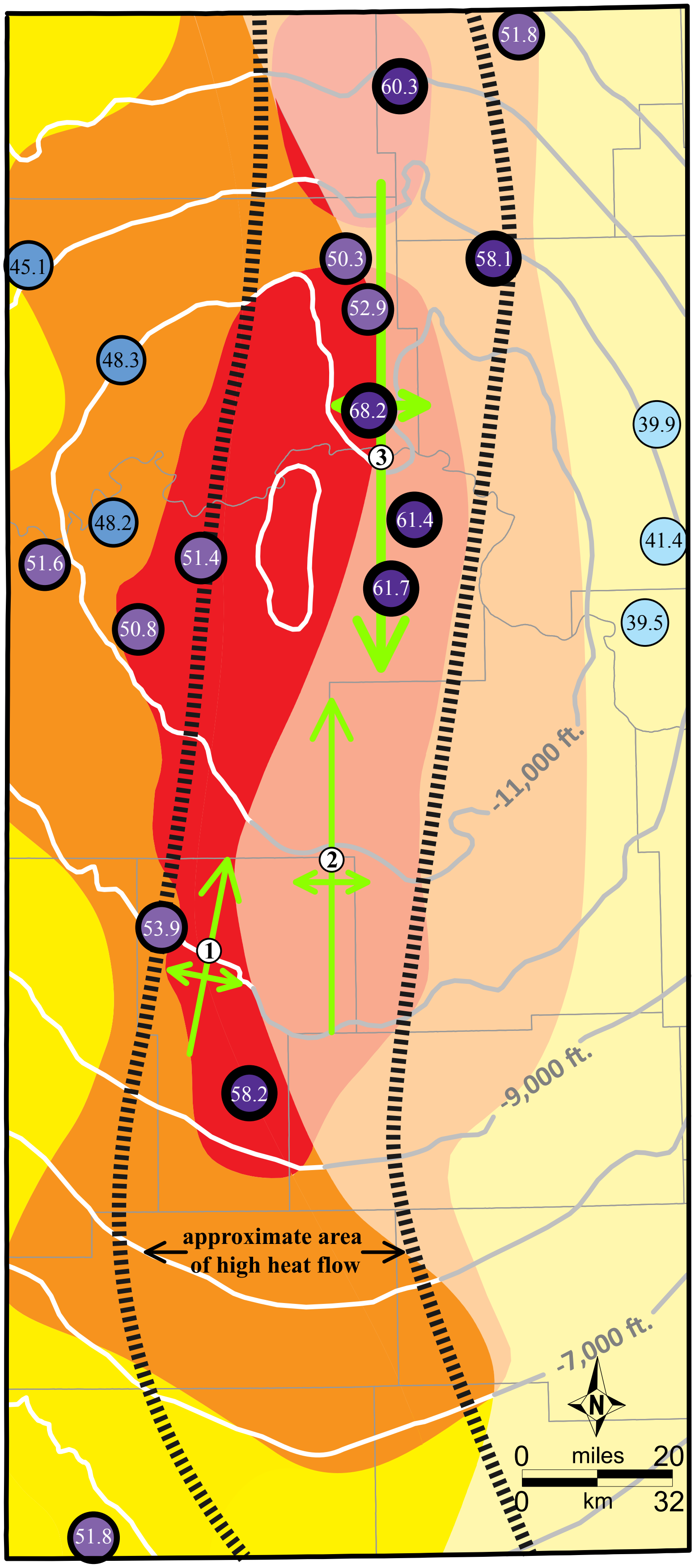

Figure 22. Map examining calculated heat flow values in relation to kukersite thermal maturity and structural depth. The blue (lower heat flow) to purple (higher heat flow) colored circles represent temporarily abandoned wells that were temperature logged and utilized to calculate subsurface-basement heat flow by McDonald (2016). The calculated heat flow values are in milli watts per meter squared (mW/m2). White-light grey line represent structure contours (feet below sea level) for the Red River Formation top. Yellow coloration represents where the Red River D interval has reach the peak mature stages of oil generation for kukersite thermal maturity, orange = late mature, and red = overmature. Bold thermal maturity colors depict where kukersites present and light colors depict where kukersites absent. The green line symbols represent various anticline structures: 1 = Billing Nose Anticline, 2 = Little Knife Anticline, and 3 = Nesson Anticline.

Section III:

Conclusions

- A series of 8-10 kukersites can be identified and correlated in the Red River D interval using both core and wireline logs. In core, kukersites commonly appear as 1-2 foot thick darkly colored, organic-rich (typically 1-10% TOC) carbonate mudstone to fossil wackestone that are laminated to moderately burrowed in texture. They can also be identified and correlated on wireline logs, where the moderately organic-rich kukersites (1-4% TOC average) display only elevated resistivity signatures while more organic-rich kukersites (5-10% or more) display both elevated resistivity and porosity (neutron, density, sonic) log signatures.

- Compositely, the Red River D interval kukersites extend continuously 20-30 miles eastward from the Montana border into western North Dakota as well as from southern Saskatchewan to northwestern South Dakota. The kukersites commonly reach net thicknesses of 6 to 12 feet across the western quarter of North Dakota and thin eastward across the state where they disappear in the subsurface.

- Limited lateral migration of generated hydrocarbons appears to have occurred within the Red River C and D intervals across the area of kukersite extent based on the systematic increase in API oil gravity and GOR of produced hydrocarbons from those two intervals. However, lateral migration does appear to have occurred within the C-D intervals beyond the area of kukersite extent.

- Kukersite thermal maturity with respect to oil generation, based on geochemical data (HI and Tmax) and produced hydrocarbon characteristics, ranges from peak mature along the western corners of North Dakota transitioning to late mature and overmature towards the central portions of the Williston Basin.

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APPENDIX:

K2 Thermal Maturation

The K2 kukersite was found to be overall both the most organic rich and laterally continuous Red River kukersite identified and correlated by this study. The K2 kukersite was also sampled and analyzed for LECO TOC and Rock-Eval pyrolysis from six different spatially dispersed cores at variable levels of thermal maturity (Fig. K1). These characteristics make the K2 kukersite an ideal candidate to examine the thermal decomposition of an individual Red River kukersite using standard source rock geochemical data (e.g. TOC, S2, HI, and Tmax). A series of geochemical plots were prepared to example the trends of both individual core chip samples and the average values by core data set (Figs. K2-K4). Table K1 provides a summary of these K2 kukersite data.

Kukersite Extent and Thermal Maturity - Southern Saskatchewan

Early drafts of this study underestimated the level of thermal maturity for Red River kukersites across the study area due to the lack of thermally immature kukersites within North Dakota's portion of the Williston Basin. In order to correct that initial underestimation, previously generated geochemical and thermal maturity data was compiled for southern Saskatchewan, where immature Red River kukersites had previously been studied and reported (Osadetz and Snowdown, 1995; Fowler et al., 1998). This pre-existing data was spatially plotted and examined (e.g. Figs. S1-S4) in order to incorporate it with the data generated by this study to create a more complete interpretation of Red River kukersite thermal maturity.

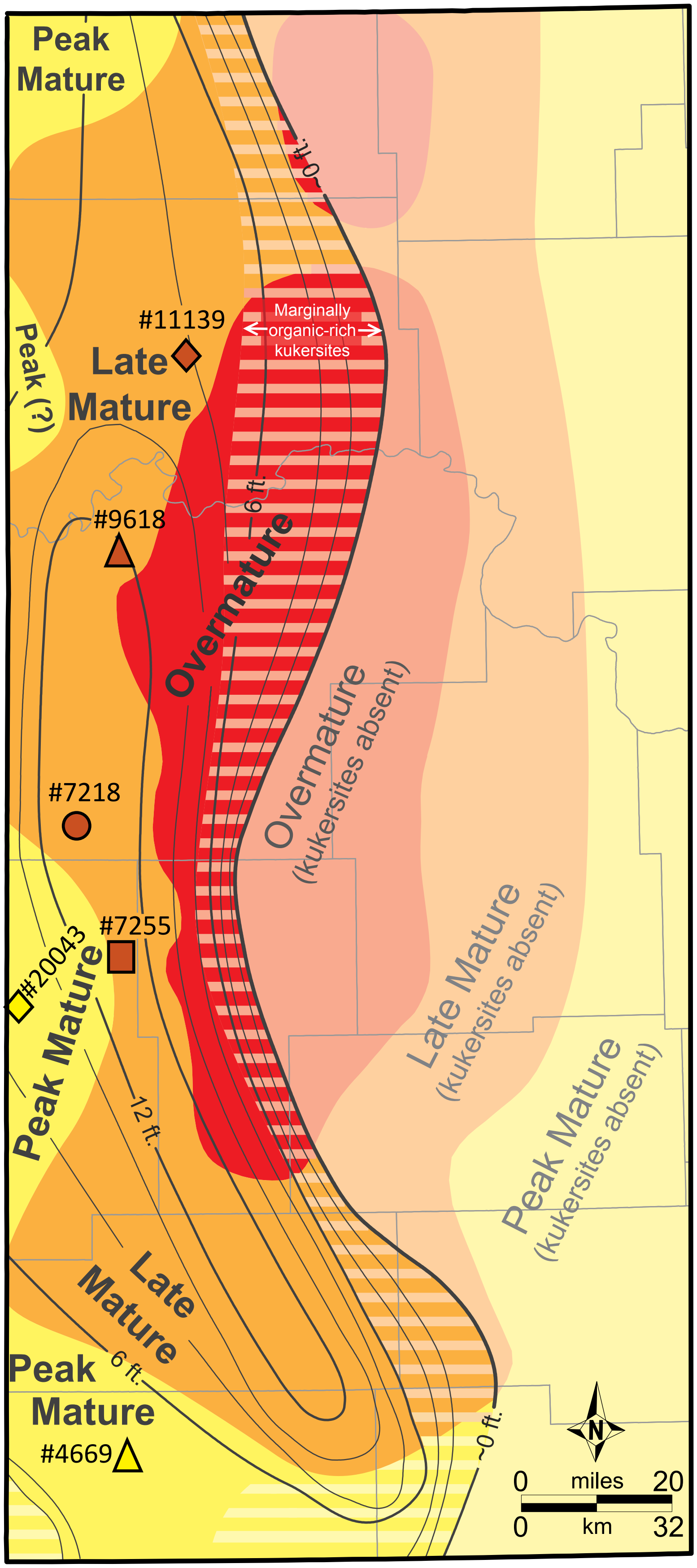

Figure K1. Lateral extent, net thickness, and interpreted thermal maturity map for Red River D interval kukersites for western North Dakota with symbols depicting the locations of cores with analyzed samples of the K2 kukersite. Bolder colored areas (left side of map) depict the extent of Red River D interval kukersites. The solid bold colors represent where the kukersites average higher TOC concentrations (>2 wt. %) and the diagonal lined areas represent where the kukersites are more marginally organic-rich averaging 0.5-2.0 wt. % TOC. The contour lines are the approximate net thickness of the organic-rich kukersites (>1%TOC). Peak, Late, and Overmature areas refer to the interpreted stages of oil generation. Light grey lines depict county outlines.

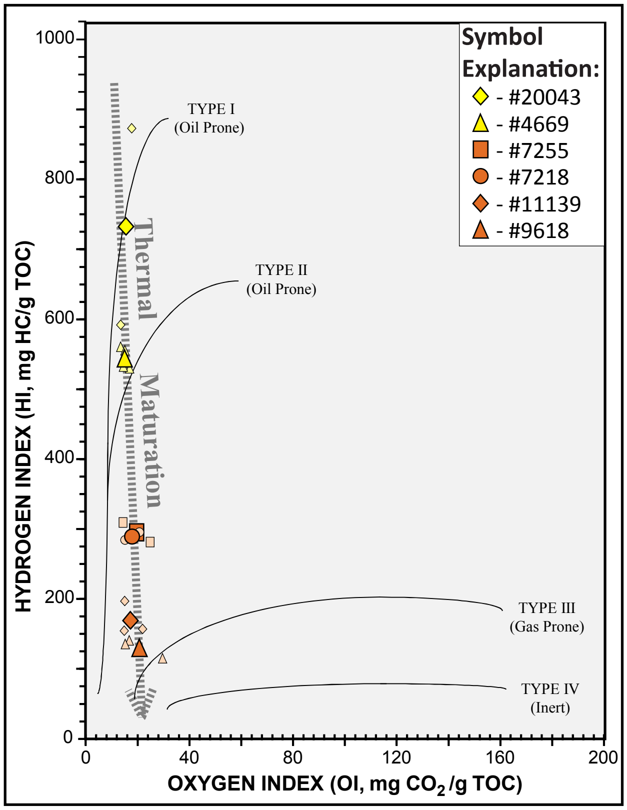

Figure K2. Modified Van Krevelen diagram depicting core chip samples from the K2 kukersite. The smaller, lighter colored symbols represent individual core chip samples, and the larger, bolder colored symbols are the average values by well of two or more individual samples. The symbol explanation shows the North Dakota Industrial Commission well identification number. Yellow symbols are interpreted as peak mature oil generation window, and brown symbols are late mature. The K2 kukersite is the most consistent of the kukersite beds both in lateral distribution and organic-richness, which makes it the ideal horizon to examine the thermal maturation of an individual petroleum source bed within the Red River Formation. Note the large decrease in hydrogen index (HI) and slight increase in oxygen index (OI) with interpreted increased thermal maturity of the K2 kukersite. HI decreases as kerogen is converted into hydrocarbons. OI appears to slightly increase because the S3 content within kukersite samples remains relatively constant while TOC decreases with increased thermal maturity as the kerogen (S2) component of TOC is converted to hydrocarbons.

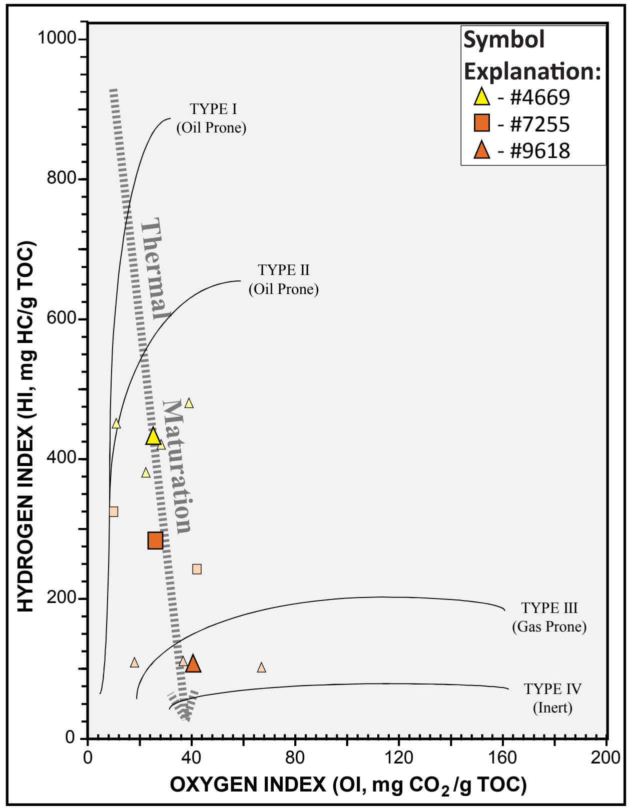

Figure K3. Modified Van Krevelen diagram depicting core chip samples from the K3 kukersite. The smaller, lighter colored symbols represent individual core chip samples, and the larger, bolder colored symbols are the average values by well of two or more individual samples. The symbol explanation shows the North Dakota Industrial Commission well identification number. Yellow symbols are interpreted as peak mature oil generation window, and brown symbols are late mature. Note the moderate decrease in hydrogen index and slight increase in oxygen index (OI) with interpreted increased thermal maturity of the K3 kukersite, a similar trend to the K2 kukersite as shown in Figure K1. The total organic carbon concentration in the K3 is lower (and more variable) than the K2 which makes the increase in OI more pronounced.

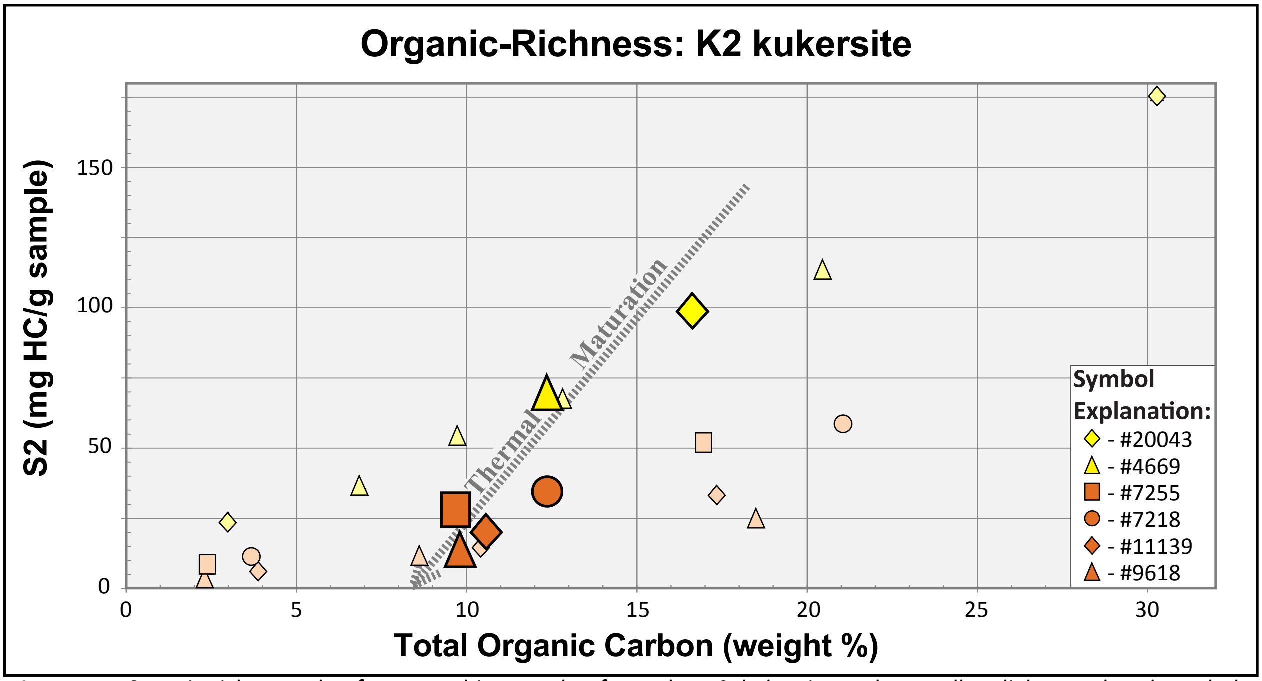

Figure K4. Organic-richness plot for core chip samples from the K2 kukersite. The smaller, lighter colored symbols represent individual core chip samples, and the larger, bolder colored symbols are the average values by well of two or more individual samples. The symbol explanation shows the North Dakota Industrial Commission well identification number. Yellow symbols are interpreted as peak mature oil generation window, and brown symbols are late mature. Note how the average S2 and TOC values decrease with a relatively linear trend with increased thermal maturity.

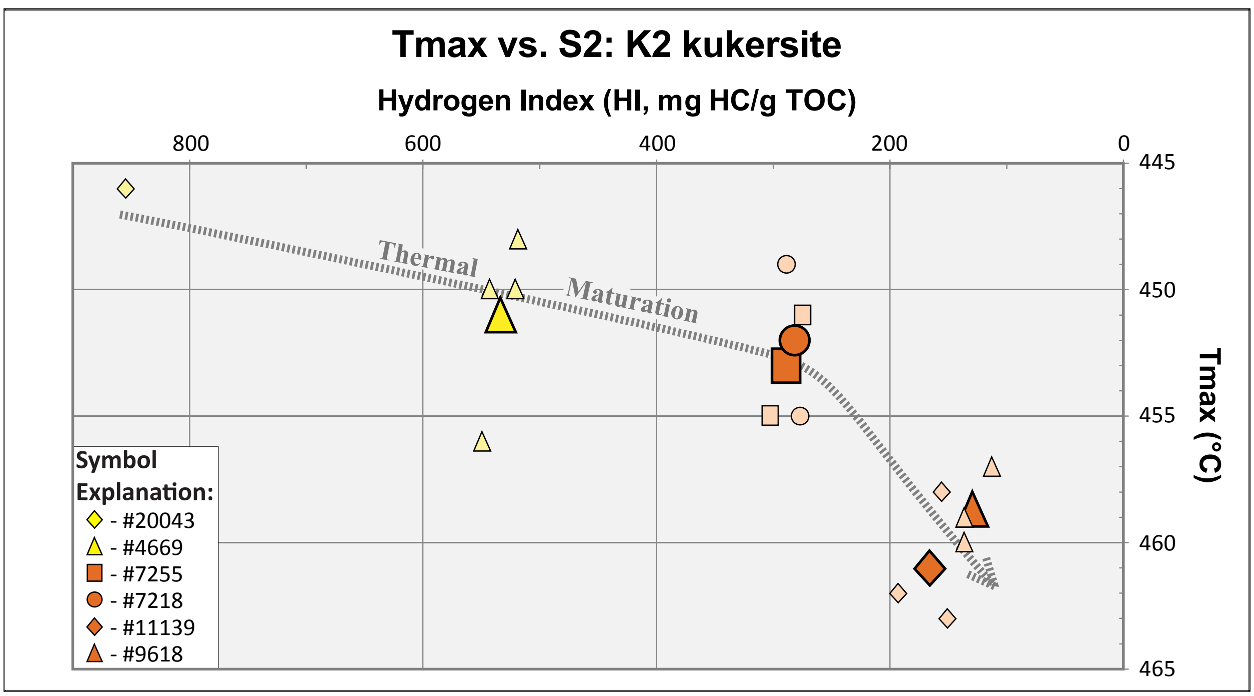

Figure K5. Hydrogen Index (HI) versus Tmax plot for core chip samples from the K2 kukersite. The smaller, lighter colored symbols represent individual core chip samples, and the larger, bolder colored symbols are the average values by well of two or more individual samples. The symbol explanation shows the North Dakota Industrial Commission well identification number. Only one sample from the K2 within core #20043 yielded a reliable Tmax value based on the pyrogram data. Overall, HI values decrease with increasing Tmax, but with a non-linear trend. Based on this diagram, a deflection in the HI versus Tmax trend occurs around HI = 300 mg HC/g sample and Tmax = 452°C. This deflection point may represent the transition from the peak to late mature oil generation window. Samples from wells #7255 & #7218 are interpreted to have reached the beginning of the late mature oil generation window, but may instead represent the end of the peak mature window of oil generation.

Table K1. Geochemical data for the K2 kukersite, average values in italics.

NDIC #	Depth (ft)	TOC	S1	S2	S3	Tmax	HI	OI
20043	11928.6	30.3	4.96	175.5	0.51	443*	580	2
20043	11929.6	3.0	0.9	25.5	0.19	446	855	6
		16.6	*2.93*	*100.5*	*0.35*	*446*	*717*	*4*
4669	9841.1	20.5	1.75	112.3	0.36	456	549	2
4669	9841.5	9.7	0.47	52.9	0.34	450	544	3
4669	9841.7	12.8	0.54	66.4	0.35	450	521	3
4669	9842.25	6.9	0.83	35.5	0.37	448	519	5
		12.4	*0.90*	*66.8*	*0.36*	*451*	*533*	*3*
7255	12613.25	17.0	1.83	51.3	0.47	455	303	3
7255	12614	2.4	0.66	6.6	0.33	451	275	14
		9.7	*1.25*	*28.9*	*0.40*	*453*	*289*	*8*
7218	13008.35	21.1	2.28	58.6	0.7	455	278	3
7218	13009.3	3.7	1.15	10.6	0.35	449	289	10
		12.4	*1.72*	*34.6*	*0.53*	*452*	*283*	*6*
9618	13661.1	2.3	1.14	2.6	0.44	457	113	19
9618	13661.5	18.5	4.85	24.5	0.69	459	132	4
9618	13661.7	8.6	2.7	11.9	0.45	460	138	5
		9.8	*2.90*	*13.0*	*0.53*	*459*	*128*	*9*
11139	13676	10.5	2.56	15.8	0.34	463	151	3
11139	13677	17.3	1.64	33.5	0.6	462	193	3
11139	13677.6	3.9	1.22	6.0	0.42	458	154	11
		10.6	*1.81*	*18.4*	*0.45*	*461*	*166*	*6*

*unreliable Tmax value due to irregular pyrogram curve

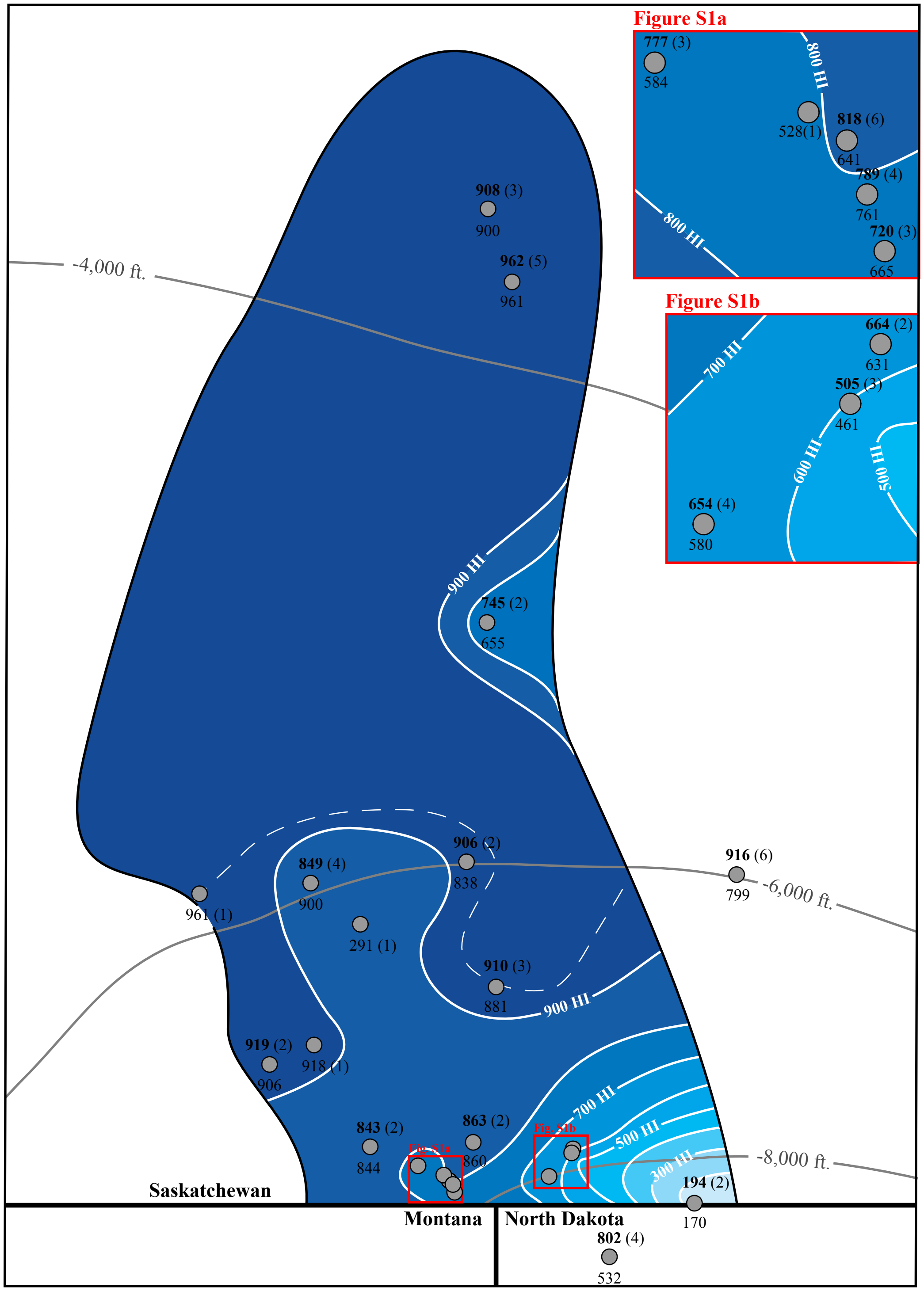

Figure S1. Map depicting the average hydrogen index (HI) of kukersites within the Red River D interval (upper Yeoman Formation) across southern Saskatchewan utilizing the data set from Osadetz and Snowdon (1995). The grey circles represent control wells with kukersite core chip data. Above each control well symbol is the HI value calculated from the average TOC and average S2 from kukersite core chip samples of that well/core, and below is the average of individual HI values from kukersite core chip samples. In parentheses is the number of analyzed kukersite core chip samples from that well/core. Figures S1a and S1b provide close-up veiws of areas with high data density. The dashed white line represents where Fowler et al. (1998) observed fluorescence indicative of oil generation within G. Prisca from core samples. The grey lines are structure contours (feet below sea level) on the Herald (~Red River) Formation top from Kreis and Haidl (1996). The extent of Red River kukersites in southern Saskatchewan is from Osadetz and Haidl (1989).

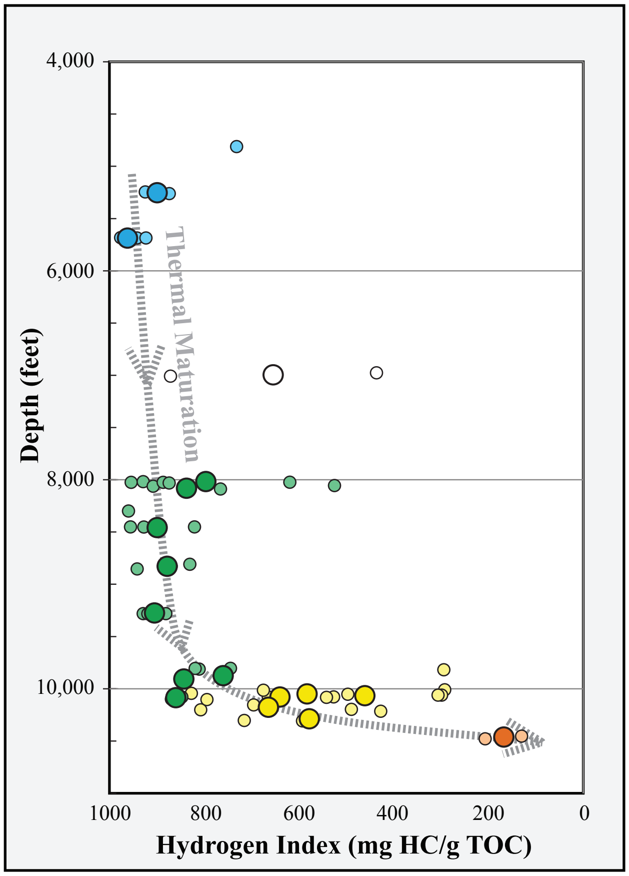

Figure S2. Hydrogen Index (HI) versus depth diagram of kukersite samples from southern Saskatchewan (data from Osadetz and Snowdon, 1995). The small circles represent individual core chip samples and the large circles are average values by core. Colors relate to interpreted level of thermal maturity: blue = immature, green = early mature oil generation, yellow = peak mature oil generation, and orange/brown = late mature.

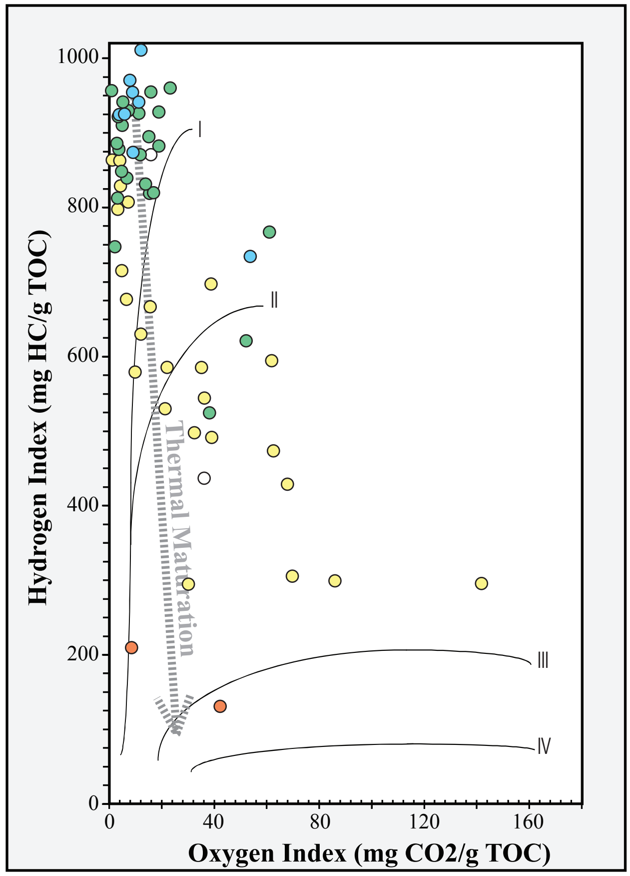

Figure S3. Modified pseudo-Van Krevelan diagram displaying Rock-Eval pyrolysis geochemical data from southern Saskatchewan kukersites (data from Osadetz and Snowdon, 1995). All samples depicted are individual core chip samples. Colors relate to interpreted level of thermal maturity: blue = immature, green = early mature oil generation, yellow = peak mature oil generation, and orange/brown = late mature.

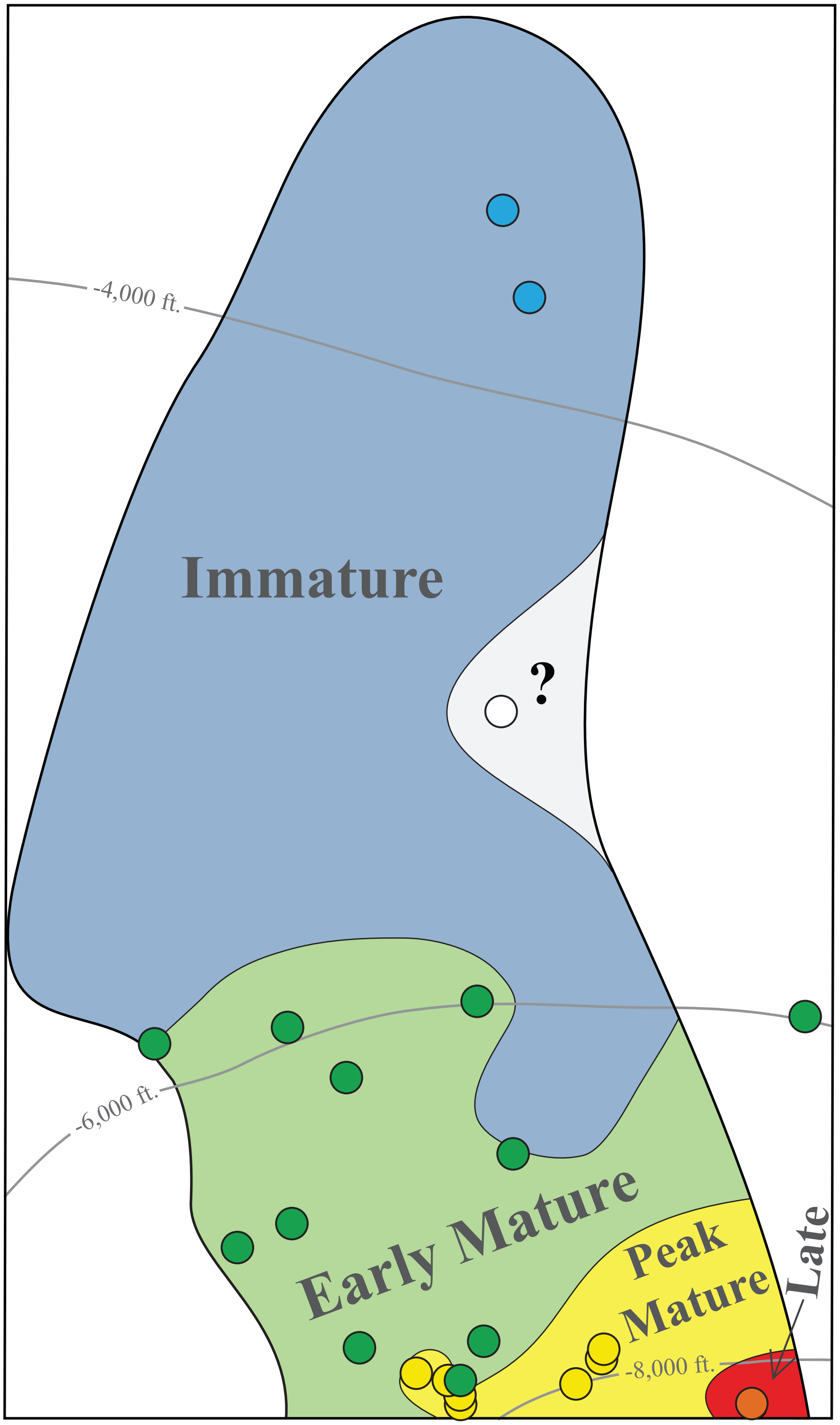

Figure S4. Interpreted map of thermal maturity with respect to oil generation for Red River kukersites in southern Saskatchewan. The early mature oil generation window is interpreted where Fowler et al. (1998) observed fluorescence indicative of oil generation from G. Prisca in core samples, which is also approximately where the average kukersite HI drops below 900 mg HC/g TOC (Figs. S1 and S2). The peak mature oil generation window is interpreted where the average kukersite HI drops below 800 mg HC/g TOC and proceeds to rapidly drop towards the south-southeast (Figs. S1 and S2). Average kukersite HI values decrease in conjuncture with increasing Tmax values across southern Saskatchewan (Fig. 19). The grey lines are structure contours (feet below sea level) on the Herald (~Red River) Formation top from Kreis and Haidl (1996). The extent of Red River kukersites in southern Saskatchewan is from Osadetz and Haidl (1989).