Hydrocarbon Generation Significance of Kukersites, the Prospective Petroleum Source Beds of the Red River Petroleum System – Williston Basin, North America

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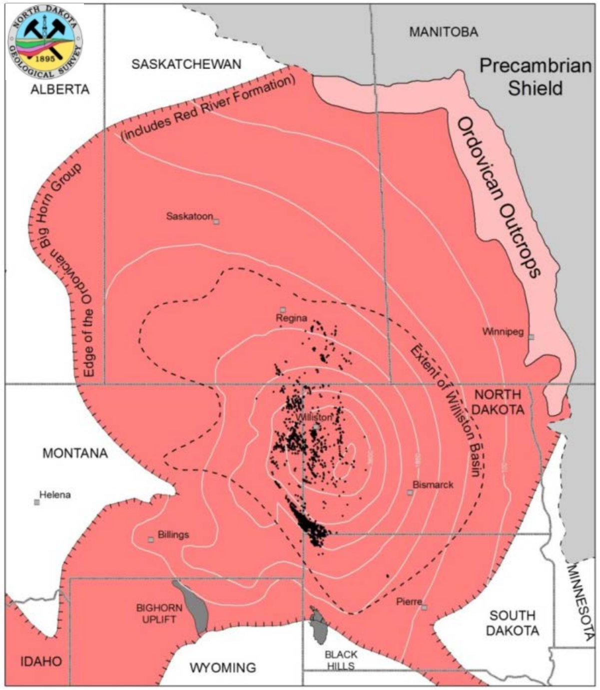
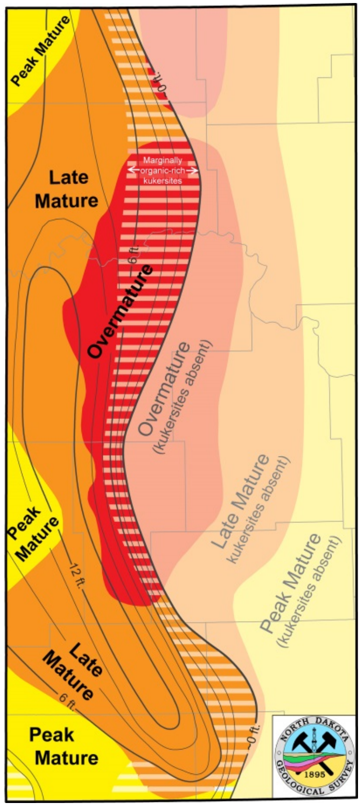
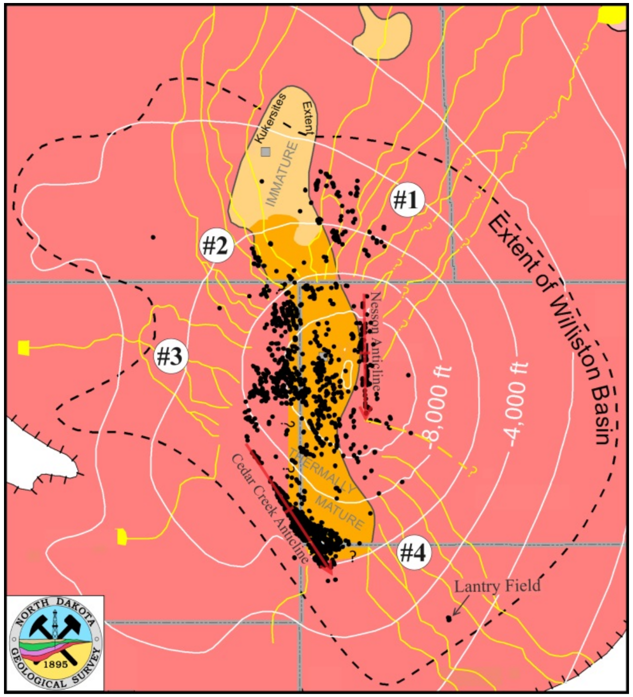
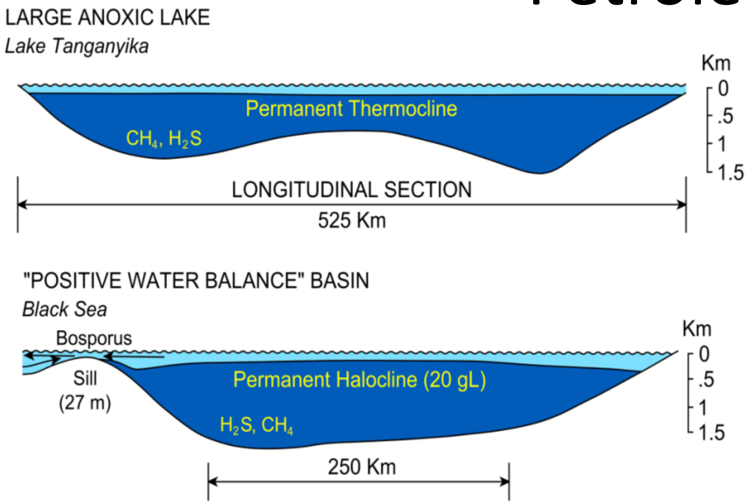
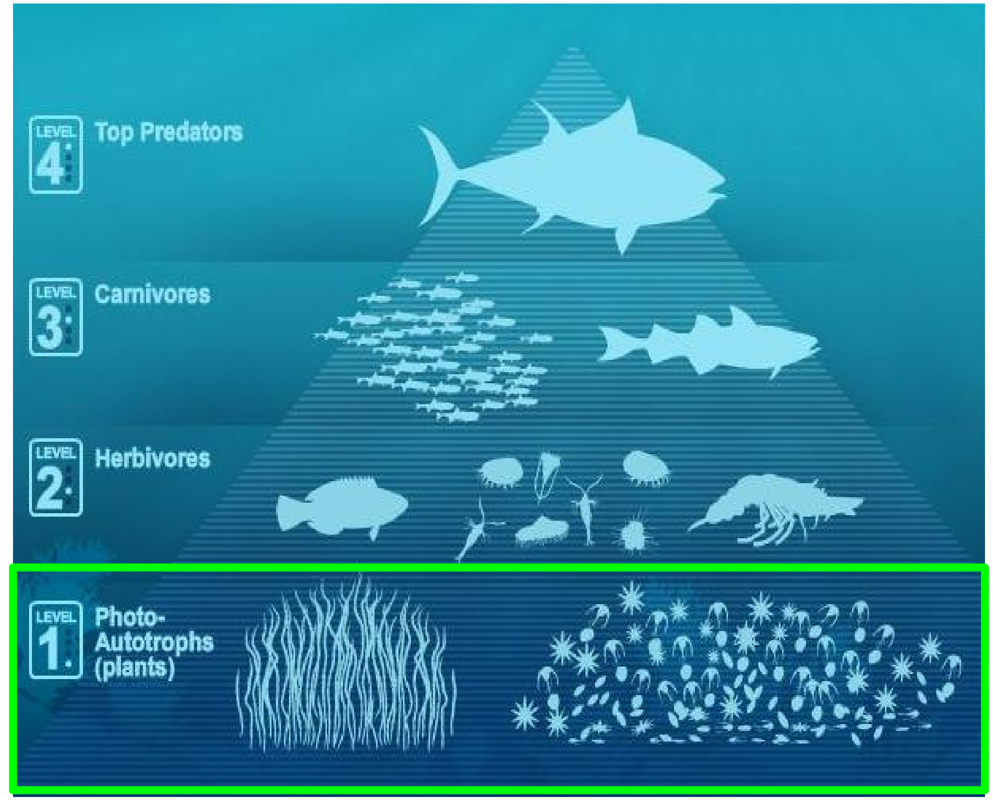






Petroleum Source Beds

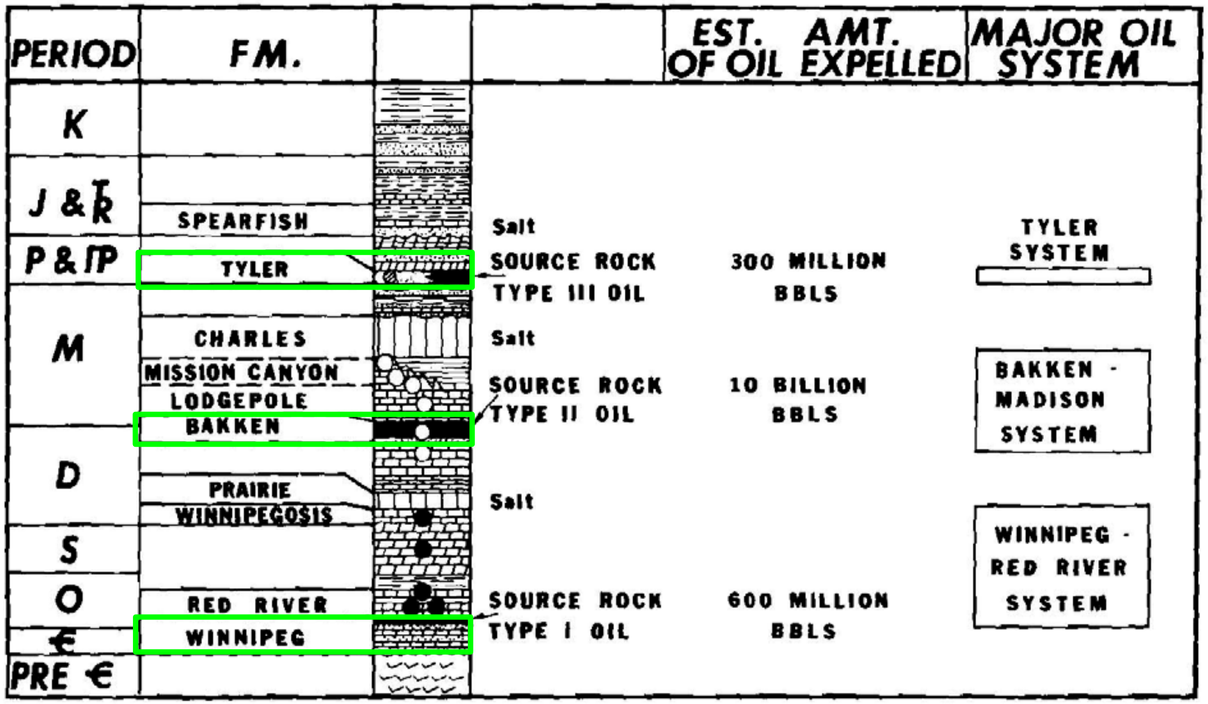




Petroleum source beds are accumulations of organic-rich mudstone (e.g. shale) in which a significant portion of the original organic material deposited was capable of converting into oil and/or hydrocarbon gas under sufficient thermal conditions. Most petroleum source beds are believed to have formed within subaqueous settings such as fresh water (lacustrine) lakes or marine seaways. Within such aquatic settings, the majority of the organic biomass is comprised of photo-autotrophs, (sea plants).

Petroleum Source Beds of the Williston Basin - 1974

Williston Basin Source Rocks (Dow, 1974)



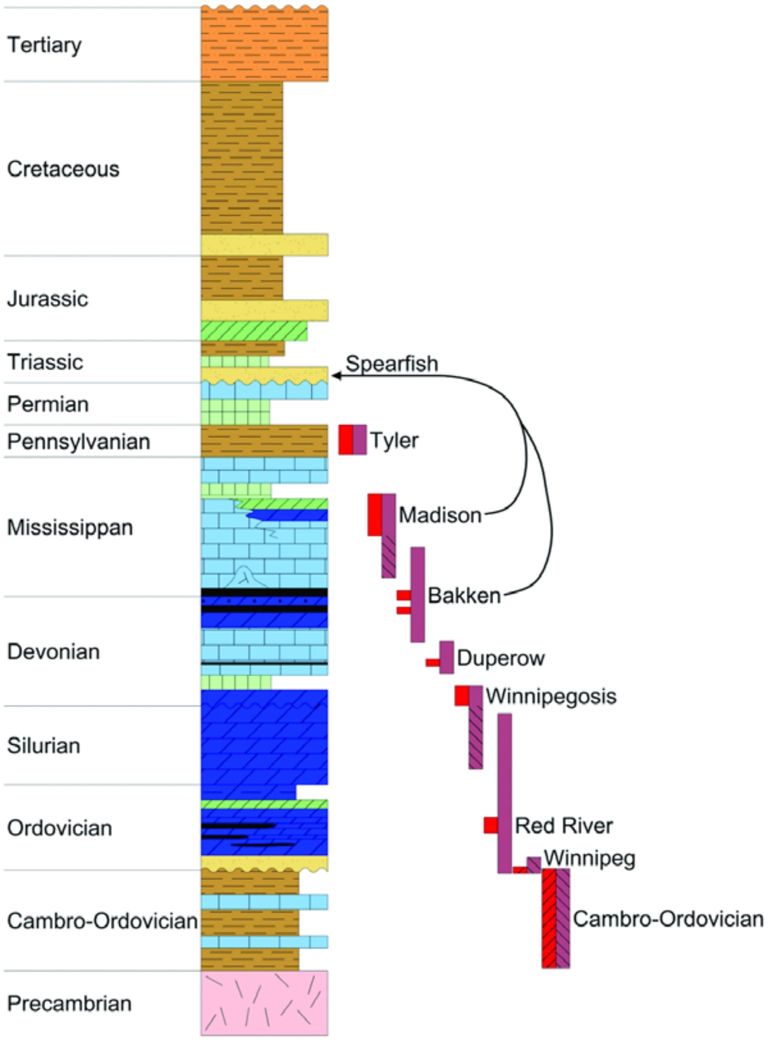
2—Schematic columnar section showing stratigraphic terminology, vertical distribution of source rocks, reservoirs, and evaporite seals, and estimated amount of oil expelled. Not drawn to scale.

<u>Publication:</u>

Dow, W.G., 1974, Application of Oil –Correlation and Source-Rock Data to Exploration in Williston Basin: AAPG Bulletin, v. 58, no. 7, p. 1253-1262.

Three formations within the Williston Basin were originally identified and examined with petroleum source beds in reports published by Dow (1974) and Williams (1974), including the Winnipeg (Icebox Formation), Bakken, and Tyler Formations. Dow and Williams also estimated the volume of expelled oil from each of the petroleum source beds identified in their study.

Petroleum Source Beds of the Williston Basin - 2012



<u>Publication:</u>

Lillis, P. G., 2012, Review of Oil Families and Their Petroleum Systems of the Williston Basin: *in* The Mountain Geologist, v. 50, no. 1, p. 5-31.

Five documented petroleum systems with good oil-source correlations:

1) Red River (Ordovician)
2) Winnipegosis (Devonian)
3) Bakken (Mississippian-Devonian)
4) Madison (Mississippian)
5) Tyler (Pennsylvanian)

Three additional prospective systems with documented source beds, but no oil-source correlations:

1) Winnipeg (Ordovician)
2) Duperow (Devonian)
3) Birdbear (Devonian)

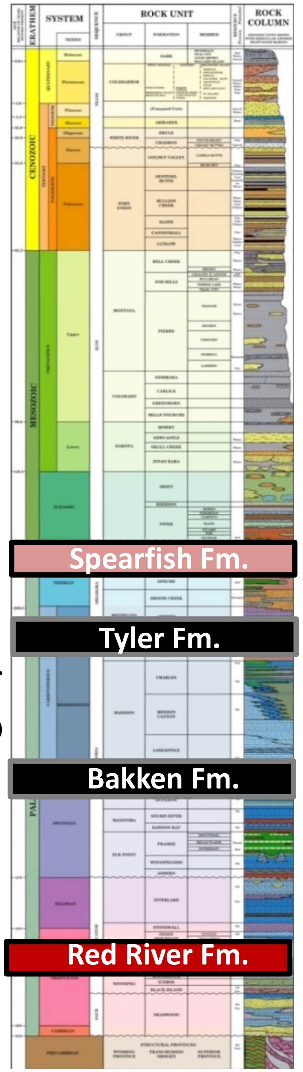
One hypothetical system:

1) Deadwood (Cambrian-Ordovician)

Since the early investigations by Dow (1974) and Williams (1974), petroleum source beds have been identified in eight formations within the Williston Basin. The geologic understanding of each of these petroleum source bed intervals varies, and continued work is needed to better understand the lateral extent, level of thermal maturity, and hydrocarbon generation significance of these source beds.

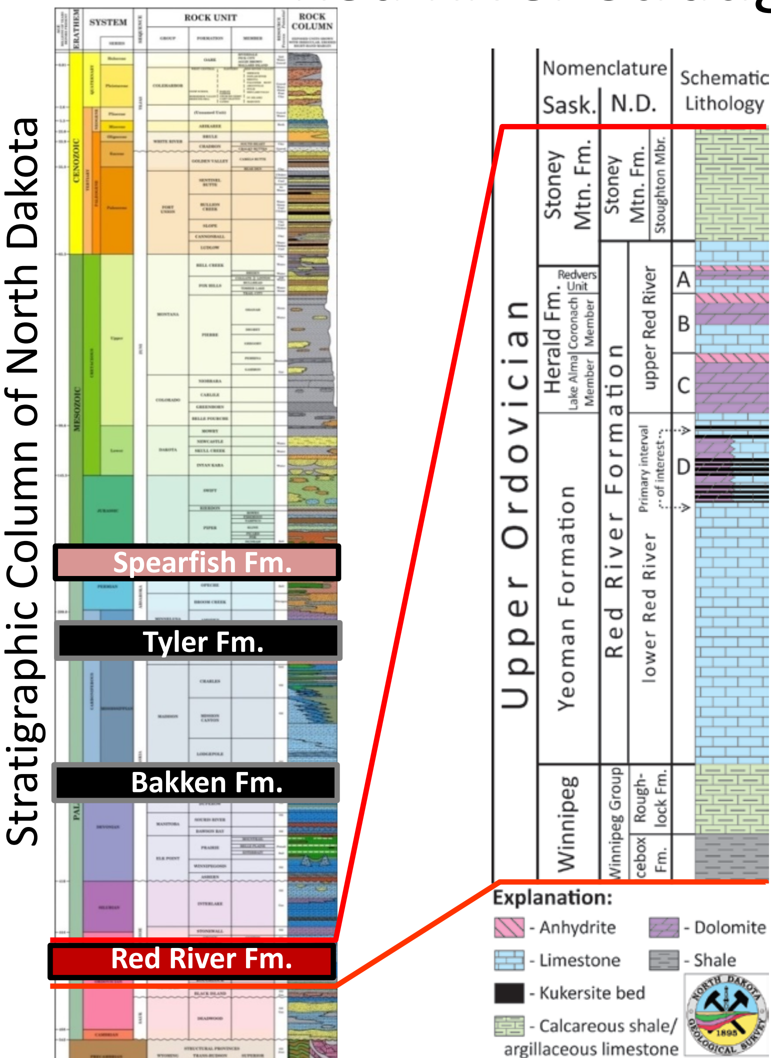
Red River Stratigraphy

Stratigraphic Column of North Dakota



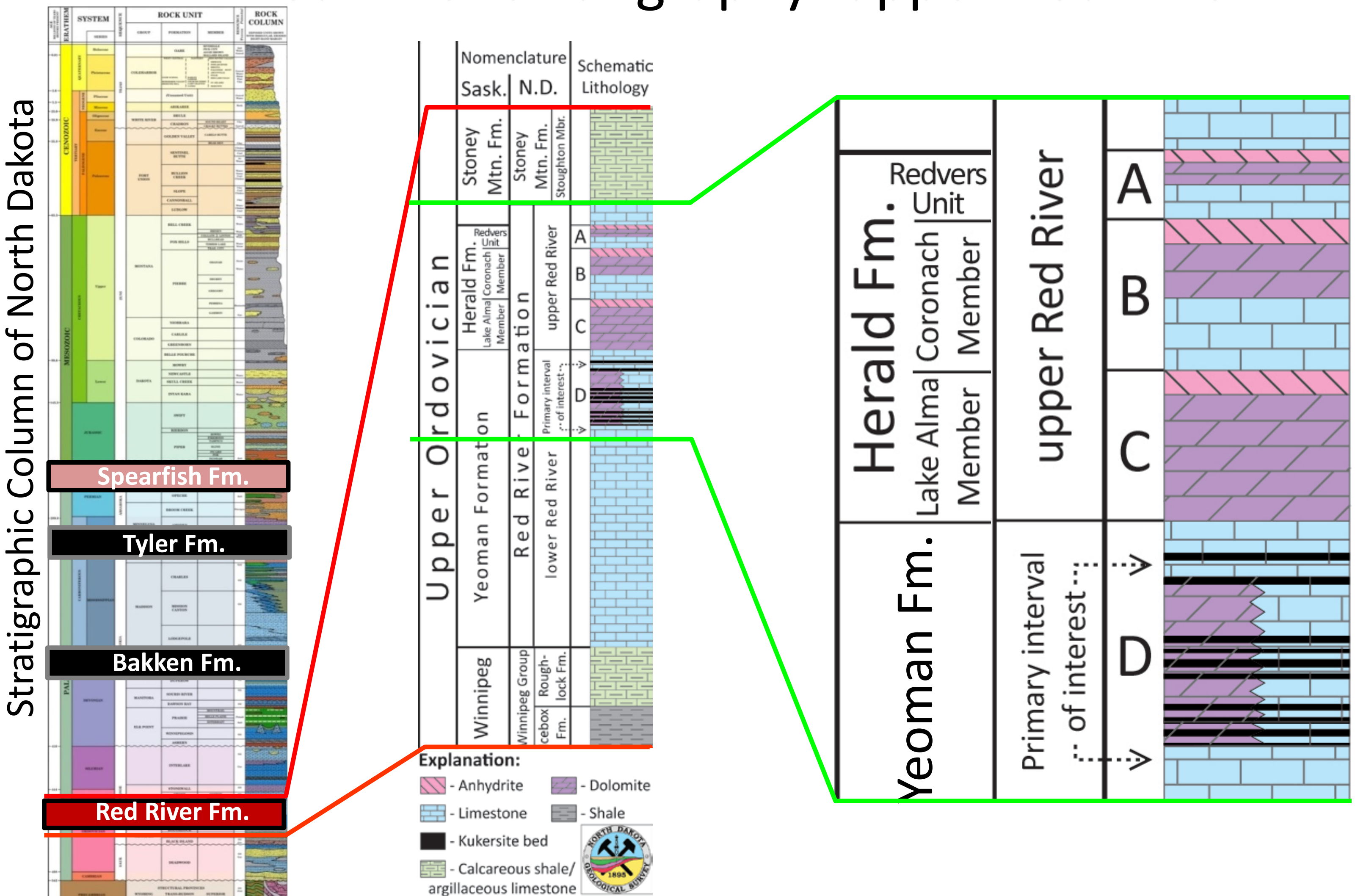
Petroleum source beds of the Ordovician Red River Formation were not identified/examined by Dow (1974) and Williams (1974) in their studies of Williston Basin source beds. The Red River Formation is one of the deepest sedimentary units within the Williston Basin, and is located beneath the prolific Bakken and Three Forks Formations.

Red River Stratigraphy: lower Red River



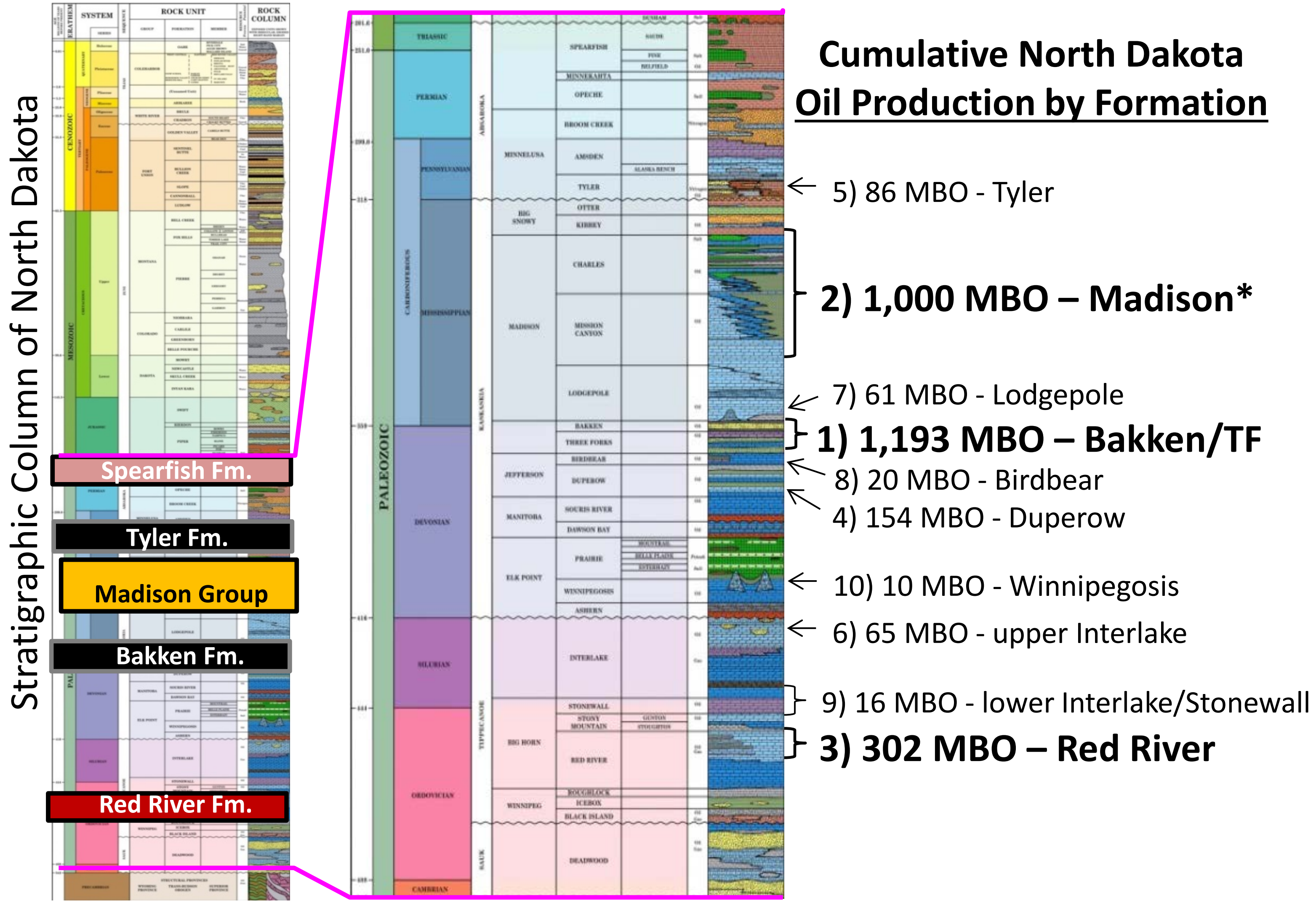
The Red River Formation consists of informal upper and lower subunits. The lower Red River, approximately equivalent to the Yeoman Formation of Saskatchewan (Kendall, 1976), makes up ~two-thirds of the Red River section. The lower Red River consists of burrow-mottled lime mudstone to fossil wackestone that has been partially to completely dolomitized near the top of the interval. The dolomitized burrow-mottled facies forms hydrocarbon reservoirs that contain 10-20% porosity and is referred to as the "D" zone/porosity. The "D" zone also contains the prospective petroleum source beds reviewed in this study.

Red River Stratigraphy: upper Red River



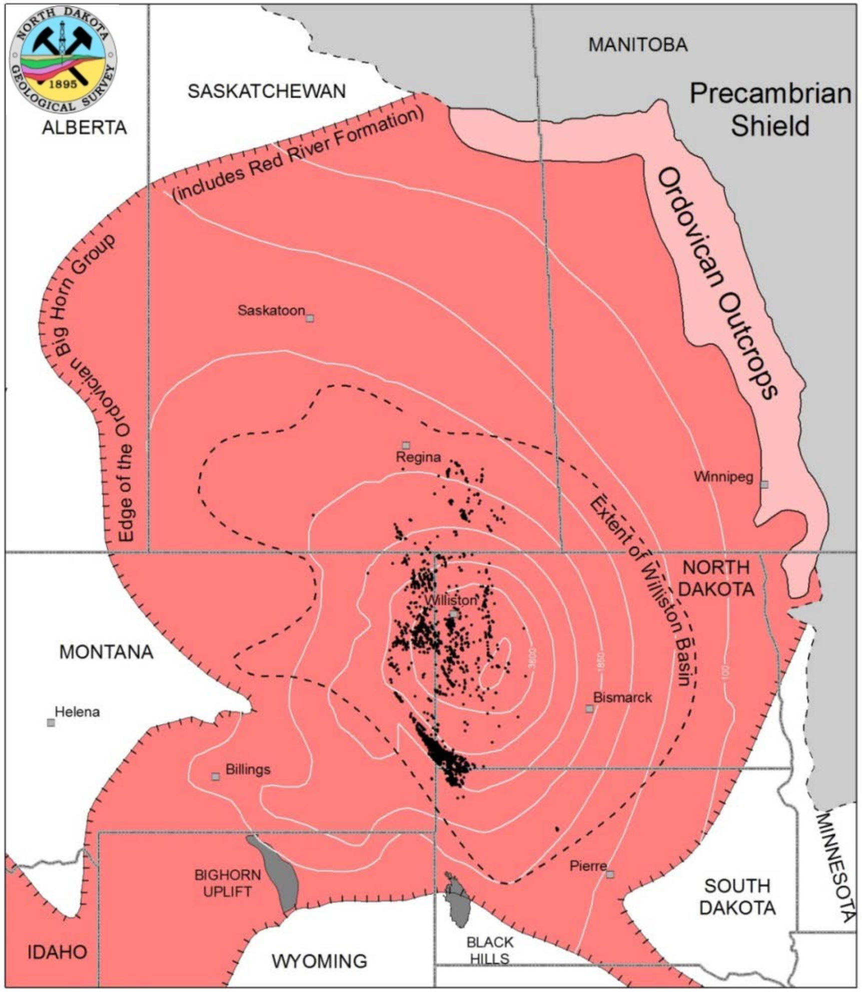
The upper Red River, approximately equivalent to the Herald Formation of Saskatchewan (Kendall, 1976), is comprised of three cycles of sedimentation referred to in descending order as the A, B, and C cycles/zones. These cycles have previously been interpreted as shallowing, brining upward sequences, grading from lime mudstone-fossil wackestones deposited in a normal marine conditions (base) to laminated dolomite (middle) to basin-centered, nodular to bedded anhydrites (top) (Longman et al., 1983). The laminated dolomite facies of each cycle also form hydrocarbon reservoirs.

Red River Hydrocarbon Production



In terms of cumulative hydrocarbon production, the Red River Formation is the third most significant sedimentary unit within the Williston Basin of North Dakota. Oil and/or gas has been commercially produced from 19 different formations of western North Dakota. The Red River Formation has produced over 300 million barrels of oil to date and ranks behind only the Bakken-Three Forks Formations and the Madison Group in cumulative oil production in ND.

Red River Hydrocarbon Production

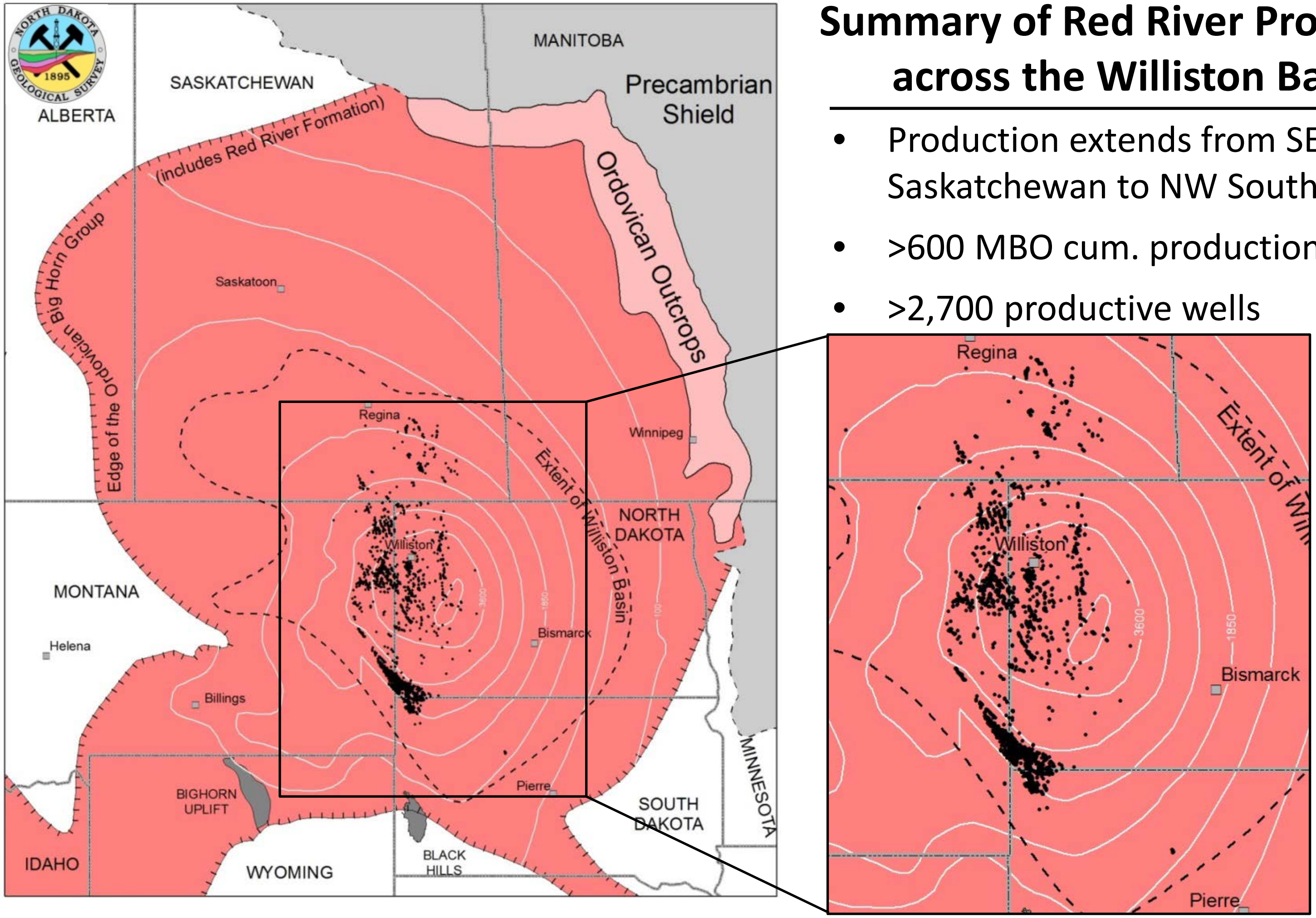


Summary of Red River Production across the Williston Basin:

- Production extends from SE Saskatchewan to NW South Dakota
- >600 MBO cum. production
- >2,700 productive wells

Red River hydrocarbon production extends beyond western North Dakota. The red colored portion of the map above shows the extent of the Ordovician Bighorn Group, which includes the Red River Formation and equivalent units, and the dashed line represents the approximate extent of the Williston Basin. The Red River Formation extends throughout the entire Williston Basin and beyond. The regional extent of the Bighorn Group is borrowed from Kendall (1976).

Red River Hydrocarbon Production

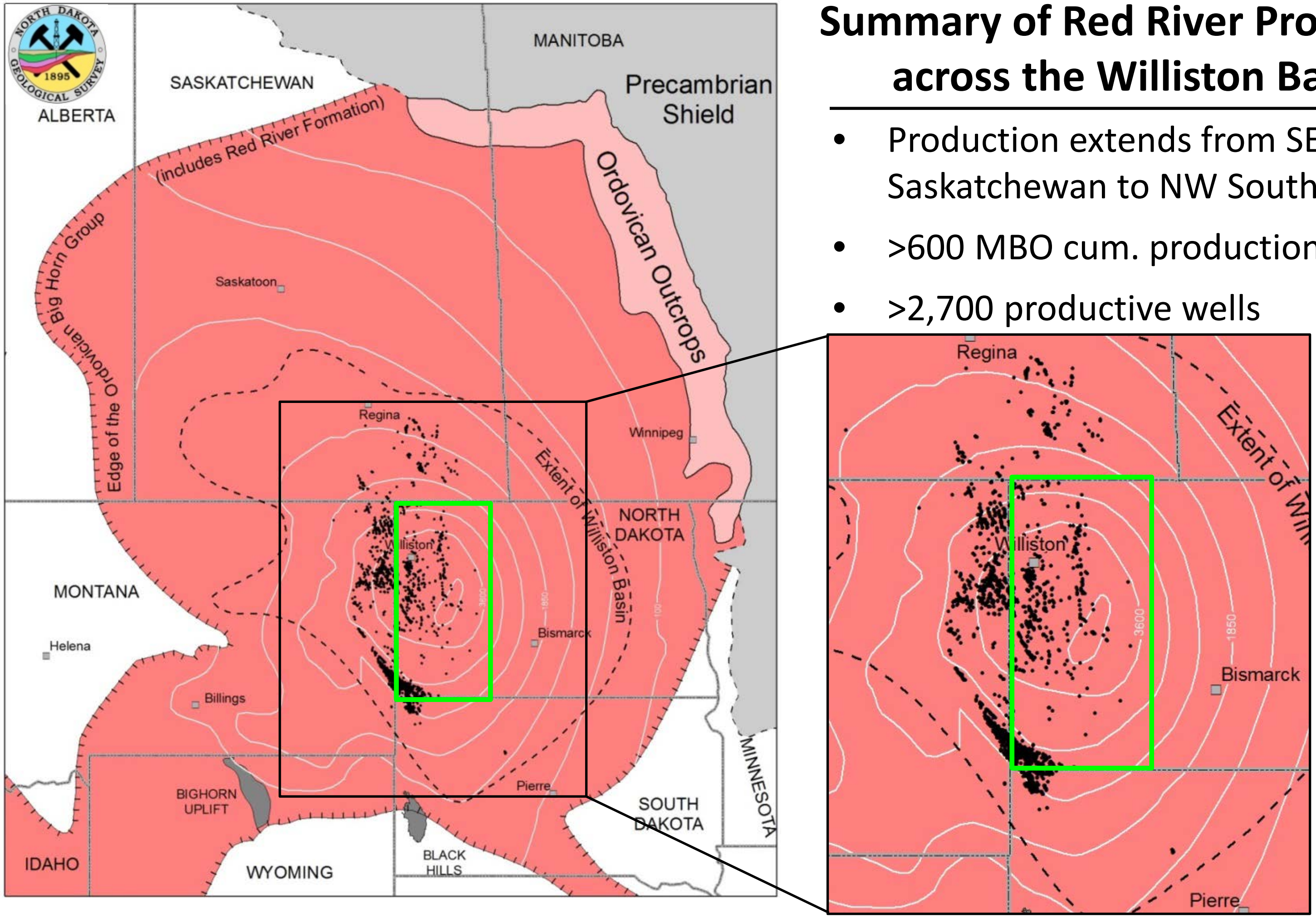


Summary of Red River Production across the Williston Basin:

- Production extends from SE Saskatchewan to NW South Dakota
- >600 MBO cum. production
- >2,700 productive wells

Red River hydrocarbon productive wells (black dots) extend from southern Saskatchewan down through eastern Montana, western North Dakota, and into northwestern South Dakota. Basinwide, over 2,700 vertical and horizontal wells have produced more than 600 million barrels of oil from the Red River Formation, as well as significant amounts of hydrocarbon gas.

Red River Hydrocarbon Production

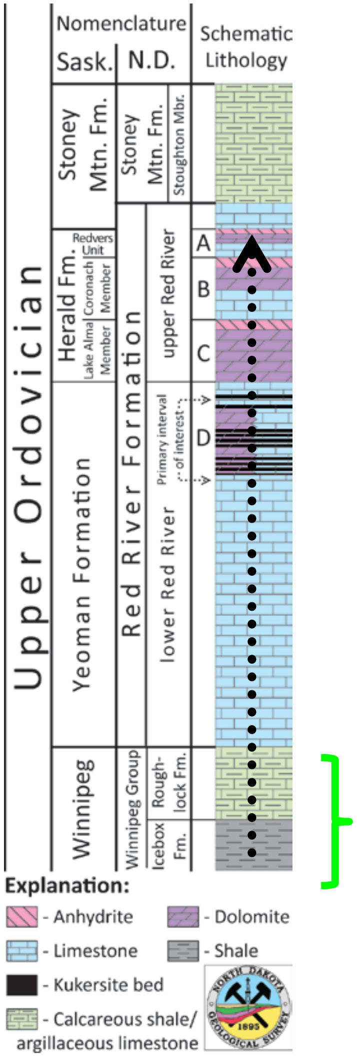


Summary of Red River Production across the Williston Basin:

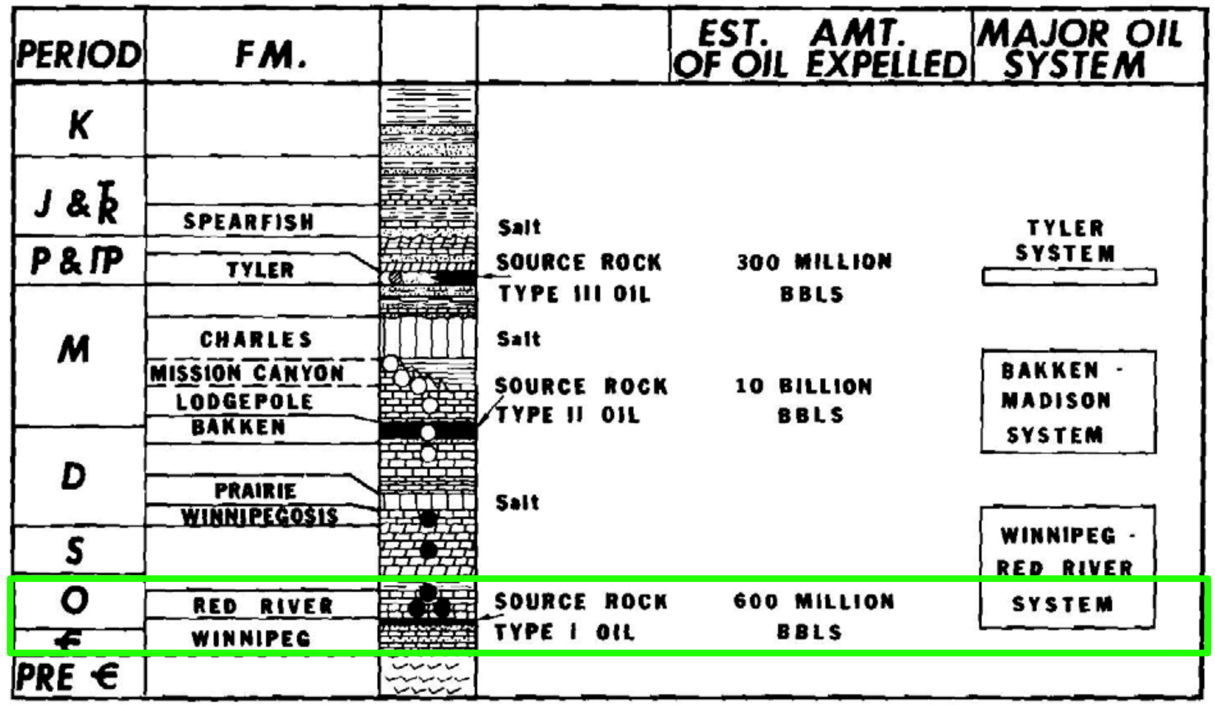
- Production extends from SE Saskatchewan to NW South Dakota
- >600 MBO cum. production
- >2,700 productive wells

The study area (green outline) is approximately the western quarter of North Dakota. The study results, however, have basinwide implications for the Red River Petroleum System.

Source of Red River Hydrocarbons



Williston Basin Source Rocks (Dow, 1974)



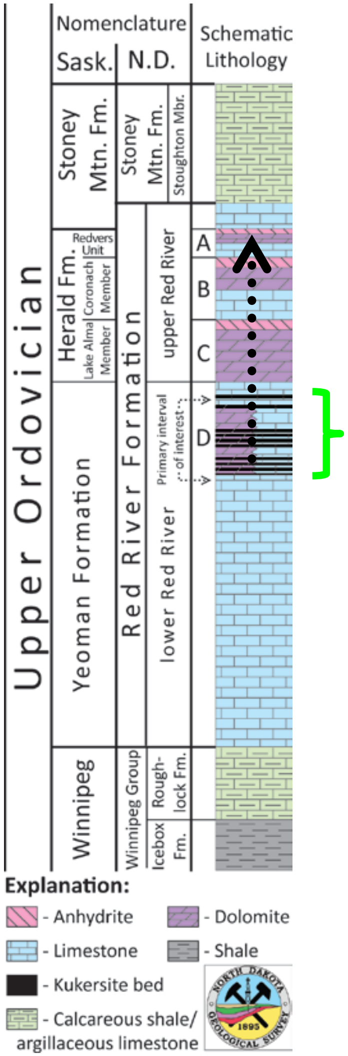
2—Schematic columnar section showing stratigraphic terminology, vertical distribution of source rocks, reservoirs, and evaporite seals, and estimated amount of oil expelled. Not drawn to scale.

Publication:

Dow, W.G., 1974, Application of Oil –Correlation and Source-Rock Data to Exploration in Williston Basin: AAPG Bulletin, v. 58, no. 7, p. 1253-1262.

Dow (1974) and Williams (1974) initially proposed that Red River hydrocarbons were sourced by organic-rich shale in the underlying Icebox Formation, and estimated that the Icebox had expelled approximately 600 million barrels of oil. Cumulative production from the Red River Formation across the Williston Basin currently totals over 600 million barrels of oil.

Source of Red River Hydrocarbons



Red River "D" zone (upper Yeoman Fm.) has been described to contain kukersites (a.k.a. kerogenites), 6-18 in. thick organic-rich mudstone beds. Kukersites are organic-rich mudstone beds that contain abundent amounts of the algal microfossil *Gloeocapsomorpha prisca (G. Prisca)*
(Kendall, 1976; Carroll, 1979; Longman et al., 1983; Osadetz and Snowdon, 1995; Stasiuk and Osadetz, 1990; Fowler et al., 1998; Nesheim et al., 2015)

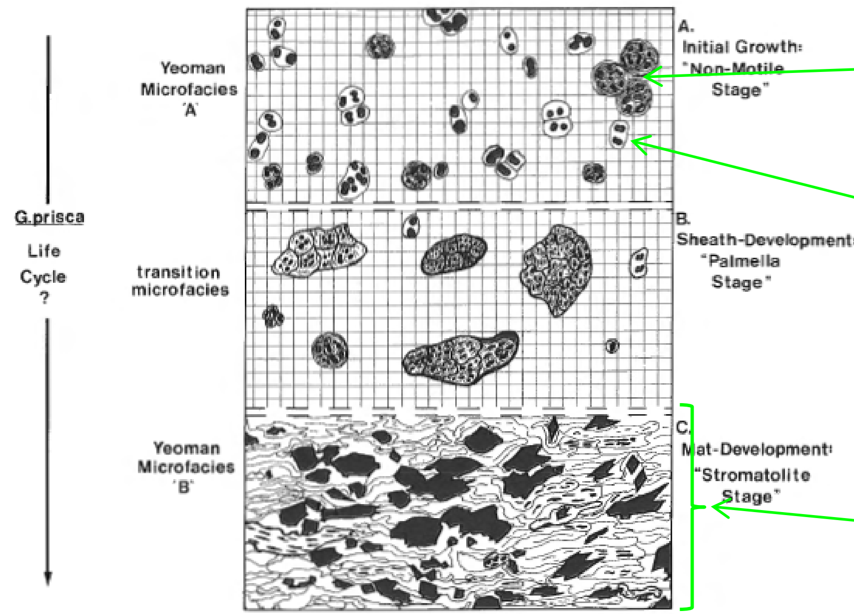
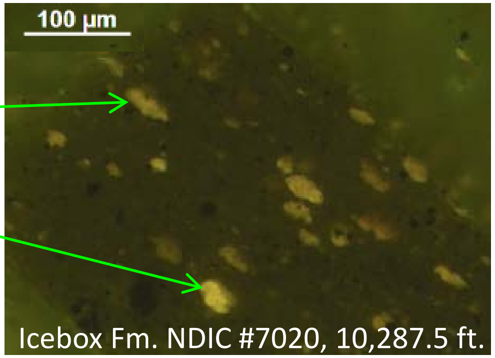
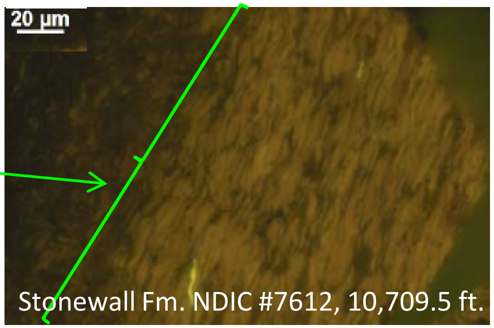


Figure 5. Proposed life cycle scenario for Gloeocapsomorpha prisca alginite in Upper Ordovician, Yeoman Formation, Saskatchewan. See text for explanation of the relationship between preserved alginite microfacies and growth stages of G. prisca.

(above figure from Stasiuk and Osadetz, 1990)



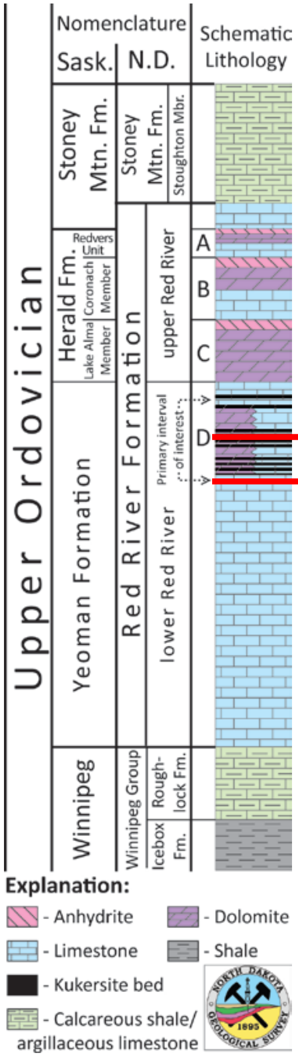


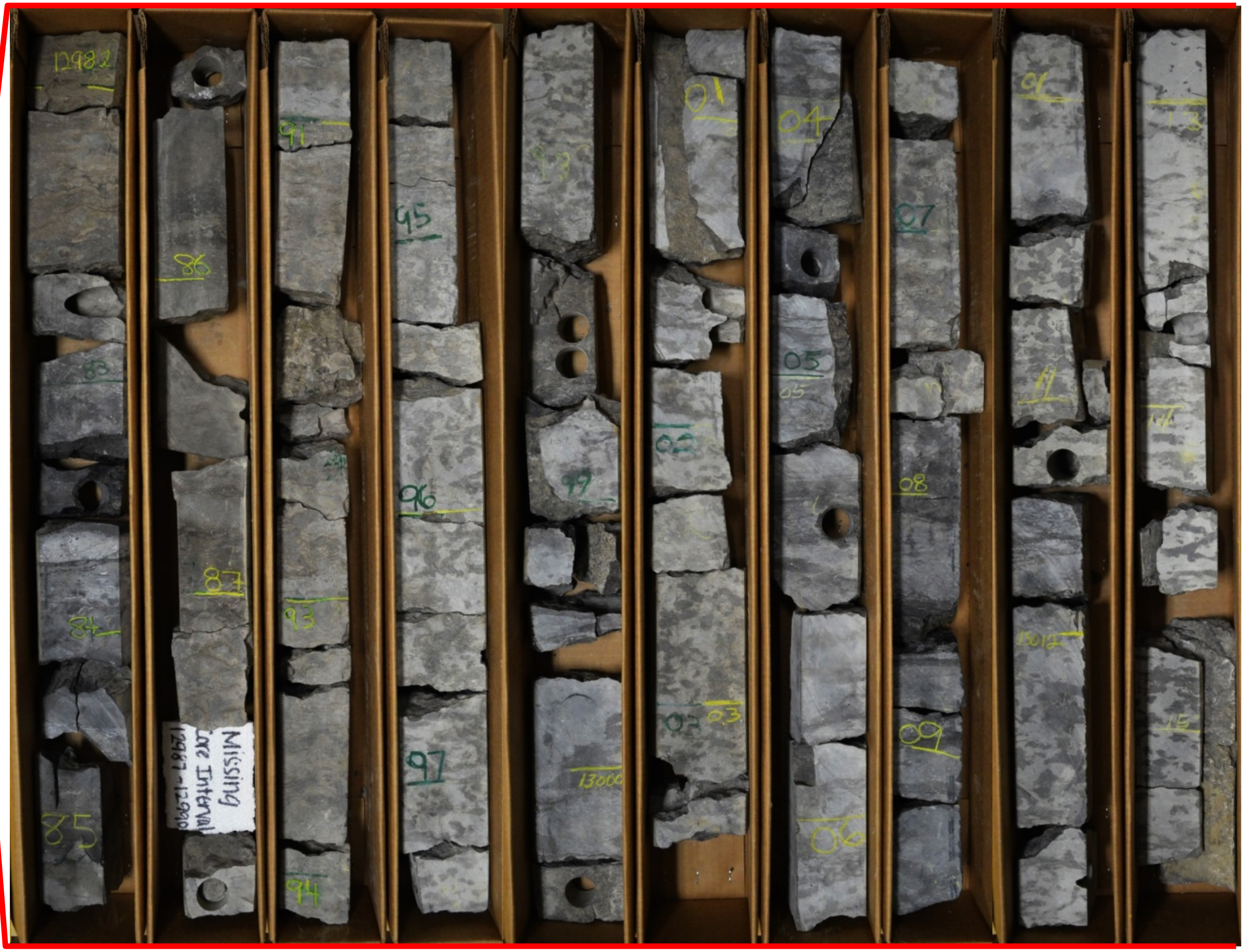
Photographs from Paul Hackley (USGS)

Numerous publications have described prospective source beds, referred to as kukersites, within the Red River "D" zone, the upper portions of the lower Red River. Red River kukersites have been studied in southern Saskatchewan (Osadetz et al., 1989; Osadetz and Haidl, 1989; Osadetz and Snowden, 1995), but have not been investigated within the remainder of the Williston Basin.

Red River Kukersites in Core

Terra Resources BNRR #1-17 (NDIC: 7218, API: 33-053-00955-00-00)

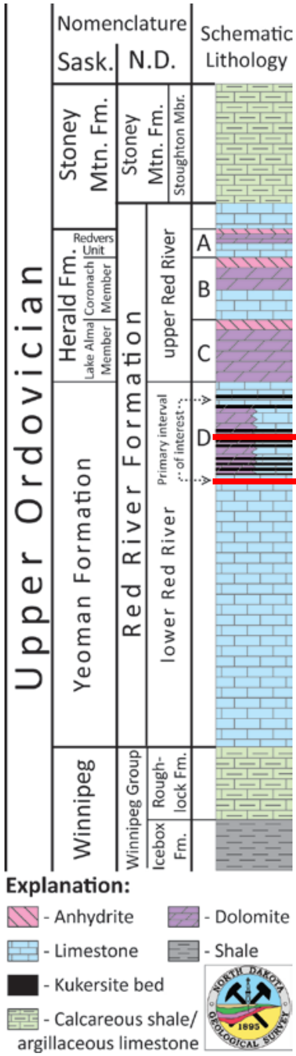




The core box photograph set displayed above shows the lower half of the Red River "D" zone from Terra Resources BNRR #1-17.

Red River Kukersites in Core

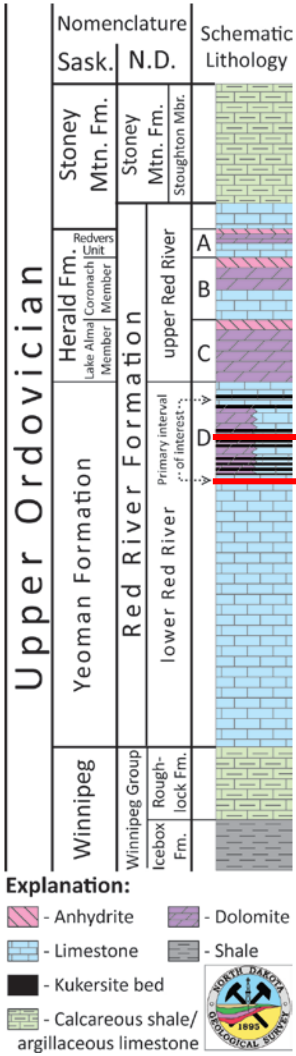
Terra Resources BNRR #1-17 (NDIC: 7218, API: 33-053-00955-00-00)

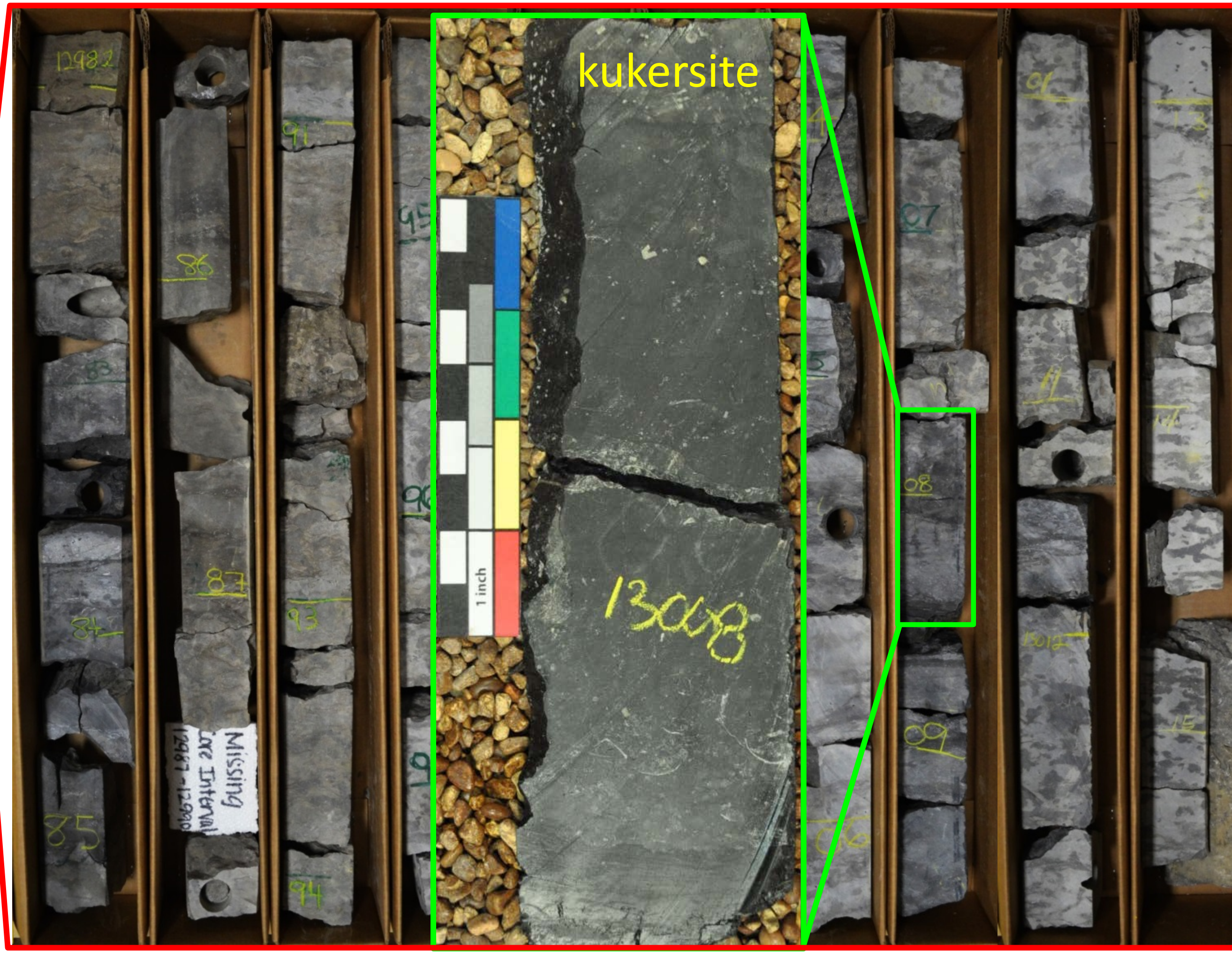


Most of the "D" zone consists of burrow-mottled dolomitic to lime mudstone to fossil wackestone. The color mottled texture has been previously interpreted as *Thalassinoides* burrows, which form a three-dimensional, interconnected framework of centimeter diameter scale burrows.

Red River Kukersites in Core

Terra Resources BNRR #1-17 (NDIC: 7218, API: 33-053-00955-00-00)

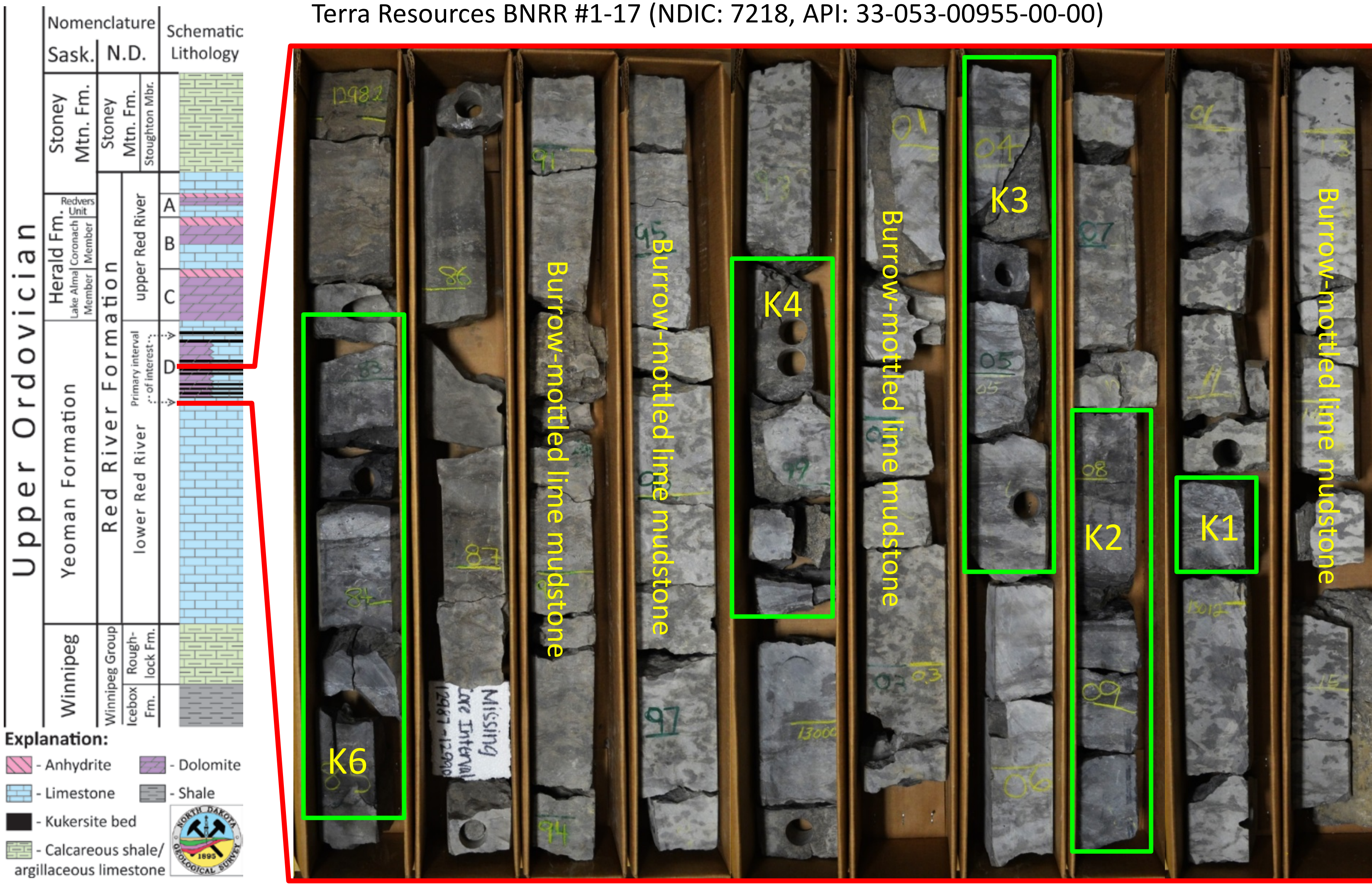




In addition to the burrow-mottled facies, the "D" zone also contains thin beds of organic-rich mudstone (kukersites). Kukersites are darker in color than the burrow-mottled facies and also lack the *Thalassinoides* burrow-mottled texture.

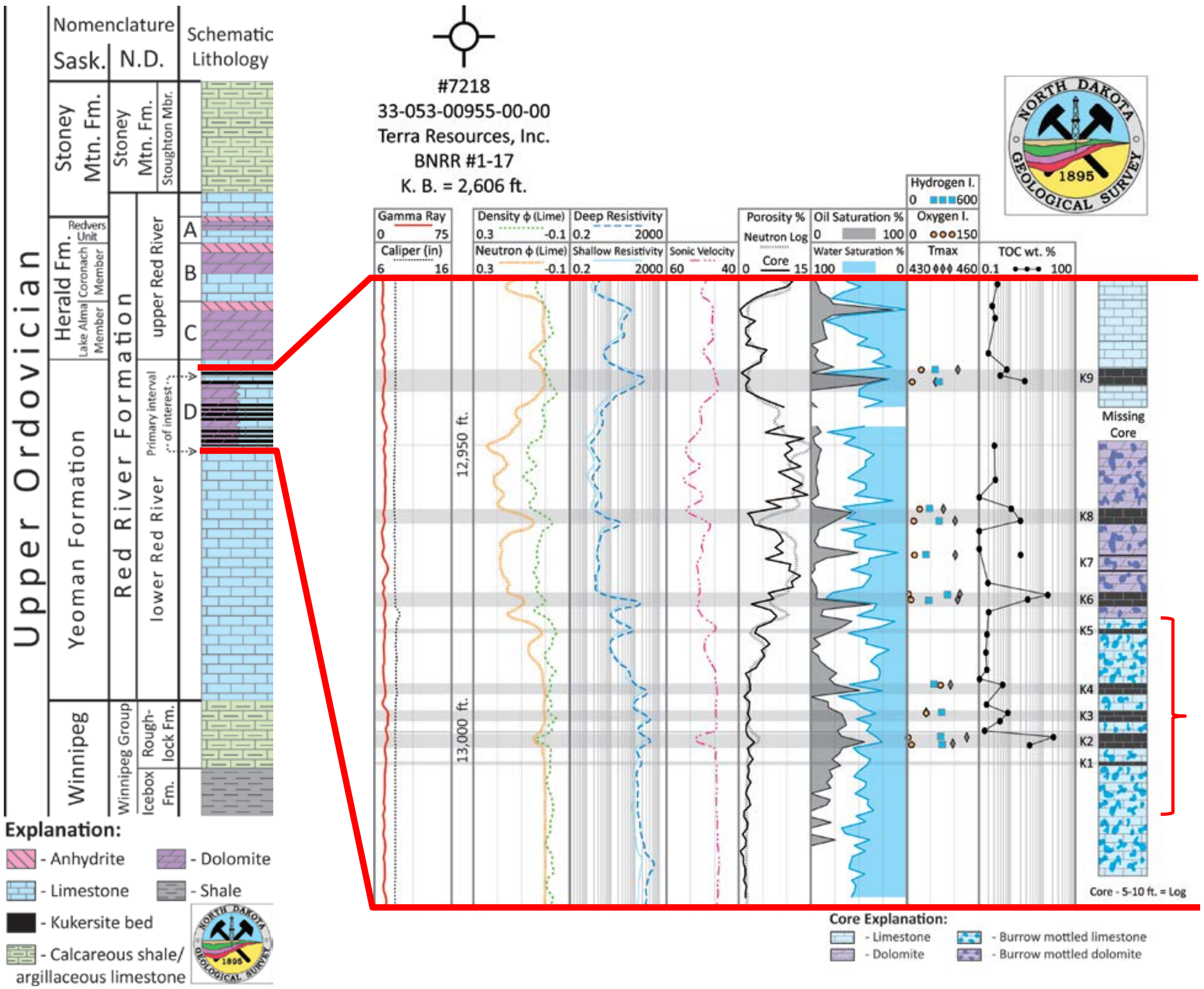
Red River Kukersites in Core

Terra Resources BNRR #1-17 (NDIC: 7218, API: 33-053-00955-00-00)



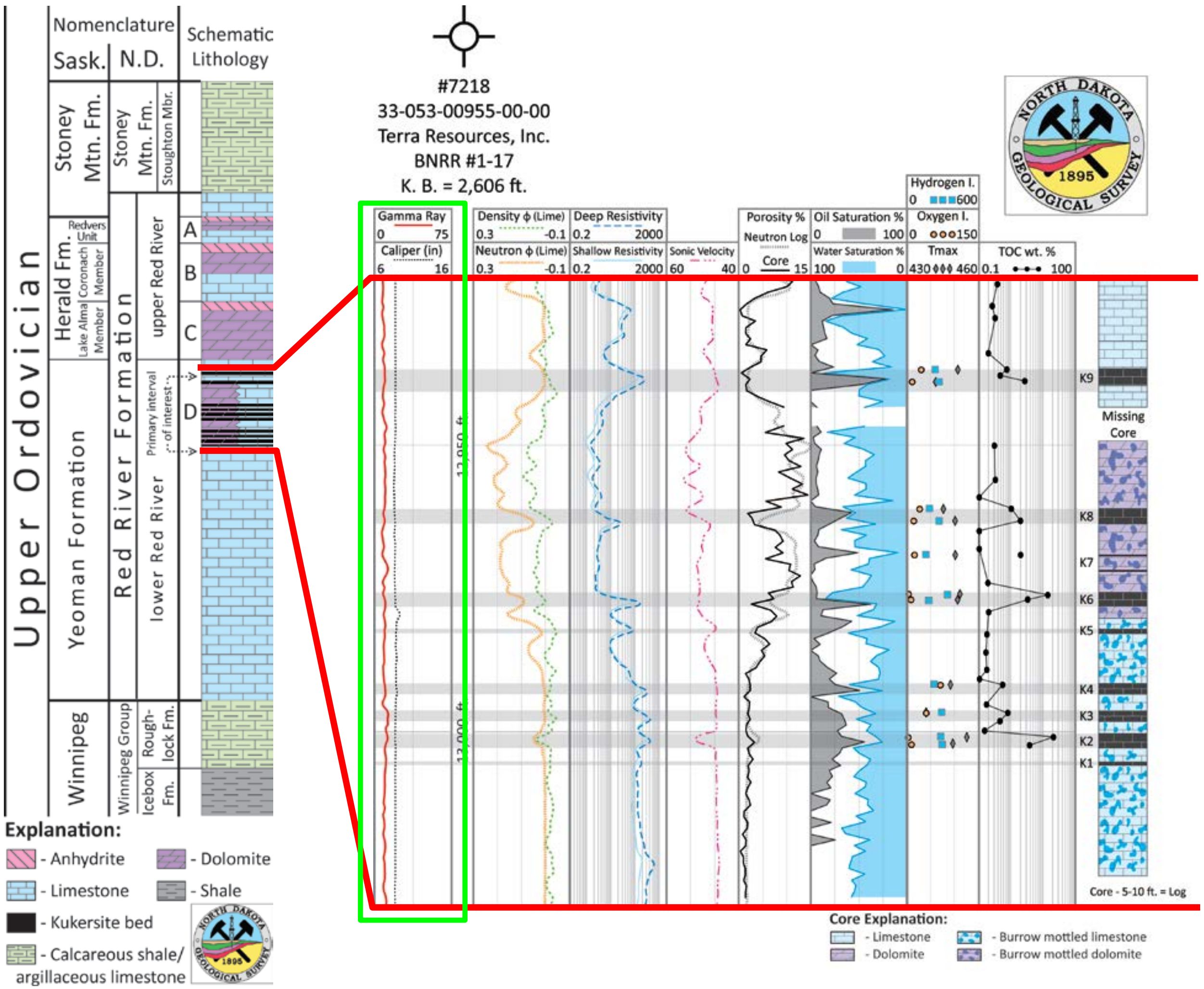
Most of the Red River "D" zone consists of burrow-mottled limestone and dolomite. The interbedded kukersites account for less than one-third of the interval when present. Individually, kukersites (green outlined intervals labeled K1 to K6) are typically one- to two-feet (0.3-0.6 m) thick in western North Dakota, but also thin as well as thicken locally to upwards of 8 ft. (2.4 m) individually.

Red River Kukersites: Wireline Log Signatures



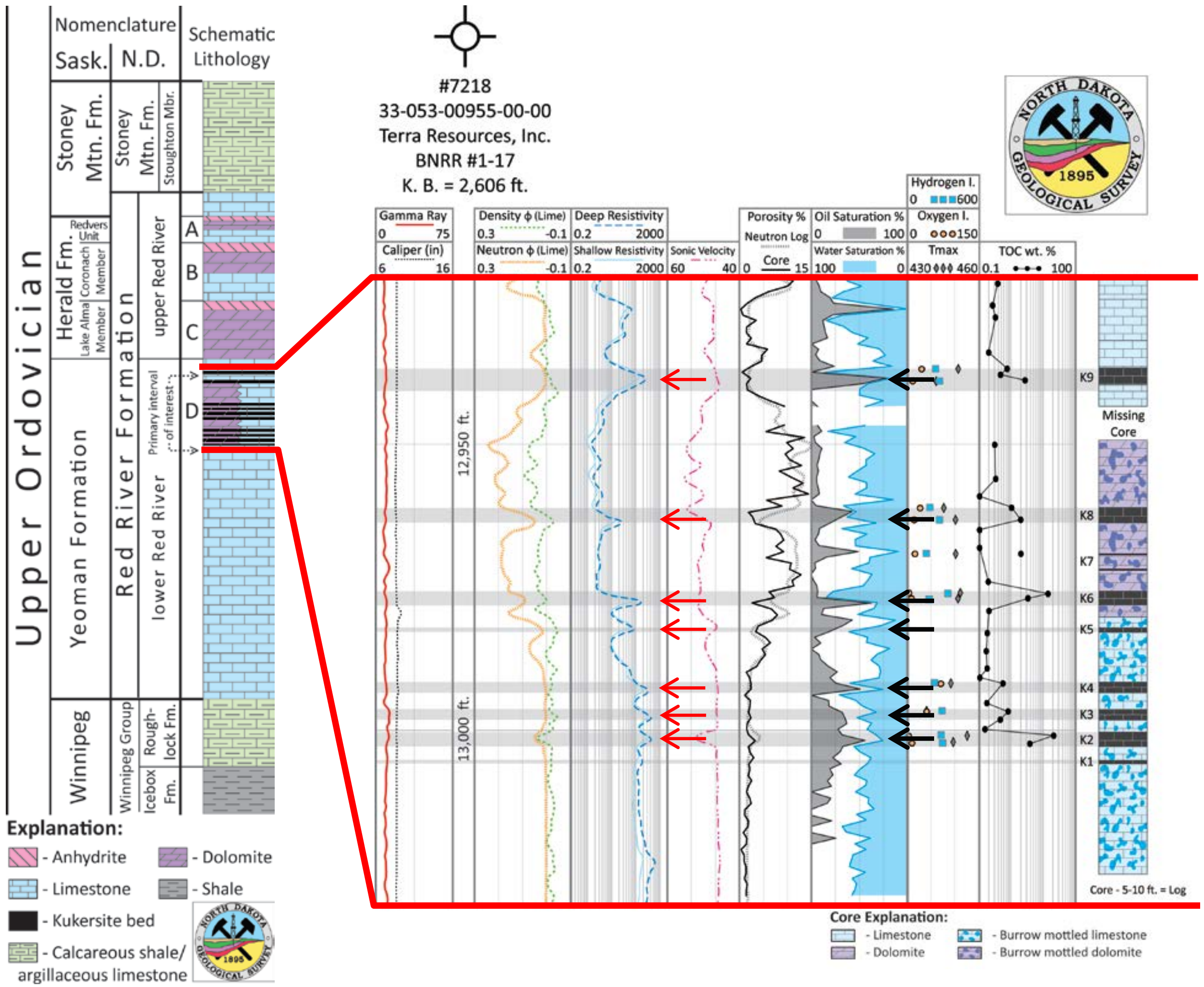
Red River kukersites have several notable wireline log signatures. The above figure is a wireline log suite with core data and an illustrated core of the Red River "D" zone from Terra Resources BNRR #1-17. The red bracket indicates the approximate box core photograph interval from previous slides.

Red River Kukersites: Wireline Log Signatures



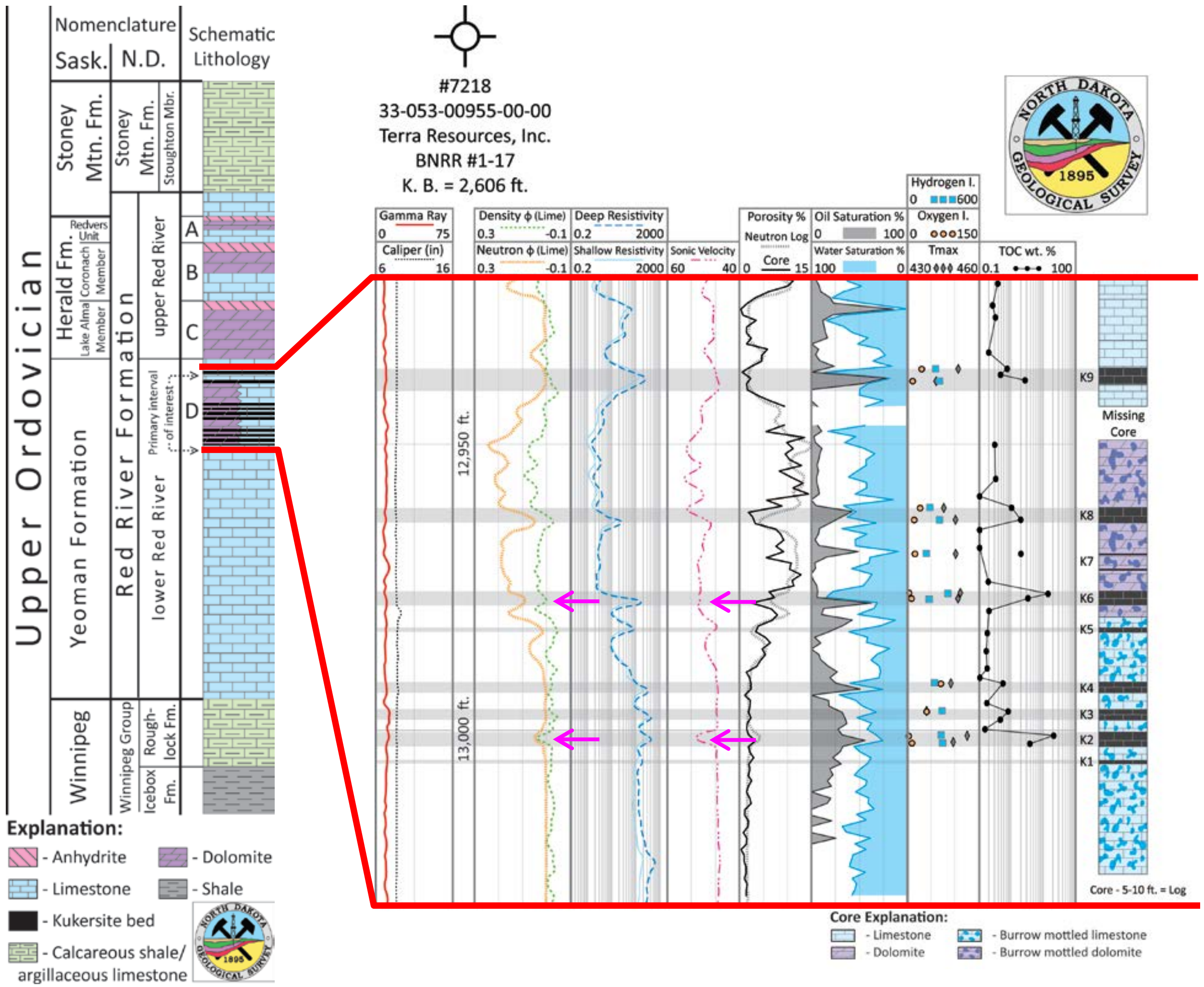
Both the kukersites and the interbedded burrow-mottled facies display very low, indistinguishable gamma-ray wireline signatures, thought to be caused by negligible clay content throughout the entire section. The negligible gamma-ray signature makes mapping and correlating kukersites more difficult than many other petroleum source beds which typically correspond with high gamma-ray log signatures.

Red River Kukersites: Wireline Log Signatures



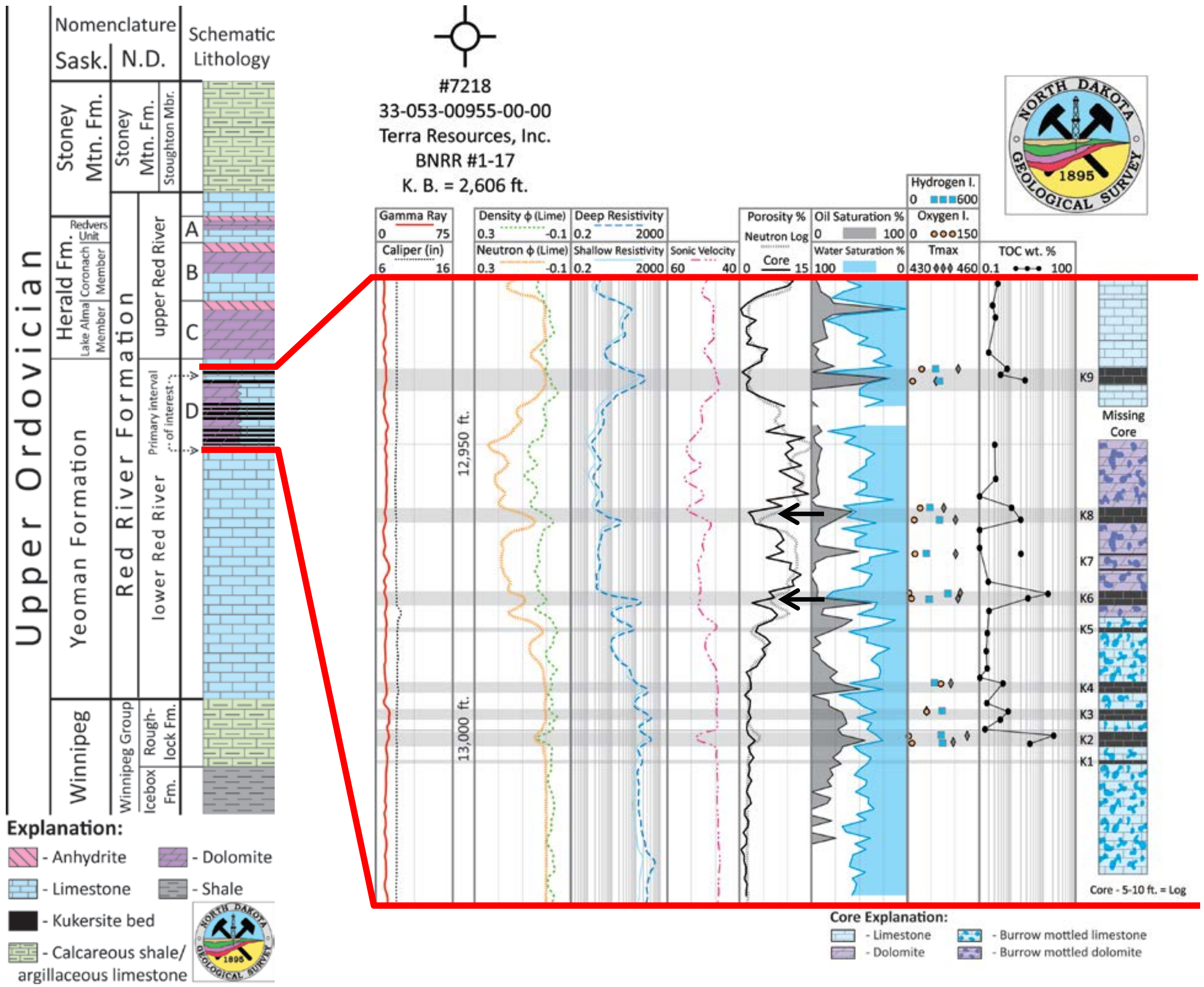
However, Red River kukersites do display high resistivity signatures (red arrows) when they are ≥1 ft. (≥0.3 m) thick, which is likely a function of their high oil saturations (black arrows). In this case, thermally mature kukersites have generated and expelled oil (electrically resistive) that has displaced most of the natural formation water (electrically conductive). Kukersites that are <1 ft. (<0.3 m) thick sometimes yield subtle resistivity signatures as well depending on the quality/resolution of the wireline log.

Red River Kukersites: Wireline Log Signatures



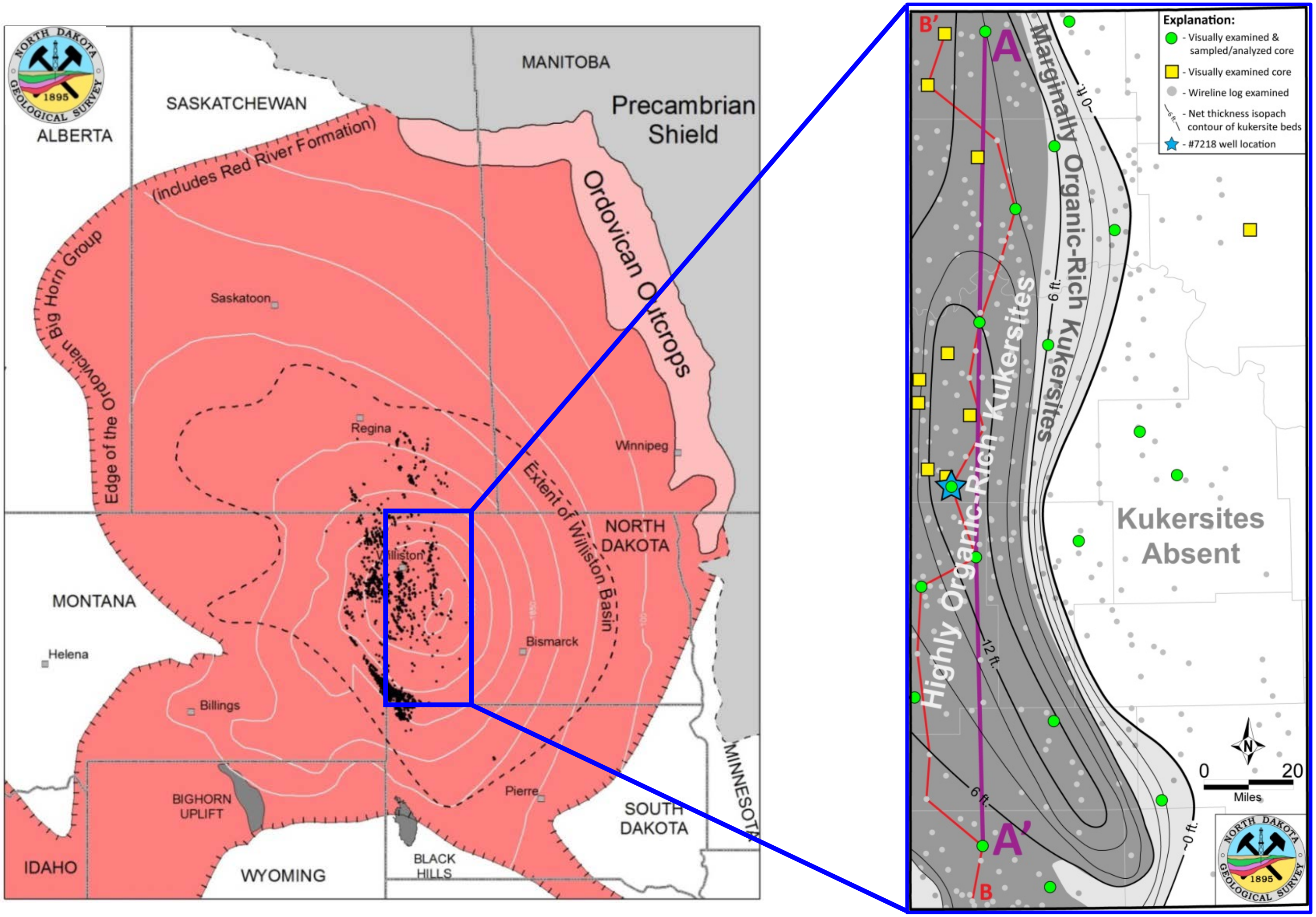
The more organic-rich kukersites, which average >5 wt. % TOC (total organic carbon), also correlate with subtle wireline log porosity and sonic travel time signatures (pink arrows). High concentrations of organic carbon significantly decrease the rock density to create these log porosity-sonic travel time signatures. When interbedded with low porosity (<2%) burrow-mottled limestone, the wireline porosity/sonic log signature is easy to observe (e.g. K2 above), but is more difficult when the organic-rich kukersite (e.g., K6 above) is interbedded with porous (10-20%) dolomite.

Red River Kukersites: Wireline Log Signatures



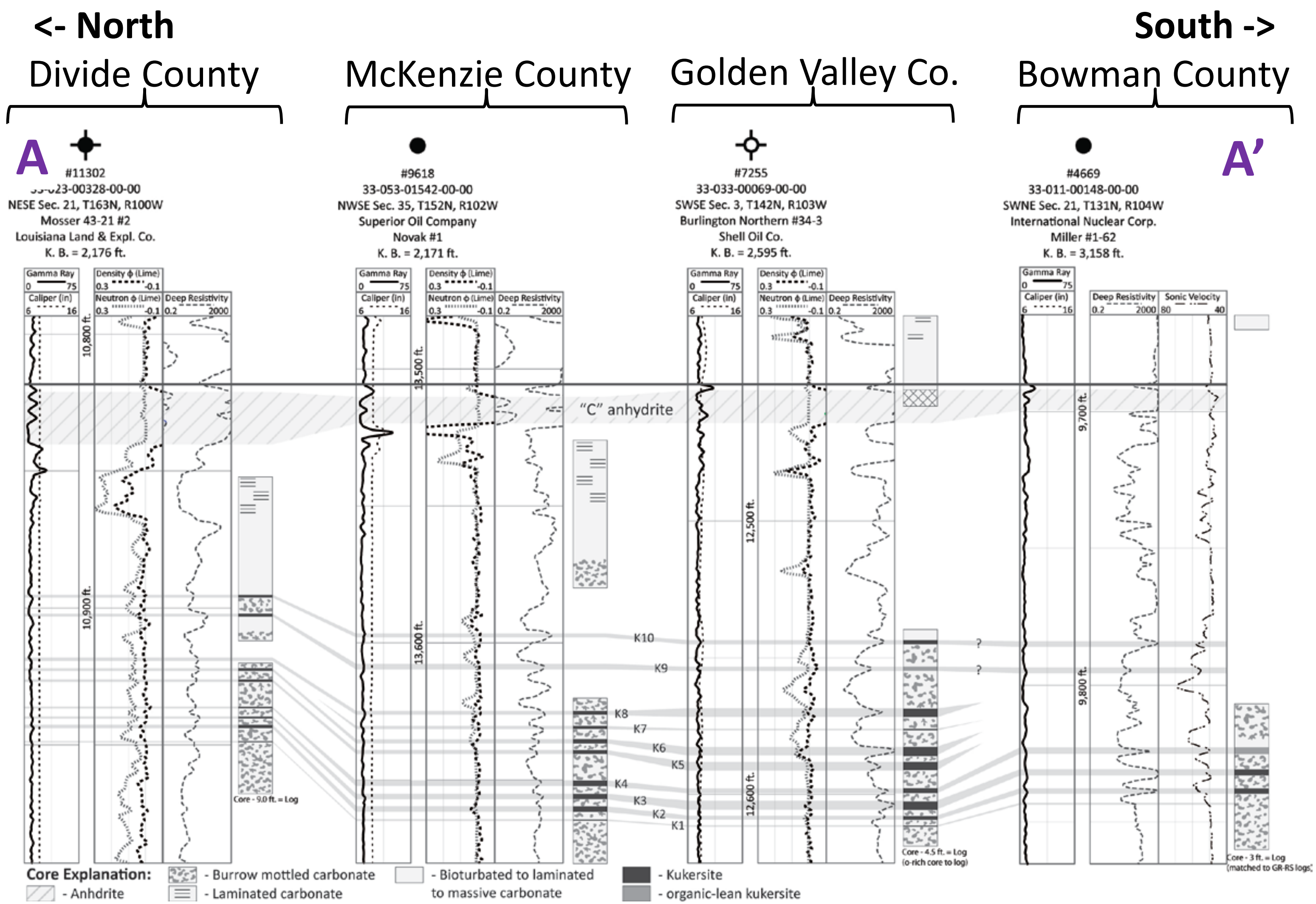
In addition to being petroleum source beds, kukersites may also form hydrocarbon seals when interbedded with porous dolomite. The porous dolomitized burrow-mottled facies contains 10-20% porosity with permeability values of 10's to 100's of millidarcies (md) while the kukersites contain <5% porosity and <1 md permeability. However, being ≤2 ft. (≤0.6 m) thick, minor faults can offset the kukersites and open communication between the burrow-mottled dolomite beds.

Red River Kukersite Net Thickness and Extent



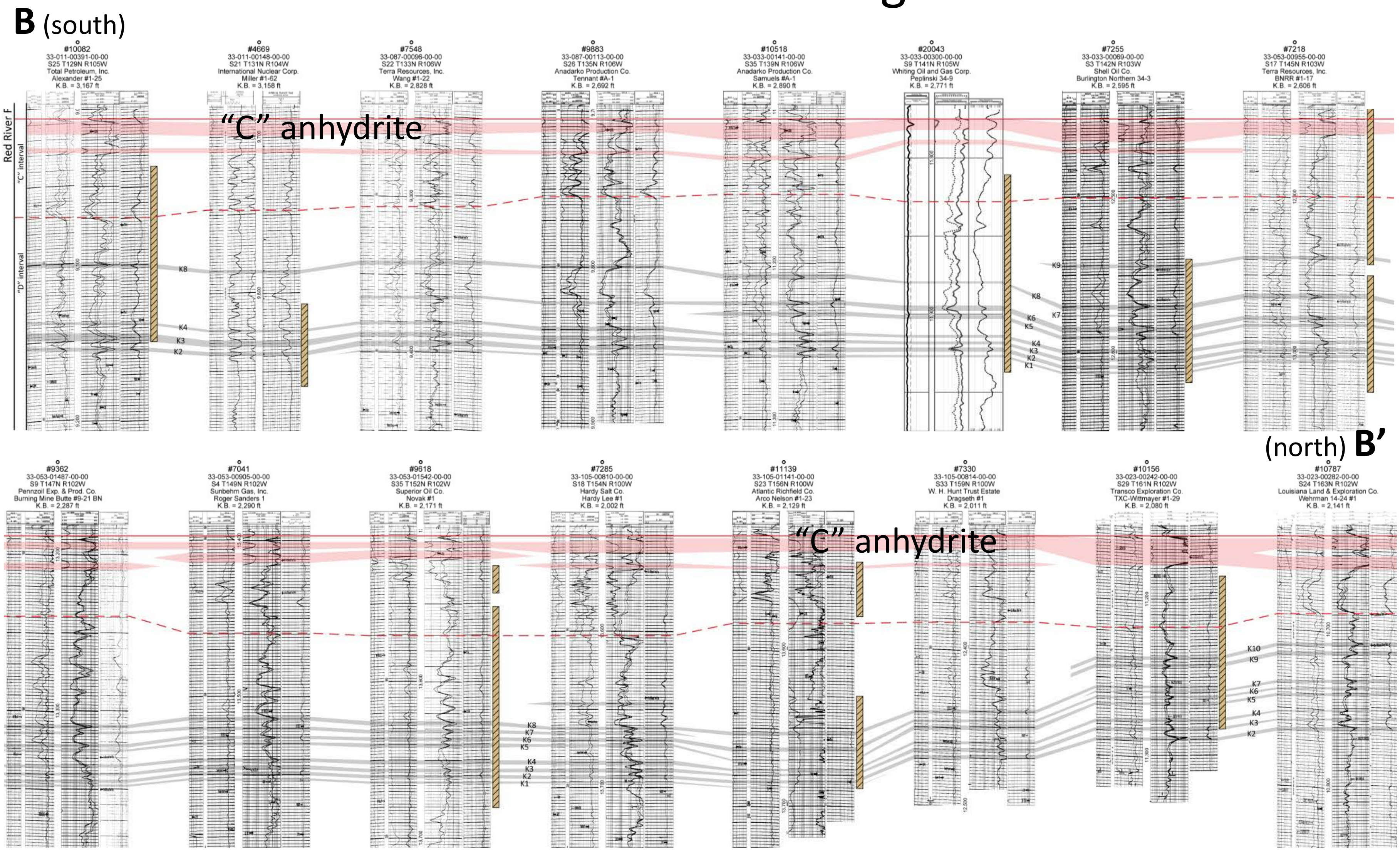
The extent and net thickness of Red River kukersites was mapped across western North Dakota using over two dozen cores and several hundred wireline logs of the Red River “D” zone. Red River kukersites extend 20-40 miles (32-64 kilometers, km) eastward from the Montana border into western North Dakota, and stretch from the Saskatchewan to South Dakota borders. Red River kukersites range from being absent eastwards to reaching combined net thicknesses of over 12 feet (3.7 meters, m) in the study area.

Kukersite Core and Wireline Log Correlations



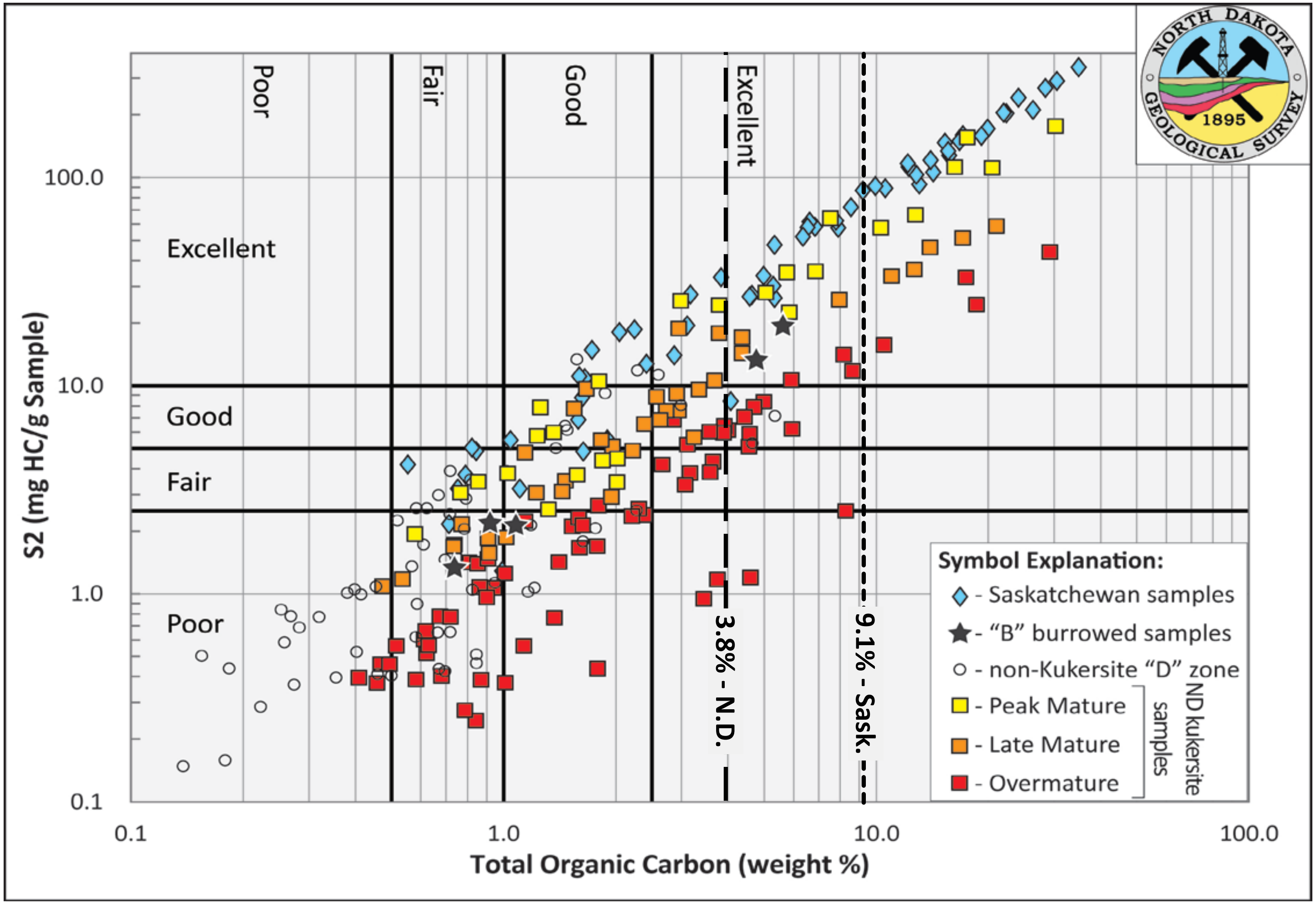
Ten distinct kukersites, referred to informally as K1 through K10 in ascending order, were identified and correlated across the study area. Correlations of the K9 and K10 kukersites are less robust due to fewer cores examined spanning their stratigraphic interval. The K2 and K6 beds are often the most organic-rich kukersites and can be correlated using their porosity-sonic wireline log signatures in addition to resistivity.

Kukersite Core and Wireline Log Correlations



The above sixteen well stratigraphic cross-section ("C" anhydrite as datum) shows correlations of the ten kukersites (grey shaded intervals) from the South Dakota (South) to Saskatchewan (North) border. Overall, the Red River "D" zone kukersites correlate with limited vertical depth change in relation to the "C" anhydrite until they reach proximity to the Saskatchewan border, where they shallow in relation to the "C" anhydrite.

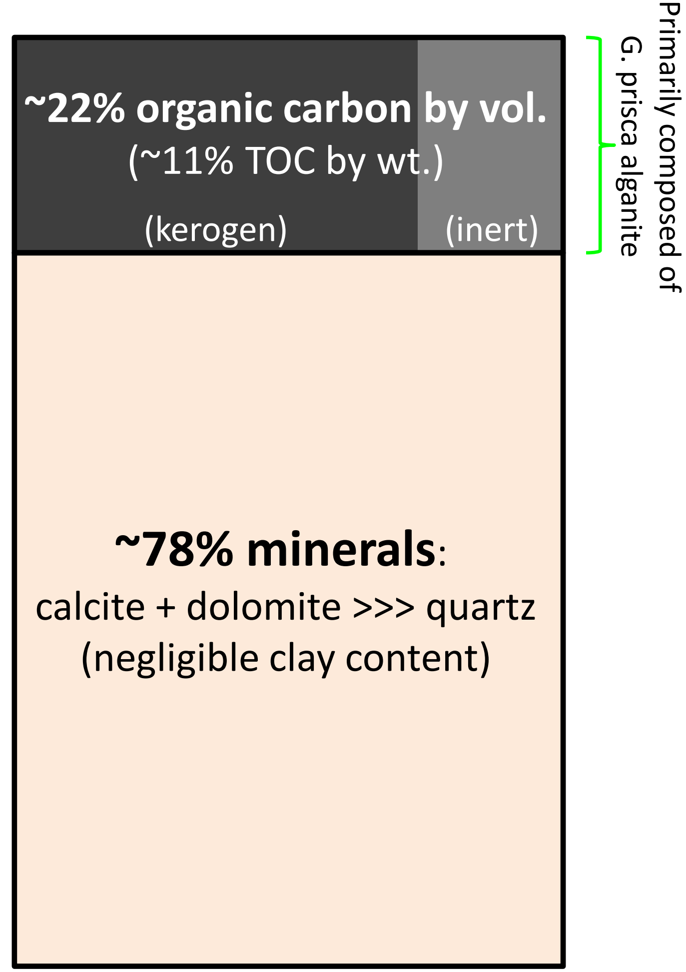
Kukersite Organic Richness



Over 400 Red River core chip samples were collected and analyzed using LECO TOC, and samples with ≥0.5 wt. % TOC were also analyzed using RockEval 6 pyrolysis. Kukersite core chip samples from western North Dakota were found to contain <0.5% up to 30% TOC, and combined to average 3.8% TOC. Red River (upper Yeoman Fm.) kukersite core chip samples from southern Saskatchewan were previously reported to average 9.1% TOC (Osadetz and Snowdon, 1995). The difference, as reviewed below, may be primarily a function of thermal maturity.

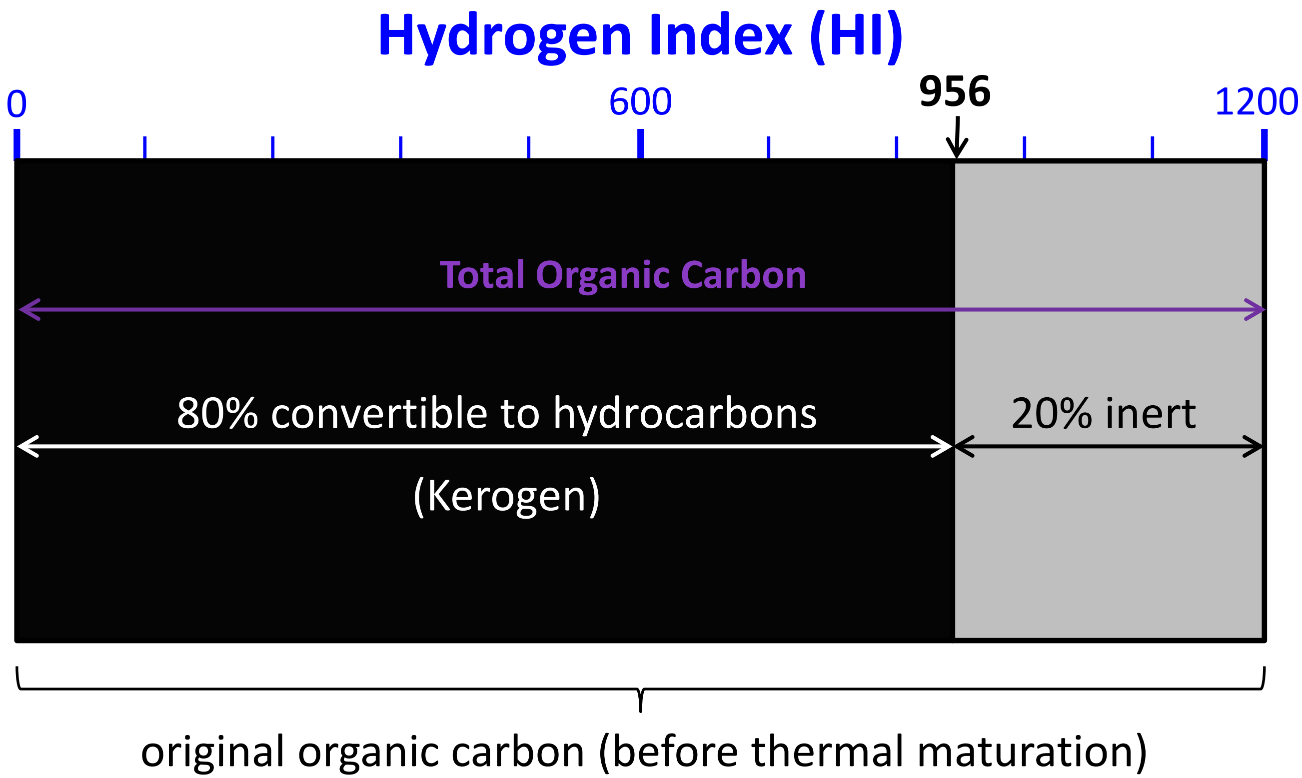
Red River Kukersites – Original Organic Richness

International Nuclear Corp. Miller 1-62 (NDIC: 4669, API: 33-011-00148-00-00)



Immature to early mature kukersite samples (collected from depths less than 9,500 ft. or 2,900 m – see appendix slides) from Osadetz and Snowdon (1995) combine to average ~11 wt. % TOC, which may be a good approximation for the average original TOC of Red River kukersites in the Williston Basin. 11 wt. % TOC translates to approximately 22% by volume due to density differences between organic carbon versus carbonate minerals. Preliminary XRD data on North Dakota kukersite samples reported mineral assemblages of primarily calcite and dolomite with 1-3% quartz and only trace amounts (<1%) of clay.

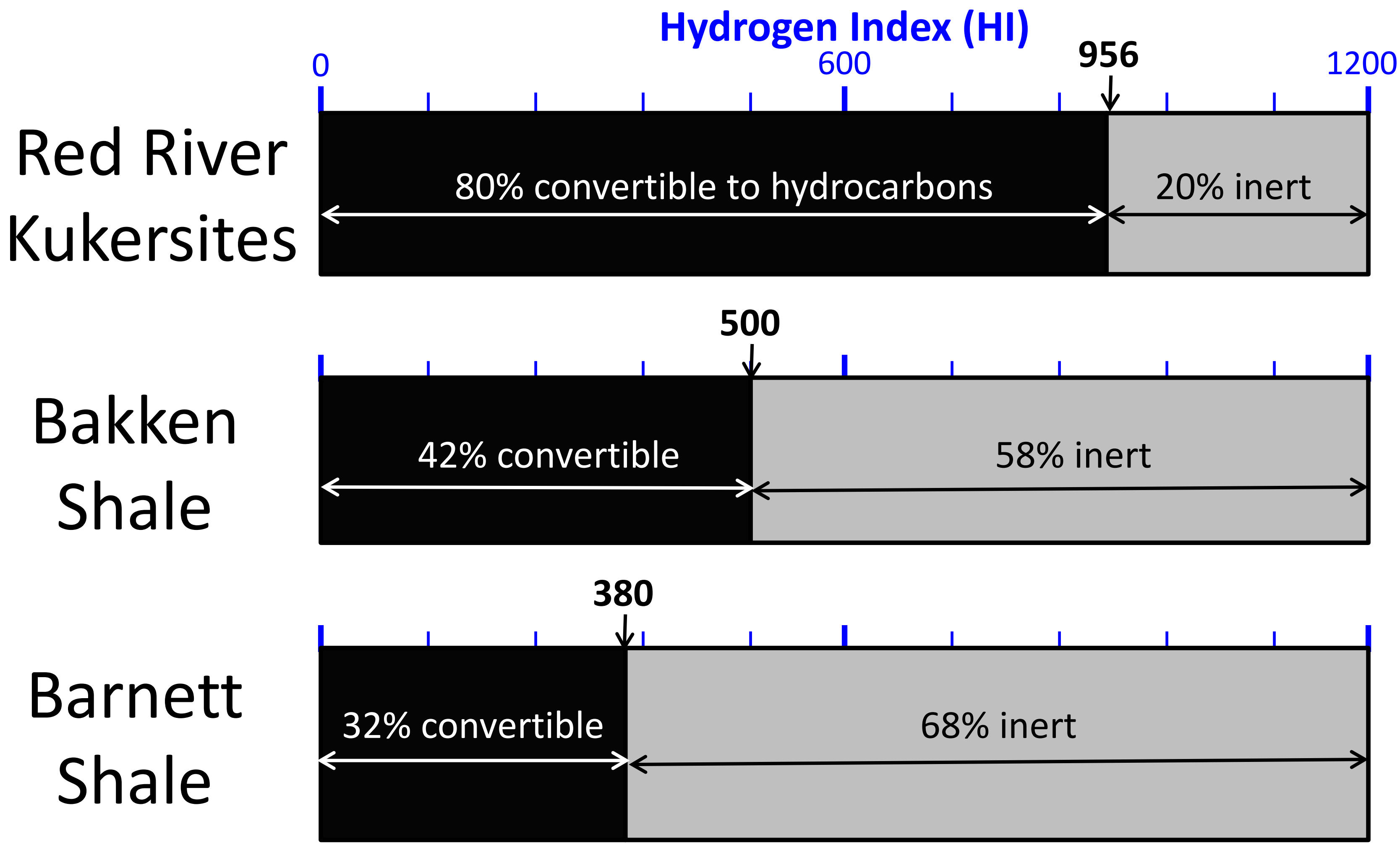
Red River Kukersites – Original Organic Richness



Red River Kukersites - ~75% original TOC convertible to hydrocarbons (original HI ≈ 956) (Osadetz and Snowdon, 1995)

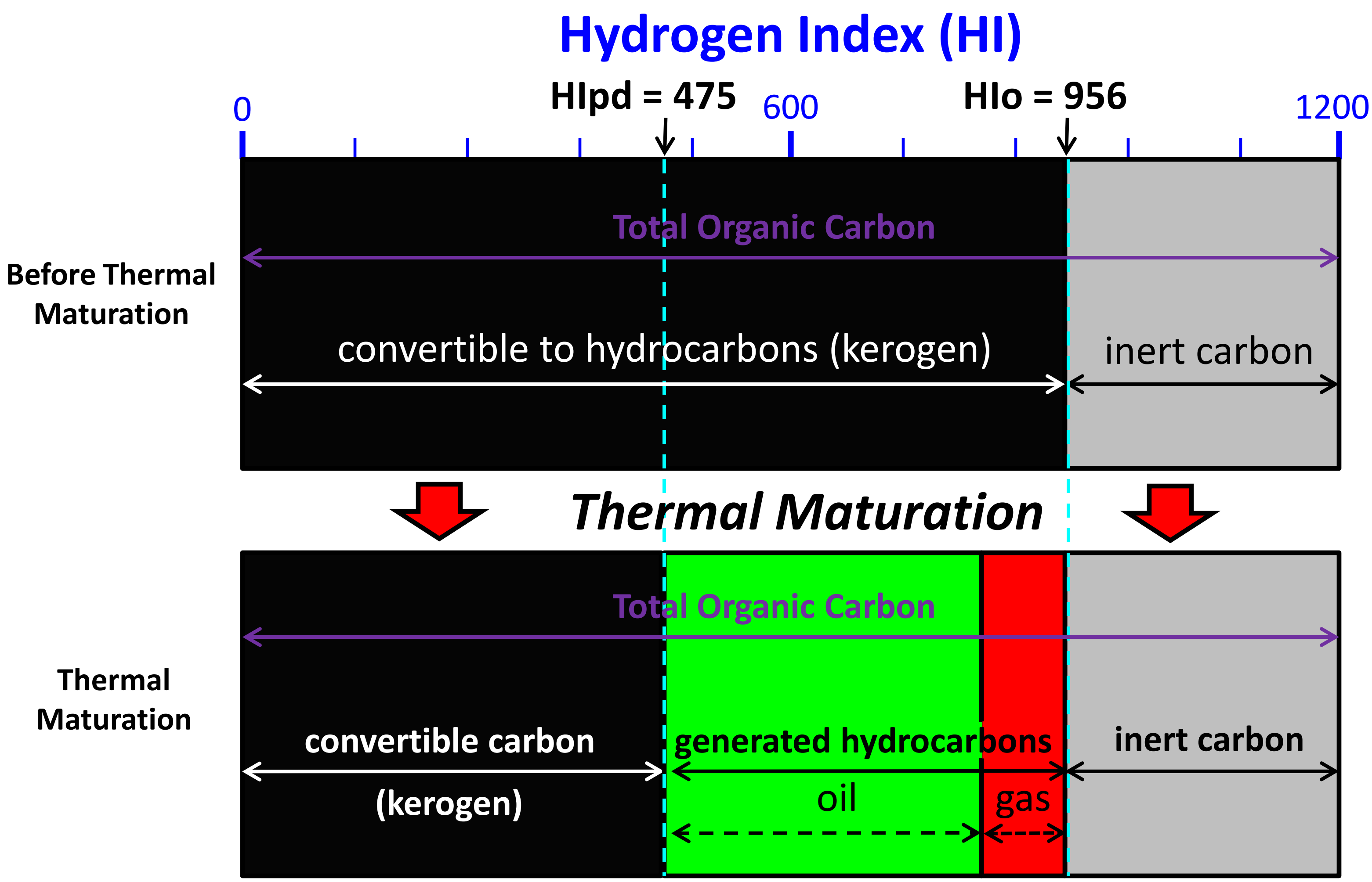
Osadetz and Snowdon (1995) inferred an original Hydrogen Index (HI) of 956 for Red River kukersites based on immature to marginally mature samples from southern Saskatchewan. HI is the ratio of kerogen to total organic carbon, on a scale of 0 to 1200. An original HI of 956 would mean that approximately 80% of the original total organic carbon deposited within Red River kukersites was composed of kerogen, which is organic carbon capable of converting into hydrocarbons (oil and gas). All petroleum source beds contain variable amounts of inert organic carbon, which is incapable of converting into hydrocarbons.

Comparison of Original Hydrogen Index



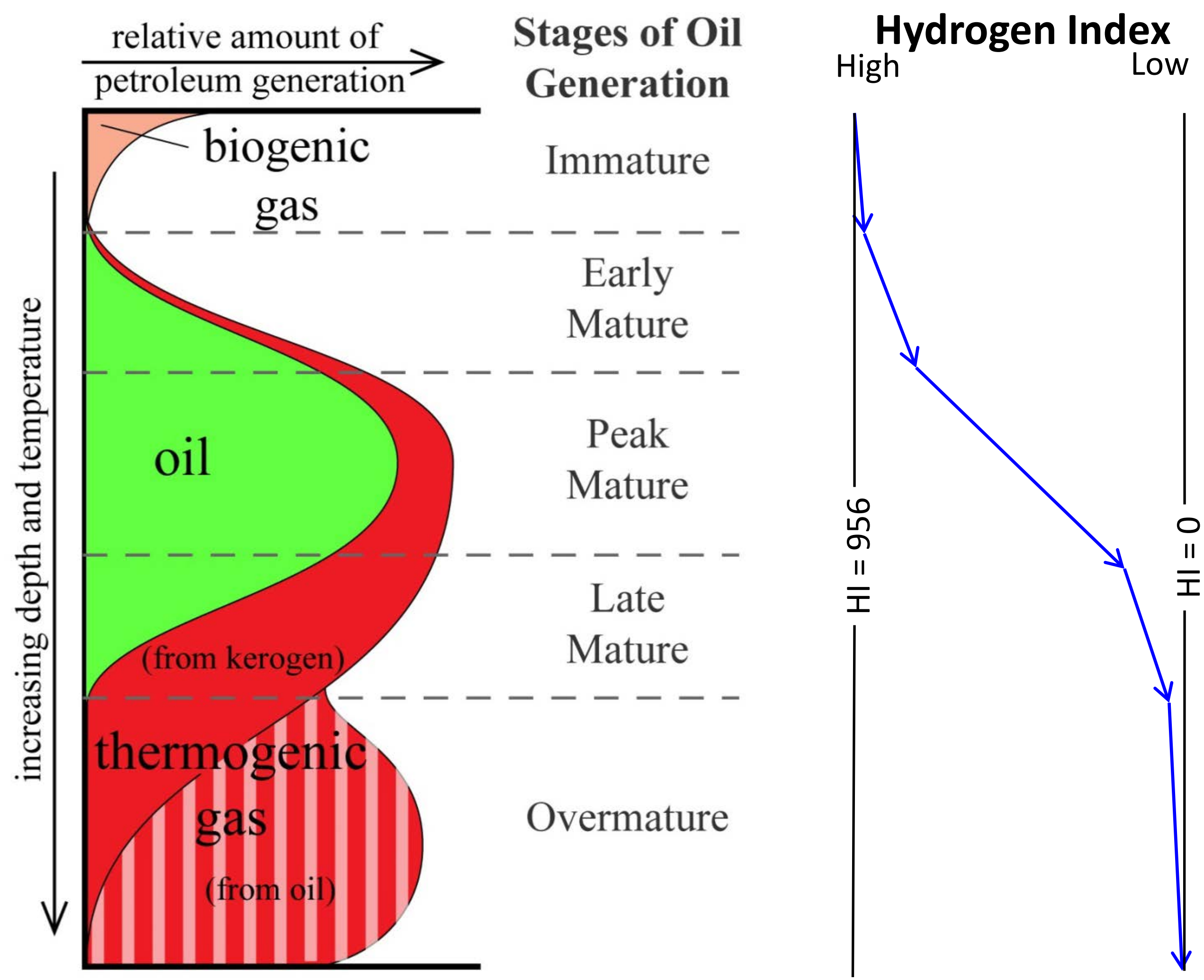
Most other petroleum source beds, such as the Bakken and Barnett shales, are thought to have averaged original HI values of less than 600 (Barnett - Jarvie, 2007), meaning less than half of the original organic carbon deposited within those source beds was composed of kerogen.

Thermal Maturation and Hydrogen Index



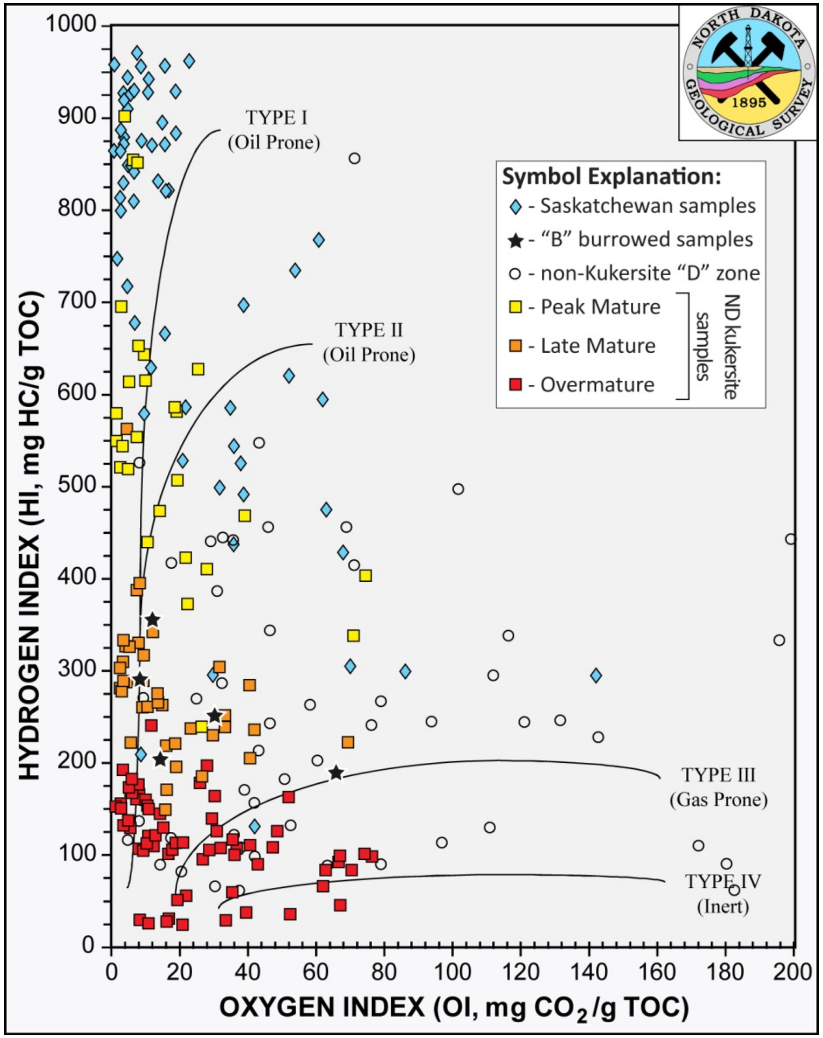
As petroleum source beds undergo thermal maturation, and kerogen converts into hydrocarbons, the HI of the source rock decreases as the ratio of kerogen to total organic carbon decreases. However, expulsion of generated hydrocarbons will increase the HI of a petroleum source bed. So while HI overall decreases with increased levels of thermal maturity and oil generation, the relationship is moderately complicated.

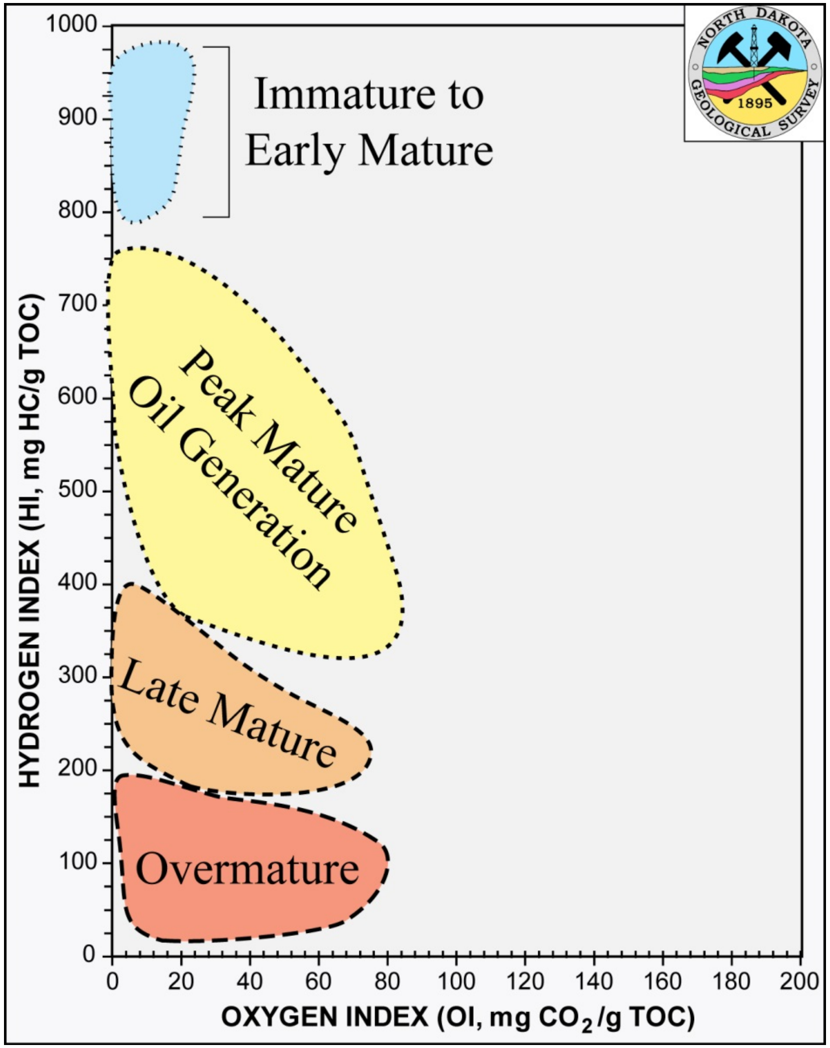
Thermal Stages of Oil and Gas Generation



HI decreases slightly during both the immature stage of oil generation through bacterial activity and the early mature stage as minor amounts of oil and/or gas are thermally generated. The peak mature stage represents when the greatest quantity of kerogen is converted primarily to oil with some associated hydrocarbon gas which results in a substantial decrease in HI. By the late to overmature stages, only small amounts of kerogen remain and corresponding low HI values continue to slowly decrease as thermal maturation continues.

Kukersite Thermal Maturity

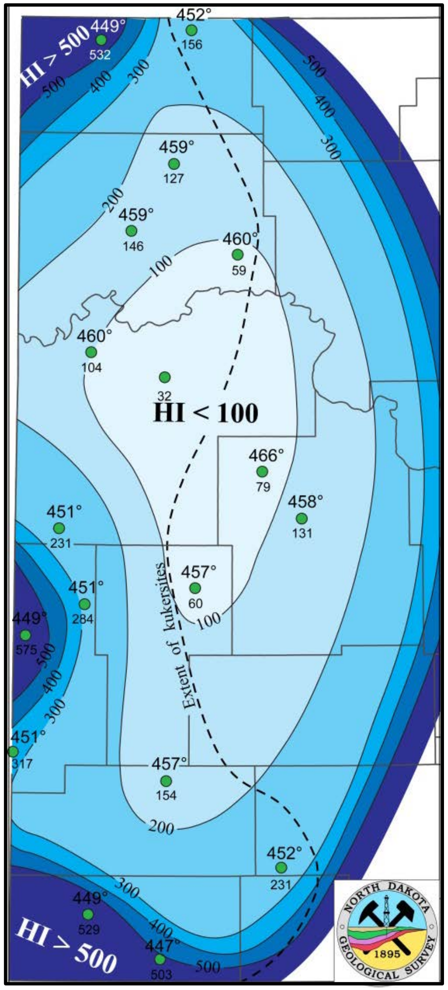




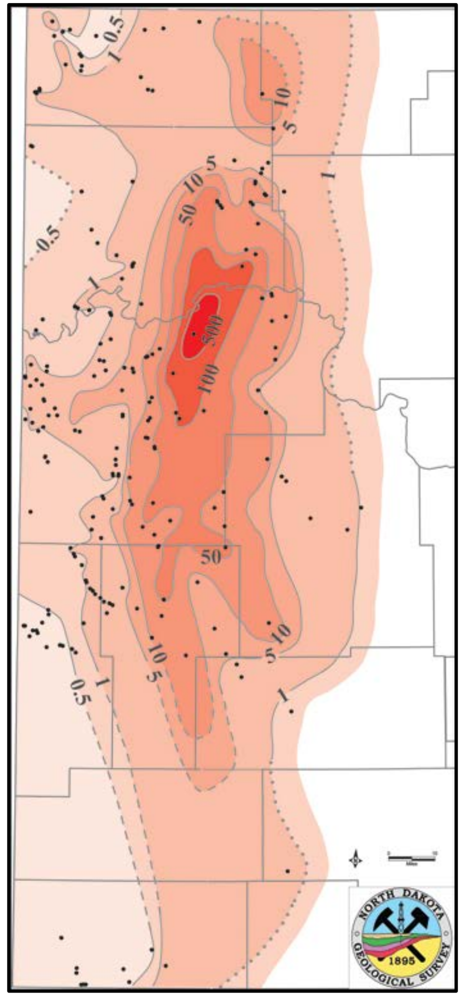
Kukersite sample sets from western North Dakota were divided into three levels thermal maturity (peak, late, and overmature) based on the HI value range within individual cores. Most of the Saskatchewan kukersite samples analyzed by Osadetz and Snowden (1995) contained very high HI and low OI (Oxygen Index) values indicating Type I kerogen which is very prone to generating oil. The lower HI values of kukersite samples from western North Dakota versus southern Saskatchewan is thought be primarily a result of differences in thermal maturity.

Thermal Oil and Gas Generation

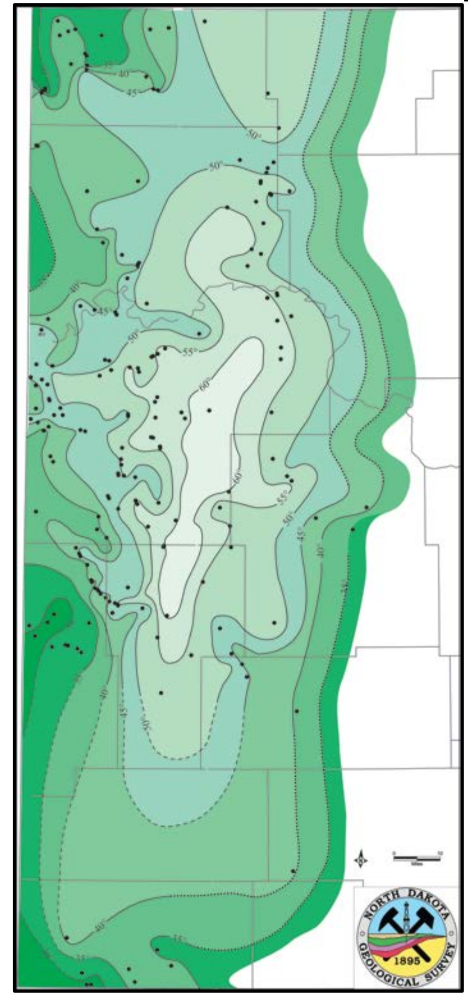
Average kukersite HI



"C" & "D" zone GOR

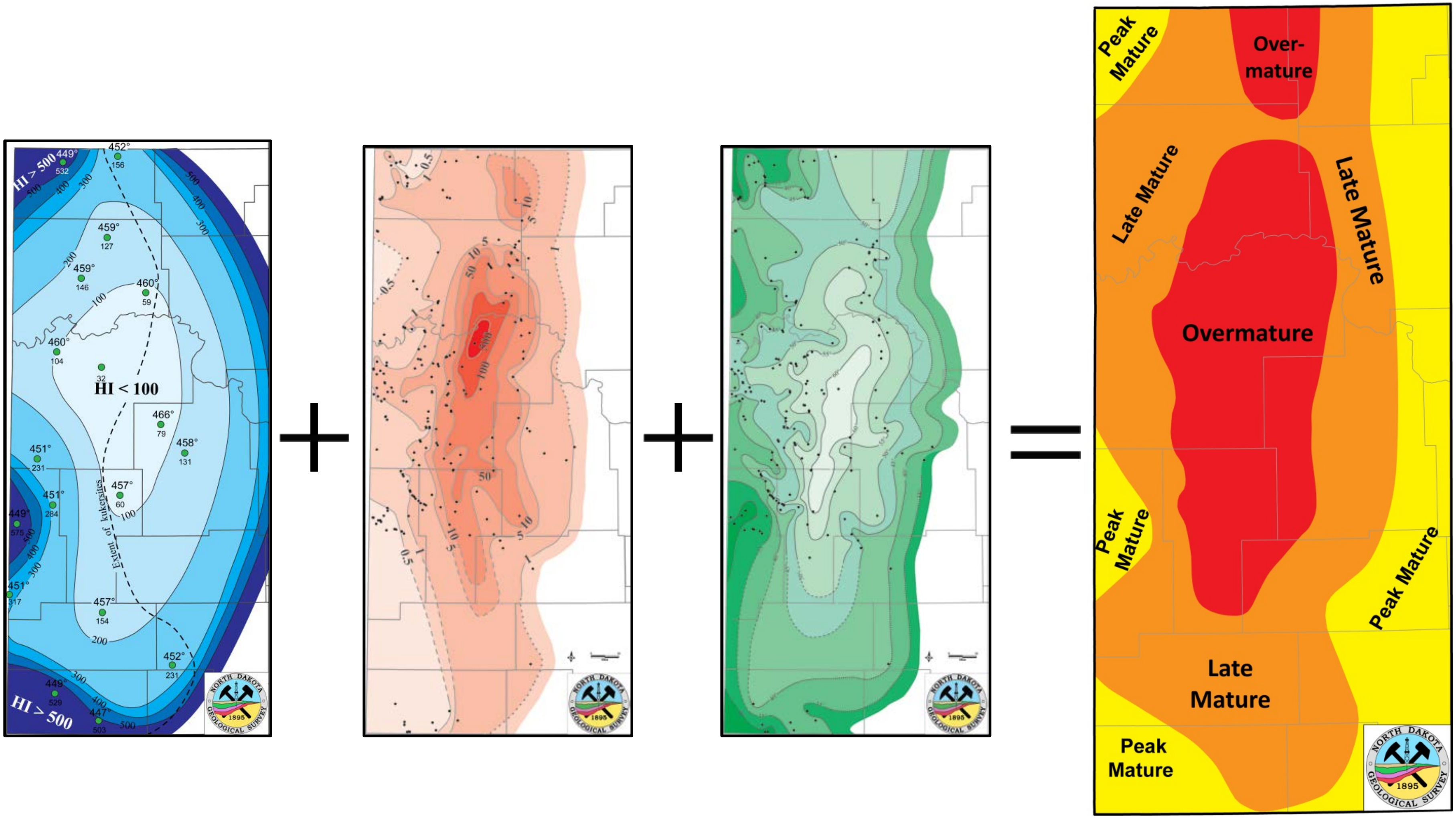


"C" & "D" Zone API Oil Gravity



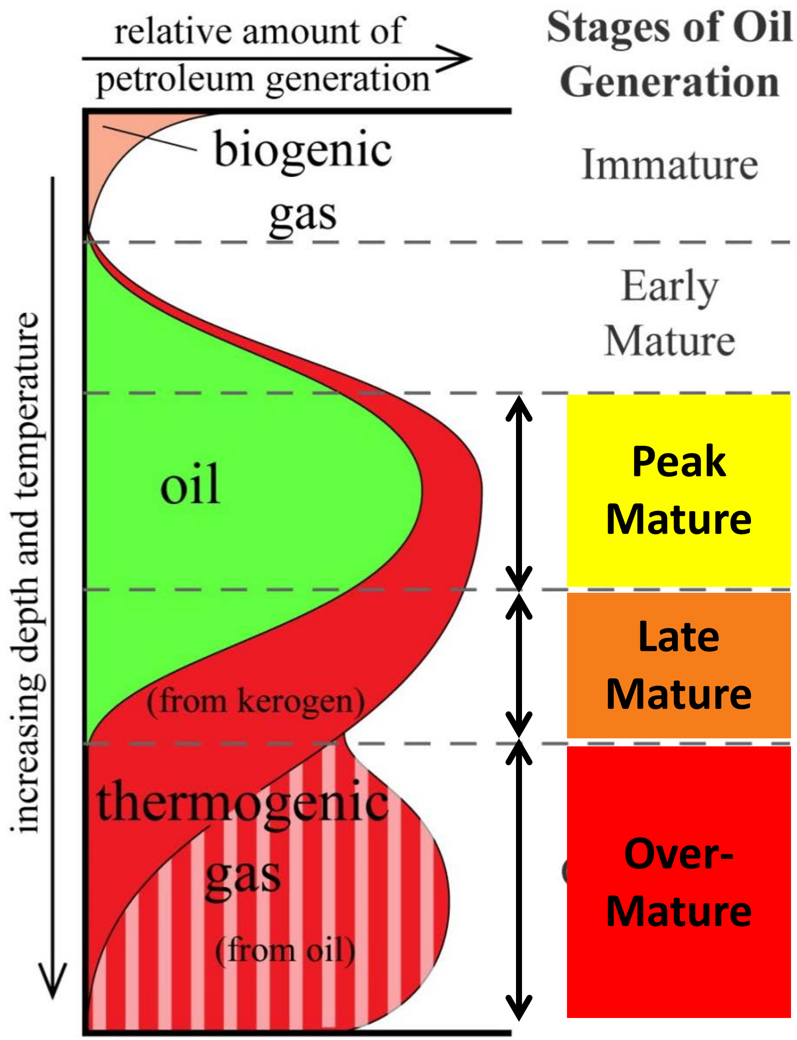
The average HI of kukersite samples from individual Red River "D" zone cores was contoured for the study area. Beyond the area of kukersite extent, the Red River Formation contains occasional organic-rich (>0.5% TOC) laminations that are useful for thermal maturity mapping, but do not appear to constitute a significant volume of source rock. Gas to oil ratios (GOR) and API oil gravity were contoured for produced hydrocarbons from the "C" and "D" zone reservoirs, which are proximal to the kukersites.

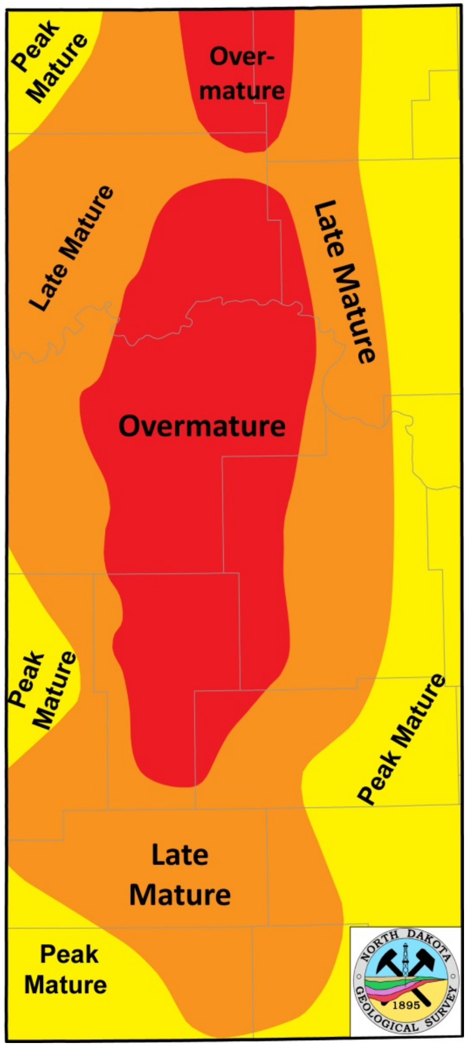
Thermal Oil and Gas Generation



Decreasing kukersite HI averages were found to correspond with increasing Tmax as well as the GOR and API oil gravity of produced hydrocarbons from “C” and “D” zone reservoirs, an indication that the kukersites are locally sourcing the “C” and “D” zone reservoirs. Kukersite thermal maturity was mapped using average HI as the primary data set, and the GOR and API oil gravity data of “C” and “D” zone production as secondary datasets. Kukersite thermal maturity was spatially subdivided into three levels/stages of thermal maturity which are interpreted to range from peak to overmature.

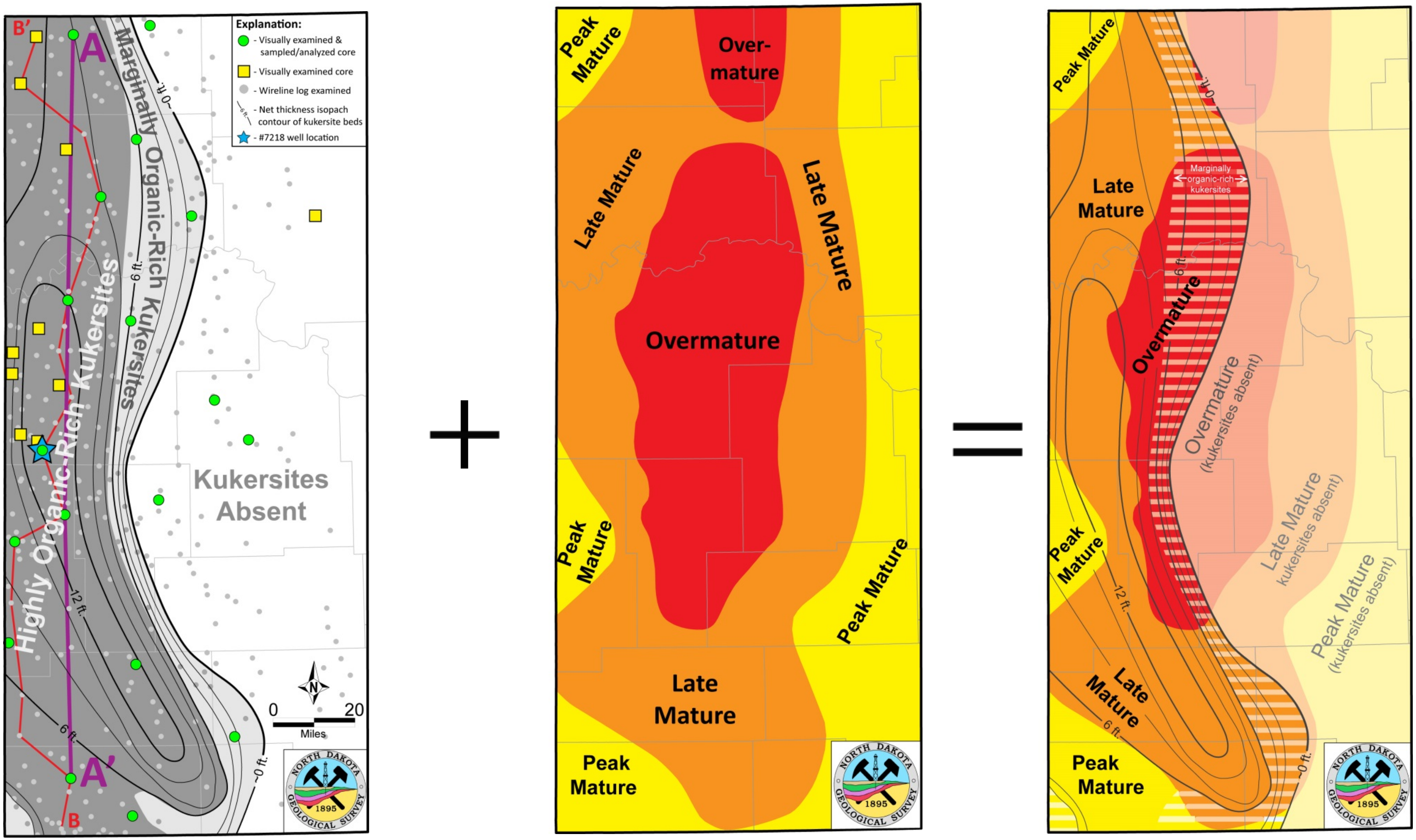
Thermal Oil and Gas Generation





The peak mature oil generation window is interpreted where kukersite HI values were found to decrease rapidly. The overmature window is interpreted where kukersite HI values are very low (<100) and the GOR of "C" and "D" zone production increases rapidly with greater depth/thermal maturity. The late mature oil generation window is implied for the intermediate area, where kukersite HI values are relatively low and decrease gradually while production GOR slowly increases.

Thermal Oil and Gas Generation



Combining the thermal maturity map with the kukersite extent-net thickness map, kukersites range from peak to overmature in the study area. Eastward of the kukersite extent area, the Red River Formation is within the oil generation window and beyond, but the Red River appears to lack a significant quantity of source rock.

Generated Hydrocarbon Volume

Equation (modified from Schmoker, 1994)

$$\underbrace{\frac{TOC_o}{100} \times \rho \times A \times T}_{\text{mass of original organic carbon (grams of TOC)}} \times \underbrace{[HI_o - HI_{pd}]}_{\text{HC generated per gram TOC}} \times \underbrace{\frac{1}{C}}_{\text{conversion to bbls oil}}$$

Units: TOC_o (wt. %); ρ g/cm^3; $A \times T$ cm^3; $[HI_o - HI_{pd}]$ mg HC/g TOC; $\frac{1}{C}$ bbls/mg

TOC_o = original total organic carbon
ρ = formation density
A = area of source rock unit
T = average source rock net thickness

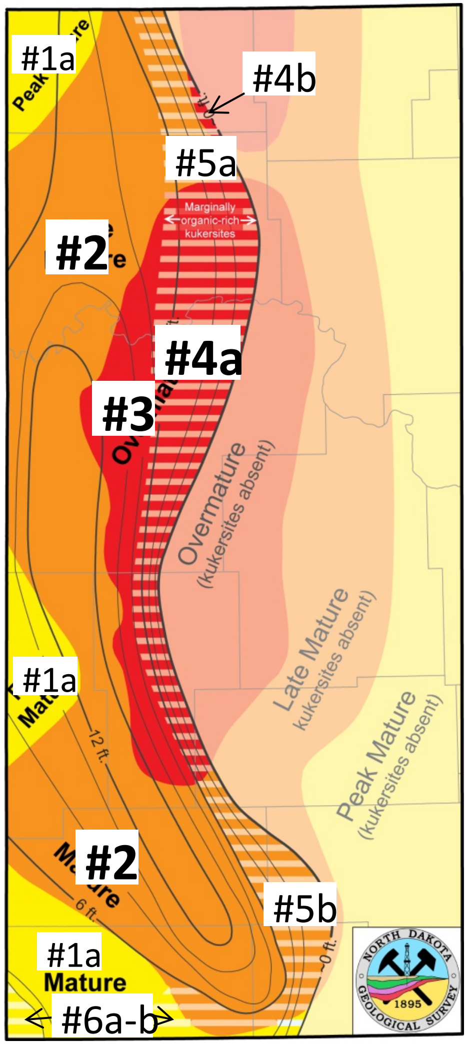
HI_o = original hydrogen index
HI_{pd} = present day hydrogen index
*C = 1.3514×10^8 mg/barrel of 35° API oil
HC = hydrocarbons

*C was calculated assuming 850 kg/m^3 = 35° API oil density, and 1 bbl oil = 6.2898 m^3

Table — Osadetz and Snowdon (1995)

Fig. X Area #	A (cm2 x 10E-10)	T (cm)	TOCo	HIo	HIpd	ρ (g/cm3)	Gen. HC (BBOE)
#1a-c	3,807	213	10	956	544	2.46	6.08
#2	12,087	290	10	956	190	2.46	48.88
#3	1,950	290	6	956	60	2.46	5.53
#4a-b	484	76	2	750	520	2.73	0.03
#5a-b	2,435	107	2	750	166	2.73	0.61
#6a-b	3,735	122	2	750	45	2.73	1.30
						Total	*62.44*

Red River Kukersite with HIo = 956 would have **generated ~62 billion barrels of oil equivalent**



The kukersite extent area was divided into six subunit sets based on interpreted thermal maturity and average kukersite TOC content (both present day and calculated original average values). An average original TOC for kukersites within each subunit was calculated using the appendix equations of Jarvie et al. (2007), and volumetric hydrocarbon generation calculations were made using a slightly modified equation from Schmoker (1994). Assuming an original HI of 956, Red River kukersites have generated approximately 62 billion barrels of oil equivalent (BBOE) in western North Dakota.

Generated Hydrocarbon Volume

Equation (modified from Schmoker, 1994)

mass of original organic carbon (grams of TOC) — HC generated per gram TOC — conversion to bbls oil

$$\frac{TOC_o}{100} \times \rho \times A \times T \times \left[HI_o - HI_{pd}\right] \times \frac{1}{C}$$

(wt. %) — g/cm^3 — cm^3 — mg HC/g TOC — bbls/mg

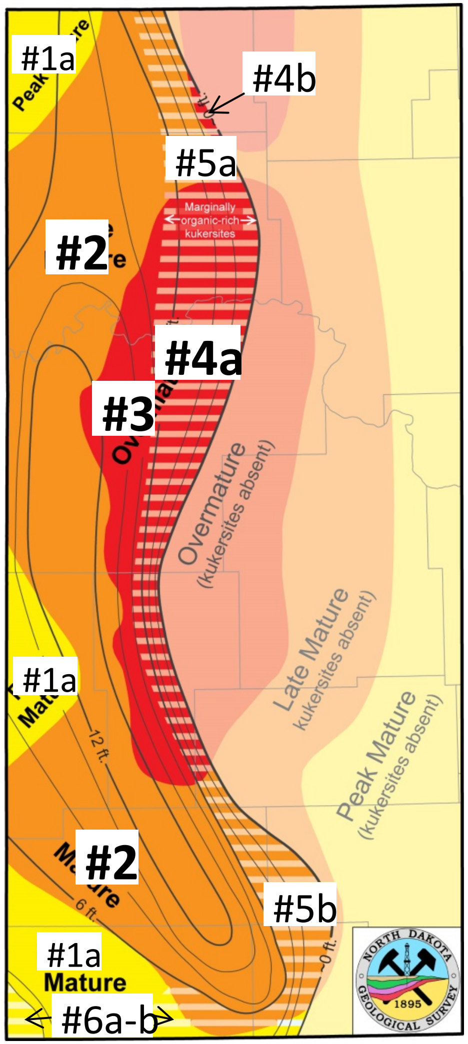
TOC_o = original total organic carbon
ρ = formation density
A = area of source rock unit
T = average source rock net thickness

HI_o = original hydrogen index
HI_{pd} = present day hydrogen index
*C = 1.3514×10^8 mg/barrel of 35° API oil
HC = hydrocarbons

*C was calculated assuming 850 kg/m^3 = 35° API oil density, and 1 bbl oil = 6.2898 m^3

Table

Fig. X Area #	A (cm2 x 10E-10)	T (cm)	TOCo	HIo	HIpd	ρ (g/cm3)	Gen. HC (BBOE)
#1a-c	3,807	213	5.9	750	544	2.46	1.79
#2	12,087	290	5.9	750	190	2.46	21.08
#3	1,950	290	3.8	750	60	2.46	2.70
#4a-b	484	76	1.6	600	520	2.73	0.01
#5a-b	2,435	107	1.6	600	166	2.73	0.37
#6a-b	3,735	122	1.6	600	45	2.73	0.82
						Total	*26.77*

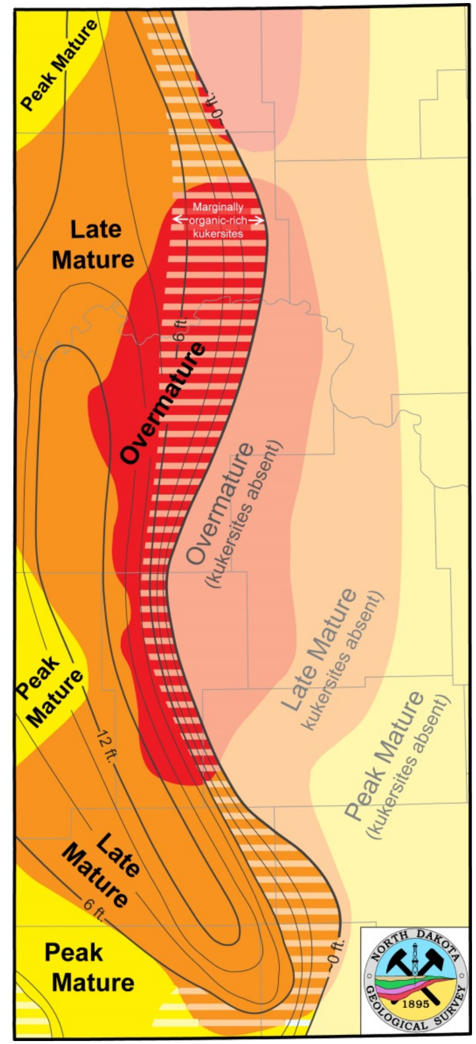


Red River Kukersite with HIo = 750 would have **generated <u>~27 billion barrels</u> of oil equivalent**

As a more conservative estimation, original TOC values and generated hydrocarbon volumes were also calculated using an original HI of 750, which still yields a total hydrocarbon generation volume of approximately 27 BBOE. In both sets of calculations, the original HI of kukersites in the eastern, marginally organic-richness trend area (diagonal line area) was slightly lowered, assuming that original/present day TOC and HI share some correlation.

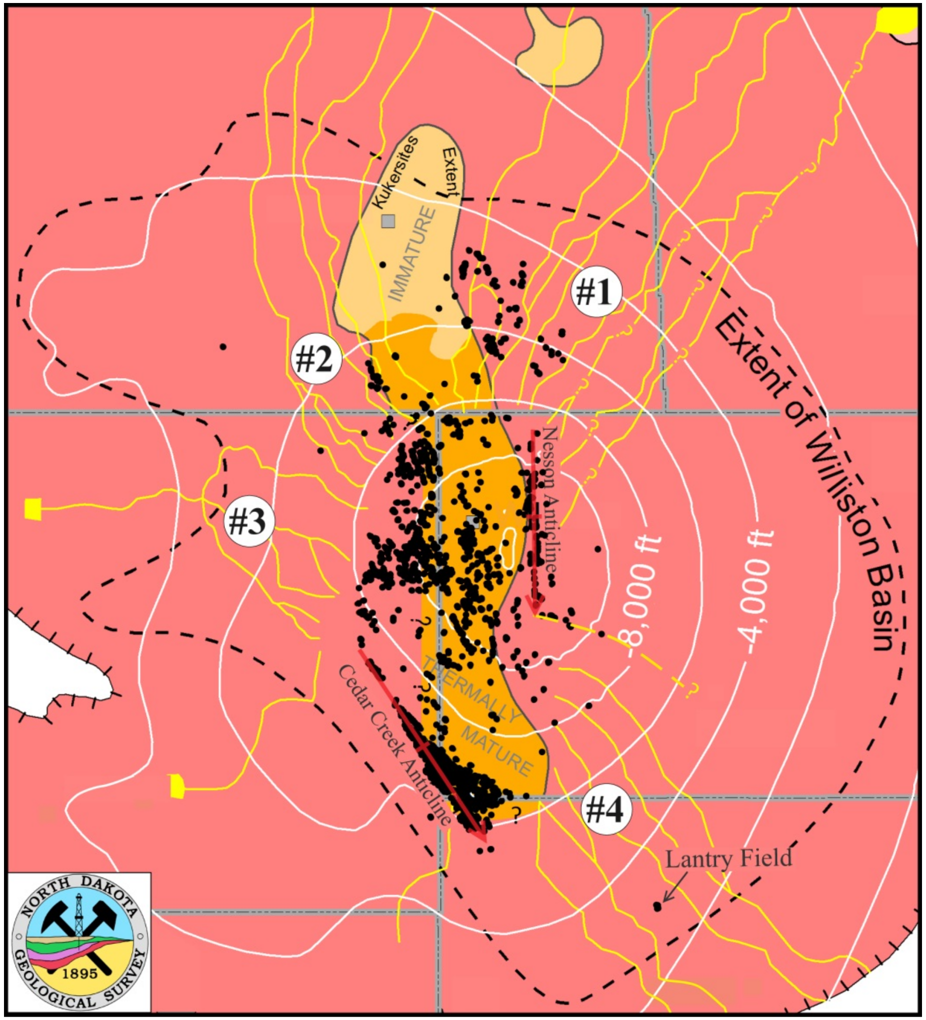
Generated Hydrocarbon Volume

- Red River Kukersites have generated approximately **27 to 62 billion barrels of oil equivalent (BOE)** beneath North Dakota's portion of the Williston Basin.
- Thermally mature Red River kukersites also appear to extend into Saskatchewan, South Dakota, and Montana.
- Cumulative Red River production across the Williston basin is ~0.62 billion barrels of oil, which is only 1-2% of the estimated hydrocarbon generation volume within western North Dakota.



The two sets of calculations provide an approximate range of 27 to 62 BBOE for the total amount of hydrocarbons generated within the Red River Formation of western North Dakota, more than enough to account for cumulative, basin-wide Red River production.

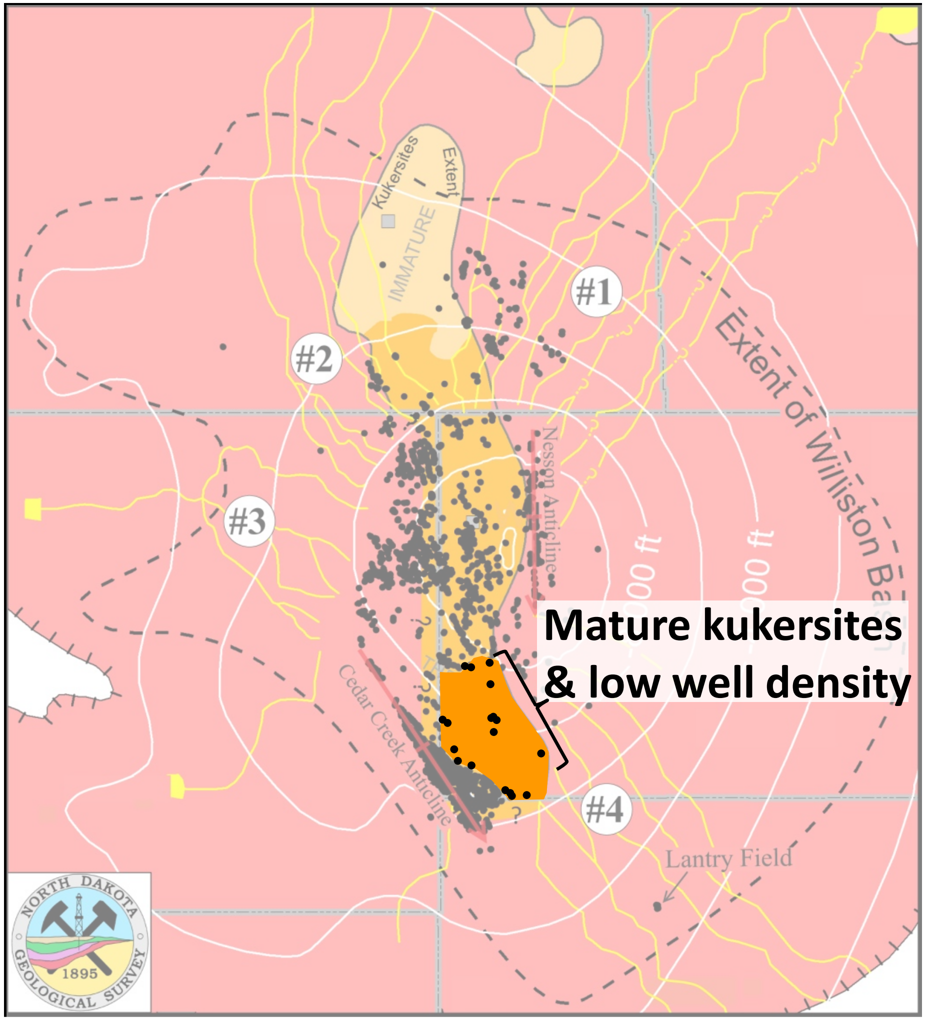
Implications for Future Red River Hydrocarbon Exploration



Yellow lines = hydrocarbon migration pathways modelled by Khan et al. (2005).

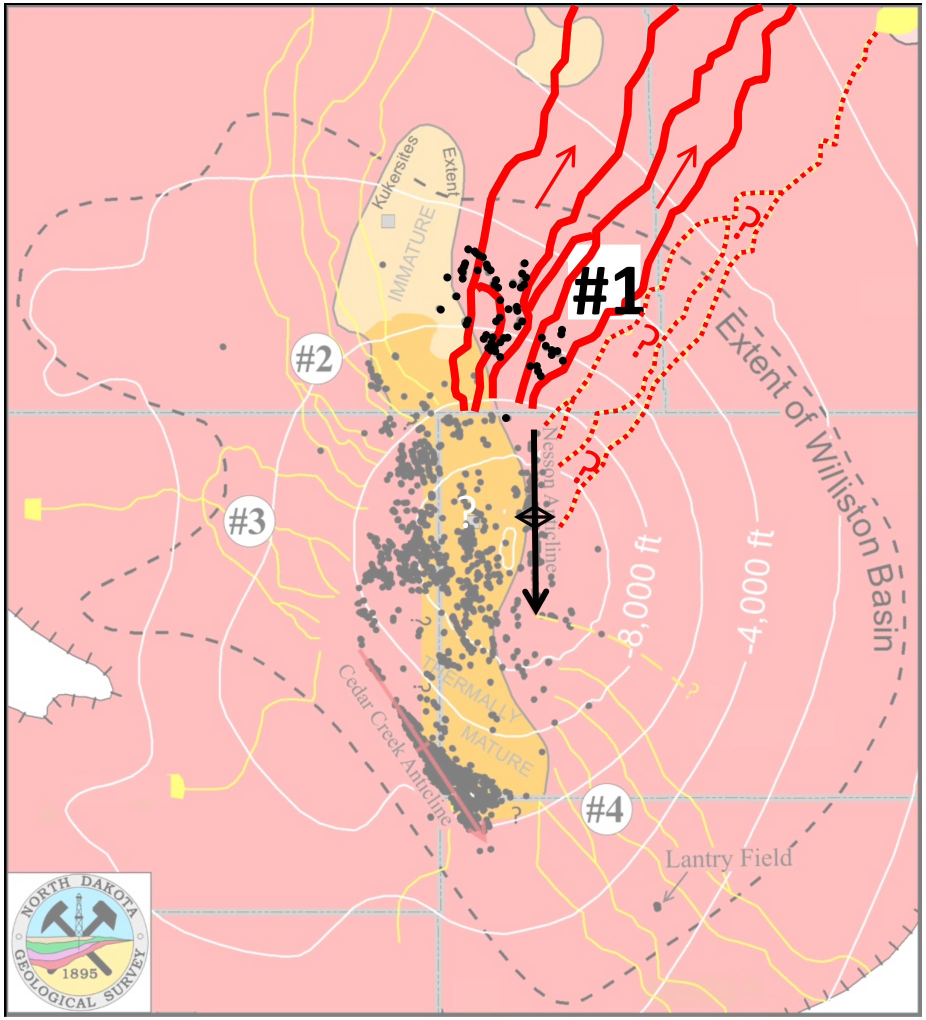
Tying the results of this study back into a regional, basin-wide Red River exploration and development picture, several inferences can be drawn. On the above map, Red River hydrocarbon migration pathways (yellow lines) modeled by Khan et al. (2005) are shown which mostly follow one of four generalized trends (#1-#4). The dark orange represents the approximate extent of thermally mature kukersites, and light orange represents immature kukersites. Black dots depict Red River producers.

Implications for Future Red River Hydrocarbon Exploration



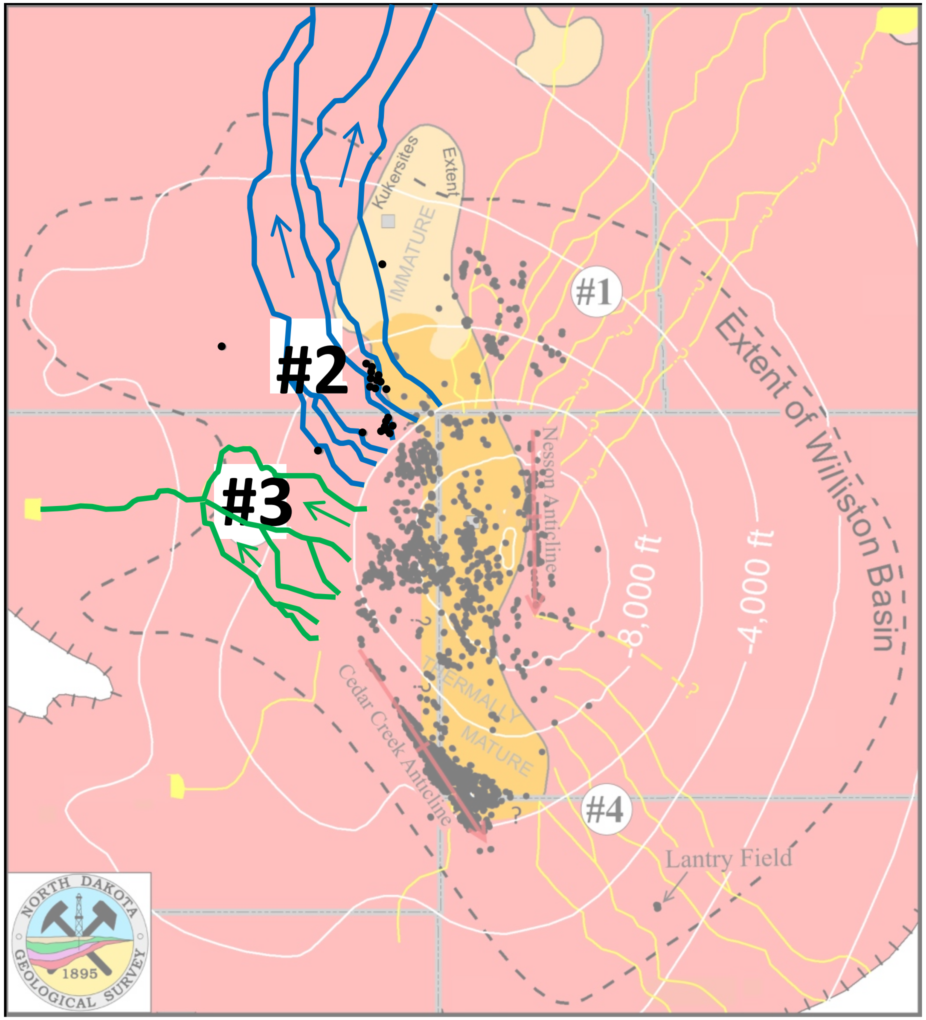
Most Red River production in western North Dakota overlays the extent of thermally mature kukersites identified during this study. Southwestern North Dakota contains an area (bold orange) located northeast of the Cedar Creek Anticline which contains thermally mature kukersites and a number of spatially dispersed Red River producers, but an overall very low well density. This low well density area with thermally mature kukersites may represent an under explored/developed portion of the Red River petroleum system.

Implications for Future Red River Hydrocarbon Exploration



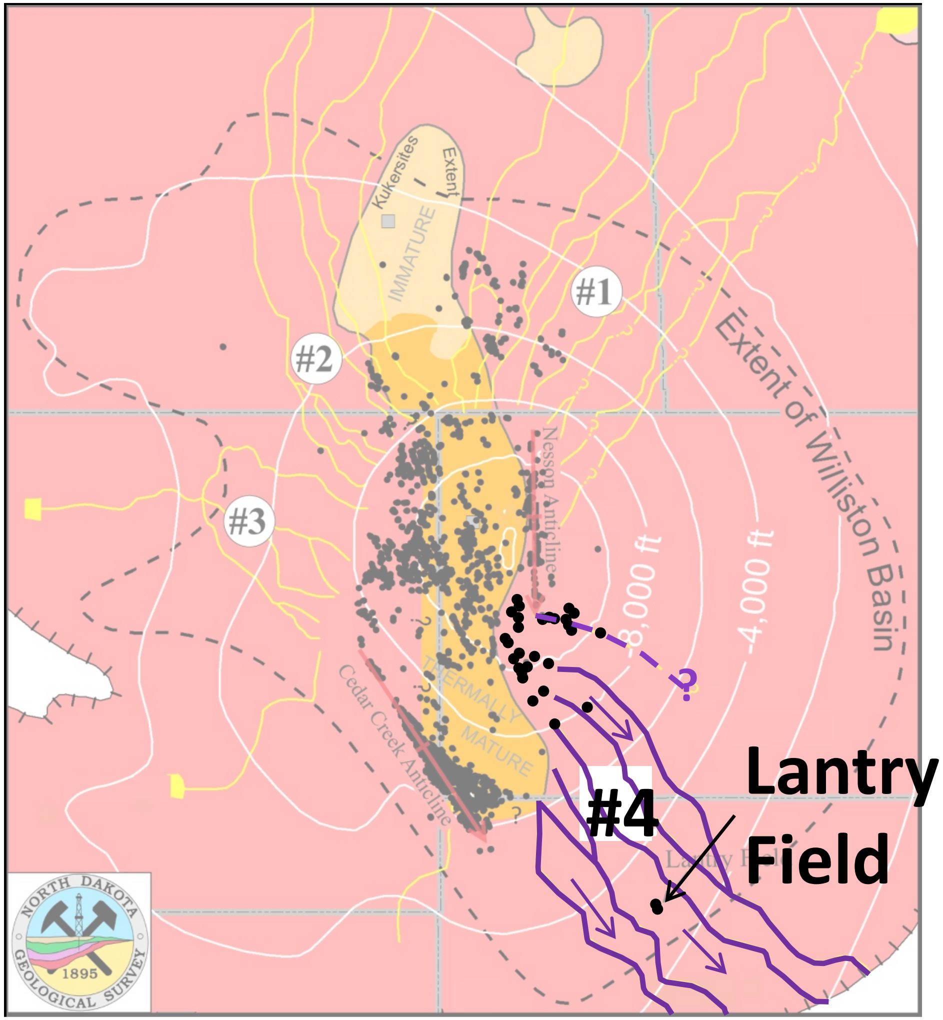
The northern hydrocarbon migration pathways of trend #1 (solid red lines) trace back to thermally mature kukersites, and also correlate with numerous Red River producers in southeastern Saskatchewan. The southern migration pathways of trend #1 (dotted red lines) intersect the Nesson Anticline before reaching thermally mature kukersites and do not correlate with Red River production. The Nesson appears to form a barrier to eastward Red River hydrocarbon migration.

Implications for Future Red River Hydrocarbon Exploration



Two additional hydrocarbon migration trends are modeled to flow north-northwest through Saskatchewan (#2 – blue lines), and west-northwest through eastern Montana (#3 – green lines). Presently, there are no publically available maps for Red River kukersites of eastern Montana, although published Red River studies of the area have mentioned their presence (Kohm and Louden, 1978). Both migration trends #2 and #3 likely trace back to thermally mature kukersites and could represent viable areas to explore for migrated Red River hydrocarbons.

Implications for Future Red River Hydrocarbon Exploration



A fourth hydrocarbon migration trend (#4 – purple lines) is modeled to flow southeast out of the Williston basin. This migration trend originates northeast of the Cedar Creek Anticline to just south of the Nesson Anticline. Migration trend #4 overlaps with Red River production in southwestern North Dakota and the Lantry Field of central South Dakota, which represent Red River production beyond the extent of thermally mature kukersites, similar to southern Saskatchewan. Future exploration along migration trend #4 may yield additional Red River discoveries.

Conclusions:

- Ten distinct kukersites (petroleum source beds) are present within the “D” zone of the Ordovician Red River Formation that can be correlated regionally using core and wireline logs.
- Kukersites in the Red River “D” zone are continuously present beneath approximately the western quarter of North Dakota, extending 20-40 miles (32-64 km) east of the Montana border.
- Red River kukersites have generated an estimated 27 to 62 BBOE from North Dakota’s portion of the Williston Basin.
- Cumulative, basin-wide Red River production accounts for only 1-2% of the estimated generated volume and suggests a substantial amount of petroleum resource has yet to be discovered and developed in the Red River Formation.
- Thermally mature Red River kukersites appear to extend into eastern Montana and northwestern South Dakota, where they have yet to be thoroughly examined.

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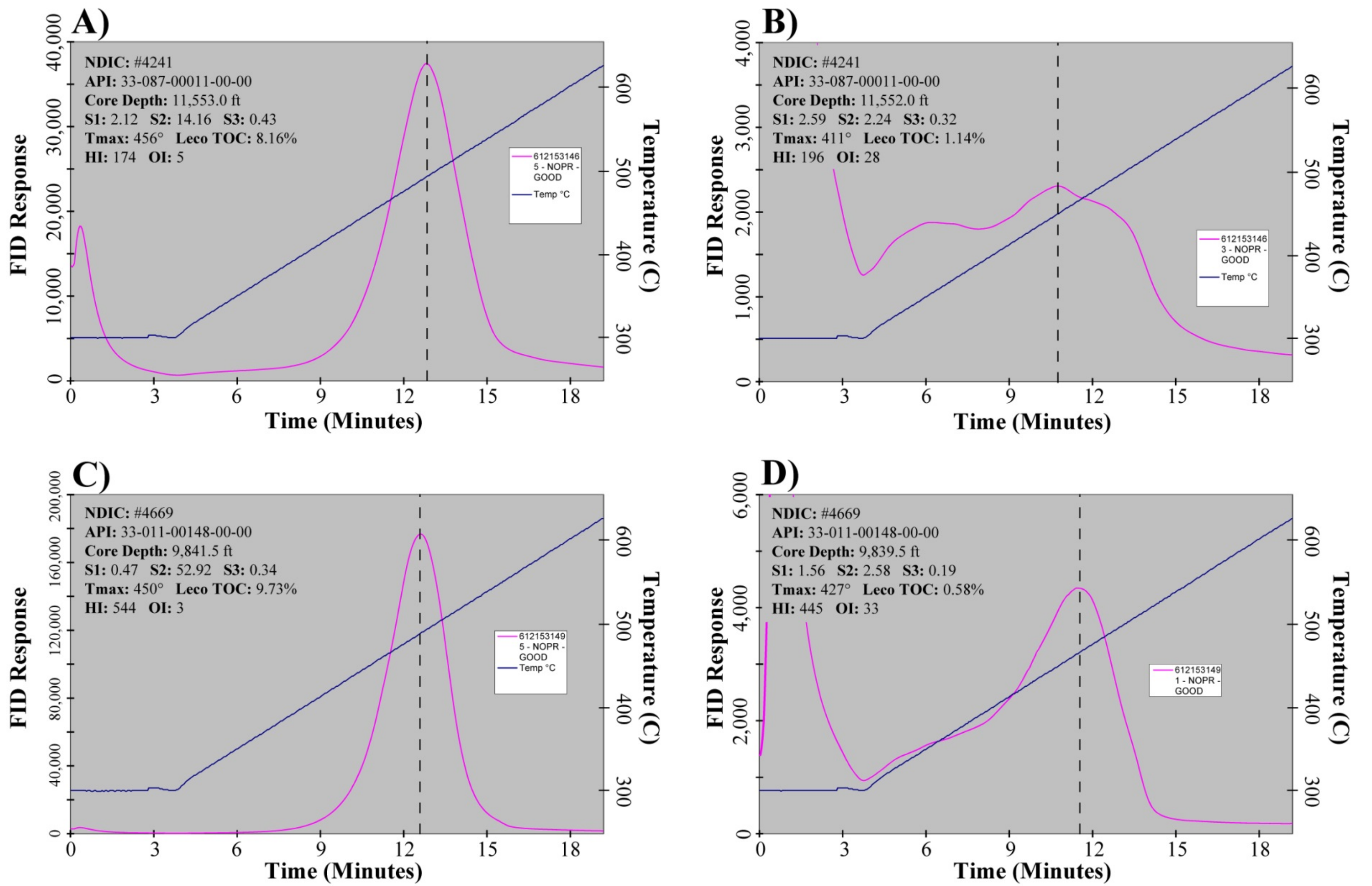
www.dmr.nd.gov/ndgs

- *Visit the ND Geological Survey website for additional publications on the Red River Formation as well as other oil and gas producing units of North Dakota.*
- *The TOC and RockEval pyrolysis data produced through this study is also available through the ND Geological Survey website.*

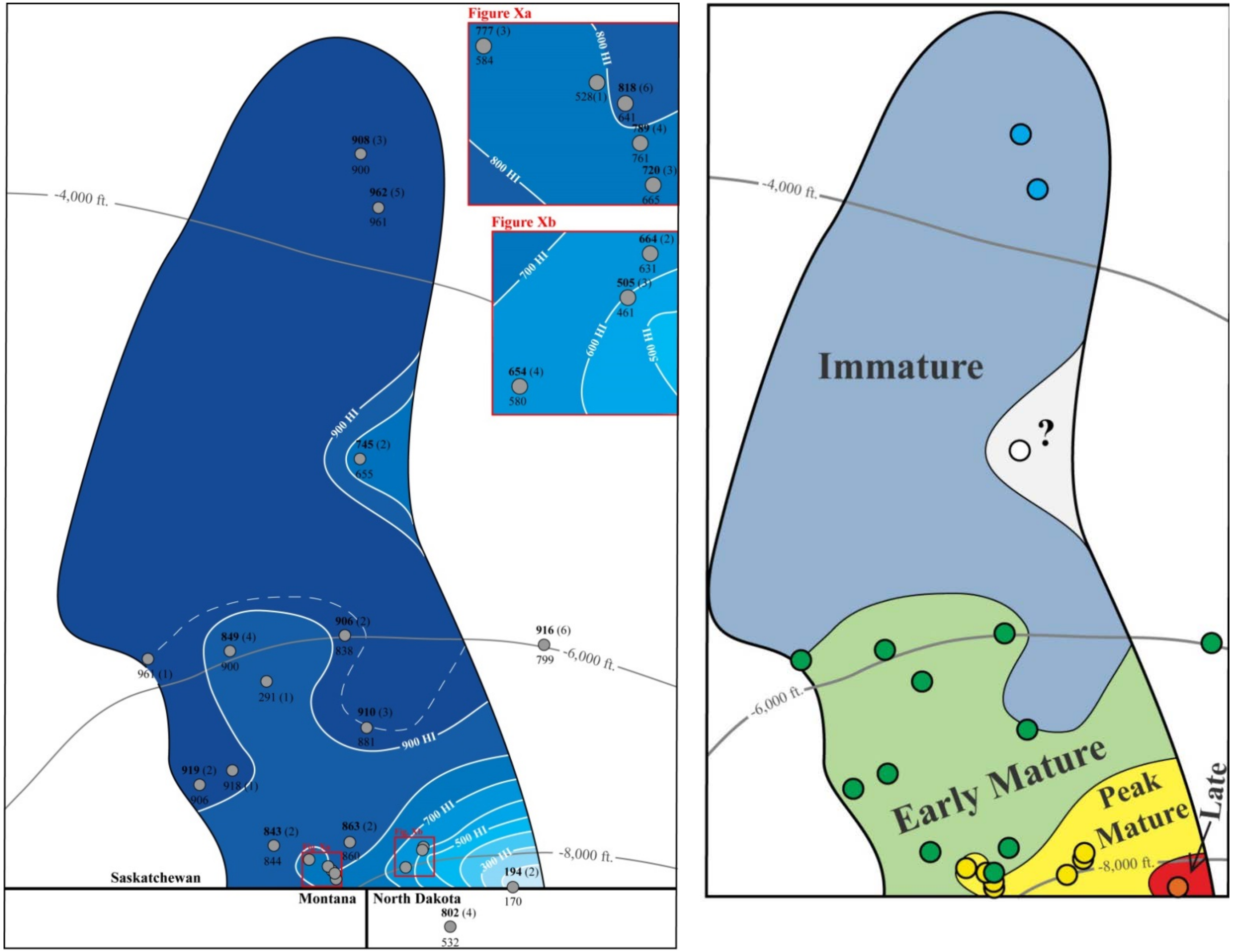
Appendix: Tmax Data Screening for the North Dakota Data Set



Above are example pyrograms used to determine Tmax values from four of the kukersite samples analyzed for this study. On the left (A & C) are examples of good to excellent pyrograms that are thought to correlate with reliable Tmax values. On the right (B & D) are examples of poor, low quality pyrograms which correlate with unreliable (B) to questionable (D) Tmax values. For most of the individual core data sets, only the reliable Tmax values from good to excellent quality pyrograms were used for thermal maturity mapping and investigation. A few exceptions occurred where only questionable Tmax values were produced from higher maturity cores.

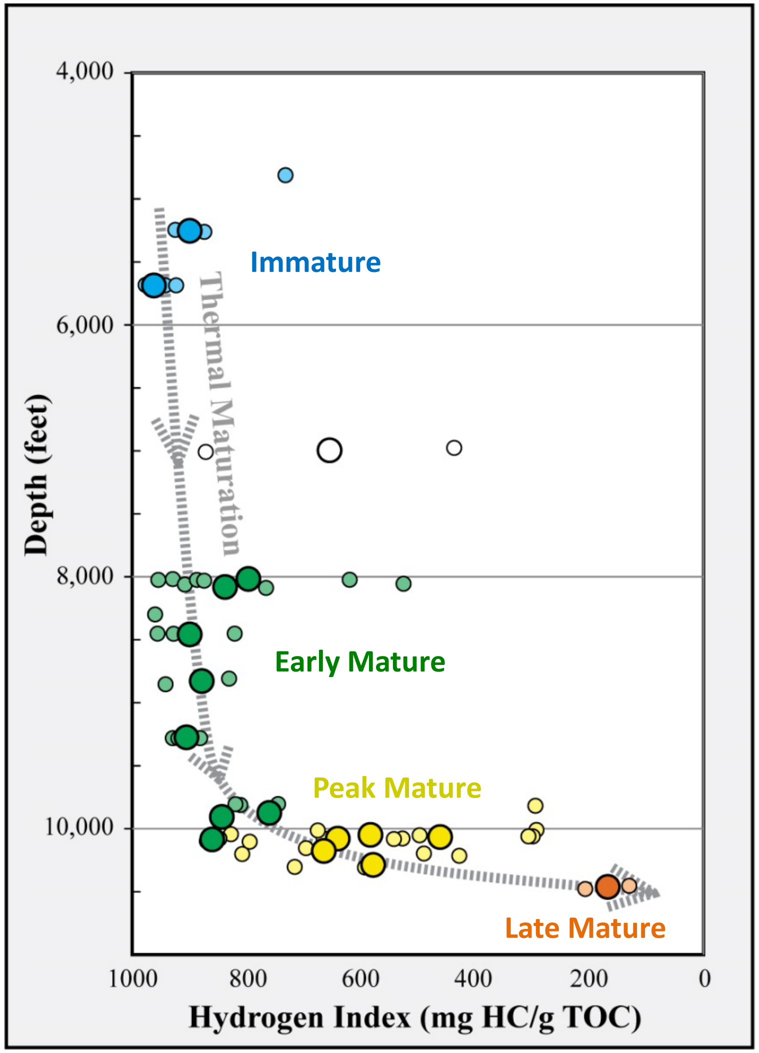
Appendix: Red River Kukersite Thermal Maturity, southern Saskatchewan

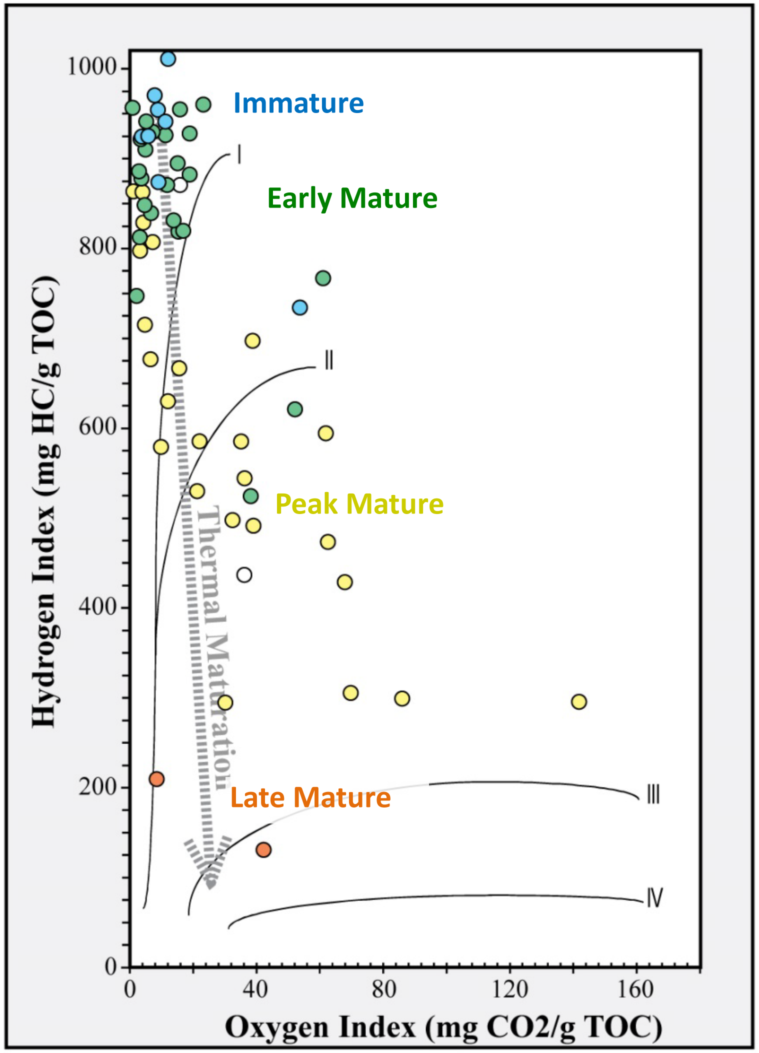
*Data borrowed and contoured from Osadetz and Snowdon (1995).



Hydrogen Index (HI) map (left) and interpreted levels of thermal maturity (right) of Red River (upper Yeoman) kukersites of southern Saskatchewan. Grey circles (left, HI map) represent well/core locations, bold number above each symbol are the HI values calculated from the average TOC and S2 values from 2 or more kukersite core chip samples, the number in parentheses represents the number of kukersite core chip samples analyzed within a given core, and the number below each core location is the average HI of kukersite samples within the given core. Kukersite geochemical data was borrowed and contoured from Osadetz and Snowdon, (1995). The white dashed line (left map) depicts the interpreted probable extent of mature disseminated *G. Prisca* from Fowler et al., 1998). Grey lines are structure contours on the Red River Formation Top.

Appendix: Red River Kukersite Thermal Maturity, southern Saskatchewan





Geochemical data from Red River kukersites samples from Osadetz and Snowdon, (1995) color coated based on depth/interpreted level of thermal maturity. The small symbols represent individual core ship samples and the large circles represent core averages from which two or more kukersite core chip samples were analyzed from the same core. Note the very high HI values (>800) for most kukersite samples from depths less than 9,500 ft. Depths are in true vertical depth.