[PS]Source Rock Potential of the Bakken Shales in the Williston Basin, North Dakota and Montana*

Hui Jin[1] and Stephen A. Sonnenberg[1]

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Abstract

The lower and upper Bakken shales are world class source rocks in the Williston Basin, sourcing reservoirs in the Bakken, upper Three Forks, and lower Lodgepole formations, which comprise the economically significant Bakken Petroleum System (BPS). 10 to 400 billion barrels of oil in place have been estimated to have been generated from the Bakken shales, charging both unconventional and conventional plays in the BPS.

The objective of this study is to understand the source rocks' potential and its relationship with Bakken oil present in reservoirs of the BPS across the Williston Basin. For bulk geochemical characteristics of Bakken shales, important parameters, such as organic richness, kerogen type, and source rock maturity, are derived from TOC and pyrolysis analysis in Rock-Eval and or Source Rock Analyzer™ (SRA). Over thousand TOC and pyrolysis results, providing good coverage of the North Dakota and Montana portions of the Williston Basin, have been collected from CSM SRA Lab and USGS Geochemistry database.

Based on the TOC and pyrolysis results of Bakken samples, lower and upper Bakken shales exhibit a wide range in Total Organic Carbon (TOC) contents, from 1 wt.% at shallower basin margins up to 35 wt.% in the deeper basin. This high variation of TOC content may result from mixed effects of the original depositional environment and progressive post-depositional diagenesis and catagenesis (maturation). Based on the modified van-Krevelen diagram, the kerogen type present in Bakken shale is primarily Type I/II, but along the shallow east flank of the basin there is Type III kerogen input. The pyrolysis temperature (Tmax) of 425ºC, production index (PI) of 0.1, and conversion fraction (f) of 0.1~0.15, correspond to a threshold of intense HC generation from mature source rocks. During maturation and HC generation, TOC contents are diminished by about 7~8 wt.% in thermally mature areas of the Williston Basin. Early results indicate that the upper and lower Bakken shales in the central, deeper Williston Basin are organic rich, contain oil-prone kerogen, and are thermally mature and in the oil generation window.

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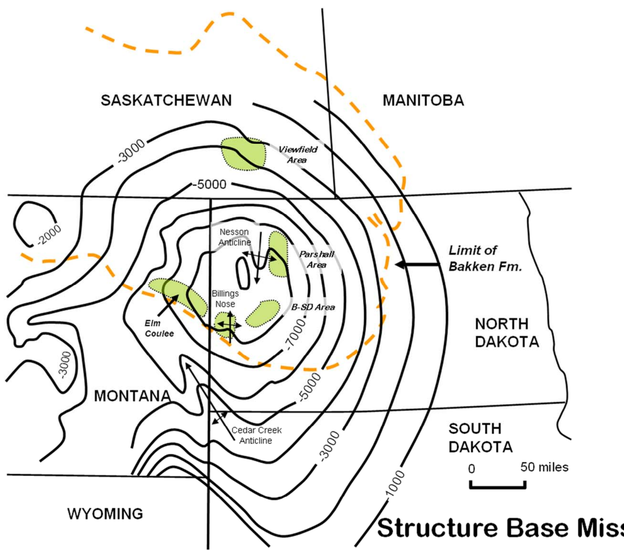


Figure 1. Index map of the Williston Basin illustrating the structure at the base of the Mississippian. The limits of the Bakken are shown by the dashed line. Recent giant discoveries (the past 10 years) include Elm Coulee of Montana, Parshall area of North Dakota, and the Viewfield area of Saskatchewan.

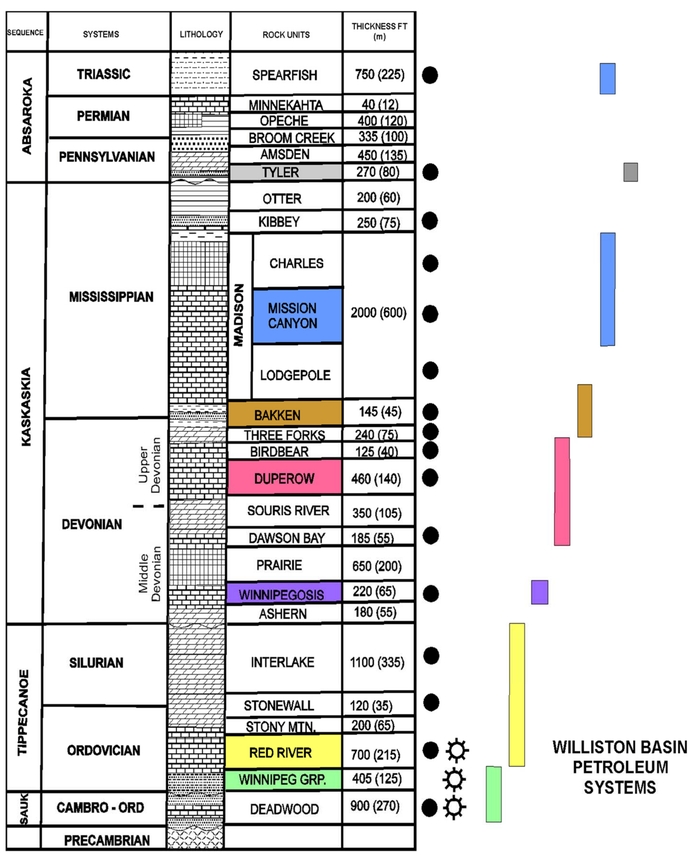


Figure 2. Stratigraphic column for Paleozoic and Lower Mesozoic units of Williston Basin with extents of various petroleum systems shown. The Bakken petroleum system consists of source beds in the Bakken and reservoirs in the lower Lodgepole, Bakken, and upper Three Forks (Modified from LeFever et al., 1991 and Anna, 2010).

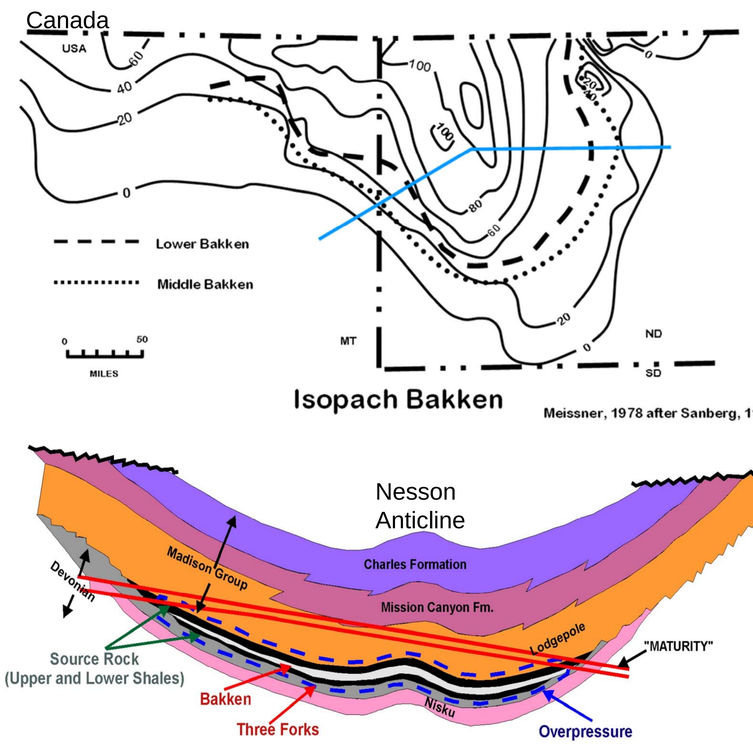


Figure 3. Isopach map and cross section of Bakken illustrating the maturity area of the Bakken and associated overpressure.

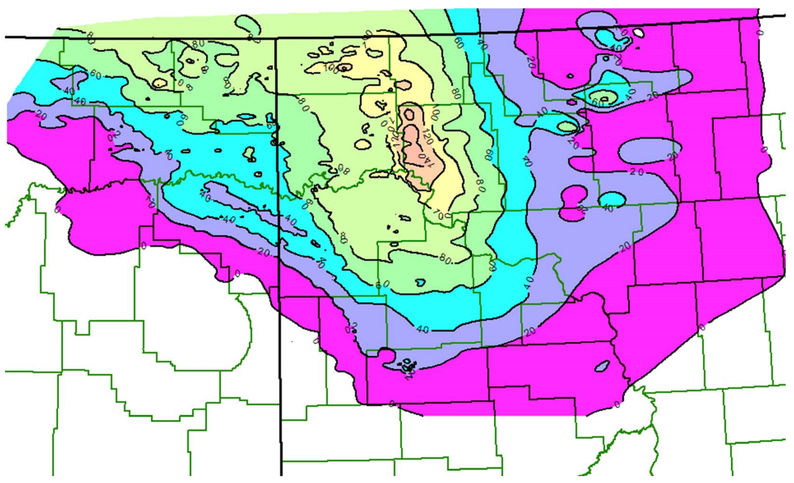


Figure 4. Isopach map of Bakken Formation, U.S. part Williston Basin. Thickness ranges from wedge-edge to over 140 ft.

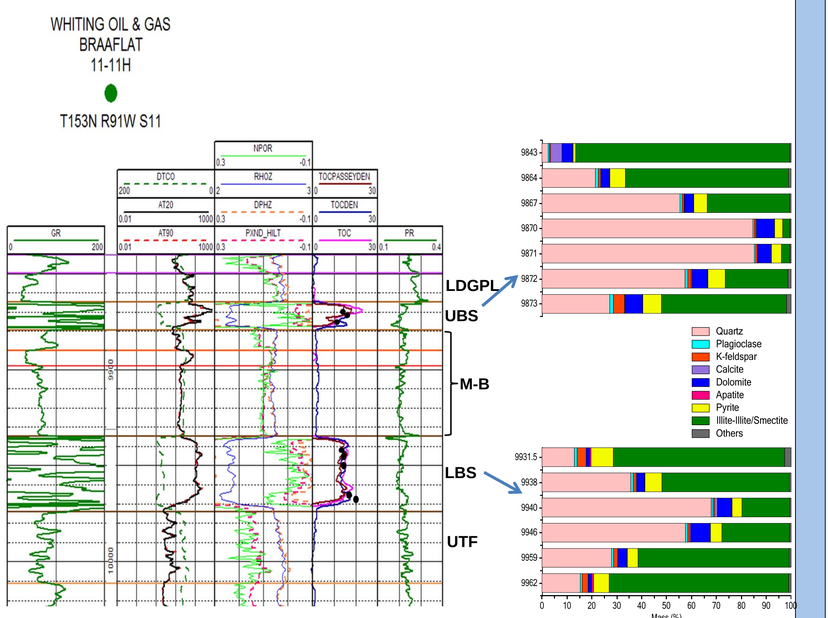


Figure 5. Well logs of Whiting Braaflat Bakken petroleum system interval (Sec. 11-T153N-R91W). Mineralogy (XRD) of Bakken shales shown in chart to right. Current targets of horizontal drilling are the middle member of the Bakken and the upper Three Forks.

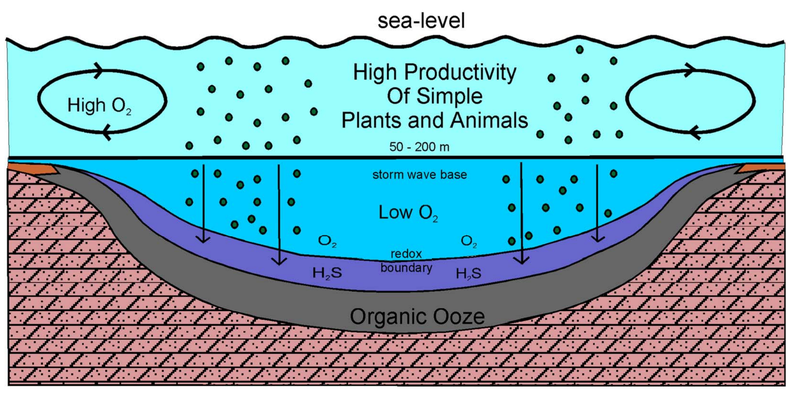
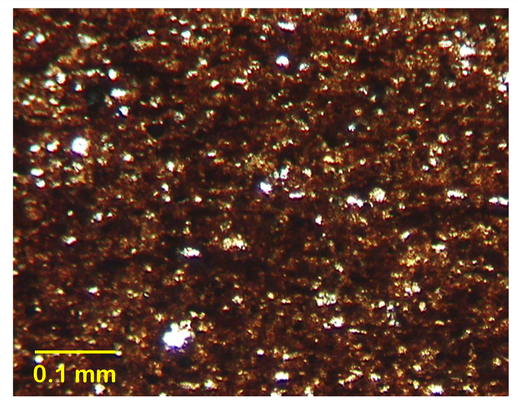
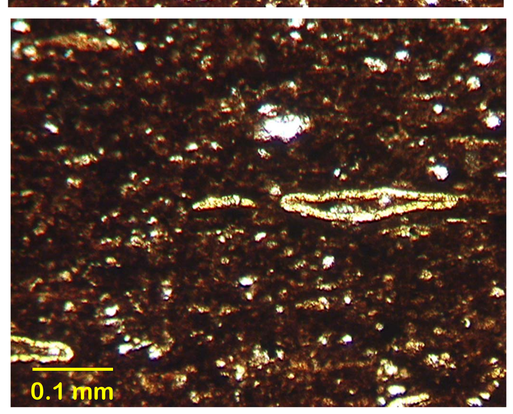


Figure 6. Deposition setting of upper and lower Bakken shales under anoxic conditions (modified from Smith and Bustin, 1996; Meissner et al., 1984).



Braaflat 9864
Upper Bakken shale
Sec. 11-T153N-R91W

TOC 14.1
Tmax 431
HI 566
PI 0.07



Braaflat 9940
Lower Bakken shale
Sec. 11-T153N-R91W

TOC 14.0
Tmax 431
HI 582
PI 0.09

Figure 7. Petrographic thin section observation of upper and lower Bakken shales (Sec. 11-T153N-R91W) with TOC and pyrolysis results indicated.

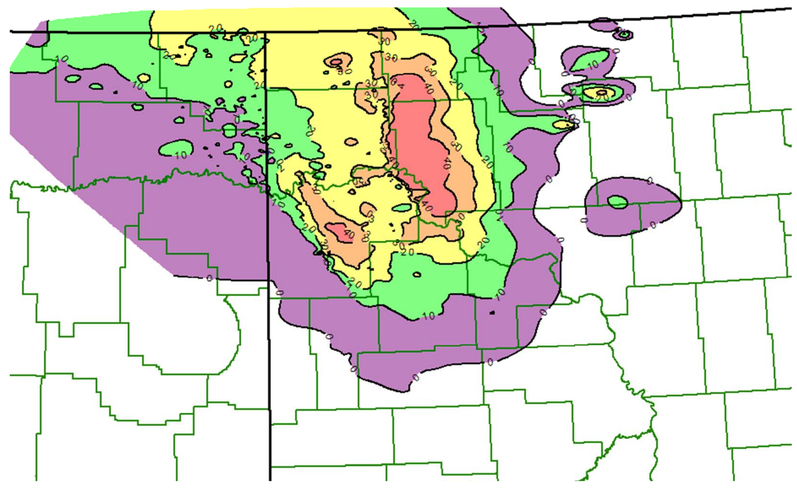


Figure 8. Isopach map of lower Bakken shale. Thickest area is east of the Nesson anticline and generally coincides with the Parshall area.

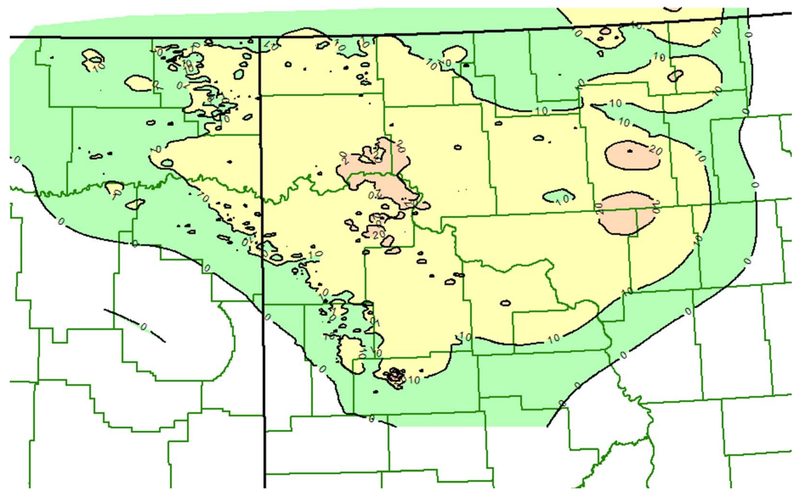
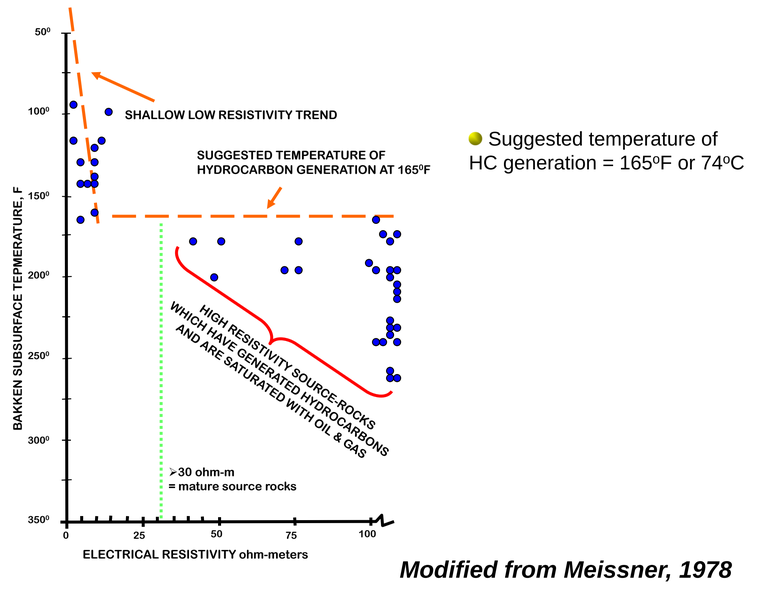


Figure 9. Isopach map of upper Bakken shale. Thickness ranges from a zero edge to over 20 ft.



Modified from Meissner, 1978

Figure 10. Plot of Bakken subsurface temperature and resistivity of Bakken shales (modified from Meissner, 1978). Resistivities of Bakken shales change dramatically at bottom hole temperatures above 165ºF. The high resistivity is due to source rocks having generated hydrocarbons. Mature oil-wet source rocks are thought to be present above 100 ohm-m. The transition from water-wet to oil-wet occurs from 25 to 100 ohm-m.

Source Rock Potential of the Bakken Shales
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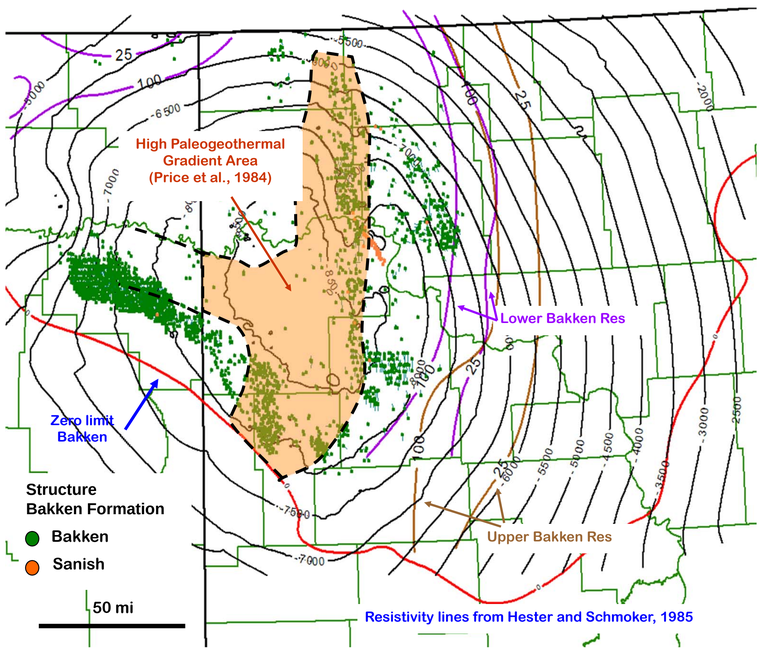

Figure 11. Structure map top Bakken showing limits of upper Bakken shale, middle Bakken, and lower Bakken shale. Also shown are iso-resistivity lines for the upper and lower Bakken shales from Hester and Schmoker (1985). The shaded area is a high paleo-geothermal gradient area modified from Price et al. (1984).

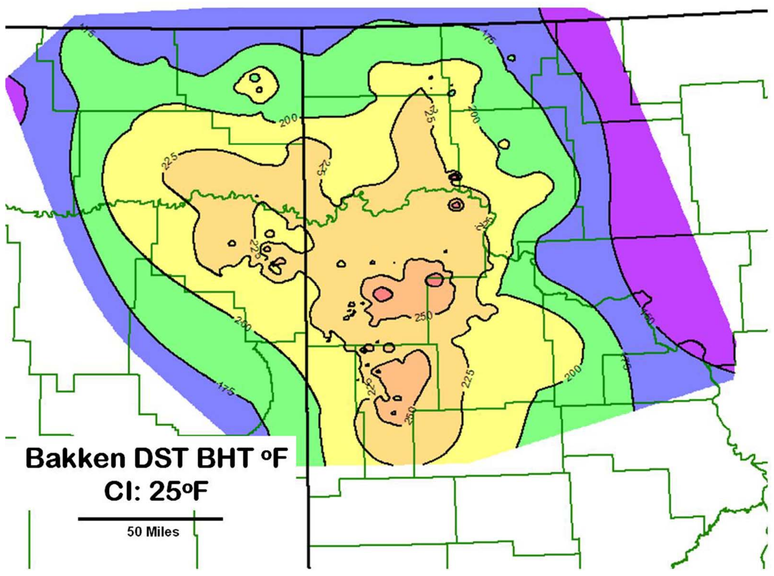

Figure 12. Bakken temperature map (uncorrected) from Bakken DST data base. The high paleo-geothermal gradient areas are still temperature anomalies in the Williston Basin.

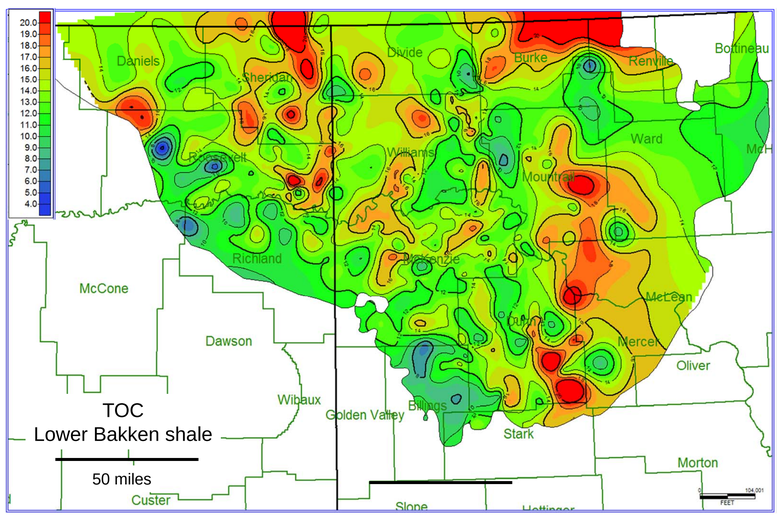

Figure 13. TOC map for Lower Bakken shale. TOC ranges from 10 to 20 wt % across much of the area. Highest values associated with lower Bakken thick east of the Nesson anticline and coincident with Parshall field.

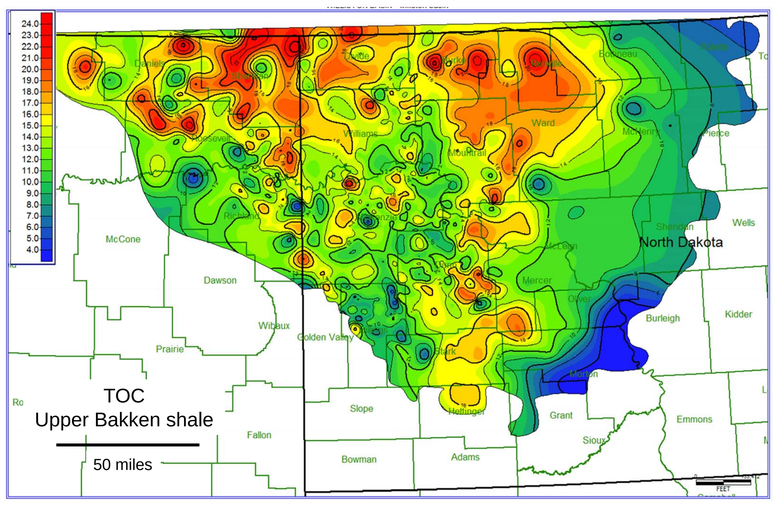

Figure 14. TOC map for Upper Bakken shale. Low north-south trending zone in middle of map coincides with high geothermal gradient area.

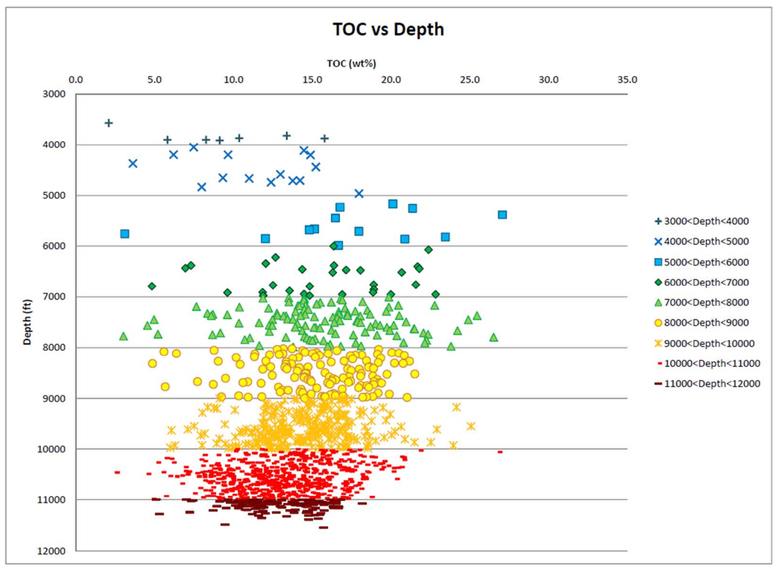

Figure 15. TOC values in Bakken shales versus depth. TOC ranges from 10 to 20 wt.% across much of the area. TOC decreases from 18~20 to 11~12 wt.% with increasing depth.

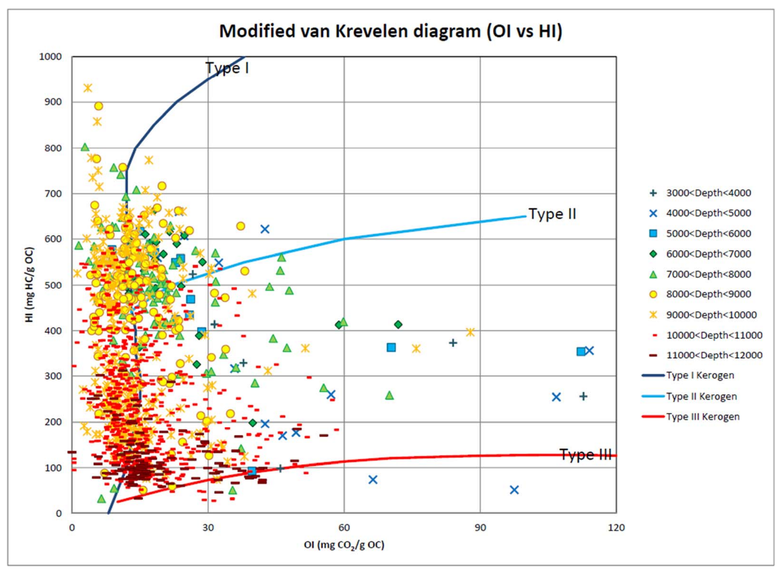

Figure 16. Modified van-Krevelen diagram for the Bakken Formation of Williston Basin. Published data from USGS Energy Geochemistry Database, Price et al. (1984) and Jarvie et al. (2011). Majority of samples indicate a Type-I and II oil-prone kerogen (algal origin). Legend shows source rock data by depth interval. HI is hydrogen index (S2/TOC). OI is oxygen index (S3/TOC).

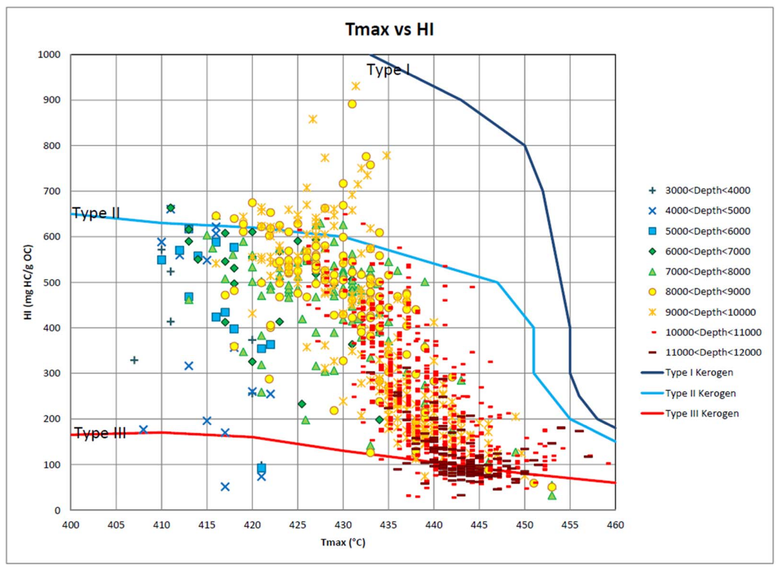

Figure 17. A plot of HI versus Tmax illustrates that the type of kerogen is a Type I/II for majority of immature source rock. With increasing maturity, values plot in the lower right-hand quadrant.

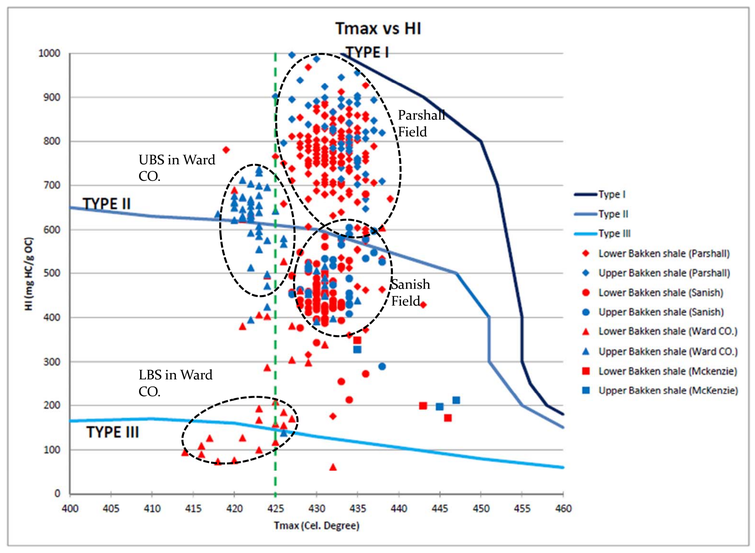

Figure 18. Organofacies change within and between upper and lower Bakken shales.

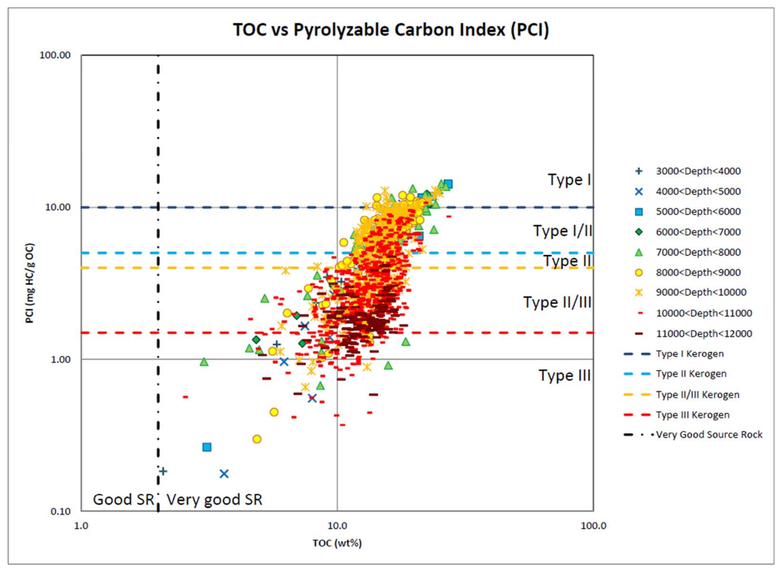

Figure 19. TOC versus pyrolyzable carbon index (PCI) indicates the quality of the source rock according to TOC (wt. %) and kerogen types according to PCI. The quality of the source rock is very good and the kerogen type is Type I/II. Maturation of samples shifts Type I/II kerogen into values that appear to be Type III.

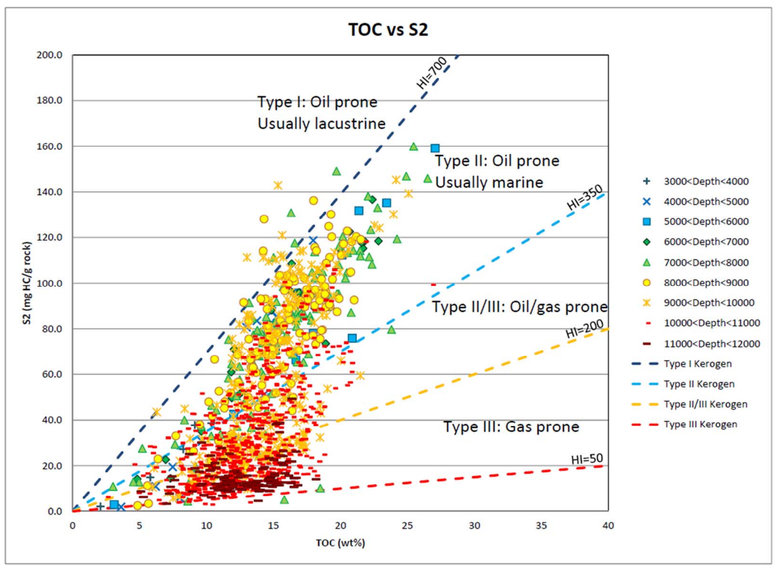

Figure 20. Plot of S2 versus TOC. Data from immature areas plots as Type I/II kerogen. Data from 3000-6000 ft plots as mixed Type II/III.

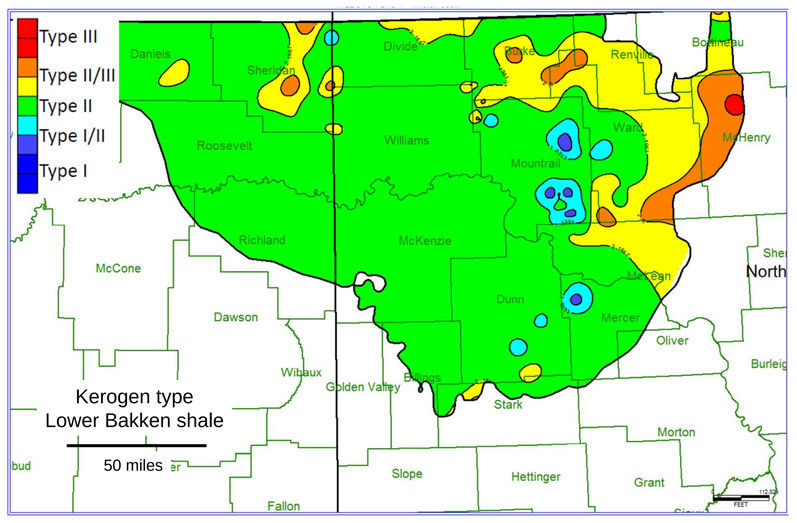

Figure 21. Kerogen type map for Lower Bakken shales. In deep and central basin, kerogen type is predominantly Type II, while a mixed Type II/III kerogen is present on the shallow east flank of the basin. In the intermediate basin, Type I kerogen with a circular occurrence is present.

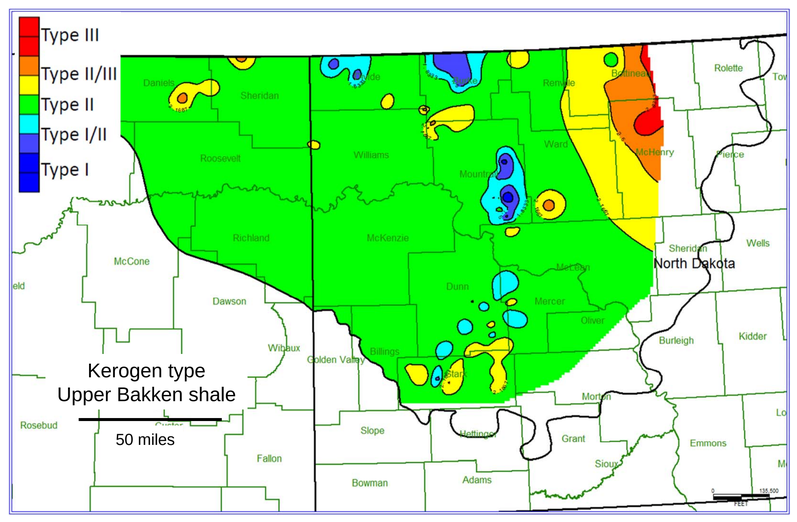

Figure 22. Kerogen type map for Upper Bakken shales. In deep and central basin, kerogen type is predominantly Type II, while a mixed Type II/III kerogen is present on the shallow east flank of the basin. In the intermediate basin, Type I kerogen with a circular occurrence is present.

Source Rock Potential of the Bakken Shales
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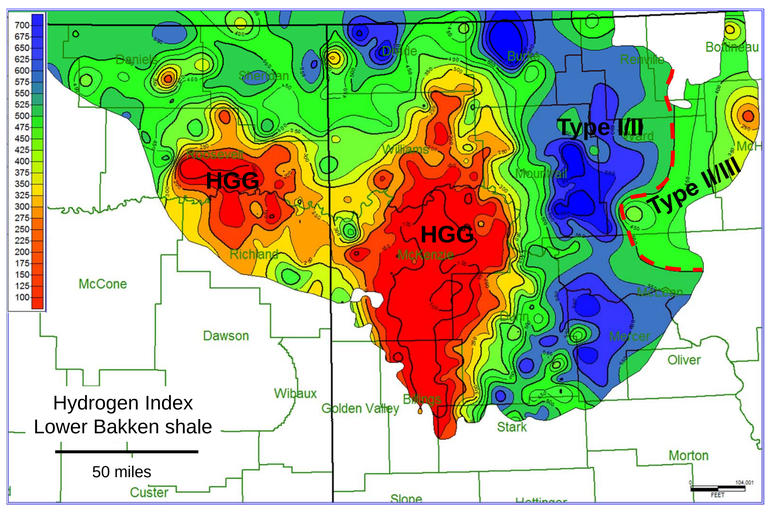

Figure 23. Hydrogen Index map for Lower Bakken shales. HGG stands for high geothermal-gradient area. The low values on the shallow east flank of the basin may represent a mixed Type II/III kerogen.

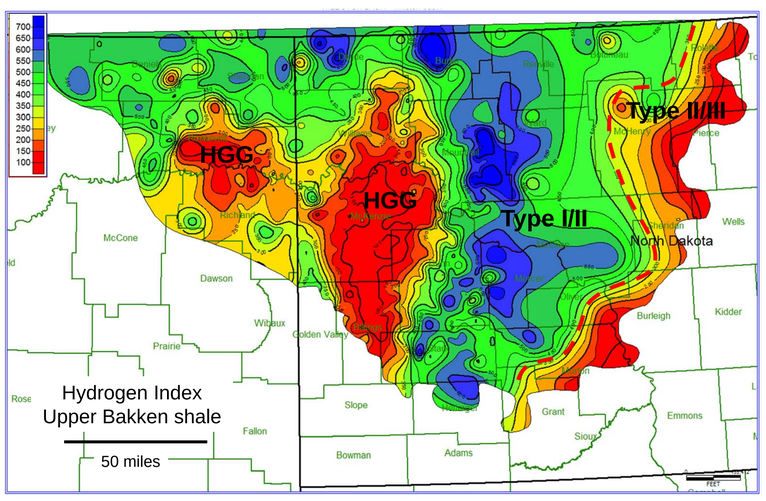

Figure 24. Hydrogen Index map for Upper Bakken shales. HGG stands for high geothermal-gradient area. The low values on the shallow east flank of the basin may represent a mixed Type II/III kerogen.

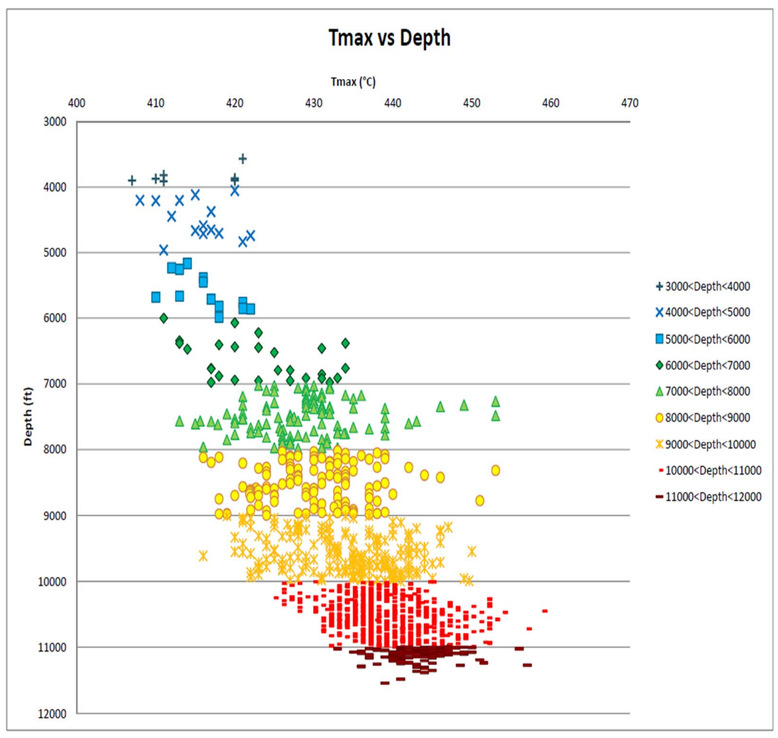

Figure 25. Plot of Tmax versus Depth. Tmax is increasing with increasing depths. Tmax from high geothermal gradient areas are higher than values from normal gradient areas.

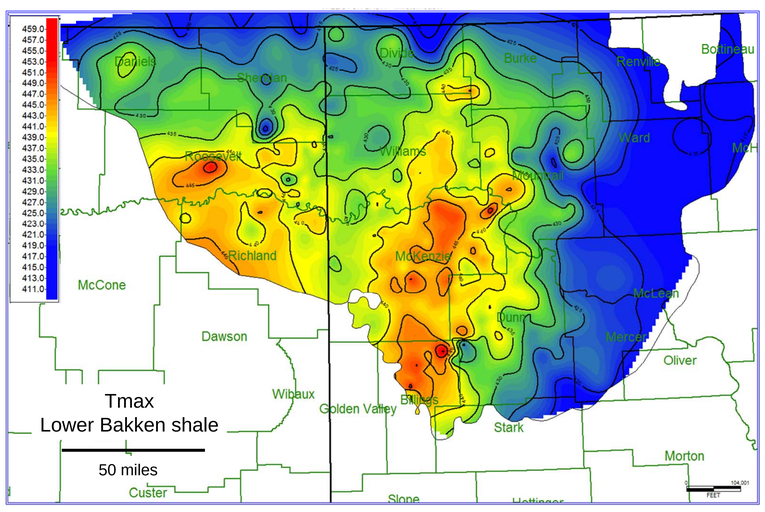

Figure 26. Tmax map for Lower Bakken shales.

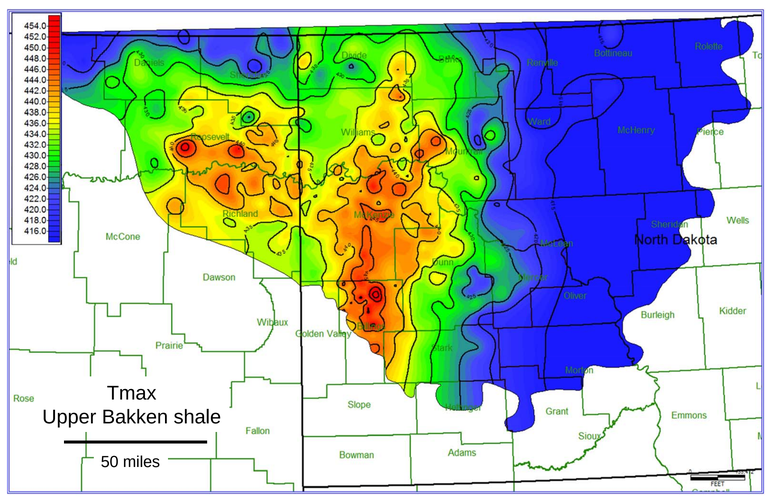

Figure 27. Tmax map for Upper Bakken shales.

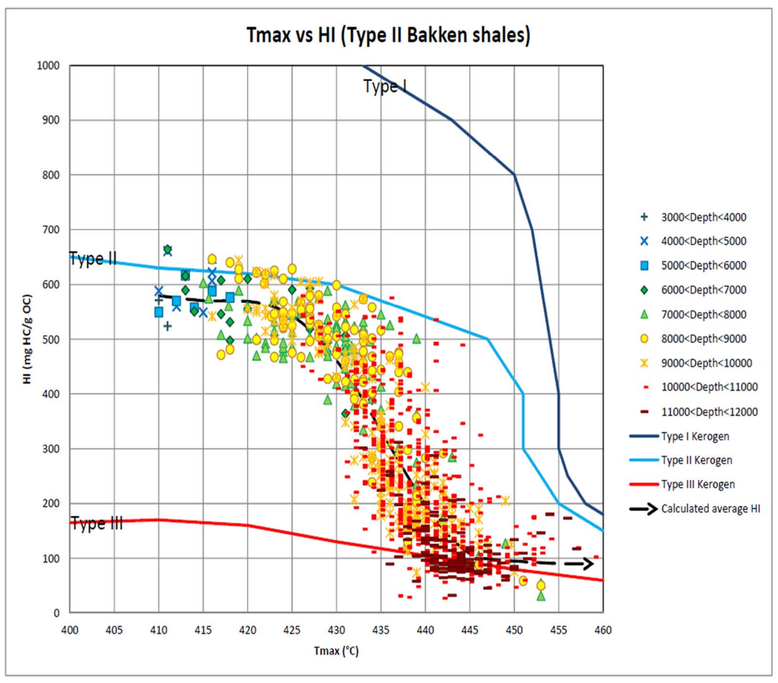

Figure 28. A plot of HI versus Tmax of Bakken shales with mainly Type II kerogen. It illustrates a good trend of decreasing HI with increasing maturity, and HI values plot in the lower right-hand quadrant towards to the end of oil window. Dashed line is a trend for averaged HI values during maturation, which are calculated from the regressed equation.

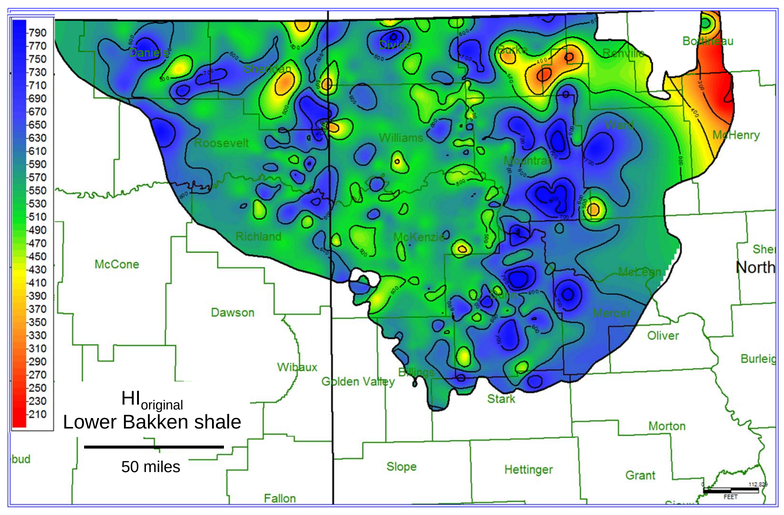

Figure 29. Original HI map for Lower Bakken shales. The low values on the shallow east flank of the basin may represent a mixed Type II/III kerogen, highest values (Type I kerogen) in intermediate basin, and normal values (~600 HI, Type II kerogen) in deeper basin.

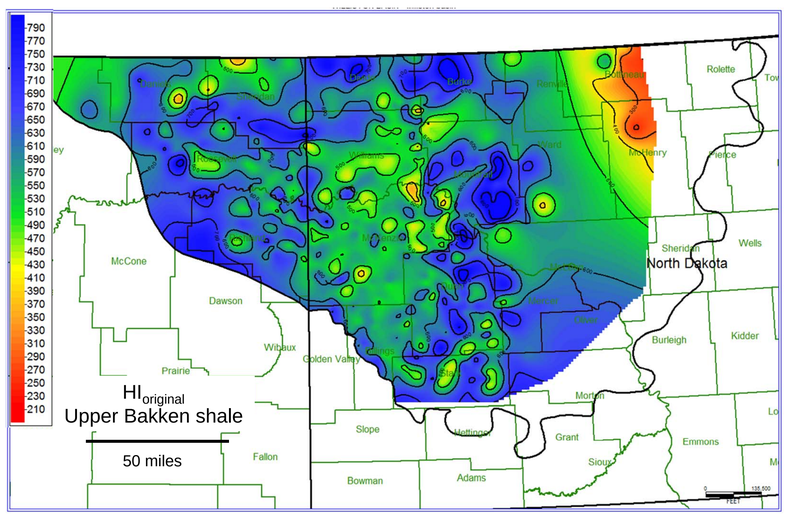

Figure 30. Original HI map for Upper Bakken shales. The low values on the shallow east flank of the basin may represent a mixed Type II/III kerogen, highest values (Type I kerogen) in intermediate basin, and normal values (~600 HI, Type II kerogen) in deeper basin.

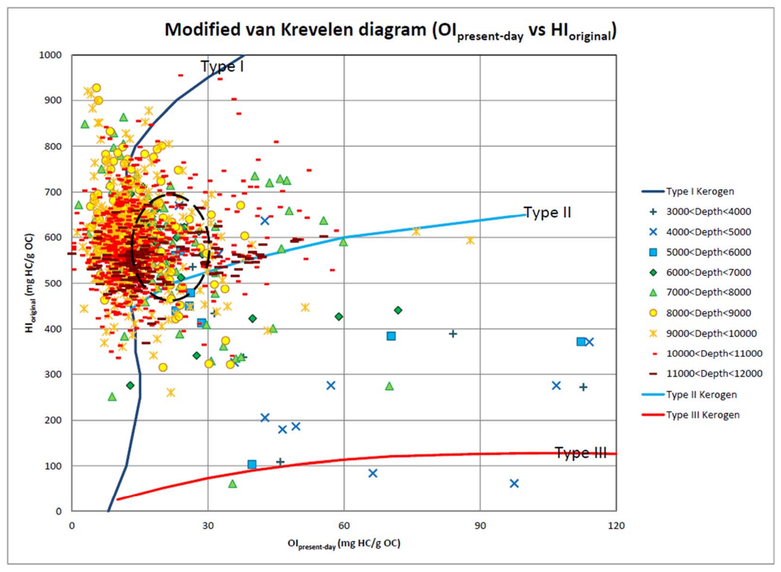

Figure 31. Modified van-Krevelen diagram ($HI_{original}$ vs $OI_{present-day}$) for the Bakken shales. OI values are not restored to their original values, but by an assumption of ~15 OI decrease during maturation, the dashed circle outlines the possible plot of original HI and OI of Bakken shales before catagenesis, which suggests mainly Type I/II kerogen.

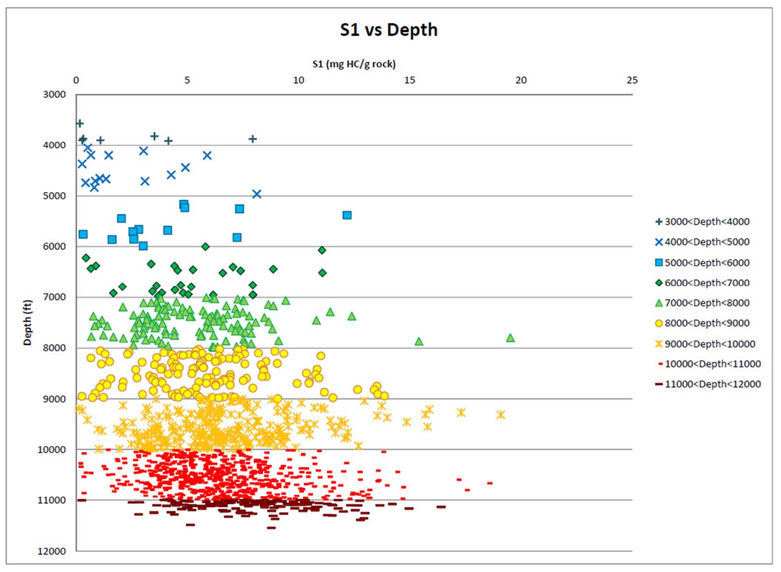

Figure 32. Plot of S1 versus depth. S1 generally increases with depth. High S1 values from 7500 to 9000 ft come from the high HI areas (lower and upper Bakken shales) east of the Nesson anticline..

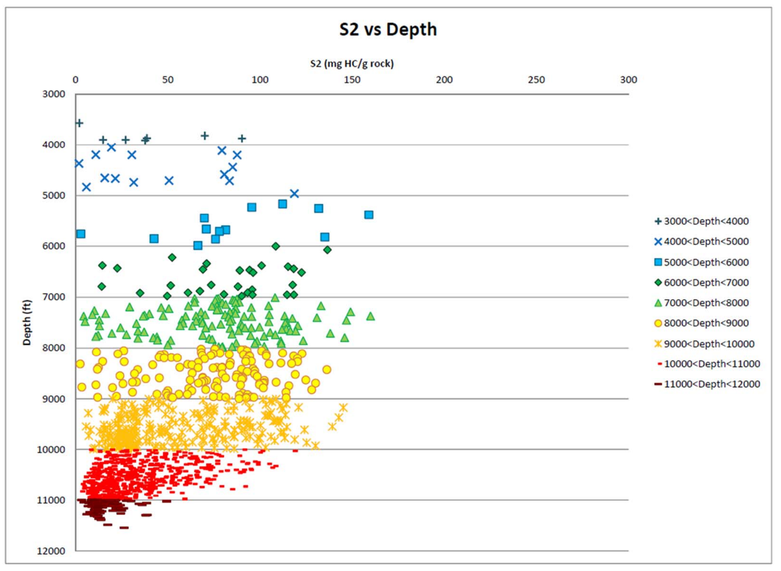

Figure 33. Plot of S2 with depth. S2 values decrease at depths greater than 7500 ft due to thermal cracking of organic matters..

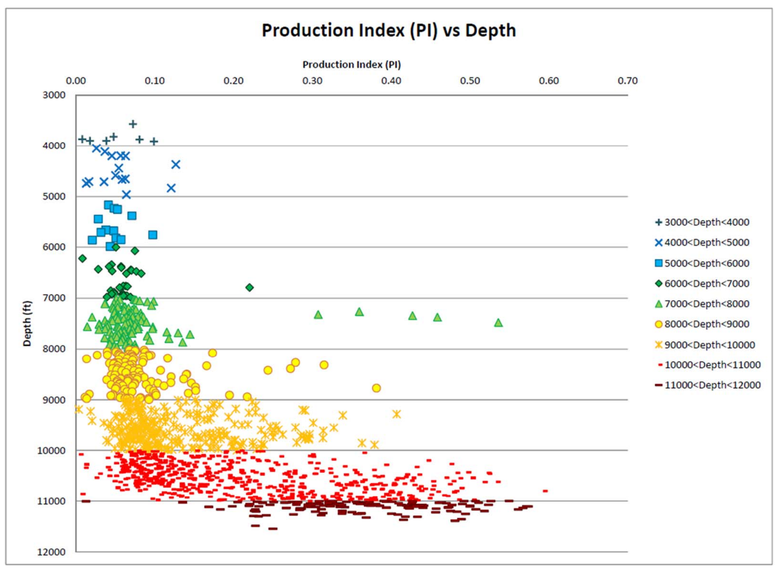

Figure 34. Plot of Production Index (PI, S1/(S1+S2)) versus depth for Bakken shales. The oil generation window occurs between values of 0.1 and 0.4. Some deepest Bakken shales enter gas generation window.

Source Rock Potential of the Bakken Shales
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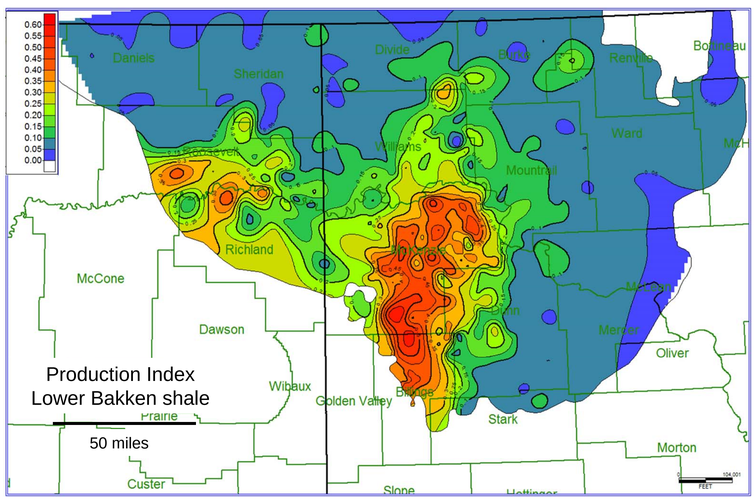

Figure 35. Production Index map for Lower Bakken shale. The highest PI numbers occur in the high geothermal-gradient area.

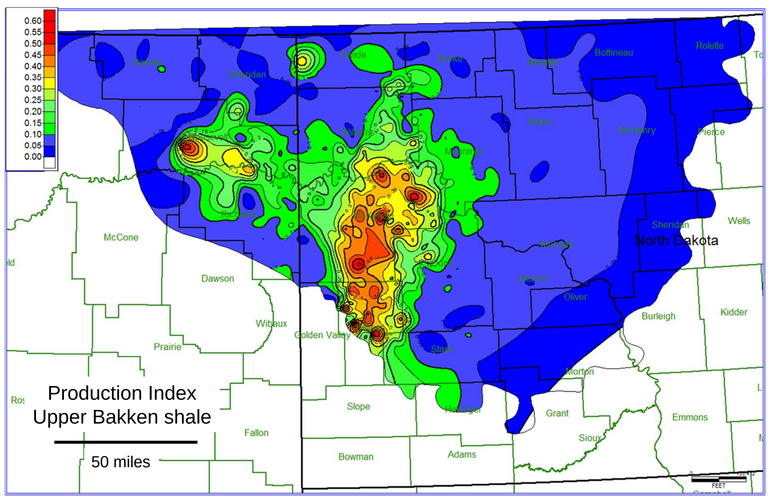

Figure 36. Production Index map for Upper Bakken shale. The highest PI numbers occur in the high geothermal gradient area.

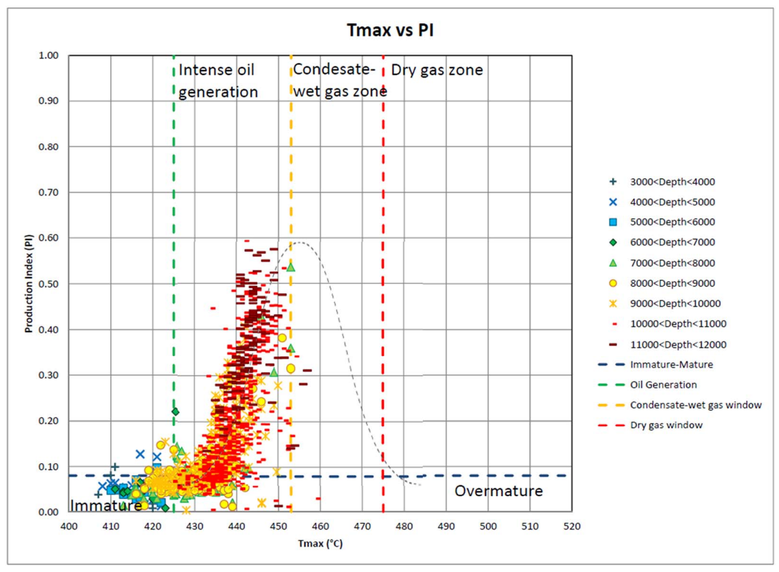

Figure 37. Plot of Production Index versus Tmax (ºC). Values above a PI of 0.1 and Tmax of 425ºC indicate thermal maturity of source rock.

Equations : from Peters et al. (2005)

$$f = \frac{1 - HI_X * \{1200 - \left[\frac{HI_O}{1 - PIO}\right]\}}{HI_O * \{1200 - \left[\frac{HI_X}{1 - PIX}\right]\}} \quad (1)$$

$$TOC_O = \frac{83.33 * (HIX)(TOCX)}{[HIO(1-f) * (83.33 - TOCX) + HIX(TOC_X)]} \quad (2)$$

Figure 38. Equations for conversion fraction (f) to petroleum and TOC_O(original TOC). HI_X and HI_O represents present-day and original HI, respectively. PI_X and PI_O represents present-day and original PI, respectively, and PI_O is assumed to be 0.03. TOC_X is present-day TOC value.

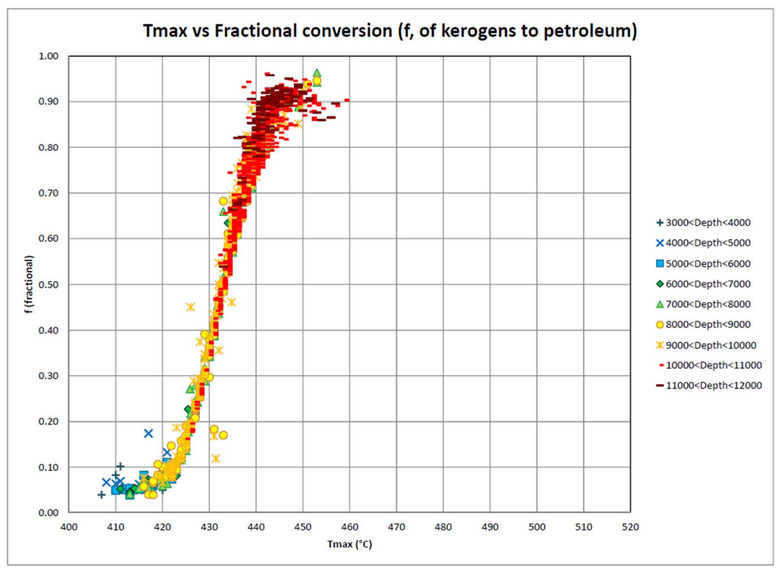

Figure 39. Plot of conversion fraction (f) versus Tmax (ºC). After 423~425ºC Tmax, f increase dramatically, indicating thermal maturity of source rock. It tails off, reaching 0.9~1, when Tmax is at ~450ºC.

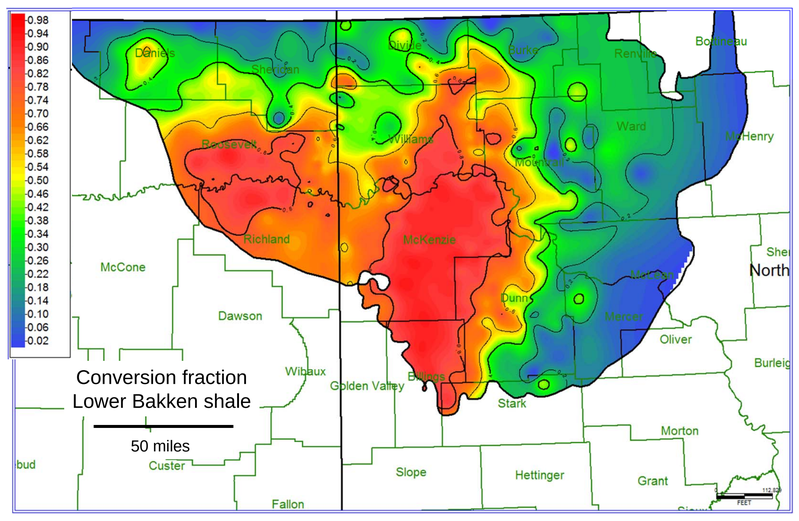

Figure 40. Conversion fraction (f) map for Lower Bakken shale. High fractional conversions in basin center and eastern Montana with HGG.

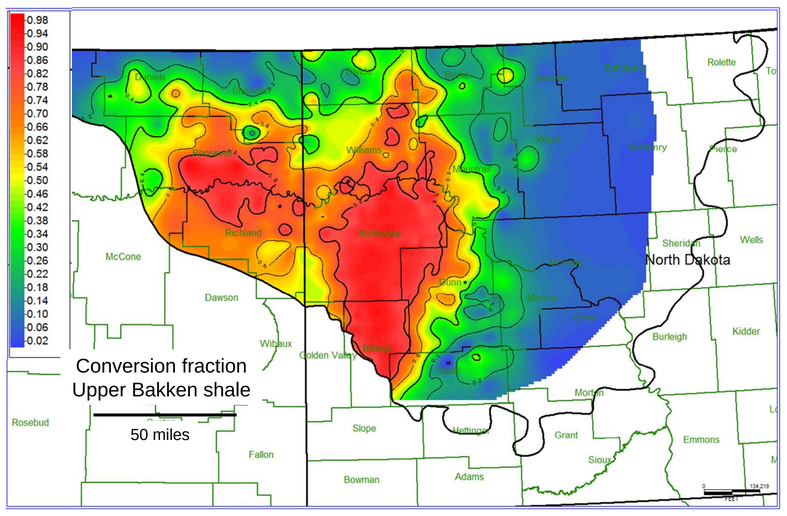

Figure 41. Conversion fraction (f) map for Upper Bakken shale. High fractional conversions in basin center and eastern Montana with HGG.

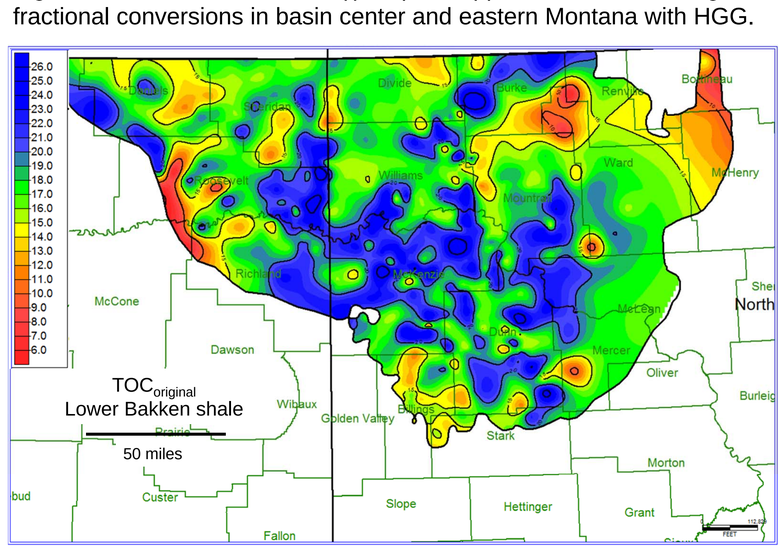

Figure 42. Original TOC map for Lower Bakken shale.

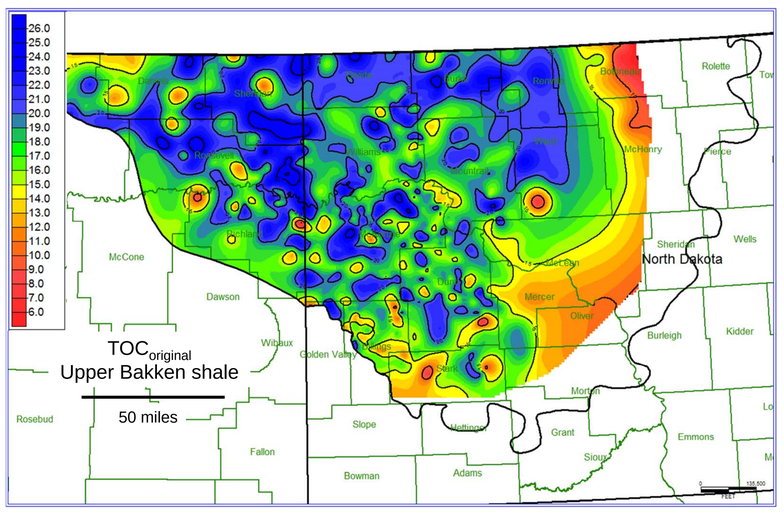

Figure 43. Original TOC map for Upper Bakken shale.

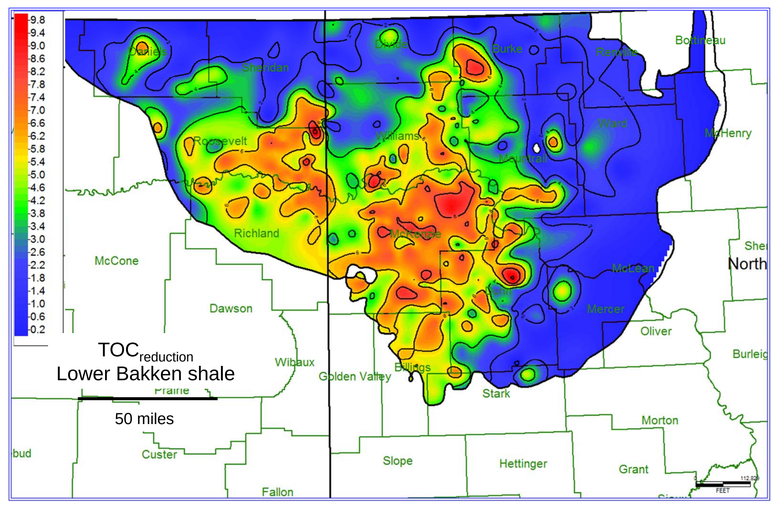

Figure 44. TOC reduction map for Lower Bakken shale. The highest TOC reduction occurs in the high geothermal gradient area.

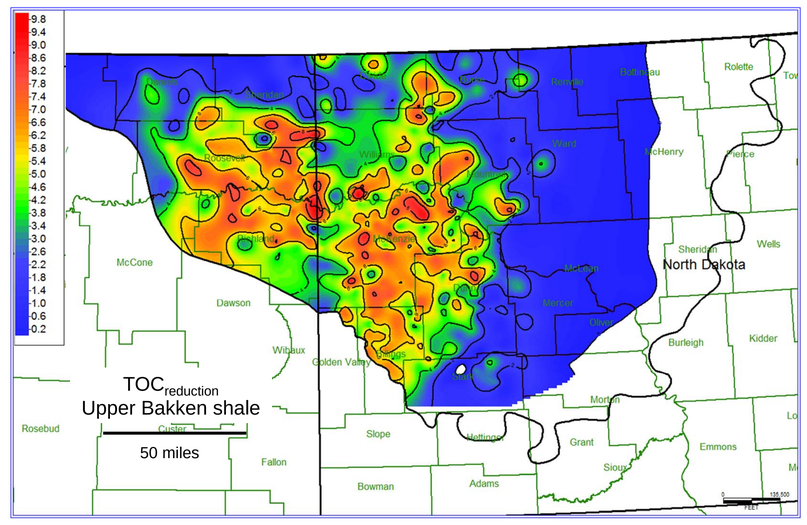

Figure 45. TOC reduction map for Upper Bakken shale. The highest TOC reduction occurs in the high geothermal gradient area.

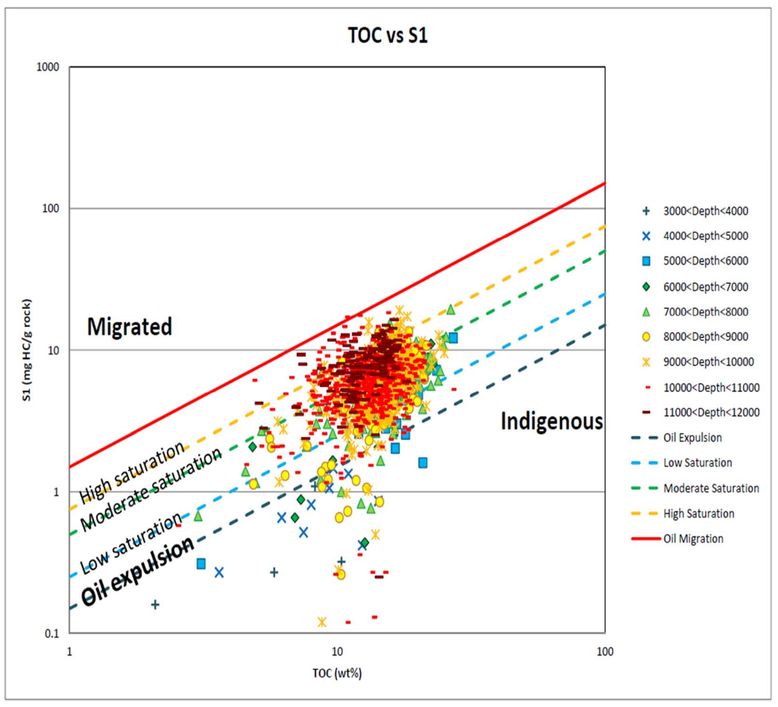

Figure 46. Plot of S1 versus TOC. Values above blue line indicate migrated hydrocarbons, whereas below, indigenous hydrocarbons. Deeper Bakken shales are saturated with indigenous oil. The plot suggests no migration of hydrocarbons into shales has taken place, but Bakken generated oils are migrated out of shales, sourcing mid-Bakken, upper Three Forks, and lower Lodgepole formations.

Conclusions

Pyrolysis information for the Bakken is abundant for the Williston Basin. Some general conclusions are as follows:

- High lateral and vertical TOC variation in Bakken shales, due to paleo-deposition and thermal maturation; Original TOC values across much of the basin are averaged about 20 wt%;
- Bakken Shale kerogen type: mainly mixed Type I and Type II in deep basin, Type II/III in shallower parts of basin; heterogeneity of upper and lower Bakken shales;
- The Bakken shales have very high initial HI values (e.g. in Parshall Field; and look similar to Green River oil shales) and plot as Type I kerogens; Original HI values for the majority of upper and lower Bakken shales are around 600;
- The high paleo-geothermal gradient area of Price et al. shows up on maps of PI, Tmax, HI, f and $TOC_{reduction}$; extends into Montana; TOC values are up to 7~8 wt.% lower in thermally mature areas;
- Intense generation of hydrocarbons in the Bakken coincides with Tmax values of 425ºC and PI values greater than 0.1; f values dramatically increase above 0.1~0.15;
- The depth of intense hydrocarbon generation can be deduced from S1/TOC versus depth plots and PI versus depth plots.

Colorado School of Mines
Bakken Consortium

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