[PS]Bakken Mudrocks of the Williston Basin, World Class Source Rocks*

Stephen A. Sonnenberg[1], Hui Jin[1], and J. Frederick Sarg[1]

Search and Discovery Article #80171 (2011)
Posted July 11, 2011

*Adapted from e-poster presented at AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 10-13, 2011

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Abstract

Bakken mudrocks are extremely important source rocks for the Bakken petroleum system of the Williston Basin. Published estimates of oil generated from the source rocks range from 10 to 400 billion barrels.

The mudrocks are variable in mineral composition and total organic carbon content. The dominant minerals present are quartz, feldspar, pyrite, dolomite, and illitic clay. The quartz is both detrital and biogenic in origin. Recognizable biogenic components in the mudrocks include: conodonts, fish bones, radiolaria (recrystallized), large algal spores (tasmanite), small cephalopods, small brachiopods, small corals and ostracodes. Thin black limestones are locally present in the lower Bakken mudrock. A thin siltstone interval is also locally developed in the lower part of the lower Bakken mudrock.

TOC content appears to vary inversely with percentage of biogenic silica (radiolarian). The TOC content of the mudrocks averages 11 wt%. The type of kerogen present is largely Type I/II based on visual and pyrolysis analysis. The mudrocks are red to brown in color where immature and black where mature. The mudrocks appear to be mostly finely laminated but small ripple forms are also present indicating bottom current activity.
The mudrocks were deposited largely under anoxic conditions, probably due to density stratification of the ocean water column in a restricted basin setting. Some burrowing has been reported in the mudrocks suggesting times of more oxic conditions.

Knowledge of petrophysical properties, TOC content, organic facies, mineralogy, fracturing, and source rock maturity of the Bakken mudrocks are important to the understanding of hydrocarbon occurrence and distribution in the Bakken petroleum system.

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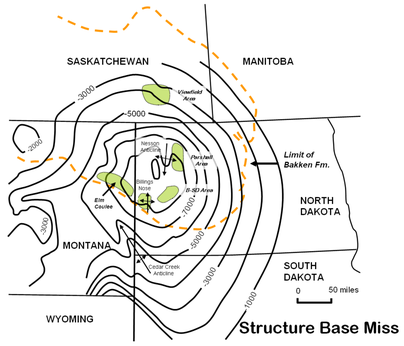


Figure 1. Index map of the Williston Basin illustrating the structure at the base of the Mississippian. The limits of the Bakken are shown by the dashed line. Recent giant discoveries (the past 10 years) include Elm Coulee of Montana, Parshall area of North Dakota, and the Viewfield area of Saskatchewan.

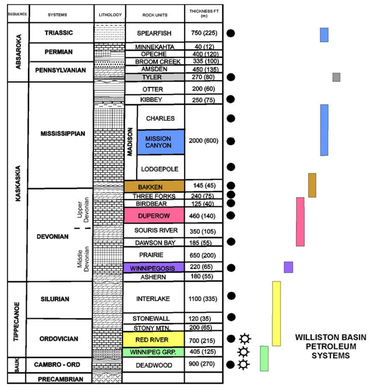


Figure 2. Stratigraphic column for Paleozoic and Lower Mesozoic units of Williston Basin. Also shown are extents of various petroleum systems. The Bakken petroleum system consists of reservoirs in the lower Lodgepole, Bakken, and upper Three Forks and source beds in the Bakken. Modified from LeFever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

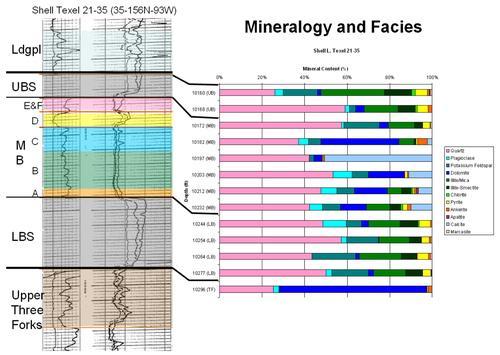


Figure 3. Well log (gamma-ray and resistivity) of Shell Texel Bakken petroleum system interval (Sec. 35-T156N-R93W). Mineralogy (XRD) of Bakken shown in chart to right. The middle Bakken can be subdivided into at least six distinct facies. Current targets of horizontal drilling are the middle member of the Bakken and the upper Three Forks.

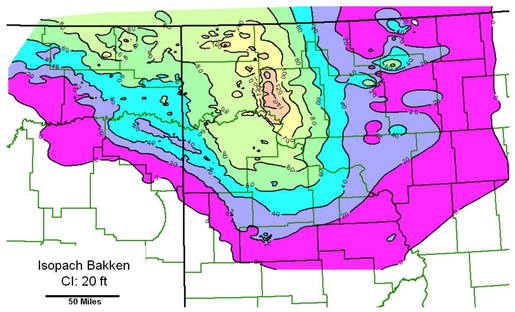


Figure 4. Isopach map of Bakken Formation, U.S. part Williston Basin. Thickness ranges from wedge-edge to over 140 ft.

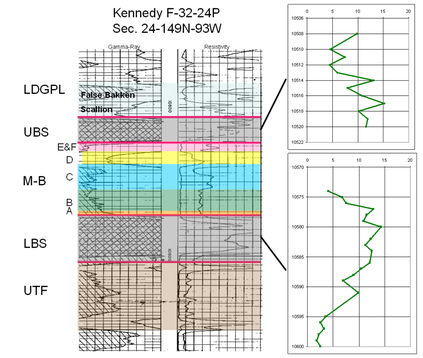


Figure 5. Well log (gamma-ray and reisistivity) for the Kennedy F-32-24P (Sec. 24-T149N-R93W). Bakken petroleum system consists of lower Lodgepole, Bakken, and upper Three Forks. Source beds are mainly upper and lower Bakken shales (note TOC content). Secondary source bed exists in False Bakken. Reservoirs are lower Lodgepole, Bakken, and upper Three Forks.

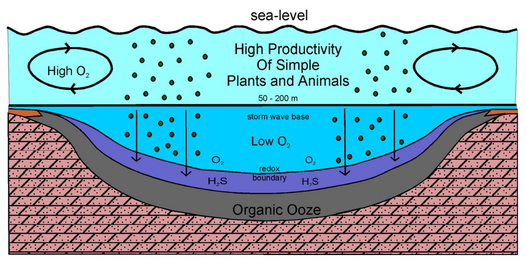


Figure 6. Deposition setting of upper and lower Bakken shales under anoxic conditions (modified from Smith and Bustin, 1996; Meissner et al., 1984).

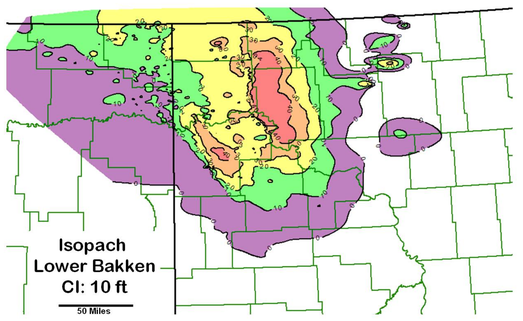


Figure 7. Isopach map of lower Bakken shale. Thickest area is east of the Nesson anticline and generally coincides with the Parshall area.

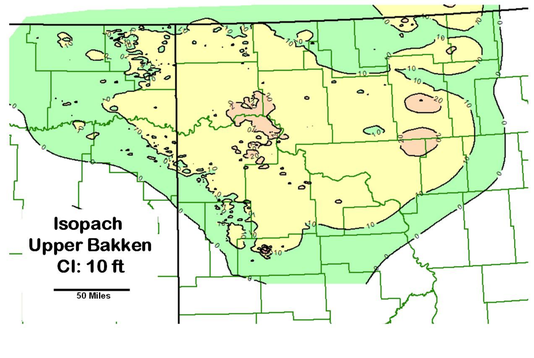
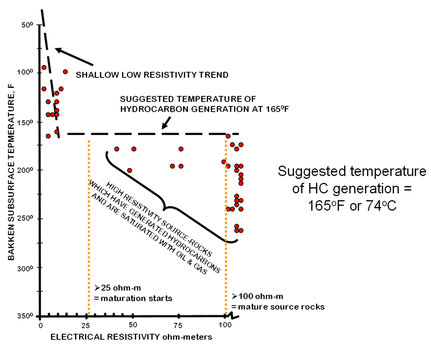


Figure 8. Isopach map of upper Bakken shale. Thickness ranges from a zero edge to over 20 ft.



Suggested temperature of HC generation = 165ºF or 74ºC

Figure 9. 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.

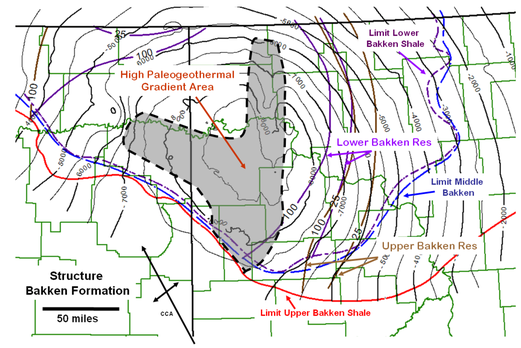


Figure 10. Structure map top Bakken showing limits of upper Bakken shale, middle Bakken, and lower Bakken shale. Also shown are iso-resistivity lines for the upper and lower Bakken shales from Hester and Schmoker (1985). The shaded area is a high paleogeothermal gradient area modified from Price et al. (1984).

Bakken Mudrocks of the Williston Basin

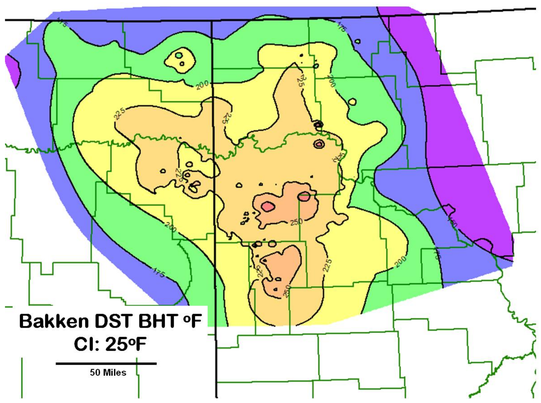


Figure 11. Bakken temperature map (uncorrected) from Bakken DST data base. The high paleogeothermal gradient areas are still temperature anomalies in the Williston Basin.

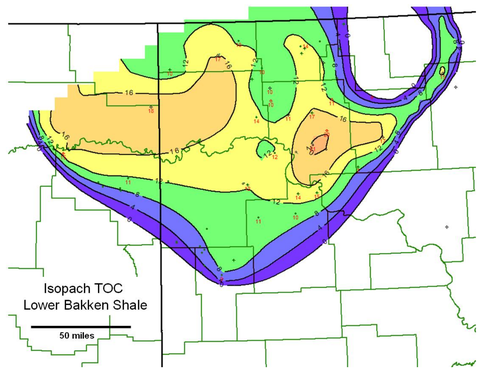


Figure 12. Isopach TOC values in lower Bakken shale. TOC ranges from 10 to 20 wt % across much of the area. Highest values associated with lower Bakken thick east of the Nesson anticline and coincident with Parshall field.

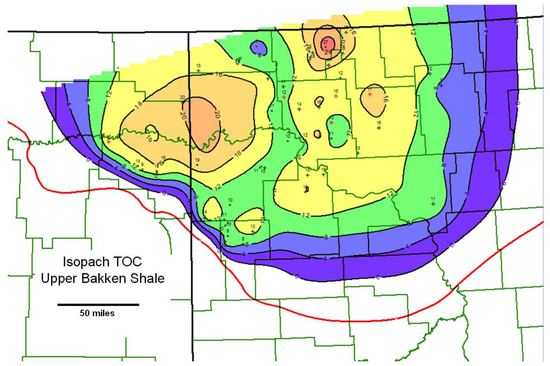


Figure 13. Isopach TOC upper Bakken shale. Low north-south-trending zone in middle of map coincides with high geothermal gradient area.

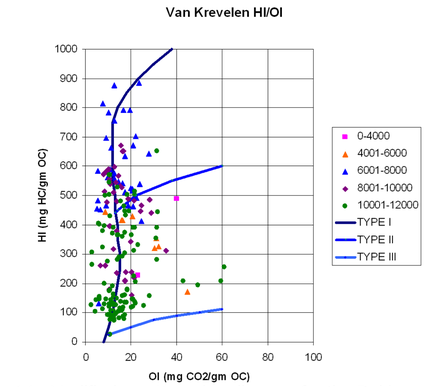


Figure 14. Modified van Krevelen diagram for the Bakken Formation of Williston Basin. Published data from Webster (1984) and Price et al. (1984). Majority of samples indicate a Type-I and II oil-prone kerogen (algal origin). Legend shows source rock data by depth interval. HI is hydrogen index (S2/TOC). OI is oxygen index (S3/TOC).

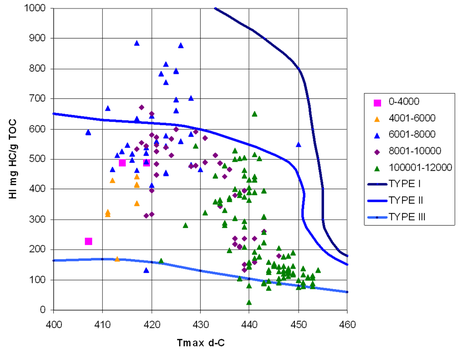


Figure 15. A plot of HI versus Tmax illustrates that the type of kerogen is a Type I/II for immature source rock. With increasing maturity, values plot in the lower right-hand quadrant.

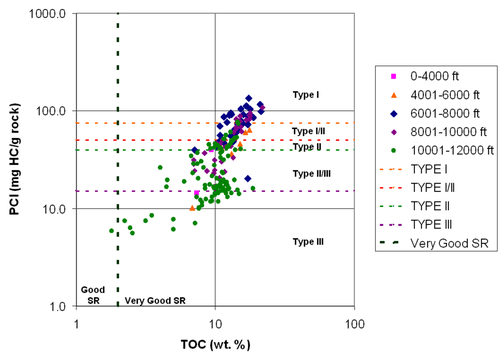


Figure 16. TOC versus pyrolyzable carbon index indicates the quality of the source rock according to TOC (wt. %) and kerogen types according to PCI. The quality of the source rock is very good and the kerogen type is Type I/II. Maturity of samples shifts Type I/II kerogens into values that appear to be Type III.

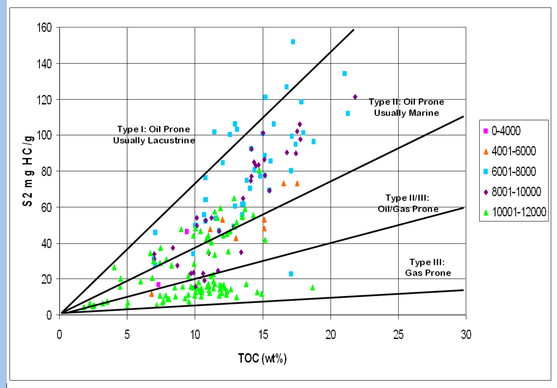


Figure 17. Plot of S2 versus TOC. Data from immature areas plots as TypeI/II kerogen. Data from 0-6000 ft plots as mixed Type II/III.

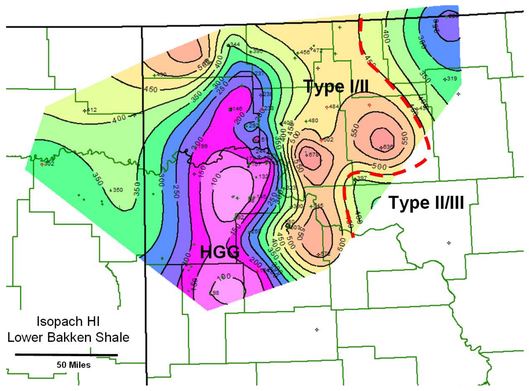


Figure 18. Isopach of HI values for lower Bakken shales. HGG stands for high geothermal-gradient area. The low values on the shallow east flank of the basin may represent a mixed Type II/III kerogen.

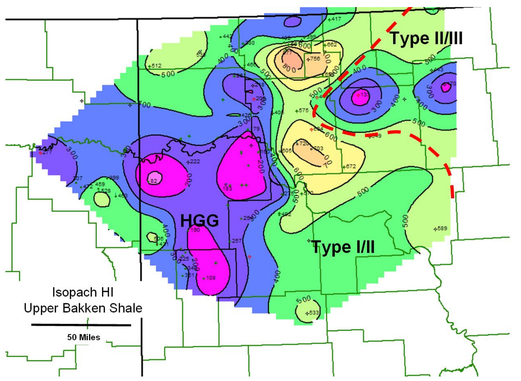


Figure 19. Isopach of HI values for upper Bakken shales. HGG stands for high geothermal-gradient area. The low values on the shallow east flank of the basin may represent a mixed Type II/III kerogen.

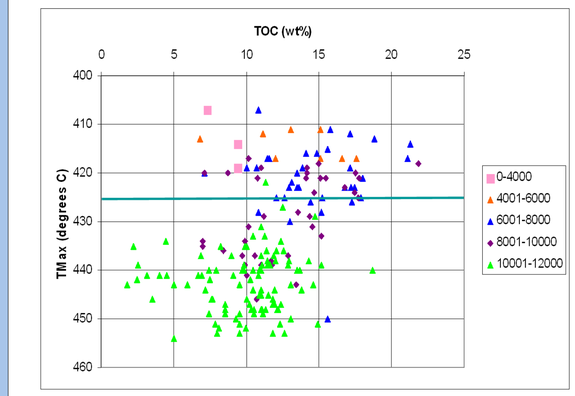


Figure 20. Plot of TOC versus Tmax for Bakken shales. Price et al. (1984) proposed that onset of maturity coincides with the 425oC line. Tmax values from samples taken at depths greater than 10,000 ft are greater than 425oC.

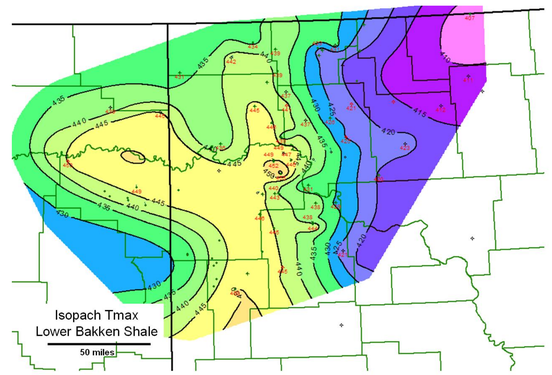


Figure 21. Isopach Tmax values for lower Bakken shale.

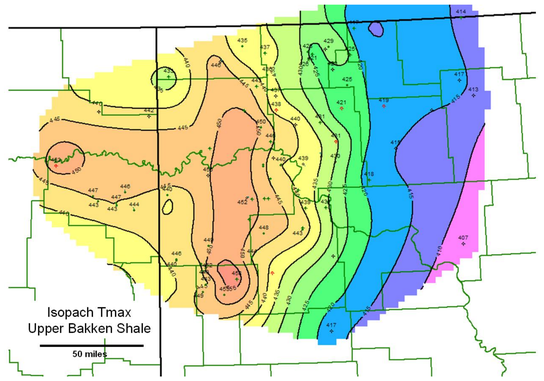
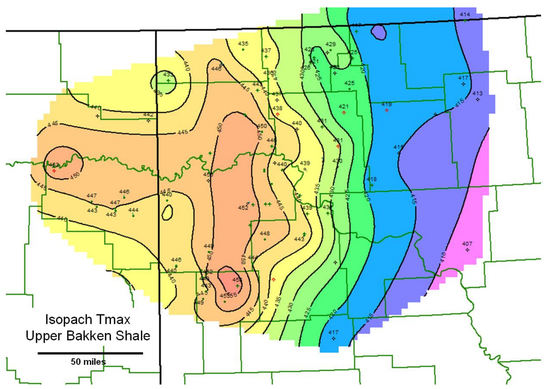


Figure 22. Isopach Tmax values for upper Bakken shale.

Bakken Mudrocks of the Williston Basin



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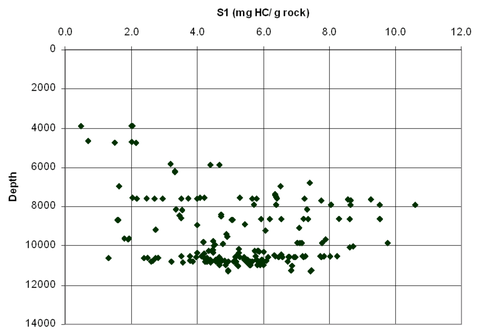

Figure 23. Plot of S1 versus depth. S1 generally increases with depth. High S1 values from 7500 to 9000 ft come from the high HI areas (lower and upper Bakken shales) east of the Nesson anticline.

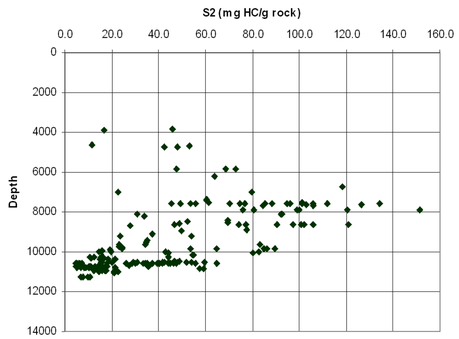

Figure 24. Plot of S2 with depth. S2 values decrease at depths greater than 6500 ft.

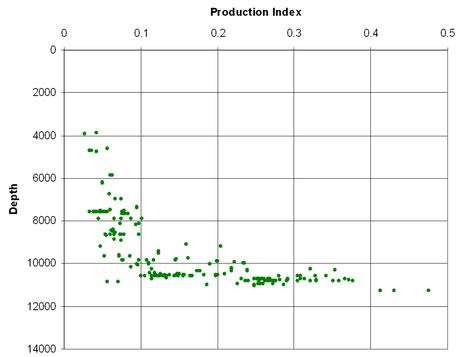

Figure 25. Plot of Production Index versus depth for Bakken shales. The oil generation window occurs between values of 0.1 and 0.4.

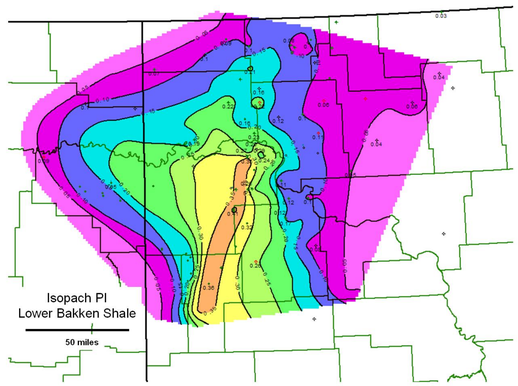

Figure 26. Isopach map of Production Index for lower Bakken shale. The highest PI numbers occur in the high geothermal-gradient area.

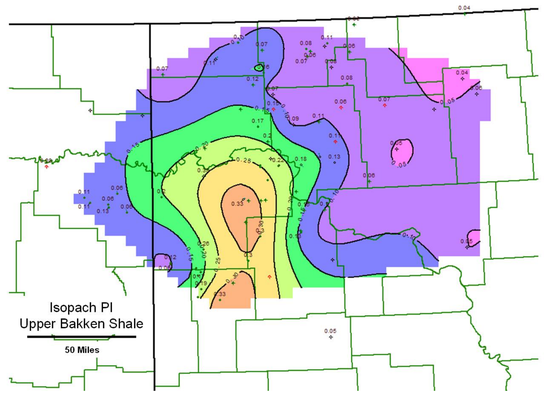

Figure 27. Isopach map of Production Index for upper Bakken shale. The highest PI numbers occur in the high geothermal-gradient area.

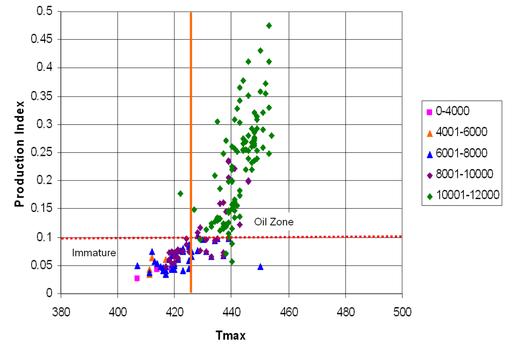

Figure 28. Plot of Production Index versus Tmax (oC). Values above a PI of 0.1 and Tmax of 425oC indicate thermal maturity of source rock.

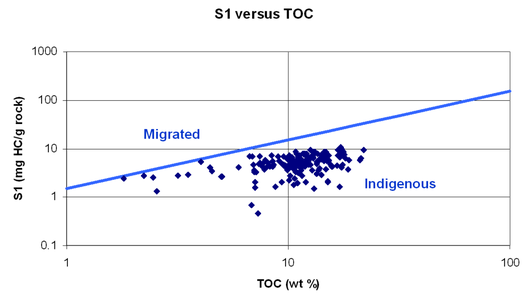

Figure 29. Plot of S1 versus TOC. Values above blue line indicate migrated hydrocarbons, whereas below, indigenous hydrocarbons. The plot suggests little if any migration of hydrocarbons has taken place.

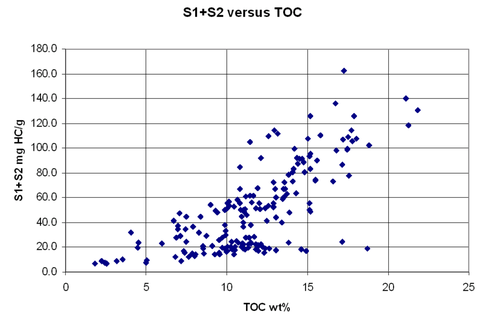

Figure 30. A plot of S1+S2 versus TOC illustrates a general correlation of increasing S1+S2 with increasing TOC.

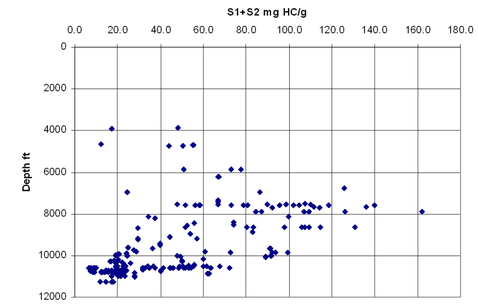

Figure 31. A plot of S1+S2 versus depth illustrates that S1+S2 values increase significantly at depths of 7000 ft and greater. The plot also shows quite a bit of scatter.

CONCLUSIONS

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

The high paleogeothermal-gradient area of Price et al. shows up on maps of PI, Tmax, and HI;

TOC values are up to 4% lower in thermally mature areas;

The Bakken shales have very high initial HI values (and look similar to Green River oil shales) and plot as Type I kerogens;

Intense generation of hydrocarbons in the Bakken coincides with Tmax values of 425oC and PI values greater than 0.1;

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

Samson · Marathon · XTO Energy · EOG Resources · Fidelity Exploration & Production Company · Total · The Energy of enerplus · AEP · Whiting · Whiting Petroleum Corporation · SAVANT · Red Willow Production Company · Anschutz Exploration Corporation · The Discovery Group Inc · Mike Johnson Consulting Geologist · Chesapeake Energy · Husky Energy · Newfield · Hendricks and Associates, Inc. · Statoil · Rosetta Resources · MJ Harden · TGS