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Assessment of Undiscovered Technically Recoverable Oil and Gas Resources of the Bakken Formation, Williston Basin, Montana and North Dakota, 2008

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Bakken Formation Oil Generation and "Oil Window"

Atomic H/C Ratio and the Hydrogen Index

The atomic H/C ratio of isolated kerogen has been shown to be an excellent indicator of the extent of oil generation (fig. 19; Lewan, 1985); however, obtaining the atomic H/C ratio is tedious and requires isolation of the kerogen with HF, HCl, and ZnBr. Espitalie and others (1977) had shown that a good substitution for the atomic H/C ratio of isolated kerogen is the hydrogen index (HI) determined by routine Rock Eval pyrolysis (fig. 20). However, in organic-rich rocks with HI> 450, HI must be further calibrated above this level for its utility as a measure of the extent of oil generation. In this study, HI was calibrated to the transformation ratio (TR) determined from a series of one-dimensional (1D) models using the commercial program PetroMod 1D (IES Integrated Exploration Systems).

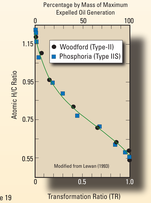

Figure 19

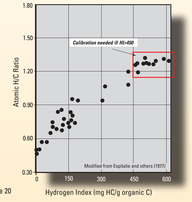

Figure 20

Contouring of the Hydrogen Index and 1D Models

Hydrogen index data from the USGS organic geochemistry database of both the upper shale member and lower shale member of the Bakken Formation were contoured and then entered into a USGS geographic information system (GIS) database (fig. 21). The upper shale data were used for maturity evaluation of the Bakken Formation because this member is of greatest geographic extent and relatively lowest in thermal maturity. Approximate locations of five modeled wells in areas of the Williston Basin with different heat and burial histories and HI values indicating different degrees of thermal maturity are shown in figure 21. 1D models using Woodford Shale Type II hydrous pyrolysis kinetics were generated in PetroMod (fig. 22) to determine the TR of the upper and lower shale members of the Bakken Formation in the set of five wells across the Williston Basin.

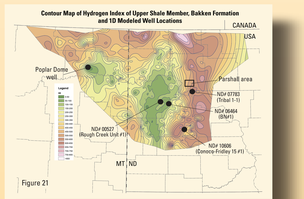

Figure 21

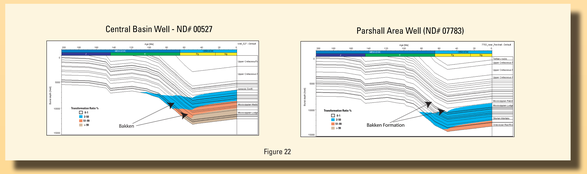

Figure 22

Bakken Oil Generation and "Expulsion Threshold"

Results of the five modeled wells are summarized in figure 23 and calibration of the TR to HI for these wells is plotted in figure 24. For comparison, the TR versus HI profile of figure 24 mimics profiles of those calculated for weight percent carbon loss versus the atomic H/C ratio for typical kerogen types as reported from Baskin (1997, see fig. 24 inset). Calibration of the HI as a measure of thermal maturity to extent of oil generation with respect to the TR for Bakken shale source rocks indicates that oil generation starts at an HI of about 630 to 650 and ends at an HI of about 100 (fig. 24). Data for total organic carbon (TOC) was also plotted for each range of contoured HI along the eastern "HI wall" where there is a steep change in HI contours and also a general progressive loss of TOC with decreasing range of HI to about HI = 400 (fig. 25). The range of HI from 650 to 400 is thus considered the primary range of oil generation and is referred to here as the "expulsion threshold" (figs. 24, 25).

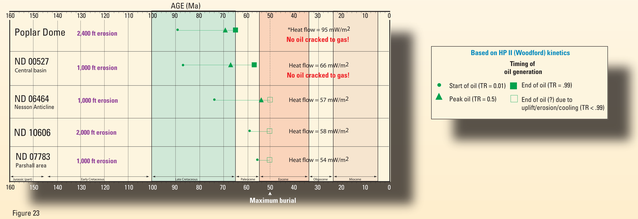

Figure 23

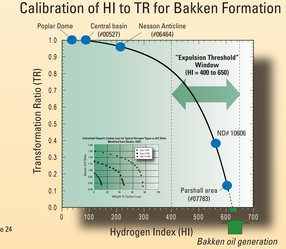

Figure 24

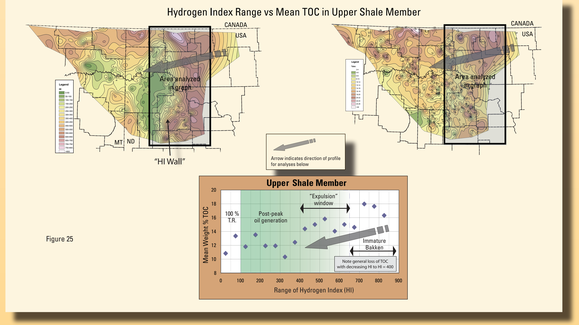

Figure 25

Hydrocarbon Generation and Expulsion Fractures

Both vertical and horizontal microfractures are evident in cores of the lower and upper shale members of the Bakken Formation (fig. 26). These microfractures, interpreted as the result of hydrocarbon generation, were considered in the geologic model for defining the assessment units for the Bakken-Lodgepole TPS. Pitman and others (2001) and LeFever (2007) described horizontal microfractures in core of the Bakken Formation and suggested that these microfractures resulted from "superlithostatic" pressures formed in response to increased fluid volumes during hydrocarbon generation (fig. 26). Similarly, Lash and Engelder (2005) studied horizontal microfractures in the Devonian Dunkirk Shale (fig. 26) and concluded that microfractures were the result of kerogen-to-bitumen and bitumen-to-oil generation and that kerogen particle shape and shale or siltstone planar fabric are important to the formation of horizontal microfractures (fig. 26). Microfractures formed by hydrocarbon generation are much different than vertical fractures formed by local or regional tectonic stress.

Vertical and Horizontal "Expulsion(?) Fractures," Lower and Upper Shale Members

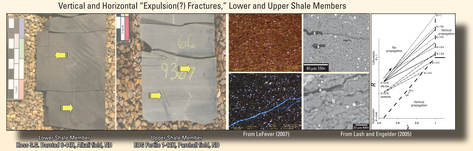

Figure 26

"Oil Window" Determination for Bakken Continuous Accumulation

The area of the oil generation window for the Bakken composite continuous reservoir was determined using a combination of the resulting contour maps of both the HI and log resistivity well data from Hester and Schmoker (1985) of the upper shale member. The area where log resistivity was >100 ohm-m was assumed to be mature for oil generation (figs. 27, 28). Thus, the oil window for the Bakken continuous oil accumulation is defined as that area where the upper shale member has HI>650 and (or) log resistivity >100 ohm-m (fig. 29).

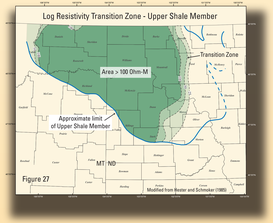

Figure 27

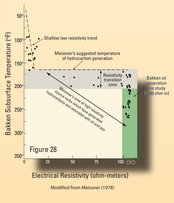

Figure 28

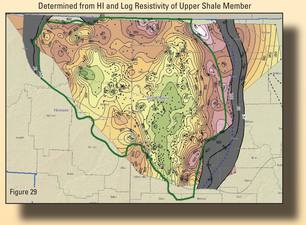

Figure 29

Geologic Model and Continuous Assessment Units

The geologic model used to define continuous assessment units (AU) generally assumed levels of thermal maturity and generation capacity of the Bakken Formation from the HI and TR, structural complexity of the Williston Basin, and lithofacies and petrophysical character of the middle sandstone member. Five continuous AUs were defined within the Bakken oil generation window (figs. 30, 31). Two of the continuous AUs were defined within the "expulsion threshold" parameters, the Eastern Expulsion Threshold AU and the Northwest Expulsion Threshold AU, and between the HI contours of 400 and 650 (fig. 30). A Nesson-Little Knife Structural AU was defined within an area of major structural elements and from a structure contour map generated at the top of the Bakken Formation (fig. 31). An Elm Coulee-Billings Nose AU was defined in part by the edge of the Devonian Prairie Salt (fig. 30). A Central Basin-Poplar Dome AU was also defined where remaining generation capacity of Bakken shale source rocks is low or completely exhausted and have HI<400 and TR>0.8 (see fig. 25).

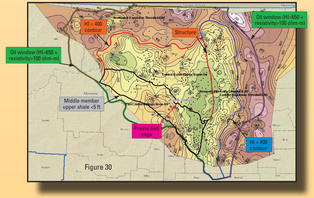

Figure 30

Figure 31