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Organofacies study of the Bakken source rock in North Dakota, USA, based on organic petrology and geochemistry

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ABSTRACT

Samples taken from the Upper and Lower members of the Bakken Formation in four wells that were drilled in a northeast - southwest trend along the eastern margin of the Williston Basin in central-western North Dakota were investigated in order to present an overview of source-rock quality and depositional environment conditions for the main purpose of establishing an organofacies model. Several techniques such as Rock-Eval 6 pyrolysis, X-Ray fluorescence elemental analysis, vitrinite reflectance, organic petrography and visual kerogen assessment using reflected and transmitted white light and UV light microscopy on whole-rock pellets were combined to draw the best possible conclusions. The results indicate that kerogen is mainly marine type II with increasing in maturity towards the central and SW portions of the basin. Detailed organic petrography of the samples showed that solid bitumen, amorphous matrix bituminite, granular bitumen, alginite, acritarchs, and liptodetrinite are the most abundant macerals. In order to properly determine the Bakken organofacies, the original hydrogen index (HI_o) was restored using various mathematical models and empirical methods. The mathematically restored HI_o from thermally mature samples ($HI_{o\text{-Calculated}}$) was then compared to the HI values from thermally immature samples ($T_{max} < 430\,°C$, here interpreted as HI_o) for further verification. Although the agreement between the Rock-Eval pyrolysis HI_o and the $HI_{o\text{-Calculated}}$ by the two mathematical equations was excellent, the VKA-derived HI_o values were underestimated by about 125 mg HC/g TOC. In the next step, the above parameters were integrated to identify the organofacies based on three different models. It was found that organofacies B is the most abundant organofacies present in the Bakken source rock. Furthermore, elemental analysis reflected a high concentration of “strong euxinic affinity” trace elements such as Mo, V, and Zn, representing an anoxic/euxinic depositional environment condition for the Bakken Shale.

1. Introduction

The Bakken petroleum system in Williston Basin is one of the most important unconventional shale plays in North America. The Late Devonian to Early Mississippian Bakken Formation is a widespread clastic formation and occupies portions of North Dakota, Montana, and the Canadian provinces of Saskatchewan and Manitoba. The Bakken Formation consists of three members; the upper and lower members which are black organic-rich shales and the middle member, which is comprised of carbonaceous sandstone and siltstone (LeFever et al., 1991; LeFever, 2008). In North Dakota, all three members of the Bakken Formation have an onlap truncation pattern with surrounding sediments and each member has more extensive spread than the older one. The onlapping geometry of the members could have occurred due to a transgression of the Late Devonian-Early Mississippian Sea (Webster, 1984; Meissner, 1991). The Bakken Formation is underlain by the Three Forks Formation and is overlain by the Lodgepole Formation (Fig. 1). This succession creates the Bakken Petroleum System. This system is characterized by low porosity and permeability reservoirs, organic-rich source rocks, and a regional hydrocarbon charge (Sonnenberg and Pramudito, 2009).

Conodonts, Tasmanites algae, amber-colored spores, small cephalopods, ostracodes, small brachiopods, and also fish remains are the most abundant fossil assemblages of the Bakken (Wall, 1962; Hayes, 1985). Presence of the mentioned fauna and flora assemblages, as well as the planar and thin laminations in the Bakken Shale, indicate that deposition has taken place in very low energy water conditions. The very high concentrations of organic matter and pyrite in the lower and upper Bakken represent a reducing, deep stratified, and anoxic depositional environment while the middle Bakken was deposited in well

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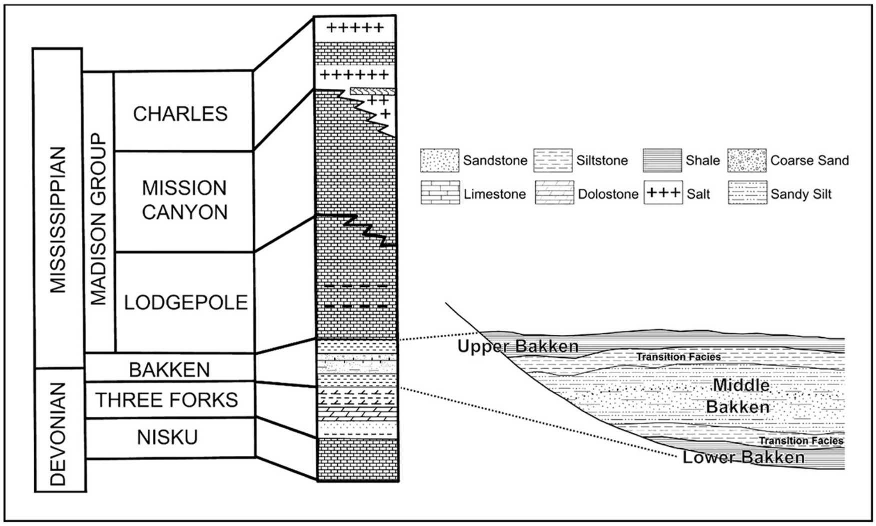

Fig. 1. Stratigraphic column of the Bakken Formation in Williston Basin, North Dakota (modified after Sonnenberg and Pramudito, 2009; Kuhn et al., 2010).

oxygenated water (LeFever et al., 1991). The concept of the Devonian-Mississippian "Black Shale Sea" of North America (Ettensohn and Barron, 1981) and also a stratified water column in the Williston Basin during Bakken deposition (Lineback and Davidson, 1982) is confirmed by the presence of nectonic (fish, cephalopods, and ostracodes), planktonic (algal spores), and epiplanktonic (inarticulate brachiopods) fossil fauna abundance (Webster, 1984).

The Bakken Formation has a maximum thickness of 150 ft. (~50 m) in the central part of the basin without any surface outcrop (LeFever et al., 1991). The formation is a unique case study for geochemical analysis since all stages of thermal maturity (from immature to relatively post-mature stages) can be recognized within a single stratigraphic unit (Webster, 1984). The upper and lower shales of the Bakken consist mostly of hard, brittle, waxy-looking black shale, having a very dark brown color. The upper shale mostly consists of organic matter with lesser amounts of clay, silt, and dolomite grains whereas the lower shale member appears to become less organic-rich and more-clayey, silty, and dolomitic (Meissner, 1991).

Majority of the studies on this formation have focused on the petrophysical properties of the middle Bakken, which is the reservoir and the productive zone of the Bakken Formation (Zeng and Jiang, 2009; Havens and Batzle, 2011; Sayers and Dasgupta, 2014; Alexeyev et al., 2017). Such studies aimed to demonstrate various methods to increase production from the formation (Chen and Wang, 2012; Wilson, 2014; Ruhle, 2016). In this regard, studies that would address the upper and lower members' characteristics, such as constituent organofacies or rock-forming macerals, are limited, specifically on the American side of the basin. Because of the importance to gather more information on the geochemical behavior of the Bakken, the focus of this study was directed toward an in-depth understanding of the organofacies present in the Bakken source rock, in a NE-SW trend (Fig. 2). To achieve this objective, we acquired and combined data from organic petrography and geochemistry to provide a better insight into the organic matter characteristics, particularly the constituent organofacies of the Bakken Formation in the Williston Basin, North Dakota.

2. Materials and methods

Thirteen samples were selected from the Upper and Lower members of the Bakken Formation, from two separate wells that were drilled in the deeper portions (Well #1 and #2) of the basin (Fig. 2). Two other samples were added to the batch from two separate wells (Well #3 and Well #4) that were drilled in the shallower depths of the basin to represent the immature Bakken. Thus, the present study, which has a NE-SW trend, covers a limited area along the eastern margin of the Williston Basin in central-western North Dakota. Sample descriptions, including depths, are summarized in Table 1. Samples were analyzed by Rock-Eval 6 pyrolysis to determine dispersed organic matter types, thermal maturity, and hydrocarbon generation potential. To fulfill this goal, approximately 60 mg of washed and ground bulk samples were used. After 3 min of isothermally heating the sample in the pyrolysis chamber in an inert N_2 atmosphere, the temperature was increased with a rate of 25 °C/min up to 650 °C. Residual carbon from the previous steps (pyrolysis stage) was burnt in the oxygen oven during the oxidation stage. By measuring the amount of hydrocarbons, CO, and CO_2 as the byproducts of thermal cracking and combustion of organic matter, specific parameters were recorded during a full-cycle of Rock-Eval pyrolysis using the IFP's trademarked Basic/Bulk-Rock method (Table 2). All samples were analyzed un-extracted. For more details, please refer to Behar et al. (2001) and Carvajal-Ortiz and Gentzis (2015).

TOC (wt%), representing organic richness, S_1 an S_2 (mg HC/g Rock), free oil content and remaining hydrocarbon potential, respectively, and T_{max} (°C) as an indicator of thermal maturity are the main outcomes of geochemical analysis by RockEval pyrolysis. Using these parameters, other indices can be calculated such as: HI ($S_2 \times 100$/TOC), OI ($S_3 \times 100$/TOC) and $S_1 + S_2$. The full description of the pyrolysis procedure and the resulting parameters can be found in Behar et al. (2001).

Furthermore, the samples were investigated for VR_o-Eq (%) to provide additional information about the maturity levels of the organic matter (Table 3). The conversion equations were adopted from Jarvie et al. (2001) for the Barnett Shale. Vitrinite reflectance (VR_o) and UV light analysis (fluorescence) was performed using a Zeiss Axio Imager A2M microscope under TSOP/ICCP protocols and suggested procedures with a sapphire and a YAG (Yttrium-Aluminium-Garnet) standard of 0.47% R_o and 0.97% R_o, respectively. For organic petrography under incident light microscopy, polished epoxy-mounted whole-rock blocks were prepared after crushing the samples to 840 μm. The blocks (pellets) were grinded using a set of 600 and 400 grit polishing cloths and then polished using 0.3 and 0.05 μm alumina powder via an automated Buehler EcoMet/AutoMet 250 system. Measurements were based on Bitumen R_o (%) and were converted to vitrinite R_o-equivalent using the Jacob (1985) formula:

$$VR_{O(equivalent)} = BR_O \times 0.618 + 0.4 \quad (1)$$

where VR_o is percentage of vitrinite reflectance and BR_o is the percentage of bitumen reflectance. The corresponding results are found in