

## The Bakken Formation within the Northern Part of the Williston Basin: a Comprehensive and Integrated Reassessment of Organic Matter Content, Origin, Distribution and Hydrocarbon Potential

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### Summary

This paper presents the findings of a integrated and comprehensive assessment of the oil generative potential for the Lower and Upper Bakken within the northern portion of the Williston Basin, using high resolution sampling of core from over 40 boreholes, analyses show the total organic carbon (wt% TOC) content for the Bakken Formation is not constant throughout any cored depth interval, but exhibits an extreme degree of variability both with depth *and* across northern portion of the Williston Basin. This is replicated by a variation in S<sub>1</sub>, S<sub>2</sub>, T<sub>max</sub> and HI across the study area and mirrored by the variation in yield of extractable organic matter (EOM), saturate, aromatic and NSO compounds as well as total sulphur, g.c.-fingerprint analysis, Pr/Ph ratios, short-chain/long-chain ratios, and the abundance and distribution in biomarkers. The dominant type of organic matter is a Type II fluorescing *Bituminite*, but relatively high amounts of total sulphur and organic sulphur within the kerogen indicate the localized presence of a Type IIs kerogen, with implications for the early generation of hydrocarbon at low levels of thermal maturity. The presence of sulphur is supported by the relatively high abundance of aryl isoprenoids within the total extract.

A depth-wise and basin-wide variation in transition metal concentration, notably Molybdenum, Chromium, Nickel and Vanadium, key molecular 'fingerprints' and diagnostic biomarkers within the Upper and Lower Bakken shale, indicate the existence of a stratified water column characterized by photic-zone anoxia during deposition. Key biomarkers also indicate the periodic occurrence of cyanobacteria, green sulfur bacteria (e.g., *Chlorobiaceae*) within the water column as the primary OM producers with anaerobic *Bacterivorous Ciliates* acting as 'decomposers'; suggesting that amorphous kerogen within the Upper and Lower Bakken (identified as *Bituminite*) was bacterially reworked by the *Bacterivorous Ciliates*.

Some of the broader implication from this study includes support for a paleo-water depth during the Upper and Lower Bakken that is at least 100m a mechanism and process that explains the origin and composition of the amorphous kerogen, an explanation for the presence of high amounts of sulphur and pyrite within the shale, the variation in organic matter content, variation in biomarker distribution and presents a challenge to the established notion that precursor organic matter is extensively reworked, and hence transformed into amorphous kerogen, exclusively within the sediment.

### Introduction

Both the Lower and Upper Bakken shale have generated and retained vast amounts of oil, particularly within the USA portion of the subcrop, with estimates range from 271 to 500 billion bbl oil (4.3 to 8.0 x 10<sup>10</sup> m<sup>3</sup>). However, despite advances in technology, the exploration and production of the Bakken remains a high-risk venture due, in part to assessments founded on the classical theory of oil generation and the basin-wide assessment of production and source potential derived from drill cuttings, limited core sample or wire-line logs.

The black shales of the Upper and Lower Bakken have been the focus of a number of previous geochemical and petrographically-based studies that generally conclude that the organic-rich Upper and Lower Bakken are primarily composed of a marine-derived amorphous kerogen (characterized as Type II-kerogen with an associated Hydrogen Index (HI) of 615 mg hydrocarbon/gTOC) (Osadetz *et al.*, 1992; Osadetz and Snowdon, 1995), with an apparent emphasis upon the presence of *Tasmanites* which is a Type I kerogen (Christopher, 1961; Stasiuk *et al.*, 1990), generally considered immature with respect to the generation of hydrocarbon and perhaps inappropriately described as a 'flooding surface'. However, several questions remain unresolved; firstly why does the amount of organic matter, expressed as wt.% TOC, vary from about 32.0wt.% to 1.0wt.%TOC within a 'flooding surface' and is that variation consistent across the sub-basin; secondly what is the exact character and composition of the organic matter within the Upper and Lower Bakken since *Tasmanites* is not a Type II kerogen and lastly, why does a stratigraphically shallower formation (i.e. Lodgepole Formation) appears to have a higher level of thermal maturity (*cf.* Jiang *et al.*, 2001)

The overall goal of this project was to conduct a regional assessment of the petroleum potential of the Upper and Lower Bakken within the northern portion of the Williston Basin, and to plausibly explain the apparent spatial and temporal variation in organic matter, source characteristics and hydrocarbon potential and identify probable reasons for any variation. The intent is to also provide an understanding of those conditions that led to the formation, accumulation and occurrence of organic matter within the Bakken shale and identify and understand those processes and conditions that controlled the formation, preservation, alteration and ultimately the geochemical characteristics of the organic matter within the Bakken shale.

## Method

Drill core from 30 wells were selected for analysis based upon core availability, core recovery, the location of wells and the association with areas of proven hydrocarbon generation. High-resolution sampling was achieved by obtaining 20 to 25g of sample from up to 30 sample sites throughout the Upper and Lower Bakken cored intervals within each well. Weathered material was initially removed from each sample, and the cleaned samples were subsequently pulverized for 10 seconds using a Tema mill to less than 105 µm, homogenized and split into a number of sub-samples for analysis.

The evaluation of hydrocarbon potential and thermal maturity was achieved using Rock-Eval VI pyrolysis methodology. Source extraction, to remove the extractable organic matter (i.e. bitumen), was carried out using the Soxhlet/soxtec extraction method and the extract fraction subsequently fractionated using column chromatography into hydrocarbon (saturate and aromatic) and non-hydrocarbon (e.g., nitrogen-, sulphur- and oxygen-bearing compounds) fractions. Further analysis was conducted using gas chromatography and gas chromatographic-mass spectrometry to investigate the distribution of molecular markers (biomarker) and other hydrocarbon compounds in the aliphatic and aromatic fractions. As part of a source screening, an examination of the amount of total sulphur present in the sample was also examined using LECO Elemental Analyzer. Petrographic analysis was conducted using a Leitz Orthoplan research microscope set for epifluorescence using a 4-λ PLOEMOPAK, filter block "G" (BP 250 to 460nm, RKP 510 nm, LP 520 nm), with a 100w Hg lamp with a x25 air objective and x10 oculars. Point count analysis was conducted using an interpoint and inter-line distance of 50µm. Five hundred counts per sample were conducted according to published guidelines (ICCP, 1971).

## Results and Discussion

The total organic carbon (wt% TOC) content for the Upper and Lower Bakken Formation is not constant throughout the cored intervals, but rather exhibits an extreme degree of variability with depth and across southern Saskatchewan. Results from this study clearly show a depth-wise *and* spatial variation in TOC that reflects the depth-wise *and* spatial variation in 'bitumen content' (S1), the amount of kerogen (as S2), associated Hydrogen Index, pyrite and total sulphur content within both the Upper and Lower Bakken shales. For example, within a given borehole the TOC can vary from ~24wt.% to 1wt.%.

This depth-wise pattern is mirrored in the yield of extractable organic matter (EOM), which is in agreement with the values for S1, showing a temporal variation in the proportion of saturate, aromatic and nitrogen- sulphur- and oxygen-bearing (NSO) compounds. The relatively high proportion of NSO compounds within the EOM is consistent with the determined thermal maturation state, but may also reflect the incorporation of sulphur into the kerogen during diagenesis.

The Upper and Lower Bakken represent a '*sediment starved lithology*', in that the organic matter comprises the 'matrix' material within the Bakken shale. Previously misidentified, the matrix material can be convincingly demonstrated to be amorphous organic matter using the autofluorescence alteration characteristic of the amorphous kerogen, in which the autofluorescence intensity increases due to the prolonged exposure of the samples to violet and ultra-violet light . Autofluorescing carbonates do not exhibit this behavior.

In this way, the amorphous organic matter was identified as the maceral *Bituminite*, which is an amorphous maceral characterized by a dull yellow-brown autofluorescence (Figure 2) and the characteristic maceral of *Marinite* (a 'marine' oil shale). Detailed petrographic analysis also shows that there is not only a variation in the subtype of *Bituminite* across the basin (spatially) but also vertically within each interval. Two sub-types of *Bituminite* dominate the Upper and Lower Bakken identified as *Bituminite* A or C. Typically *Bituminite* A or C rarely occur within the same depth interval, substituting for each other. *Bituminite* A dominates the central sub-crop area of southern Saskatchewan whereas *Bituminite* C occurs towards the eastern and western margins. Using this pattern as a framework, a number of other petrographic characteristics helped identify and define a number of correlatable *Organic Facies* that typify the organic matter distribution throughout the Upper and Lower Bakken.

A number of molecular fingerprints for the *Organic Facies* dominated by *Bituminite* 'A' or 'C' were identified using saturate and aromatic biomarkers. For example, the *Organic Facies* dominated by *Bituminite* 'A' contains alkyl-benzenes and tends to have a relatively high abundance of aryl isoprenoids and a *Gammacerane*. *Bacterivorous Ciliates* synthesize tetrahymanol, which is the precursor compound of the biomarker gammacerane, and therefore a concentration of gammacerane within a given sample indicates the presence of anaerobic *Bacterivorous Ciliates* within, or just below the chemocline in the paleo-water column. In addition, the presence of abundant products of isorenieratene; 2,3,6-trimethyl aryl- and diaryl-isoprenoids, which are likely derived from green sulfur bacteria *Chlorobiaceae*, points towards a significant contribution of *primary* organic matter from anoxygenic, sulphide oxidizing phototrophic bacteria. Anoxygenic, sulphide oxidizing phototrophic bacteria exist within the photic zone but below the chemocline within the anoxic (euxinic) zone, as shown in the accompanying Figure. Thus, indicating not only the presence of green sulphur bacteria *Chlorobiaceae* and anaerobic *Bacterivorous Ciliates*, but also clearly indicating that the anaerobic *Bacterivorous Ciliates* fed upon green sulphur bacteria within the water column; that is the organic matter associated with the primary organic matter created by the sulphide-oxidizing phototrophic bacteria *Chlorobiaceae* was reworked by the *Bacterivorous Ciliates* resulting in the formation of a structureless amorphous organic matter with no definitive morphology identified by petrographic analysis as *Bituminite*. Therefore, the presence of *Gammacerane* acts as an indicator for stratified water column (Sinninghe Damsté *et al.*, 1995) and isorenieratene is an indicator of photic zone anoxia (Summons and Powell, 1987; Koopmans *et al.*, 1996).

The presence/absence or variation in

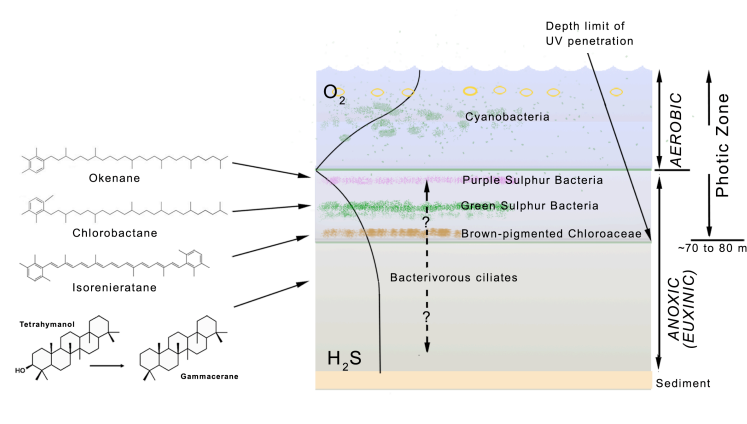


Figure 1. A proposed and generalized paleo-depositional environment for the Lower and Upper Bakken, showing the presence of a chemocline, the existence of euxinic conditions, various biologic entities and their associated depth of occurrence and associated biomarkers.

these biomarkers indicates either subtle variations in the depth of the photic zone and/or a variation in depth of the hydrogen sulphide (H<sub>2</sub>S) chemocline (Figure 1). The maximal abundance in sedimentary isorenieratene derivatives represent periods when the H<sub>2</sub>S chemocline was relatively shallow, overlapping within the photic zone as shown in Figure 1. The presence of both isorenieratene, or its derivatives, and gammacerane strongly implies the presence of a stratification of water column with euxinic zone extending into the photic zone.

In contrast, a low concentration or absence of isorenieratene derivatives corresponds to a relative absence in green sulfur bacteria *Chlorobiaceae* because the chemocline was located below the photic zone, the presence of gammacerane alone implies that the top of the euxinic zone (i.e., chemocline) was below the photic zone. A high bacterial productivity within a stratified water column is also inferred because tetrahymanol is biosynthesized by the ciliates, when their diet is deprived of sterols. This is also consistent with dominance of bacterially reworked amorphous kerogen within both Upper and Lower Bakken. This association implies that the bacterial reworking of organic matter took place within the water column, since *Bacterivorous Ciliates* do not typically live within the sediment.

Analysis also reveals the presence of high amounts of elemental sulphur, that also exhibits a depth-wise variation, ranging from 1.3wt% to 8.1wt% for the Upper Bakken, and from ~0.25wt% to typically 6.5wt% for the Lower Bakken, with two samples showing a high total sulphur content of 13.0wt%. Using conventional maturity parameters, the Type II kerogen would be considered relatively immature, however  $T_{max}$  shows a strong inverse relationship ( $R^2 = 0.82$ ) with total sulphur. The implication being that the presence of sulphur may influence the early generation of hydrocarbon at relatively low levels of thermal maturity. However, the extremely high amount of micro-framboids of pyrite (up to 24 vol%) within the Bakken shale necessitates a series of complex de-mineralization steps using hydrochloric and hydrofluoric acid and chromium chloride. The presence of alkyl-benzenes within the extract strongly suggests the presence of organic sulphur within the kerogen, and even with an aggressive, unprecedented double treatment of CrCl<sub>3</sub>, analysis still generate Atomic S/C ratios ranging from 0.02 to 0.06, indicating the localized presence of medium to high sulphur-bearing Type IIs kerogen *in places*.

Using a variety of formation specific kinetics, clearly supports the early generation of hydrocarbon at relatively lower levels of thermal maturity. Using formation specific kinetics (e.g.  $E_a$ ,  $A$ , w-factor,  $S_{org}$ ) with the *Organic Facies* data identifies 'micro kitchens' of early generation in a series of 3D dynamic petroleum systems models across the northern part of the Williston Basin. When using standard kinetic parameters, the Bakken essentially remains immature.

## Conclusions

This study has shown that the kerogen within the Upper and Lower Bakken is dominated by the amorphous kerogen *Bituminite* and occurs as a Type II / Type IIs. Correlatable *Organic Facies* were also defined, using organic petrography and/or biomarker analysis, that are associated with key molecular 'fingerprints' within both the Upper and Lower Bakken shale; resulting in significant differences in petroleum potential and hydrocarbon generation across the Bakken subcrop.

Broader implications include support for a paleo-water depth during the Upper and Lower Bakken that accommodates both a photic zone and euxinic bottom water conditions, a mechanism and process that explains the origin and composition of the amorphous organic matter within the Bakken, helps explain the presence of high amounts of sulphur and pyrite within the shale and presents a new interpretation that the amorphous kerogen was originally derived by cyanobacteria/sulphur reducing bacteria and subsequently reworked within the water column by *Bacterivorous Ciliates*.

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