

Palaeodepositional environment of the Bakken shales of Saskatchewan: insights from biomarker study

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Summary

This study presents a detailed source characterization in relation to depositional condition during the deposition of the Bakken shales, using a biomarker approach. The geochemical characteristics for the Bakken shales is investigated using core samples to conduct a depth biomarker profile, examining the organic matter input and depositional markers within the Bakken shales in the northern part of the Williston Basin.

The Bakken shales are reported to consist mainly of Type II kerogen, with some distinct molecular 'fingerprints' associated with the source of their organic matter and depositional environment. These molecular discriminants distinguish the Bakken shales from other sources within the Williston Basin and are also employed as a means to trace Bakken oils, identify migration pathways and define petroleum systems. Results from this study suggest a significant variation in concentration of steranes, hopanes and gammacerane within a single borehole and also when compared spatially. The results reveal variations in depositional settings, with the presence of multiple source facies within the Bakken shales. The top section of the Lower Bakken shale relates to a dysoxic condition, hosting a number of phytoplankton communities including algae and cyanobacteria while the other half through the base of the Lower Bakken suggests the presence of water column stratification, associated with photic zone euxinia, the presence of green sulphur bacteria and ciliates. This is evident from the high concentrations of gammacerane, presence of aryl isoprenoids and isorenieratane. Similar variations were noted for the Upper Bakken shale, although these variations were irregular. Based on these analyses, a generalized characteristic is inapplicable to characterize the Bakken shale. The Type II kerogen within the Upper and Lower Bakken shales are maceral assemblages consisting of a number of biological entities and not a single organic matter Type, as defined by bulk pyrolysis parameters. This study identified a number of molecular fingerprints, associated with multiple source facies within the Bakken shale. This study not only provide an understanding of heterogeneity in hydrocarbon potential for the Bakken shales but also documents a number of characteristics useful for oil to source correlation studies as well as defining an accurate petroleum system.

Introduction

The Bakken Formation is generally sub-divided into Upper, Middle and Lower Members based upon their respective lithological characteristics, within which the Upper and Lower Bakken members are composed of non-calcareous, fissile, pyritic organic-rich shale that exhibit an apparent degree of lithological uniformity throughout the Williston Basin (e.g., Christopher, 1961). 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 both primarily composed of a marine-derived amorphous kerogen characterized as mainly Type II kerogen (Osadetz *et al.*, 1992; Osadetz and Snowdon, 1995), contains remnants of *Tasmanites* of Type I kerogen (Christopher, 1961; Stasiuk *et al.*, 1990). However, several questions remain unresolved; for instance the variation in organic matter abundance, kerogen Type and palaeodepositional setting governing organic matter deposition.

Using high-resolution core sampling, this study focus on regional geochemical analysis of the Upper and Lower Bakken, explaining the apparent spatial and temporal variation in organic matter, source characteristics and hydrocarbon potential. This study also seeks to 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 32 boreholes were selected for analysis based upon core availability, core recovery and the location of boreholes. High-resolution sampling was achieved by obtaining 20 to 25g of up to 30 sampling point throughout the Upper and Lower Bakken cored intervals within each borehole. Core samples were cleaned with weathered material removed using organic solvent. Samples were 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. Source extraction was done to remove the extractable organic matter (i.e. bitumen), 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) in the saturate and aromatic fractions.

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 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.

A number of molecular fingerprints within the Upper and Lower Bakken were identified using saturate and aromatic biomarkers. 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 of gammacerane, a marker for water column stratification also points to the presence of *Bacterivorous Ciliates* since they synthesize tetrahymanol, a precursor compound for gammacerane. In addition, the presence and variation 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 organic matter from anoxygenic, sulphide oxidizing phototrophic bacteria. These anoxygenic, sulphide oxidizing phototrophic bacteria exist within the photic zone and at the chemocline within the anoxic (euxinic) zone. The presence/absence or variation in these biomarkers indicates a more dynamic depositional setting with

either subtle variations in the depth of the photic zone and/or a variation in depth of the hydrogen sulphide (H₂S) chemocline. The presence of both isorenieratene, or its derivatives, and gammacerane strongly implies the presence of a stratification of water column with chemocline extending into the photic zone. In contrast, a low concentration or absence of isorenieratene derivatives corresponds to a change in chemocline position, as the presence of gammacerane alone implies that the top of the euxinic zone (i.e., chemocline) was below the photic zone.

A parallel petrographic study indicates that the geochemically defined Type II kerogen within the Upper and Lower Bakken shale is an assemblage of macerals generally dominated by the amorphous maceral *Bituminite*. For example, an *Organic Facies* dominated by *Bituminite* 'A' tends to have a relatively high abundance of aryl isoprenoids and *Gammacerane* although the concentration is variable depending on the chemical reactions taking place within the water column. Thus, indicating not only the presence of green sulphur bacteria *Chlorobiaceae* and anaerobic *Bacterivorous Ciliates*, but also supporting the feeding association between the anaerobic *Bacterivorous Ciliates* and green sulphur bacteria within the water column (cf. Sinninghe Damsté *et al.*, 1995). Dominance in amorphous organic matter is supported from the microbial reworking relationship between sulphide-oxidizing phototrophic bacteria and ciliates resulting in a structureless amorphous organic matter with no definitive morphology identified by petrographic analysis as *Bituminite*.

On the basis of a newly established framework, this study proposed a wide range of geochemical characteristics and molecular proxies within the Upper and Lower Bakken shale, that further enhance our understanding of variations in organic matter (i.e. kerogen) that occurs with the Upper and the Lower Bakken shale, the reconstruction of the paleodepositional setting, the distribution and relative abundance of molecular compounds as well as implications for hydrocarbon generation.

Conclusions

The detailed high-resolution geochemical analysis of Bakken core in this study has shown that the Type II kerogen within the Upper and Lower Bakken is dominated by amorphous kerogen (*Bituminite*). This study has also identified key molecular 'fingerprints' and the existence of significant variation in saturate and aromatic biomarkers within the Upper and Lower Bakken shales. This study also documents the compositional differences in the Bakken shales with implication in regional variability in petroleum potential and hydrocarbon generation.

Broader implications of this study include support for a paleo-water depth during the Upper and Lower Bakken that is excess of the photic zone, a mechanism and process that explains the origin and composition of the amorphous organic matter within the Bakken, helps to explain the presence of high amounts of sulphur and pyrite within the shale and presents a challenge to the established notion that precursor organic matter is extensively reworked, and hence transformed into amorphous kerogen, within the sediment by sulphate-reducing bacteria.

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