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Reconstructing the palaeoecosystem and palaeodepositional environment within the Upper Devonian–Lower Mississippian Bakken Formation: A biomarker approach

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ABSTRACT

Biomarkers have been used extensively to correlate oil families, oil–source rock relationships and source inputs, and to help identify the palaeodepositional environment for a given geological sedimentary unit. Despite their application in characterising the Bakken Formation shales, a number of biomarkers still appear unable to provide us a consistent understanding regarding heterogeneity in source organic matter and palaeoenvironment. Here, we infer the palaeodepositional environment within the Bakken Formation shales using a biomarker suite and biomarker depth profiles. We also use the occurrence and abundance of biomarkers to define organic facies and to make inferences regarding biotic interactions drawn from modern analogues. The variations and co-occurrence of biomarkers is explained by the existence of a proposed complex algal–bacterium–bacteriovore palaeoecosystem. This approach not only helps explain the depth variation in occurrence and concentration of biomarkers and the molecular composition of associated organic matter, but also advances the use of biomarker analysis and biomarker associations to determine a complex environment-sensitive palaeoecosystem.

1. Introduction

Biomarkers are used to provide a fairly robust link to precursor organic matter and associated depositional palaeoenvironment (Mackenzie et al., 1982; Peters and Moldowan, 1993). In particular, steranes and hopanes are typically used to assess the relative biological contribution of eukaryotic (i.e. algae) and prokaryotic (i.e. bacteria) organisms, respectively (Peters and Moldowan, 1993; Peters et al., 2005a, 2005b). This is increasingly augmented by the use of other key marker compounds such as isorenieratane, aryl isoprenoids, and gammacerane, in a growing number of studies of both ancient and modern marine as well as lacustrine depositional settings (e.g., Sinninghe Damsté et al., 1995a; Song et al., 2013). Biomarkers are also used extensively to identify various biological precursors that constitute the organic matter within a given source rock, and to make inferences regarding the nature of the palaeodepositional system and/or the organic input. However, most studies generally fall short of providing a causal link between the palaeoecology that governs those biological precursors and, in turn, biomarker occurrence and abundance. For instance, gammacerane has been used as a marker for the presence of water stratification (Sinninghe Damsté et al., 1995b). On the other hand, gammacerane is also linked to bacterivorous ciliates in the palaeodepositional environment, since tetrahymanol (a precursor for gammacerane) is biosynthesized mainly by the ciliates (Harvey and McManus, 1991; Kenig et al., 1995; Sinninghe Damsté et al., 1995b; Kluska et al., 2013).

Isorenieratane and aryl isoprenoids, which are derivatives of isorenieratene (a carotenoid pigment), have been linked to green sulfur bacteria (GSB) (Chlorobiaceae) (Liaaen-Jensen, 1978; Koopmans et al., 1996a). In addition, paleorenieratane is also linked to extinct species of Chlorobiaceae (Requejo et al., 1992; Hartgers et al., 1994; Koopmans et al., 1996a; Clifford et al., 1998; Melendez et al., 2013; French et al., 2015). Chlorobiaceae are photoautotrophic anaerobic organisms that require both light and hydrogen sulfide (H_2S), and therefore their presence in the palaeoenvironment indicates that an anoxic water mass has extended into the photic zone (Summons and Powell, 1986, 1987; Sinninghe Damsté et al., 1995a, 2001; Koopmans et al., 1996a). These biomarkers provide not only evidence of redox condition in the water column but also a link to the source of organic matter. The distributions of aryl isoprenoids and the aryl isoprenoid ratio (AIR) are used, in the manner of Schwark and Frimmel (2004), as an index to indicate and assess the duration of seasonal fluctuation, occurrence of intermittent/persistent

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photic zone anoxia (PZA) within the palaeo-water column. The term photic zone euxinia (PZE) is used in this study because of the inferred presence of sulfide. The collective use of these biomarkers is therefore useful in interpreting the palaeodepositional environment and source of organic matter.

Using the Devonian to Lower Mississippian Bakken Formation (i.e., Upper and Lower Member shale), we report here the findings and interpretation of a detailed study based upon the high-resolution sampling of uncontaminated core. We generated multiple biomarker depth profiles and present a biomarker-based approach which proposes a causal link between various palaeoecological niches within a stratified water column that in turn governs the production and initial transformation of organic matter. This study, therefore, aims to improve our present understanding regarding the depositional setting as well as the variation in organic matter and hydrocarbon potential for the Bakken Formation shale. Our approach is based on much higher sampling (temporal) resolution than is commonly reported, using approximately 1 sample per 10 cm.

2. Geology and depositional setting

The Bakken Formation is a siliciclastic/carbonate unit occurring from 40 m to 3700 m depth below the present land surface in southern Saskatchewan, southwestern Manitoba, western North Dakota and northeastern Montana, all within the Williston Basin (LeFever, 1991; Smith and Bustin, 1996). The Bakken Formation is subdivided into three informal Members, consisting of the Upper, Middle and Lower Members (Nordquist, 1953; Kume, 1963; Price et al., 1984; Lefever, 1991; Meissner, 1991). The Upper and Lower Members of the Bakken Formation, the focus of this study, are comprised of hard, siliceous, pyritic, generally non-calcareous organic-rich shales with high hydrocarbon producing potential (Christopher, 1961; Webster, 1984; Osadetz and Snowdon, 1995; Smith and Bustin, 2000). The Middle Member, however, consists of mainly siltstone, sandstone and carbonate rocks. In the study area (southeastern Saskatchewan) (Fig. 1), the Upper and Lower Bakken Members attain a thickness of approximately 2 m and 8 m respectively (Osadetz and Snowdon, 1995; Kreis et al., 2006).

The Bakken Formation was deposited during the Late Devonian and Early Mississippian (Fig. 2). The Bakken Formation is thought to reflect two successive episodes of moderately deep-water deposition (>200 m), ultimately resulting in the organic-rich Bakken Formation shales (Smith et al., 1995; Smith and Bustin, 1996). There is no consensus regarding a modern analogue for the depositional environment of the Bakken shales, although a number of depositional settings have been proposed. LeFever (1991) implied a relatively uniform depositional environment spanning a large area, while others proposed depositional models that include marine swamp (Fuller, 1956; McCabe, 1959), shallow sea (Christopher, 1961), stagnant marginal marine lagoonal environment (Webster, 1984) and an anoxic stratified water column (Lineback and Davidson, 1982; Webster, 1987; LeFever et al., 1991; Smith and Bustin, 1996). At one time the Bakken shales were also thought to have accumulated as part of a continent-wide anoxic event (Meissner et al., 1984).

Recent studies, however, reported some periods of dysoxic conditions, supported by rare burrowing activity and the presence of chondrites near the top of the Lower Bakken Member (Smith and Bustin, 2000; Angulo et al., 2008; Angulo and Buatois, 2012). Most studies on depositional environment of the Bakken shales mainly involve sedimentology and ichnology, with very few on geochemical characteristics. Interpretations of anoxic bottom water conditions were based mainly on abundant organic carbon, a key characteristic of these Bakken shales. Studies based on geochemical parameter and biomarker occurrences (e.g., pristane (Pr) to phytane (Ph) ratio; gammacerane) are often not consistent within the Bakken (Osadetz et al., 1992; Jiang et al., 2001).

3. Sampling and methods

Samples were obtained from conventional core cut from a single vertical borehole (01/15-25-010-08W2M) located within southern Saskatchewan, Canada (Fig. 1). The high-resolution sampling per unit depth, was achieved by obtaining 20–25 g from each of the 18 sampling intervals. Within the Upper Bakken Member, 7 samples were obtained over an interval of 0.7 m and within the Lower Bakken Member, 11 samples were obtained over an interval of 3.3 m. Samples were pulverized for 30 s using a Tema mill to a

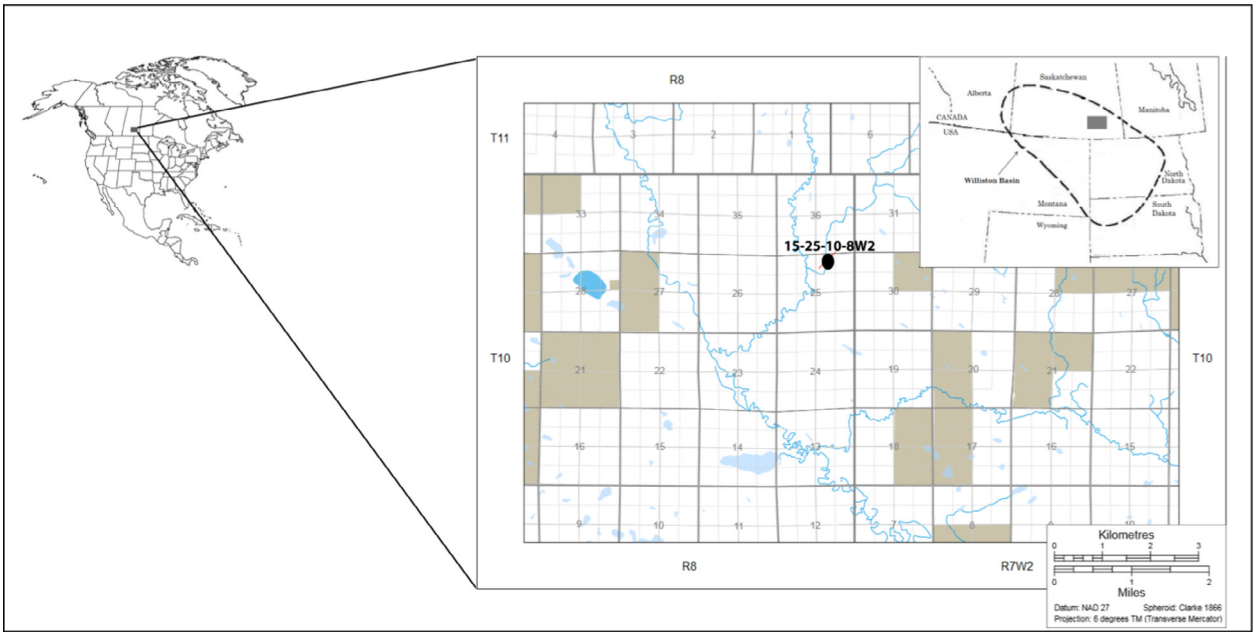

Fig. 1. Study area and location of borehole used in this study.