Geological Controls on Petroleum Fluid Property Heterogeneities in Carbonate Bitumen and Heavy Oil Reservoirs from Northern Alberta

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Summary

A combined geochemical, geological and microbiological analysis of an actively biodegrading oil column has been carried out on core from the Peace River oil sands. Consistent with numerous investigations of oil columns, gradients are seen in the viscosity and hydrocarbon composition data which respond to diffusion fed gradients within the oil column due to the zone below the oil column referred to as the oil-water transition zone (OWTZ) where enhanced microbial abundance is recorded. Gradients may be perturbed by the presence of shales which are seen offsetting the viscosity and geochemical profiles. While bioreactive compounds are seen responding to biodegradation, the bioresistant compounds such as the mono-aromatic steroids possess unique distributions that may be used to recognize source information even in these severely biodegraded oils. The compositions appear remarkably uniform across significant shale barriers suggesting the reservoirs where charged above and below the shales with a uniform oil composition. The shales often compartmentalize the reservoirs such that biodegradation systematics may differ above and below the shales. Meanwhile, low conversion rates detected amongst molecular maturity parameters and lack of diamondoids suggests the original source(s) were likely exposed to the early oil window stage of petroleum generation.

Introduction

The source(s) that have potentially contributed to the heavy oil and oil sands deposits of Northern Alberta have long been debated using mass balance considerations (Creaney and Allan, 1990) or molecular evidence (Riediger et al., 1999). For example, the presence of C_{28} bisnorhopane (amongst others) is often used to identify a contribution from the Exshaw Formation, while its absence may be attributed to a charge from the Duvernay Formation. However, as is often a feature of the Grosmont bitumen, the steranes and hopanes may have been completely destroyed thereby limiting their application as indicators for oil-source correlation. The geochemical fingerprints from the highly resistant aromatic steroid hydrocarbon compounds and the diamondoids possess unique distributions that enable recognition of source charge contributions and reservoir filling history even at advanced degradation levels and also retain valuable information regarding source maturity. Based on the limited inventory of end-member oil types, we can make some assertions regarding the source contributions to the oil sands and Grosmont bitumen.

Heavy oils and oil sands are formed by microbial degradation of conventional crude oils over geological timescales. The role of charge/mixing, water, nutrient supply, reservoir architecture and oil source type have been cited as potential controls on the process of degradation (Head et al., 2003). In general, the viscosity of the bitumen residing at the base of an oil column may be an order of magnitude higher than the bitumen higher up in the reservoir. While this is a general rule, steps in physical property and composition profiles may coincide with present day geological features such as lithological barriers.

The geochemical data are interpreted within a geological framework to assess migration / charging and mixing along with the impact of biodegradation associated with the bitumen deposits in the Peace River and Athabasca oil sands and the Grosmont bitumen accumulations.

Results and Discussion

Oil Sands

A detailed integrated geochemical, geological and microbiological investigation was conducted on core material recovered from a well penetrating the Bluesky Formation reservoir (Cretaceous) of the Peace River oil sands. The oil column was 15.75 m thick to the top of the OWTZ while, significant oil staining was also present a further 8.75 m below the top of the OWTZ with decreasing oil saturation towards the base of the reservoir. The dead oil viscosity at 20 ºC was 50,000 cP at the top of the oil column and increased to 1.4 McP at the oil-OWTZ contact, with a further increase to the maximum 10.5 McP within the OWTZ (Bennett et al., 2013).

A number of saturated and aromatic hydrocarbon compounds showing marked compositional gradients through the oil column with decreasing concentrations with increasing depth (Fig. 1). Close inspection of the concentration profiles relative to depth indeed reveals that the different compounds appear to be completely consumed (concentration below detection limit) at different depths within the reservoir (Fig. 1). The different concentration profiles that are observed for the representative saturated (n-C_{30} and pristane) and aromatic (2-methylphenanthrene and 2,6- plus 2,7-dimethylnaphthalene) hydrocarbons shown in Fig. 1 reflect different rates of removal of each species, with the most biodegradation-susceptible components (n-alkanes) being removed higher in the OWTZ (basically at the base of the oil column proper), while the more resistant components persist further into the biodegradation bioreactor within the OWTZ.
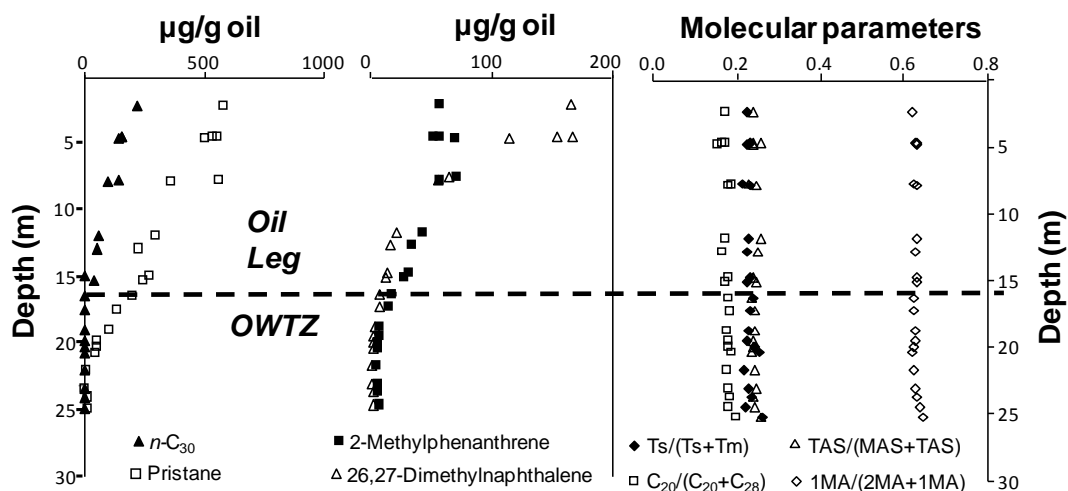

Figure 1. Plots of molecular parameters based on hydrocarbon compounds and concentration profiles (µg/g oil or parts per million) representing saturated and aromatic hydrocarbons. The depth is scaled according to the depth relative to the top of the reservoir, directly beneath the top shale cap rock. Modified from Bennett et al. (2013).

The core samples were submitted for microbiological investigation. The qPCR data suggest on the order of 10^6 to 10^7 cells/gm of sediment are present within the upper part of the OWTZ, numbers that are consistent with an active biological system and around 10^4 to 10^5 cells/gm are seen in the oil column and lower part of the OWTZ(Bennett et al, 2013). The coincidence between the enhancement in bacterial abundance and the associated consumption of hydrocarbon compounds is consistent with the notion that microbial activity and abundance in the deep subsurface is elevated at geochemical interfaces (Parkes et al., 2005).

In summary, through the oil column, gradients in biodegradation related oil physical and chemical properties are driven mainly by diffusion fed gradients resulting from the bioreactor within the OWTZ.

The profiles suggest vertical fluid communication through the entire oil column. In this second case study, shales were indicated within the oil column. In general, vertical fluid communication may be interrupted by the presence of shales acting as barriers or baffles. In Figure 2a, the C_4-alkylnaphthalene concentration data and the viscosity profiles are offset at the depth where the shale is located. The shale has compartmentalized the reservoir into two reservoirs and accordingly the lower compartment is exposed to the water leg and resulting higher level of biodegradation and more viscous oils. In Fig. 2b the viscosity profile and methylphenanthrene concentration data proceed uninterrupted across the shale suggesting the oil column is in vertical fluid communication.
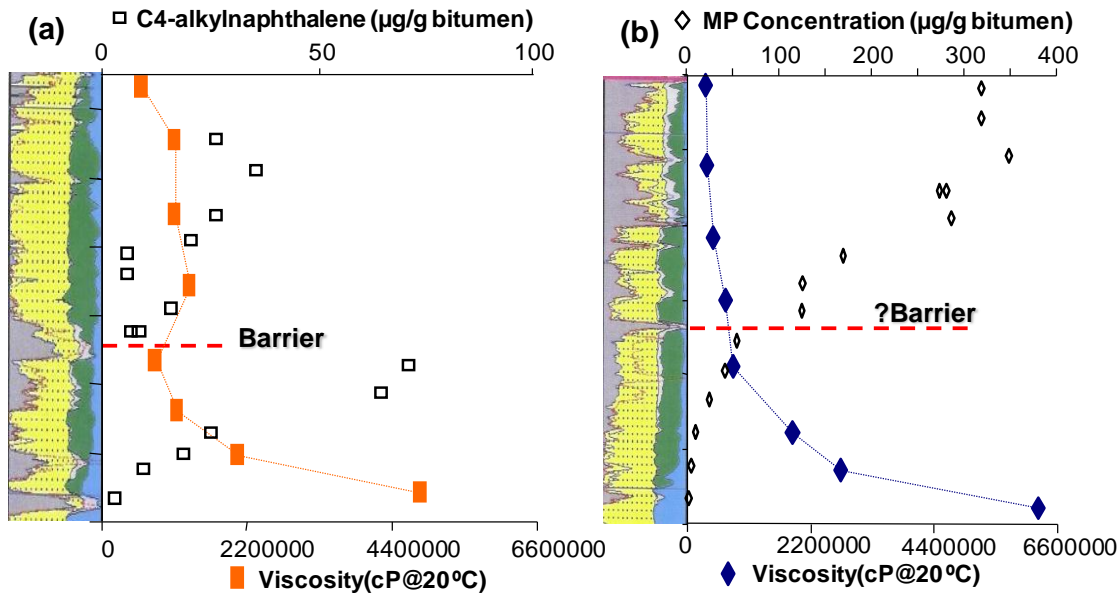

Figure 2. Plots of viscosity and geochemical data versus depth in wells 1 and 2. Figure modified from Fustic et al. (2011). MP = Methylphenanthrenes.

Carbonate bitumen

During our studies of the Grosmont bitumen, we have found that molecular parameters based on the abundance of C_{27} 18 α (H)-22,29,30-trisnorneohopane (Ts) relative to C_{27} 17 α (H)-22,29,30-trisnorhopane (Tm), i.e. Ts/(Ts+Tm) and the steroid aromatization parameter (mono-aromatic steroids versus tri-aromatic steroids) display strong resistance to biodegradation. The depth profiles of the molecular parameters (Fig.3) are remarkably uniform within the UGM2 and UGM3 units and the trends also appear uninterrupted by the presence of the shale break. A similar observation may be seen amongst the quantitative data obtained for the biodegradation resistant C_{24} tetracyclic terpane and Ts, thus molecular ratios and concentration data suggests the oils in UGM2 and UGM3 are genetically related.
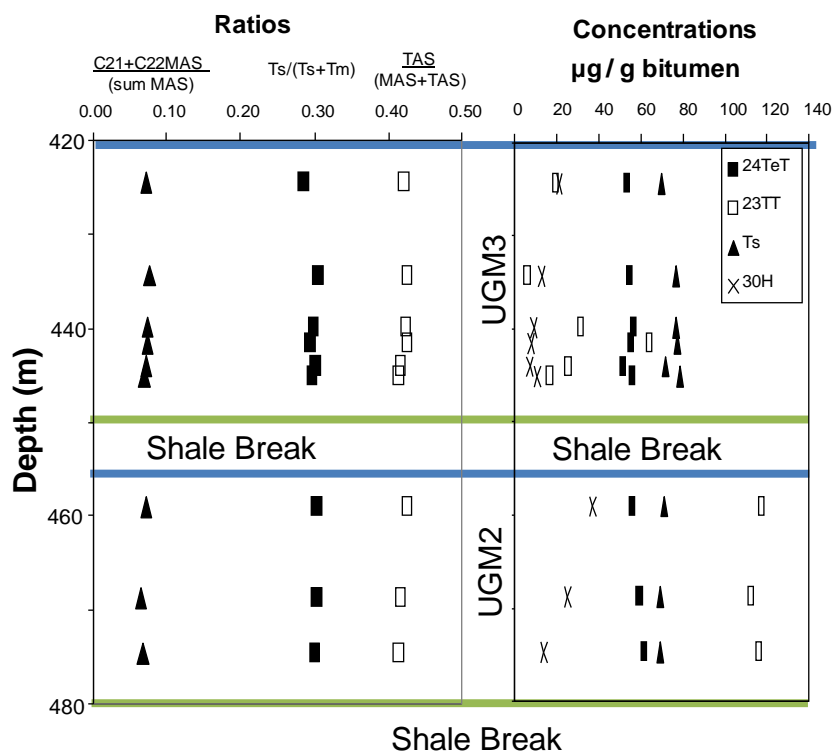
Figure 3. Molecular maturity parameters and molecular concentration (μg/g bitumen) data versus depth (m) for the Upper Grosmont units 2 (UGM2) and 3 (UGM3).

In contrast, the behavior of compounds that appears sensitive to biodegradation under the severe conditions experienced by the Grosmont bitumen exhibit changes within the reservoir units which show very different distributions between UGM3 and UGM2. The concentration data for the C_{23} tricyclic terpane and C_{30} $\alpha\beta$ hopane (Fig. 3) indicate the biodegradation behavior is specific to the reservoir units UGM2 and UGM3. In addition, further evidence for different biodegradation systematics between reservoir units UGM3 and UGM2; is recorded by the relative distributions of hopanes versus 25-norhopanes. In UGM3, the biodegradation of hopanes occurs without the formation of 25-norhopanes, whereas in UGM2 hopane degradation occurs with the formation of 25-norhopanes. The molecular evidence indicates there are very different degradation systematics operating within the UGM3 and UGM2 reservoir units implying that the laterally extensive shales within the Grosmont Formation represent barriers to vertical fluid communication leading to unique biodegradation processes in the individual reservoir compartments.

In the heavy oil and bitumen province of Alberta, the impact of biodegradation on oil composition is seen among many groups of compounds and affects many traditional geochemical proxies for understanding source thermal maturity or source facies composition. In our studies of the severely altered bitumen deposits in Alberta, including the oil sands reservoired in the Cretaceous Bluesky Formation (Peace River Oil sands), Cretaceous McMurray Formation (Athabasca oil sands) and the carbonates of the Devonian Grosmont Formation, we have found that some compounds that appear to be highly resistant to biodegradation retain information that may be indicative of oil source and thermal maturity. Thus Ts/(Ts+Tm), the methyl adamantane index [MAI = 1-MA/(1-MA+2-MA)], the ratio of short side-chain tri-aromatic steroid hydrocarbons to long side-chain components [$C_{20}/(C_{20}+C_{28})$], and the steroid hydrocarbon aromatization parameter [TAS/(TAS+MAS)] (TAS is the total C_{26}-C_{28} tri-aromatic steroid hydrocarbons and MAS is the total C_{27}-C_{29} mono-aromatic steroid hydrocarbons), all show increases with increasing maturity and the defining compounds are all preserved in most of the oil sands reservoirs and are thus suitable for maturity profiling. There are exceptions when using the [$C_{20}/(C_{20}+C_{28})$] TAS ratio whereby the C_{20} (and C_{21}) TAS may be degraded prior to the side chain

containing compounds (e.g. in severely degraded Grosmont bitumen), although in the Peace River oil sands, this tends not to be the case. Interestingly, even though compositional and physical property gradients are very large in oil sands reservoirs, these molecular ratios are usually highly uniform within a single well profile, indicating the original source characteristics of the oils have been maintained with little, later and more mature oil charge contributing to the fluid composition (Figs. 2 and 3).

Interpretation of all of the molecular ratios obtained from the reservoir, within the context of a dataset from a marine-shale sourced, calibration oil maturity suite, from the North Sea (Bennett et al., 2002), indicates the oil residing in the Peace River and Athabasca Oil Sands and the Grosmont bitumen was likely to have been generated from its source rocks during the early part of the oil window with a source thermal maturity of ca. 0.5 – 0.6 vitrinite reflectance equivalent (%Ro). In addition, where samples have been preserved to enable recovery of diamondoid compounds, they are recorded in low concentrations (C_0-C_3-alkyladamantanes: 150 - 230 μg /g oil) supporting the origin of the petroleum as being from a source at the early oil window level of thermal maturity (Adams et al., 2012). Although the Albertan heavy oils are heavily and severely biodegraded, a major reason for their low API gravity and high viscosity is that they also start life as a polar-compound rich, high sulfur content, low API oil charge likely in the low 20's API range (Adams et al., 2012). The low conversion rates amongst the molecular ratios along with the low concentrations of diamondoids support the contribution of an oil charge expelled from source rocks exposed to the early oil window stage of petroleum generation.

Conclusions

The molecular evidence based upon the biodegradation resistant compounds suggests the Peace River and Athabasca oil sands and Grosmont bitumen is predominantly charged from source rocks exposed to the early oil window stage of petroleum generation. The uniform profiles exhibited by the molecular parameters (and concentration data) based upon the biodegradation resistant compounds suggests the feedstock that filled the reservoirs above and below shale barriers was also genetically related. Subsequently, within their respective compartments, isolated locally by shale barriers, the oils underwent biodegradation according to local conditions that are unique to each reservoir unit.

Acknowledgements

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