

## Tracking Out-of-zone Hydraulic Fracturing in the Bakken with Naturally Occurring Tracers

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### Summary

Precise horizontal drilling and hydraulic fracturing resulted in a spectacular increase in the volume of petroleum produced from the late Devonian/early Mississippian Bakken Formation in the Williston Basin of USA and Canada. Propagation of hydraulic fracturing outside the thin production zone and into the adjacent carbonate aquifers may result in increasing water co-production and reduction in well profitability. This study focuses on the applicability of naturally occurring tracers, such as the stable isotopes of water (i.e.,  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) and the concentrations and/or stable isotope compositions of selected dissolved elements, for identifying the sources of waters/brines co-produced from horizontal Bakken wells subjected to hydraulic fracturing. This study demonstrates that the naturally occurring tracers can be used successfully to identify the presence and/or quantify the fraction of non-Bakken fluid(s) in co-produced water samples.

### Introduction

The Bakken Formation in USA and Canada consists of a thin dolomitic silt/sandstone, a.k.a., the Middle Bakken, sandwiched between two organic-rich marine shales (Halabura et al., 2007). Petroleum was generated in the shales and remains for the most part within the Middle Bakken, which is estimated to contain from 300 to 500 bbl of high quality oil (40 API). The low to very low permeability of the host lithologies (i.e., 1.0 to 0.01 md), however, necessitates the use of hydraulic fracturing, which has transformed the previously uneconomic zone into a vast reservoir containing between 3 and 24 bbl of recoverable oil (Flaherty and Kraus, 2006). Excessive water co-production following high volume multistage hydraulic fracturing of horizontal wells, however, has been of particular concern to the industry. While the mature parts of the Bakken reservoir, located in the central parts of the Williston Basin are water unsaturated, various degrees of water saturation occur near the edges of the basin including most Canadian oil fields. Instances of unexpected production of significant amounts of water following well stimulations, albeit more common in the Canadian oil fields, are also occurring in mature parts of the reservoir raising questions about the origin of the co-produced water. Both the overlying (i.e., the Mississippian Lodgepole) and the underlying (the Devonian Torquay and Nisku/Birdbear) formations are water-saturated. Hence, it has been hypothesized that excessive well stimulation may have resulted in fracture propagation into these formations. While standard formation-water identification techniques have been largely unable to provide unambiguous answers to those questions, naturally occurring tracers have met with greater success.

## Methods

A number of naturally occurring tracers have been used to identify the origin of formation-waters and brines. These include the stable isotopes of oxygen and hydrogen (e.g.,  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ; e.g., Clayton *et al.*, 1966; Hitchon and Friedman, 1969; Connolly *et al.*, 1990) and the concentrations and/or isotope compositions of several major and trace dissolved elements and compounds such as Na, Ca, Sr, Cl,  $\text{SO}_4$ , Br and I (e.g., Carpenter, 1978; Hanor, 1994).

The concentrations of dissolved major elements and compounds are traditionally used to track the origin and nature of co-produced waters. However, due to the non-conservative nature of most dissolved species, i.e., their participation in water/rock interaction, mineral dissolution and precipitation reactions, many formation-waters have non-unique dissolved element compositions. In other words, waters and brines residing in reservoirs of similar mineralogy are often of similar dissolved element composition, and thus difficult to distinguish. Also, the concentrations and ratios of many dissolved elements may be significantly impacted by contamination with drilling and completion fluid additives.

In contrast, the oxygen and hydrogen stable isotope compositions of natural waters are independent of their dissolved solute contents and thus provide important information on the nature and origin of water only. The stable isotope values comprise the ratios of the most abundant (lighter) to the least abundant (heavier) stable isotopes. Stable isotope results are reported in a delta ( $\delta$ ) notation, which comprises the permil ( $\text{‰}$ ) deviation from an internationally accepted standard (Coplen, 1995) and could bear either a positive (i.e., higher than the standard) or a negative (i.e., lower than the standard) sign. In the formula below,  $R_{\text{sample}}$  corresponds to the  $^{18}\text{O}/^{16}\text{O}$  ratio of the sample and  $R_{\text{standard}}$  is the  $^{18}\text{O}/^{16}\text{O}$  ratio of the reference standard (i.e., mean ocean water or SMOW).

$$\delta^{18}\text{O} = \left( \left( \frac{R_{\text{sample}}}{R_{\text{std.}}} \right) - 1 \right) \cdot 1000$$

The value of stable isotope data as tracers is based on the ability of different physical, chemical and/or biological processes to impact the isotope ratios due to the difference in the masses of the molecules composed of different isotope species (e.g.,  $\text{H}_2^{18}\text{O}$  vs.  $\text{H}_2^{16}\text{O}$ ; O'Neil, 1986). The most common processes that control the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  of natural waters are evaporation and water-rock interaction. Both processes are temperature dependent and cause large fractionations (i.e., separations between the stable isotope compositions of the reacting substances), which eventually results in formation-waters from different petroleum reservoirs having distinct stable isotope compositions (cf. Rostron and Holmden, 2000).

The dissolved halogen elements Cl and Br and their stable isotopes  $\delta^{37}\text{Cl}$  and  $\delta^{81}\text{Br}$  provide information on the origin of dissolved solutes in the formation-waters, i.e., whether these originate from relic seawater, dissolution of evaporites or residual evaporitic brine (Hanor, 1994). In contrast to most other dissolved elements, Cl and Br are conservative, i.e., at the temperatures (and pressures) found in hydrocarbon reservoirs these do not participate in water/mineral interaction processes other than the dissolution of evaporate minerals (Carpenter, 1978). Therefore, these are also powerful naturally occurring tracers.

## Results

The results of the analyses of the stable isotope compositions of a subset of co-produced water samples collected from 36 Bakken wells from a major Canadian oil field are presented on Figure 1. Most wells were subjected to hydraulic fracturing. Prior sampling established the stable isotope compositions of the Bakken formation-water in the area as well as the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  compositions of the

formation-waters from the overlying Lower Mississippian Lodgepole zone and the underlying Birdbear/Nisku aquifer (not shown). The  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  compositions of local precipitation used to construct the local meteoric water line are derived from the Global Network of Isotopes in Precipitation database (IAEA/WMO, 2001)

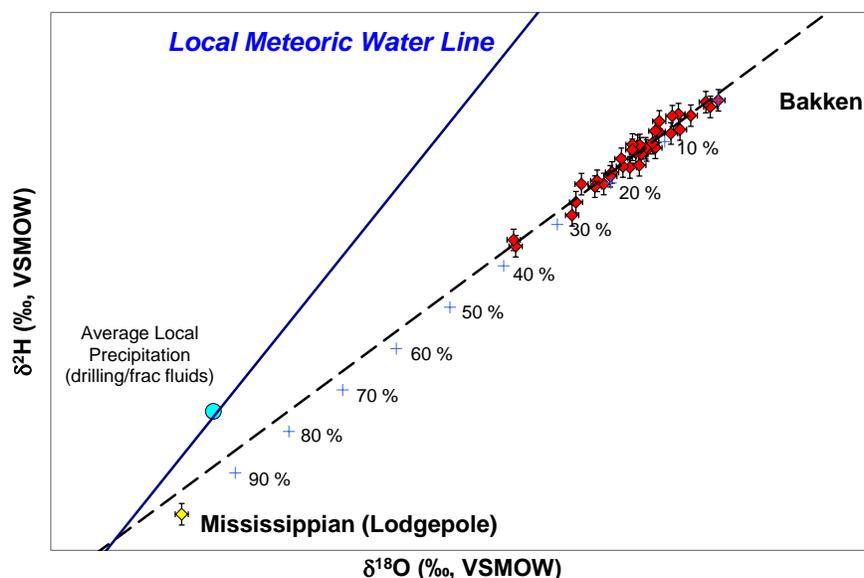


Figure 1. Stable isotope compositions of co-produced water samples collected from 36 Bakken wells. Plotted are also: the composition of local precipitation and the local meteoric water line; the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  of local Bakken and Mississippian Lodgepole formation-water end-members; a theoretical binary mixing line between the two end-members and a regression line defined by the 36 samples.

Results demonstrate that a large number of wells contain water external to the Bakken zone. The regression line defined by the 36 data points closely follows a binary mixing trajectory between the stable isotope compositions of local Bakken and Lodgepole formation-waters, which indicates that external water is predominantly of local Lodgepole origin. A follow up study in the general area involving 587 wells established that 70 % of these contained external water with only 9 % of those samples identified as containing flowback water. The average fraction of Mississippian water was estimated at 34 % with some samples containing as much as 100 % external water. Water from the underlying Birdbear/Nisku zone was detected in samples from six wells only. The presence of Lodgepole formation-water in so many Bakken wells clearly indicates a significant propagation of hydraulic fractures outside the Bakken zone and into the overlying Mississippian aquifer.

## Conclusions

This study demonstrates that naturally occurring tracers such as the stable isotopes of water  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  and selected dissolved species and/or their stable isotope compositions can be used successfully to establish the presence and/or to quantify the fraction of external water in the Middle Bakken reservoir. The stable isotope and dissolved element compositions of the co-produced water samples indicate that hydraulic fracturing propagates predominantly upwards into the overlying water-saturated Mississippian Lodgepole Formation, and it is contributing significantly to excessive water production from stimulated Bakken wells. Modifications to the current hydraulic fracturing practices could,

therefore, result in a reduction of unwanted water co-production and in an improvement of the economics of new Bakken wells.

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