Souring of Kaybob Duvernay Wells: Investigation of Hydraulic Fracture Barrier Effectiveness, Completions Design and Pre-Duvernay Structural Features*

Gareth R. Chalmers

Search and Discovery Article #10864 (2016)**
Posted September 26, 2016

*Adapted from oral presentation given at AAPG Annual Convention & Exhibition, Calgary, Alberta, Canada, June 19-22, 2016
**Datapages © 2016 Serial rights given by author. For all other rights contact author directly.

1Shell Canada, Calgary, Alberta, Canada (garethchalmers@gmail.com)

Abstract

The Devonian Duvernay Formation is an organic-rich mudrock that is a prolific self-sourcing light oil to condensate-rich gas reservoir in the Kaybob region of Central Alberta. Well tests show initial rates up to 3900 boe/d with EUR values less than 1.6 MMBOE. As the Duvernay play appraisal progressed since 2010, more wells are testing or producing sour hydrocarbons (0.5-8000 ppm) from a sweet hydrocarbon play. A need to understand and model the processes that sour Duvernay wells is crucial as souring impacts the economics, health and safety of operations. Both the underlying Beaverhill Lake Group and the Duvernay laterally equivalent Leduc Formation contain conventional oil and gas pools that are sour (< 45%). These sour pools are the most probable source of the H$_2$S seen in ~10% of drilled wells (June, 2015) within the Kaybob Duvernay play. The possible reasons for souring include artificial and natural fracture conduits, proximal Leduc reef facies changes, communication between existing sour Duvernay and Beaverhill Lake wells or in-situ thermal sulfate reduction processes. The most likely cause of this souring is artificial fracturing and the increase in sour wells over time is due to, in part, the increase in hydraulic fracture fluid volumes from 5-10 m$^3$/m to 25-35 m$^3$/m (2012-2015).

Companies have increased in hydraulic fracture volume designs based on observation that the EUR increases with increasing hydraulic fracture fluid volumes (including proppant loading). Cross plotting the hydraulic fracture fluid volume (m$^3$/m) and the basal fracture barrier thickness indicates that as the basal fracture barrier thins (< 18 m) the barrier becomes less effective and the risk of souring increases. The basal fracture barrier consists of the Duvernay middle carbonate, Majeau Lake and Waterways...
formations. Increasing the hydraulic fracture fluid volume (i.e. from 15m$^3$/m to 30m$^3$/m) will reduce the effectiveness of the basal fracture barrier and also increase the risk of souring Duvernay wells in areas where the fracture barrier is greater than 18 m thick. Sour risking map has been created for the Kaybob Duvernay play based the basal fracture barrier thickness and mapping of Beaverhill Lake pools and Leduc reefs.
References Cited


SOURING OF KAYBOB DUVERNAY WELLS: INVESTIGATION OF FRAC BARRIER EFFECTIVENESS, COMPLETIONS DESIGN AND PRE-DUVERNAY STRUCTURAL FEATURES

Gareth Chalmers
Shell Canada

Modified from Oldale and Munday 1994 (WCSB Atlas)
DEFINITIONS AND CAUTIONARY NOTE

The New Lens Scenarios referred to in this presentation are part of an ongoing process used in Shell for 40 years to challenge executives’ perspectives on the future business environment. We base them on plausible assumptions and quantification, and they are designed to stretch management to consider even events that may be only remotely possible. Scenarios, therefore, are not intended to be predictions of likely future events or outcomes and investors should not rely on them when making an investment decision with regard to Royal Dutch Shell plc securities.

Reserves: Our use of the term “reserves” in this presentation means SEC proved oil and gas reserves.

Resources: Our use of the term “resources” in this presentation includes quantities of oil and gas not yet classified as SEC proved oil and gas reserves. Resources are consistent with the Society of Petroleum Engineers 2P and 2C definitions.

Organic: Our use of the term Organic includes SEC proved oil and gas reserves excluding changes resulting from acquisitions, divestments and year-average pricing impact.

Resources plays: our use of the term ‘resources plays’ refers to tight, shale and coal bed methane oil and gas acreage.

The companies in which Royal Dutch Shell plc directly and indirectly owns investments are separate entities. In this presentation “Shell”, “Shell group” and “Royal Dutch Shell” are sometimes used for convenience where references are made to Royal Dutch Shell plc and its subsidiaries in general. Likewise, the words “we”, “us” and “our” are also used to refer to subsidiaries in general or to those who work for them. These expressions are also used where no useful purpose is served by identifying the particular company or company. “Subsidiaries”, “Shell subsidiaries” and “Shell companies” as used in this presentation refer to companies over which Royal Dutch Shell plc either directly or indirectly has control. Companies over which Shell has joint control are generally referred to as “joint ventures” and companies over which Shell has significant influence but neither control nor joint control are referred to as “associates”. In this presentation, joint ventures and associates may also be referred to as “equity-accounted investments”. The term “Shell interest” is used for convenience to indicate the direct and/or indirect ownership interest held by Shell in a venture, partnership or company, after exclusion of all third-party interest.

This presentation contains forward-looking statements concerning the financial condition, results of operations and businesses of Royal Dutch Shell. All statements other than statements of historical fact are, or may be deemed to be, forward-looking statements. Forward-looking statements are statements of future expectations that are based on management’s current expectations and assumptions and involve known and unknown risks and uncertainties that could cause actual results, performance or events to differ materially from those expressed or implied in these statements. Forward-looking statements include, among other things, statements concerning the potential exposure of Royal Dutch Shell to market risks and statements expressing management’s expectations, beliefs, estimates, forecasts, projections and assumptions. These forward-looking statements are identified by their use of terms and phrases such as “anticipate”, “believe”, “could”, “estimate”, “expect”, “goals”, “intend”, “may”, “objectives”, “outlook”, “plan”, “probably”, “project”, “risks”, “schedule”, “seek”, “should”, “target”, “will” and similar terms and phrases. There are a number of factors that could affect the future operations of Royal Dutch Shell and could cause those results to differ materially from those expressed in the forward-looking statements included in this presentation, including (without limitation): (a) price fluctuations in crude oil and natural gas; (b) changes in demand for Shell’s products; (c) currency fluctuations; (d) drilling and production results; (e) reserves estimates; (f) loss of market share and industry competition; (g) environmental and physical risks; (h) risks associated with the identification of suitable potential acquisition properties and targets, and successful negotiation and completion of such transactions; (i) the risk of doing business in developing countries and countries subject to international sanctions; (j) legislative, fiscal and regulatory developments including regulatory measures addressing climate change; (k) economic and financial market conditions in various countries and regions; (l) political risks, including the risks of expropriation and renegotiation of the terms of contracts with governmental entities, delays or advancements in the approval of projects and delays in the reimbursement for shared costs; and (m) changes in trading conditions. All forward-looking statements contained in this presentation are expressly qualified in their entirety by the cautionary statements contained or referred to in this section. Readers should not place undue reliance on forward-looking statements. Additional risk factors that may affect future results are contained in Royal Dutch Shell’s 20-F for the year ended December 31, 2014 (available at www.shell.com/investor and www.sec.gov). These risk factors also expressly qualify all forward looking statements contained in this presentation and should be considered by the reader. Each forward-looking statement speaks only as of the date of this presentation, 22nd June, 2016. Neither Royal Dutch Shell plc nor any of its subsidiaries undertake any obligation to publicly update or revise any forward-looking statement as a result of new information, future events or other information. In light of these risks, results could differ materially from those stated, implied or inferred from the forward-looking statements contained in this presentation.

We may have used certain terms, such as resources, in this presentation that United States Securities and Exchange Commission (SEC) strictly prohibits us from including in our filings with the SEC. U.S. Investors are urged to consider closely the disclosure in our Form 20-F, File No 1-32575, available on the SEC website www.sec.gov.
## HSE RISKS – H2S EXPOSURE

<table>
<thead>
<tr>
<th>Exposure Conc. (ppm)</th>
<th>Possible Health Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1</td>
<td>Smell it</td>
</tr>
<tr>
<td>&lt; 10</td>
<td>No known adverse effects; need respiratory protection</td>
</tr>
<tr>
<td>20-50</td>
<td>Eye, nose, throat, lung irritation</td>
</tr>
<tr>
<td>100-150</td>
<td>Severe respiratory irritation, loss of smell sense, &gt; 8hrs can be fatal</td>
</tr>
<tr>
<td>200-300</td>
<td>Headaches, drowsiness, several hrs lungs fill with fluid</td>
</tr>
<tr>
<td>300-500</td>
<td>1 to 4 hrs = unconsciousness and death</td>
</tr>
<tr>
<td>500-700</td>
<td>1 hr knockdown and possibly fatal</td>
</tr>
<tr>
<td>&gt; 700</td>
<td>Immediate knockdown – may be fatal</td>
</tr>
</tbody>
</table>

*From Enform H2S Alive, hydrogen sulphide training*
DVRN Shale is sweet reservoir
Several wells soured in 2012 (ppm)
< 10% wells soured in 2014
TYPE LOG – DVRN WELL IN KAYBOB

DVRN Reservoir
DVRN Carbonate
Majeau Lake Fm
Beaverhill Lake Grp
DEVONIAN BEAVERHILL LAKE GROUP - PALAEOENVIRONMENTS

- Modified from Oldale and Munday 1994 (WCSB Atlas)

TRANSGRESSIVE SEQUENCE ISOPACH

Swan Hills Deposition

Waterways Deposition

REGRESSIVE SEQUENCE ISOPACH

Field Area

Swan Hills Mbr:
- SHM Carbonate Reefs & Banks
- Porosity development on windward side

Waterways Fm:
- Argillaceous carbonates and shales - contrasting rock strength and stresses
- Primary and secondary porosity development with the SHM platform and reefs trapped sour HCs during migration updip
- Overlain by basin-slope shales/argillaceous carbonates seal
- Leduc and Swan Hills Reefs are sour
- Can be 5-30% H2S in reservoir (Krouse et al., 1988)
H2S SOURCES IN BHL AND LEDUC CARBONATES

- H2S in WCSB carbonate reservoirs
- From either bacterial sulphate reduction (BSR) or thermochemical sulphate reduction (TSR)
- Organic matter or light hydrocarbons are the catalyst
- Abiogenic (TSR; > 90 °C) and biogenic reactions (< 90 °C)
- Sulphur isotopes - biogenic reaction fewer positive values
  - TSR more positive and similar to evaporite values (sulphate sourced from anhydrite)
  - Sulphur isotope samples from Leduc is +13.4 to +21.3 ‰ (Krouse)
  - Kaybob samples show a range between +20.3 to +22.8 ‰
NORTH-SOUTH X-SECTION, KAYBOB

Datum: Top of Ireton Fm

Duvernay Carbonate

Waterways Fm

Ireton Fm

Duvernay Fm

Swan Hills Mbr

Lower Sour Risk

Mod to High Sour Risk

High Sour Risk
DUVERNAY MIDDLE CARBONATE

Perdrix (Duvernay) Outcrop, Roche Miette

Middle Duvernay Carbonate:
Alternating carbonate and shale package
Geomechanical stratigraphy in DVRN

- Lithological changes related to depositional/accommodation changes
  - DVRN Carbonate
  - Waterways Fm (BHL Gp)

- Increasing heterogeneity will increase contrasting rock strengths and internal rock stresses
  - Reduce fracture effectiveness

- Ineffective fracs still grow into underlying strata – low proppant placement, increased tortuosity = poor communication
Presenter’s notes: Combination of frac intensity (frac fluid per metre, as well as proppant tonnage per metre) and the basal frac barrier thickness (DVRN Carbonate + Majaeu Lake + Waterways) will influence whether a DVRN well will sour or not. Porosity needs to develop within the Swan Hills member (reef or platform) in order for DVRN well to sour. When the barrier is thin, like adjacent to the Leduc Reef, no frac design mitigation will stop the well from souring (i.e., both low and high intensity fracs will sour the well).
Presenter’s notes: SHM and Leduc carbonates are critically sour (1-30%) while DVRN sour wells are in the ppm range indicating the fracs that are communicating are ineffective tortuous fracs. Initially sour wells were seen only within the high risk area surrounding the Leduc reefs but this risk expanded to include wells souring further away from the Leduc Reefs and a new model developed that included the thickness of Waterways Formation and sour wells developed where high intensity fracs were placed in wells over thin Waterways Fm and porosity developed within the Swan Hills Mbr below.
Presenter’s notes: Water chemistry shows that with DVRN well that have a higher water recovery during production (1 year) heavier the oxygen isotope from the water is, with respect to the sourced frac water, these wells are still sweet wells but show that even these wells are penetrating into the Waterways and sourcing water from the water-bearing carbonates in the Waterways Formation.
CARBON ISOTOPIC COMPOSITION OF PRODUCING FLUIDS

Carbon Isotope Ratio vs VRE

$R^2 = 0.83$

Isotopically heavier

More mature

13-Carbon Isotope Composition of Producing Ethane ($\%$)

Well within 2 km of Leduc Reef
CONCLUSIONS

- DVRN reservoir is considered a baffle that creates ineffective fracs (high tortuosity) with some growing into underlying strata
- This is highlighted by H2S, carbon and oxygen isotopic compositions of flowback water
- H2S concentration is in ppm from producing DVRN wells which are sourced from critically sour BHL (30%) - indicating fracs are inefficient
- Risk of souring increases with thinning of Waterways Fm and/or an increase in frac intensity (increase fluid and proppant volumes/metre)
- Mapping the BHL group should be used in conjunction with the frac design as part of the risk management when developing the DVRN play