Decoupling reservoir and completion effects in multi-stage fractured horizontal wells

How to tell if you have an optimal fracturing strategy

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Why do we care?

• Multi-stage horizontal well fracturing is the biggest thing in the oil/gas industry today
  – It is an expensive process
  – Stage sizes are getting bigger
  – Costs are a significant portion of total well cost
WCSB trends for all multi stage horizontal wells

All data – oil + gas wells

<table>
<thead>
<tr>
<th>Completion Date Year</th>
<th>Well Count (in Brackets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 (15)</td>
<td></td>
</tr>
<tr>
<td>2006 (109)</td>
<td></td>
</tr>
<tr>
<td>2007 (132)</td>
<td></td>
</tr>
<tr>
<td>2008 (700)</td>
<td></td>
</tr>
<tr>
<td>2009 (931)</td>
<td></td>
</tr>
<tr>
<td>2010 (2024)</td>
<td></td>
</tr>
<tr>
<td>2011 (1205)</td>
<td></td>
</tr>
</tbody>
</table>
WCSB trends for all horizontal wells
All data – oil + gas wells
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WCSB trends for all horizontal wells
All data – oil + gas wells
Cardium Oil Wells Only

- 820 wells in entire database
  - as of January 18 2012
- Review data from 2008 onwards
Cardium Oil Wells Only

Well Count in Brackets

Completion Date Year

<table>
<thead>
<tr>
<th>Year</th>
<th>Stages Actual (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>6</td>
</tr>
<tr>
<td>2009</td>
<td>51</td>
</tr>
<tr>
<td>2010</td>
<td>390</td>
</tr>
<tr>
<td>2011</td>
<td>353</td>
</tr>
</tbody>
</table>
Cardium Oil Wells Only

Avg. Completed Horizontal Well Length (m)

<table>
<thead>
<tr>
<th>Completion Date Year</th>
<th>Avg. Completed Horizontal Well Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 (1)</td>
<td>600</td>
</tr>
<tr>
<td>2009 (37)</td>
<td>800</td>
</tr>
<tr>
<td>2010 (166)</td>
<td>1,000</td>
</tr>
<tr>
<td>2011 (53)</td>
<td>1,200</td>
</tr>
</tbody>
</table>

Well Count in Brackets
Cardium Oil Wells Only
Cardium Oil Wells Only

![Graph showing average proppant per stage over years (2008-2011)]

Well Count in Brackets
Are we getting a Satisfactory ROI?

• How do we make decisions about
  – Length of horizontal well
  – Number of stages
  – Amount of proppant in each stage
  – Treatment ‘system’
    • Open hole ‘ball and seat’
    • Cased hole
Possible Answers

1. What the experts/salesmen recommend
2. Faith
   - George Mitchell started the ‘revolution’ in the Barnett
3. What the guy beside me is doing
4. Reservoir simulation modeling
   - A sure sign of desperation ?!
5. Empirical + anecdotal evidence
   - Predominant strategy but requires a lot of experience
6. Statistical analysis of historical production response
Cardium Oil Wells Only

Do you believe?
Not so clear there is a trend
Production Response of Wells

- Early time dominated by permeability ($k$) and skin effects ($S$)
  - Can split them apart
  - Skin is the completion (fracture treatments)
- Late time dominated by well drainage area and productivity index
  - Productivity index lumps $k$ and $S$ into single term
  - Not possible to split apart
Early Time Flow Regimes

• Dominated by Linear Flow
• Extensively studied by Bob Wattenbarger at Texas A & M
  – Breakthrough in analysis procedure in late 1990’s
Linear Flow

1. Identified by modified Fetkovich plot
2. Use Neal-Wattenbarger plot to calculate properties at times when linear flow has been identified
1. Fetkovich Plot

Gas Rate Versus Time

Function
\[ Q_g = 2000 \ t^{-1/2} \]

Slope = \(-1/2\)
During Linear Flow

\[ Q \propto LFP^*(P_i - BHP)/t^{0.5} + \text{Skin Term} \]
Slope of line \( \propto 1/LFP \)

\[ LFP = 2*k^{0.5}\text{Length}*h \]

LFP is short for the Linear Flow Parameter

\[ S \propto Y \text{ Intercept} \]

2. Neal-Wattenbarger Plot

- Skin=0
- Skin=10
- Skin=100

From SPE 143229
Missed opportunity is the area between the two curves $S_{Ac} = 100$ and $S_{Ac} = 0$ (Ideal Case). Which is the cumulative lost production. Increases for all time.

\[ \frac{(P_i - BHP)}{q} \]

2. Neal-Wattenbarger Plot

From SPE 143229
What about a variable skin case?
Happens when well is cleaning up.

Missed opportunity is the area between the blue curve and the $S_{Ac} = 0$ line.
Assuming full cleanup.
Fixed amount of volume lost.

From SPE 143229
Linear Flow Parameter (LFP) Discussion

$LFP = 2 * k^{0.5} * Length * h$

- Assume from production analysis one can determine the LFP
  - Made up of 3 parameters
    1. Zone thickness, $h$ (easiest to determine)
      - Geology or logs
      - Easier for thin reservoirs such as Cardium oil wells versus thick Montney gas wells
    2. Length (Two Choices)
    3. Permeability, $k$
      - Calculated based on choices made in 1. + 2.
      - Do we believe the permeability we are getting?
Length Choices

1. Early Time Linear Flow
2. Late Time Linear Flow
Well is black line
Fractures are solid gray lines
No flow boundaries are dashed gray lines
Flow can only occur into the well through the fractures

1. Length = Sum of all fracture lengths which normally can be estimated

Early time linear flow into the central fracture
Is Early Time Linear Flow Possible?

• Time to bounded flow equations can be used to calculate the end of the flow regime between fractures

\[ y = 0.1591 \sqrt{\frac{kt}{(\phi \mu c_t)_i}} \]

• Even for micro-darcy gas reservoirs the time for fracture interference < 60 days
  – Significant early time linear flow is uncommon
Well is black line
Fractures are solid gray lines
No flow boundaries are dashed gray lines
Flow can only occur into the well through the fractures

2. Length = Distance between toe and heel fracture treatment

**Consequences**
1. Flow convergence will cause a skin effect
2. Closer the fracture spacing the less the skin effect
3. Using production analysis, does the skin effect decrease with more stages?
Illustration of Vertical Flow Convergence Inside Fracture Plane
Well goes into Page (plot on right only)

Normal Linear Flow

Flow Convergence at Well Causing a Vertical Skin Effect

Important in thick reservoirs (Montney)
Not important in thin reservoirs (Cardium)

From SPE 143229

For skin formula see SPE 126754 (or ‘References’ at end of presentation)
Example #1

• Upper Montney Gas Wells (SPE 149331)
  – Wells Ground Birch Upper + Lower, called GBU + GBL, are stacked above one another
• Full Upper Montney Height 175 meters
• GBU
  – has 28.5 m lobe (sub-zone) thickness
  – assumed to be fracture height
  – 6 perf clusters
  – 17 sets of perforations
  – 100 meter perforating spacing
  – 67 tonnes per perforated interval
5 flow periods defined corresponding to shut-in times
Note transient spikes even after small shut-ins
1. Indicator of good stimulation
2. Have a number of ‘free’ build-ups
3. Question: Does the performance of the well change with time. Can be resolved by comparing successive flow periods.
GroundBirch
Production Comparisons
QGC/Dm versus tmbg1

Flow regime identification plot

½ Slope = Thin Blue Line
indicates late time linear flow
Analysis of GBU only

Superposition calculations unaffected by flow period splits in any plots. It is strictly a plotting device.

½ Slope = Blue Line
Traditional square root plot has problems when shut-ins occur, causing difficulties in determining the y-intercept, even for high quality datasets such as this one.
Replace $t^{0.5}$ with superposition linear time
Plot introduced by Wattenbarger’s group in the 1990’s
Issues: Never sure which points are actually sequential in time.
Use all data for this plot (no filtering).
There is a danger of a false signal.
Superposition emphasizes flow regime one is looking for.
Modeling necessary to double check any interpretation.

\[ t_{ls} = \sum_{j=1}^{n} \frac{q_j - q_{j-1}}{q_n} \sqrt{t - t_{j-1}}, q_n > 0 \]
Analysis Line = Thin Blue Line
Definitely in linear flow in FP_4 (previous Fetkovich plot) so analysis is possible.
Plot suggests Linear Flow may extend into FP_2. This may be false interpretation as Fetkovich plot does not seem to supported this.
Final check is to run models.
Y intercept indicates skin effects.
History match plot with the one dimensional model of Bello + Wattenbarger
SPE 143229
History match plot with the one dimensional model of Bello + Wattenbarger
SPE 143229
Maximum Potential for well: Remove all the skin effects without changing the LFP term. Result is the black line.

Why not negative skin? Theoretically possible but not seen in practice.
Transient Performance Ratio (TPR) at T=393 days
Ratio of actual to ideal production
Actual Cum Gas = 33.5
Ideal Cum Gas = 41.5
Incremental = 8.0 x 10^6 m³
TPR = 33.5/41.5 = 0.81 or 81%
Vertical Skin Effects

• Calculations given on previous slide will overestimate ‘perfect’ stimulation case as vertical skin component still exists because the interval is thick.

• One can estimate vertical skin by various means and adjust the Y intercept to account for this.
  – See reference section at end of presentation for details.
Example #1 – Conclusions

• Skin effects are apparent
  – Some of these are probably vertical skin effects
• The maximum potential of the well when all skin effects have been removed has been quantified
  – Incremental production over the actual case at a set point in time can be calculated
• Rational decisions based on realistic upside can be made
  – Do we want to change the treatment design?
Example #2 – Cardium Oil Well

- Drilled, completed + fractured in 2010
- Daily production data
- Wells are produced with pump jacks
  - no BHP or fluid levels known
- Net Pay \( \approx 9 \) meters
TS = 0 means
Time Start (for the flow period) = 0 days
Well in transient flow for full time interval (315 days)

$\frac{1}{2}$ Slope = Blue Line

This plot does require data filtering to ensure we do not get ‘false’ bounded flow artifacts, see ‘Filtering’ at end of presentation.
Well in transient flow for full time interval (315 days)

½ Slope = Blue Line

Cardium
Production Comparisons
QOC versus tmbo1

Calendar Day Oil Rate (m3/d)

First Order Oil Material Balance Time (days)
Looks like positive y intercept but how do you draw a line?
Looks like positive y but are we sure?
TS = 0 means
Time Start (for the flow period) = 0 days

Subsequent flow periods move to right
Line through Flow Period beginning at TS=91
Very nearly through origin
Line through Flow Period beginning at TS=157
Very nearly through origin
Interpretation
Well cleaning up for first 91 days, then producing undamaged. Frac design is OK. Maybe too many stages

Question: How can you have clean-up on a gelled oil treatment?

Line through Flow Period beginning at TS=157 Very nearly through origin
Example #2 – Conclusions

• Fracture treatment shows initial damage
• Damage is gone after 91 days.
  – Interpreted to be clean-up type damage removal as opposed to fracture convergence effects, which would be permanent
Example #3 - Cardium Oil Group

- 9 wells: Drilled and completed in 2010
- Previous Cardium Well 19 in group
- Cased Hole
- Pay Thickness: 6 – 13 m
- Well Length: 900 – 1330 m
- Stages per well: 13 – 18
- Distance between stages: 75 m
- Proppant per stage: 18 – 25 tonnes
- Fracture Fluid: Gelled Oil
How do you explain the impact of fracturing on the production behavior?
Most wells have linear flow followed by bounded flow.
Initial Line for Cardium Well 19

Low LFP or Low Permeability

High LFP or High Permeability

Cardium Production Comparisons
1/QOC versus SupertLo

- Cardium Well 19
- Cardium Well 12
- Cardium Well 9
- Cardium Well 10
- Cardium Well 14
- Cardium Well 15
- Cardium Well 18
- Cardium Well 7
- Cardium Well 17
Low LFP wells

Lowest LFP well #19 has been shown to clean-up after 90 days. There are clean-up issues with tighter wells, but not significantly so.

Cardium Production Comparisons
1/QOC versus SuperLo

Initial Line for Cardium Well 19
Cardium
Production Comparisons
1/QOC versus SuperTLo

High LFP wells
Cardium
Production Comparisons
1/QOC versus SupertLo

High LFP wells

- Cardium Well 7
- Cardium Well 9
- Cardium Well 14
- Cardium Well 15
High LFP wells have very little skin.
Successful stimulation program
Do we need longer wells (to increase LFP): No
Are we over fracturing ???
We have gone from this ????
To full understanding
Example #3 – Conclusions

• Fracture treatment results are optimal showing no permanent skin damage.
  – Low permeability wells show clean-up effects
  – High permeability wells show no clean-up effects with close to zero skin
• Maybe fewer stages would accomplish the same thing
Example #4
Garrington – Cardium Wells

- Ball & Seat Treatments Only
  - Open hole completion
- Monthly production data
- Database to get treatment details
- Compare 2009 to 2010 treatments
  - Not enough data to compare earlier dates
Example Well 1
Well 05-33 Monthly Data

Cardium Garrington
Production Comparisons
QOC and Time versus tmbo1

Linear flow identified
Can use Neal-Wattenbarger plot

½ Slope = Blue Line
Example Well 1
Well 05-33 Monthly Data

Cardium Garrington
Production Comparisons
1/QOC and Time versus SuperpLo
Example Well 2
Well 06-02 Monthly Data

Cardium Garrington
Production Comparisons
QOC and Time versus tmbo1

½ Slope = Blue Line

Linear flow identified
Can use Neal-Wattenbarger plot
Example Well 2
Well 06-02 Monthly Data

Cardium Garrington
Production Comparisons
1/QOC and Time versus SuperpLo

Graph showing 1/Calendar Day Oil Rate (dt/m2) vs. Time (Days) with data points and a trend line.
Example Well 3
Well 14-30 Monthly Data

Cardium Garrington
Production Comparisons
QOC and Time versus tmbo1

\( \frac{1}{2} \) Slope = Blue Line

Linear flow identified
Can use Neal-Wattenbarger plot
Linear flow only clearly identified between 240 – 270 days from previous slide.
## Cardium Garrington Results

<table>
<thead>
<tr>
<th>Property</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Count</td>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td># Actual Stages</td>
<td>8.75</td>
<td>10.89</td>
</tr>
<tr>
<td>Average Well Length (m)</td>
<td>1060</td>
<td>1071</td>
</tr>
<tr>
<td>Average Frac Spacing (m)</td>
<td>122</td>
<td>114</td>
</tr>
<tr>
<td>Average Prop/Stage (tonnes)</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Late Time Fully Cleaned Up (% of wells)</td>
<td>75</td>
<td>58</td>
</tr>
<tr>
<td>TPR (% at 365 days)</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>365 Day Average Transient Cum Oil (m3)*</td>
<td>3602</td>
<td>3570</td>
</tr>
<tr>
<td>365 Day Average Opportunity Oil (m3)**</td>
<td>357</td>
<td>307</td>
</tr>
</tbody>
</table>
* What is Transient Cumulative?

- Wells go into bounded flow at different times
  - Might even be in time frames less than what we want to compare production profiles to
- The proposed technique focuses on transient flow. Once the properties (LFP and skin) are determined we use these properties to compute transient production profiles (think infinite acting reservoir) for all cases and then compare.
  - See SPE 15432 for formulae
** What is Opportunity Oil? 

• For a specified point in time, this is the difference between the transient cumulative oil production as determined from analysis and the ideal case with $S = 0$ at all times
Example #4 - Conclusions

- Monthly data is OK if data sets clean
  - Daily data is really needed to reconcile complex behavior and is certainly more robust
- 122 m (2009 value) between stages seems like a good value
  - Might even be able to have a greater distance between stages
  - No data for lower number of stages, so unable to investigate how efficient they might be
- No evidence that more fracture treatment stages from the 2009 to 2010 program was better
  - Would eliminate 3 stages
Overall Conclusions

1. Superposition linear time is a powerful diagnostic tool
2. Necessary to split production data into flow periods to gain additional insight
3. A methodology (still evolving) has been presented to systematical appraise fracture treatments
   - Works best for tight gas/oil plays
   - For shale plays where an SRV is created by the treatments other factors also become important
4. More analysis is required on the smaller number of stages cases
Acknowledgements

  – Principal, Introspec Energy Group Inc.

• Kaush Rakhit, M.Sc., P.Geol.
  – President, Canadian Discovery Ltd.

• Neil Watson, P.Geol.
  – Consulting Services Director, Canadian Discovery Ltd.
Filtering of Modified Fetkovitch Plot

- ‘First Order Material Balance Time’ = Cum/Rate term (X Axis) needs filtering otherwise false unit slopes generated when significant rate variation occurs.
- Take weighted average of user specified number of points near point of interest.
- If the point of interest is within a certain fraction of the weighted average accept the point of interest value, otherwise reject.
- Consequences of filtering:
  - All high rate change events including transient spikes are eliminated.
  - Proper flow regime identification is possible.
Filtering of Neal-Wattenbarger Plot

- Use all points
  - no filtering
- Accentuates linear flow
  - This is what we want
  - May fool ourselves
    - Must perform forward modeling (analytical or numerical modeling) to make sure we choose correct line
  - Plot is poor at picking alternative flow regimes or transitions into other flow regimes
    - Flow regimes identified by the ‘Modified Fetkovich’ plot
    - Need to use both plots together for a proper interpretation
References

Formula for Vertical Skin

• SPE 126754, Bello + Wattenbarger - Equation 3

\[ s_c = \frac{k_f x_e [m(p_i) - m(p_{wf})]}{1422 q_g T} = -\ln \left[ \frac{\frac{\pi r_w}{h} \left( 1 + \sqrt{\frac{k_v}{k_H}} \right) \sin \left( \frac{\pi d_z}{h} \right)}{h} \right] \]

• M.J. Economides gives an alternative formula for this skin in various papers + books including SPE 98047

\[ s_c = \frac{kh}{k_f w} \left[ \ln \left( \frac{h}{2r_w} \right) - \frac{\pi}{2} \right]. \]
References

Incorporating Skin into Y Intercept Term

• SPE 15432, Neal and Mian
  – Equations 1 through 13