"Shale Engineering"

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Gaffney, Cline & Associates
Agenda

• Objectives
• Economic importance (Global and Local)
• The problem and approaches
• Shale engineering concepts
• Models description
  – Model A Near Wellbore (One frac stage)
  – Model B Frac Stages (well construction model)
• Comparison with historical performance
• Well spacing – field development concepts
• Conclusions
Objectives

• Provide a methodology to describe the formation and the reservoir created by the well construction (SRV)

• Predict production, but also a

• Practical platform for field development design and optimization

• Contrary to the traditional exploration shale reservoirs are there, we know that and do not require the discovery but the conceptual proof
### Why Is This Important?

More than 300 bn US$ in transactions since 2008

### North American Shale Gas Plays

- **Horn River:** 500 Tcf
- **Montney:** 500 Tcf
- **West Coast:** 41 Tcf
- **Rocky Mountain:** 58 Tcf
- **Southwest:** 87 Tcf
- **Gulf Coast:** 105 Tcf
- **Northeast:** 473 Tcf
- **Midcontinent:** 63 Tcf
- **All Other Canadian Shale:** 611 Tcf

*Note: The Canadian Society for Unconventional Gas categorizes the Montney play as tight sands rather than shale gas.

### Table: Acquisitions and Merger Transactions

<table>
<thead>
<tr>
<th>Date</th>
<th>Acquirer</th>
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Canadian Shale Resource Estimates: Canadian Society for Unconventional Gas, 2011
Table 1-2. Risked Gas In-Place and Technically Recoverable Shale Gas Resources: Six Continents

<table>
<thead>
<tr>
<th>Continent</th>
<th>Risked Gas In-Place (Tcf)</th>
<th>Risked Technically Recoverable (Tcf)</th>
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<td>North America</td>
<td>3.858</td>
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<td>South America</td>
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<td>Total</td>
<td>22.016</td>
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</table>

A more detailed tabulation of shale gas resources (risked gas in-place and risked...
The Problem

- Shale reservoir performance prediction is more complex than more traditional formations
- Does a good fit imply a meaningful extrapolation?
- Type curves are widely used and, potentially, abused
- What other options are there?

Figure 12. Normalized Haynesville Shale production rate decline based on differing hyperbolic exponents.
Common Approach: Analogy and Statistics

- Does not involve natural constraints
- Difficult to explain well design effects
- Optimization is based on “trial and error”
- Large investments for “know-how”
- Geo-mechanical effects are ignored
- Long term predictions are questionable

Not all shale formations are the same!

Assimilation of historical data and building of “type curves” has drawbacks:

- Type Well
  - Most critical assumption is often over-simplified

Source - © 2010 Responsible Drilling Alliance
“Shale Engineering”
Advanced Reservoir Engineering for Shales

- In-Place Description
- Statistical Analysis and “Type Wells”
- Performance

**Shale Engineering Modeling**

- Based on geo-mechanics
- Implements physical shale properties
- Describes properties of the induced reservoir after stimulation
- Matches observed performance
- Interprets and implements micro-seismic
- Optimizes well design and field development
- Provides early predictions of long term production behavior
Performance prediction challenges

• Formation description requires special attention
  – Regional and local trends need to be addressed
  – Ro, rock mechanics, stresses, TOC, are important to know
  – Matrix properties are difficult to measure in logs and even in cores
  – Natural fractures are difficult to quantify

• Conventional reservoir engineering tools may not apply
  – Relation to in-place volumes is questionable
  – Material balance approach does not apply
  – Flow is not directly related to pressure difference
  – The effect of natural fractures is often misunderstood
  – DCA is impractical and uncertain

Massive hydraulic stimulation creates an artificial reservoir; the bounds and quality need to be understood
Shale Model Description

NATURAL

- Natural fractures
- Dual Permeability
- Fracture
- Anisotropy

INDUCED MAJOR

- Proppant placement

NATURAL

- Matrix

INDUCED MINOR

- Non-Darcy flow
- Gas Desorption

Stimulated Rock Volume (SRV)
Stimulation Sequence

1. **DRILLING**
2. **HYDRAULIC PRESSURE**
   - $\sigma_{\text{max}}$
   - $\sigma_{\text{H}}$

**Shear Induced Fractures**

**Pressure** = $\sigma_{\text{Hmin}}$

**Proppant Placement**

**Production**

**Stimulated Reservoir Volume (SRV)**
From **Natural** Shale to the **Artificial** Reservoir

**Benefits**

- Enhancing reservoir understanding
- Exploiting modern technology
Modeling Approach – Build Two Models

A. Fracture propagation model
   - Fine grid (models minutes)
   - Stimulation and backflow timeframe
   - Matches frac and microseismic surveillance
   - Outputs stimulated rock volume (SRV) permeability
   - Models fracture propagation

B. Full well model
   - Coarse grid (models decades)
   - Uses SRV attributes from model A
   - Adjusts frac stage contribution to PLT measurements
   - Adjusted to historical production rates and pressures
   - Provides long term production forecast

• Model Attributes
  - Flow tied to geomechanics through dilation-compaction tables
  - Compositional formulation
  - Gas desorption
  - Non-Darcy matrix flow
Model Objectives

- SRV description related to hydrofrac (model A)
- Long term well performance (model B)
Stimulated Reservoir Volume (SRV)

Model A Gridding

Wellbore node

Proppant nodes

$\sigma_{\text{max}}$

$\sigma_H$

$\sigma_H$

$\sigma_H$

$\sigma_H$

$\sigma_H$
• Challenging well: *foam frac, tight sand/shale/partially depleted*
  – Used detailed rock and performance description
  – Matched stage development with surface measurements
  – Matched post-frac production rates
• Micro-seismic events do not relate to production response
• Do all micro-seismic events relate to fluid presence?
• Production seems dependent on natural fractures
Comparing Projections with Actual Results

Stage 7

Difference in pre-existing natural fractures

Stage 3
Model B - Shale Engineering Predictive Model

Matched production history and production logging

✓ Frac stage contribution match
✓ Proppant placement match
✓ Well History match

Fracture Conductivity (Closure)

Pressure drop, psi

Narrow Uncertainty
Comparison with Historical Performance

Tuned for:

– Grid scaling
– Geomechanical effects
– Matrix parameters
– Initial pressure
– Proppant properties
– Gas desorption
– Water saturation

About 63 runs
Initial trends can be influenced by:

– Fluid unloading
– Surface pressure restrictions
– Interaction with other wells or formations through natural fractures
Spacing Determination

- Biggest game changer, reducing spacing by 25%
- Reducing spacing by 30% does not add significant value

Composite performance from a multi-square-mile development module
Multi-Point Validation

• Production history
  – Pressures and rates
  – Fluids

• Stage contribution
  – Production logging
  – Flow back data

• Stimulated rock volume
  – Hydrofrac plots
  – Microseismic shape
Conclusions

• “Shale Engineering” provides a new look at shale performance
  – Includes rock mechanics
  – Models mass transfer through diffusion
  – Describes the induced reservoir

• Transverse fracture stages do not perform similarly
  – Despite using similar design along a relative uniform formation
  – Subtle differences in natural fractures and stress conditions may trigger differences in the induced reservoir (SRV)

• Micro-seismic events may reflect rock-to-rock interaction
  – Overstate spacing assumptions
  – Un-interpreted micro-seismic plots do not relate to the induced reservoir (SRV)
• The hysteretic permeability models that are employed in numerical modeling can offer a description of the SRV and can be also used in addressing longer term geomechanical effects in a practical manner.

• The application of this methodology in a challenging shale play shows that differences in production by stage can be explained by observed differences in the natural fracture network.

• The information gathered during the initial months of the well’s operation can be used to fine tune numerical modeling at many levels, such as at individual frac stages, in reconciling production logs and initial performance, and in offering a narrow band of uncertainty for long term predictions.
Questions?
Shear Fracture Activation Model

Pre-slip:
Small open aperture ($a_o$)

Post-slip:
Larger open aperture ($a_o$)

Effective normal stress

Permeability

Shear slip

$\sigma_{n_{closure}}$
Modeling uncertainty in the permeability of stress-sensitive fractures

Moos, D.
GeoMechanics International, Menlo Park, CA, USA
Barton, C.A.
GeoMechanics International, Menlo Park, CA, USA

Parameter | Unstimulated | Stimulated | Uncertainty
--- | --- | --- | ---
$a_o$ | 10 | 10 | ± 10%
A | 0.1 | 0.18 | ± 10%
B | 10 | 100 | ± 10%

\[ a = \frac{A}{1 + 9 \frac{\sigma_n}{B}} a_o \]
Tuning the empirical hysteresis curves

- Theoretical
- Laboratory
- Stress conditions
- Rock properties
- Special tests

Frac Pressure
Slope ~ Bulk Modulus

Critical Pressure inferred from in-situ stress
Shape based on theoretical model

Hysteresis measurement from special tests
Slope ~ Pore Compressibility
Test matching for fracture strength and flow properties

Predicted flowback data

Fit to injection data

Model fit is controlled by:
- Pressure at knee is controlled by fracture strength
- Slopes controlled by pre and post-stimulation flow properties
Model “A” for different frac stages

**Stage 3**

- Natural Fracture distribution is the main differentiating factor for stage stimulation performance

- Few natural fractures
- High Treatment pressure
- Smaller SRV
- Low productivity

**Stage 7**

- More natural fractures
- Low Treatment pressure
- Larger SRV
- High productivity