SPE DISTINGUISHED LECTURER SERIES

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Hydraulic Fracturing

THE Multi-Disciplinary Technology

- Geology/Geophysics
- Reservoir
- Operations
- Rock Mechanics
- Fluid Mechanics
- Chemistry
- Petrophysics
- .........

Mike Smith
NSI Technologies

Cumulative References To "Multi-Disciplinary"

Fracturing was Multi-Disciplinary Before Multi-Disciplinary Was "Cool!"

Hydraulic Fracturing Begins!
Per Usman Ahmed, Distinguished Lecture 2004-05

Well, Get Out Your Other Hand!
COMPARISONS

Fracturing Is MUCH Like a Jigsaw Puzzle
COMPARISONS

- Pieces All Pretty Simple
  (If Ignore
  - Highly Naturally Fractured Formations
  - Deviated Wells Stupidly Drilled in Wrong Direction)

- BUT, There Sure Are a LOT of Pieces!
COMPARISONS

The More Pieces We Can Assemble, The Clearer The Picture!

This Frac Will Probably Fail!
COMPARISONS

The More Pieces We Can Assemble, The Clearer The Picture!

Good Enough?

Fracturing Works Without All The Pieces!
Fracturing “Works” Without All The Pieces
Fracturing “Works” Without All The Pieces, BUT, Works 2X Better WITH the Pieces!
IDEALLY

- Reservoir
  - Sets Goals
- Fracturing
  - Answers: Can I, How Do I Achieve Goals
- Operations
  - Sets Limits

Reservoir Engineering

Fracturing (Rock Mechanics, Fluid Mechanics, Chemistry, Petrophysics, ...)

Operations
DISCIPLINES

- Reservoir Engineering
- Fracturing
- Operations
DISCIPLINES

- Reservoir Engineering
  - Permeability
  - Drainage Boundary(s)
Comment at SEP-ATW

“….. Knowing permeability would not have impacted the fracture design. ”
Most Important Variable – “k” Field Study

- 15 Cases (Wells) 
  Covering 7 Fields & 3 Formations 
  (all 8 to 10,000’, hard rock, hot, on shore)
- Low to Moderate k (est. at 0.02 to 8.1 md) 
  (est. from 0.30 to 2.70 without Hi/Low)
- 5 Wells with Pre-Frac Flow
- 3 of These with PBU 
  (all 3 PBU in one formation, k 0.7 to 1.8)
- All 15 Frac Treatments Placed As Designed
Most Important Variable – k

“Field” Study

- Initial On-Line Rate (MMCFD) (1-Month Average)
  - Predicted
  - Actual

- Wells
  - All 15 Wells
  - 5 Wells w/ Pre-Frac Flow
  - 3 Wells w/ PBU Test

- Coincidence?
- 20% of Wells Made
- 40% of Gas
Most Important Variable – $k$

"Field" Study

<table>
<thead>
<tr>
<th>Initial On-Line Rate (MMCFD)</th>
<th>Predicted</th>
<th>Actual</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% of Wells Made</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40% of Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All 15 Wells</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 Wells w/ PBU Test           | PBU       |        |           |

(1-Month Average)
Importance of “k”

Conclusion

If you do not KNOW Permeability, DON’T Blame the Fracture Models!
Reservoir Engineering
Drainage Boundaries

SPE TIG Comment
“….. Who out there today takes the time and spends the money to properly characterize multiple pay intervals of *unknown drainage area* during an active drilling campaign?”

If We Are NOT Doing This, Why Are We Here?
Drainage Area
Tight Gas & Water Fracs

10,000 ft Reservoir w/ 0.01 md permeability

Optimum Fracture
Reservoir Boundary(s)  
What About a Single Fault?

Trapping Fault at top of B Sand

Take point and Subsea depth at top of B Sand

Courtesy of Devon
Reservoir Boundary(s)
What About a Single Fault?
Frac Optimization

What Do The Reservoirs We’re Frac’ing Look Like?

Fluvial Almond:
Who knows what drainage area & aspect ratio will be?
60% NSS Wells < 40 ac

Marine bar sands:
Drainage area could be 80-160 ac
Frac Optimization
Agarwal-Gardner TC Analysis – “Well Average” Pay & Permeability

**Pay Thickness**
- Average \( h = 87 \) ft

**Permeability**
- **AGTC Perm (150)**
  - 23% 0.01-0.02 md
  - 10% 0.02-0.03 md

- **MFO Perm (54)**
  - 0.005 md

Of 27 SS Wells (18% total), 21 > 0.01 md

Courtesy of bp
Frac Optimization
Agarwal-Gardner TC Analysis – “Effective” Reservoir Area

Of 27 SS Wells, 17 > 80 acres

Aspect Ratio

= 1  
= 2

Ideal $x_f$

<table>
<thead>
<tr>
<th>Acres</th>
<th>Xf (1:1)</th>
<th>Xf (2:1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>375’</td>
<td>530’</td>
</tr>
<tr>
<td>40</td>
<td>530’</td>
<td>750’</td>
</tr>
<tr>
<td>80</td>
<td>750’</td>
<td>1060’</td>
</tr>
<tr>
<td>160</td>
<td>1060’</td>
<td>1500’</td>
</tr>
<tr>
<td>320</td>
<td>1500’</td>
<td>2100’</td>
</tr>
</tbody>
</table>

Courtesy of
Importance of Reservoir Boundaries

**Conclusion**

If You Haven’t Talked to the G & G Folks, DON’T Blame the Fracture Models!

**Boundaries TRUMP** $x_f$ & $k_f w$!
DISCIPLINES

- Reservoir Engineering
- Fracturing
- Operations
Fracturing
- Rock Mechanics
  - Role of "Other" Horizontal Stress
  - Role of Effective Stress
  - Role of Intermediate Stress
- Thermodynamics/Heat Transfer
- Treatment Design, Conservation of Mass (or What is a TIP Screenout?)
- Mathematics & Modeling
The “Other” Horizontal Stress

We’re all familiar with Overburden, and with Closure Stress. But, What About the “Other” Horizontal Stress?
The “Other” Horizontal Stress Effects on Breakdown & Logs

Unequal Stresses Lead to High, Tensile Hoop Stress. Well Fractures While Drilling!
Typical Completion “Problem”
Typical Completion Problem

Formation Breakdown is (Or Should Be) a Primary Concern

200% "Pay" Uniformly Spread Over 700% of Rock!
\[ S_{H\text{-Max}} \gg S_{H\text{-Min}} \]

East Texas Example

So wellbore fractures during drilling.
$S_{H-\text{Max}} \gg S_{H-\text{Min}}$

East Texas Example

No Breakdown Problems so All Zones Fracture & Contribute.

Tracers Provide Good Data for Fracture Height

Courtesy of bp
The “Other” Horizontal Stress Effects on Breakdown & Logs

Equal Stresses Lead to High, Compressive Hoop Stress.

A “Stress Cage” Around Well!
\( S_{H-Max} = S_{H-Min} \)

South Texas Example

Stress Cage Around Well so Tracer Log is Misleading

Courtesy of Chevron

SPE 76812
Fracturing
- Rock Mechanics
  - Role of “Other” Horizontal Stress
  - Role of Effective Stress
  - Fracture Mechanics (Multiple Fractures)
- Thermodynamics/Heat Transfer

Treatment Design, Conservation of Mass (or What is a TIP Screenout?)

Mathematics & Modeling
Fracturing – Rock Mechanics
Role of Effective Stress
On Height Confinement

“Interface Slip”, or
“Elastic Debonding”,
or “Another Name”
ALL Require Some
Slippage, and Thus,
This Behavior is Related
to Effective Stress

\[ \text{OB} - P_{\text{Res}} \]
What Provided Height Confinement?
“Slip”, Yes
BUT
ONLY for Low Effective Stress

Net Overburden Stress (psi)
(Overburden - Pore Pressure)

Tensile Strength for Bounding Formation (psi)

Atoka Shale

Fracture Stopped At Interface
Fracture Crossed Interface

After Larry Teufel
Texas A & M

500 1,000 1,500 2,000 2,500
500 1,000 1,500 2,000 2,500

500 1,000 1,500 2,000 2,500
500 1,000 1,500 2,000 2,500
Fracturing
- Rock Mechanics
  - Role of “Other” Horizontal Stress
  - Role of Effective Stress
  - Fracture Mechanics (Multiple Fractures)
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Treatment Design, Conservation of Mass (or What is a TIP Screenout?)

Mathematics & Modeling
Fracturing Mechanics

TIG Comment
If you assume a reasonably tectonically relaxed stress regime: Is the potential effective stress increase, for a nominal range of rock fabric, from being as much as 90 deg out of phase as problematic (i.e.; harder to create width, length, and / or place proppant) as the often discussed initiation of multiple fractures in multiple directions has been hypothesized?
EFFECT OF SEGMENT INTERACTION
Perkins-Kern-Nordgren (PKN) model

- interaction
  → strongly affects pressures
- neglecting interaction
  → pressure overestimated by an order of magnitude

After Leonid Germanovich,
SPE ATW, 2004
PHYSICAL EXPERIMENT

FEM model
Fracturing

- Rock Mechanics
  - Role of “Other” Horizontal Stress
  - Role of Effective Stress
  - Fracture Mechanics (Multiple Fractures)

- Thermodynamics/Heat Transfer

- Treatment Design, Conservation of Mass (or What is a TIP Screenout?)

- Mathematics & Modeling
“Conventional wisdom was that the frac fluid had very little cooling effect on the formation, and what little effects there were quickly disappeared. During the treatment, the fluid experiences a rapid rise in temperature as it "turns the corner" and enters the fracture. As a result BHST could be used for designing fluid systems and breaker schedules. I have a feeling that most industry practitioners (myself included) are still using BHST”
Low Permeability, Low Fluid Loss

Conventional Wisdom is 90% Right

Pretty Good!
High Permeability, High Fluid Loss

Deep Water GOM Frac-Pack

Lots of Cooling

So Fluid is All Cold!

Conventional Wisdom Not So Good!

Consequences?
High Permeability, High Fluid Loss
Deep Water GOM Frac-Pack

Design, Based on Mini-Frac Analysis, called for a Tip Screenout (TSO) Net Pressure Increase of about 400 psi.

Mini-Frac Fluid Used
High Concentrations of High Temperature Breaker!
High Permeability, High Fluid Loss
Deep Water GOM Frac-Pack

Achieved –
“0” TSO
Net Pressure Gain

Post-Frac Skin of +22

Sand Control Failure!

Whoops!
Fracturing

- Rock Mechanics
  - Role of “Other” Horizontal Stress
  - Role of Effective Stress
  - Role of Intermediate Stress
- Thermodynamics/Heat Transfer
- Treatment Design, Conservation of Mass (or What is a TIP Screenout?)
- Mathematics & Modeling
Fracturing
Mathematics & Modeling

TIG Comment
“….. significant disconnect between what wells should be producing based on the 3D model propped length”
Fracturing
Mathematics & Modeling

TIG Comment
“….. significant disconnect between what wells should be producing based on the 3D model propped length”

Of Course, we know he did not “really” mean “3D Model”. He really meant “Pseudo 3D Model”! There is a difference.
Fracturing – Mathematics/Modeling

Imaginary Case Study

Closure Stress (psi) vs. TVD (ft)

- Shale Stress Tests
- 0.95 psi/ft
- Pre-Frac Flow
- 35 deg Dev

Gamma Ray API vs. TVD (ft)
Fracturing – Mathematics/Modeling

P3D Model 1
At Closure

Propped Fracture Contour

P3D Model 2
At Shut-In/Closure

Propped Fracture Contour
Fracturing – Mathematics/Modeling

3D Model 1
At Shut-In

Propped Fracture Contour

3D Model 2
At Shut-In

Propped Fracture Contour
Fracturing – Mathematics/Modeling
Pseudo Means Approximate!

Pseudo - False or counterfeit; fake.
Source: The American Heritage® Dictionary of the English Language

Question.
- If we do not believe our current P3D models,
  and
- We are not willing to move to more rigorous tools,
  then
- Why do we not simply stop using models?
DISCIPLINES

- Reservoir Engineering
- Fracturing
- Geophysics
- Operations
Risks - Geologic Uncertainty
Mini-Frac Sudden Screenout!

![Graph showing pump rate (bpm) vs. time (min) with corresponding Tr Press (psi)]
Recent Earthquake Activity in the USA
Magnitude 2.9 - OKLAHOMA
2004 April 22 16:13:02 UTC

Preliminary Earthquake Report
U.S. Geological Survey, National Earthquake Information Center
World Data Center for Seismology, Denver

A micro earthquake occurred at 16:13:02 (UTC) on Thursday, April 22, 2004. The magnitude 2.9 event has been located in OKLAHOMA. (This event has been reviewed by a seismologist.)

| Magnitude | 2.9 |
| Date-Time | Thursday, April 22, 2004 at 16:13:02 (UTC) |
| Location | 34.804°N, 97.677°W |
| Depth | 5 km (3.1 miles) set by location program |
| Region | OKLAHOMA |
| Distances | 7 km (4 miles) W (261°) from Erin Springs, OK |
| Source | Oklahoma Geological Survey, Leonard, USA |
| Event ID | ushpbn |
| Felt Reports | mbLg 2.9 (TUL). Felt at Erin Springs and Lindsay. |

Tectonic Summary
Location Maps:
2-degree | 10-degree
NEIC Maps
DISCIPLINES

- Reservoir Engineering
- Fracturing
- Geophysics

- Operations – We’re Out of Time!
Thank You!

Hugoton Infill After SPE 20756

For Most Operators 1990 Results Same As 1950!