Welcome!
The webinar will begin promptly at Noon (CST)

Dr. Jon Olson
Professor
Chairman
Petroleum and Geosystems Engineering Department
The University of Texas at Austin

Dr. Mukul Sharma
Professor
"Tex" Moncrief Chair
Department of Petroleum and Geosystems Engineering
The University of Texas at Austin

Dr. Zoya Heidari
Assistant Professor
Department of Petroleum and Geosystems Engineering
The University of Texas at Austin

Shale Fracturing: The Geology And Technology That Sustained The Boom
Shale Fracturing: the geology and technology that led to the boom

Dr. Jon E. Olson
Chair and Professor
Petroleum & Geosystems Engineering
Outline

- why is fracturing important
- what is a hydraulic fracture
- lessons from geology
- fracture mechanics tests in the lab
- small-scale fluid injection experiments to demonstrated hydraulic fracture complexity
Barnett Shale: Technology Matters

- 2011 – horizontal well, 15 fracs
- 1996 – vertical well, single frac without fracturing

Cumulative Production, Mscf

Time, months

Dr. Jon Olson
US Natural Gas Production

from US Energy Information Agency, through July 2015

Gross Production

from Conventional Gas Wells

from Oil Wells

from Coalbed Methane Wells

from Shale Gas Wells

Daily Rate, Bscf/day (averaged monthly)
What is a hydraulic fracture?
Rock Failure Modes: dispelling myths

unconfined compressive test

hydraulic fracturing in acrylic
Gross Fracture geometry is systematic & predictable

$S_{Hmax},$ maximum horizontal stress

$S_{hmin},$ minimum horizontal stress
Hydraulic Fracture Geometry

- Horizontal well with multiple transverse fractures
- Horizontal well with longitudinal fracture
- Vertical well with vertical fracture
Lessons on fracture propagation and interaction from geology
Systematic natural fractures

Muddy Gap, WY

\[ S \propto H \]

Jon Olson
UT-Austin, FRAC

thick beds
Impact of lithology on fracture growth

- natural fracture spacing in shales often closer than other lithologies
- depends strongly on mineral make-up of rock
- ductile clay layers can be fracture arrestors within more brittle shale interbeds

Dr. Jon Olson
Impact of lithology on fracture growth

- natural fracture spacing in shales often closer than other lithologies
- depends strongly on mineral make-up of rock
- ductile clay layers can be fracture arrestors within more brittle shale interbeds
Impact of lithology on fracture growth

ductile clay barrier

fracture arrest

Huron Shale, Ohio
Fracture Interaction with Bedding Planes

- Siliceous mudstone, Miocene Monterrey Fm.
- Vertical quartz-filled fracture selectively propagates across gray beds (marly), along white beds (phosphatic)
Fracture Interaction with Bedding Planes

- Siliceous mudstone, Miocene Monterrey Fm.
- Vertical quartz-filled fracture selectively propagates across gray beds (marly), along white beds (phosphatic)

from Portuguese Bend, Palos Verdes, CA

Dr. Jon Olson
Natural-natural fracture interaction

Miocene Monterey Formation, Palos Verdes, CA

Jon Olson, UT-Austin, FRAC
Natural-natural fracture interaction

Diverting along the interface of thicker fracture

Miocene Monterey Formation, Palos Verdes, CA

Jon Olson, UT-Austin, FRAC
Natural-natural fracture interaction

Fracture crossing of thinner frac
Natural-natural fracture interaction

Miocene Monterey Formation, Palos Verdes, CA

bedding plane
Natural-natural fracture interaction

Miocene Monterey Formation, Palos Verdes, CA

bedding-parallel vein

bedding plane
Natural-natural fracture interaction

Miocene Monterey Formation, Palos Verdes, CA

cross-bed vein #1

bedding-parallel vein

bedding plane

Jon Olson, UT-Austin, FRAC
Natural-natural fracture interaction

Miocene Monterey Formation, Palos Verdes, CA

Cross-bed vein #1

Cross-bed vein #2a

Cross-bed vein #2b

Bedding-parallel vein

Bedding plane

Jon Olson, UT-Austin, FRAC
Natural-natural fracture interaction

Miocene Monterey Formation, Palos Verdes, CA

Diverting along the interface of thicker fracture

cross-bed vein #1

cross-bed vein #2a

cross-bed vein #2b

bedding-parallel vein

bedding plane

Jon Olson, UT-Austin, FRAC
Natural-natural fracture interaction

Miocene Monterey Formation, Palos Verdes, CA

Jon Olson, UT-Austin, FRAC
Natural Fracture Summary

• natural veins fluid-driven fractures occurring at depth (i.e., good analogy for hy-frac)
• bedding planes and pre-existing veins can divert fracture propagation (frictional interfaces would do same)
• vein thickness increases chance of diverting propagation
Fracture Mechanics Testing of Cores – Marcellus Shale
Marcellus Core Testing

- test vein strength, fracture interaction with Marcellus Core
- saw and grind samples rather than plug to reduce damage/breakage
- propagate induced fractures using Semi-Circular Bending test

from
Lee, Olson, Holder, Gale and Myers, 2015, JGR
doi:10.1002/2014JB011358
Marcellus Core Testing

- test vein strength, fracture interaction with Marcellus Core
- saw and grind samples rather than plug to reduce damage/breakage
- propagate induced fractures using Semi-Circular Bending test

from
Lee, Olson, Holder, Gale and Myers, 2015, JGR
doi:10.1002/2014JB011358
Marcellus Core Testing

- test vein strength, fracture interaction with Marcellus Core
- saw and grind samples rather than plug to reduce damage/breakage
- propagate induced fractures using Semi-Circular Bending test

from Lee, Olson, Holder, Gale and Myers, 2015, JGR doi:10.1002/2014JB011358
Marcellus Core Testing

- test vein strength, fracture interaction with Marcellus Core
- saw and grind samples rather than plug to reduce damage/breakage
- propagate induced fractures using Semi-Circular Bending test

from Lee, Olson, Holder, Gale and Myers, 2015, JGR
doi:10.1002/2014JB011358
Marcellus Core Testing

- test vein strength, fracture interaction with Marcellus Core
- saw and grind samples rather than plug to reduce damage/breakage
- propagate induced fractures using Semi-Circular Bending test

from Lee, Olson, Holder, Gale and Myers, 2015, JGR doi:10.1002/2014JB011358
Failure Occurs Within the Cement

- sample diameter = 2-4 in
- vein thickness = 0.01-0.075 in
- failure along flaws in calcite vein-fill (fluid inclusion trails and cleavage)

failed SCB sample

thin section of calcite vein fill

plane polarized light
crossed nicols
Multiple Saw Cuts & Grinding
Diameter = 2.5 in
Thickness of the vein= 0.009 in

**SCB test Results**

Crossing preferred at more orthogonal approach angle

Cross ($\theta_o = 90^\circ$)

Step over ($\theta_o = 81^\circ$)

Divert ($\theta_o = 58^\circ$)

Divert ($\theta_o = 43^\circ$)
Impact of Vein Thickness

crossing preferred for thinner veins

Multiple Saw Cuts
Diameter = 2.5 in
$\theta_o = 90^\circ$
Testing summary

• demonstrated that well-cemented veins can provide planes of weakness
• tests at varying approach angles can quantify vein strength
• critical energy release rate of veins \( \sim \frac{1}{4} \) shale matrix

\[
G_c = \frac{K_{IC}^2}{E^*}
\]

• vein toughness, \( K_{IC} \), was estimated to be higher than shale
  \( K_{IC}(\text{vein}) \sim 0.8 \text{ MPa-m}^{1/2} \)  \( K_{IC}(\text{shale}) \sim 0.5 \text{ MPa-m}^{1/2} \)
• failure depends on strength and stiffness of veins
Small-scale Laboratory Hydraulic Fracture Experiments
Hydraulic fracturing in fractured reservoirs

Fisher et al. 2004

Warpinski & Teufel, 1987

Fig. 4—Authors’ visualization of results of fracture treatment in jointed rock mass.
Physical Experiments: Interaction between cemented flaws and fluid driven cracks

hydrostone = gypsum-based cement
Pour Hydrostone Blocks with Embedded Discontinuities

Natural Fractures (glass slides)

$S_{h,max}$

Natural Fractures (glass slides)

$S_{h,max}$
Load Frame – apply $S_{\text{vert}}$, $S_{\text{Hmax}}$, $S_{\text{hmin}}$
Uncovering Hydraulic Fractures
Complex Interaction – Oblique Case

wellbore

natural fracture
Complex Fracture propagation/interaction

Bahorich et al., SPE 190197
Complex Fracture propagation/interaction

Bahorich et al., SPE 190197
Complex Fracture propagation/interaction

diverts along natural fracture

mixed mode I-II non-planar curving

Bahorich et al., SPE 190197
Complex Fracture propagation/interaction

- Part of fracture propagates under natural fracture.
- Mixed mode I-II non-planar curving.
- Diverts along natural fracture.

Bahorich et al., SPE 190197
Summary

• shale gas has made energy more affordable and secure in the United States
• much of hydraulic fracture complexity has an analogy in natural fracture examples
• one key to complexity is the interaction of hydraulic fractures with natural fractures
• laboratory testing can be used to quantify pre-existing fracture strengths and to run small-scale hydraulic fracture tests to illustrate potential geometries
Acknowledgment:
FRAC Consortium Sponsors

http://www.beg.utexas.edu/frac
Well Spacing, Fracture Spacing, Sequencing and Fluid Management in Pad Fractured Horizontal Wells

Mukul M. Sharma
University of Texas at Austin
JIP FACT SHEET
Sponsors for 2014-15

1. Air Liquide
2. Anadarko Petroleum
3. Aramco
4. Baker Hughes
5. BHP Billiton
6. BP
7. Chief Oil & Gas
8. Chevron
9. ConocoPhillips
10. Devon Energy
11. Eni
12. Ferus
13. FSTI Inc.*
14. Hess
15. Linde
16. Lubrizol*
17. MeadWestVaco (MWV)
18. Nalco (Ecolabs Inc.)*
19. Nexen Energy ULC
20. Noble Energy*
21. Oxy
22. Pioneer
23. PEMEX
24. Praxair
25. Range Resources
26. Sanchez Oil & Gas*
27. Schlumberger
28. Shell
29. Southwestern Energy
30. Statoil
31. Talisman
32. Unimin
33. Weatherford
34. Wintershall

• RPSEA / DOE: 2 projects for $2,400,000 for 2013-2016
• The State of Texas pays faculty salaries.
• Your funds are leveraged about 50:1

Other potential members that have expressed interest:
• PTT
• Petrobras
• ONGC
• Chesapeake
The People Involved

Graduate Students:

- Murtadha Al Tammar
- Prateek Bhardwaj
- Michael Brothers
- Chris Blyton
- Eric C. Bryant
- Michael Carey
- Deepen Gala
- Chang Min Jung
- Hojung Jung
- Emmanouil Karantinos
- Ashish Kumar
- Dongkeun Lee
- Hisanao Ouchi
- Javid Shiriyev
- Igor Shovkun
- Kaustubh Shrivastava
- Jeffrey Stewart
- Sanjay Surya
- Haotian Wang
- Chu-Hsiang Wu
- Weiwei Wu
- Mingyuan Yang
- Shiting Yi
- Jason York
- Peng Zhang
- Junhao Zhou
- Saud Alquwizani*
- Samarth Agarwal*
- Saptaswa Basu*
- Stephen A. Bryant*
- Jameson P. Gips*
- Jongsoo Hwang*
- Eric R. Lehman*
- Lionel Ribeiro*
- Roman Shor*
- Do Shin*

Research Staff:

- Yaniv Brick
- Philip Cardiff
- Ajeetha Kamilla
- Jin Lee
- Ripudaman Manchanda
- Anand S. Nagoo
- Rodney T. Russell

*研究生
Top Five Ideas Worth Trying

1. Treat fracture design as a multi-frac, multi-well problem. This will provide the optimum,
   – Well spacing, fracture spacing, fracture sequencing
   – Fracture design
2. Liquids lifting through entire life of well
   – Wellbore trajectory
   – Artificial lift design
3. Better zipper frac sequencing
4. Improve proppant placement
5. Refracturing
   – New methods to divert fluids during refracturing
   – Better candidate selection
Pad Fracturing: The Big Picture
Learning from Experience

- There is no general consensus on most recommendations regarding well spacing, proppants, pumping rates, fluids, flowback……
  - Too many variables
  - Too few wells and too little data
  - Expensive learning

- There is a real and significant financial benefit to accelerating the learning process (capital efficiency).

- How do we accomplish this?
  - Learn from existing wells (data analysis)
  - Physics based models
  - Combine the two (iterate).
Multiple Non-Planar Fracture Propagation
Fracture Stage with 4 Perforation Clusters
Signatures of Fracture Complexity / Interference

Fracture Trajectory vs. Distance from Stage 1 (ft)

Net Closure Pressure vs. Stage Number

Ref: Roussell and Sharma, 2012, ARMA 12-633
Complex Fracture Networks

In addition to stress shadowing, fracture complexity also arises due to:

- Complex rock fabric
- Natural fractures
- Bedding planes
- Heterogeneity
- Stress anisotropy
- Shear failure

Stress interference, natural fractures, heterogeneities, pore pressure depletion, rock fabric can all lead to fracture complexity.

Fracture Complexity is a Strong Function of Rock Fabric and Local Stress Contrast

Barnett Shale, Devon
(Fisher et al. 2005)

Bossier TGS, Anadarko
(Sharma et al. 2004)
Effect of Rock Fabric and Stress Anisotropy

Yellow cells discretize planes-of-weakness, small *in-situ* stress contrast.

Same planes-of-weakness but increased *in-situ* stress contrast.

Ref: SPE 173374- Arbitrary Fracture Propagation in Heterogeneous Poroelastic Formations Using a Finite Volume-Based Cohesive Zone Model • Eric C. Bryant, M. M. Sharma, 2015.
We Can Control Fracture Complexity, To Some Degree

\[ \sigma_{h\text{min}} \text{ is increased close to the propped-open fracture and exceeds the original } \sigma_{h\text{max}} \text{ value causing reorientation of the } \sigma_{h\text{max}} \text{ direction.} \]

Fractures that propagate in regions of low stress contrast are likely to show more fracture complexity.
Pad Fracturing Design Workflow

3-D Fracture Model: Estimate fracture dimensions / complexity

3-D Fracture Interference Model: Estimate number of fractures per stage

3-D Reservoir Model: Simulate production, reservoir drainage and NPV.

Parametric Study: Well spacing, fracture spacing and fracture dimensions.

Fracture Design Recommendations: Sand volume, fracture sequencing, fluids, proppant schedule.
Estimating Optimum Well Spacing and Fracture Spacing ($L_f = 160$ ft)

$L_f=160$ ft Gas Price=5 NPV for 30 Years

Max NPV=27.8 MMUSD @ $W=660, F=100$
Summary

• There are many reasons to treat the fracture design problem on a pad scale (a multi-well, multi-frac problem):
  – Interference between fractures
  – Fracture complexity / reservoir heterogeneity
  – Some ability to control fracture complexity

• Computing pore pressure, stress and failure maps is important for:
  – Establishing well spacing
  – Selecting locations for infill or step-out wells
  – Selecting fracture spacing in the new well
  – Fracture designs in new wells
  – The feasibility of an infill well
Top Five Ideas Worth Trying

1. Treat fracture design as a multi-frac, multi-well problem. This will provide the optimum,
   – Well spacing, fracture spacing, fracture sequencing
   – Fracture design

2. Liquids lifting through entire life of well
   – Wellbore trajectory
   – Artificial lift design

3. Better zipper frac sequencing

4. Improve proppant placement

5. Refracturing
   – New methods to divert fluids during refracturing
   – Better candidate selection
Wellbore Liquids Management

- Well productivity is a strong function of wellbore liquids loading and wellbore trajectory.
- Every unconventional well will be on artificial lift for 90% of its life.
- To properly manage wellbore fluids we must:
  - Unload liquids from fractures and the wellbore
  - Unload liquids from the reservoir matrix
  - Integrate wellbore models with reservoir inflow
  - Properly design and manage artificial lift.
  - Obtain good estimates of BHP from THP
How Good Are Our Wellbore Models?

Cousins, Denton and Hewitt (1965) – Exp. # 49, data also in Table 12.1 of Wallis’s One Dimensional Flow textbook

Dr. Mukul Sharma

Figure 4.13.2: Comparisons of different model predictions for a dataset from Hewitt et al. (1961).


Figure 4.13.4: Comparisons of different model predictions for a dataset from Crowley et al. (1986).
How Good Are Our Wellbore Models?


Also available from Theofanous, T. G., Amarasooriya, W. H.: Dataset no. 1 - pressure drop and entrained fraction in fully developed flow, Multiphase Sci. and Tech., v. 6, part 1, pp. 5-13 (1992)
How Good Are Our Wellbore Models?

Figure 7.13.10: Comparisons of different model predictions for well J of Kumar (2005).

Figure 7.13.14: Comparisons of different model predictions for well case 6 of Chierici et al. (1974).


Slightly-Inclined Flow: Horizontal Wells

- In long laterals, segmentation is important because of the need to:
  - Capture the local multiphase flow development
  - Different wellbore regions and reservoir zones
  - Different well inflow from multiple entry points with productivity indices (PIs)
  - Different lithologies, rock qualities, stress gradients

Toe-Up Wellbore PFF Simulator
Toe-Up Wellbore: PFF Simulator Comparison with Well Data

Correct trend is captured for both pressure and gas holdup
Undulating Wellbore
PFF Simulator

Dr. Mukul Sharma
Undulating Wellbore

PFF Simulator
Liquids Unloading

- Obtaining good estimates of BHP from THP
- Effect of wellbore trajectory on well productivity
- Unloading of liquids from fractures
- Integrating wellbore models with reservoir inflow
- Unloading of liquids from the reservoir matrix
- Design of artificial lift.
Liquid Loading Inside Fracture

- Competing forces: drawdown vs. gravity vs. capillary
- Capillary forces inhibiting flow of water
- Gravity pulling liquid to the bottom
- Turner’s critical velocity for vertical gas wells:
  - For $\sigma = 60$ dynes/cm, $\rho_L = 58$ lb/ft$^3$, $\rho_g = 3$ lb/ft$^3$,

$$U_{crit} = 8.4 \text{ ft/s}$$
Can the Gas Lift the Liquid in the Fracture?

Lets assume,

- Well produces (Q) = 5 MMscfd
- No. of fracs (N) = 50
- Upward flow area of frac (A) = Width * length = 0.03 ft * 100 ft = 3 ft²
- Bg = 1000 scf/ft³ and Porosity (ϕ) = 0.4
- The gas velocity within the fracture is:

  \[ \frac{Q}{N \times Bg \times A \times \phi} = 0.0006 \text{ ft/sec} \]
Integrating Wellbore Flow with Reservoir Inflow

➢ To model the impact of wellbore trajectory on hydraulically-fractured horizontal well productivity it is important to account for the effect of water unloading in the wellbore the fracture and the rock matrix.
Integrating Wellbore Flow with Reservoir Inflow

Dr. Mukul Sharma
Liquids Removal Takes Time

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix Permeability</td>
<td>1 μD</td>
</tr>
<tr>
<td>Fracture Permeability</td>
<td>2 D</td>
</tr>
<tr>
<td>Drawdown</td>
<td>2000 psi</td>
</tr>
</tbody>
</table>

Variation of water saturation inside Fracture

Variation of water saturation in matrix near fracture
Water and Condensate Blocking

- Water /condensate blocking can cause a severe reduction in gas and condensate relative perms.
- Chemical treatment using a non-ionic fluorinated surfactant increases gas and condensate relative permeability by a factor of 2.
- Proppant can be treated as well to improve proppant-pack conductivity.
- 6 field trials conducted. More underway.
References


• “Evaporative Clean-up of Water-Blocks in Gas Wells”, SPE 94215, presented at the 2005 SPE Production and Operations Symposium held in Oklahoma City, OK, April 17-19, 2005, J. Mahadevan and M.M. Sharma.

Top Five Ideas Worth Trying

1. Treat fracture design as a multi-frac, multi-well problem. This will provide the optimum,
   - Well spacing, fracture spacing, fracture sequencing
   - Fracture design
2. Liquids lifting through entire life of well
   - Wellbore trajectory
   - Artificial lift design
3. Better zipper frac sequencing
4. Improve proppant placement
5. Refracturing
   - New methods to divert fluids during refracturing
   - Better candidate selection
Q&A
Please enter your questions in the chat box on the left.

Dr. Jon Olson
Professor
Chairman
Petroleum and Geosystems Engineering Department
The University of Texas at Austin

Dr. Mukul Sharma
Professor
"Tex" Moncrief Chair
Department of Petroleum and Geosystems Engineering
The University of Texas at Austin

Dr. Zoya Heidari
Assistant Professor
Department of Petroleum and Geosystems Engineering
The University of Texas at Austin

Shale Fracturing: The Geology And Technology That Sustained The Boom
Thank you!

To receive CEU verification, please visit the link below and complete a short survey. You MUST click on this link and fill out the information now to be eligible for CEU verification (only takes 30 seconds).

https://www.surveymonkey.com/r/6FFFRJY

If you did not already pay the $25 fee for CEU verification, please call 512-232-5199 or 512-471-3506 to pay the fee within 24 hours

Dr. Jon Olson: jolson@austin.utexas.edu

Dr. Mukul Sharma: msharma@mail.utexas.edu

Dr. Zoya Heidari: zoya@austin.utexas.edu

Comments? cpge@utexas.edu