Advancing Reservoir Performance

Unconventional Completions
Wellbore Completions and Fracturing

Society of Petroleum Engineers Webinar
October 9, 2013

Aaron Burton – Completion Manager
Sergey Kotov – Stimulation Manager
Baker Hughes' Unconventional Resources Team

Poll Question

What is your job title?

Engineer

Geologist

Geophysicist

Consultant

Educator

Poll Question

Who is your employer?

E&P Company

NOC

Government

Academia

Consultant

Non-governmental Organization

Environmental Organization

Poll Question

How many years of experience do you have?

0-5

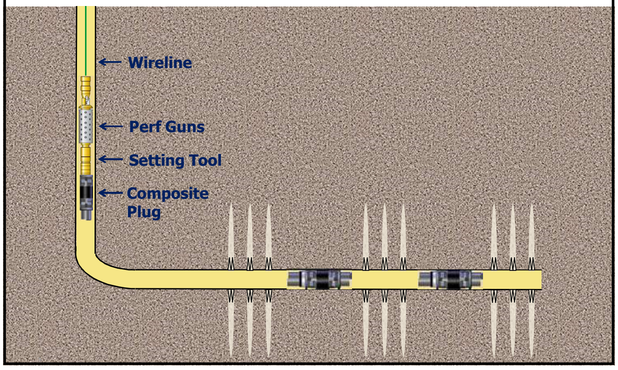
6-10

11-15

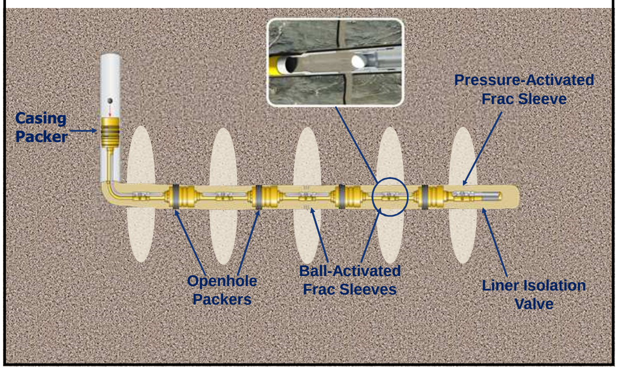
16-20

20+

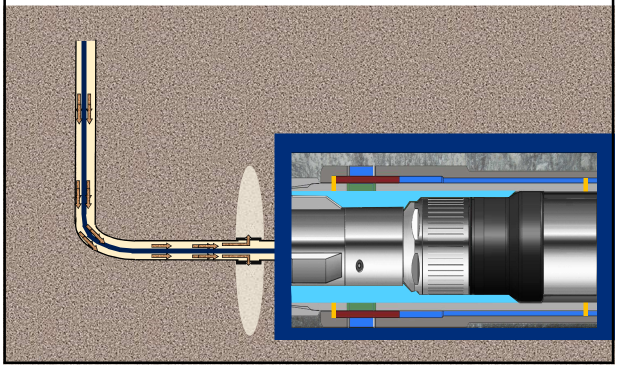
Plug-and-Perf



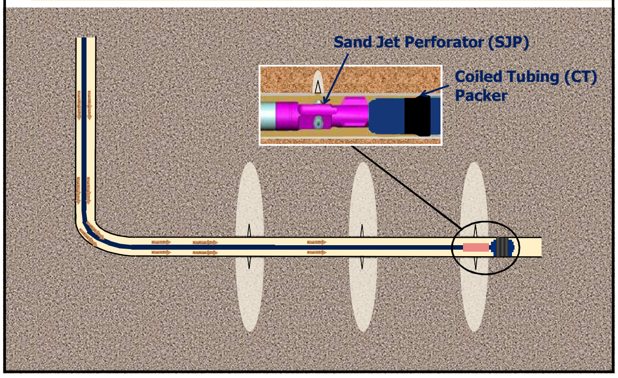
Ball-Activated Completion System



Coiled Tubing-Activated Completion System



Coiled Tubing-Activated Completion System



Q&A Break

Poll Question

Which do you think is the best completion option for unconventional formations?

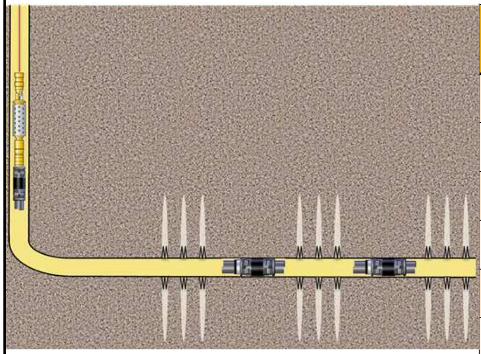
a) Plug-and-Perf
b) Ball-Activated Completion Systems
c) Coiled Tubing-Activated Completion Systems
d) It depends on the application

Completion Comparison

All Completion Systems
- Isolate using openhole or cemented liner
- Isolate multiple stages effectively
- Require different services and procedures to execute the frac job

How do we choose the right completion?

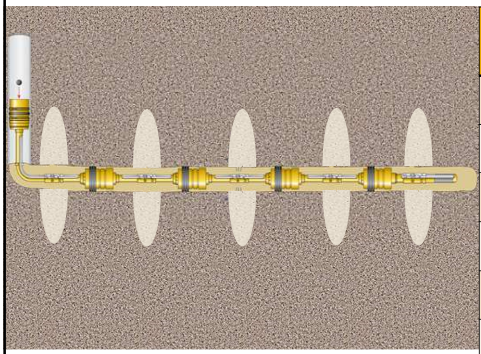
Plug-and-Perf



Benefits and Considerations
Virtually unlimited number of stages
Flexible stage placement
Contingency options due to full-bore diameter
Requires multiple services to execute the frac
Rig up and rig down wireline and pressure between each stage
Requires plug mill-out, full production ID

SPE166431 • Unconventional Completions: Which is the Right one for Your Application

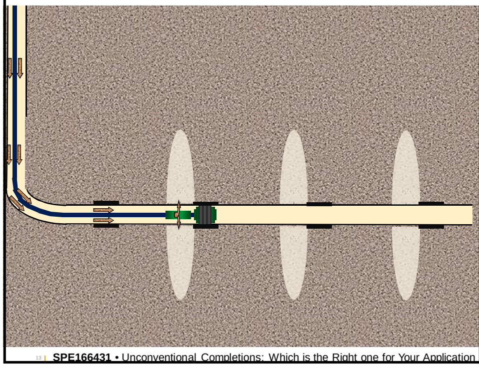
Ball-Activated Completion Systems



Benefits and Considerations
Limited number of stages
Fixed stage placement
Contingency options limited by ball seat diameters
Only requires pressure pumping units to execute fracturing
Nonstop fracturing operations
No millout required, reduced production ID

SPE166431 • Unconventional Completions: Which is the Right one for Your Application

Coiled Tubing-Activated Completion Systems



Benefits and Considerations
Virtually unlimited number of stages
Fixed stage placement with sleeves, flexible with SJP
Contingency options with full diameter and CT in hole
Requires multiple services to execute the frac
Frac shuts down to move CT to next stage
No millout required, full production ID

SPE166431 • Unconventional Completions: Which is the Right one for Your Application

Q&A Break

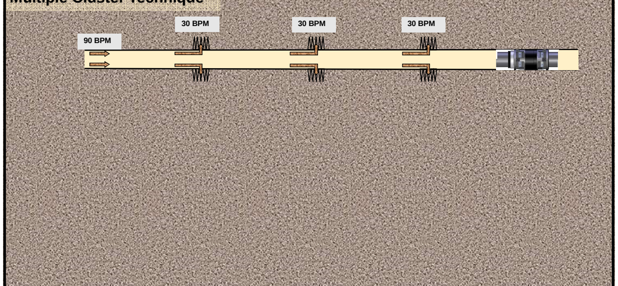
Poll Question

Which do you think is the best completion option for unconventional formations?

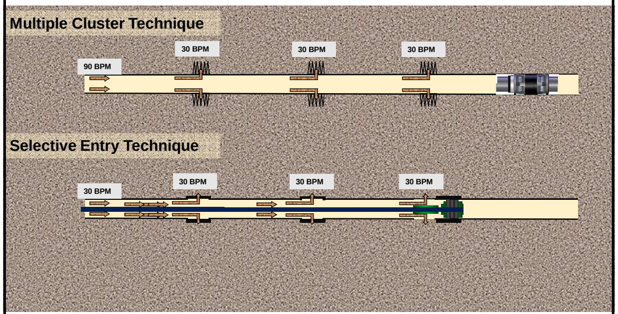
a) Plug-and-Perf
b) Ball-Activated Completion Systems
c) Coiled Tubing-Activated Completion Systems
d) It depends on the application

Multiple Clusters vs. Selective Entry

Multiple Cluster Technique



Multiple Clusters vs. Selective Entry



Case History - Horsepower Reduction

Granite Wash Case History

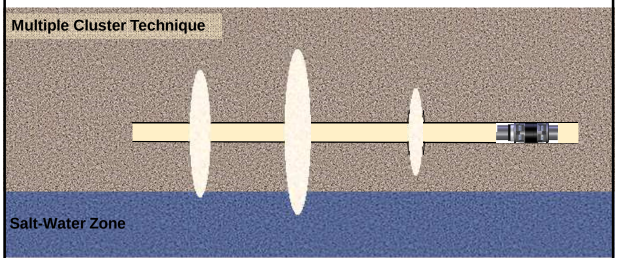
Table 1. Stimulation job results – Comparative Summary Table

Parameter / Well:	A (Plug and Perf)	B (Targeted)	Variance
Number of Frac Stages:	10 (with 3 clusters per stage)	30	None
Frac Spacing (ft):	165	164	None
Fluids Type:	HCl Spearhead, Slickwater fluid	HCl Spearhead, Slickwater fluid	None
Proppant Type:	100 mesh sand, 40/70 Ottawa white and Resin Coated with 2% resin coating	100 mesh sand, 40/70 Ottawa white and Resin Coated with 2% resin coating	None
Total Clean Fluid Pumped (gal):	9,344,170	9,568,993	+2.4%
Total Proppant Placed (lbs):	3,675,280	3,772,380	+2.6%
Average Frac rate (bpm):	99	40	-60%
Average Treating Pressure range (psig):	5,852 to 6,801	4,125 to 6,935	-30% to +2%
Average HHP range:	13,889 to 16,387	3,004 to 5,517	-78% to -66%
Maximum HHP required:	20,630	6,693	-68%

SPE 163820 • A Comparison of Proppant Placement, Well Performance, and Estimated Ultimate Recovery Between Horizontal Wells completed With Multi-Cluster Plug & Perf and Hydraulically Activated Frac Ports in a Tight Gas Reservoir

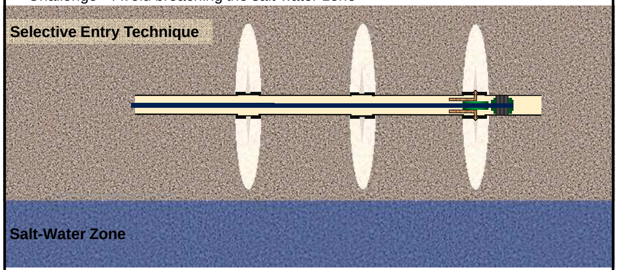
Fluid Displacement and Height Containment

Challenge – Avoid breaching salt-water zone



Fluid Displacement and Height Containment

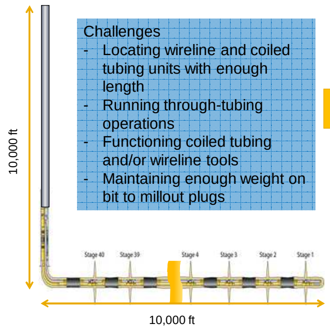
Challenge – Avoid breaching the salt-water zone



Wells with Longer Laterals

Challenges
- Locating wireline and coiled tubing units with enough length
- Running through-tubing operations
- Functioning coiled tubing and/or wireline tools
- Maintaining enough weight on bit to millout plugs

Ball-Activated Completions



Extended Number of Stages

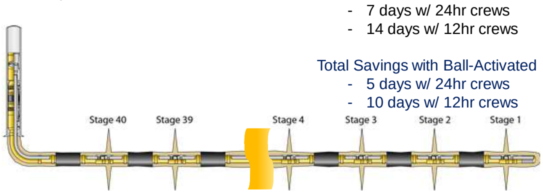
Assumptions:
- 40 stage frac job
- 1 hour/stage in frac plan
- No operational issues

- 3 hours RU/RD time between stages

Ball-Activated Completion
40 hours total to stimulate
- 2 days w/ 24hr crews
- 4 days w/ 12hr crews

Plug-and-Perf
160 hours total to stimulate
- 7 days w/ 24hr crews
- 14 days w/ 12hr crews

Total Savings with Ball-Activated
- 5 days w/ 24hr crews
- 10 days w/ 12hr crews



Low Number of Stages

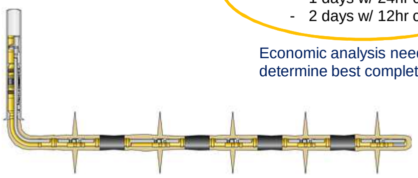
Assumptions:
- 5 stage frac job
- 1 hour/stage in frac plan
- No operational issues

- 3 hours RU/RD time between stages

Ball-Activated Completion
5 hours total to stimulate
- 1 days w/ 24hr crews
- 1 days w/ 12hr crews

Plug-and-Perf
20 hours total to stimulate
- 1 days w/ 24hr crews
- 2 days w/ 12hr crews

Economic analysis needed to determine best completion



Appraisal Phase

- Objectives
  - Data gathering
  - Understand the Reservoir
- Risks
  - Uncertain of stage placement during completion
  - Poorly drilled wells
  - Screenouts
- Completion Requirements
  - Stage placement on the fly
  - No increase on OD and stiffness
  - Full bore ID in the liner

Plug-and-Perf or CT-Activated with SJP

Development Phase

- Objectives
  - Cost savings
  - Efficient operations
  - Maximize production
- Completion Options
  - Ball-Activated Completion System
    - Nonstop fracturing, improved logistics
  - Coiled Tubing-Activated Completion System
    - Recovery from screenout, fluid displacement
  - Plug-and-Perf
    - Simultaneous operations, shortage of fracturing supplies

Q&A Break

Poll Question

Which do you think is the best completion option for unconventional formations?

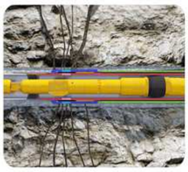
a) Plug-and-Perf
b) Ball-Activated Completion Systems
c) Coiled Tubing-Activated Completion Systems
d) It depends on the application

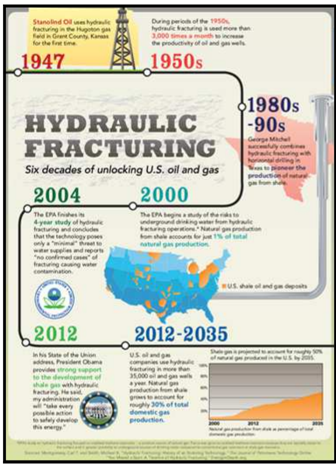
Conclusion

Plug-and-Perf

Ball-Activated

Coiled Tubing-Activated



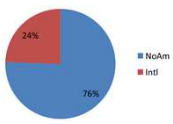


Hydraulic Fracturing History

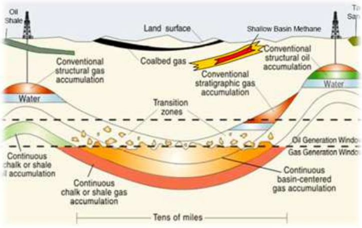
Global Fracturing Market

$ 4 billion – 1999

$ 50 billion - 2013



What is Unconventional?



- ✓ Tight Gas
- ✓ Tight Oil
- ✓ Shale Gas
- ✓ Shale Oil
- ✓ CBM

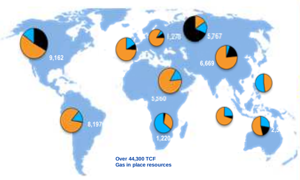
" A reservoir that can not be produced at economic flow rates nor recover economic volumes of natural gas unless the well is stimulated by a large hydraulic fracture treatment or produced by a horizontal wellbore or multilateral wellbores."

(S.A. Holditch)

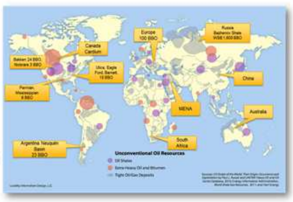
Global Distribution of the Unconventional Oil and Gas Resources

Unconventionals: Forecasted to Grow Rapidly

Unconventional Gas Resources, 44,300Tcf



Unconventional Oil Resources, 2-3Tbbl



Source: Baker Hughes, EIA, SPE 68755, Kawata & Fujita from Rogner

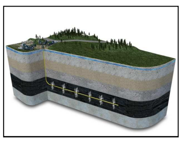
Potential emerging markets outside of the United States

- Existing resource
- Demand
- Nations desire to develop for consumption and export

Developing Shale Reservoirs

- **Two Key Elements** of shale gas/oil **development:**
  1. **Horizontal Wells** (***Maximize Reservoir Volume*** *and* ***Natural Fractures*** *Connected to* ***Well***)
  2. **Multi-Stage Fracturing**

- Shale well **Productivity & Recovery** depend on: **Reservoir Quality and**
- **successful execution of Effective Hydraulic Fracturing**

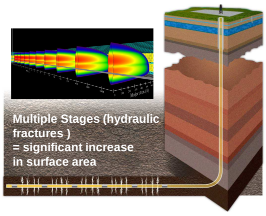


Horizontal Wells - Advantages

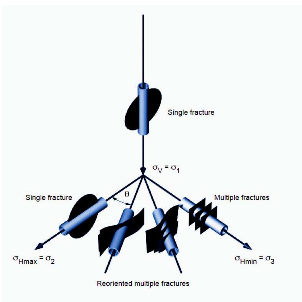
- **Maximise wellbore contact with reservoir**
- **Maximise number of frac stages**

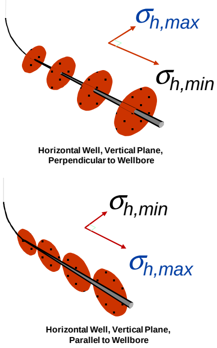
Increase size of "artificial reservoir"

- Reduce surface footprint
  - 100 ft open hole vertical wellbore, 8.5" diameter = **222** sq ft
  - 5,000 ft open hole horizontal wellbore, 8.5" diameter = **11,126** sq ft
  - 100 ft radial fracture = **62,832** sq ft



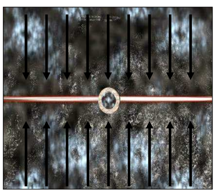
Basic Fracture Geometries



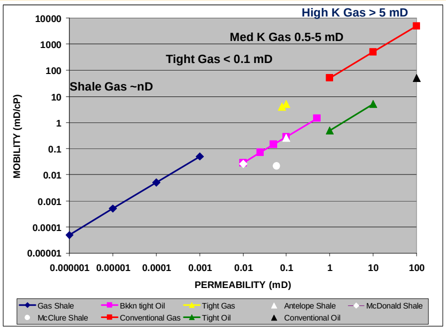


Fracture Treatment Objectives

- **Increase productivity**
  - Low permeability reservoirs
  - Damaged zones (by-pass damage)
  - Connect natural fractures
  - Increase drainage area
  - Increase drainage height *(stringers & horizontal wells)*
- **Decrease wellbore pressure drop to minimize:**
  - Formation sand and frac sand production
  - Gas production over-run of oil
  - Water production
  - Asphaltenes, paraffins, and scale deposition
- **Increase injectivity** *(injection wells)*



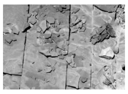
Mobility, a Critical Driving Parameter



Randy LaFollette, Baker Hughes

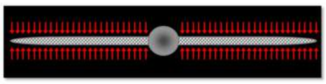
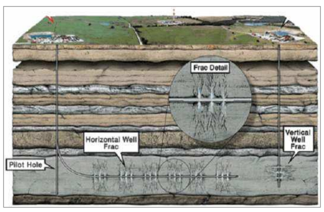
The Challenges

- **Fracture geometry**
  - *Not creating expected length*
  - *Brittle or ductile rock - complex fracture network*
  - *Growth out of zone, faults, wet zones…*
- **Proppant transport**
  - *Prop falling out of zone*
  - *Prop pack not connected to perfs*
- **Final conductivity**
  - *Gel damage, breaker/clean-up issues*
  - *Proppant crushing, non-Darcy flow*
- **Reservoir properties** *(not as expected)*
- **Geohazards**
  - *Faults*
  - *Karsts*
  - *Wet zones*

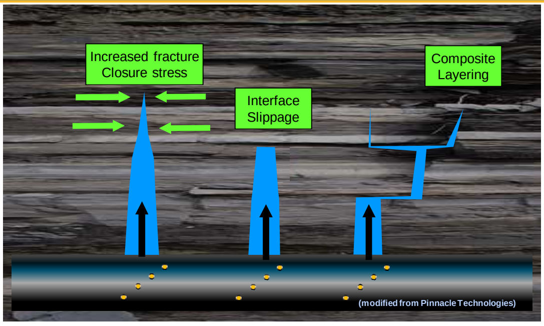



Geomechanics & Hydraulic Fracture Complexity

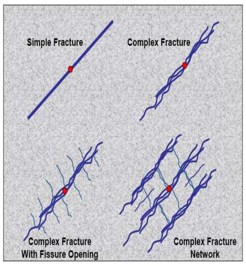
- **Classic bi-wing fracture**
  - *Not effective for shale gas*
- **Complex fracture growth**
  - *Requirement for sealed natural fracture shale gas systems*
  - *Lowers the distance to the gas*
  - *Lower mobility – lower spacing between fractures*

Fracture Height Confinement Mechanisms

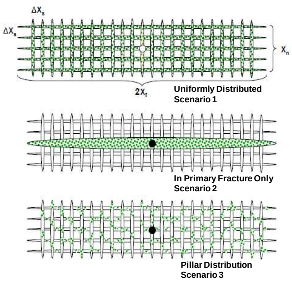


Various Degree of Complexity



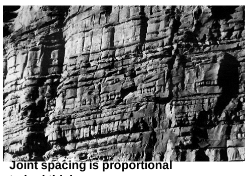
(SPE 114173) (SPE 119890) (SPE 115769)

Proppant Distribution Scenarios



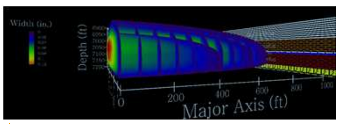
Shale Outcrops

Discrete fracture network modeling, based on shale joint structure.



Joint spacing is proportional to bed thickness (Olsen)

Marcellus Outcrop (Engelder and Lush, 2008)



Discrete Fracture Network 3D view (X-Z plane), $\lambda = b/a = 0.5$

Functions of Fracturing Fluid

- **Initiate and Propagate Fracture**
- **Easy to Handle at Surface (Batch or Continuous)**
- **Viscosity**
  - *Transport Proppant to Well*
  - *Carry Proppant into Fracture*
  - *Support Proppant in Fracture*
  - *Minimize Leakoff*
- **Other requirements**
  - *Cost effective*
  - *Environmentally acceptable*
  - *Low friction pressure*
  - *Controlled break*
  - *Non-damaging*
  - *Compatible with various quality mix waters*

Conventional Frac Fluids

- **Water Based**

Guar, HPG,CMHPG or CMG Polymer

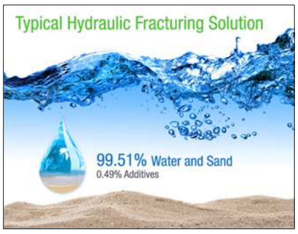
- *Slick Water*
- *Linear Gel*
- *Crosslinked Fluids (various crosslinkers)*
- *High pH and Low pH Fluids*
- *Low Polymer Systems*
- *Energized Systems*

Specialty Frac Fluids

- **Non-Aqueous**
  - *Hydrocarbon based*
  - *Methanol based*
  - *Liquid CO2*
  - *LPG*
- **Low Aqueous**
  - *N2 Foams, CO2 Foams, Binary Foams*
- **Fresh Water Alternatives**
  - *Recycled frac flowback / produced water*
  - *Formation brine*
  - *Sea Water*
- **Extreme Conditions**
  - *High Temperature*
  - *High Pressure*
  - *High Salinity*

Frac Fluids

- Why So Many Fluids:
  - Different Formations
    - Base Lithology
    - Additional Mineral Components
  - Different Formation Fluids
  - Different Objectives
  - Different Pumping Configurations
  - Etc.



Stimulation Additives

- **Polymers**
- **Buffering Agents**
- **Crosslinking Agents**
- **Breakers**
- **Surfactants**
- **Foaming Agents**
- **Bactericides**
- **Clay Control Agents**
- **Friction Reducers**
- **Fluid Loss Additives**
- **Diverting Agents**
- **Scale Inhibitors**
- **Gel Stabilizers**
- **Propping Agents**

Function of Fracturing Proppants

- Keep the fracture *Propped Open* throughout the created fracture area
  - *Across the length and height of the interval*
- Provide sufficient conductivity contrast to accelerate flow to the wellbore
  - *Provide permeable pathway*
  - *Maintain fracture width*
- Act as a diverting agent to aid development of complex fracturing

Types of Proppant


Ottawa Frac Sand


ULWP


Low Density Ceramic

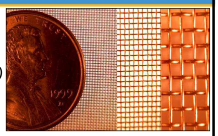

Brown Frac Sand

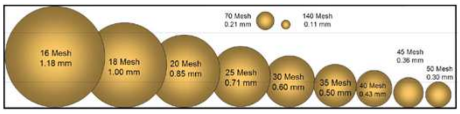

Resin-Coated Sand


Sintered Bauxite

Considerations Related to Proppant Type

- *Cost*
- *Strength vs Stress*
- *Size and Size Distribution*
- *Defined by mesh size (16/30, 20/40, 30/50, 40/70)*
- *Roundness*
- *Concentration*
- *Embedment*
- *Debris (fines)*
- *Elasticity or Deformation*


Mesh refers to the number of openings per inch



SPE 110679

Proppant Transport Challenges

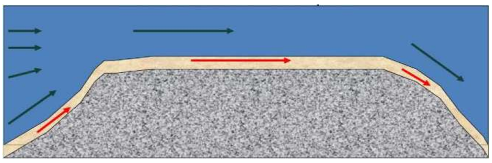
Place proppant across maximum created fracture area

- Less dense proppants are easier to transport
  - *Trade-off - typically insufficient strength*
- Smaller diameter proppants are easier to transport
  - *Trade-off - reduced permeability*
- Increased fluid viscosity can improve transport
  - *Tradeoff - damage from fluid residuals*
- Increasing fluid Specific Gravity can improve transport
  - *Tradeoff - difficulty recovering load fluid*
- Proppant holdup, proppant bridging

Thin-Fluid Transport

It is different from Suspension Transport

Proppant drops out of fluid quickly. All solid transport is in a thin "traction carpet".



Barree&Associates

Bank height builds to an equilibrium based on fluid velocity. A clear fluid layer is maintained above the settled bank. The bank advances by "dune building"

Slick Water or Crosslinked Gel?

Conventional fracturing - crosslinked fluid systems

to carry proppant deep into the fracture

- **Advantages:**
  - *Easy on equipment*
  - *Good proppant transport*
  - *Low friction pressure*

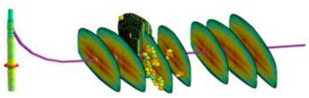
Slick Water Fracturing

- Water with friction reducer (linear gel – hybrid fracs)
- No proppant transport capabilities
  - *Rely purely on turbulent flow*
  - *Hard on equipment!*

- **Advantages**
  - *Cheap*
  - *Quick fluid recovery*
  - *Operationally simple*
  - *In certain formations, might produce better height containment*

Shale Frac Rules of Thumb (are there any?)

- **Distance between frac stages = 1 to 1.5 x zone height (250 – 350ft)**
- **Distance between perf clusters = 35 to 75+ ft**
- **Length of perf cluster = 1 to 2 ft**
- **# of perf clusters in each stage is 4 to 8 (roughly 1.5 bpm/perf 10-20 bpm per cluster)**
- **# stages – depends on lateral length, 10 to 40+**
- **Slickwater / Linear Gel / Hybrid / Cross-linked**
- **Great variations of Fluid and Proppant Volumes**



Contact within Formation

Slick Water / Linear Gel Treatment

- **Dry Gas shale or wells with low liquid content**
  - High rates +100 bpm (carry proppant)
  - Link up natural fractures using low proppant concentrations in low vicousity fluid
  - Infinite conductivity to gas but limited conductivity to liquids

Marcellus, Barnett, Fayeteville

Hybrid Frac Treatment

- **Gas/condensate/liquids shales with significant liquid content**
  - Combination of liner and cross-linked gel
  - Lower treatment rates, 60-80 bpm
  - Create a more conductive fracture to enhance liquids recovery.

Eagle Ford, Utica

Crosslinked Frac

- **Oil bearing shale or wells with higher oil/gas ratios**
  - Reduced rates 40-60 bpm
  - Higher proppant concentrations, larger proppant mesh size
  - Create a highly conductive fracture to maximize liquids recovery.

Bakken, Eagle Ford, Niobrara

Q&A Break

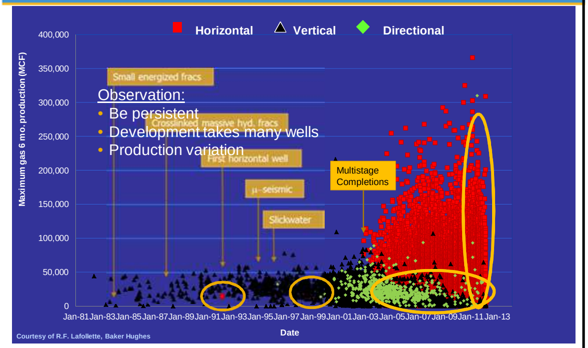
Poll Question

Which do you think is the best fluid for unconventional formations?

a) Slick Water
b) Hybrid
c) Crosslinked
d) It depends on the application

Unconventional Development – Learning Curve

Barnett Shale Development



56

When Production Results Fall Short

Many operators are struggling with lower than expected or inconsistent production results

1 in 4 frac jobs do not meet performance expectations*

73% of operators admit they don't know enough about the subsurface to develop an effective fracture design*

Only 10% of the 15,000 horizontal wells drilled annually in the US are logged**

As a result, only 40% of all frac stages contribute to production***

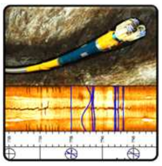
Effectiveness and Efficiency are the KEY

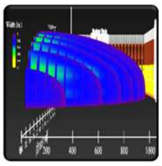
*Welling, 2012
**SPE Workshop Prague, 2012
***E&P, 2012, 2013

57

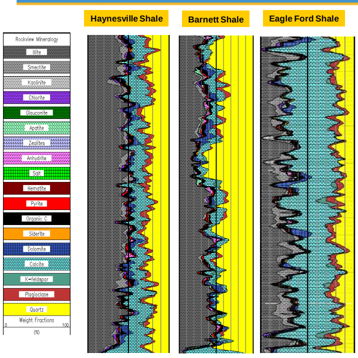
Three Critical Decisions Can Impact Recovery


Selecting the optimal interval for lateral placement

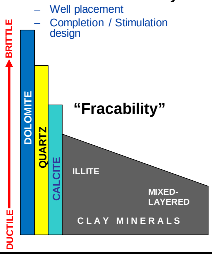

Placing frac stages in optimal zones along the lateral


Designing fractures with optimal conductivity, proppant distribution and reservoir contact

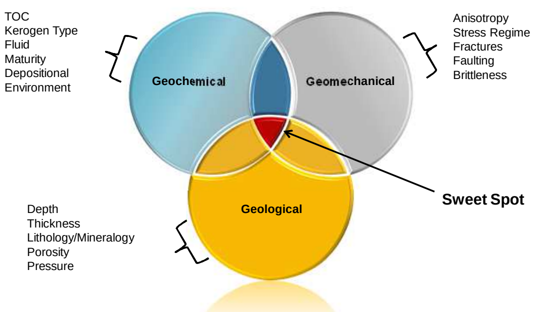
Shale Reservoir Lithology and Mineralogy

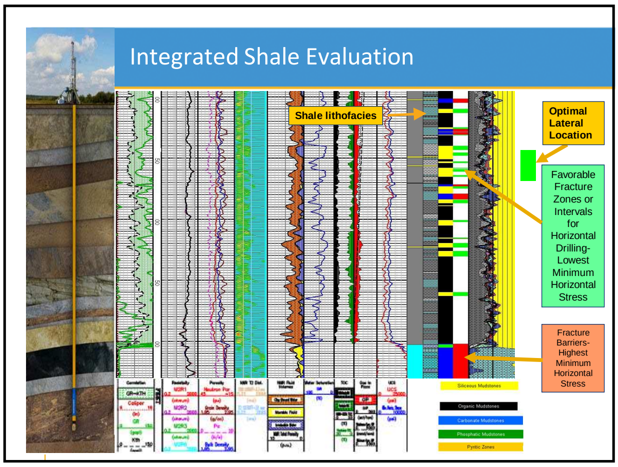


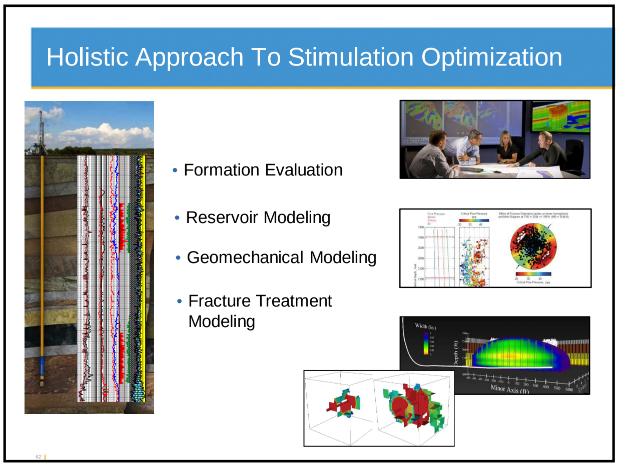
- **Shales** are DIFFERENT:
  - Mineralogy
  - Lithofacies
  - Geomechanical properties
  - Porosity
  - TOC
- **Production driven by**:
  - Well placement
  - Completion / Stimulation design

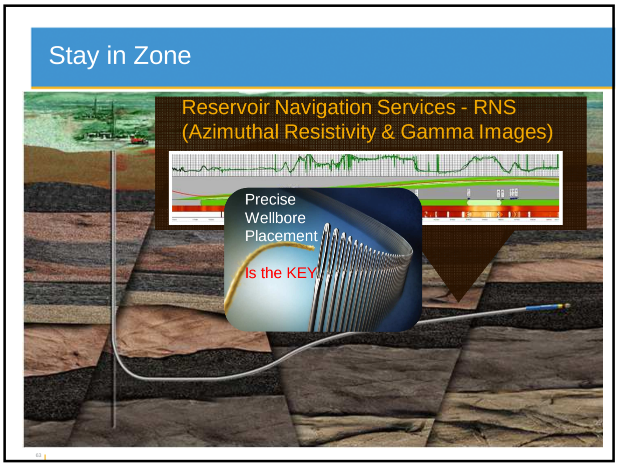


Unconventional Sweet Spot Characteristics




Integrated Shale Evaluation
Shale lithofacies
Optimal Lateral Location
Favorable Fracture Zones or Intervals for Horizontal Drilling- Lowest Minimum Horizontal Stress
Fracture Barriers- Highest Minimum Horizontal Stress


Holistic Approach To Stimulation Optimization
• Formation Evaluation
• Reservoir Modeling
• Geomechanical Modeling
• Fracture Treatment Modeling


Stay in Zone
Reservoir Navigation Services - RNS
(Azimuthal Resistivity & Gamma Images)
Precise Wellbore Placement
Is the KEY!

Identify and Evaluate The Right Stimulation Zones

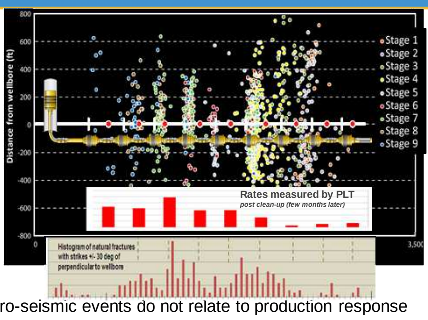
Reduce uncertainty
with accurate reservoir characterization

Reduce costs
by optimizing wellbore placement and completion design

Increase production
by precisely identifying stimulation zones

- Porosity
- Permeability
- Water saturation
- Mineralogy
- Shale lithofacies
- Total organic content
- Level of maturity
- Hydrocarbon-in-place
- Fracture characterization
- Geomechanical rock properties
- Pressure gradient
- Stress regime
- Siliceous brittleness index

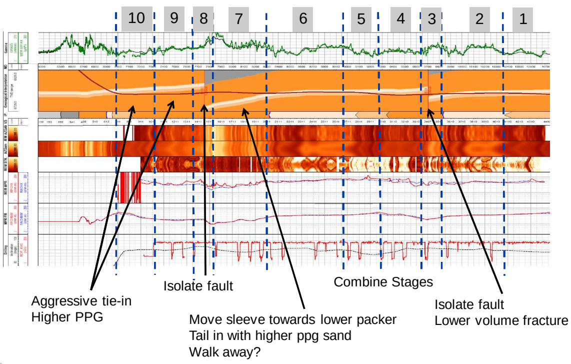
Stage Optimization



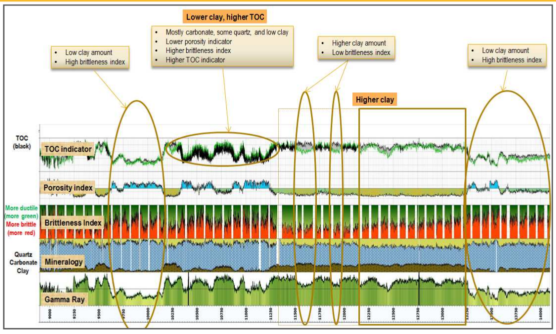
- Micro-seismic events do not relate to production response
- Do all micro-seismic events relate to fluid presence?
- Production seems dependent on natural fractures

CSUG/SPE 146912

Completion Recommendations



Layout With Frac Stage Locations



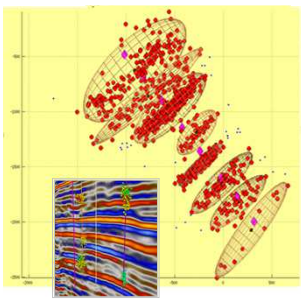
67

Fracture Treatment Monitoring Methods

- **Conventional Temperature and Tracer Surveys**
  - *Data near well-bore vicinity*
  - *Fluids & proppants 'traced'*
- **Distributed Temperature Sensing (DTS)**
  - *Fiber Optics*
- **Distributed Acoustic Sensing (DAS)**
  - *Fiber Optics*
- **Production Logging**
  - *Spinner surveys*
  - *Flow & Temperature*
- **Microseismic Monitoring**
  - *During fracture treatment / Near real-time*
  - *Managing treatment and post-treatment analysis*
  - *Recording sondes placed in nearby observation well*
  - **Currently most frequently used/effective Monitoring Method**

68

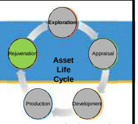
Microseismic Monitoring



- Real-time microseismic monitoring is useful for in-job decisions:
  - *Alert to approaching hazards Faults, Karsts, Wet zones*
  - *Confirm diversion efficiency*
- Microseismic fracture mapping may provide information about the created fractures:
  - *Geometry & azimuth*
  - *Fracture density*
  - *Stimulated reservoir volume*
  - *Reservoir stress orientation*
- Information is most useful for optimization of subsequent treatments

69

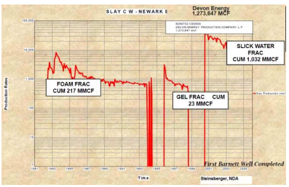
Rejuvenation



Courtesy of Baker Hughes

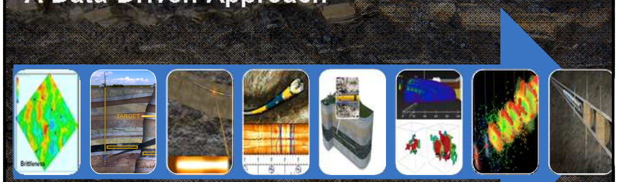
Evaluate Wells for Re-Frac

- Unconventional wells **decline rapidly** to low rates after only few years (**65-85% in 1st Year**)



- **Initial Frac Treatments Fail** over time:
  - Fractures closing or plugging
  - Proppants crushed, embedded, or flowed back into well
  - Reorientation of stress field after well being produced
  - Improper initial Frac fluid

A Data-Driven Approach



Delineate Sweet Spots

High-Grade Acreage

Optimize Lateral Placement

Drilling Precision and Efficiency

Characterize The Lateral

Effective Wellbore Completions

Optimize Fracture Design

Monitoring and Refining Fracture Performance

Improve Ultimate Recovery

To Optimize Recovery and Maximize Value

Q&A Break

Poll Question

Which do you think is the best fluid for unconventional formations?

a) Slick Water
b) Hybrid
c) Crosslinked
d) It depends on the application