Best Practices in Hydraulic Fracturing

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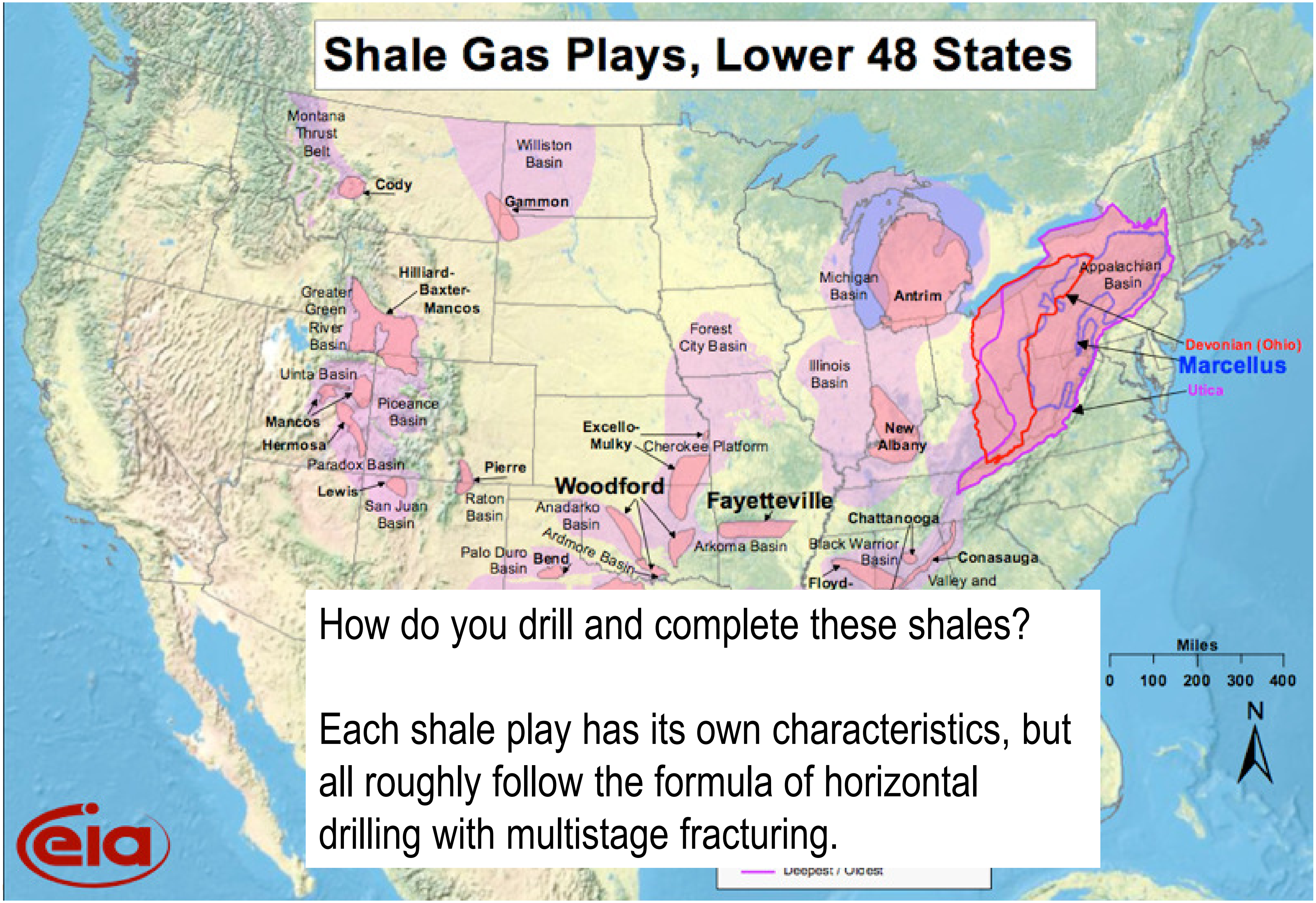
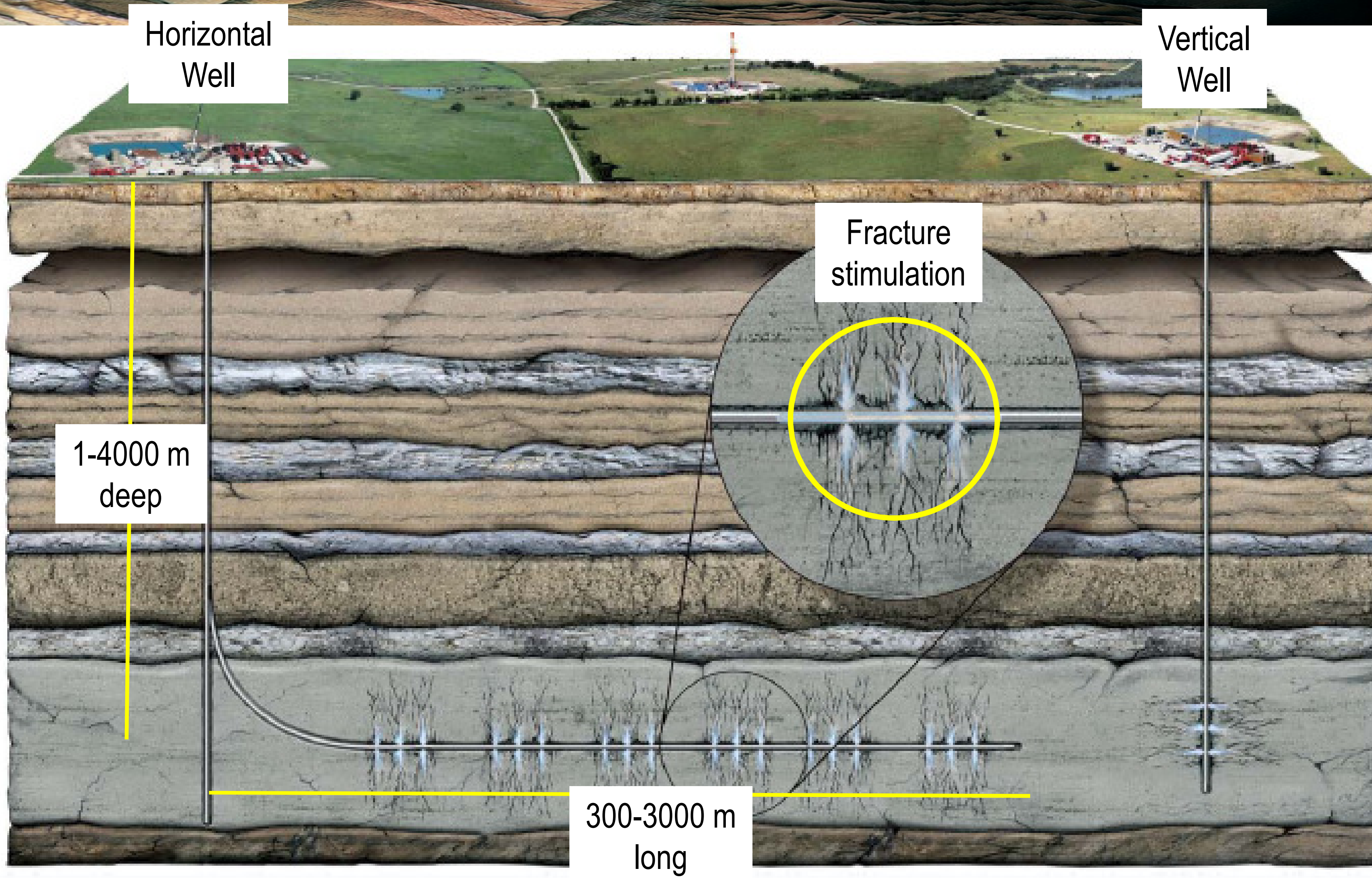


How do you drill and complete these shales?

Each shale play has its own characteristics, but all roughly follow the formula of horizontal drilling with multistage fracturing.

Stimulating a Horizontal Shale Well



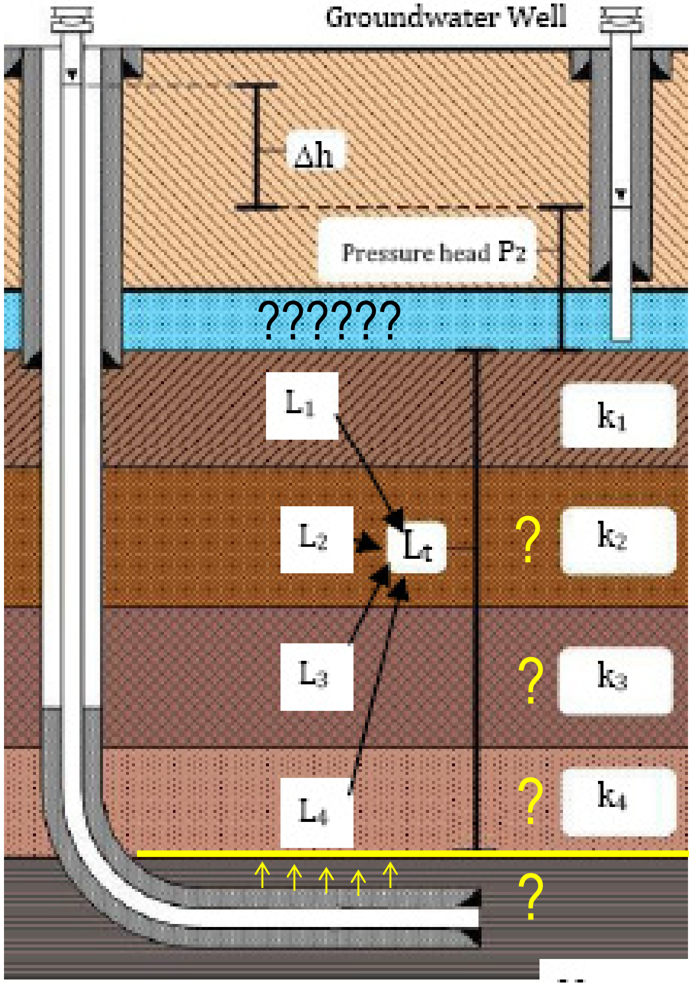
3 Key Elements of Horizontal Fracturing

1. Water fracs
2. Microseismic Mapping
3. Mechanical Isolation

Fracturing animation

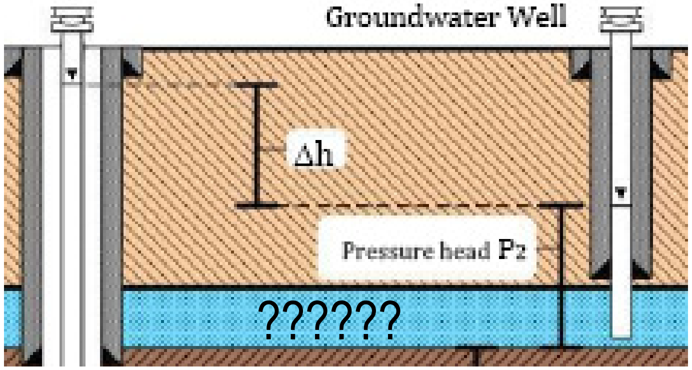
What Should be Done Prior to Horizontal Drilling?

1. Establish a baseline of potential contaminants in aquifers
   - Natural gas
   - Natural dissolved solids
   - Identification of pre-existing pollution
2. Identify barriers to hydraulic frac growth in the reservoir
3. Construct a reservoir model, including mechanical properties of rocks, identification of natural fractures, amount and type of hydrocarbons
4. Water sources and disposal
5. Logistics



Colorado Required Initial Baseline Testing

(4) Water well sampling. The Director shall require ***initial baseline testing*** prior to the first interior infill well or boundary well ("proposed GWA infill well") drilled within a governmental section. The following shall be used as guidance for the Director in establishing initial baseline testing:

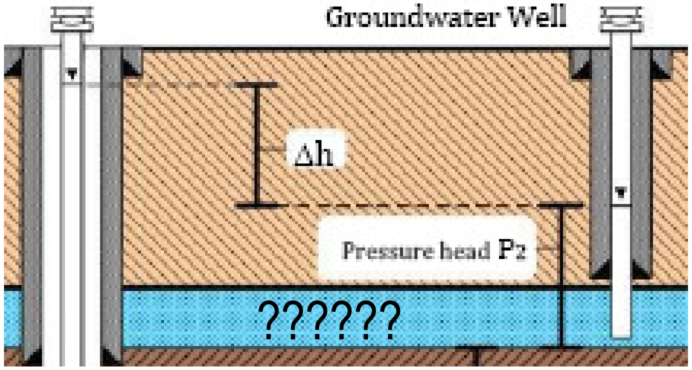


A. Within the governmental quarter section of the proposed GWA infill well, ***the closest water well*** ("water quality testing well") completed in the Laramie/Fox Hills Aquifer shall be sampled.

Colorado Required Initial Baseline Testing

E. Initial baseline testing shall include laboratory analysis of all ***major cations and anions***, ***total dissolved solids, iron and manganese***, ***nutrients (nitrates, nitrites, selenium)***, ***dissolved methane***, pH, and specific conductance.

F. If ***free gas*** or a ***methane concentration level greater than 2 mg/l*** is detected in a water quality testing well, compositional analysis shall be performed to determine gas type ***(thermogenic***, ***biogenic*** or an intermediate mix of both). If the testing results reveal biogenic gas, no further isotopic testing shall be required. If the testing results reveal thermogenic gas, carbon isotopic analyses of methane carbon shall be done



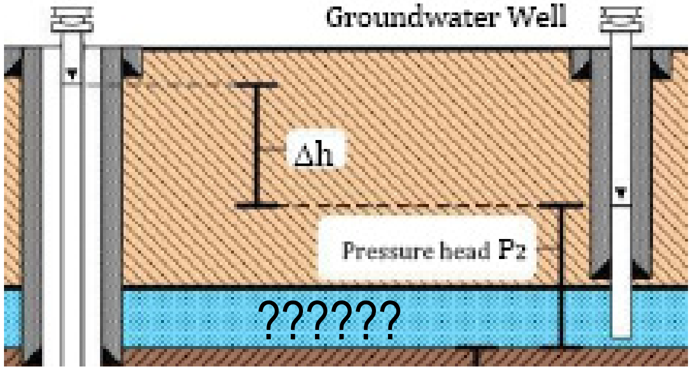
Colorado Required Initial Baseline Testing

Thermogenic gas is formed at deeper depths by:

(1) thermal cracking of sedimentary organic matter into hydrocarbon liquids and gas and

(2) thermal cracking of oil at high temperatures into gas

thermogenic gas can be dry, or can contain significant concentrations of "wet gas" components (ethane, propane, butanes) and condensate (C_{5+} hydrocarbons)



Biogenic gas is formed at shallow depths and low temperatures by anaerobic bacterial decomposition of sedimentary organic matter.

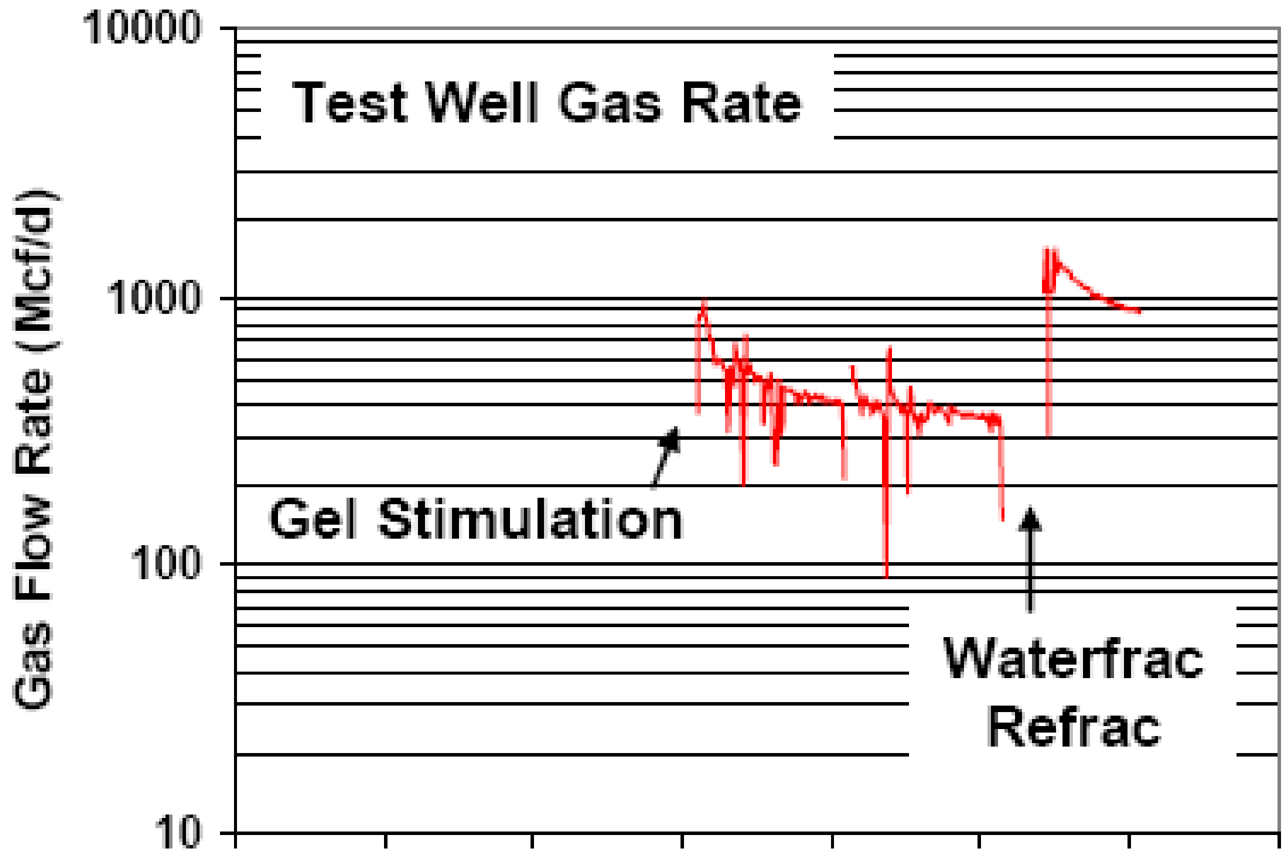
Biogenic gas is very dry (i.e., it consists almost entirely of methane).

Fracturing Fluids

Waterfracs

- Slickwater (water with friction reducer)
- Low sand concentrations
- 1- 5 million gallons per frac
- Low fluid loss

Why Waterfrac? And look at the Refrac!!!



SPE 95568 (Devon)

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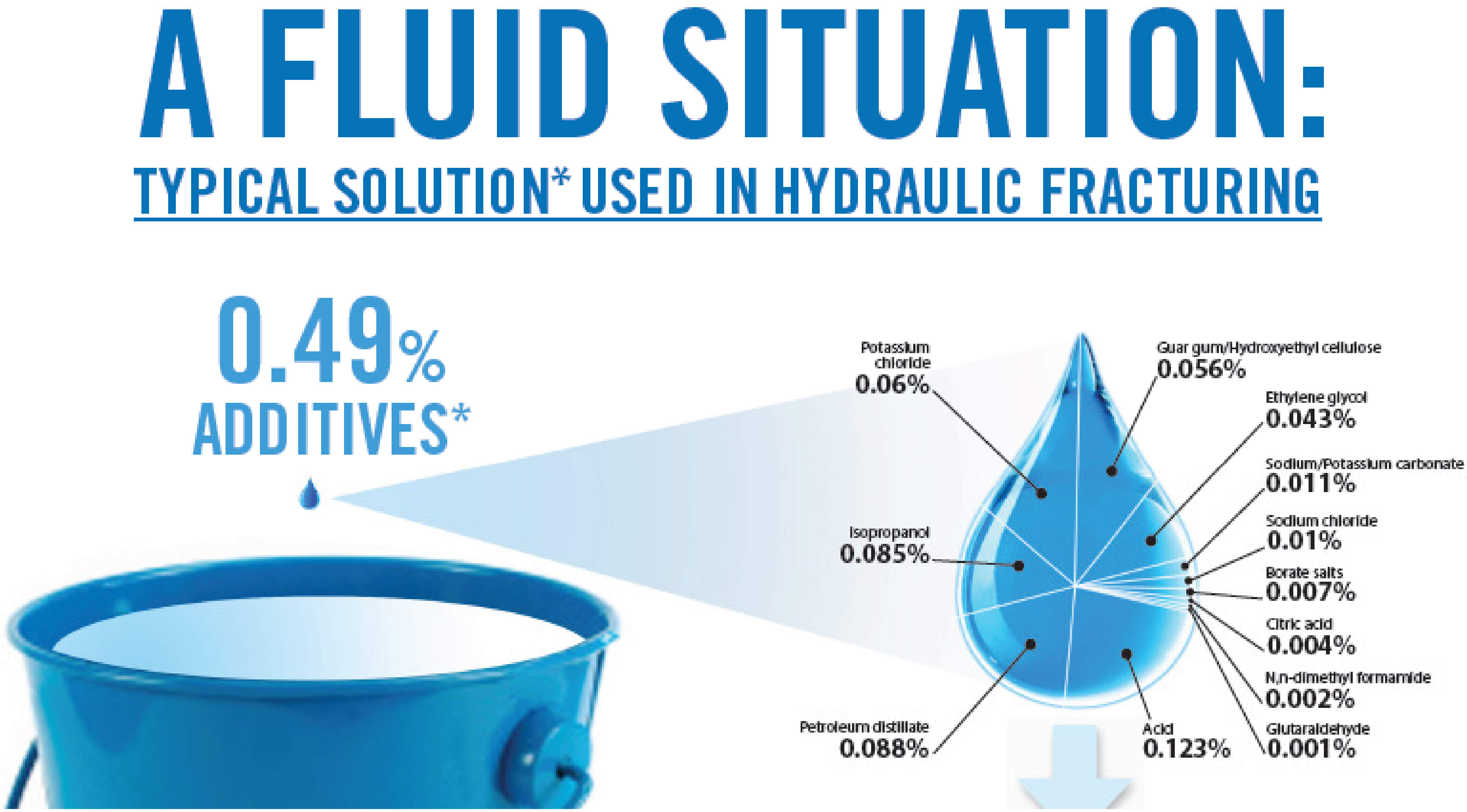
Water Frac Fluids

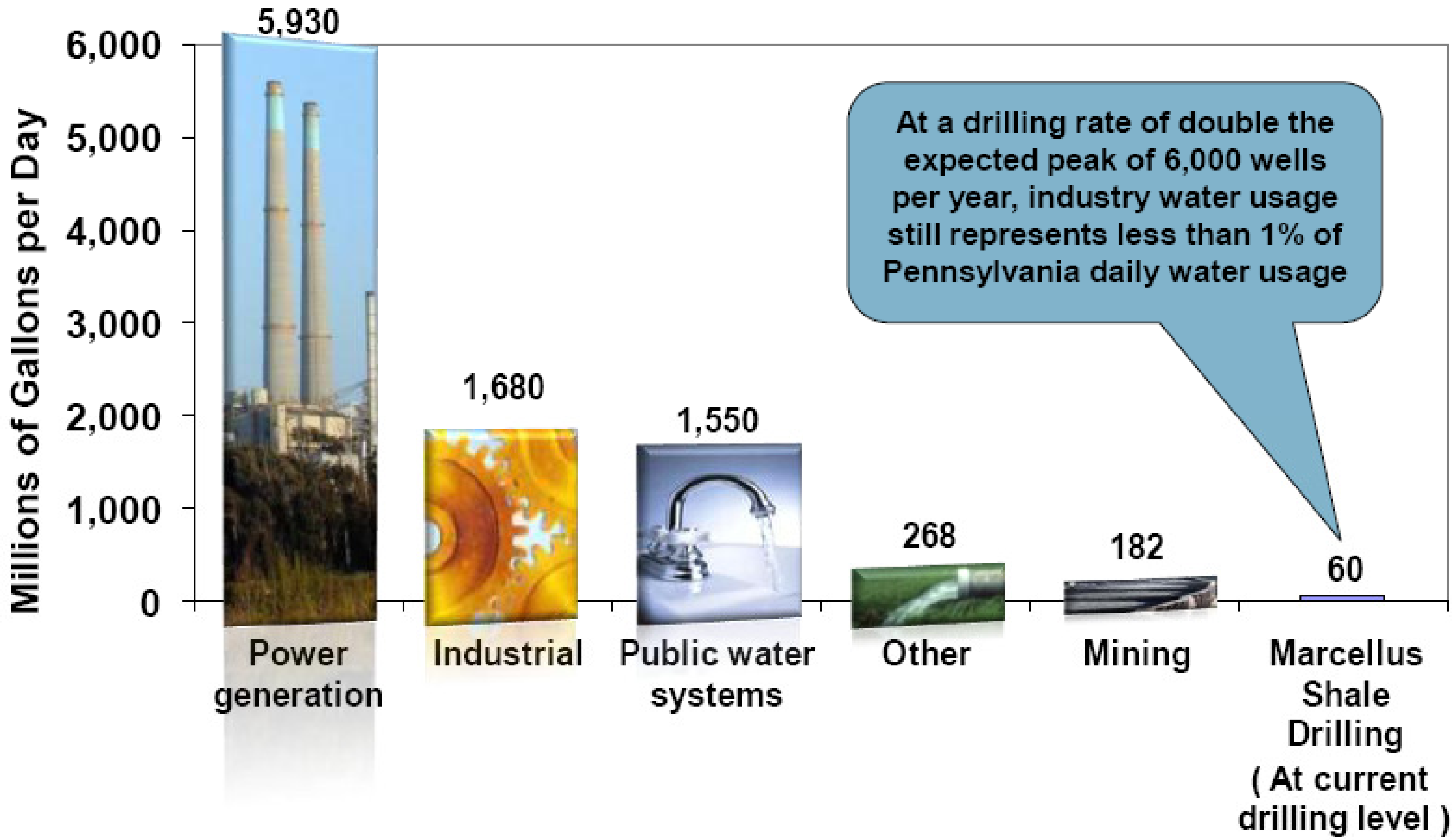


Water Frac Fluid Additives

- Additives are driven to being “green”
- The less impact on the environment, the less public resistance to “fracking”.

Compound*	Purpose	Common application
Acids	Helps dissolve minerals and initiate fissure in rock (pre-fracture)	Swimming pool cleaner
Glutaraldehyde	Eliminates bacteria in the water	Disinfectant; Sterilizer for medical and dental equipment
Sodium Chloride	Allows a delayed break down of the gel polymer chains	Table Salt
N, n-Dimethyl formamide	Prevents the corrosion of the pipe	Used in pharmaceuticals, acrylic fibers and plastics
Borate salts	Maintains fluid viscosity as temperature increases	Used in laundry detergents, hand soaps and cosmetics
Polyacrylamide	Minimizes friction between fluid and pipe	Water treatment, soil conditioner
Petroleum distillates	"Slicks" the water to minimize friction	Make-up remover, laxatives, and candy
Guar gum	Thickens the water to suspend the sand	Thickener used in cosmetics, baked goods, ice cream, tooth-paste, sauces, and salad dressing
Citric Acid	Prevents precipitation of metal oxides	Food additive; food and beverages; lemon juice
Potassium chloride	Creates a brine carrier fluid	Low sodium table salt substitute
Ammonium bisulfite	Removes oxygen from the water to protect the pipe from corrosion	Cosmetics, food and beverage processing, water treatment
Sodium or potassium carbonate	Maintains the effectiveness of other components, such as crosslinkers	Washing soda, detergents, soap, water softener, glass and ceramics
Proppant	Allows the fissures to remain open so the gas can escape	Drinking water filtration, play sand
Ethylene glycol	Prevents scale deposits in the pipe	Automotive antifreeze, household cleansers, deicing, and caulk
Isopropanol	Used to increase the viscosity of the fracture fluid	Glass cleaner, antiperspirant, and hair color

How Water Usage Stacks Up in Pennsylvania



Source: USGS, Pennsylvania Water Consumption

Geologic Considerations

What is a Shale?

Now we are trying to produce this shale that is ~1000 times less permeable than tight sands.

And a million times less permeable than conventional Sands.

“milliDarcy”	“microDarcy”	“nanoDarcy”
~0.1 to 10,000 mD	~0.001 to 0.1 mD	~0.000,010 to 0.001 mD

Courtesy, Mike Vincent, consultant

What is a ***Desirable*** Gas Shale?

Brittle Shale (Complex Fracturing):

low Poisson's Ratio & high Young's Modulus
moderate Clay content : < 40%
bounded by frac barriers

Gas-in-place (Bcf per square mile) :

30 is good, 150 is better

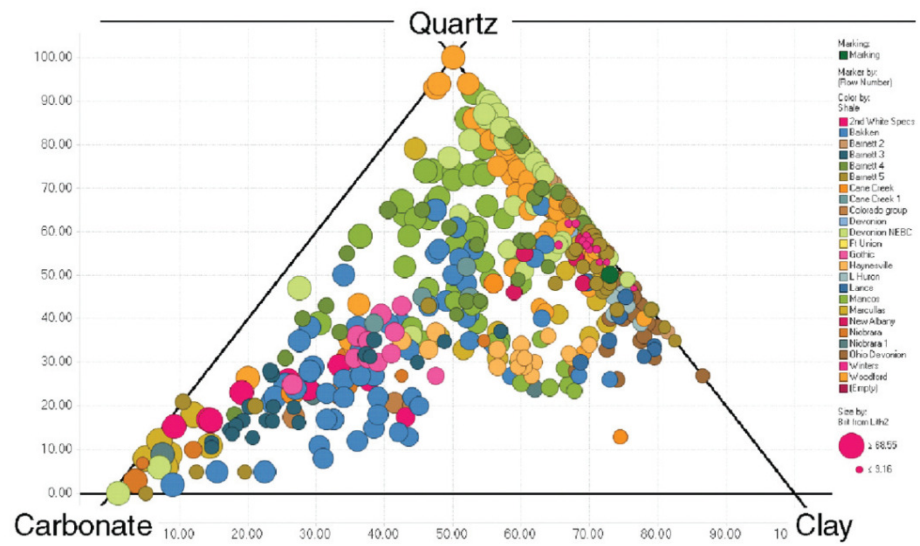
Permeability greater than 100 nanodarcies

Porosity: > 4%

TOC: >2% (1-3% is typical, 5-15% is great)

Moderate Water Saturation < 45%

Thick zone : >100 ft



Courtesy, Halliburton

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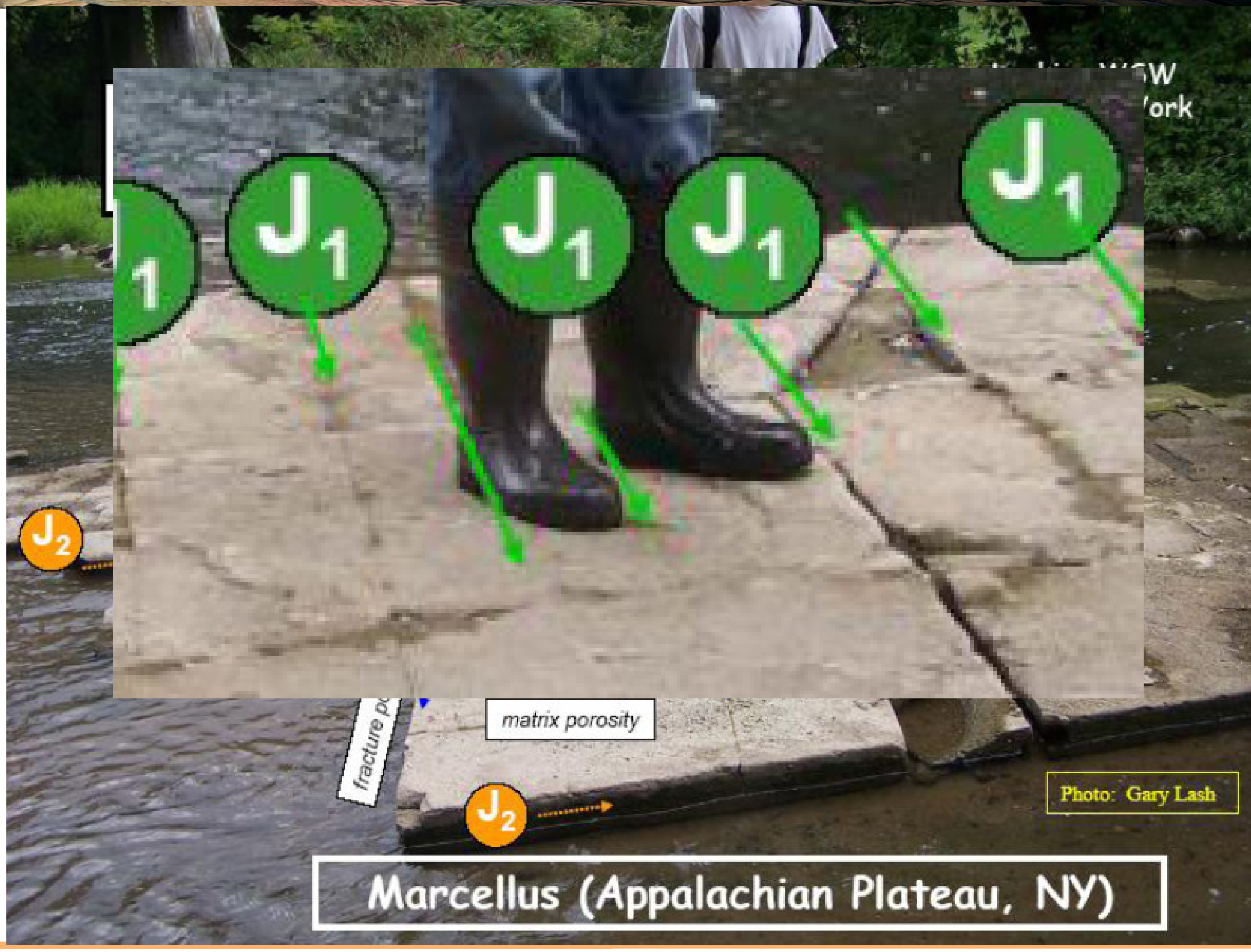
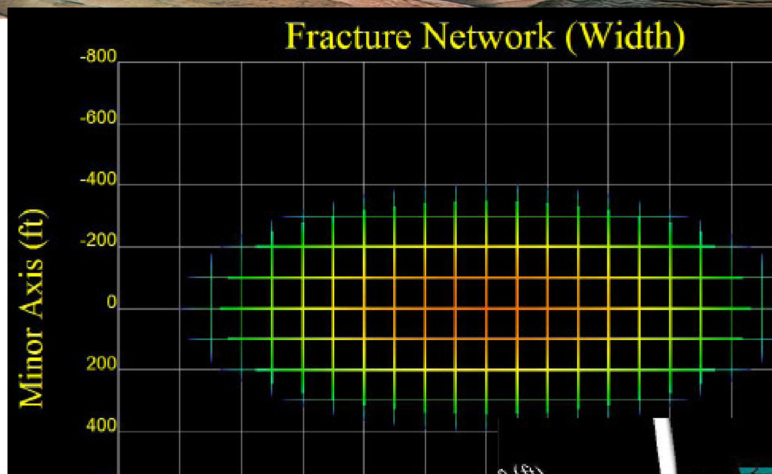
Natural Fracture Networks Are a Key



We Predict a Stimulated Reservoir Volume



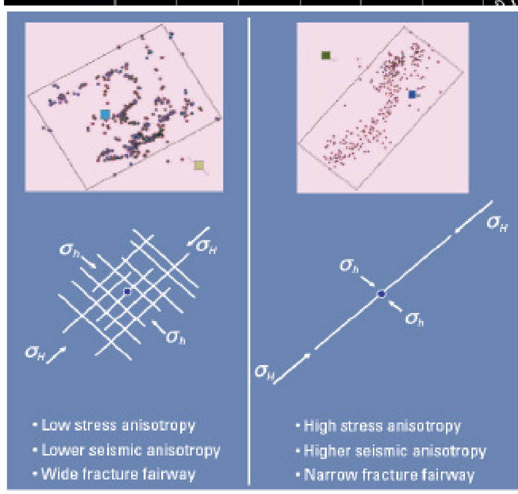
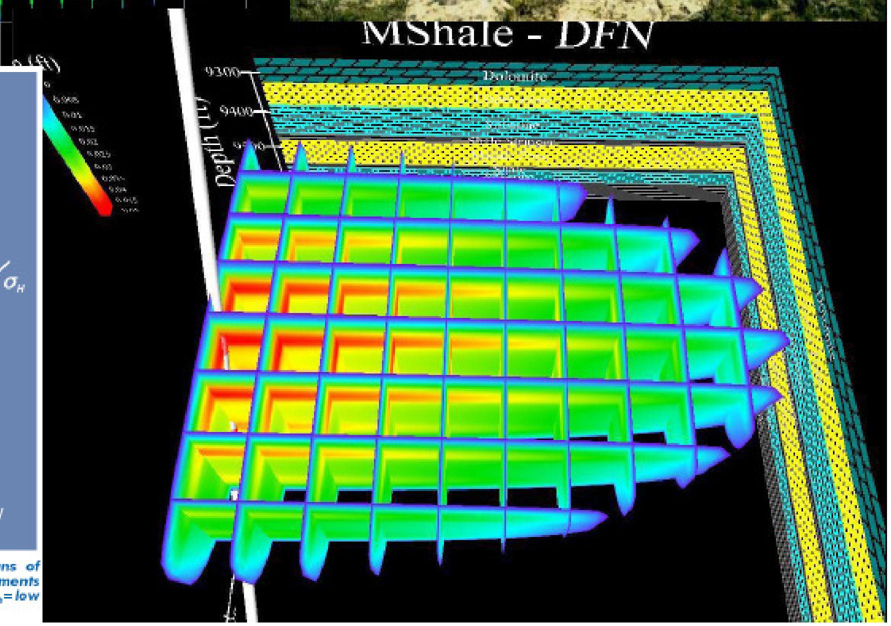


Fig. 4—Contrasting fracture-fairway geometries shown by means of microseismic mapping, confirming stress-anisotropy measurements acquired with a 3D sonic scanner tool, where σ_H=high stress and σ_h= low stress. (Image courtesy of Schlumberger.)

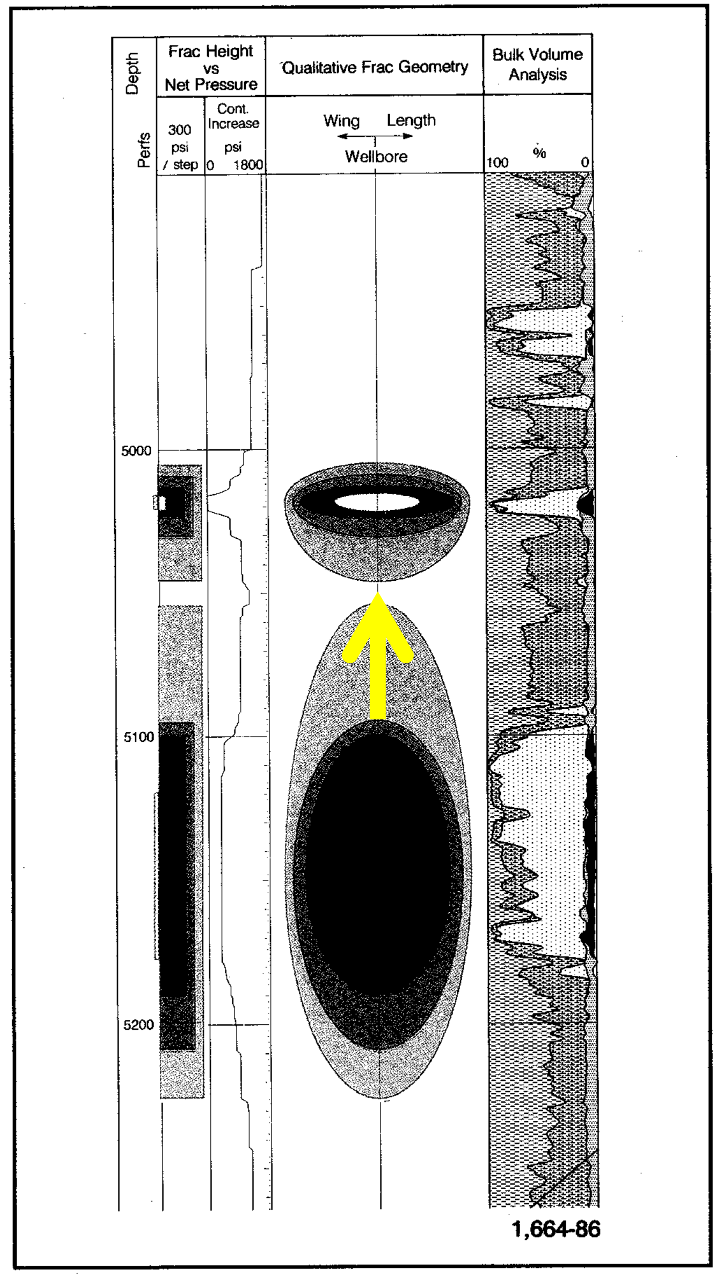


What about Vertical Heterogeneity?

Prediction of Barriers to Fracture Growth

The Di-Pole Sonic log predicts the mechanical properties of the rock by measuring the compressional and shear waves in formations that the wellbore has been drilled through

This can then be used to predict at what pressure surrounding rocks will fracture, and fracture growth will, or will not be contained



Determination of Fracture Barriers

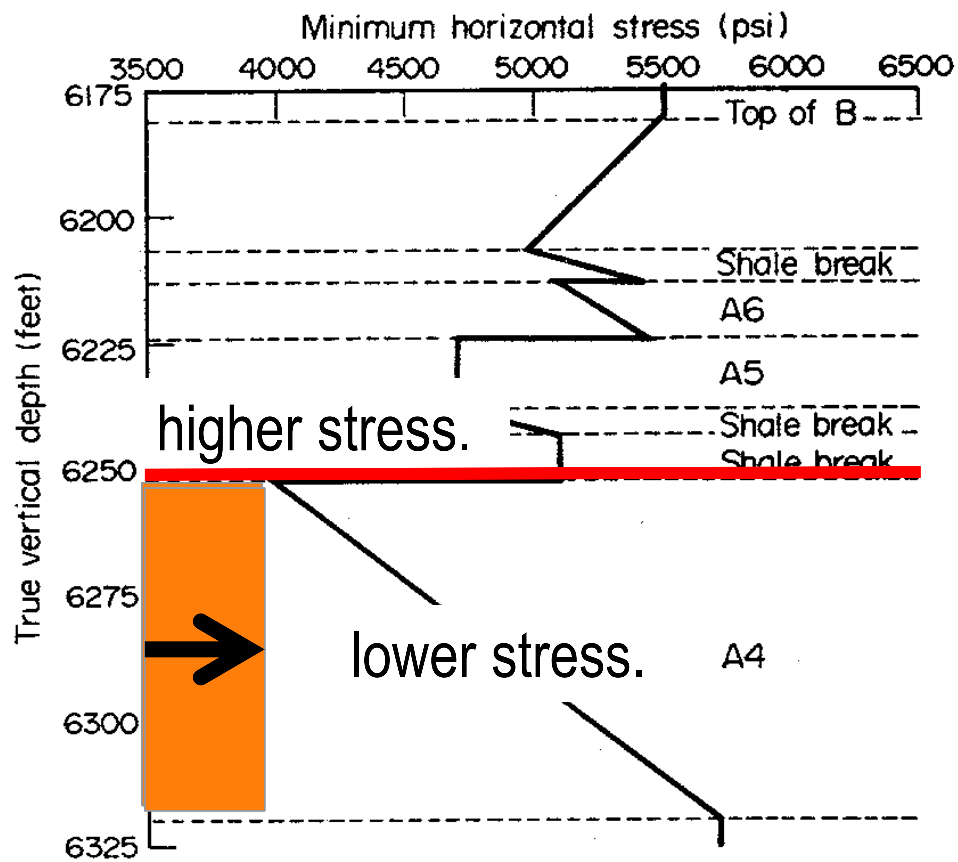
Most induced fractures are vertical and are driven toward lower horizontal stress.

For instance a fracture growing in A4

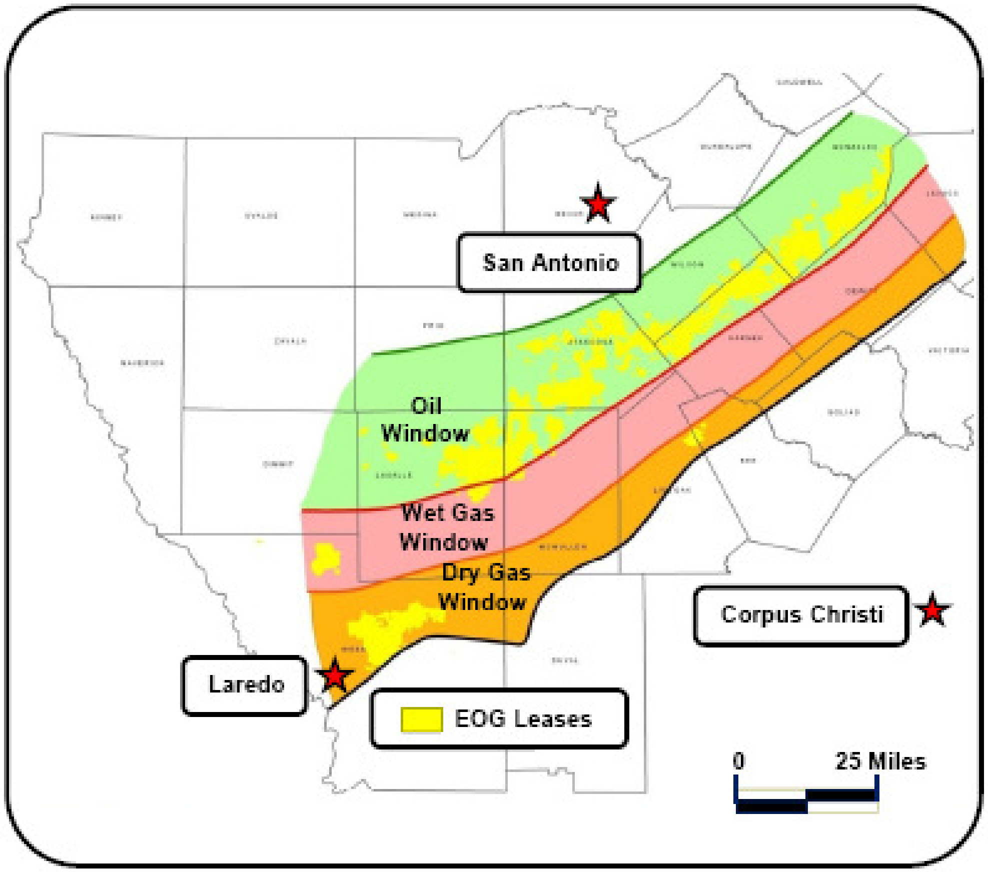
will have a difficult time breaking across the shale above, which is higher stress (in red), and instead will move to the lower stress and stay in zone.

To predict where the fracture goes, you must predict what the stresses are, and for this, you need to know what the rock properties are

The rock properties, such as Poisson's ratio and Young's Modulus, must be determined from cores or logs.



Shales May Have Gas, Wet Gas, or Oil



Eagleford Trend, South Texas (Source – EOG)

Why is wet gas so important?

$5.00 NYMEX equates to $7.28 per mcf price

$5.00 NYMEX Henry Hub
$75.00 NYMEX WTI
Based on 9/09 Gas Quality (1)
Assumes Cryogenic Only

Wellhead Production
1 mcf of Natural Gas

	Natural Gas & Ethanes	NGLs	Condensate
Production by product	.900 mcf	2.450 gallons/mcf	.013 bbls/mcf
Gross realized by product	$4.96 net	$1.62 net (2)	$0.69 net
		$7.28 per mcf	
Gathering, transportation and operating expenses		$0.75 to $1.75	Will decline over time as volumes increase

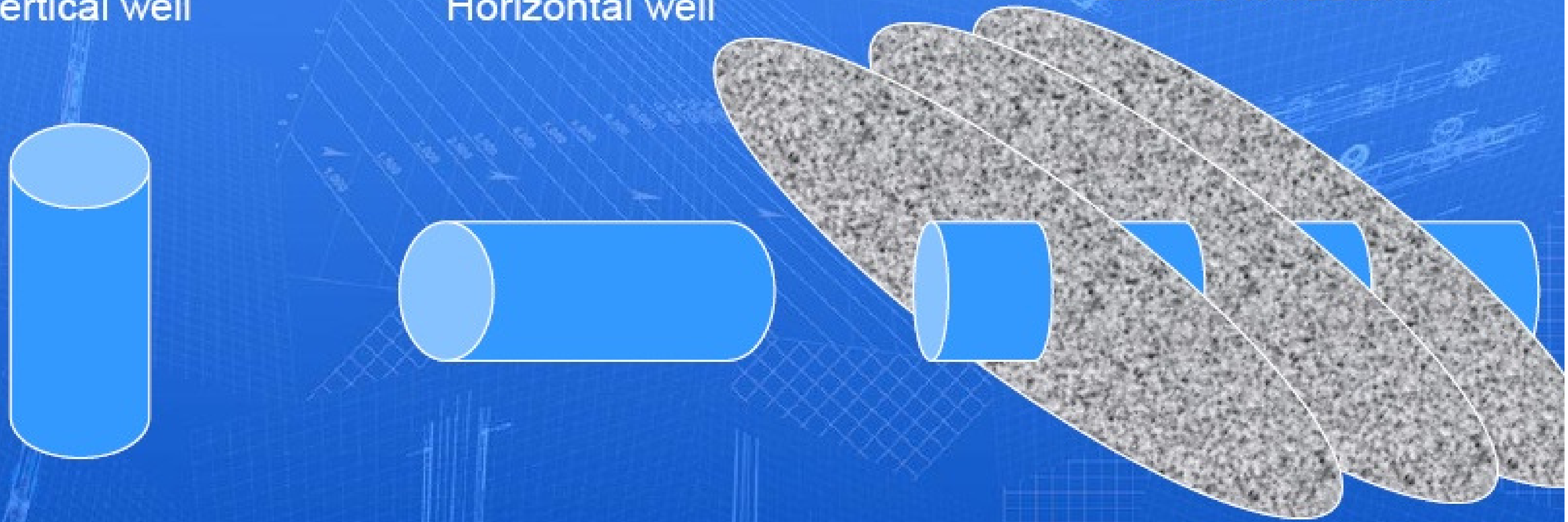
Horizontal Completion Technology

Why not just a horizontal well?

100 ft
Vertical well

2,000 ft
Horizontal well

2,000 ft
Horizontal well with
10 x150 ft fractures



160 ft^2 of contact

3,207 ft^2 of contact

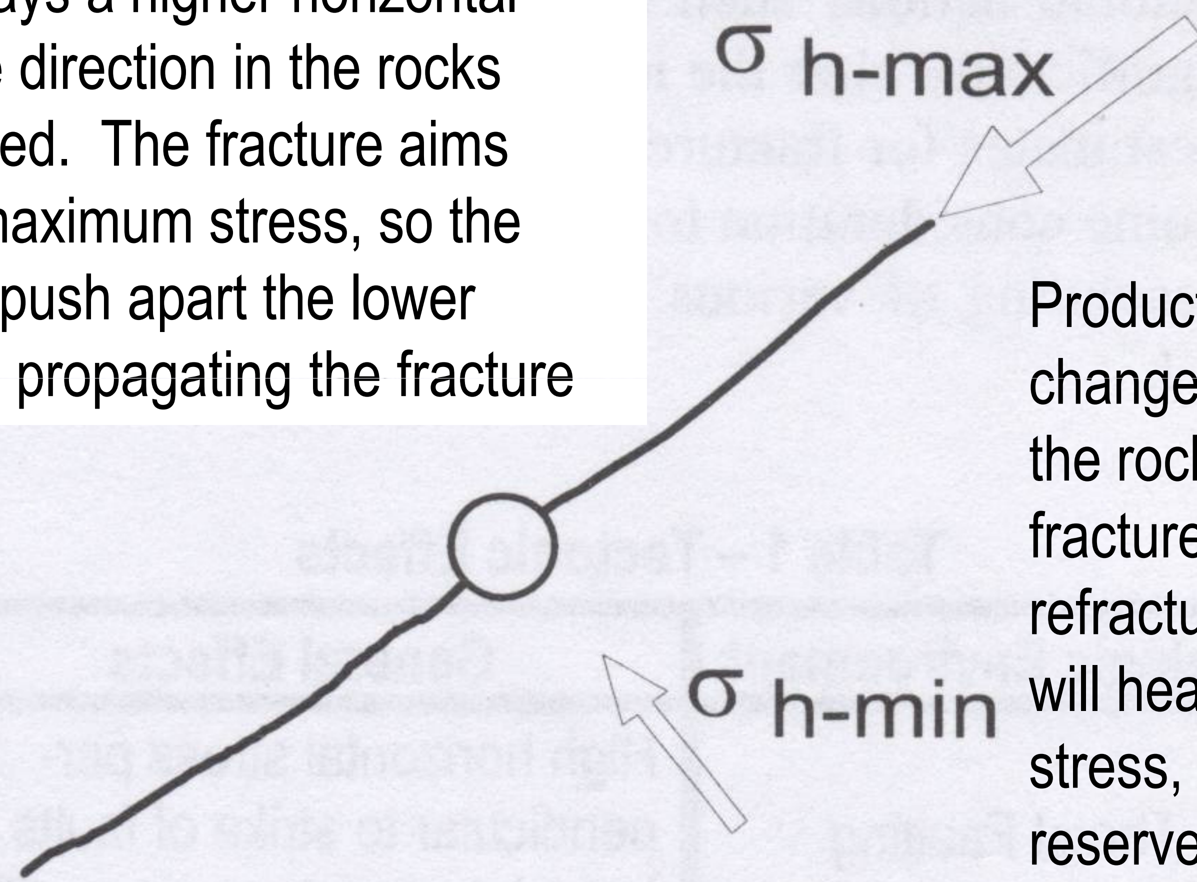
20 x vertical

153,207 ft^2 of contact

957 x vertical
48 x horizontal

Fracture Design Stress Effects

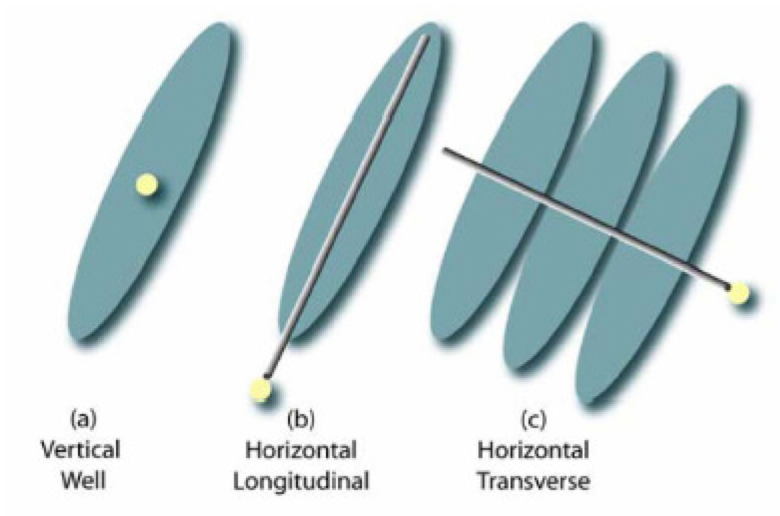
There is always a higher horizontal stress in one direction in the rocks being fractured. The fracture aims toward the maximum stress, so the fracture can push apart the lower stress rocks, propagating the fracture

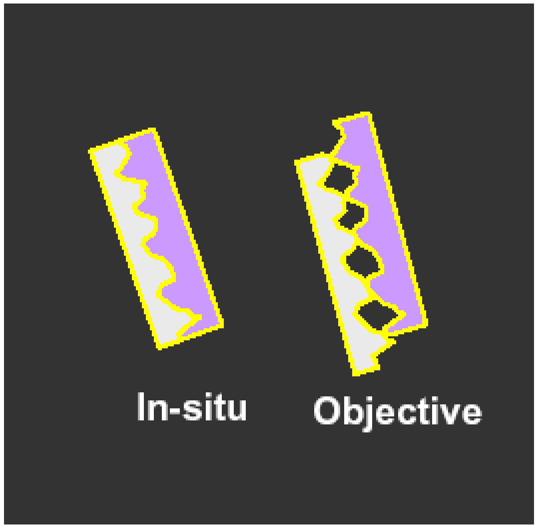


Production may change the stress in the rock. A new fracture formed from refracturing the rock, will head to high stress, and new reserves

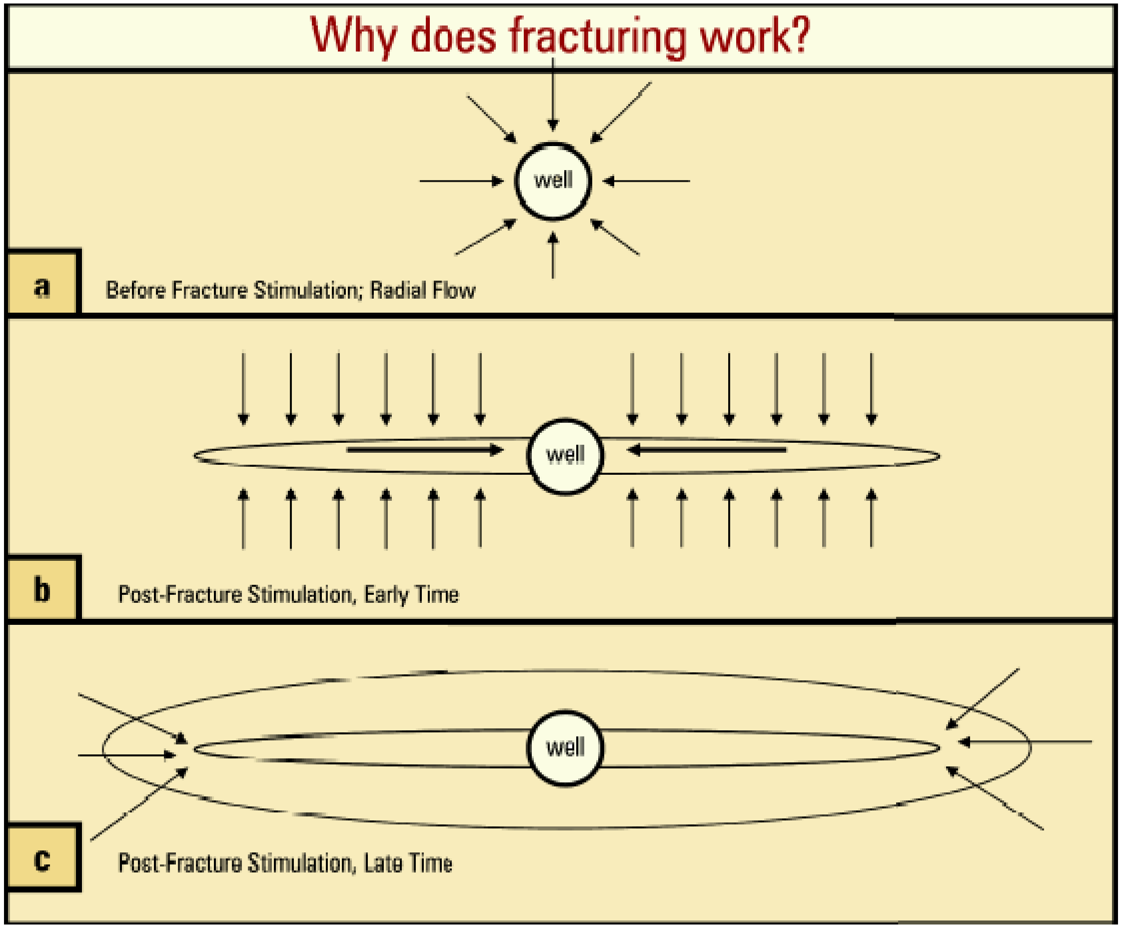
Waterfracs – Transverse Orientation

- Transverse fracs better than longitudinal
- Potential to activate existing fracture systems
- Paleofracture orientation?

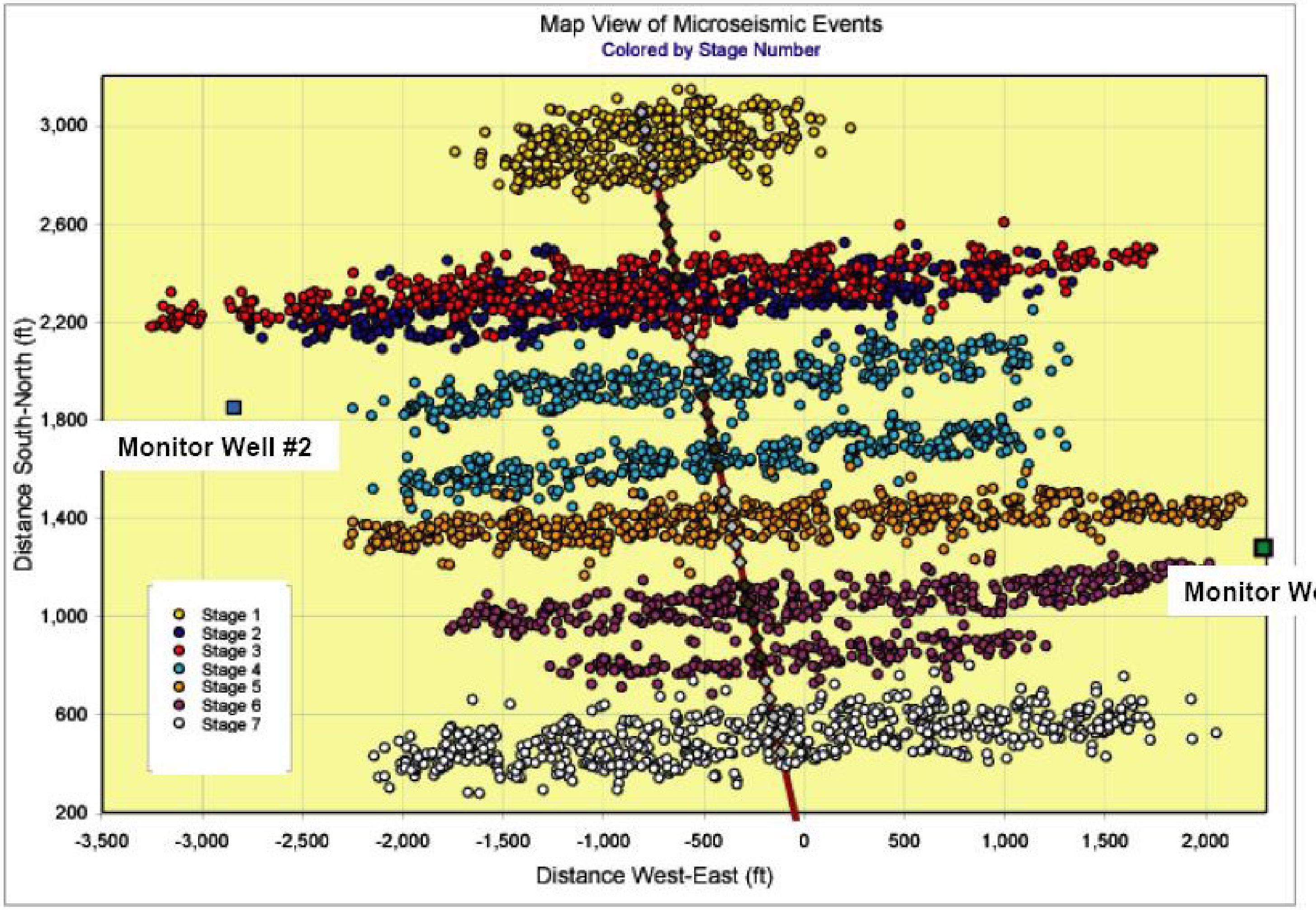




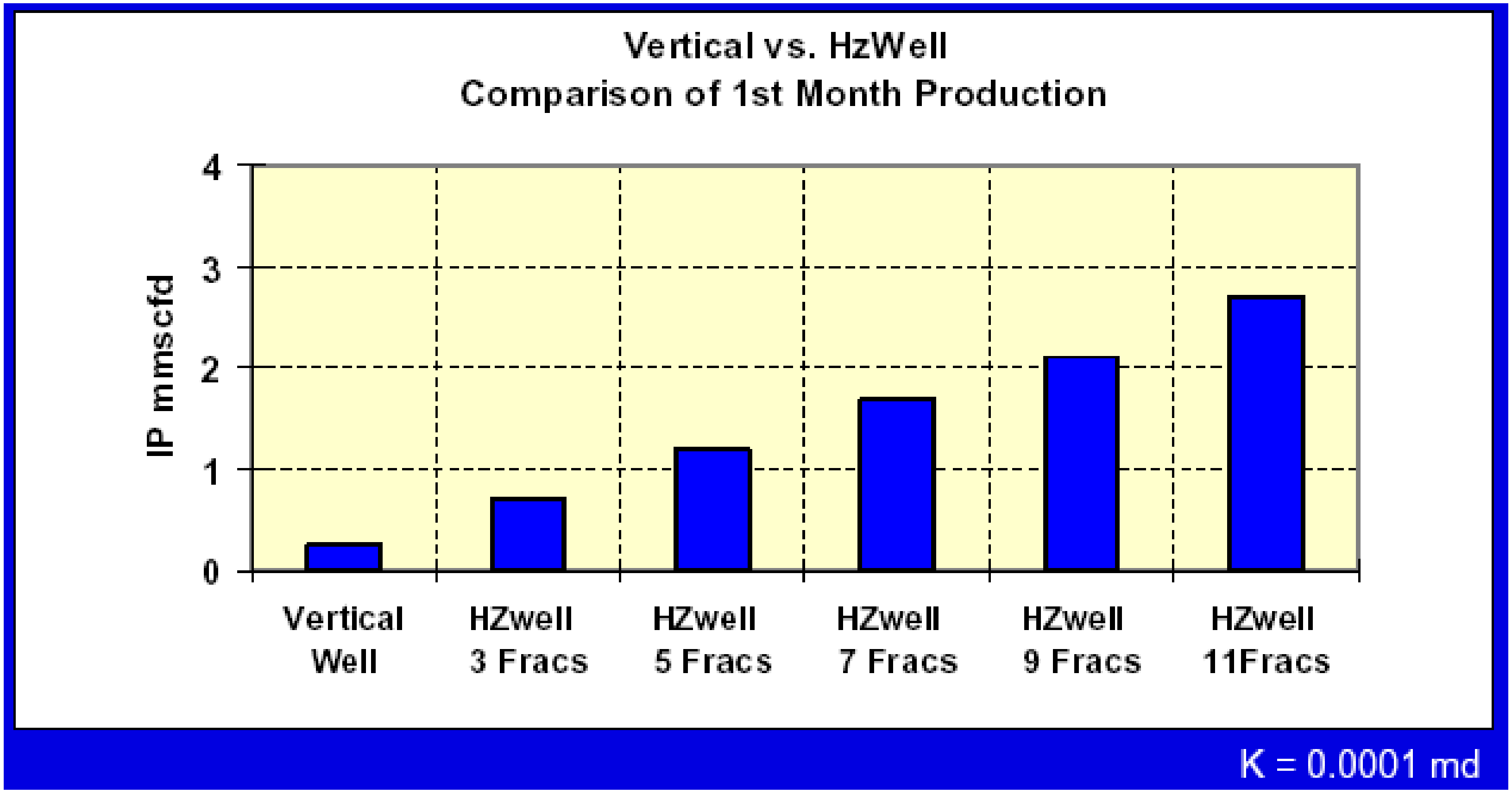
Fracturing Traditional Model (and Wrong in Shales)



Horizontal Completions (Complex Fracturing)



Demand for more fracs in Barnett (and other shales too!!!)

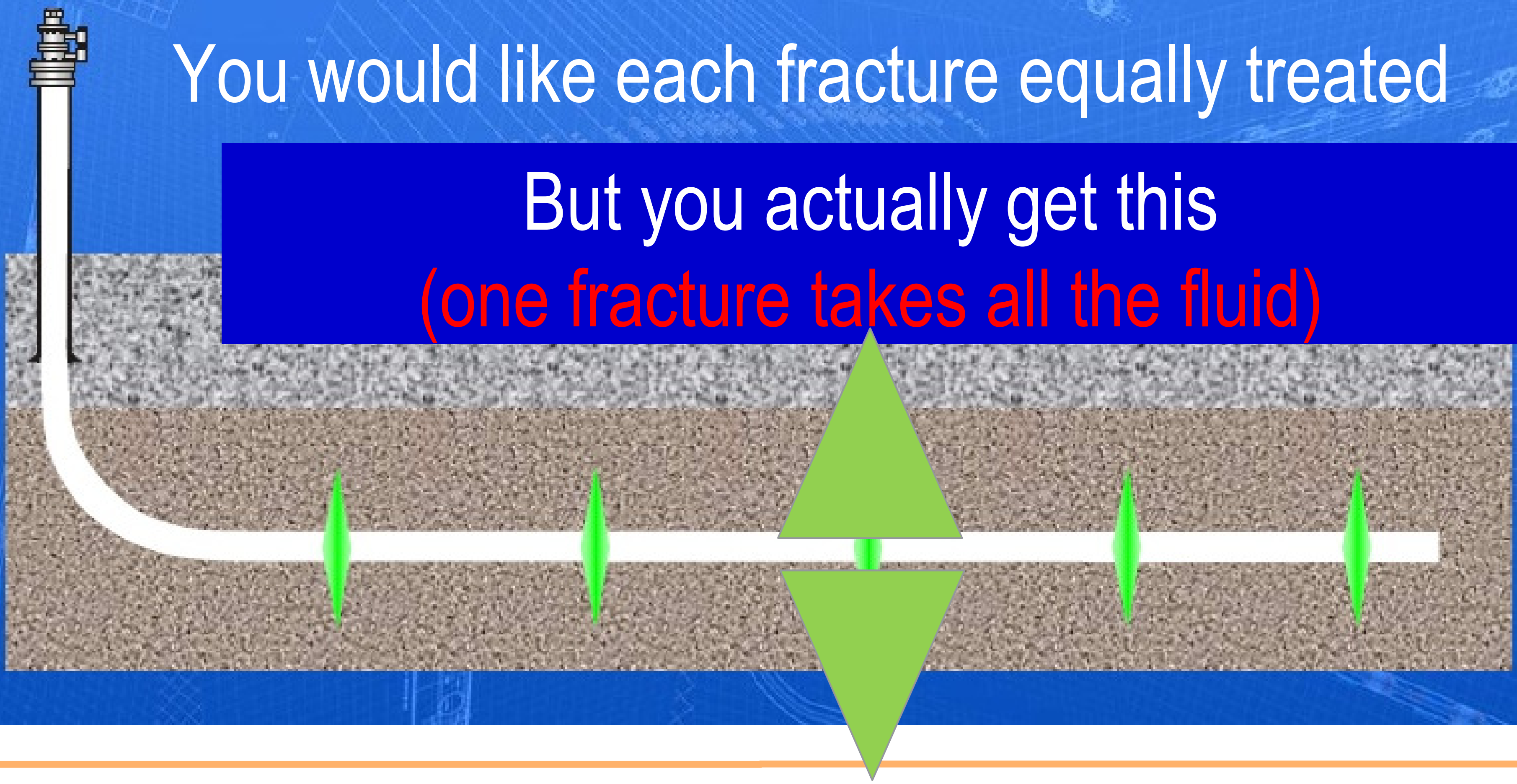


Why not an openhole, fracture stimulated well?

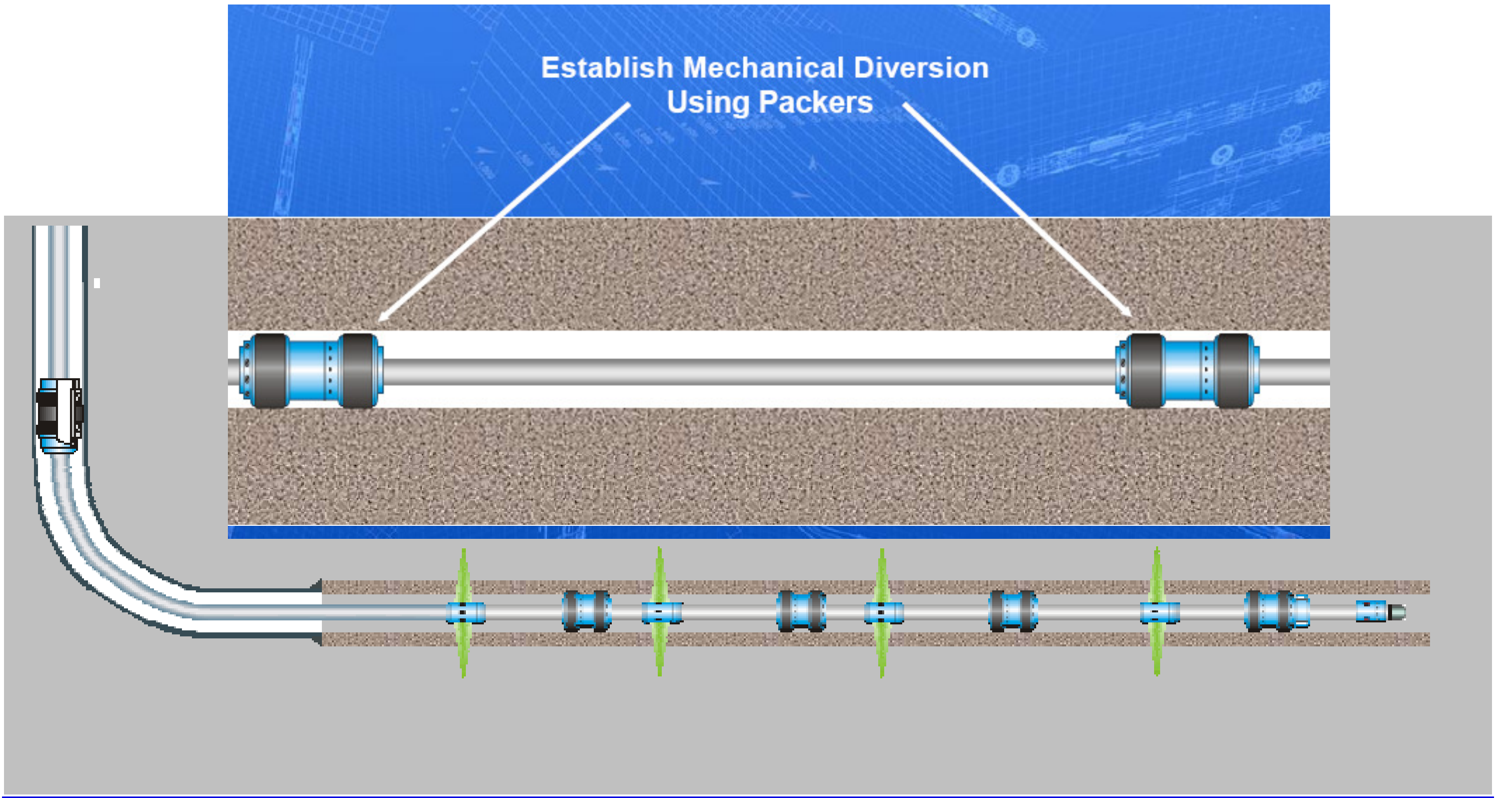
You would like each fracture equally treated

But you actually get this

(one fracture takes all the fluid)

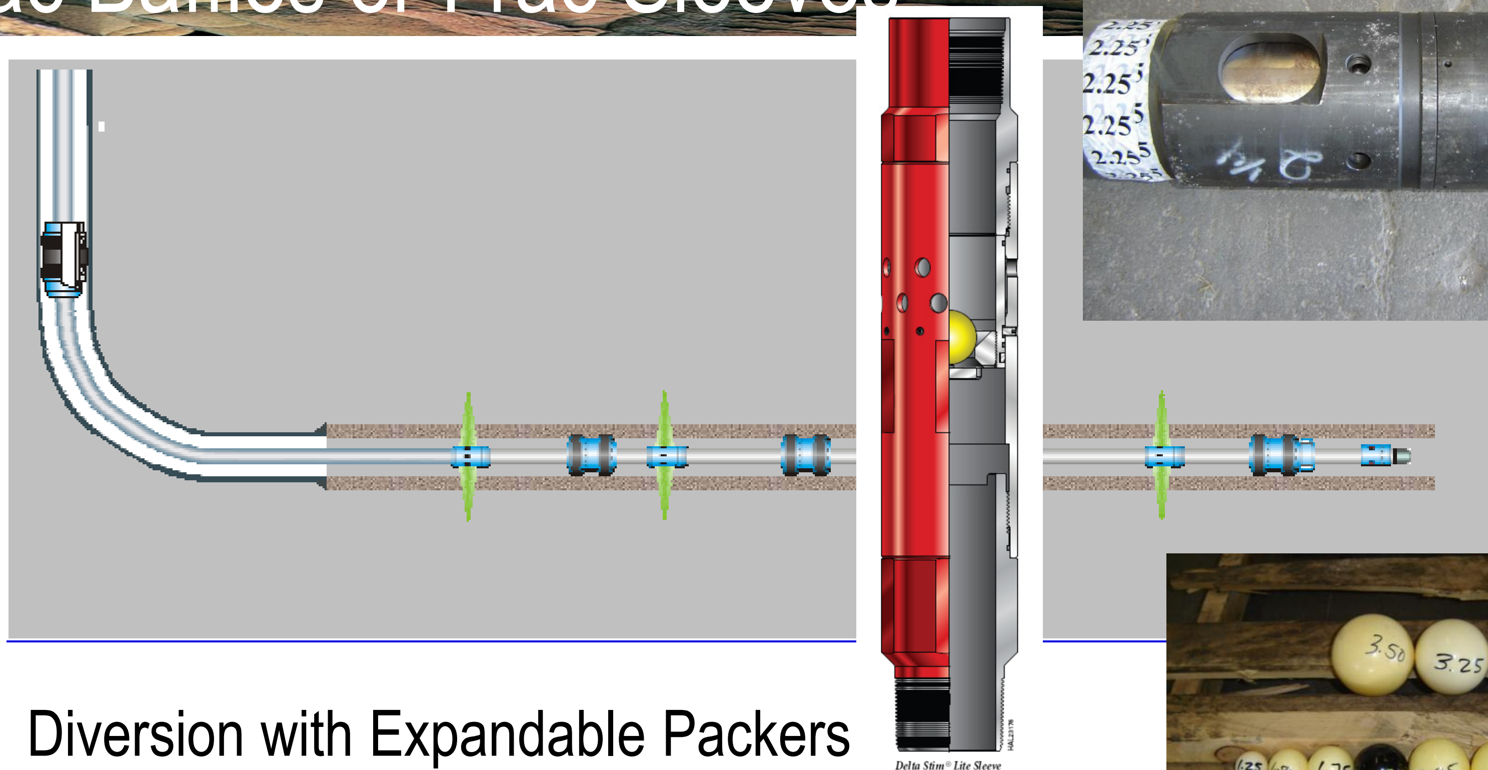


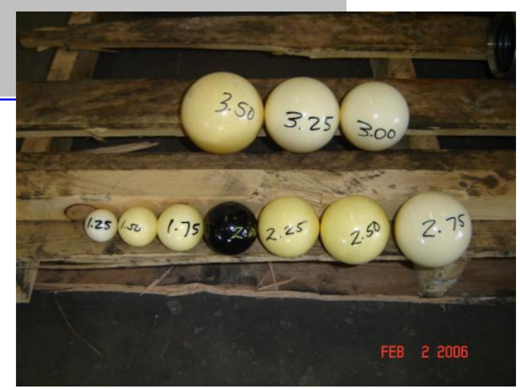
Horizontal Completions with Mechanical Packers



Allow multiple stimulations along horizontal interval

Horizontal Completions
Frac Baffles or Frac Sleeves

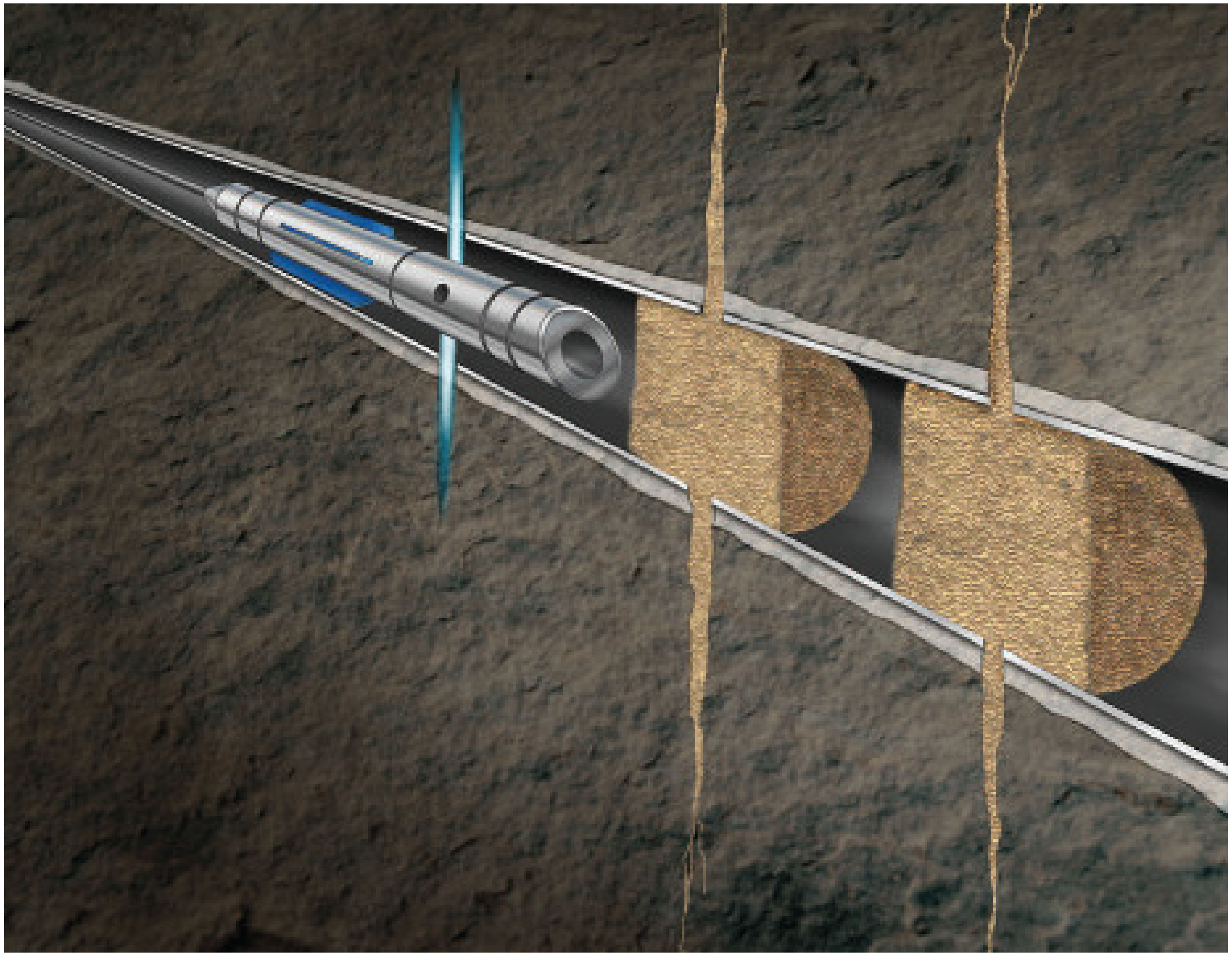




Diversion with Expandable Packers

Sleeves are actuated with balls

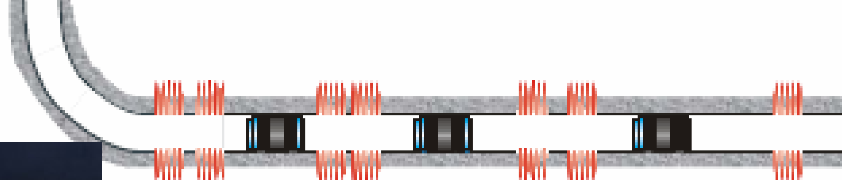
Coiled Tubing Frac System

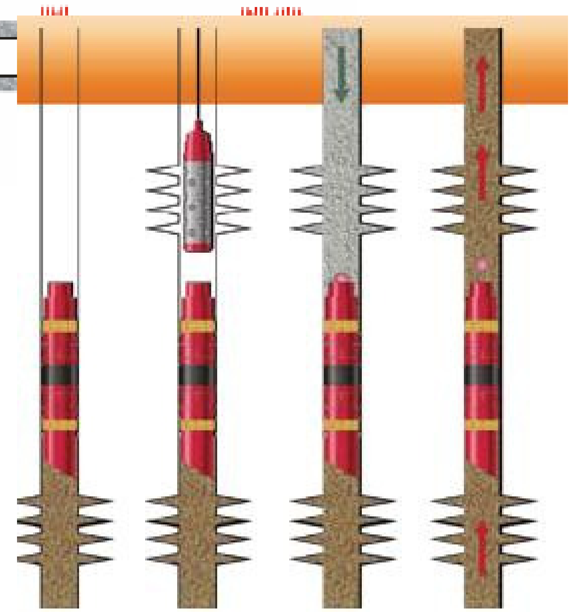


Courtesy, Halliburton

Horizontal Completions
Cemented Perf and Plug

1. Annular Isolation (and diversion accomplished with cement)
2. Frac stages initiated through perforations with stages isolated with composite plugs
3. Bridge plugs are removed with coiled tubing drilling.





composite bridge plug

Green Completions

Green completions take place during the clean-up stage of the completion, after a well has been "fracked."

The clean-up involves removing the water necessary to frack the well. During this flow back, natural gas is produced with the water.

What makes the well completion "green," or environmentally friendly, is that the gas is separated from the water and placed in a pipeline instead of being released to the atmosphere.

Green completions have been Devon's standard practice in the Barnett Shale since 2004.

Devon has reduced methane emissions by more than 25 billion cubic feet in the Barnett Shale area of north Texas during 2,000 green completions.

Green Completions

First, a sand separator (shown at right in this photo) filters out any sand, sending it through a 2-inch pipe into the disposal tank. That filtering leaves a mixture of natural gas and water.

The second piece of equipment (in the left side of this photo) separates the water, which then reunites with the sand in the disposal tank.

The gas, meanwhile, is diverted into a separate pipe and eventually is sent by ***pipeline*** to a processing plant.

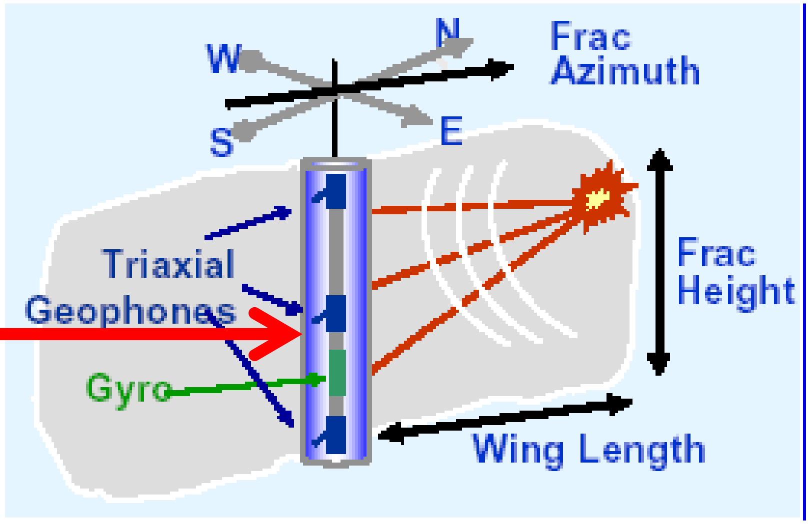
The key to the green completion is that a pipeline must be available for immediate usage.

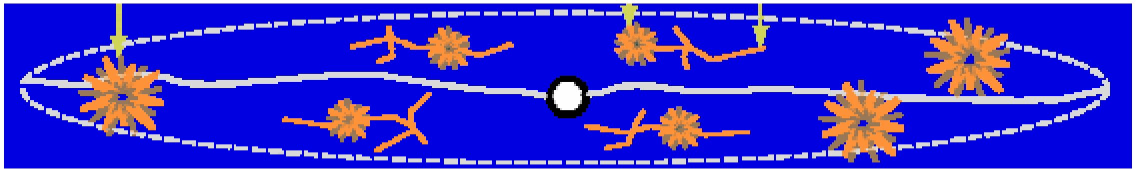
Microseismic

Microseismic Improves Diagnostics

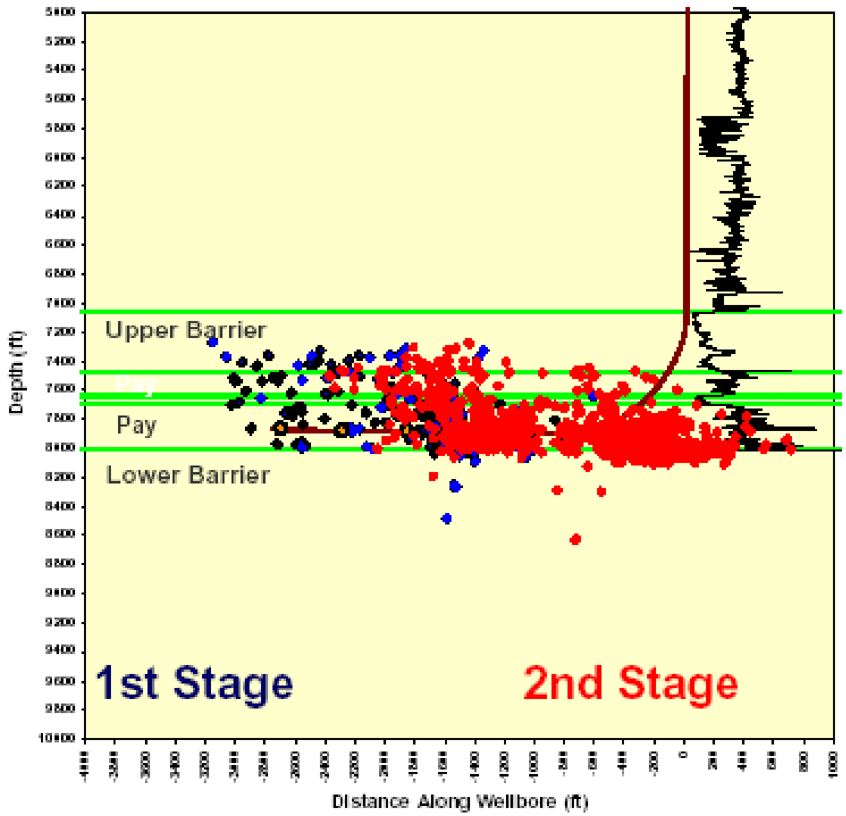
Microseismic

- Maps the fracture growth
- Identifies azimuth
- Measures frack distance from aquifer
- Requires observation well





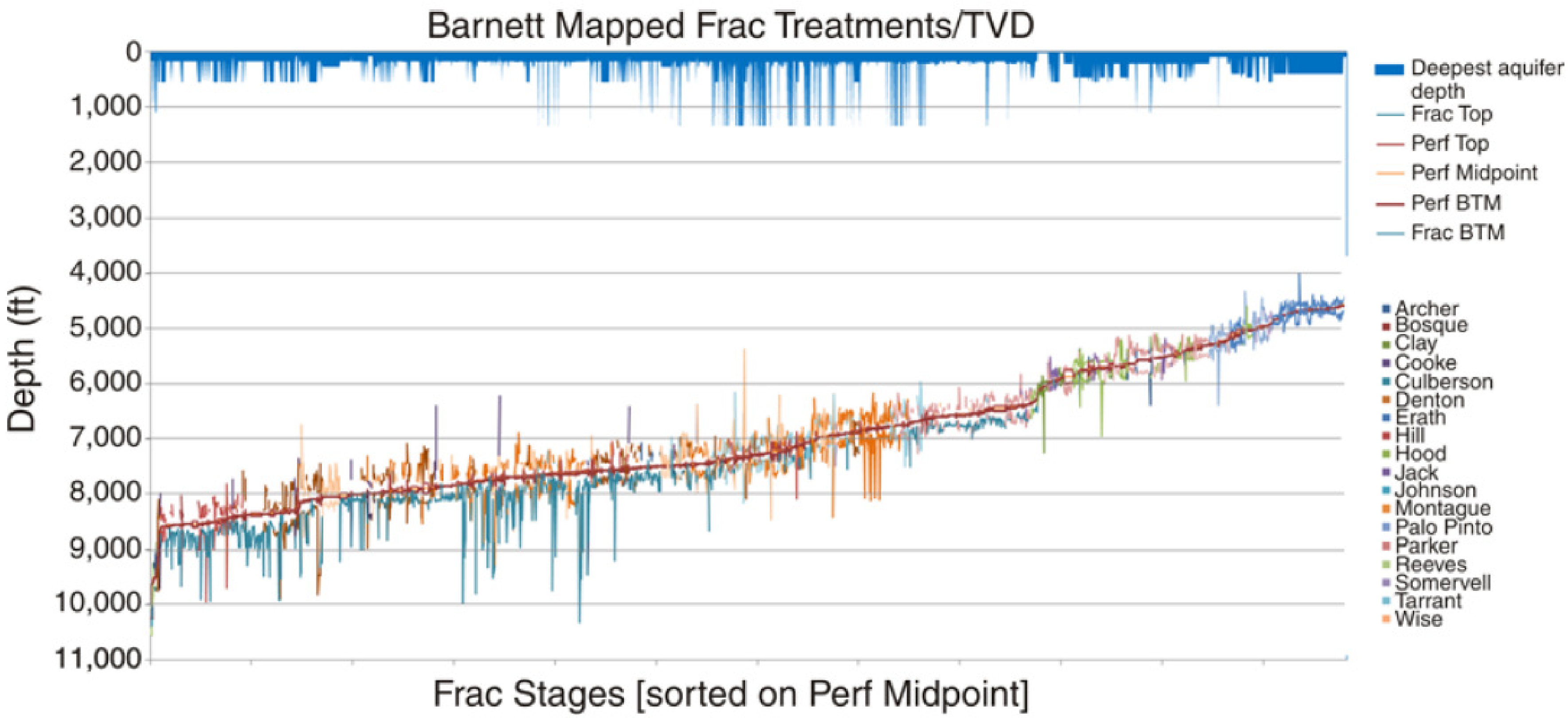
Microseismic Barnett Shale Horizontal



Side View

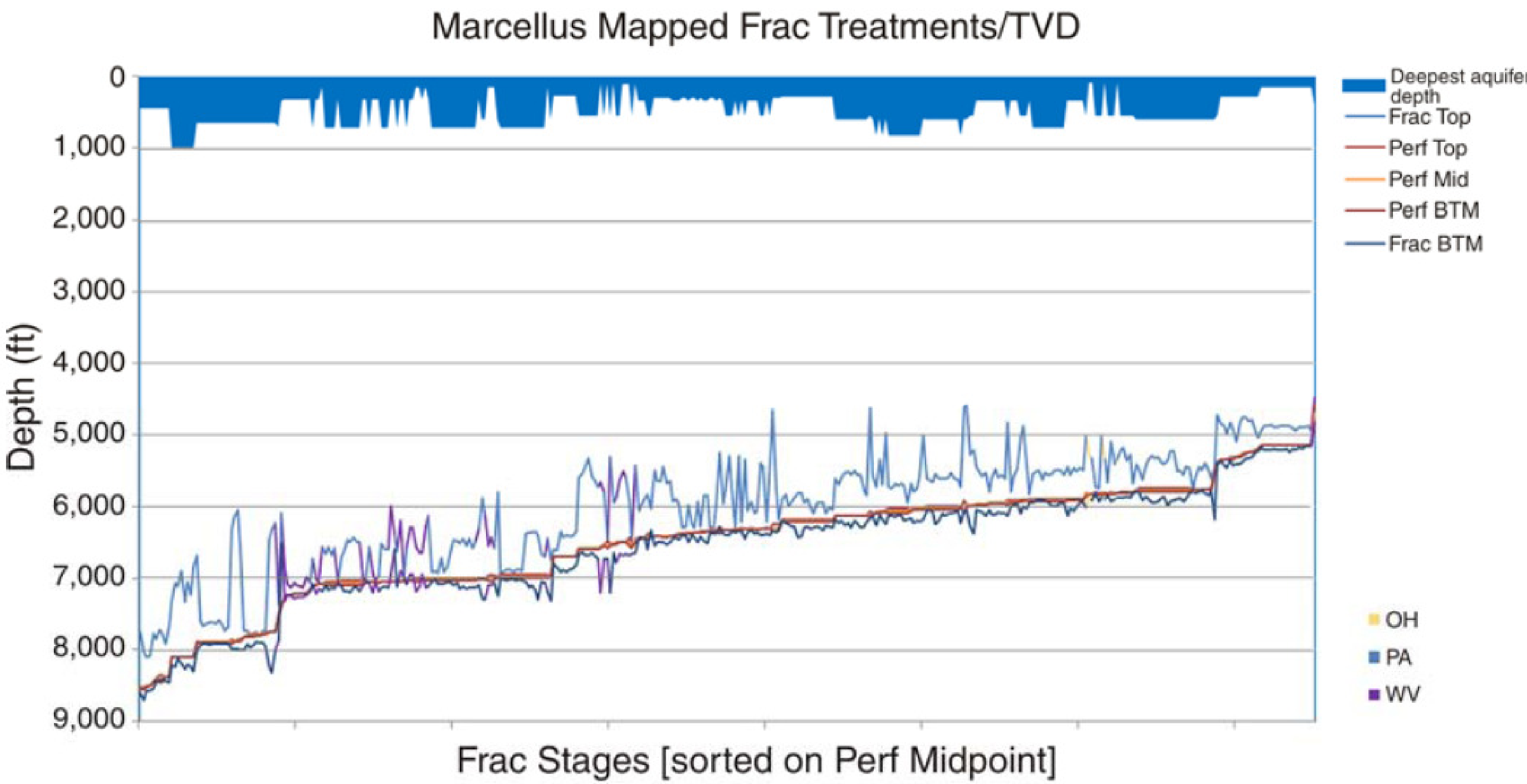
Plane View

Barnett Microseismic Fracture Heights vs. Deepest Aquifer



SPE 145949

Marcellus Microseismic
Fracture Heights vs. Deepest Aquifer



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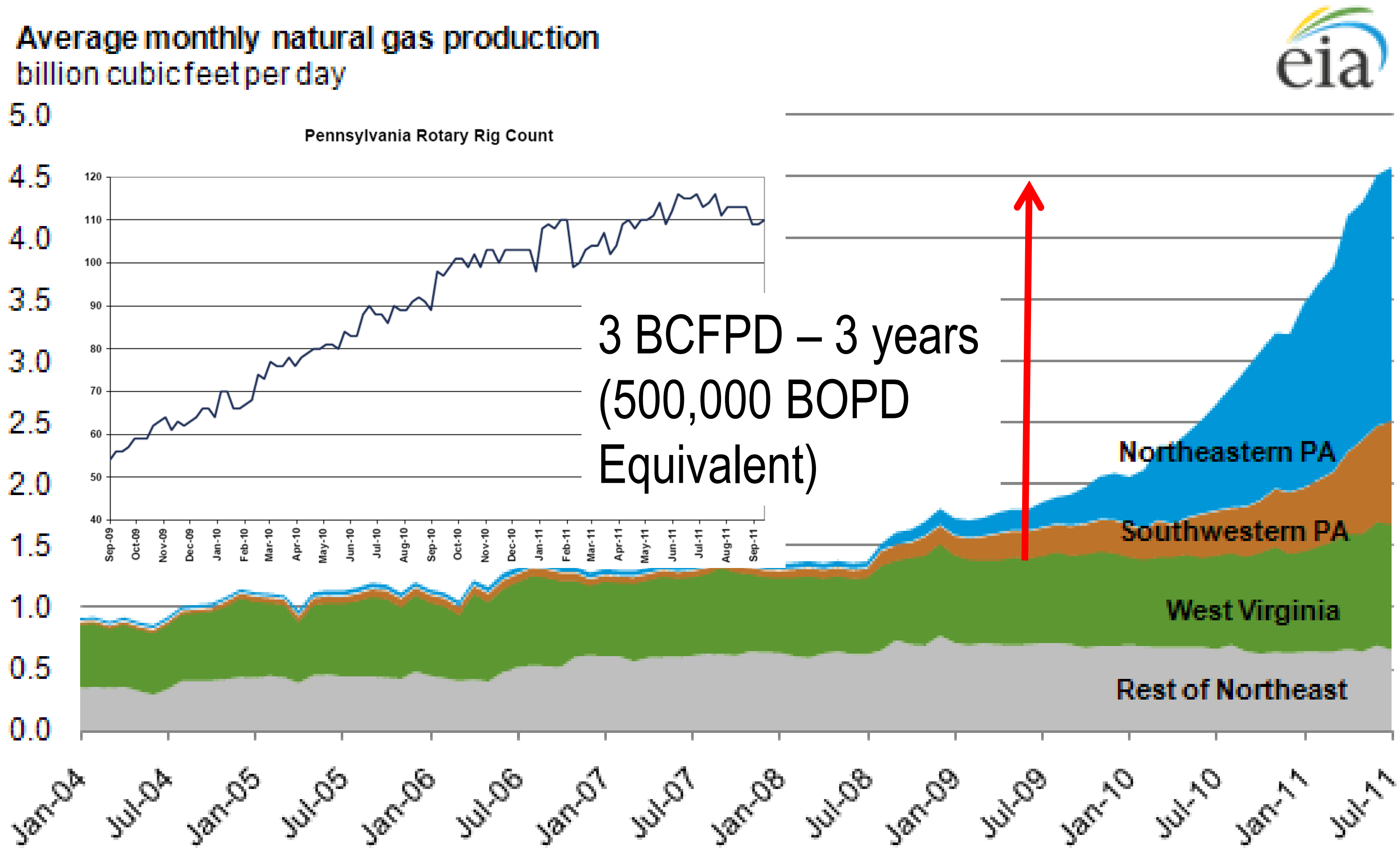
Marcellus Case History

Impact of 100 Rigs on Marcellus Gas Production



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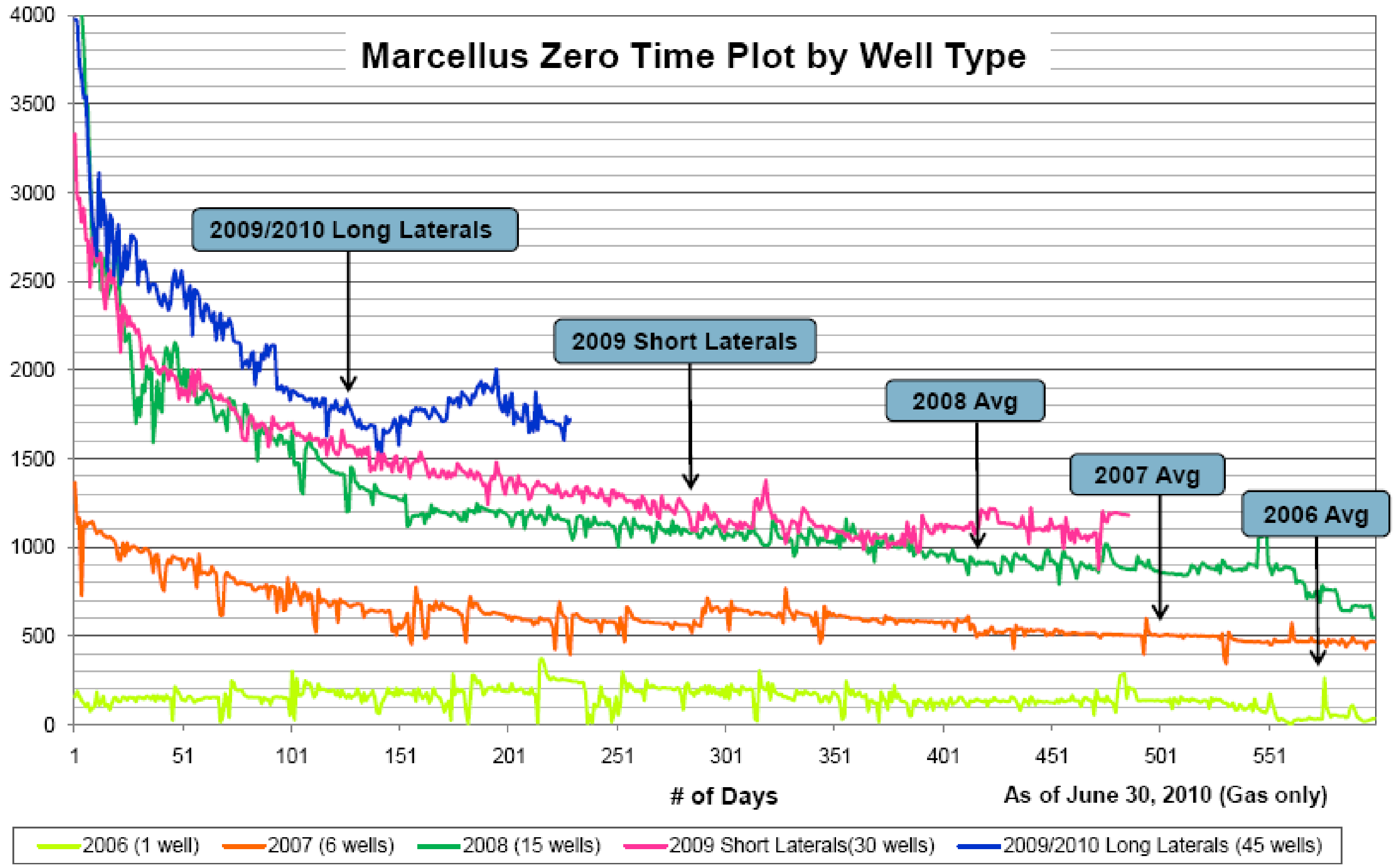
Range Marcellus Shale Fracs

Bigger Jobs and Lower Costs – Better Well Results

	Proppant, lbs.	Water, gallons	Stages	Lateral Length, ft
2006	923,000	2,225,000	3	1,794’
2007	2,765,000	2,646,000	7	2,198’
2008	3,418,000	3,127,000	8	2,495’
2009 (Short)	3,241,000	3,227,000	8	2,514’
2009 & 2010 (Long)	5,154,000	3,887,000	10	3,038’

Experimenting With Longer Laterals (2,900’ to 5,000’) and More Stages (9-17)

Marcellus Well Results – Range Resources



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Range Resources Marcellus Well Costs

Based upon ~3,000 foot lateral, 10 stage frac and 6 well pad

Site Preparation[1]	$ 270,000
Drilling	1,300,000
Tubulars	330,000
Facilities	250,000
Completion Operations [2]	1,850,000
	$ 4,000,000

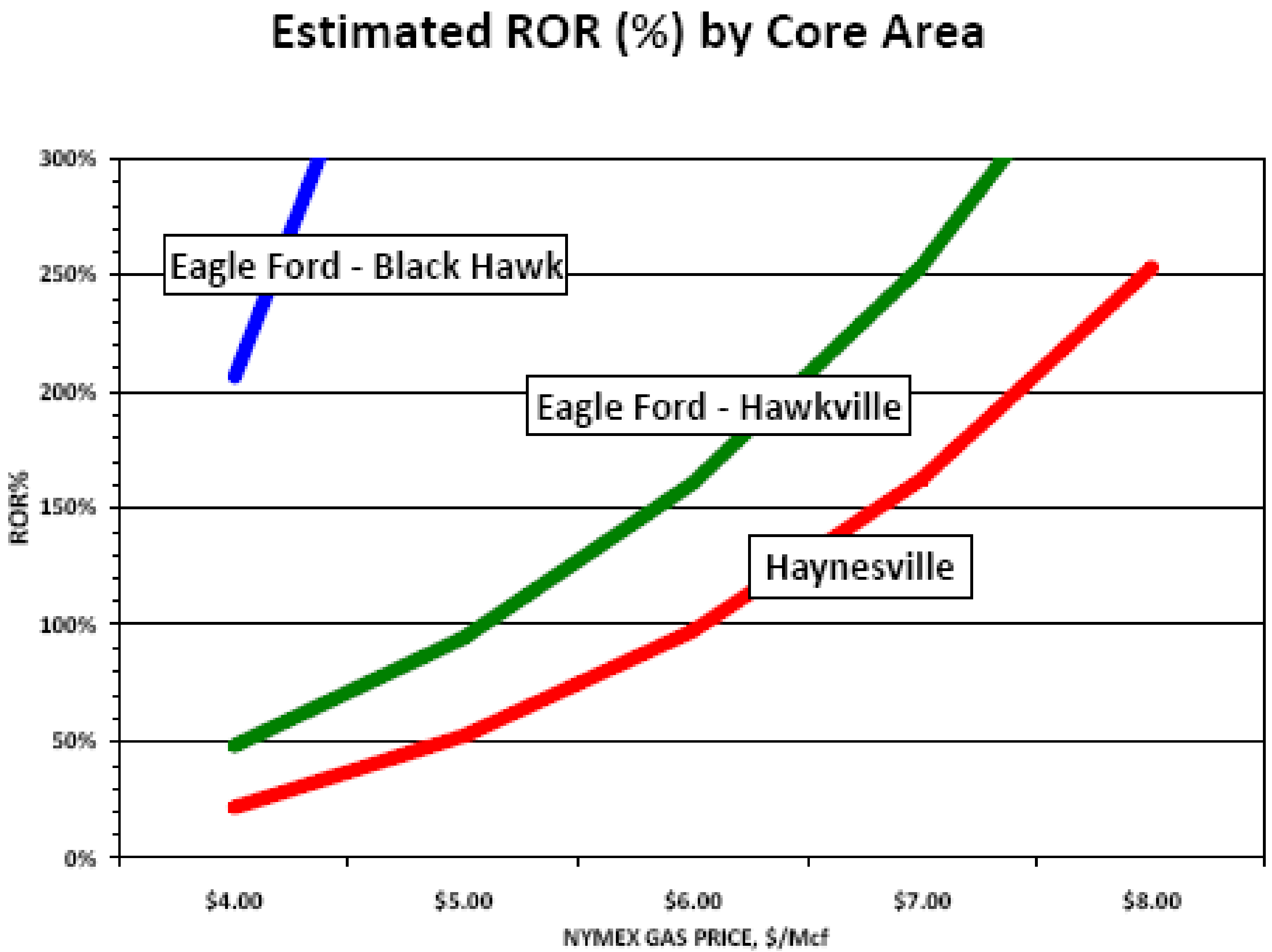
Completion (fracking) costs much more than drilling

Conclusions

1. Shale plays are very widespread
2. Each shale play is different, and needs careful evaluation
3. Shales may produce natural gas, natural gas liquids and/or oil
4. Shale completions are still improving
5. Aquifers can and are being protected

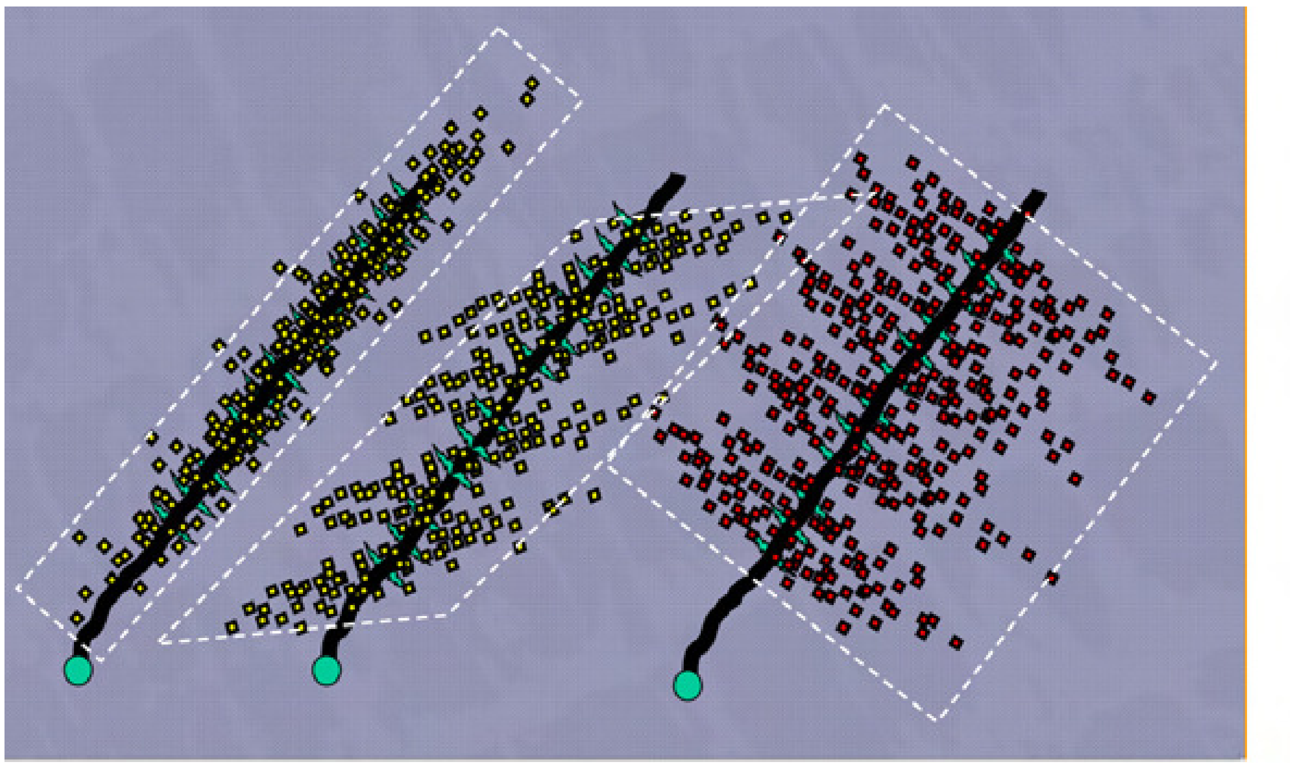
Extra Slides

Eagleford Oil and Wet Gas



How will the Rocks Break?

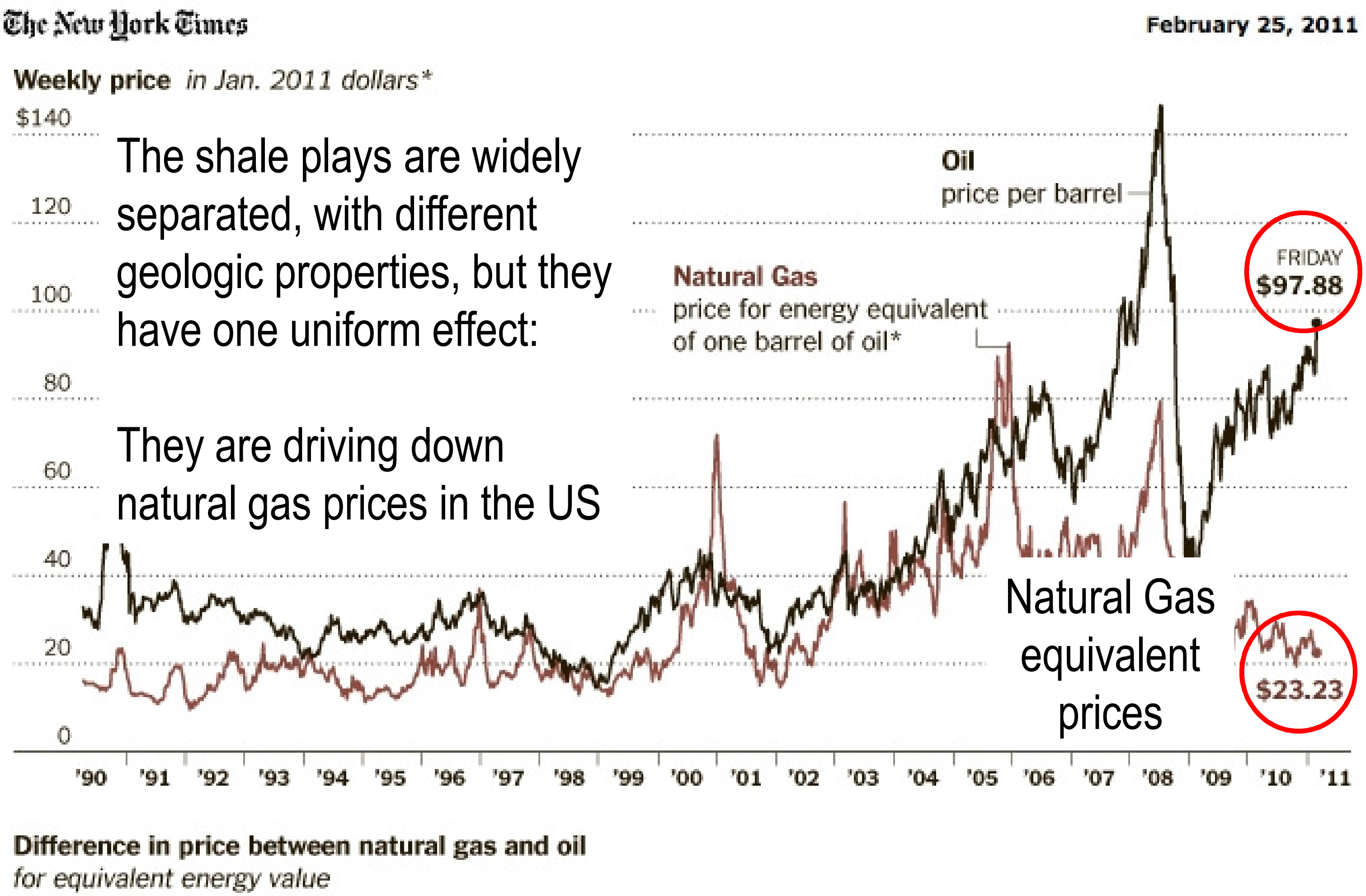
We will achieve different Stimulated Reservoir Volume (SRV) and drainage area depending on how wellbore is placed relative to the stress fields



16. Importance of SRV and network azimuth for lateral orientation and well placement

SPE 119890

Natural Gas Cheap Compared to Oil, Driven by Shale Gas Production

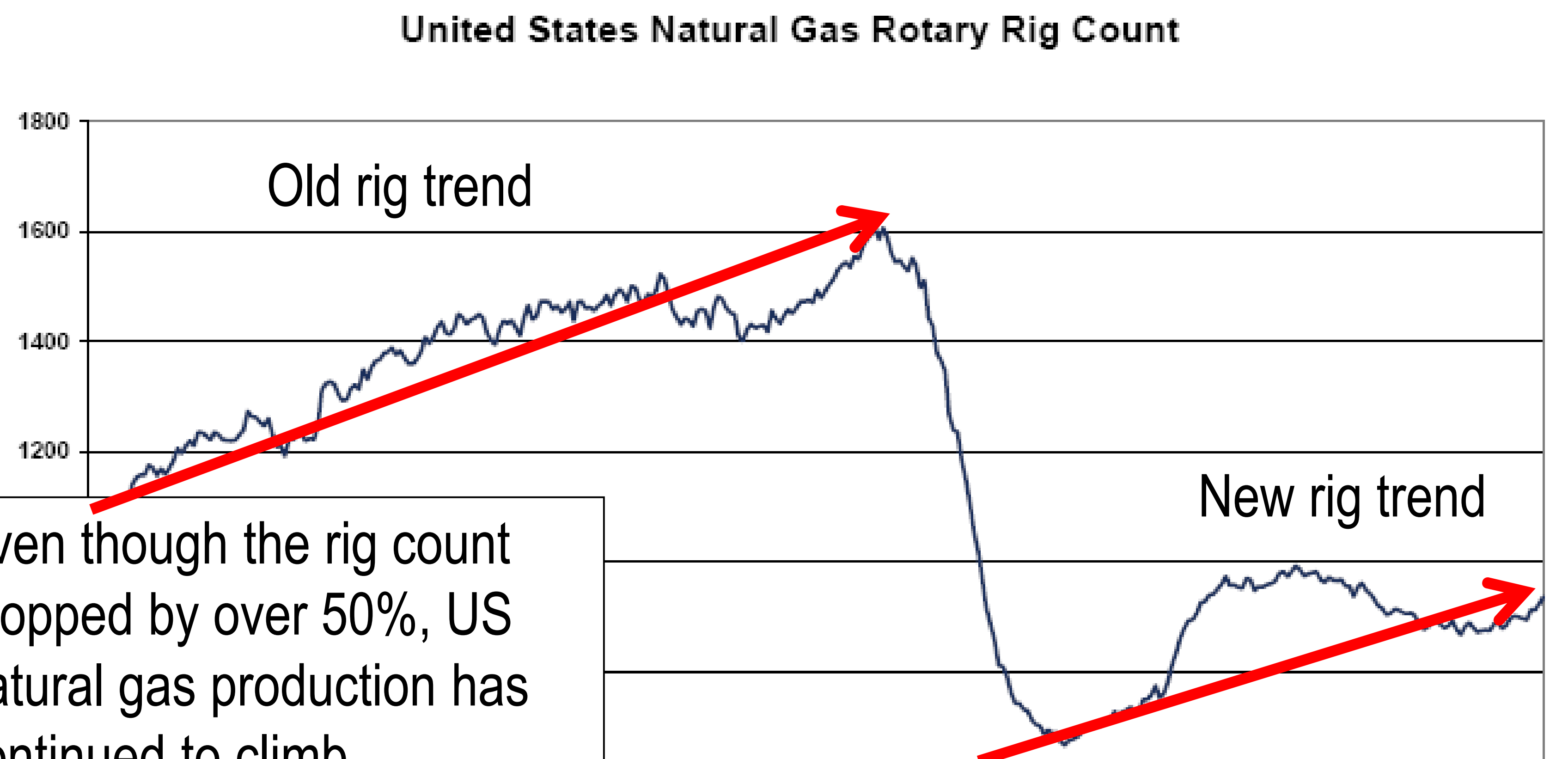


The shale plays are widely separated, with different geologic properties, but they have one uniform effect:

They are driving down natural gas prices in the US

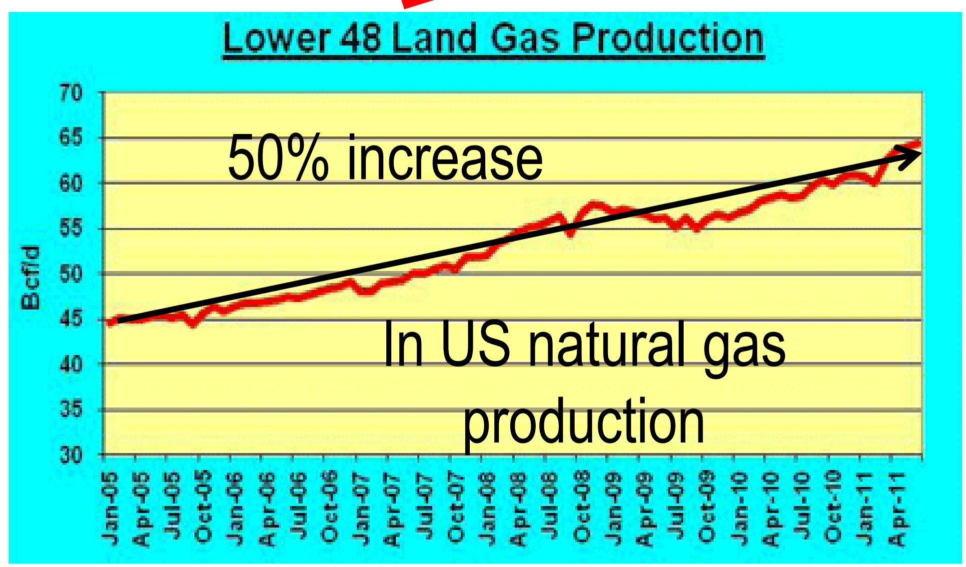
Crude oil prices

Natural Gas equivalent prices

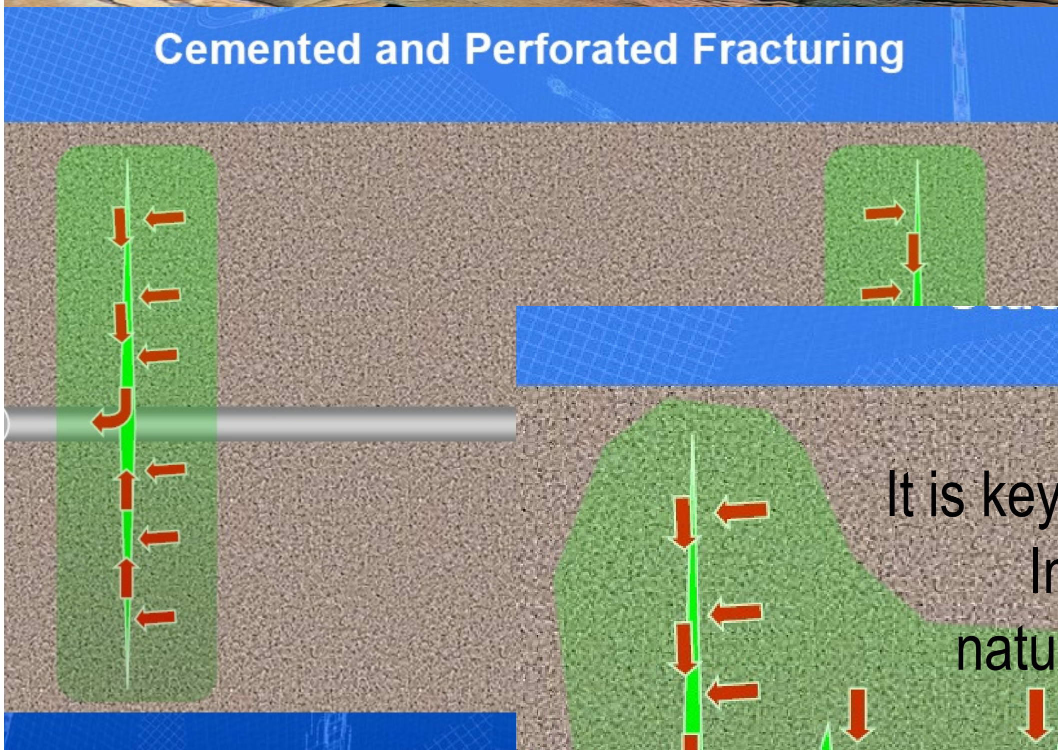


Even though the rig count dropped by over 50%, US natural gas production has continued to climb.

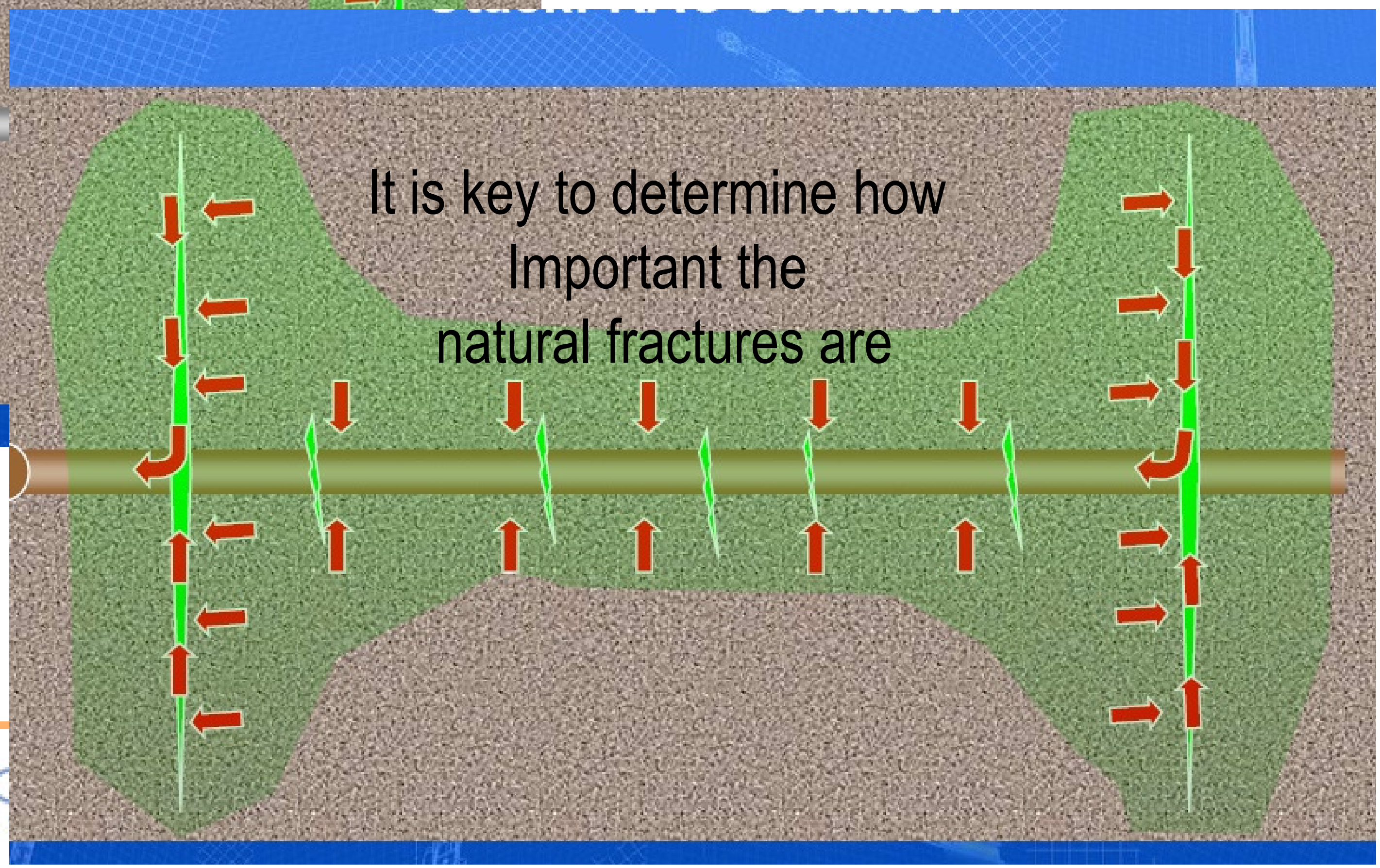
This is due to better completions, producing more gas with less rigs!!



Natural Fractures – How to Take Advantage

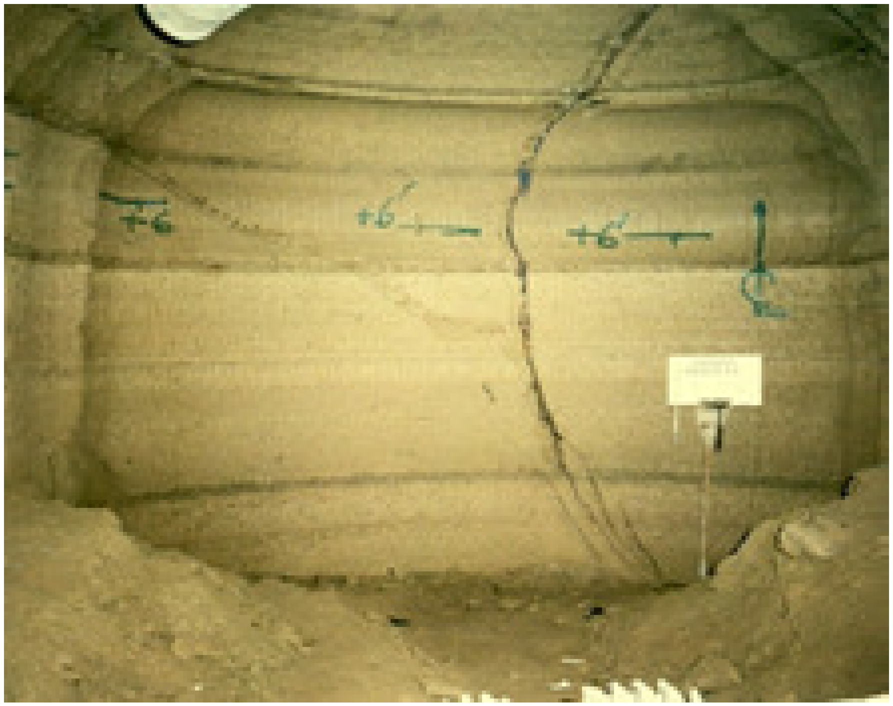


What about natural fractures?

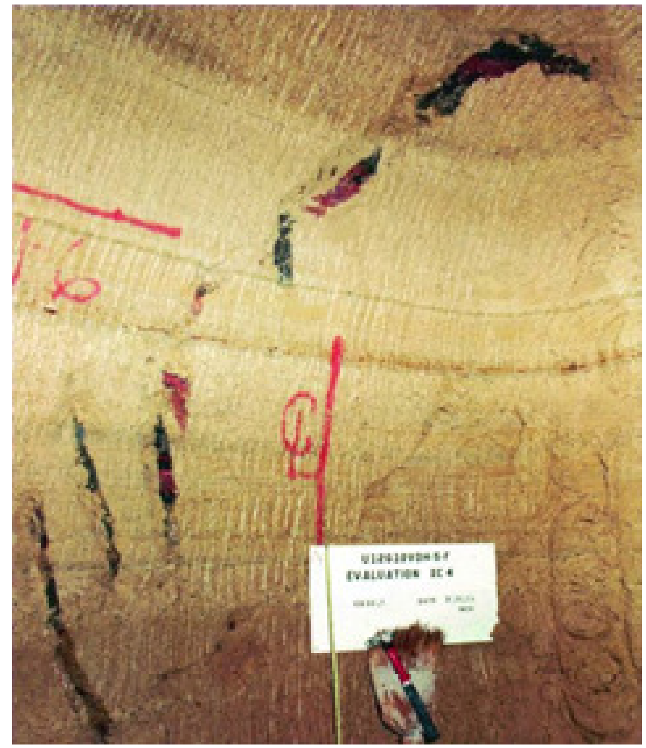


It is key to determine how Important the natural fractures are

(Very Complex Fracturing)

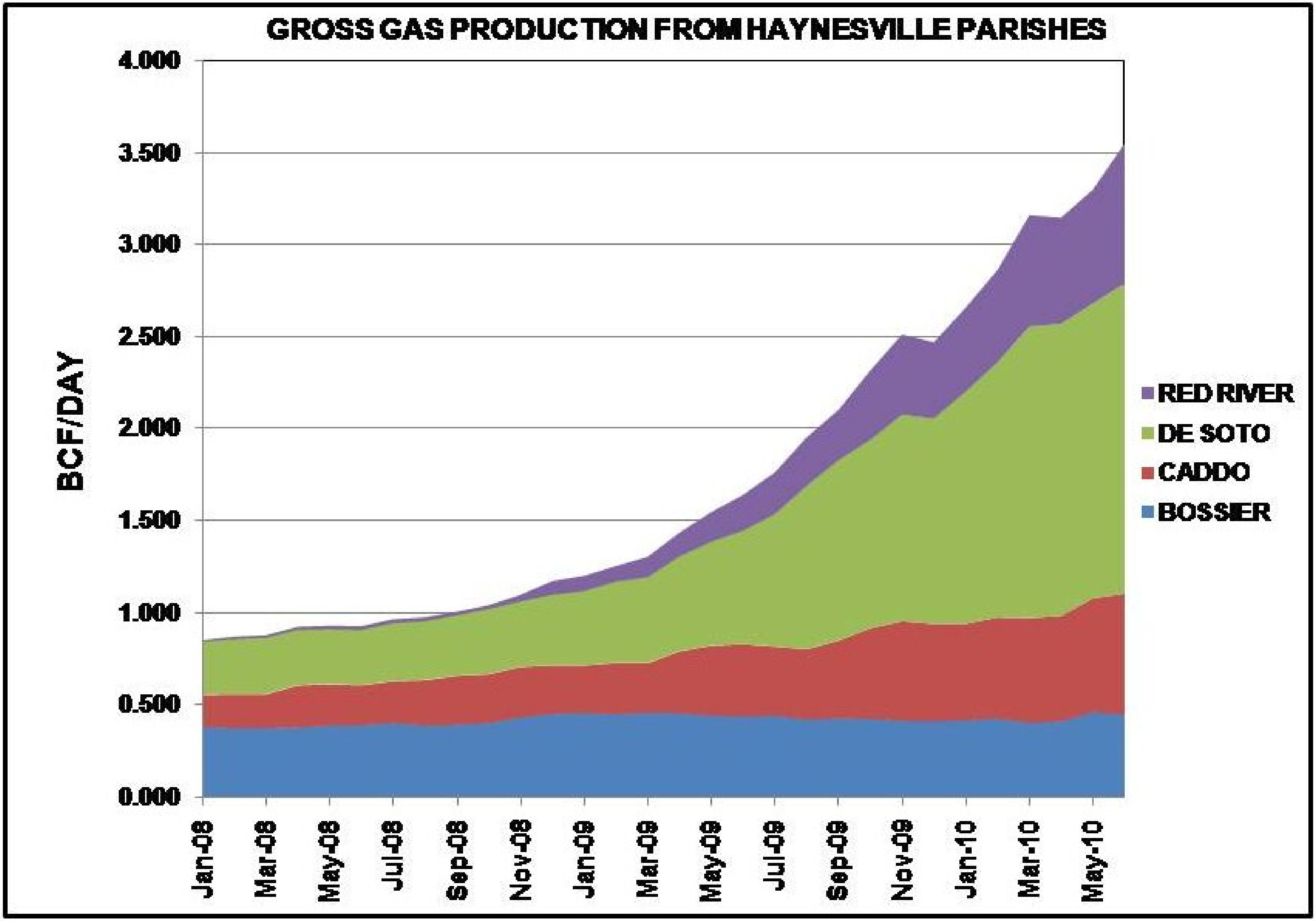


Warpinski, Sandia Labs. Nevada Test Site, Hydraulic Fracture Mineback

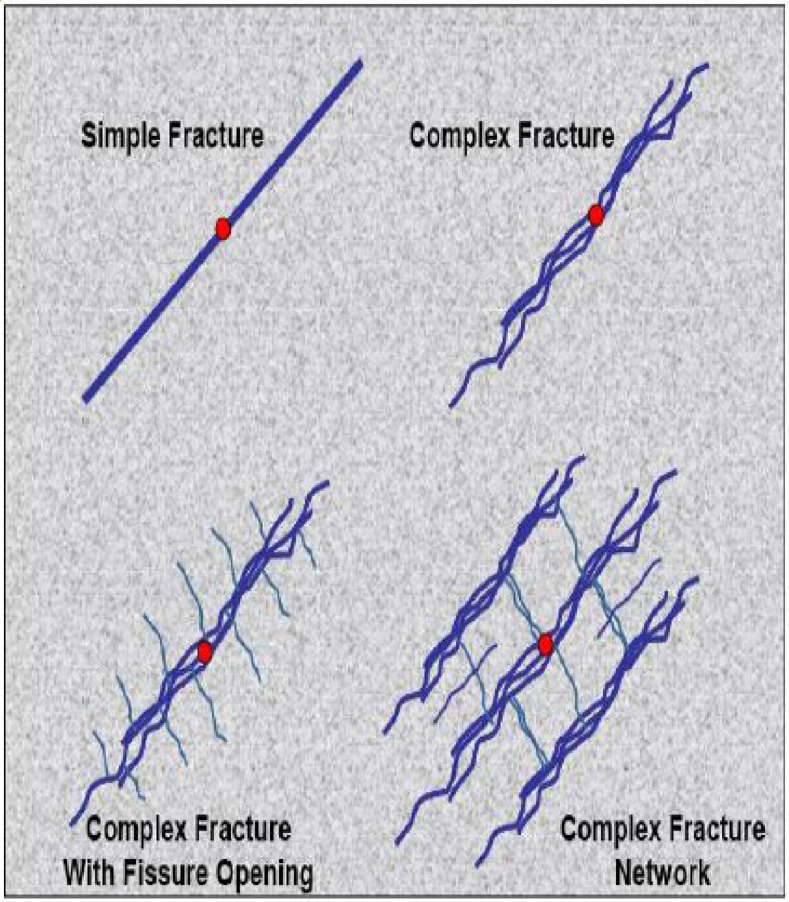


See SPE 119143 for discussion of implications of frac complexity

Logistics – Stimulation


GROSS GAS PRODUCTION FROM HAYNESVILLE PARISHES
BCF/DAY
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Jan-09
Mar-09
May-09
Jul-09
Sep-09
Nov-09
Jan-10
Mar-10
May-10
RED RIVER
DE SOTO
CADDO
BOSSIER

Complex Fracture Geometries



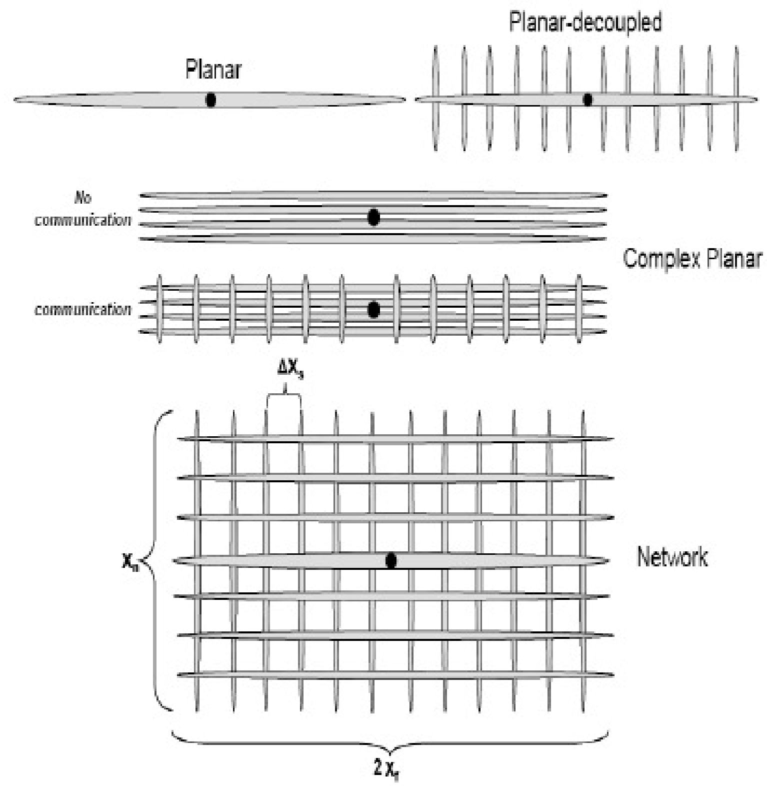


Figure 1 - Fracture growth and complexity scenarios

(SPE 114173)
(SPE 119890)

(SPE 115769)

Discrete Fracture Network (DFN) Model