# Technology and Environmental Impact of Shale Gas Development

Presentation to:

Select Committee on the Risks and Benefits of Hydraulic Fracturing

*Photograph by Damien Tremblay*

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University of Alberta

November 15, 2013

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# Outline

- Shale Gas as a Hydrocarbon Resource
- **Well Construction**
- **Hydraulic Fracturing**
- **Induced Seismicity**
- Water Management Issues
- **Monitoring for Environmental Impacts**
- **Risk Management Practices for Shale Gas Development**

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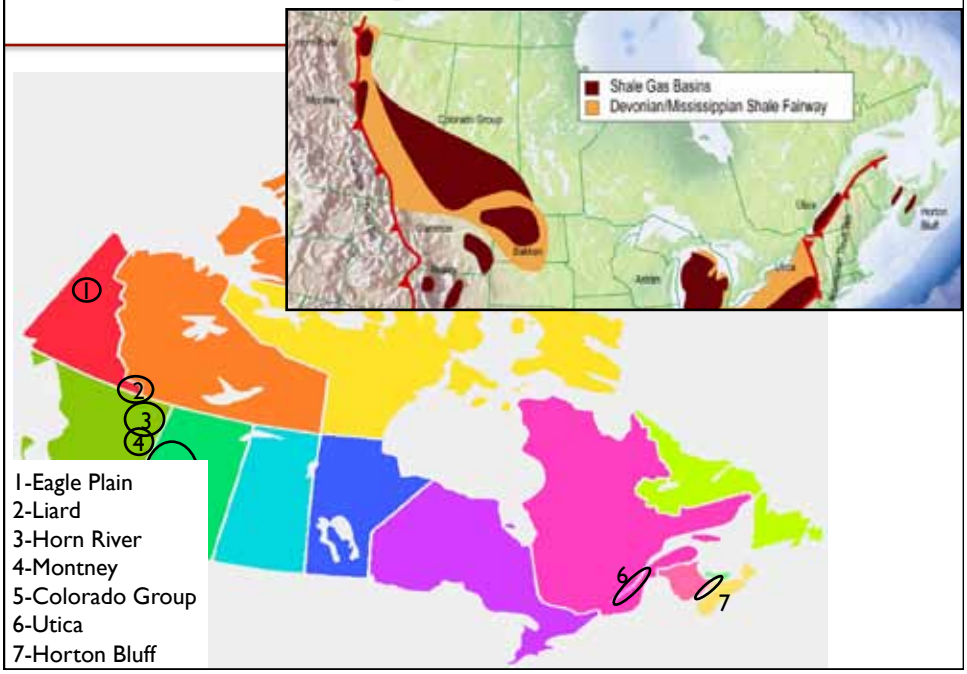
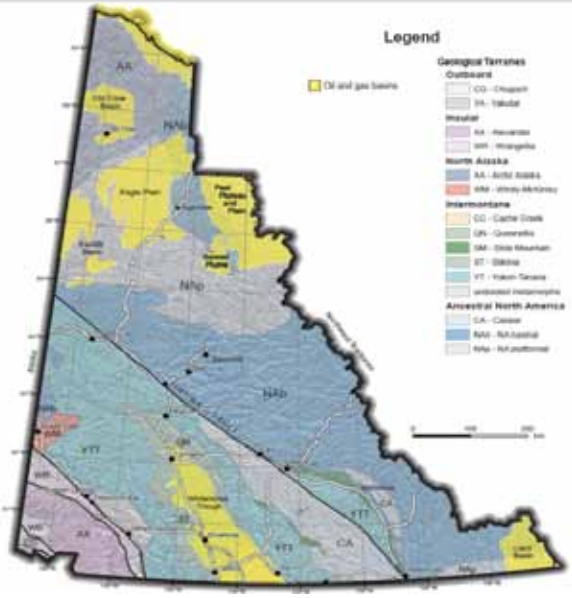
# Canadian Shale Plays




1-Eagle Plain
2-Liard
3-Horn River
4-Montney
5-Colorado Group
6-Utica
7-Horton Bluff

# Yukon`s Shale Plays

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Scoping Study of Unconventional Oil and Gas Potential, Yukon. Hayes and Archibald, 2012

## Gas Shale "Reservoir"

- **Properties: organic content, mineralogy, maturity, natural fractures, porosity, k…**
- **The gas in the shale is stored in:**
  - Natural fractures, fracture connected pore space
  - Adsorbed on mineral surfaces
  - Adsorbed on organic material
- **The reservoir is:**
  - Continuous and laterally extensive
  - Thick – usually > 20 m
- **Horizontal wells & fracturing are the "key"**

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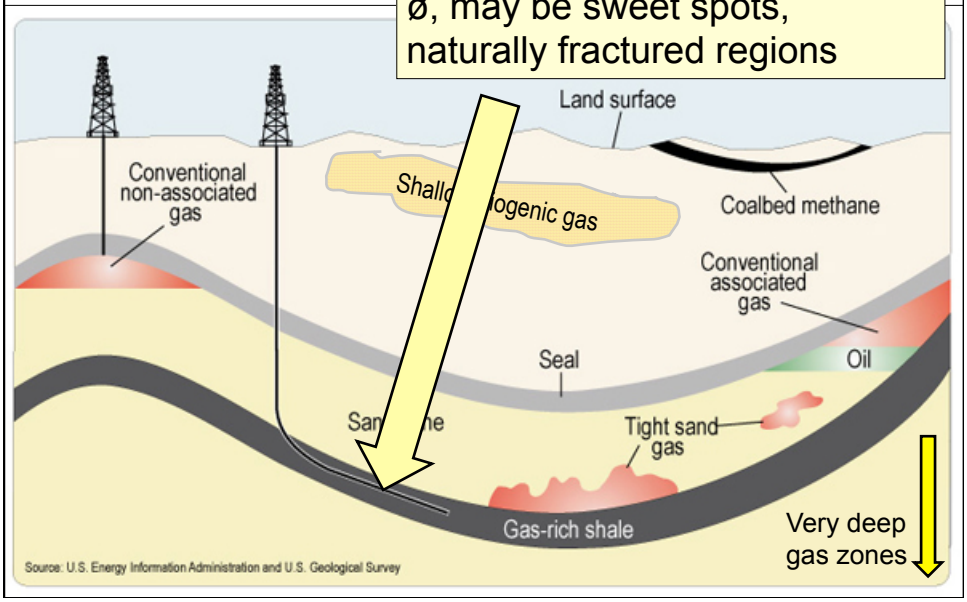
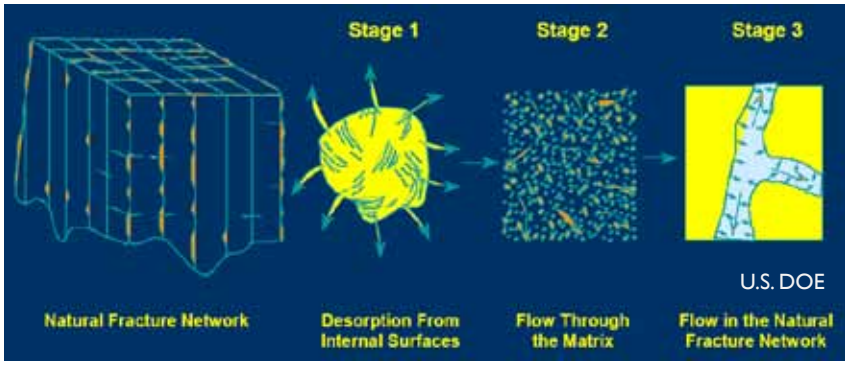
## Gas Occurrence

Shale Gas: continuous formation, no "trap", low k, low ø, may be sweet spots, naturally fractured regions



## Shale Gas Reservoir Mechanisms

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## Key Reservoir Parameters

- Brittle Rock – **Helps maximize extent of induced fracture network**
  (Brittle Rock will Frac like Glass = better SRV)
- Stress Regime – **Relates to pattern orientation and well spacing**
- Over-pressure – **May require high strength Frac proppants**
- Local Lithology Variations
- Faults, Karsts, Water

  **Relates to well productivity**
- Organic Content
- Micro-porosity

  Total Porosity increases at higher TOC
  **Relates to gas in place**
  TOC decreases at higher $R_o$
- Thermal Maturity ($R_o$) - **>Mature = Dry Gas <Mature = Wet Gas**

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R. Kennedy (Baker Hughes) "Shale Gas Challenges / Technologies over the Asset Life Cycle"
U.S. – China Oil and Gas Industry Forum, Sept. 2010

## Gas Shale Basics (for U.S. Basins)

- Formation Thickness, **6 – 180 m** (net)
- Depth, **1900 – 4000 m**
- Well **IP's, 2 – 10+ MMcfd**
- Primarily **Dry Gas**
- Some produce small amounts of water
- Typical Decline:
  - Initial **Flush** Flow
  - **1st Yr** Steep Decline (**65-80 %**)
  - Produces slowly over time, **25+ Yrs**

All Shales Are Not the Same (Geology Varies Even in the Same Basin)

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R. Kennedy (Baker Hughes) "Shale Gas Challenges / Technologies over the Asset Life Cycle" U.S. – China Oil and Gas Industry Forum, Sept. 2010

## What's Next?

- **Extensive exploration required in Yukon.**
- **Liard Basin and Eagle Plain are highly prospective.**
- **Exploration wells, coring and sampling are required to obtain key reservoir parameters.**
- **Infrastructure.**
- **Analysis of water source and disposal zones.**
- **Environmental impacts.**

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## Definitions

- **Shale is a fine grained, sedimentary rock mainly consisting of clays, Silica, Carbonates, and organic material.**
- **Highly variable in composition.**
- **Shale gas is typically a source rock, meaning that the hydrocarbons were created in the rock and stayed there.**
- **Majority of the conventional hydrocarbons were once created in shale and migrated elsewhere.**

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## Sample


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# Mineralogy

- **Mineralogy of Besa River Shale (Southeast Yukon)**

High Quartz Content (Brittle)

| Sample | Quartz | Albite | Calcite | Dolomite | Pyrite | Illite | Kaolinite | Chlorite | Total Clays | Total Carbonate | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Besa River** | | | | | | | | | | | |
| Lower black mudrock | | | | | | | | | | | |
| BRS2563-1 | 89.5 | 0.0 | 0.3 | 0.5 | 0.4 | 9.3 | 0.0 | 0.0 | 9.3 | 0.8 | 100.0 |
| BRS2563-3 | 87.4 | 0.0 | 0.7 | 0.2 | 0.7 | 11.0 | 0.0 | 0.0 | 11.0 | 0.9 | 100.0 |
| BRS2563-5 | 85.7 | 0.0 | 0.0 | 1.0 | 1.0 | 12.3 | 0.0 | 0.0 | 12.3 | 1.0 | 100.0 |
| BRS2563-7 | 81.5 | 0.0 | 0.0 | 0.4 | 0.8 | 17.5 | 0.0 | 0.0 | 17.5 | 0.4 | 100.0 |
| BRS325-1 | 90.5 | 0.0 | 0.0 | 0.5 | 0.6 | 8.4 | 0.0 | 0.0 | 8.4 | 0.5 | 100.0 |
| BRS325-3 | 93.5 | 0.0 | 0.0 | 1.0 | 0.6 | 5.9 | 0.0 | 0.0 | 5.9 | 1.0 | 100.0 |
| BRS325-5 | 74.2 | 0.0 | 0.3 | 0.2 | 0.6 | 24.8 | 0.0 | 0.0 | 24.8 | 0.4 | 100.0 |
| BRS325-7 | 58.8 | 0.0 | 0.6 | 39.1 | 0.4 | 1.0 | 0.0 | 0.0 | 1.0 | 39.8 | 100.0 |
| Upper black shale | | | | | | | | | | | |
| BRS-c15-I331-1 | 73.2 | 0.0 | 0.0 | 0.5 | 0.3 | 26.0 | 0.0 | 0.0 | 26.0 | 0.5 | 100.0 |
| BRS-c15-I331-2 | 58.5 | 0.0 | 0.0 | 0.6 | 0.5 | 40.5 | 0.0 | 0.0 | 40.5 | 0.6 | 100.0 |
| BRS-c15-I331-3 | 66.6 | 0.2 | 1.7 | 0.0 | 0.4 | 31.1 | 0.0 | 0.0 | 31.1 | 1.7 | 100.0 |
| BRS-c15-I331-5 | 43.8 | 0.0 | 0.0 | 0.3 | 0.3 | 55.5 | 0.0 | 0.0 | 55.5 | 0.3 | 100.0 |
| BRS-c15-I331-7 | 62.1 | 0.0 | 1.4 | 1.2 | 0.3 | 34.8 | 0.0 | 0.0 | 34.8 | 2.6 | 100.0 |
| BRS1331-2 | 22.1 | 0.0 | 0.0 | 0.0 | 0.2 | 76.0 | 1.7 | 0.0 | 77.7 | 0.0 | 100.0 |
| BRS1331-3 | 37.1 | 0.0 | 0.0 | 0.0 | 0.3 | 61.0 | 1.6 | 0.0 | 62.6 | 0.0 | 100.0 |
| BRS1331-4 | 18.2 | 0.0 | 0.0 | 0.0 | 0.4 | 64.8 | 14.3 | 2.5 | 81.4 | 0.0 | 100.0 |
| BRS1331-6 | 20.9 | 0.0 | 0.0 | 0.0 | 0.1 | 52.9 | 22.5 | 2.8 | 78.4 | 0.0 | 100.0 |
| BRS1331-7 | 20.3 | 0.0 | 0.0 | 0.0 | 0.5 | 67.4 | 11.7 | 0.0 | 79.1 | 0.0 | 100.0 |
| BRS1331-8 | 34.4 | 0.0 | 0.0 | 0.0 | 0.9 | 46.5 | 17.5 | 0.9 | 64.7 | 0.0 | 100.0 |
| BRS1331-9 | 25.4 | 0.0 | 0.0 | 0.0 | 0.7 | 55.7 | 18.1 | 0.1 | 73.9 | 0.0 | 100.0 |
| BRS1331-10 | 11.1 | 0.0 | 0.0 | 0.0 | 0.6 | 69.0 | 17.9 | 1.5 | 88.5 | 0.0 | 100.0 |
| BRS1331-11 | 18.6 | 0.0 | 0.0 | 0.0 | 0.6 | 68.6 | 10.3 | 1.9 | 80.7 | 0.0 | 100.0 |

High Clay Content (Ductile)

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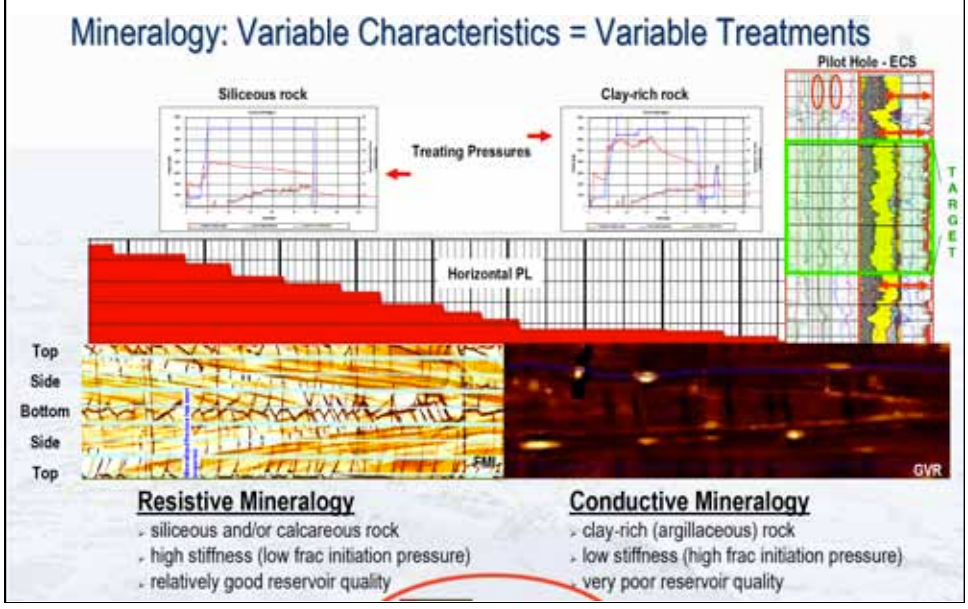
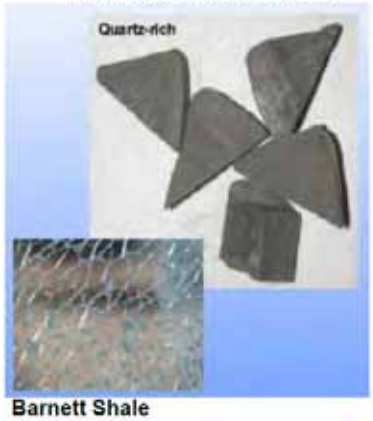
# Why is Mineralogy Important?



## Brittleness

High clastic content shales are brittle and shatter, providing multiple dentrict fracture swarms. High clay content shales are plastic and absorb energy, providing single-planar fracs.

**12A. Quartz-Rich (Brittle)**




**Barnett Shale**

**12B. Clay-Rich (Ductile)**


**Cretaceous Shale**

Source: CSUG, 2008

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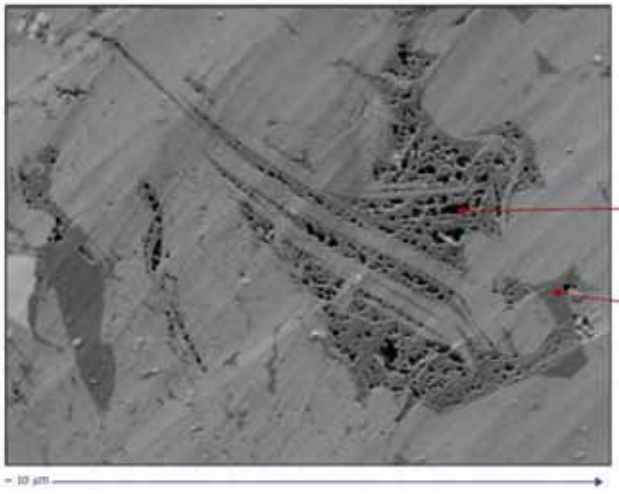
## Pores and Organic Content




**Nanopores in Maturing Kerogen**

Source: Reed et al. Texas SEG

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## Properties

- Low Permeability, ranges between 1 nano-darcy to 500 micro-Darcy.
- Low porosity, usually 1%-5%.
- Total Organic Content (TOC), typically 1%-20%.
- High Stiffness E>60 GPa (Comparable to concrete).
- Deep and thick formations, usually 1500 to 5000 meters deep and 20-200 meters thick.
- Natural Fractures.

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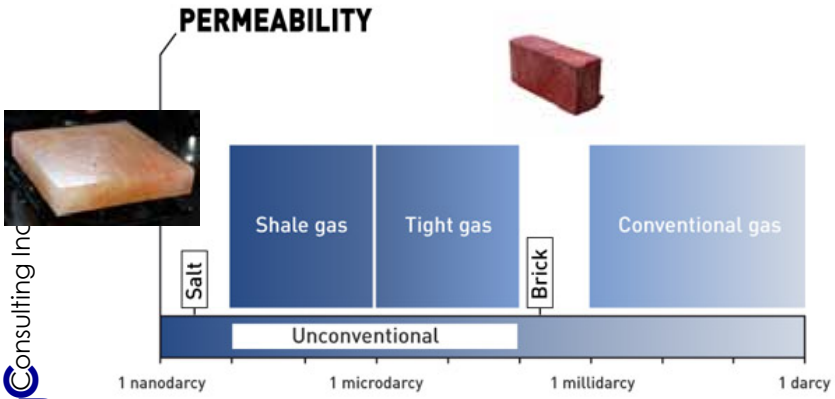
## Permeability

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## Natural Fractures in Utica Shale

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## Devonian Fractured Shale

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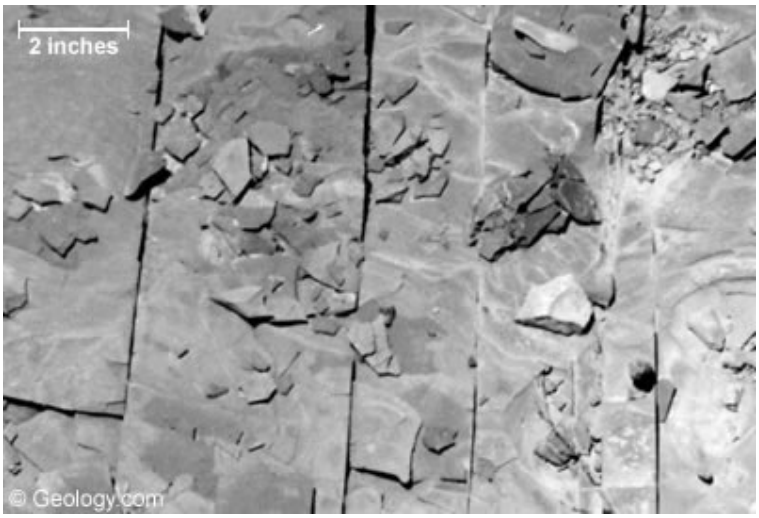

# Besa River Shale properties

| Sample | Porosity (%) | Permeability (md) |
|---|---|---|
| **Besa River** | | |
| Lower black mudrock | | |
| BRS325-1 | 1.16 | 0.0054 |
| BRS325-3 | 0.58 | 0.0008 |
| BRS325-5 | 1.24 | 0.0083 |
| BRS325-7 | 0.35 | 0.0006 |
| BRS2563-1 | 1.61 | 0.0218 |
| BRS2563-3 | 2.14 | 0.0363 |
| BRS2563-7 | 1.06 | 0.0048 |
| Upper black shale | | |
| BRS-C15-1331-1 | 5.4 | 0.0054 |
| BRS-C15-1331-3 | 5.32 | 0.0044 |
| BRS-C15-1331-5 | 6.35 | 0.0212 |
| BRS1331-1 | 3.88 | 0.0024 |
| BRS1331-3 | 6.8 | 0.0099 |
| BRS1331-4 | 6.84 | 0.0114 |
| BRS1331-5 | 5.06 | 0.0135 |
| BRS1331-6 | 5.23 | 0.0193 |
| BRS1331-11 | 4.6 | 0.0107 |

High Porosity Region (High gas content)

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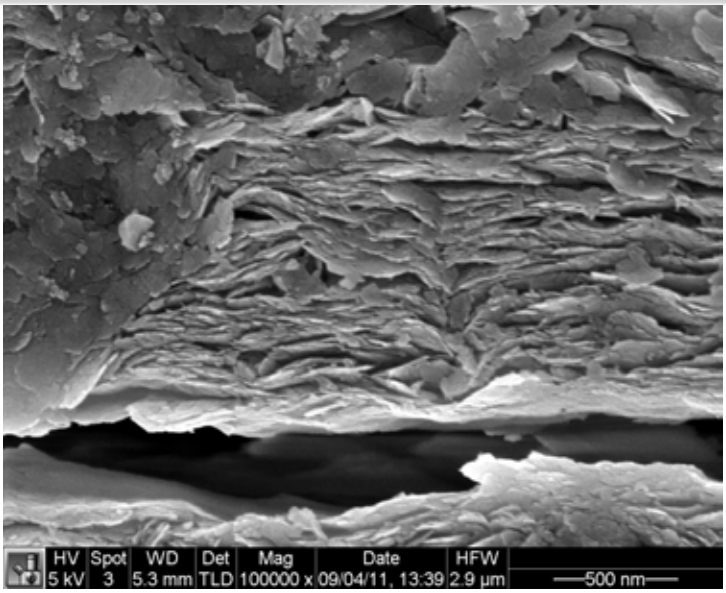
# Eagleford Shale




Zoback, 2011, NEA Shale Gas Talk

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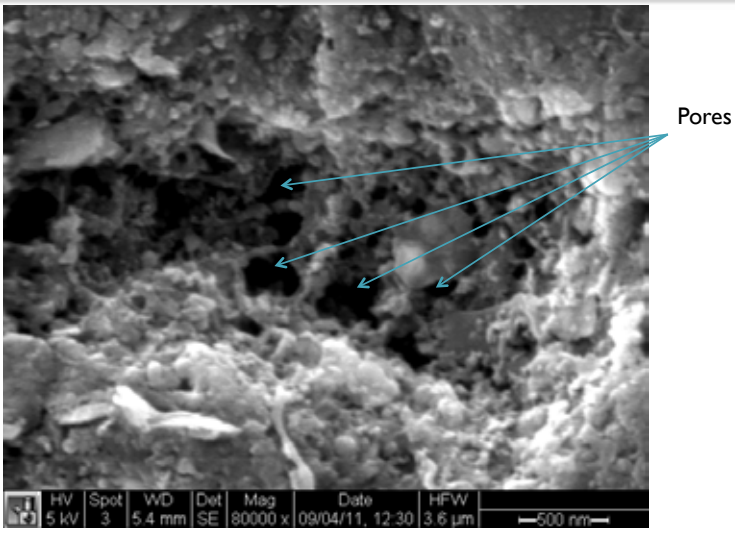
## Pore Structure




Zoback, 2011, NEA Shale Gas Talk

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## Properties

- **Shale Gas plays are challenging mainly due to a very low permeability matrix.**
- **Economic flow rates can not be achieved using conventional technologies.**
- **Recovery factor is generally 5-30%.**
- **Production from a well is initially high, but declines rapidly in the first year until it reaches a plateau.**
- **A well is planned to produce for a few decades.**

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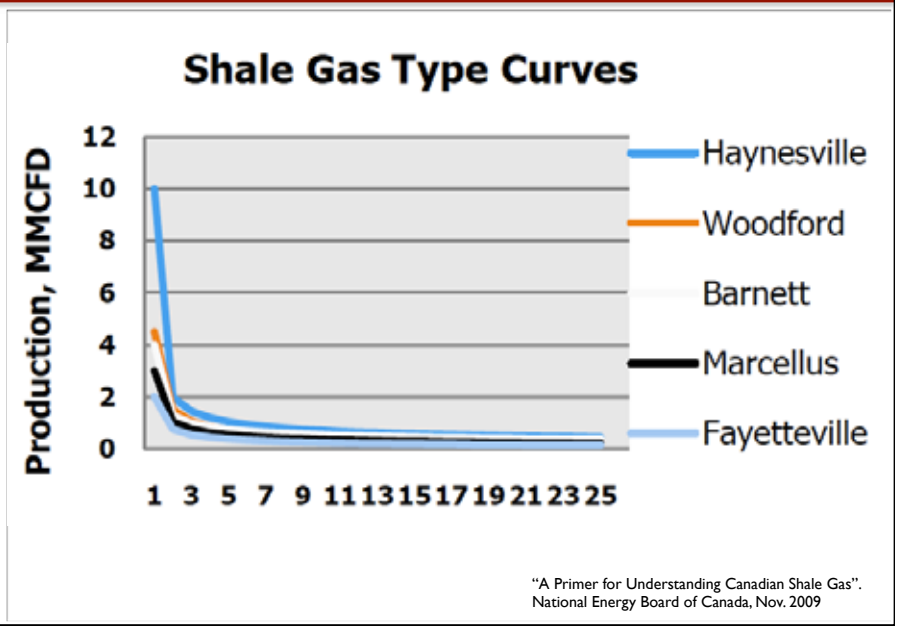
## Gas Production from a well in Shale




"A Primer for Understanding Canadian Shale Gas". National Energy Board of Canada, Nov. 2009

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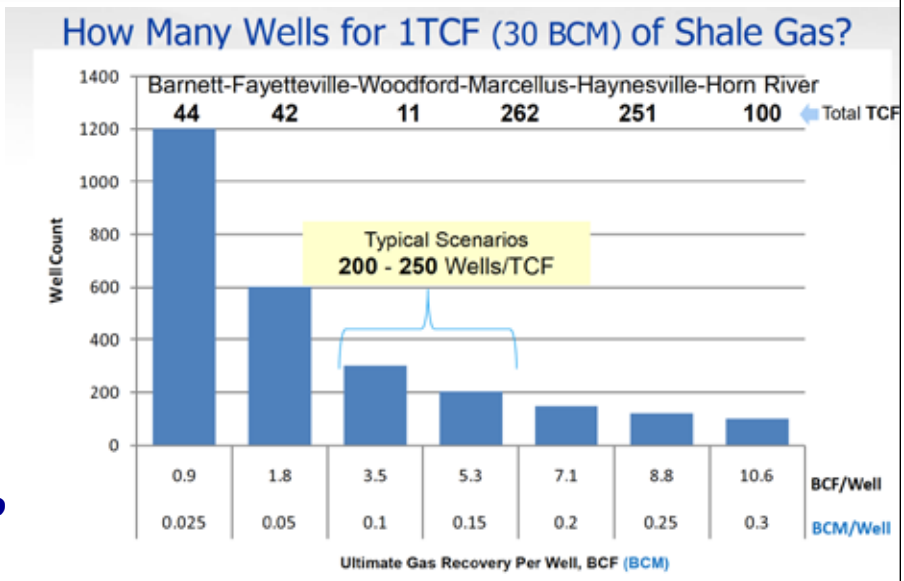
## Shale Gas Development Requires a Large Number of Wells!

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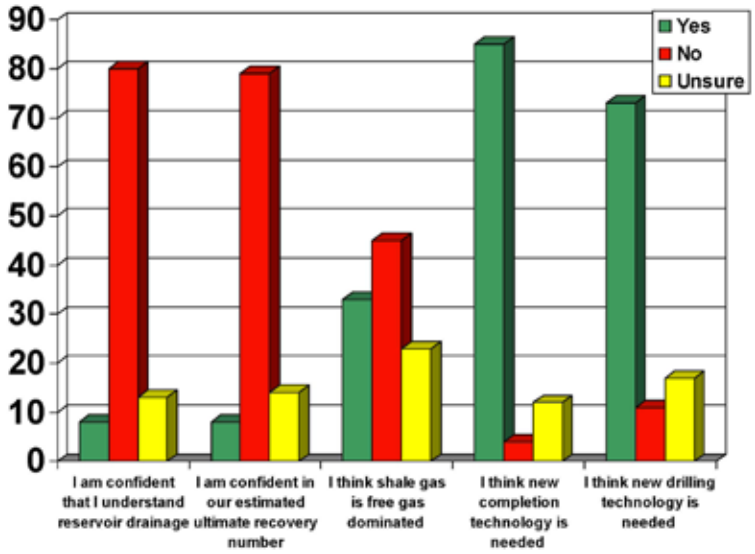
## SPE Shale Gas Production Conference - Survey

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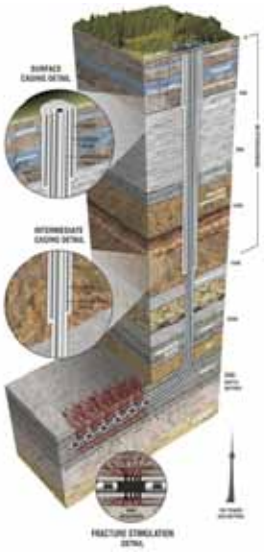
# Well Construction



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## Outline

- **Well Design**
- **Casing Design**
- **Hydraulic Fracturing Design**
- **Completion Design**
- **Post Completion**

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## Shale Gas Evaluation and Stimulation Workflow (SPE 123586)

- Plan the well construction and formation evaluation program.
- **Begin well construction.**
- **Obtain shale-formation samples. Obtain openhole log data.**
- **Complete well construction.**
- Evaluate shale-formation samples in the laboratory.
- Construct a petrophysical-log model based on openhole logs.
- Calibrate the petrophysical-log model using the information obtained from the formation-sample analysis.
- Select completion intervals in shale based on petrophysical-log model & mud-log information.
- Complete preliminary completion program and stimulation design.
- Perform DFIT on the Stage 1 shale interval. Analyze Stage 1 DFIT data.
- Update petrophysical-log model using the DFIT data.
- Consider special diagnostic methods for the fracture treatment (i.e., proppant tracer, fluid tracer, and microseismic mapping).
- Finalize fracture-treatment design.
- Perform hydraulic-fracture stage treatments.
- Flow test well.
- Clean out well to total depth.
- Perform postfrac-diagnostic analysis of tracers, microseismic mapping, and fracturing-treatment data.
- Run production-log survey at 2 to 4 weeks post frac stimulation and analyze.
- Run production-log survey 4 to 6 months post frac and analyze.

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## Well Design

- After exploration phase, wells are designed for the specific formation.
- Wells are usually designed as part of well pads.
- Well pads consist of multiple wells drilled from the same location on surface to minimize surface print.
- The surface location of the well pads are selected according to the terrain of the area, distance from majorly populated areas, infrastructure available, etc.

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## Horizontal Drilling

- Classic oil and gas wells were all vertical.
- With the advent of new technologies it is now possible to deviate a vertical well to a horizontal direction.
- Horizontal wells can be a few hundred meters to a few kilometers. This means that a single well can contact a large volume of the reserve.
- The downside is the high cost of these well. A few millions of dollars per well, depending on depth and the length of the well.

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## Horizontal wells

- **A horizontal well starts with a vertical well which deviates at a certain depth and takes a horizontal direction.**
- **The point where the vertical well is deviated is called ”kick off” point.**
- **The direction of the horizontal well is determined by the direction of in-situ stresses.**
- **The trajectory of the horizontal well can never be perfectly horizontal.**
- **The length of the horizontal section is usually 1-2 km.**

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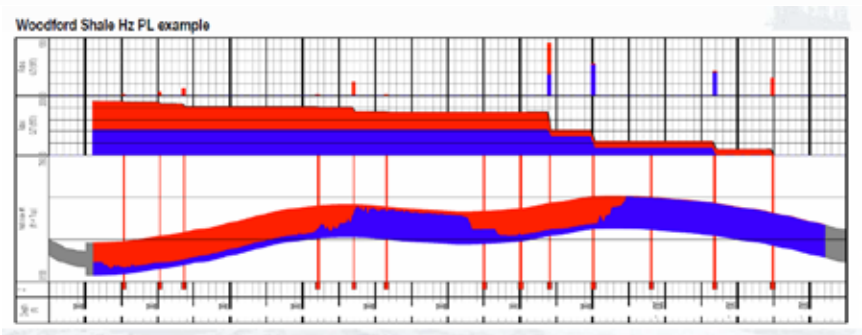
## Well Trajectory




The well trajectory is never perfectly horizontal

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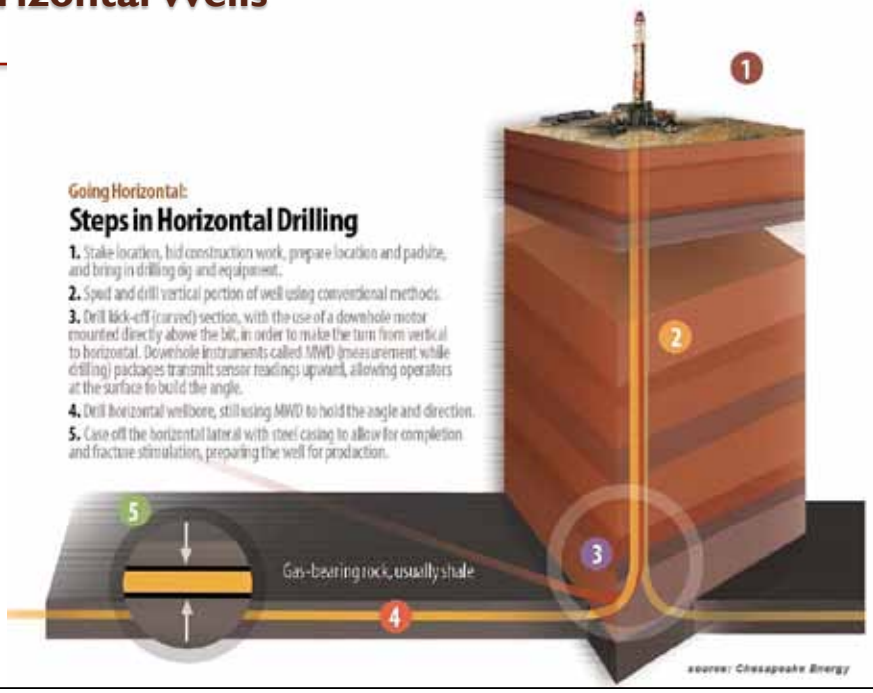
# Horizontal Wells

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# Design Parameters

- **Well Separation**
  - Based on optimal placement according to simulations and hydraulic fracturing efficiency.
- **Horizontal length**
  - Depends on lease boundary, drilling capabilities, production capacity, etc.
- **Lateral Uncertainty**
  - The experience of the driller and the drilling technology at hand.

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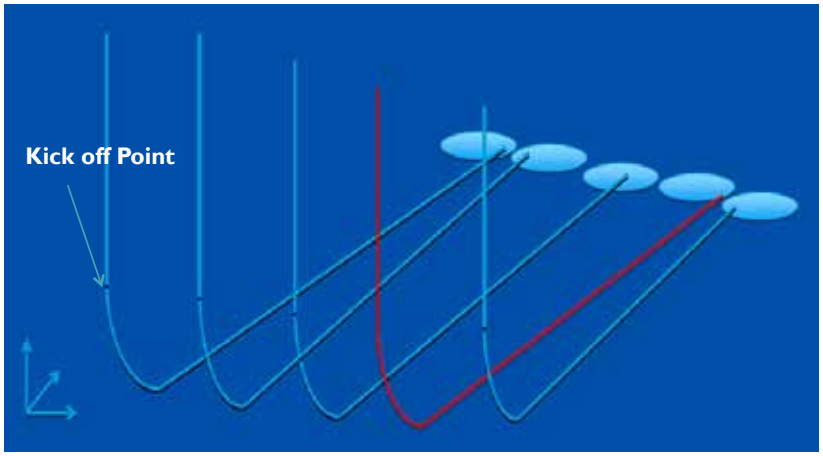
## Lateral Uncertainty

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## Casings

- During well construction, steel pipes are connected together and put into the well. This thick pipe is called "Casing".
- Casing is important for protecting the well integrity and preventing influx of drilling fluids into underground water.
- The first casing is set at a shallow depth which is called "Conductor Casing".
- The drilling continues and the next casing is set below the underground water sources. This casing is called "Surface Casing".

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## Casings

- **Depending on the geology and formations that the well passes through few more casings are set. These casings are called "intermediate Casing".**
- **Intermediate casings are passed through the previous casings.**
- **When the target is reached, the last casing is inserted which is called "Production Casing".**

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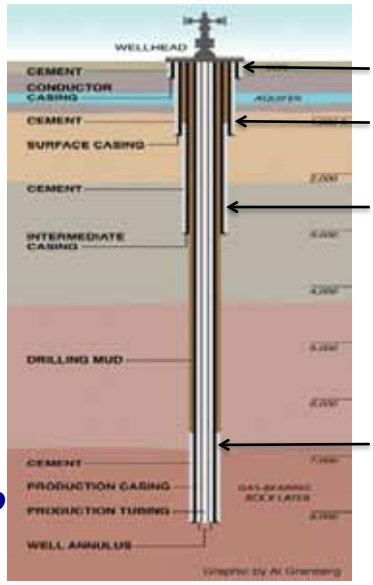
## Casings

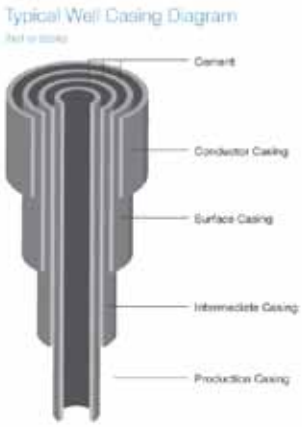



Conductor Casing

Surface Casing

Intermediate Casing

Production Casing

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## Casings

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## Cementing

- **The casings are set in place by cementing.**
- **The cements fills the space between the outer surface of the casing pipe and the surface of the wellbore.**
- **After each cementing the integrity of the cement job is tested and then the drilling continues.**

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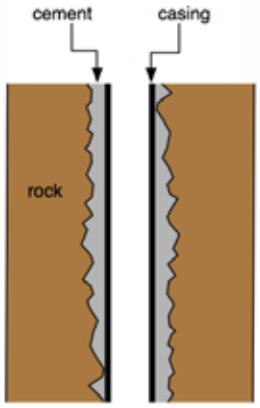
## Cement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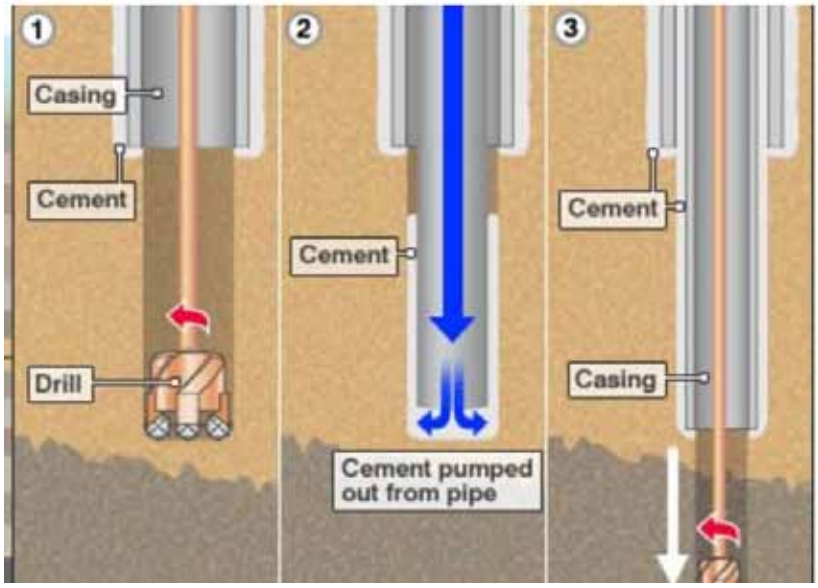
## Cementing

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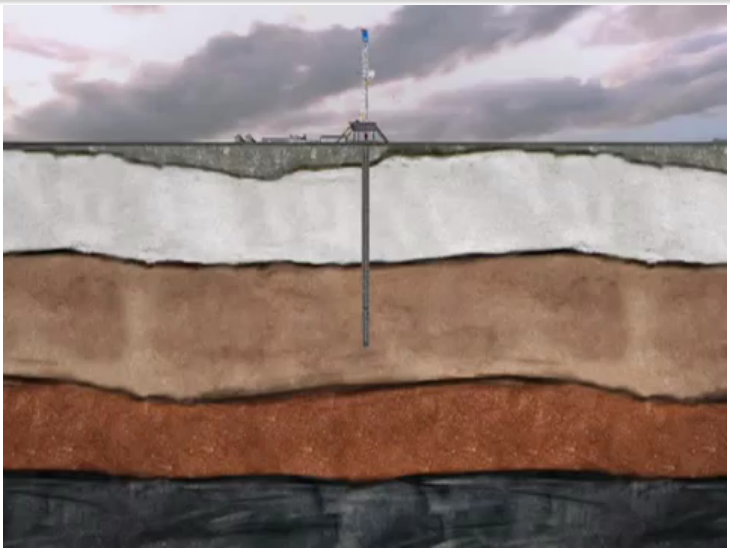
## Cement Process Animation



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## Well Evaluation Programs

- Logging – Surface Hole (620m to surface, Completed)
  - GR / SP / Res / Density / Neutron
  - Sonic
- Coring
  - Interval 1: 3120 – 3138m
- DST (Drillstem Tests)
- Logging – TD section
  - GR / SP / Res / Density / Neutron (to surface shoe)
  - Sonic Compressional and Dipole Shear (to surface shoe)
  - NMR (interval of interest)
  - Formation Elemental Analysis (interval of interest)
  - Borehole Image Log
  - MDT – formation pressure & samples (TBD)
  - MDT – minifrac (TBD)
  - MDT – vertical interference test (TBD)
- Logging – Cased hole
  - Ultra sonic cement imager (entire production casing string)
- MMV Baselines
  - VSP (Zero-Offset)
  - RST

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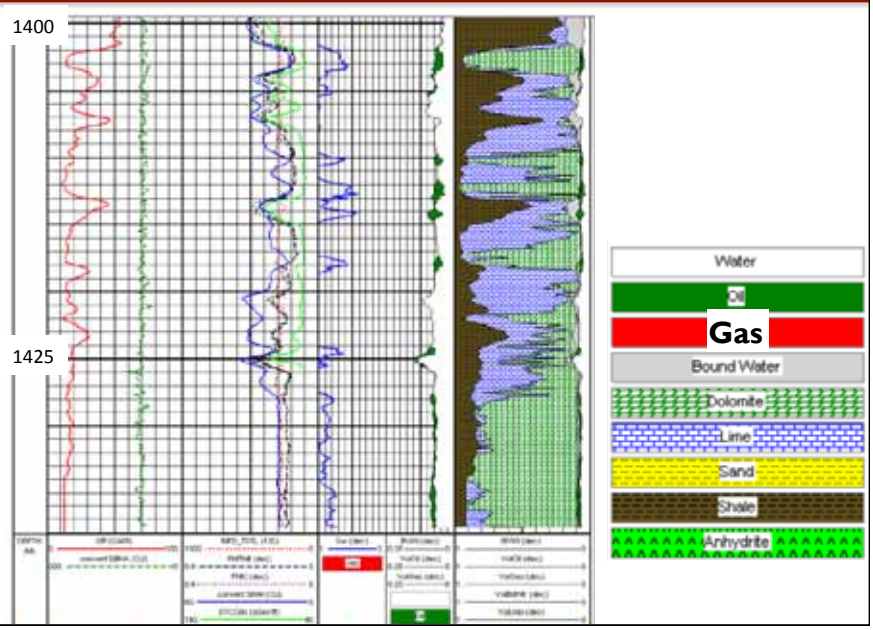
## Behind Casing Assessment: RST Log

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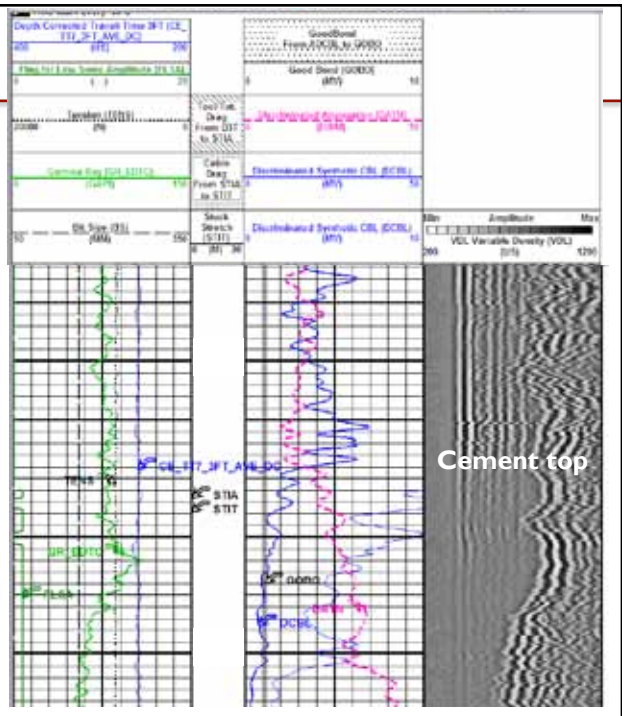
## Sonic Scanner

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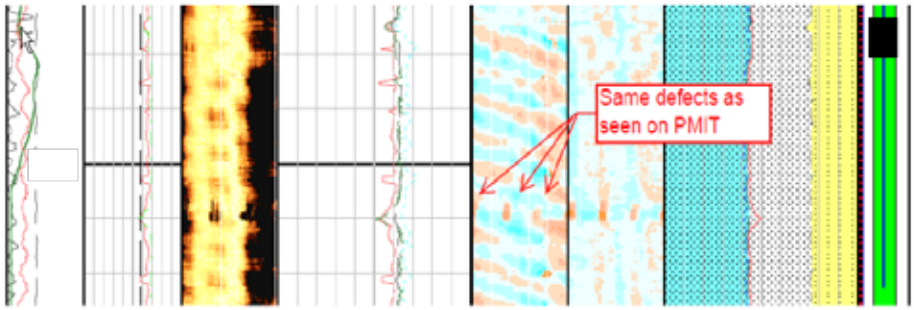
## Isolation Scanner

The PMIT log showed a clear defect at , and the USI picks this event up as well, but with less clarity due to eccentering. The same three evenly spaced defects can be observed

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## Hydraulic Fracturing

- **After the drilling is completed, hydraulic fracturing is done.**
- **Hydraulic fracturing process involves injecting fluids at high pressures.**
- **When the fluid pressure exceed the formation stress and strength, fractures are created.**
- **Proppants (sand) is pumped with the fluid to enter the cracks and keep them open when the injection stops.**

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## Multistage Hydraulic Fracturing

- **HF is done at different stages in the horizontal wells.**
- **A HF job can have 6-20 stages.**
- **At each stage a piece of the horizontal section of the well is isolated and hydraulically fractured.**
- **Then a second section is isolated and fractured, this process continues until the desired length of the well has been hydraulically fractured.**

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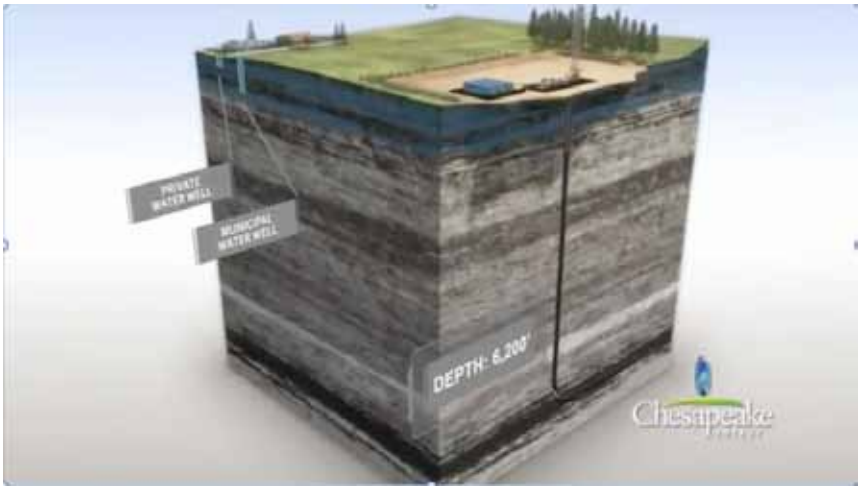
## Video of Multistage Fracturing Process

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## Hydraulic Fracture Design

- **Important design parameters of a HF job include:**
  - Choice of fluid (water, propane, Nitrogen, foam, etc.)
  - Choice of the additives (Friction reducers, acids, etc.)
  - The size of proppant (mean size of sand particles)
  - The volume of fluid required
  - The rate which the fluid should be injected
  - The maximum pressure of fluid required (selecting proper pumps)
  - Number of stages

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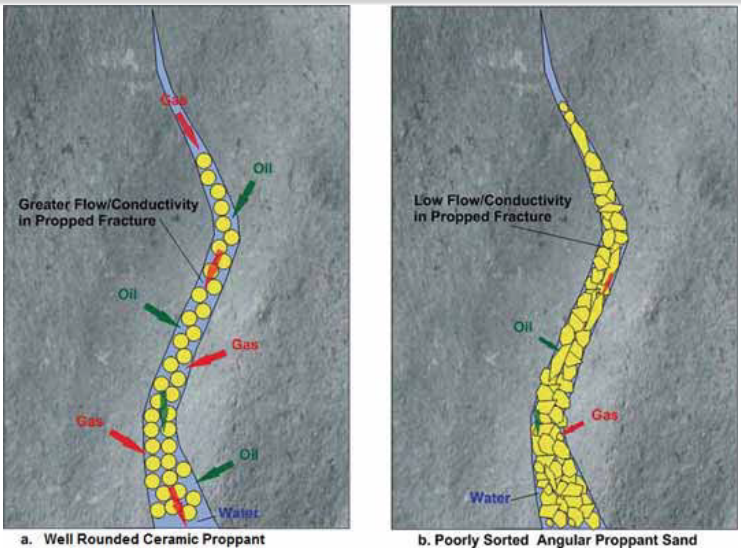
## Proppant




a. Well Rounded Ceramic Proppant

b. Poorly Sorted Angular Proppant Sand

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## Completion Methods

- Open Hole Completion
- Cased Hole Completion
- Multi Lateral Completion

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## Open Hole Completion

- In this type of completion, the section of the well inside the reservoir is simply open.
- The wellbore has no support.
- Gas flows from the formation directly into the wellbore.
- The formation rock (Shale) has to be strong for this type of completion.

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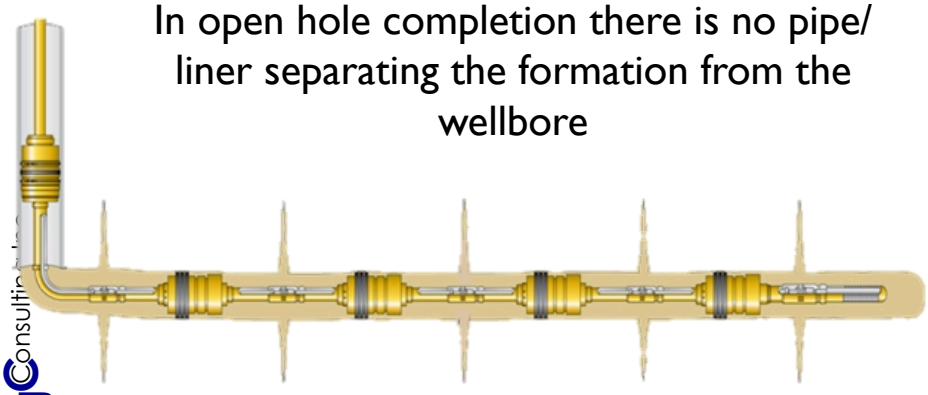
## Open Hole Completion

In open hole completion there is no pipe/ liner separating the formation from the wellbore



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## Cased Hole Completion

- **In this type of completion, there is a casing inside the wellbore, separating the formation from the wellbore.**
- **The casing provides support for the well.**
- **After the casing is set, it will be perforated.**
- **Perforations are holes that are created in the casing so that gas can flow through them into the casing.**
- **Hydraulic fracturing is done after the perforations are created.**

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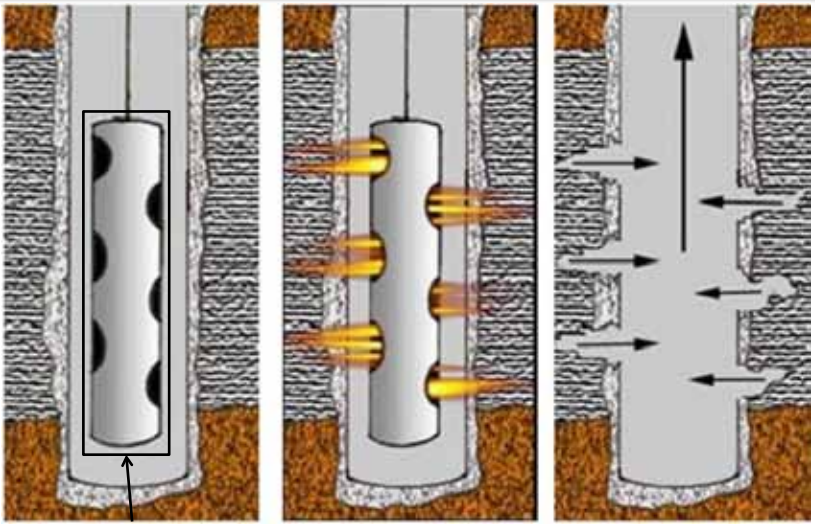
# Perforation



Perforation Gun

Gun shoots a jet of hot gas to perforate the casing

The perforations let the gas flow into the wellbore

http://www.oilinisrael.net

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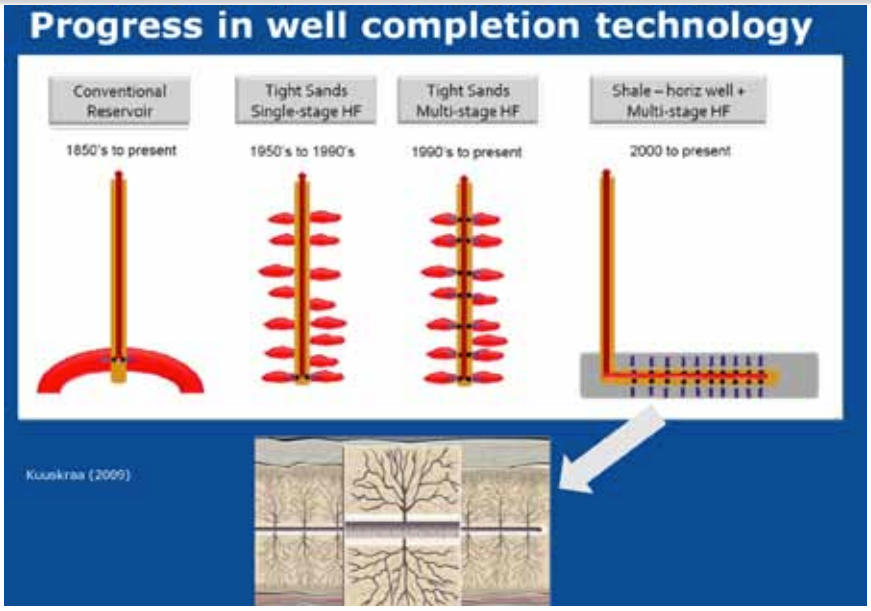


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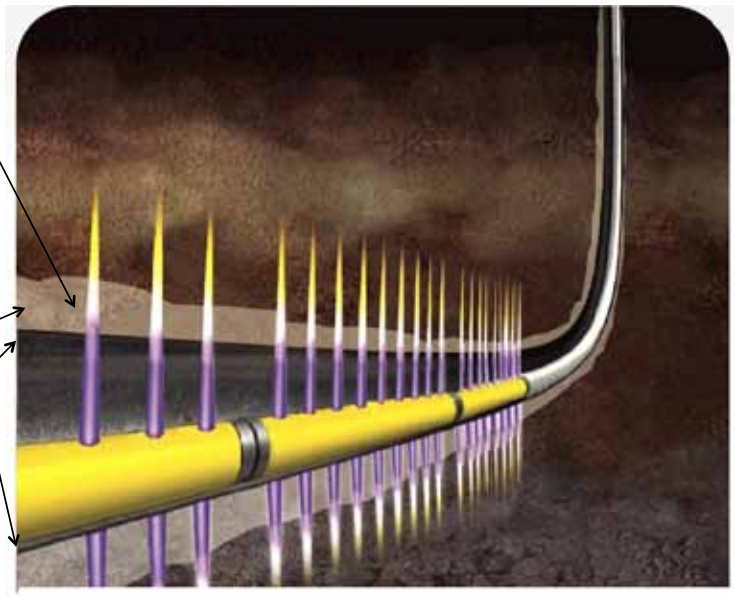
# Perforation




Baker Hughes 2009

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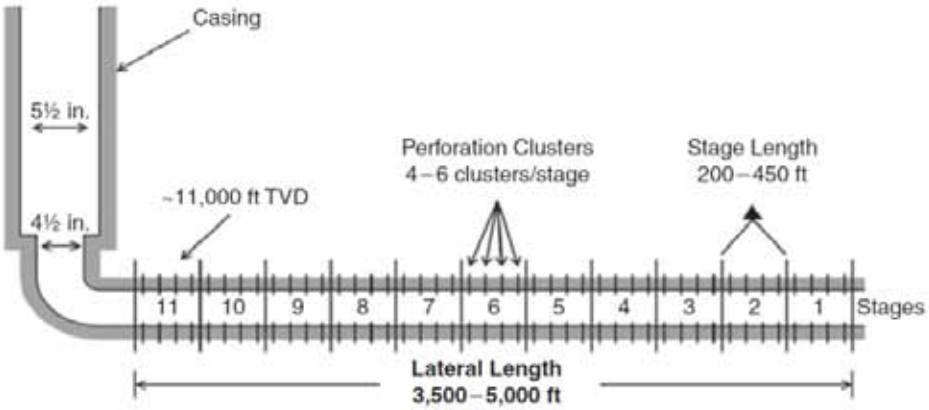
# 11 Stage Haynesville Completion

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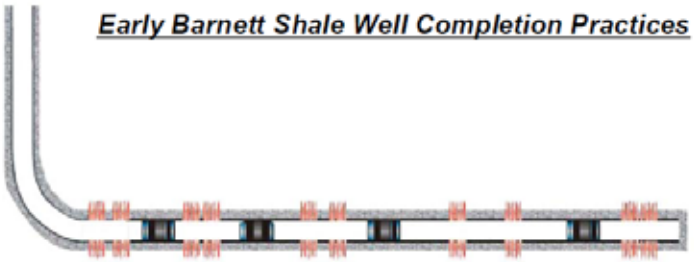
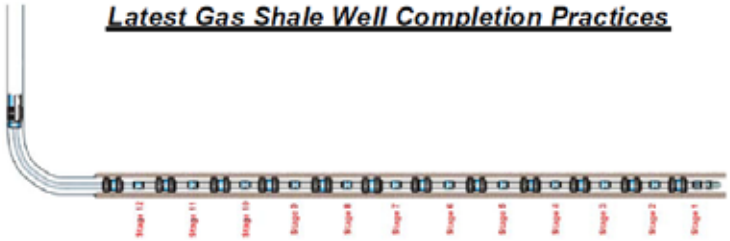
Thomson et al., 2011

# Cased Hole Completion (Barnett Shale)




Cased, Cemented, Perforated and Isolated Horizontal Wellbore




A 12 Stage Open Hole Completion System Using Open Hole Packers for Mechanical Diversion

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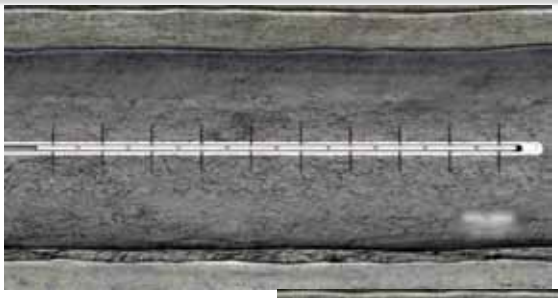
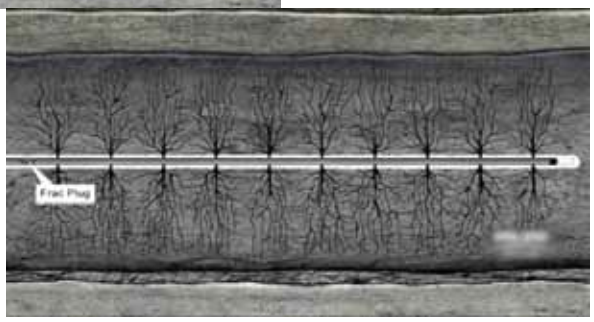
# Perforation followed by Hydraulic Fracturing



After Perforation

After Fracking



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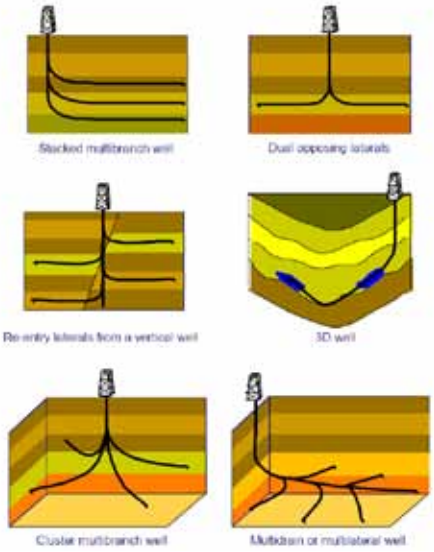
## Multilateral Completion

- **In this type of completion, the wellbore is branched off to different directions allowing to contact a large volume of the reservoir or produce from different layers.**
- **This type of completion is very difficult and expensive.**
- **Most common in off-shore wells, where the cost of drilling multiple wells is very high.**

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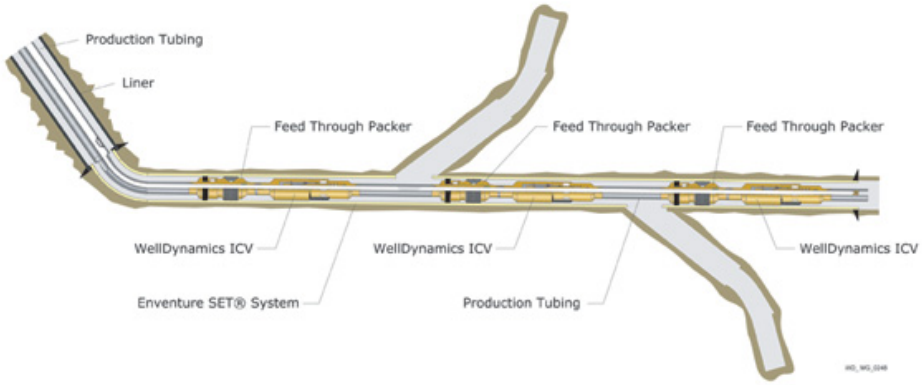
## Multilateral Completion

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## Post Completion

- After completion the well is put on production.
- Almost all the equipment are removed from the surface and the water storage pools are filled.
- The surface footprint is reduced to a third or less of what it was while drilling.
- Only a wellhead and a few other equipment are left on the surface.

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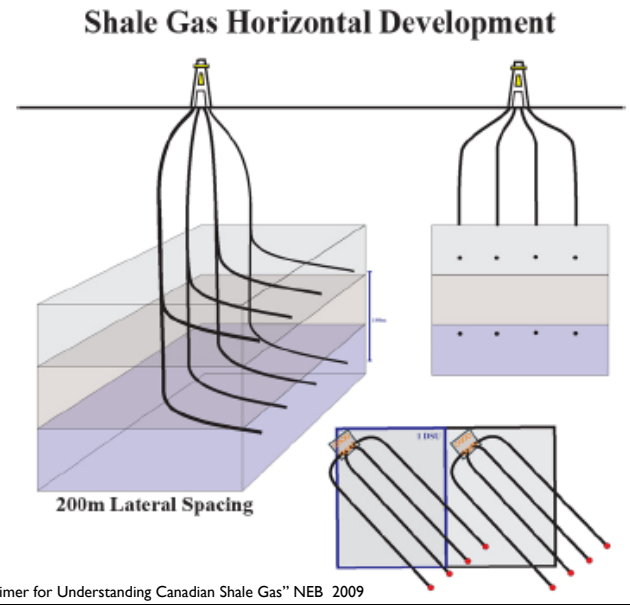
## Keeping Footprint to a Minimum




A Primer for Understanding Canadian Shale Gas" NEB 2009

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## During Completion

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"The Pennsylvania Shale Gas Experience". Doug Mehan, PennEnergy Resources, LLC.

## After Completion

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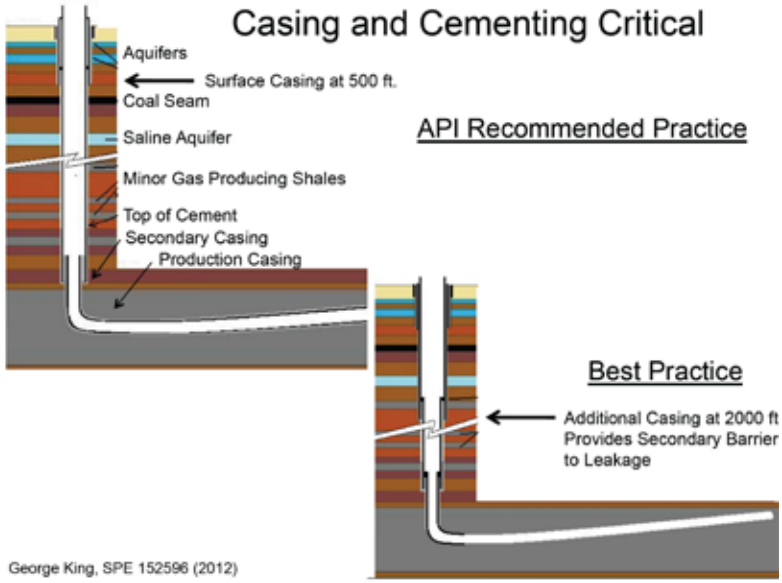
"The Pennsylvania Shale Gas Experience". Doug Mehan, PennEnergy Resources, LLC.

## Well Construction Guidelines

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# Hydraulic Fracturing

# Part I

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## Hydraulic Fracturing Uses

- **To enhance well productivity (drainage area)**
  - Propped fractures in conventional oil reservoirs
  - Geothermal well fracturing
  - Shale gas development
  - CBM - Coal Bed Methane
- **To introduce thermal energy (steam fracturing in heavy oil EOR - CSS)**
- **To measure stress (Minifrac™, LOT, XLOT)**
- **For massive solid waste injection (SFI)**
  - Drill cuttings annular reinjection
  - Biosolids injection and carbon sequestration
- **For acidizing, for "choking" rates, other uses**

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## Hydraulic Fracturing Process

**1. Pump Pad**
- Causes rock to **fracture**
- Creates fractures to accept **Proppant**

**2. Pump Slurry**

**Proppant** (size-graded particles, spherical white sand / man-made) mixed into fluid **Slurry**; pumped in to prop open created **fractures**

**3. Flush**

Clean fluid to clear surface lines & well tubulars of proppant; pumps **shut down**

**4. Bleed Off** well **pressure** to allow fractures to close on proppant

**5. Recover** injected fluid by **flowing/lifting** well
(Typically recover **<30%** of frac fluid)

Baker Hughes

## Fracturing Fluid

**Fracturing Fluid = Base Fluid + Additives + Proppant**

- **Base** fluid – water or oil
- **Additives** – Gelling Agents, Crosslinkers (polymers), Friction Reducers, Breakers, Surfactants & Non-emulsifiers, Biocides
- **Proppants** – White Sand (for Shales), Brown Sand, Low Density Ceramics, Resin-coated Sand, Sintered Bauxite

**Typical Shale Frac Basic Materials Per Stage**

| SHALE | STAGES | *Xf ft | COMPLETION METHOD | FLUID TYPE | FLUID VOLUME Bbls/Stage | PROPPANT TYPE | PROPPANT Total Lbs. |
|---|---|---|---|---|---|---|---|
| BARNETT | 7-9 | 300-400 | Plug-N-Perf | Acid, SW | 14,000 | Ottawa/Lite | 550,000 |
| FAYETTEVILLE | 8-11 | 250-300 | Plug-N-Perf/OH | Acid, SW | 6,500 | Ottawa | 300,000 |
| HAYNESVILLE | 8-11 | 300 | Plug-N-Perf/OH | Acid, SW /Poly | 11,400 | Other | 330,000 |
| MARCELLUS | 6-8 | 300-400 | Plug-N-Perf/OH | Acid, SW | 16,000 | Ottawa | 785,000 |
| WOODFORD | 8-10 | 250 | Plug-N-Perf/OH | Acid, SW | 18,500 | Bauxite/Other | 255,000 |
| EAGLE FORD | 8-10 | 350 | Plug-N-Perf | Acid, SW | 12,800 | Ottawa/DC | 300,000 |

* Fracture half length estimated SW = Slickwater OH = Openhole

Baker Hughes

## Technologies

- **Two technologies have made shale gas an economical energy source:**
  - Horizontal Drilling
  - Hydraulic Fracturing

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## Hydraulic Fracturing

- Hydraulic Fracturing is the process of injecting a fluid (typically water) at high pressures to create fractures in the formation.
- HF is necessary in shale formations. Since matrix permeability is too low, fractures are a must for for the gas to flow.
- Usually proppant (sand) is injected with the fracturing fluid to keep the fractures open after the treatment.
- Choice of fracturing fluid depends on depth, lithology, availability, cost,...etc.

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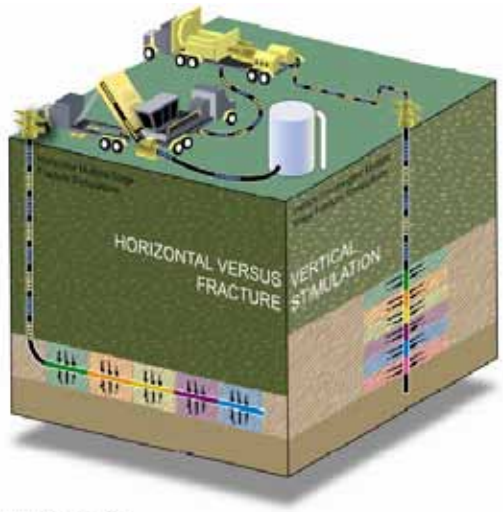
## Multiple Staged Hydraulic Fracturing




Source: JuneWarren Publishing, 2008.

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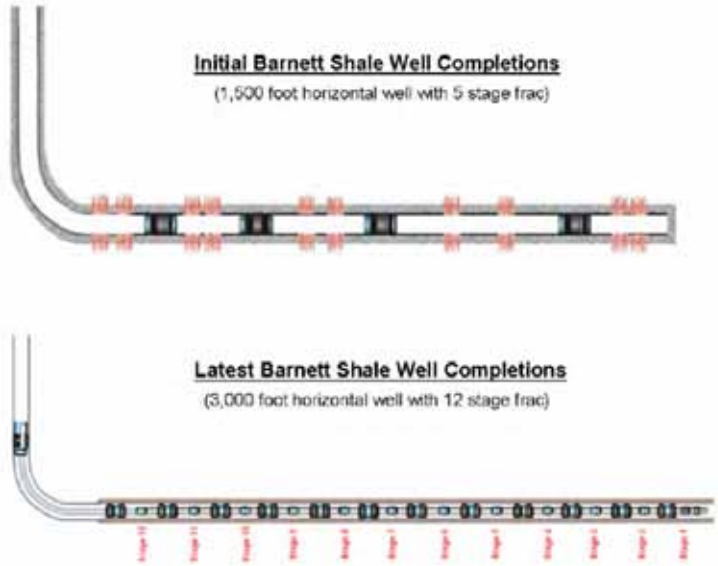
## Well Completions




"World's Shale Gas Resources: An Initial Assessment of 14 Regions Outside of United States". U.S. Energy Information Administration. 2011.

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## Outline

- History
- Process
- HF Benefits
- Fracture Growth Complications
- Controls on Fracture Direction and Geometry
- Recent Developments in Hydraulic Fracturing

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## History

- **"Fracing" or "Fracking": Hydraulic Fracturing**
- **First used in the United States in 1947**
- **Fluids pumped at high pressures into strata to create fissures to allow more natural gas to escape**
- **Fracturing in 800-2000 m horizontal wells**
- **Fracturing fluids are composed typically of:**
  - 90% water
  - 9.5% sand or inert granular propping agent
  - 0.5% other chemicals

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Freeing Up Energy, Hydraulic Fracturing: Unlocking America's Natural Gas Resources, API, July 19, 2010. (API, Freeing Up Energy).

## History

- **First commercial gas well in US produced from shale in Fredonia, NY (1821)**
- **Ohio Shale – Big Sandy Field (1880)**
- **Antrim Shale – Michigan (1940's)**
- **Barnett Shale –Ft Worth Basin (1982)**
- **US shale gas expands (2003)**
- **Horn River Shale, Canada (2006)**
- **Montney Shale, Canada (2007)**

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## History

- The important Shale Gas technologies have been developed in North America in the last ten years (US + Canada)
- Shale Gas (and other unconventional gas) will be found in all major basins in the world
- The methods used will be largely those already developed (horizontal wells + HF)
- Shale Gas should help displace coal
- Reducing greenhouse gas emissions…

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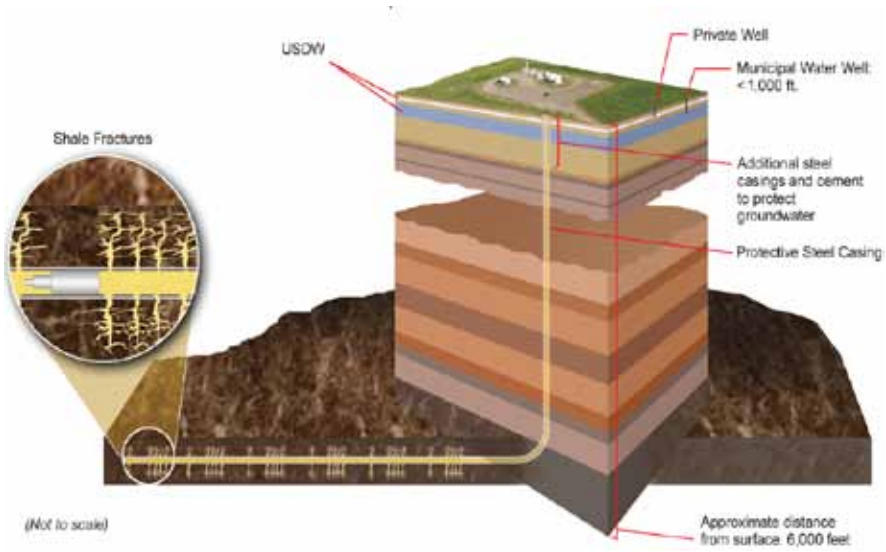
## Process

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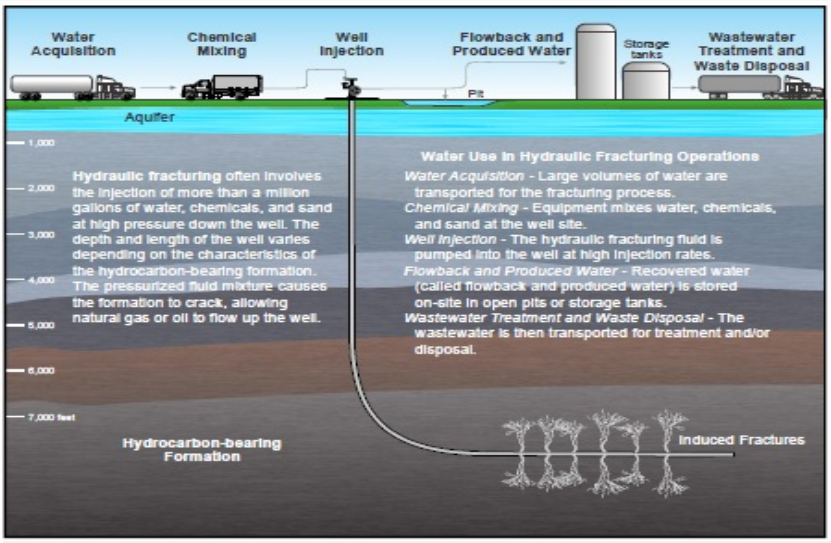
## Process




Source: Draft Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, EPA/600/D-11/001, February 2011 (EPA Frac Study Plan)

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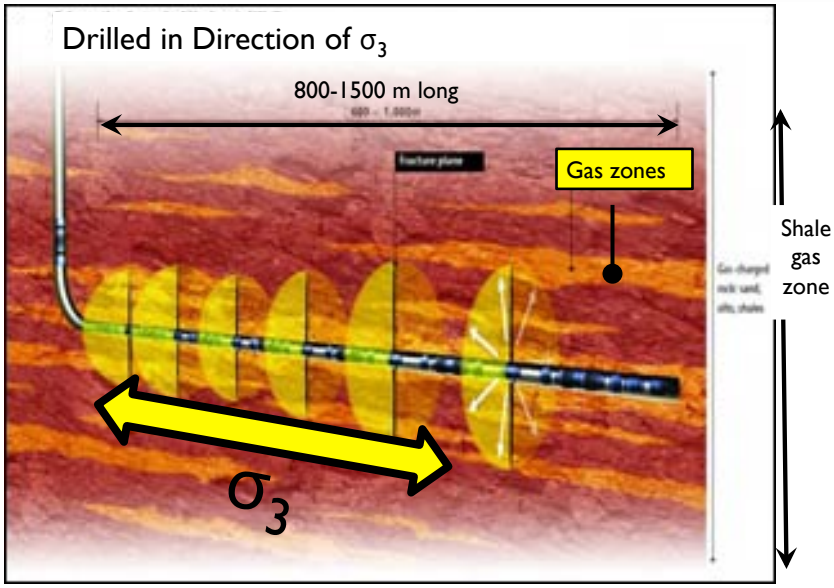
## Process

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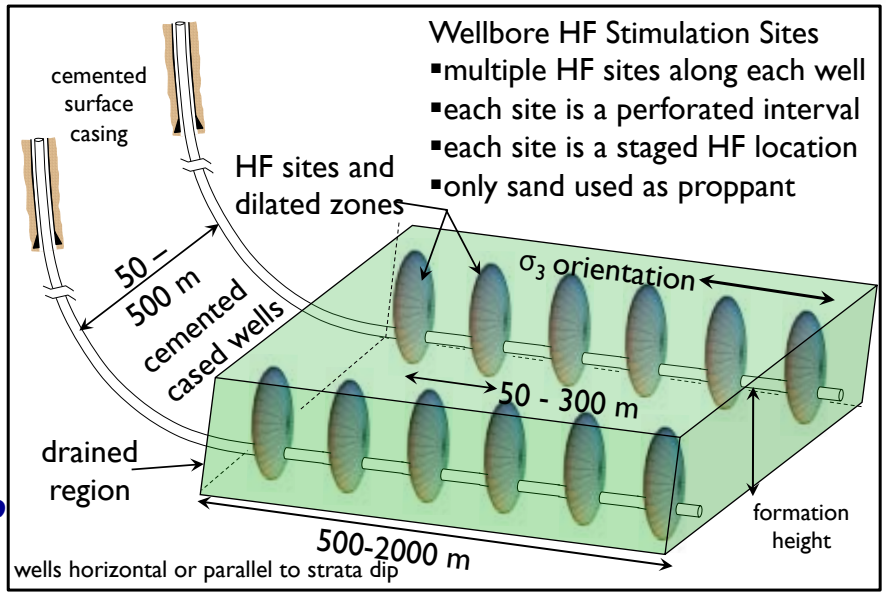
## Process

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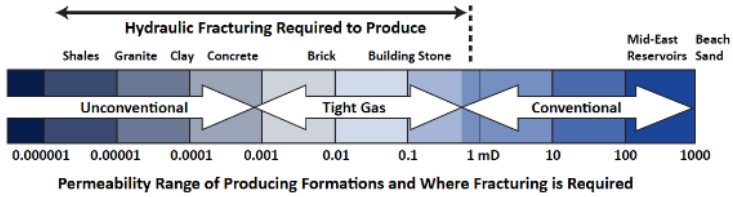
## Hydraulic Fracturing Benefits

- **Fracturing increases the surface area**
  - Accelerates diffusion processes such as gas coming out of shale toward low pressure wells
- **Fracturing increases the contacted volume**
  - A greater volume of shale is "connected" to well
- **Permeability is increased by the fractures**
- **Fracturing can link up vertically separated zones to produce from one well**

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## Hydraulic Fracturing Benefits

- **To enhance well productivity (drainage area)**
  - Propped fractures in reservoirs, geothermal well fracs, access to naturally fractured zones ....
- **To introduce thermal energy (steam fractures)**
- **To measure stress (MinifracÔ, LOT, XLOT)**
- **For drill cuttings annular reinjection - CRI**
- **For massive solid waste disposal**
- **For acidizing, for "choking" rates**
- **Other uses**

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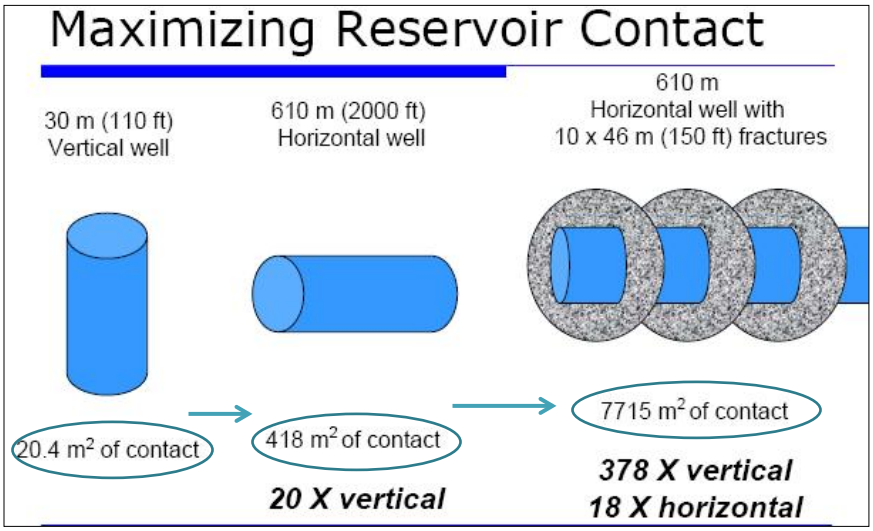
## Hydraulic Fracturing Benefits

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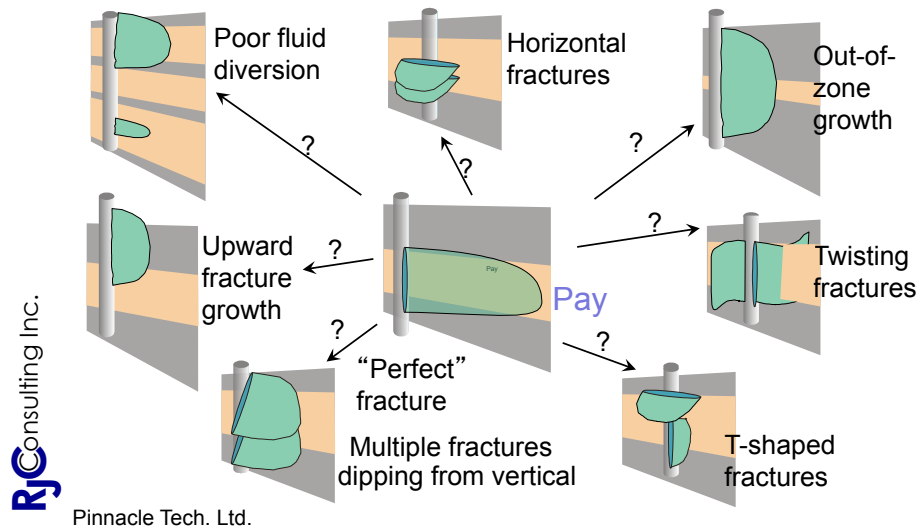
## Fracture Growth is Complex!

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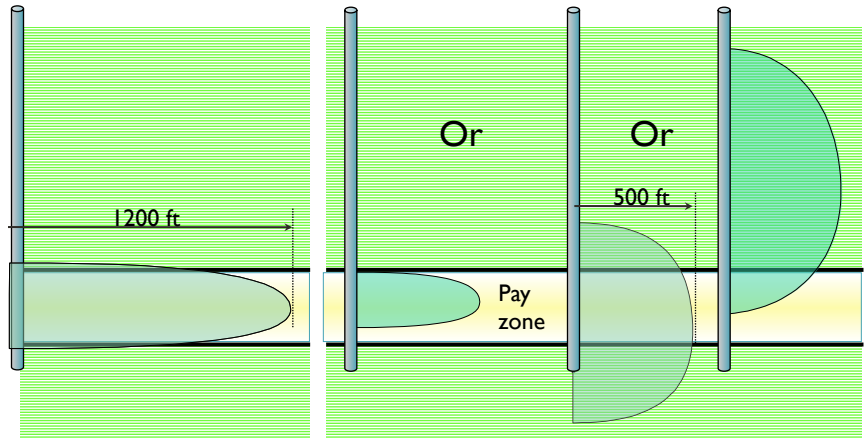
## Fracture Growth Complications




What we want

What we get

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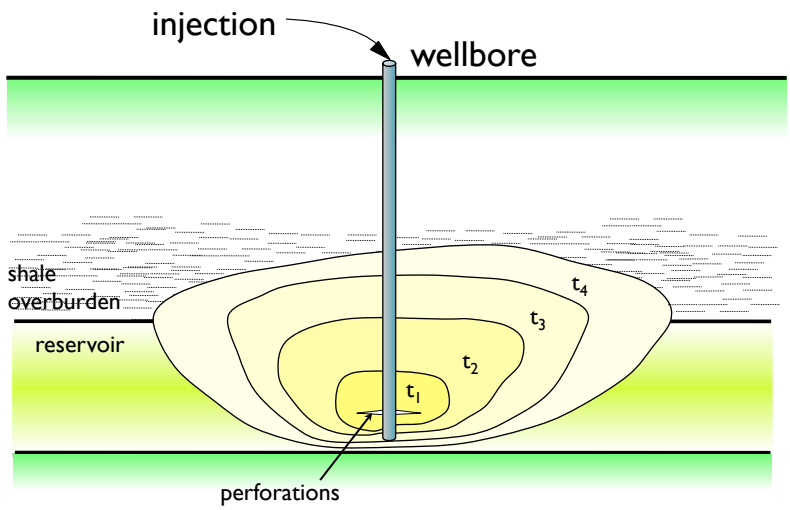
## Fracture Growth Complications
## * Fractures Rising Out of Zone

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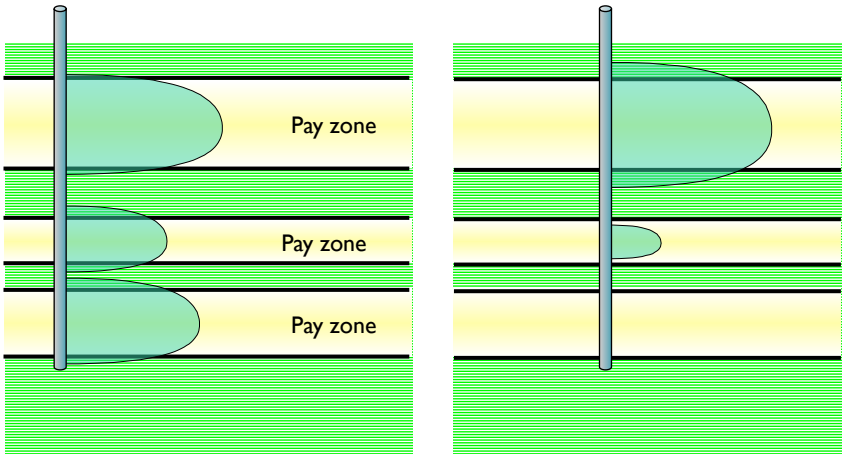
## Fracture Growth Complications
## * Multi zone Fracturing




What we want

What we get

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## Controls on Fracture Direction and Geometry

- **In situ stresses are the major control!!!**
- **Fractures propagate normal to $\sigma_3$**
- **Local fracture propagation direction may be affected by following :**
  - The fracturing process itself
  - Local fabric: joints, fractures, bedding, but for short distances only
  - Different stresses in adjacent strata
  - Depletion and pressurization
  - Formation stiffness effects
  - Permeability effects
  - Thermal effects

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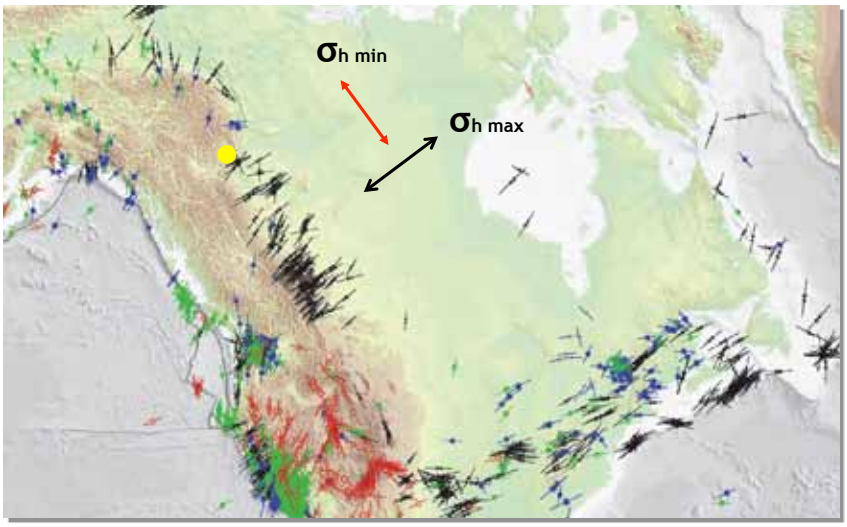
## Regional Stress Directions

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## Controls on Fracture Direction and Geometry

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**Change in direction due to process itself**

- **A fracture pushes the rock apart, and the pressures are higher than $\sigma_3$**
- **As the fracture L grows, the aperture also grows, and this increases the stress normal to the fracture**
- **Near the well, it now becomes easiest to propagate in a different direction**
- **This is done deliberately in “”Frac’n Pack”**
- **Also, the injection plane may flip back and forth between the two directions**
- **This has been measured in real frac jobs…**

## Local, Reservoir, Regional Scales

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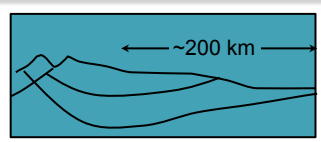
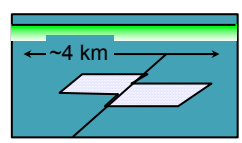
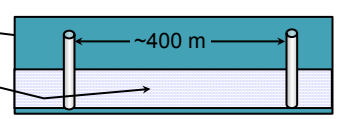
- **Regional Scale Stresses**
  - Basin scale: 50 km to 1000 km
  - Often called “far-field stresses”




- **Reservoir Scale Stresses**
  - A reservoir, or part of a reservoir
  - Scale from 500 m to several km
  - Salt dome region: 5-20 km affected zone



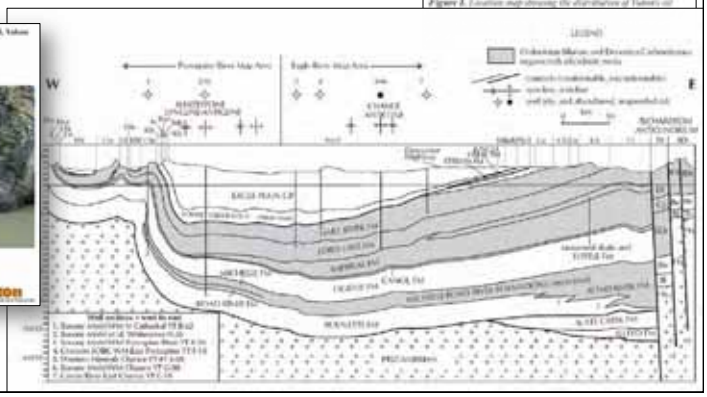

- **Local Scale Stresses**
  - Borehole region: 1-5 m
  - Drawdown zone (well scale) 100-1000 m




- **Small Scale Stresses (less than 10-20 cm)**

# Eagle Plain Basin

- ….. Carboniferous shales offer substantial reservoir potential in Eagle Plain Basin. Further work is required to map out the most prospective fairways in terms of thickness, burial depth, organic richness and maturity. The most apparent risk is loss of reservoir pressure and integrity approaching outcrop on the eastern flank of the basin.



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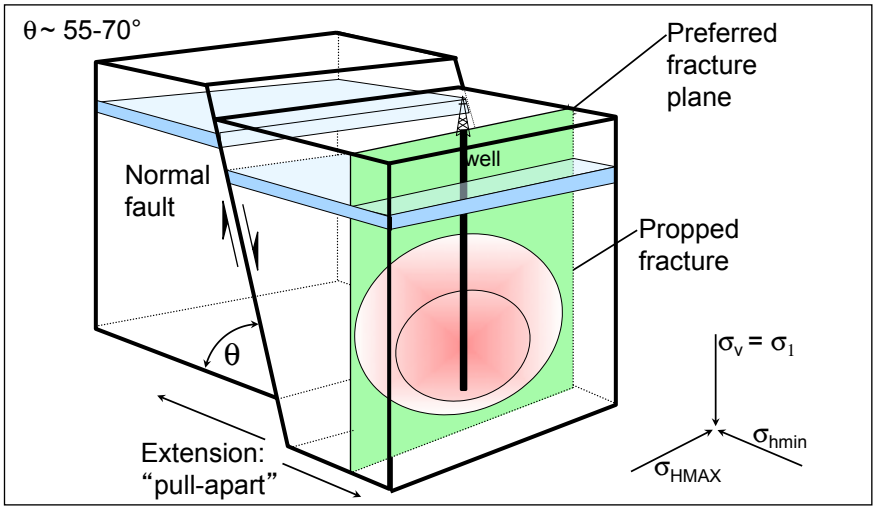
# Normal Faults and Fractures

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## Fracturing & Normal Fault Regime

- $\sigma_v = \sigma_1$, $\sigma_{Hmax} = \sigma_2$, $\sigma_{hmin} = \sigma_3$
- **Regions of crustal extension**
- **Rifts, above domes, cont. margin basins**
- **Horst-graben structures, listric faults**
- **Faults are steep, 60-70° dip angle**
- **Fault movement is down-dip**
- **Fractures in this regime are:**
  - Vertical in attitude
  - Parallel to the strike of the fault plane

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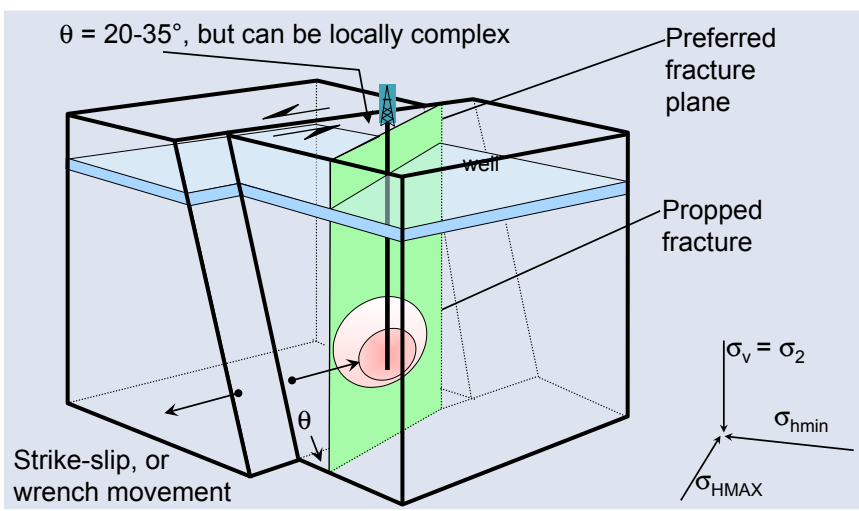
## Strike-Slip Faults & Fractures

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## Fracturing & Strike-Slip Faults

- $\sigma_v = \sigma_2$, $\sigma_{Hmax} = \sigma_1$, $\sigma_{hmin} = \sigma_3$
- **Regions of lateral crustal movement**
- **Transforms, thrust fault flanks, plate slip boundaries (San Andreas, Venezuela)**
- **Faults are steep, >75° dip angle**
- **Fault motion is in the strike direction**
- **Fractures in this regime are (complex, but):**
  - Usually vertical in attitude and
  - At an angle of ~20-35° to the strike of the fault

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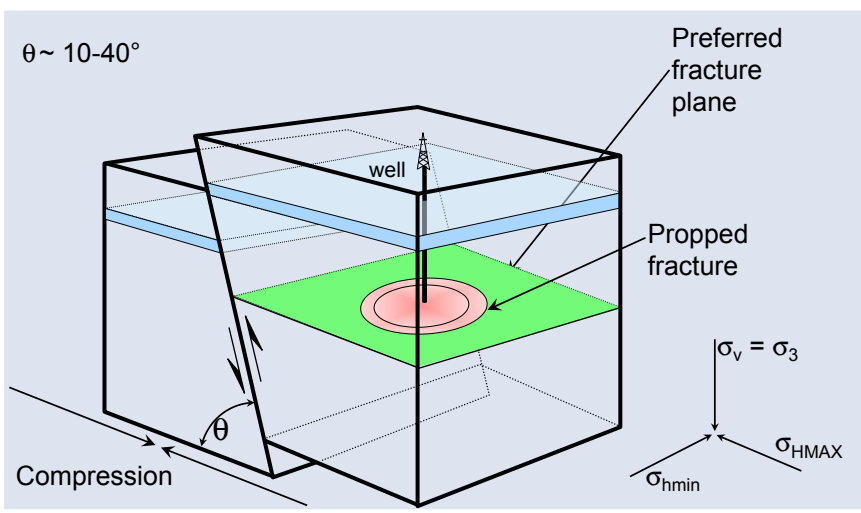
## Fractures Near Thrust Faults

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## Fracturing and Thrust Faults

- $\sigma_v = \sigma_3, \sigma_{HMAX} = \sigma_1, \sigma_{hmin} = \sigma_2$
- **Regions of crustal compression**
- **Near compressional mountains (Rockies), subduction zones, continental plate collision**
- **Faults are shallow, 10-40° dip, sometimes following a particularly weak shale bed**
- **Fault movement is up-dip**
- **Fractures in this regime are:**
  - Horizontal in attitude (usually gently climbing)

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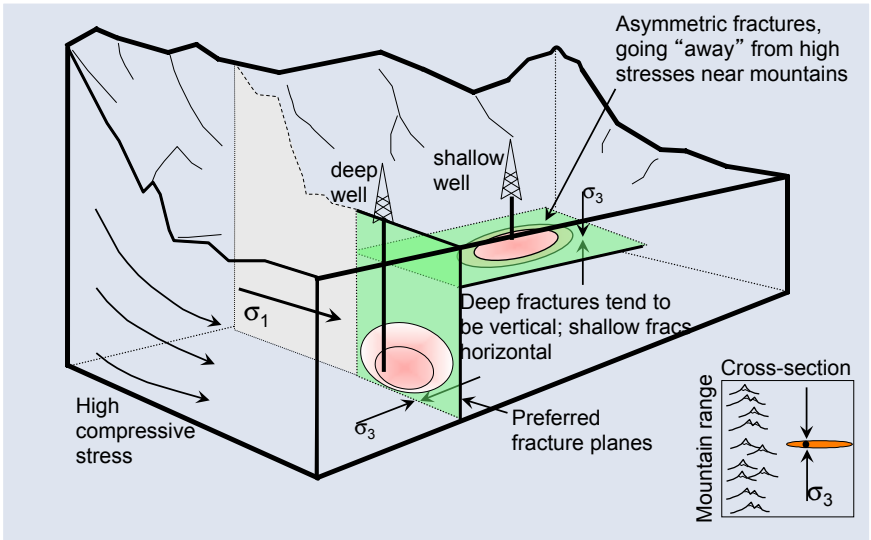
## Fractures Near Mountains

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## Fractures Near Mountains

- **Near a compressional regime, deep fractures are usually:**
  - Vertical in attitude and ⊥ to the mountain front
  - Asymmetric, mountain arm often much shorter
  - Reflecting a strike-slip regime!
- **However, shallow fractures are usually:**
  - ~Horizontal in attitude (gently rising)
  - Asymmetric, extending away from front
  - Reflecting a thrust regime
- **Depends also on how close to active thrusts**

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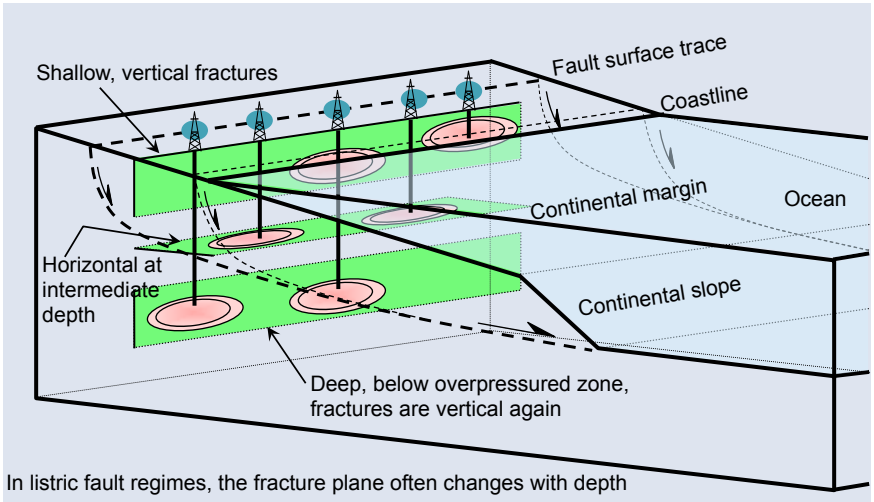
## Fractures in Listric Regimes




In listric fault regimes, the fracture plane often changes with depth

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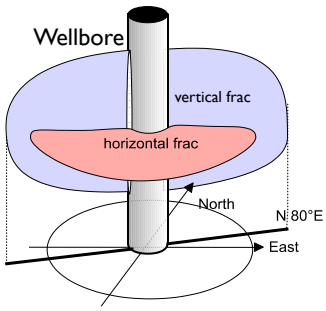
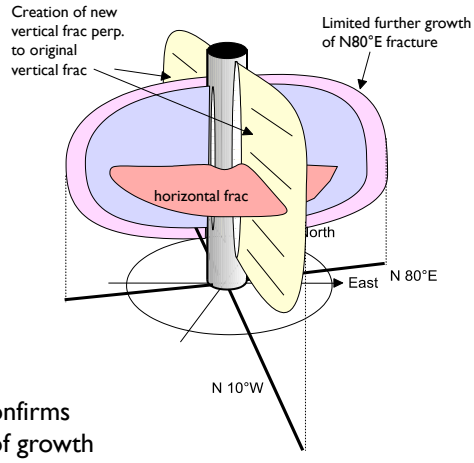
## Controls on Fracture Direction and Geometry

Fracture geometry after first 2/3 of main treatment




Probable fracture geometry at end of pumping




Tiltmeter data during fracturing confirms multiple orientations and flipping of growth plane (California)

Courtesy Pinnacle Technologies

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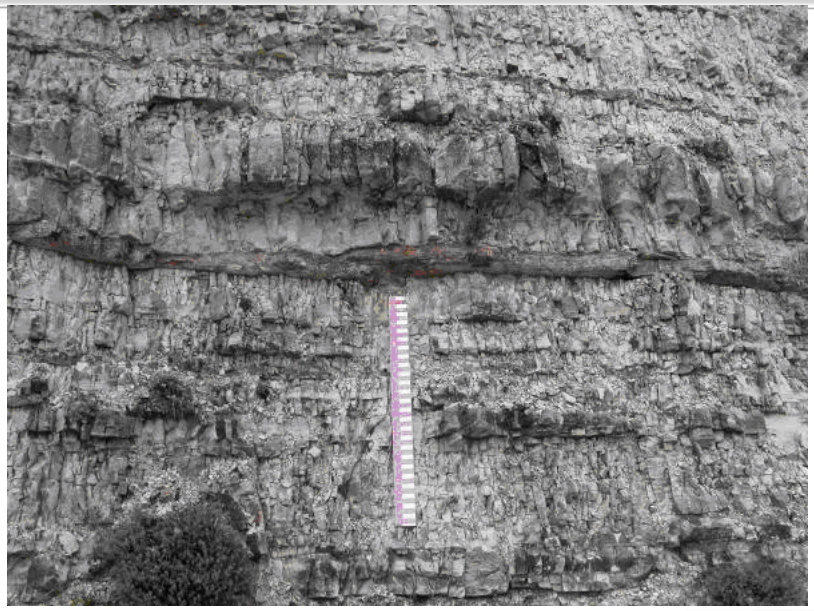
## Controls on Fracture Direction and Geometry



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## Controls on Fracture Direction and Geometry * Different Stresses in Strata Effect

- **Often, fractures do not rise out of the zone, they stay in the zone and propagate laterally. Why?**
- **This usually means that $\sigma_{hmin}$ in the upper zone is larger than in the lower zone**
- **This is a barrier to upward propagation**
- **It is easier to grow laterally that to grow upward, which needs a higher fracturing pressure**

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## Controls on Fracture Direction and Geometry * Formation Stiffness Effects

- **Rock stiffness (E) affects aperture:**
  - high E, low aperture;
  - low E, large aperture
- **Aperture affects hydraulic pressure distribution in the fracture (low aperture = higher losses)**
- **Therefore, high E impedes propagation in that stratum, low E enhances propagation**
- **Some rocks can deform plastically (UCS, chalk, coal, high f dirty sands ...)**

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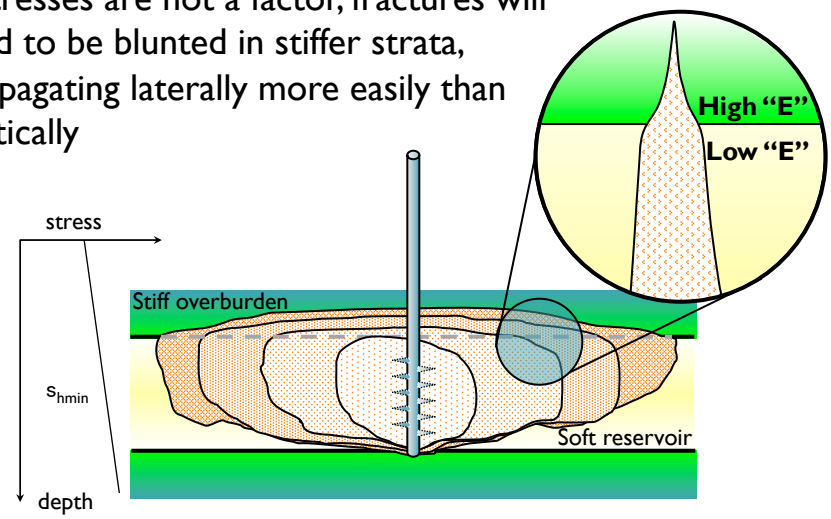
## Controls on Fracture Direction and Geometry * Formation Stiffness Effects

If stresses are not a factor, fractures will tend to be blunted in stiffer strata, propagating laterally more easily than vertically

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## Recent Developments in Hydraulic Fracturing

- **Multistage fracturing, as many as 40 stages in one long well**
- **Simultaneous fracturing of 5-7 perforation intervals in a single well using high-rate gel fractures**
- **Slick-water fracturing (friction reducers such as acrylic amides)**
- **Reduction in need for chemicals (better environmental protection)**
- **And so on,,,**

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# Hydraulic Fracturing

# Part 2

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## Outline

- Fracturing Equipment
- Fracture fluids
- Additives
- Water issues
- Monitoring

Apache

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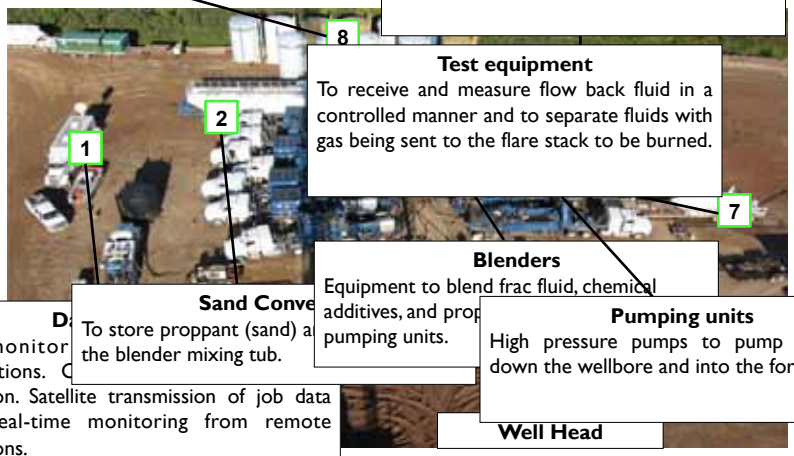
# Hydraulic Fracturing Job Site




**Water Storage tanks**
Tanks to store the frac fluid on location prior to pumping.

**Chemical vans**
Storage, transportation and metering units to feed additives into the frac fluid stream as it is being pumped down the well

**Test equipment**
To receive and measure flow back fluid in a controlled manner and to separate fluids with gas being sent to the flare stack to be burned.

**Blenders**
Equipment to blend frac fluid, chemical additives, and prop pumping units.

**Sand Conve**
To store proppant (sand) a the blender mixing tub.

**D**
To monitor operations. C location. Satellite transmission of job data for real-time monitoring from remote locations.

**Pumping units**
High pressure pumps to pump the fluid down the wellbore and into the formation.

**Well Head**

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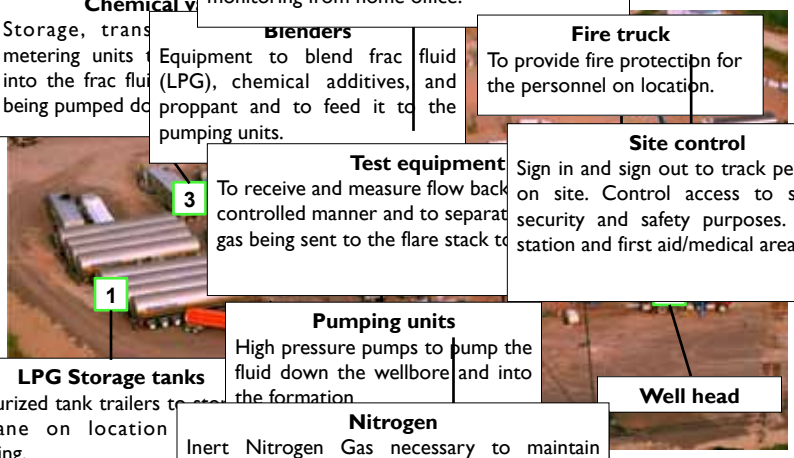
# Propane Frac




**Data/satellite van**
To monitor and control treatment operations. CC TV coverage of entire location. Satellite transmission of job data for real-time monitoring from home office.

**Chemical v**
Storage, trans metering units into the frac flui being pumped do

**Blenders**
Equipment to blend frac fluid (LPG), chemical additives, and proppant and to feed it to the pumping units.

**Fire truck**
To provide fire protection for the personnel on location.

**Test equipment**
To receive and measure flow back controlled manner and to separat gas being sent to the flare stack to

**Site control**
Sign in and sign out to track personnel on site. Control access to site for security and safety purposes. Muster station and first aid/medical area.

**Pumping units**
High pressure pumps to pump the fluid down the wellbore and into the formation

**LPG Storage tanks**
Pressurized tank trailers to propane on location pumping.

**Nitrogen**
Inert Nitrogen Gas necessary to maintain positive pressure in the LPG storage vessels and to provide an inert gas for purging.

**Well head**

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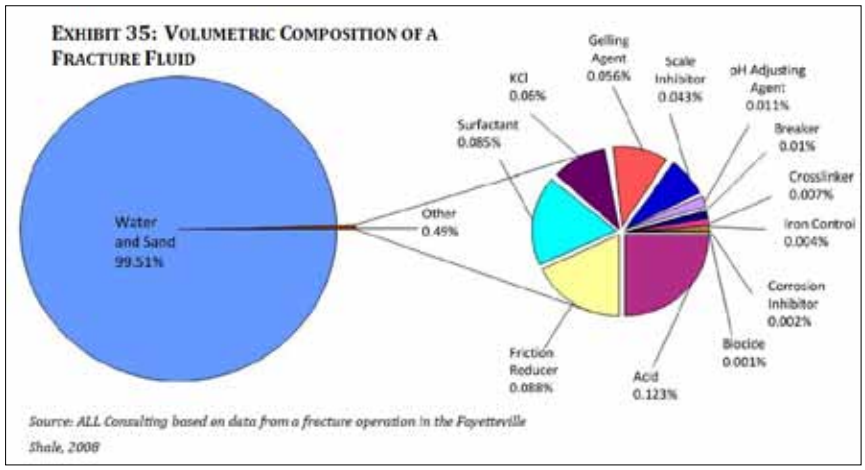
Reproduced from http://www.cbc.ca/nb/features/fracturedfuture/annotated_site.html

# Fracture Fluid Composition

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# Base Fluid Systems

- **Slickwater Applications**
  - Low Friction
  - Low Viscosity (<5cp)
  - Low Residue, less damaging
  - Low Proppant Transport capabilities
- **Linear Gel Applications**
  - Mild Friction Pressures
  - Adjustable Viscosity (10<x<60cp)
  - High Residue, more damaging
- **Crosslinked Applications**
  - High Friction
  - High Viscosity (>100cp)
  - Excellent Proppant Transport capabilities
- **Energized Fluid Applications**
  - Carbon Dioxide
  - Nitrogen
  - Water Sensitive Formations
  - Depleted Under pressured wells
  - Low Permeable Gas Formations
  - High Proppant Transport capabilities
- **Gelled Oil Fluids**
- **Acidizing Services**

- High Residue, more damaging
- Expensive
- Complex Chemical Systems
  - pH and Temp. dependent

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## Additives

- Proppant – sand or artificial beads – inert
- Gelling agents for viscosity, helps propping
- Biocide – to preserve the gelling agents
- Vis-breaker – delayed viscosity reduction
- Fluid-loss additives (not used in shale gas)
- Anti-corrosion agents
- Friction reducers (acrylamides, anionic polymers, etc. About 0.05 to 0.2% by vol)
- Acids to dissolve $CaCO_3$ in natural fracutres
- And others

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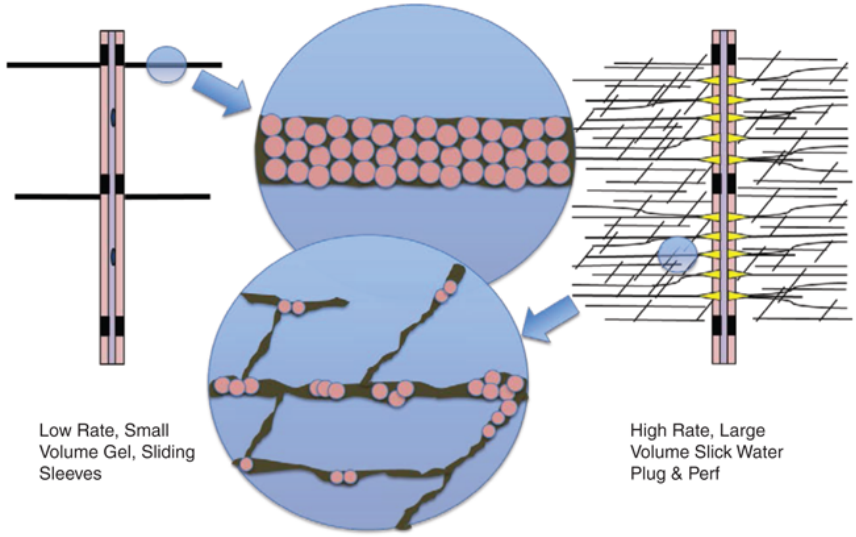
http://www.epa.gov/OGWDW/uic/pdfs/cbmstudy_attach_uic_ch04_hyd_frac_fluids.pdf

## Slick-Water Application

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## Proppant Permeability

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## Proppants

- **Frac Sand (<6,000psi)**
  - Jordan
  - Ottawa
  - Brady
- **Resin-Coated Frac Sand (<8,000psi)**
  - Super LC® (Santrol) [Cureable]
  - AcFrac Black® (Borden) [Precured]
- **Intermediate Strength Ceramics (<10,000psi)**
  - Econoprop® (Carbo Ceramics)
  - Nap-Lite® (Norton-Alcoa)
- **High Strength Ceramics (<15,000psi)**
  - Carboprop® (Carbo Ceramics)
  - Sinterball® (Sintex)

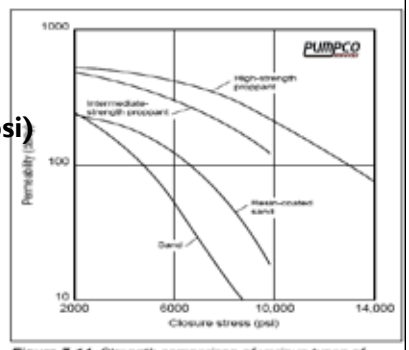


*Figure 7-14. Strength comparison of various types of proppants.*

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## Water Use for a Fractured Well

- **Water is needed for Drilling**
  - Perhaps as much as 2000 - 4000 m3
  - Clear water drilling for the upper part, then drilling fluids
  - Drilling muds can be re-used for other wells in the pad, reducing water use
- **Water is needed for Fracturing**
  - Depends on the number and the size of the fractures in the well
  - From 10,000 to 30,000 m3/well
  - Handling the flowback properly is necessary!

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## Water Demand for Drilling/Fracturing


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Arthur, J.D, B.K. Bohm and B.J. Coughlin 2010. Summary of Environmental Issues, Mitigation Strategies and Regulatory Challenges Associated with Shale Gas Development in the U.S and Canada.

## Flowback Treatment

- **Fracturing flow back is saline, contains some heavy metals, chemical traces, etc.**
- **This flowback CANNOT be dumped on the ground or into streams – contamination!**
- **Options are:**
  - Clean up of the chemicals at a treatment plant and dump the saline water into ocean
  - Filter out all solids and use deep well disposal
  - No treatment and direct reinjection at depth using Slurry Fracture Injection

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## Water Disposal Options


Arthur, J.D, B.K. Bohm and B.J. Coughlin 2010. Summary of Environmental Issues, Mitigation Strategies and Regulatory Challenges Associated with Shale Gas Development in the U.S and Canada.

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## HF Monitoring Objectives

- **Gives information about the volume of opened fractures, the general orientation of the fractures, etc.**
- **Better flow models for analysis**
- **And so on…**

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## HF Monitoring Methods

- **Precision real-time tilt monitoring (<3000m)**
  - Surface and subsurface deformation measurements during HF
- **Microseismic monitoring using geophones at depth relatively near the fracture site**
  - Concept of the stimulated zone which can be far larger than the propped zone
- **Pressure-time response in the injection well**
- **Impedance tests in a propped fracture**
- **Borehole geophysical logging (T, tracers)**
- **Other methods are problematic at best**
- **Implies a "poorer" method of monitoring**

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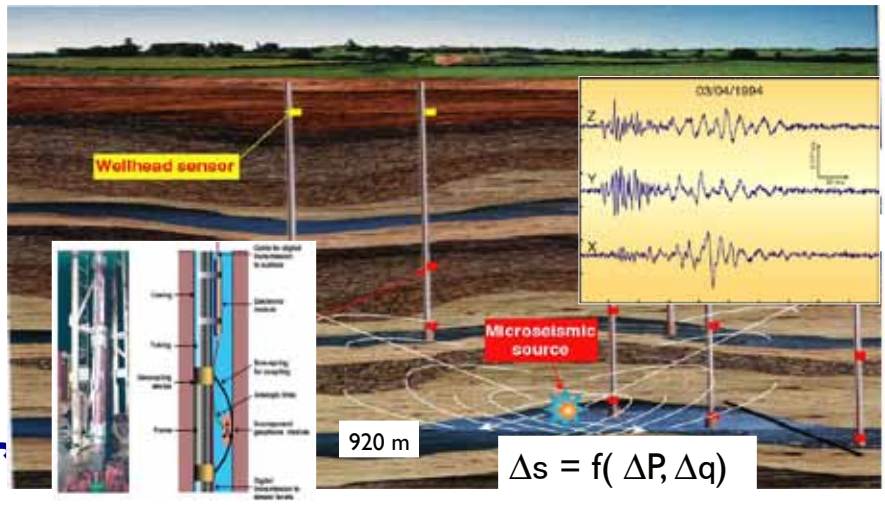
## Microseismic Monitoring Concept




$\Delta s = f(\Delta P, \Delta q)$

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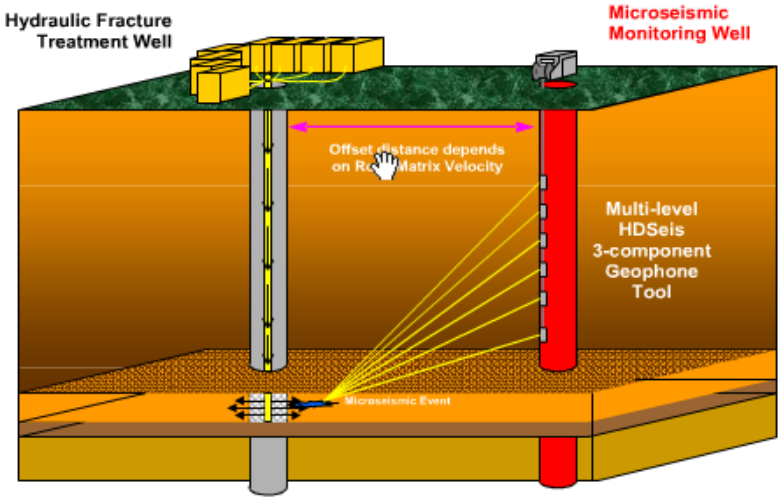
## Microseismic HF Monitoring Concept




Microseismic Hydraulic Fracture Monitoring Technique

GeoSpace Technologies

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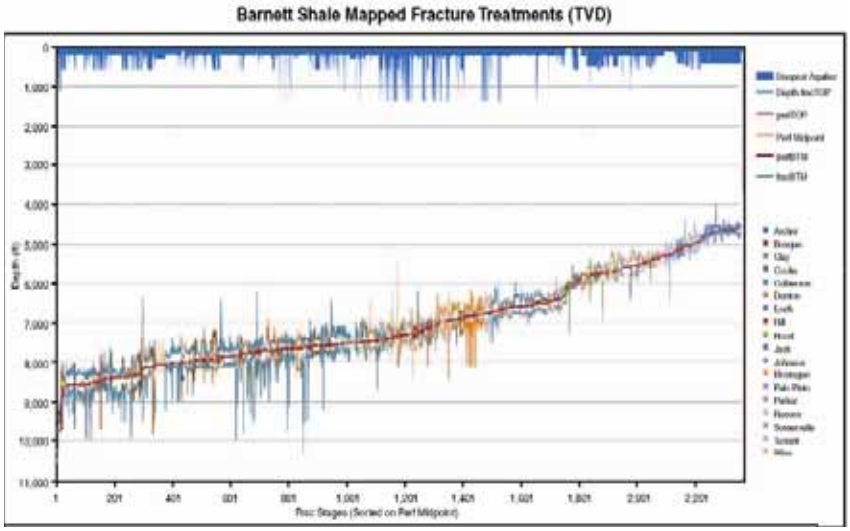
# Microseismic Monitoring

- **Monitoring of upper and lower limits of fracture height growth relative to the position of fresh water**

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