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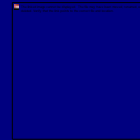
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Non-conventional Geomechanics for Unconventional Resources

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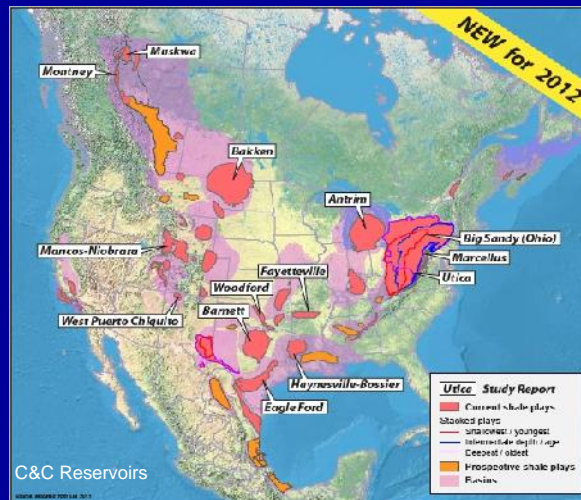
hamed.soroush@petrolern.com

Outline

- Importance of geomechanics to development of unconventional resources
- Special geomechanical considerations for unconventional resources:
 - Non-conventional vs. conventional geomechanics
 - Rock property estimation (anisotropic formations)
 - Near wellbore stresses and development of breakouts
 - Wellbore stability in anisotropic formations
 - Under-balanced drilling feasibility
 - Hydraulic fracturing and determination of formation brittleness
 - Maximizing production from critically stressed fractures
 - Reservoir evolution due to depletion
- Summary and conclusions

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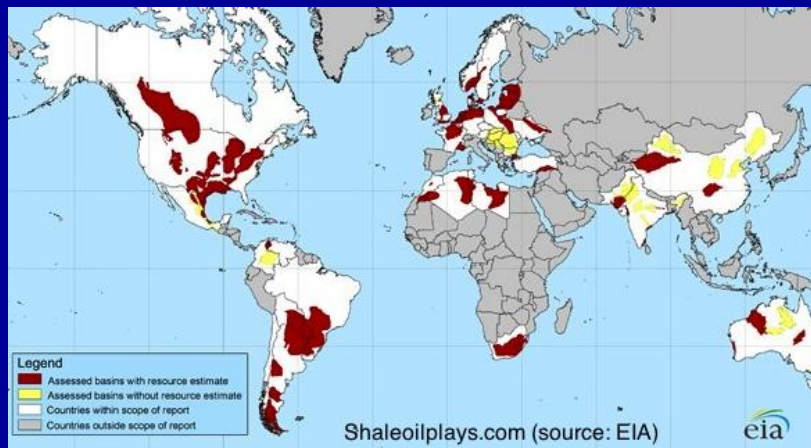
North American Shale Plays



~2300 TCF (85% Shale Gas)
 "100 years of Natural Gas" U.S.

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Global Shale Plays

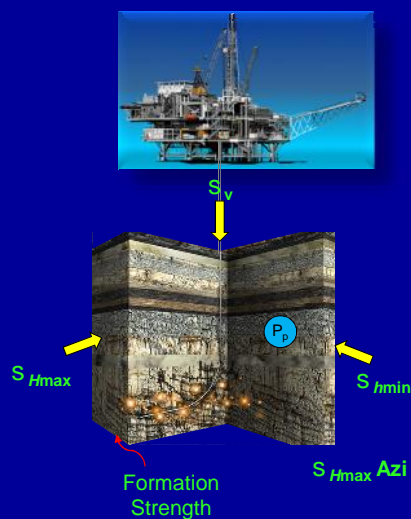


~22,600 TCF of Recoverable Reserves
Current use ~160 TCF/year

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How Important is Geomechanics for Unconventional Resources?

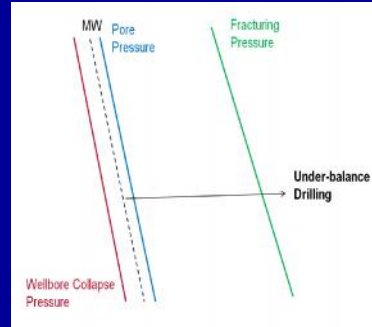
- Geomechanics for unconventional resources differs from conventional reservoirs due to:
 - Inelastic matrix behavior
 - Stress sensitivity
 - Rock anisotropy (Cleats, laminations and natural fractures)
 - Rock rheology
 - Low matrix permeability
- Effective horizontal drilling and hydraulic fracturing technologies required.
- Success heavily dependent on the stress regime and rock property.



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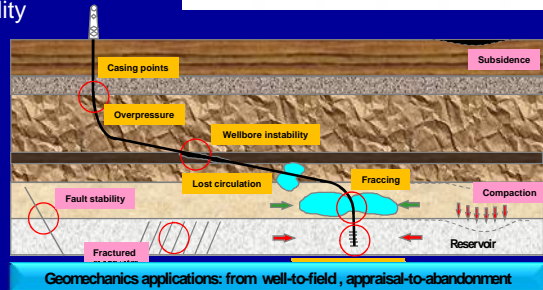
Where Does Geomechanics Help?

- Select optimum mud weight and mud chemistry for safe drilling
- Optimize well trajectory
- Maximize production from critically stressed natural fractures
- Design and optimize hydraulic fracturing operation
- Model depletion effect on the reservoir productivity and compaction
- Underbalanced drilling feasibility



For:

- Heavy oil
- Gas shale
- Oil shale
- Tight sand
- Coal bed methane
- Gas hydrates



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Non-conventional vs. Conventional Geomechanics

	Conventionals	Unconventionals
Wellbore instability	Dominated by mechanical failure	Dominated by physico-chemical effects
Rock behavioral models	Elastic to elastoplastic	Inelastic
Rock mechanical characteristics	More brittle	More ductile
Rock properties	Isotropic to anisotropic	Usually transversely isotropic (TI)
Stress regime	Usually anisotropic	Less anisotropic to isotropic
Rock-fluid interaction	Mechanical	Mechanical-chemical
Natural fractures	Close/open depends on their orientation	Healed/less permeable
Borehole enlargement	More breakout	More washout
Pore pressure estimation	Measurement	Prediction
Hydraulic fracturing efficiency	Higher	Lower
Depletion related deformation	Faulting	Compaction

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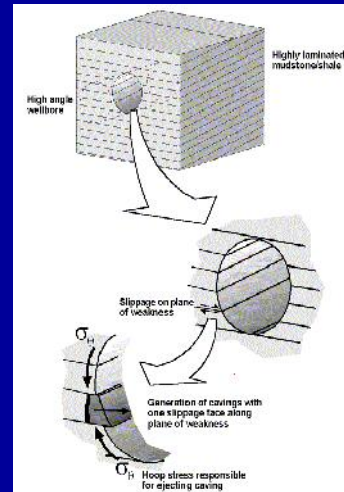
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Anisotropic Formations

- Properties are different in different directions.
- If properties are the same along different directions in one horizon but different normal to that, rock is Transversely Isotropic (TI). Then 5 elastic constants are required:
- Shear failure characteristics of weak planes are overriding.

$$E_c, \epsilon_{vh}, E_h, \epsilon_{hh}, G_{vh}$$



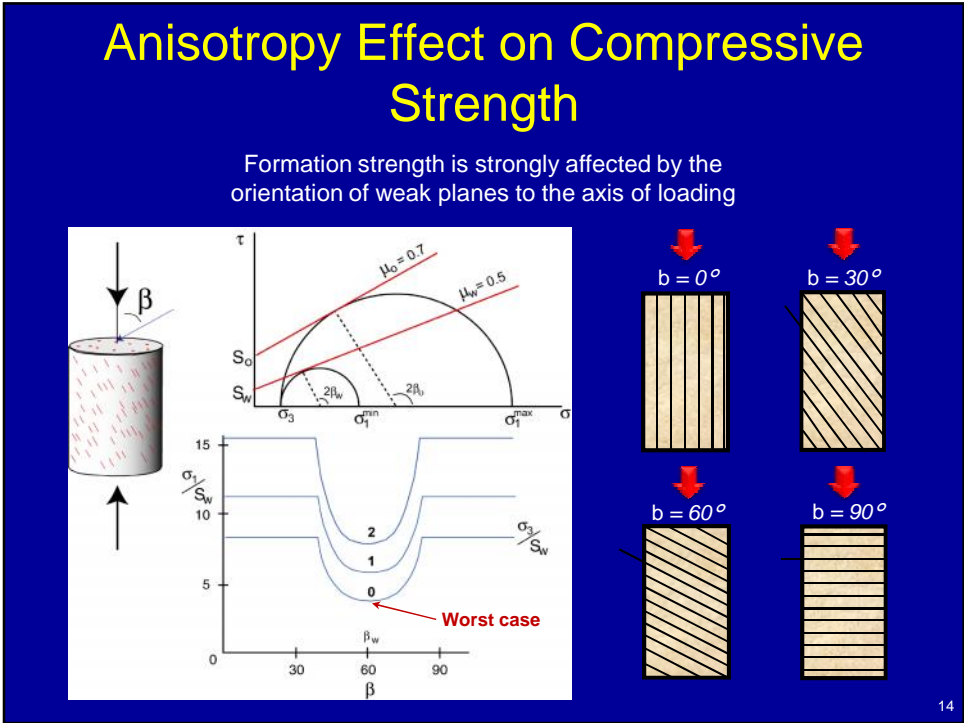
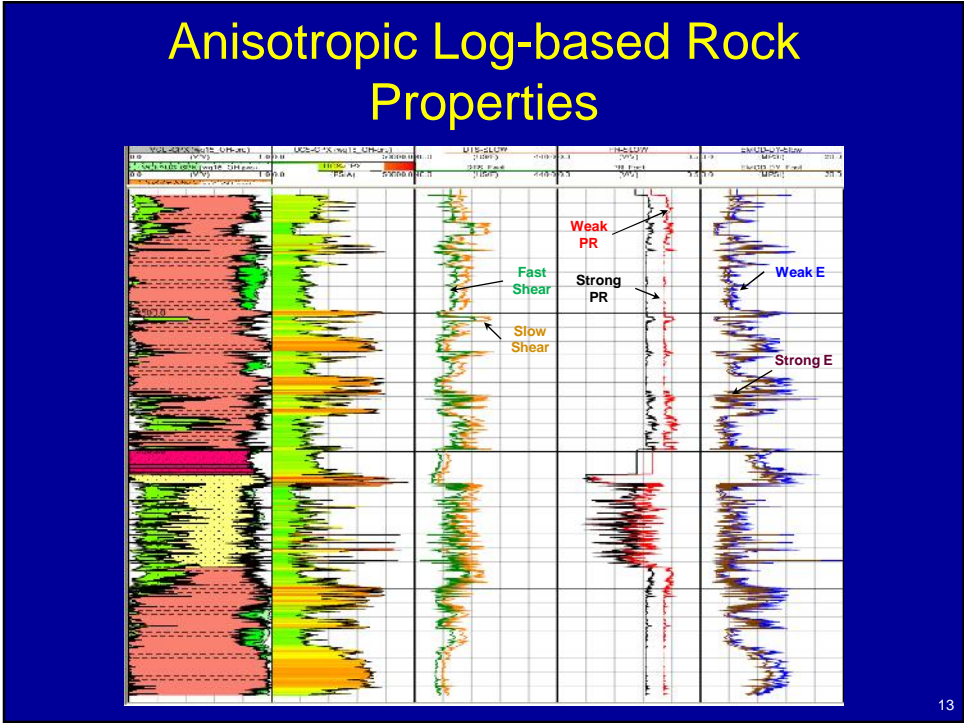
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How About Unconventionals?

- Shales and coals are usually TI.
- Spacing between weak planes is small relative to the borehole diameter.
- The effect MUST be taken into account in even borehole scale analysis.



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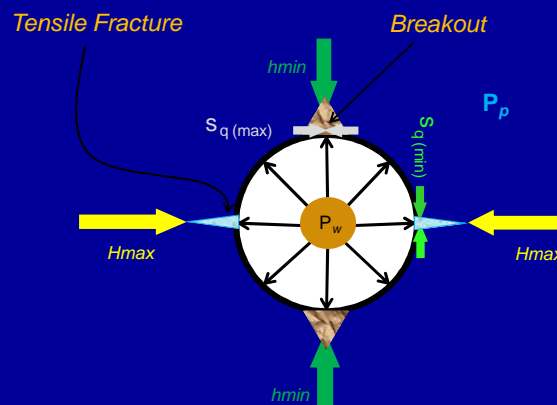
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Near Wellbore Stresses

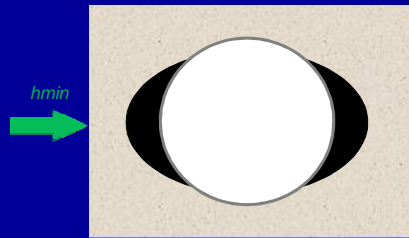
- Max hoop stress acts perpendicular to S_{hmin} direction
- Min hoop stress acts perpendicular to S_{Hmax} direction
- Shear failure expected along S_{hmin} while tensile fracture along S_{Hmax}



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Borehole Breakout in Isotropic Formations

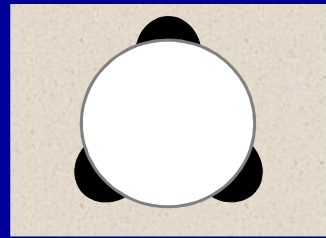
Isotropic borehole failure in anisotropic stress regime



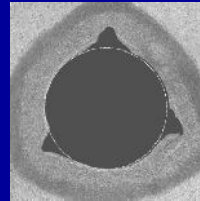
(CSIRO, 2006)



Isotropic borehole failure in isotropic stress regime



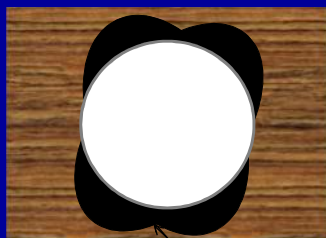
(Haimson, 2008)



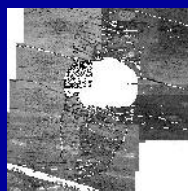
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Borehole Breakout in Anisotropic Formations

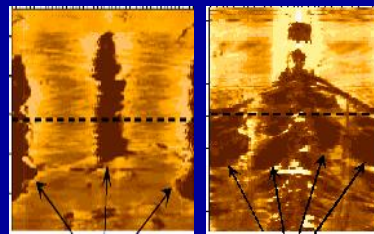
Anisotropic rock failure in anisotropic stress regime



4-lobbed Breakouts

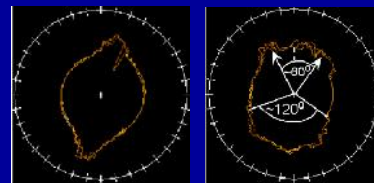


Borehole breakouts in isotropic vs. anisotropic formations



Normal Breakouts

4-lobbed Breakouts



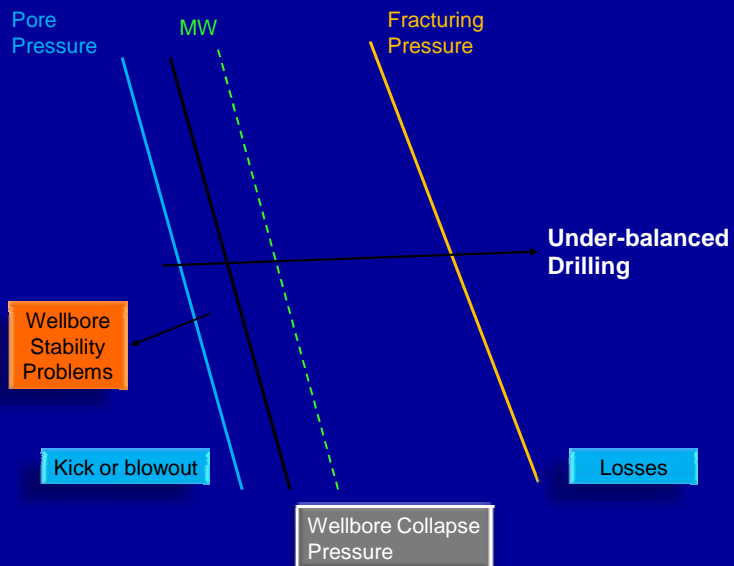
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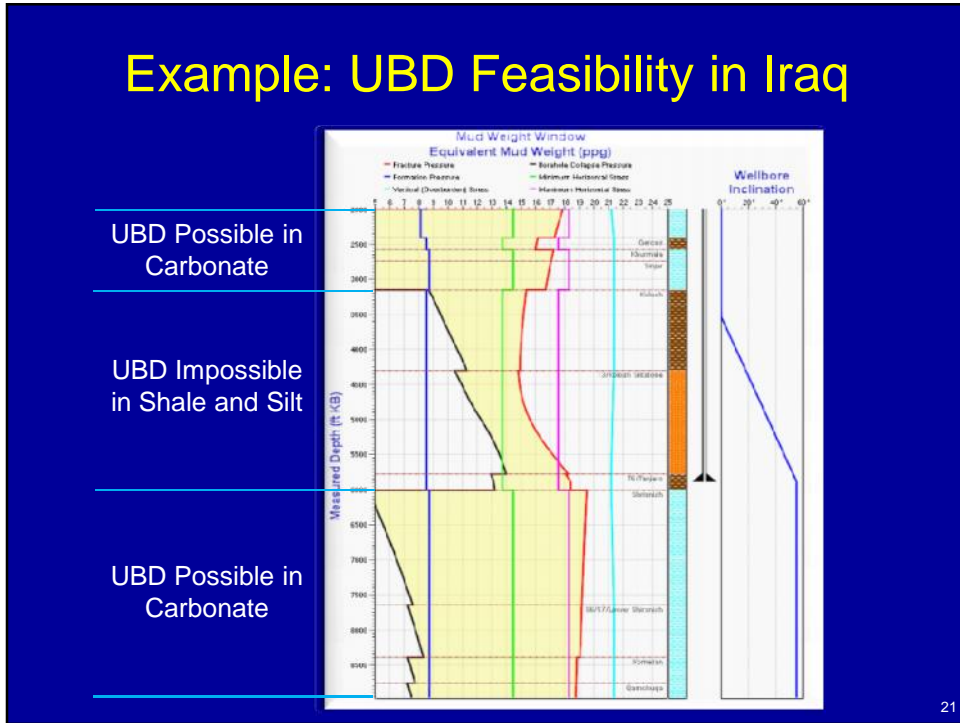
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Wellbore Stability and Under-Balanced Drilling Feasibility

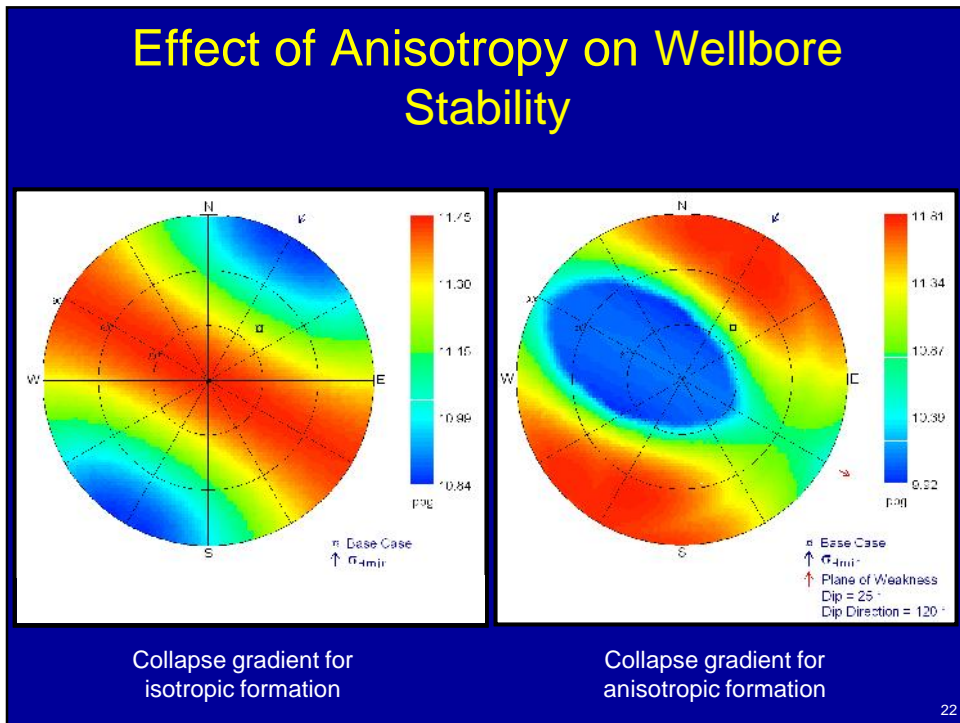


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Example: UBD Feasibility in Iraq



Effect of Anisotropy on Wellbore Stability



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Hydraulic Fracturing and Geomechanics

Applications

- To enhance well productivity/injectivity
- To introduce thermal energy (steam fractures)
- To measure stress (Minifrac, LOT, XLOT)
- To re-inject drill cuttings and massive waste injection

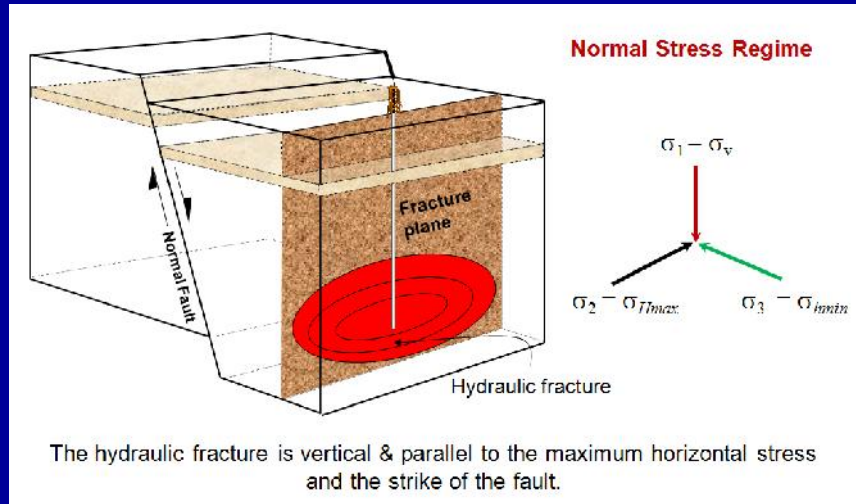
Geomechanics benefits to hydraulic fracturing

- Increase efficiency with identifying fracable intervals
- Control growth of hydrofrac
- Predict orientation of hydrofrac
- Optimize drilling direction to minimize hydraulic fracturing pressures

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Hydraulic Fracturing – Stress Effect

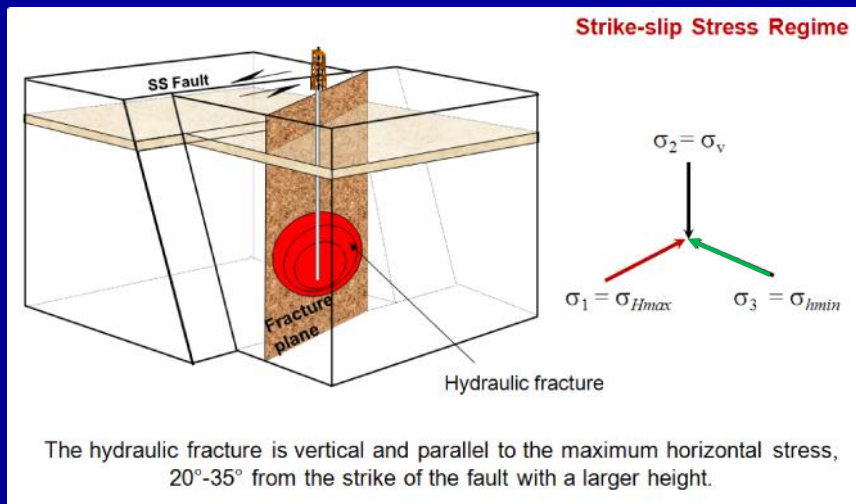
Stress regime is the dominant factor controlling direction and height growth of hydraulic fractures.



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Hydraulic Fracturing – Stress Effect

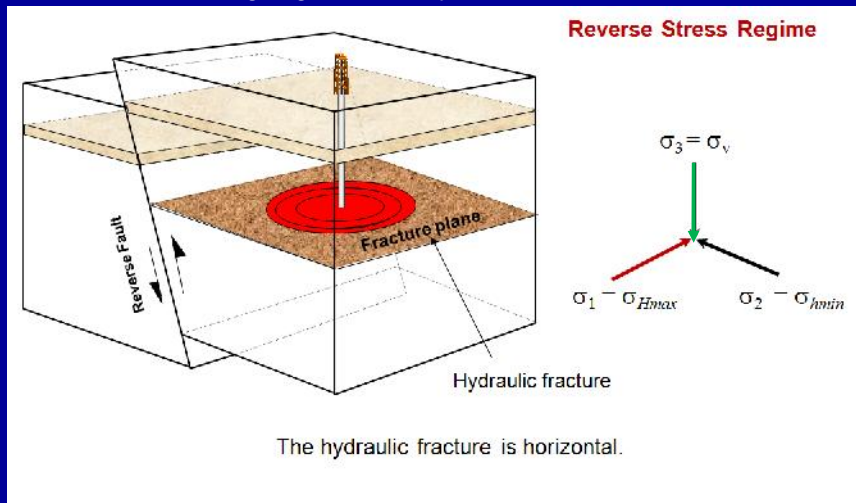
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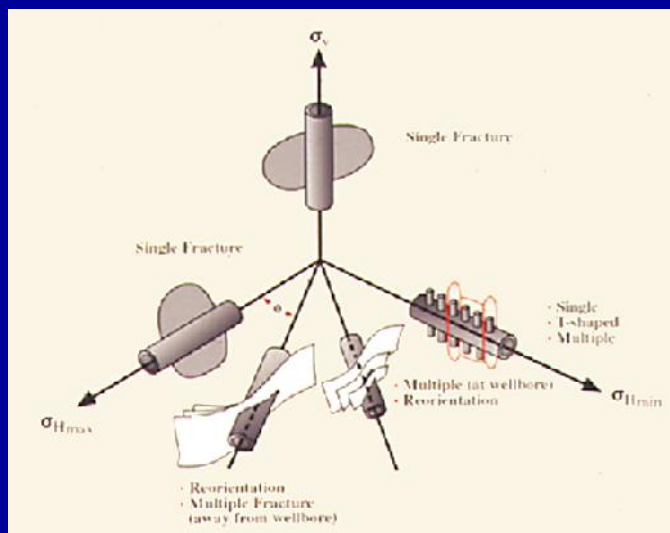
Hydraulic Fracturing – Stress Effect

Stress regime is the dominant factor controlling direction and height growth of hydraulic fractures.



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How to Manipulate Fracture Morphology?



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Where to Frac?

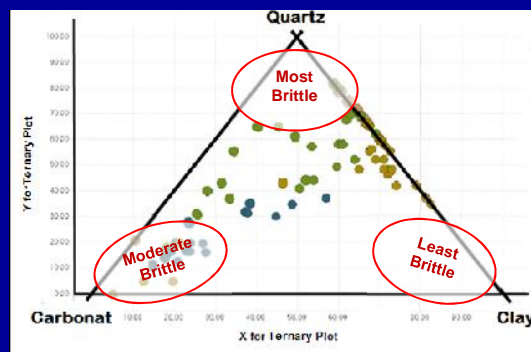
- In brittle rocks hydrofracture is more likely to be long enough to connect the highest amount of rock volume to the parent wellbore.
- Thus, it is very important to find intervals that are brittle, in order to maximize hydraulic stimulation.

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How to Determine Brittleness? Mineralogy Approach

- Q-C-C (Quartz-Clay-Carbonate) (Jarvie et al. 2007)

$$\text{BRITTLINESS \%} = \frac{\text{Quartz}}{\text{Quartz} + \text{Carbonates} + \text{Clays}}$$



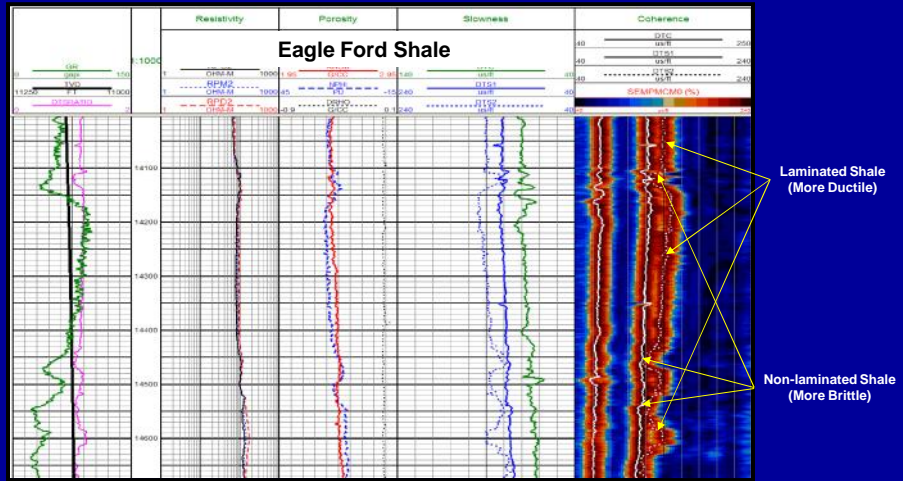
Ternary Diagram for Barnett Shale

(SPE 115258)

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How to Determine Brittleness? Anisotropy Method

- Less anisotropic formations are more brittle!



(SPE 125525, SPE 132990, Schön et al. 2006)

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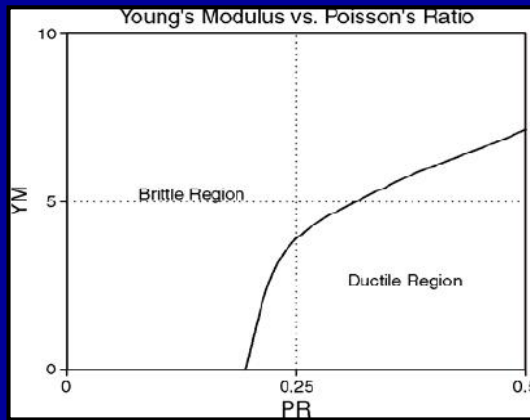
How to Determine Brittleness? Dynamic Elastic Constants Method

Brittle rocks have higher YM and lower PR

$$YM_{BRIT} = \frac{YM - YM_{Min}}{(YM_{Max} - YM_{Min})} * 100$$

$$PR_{BRIT} = \frac{PR - PR_{Max}}{(PR_{Min} - PR_{Max})} * 100$$

$$BRIT_{avg} = \frac{YM_{BRIT} + PR_{BRIT}}{2}$$



(SPE 106623)

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How to Determine Brittleness? Laboratory Methods

- Punch penetration test (Saffet, 2009)
- Compressive and tensile strengths measurement:
 - $BI = (\sigma_c - \sigma_t) / (\sigma_c + \sigma_t)$ (Hunca & Das, 1974)
 - $BI = (\sigma_c \times \sigma_t) / 2$ (Altindag, 2002)

Rock brittleness classes (Goktan & Yilmaz, 2005)		
Class	BI	Description
1	>25	Very brittle
2	15 < BI < 25	Brittle
3	10 < BI < 15	Moderately brittle
4	BI < 10	Low brittleness

Best rock to frac

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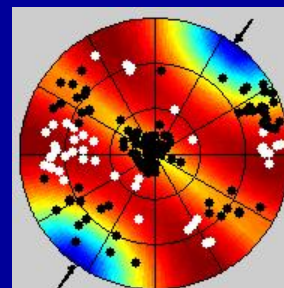
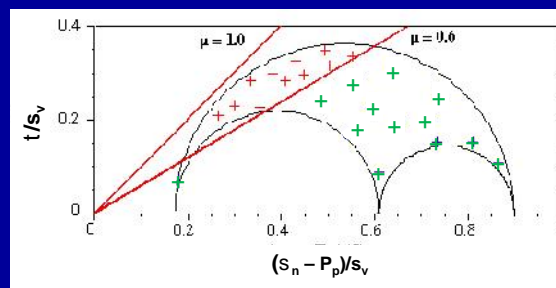
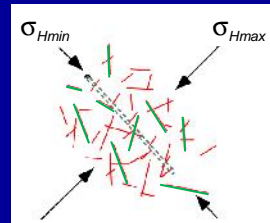
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Maximizing Production from Critically Stressed Fractures

- Not all the fractures are productive.
- Critically stressed fractures should be recognized.
- Wellbore should intersect this type of fractures.



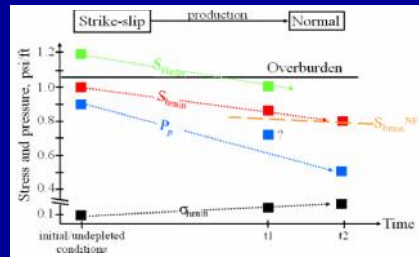
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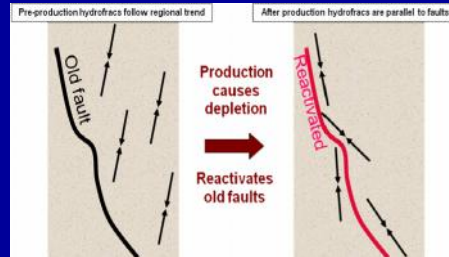
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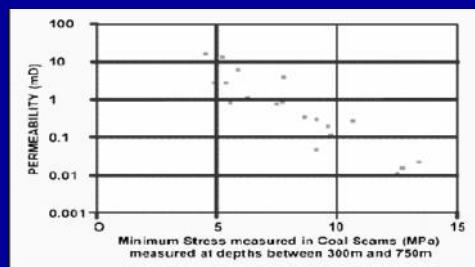
Reservoir Evolution Due to Depletion



Effect of depletion on in-situ stresses



Effect of depletion on hydraulic fracturing



Reduction of permeability due to effective stress increase (depletion) in coal bed methane

(ARMS6-2010-022)

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Summary and Conclusions

- Geomechanical modeling is critical for development of unconventional resources.
- Non-conventional geomechanical approaches should be utilized for unconventional resources.
- Anisotropic rock mechanical properties must be taken into account.
- Planes of weakness have remarkable influence on wellbore stability of unconventional wells.
- UBD is an added value to exploration of unconventional reservoirs, however, geomechanical study is essential to determine feasibility.
- Success and efficiency of hydraulic fracturing operation depend strongly on the accuracy of the geomechanical model.
- Fracture analysis under stress is a requirement to maximize production from tight formations.
- Knowledge of stress and reservoir property evolution during production is a key to increase the life of the reservoir.

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