

PERFORATING FOR FRACTURING IN UNCONVENTIONAL RESERVOIRS

SLAP 16-7

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AGENDA

TOPICS

- Disclaimer, copyright and legal notice
- Two facts about unconventional
- Multi-fractured horizontal wells
- Geomechanics and fracture initiation
- At which perforations does the fracture initiate?
- Vaca Muerta's stress scenarios – frac initiation
- Vertical vs horizontal well – impact on fracturing
- Vaca Muerta's geomechanics impact
- Breakdown analysis
- Estimation of breakdown pressure
- Perforations analysis
- Clusters inefficiency or opportunities?
- Clusters dynamics
- Perforation strategy



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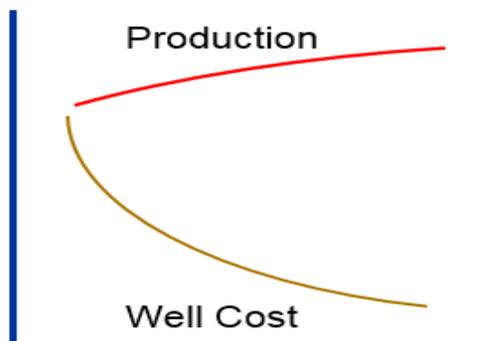
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TWO FACTS ABOUT UNCONVENTIONALS

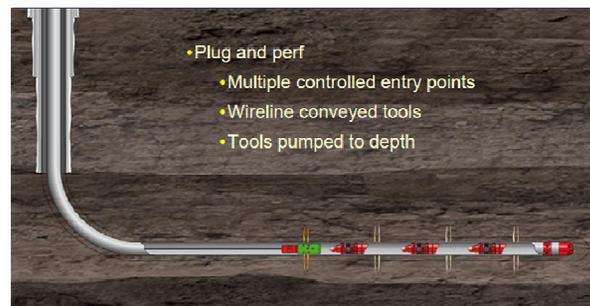
ECONOMICS

- Reservoir productivity intrinsically limited by its own very low permeability
- Economics mainly driven by well construction costs
 - Introduction of new technologies must show clear evidence of impact on cost reduction without compromising HSE aspects
 - Potential increase in productivity is an upside
- Oil & gas prices helps to balance the equation but...
 - In 2014 average breakeven price for shale oil was about 60 USD/bbl. Currently some operators have proven sustainable development at 30 – 35 USD/bbl



TECHNOLOGIES FOR COMPLETION

- From statistics:
 - Plug & Perf: 75 – 80 % (mostly all with multiple clusters)
 - Frac sleeve: 15 – 20 %
 - CT based: 5 %
- Recent market studies show same trend for upcoming years if no breakthrough technology is introduced in the market

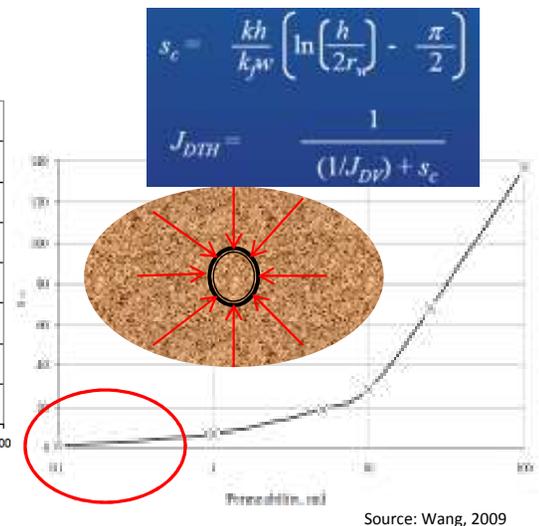
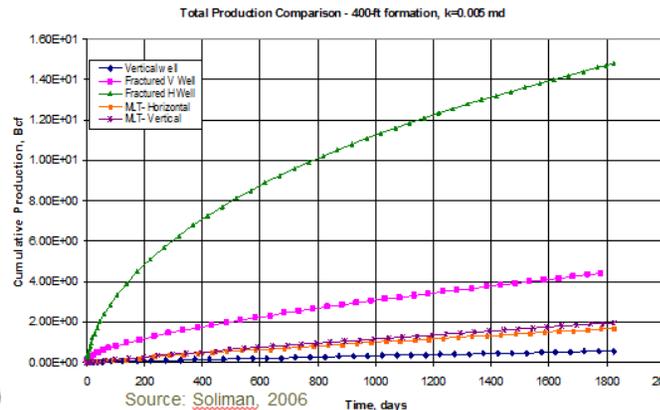
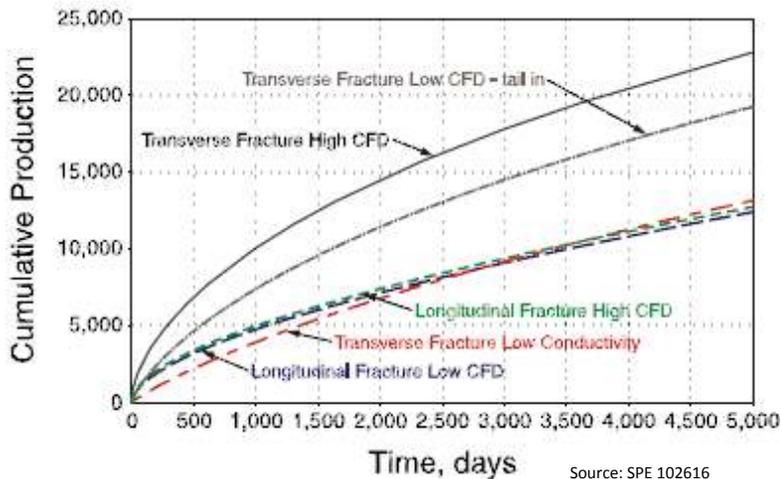


“If you want to be competitive and get favorable economics you will only depend on your constant and relentless imagination and ability to cut well construction costs!”

MULTI-FRACTURED HORIZONTAL WELLS

JUSTIFICATION BASED ON RESERVOIR ENGINEERING

- Multi-fractured horizontal wells provide highest productivity index
 - No other combination is better
 - Large number of frac stages provide higher IPs but incremental production decreases with number of fracs
 - Reservoir deliverability after fracture vs economic trade-off
- Transverse hydraulic fractures are only attractive at very low permeability
 - Below ~ 0.5 mD they are the best option as choked flow is negligible
- Multi-fractured horizontal wells with transverse hydraulic fractures are best option for unconventional reservoirs unless other exceptional reservoir characteristics dictate the opposite

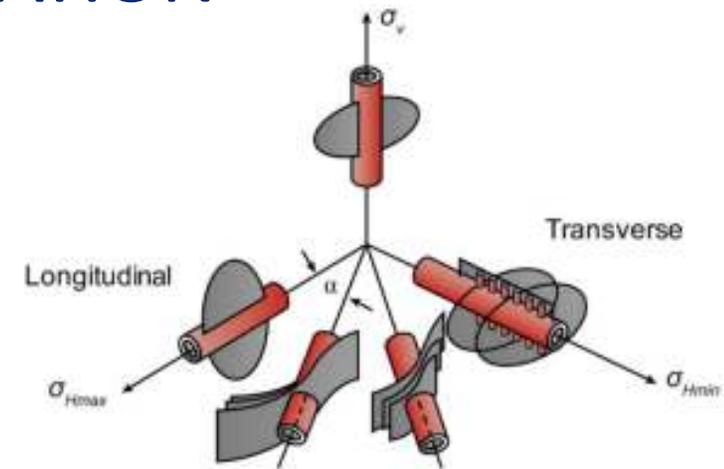


GEOMECHANICS & FRACTURE INITIATION

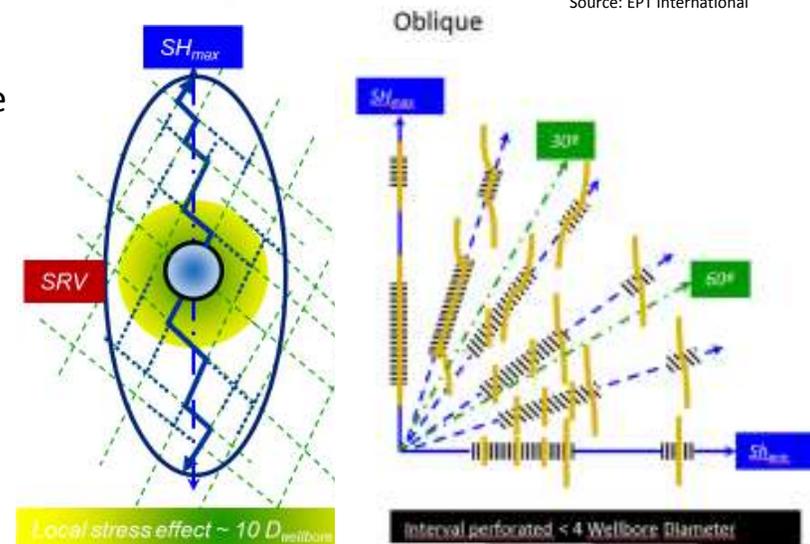
IMPACTS

- Hydraulic fracture main plane orientation dictated by geomechanics, wellbore axis must be defined with fracture orientation in mind
 - Fractures at any other angle are difficult to initiate, very common to observe high breakdown pressure, tortuosity, early screen-outs, abnormal extension pressure, no clear ISIPs, etc.
- Hydraulic fracture always grows in the same plane of the two maximum stresses
- Every connection from wellbore to reservoir is a potential source for fracture initiation but...
 - Multiple initiation points is not effective from energy perspective
 - Multiple initiated fractures might coalesce or stop growing due to internal interference caused by stress (stress shadowing), ergo: reduce length of clusters to minimize this effect
 - Short clusters = limited number of perforations (holes)

Hole Size [in]	Cluster Length [m]
6 ¼ - 6 ¾	< 0.6
8 ½	< 0.8



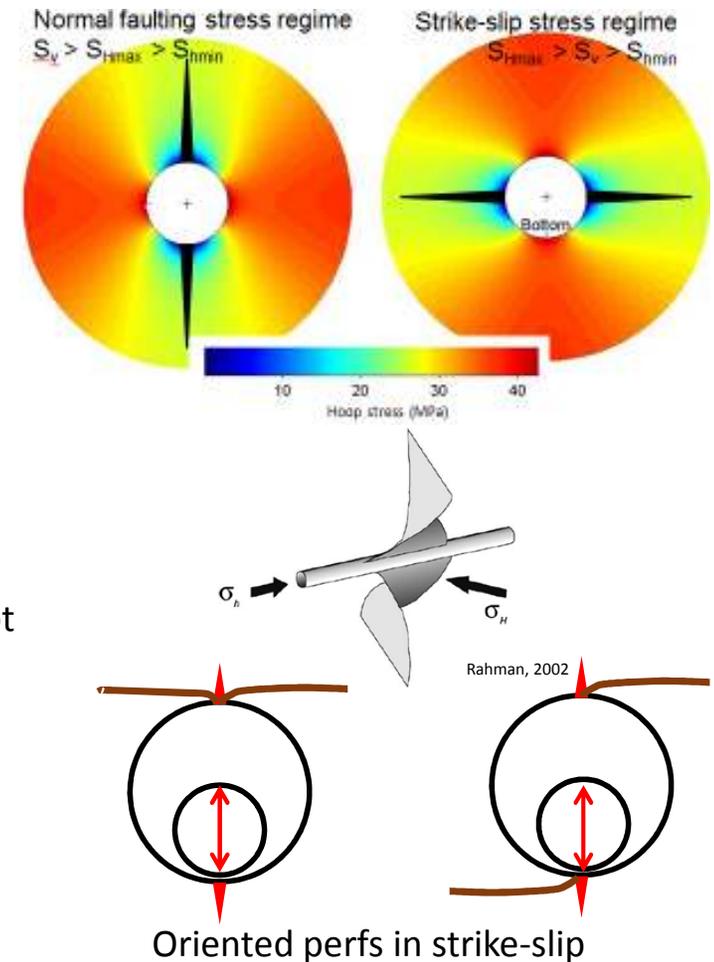
Source: EPT International



AT WHICH PERFORATIONS DOES FRACTURE INITIATE?

MAIN EFFECTS

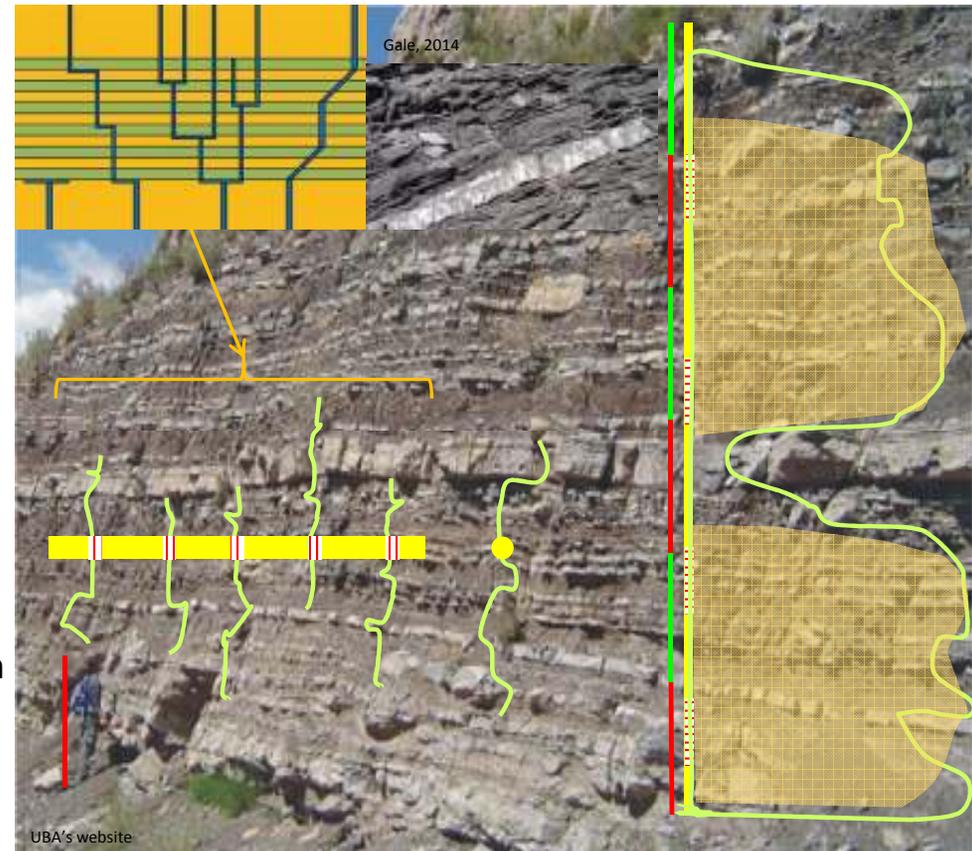
- Stress regime is the principal factor
 - Normal ($S_v > S_H > S_h$): fracture initiates at top and bottom
 - Relative easy to continue vertical propagation
 - Strike slip ($S_H > S_v > S_h$): fracture initiates at both sides of the well
 - When fracture propagates it needs to twist to align to the plane of two principal stresses
 - Thrust ($S_H > S_h > S_v$): fracture initiates at both sides of the well
 - Pancake fractures. Not good for production!
- Fabrics and lamination
 - For strike slip and thrust regimes if interfaces are relative weak or anisotropy is high, it is easier for the fracture to propagate along the bedding plane in which case only pancake fractures are obtained. Not good for production either!
- Oriented perforations to partially mitigate the problem?
 - Most likely problem is not fixed
 - Remember cost implications
- Conclusion: understand geomechanics in your area and land your wells in zones where fracture initiation is not an issue otherwise production is compromised



VERTICAL vs HORIZONTAL WELL

IMPACT ON FRACTURING

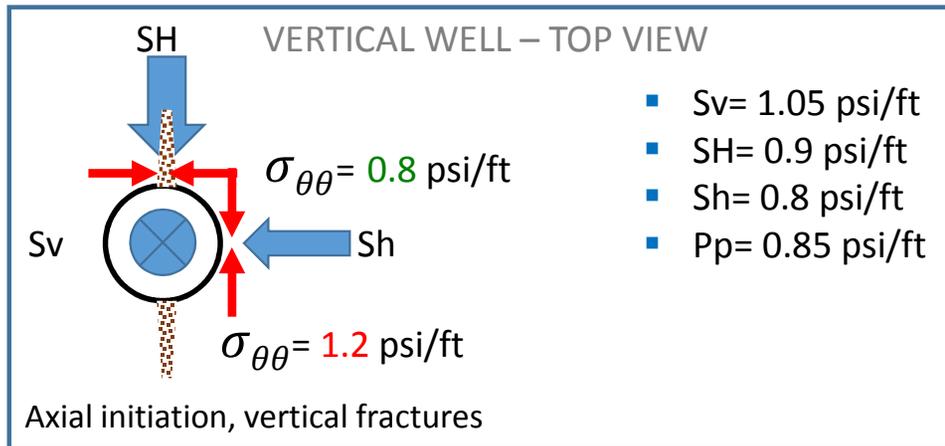
- Vertical wells
 - No matter is stress regime is either extensional or strike-slip, fracture plane will be vertical
 - Initiation and propagation are favored by this well architecture
 - Fracture will be aligned to perforations and well communicated to them
 - Tortuosity should not be a major issue
 - Easier to cover long vertical intervals even with barriers for fracture growth
- Horizontal wells
 - Initiation will depend on stress regime
 - Even if fracture plane is vertical for extensional and strike-slip, fracture has to turn to align from initiation plane to propagation one causing restrictions
 - Tortuosity might be an issue
 - Higher breakdown pressure
 - Limited fracture height if frac barriers are close to the wellbore



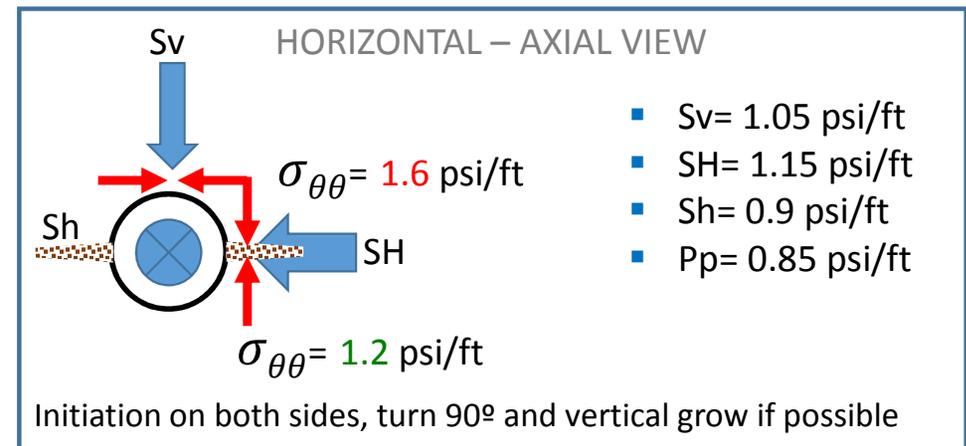
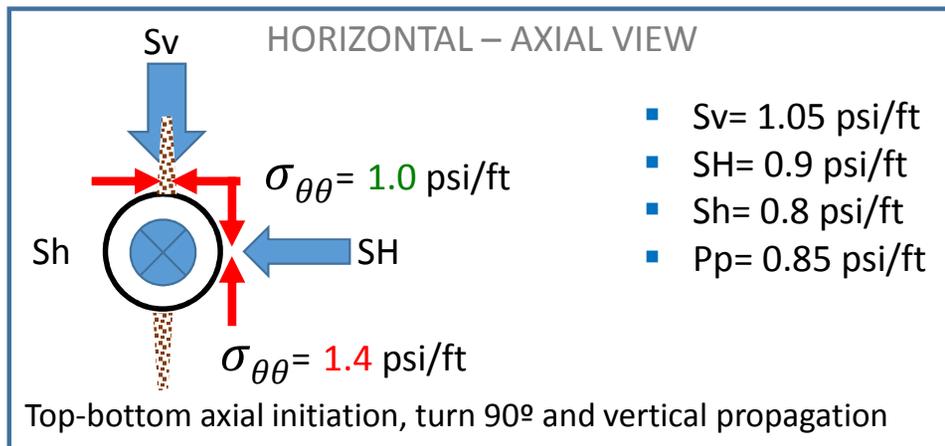
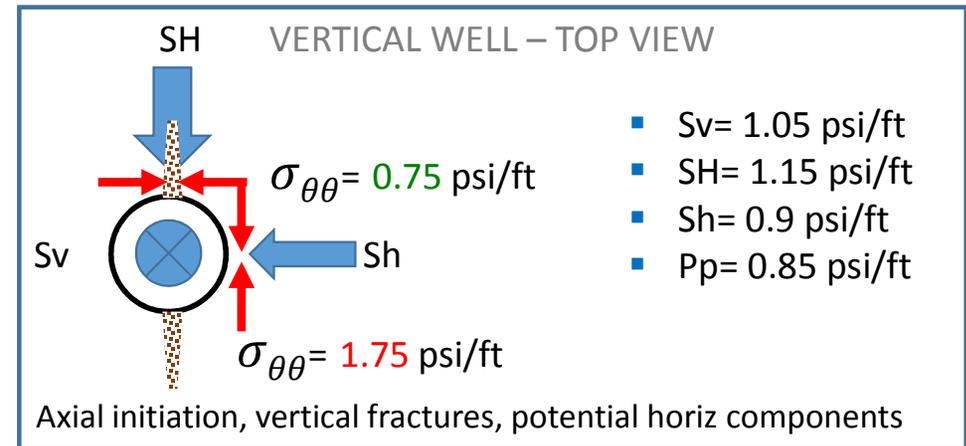
Where do we land the well?

VM'S STRESS SCENARIOS – FRAC INITIATION

EXTENSIONAL (NORMAL REGIME)



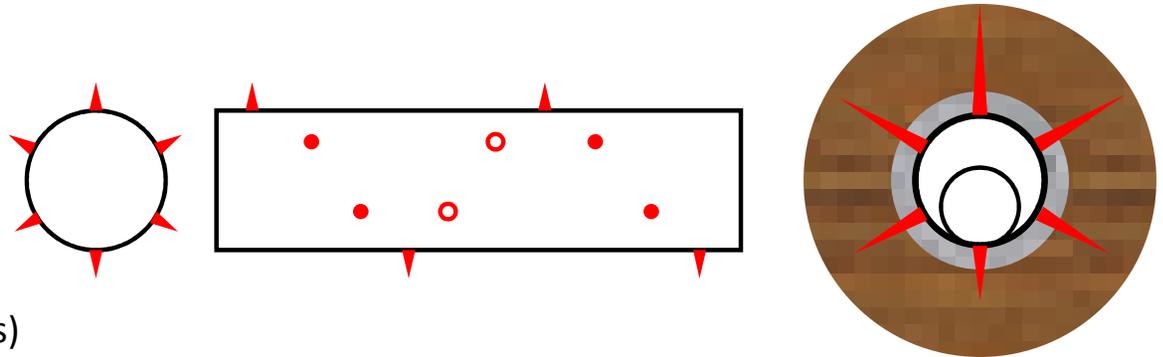
STRIKE SLIP



BREAKDOWN ANALYSIS

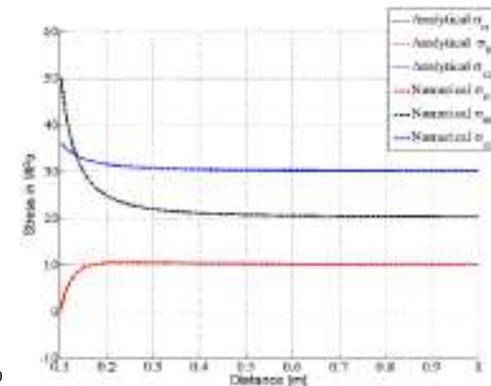
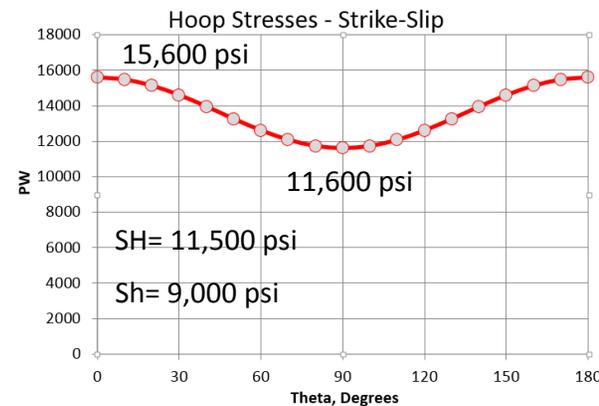
ASSUMPTIONS

- Horizontal well – normal stress regime
- 0.5 m of perforations at 6 SPF (10 holes)
- 60° phasing
- Linear elastic rock behavior
- Isotropic rock (Kirsch's equations are valid)
- Cylindrical hole (assumption for previous eqs)



REALITY

- Casing gun rests at bottom of the well
- Depending on how casing gun arrives at perforation depth, most likely perforations are not going to be aligned to principal stresses
- Charge located closest to well will produce biggest hole and shortest penetration, charge located on the opposite side has the opposite behavior
- Rocks do not behave as linear elastic, they are anisotropic and wellbore is slightly ellipsoidal (Amadei's solution even if complex is more adequate)



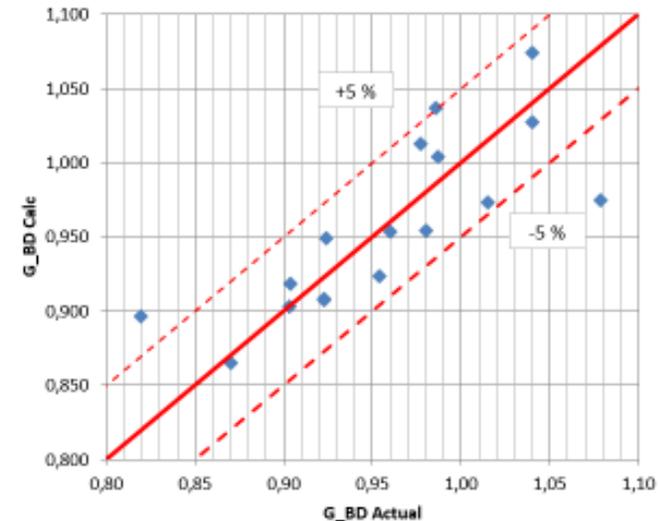
ESTIMATION OF BREAKDOWN PRESSURE

WHY? – MAIN USES

- Optimization of casing design
- Engineering of cluster design
- Horse power requirement on location
- Definition of equipment pressure rating
- Setup of pup-off valves
- What else?

PROPOSED METHOD

- Based on deep resistivity logs which is available in mostly every well and pore pressure
 - Deep resistivity not affected by potential invasion, deep radius of investigation
 - Rock properties (Young's modulus and Poisson's ratio) can be deduced from acoustic logs
 - Acoustic data linked to resistivity as shown by Faust
 - Breakdown equation is a function of rock properties and stresses
 - Originally intended and tested for tight reservoirs but lately proved also useful for shales



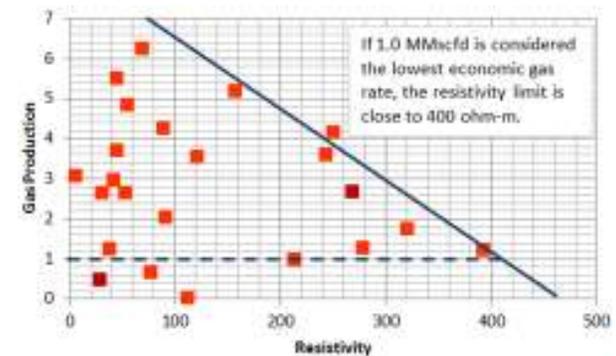
$$G_{BD} = A * RD^B + C * G_{pp}^D - E$$

A, B, C, D, E = Correlation coefficients

ESTIMATION OF BREAKDOWN PRESSURE – CONT'D

APPLICATION EXAMPLES

- Fracability analysis
 - Possible to integrate as part of petro physical analysis to flag zones with high breakdown pressure
 - Resistivity might be also used as a proxy for potential production. Another flag for picking best productive zones
- Casing design
 - Quick assessment for casing design, avoid surprises during factory drilling
 - Save casing in lowermost zones with high breakdown pressure that most likely will be of low productivity



BREAKDOWN PRESSURE PREDICTION

R_Deep Deep resistivity, Log reading minimum value
 G_Res Reservoir pore pressure gradient
 Assumption: breakdown during MFO/DFIT performed with fresh water + 2% KCL at 4 bpm
 G_Res= 0.8 psi/ft

DEPTH [in]	R_Deep [ohm-m]	WHBDP [psi]														
2300	50	874	100	868	150	861	200	853	250	845	300	837	350	829	400	821
2500	50	8272	100	8058	150	8079	200	8064	250	8058	300	8052	350	8046	400	10214
2700	50	9131	100	9151	150	9097	200	10000	250	10286	300	10548	350	10796	400	11031
2900	50	9596	100	10054	150	10416	200	10746	250	11048	300	11330	350	11595	400	11848
3100	50	10258	100	10736	150	11134	200	11487	250	11810	300	12111	350	12395	400	12665
3300	50	10920	100	11429	150	11852	200	12228	250	12572	300	12892	350	13195	400	13482
3500	50	11581	100	12122	150	12571	200	12969	250	13334	300	13674	350	13994	400	14299
3700	50	12243	100	12814	150	13289	200	13710	250	14096	300	14455	350	14794	400	15116
3900	50	12905	100	13507	150	14007	200	14451	250	14858	300	15237	350	15594	400	15933
4100	50	13567	100	14199	150	14726	200	15192	250	15620	300	16018	350	16393	400	16751
4300	50	14229	100	14892	150	15444	200	15934	250	16382	300	16799	350	17193	400	17568
4500	50	14890	100	15585	150	16162	200	16675	250	17144	300	17581	350	17993	400	18385

5 1/2" - 20# - P-100 (80% Yield Strength)
 5 1/2" - 23# - P-110 (80% Yield Strength)
 5 1/2" - 26# - P-110 (80% Yield Strength)
 Out of range of P-110 grade for these casing weight



PERFORATIONS ANALYSIS

OBSERVATIONS

- In practice at least 500 to 700 psi are required to get decent diversion thru perforations per single cluster
 - In practice it is recommended more than 2 bpm/hole
- Any relationship between these numbers?
- Assumptions for simulation:
 - 1 cluster, 0.5 m long, 6 SPF, 20 BPM/cluster
- Proven that after pumping more than 6,000 lbm of proppant, perforation does not suffer additional erosion
 - What have changed?
 - If casing gun is retrieved from well with all charges fired, why are we making the assumption that 1/3 of perforations are ineffective?

$$P_{pf} = \frac{1.975q^2 \rho_f}{C_D^2 N_p^2 d_p^4}; \text{psi}$$

where

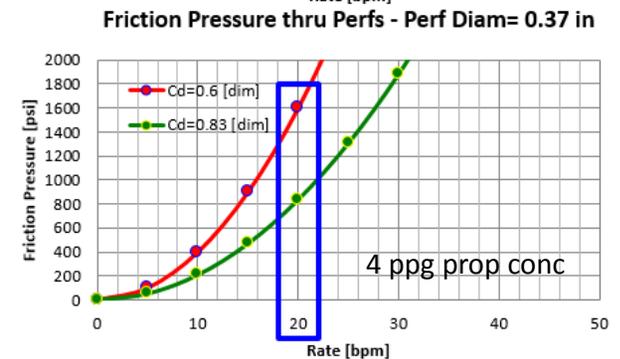
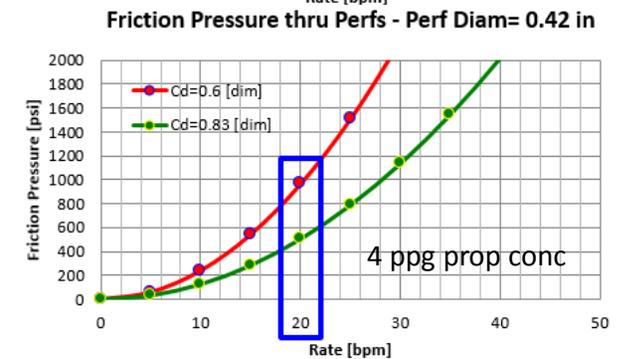
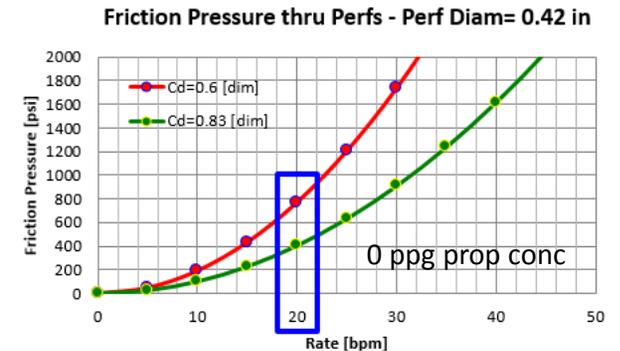
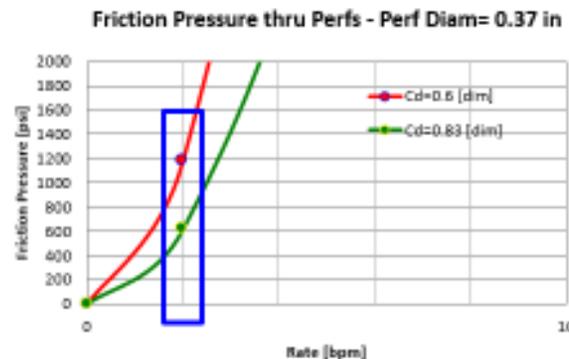
q = the total pump rate, bpm

ρ_f = the slurry density, g/cc

C_D = the perforation coefficient

N_p = the number of open perforations

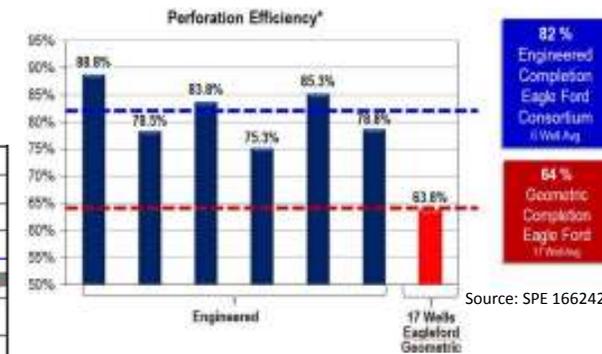
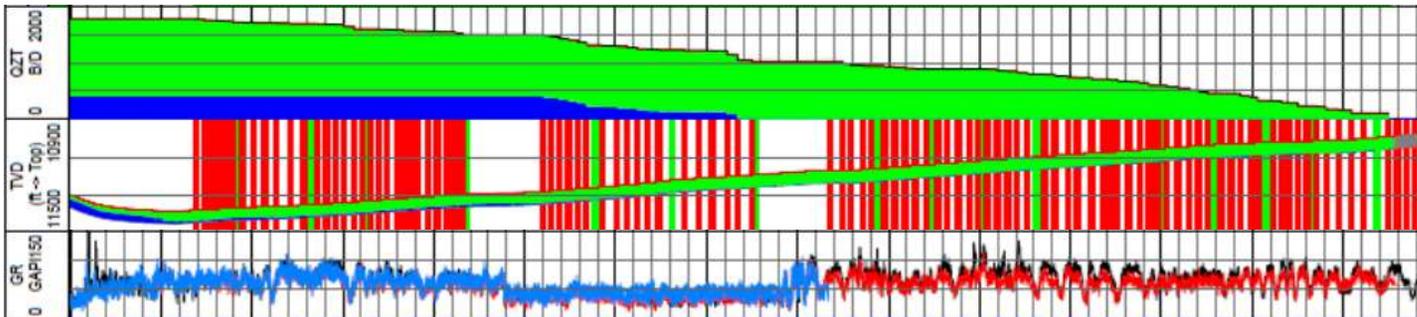
d_p = the perf diameter, inches



CLUSTER INEFFICIENCY OR OPPORTUNITIES?

FACTS & OBSERVATIONS

- Cluster perforating is another fancy name for limited entry perforation
 - We all know how many bypassed zones were left using this technique. Opportunity for WOs
 - No matter what we say it was implemented to reduce cost when tight reservoirs were uneconomical
- We measure cluster efficiency based on production per cluster
 - If highly uneven or inexistent, efficiency is low
 - We love or we blame clusters based on results
 - Are we measuring with the right technologies or just allocating production based on proxies (e.g. tracers, microseismic)?
- Are we engineering cluster design?
- Do we really understand physics behind the process?

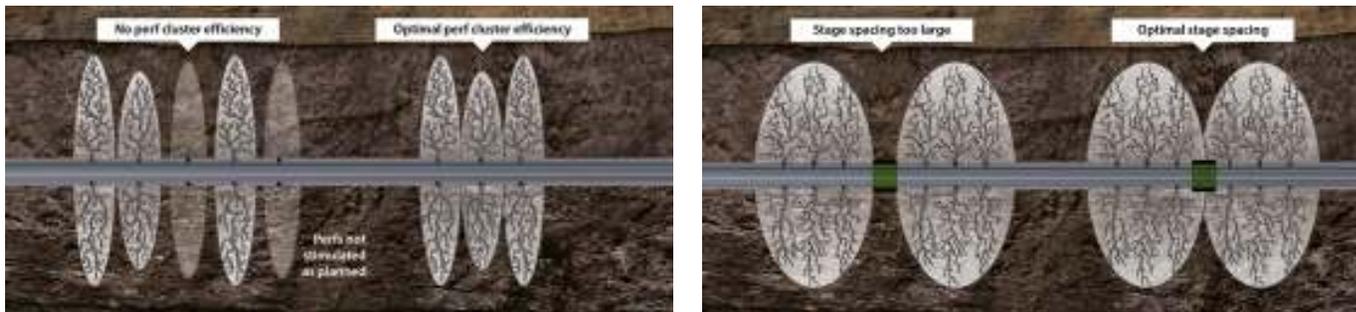


Source: SPE 166242

CLUSTERS DYNAMICS

FRAC SPACING FUNDAMENTALS

- Mainly driven by four factors:
 - Stress interference or shadowing
 - Directly related to geomechanics and poro-elastoplastic effects between hydraulic fractures
 - Production interference
 - Related to reservoir conditions that govern the process
 - Operational and/or completion design constraints (engineering)
 - Even if previous two factors are feasible, this factor might limit the number of clusters and stages (e.g. spacing to set tools, flushing of fracs, etc.)
 - Economics
 - Will dictate if there is a commercial development behind the technical approach
 - Company strategy will define which key indicators are required to have profitable economics
- Today's discussion: focus on third factor assuming others are fulfilled

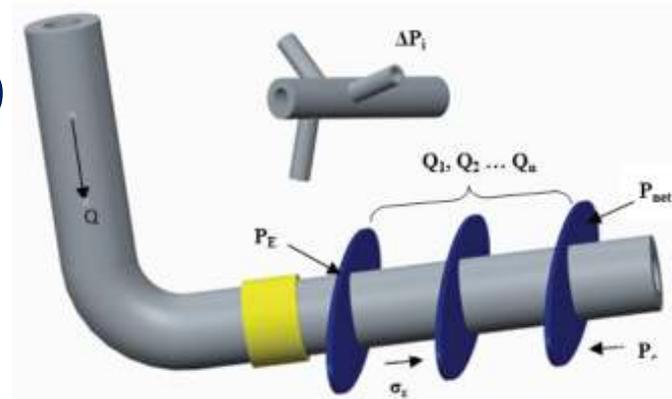


Source: Carboceramic

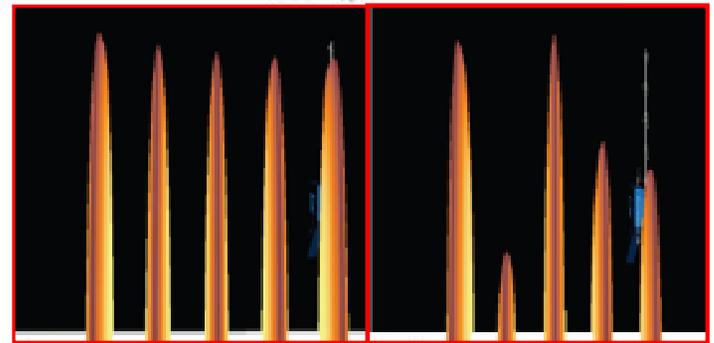
CLUSTERS DYNAMICS – CONT'D

FLUID & PROPPANT DISTRIBUTION

- Common assumptions
 - Clusters are located at zones with similar rock properties (similar reservoir quality)
 - Brittleness index for cluster positioning
 - Evenly fluid distribution based on rate if all clusters are the same of equivalent flowing area as partitioning factor
 - No difference in local velocities for fluid and proppant
 - 1D problem. Newtonian fluids
 - No pressure drop between clusters
 - All holes are open or a certain percentage does not take fluid (~30 % are not effective)
 - Perforations remain always the same
- Are these assumptions valid?
- Up to what point?
- What others are not considered?
- Complex problem that needs to couple fluid transport including proppant and fracture propagation

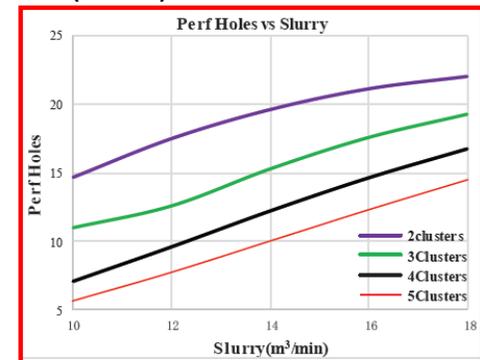


Source: Liu et al, 2016



Plan (ideal)

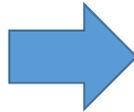
What we get



CLUSTERS DYNAMICS – POTENTIAL SOLUTIONS

FLUID & PROPPANT DISTRIBUTION

- Common assumptions
 - Clusters are located at zones with similar rock properties (similar reservoir quality)
 - Brittleness index for cluster positioning
 - Evenly fluid distribution based on rate if all clusters are the same of equivalent flowing area as partitioning factor
 - No difference in local velocities for fluid and proppant
 - 1D problem. Newtonian fluids
 - No pressure drop between clusters
 - All holes are open or a certain percentage does not take fluid (~30 % are not effective)
 - Perforations remain always the same
- Recommended approach
 - Define an integrated workflow with G&G, RE and D&C to identify best zones (reservoir quality)
 - Move away from BI. Use more engineered approaches based on solid physics
 - Use Navier-Stokes's equations in full taking advantage of CFD simulations
 - Understand fluid flow behavior with and without proppant. Different types of proppant to validate
 - Move to 2D and 3D solutions including non-Newtonian behavior. Frac fluids are non Newtonian!
 - Understand perforation dynamics. Use a fully coupled simulator to assess individual hole behavior
 - Perforations behave dynamically. Understand behavior along time while fracturing



Partner with Universities to tackle complex problems. It will benefit both parties

PERFORATION STRATEGY



TAKEAWAYS – SOME RECOMMENDATIONS

- Cluster length must be less than 4 wellbore diameters to avoid multiple fractures
- If possible 3 to 4 clusters as a maximum. As number increases efficiency decrease dramatically
- Space clusters to mitigate stress shadowing effects but remember this is not the only factor to take into account
- Perforation hole engineered to provide enough pressure drop for positive diversion but at the same time it must be able to allow flowing of slurry at maximum proppant concentration
- In practice it is easier to work with rate rather than pressure drop to get diversion. Ensure at least 2 bpm/hole
- Design with perforation hole size once it is eroded
- Big holes does not provide diversion unless high pumping rate is used
- Big charges create an important stress cage around perforation which might increase breakdown pressure
- Use regular charges in terms of amount of explosive as cement strength is very low in tension. For fracturing in unconventional reservoirs it is not required to overcome invaded zone (any?) as production is provided by the fracture, not by the reservoir itself
- All perforations at casing wall should be open (assuming charges were fired and casing gun verified at surface) but not all will take fluid as breakdown pressure is not uniform around the wellbore. QAQC always pays off
- Acid spearhead are useful to breakdown formation
- Oriented perforating is expensive so go for 60° phasing to maximize the possibility of being close to planes of principal stresses
- If conventional perforating is giving you a lot of headaches go to abrasive jetting perforation and pin point stimulation. Have you checked if stress regime is right?

QUESTIONS? THANK YOU!

