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Fracture Height Growth in Layered Formations – Comprehensive Comparison of Modeled and Observed Data

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OUTLINE

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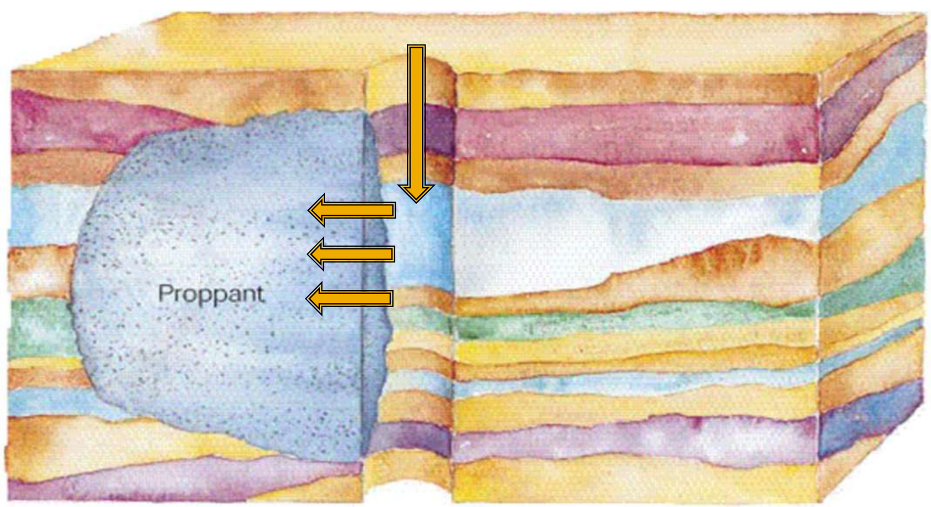
- Introduction
- Height growth in hydraulic fracturing treatment
- Fracture height prediction in layered models
- Development of fracture height growth model
- Comparison of modeled and field observations
- Modification of model for special cases
- Key parameters that influence fracture height growth
- Summary and Conclusions

Introduction

- Hydraulic fracturing: Popular well stimulation technique.
- Fluids are injected in downhole formations at pressures that exceed breakdown pressures, resulting in fractures that are then propped open to create a conductive pathway that eases the flow of hydrocarbons during the production phase.



Source: Schlumberger Oilfield Reporter

- Key formation parameters
  - Stresses & Mechanical properties
  - Petrophysical Properties
- Controllable Parameters
  - Completion Method/Design
  - Injection rates and volumes
  - Fracturing Fluid properties

Typical Description of Fracture Geometry: X_f and h_f

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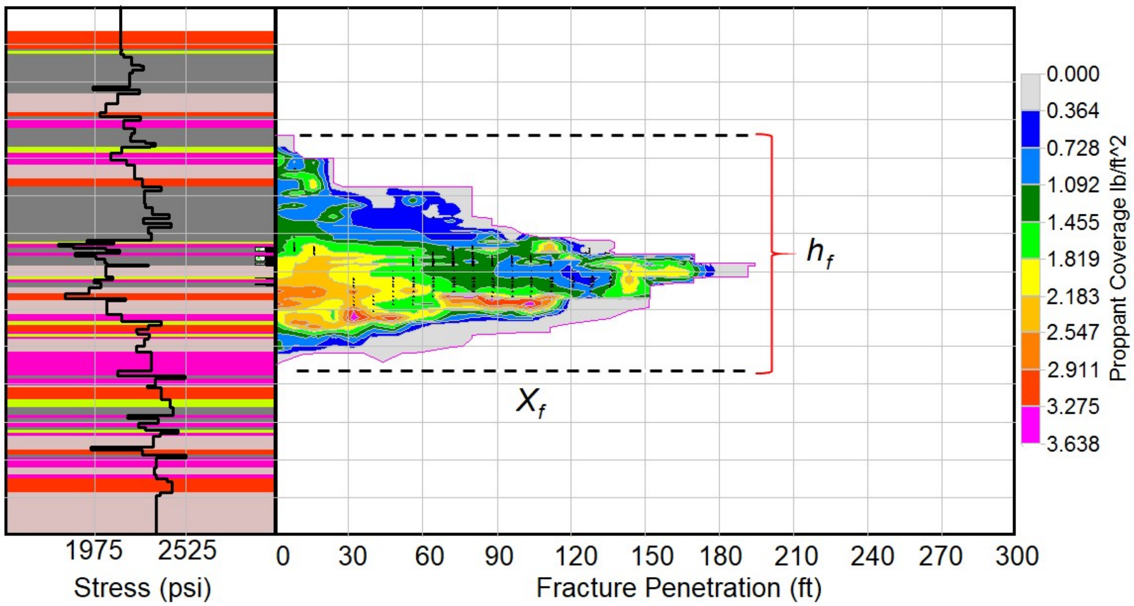
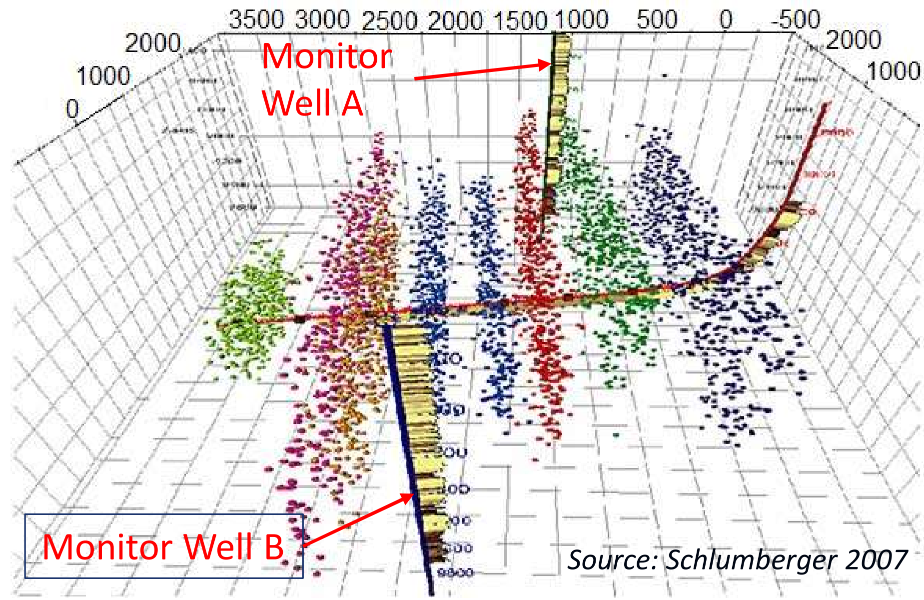
- Fractures resulting from hydraulic fracturing treatments are generally described by their length (X_f) and height (h_f) dimensions.
- Planar features may be inferred from Microseismic survey data.



Fracture dimensions of half-length (X_f) and height (h_f) from fracture modeling simulators.

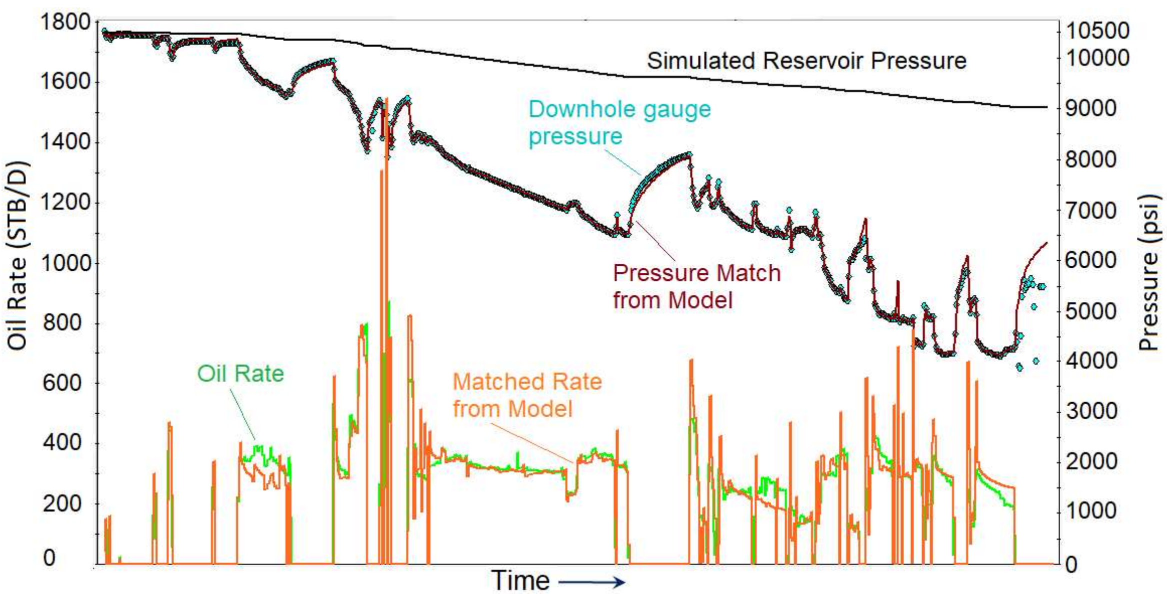


Microseismic (MS) survey data from an example well.

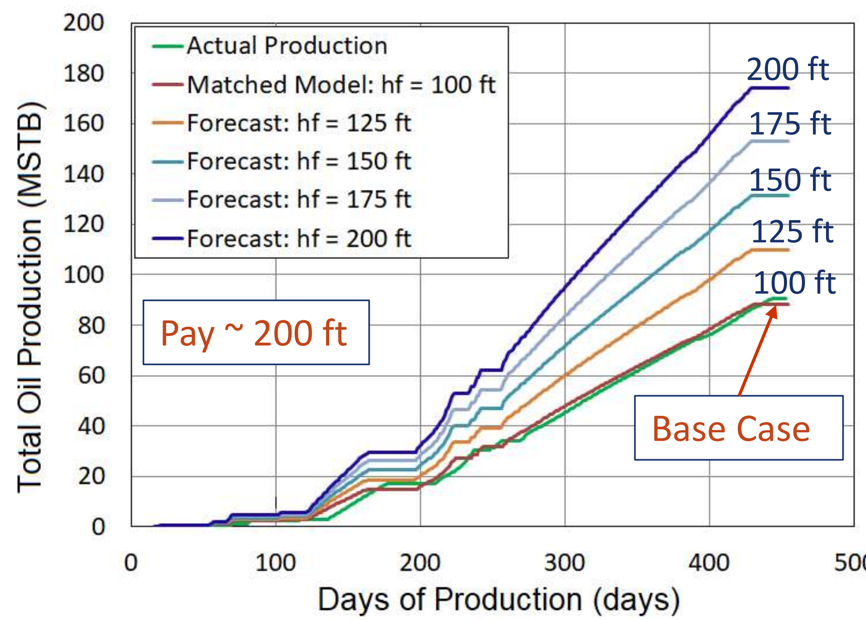
Why is h_f important in well stimulation?

- Production rates are directly proportional to payzone height.
- Fracture dimensions contributing to production are obtained by history-match.

Production history match – horizontal well treatment.

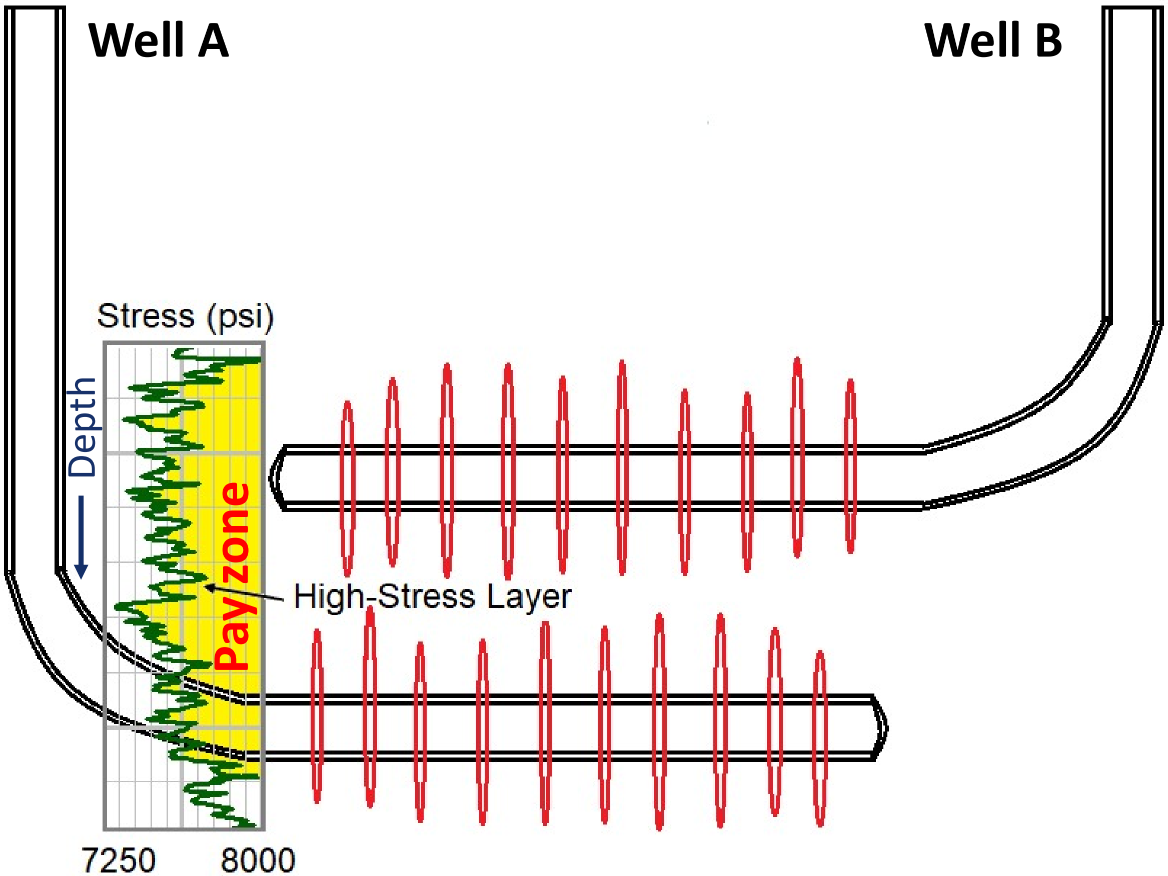


Production forecast - various fracture heights



Effective payzone coverage by propped fracture improves well performance.

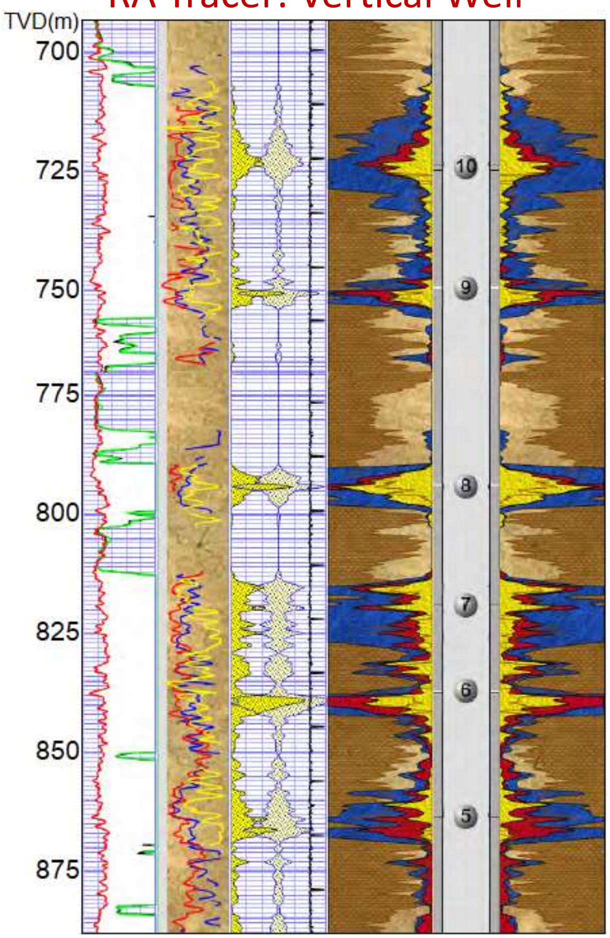
Is desired fracture height always achievable?



- High-stress layer(s) within the targeted zone can limit growth.
- Influence of geologic features.
- Expected fracture height during a treatment can influence:
  1. Well placement in horizontal well development program.
  2. Perforation depths and zoning in vertical wells.
  3. Treatment size and volume.

How tall do the hydraulic fractures grow anyway?

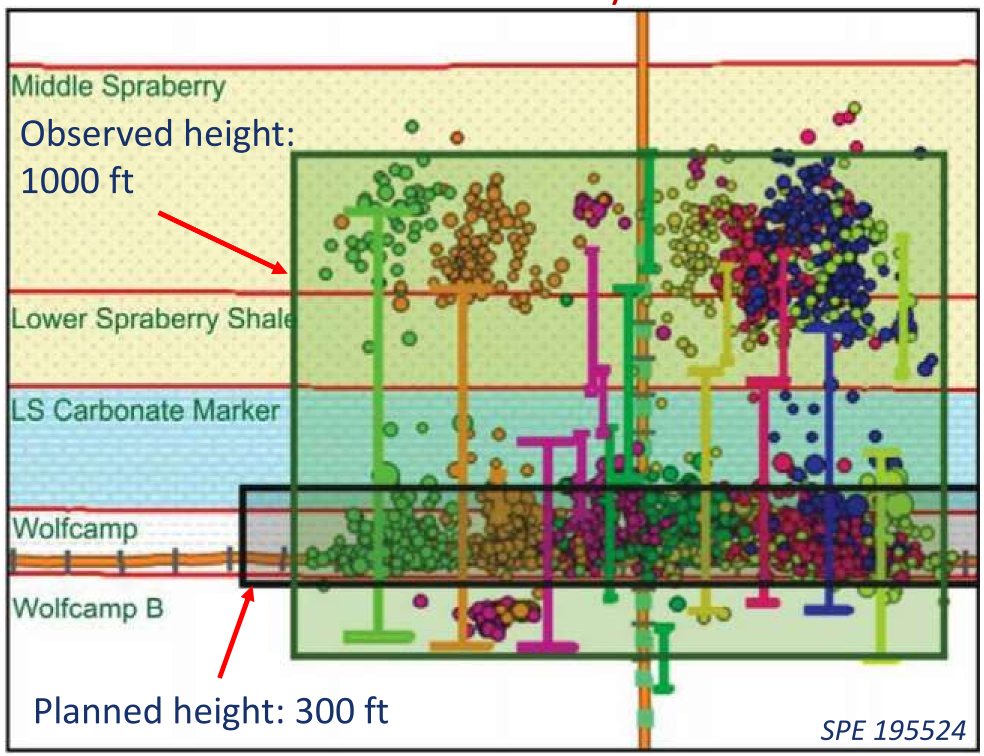
*RA Tracer: Vertical Well



*RA: Radioactive *SPE 173378, SPE 176895*

- Growth is controlled by several factors.
- Field measurements show a wide range of h_f.

Microseismic and Tiltmeter Survey: Horizontal Well



Observed fracture heights may significantly differ from planned heights.

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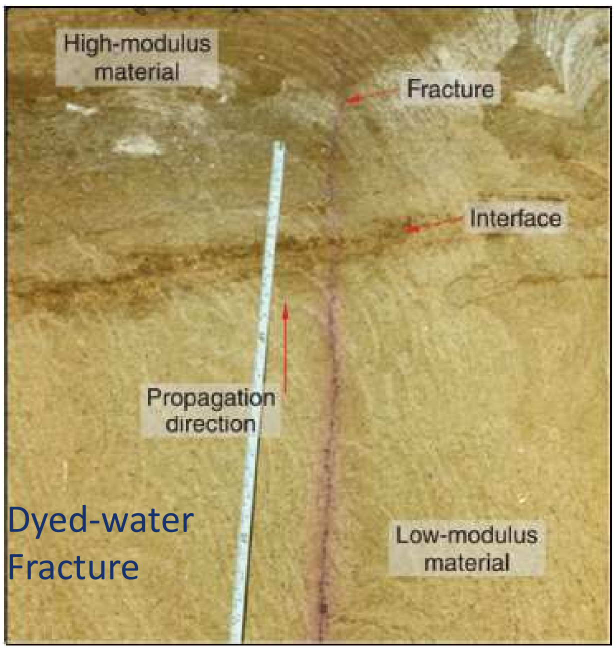
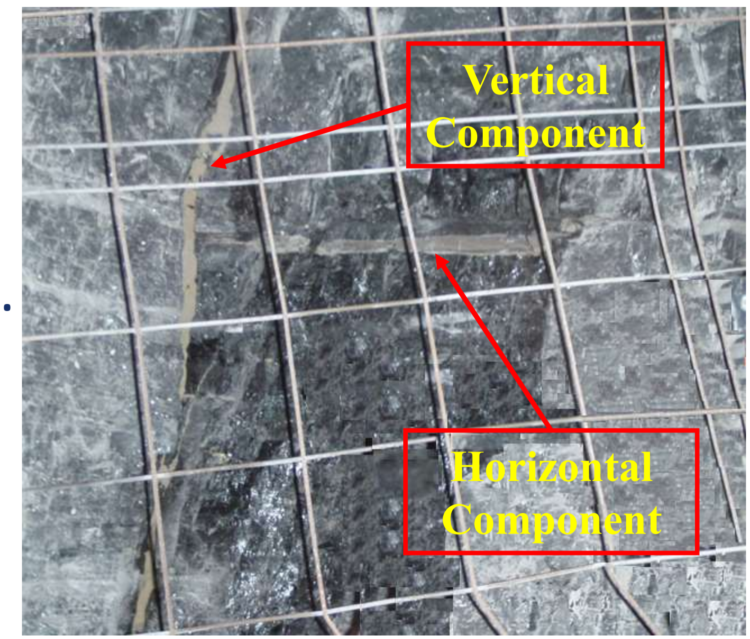
Does fracture growth terminate at interfaces?

- Interfacial bonding – weak or strong may determine fracture crossing.
- Fractures may cross the layer interfaces and continue to propagate.
- Minebacks (shallow wells) suggest presence of horizontal fracture component.



SPE 145949

At shallower depths, horizontal fracture components may develop. Their contribution to production is generally minimal.

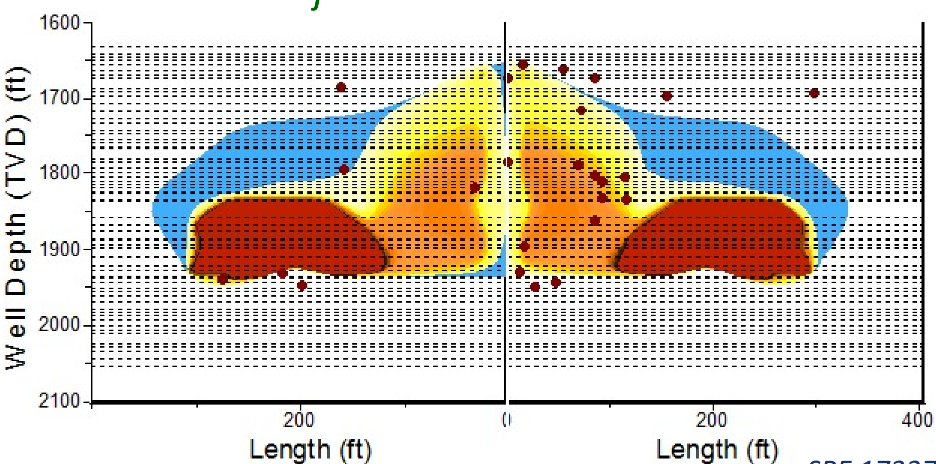


CBM Mineback

Do numerical simulators predict h_f accurately?

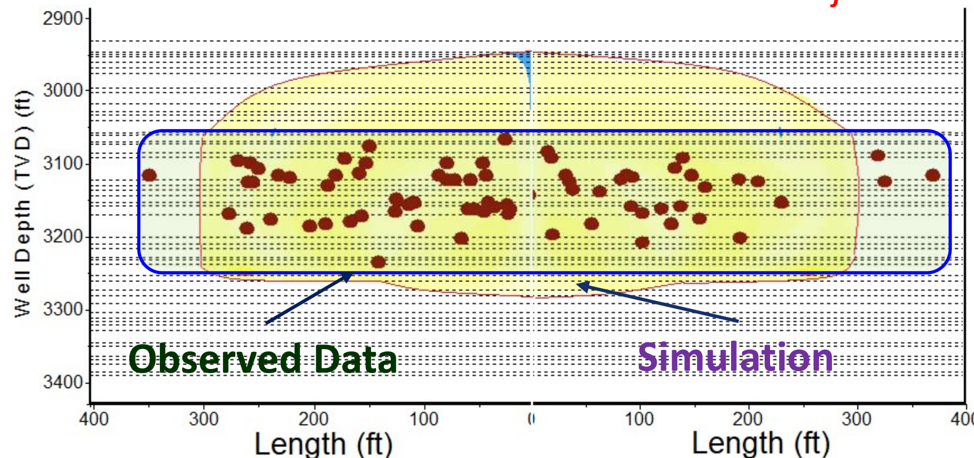
- Results vary – from reasonably good to incorrect predictions

Simulated h_f matches well with MS Events.



SPE 173378

Mismatch of predicted and observed h_f.

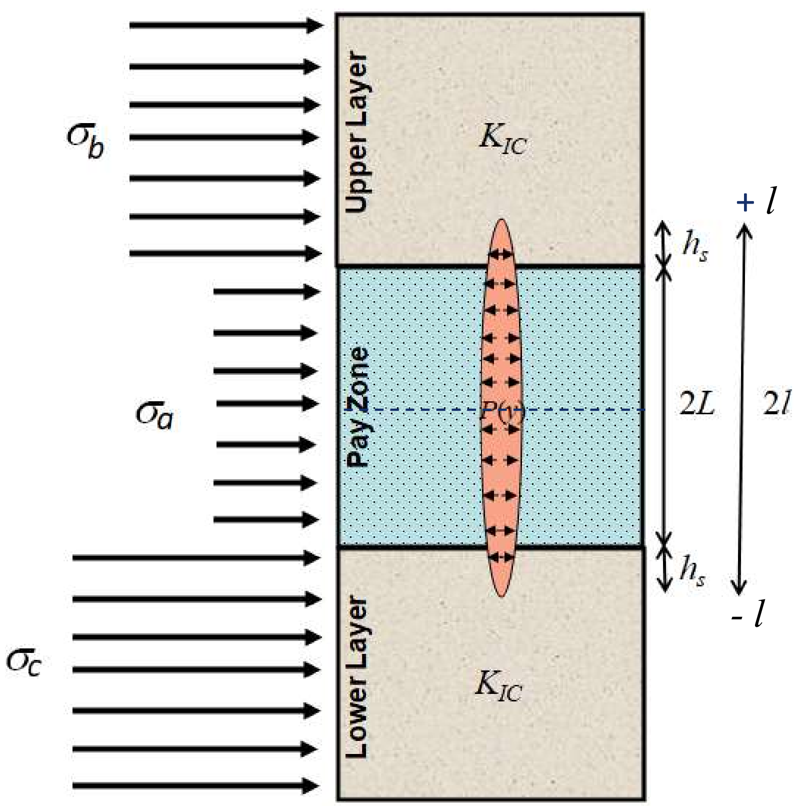


SPE 173378

- Accurate prediction of fracture height growth is important
- Steps to improve fracture height predictions:
    1. Construct semi-analytical models and benchmark with literature data.
    2. Predict fracture height and calibrate with field data to improve the model.

Fracture Height Growth Estimation

- 3-Layered Solid Mechanics Model: Force-balance method



3-Layered Model – Asymmetric Stresses

$$K_I = \frac{1}{\sqrt{\pi l}} \int_{-l}^{+l} p(y) \sqrt{\frac{l+y}{l-y}}\, dy$$

$$K_I^{top,bot} = \frac{\sqrt{\pi l}}{2}(2p - \sigma_b - \sigma_c) \pm \frac{1}{\sqrt{\pi l}}(\sigma_c - \sigma_b)\sqrt{l^2 - L^2} + \sqrt{\frac{l}{\pi}} \sin^{-1}\left(\frac{L}{l}\right)(\sigma_c + \sigma_b - 2\sigma_a)$$

h_s = fracture penetration, ft (m)
K_I = stress Intensity factor, psi$\sqrt{\text{in}}$ (kPa$\sqrt{\text{m}}$)
l = fracture half-height, ft (m)
L = mid-layer thickness, ft (m)
$p(y)$ = fracture pressure along crack-axis y, psi (MPa)
σ = stresses in layers a, b & c, psi (MPa)

Net Pressure = Fracture Pressure – Closure Stress

Detour - Critical Stress Intensity Factor (K_{Ic})

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- Fracture toughness (K_{Ic}) is material property but also geometry dependent.
- To account for possible changes as the fracture geometry evolves:
  - Fluid/tip velocity can be used to calculate K_{Ic}
  - Results can be directly incorporated in the Fracture Location vs. Net Pressure map.
- Governing equation (Pandey and Rasouli, 2021):

$$\Delta K_{Ic} = \left\{ v \left(\frac{\pi}{4}\right)^m \left(\frac{2n+1}{n}\right) \frac{1}{\phi(n)} \right\}^{\frac{n}{n+2}} \left[\frac{K x^{2-\alpha}}{(1-\alpha)\cos[(1-\alpha)\pi]}\right]^{\frac{1}{n+2}} \left[\frac{E'\alpha}{2\sin(\alpha\pi) x^{\alpha-0.25}}\right]^{\frac{n+1}{n+2}}$$

E' = plane strain modulus, psi (MPa)

m = variable, function of power law index, *n*

n, K = Power Law indices

v = fluid (or fracture tip) velocity, ft/s (m/s)

x = distance from fracture tip, ft (m)

ΔK_{Ic} = apparent stress Intensity factor, psi$\sqrt{\text{in}}$ (kPa$\sqrt{\text{m}}$)

α = exponent (function of *n*), unitless

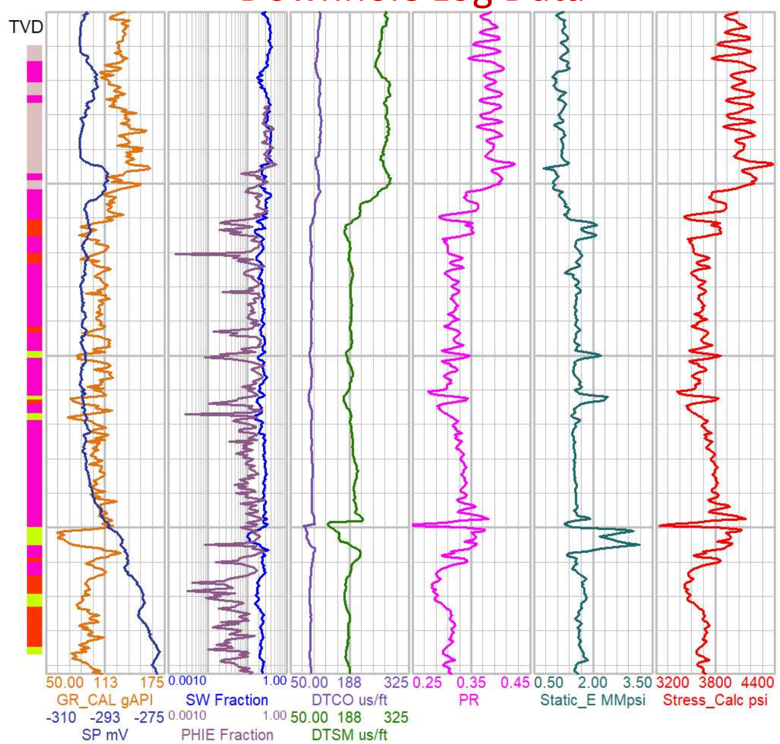
$\phi(n)$ = fluid flow equation variable

Fracture toughness may be calculated during simulations.

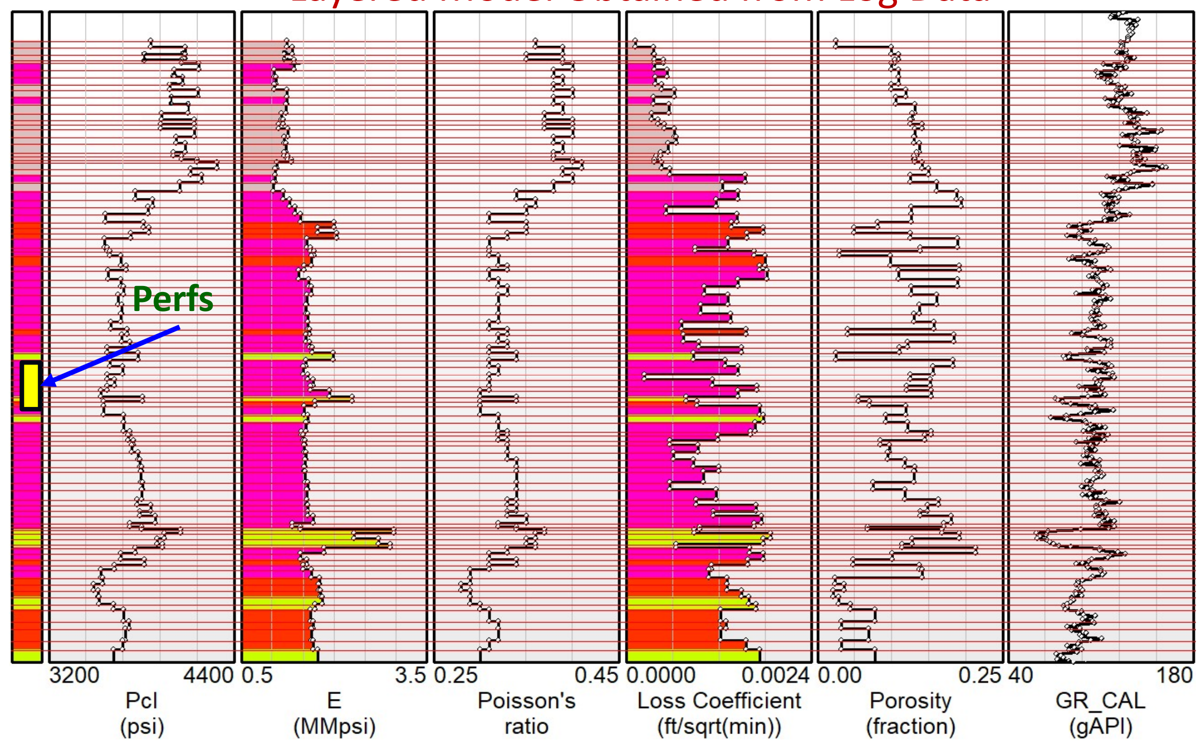
Real world cases are more complex

- Stress and mechanical property variations with depth are common.

Downhole Log Data



Layered Model Obtained from Log Data



Height growth models must account for variations in key formation properties.

Extending 3-Layer Solution to Multi-Layer Scenario

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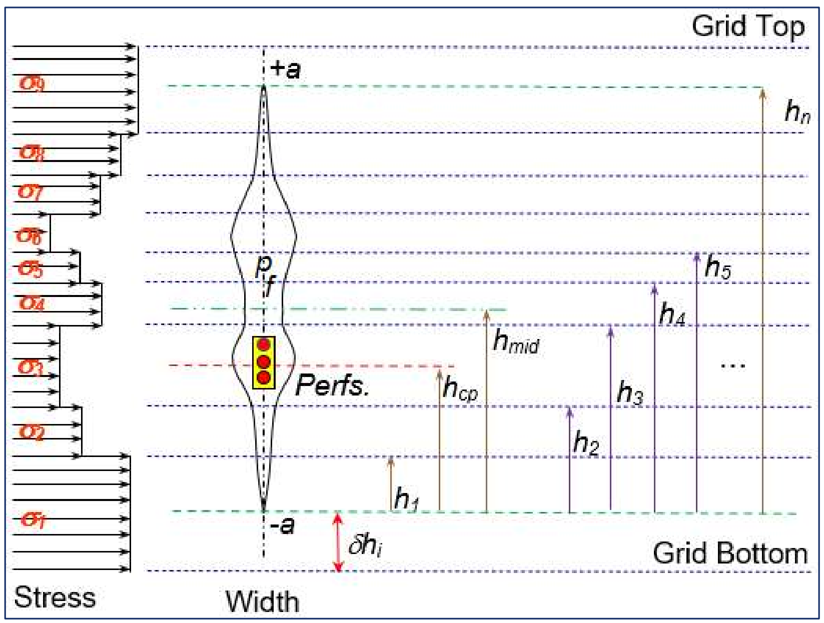
- Key Assumptions:
  - Uniformly pressurized crack with no leak-off (*no fluid flow*)
  - Fracture advances at slow-pace (*no tip effects*) in linearly elastic medium

$$K_I^{bot,top} = \sqrt{\frac{\pi h_f}{2}}\left[p_{cp} - \sigma_n + \rho_f g\left\{h_{cp} - \frac{\xi h_f}{4}\right\}\right] + \sqrt{\frac{2}{\pi h_f}}\sum_{i=1}^{n-1}(\sigma_{i+1} - \sigma_i)\left[\frac{h_f}{2}\cos^{-1}\left(\frac{h_f - 2h_i}{h_f}\right) \pm \sqrt{h_i(h_f - h_i)}\right]$$

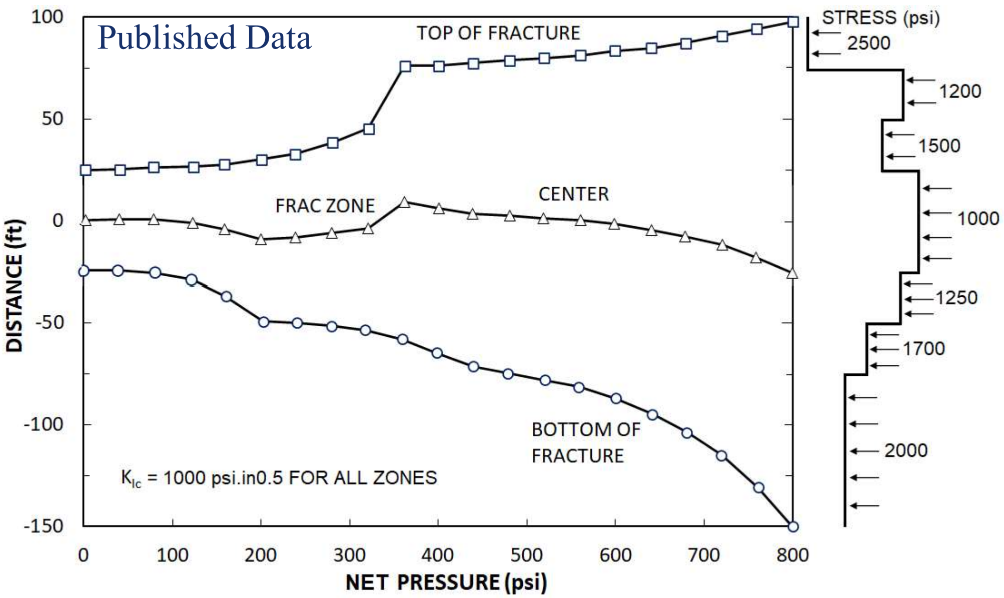


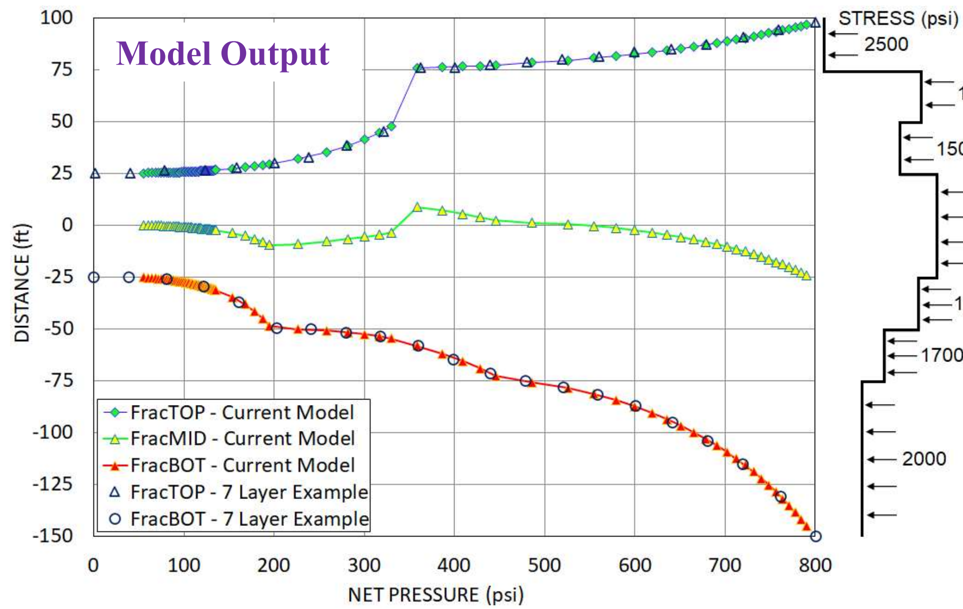
g = gravitational acceleration, ft/s² (m/s²)
h_{cp} = elevation to center of perforations, ft (m)
h_i = elevation, ft (m)
h_f = fracture height, ft (m)
K_I = stress intensity factor, psi$\sqrt{\text{in}}$ (kPa$\sqrt{\text{m}}$)
p_{cp} = pressure at center of perforations, psi (MPa)
ρ_f = fluid density, lbm/gal (kg/m³)
ξ = tip location specific value (1 or 3)
σ_n = stress at n^{th} layer, psi (MPa)

Solution is based on superposition of layered properties.

Constructing & Calibrating Height Growth Model

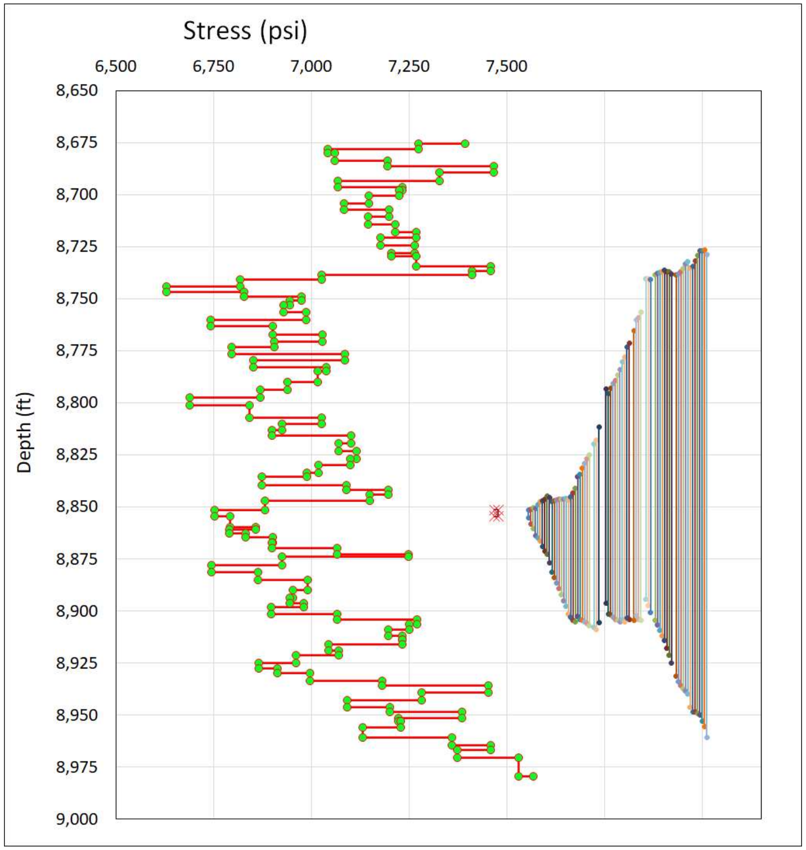
- Fracture height and location obtained by iteratively solving non-linear equations.
- Distance/Fracture Height vs. Net Pressure relation is generated as part of solution.





Fracture position and height are controlled by stress profile and fracture pressure.

Model Application: Simulated Height Growth Evolution



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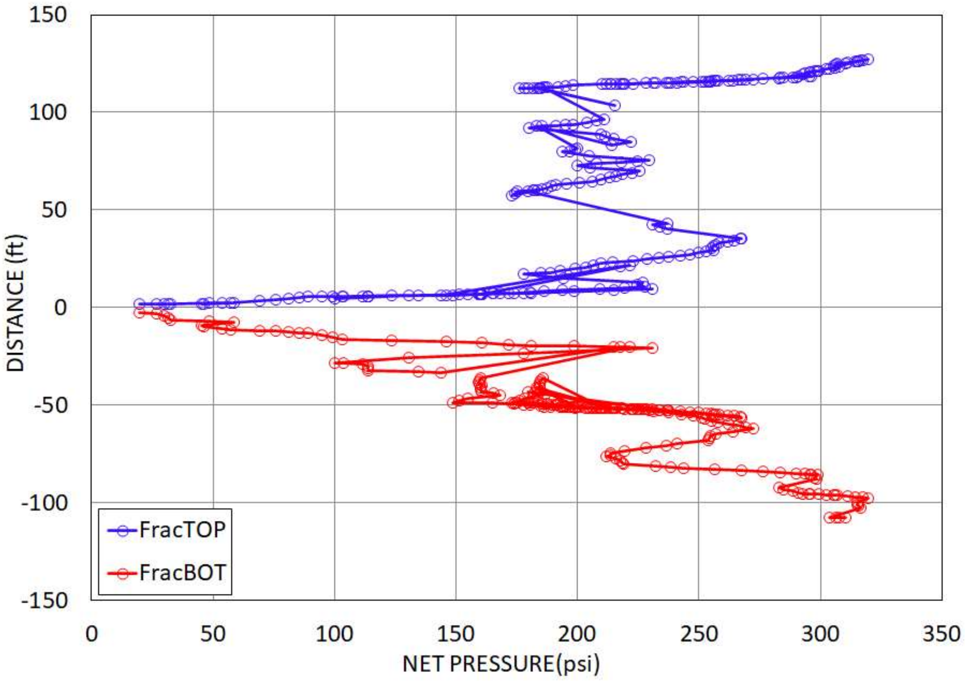
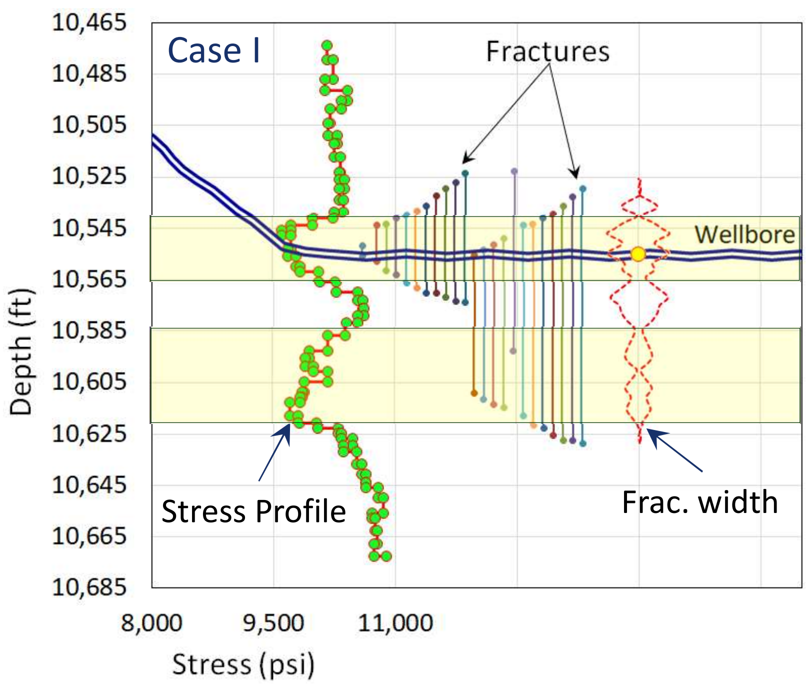
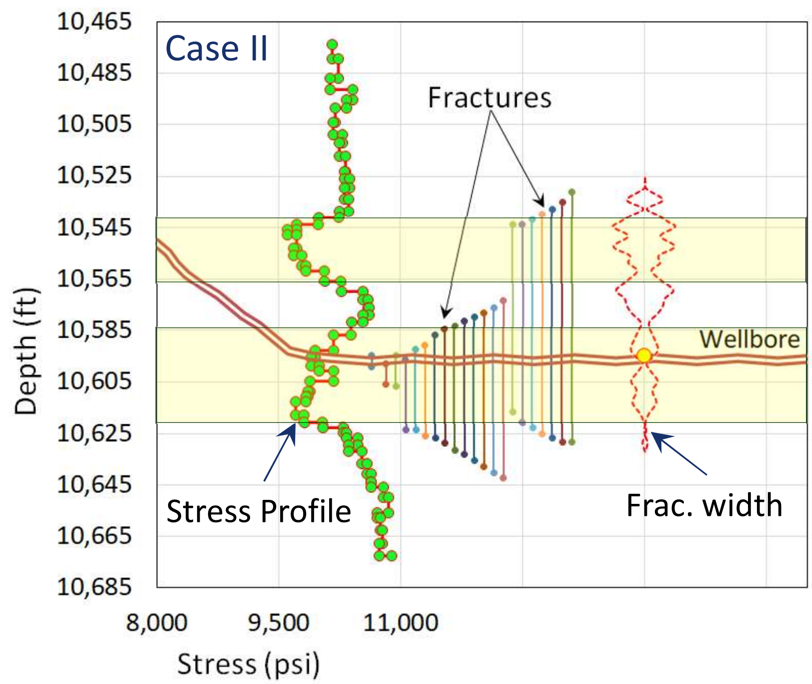
- Vertical growth requires lower net pressure as high-stress layers are breached and low stress regions are exposed.
- Upward fracture growth is initially slow because of high stress layer at 8,240 ft but eventually fracture "migrates" upwards.



Model Application: Well Placement – Real Scenario

- Case I: Upward growth initially till the middle stress barrier at 10,575 ft is overcome.
- Case II: Initial fracture containment followed by upward growth.

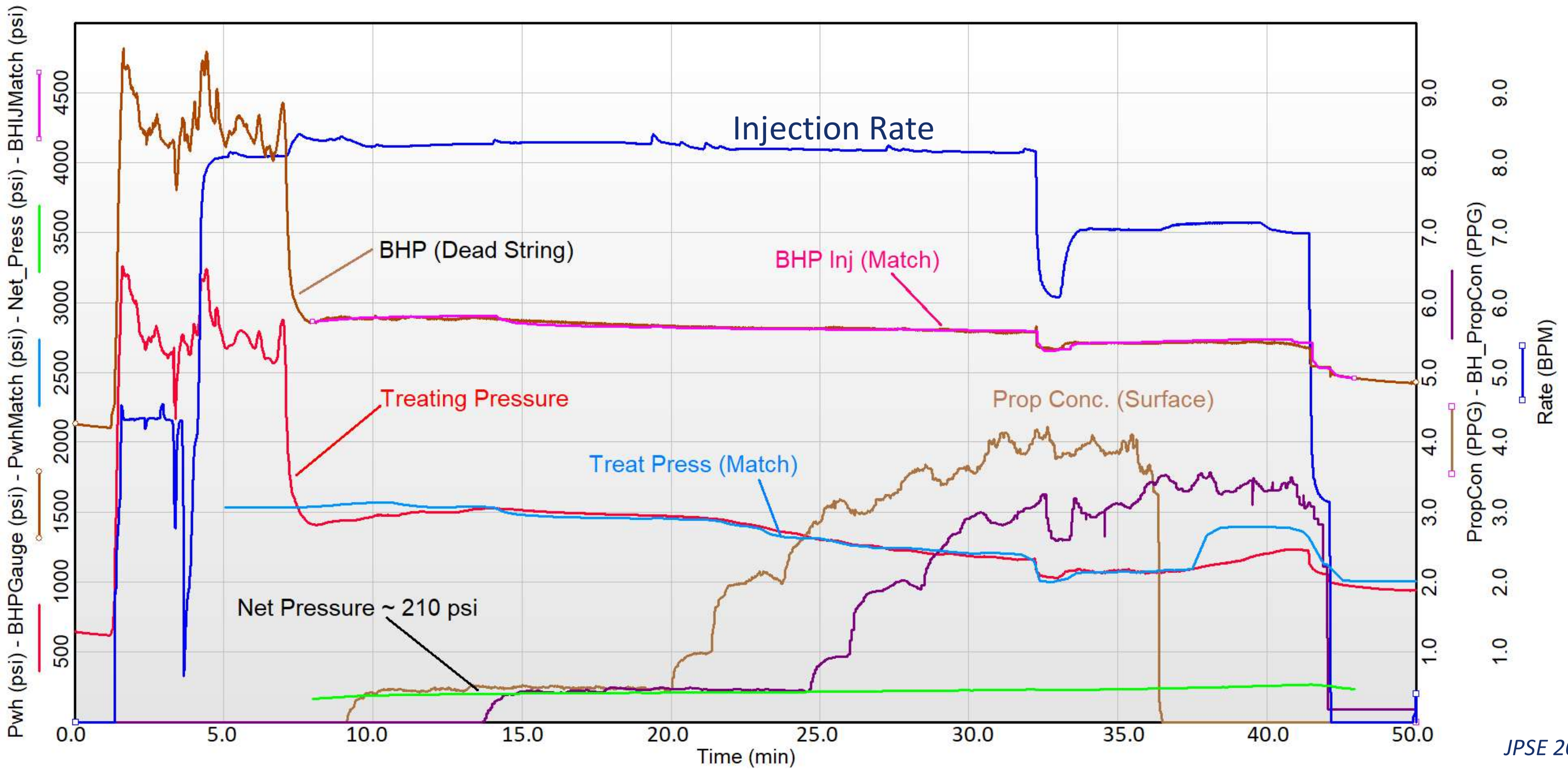




Height growth modeling can assist in optimal well placement.

Case History – I: Shallow Vertical CBM Wells

- 8.0 bbl/min; 1 ⅞ C.T. × 4 ½ in. Ann. , jet-cut holes, 20 lbm/Mgal x-linked fluid.



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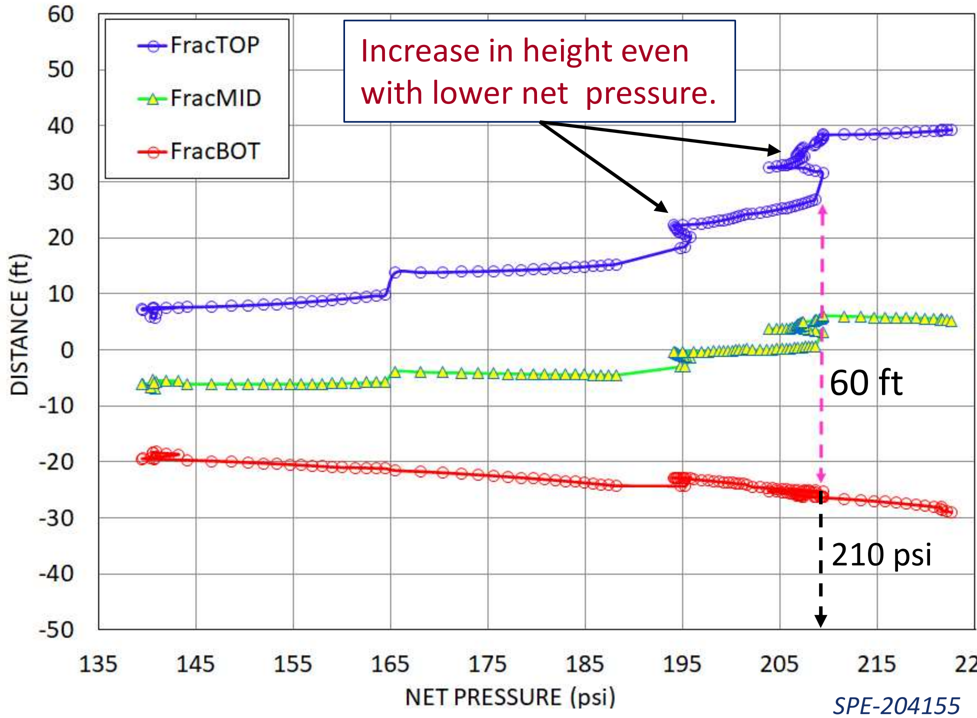
Case History – I: Shallow Vertical CBM Wells

- 8.0 bbl/min down Ann. of 1 ⅞ C.T. × 4 ½ in. casing w/ 20 lbm/Mgal x-linked fluid.
- Predicted h_f and location matches the height derived from RA Tracer.



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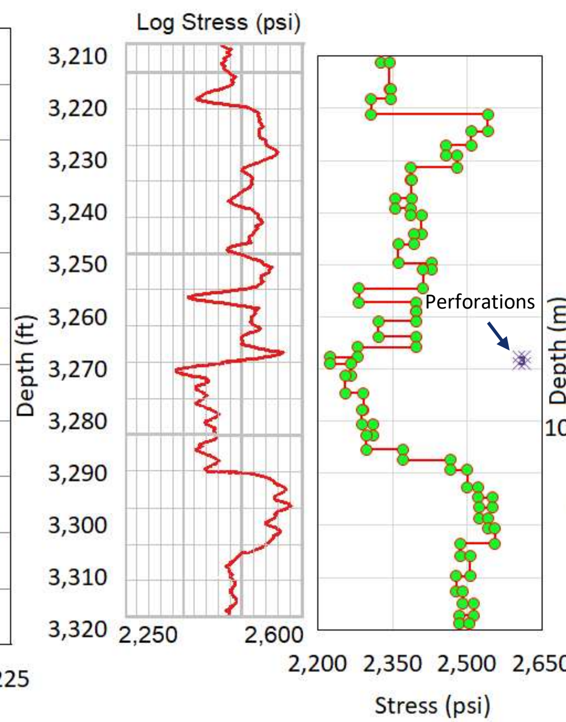

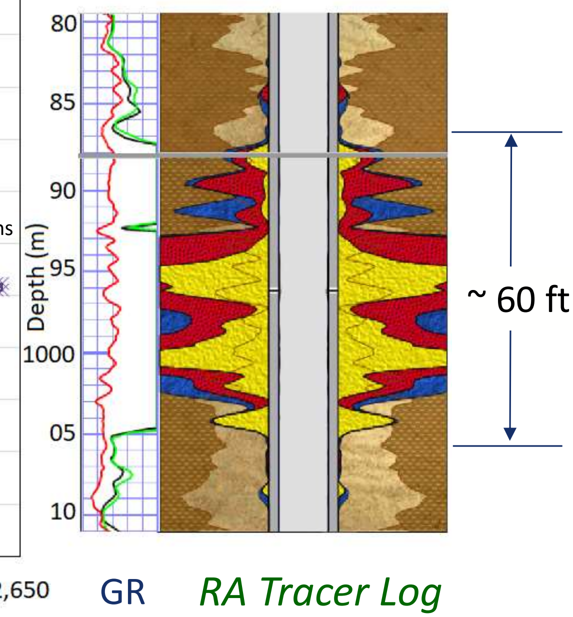

Case History – II: Shallow San Miguel Sands (S. TX)

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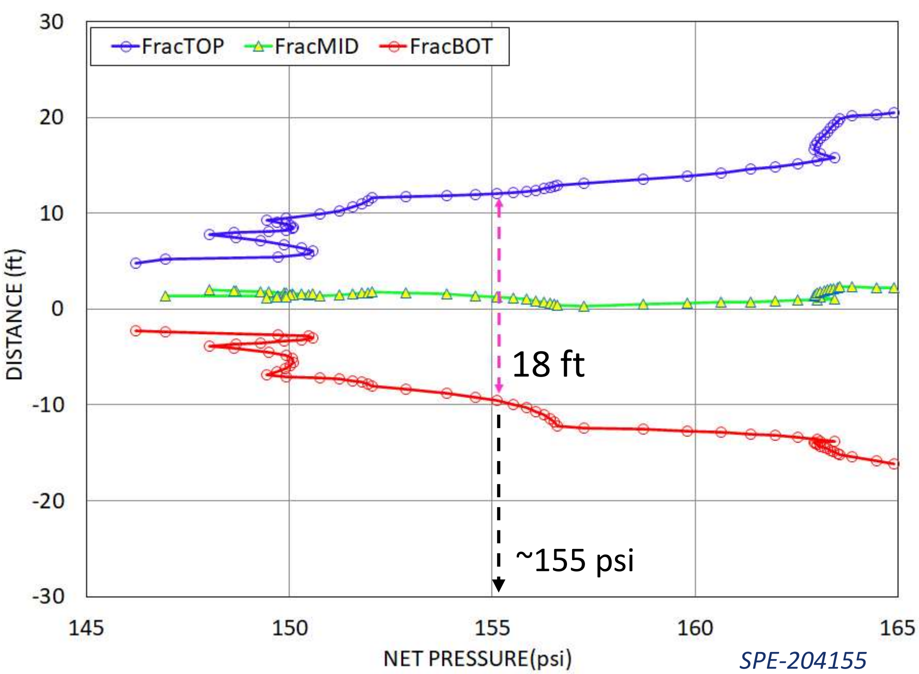
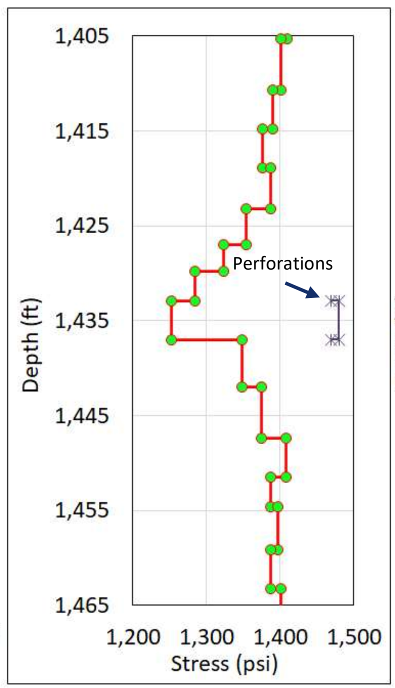
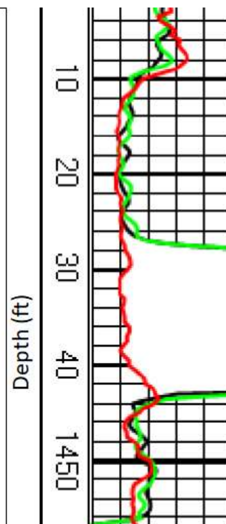
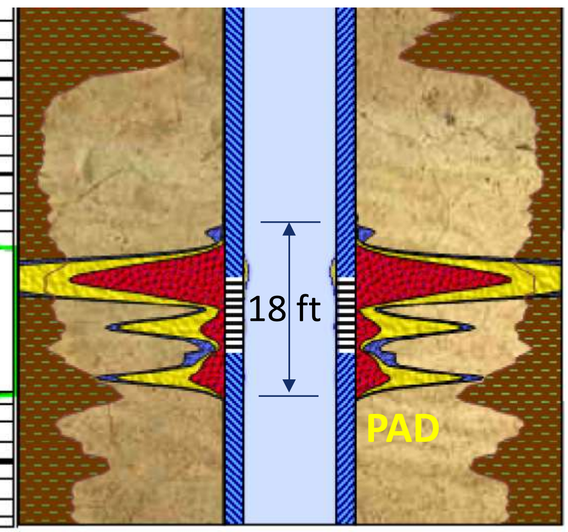
- 12 to 15 bbl/min down 4 ½ in. casing with 30 lbm/Mgal cross-linked fluid.
- BHP Injection exceeded overburden after 10 minutes of pumping.







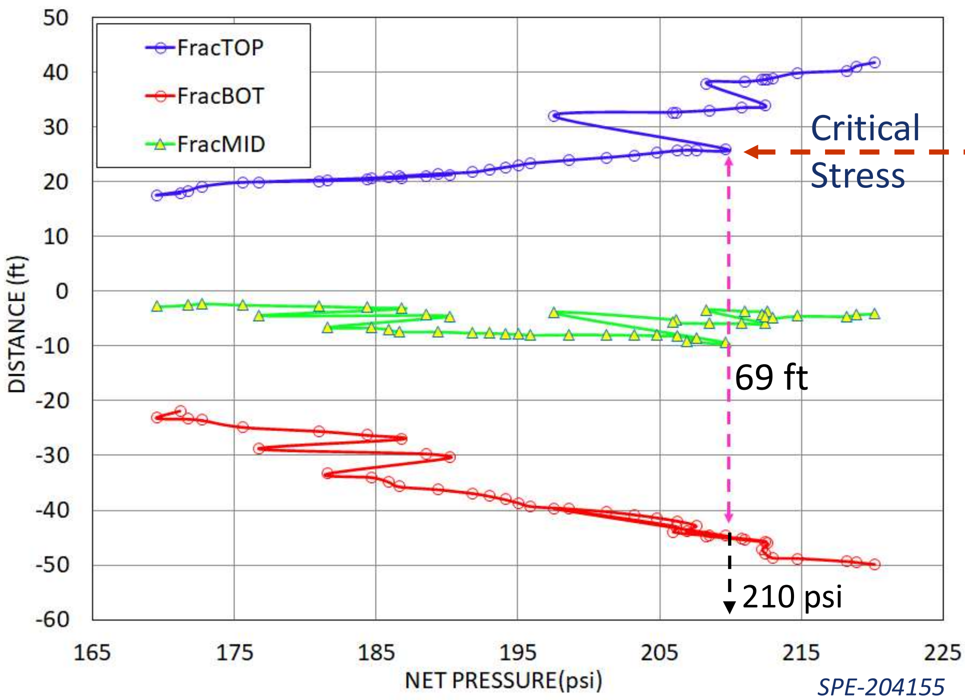
Gamma Ray

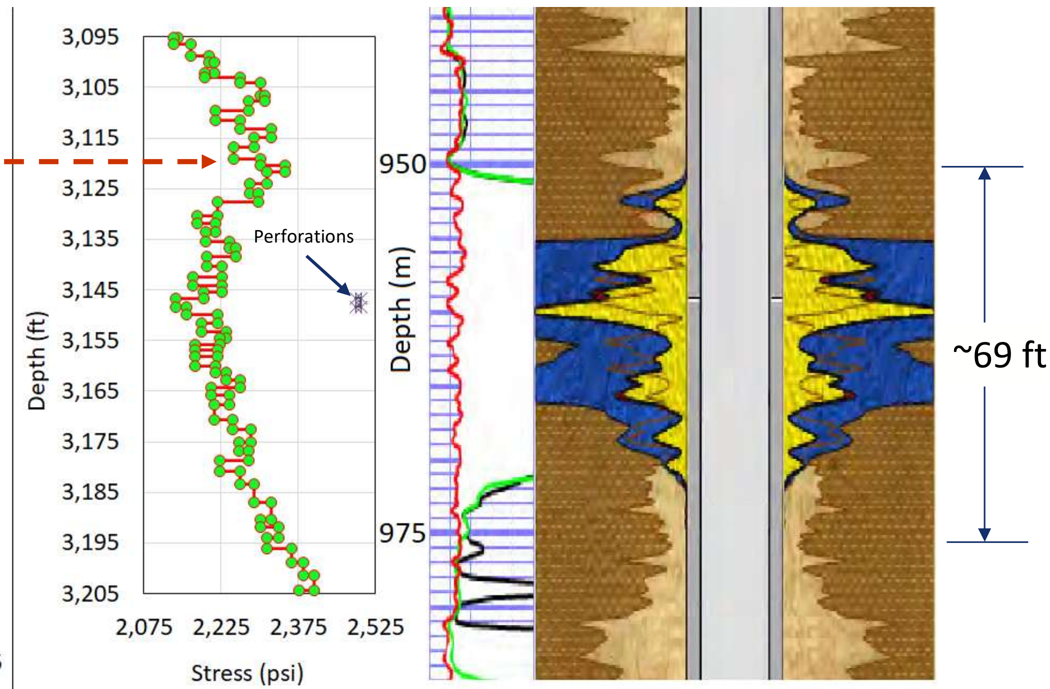


RA Tracer Log

Adjustments to Model : CBM Foam Frac Case History

- 8.0 bbl/min 65Q N_2 Foam with 20 lbm/Mgal cross-linked gel
- Model was modified to account for fluid flow induced fracture pressures.

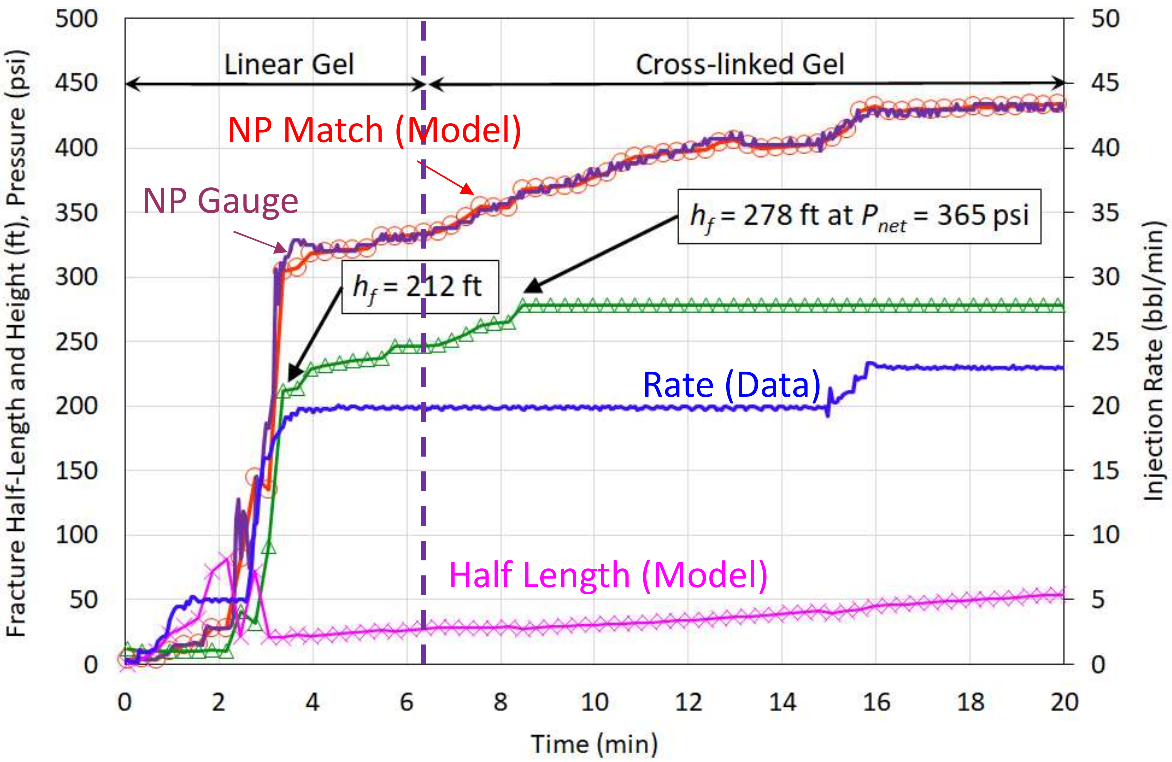




Superposition approach allows easy inclusion of other effects to base model.

Case History IV: Fracture Growth Rate (Sandstone)

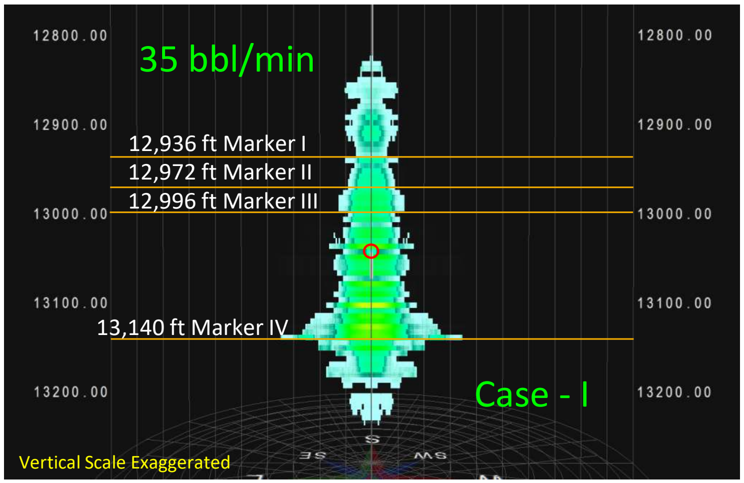
- Pressure History Match: 24.0 bbl/min with 30 lbm/Mgal x-linked gel



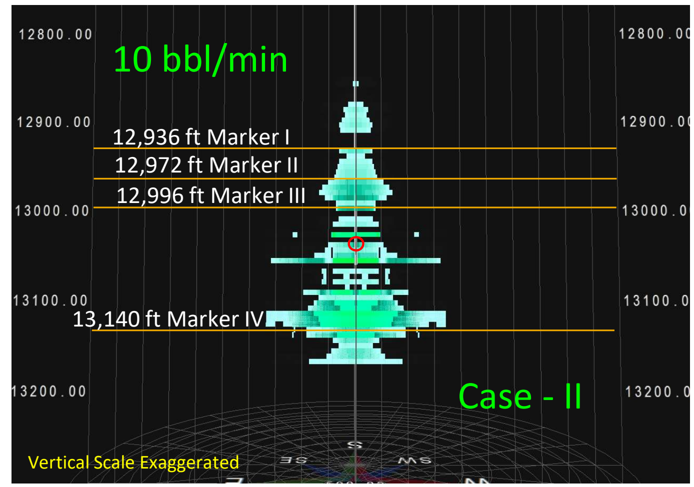
- Annulus Job: 1¾ in. x 4½ in.
- YM 3.0×10^6 psi (2.1×10^4 MPa)
- Poisson's Ratio ~ 0.25
- F.G. ~ 0.71 psi/ft (16.2 kPa/m).
- Leakoff 0.000168 $\text{ft}/\sqrt{\text{min}}$ (0.0004 $\text{m}/\sqrt{s}$)

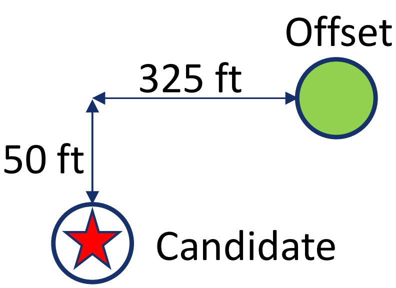
Rapid increase of injection rate can accelerate fracture height growth.

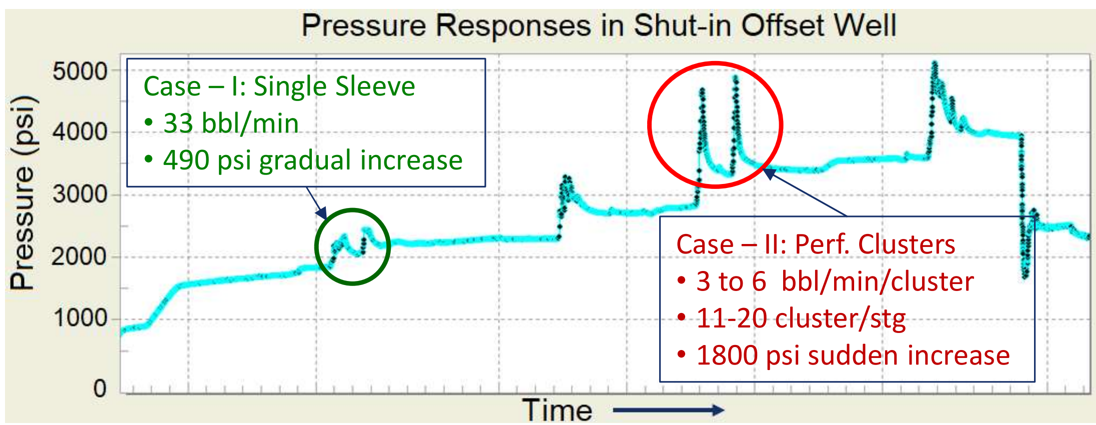
Corroboration of Model Predictions with Field Data



- Rapid h_f growth from higher injection rates appears to limit X_f as predicted.



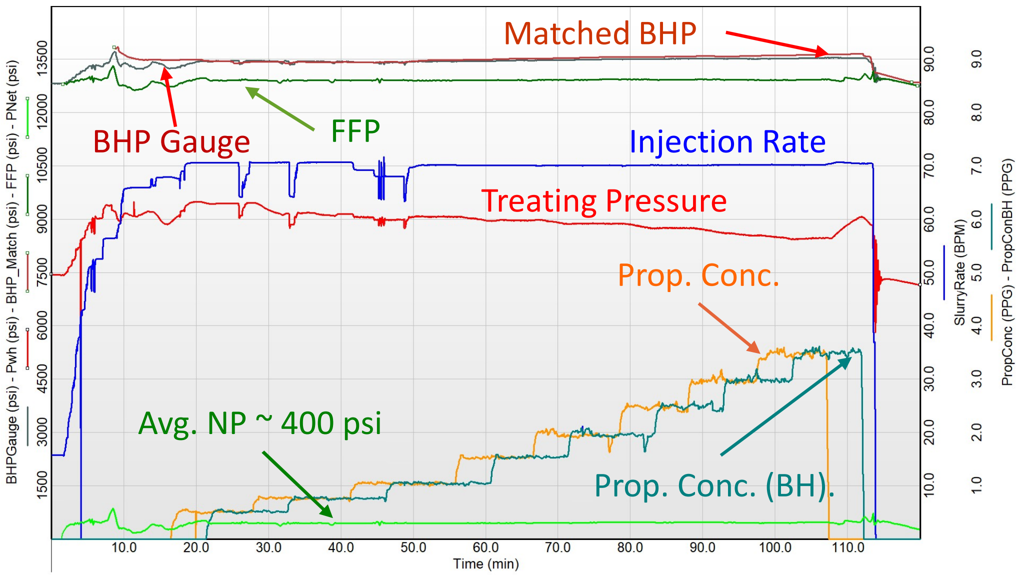




To wrap it up – Horizontal Well Case History

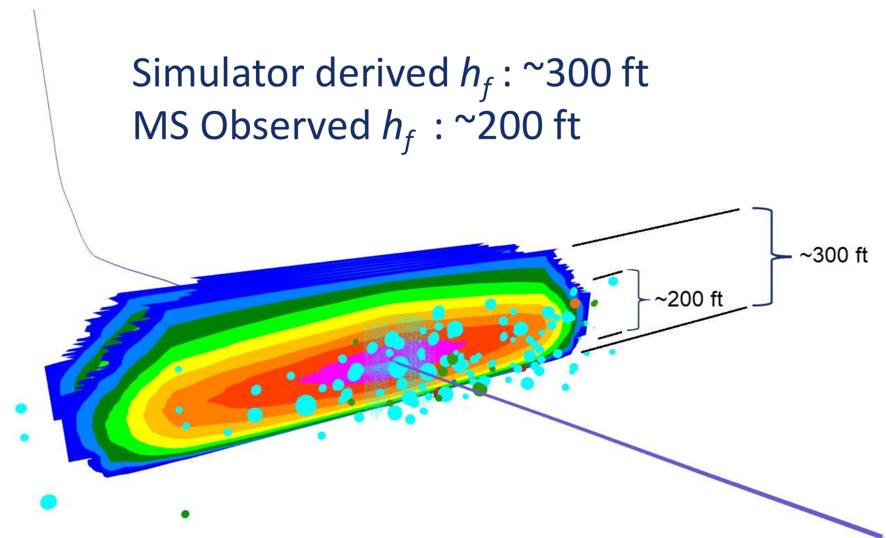
- Case History #5: 30 lbm/Mgal x-link, Shale Completion
  - Treatment pumped down 5½ in. casing at 70 bbl/min, 8 Perf Clusters, with Plug and Perf.
  - Formation Face Pressure - FFP (SPE 194351) *exceeds* the overburden during the job.
  - BHP and Microseismic measurements (survey) were carried out during the treatment.

History match of treatment data with simulator



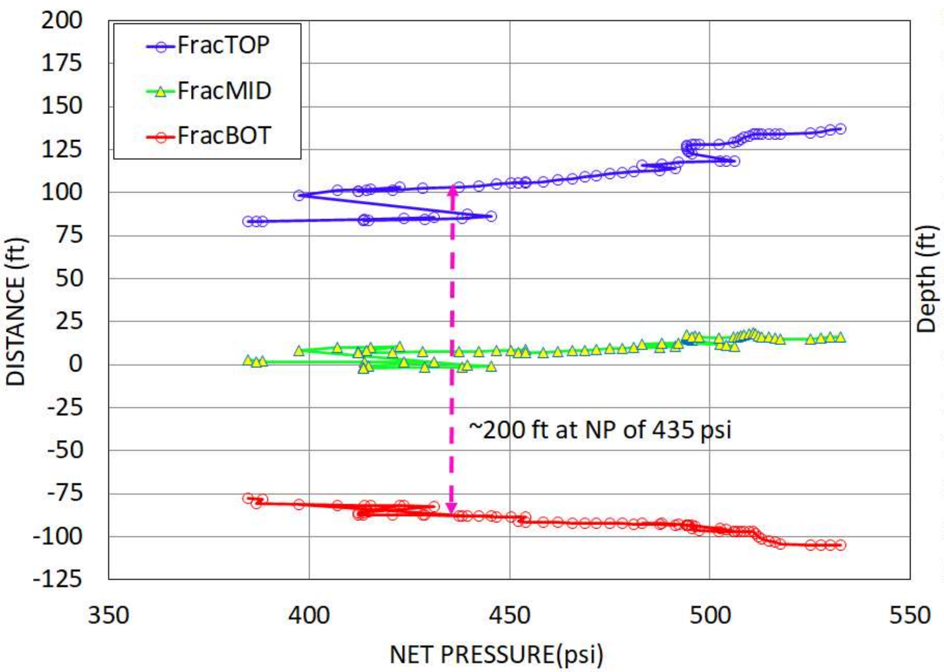
Simulator derived height > observed height

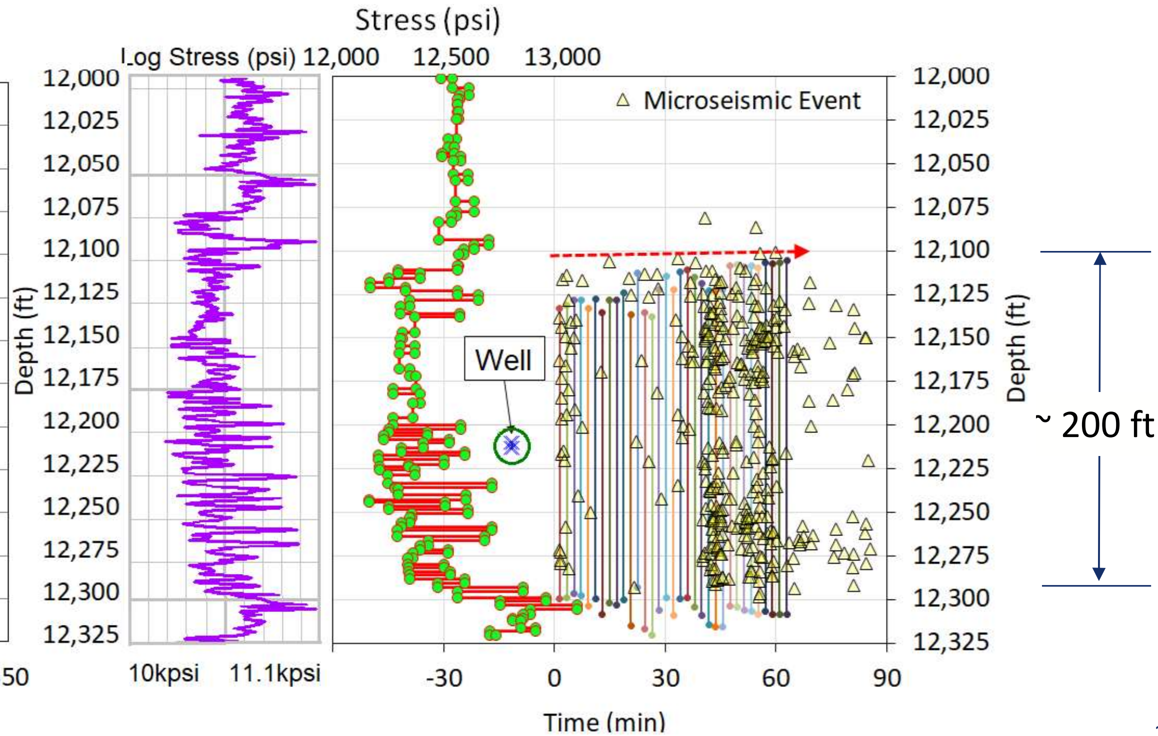
Simulator derived h_f : ~300 ft
MS Observed h_f : ~200 ft



Horizontal Well Case History…

- Case History #5: Contd..
  - Fracture location and h_f vs. NP plot generated using velocity based apparent K_{IC}.
  - With requisite NP achieved early, fracture growth is instantaneous as seen in MS data.





Summary and Conclusions

- Estimation of fracture height growth is important from both well planning and well performance perspectives.
- Semi-analytical multi-layered model can predict height growth with reasonable accuracy, but for some cases fluid-flow in the fracture cannot be ignored.
- The uncertainty of fracture toughness can be addressed by adopting dynamic velocity-based calculations.
- The fracture location and height versus net pressure mapping provides a reasonable estimate of potential fracture growth that can occur in a treatment.
- Field observations indicate that high initial injection rates result in rapid height-growth whereas low rate/viscosity combination can promote extension.
- Semi-analytical solutions such as presented here can be successfully applied to various reservoir and treatment types.

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