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PLT-Calibrated Permeability:

A Breakthrough in Carbonate Characterization

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Chevron Corporation

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Introduction

- Modeling fluid flow in carbonates a challenge.
  - Especially “excess perm” zones (vugs & fractures)
- Improved using Apparent Permeability derived from Production (PLT) Logs – “APERM”
- Distributes well-test permeability-thickness (KH) to reservoir layers
- Inherent match to fluid flow improves accuracy
- Better management of multi-layer reservoirs improves recovery

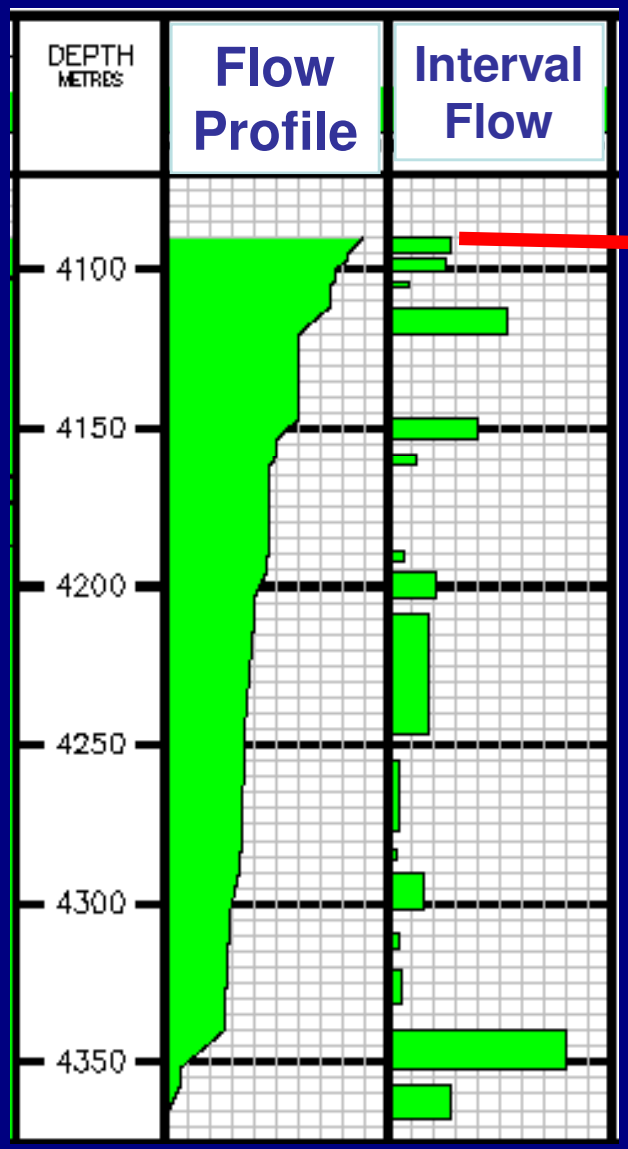
Outline

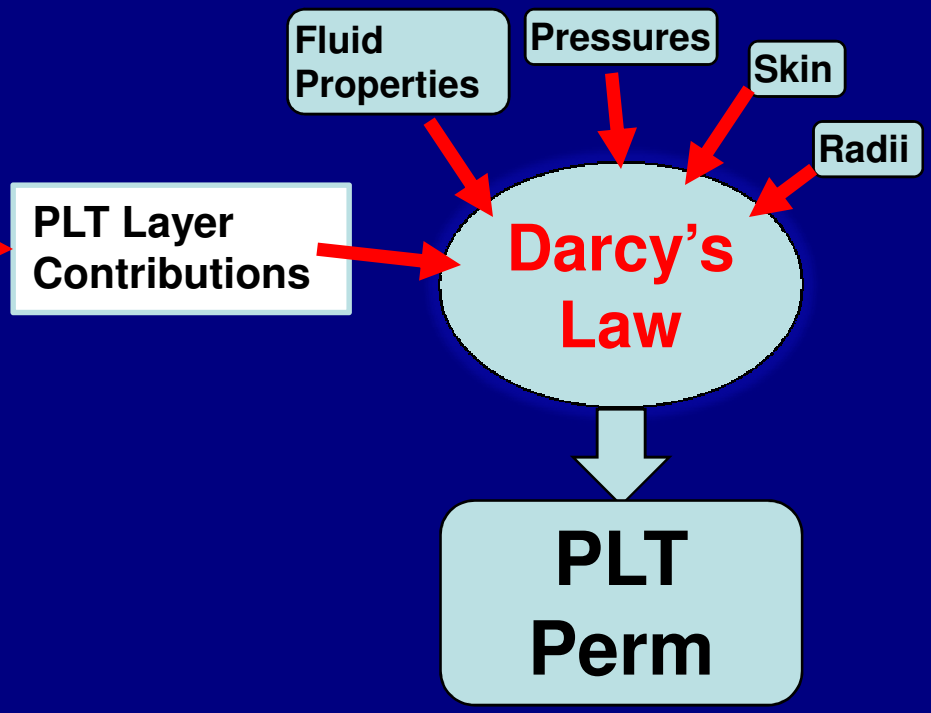
- Where technique can be used
- How it works
- Assumptions and Potential Uncertainties
- Use of Pulsed Neutron Acid Effect to distinguish damage vs. low perm
- Examples
- Validation of Process Improvement with Pulse Testing
- Lessons learned, Best Practices, and Challenges

Where Can APERM Technique Be Used?

- Any multi-layer reservoir, but most needed in Carbonates
- Best to acquire baseline flow profile on new completion.
  - Ideal if still single phase flow
  - Multiphase flow will complicate, but technique may still result in more realistic permeability
- Wells in mature reservoirs on artificial lift could be logged by injection profile

Calculation Procedure

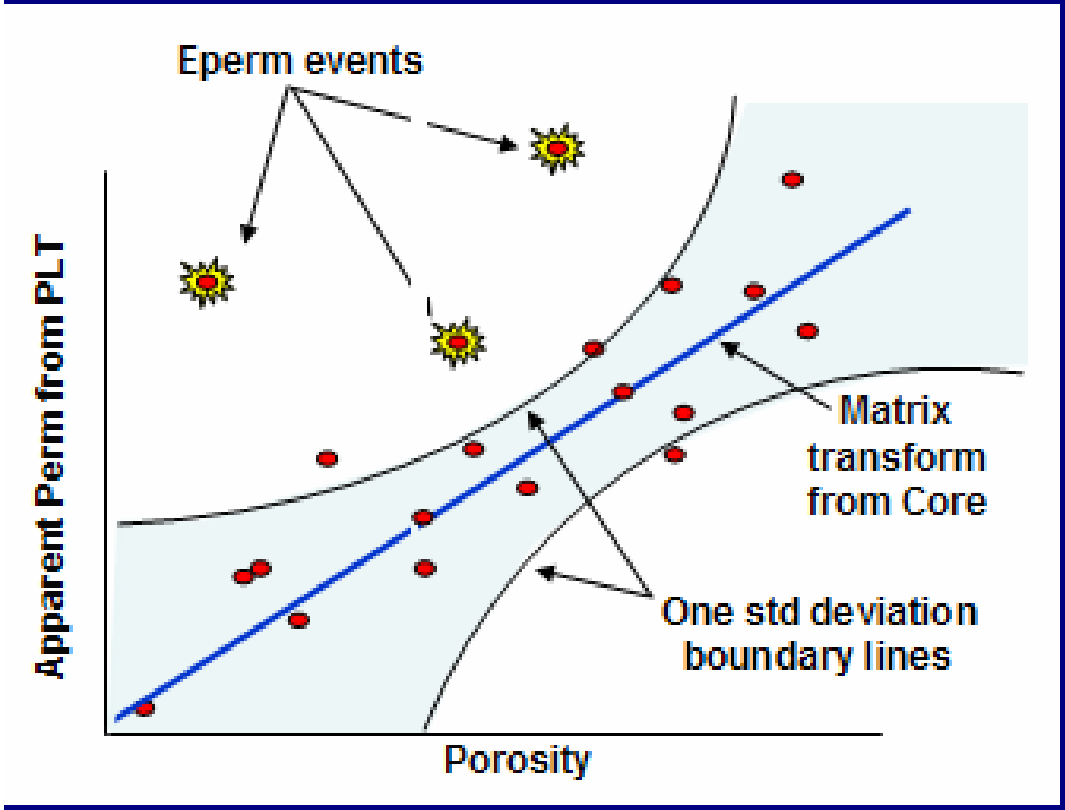




- Normalize to KH from welltest
- Use as reference to adjust transform perm.
  - Why? Preserve Wireline scale resolution in perm

Excess Permeability (Eperm)

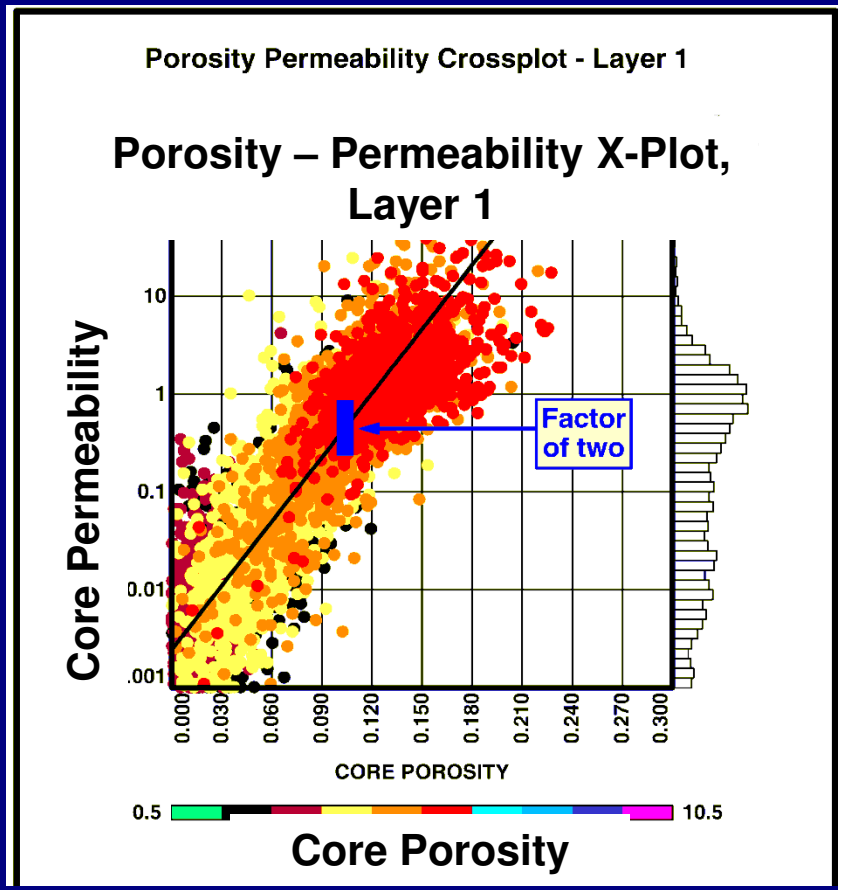
-Falls above matrix perm range.



- Due to fractures, vugs
  - Matrix perm transform will under-predict
- The most important to correctly characterize
- Technique quantifies Excess Perm zones

Impact of Potential Uncertainties

- Errors less than factor of 2 deemed not critical
- Fluid Properties Uncertainty insignificant
- Pressures: Within 10% if SIP used- Minor impact
- Drainage/wellbore radius: Minor impact
- Flow Rate: Within 10%, minor impact
- **Skin: The most significant assumption**



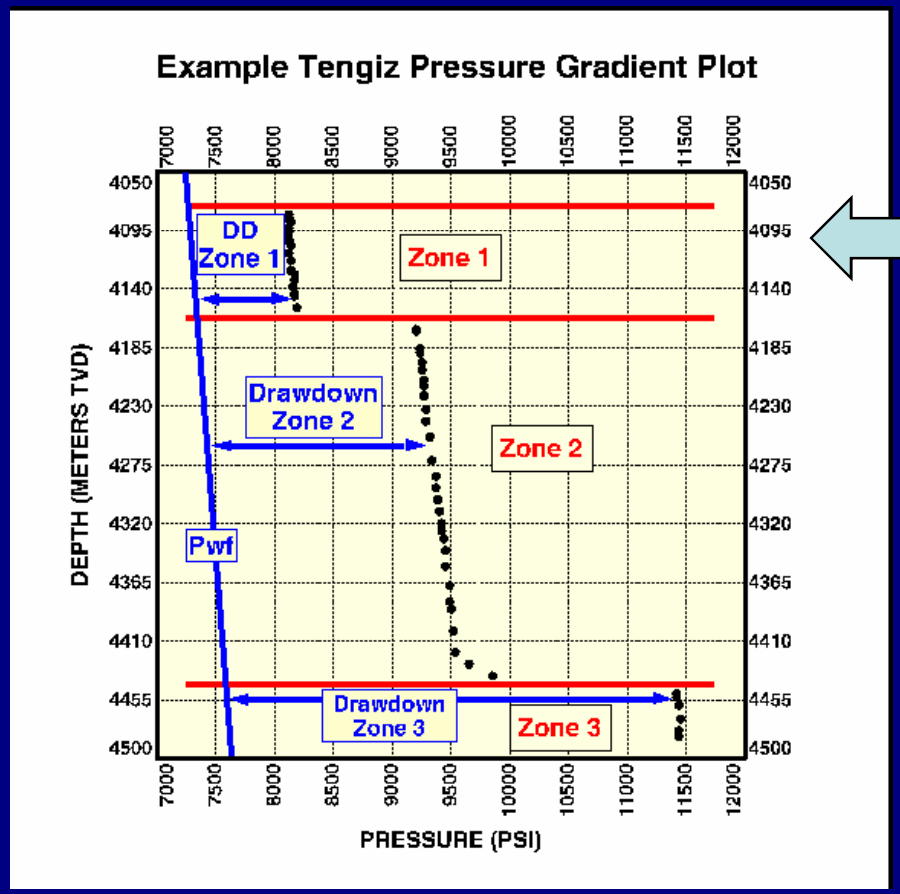
A factor of two variation in perm is within the noise.

Pressures

- Flowing pressure measured during PLT.
  - Not fatal if unable to achieve stability
- Layer Pressure: Simple if reservoir on single gradient.
- Differential Depletion:
  - Different pressures for different layers
  - Measure layer pressure using multi-rate PLT and Selective Inflow Performance (SIP) analysis

Differential Depletion

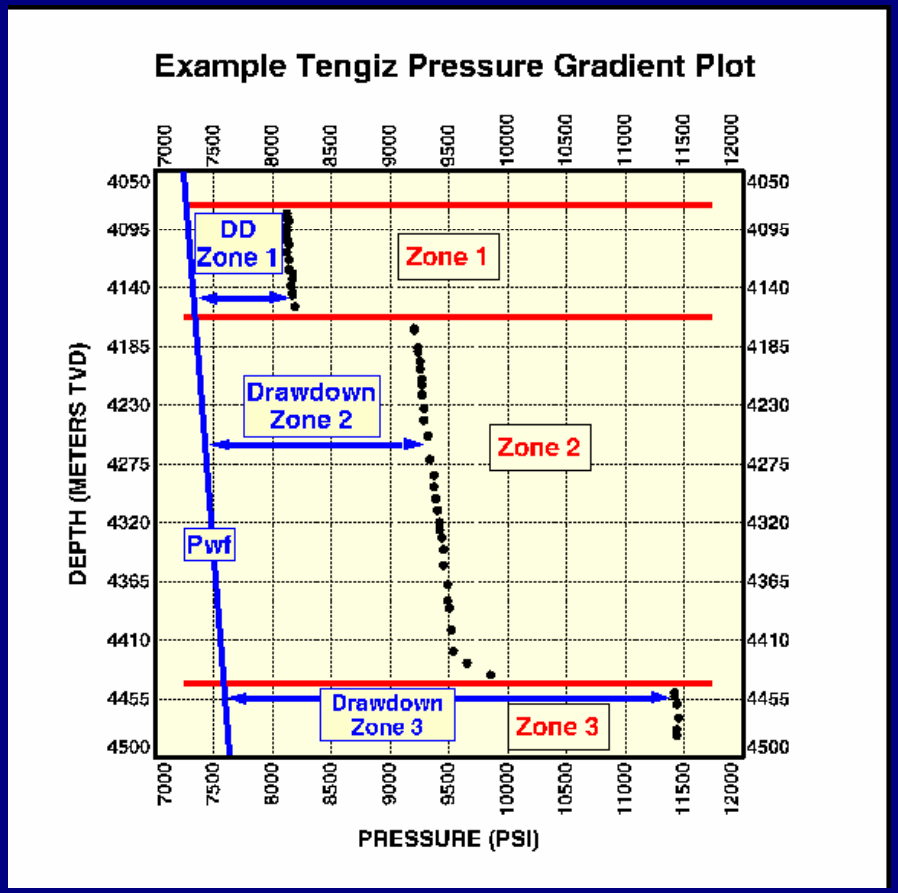
- Some zones deplete more rapidly due to higher perm or more extensive production

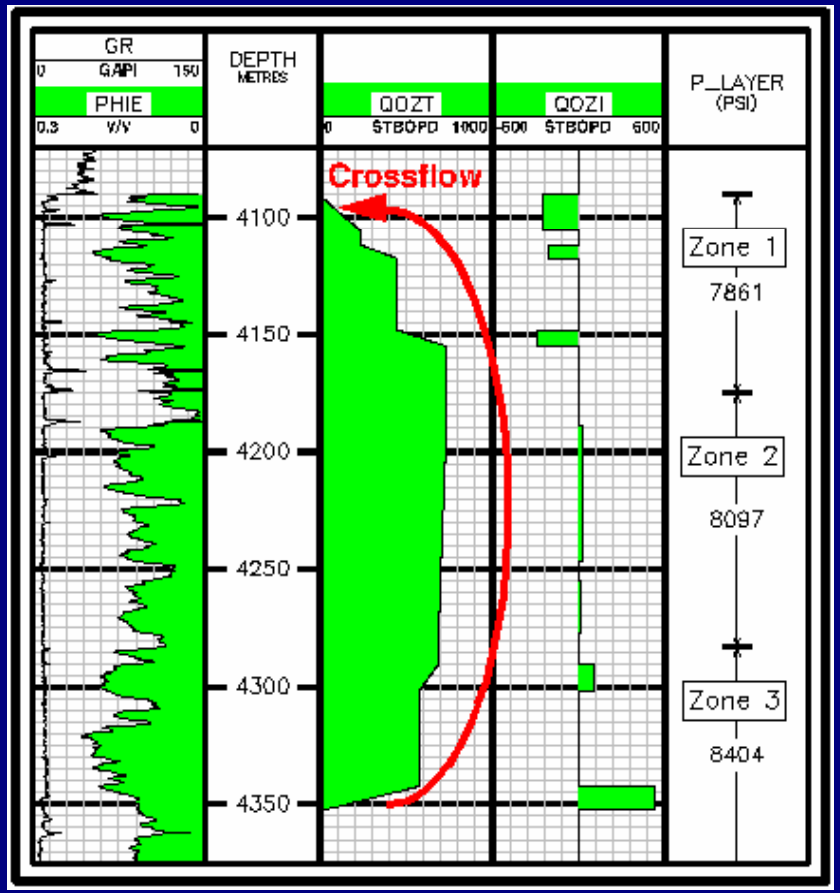


Depleted Zone

Differential Depletion

- Some zones deplete more rapidly due to higher perm or more extensive production
- Pressure differences = significant crossflow during shut-in
- If not accounted for, can have large errors in calculated perm.

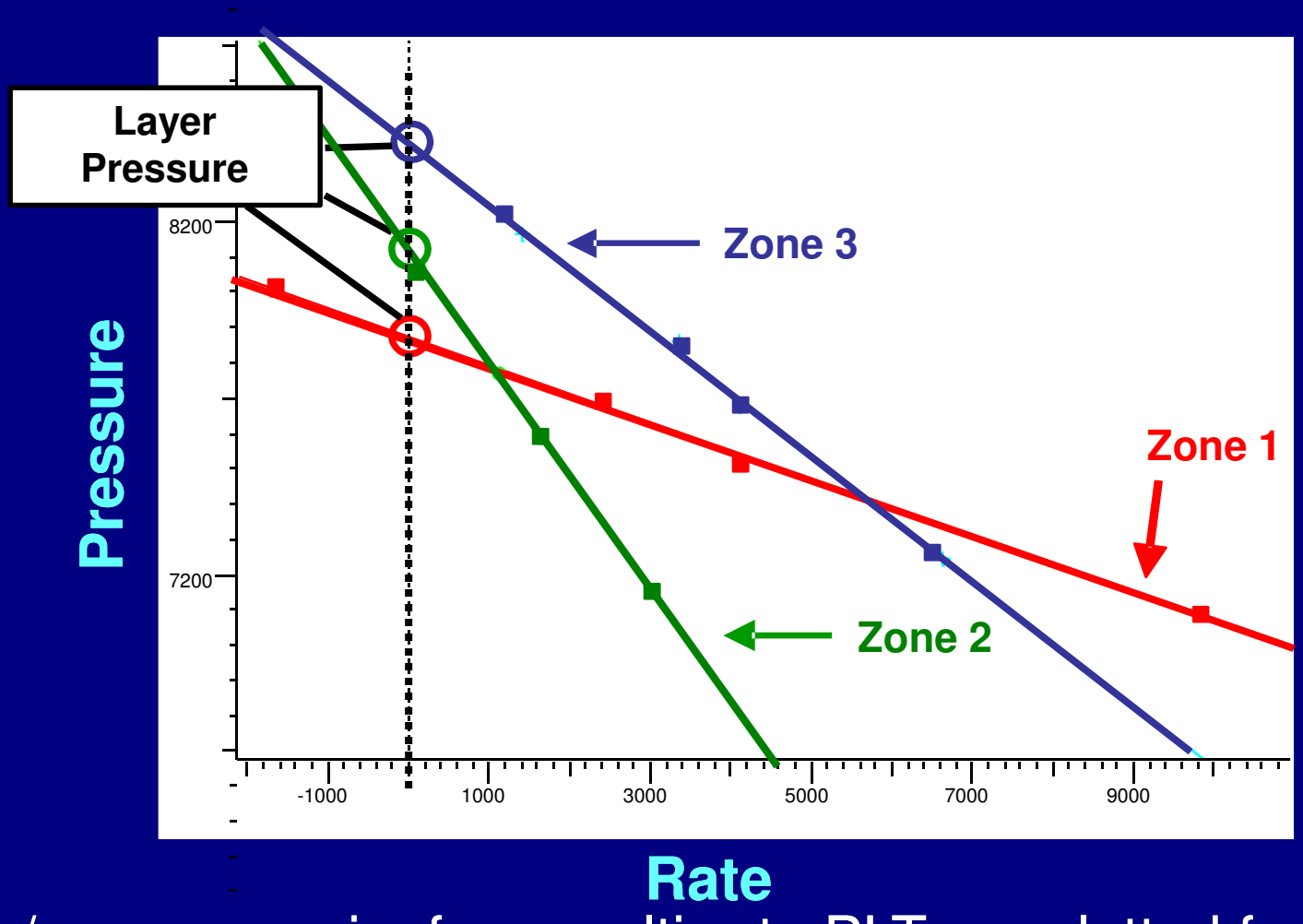




SIP Technique

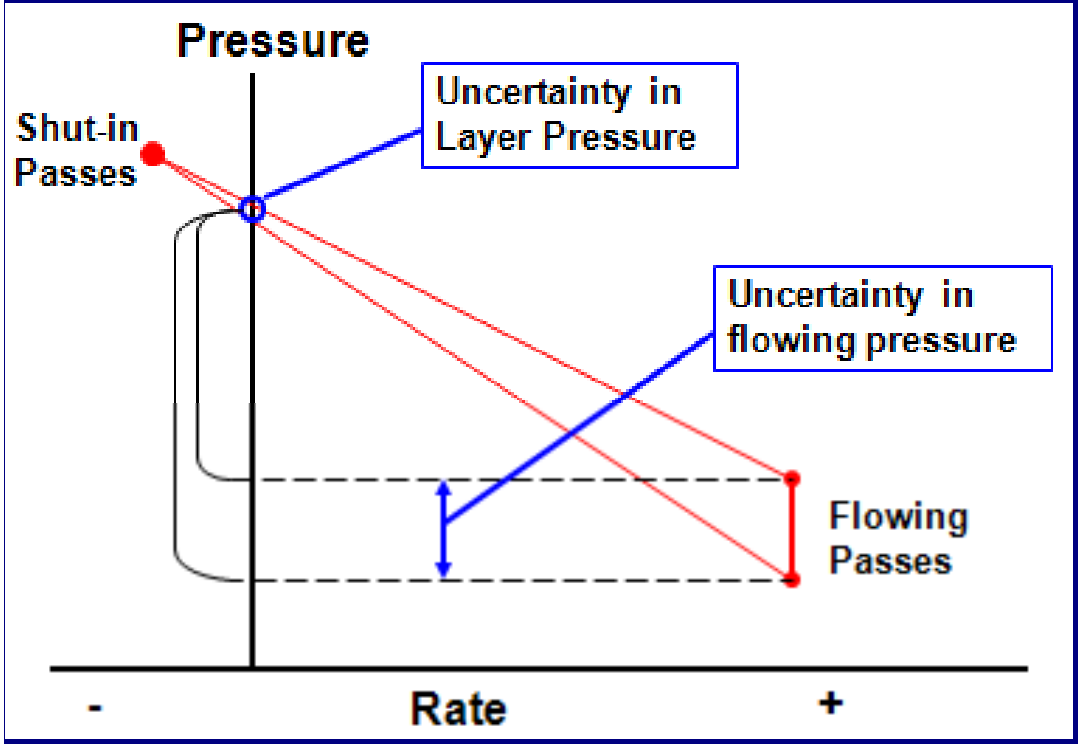
- Used to measure shut-in layer pressure.
- No layer need ever be static.
- Extrapolate to static layer pressure using Inflow Performance Relationship (IPR).
- Above bubble point, the IPR is a straight line.
  - Two points adequate to define line
- If flow below bubble point, IPR is curved, need 3-4 rates.

SIP Plot of Zone Rates & Pressures



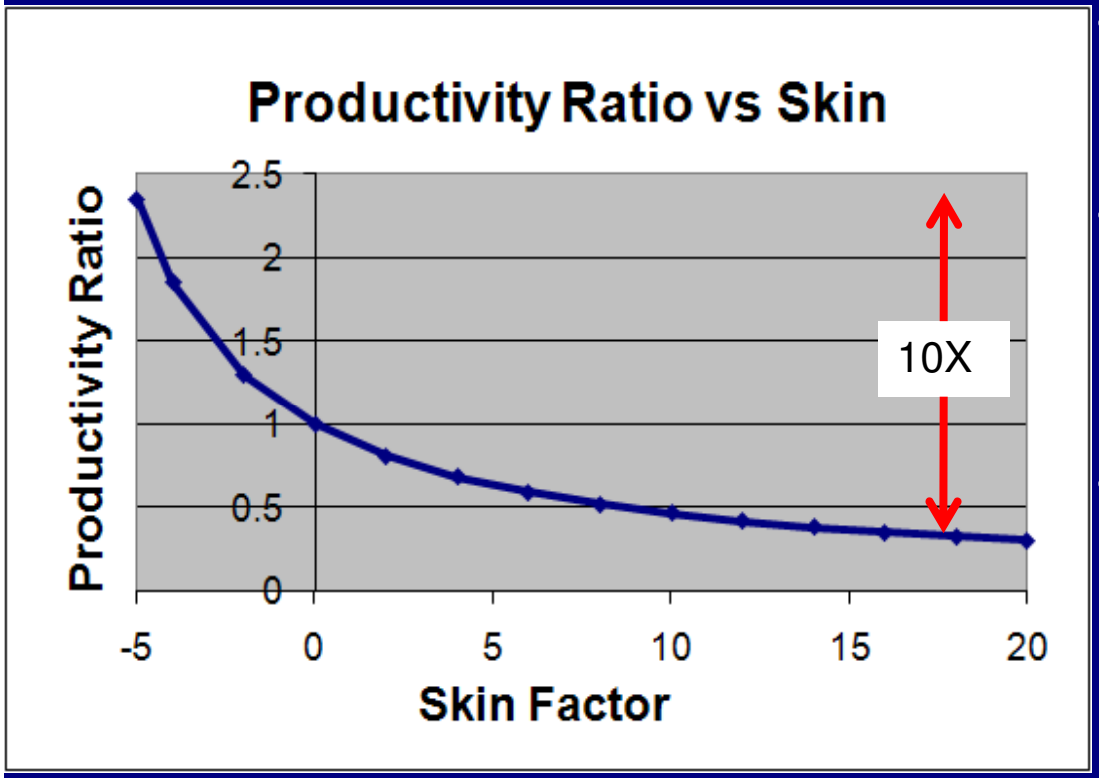
Rate/pressure pairs from multi-rate PLT are plotted for each zone. That pressure for which rate = 0 is the layer pressure

Layer Pressure Uncertainty



- Long shut-in time prior to PLT reduces uncertainty because initial SI passes are at stable pressure
- Inability to achieve stable flowing pressure in tight wells has less impact

Skin Factor



- Skin factor assumption is most important
- Normal range = 10X difference in flow rate, thence calculated perm
- If flow >> predicted, perm must be >> predicted
  - Cannot greatly over-stimulate

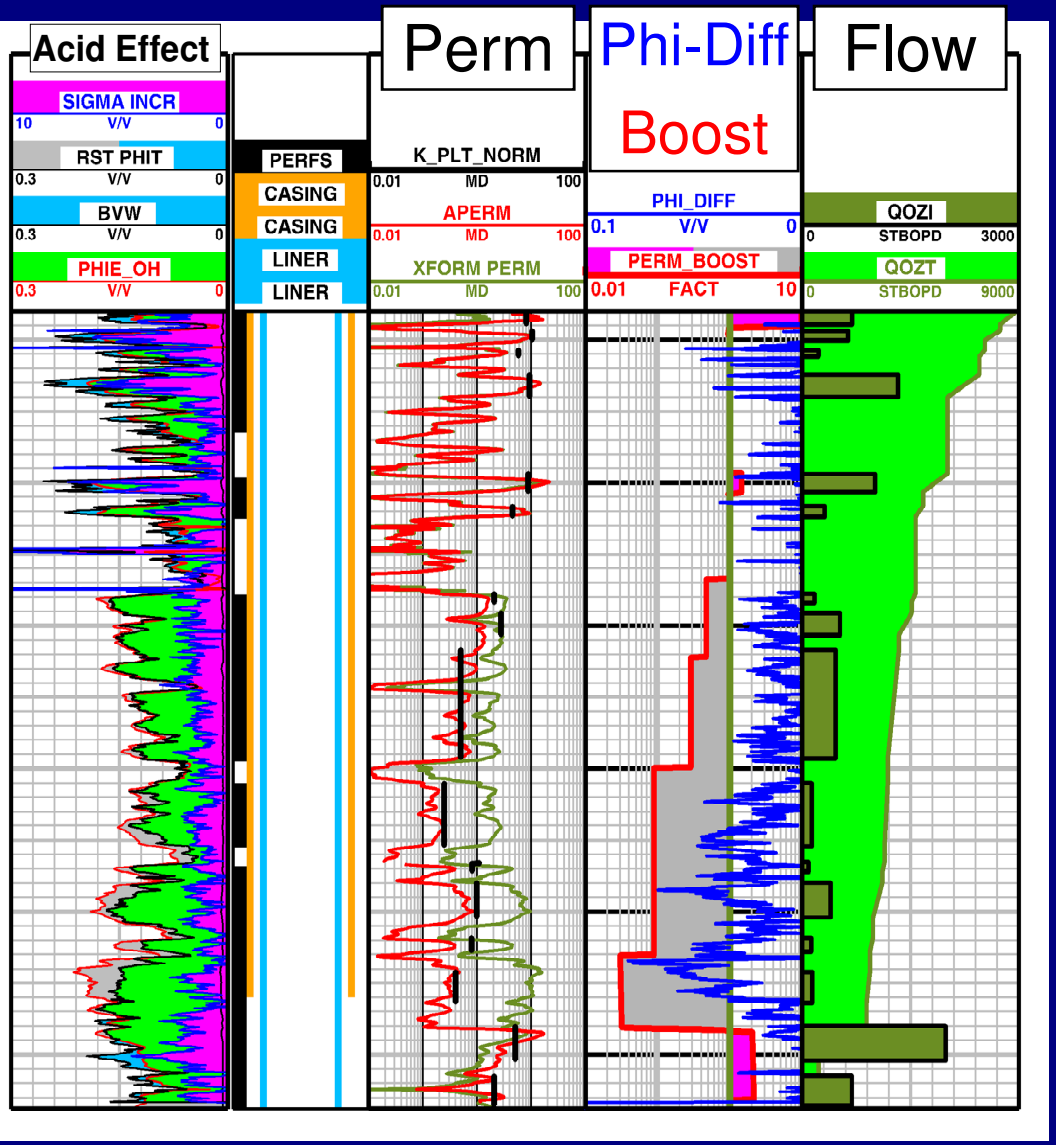
Skin Assumptions

- First pass: Use Skin (S') from pressure transient
  - OK if all zones well stimulated
- High Uncertainty When:
  - Well not stimulated
  - Large amounts of lost circulation material (LCM) used during drilling
  - Non-diverted stimulation
  - EPERM zone takes all acid, leaving remaining pay unstimulated

Acid Effect on Pulsed Neutron (PNC) Logs

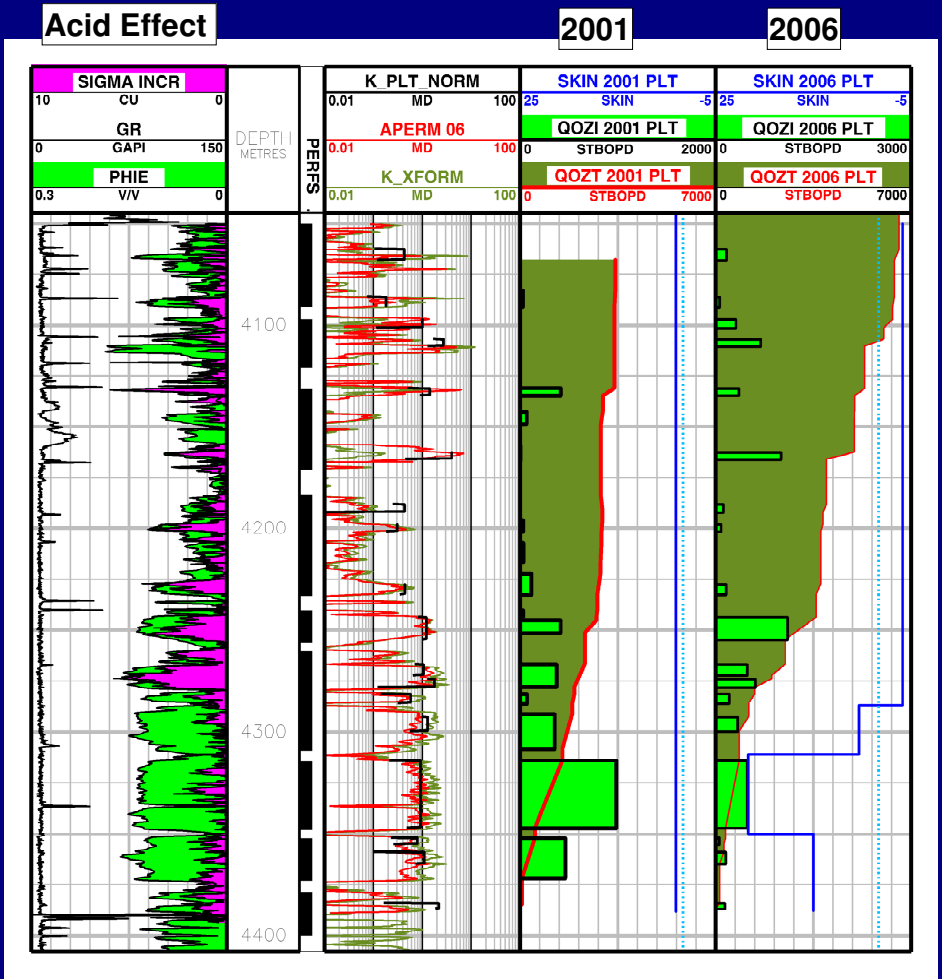
- Acid distribution is key uncertainty on many wells
- Assess by running PNC logs to measure acid effect.
- Chlorine from spent acid imbibes into connate water, increasing sigma (Σ).
  - If Sw is irreducible, effect is permanent
- Compare post-stim Σ with synthetic pre-stim Σ
  - Difference (acid effect) shaded in magenta in subsequent graphics
- If acid effect observed, and no potential damage mechanisms since stim, we assume S'= -4 (or pressure transient S')

Example of Reduced Permeability



- Flow from bottom half of zone much lower than predicted.
  - Damage? Low Perm?
- Acid effect key info.
- PNC porosity lower than old open hole neutron
- Conclusion: Perm originally too high due to bad neutron log
  - Perm reduced with confidence

Example of Poor Stimulation



- 2001 PLT lower zone flows
- 2006 PLT much less
- 2002 bullhead acid job due to scale
- Conducted PNC to detect acid
- Acid went out first good pay and not diverted below.
  - Damage not removed in lower zone

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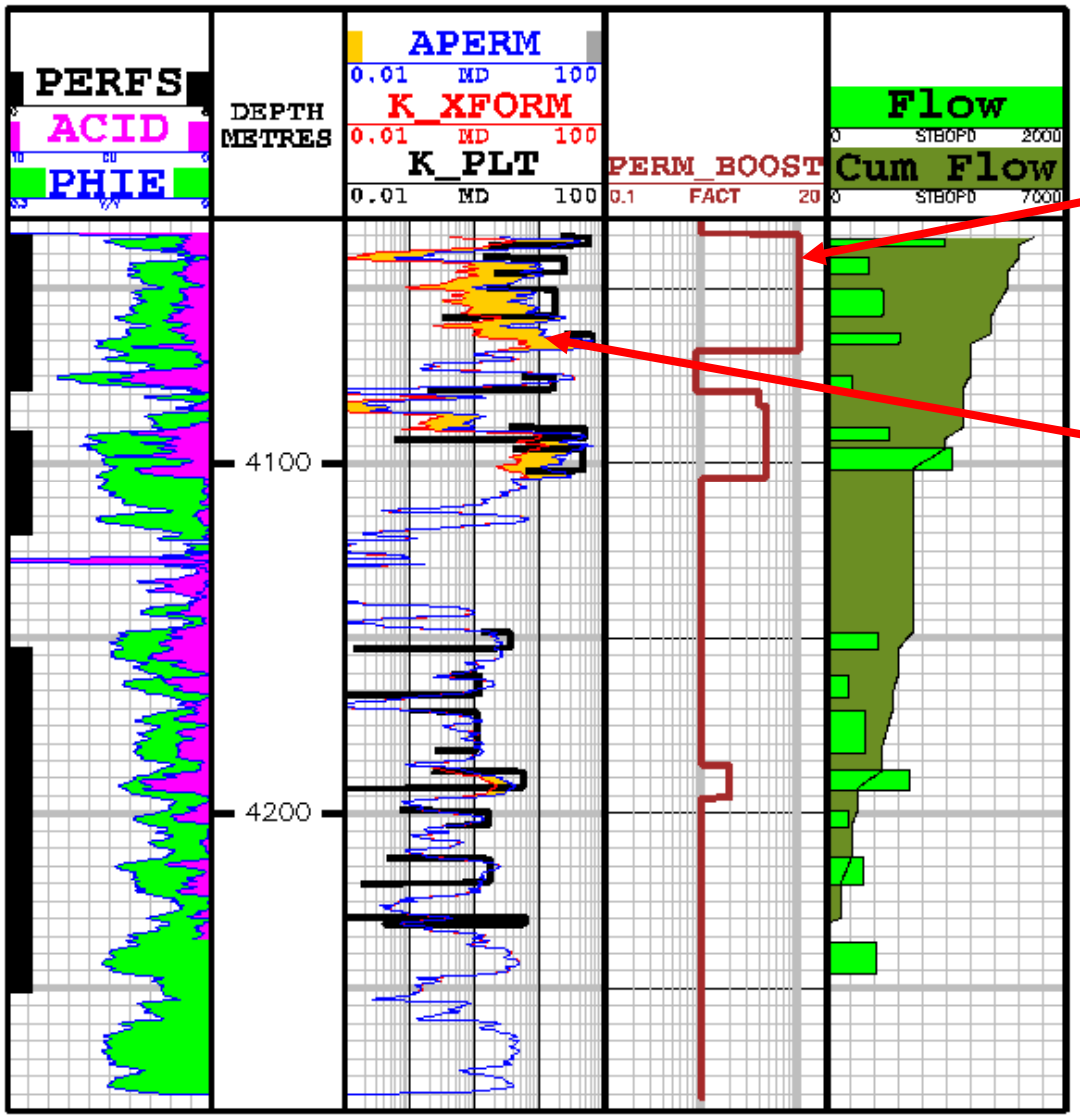
Example of Excess Perm

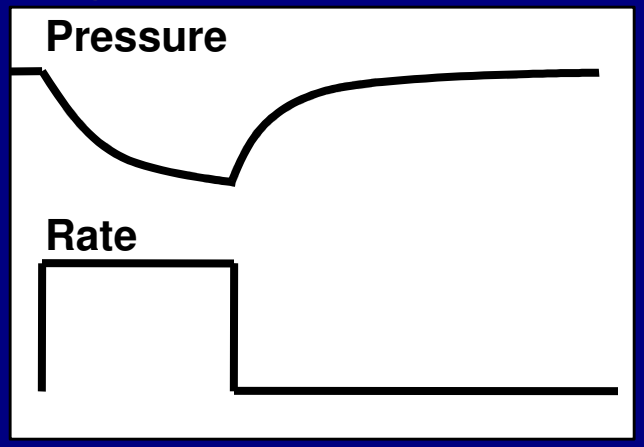


5-10X “Perm Boost” needed to explain high production rate from upper zone

Excess Perm shaded

Pressure Transient Tests Used

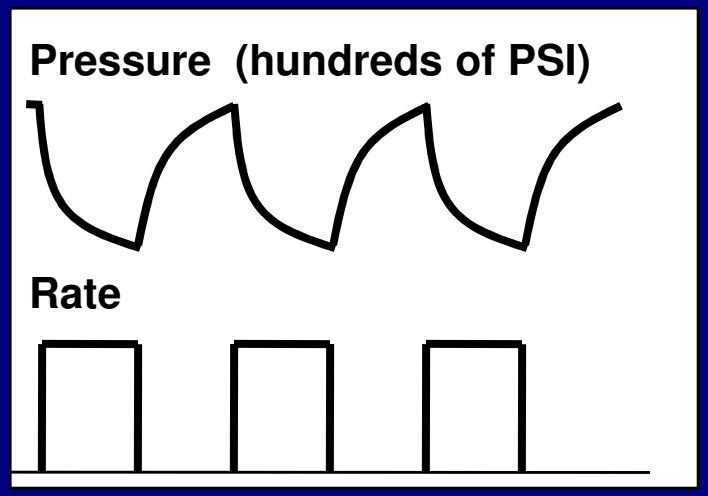
Single Well Pressure Buildup



Pressure
Permeability
Skin
Boundaries

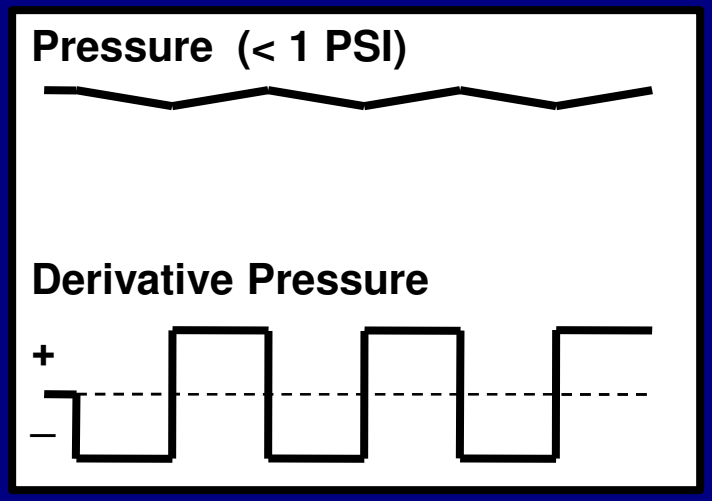
Inter-well Pulse Tests

Active Well → Observation Well

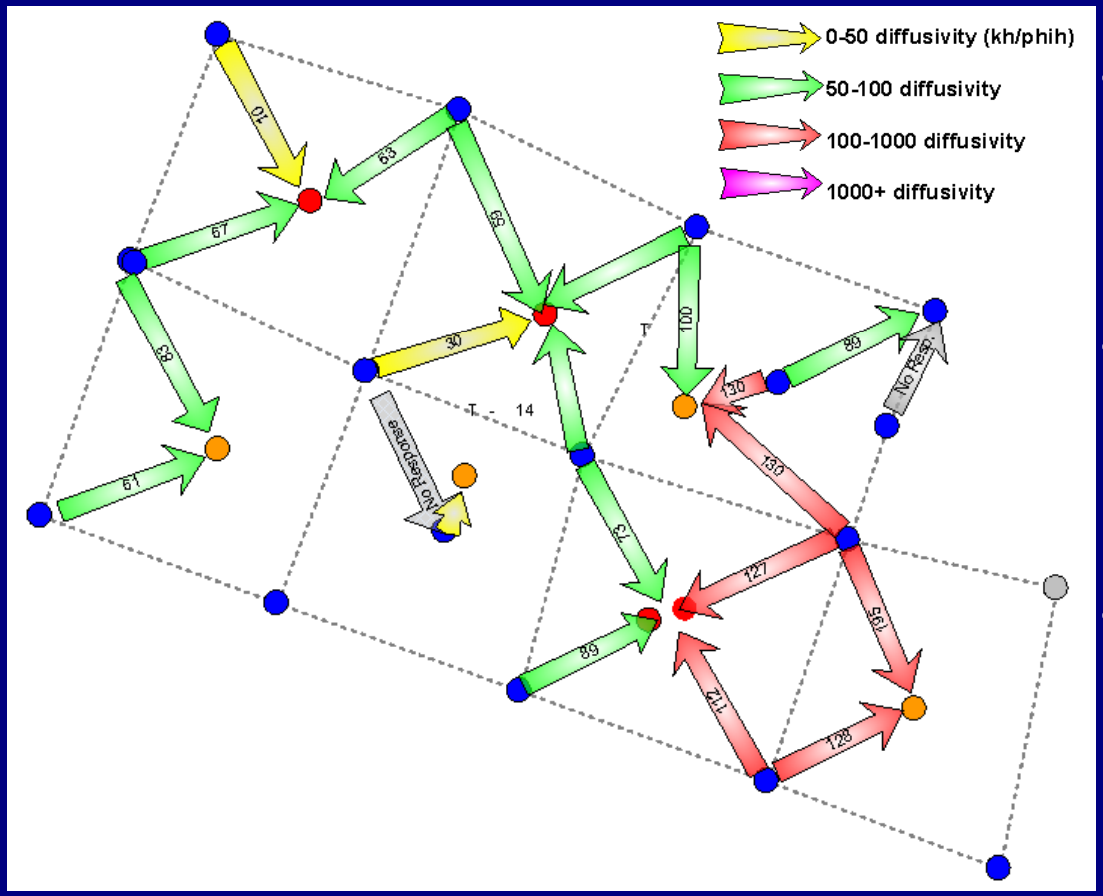


Inter-well connected pore volume (phi-h)

Inter-well connected permeability (kh)

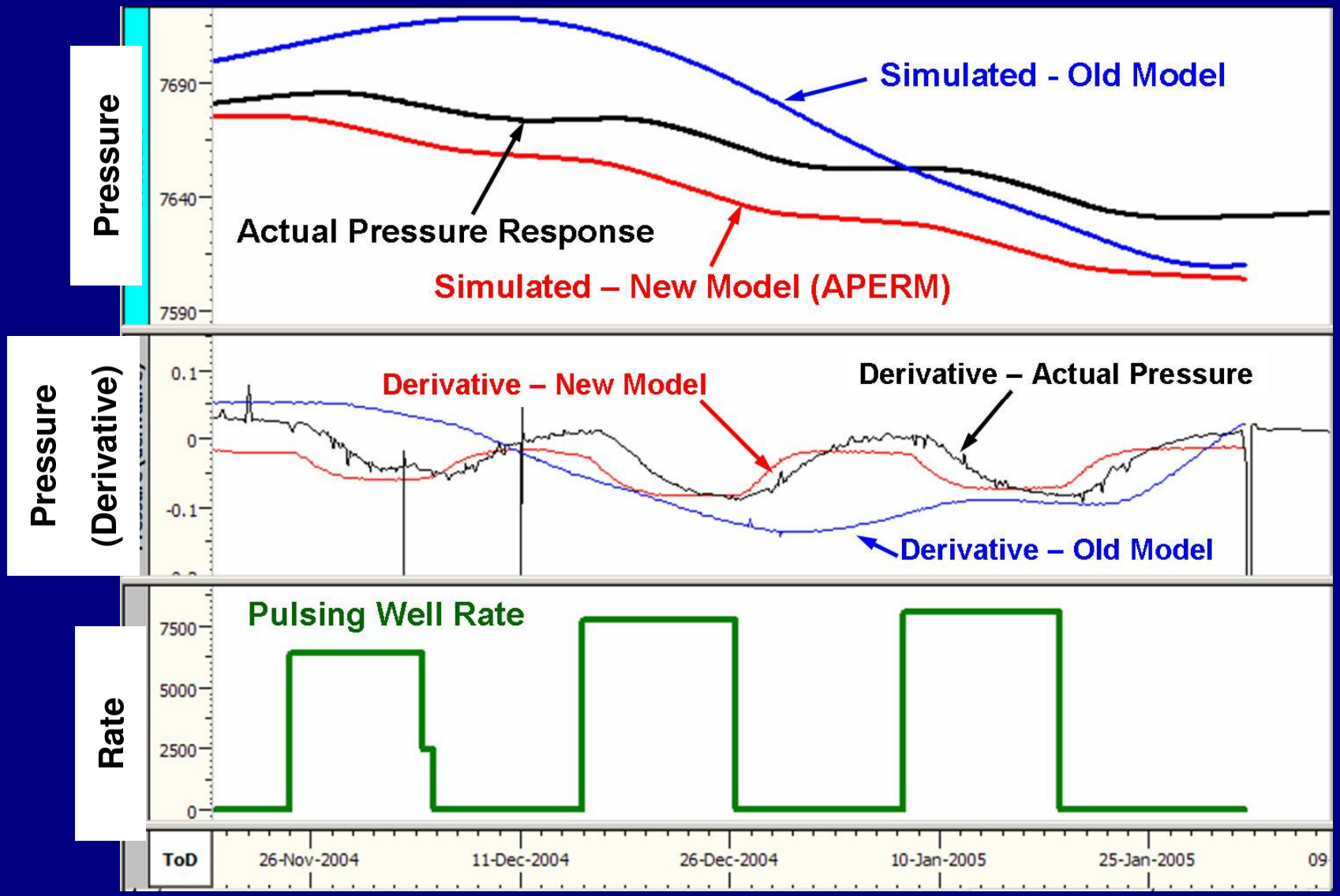


Validation of Model Improvement Using Pulse Tests

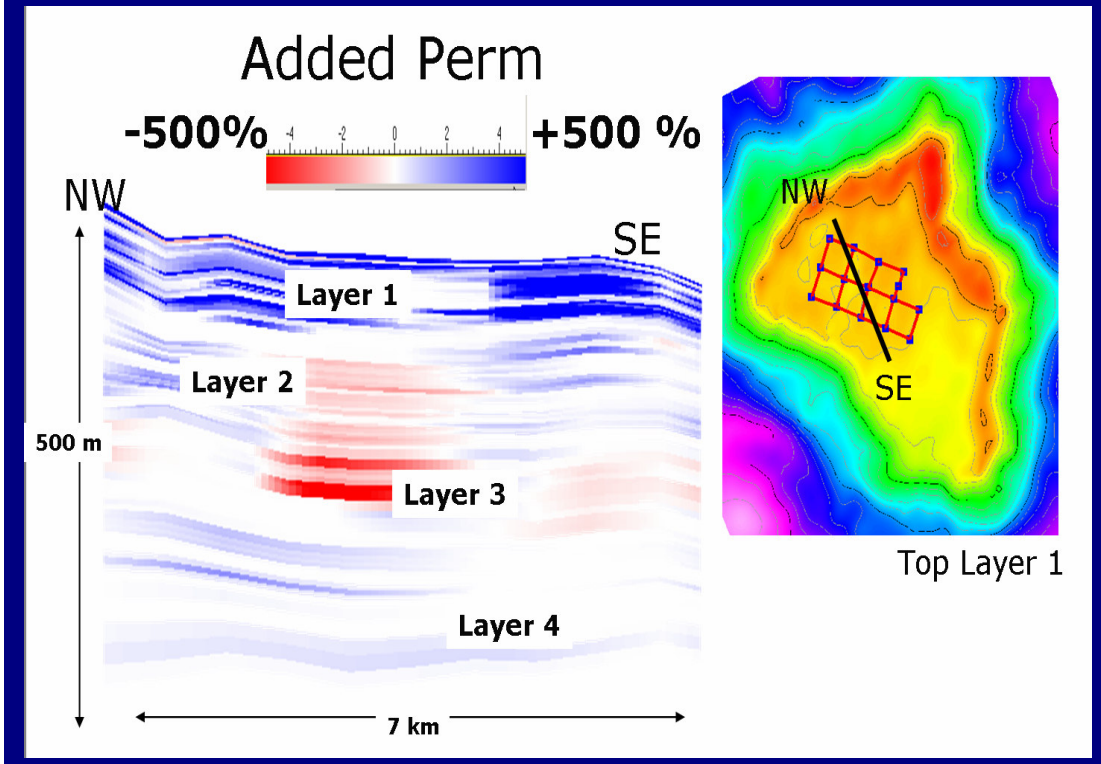


- Several inter-well pulse tests done to assess connectivity
- Poor pressure match with old transform perm based model
- New APERM model match much better

Pulse Test Validation



Incorporating APERM into Geologic Model



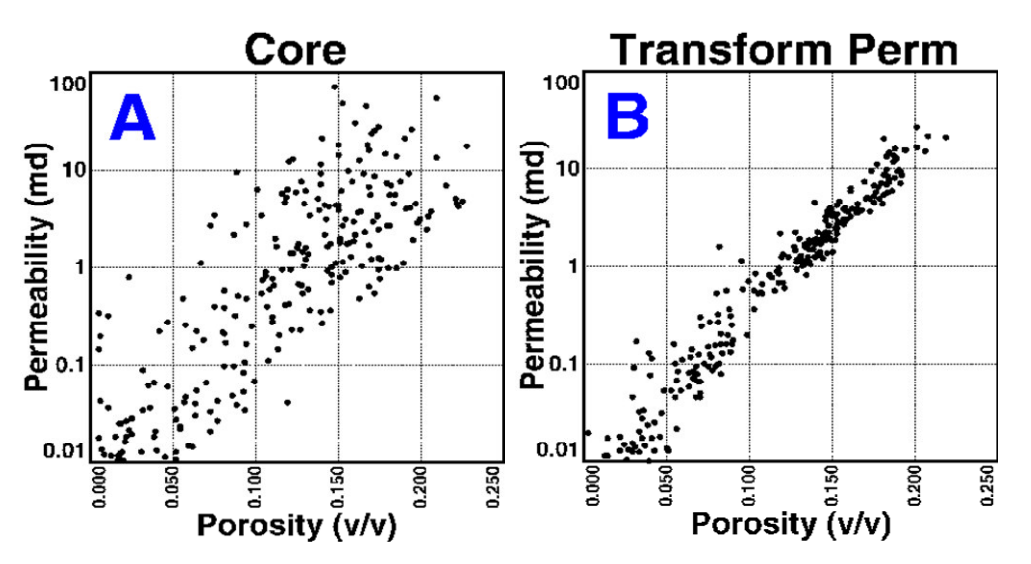
Tengiz Case Study

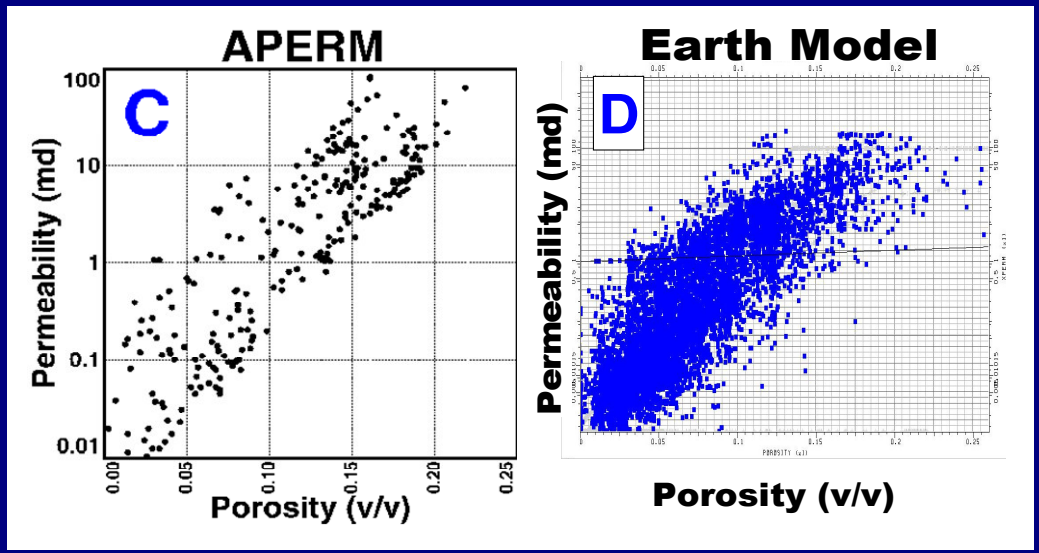
- PLT on 80% of wells
- Wells with good quality APERM used to populate geologic model
- Significant changes to permeability field were made

Spatial Mapping of “Perm Boost”

- Distribution of Perm Boost studied
- Trends highlighted previously unrecognized rock types
- APERM used as “pseudo-core” to refine perm transform
- Improve static model where PLT not possible

Restoration of Heterogeneity





- Perm transforms reduce heterogeneity
- Models based on transform perm tend to under-predict heterogeneity.
  - Breakthrough occurs earlier than predicted
- APERM restores heterogeneity to model

Lessons Learned & Remaining Challenges

- **Lessons Learned:**
  - Need stimulation to ensure profile reflects reservoir
  - PLT profiles critical to manage multilayer reservoirs
- **Remaining Challenges:**
  - Assumptions on skin for damage vs. low perm
  - High perm zones can dominate, obscuring lesser zones
  - Seeking optimum method of inter-well property distribution

Conclusions

- Method is robust workflow for incorporating PLT and Pressure Transient data into earth model
- Method is an improvement over static log based transform permeability
- Overcomes difficulties in predicting perm from well logs, particularly in Carbonates
- Effective at identifying and characterizing excess perm layers.
- Restores natural perm heterogeneity

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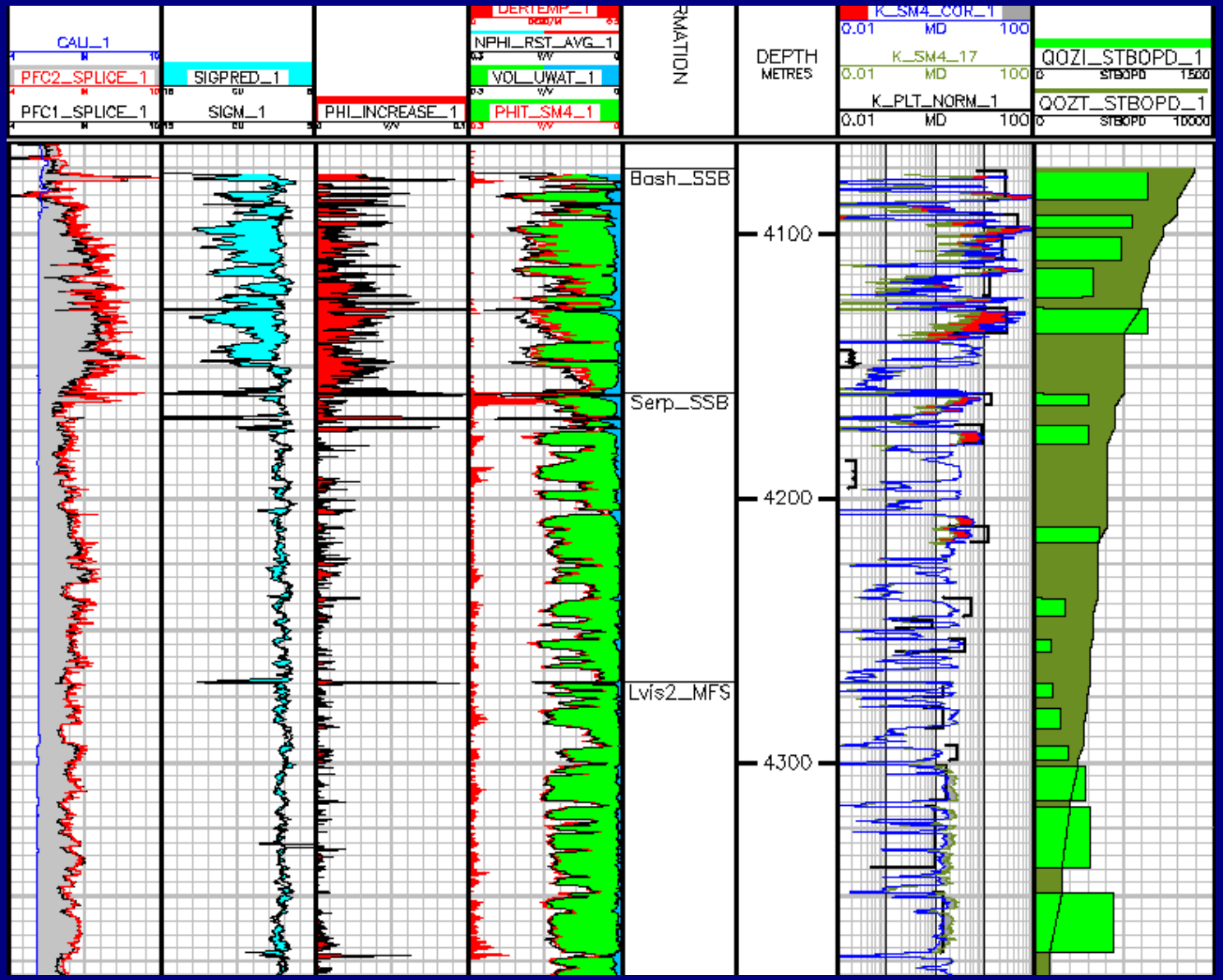
Example Stimulation in Crossflow



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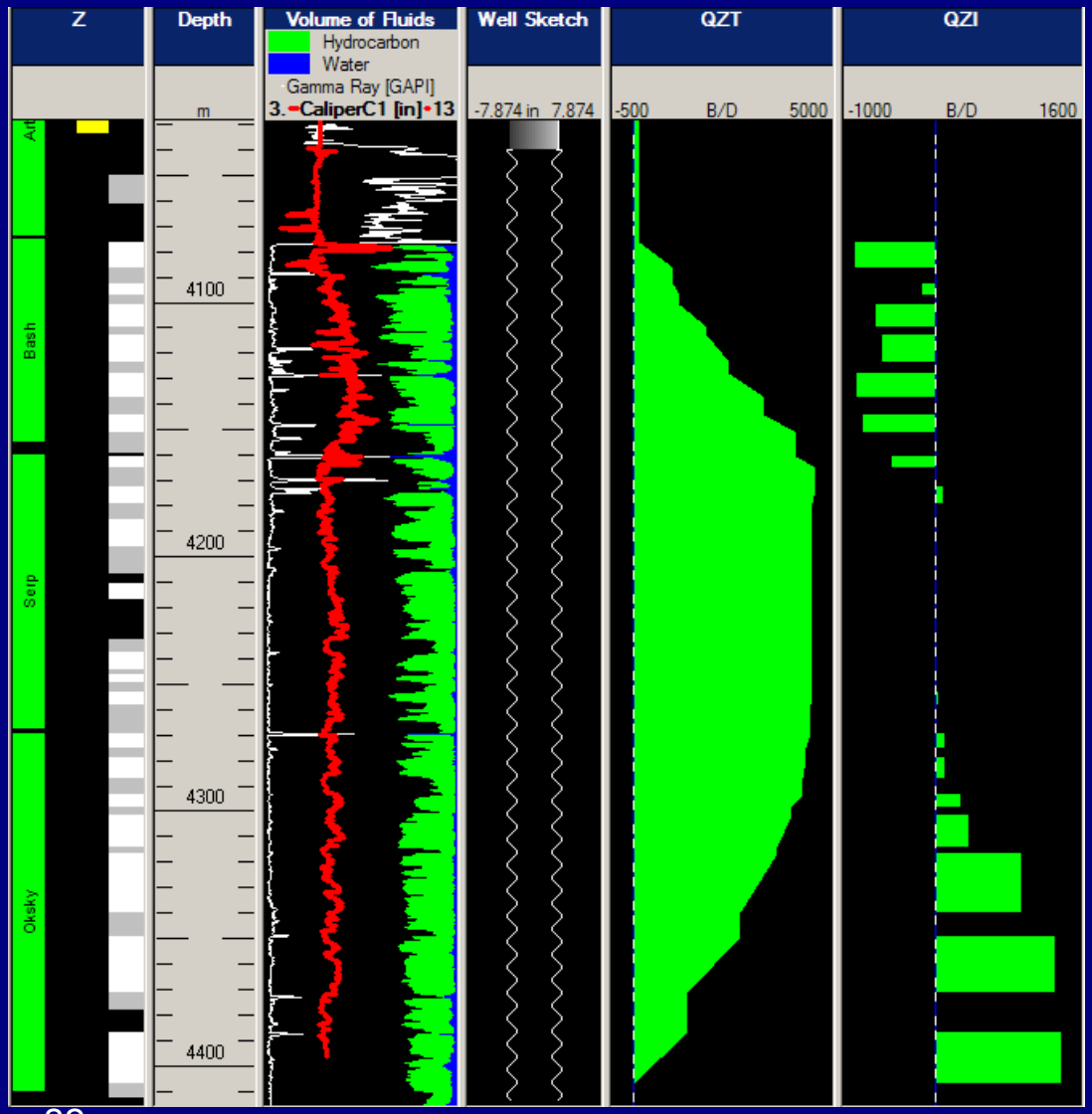
What caused this?

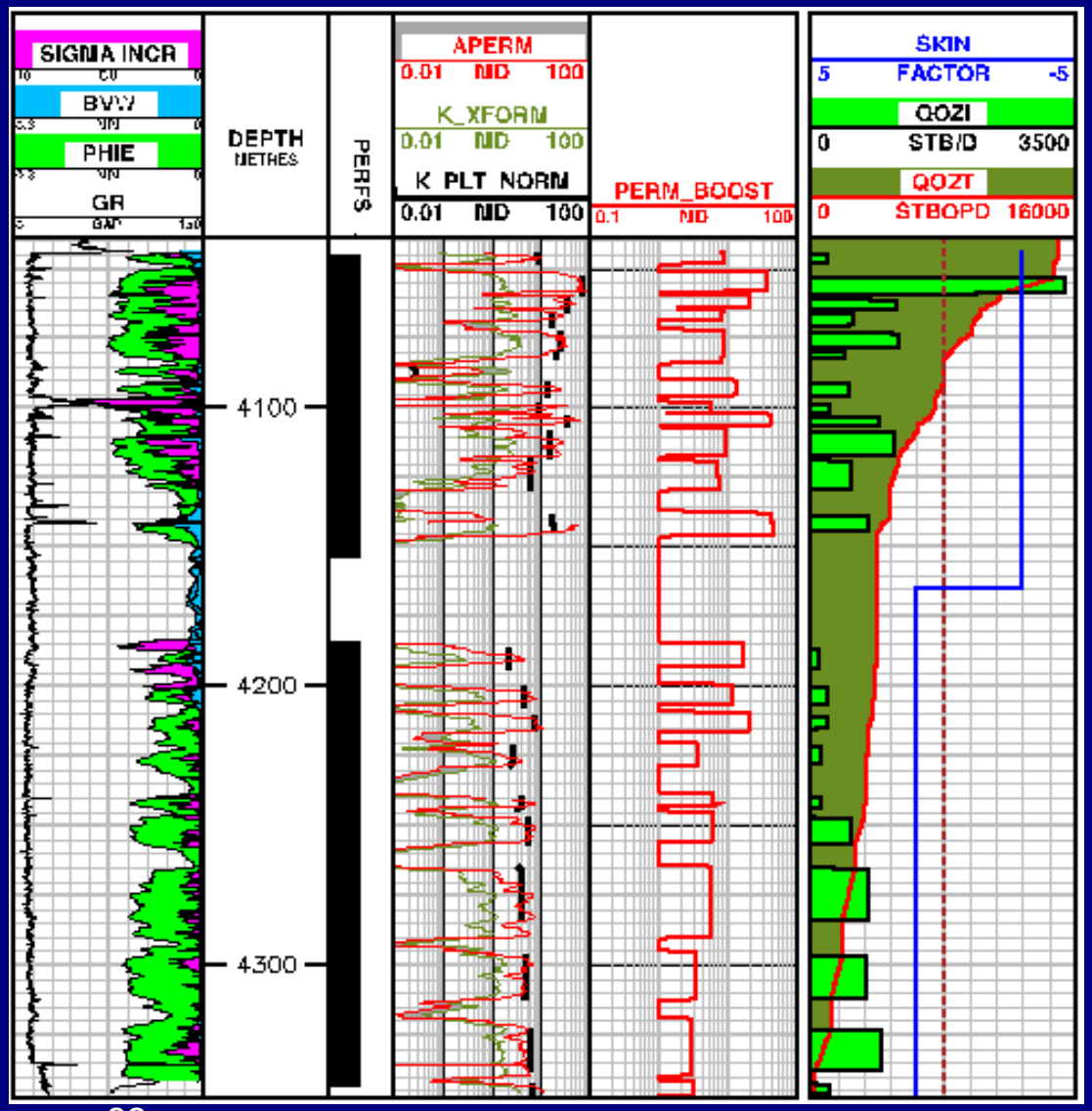


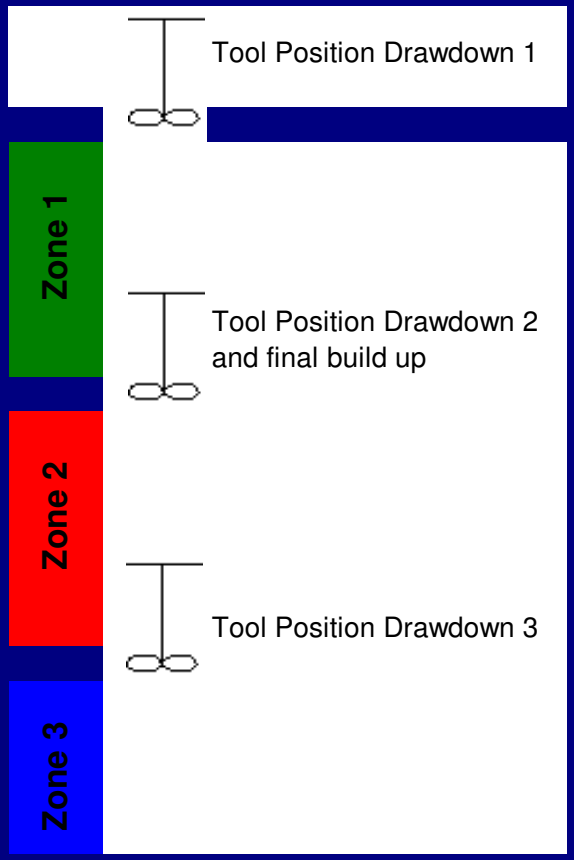
SIP Layer Pressures

7500 PSI

8500 PSI

Multi-Layer PTA Agrees with Acid Effect





MLT Analysis result: -3 skin in upper, +1 in lower. Agreement with acid effect.