Best Practices in Interpretation of DFIT Tests for Shmin, Permeability, and Pore Pressure

Mark McClure

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www.resfrac.com

mark@resfrac.com

Summary

This presentation summarizes the result of work that I've done on DFIT since 2014, first in collaboration with Mukul Sharma and Hojung Jung at UT (and Dave Cramer at ConocoPhillips), and later as part of the 2018 DFIT consortium.

The Fracture-Compliance Method for Picking Closure Pressure From Diagnostic Fracture-Injection Tests

Mark W. McClure and **Hojung Jung,** University of Texas at Austin; **Dave D. Cramer,** ConocoPhillips; and **Mukul M. Sharma,** University of Texas at Austin

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A Collaborative Study on DFIT Interpretation: Integrating Modeling, Field Data, and Analytical Techniques

Mark McClure[*1], Vidya Bammidi[2], Craig Cipolla[3], Dave Cramer[4], Lucas Martin[5], Alexei A Savitski[6], Dave Sobernheim[2], and Kate Voller[7]; 1. ResFrac Corporation, 2. Keane Group, 3. Hess Corporation, 4. ConocoPhillips Company, 5. Formerly with Apache Corporation, now with Marathon Oil Corporation, 6. Shell International Exploration and Production Inc., 7. Range Resources Corporation

Re-examining interpretations of non-ideal behavior during diagnostic fracture injection tests

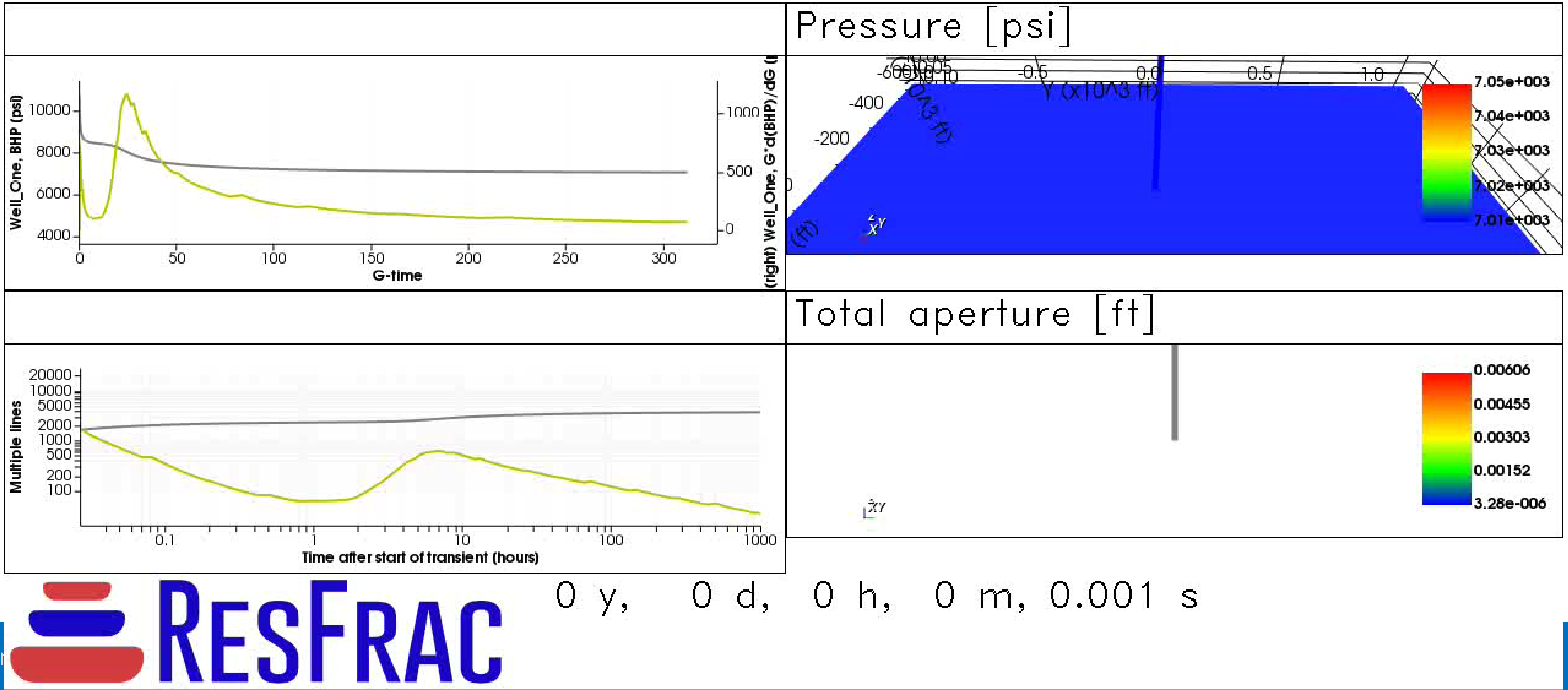
CrossMark

Hojung Jung[a,*], Mukul M. Sharma[a], Dave D. Cramer[b], Sean Oakes[b], Mark W. McClure[a]

[a] Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, Austin, TX, USA
[b] ConocoPhillips, 600 North Dairy Ashford, Houston, TX 77079, USA

What is a DFIT (Diagnostic Injection Test)

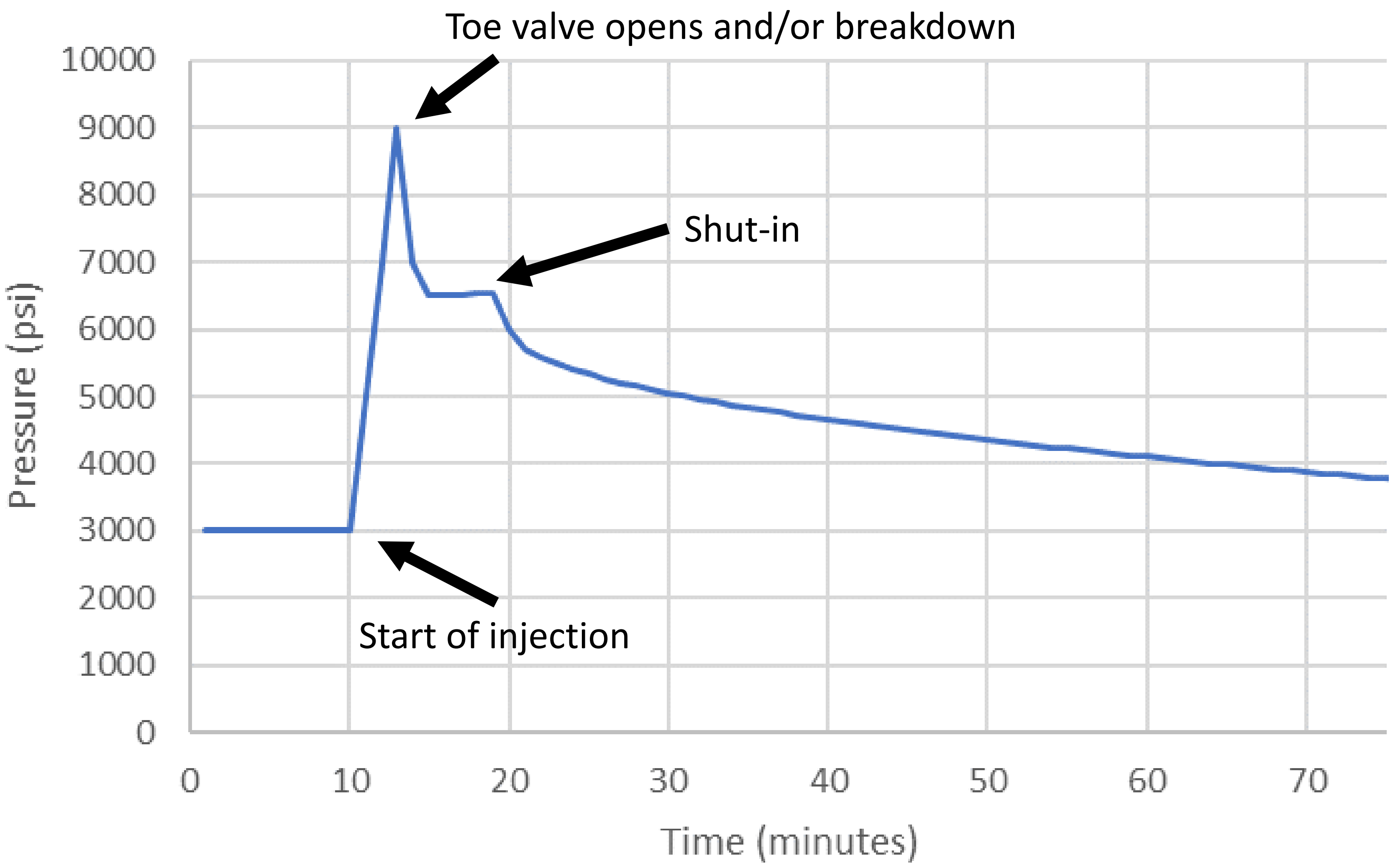
A short duration, small volume fracturing operation where a small amount (5-300 bbls) of clear water is pumped until fracture initiation. The is shut-in, allowing the well's pressure to fall-off naturally over the course of days or weeks. The pressure is analyzed to **estimate stress, permeability, and pore pressure**.



Why perform a DFIT?

- If feasible, a conventional well test (injectivity test without fracturing) can give you a good estimate for permeability.
- But in very low permeability rock, we typically cannot a inject at sufficiently low rate to avoid fracturing.
- In very low permeability, it requires an extremely long shut-in period for the wellbore to equilibrate with reservoir pressure.

Typical test sequence



Classical stress estimation methods

- Castillo (1987) summarizes the 'pre-holistic' interpretations used in petroleum engineering prior to the mid-2000s.
- Nolte (1979) derived the G-function so that it is proportional to leakoff volume after shut-in after a DFIT, *assuming Carter leakoff*.
- Closure is picked at the deviation from linearity because it is assumed that 'something' changes at closure, and that must cause a deviation from linearity.
- The holistic method deviates sharply from these classical techniques, which remain in wide-use in mining and other non-petroleum fields.

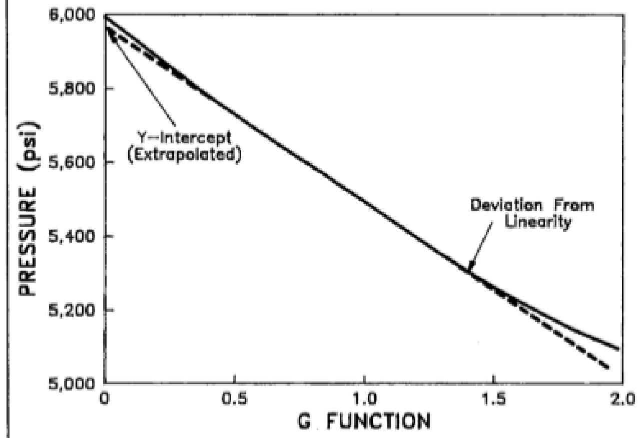


Figure 1. Pressure vs. the G-Function (Example 1).

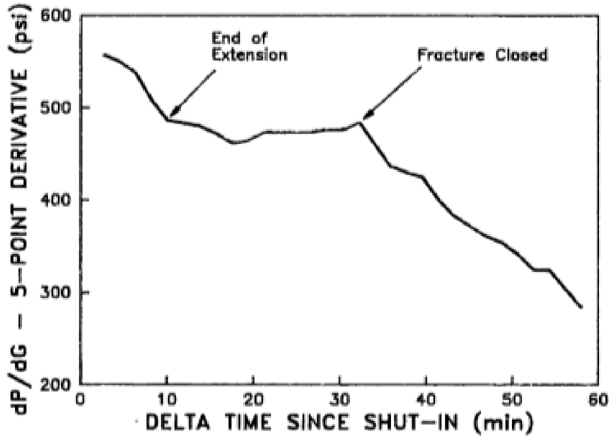


Figure 2. G-Function Derivative Plot (Example 1).

‘Holistic’ method (which I do *not* recommend) – deviates from classical methods and turns out to be systematically inaccurate

- Barree et al. (2009) recommend making a plot of G*dP/dG estimating ‘closure’ (estimating Shmin) by drawing a straight line from the origin to the tangent of the curve (near the peak).
- In some tests, leads to a much lower pick than other methods.
- For example, in the lower left plot, the Castillo method would pick closure much earlier than the ‘Holistic’ method.

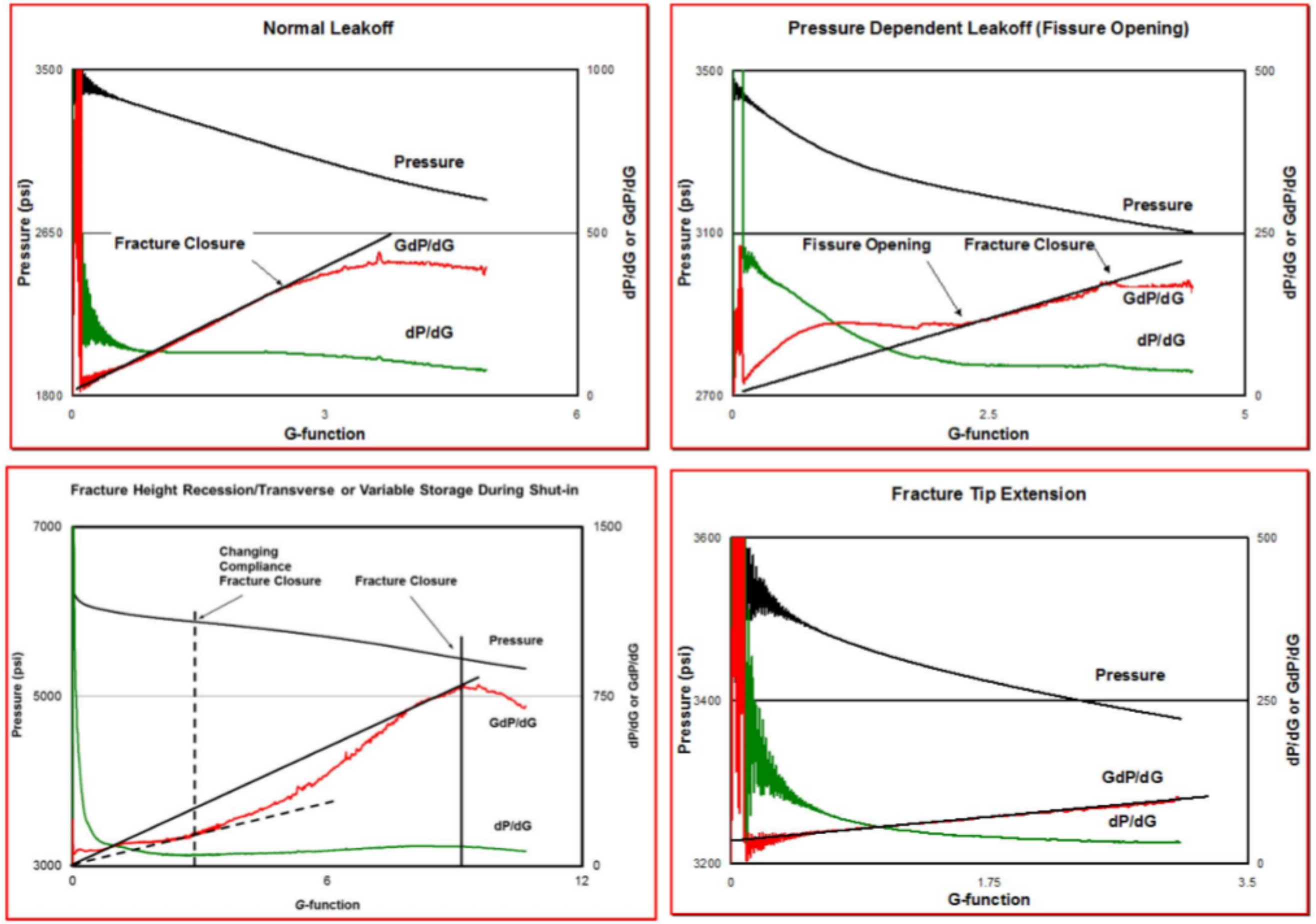
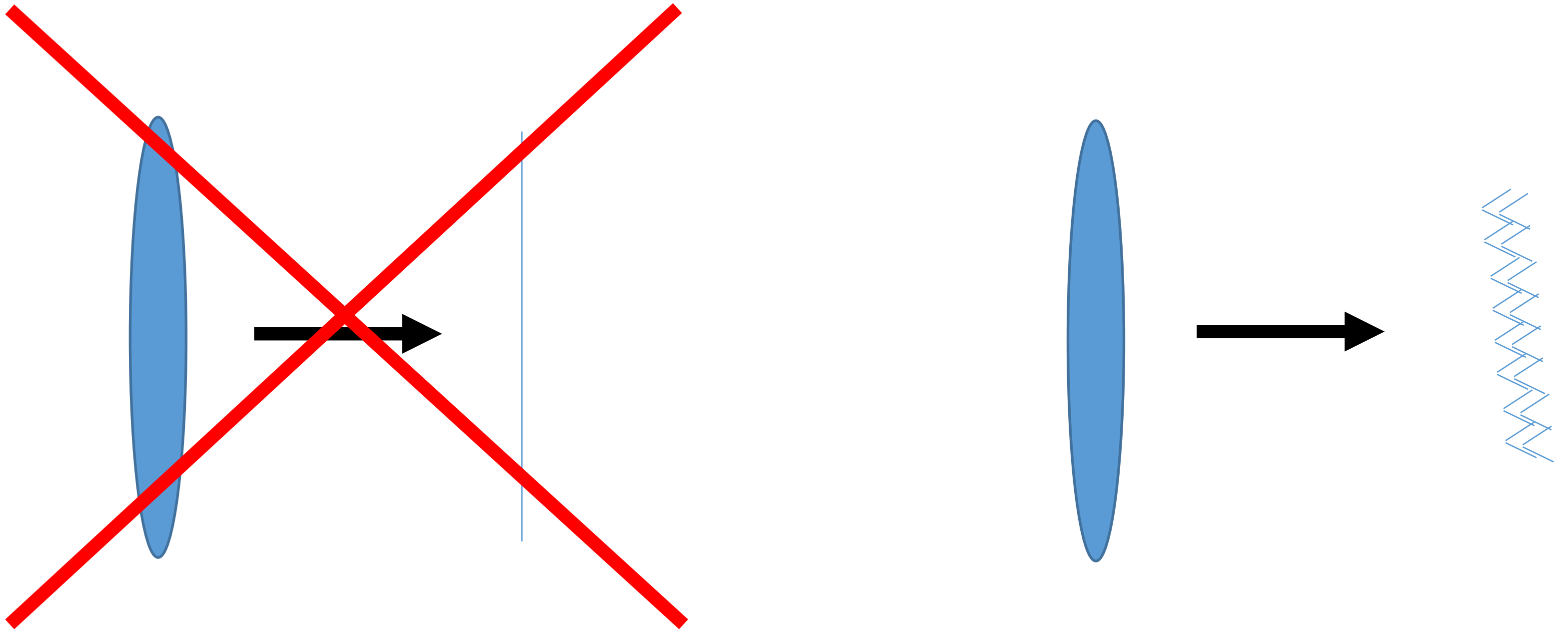


Figure 1—Classical G-function derivative analysis qualitative interpretations.

Craig et al. (2017)

When the fracture walls contact, they mate imperfectly

The crack opens because the internal fluid pressure, P, is greater than the normal stress pressing in from the surrounding rock, σ_n. Hydraulic fractures generally form perpendicular to the minimum principal stress, Shmin, so their normal stress is Shmin. So they close at a pressure approximately equal to Shmin. But here is a key nuance – fractures have roughness and the walls do not mate perfectly.



Fracture roughness in core-across studies

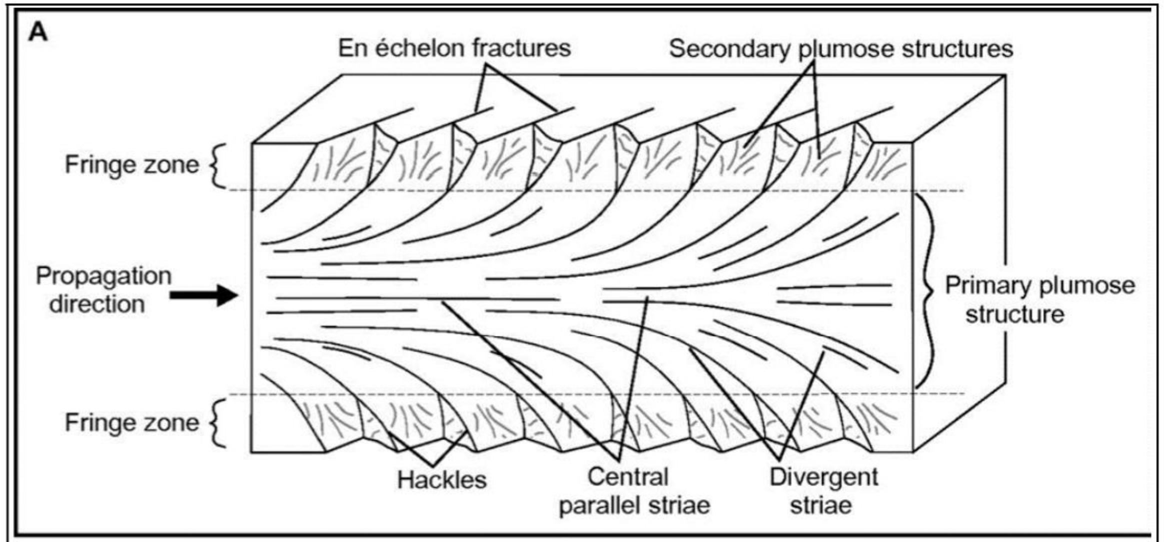


Figure 20. Diagram of plumose structure on a joint surface (from Cobain et al. (2015), their figure 6A). Note local direction of propagation indicated by twist hackles is up at the top and down at the base.

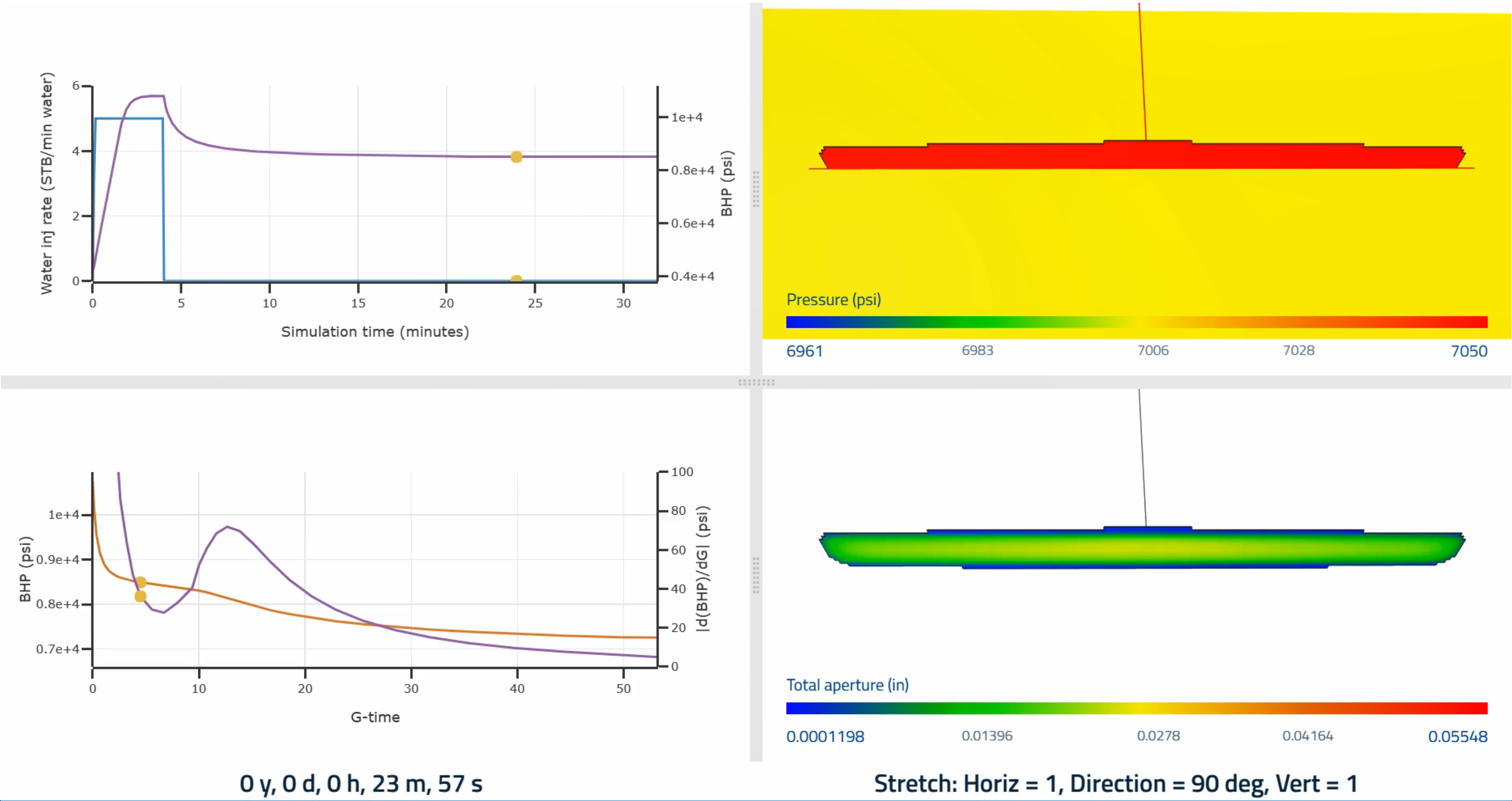
(d)

(e)

Gale et al. (2018)

The full solution

Numerical modeling makes it possible to solve the full coupled problem all in one continuous simulation. We use a fully numerical, general solution for leakoff and flow in the reservoir. We use a 'fracture contact' law to realistically describe aperture evolution after the walls contact.

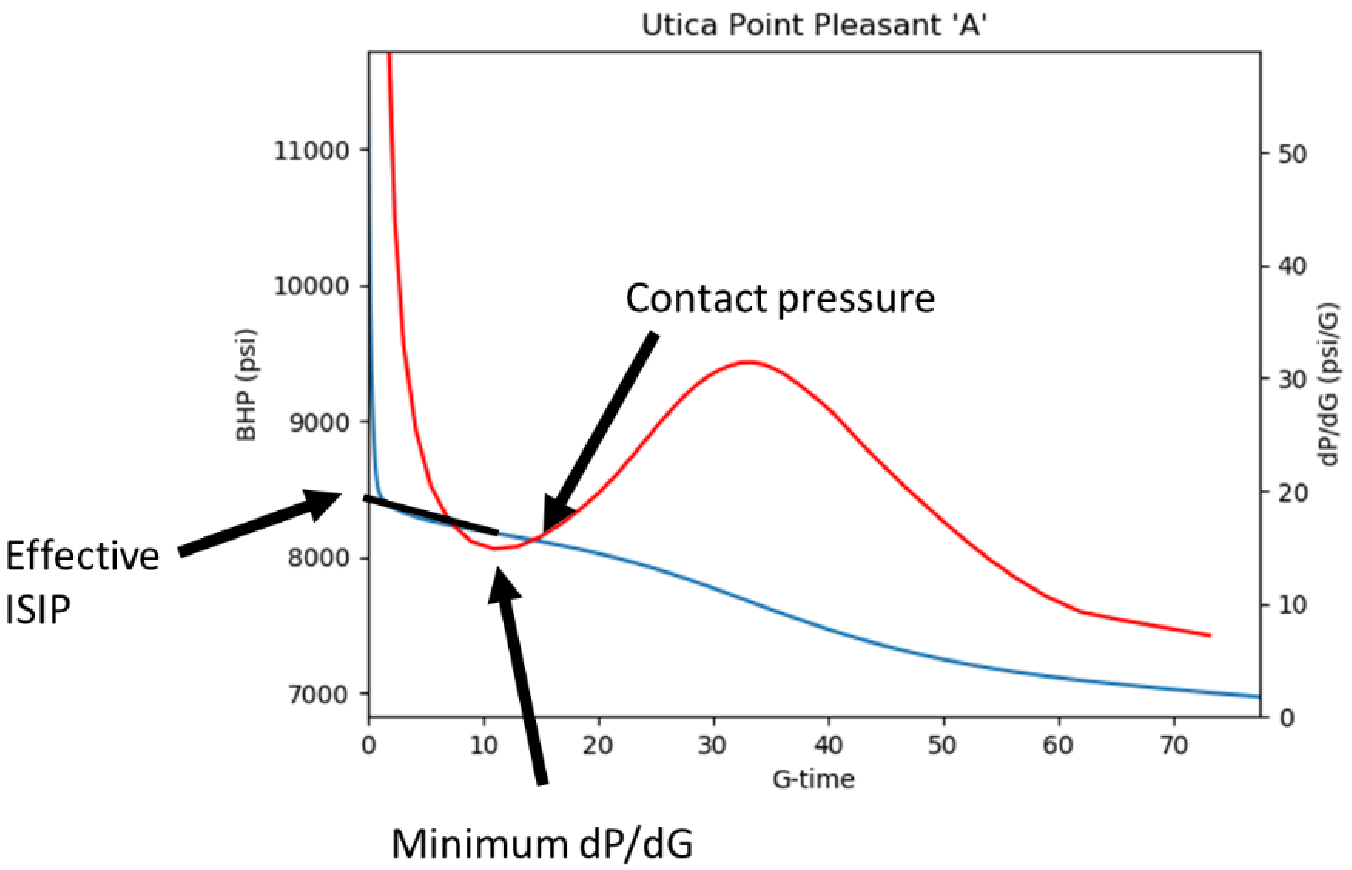


A full solution to the problem leads to the 'compliance method' – McClure et al. (2017; 2019)

The pressure derivative is 'leakoff rate divided by system storage.' When the walls contact, the fracture compliance drops, increasing derivative.

$$\frac{dP}{dG} = \frac{1}{C_t}\frac{dV}{dG}$$

The magnitude of Shmin is slightly lower (75 psi?) than the 'contact pressure' where the walls touch.



Direct strain measurements

McClure et al. (2017) compare downhole tilt-meter results from Branagan et al. (1996) with the shut-in pressure transient and find that the stress is correctly estimated by a 'compliance' approach, not the 'tangent' approach.

This interpreted reopening pressure is the same as a previously published interpretation from Gulrajani and Nolte (2001).

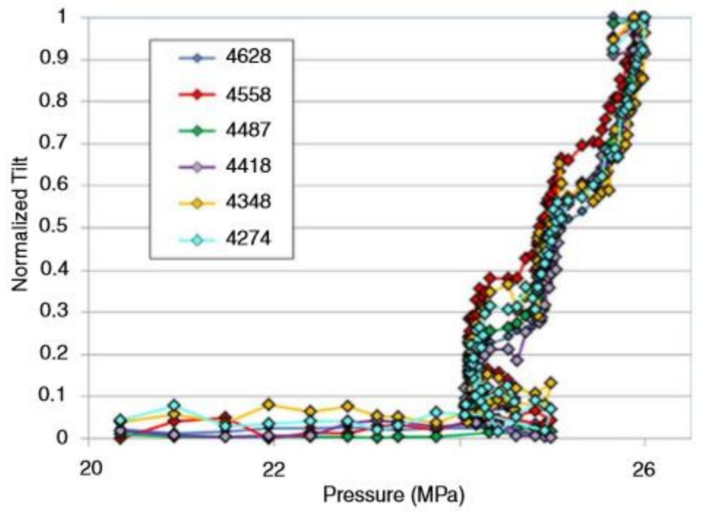
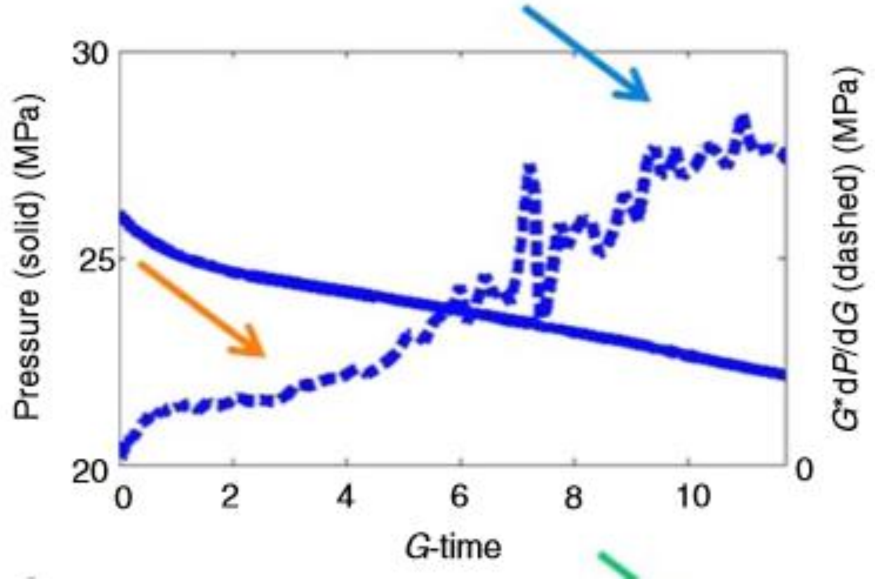
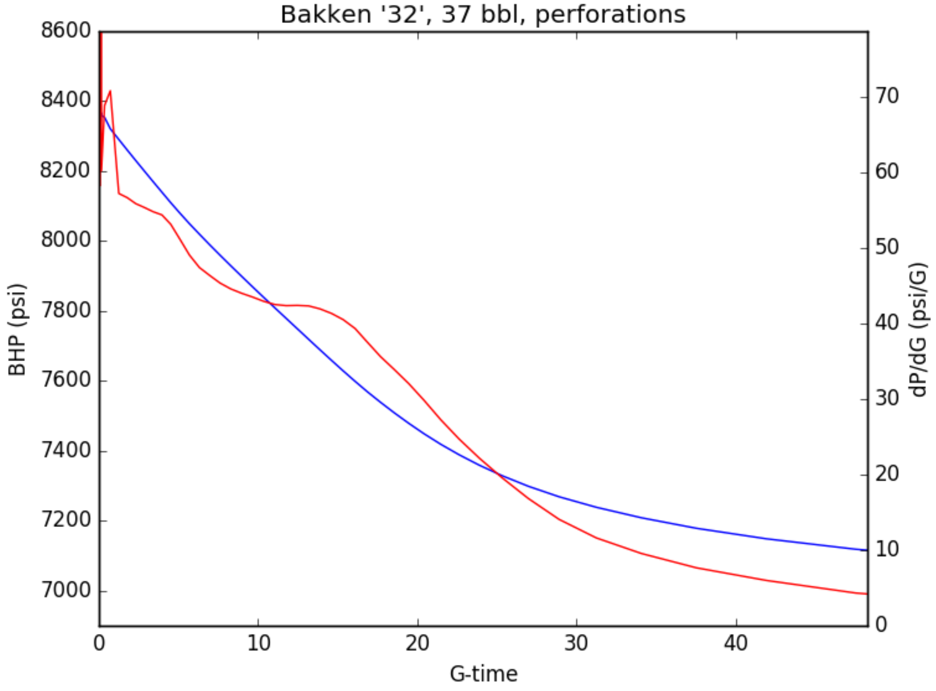


Fig. 15—Normalized tiltmeter data from Injection 2B from the GRI/DOE M-site. Data courtesy of Norm Warpinski.



Monotonic dP/dG – McClure et al. (2020)

- Not all DFITs show indication of contact. The below DFIT has monotonically decreasing dP/dG. Contact is supposed to cause dP/dG to increase. How to interpret?
- Simulations suggest a variety of processes can cause this. "Instant closure" causes this shape, and can be caused by prior injection into the interval, high permeability, or natural fractures.
- If near-wellbore tortuosity can be assumed absent, stress can be ~ISIP. But if not, stress cannot be assessed.



Monotonic dP/dG

- **Here is a published example of large volume, then small. As predicted, there is not a compliance response in the second test, and the result is consistent with instant closure.**

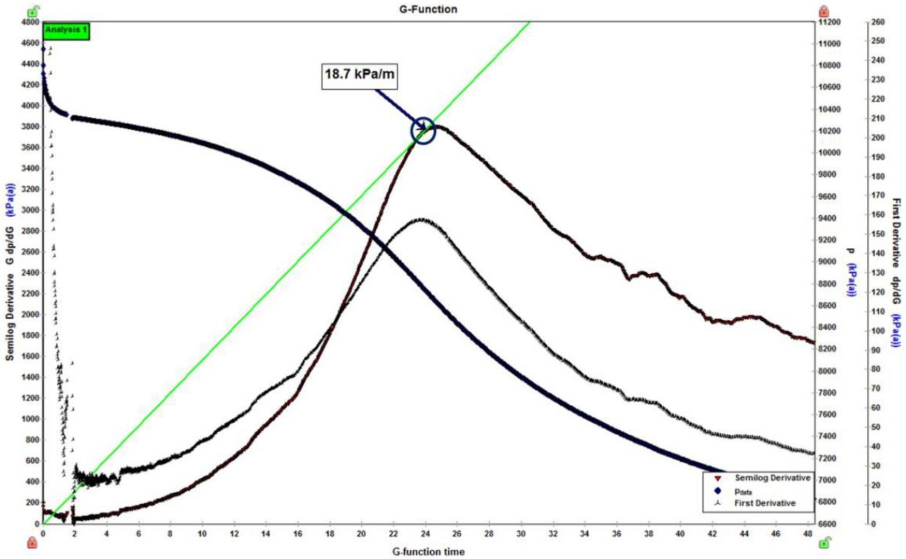


Figure 1: Example 1 - High Rate Colorado G-function example showing strong "Belly Shape" HR/TS behaviour

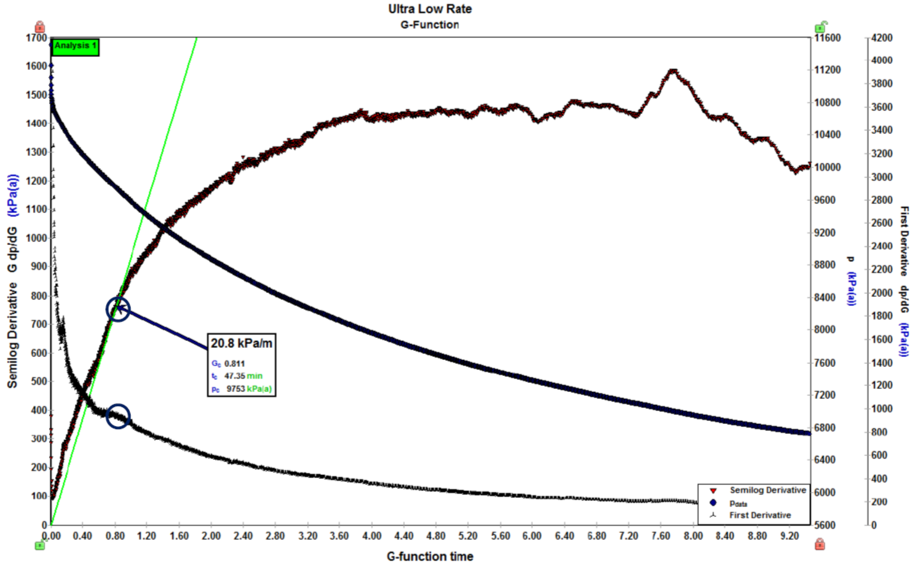
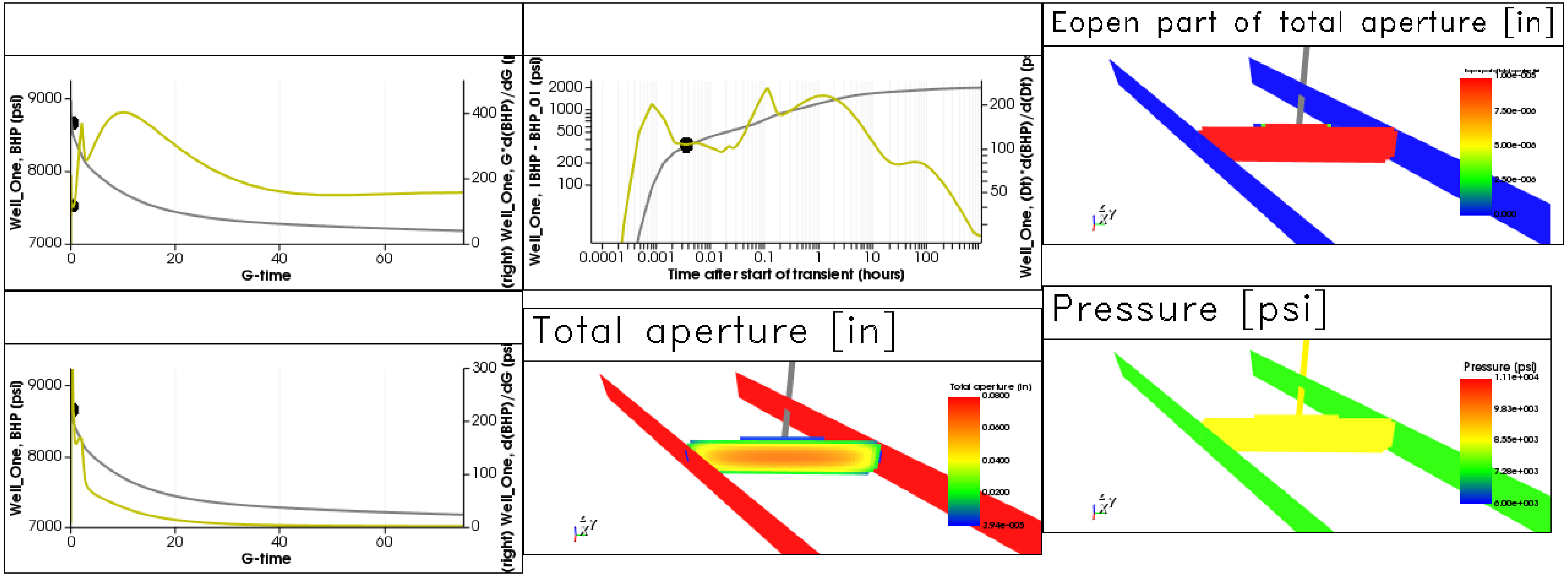


Figure 2: Example 1- Ultra-low Rate G-function (re-test)

Nicholson et al. (2017)

Monotonic dP/dG

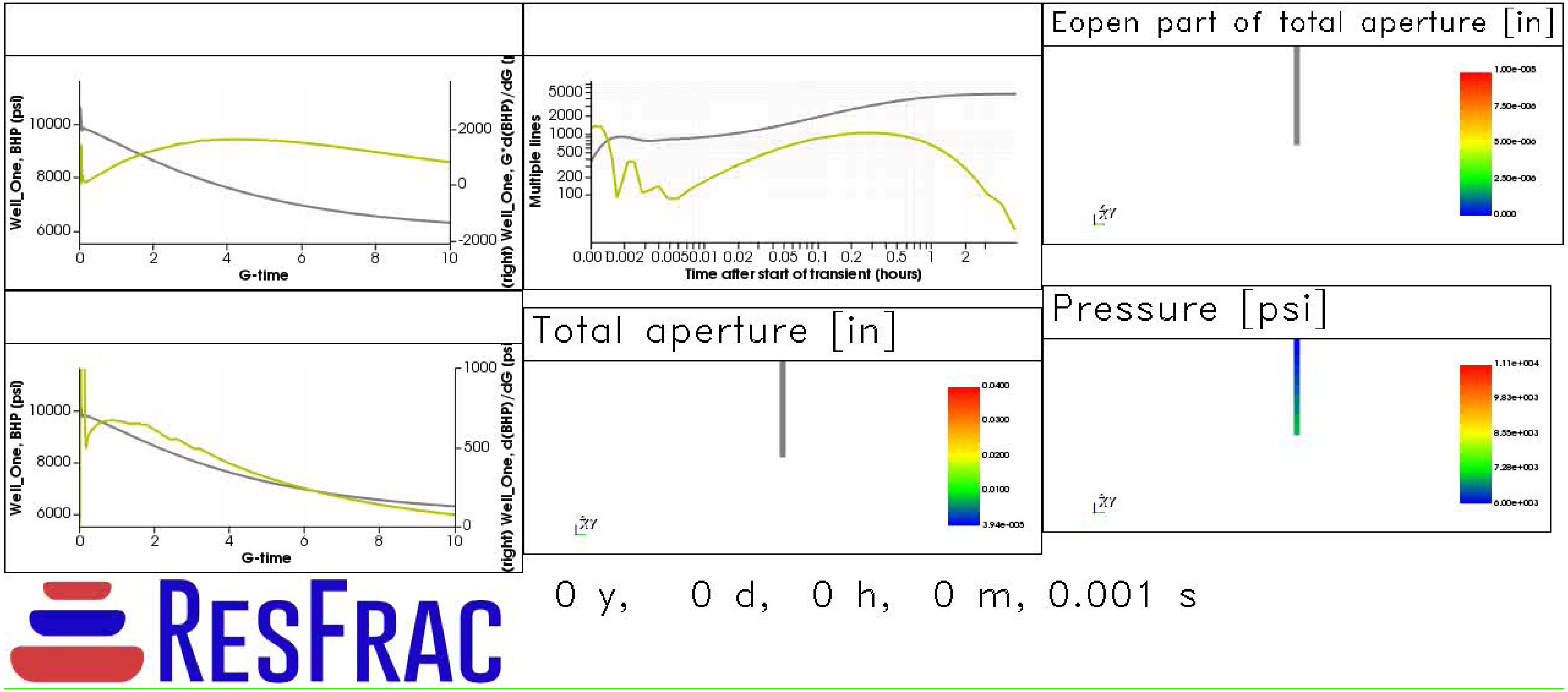
- **Here is a simulation example with high permeability natural fractures. Instant closure due to leakoff into the fractures and a monotonic dP/dG.**

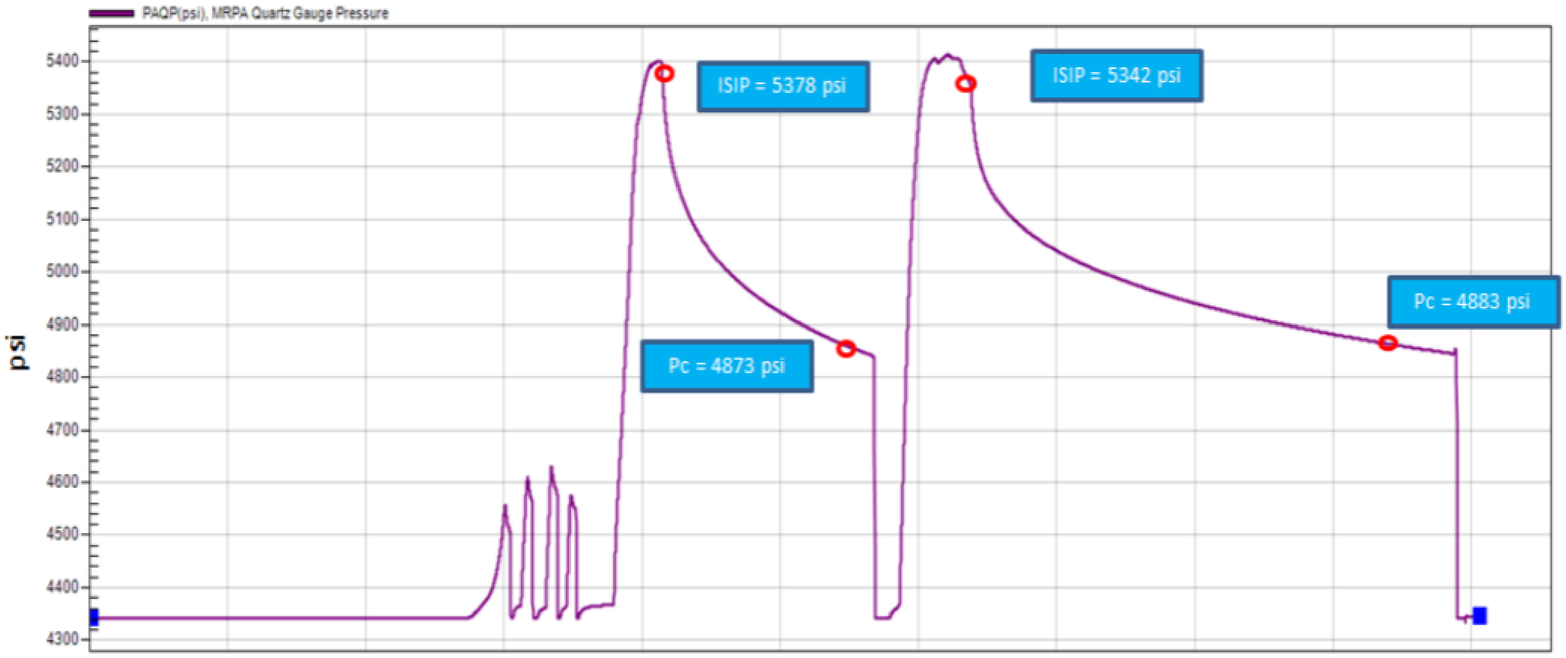


0 y, 0 d, 0 h, 4 m, 13.57 s
Stretch factor along each axis in 3D plots: X=1, Y=1, Z=1.

Monotonic dP/dG

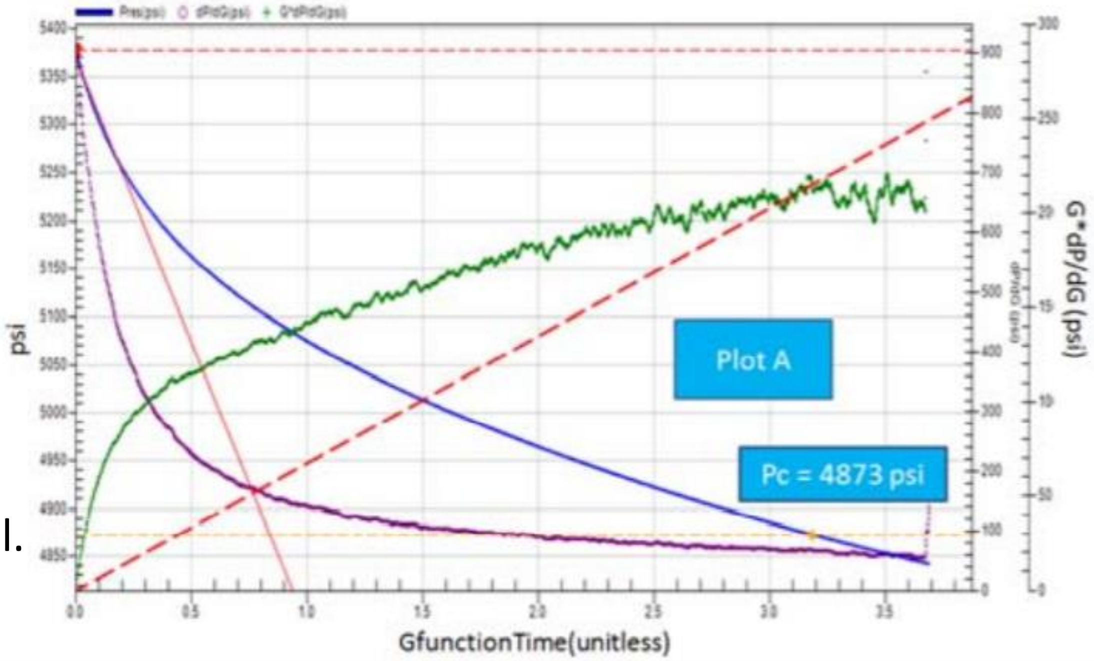
- **This simulation has 1 md and is in a gas reservoir. Because there is so much leakoff, the fracture barely opens during injection and then closes almost immediately.**

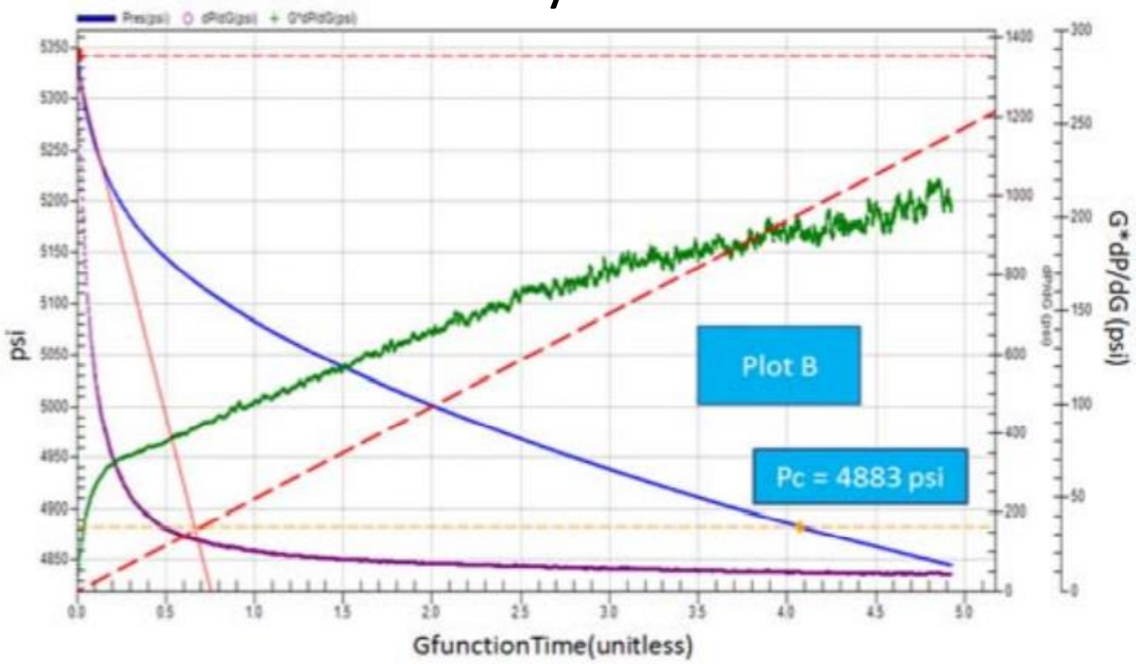




The tangent method interpretation is contradicted by the reopening pressure.

This test is performed from a vertical well – no near-wellbore tortuosity.

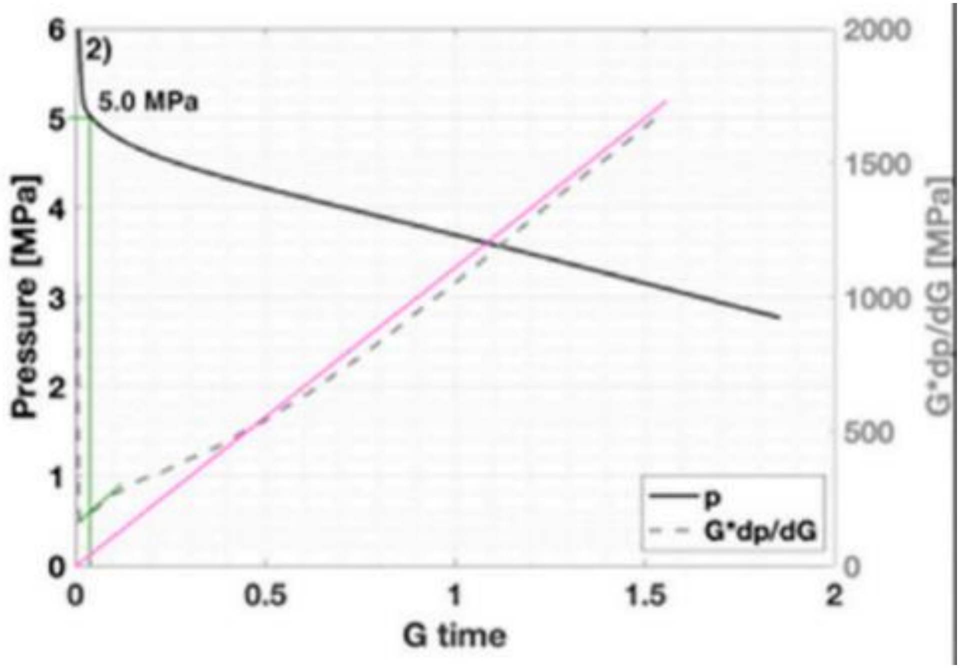


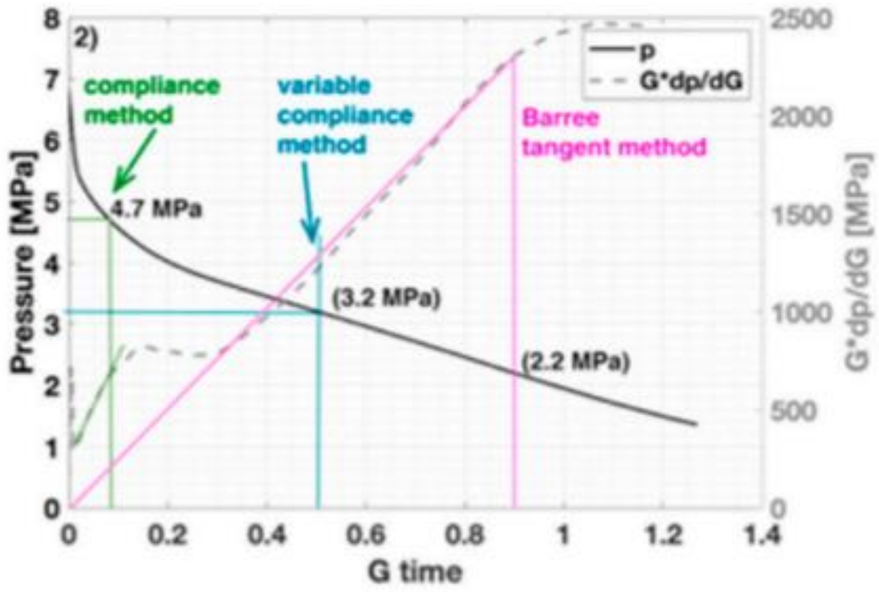


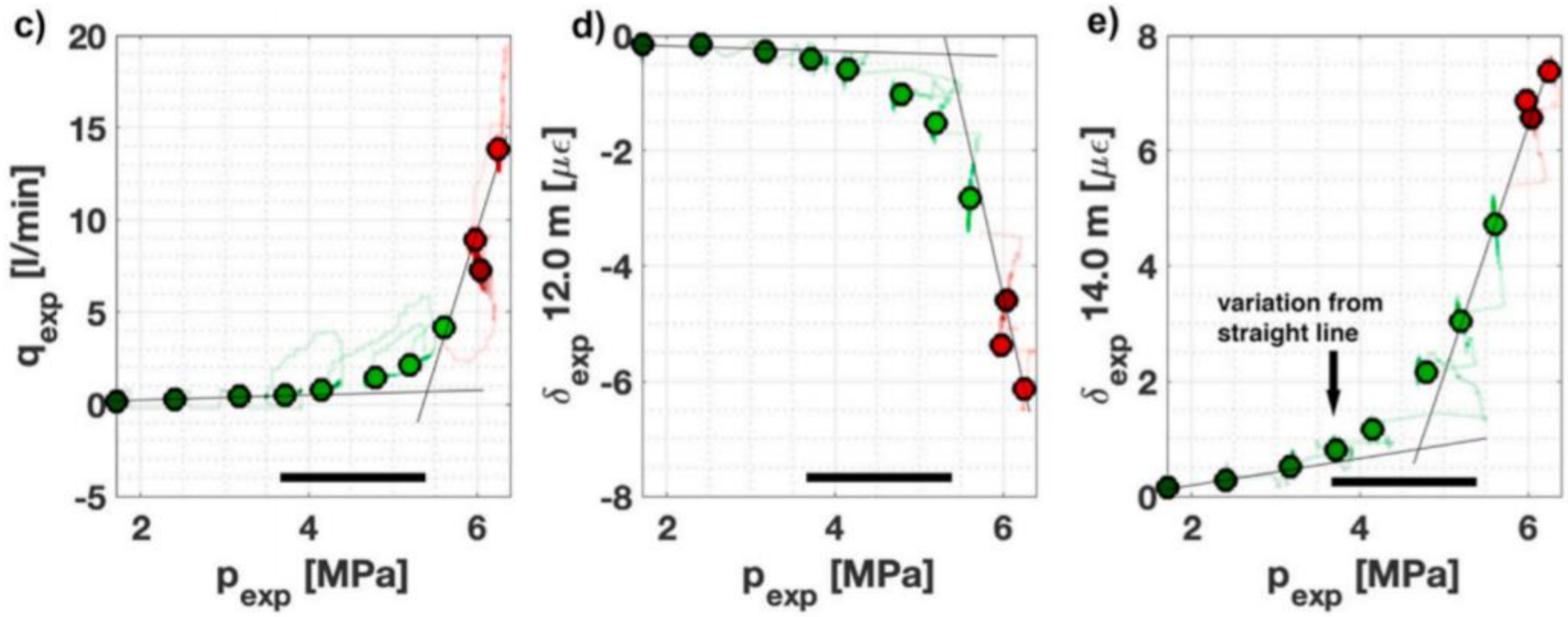
Malik et al. (2014)

In-situ measurements of closure – Dutler et al. (2020)

Tiltmeters directly watch fractures open and close. The tangent method says fractures never close during shut-in periods, even though the physical measurements show that they do.

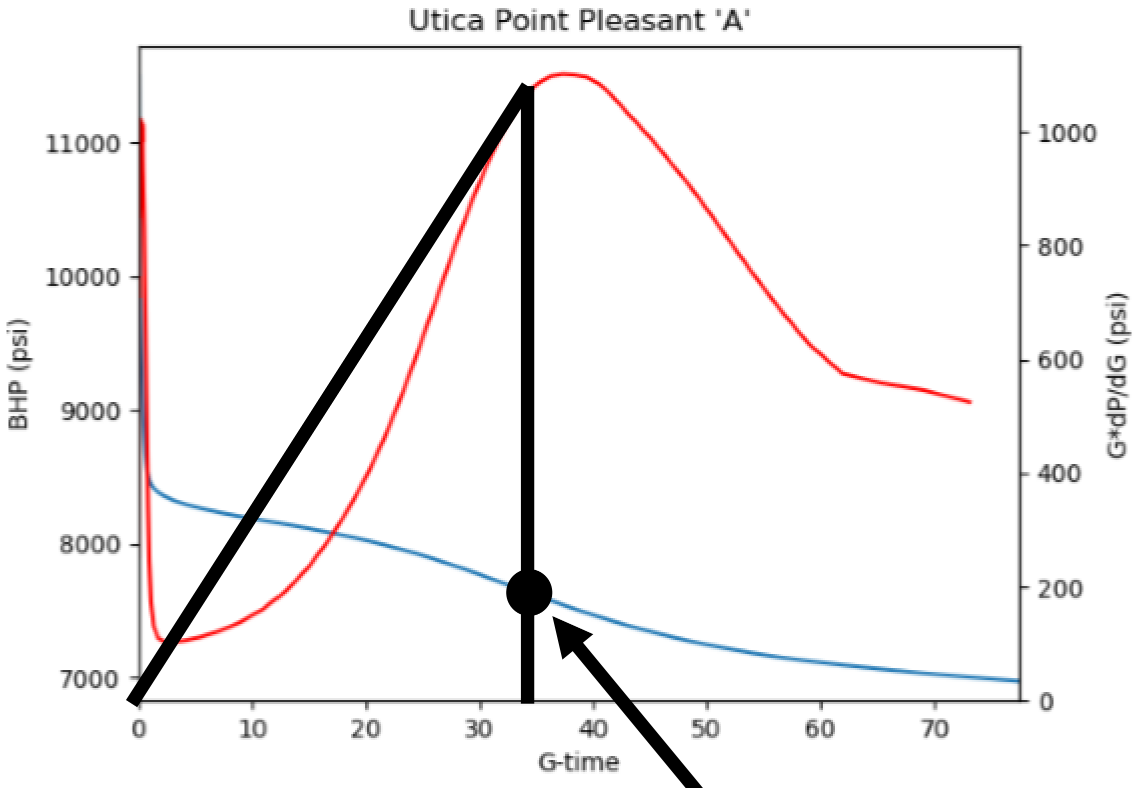




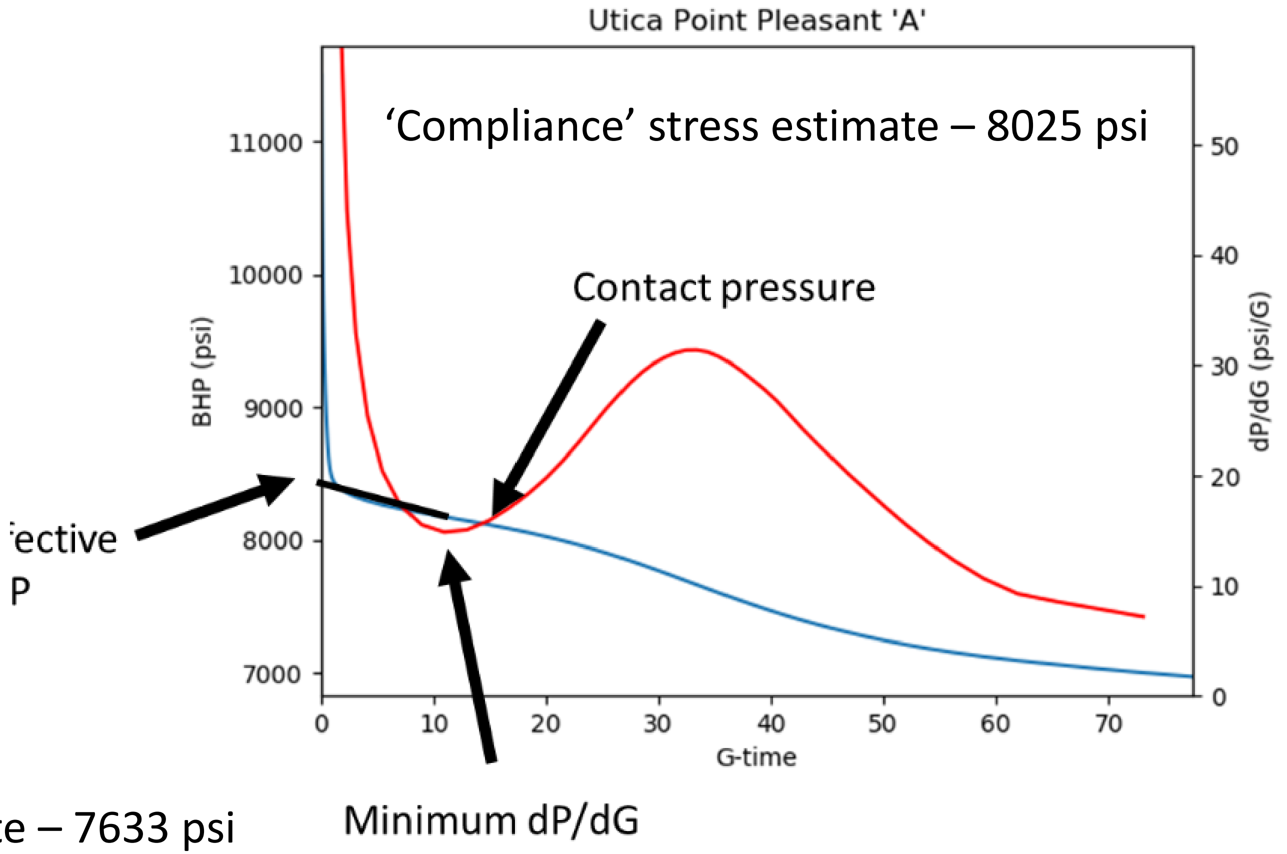


Comparison with ‘holistic’ or ‘tangent’ method interpretations

Barree et al. (2007/2009) recommends using a plot of G*dP/dG and drawing a tangent to the G*dP/dG curve. Then read pressure at that point in time. This gives a later, lower stress estimate. Sometimes, they are similar; sometimes, 1000+ psi different. Implied net pressure is often 100-500% different.



‘Tangent’ stress estimate – 7633 psi



Full interpretation procedure - see McClure et al. (2019) for full details

- The full procedure involves estimation of stress, permeability, and pore pressure.
- In a paper in February, we statistically review results from performing 60+ DFITs for operators around North America.

Thank you!

If you have any questions, please feel free to email: mark@resfrac.com

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