GEOMECHANICAL PROPERTIES OF MESOZOIC RIFT BASINS: APPLICATIONS FOR GEOSEQUESTRATION

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U.S. Department of Energy

National Energy Technology Laboratory
Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

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Presentation Outline

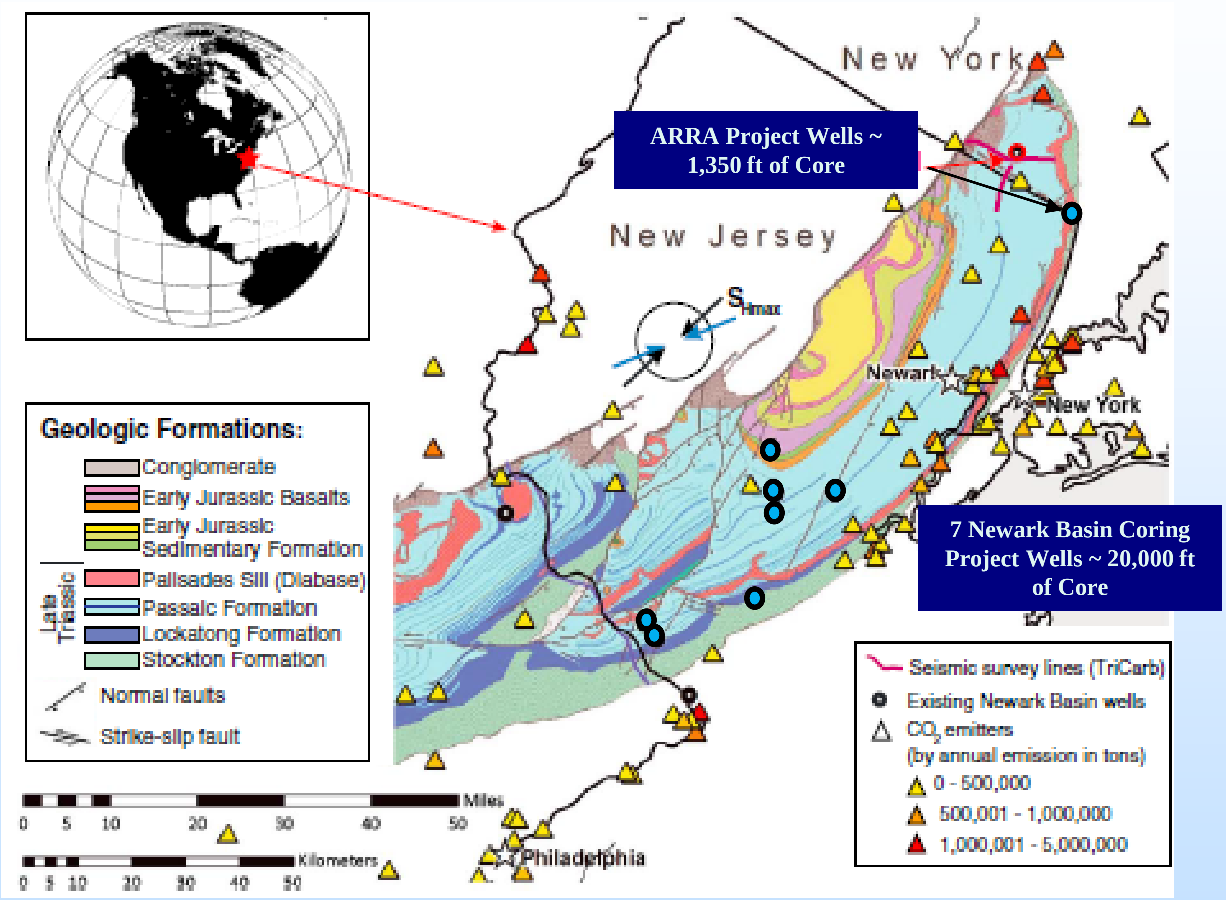
- Benefit to the Program
- Project Background
- Project Overview
- Technical Status
- Accomplishments to Date
- Synergy Opportunities
- Summary

- Appendix

Benefit to the Program

- One of the goals of the DOE Carbon Storage program includes reducing the risks associated with injection processes at potential carbon storage sites.
- A major risk associated with carbon storage comes from the possibility of reactivating preexisting faults and fractures due to injection induced pore pressure increases in the reservoir.
- Understanding the induced seismic and leakage risks associated with a geological carbon storage site will substantially increase the security of injected fluids stored at that location and reduce the uncertainty, risk, and potential damages due to the injection process.
- The results of this “case” study may be widely applied to potential field-scale geological storage projects in the future

Physiogeographic Setting of the Newark Basin & Sources of Whole Core



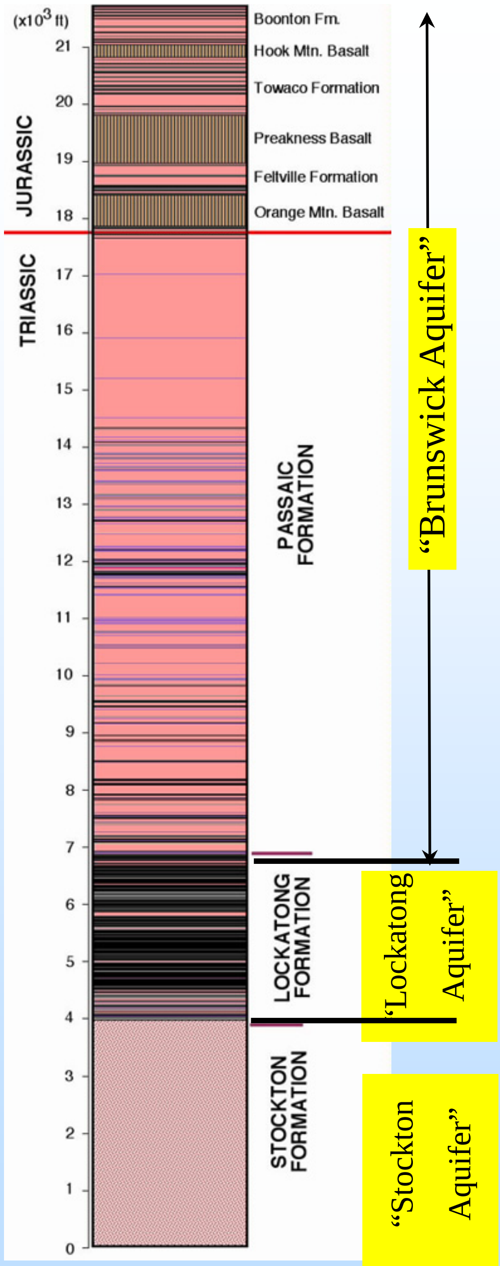
ARRA Project Wells ~ 1,350 ft of Core

7 Newark Basin Coring Project Wells ~ 20,000 ft of Core

Goldberg et al. [2003].

- Newark Basin stretches from Rockland County, New York, southwest across northern New Jersey, and into southeastern Pennsylvania (140 miles long by 32 miles wide)
- Geographic extent ~ 2,700 square miles
- The Newark Basin is in close proximity to large population areas and a heavily industrialized section of the country (28 MM tons/year CO_2 in closest NY/NJ counties)
- 1990s 7 Newark Basin Coring Project wells Central New Jersey ~3,500 ft deep – More than 20,000 feet of core
- ARRA Project drilled a Deep Borehole in 2011 with 150 feet of core and a Shallow Corehole in 2013 with 1,152 feet of core

Newark Basin Stratigraphy



Half-graben clastic infill sequence

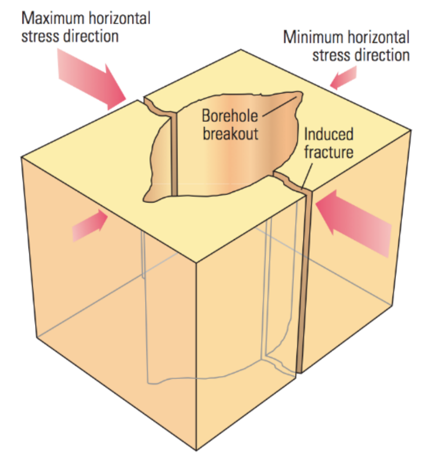
Playa lake and mudbank shales of the Passaic Fm provide secondary "seal" cap – up to 10,000 feet thick

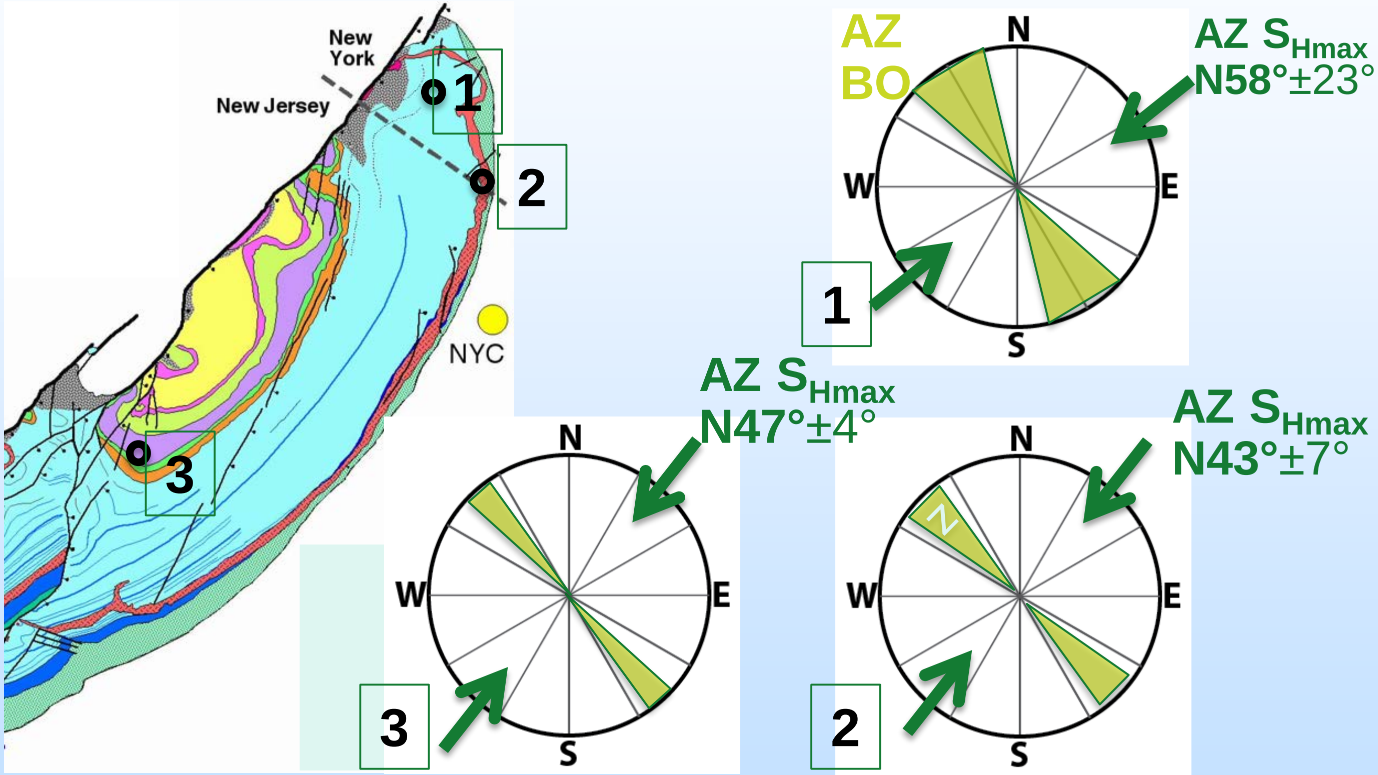
Deep lake and shallow mudflat shales of the Lockatong Fm provide primary "seal" cap – up to 3,000 feet thick. Generally includes intrusive diabase "Palisades Sill"

Fluvial-alluvial sandstones and Mudstones of the Stockton Fm – up to 6,000 feet thick (or more along border fault)

Stress Field Orientation with Position in the Newark Basin

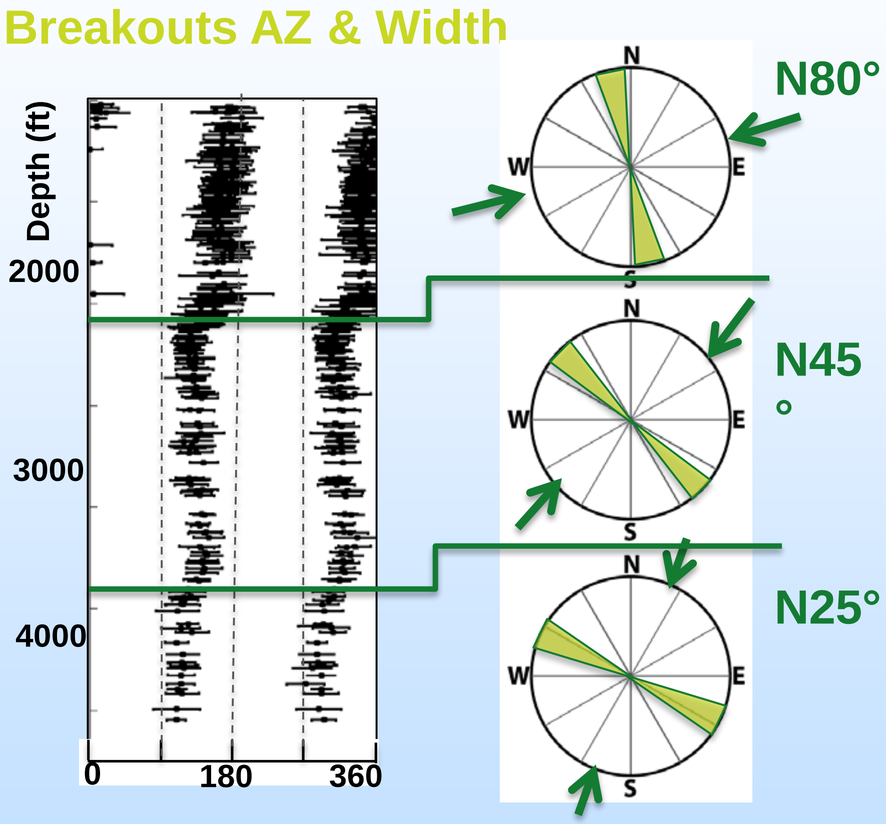
Borehole Stress Indicators: Breakouts





[Zakharova et al., 2014; Goldberg et al., 2003]

Stress Field Variation with Depth In the Newark Basin



[Zakharova et al., JGR, 2014]

- **Consistent stress orientation laterally in the basin: AZ S_{Hmax}~45°**
- **Localized stress perturbations with depth at multiple scales:**
  - overall trend of counter-clockwise rotation (~10^3 ft)
  - 2 sharp rotations by ~30 ° at 2550 and 3800 ft
  - localized (~10^{1-2} ft) deviations form the trend

Project Overview:
Goals and Objectives

- Primary goal of the project is to detail formation caprock characteristics, stresses, and mechanical properties in Mesozoic Basins using a “case study” in the northern Newark Basin.
  - Preliminary work suggested significant variability in orientations and magnitude of the principal horizontal stress with respect to depth
  - Objective is to measure lab-scale properties (BP I) to field scale mechanical properties and stresses (BPII) using an extensive core library and an existing field test well.
  - Well testing includes innovative configuration of the Schlumberger Modular Dynamics Tester tool for use in consolidated formations of high strength

- Budget Period 1 Success Criteria is defined as successful characterization/geomechanics testing of at least 18 of the 25 core planned samples selected for testing.

Technical Status – Core Testing Complete

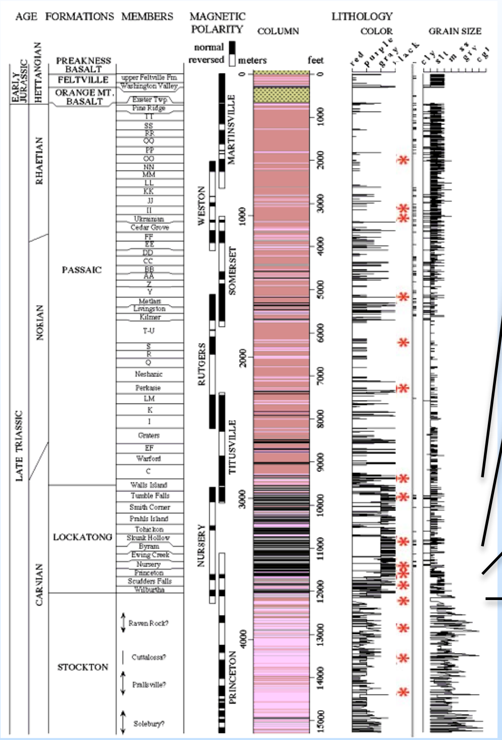
- Budget Period 1 work involved leveraging the 1,350 feet of whole core collected in the Lamont Doherty Earth Observatory Test Well No. 4 with the +/-20,000 feet of Newark Basin Coring Project whole core, all maintained at the Rutgers University Repository
- Project Team selected ~25 core sections with different lithologies, concentrating on mudstones (confining materials)
- Core Sections were screened (QA/QC) via CT Scanning and sample areas were identified for characterization and geomechanical testing.

Technical Status – Core Testing (Cont.)

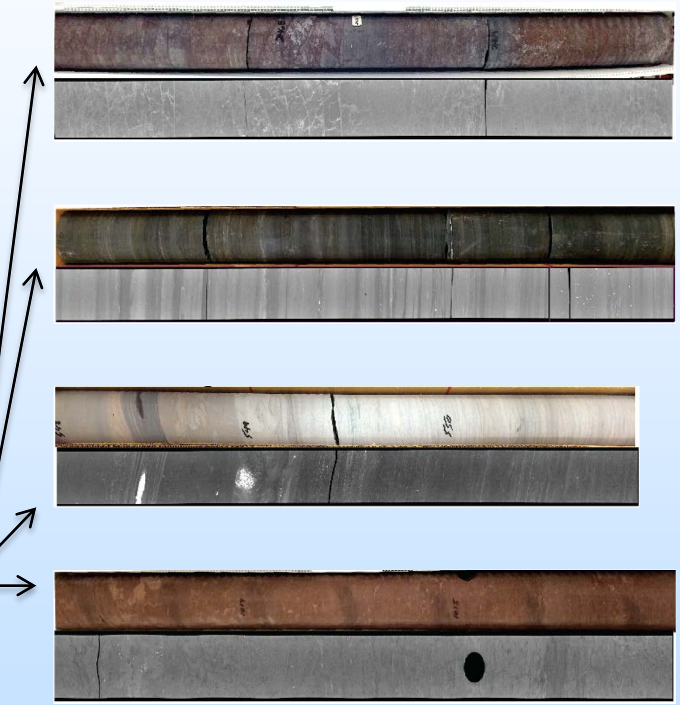
- 97 samples tested from 29 core locations in TW-4, Martinsville, Nursery, Princeton, Rutgers, Sommerset, Titusville, & Weston Cores
- Testing included:
  - Unconfined Compression Testing – 7 Samples
  - Triaxial Compression Testing – 58 Samples at 20 core Depths
  - Multi-stage Triaxial Compression Testing – 4 Samples
  - Indirect Tensile Strength (Brazilian Method) – 12 Samples
  - Fracture Toughness Testing - 4 Samples
  - Mobilized Friction Angle Testing - 3 Samples
  - Creep (2 Samples)
- Summary Report with data compilation delivered 3/2016

Rock Properties (Characterization and Geomechanical

Composite stratigraphic section

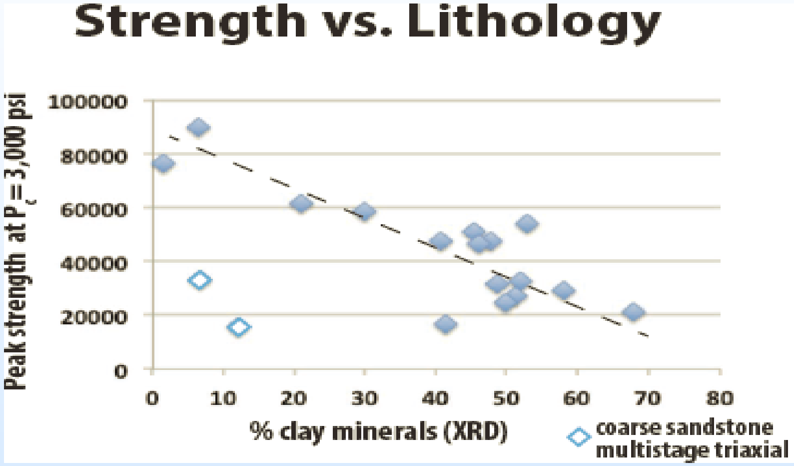


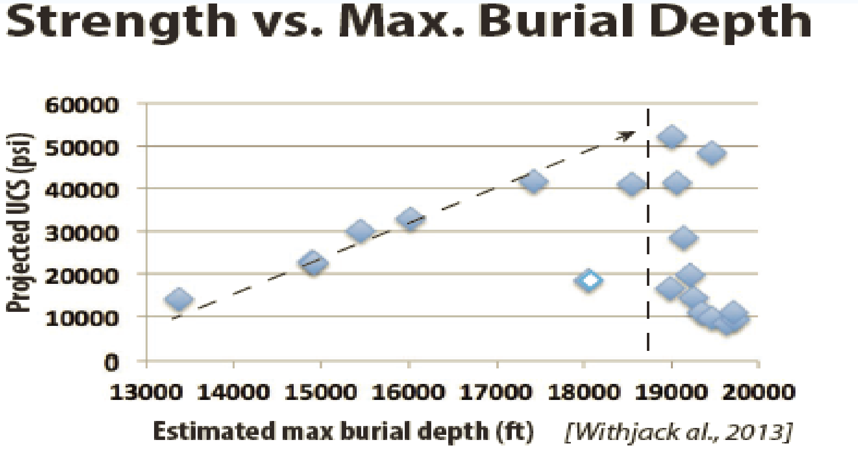
Examples of sampled core



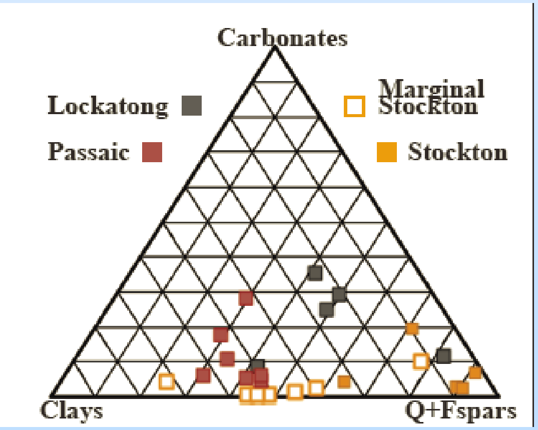
- XRD, SEM, CT scans, MICP, Vp/Vs, ρ, φ
- Unconfined compressive strength (UCS)
- Triaxial compressive strength (full envelopes)
- Brazil/tensile strength
- Oriented tests for anisotropy
- Mobilized friction angle test (fracture strength)

Core Testing Observations



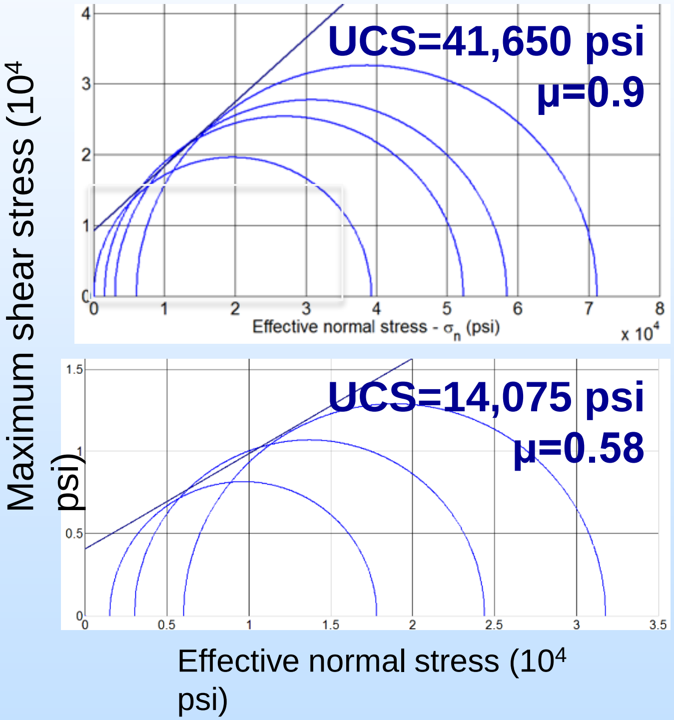


[Withjack al., 2013]



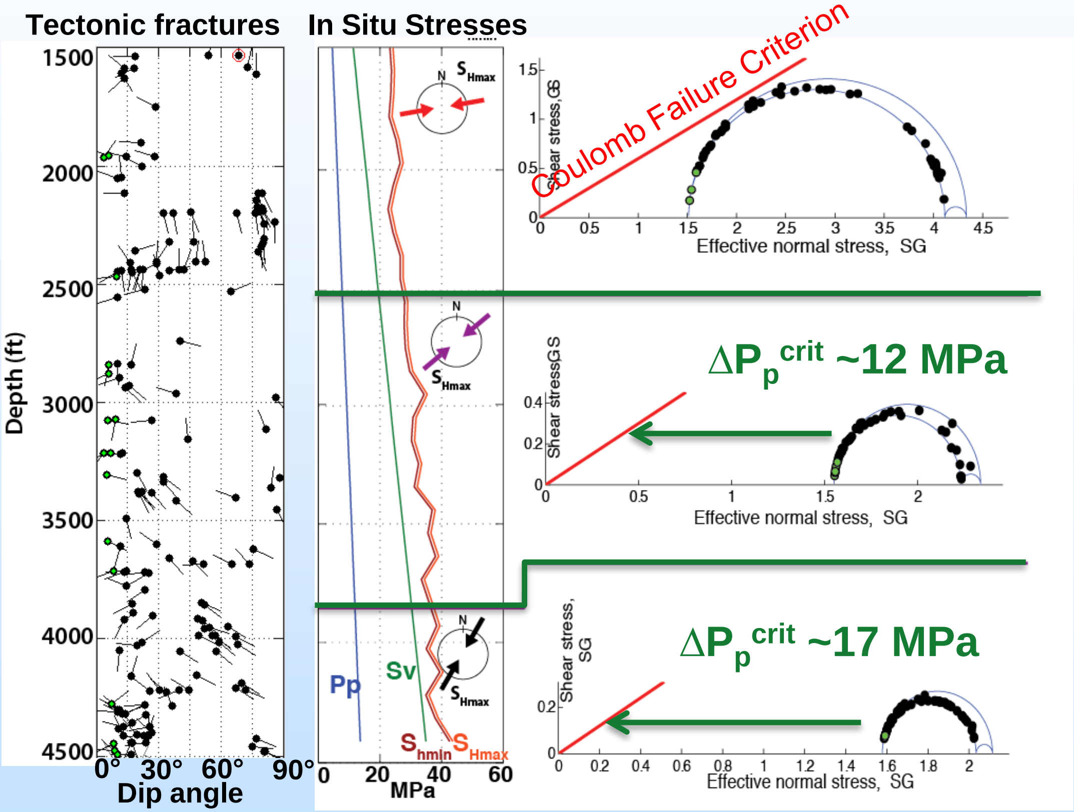
Mechanical Properties

Mohr-Coulomb failure envelopes from triaxial compressive tests



- **Large range of strength (8,000-50,000 psi for projected UCS) and coefficient of friction (0.5-1)**
- **Strength decreases with increasing clay content, but there is significant scatter around this trend**
- **Strength anisotropy up to 30% in thinly bedded mudstones and sandstones**
- **Fracture strength is ~10% of the matrix strength**

Fracture Stability



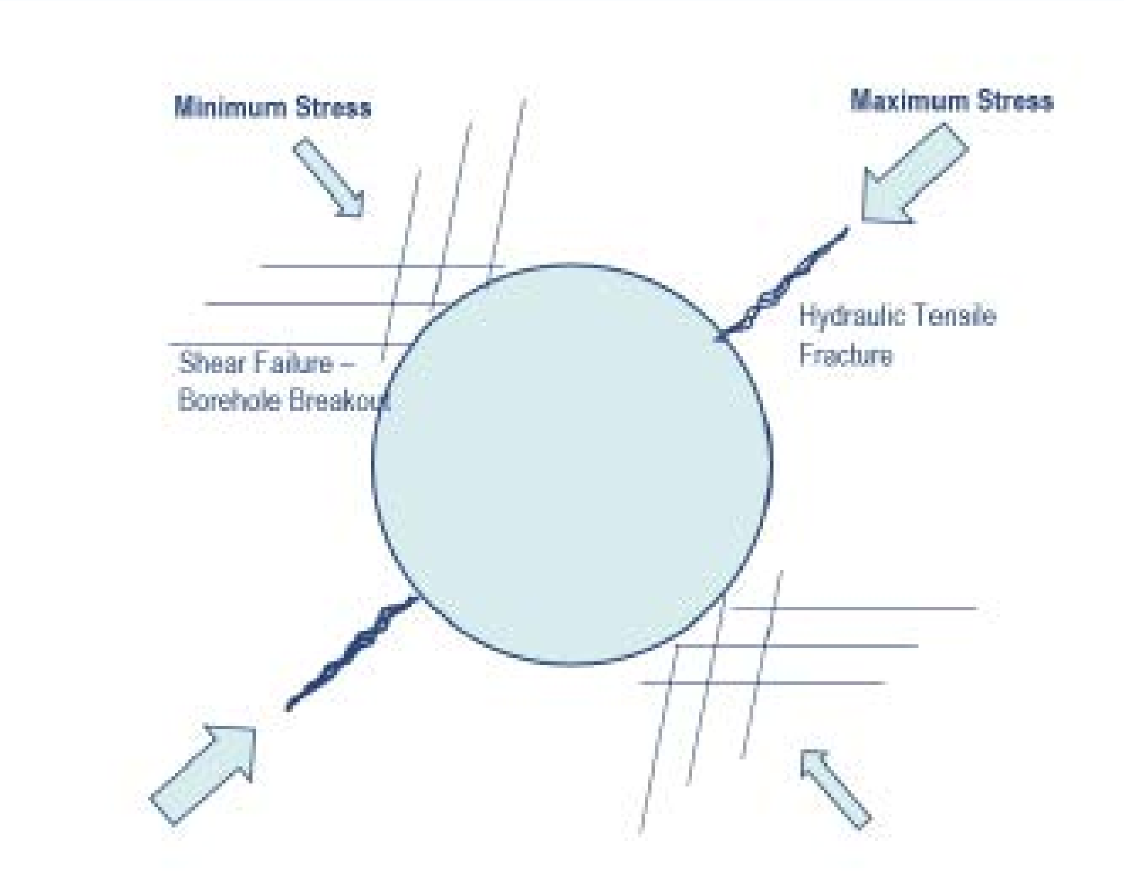
- **Shallow interval (~1500-2000 ft) is critically stressed, and carries significant risk of fracture reactivation**
- **Deeper reservoirs (>2500 ft) could allow >10 MPa increase in pore pressure**

[Zakharova et al., JGR, 2014]

Technical Status – In Situ Formation Breakdown Testing – Budget Period 2 Field Work

- Baseline Formation Microimager run in LDEO Test Well 3 (TW-3) in October 2015
  - Planning tool for selection of formation breakdown testing depths – target mudstones
  - Evaluation of borehole conditions for packer locations
  - Evaluation of natural and drilling induced fractures
- Formation Breakdown testing conducted in January 2016
  - Selected 5 Pre-Stress formation depths (Field Day 1) to 5,800 psi differential
  - Selected 6 formation breakdown depths (Field Day 2)
- Real-time analysis was used to monitor each breakdown test, which allowed for “on the fly” test depth changes based on observations
- Formation Microimager was run after Pre-stress testing (analyzed overnight) and after formation breakdown testing

In Situ Formation Breakdown Testing
Determine Maximum and Minimum Stress



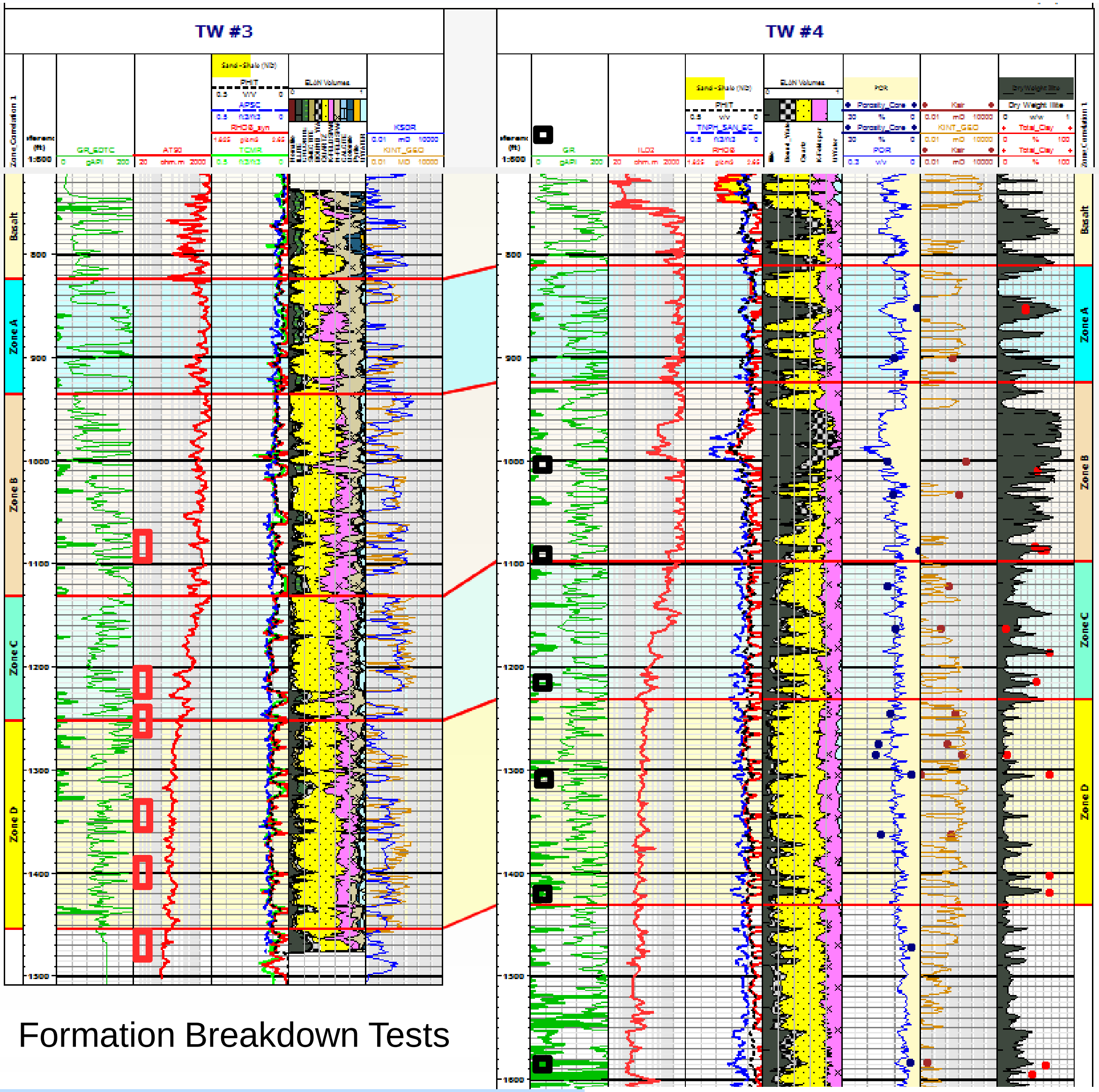
Integrated methodology to determine orientation and magnitude from open hole logging

Lamont Doherty Earth Observatory Test Wells

Closely Spaced Wellbores

-TW-4 Well completely cored through Triassic sediments

-TW-3 Well is larger diameter

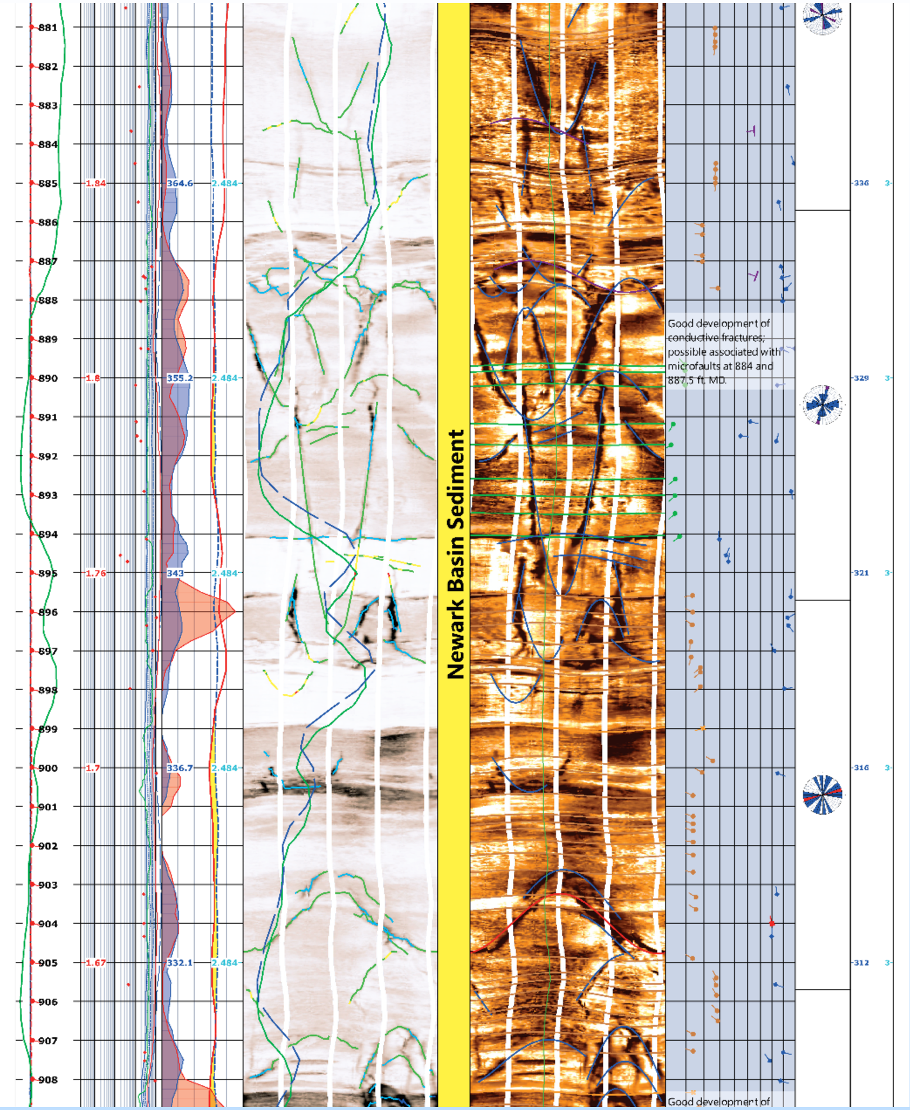


Formation Breakdown Tests

Tested Core Samples

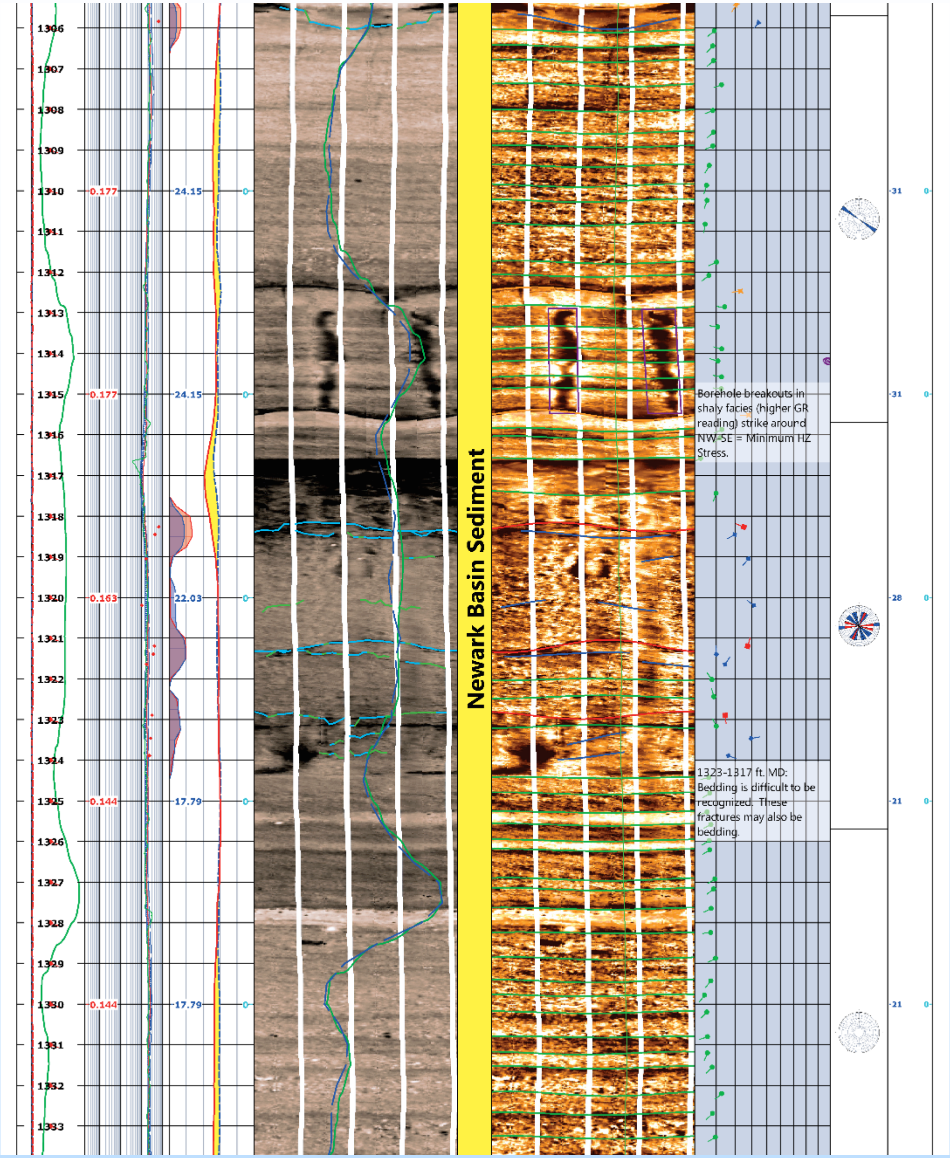
GEOSTOCK SANDIA
ENTREPOSE

Baseline Formation Micro-Imager – October 2015



- Provided an understanding of borehole conditions and locations of fractures crossing the borehole – helps with placement of test packers
- Conductive Open Fractures in the shallow Newark Basin sediments – striking SW to NE
- Observable bed boundaries and sedimentary structuring (cross-bedding) in sediments

Baseline Formation Micro-Imager – October 2015



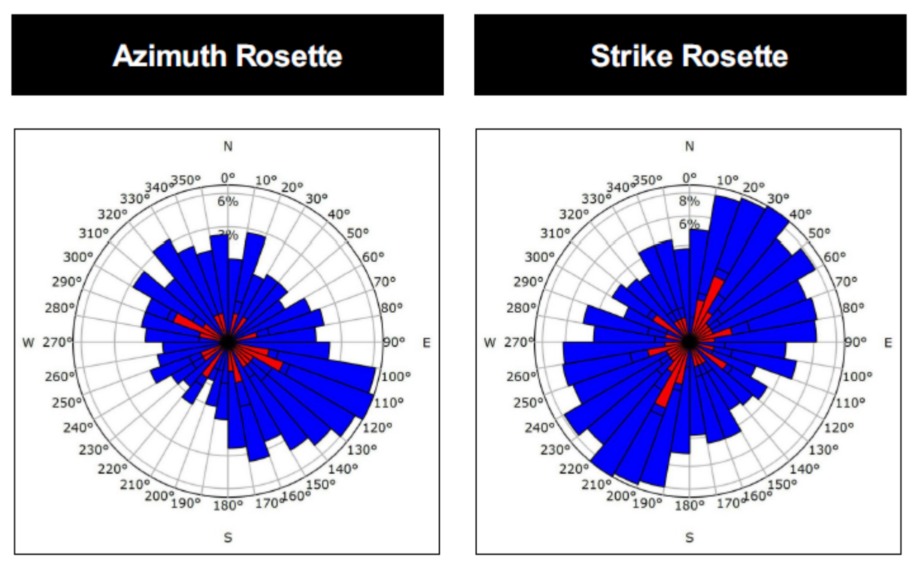
Borehole breakouts in shaly facies (higher GR reading) strike around NW-SE = Minimum HZ Stress.

1323-1317 ft. MD: Bedding is difficult to be recognized. These fractures may also be bedding.

- Example of borehole breakout in mudstone
- Strike of breakout is NW-SE
- Note coarse/pebbly sandstones containing resistive fragments

Baseline Formation Micro-Imager – October 2015

1



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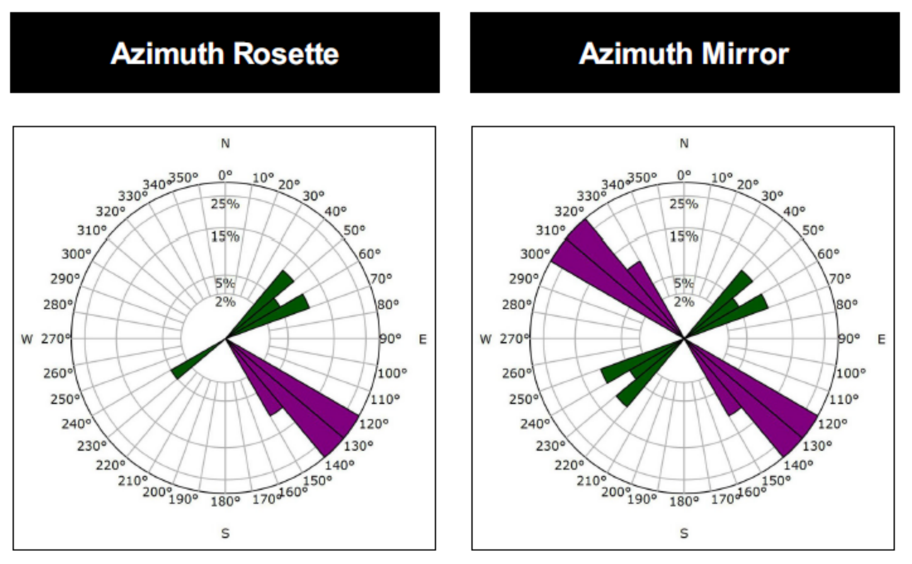
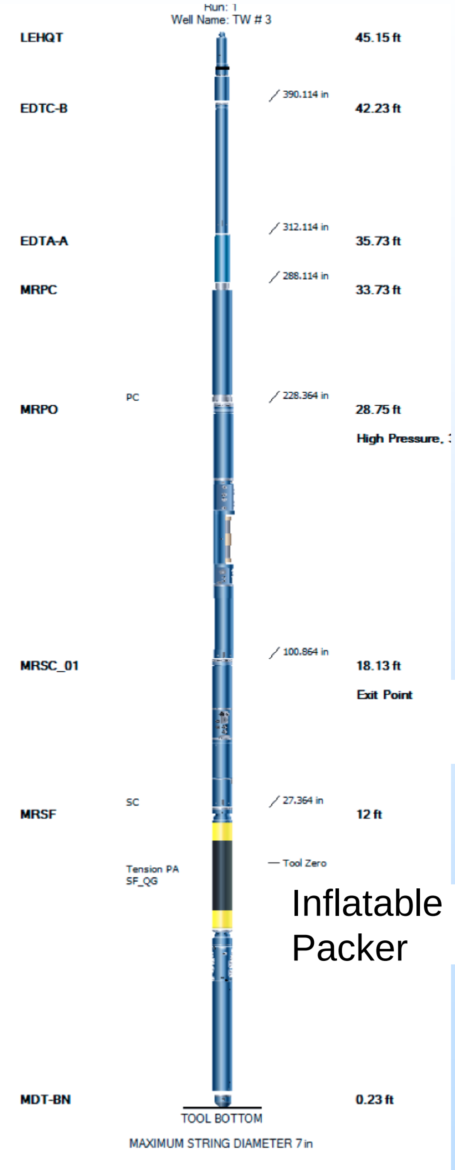


- (1) Open Fractures mainly confined in the interval from 825 to 1,175 feet – striking SW to NE
- (2) Tensile (green) drilling induced fractures are perpendicular to the borehole breakouts (purple)
- Implies that Maximum Horizontal Stress oriented SW-NE and Minimum Horizontal Stress oriented NW-SE

Formation Breakdown Testing with MDT Tool

- Statement of Technical Hurdle
  - In the deep ARRA Characterization Deep Borehole well, formation breakdown tests were attempted at 3,510 ft (maximum pressure 5,700 psi) and 2,927 ft (maximum pressure 5,500 psi), implies very high fracture pressures (gradients >1.6 psi/ft);
  - No breakdown observed at the upper-end MDT tool pressure limits
  - At the time, the tool packers could only hold ~4,000 psi differential pressure
- Improvements since the Characterization Deep Borehole
  - Addition of a Pre-stress Inflatable Packer to break down test intervals;
  - Enhanced MDT tool capabilities
  - Dedicated analysis software

Pre-Stress Sleeve Packer – 1,350 feet



Inflatable Packer

Pre-stress Packer Cycle

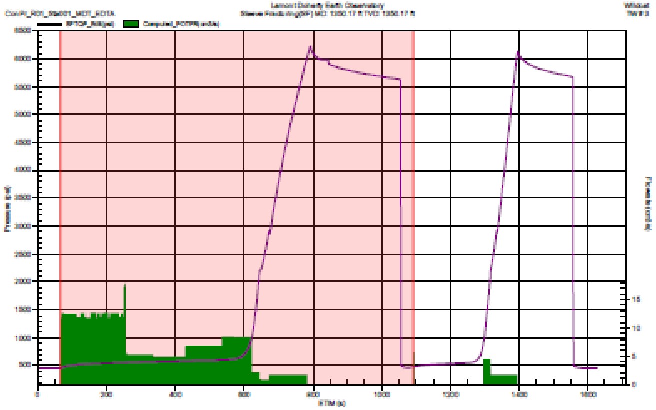
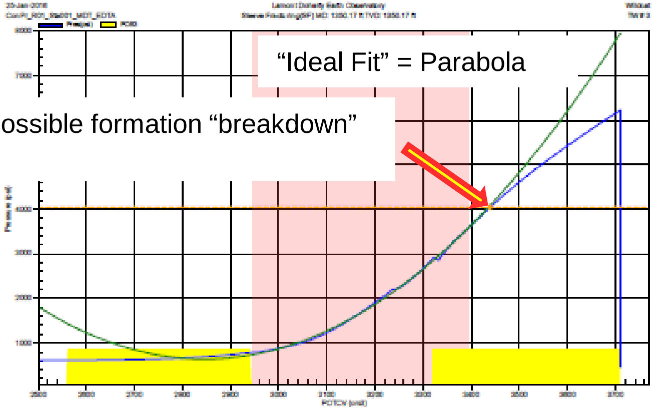


Figure 3 Cycle Interpretation Plot

Inflation Cycle



"Ideal Fit" = Parabola

Ideal Inflation is a parabola (green line)

Departure indicates possible formation "breakdown" at 4.034 psi

Figure 4 Inflation Plot

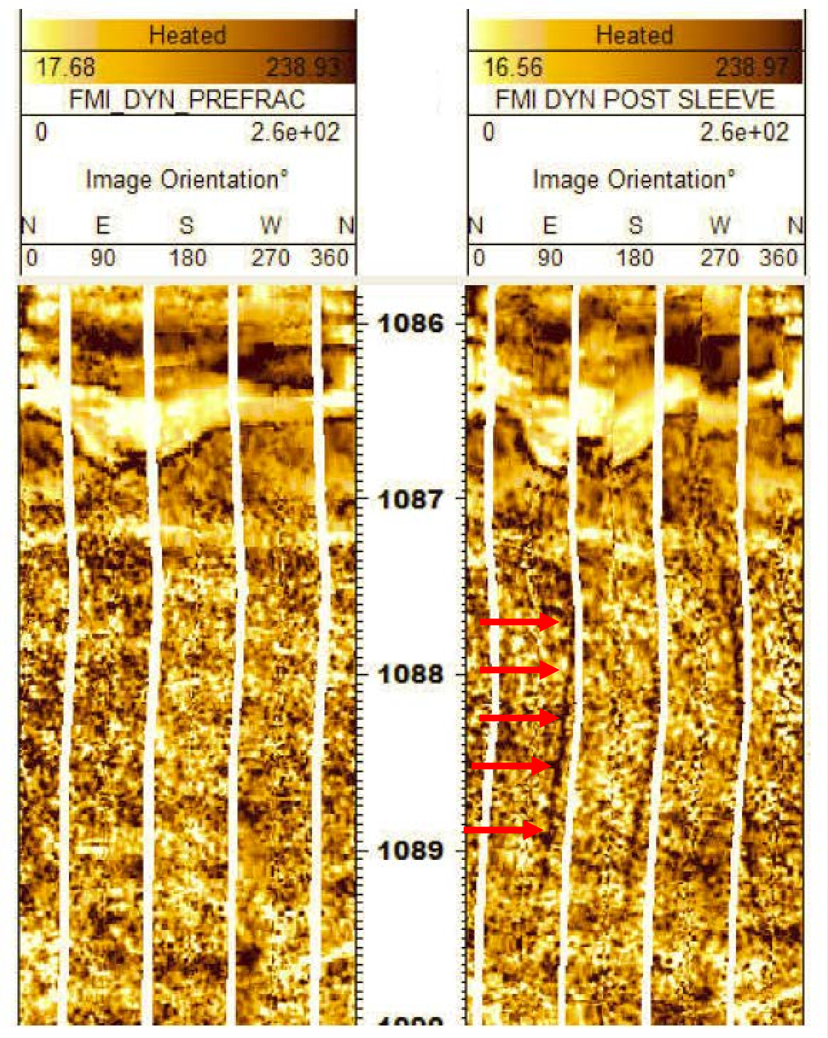
Table 2 Inflation Output Table

Parameter	Value
Pressure Type	
Volume (cm3)	3438.23
Time (seconds)	708.9
Pressure (psi)	4033.7

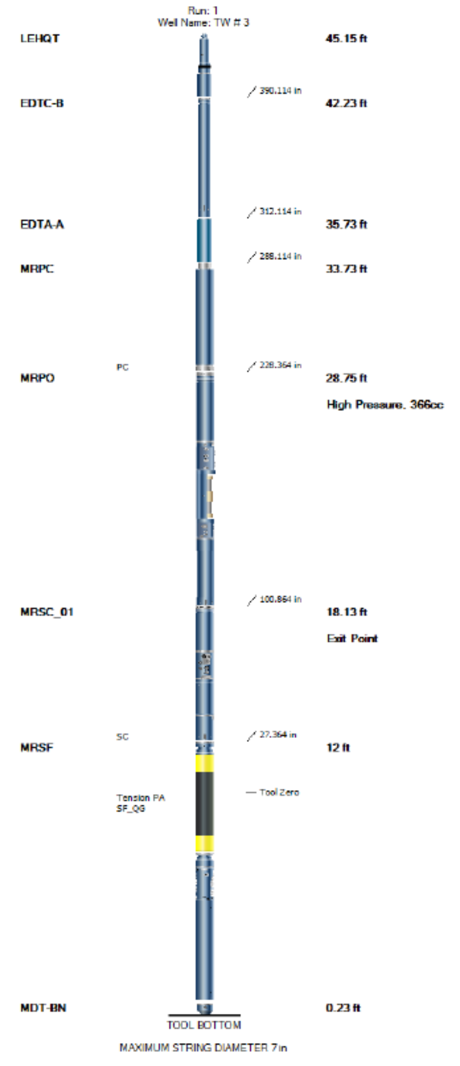
Pre-Stress Packer Summary

Pre-stress points based on unfractured “mudstones” on Open Hole Well Logs

Pre-stress packer sets run in one day (followed by Formation Microimager run)



Pre-Stress Packer Summary



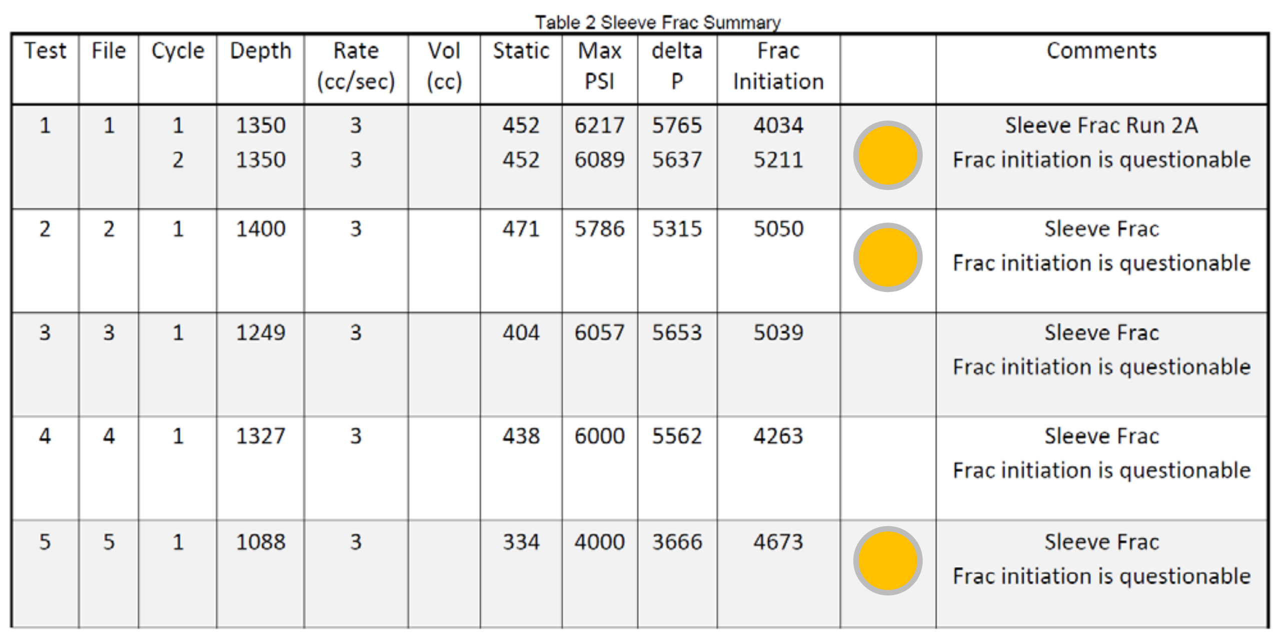


Table 2 Sleeve Frac Summary

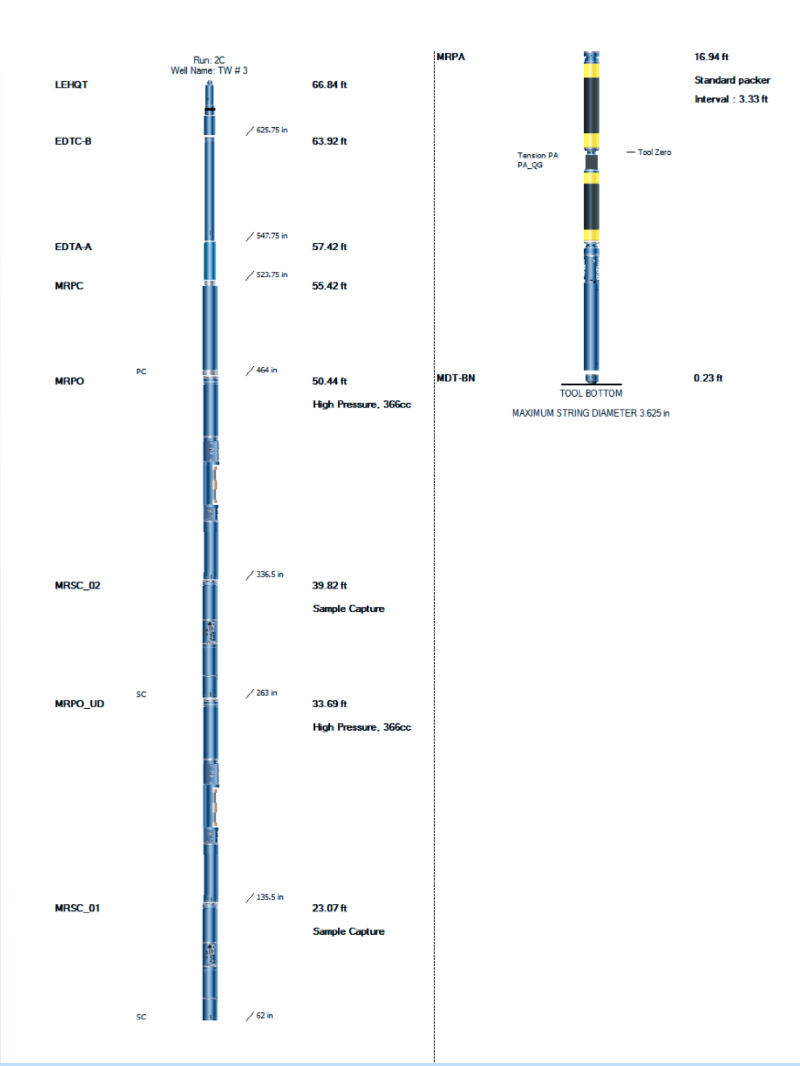
Test	File	Cycle	Depth	Rate (cc/sec)	Vol (cc)	Static	Max PSI	delta P	Frac Initiation		Comments
1	1	1 2	1350 1350	3 3		452 452	6217 6089	5765 5637	4034 5211	●	Sleeve Frac Run 2A Frac initiation is questionable
2	2	1	1400	3		471	5786	5315	5050	●	Sleeve Frac Frac initiation is questionable
3	3	1	1249	3		404	6057	5653	5039		Sleeve Frac Frac initiation is questionable
4	4	1	1327	3		438	6000	5562	4263		Sleeve Frac Frac initiation is questionable
5	5	1	1088	3		334	4000	3666	4673	●	Sleeve Frac Frac initiation is questionable

Tabulation of pre-stressed intervals with maximum inflate pressures (Max psi), delta P (psi), and estimate of breakdown

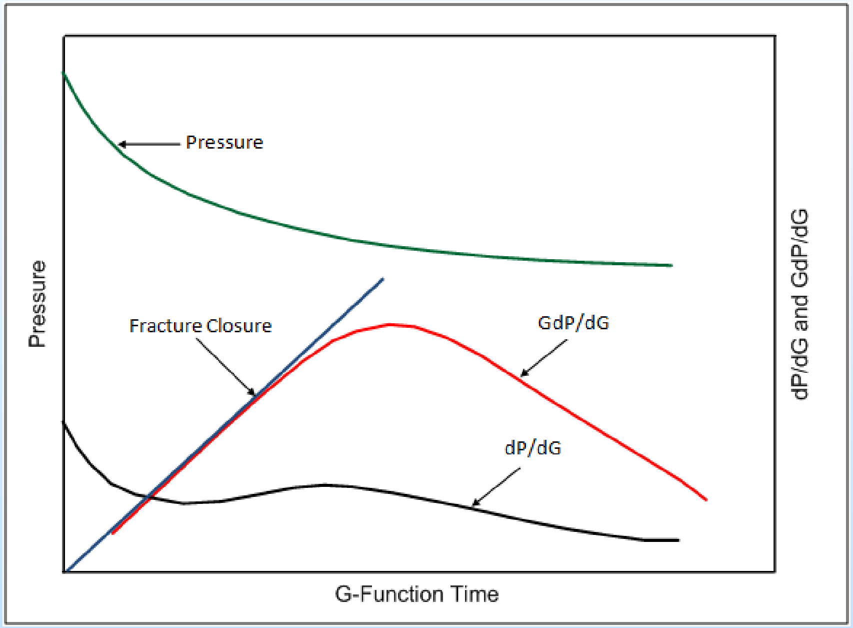
Circles show intervals tested to breakdown with MDT tool

Formation Breakdown Testing – MDT in Straddle Packer Mode

- Standard methodology available for some time
- Straddle-packers can now hold larger differential pressures, allows for greater buildup (pumping) pressures during testing
- Enhanced MDT pump can hold constant injection rates at varying pressures
- New analysis/software platform custom built for MDT Testing Services



Analysis Techniques of Formation Break-down Tests



Helpful References

- Barree, R.D., Barree, V.L., and Craig, D.P., 2007, Holistic fracture diagnostics, SPE 107877
- Bachman, R.C., Walters, D.A., Hawkes, R.A, Toussaint, F., and Settari, A., Reappraisal of the G Time concept in Mini-frac analysis, 2012, SPE 160169
- http://www.fekete.com/SAN/TheoryAndEquations/WellTestTheoryEquations/Leakoff_Types.htm

Square-Root of Time Analysis

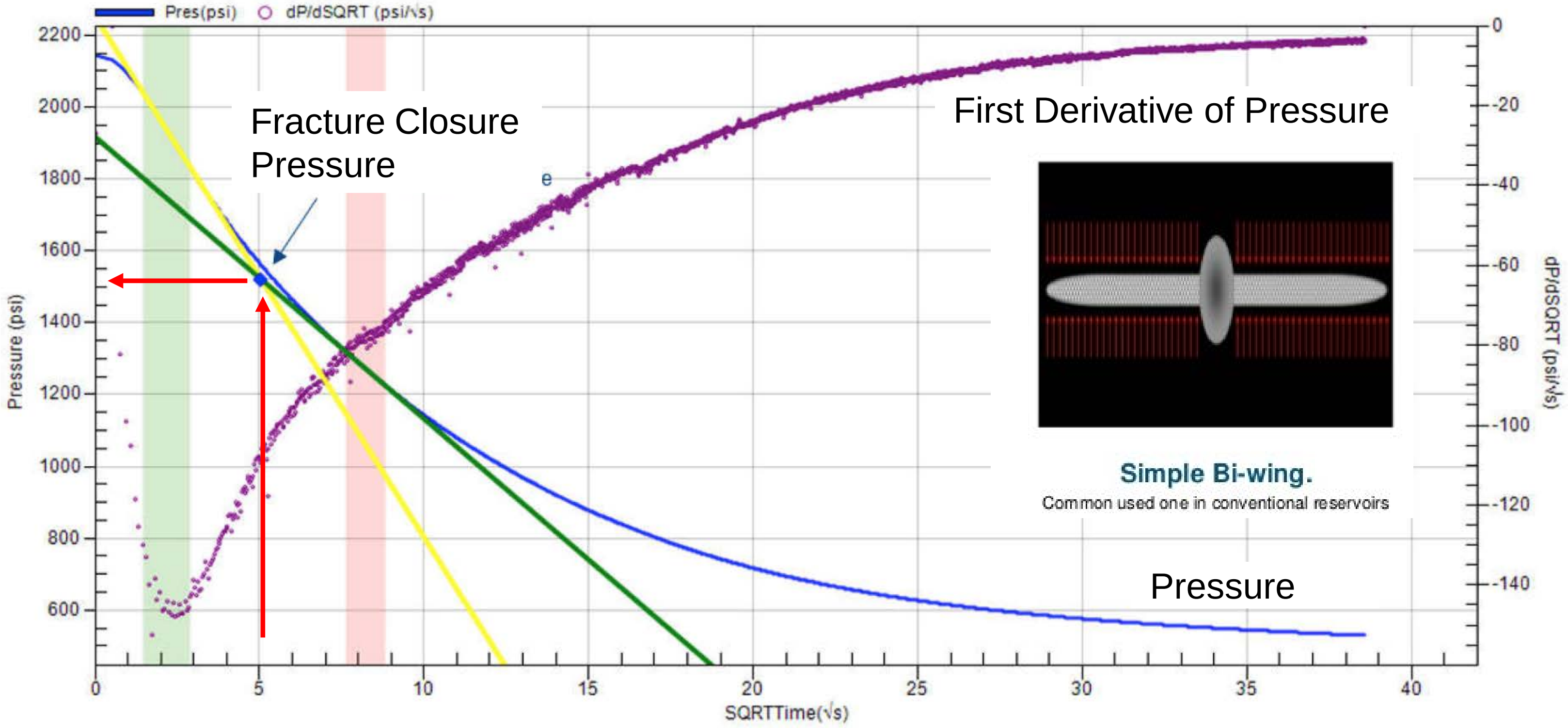
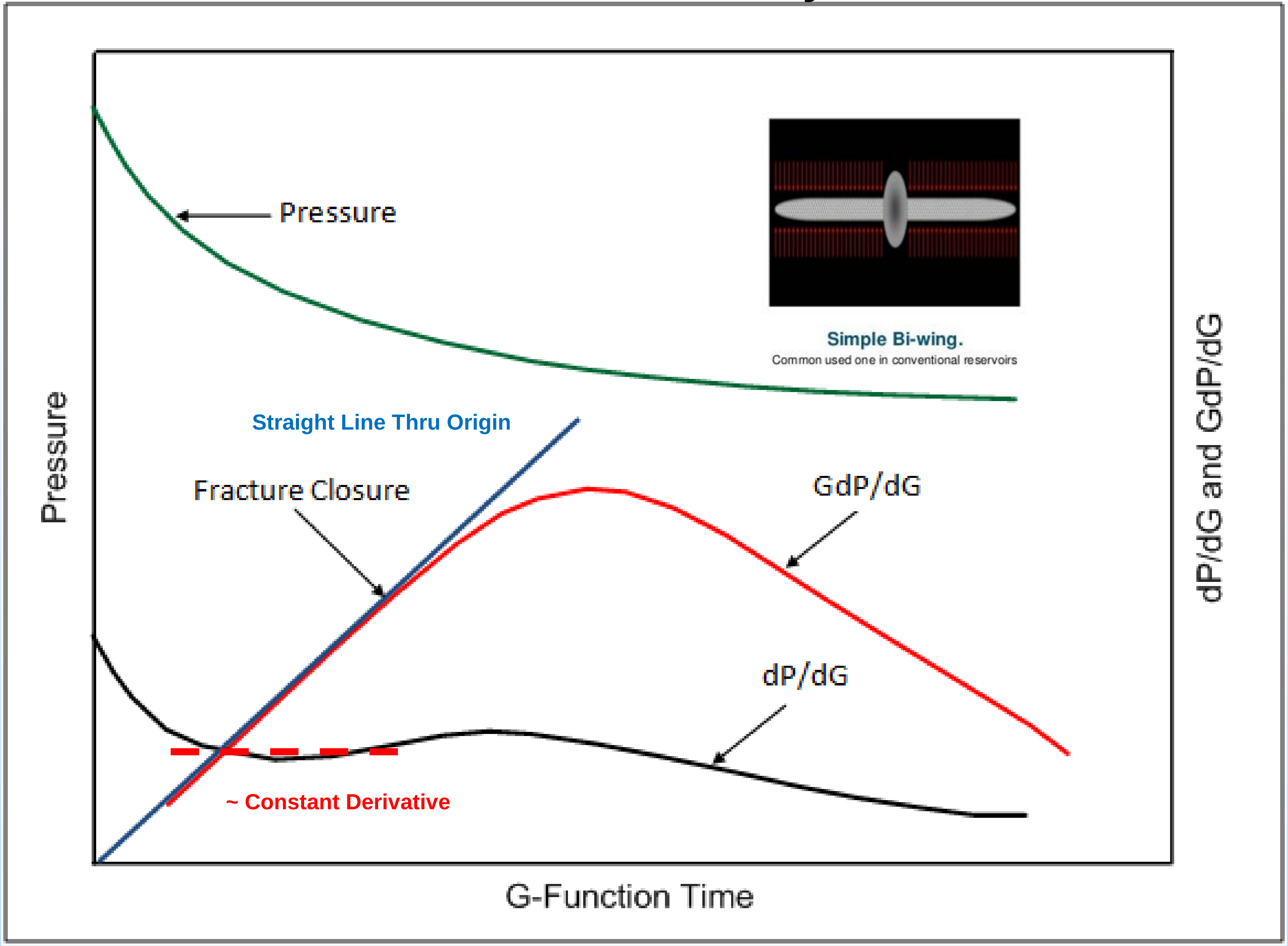


Figure 2: Square root time analysis plot. The rate of pressure decrease before the fracture closes should be higher than following. In this example the pressure derivative does show a rate change around 5 $\sqrt{s}$ which also corresponds to the intersection of the linear fit to the pressure lines before and after fracture closure. The estimated fracture closure pressure would be 1,520 psi.

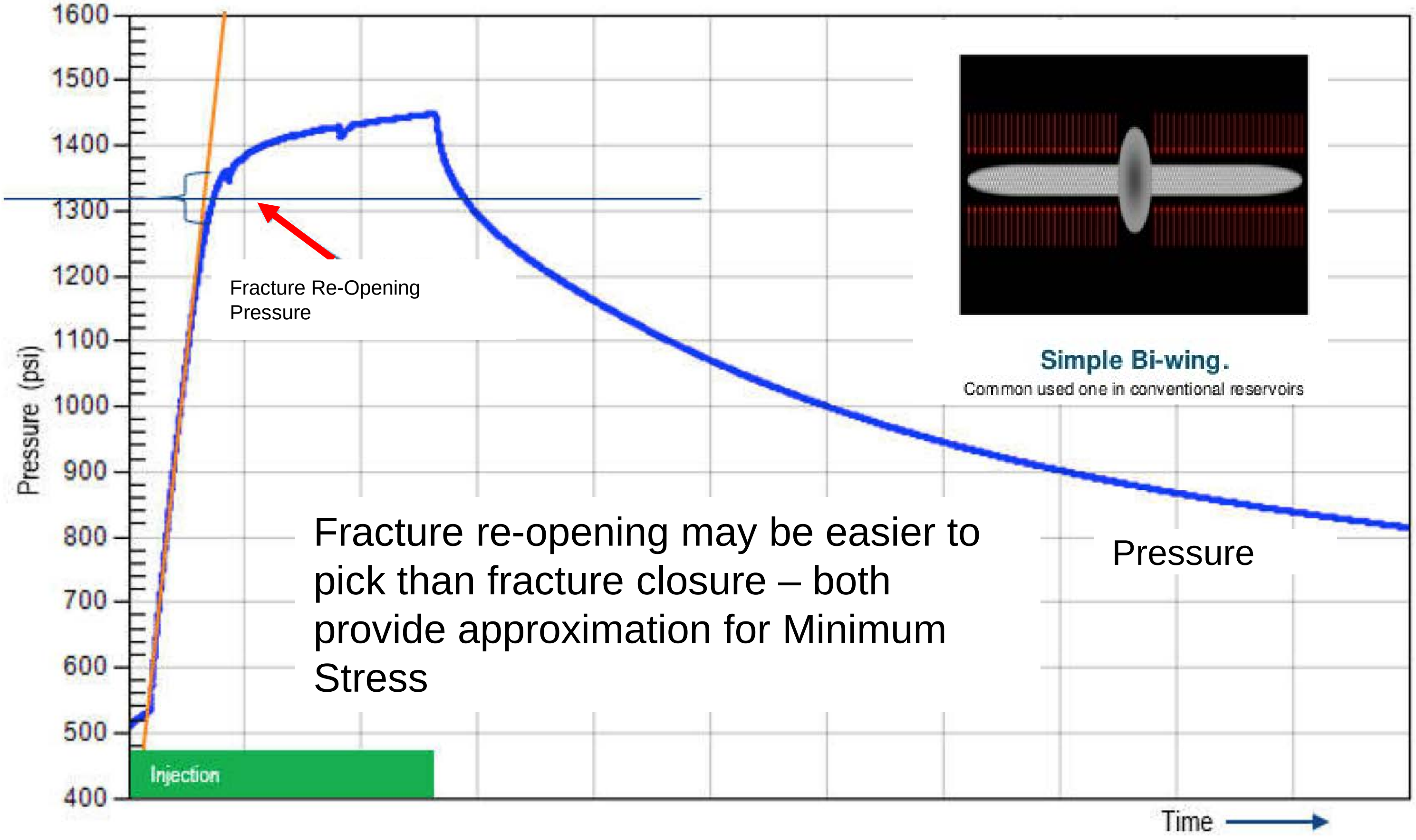
G-function Analysis



http://www.fekete.com/SAN/TheoryAndEquations/WellTestTheoryEquations/Leakoff_Types.htm

Fracture Re-Opening Analysis

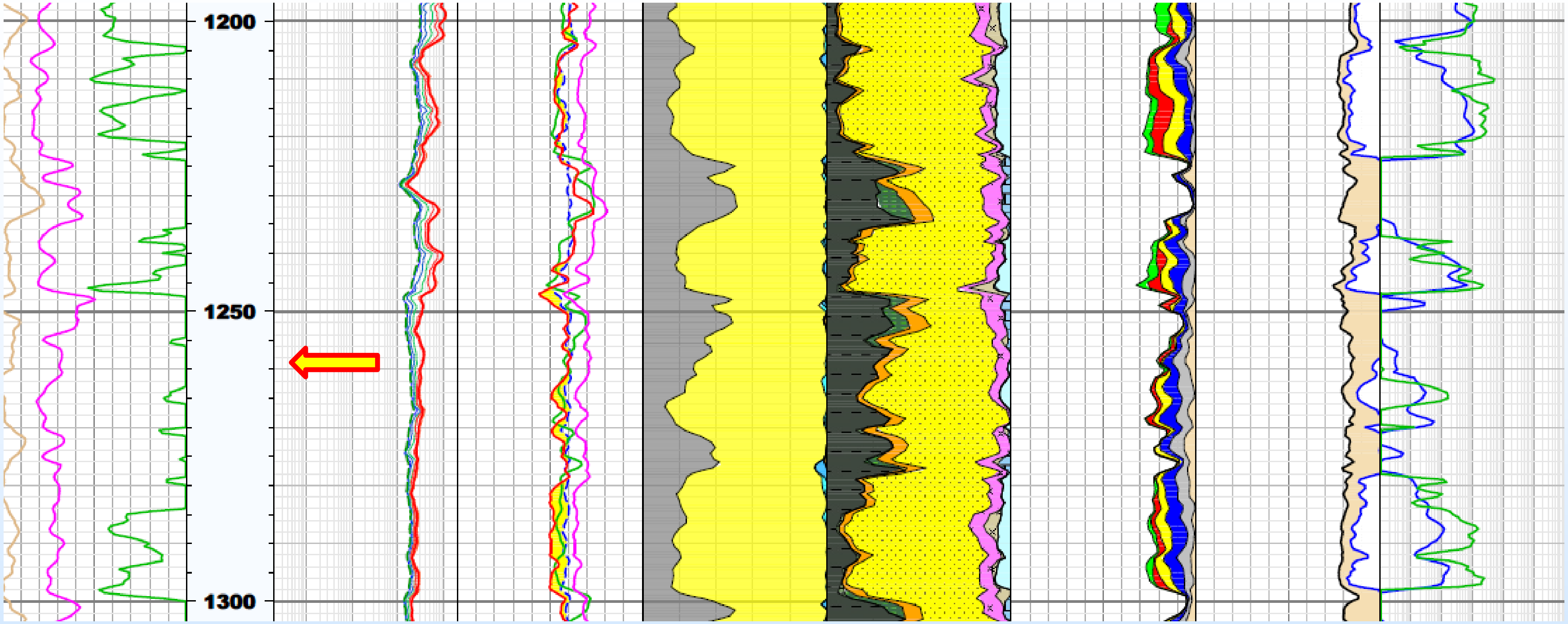
Fracture re-open pressure is picked from an injection cycle after a fracture has been initiated or when there is an existing fracture. The fracture re-open pressure can sometimes be a more reliable way to pick the minimum stress as it does not have some of the complications of various leakoff mechanisms. Figure 4 shows the fracture re-open pressure picked from an injection cycle.

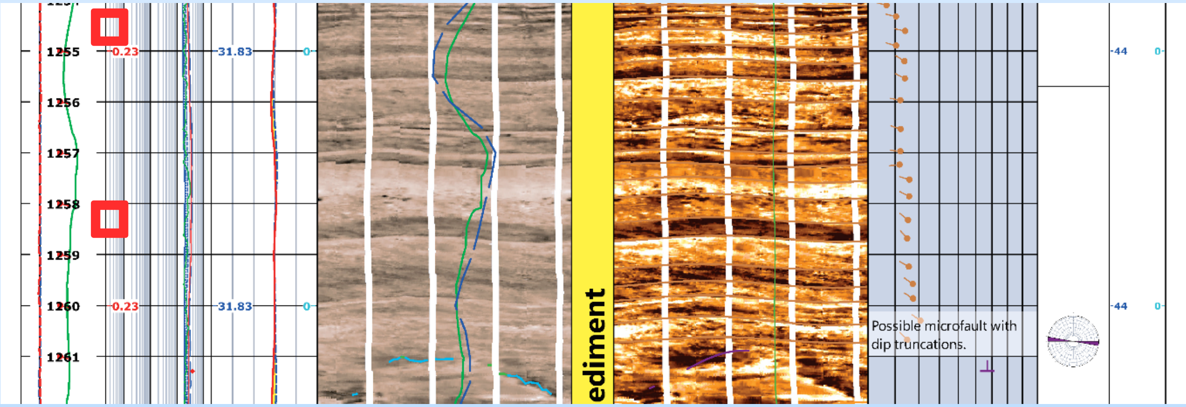


Fracture Re-Opening Pressure

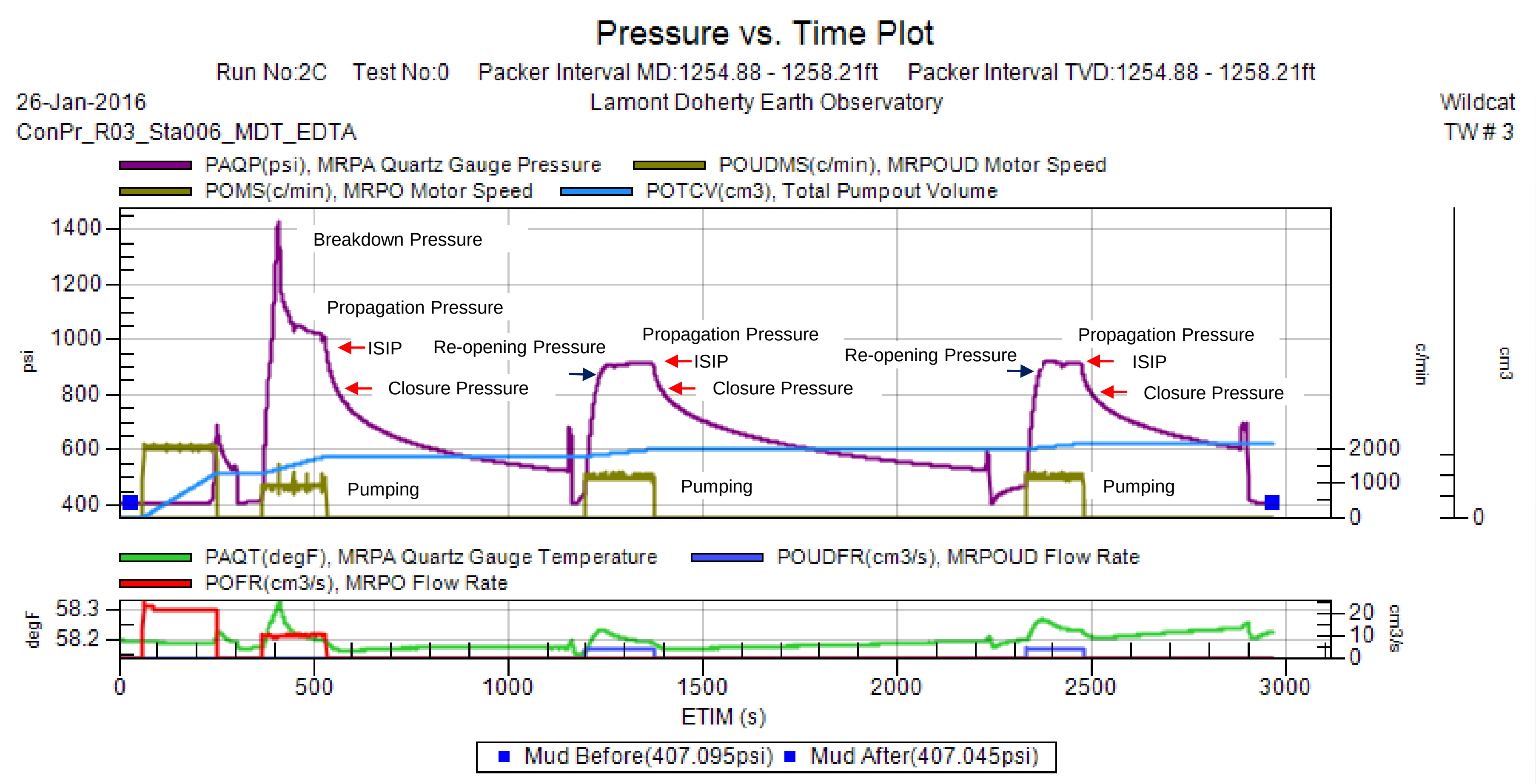
Fracture re-opening may be easier to pick than fracture closure – both provide approximation for Minimum Stress

1,257-Foot Test Interval



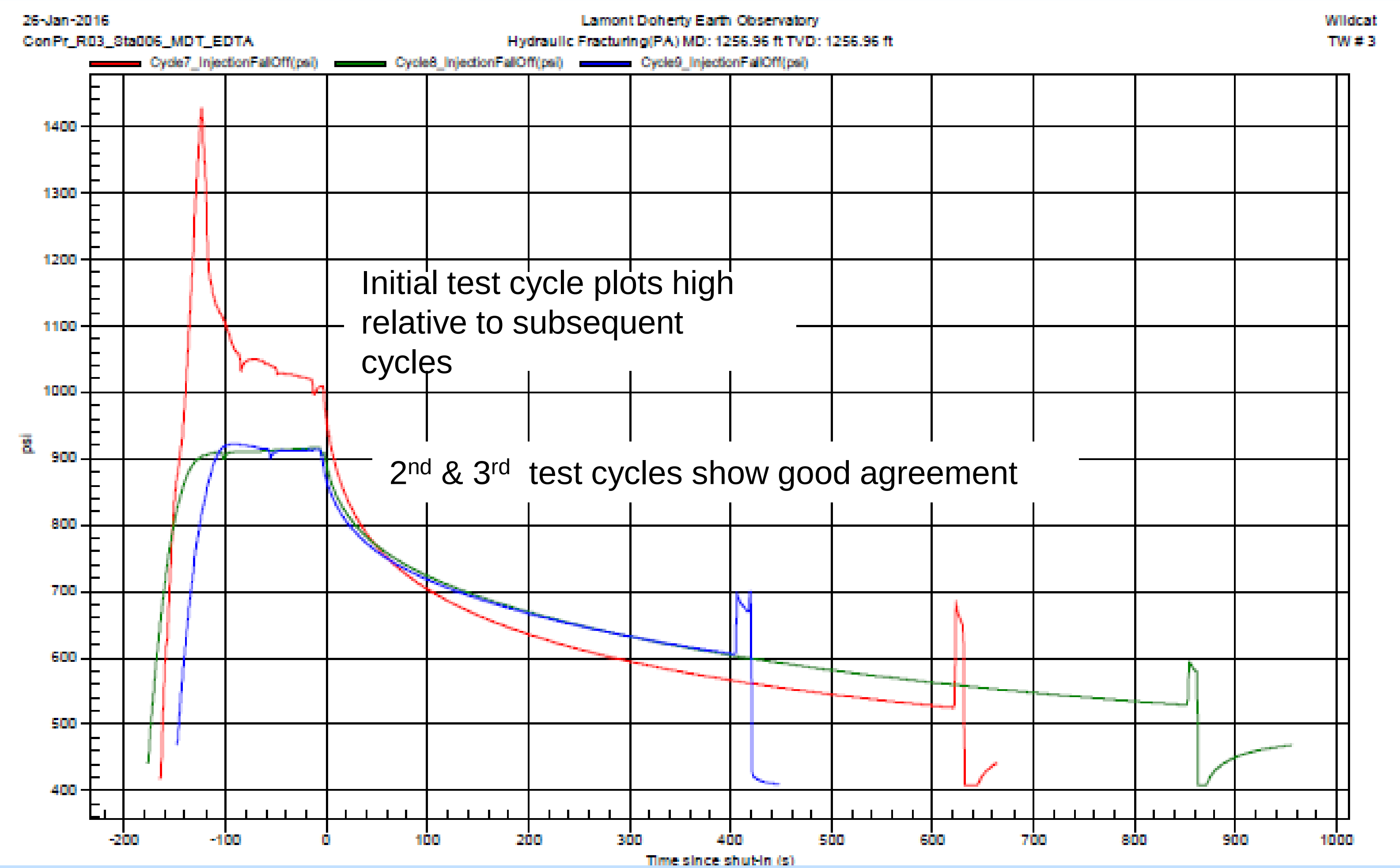


Breakdown Testing at 1,257 feet



"Text Book" Test

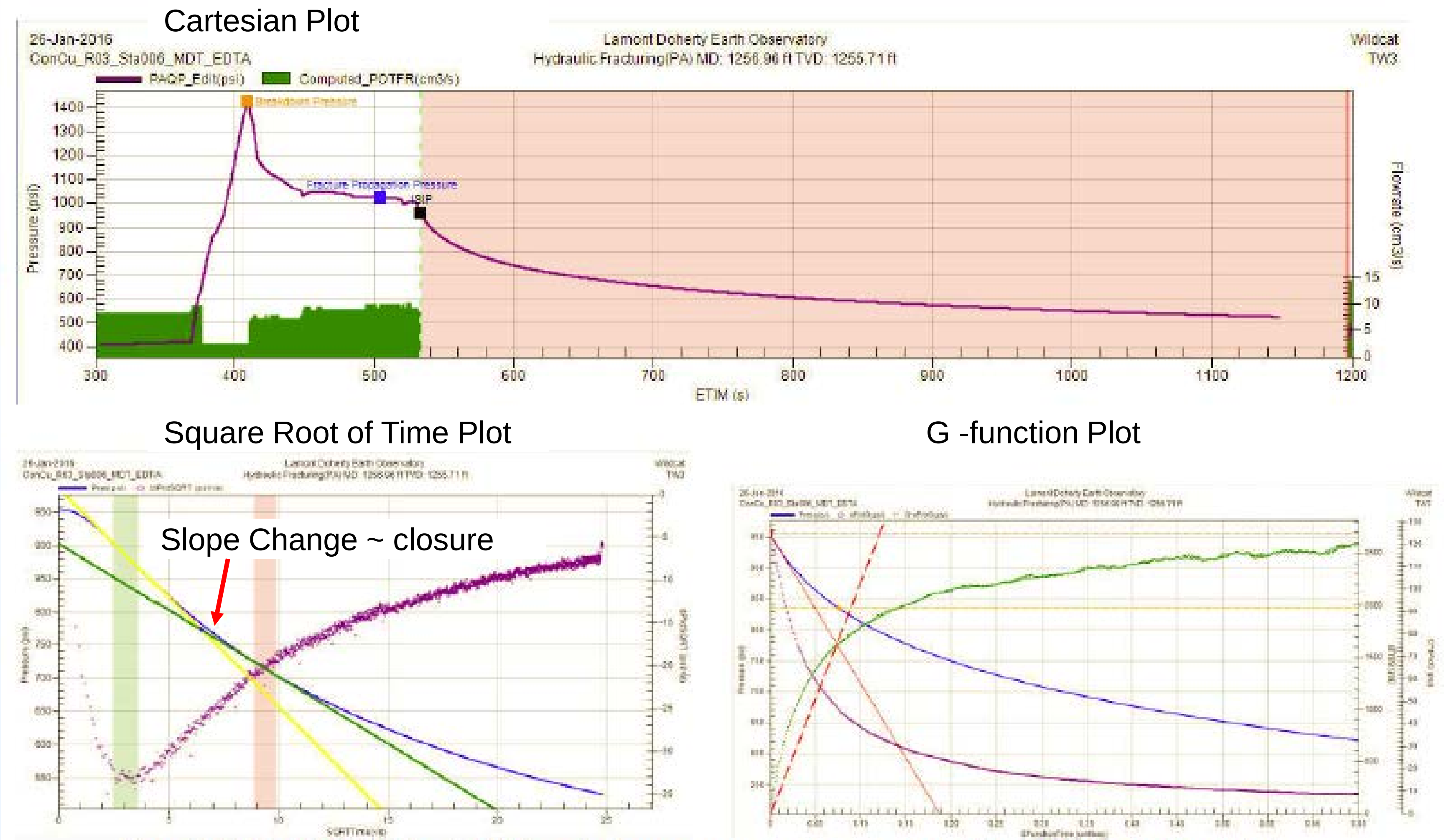
Cycle Comparison at 1,257 Feet



Initial test cycle plots high relative to subsequent cycles

2nd & 3rd test cycles show good agreement

Analysis of Cycle 1 at 1,257 Feet


Cartesian Plot

Square Root of Time Plot

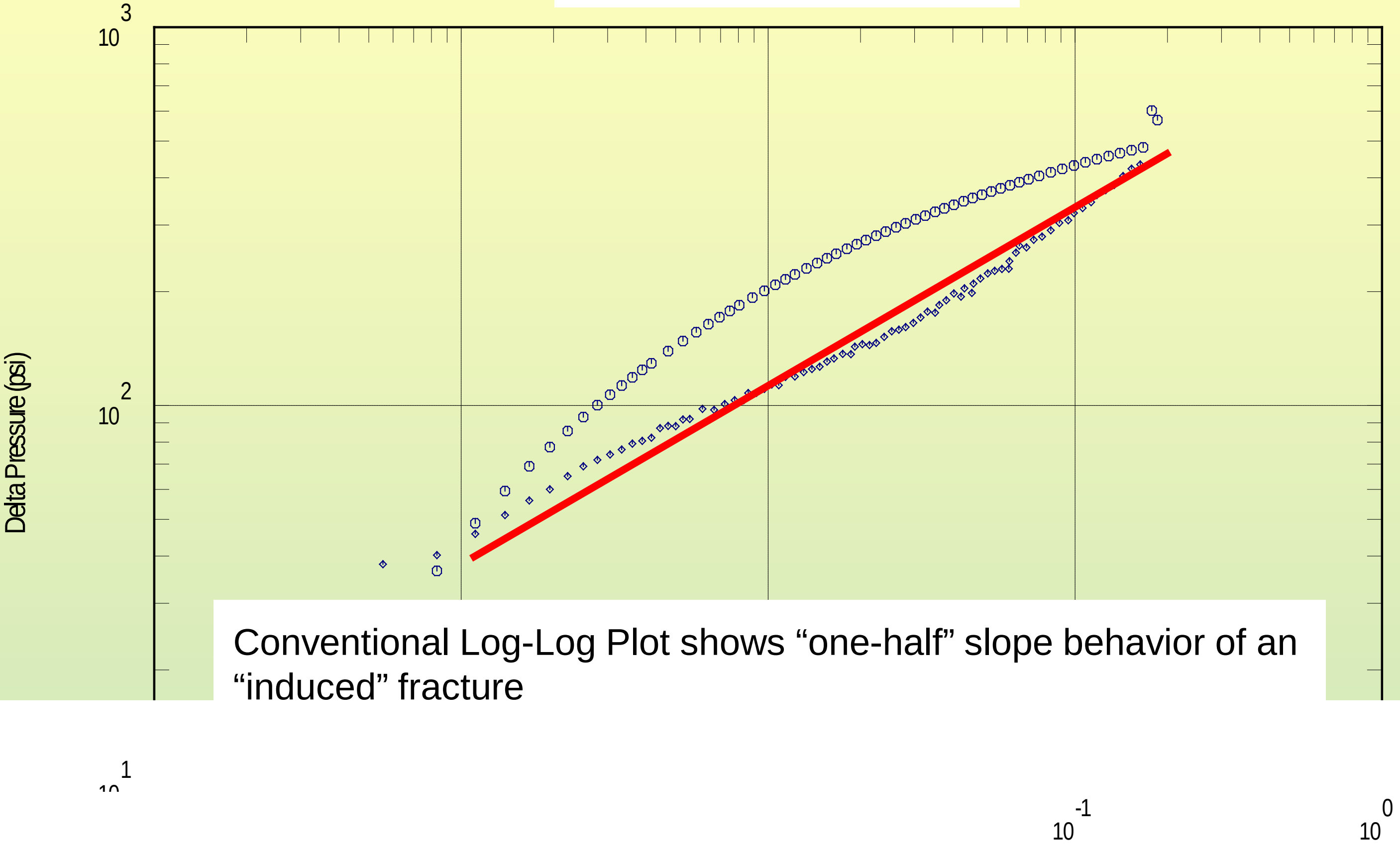
G -function Plot

Slope Change ~ closure

Figure 14: MDT-DP Microfrac 1,257 ft. cycle 1 pressure response, square root time and G-function analysis

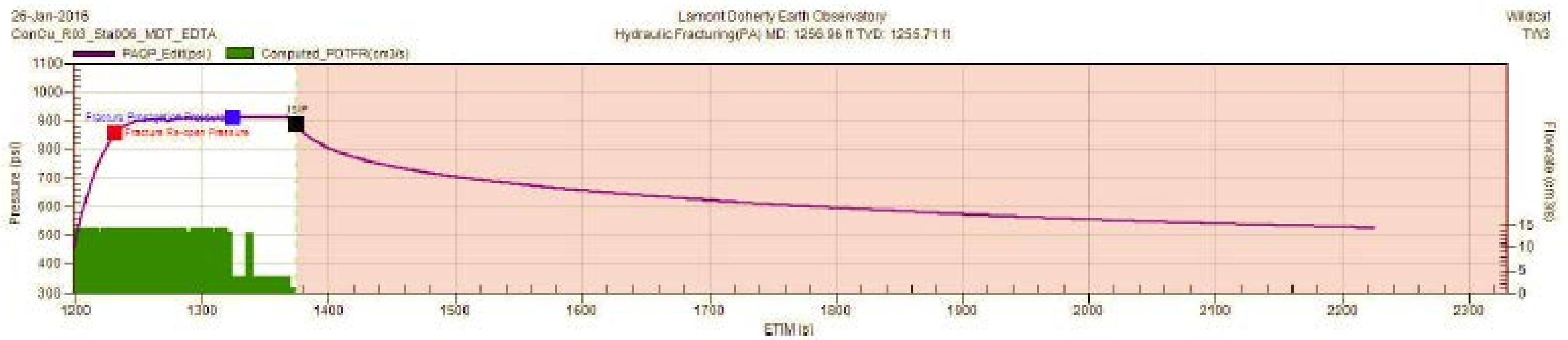
Analysis of Cycle 1 at 1,257 Feet

Transient Log-Log Plot



Conventional Log-Log Plot shows “one-half” slope behavior of an “induced” fracture

Analysis of Cycle 2 at 1,257 Feet



Square Root of Time Plot

G -function Plot

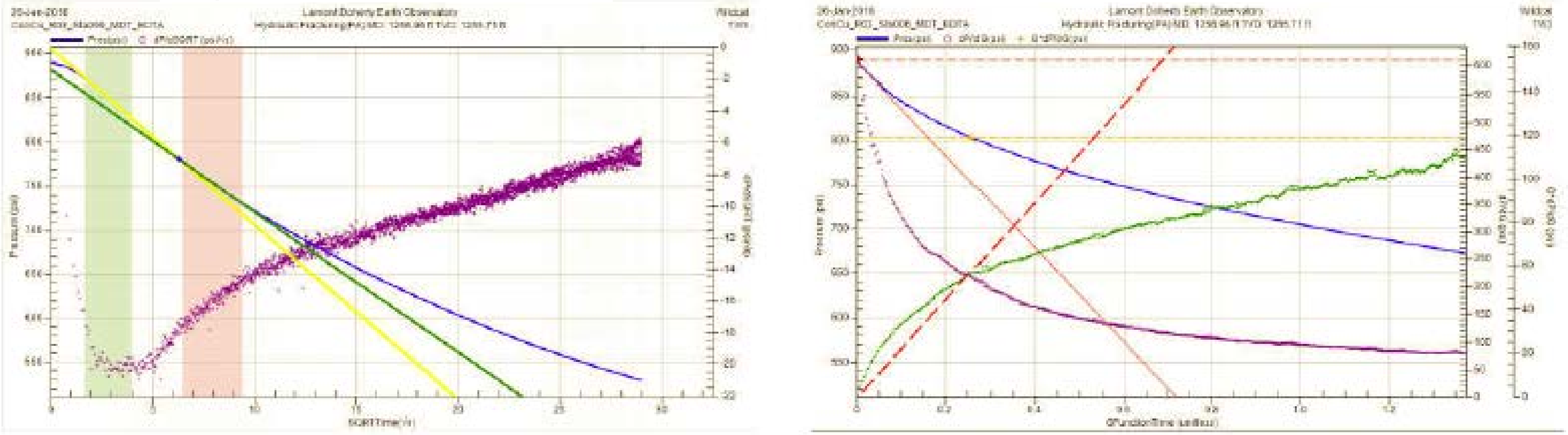
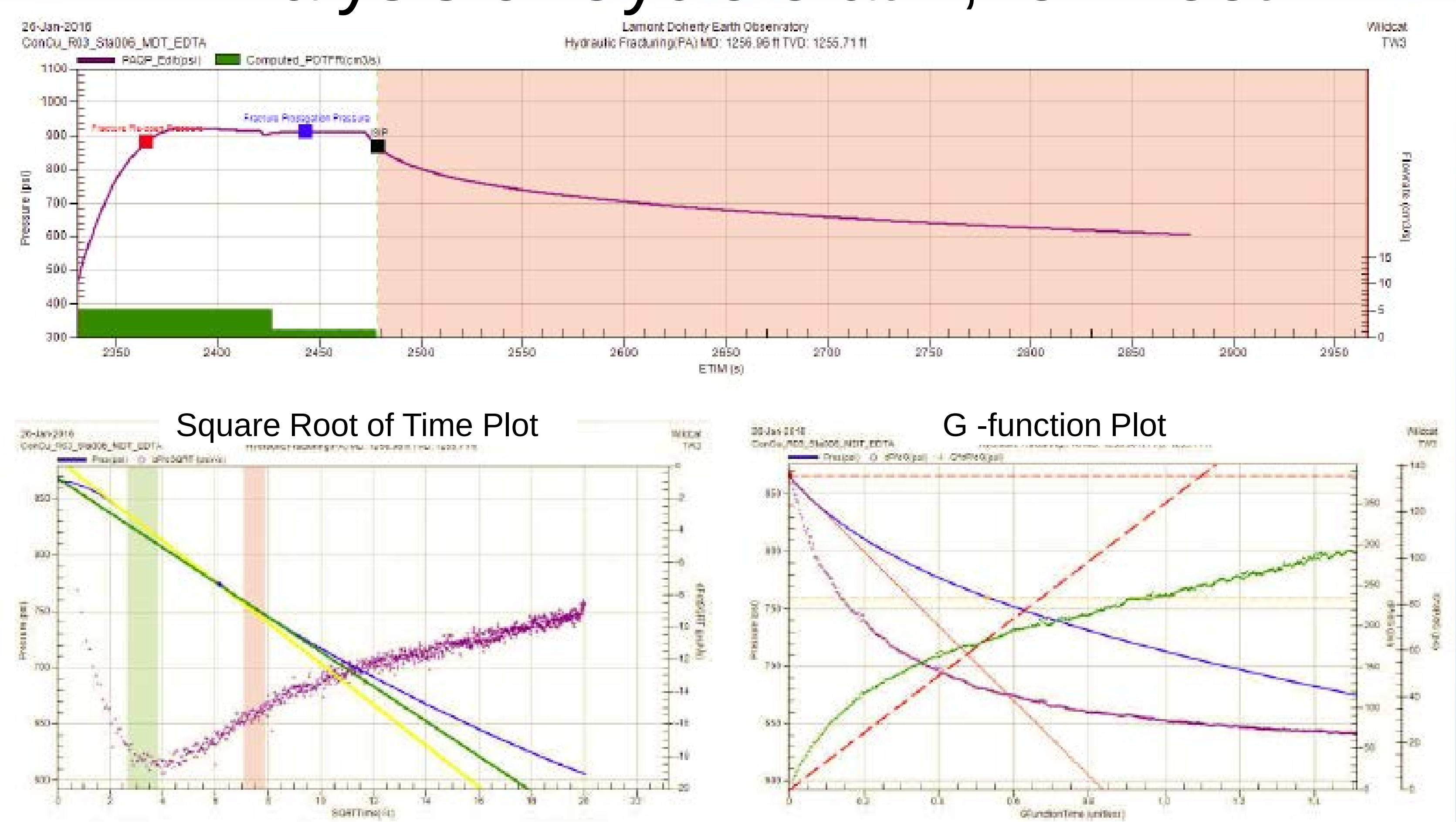


Figure 15: MDT-DP Microfrac 1,257 ft. cycle 2 pressure response, square root time and G-function analysis

Analysis of Cycle 3 at 1,257 Feet

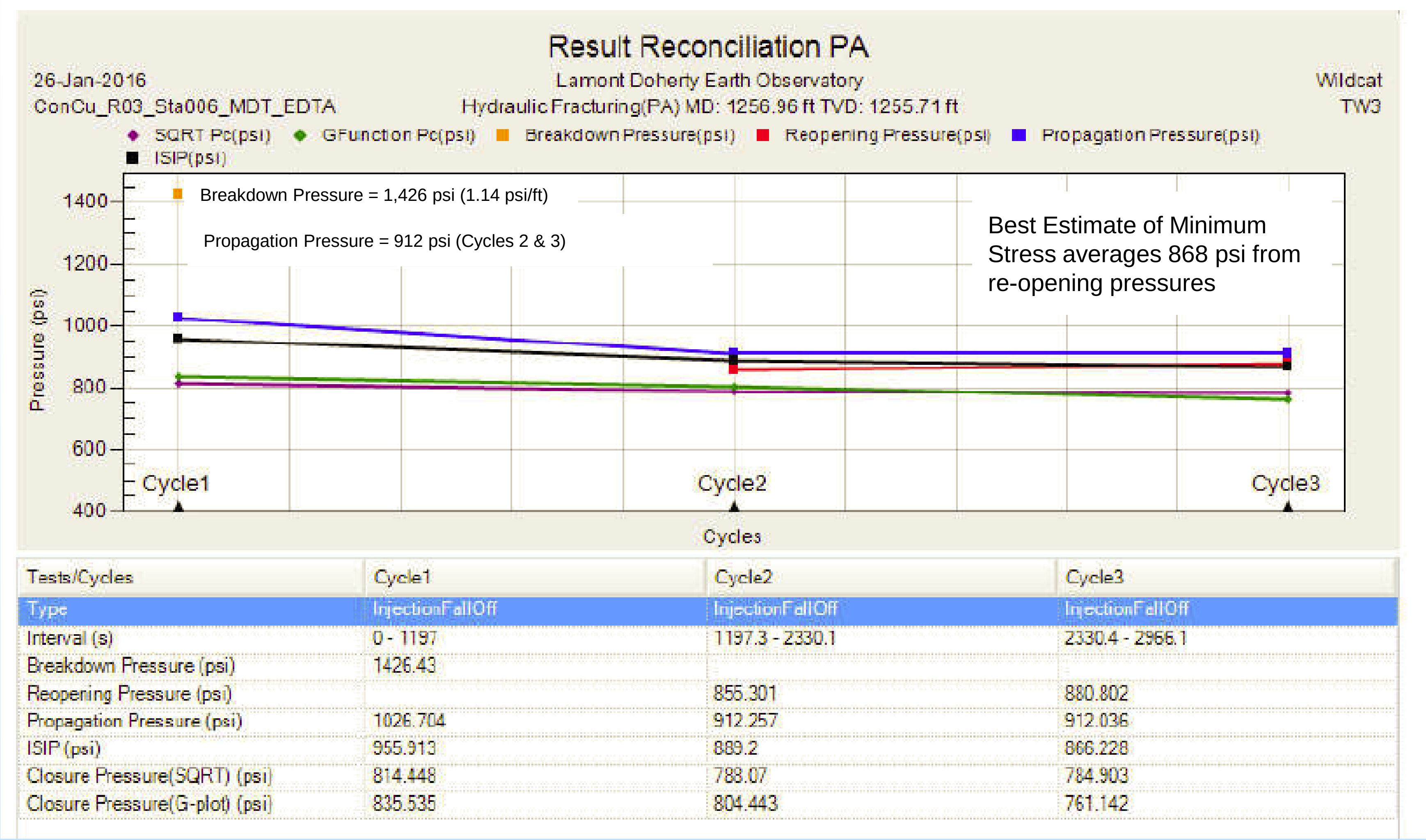


Square Root of Time Plot

G -function Plot

Figure 16: MDT-DP Microfrac 1,257 ft. cycle 3 pressure response, square root time and G-function analysis

Reconciliation at 1,257 Feet



Result Reconciliation PA

26-Jan-2016
ConCu_R03_Sta006_MDT_EDTA

Lamont Doherty Earth Observatory
Hydraulic Fracturing(PA) MD: 1256.96 ft TVD: 1255.71 ft

Wildcat
TW3

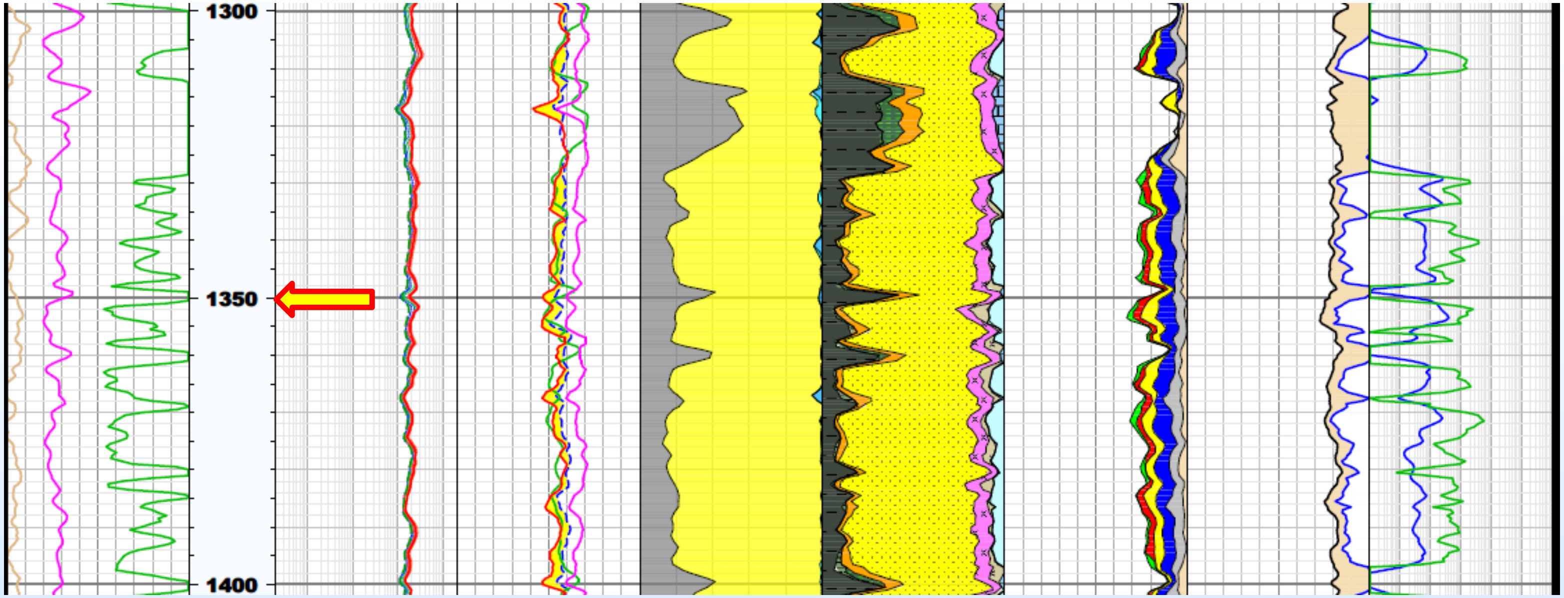
■ Breakdown Pressure = 1,426 psi (1.14 psi/ft)

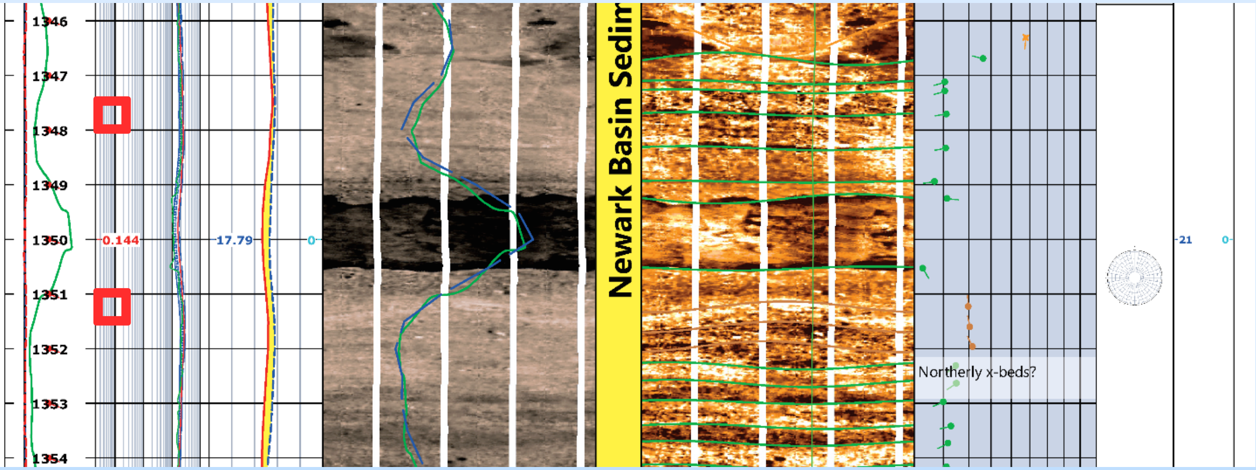
Propagation Pressure = 912 psi (Cycles 2 & 3)

Best Estimate of Minimum Stress averages 868 psi from re-opening pressures

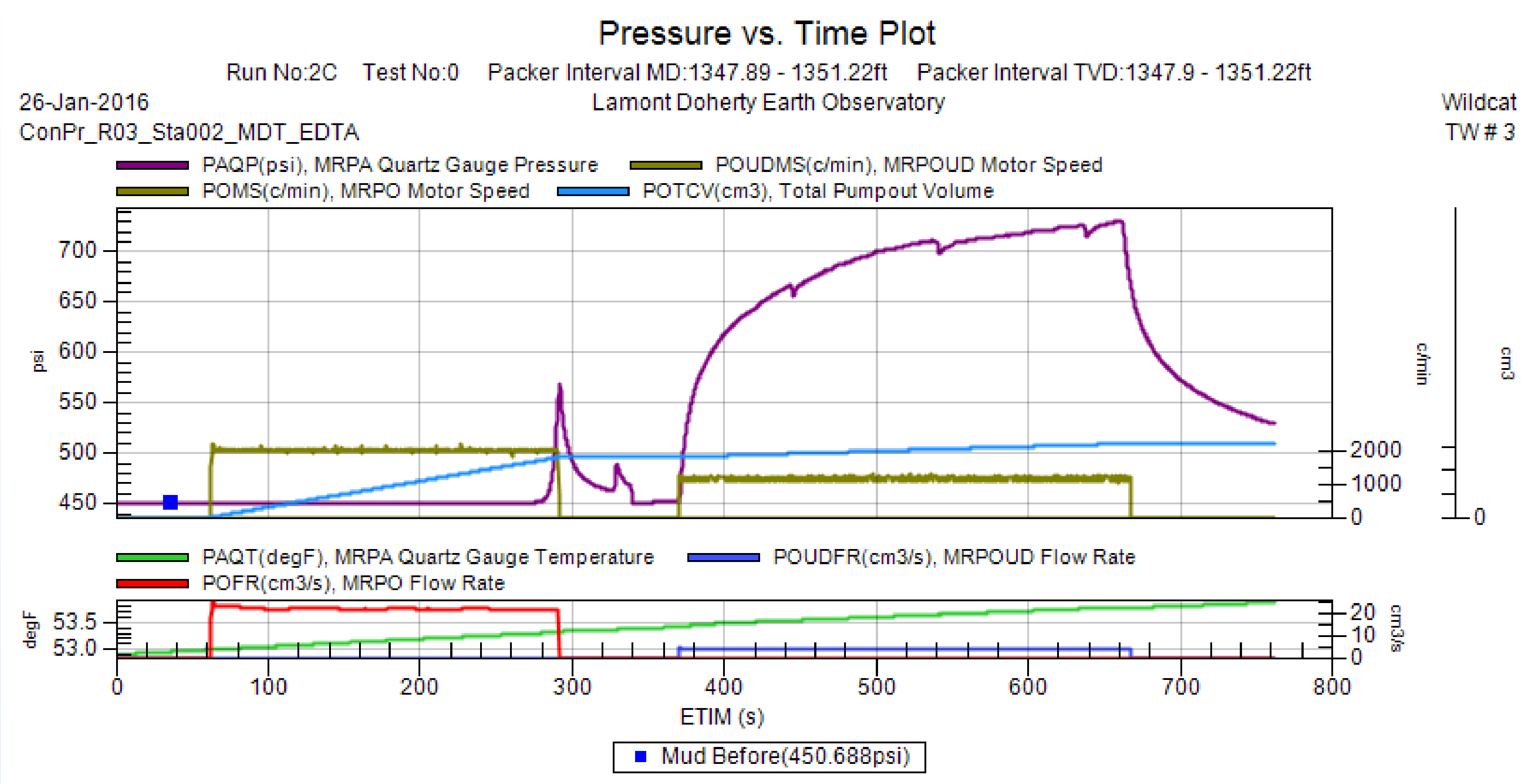
Tests/Cycles	Cycle1	Cycle2	Cycle3
Type	InjectionFallOff	InjectionFallOff	InjectionFallOff
Interval (s)	0 - 1197	1197.3 - 2330.1	2330.4 - 2966.1
Breakdown Pressure (psi)	1426.43		
Reopening Pressure (psi)		855.301	880.802
Propagation Pressure (psi)	1026.704	912.257	912.036
ISIP (psi)	955.913	889.2	866.228
Closure Pressure(SQRT) (psi)	814.448	788.07	784.903
Closure Pressure(G-plot) (psi)	835.535	804.443	761.142

1,350-Foot Test Interval





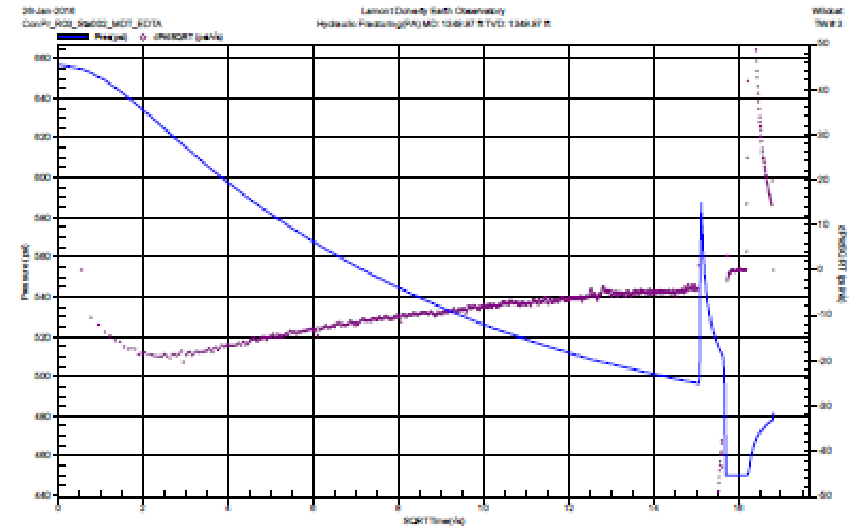
Formation Breakdown Testing – 1,350 Feet



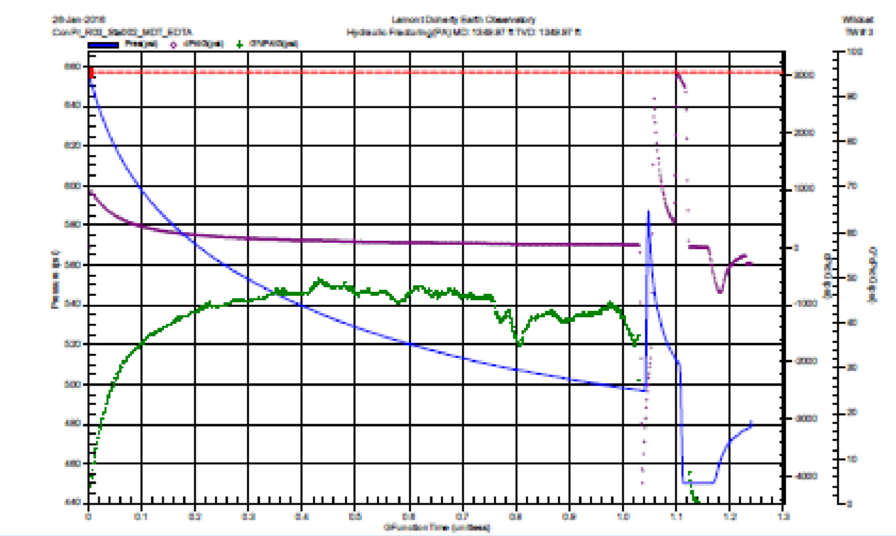
Appears to be Matrix Injection – No Breakdown

Formation Breakdown Testing – 1,350 Feet

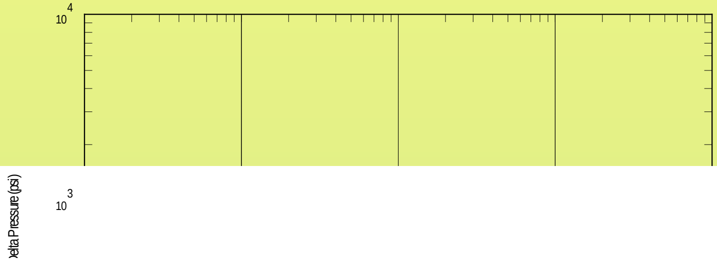
Square Root of Time Plot



G-function Plot



Transient Log-Log Plot



No evidence of breakdown
Permeability +/- 1 md

Conventional Log-Log Plot shows no “one-half” slope behavior typical of an “induced” fracture

GEOSTOCK SANDIA
ENTREPOSE

Formation Breakdown Test Summary

Depth	Breakdown (psi)	Minimum Stress (psi)	Uncertainty Range (psi)
1,232	N/A	1,030	900 – 1,100
1,257	1,426	868	800 – 900
1,400	1,900	1,567	1,140 – 2,075
1,469	1,901	1,319	1,175 – 1,375

Two tests (1,257 & 1,469') showed "Text Book" evidence of breakdown
Two tests (1,232 & 1,400') showed "fracture" behavior
Two tests (1,088 & 1,350') showed "Matrix Injection"

Accomplishments to Date

- Characterization and Geomechanical testing of the LDEO Test Well No. 4 Core & Newark Basin Core is Complete (BP1)
- Baseline Formation MicroImager Log run in October 2015
- Formation pre-stress and formation breakdown testing run in January 2016
- Post stress and after breakdown Formation MicroImager run in January 2016
- Evaluation of formation breakdown testing completed in August 2016
- Project Data entered into Petrel

Synergy Opportunities

- – Project has collecting characterization and geomechanical dataset in lithified mudstones - raw data can be shared with other projects
- – Experience/Lessons Learned with wireline conveyed formation breakdown testing can be shared with other projects
- – Abstract “Mechanical Stability of Fractured Rift Basin Mudstones: from lab to basin scale” submitted to AGU for Fall Conference – Will know in October

Summary

– Key Findings

- Large range of strength (8,000-50,000 psi for projected UCS) and coefficient of friction (0.5-1), even in similar rock types
- Pre-stress packer is can produce initial breakdown in a formations with similar characteristics to Newark Basin
- Enhanced MDT tool provides greater operational flexibility in measuring stresses in an open borehole
- MDT tool provides efficient field testing operations
- Average horizontal stress direction is consistent throughout the Newark basin, but significant stress variations with depth exist at multiple scales

Summary

- Lessons Learned – Formation Breakdown Testing
  - Pre-stress packer is capable of producing initial breakdown in a formation
  - However, breakdown features may be elusive, even in “known” breakdown intervals
  - Build flexibility into testing program – six tests run in one daylights day.
  - Pressure leak-offs following shut-in may be quick and pressure v √Sqrt of Time analysis may have high uncertainty (several 100s psi). Re-opening pressure may be more reliable indicator for minimum stress.

Summary

– Future Plans
  - Complete data reduction, analysis, and data integration
  - Develop Earth Model

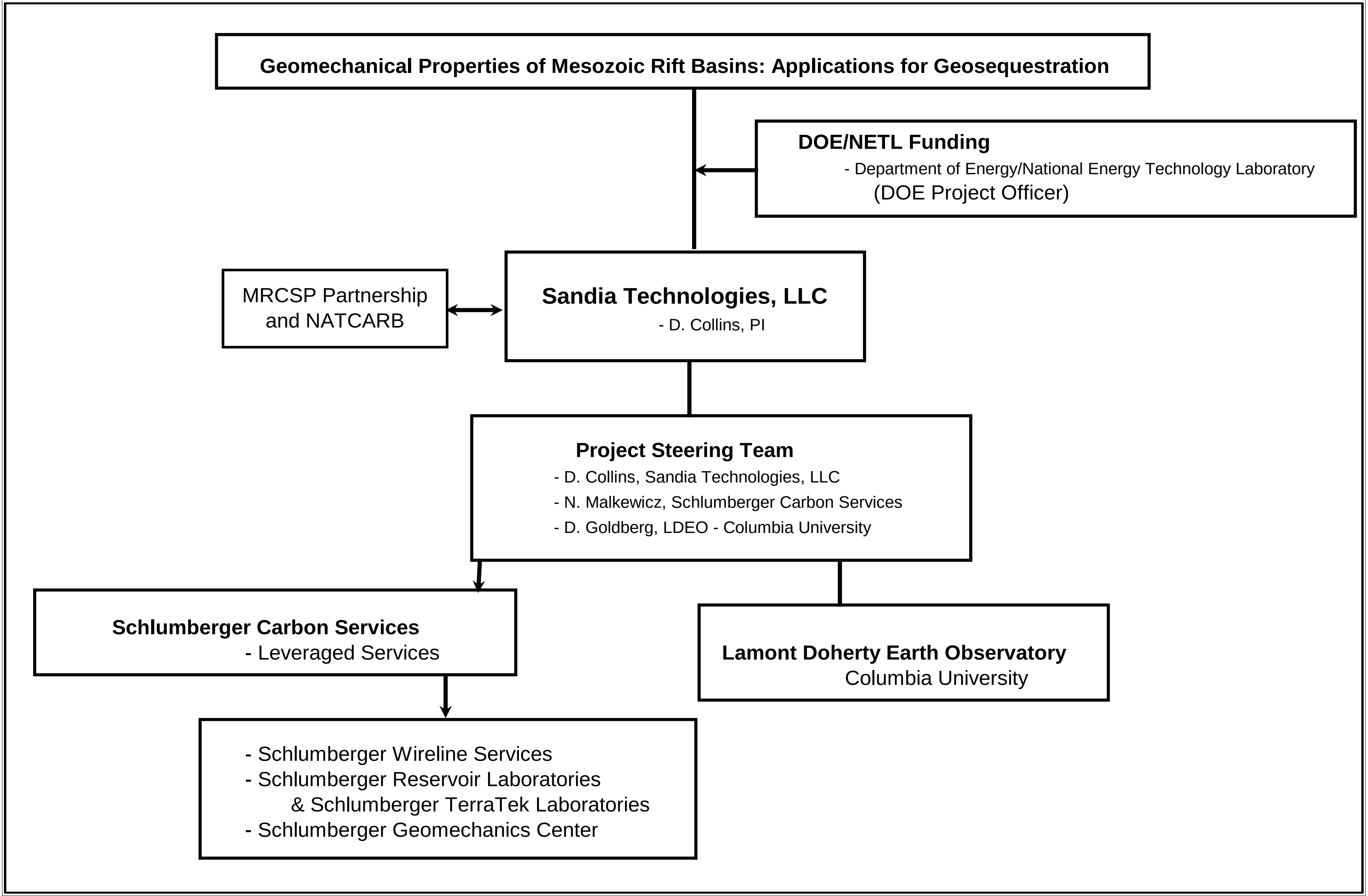
Questions?

End

Appendix

- These slides will not be discussed during the presentation, but are mandatory

Project Organizational Chart



Geomechanical Properties of Mesozoic Rift Basins: Applications for Geosequestration

DOE/NETL Funding
- Department of Energy/National Energy Technology Laboratory
(DOE Project Officer)

MRCSP Partnership
and NATCARB

Sandia Technologies, LLC
- D. Collins, PI

Project Steering Team
- D. Collins, Sandia Technologies, LLC
- N. Malkewicz, Schlumberger Carbon Services
- D. Goldberg, LDEO - Columbia University

Schlumberger Carbon Services
- Leveraged Services

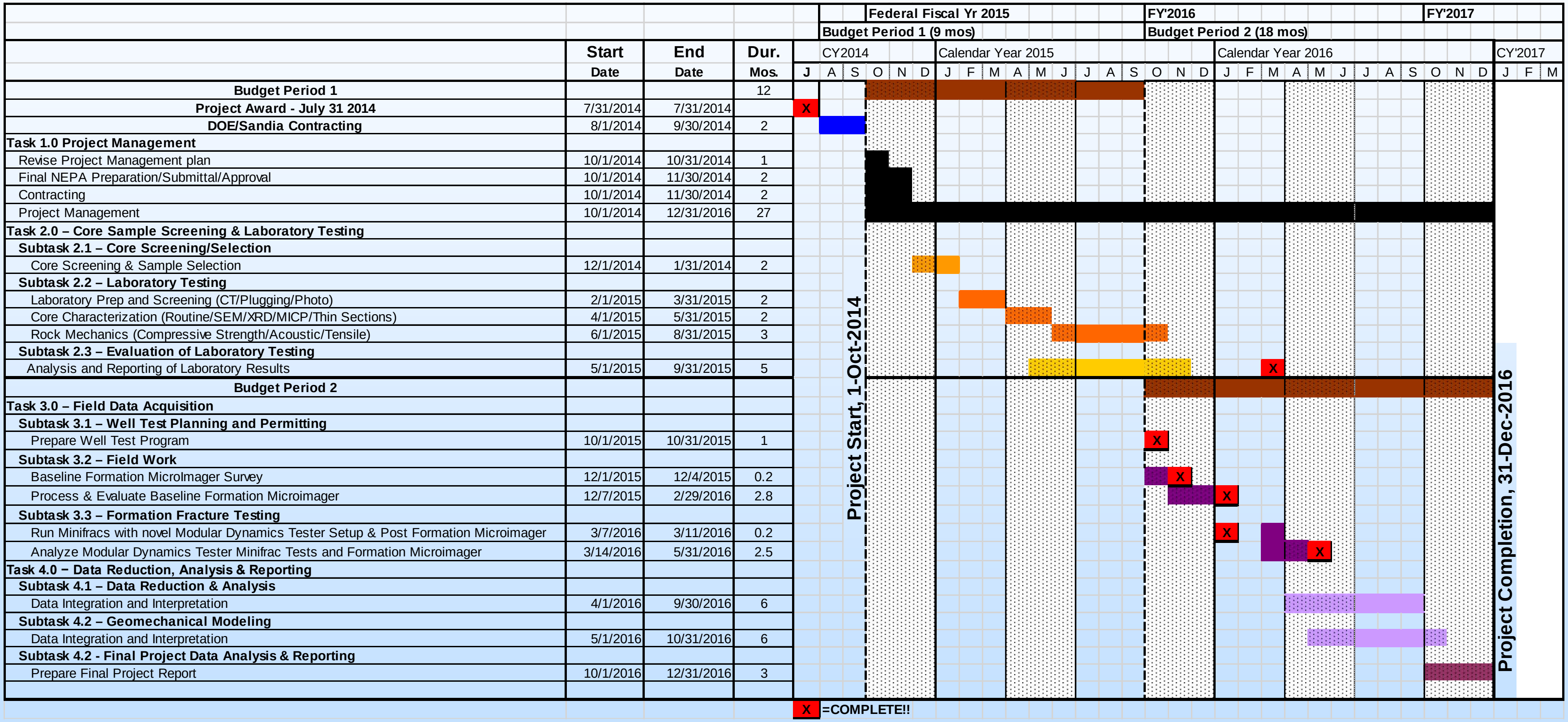
Lamont Doherty Earth Observatory
Columbia University

- Schlumberger Wireline Services
- Schlumberger Reservoir Laboratories
& Schlumberger TerraTek Laboratories
- Schlumberger Geomechanics Center

Project Organizational Chart – (continued)

- Schlumberger Carbon Services
    - Houston Rock Laboratory – routine and special core analyses
    - TerraTek Rock Mechanics lab – Salt Lake City
    - Wireline Services – Formation Microimager and Modular Dynamics Tester
    - Geomechanics Center – technical support in laboratory and field data evaluation/ analysis and modeling support to LDEO
- Lamont Doherty Earth Observatory
    - Research staff to support scientific efforts of the project, including primary data reduction/analysis, evaluation, and geomechanical modeling
    - Access to Newark Basin core library
    - Access to Test Well No. 3 for field testing program

Gantt Chart



	Start Date	End Date	Dur. Mos.
Budget Period 1			12
Project Award - July 31 2014	7/31/2014	7/31/2014	
DOE/Sandia Contracting	8/1/2014	9/30/2014	2
Task 1.0 Project Management			
Revise Project Management plan	10/1/2014	10/31/2014	1
Final NEPA Preparation/Submittal/Approval	10/1/2014	11/30/2014	2
Contracting	10/1/2014	11/30/2014	2
Project Management	10/1/2014	12/31/2016	27
Task 2.0 – Core Sample Screening & Laboratory Testing			
Subtask 2.1 – Core Screening/Selection			
Core Screening & Sample Selection	12/1/2014	1/31/2014	2
Subtask 2.2 – Laboratory Testing			
Laboratory Prep and Screening (CT/Plugging/Photo)	2/1/2015	3/31/2015	2
Core Characterization (Routine/SEM/XRD/MICP/Thin Sections)	4/1/2015	5/31/2015	2
Rock Mechanics (Compressive Strength/Acoustic/Tensile)	6/1/2015	8/31/2015	3
Subtask 2.3 – Evaluation of Laboratory Testing			
Analysis and Reporting of Laboratory Results	5/1/2015	9/31/2015	5
Budget Period 2			
Task 3.0 – Field Data Acquisition			
Subtask 3.1 – Well Test Planning and Permitting			
Prepare Well Test Program	10/1/2015	10/31/2015	1
Subtask 3.2 – Field Work			
Baseline Formation MicroImager Survey	12/1/2015	12/4/2015	0.2
Process & Evaluate Baseline Formation Microimager	12/7/2015	2/29/2016	2.8
Subtask 3.3 – Formation Fracture Testing			
Run Minifracs with novel Modular Dynamics Tester Setup & Post Formation Microimager	3/7/2016	3/11/2016	0.2
Analyze Modular Dynamics Tester Minifrac Tests and Formation Microimager	3/14/2016	5/31/2016	2.5
Task 4.0 – Data Reduction, Analysis & Reporting			
Subtask 4.1 – Data Reduction & Analysis			
Data Integration and Interpretation	4/1/2016	9/30/2016	6
Subtask 4.2 – Geomechanical Modeling			
Data Integration and Interpretation	5/1/2016	10/31/2016	6
Subtask 4.2 - Final Project Data Analysis & Reporting			
Prepare Final Project Report	10/1/2016	12/31/2016	3

X =COMPLETE!!

Bibliography

- Zakharova, N.V., Goldberg, D.S., Collins, D.J., and Malkewicz, N., 2015, Geomechanical and Petrophysical Properties of Rift Basin Mudstones: American Geophysical Union Fall Meeting, San Francisco, CA., Poster MR41C-2664.