Monitoring the Extent of CO_2 Plume and Pressure Perturbation

Project Number 1022403

William Harbert

ORISE-NETL

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Transforming Technology through Integration and Collaboration
August 18-20, 2015

NETL Research Presentations and Posters

TUESDAY, AUGUST 18, 2015

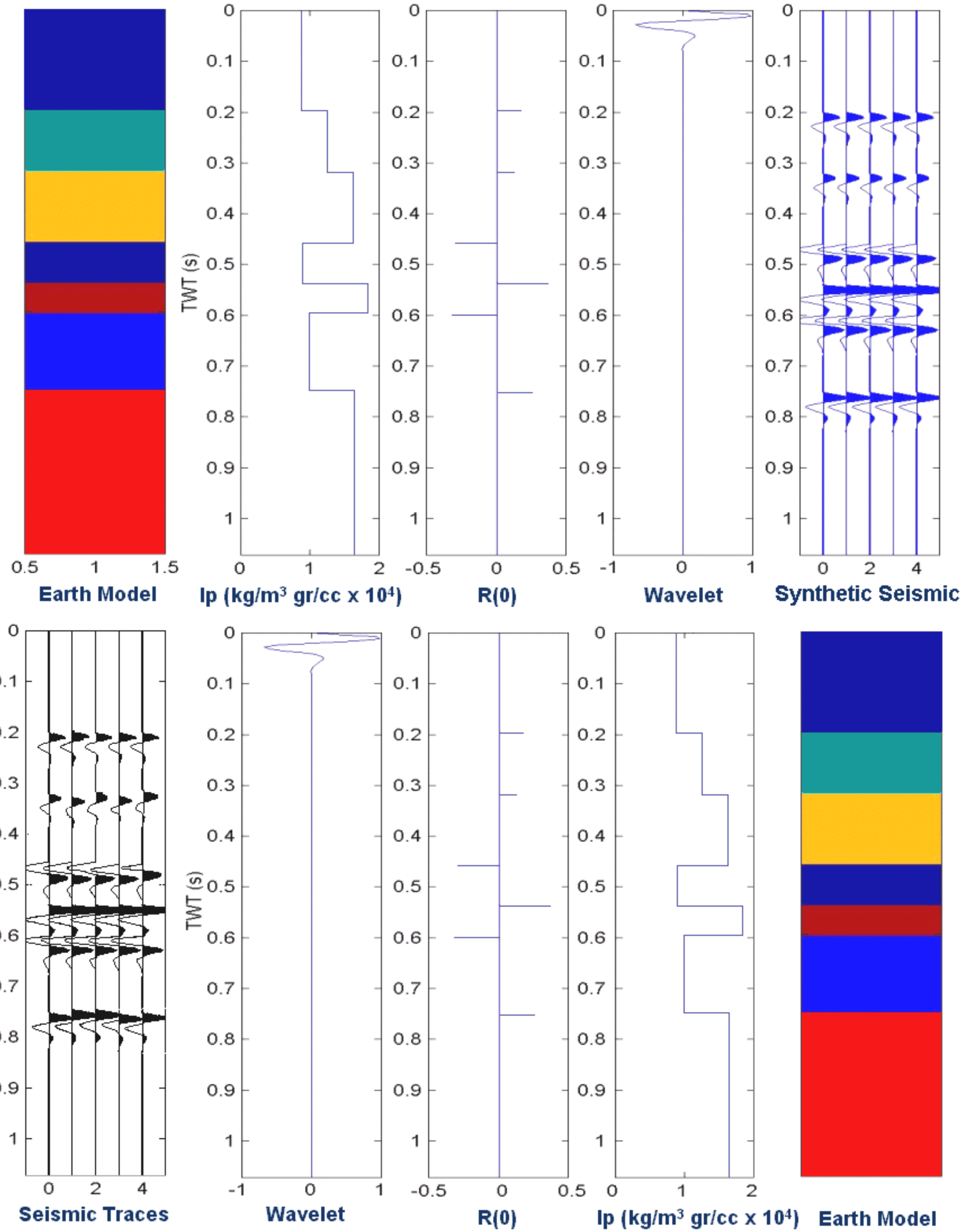
- **2:15 PM** Resource Assessment - Angela Goodman
- **5:10 PM** Catalytic Conversion of CO_2 to Industrial Chemicals - Doug Kauffman
- 6:00 p.m. **Poster Session (CORE R&D, NRAP, and RCSPs)**
  1. Dave Blaushild - Perfluorocarbon Tracer (PFT) Analysis to Support the South West Partnership,
  2. Liwei Zhang - Numerical simulation of pressure and CO2 saturation above the fractured seal as a result of CO2 injection: implications for monitoring network design
  3. NRAP, EDX, and NATCARB Grant Bromhal, Bob Dilmore, Kelly Rose, Maneesh Sharma

WEDNESDAY, AUGUST 19, 2015

- ***1:15 PM** Monitoring the Extent of CO_2 Plume and Pressure Perturbation - Bill Harbert*
- **2:05 PM** Reservoir and Seal Performance - Dustin Crandall
- **3:45 PM** Monitoring Groundwater Impacts - Christina Lopano
- 5:30 p.m. **Poster Session (SubTER, NRAP, and EFRCs)**
  1. Kelly Rose - Evaluating Induced Seismicity with Geoscience Computing & Big Data – A multi-variate examination of the cause(s) of increasing induced seismicity events
  2. NRAP, EDX, and NATCARB Grant Bromhal, Bob Dilmore, Kelly Rose, Maneesh Sharma
  3. John Tudek- EFRC
  4. Sean Sanguinito NETL CO2 SCREEN)

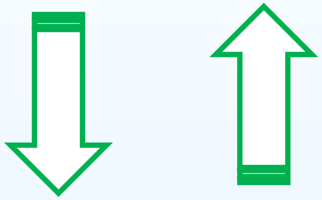
THURSDAY, AUGUST 20, 2015

- **11:25 AM** Shales as Seals and Unconventional Reservoirs for CO_2– Robert Dilmore



We use two approaches to all problems.

Forward Problem



Inverse Problem

For both problems geophysical data, reference core and geophysical well logs are required.

Every project should be well bounded by work <u>on both problems</u>.

Mantilla, 2002

Presentation Outline

- Core based petrophysical measurements, analysis and interpretation.
- Reflection seismic based reservoir monitoring and surveillance.
- Microseismic monitoring and surveillance.
- Electromagnetic methods.

Benefit to the Program

This activity supports industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.

Develops and validates technologies to ensure 99 percent storage permanence.

Develops technologies to improve reservoir storage efficiency while ensuring containment effectiveness.

Will aid in the development of Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation.

Surveillance Technologies being considered:

Storage Reservoir

Atomic Dielectric Resonance
Triaxial Gravity Gradiometry
Broad-Band Seismicity

USDW

Controlled Source or Magnetotellurics
Dual-Moment Time Domain EM

Database of previous rock physics based measurements constructed and being placed on EDX.

Proposal is a coherent approach that builds on previous research and complements on-going efforts at the COREFLOW and μCT Scanner Laboratories at NETL and aids geophysical reservoir monitoring.

Project will produce timely, cost-effective benefits given the close collaboration and support of the CO_2 partnerships.

Project Overview: Goals and Objectives

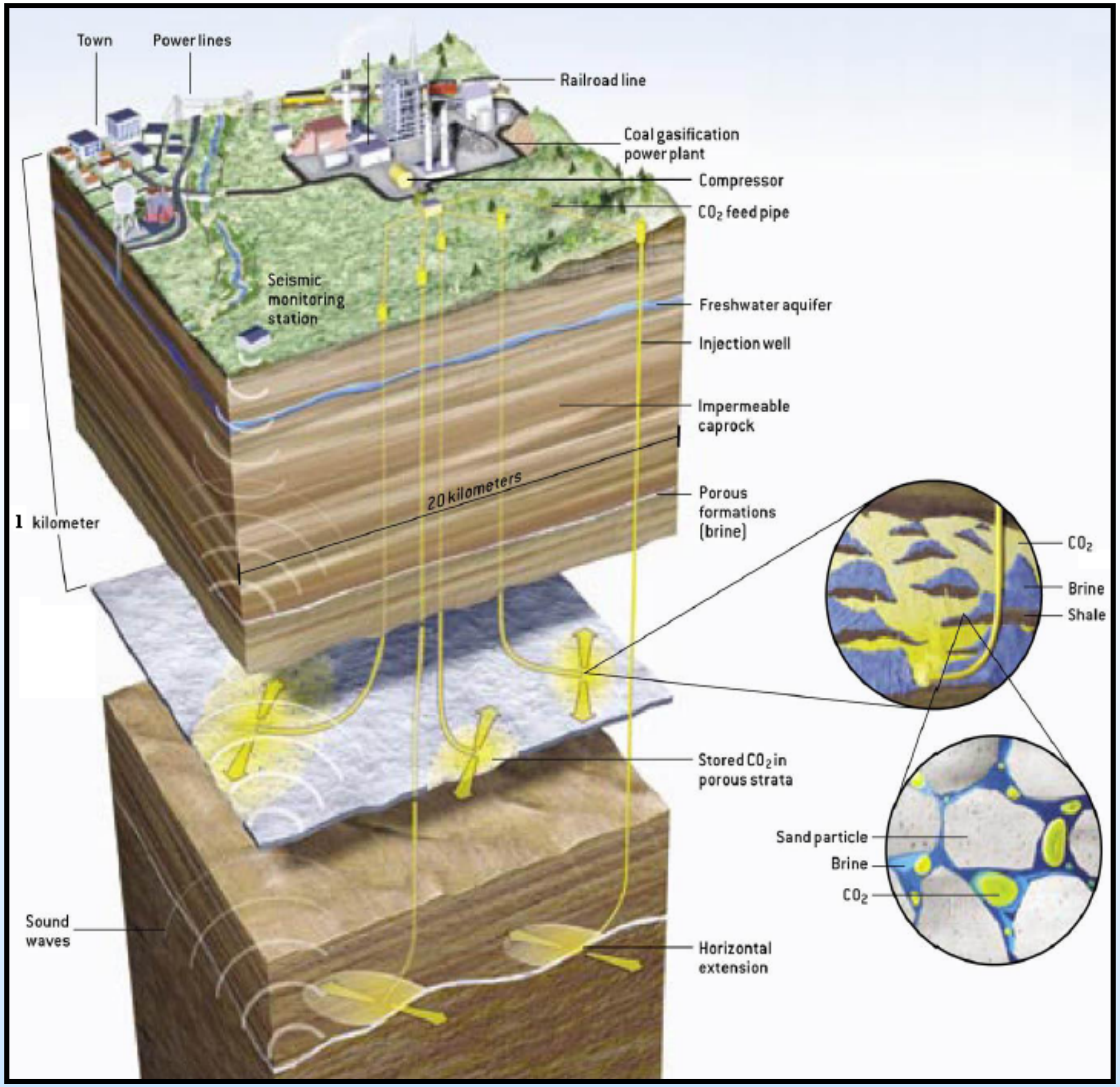
- **Monitoring the Extent of CO_2 Plume and Pressure Perturbation**

The objective of this task is to assess NETL core capabilities relative to gaps in monitoring tools and strategies that can be applied cost-effectively to quantify CO_2 and/or pressure plumes. Effective monitoring techniques for CO_2 storage areas must determine the *vertical and lateral extent of CO_2 migration* and verify that the plume remains within the intended reservoir. Monitoring must also *determine the areal extent of the pressure perturbation* caused by CO_2 injection because pre-stressed faults (if present) in these areas may be activated by increasing pore pressure (induced seismicity). A suite of complementary geophysical techniques are being developed to *address the goal of 99% storage by detecting stored CO_2 at depth and determining the effect of rising pore pressure on the geomechanical properties of the storage formation and caprock*.

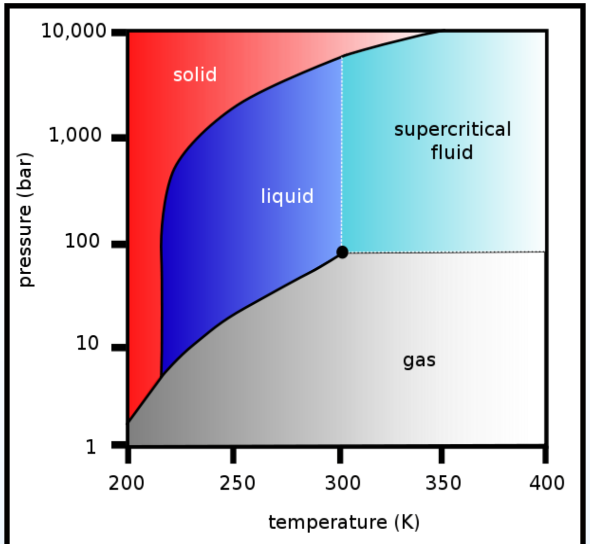
Technical Status

- Core based petrophysical measurements, analysis and interpretation.
- Reflection seismic based reservoir monitoring and surveillance.
- Micro seismic monitoring and surveillance.
- Electromagnetic methods.

Brief introduction to CO_2 sequestration in deep saline aquifers



Adopted from Friedmann, 2005



Adopted from Jacobs, 2005

- CO_2 capture reservoirs can be located at depths of 800 meters and more
- Reservoir thickness may vary from several to hundreds of meters
- Reservoir CO_2 storage capacity may reach thousands of MT (Megatons)

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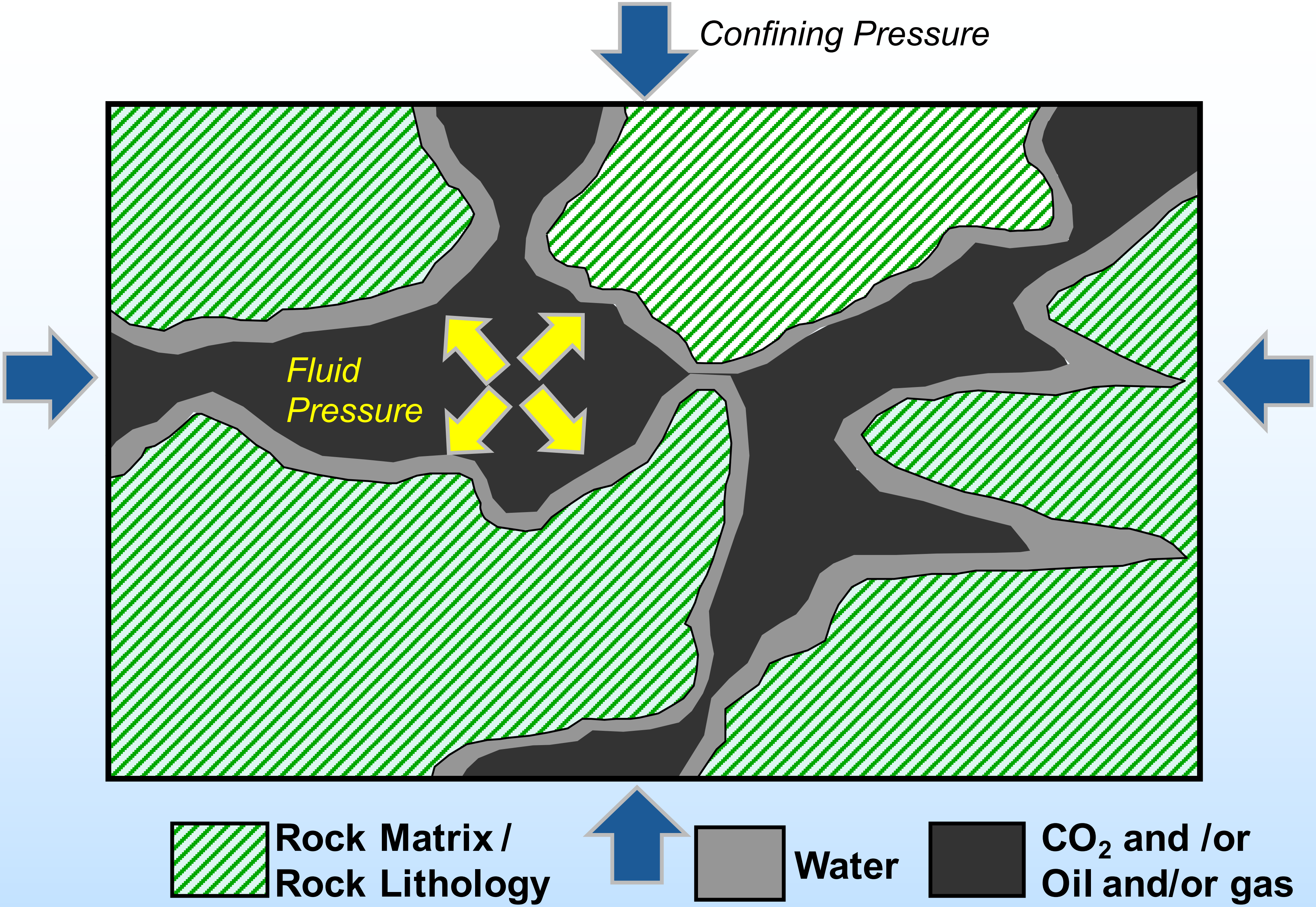
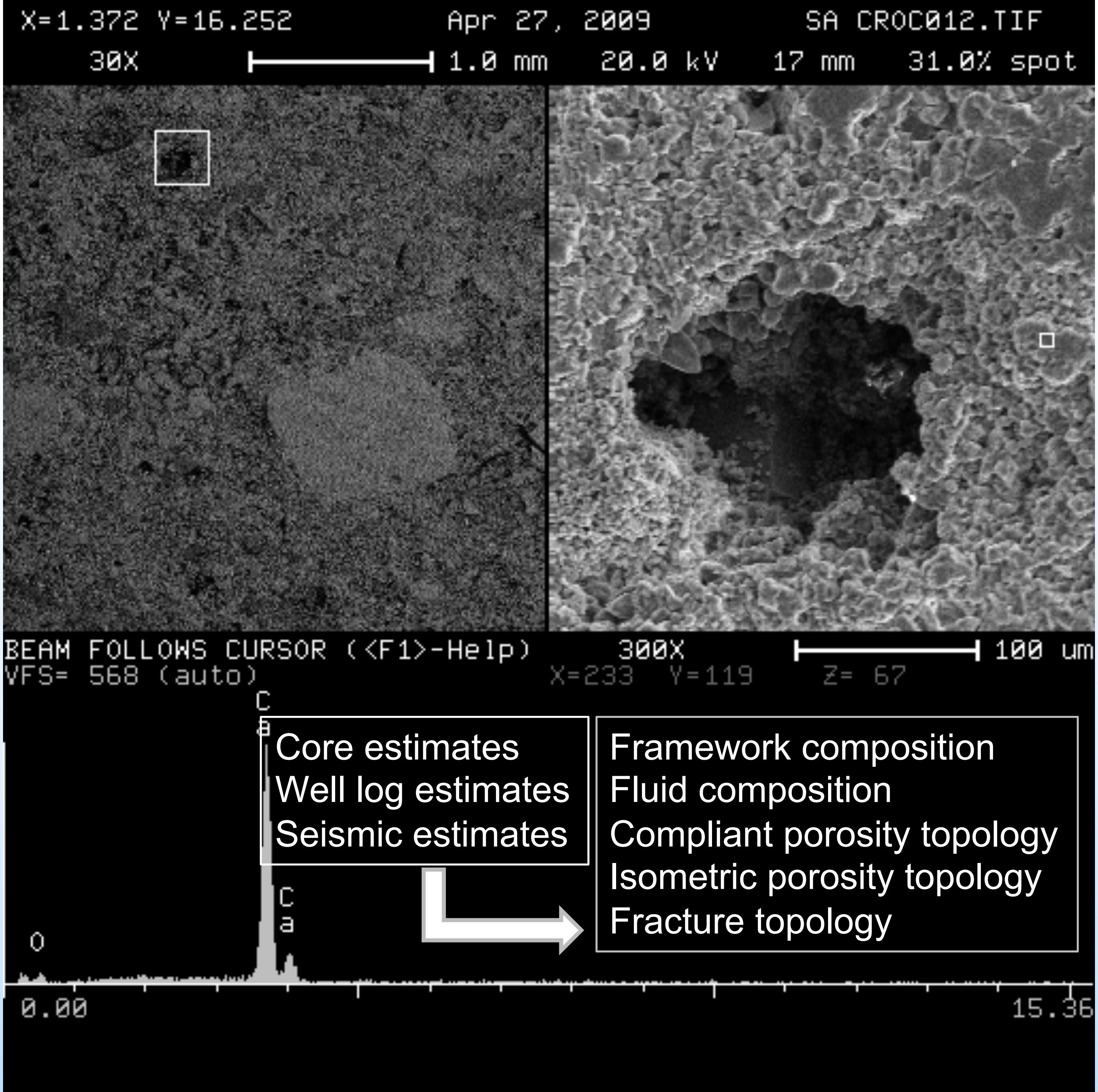
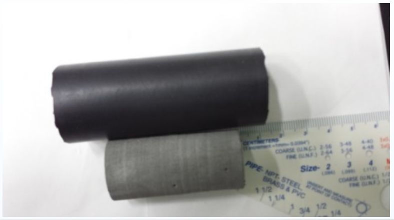
ROCK MATRIX AND PORE SPACE



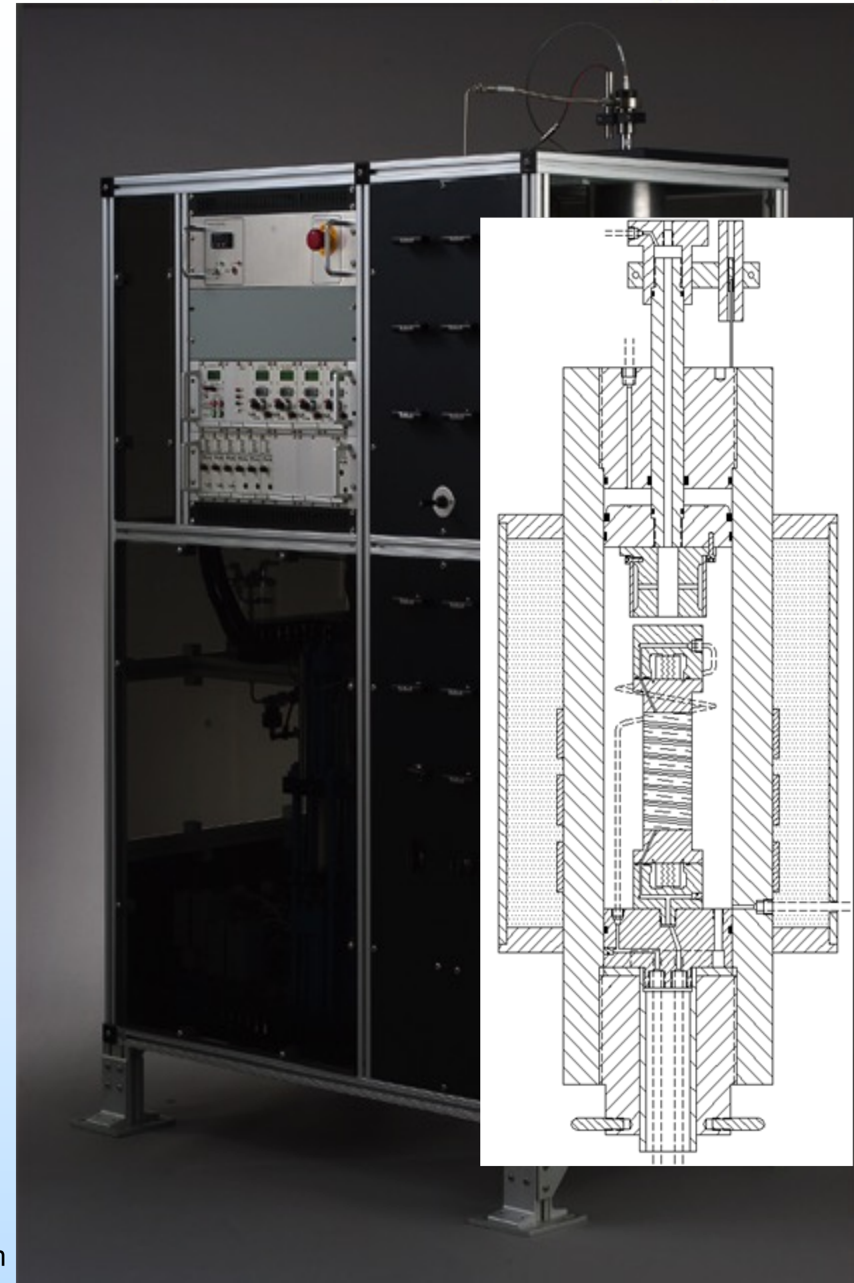

X=1.372 Y=16.252
Apr 27, 2009
SA CROC012.TIF
30X
1.0 mm
20.0 kV
17 mm
31.0% spot
BEAM FOLLOWS CURSOR (<F1>-Help)
300X
100 um
VFS= 568 (auto)
X=233 Y=119 Z= 67
Ca
Ca
O
0.00
15.36
Core estimates
Well log estimates
Seismic estimates
Framework composition
Fluid composition
Compliant porosity topology
Isometric porosity topology
Fracture topology

Experimental Setup



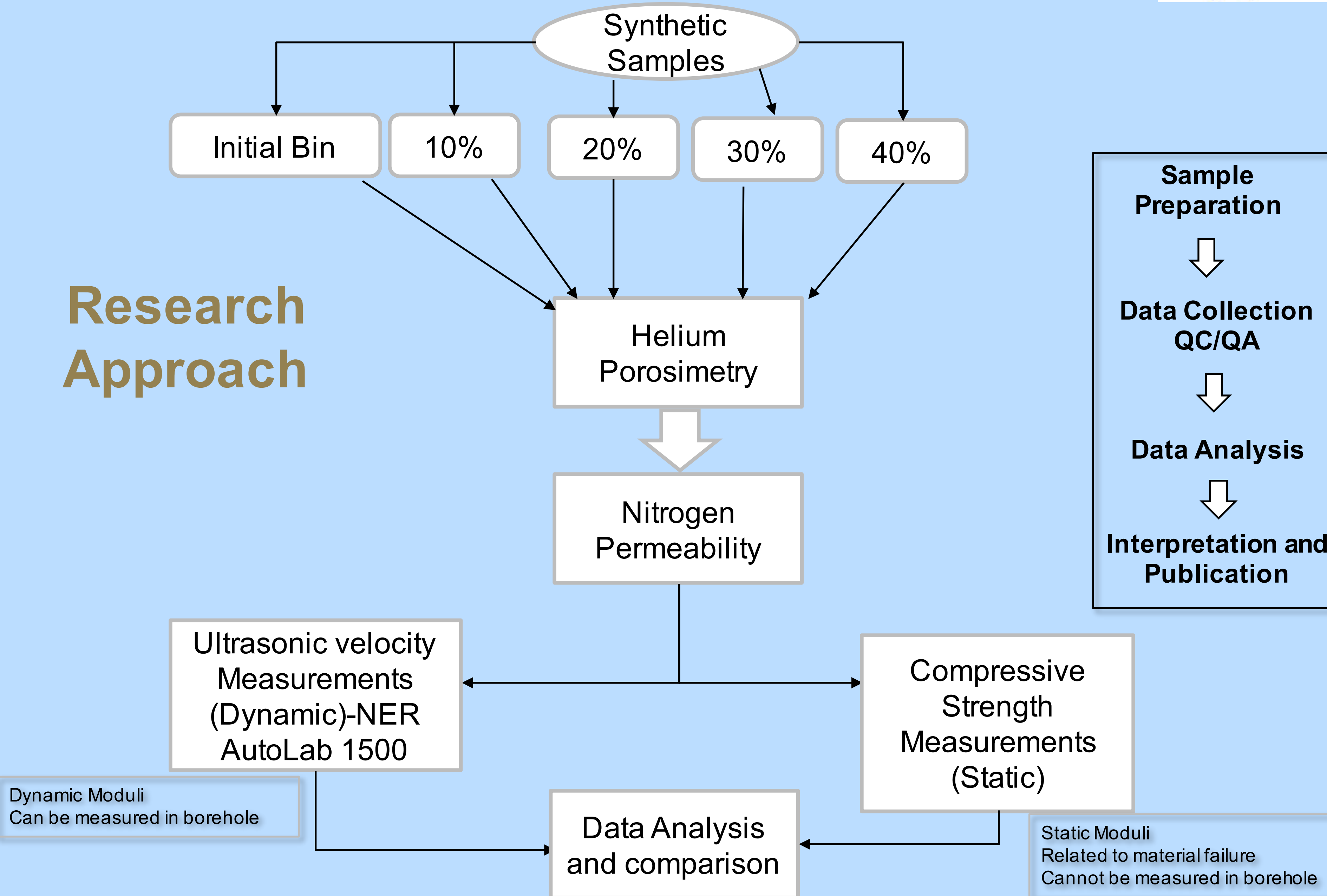
Porosimetry

Ultrasonic velocity Measurements (Dynamic)-NER AutoLab 1500

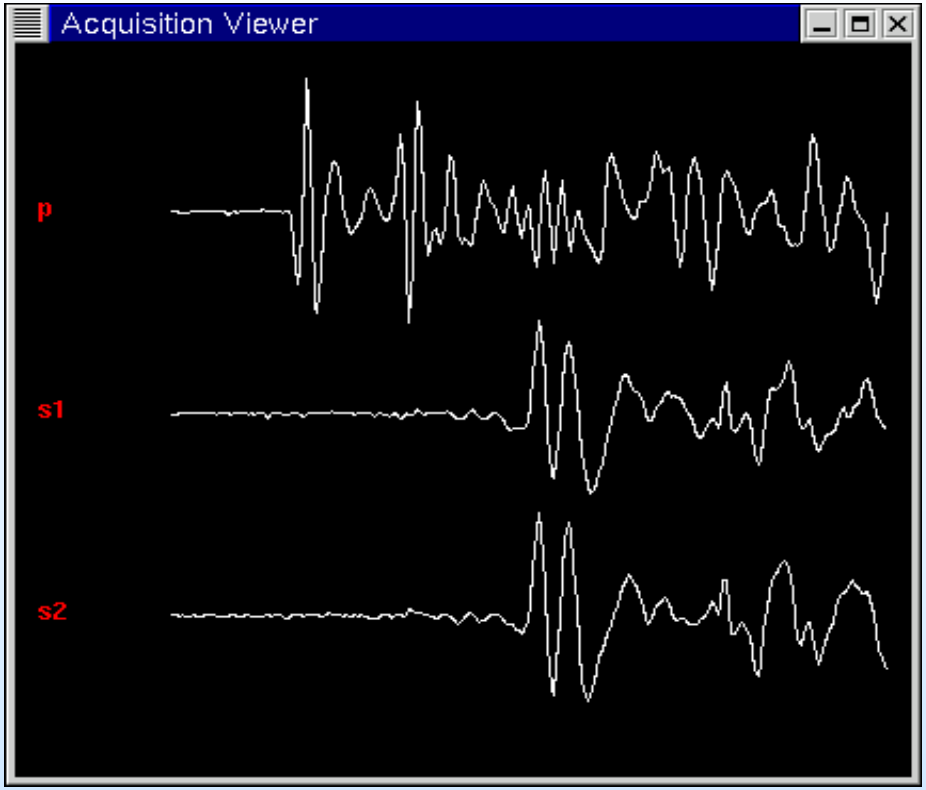


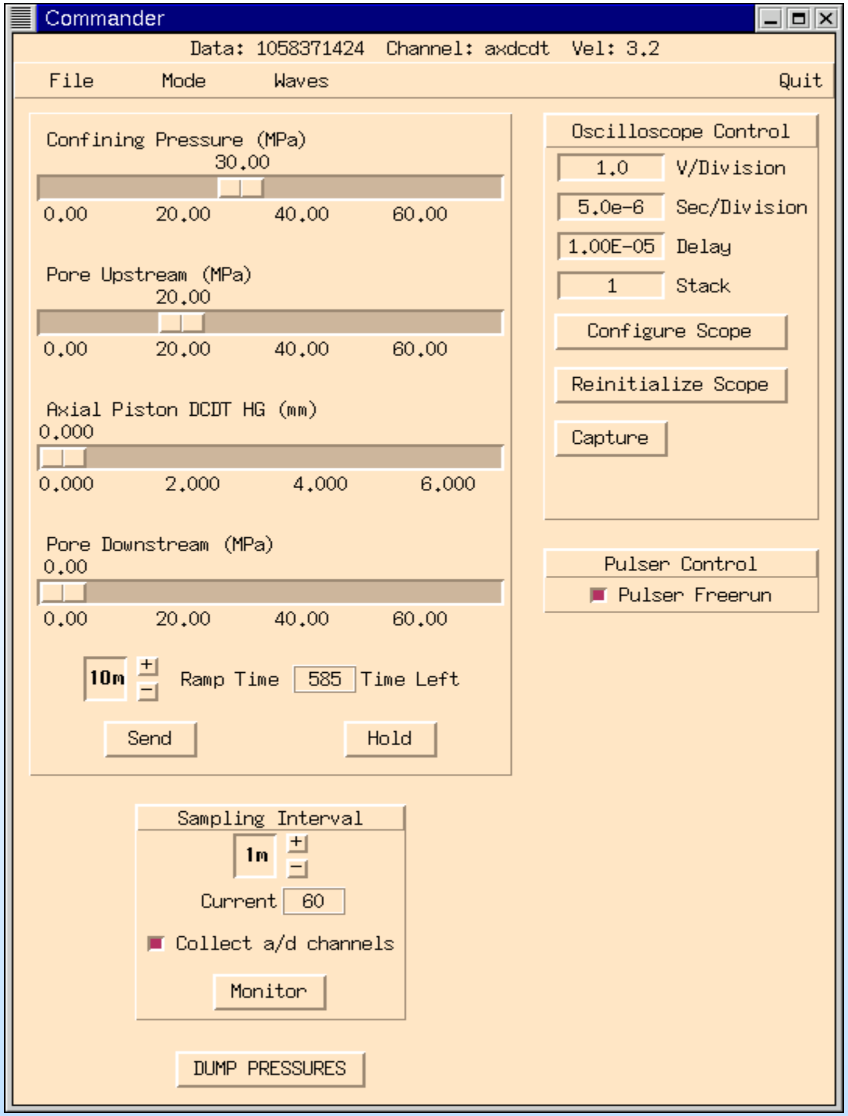
www.NER.com

Research Approach

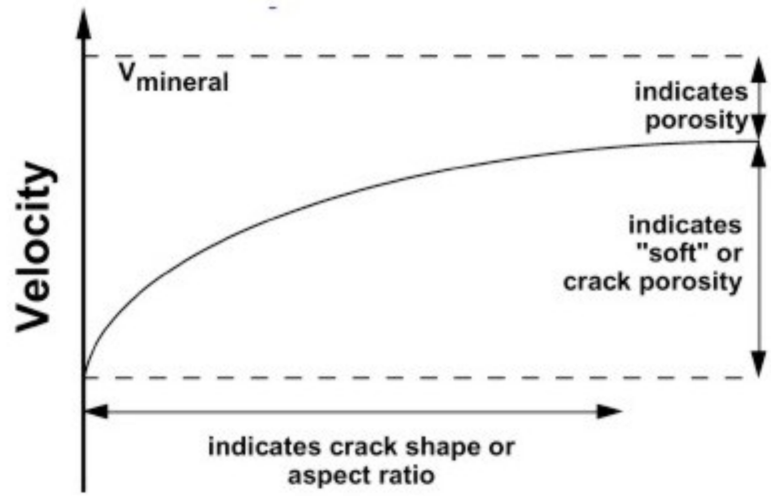


Velocity Commander and Acquisition Viewer





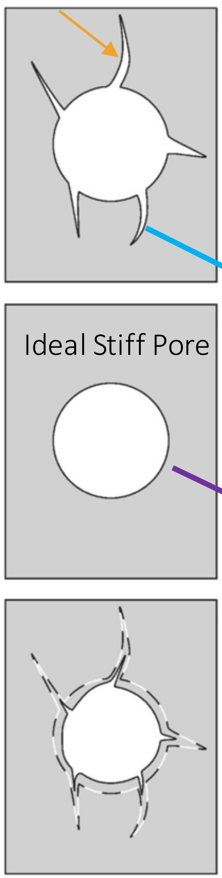
The Information in a Rock's Velocity-Pressure Curve

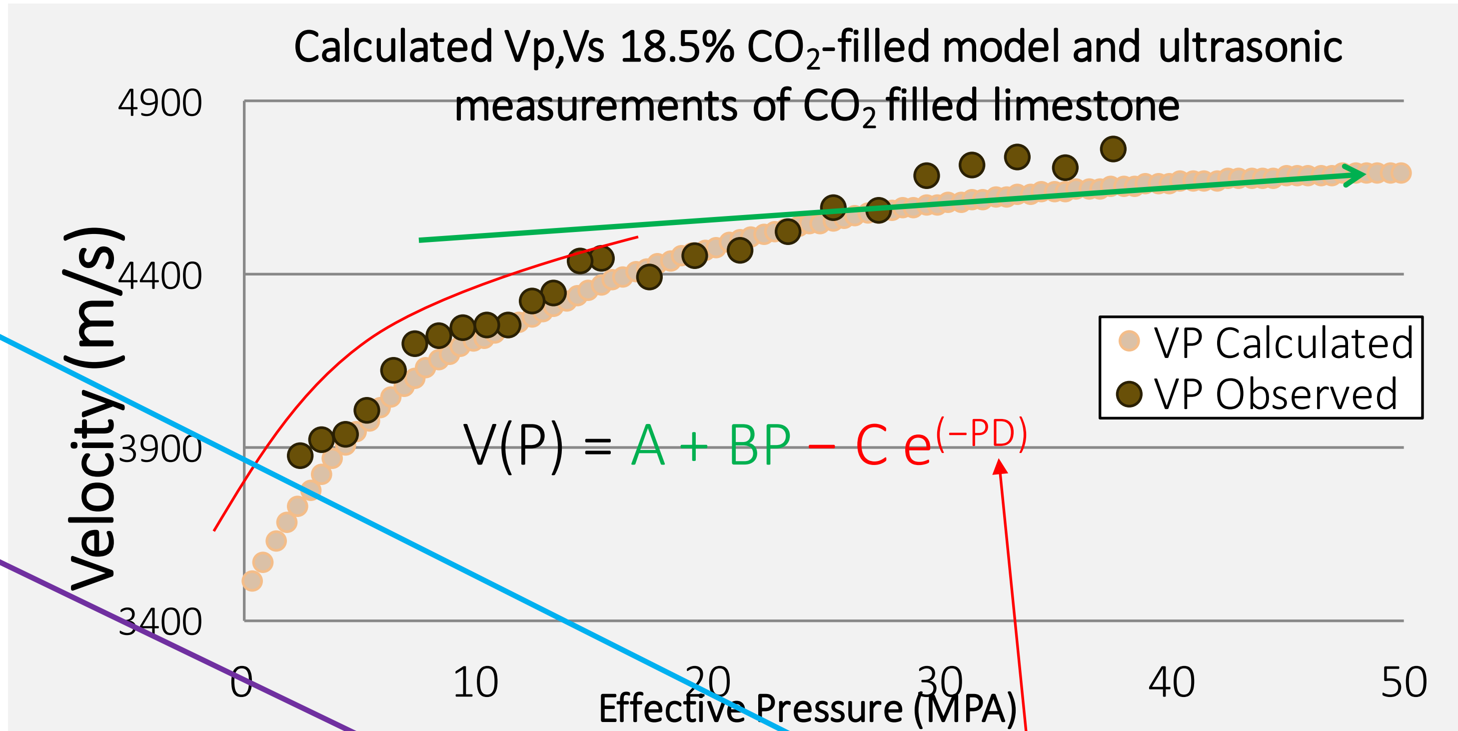


1. High pressure limiting velocity is a function of porosity
2. The amount of velocity change with pressure indicates the amount of soft, crack-like pore space
3. The range of the greatest pressure sensitivity indicates the shape or aspect ratios of the crack-like pore space

This slide is from Dr. Gary Mavko, Stanford Rock Physics Laboratory

Compliant porosity





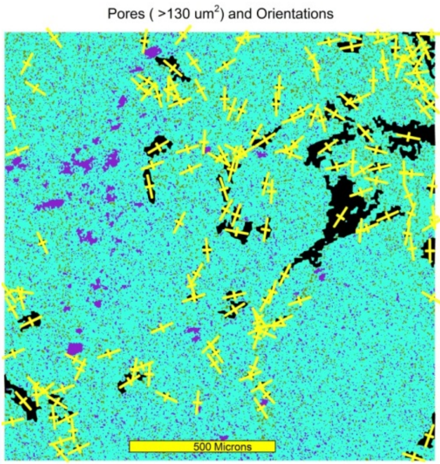
$$K_{dry}(P_{eff}) = K_{dryS}\left[1+\theta_s\left(\frac{1}{K_{dryS}}-\frac{1}{K_0}\right)P_{eff}-\phi_{c0}\theta_c e^{(-\theta_c P_{eff}/K_{dryS})}\right]$$

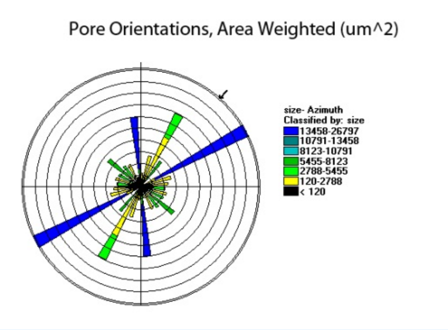
$$\mu_{dry}(P_{eff}) = \mu_{dryS}\left[1+\theta_{s\mu}\left(\frac{1}{K_{dryS}}-\frac{1}{K_0}\right)P_{eff}-\phi_{c0}\theta_c e^{(-\theta_c P_{eff}/K_{dryS})}\right]$$

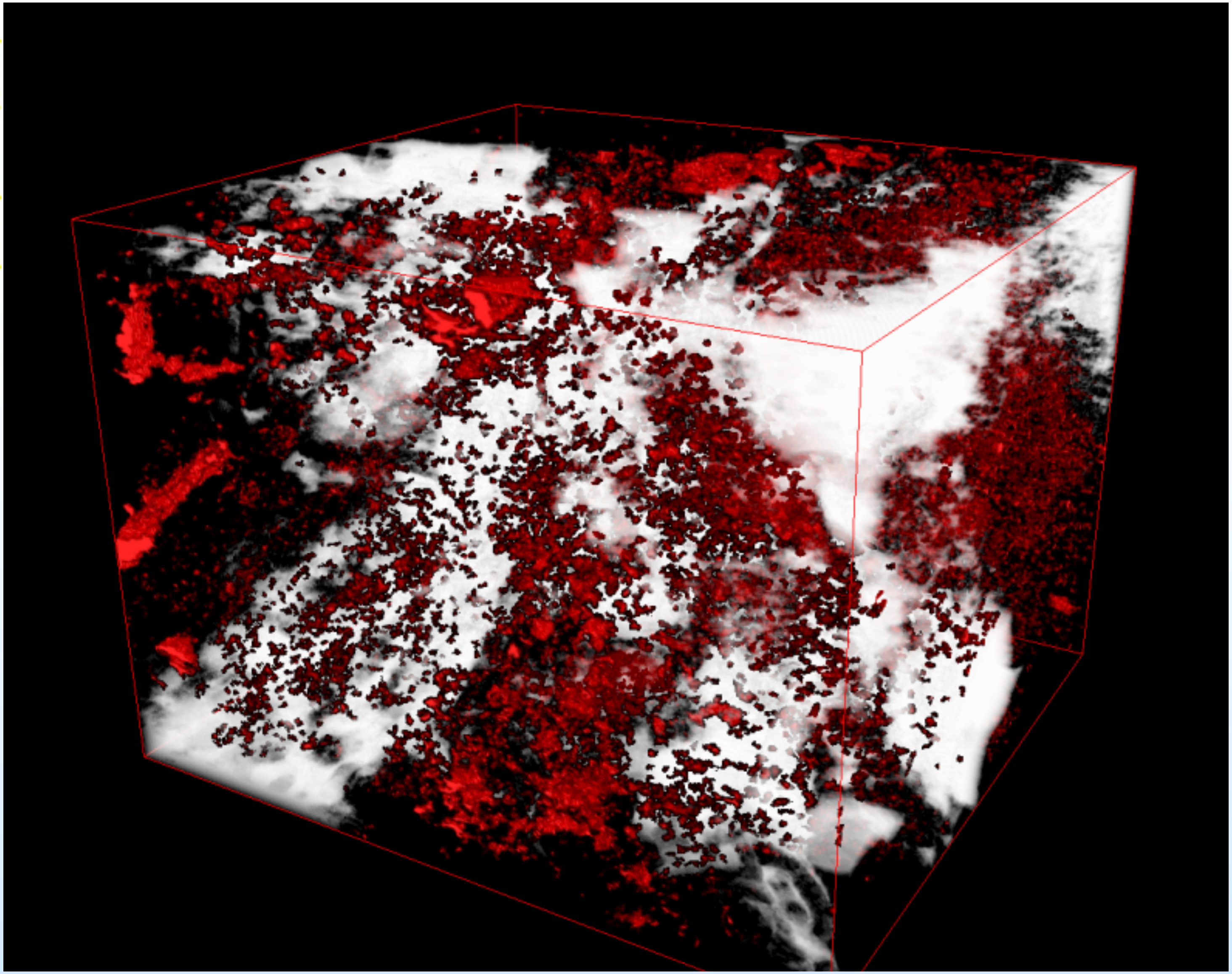
CO_2 ρ and K from NIST

Shapiro 2005

This slide courtesy Dr. Alan Mur, IKON Science





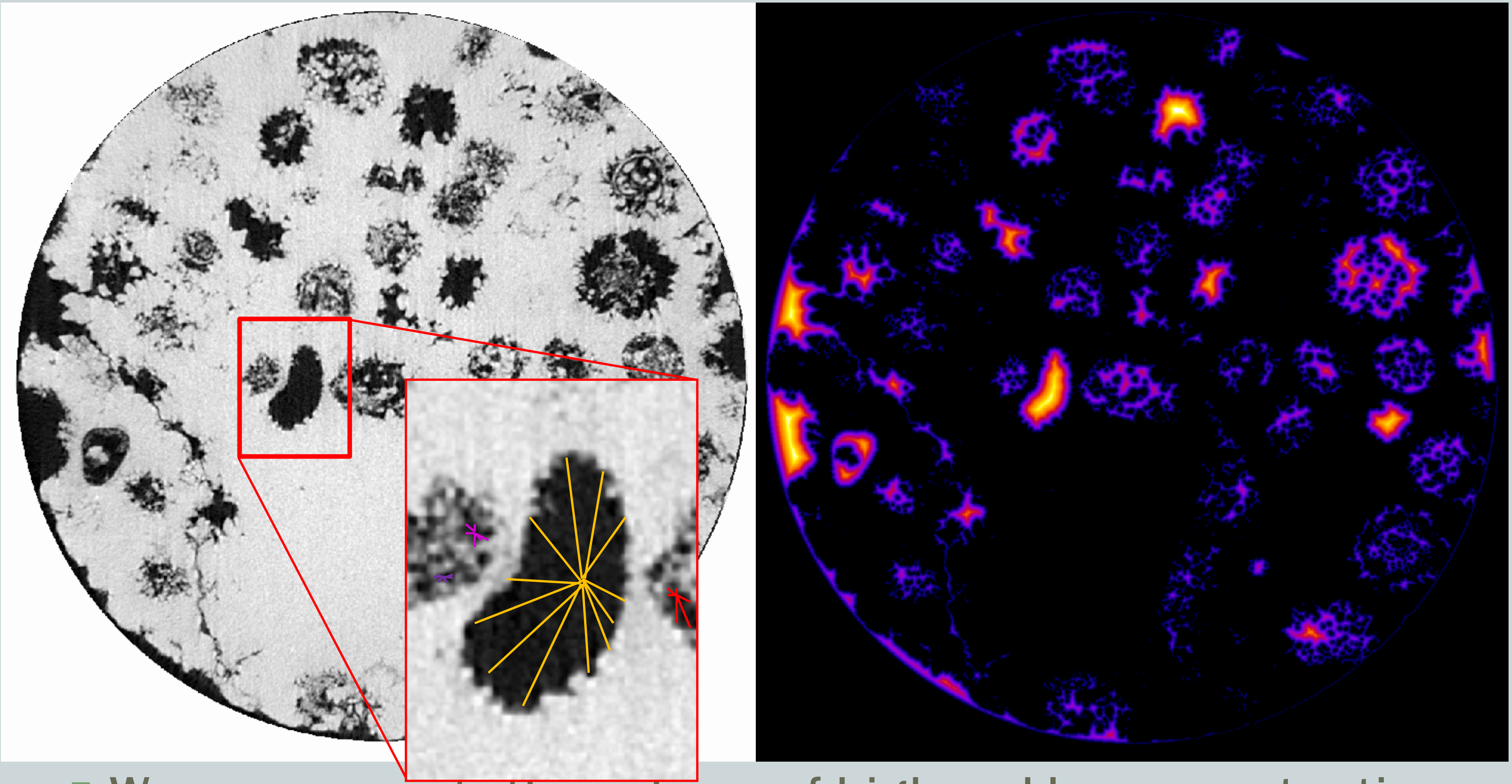


Framework composition
Fluid composition
Compliant porosity topology
Isometric porosity topology
Fracture topology

Large connected pore network shown in white and unconnected pores in red.
(Volume size 1.54 x 1.40 x 1.12 mm)

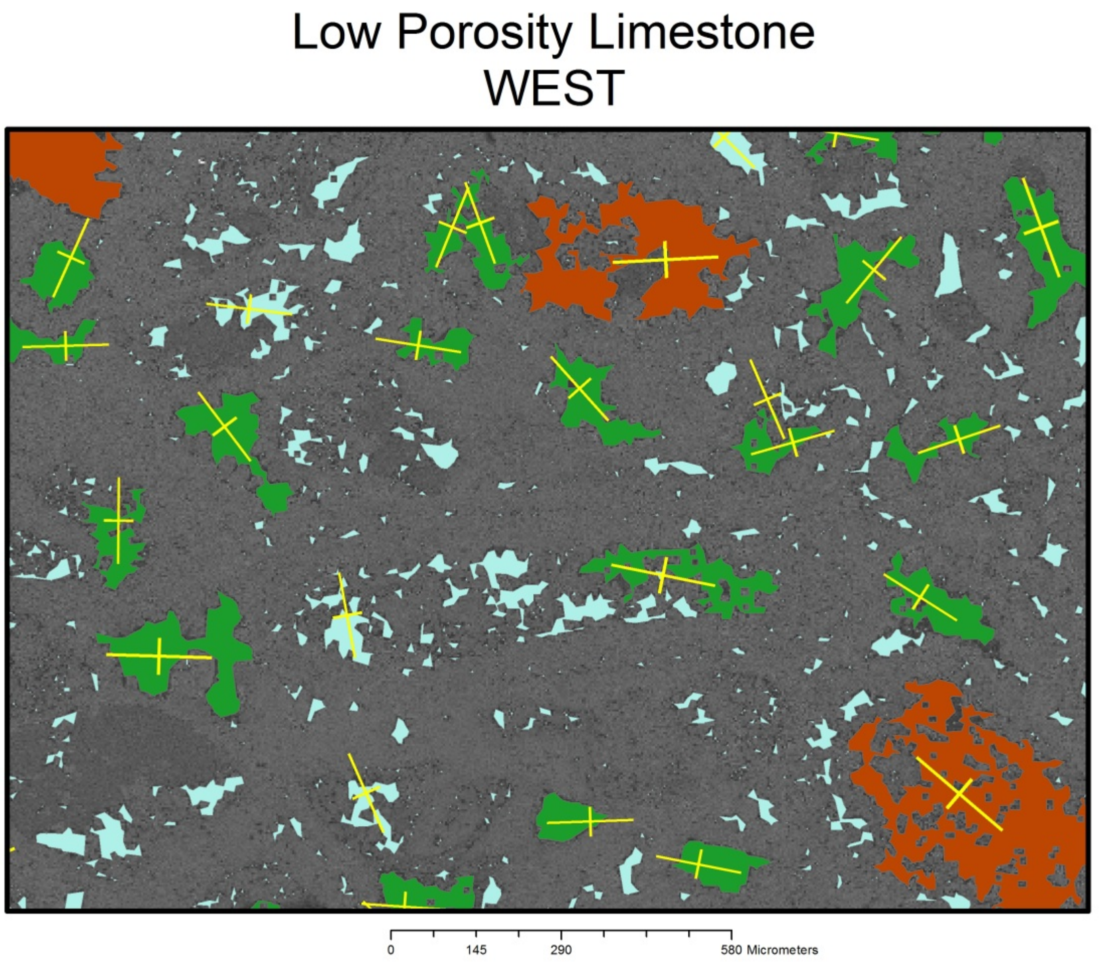
This slide courtesy Dr. Alan Mur, IKON Science

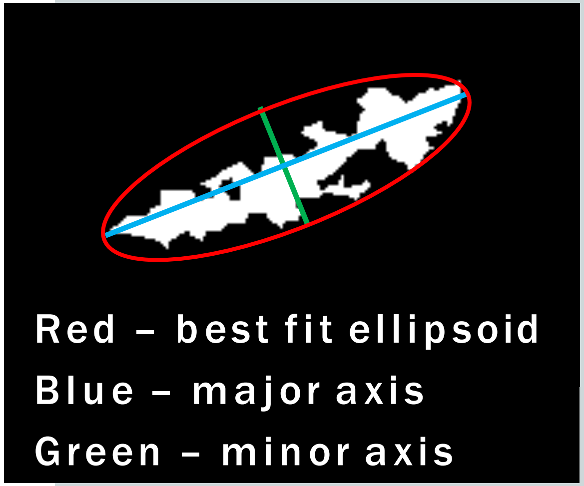
LOCAL THICKNESS: COOLER COLORS ARE COMPLIANT POROSITY (4X SAMPLE)



- We can separate the volume of high and low aspect ratio pores to quantify compliant and stiff porosity
- Results can be compared/confirmed by thickness mapping

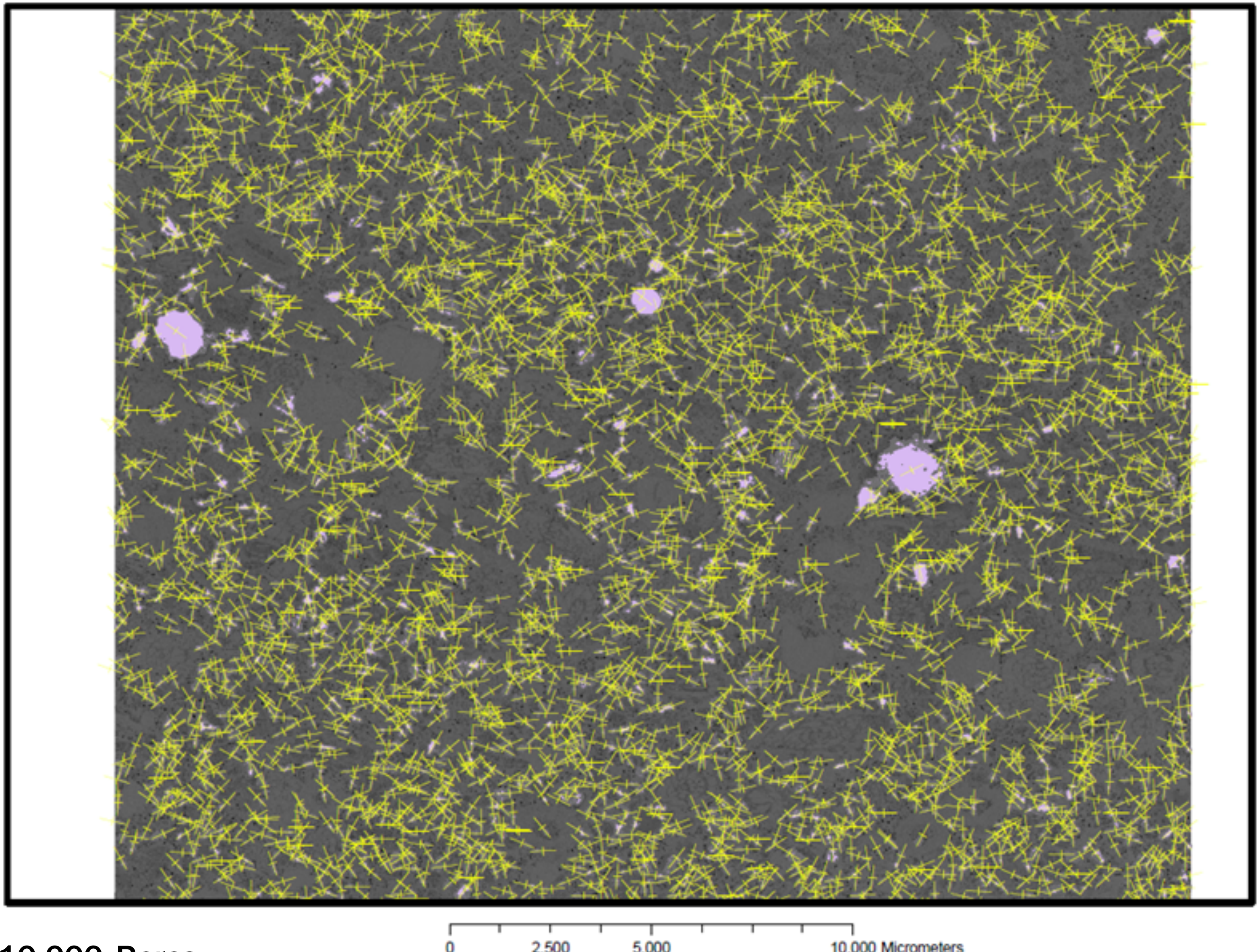
MACRO SCALE PORE ORIENTATIONS
SEM





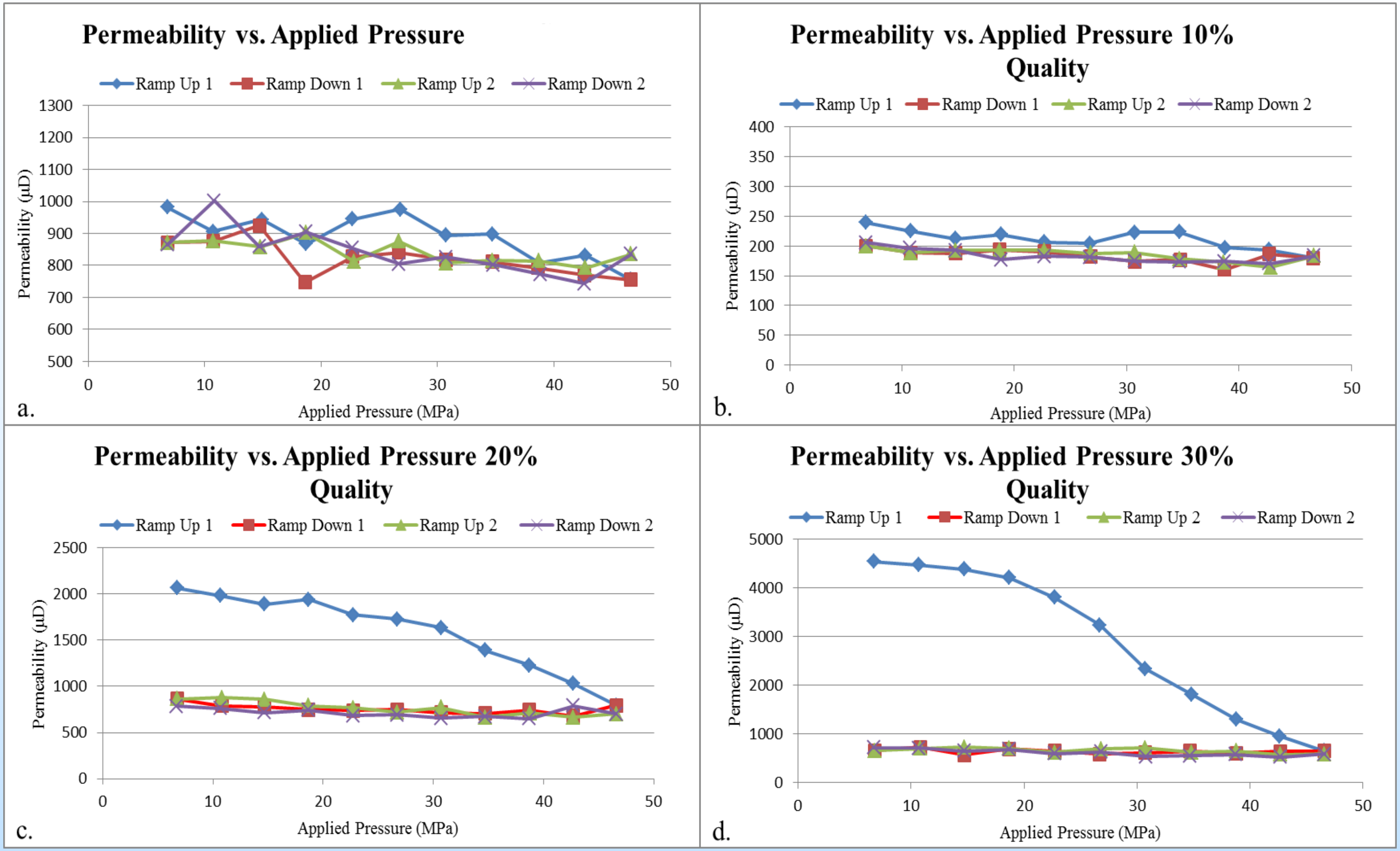
Using three mutually perpendicular, ~40x80cm SEM montages, we described a large number of pores (>10,000 pores per plane) using GIS and image processing.

WEST



~10,000 Pores

Effective Pressure Cycling Results – Permeability



Rock physics model comparison with NER AutoLab measurements modeling applied to data

- Laboratory calibrated calculation of Reuss, Voigt, RVH, and Hasin-Shtrikman (HS+) bounds.
- Direct measurement of P- and S- Velocity and Permeability dependence on effective pressure.
- Constrain accurately the effect of pore pressure and compliant porosity variation with respect to lithology within target volumes.
- Lame parameters, including Bulk Modulus and Shear Modulus variation with effective pressure.
- Normalized Bulk Modulus (K_{dry}/K_0) with respect to ϕ with various values of normalized pore stiffness (K_f/K_0).

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Seismic Variables

ρ = Density = mass/volume

K = Bulk Modulus = resistance to uniform compression

μ = Shear Modulus= resistance to shearing

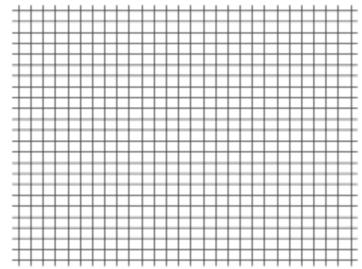
V_p = P wave Velocity

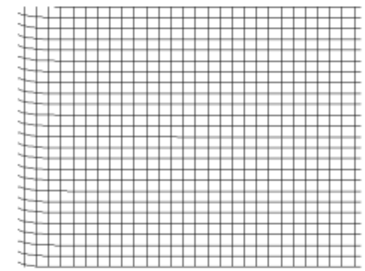
V_s = S wave Velocity

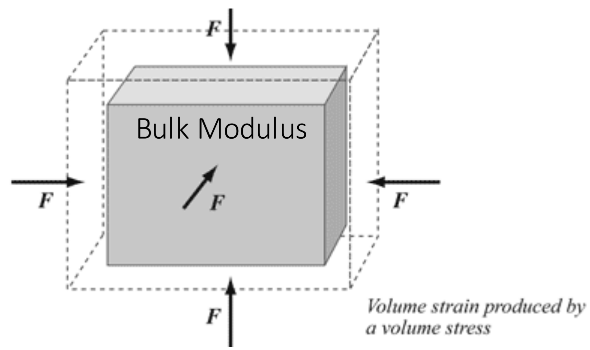
$$V_P = \sqrt{\frac{\left(K_{sat} + \frac{4}{3}\mu_{sat}\right)}{\rho_{bulk}}}$$

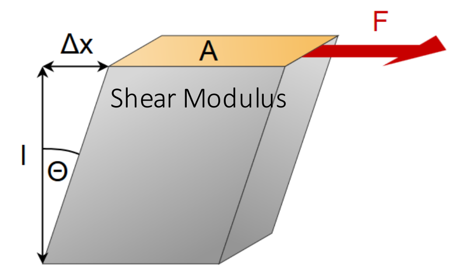
$$V_S = \sqrt{\frac{\mu_{sat}}{\rho_{bulk}}}$$

Assumes isotropy – uniform in all directions

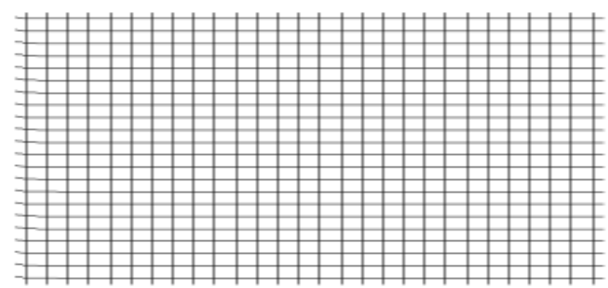








- Wikimedia Commons

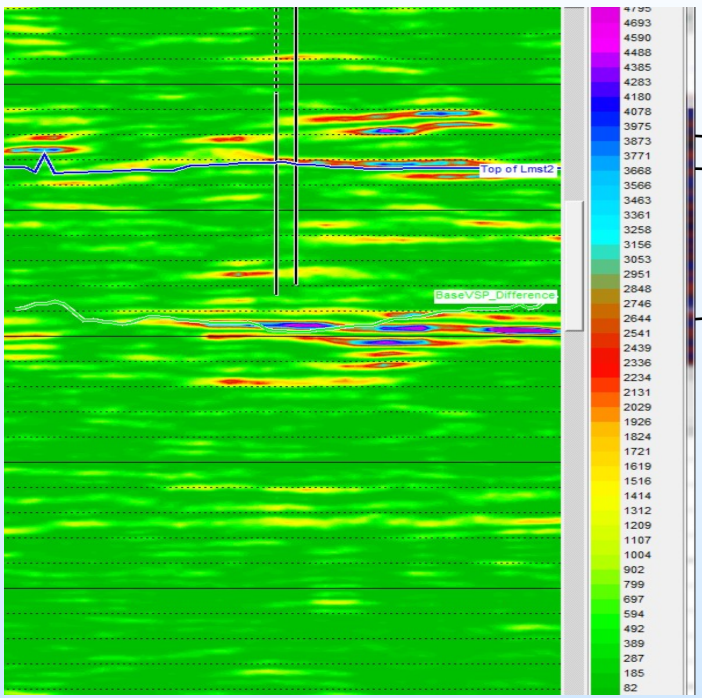


P wave velocity > S wave velocity

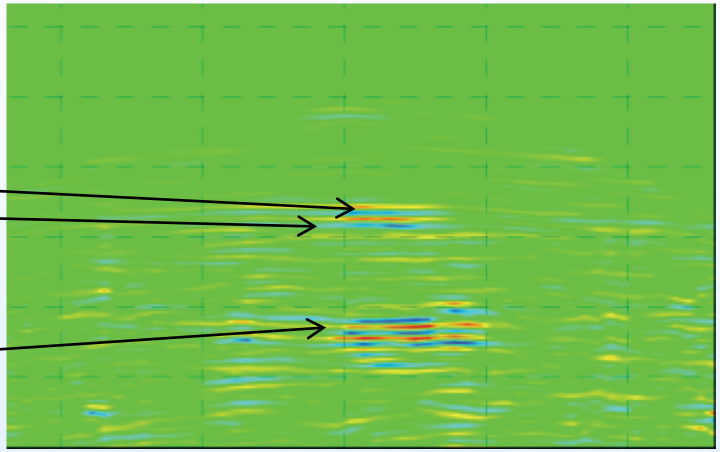
This slide courtesy Dr. Alan Mur, IKON Science

Amplitude Difference
3D Seismic

4D-VSP Comparison



((Amp1-Amp2)^2)/((Amp1+Amp2)^2



VSP Pseudo CMP Amplitude Differences

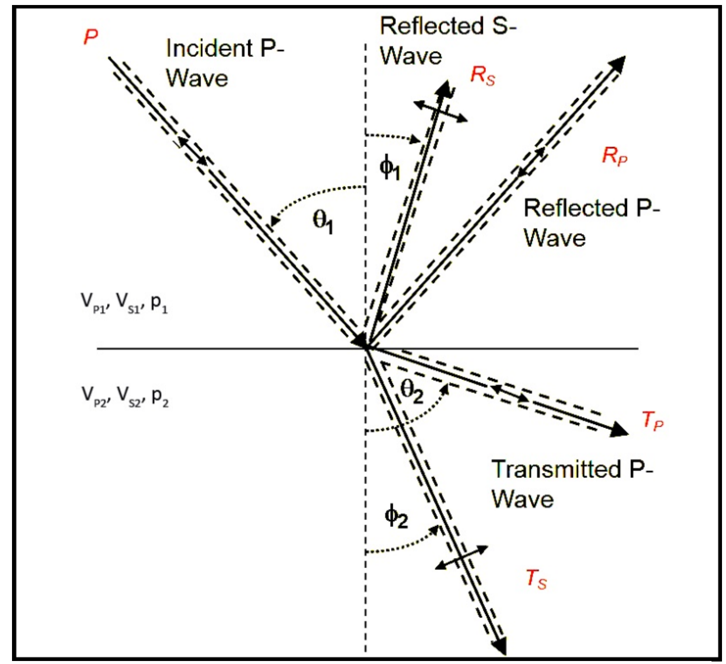
AVO: AMPLITUDE VARIATION WITH OFFSET

- When an incoming compressional P-Wave reaches an impedance (Velocity*Density) interface, it splits into four components:
  - Reflected P-Wave (R_{PP})
  - Reflected S-Wave (R_{PS})
  - Transmitted P-Wave (T_{PP})
  - Transmitted S-Wave (T_{PS})

$$\begin{pmatrix} \overset{\downarrow\uparrow}{PP} & \overset{\downarrow\uparrow}{SP} & \overset{\uparrow\uparrow}{PP} & \overset{\uparrow\uparrow}{SP} \\ \overset{\downarrow\uparrow}{PS} & \overset{\downarrow\uparrow}{SS} & \overset{\uparrow\uparrow}{PS} & \overset{\uparrow\uparrow}{SS} \\ \overset{\downarrow\downarrow}{PP} & \overset{\downarrow\downarrow}{SP} & \overset{\uparrow\downarrow}{PP} & \overset{\uparrow\downarrow}{SP} \\ \overset{\downarrow\downarrow}{PS} & \overset{\downarrow\downarrow}{SS} & \overset{\uparrow\downarrow}{PS} & \overset{\uparrow\downarrow}{SS} \end{pmatrix} = M^{-1}N$$

$$M = \begin{bmatrix} -\sin\theta_1 & -\cos\phi_1 & \sin\theta_2 & \cos\phi_2 \\ \cos\theta_1 & -\sin\phi_1 & \cos\theta_2 & -\sin\phi_2 \\ 2\rho_1 V_{S1}\sin\phi_1\cos\theta_1 & -\rho_1 V_{S1}(1-2\sin^2\phi_1) & -\rho_2 V_{S2}\sin\phi_2\cos\theta_2 & -\rho_1 V_{S2}(1-2\sin^2\phi_2) \\ -\rho_1 V_{P1}(1-2\sin^2\phi_1) & \rho_1 V_{S1}(1-2\sin^2\phi_1) & -\rho_2 V_{P2}\sin^2\phi_2 & -\rho_2 V_{S2}\sin 2\phi_2 \end{bmatrix}$$

$$N = \begin{bmatrix} \sin\theta_1 & \cos\phi_1 & -\sin\theta_2 & -\cos\phi_2 \\ \cos\theta_1 & -\sin\phi_1 & \cos\theta_2 & -\sin\phi_2 \\ 2\rho_1 V_{S1}\sin\phi_1\cos\theta_1 & -\rho_1 V_{S1}(1-2\sin^2\phi_1) & -\rho_2 V_{S2}\sin\phi_2\cos\theta_2 & -\rho_1 V_{S2}(1-2\sin^2\phi_2) \\ -\rho_1 V_{P1}(1-2\sin^2\phi_1) & \rho_1 V_{S1}(1-2\sin^2\phi_1) & -\rho_2 V_{P2}\sin^2\phi_2 & -\rho_2 V_{S2}\sin 2\phi_2 \end{bmatrix}$$



Reflection-transmission system in layered media - Snell's Law

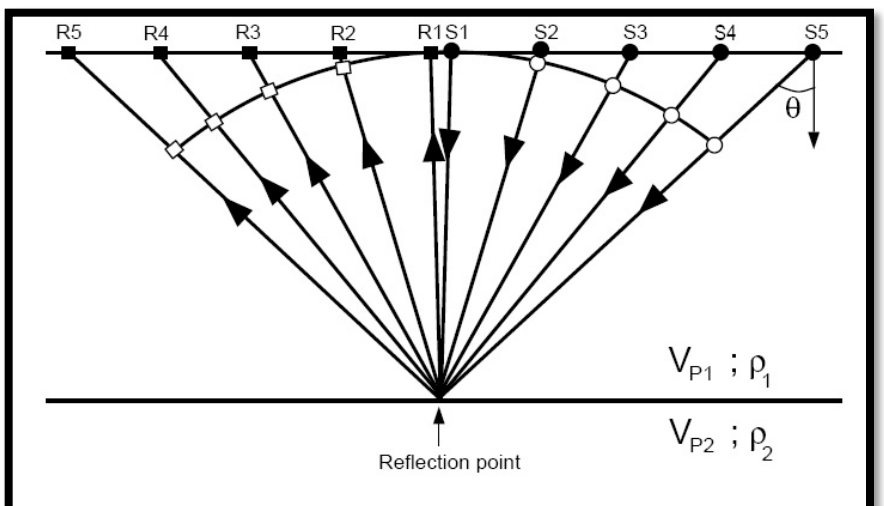
(Zoeppritz 1919, Aki and Richards 1980, Hilterman 1983, Mavko, Mukerji et al. 1998)

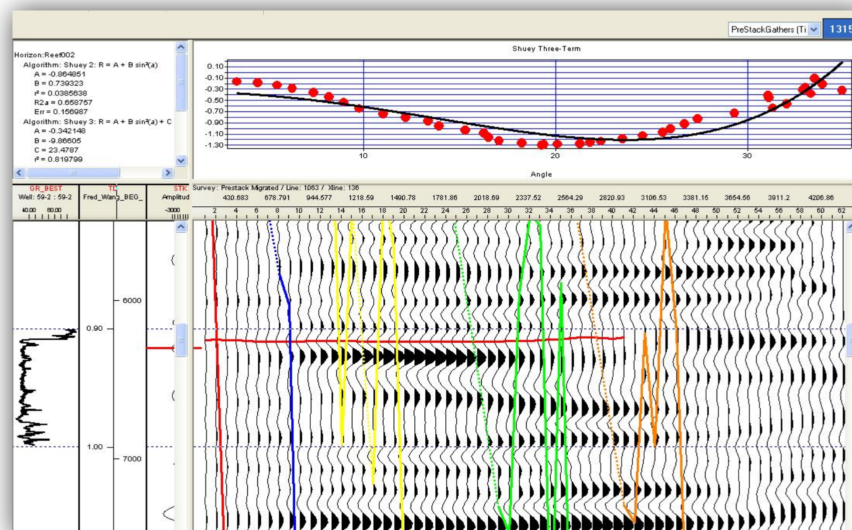
This slide courtesy Dr. Alan Mur, IKON Science

AVO ANALYSIS OF PRESTACK SEISMIC DATA

- Using Shuey's 3-term approximation to the Zoeppritz model, we fit a curve to the amplitudes at increasing angles on prestack seismic gathers around an injection well.
- The coefficients of the fitting curve are the Intercept (A), Gradient (B), and Curvature (C). (these coefficients are also physically defined).

$$R(\theta)=A(0) + B\sin^2\theta + C(\tan^2\theta - \sin^2\theta)$$





This slide courtesy Dr. Alan Mur, IKON Science

CALCULATED AVO ATTRIBUTES

A = intercept
B = gradient
r^2 = correlation
A × B
(A + B)/2 ~ Rp - Rs
(A – B)/2 ~ Rs

Shuey 2 Term

$$RC(\theta) = A + B(\sin^2\theta)$$

A = intercept
B = gradient
C = curvature
r^2 = correlation
A × B
(A + B)/2 ~ Rp - Rs
(A – B)/2 ~ Rs
A – C

Shuey 3Term

$$RC(\theta) = A + B(\sin^2\theta) + C(\sin^2\theta)(\tan^2\theta)$$

NIp = normal intercept
PR = Poisson reflectivity
r^2 = correlation
Nip × PR

Verm-Hilterman

$$RC(\theta) = NIp(\cos^2\theta) + PR(\sin^2\theta)$$

From: Rocky Roden, Chief Consulting Geoscientist, Seismic Micro-Technology, Inc.

Biot-Gassmann fluid replacement equation in Lamé terms

Biot-Gassmann Equation:
K is bulk modulus,
"sat" is saturated rock, ϕ is porosity

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_{solid}}\right)^2}{\left(1 - \phi - \frac{K_{dry}}{K_{solid}}\right)\left(K_{solid}\right)^{-1} + \left(\frac{\phi}{K_{fluid}}\right)}$$

Approximation to Biot-Gassmann Equation in Lamé terms

$$\text{Assuming } \mu_{dry} = \mu_{sat} \quad \text{substitute } \Delta\lambda = \lambda_{sat} - \lambda_{dry}$$

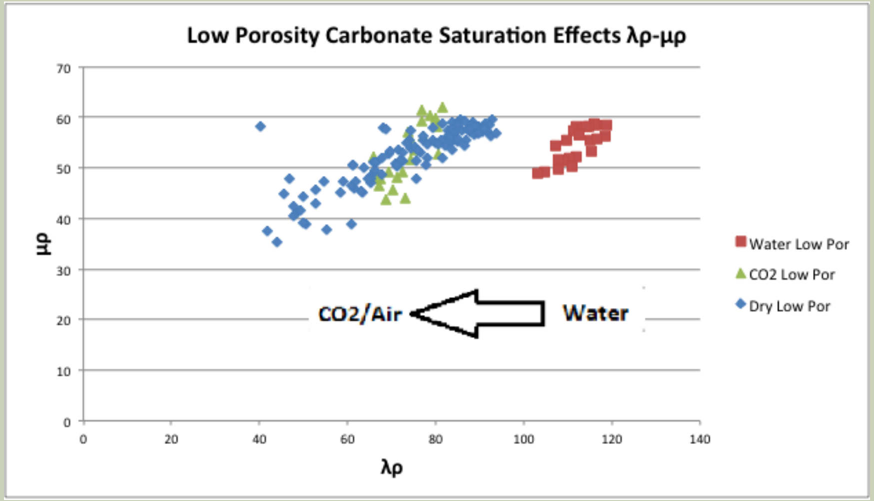
$$\Rightarrow \Delta\lambda \approx \frac{\lambda_{fluid}}{\phi}\left(1 - \frac{K_{dry}^2}{K_{solid}^2}\right)$$

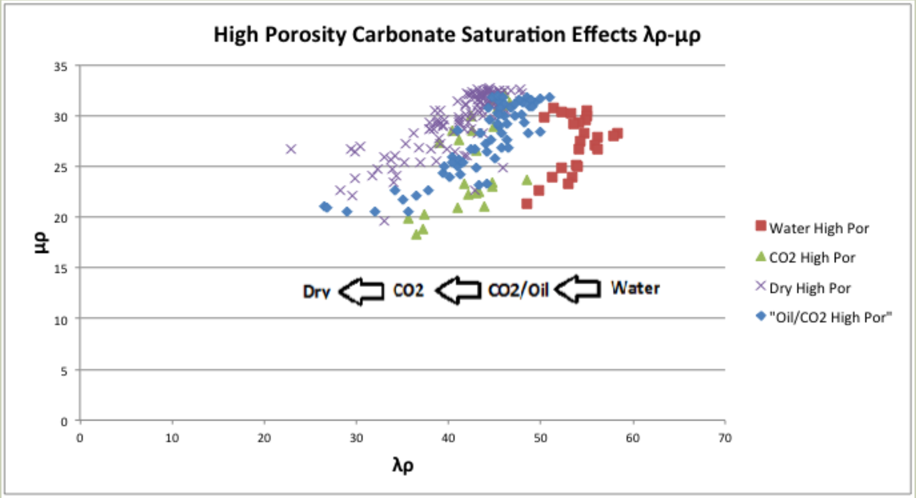
Where $\Delta\lambda$ is the "fluid term" related to $\rho\Delta\lambda$ "pore space modulus"
(from Hedlin, Russell, Hilterman and Lines 2003)

Observations:

- Low $\Delta\lambda$ sensitivity for high modulus (K_{solid}) rock e.g. Carbonates
- λ can never be negative as λ_{fluid}, ϕ, K_{dry}^2 and K_{solid}^2 are always positive

FLUID SATURATION IN λρ-μρ Coordinates

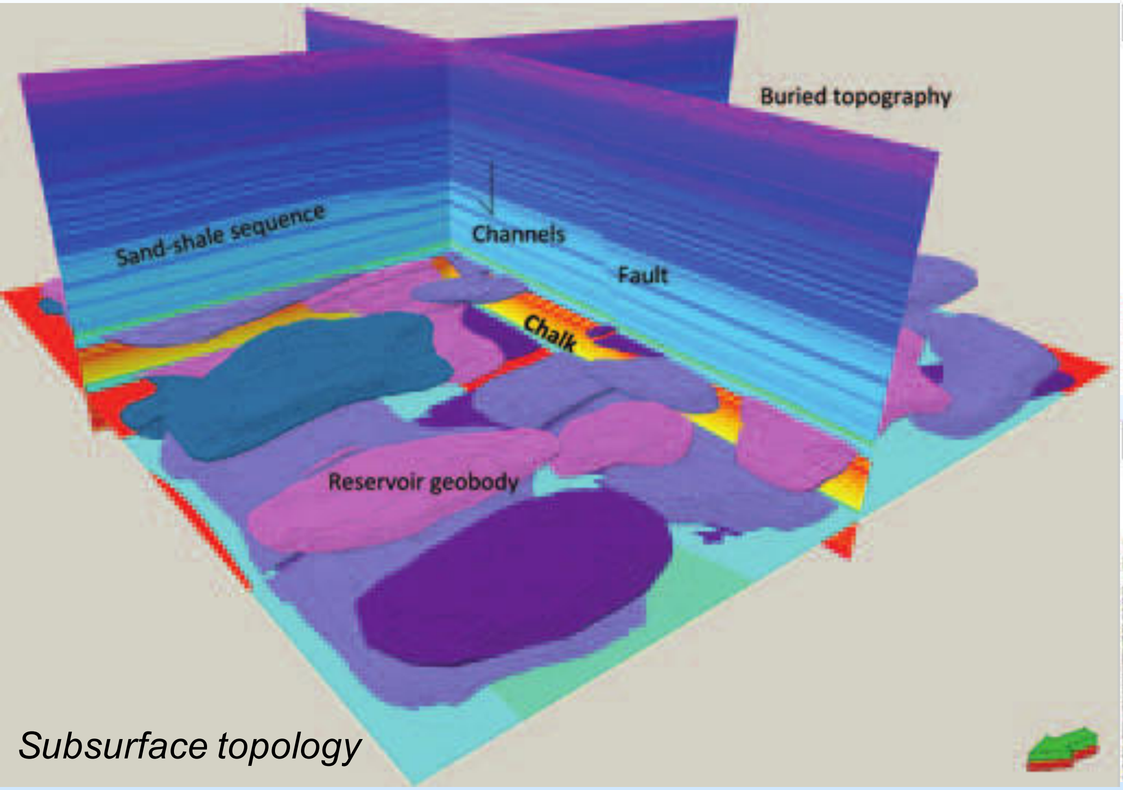


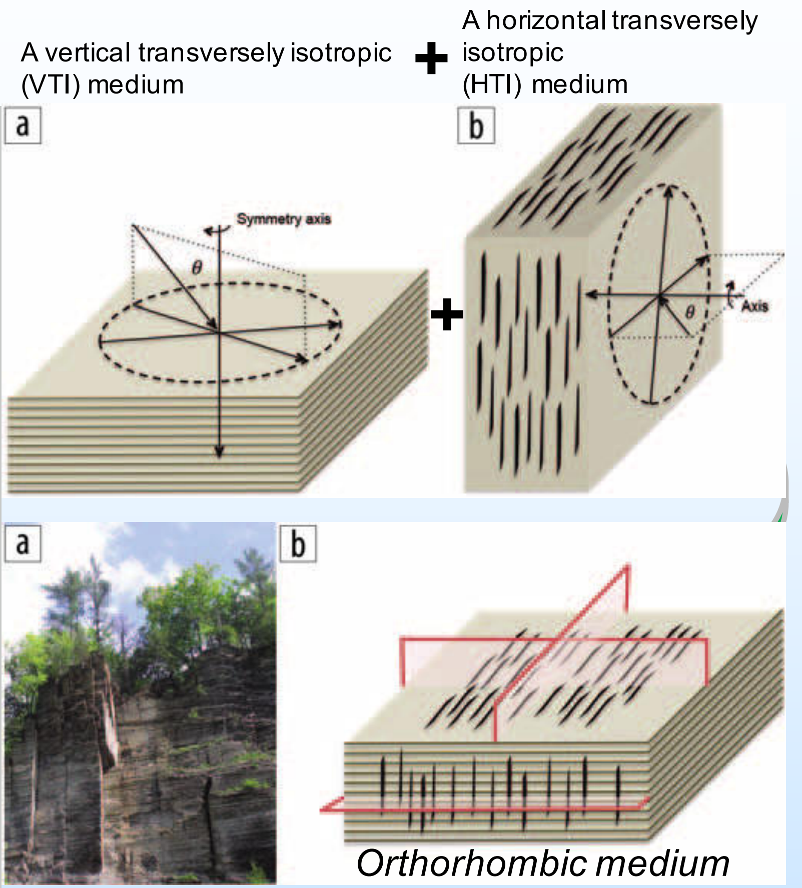


- Lamé moduli of rigidity μ and "incompressibility" λ allow the fundamental parameterization of seismic waves used to extract information about rocks in the Earth.
- The introduction of fluids into the carbonate cores causes a shift in λρ, μρ remains independent of fluid saturation.
- λρ-μρ is dependent on framework characteristics, including porosity, Higher porosity results in lower values for both λρ and μρ.

This slide courtesy Mr. Daniel Delaney

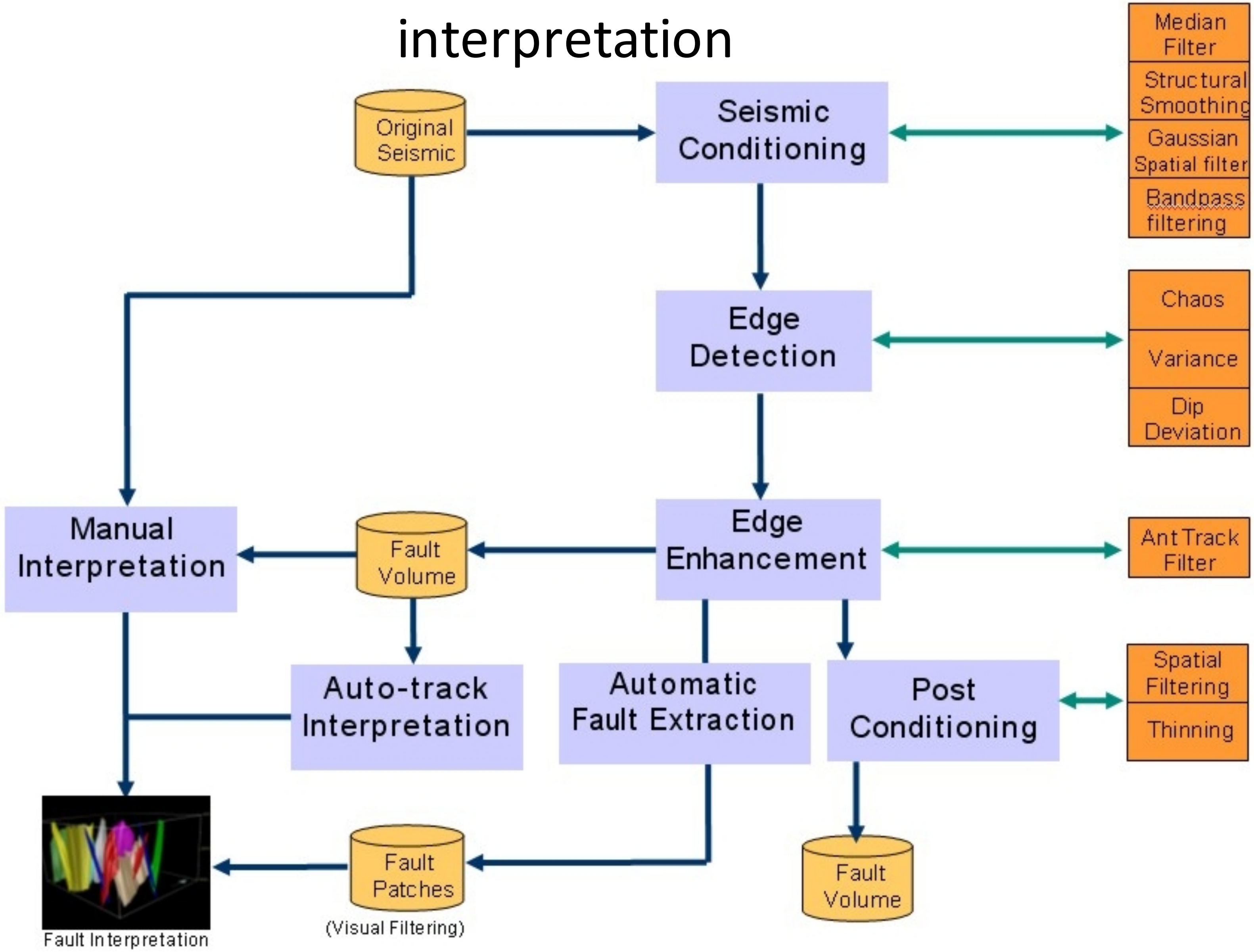
VTI / HTI Anisotropy





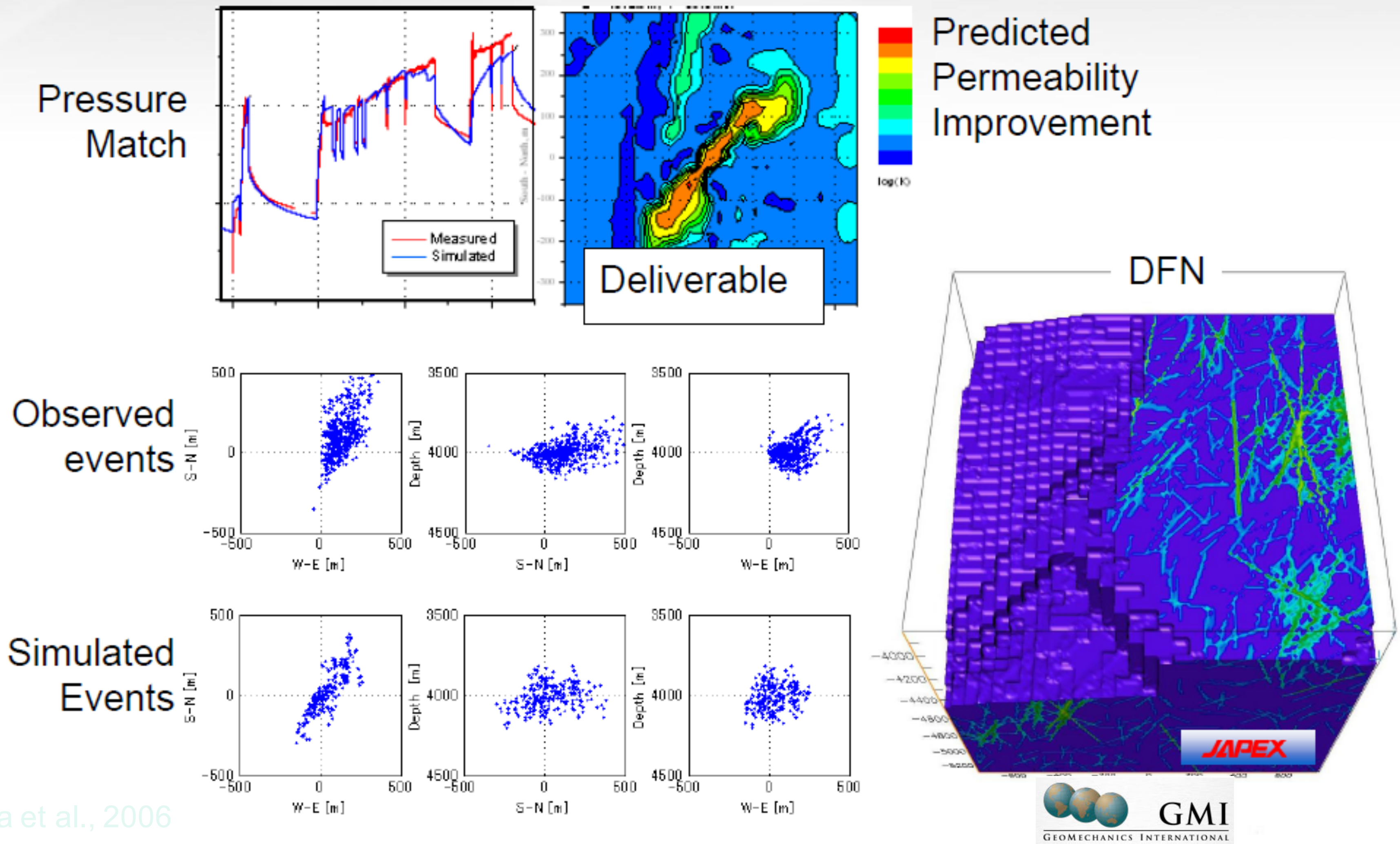
From: TLE, Elastic anisotropy in SEAM Phase II models

Ant-tracking based 3D reflection volume interpretation



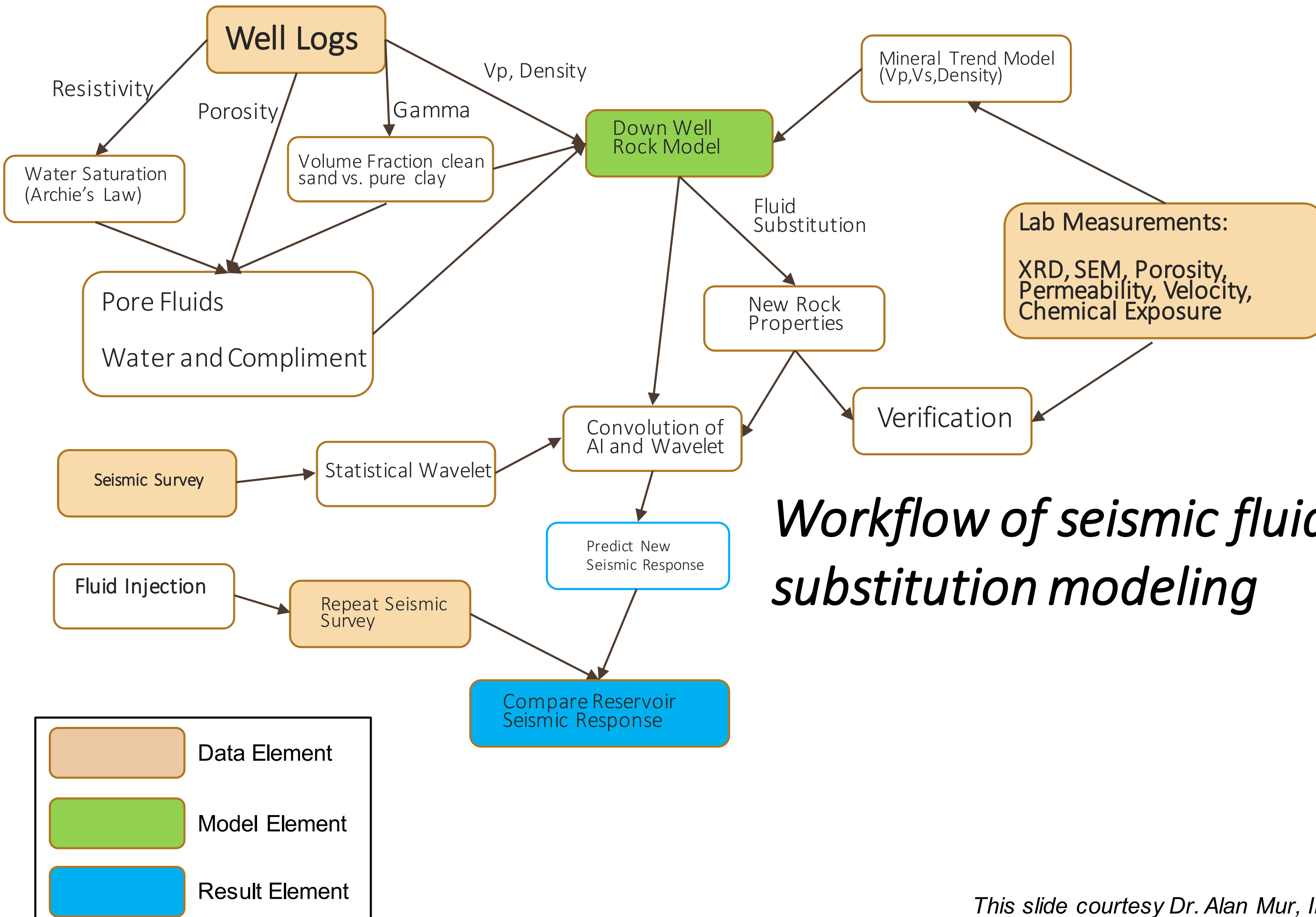
Ant-tracking based 3D reflection volume interpretation

Integrated geomechanical reservoir modeling



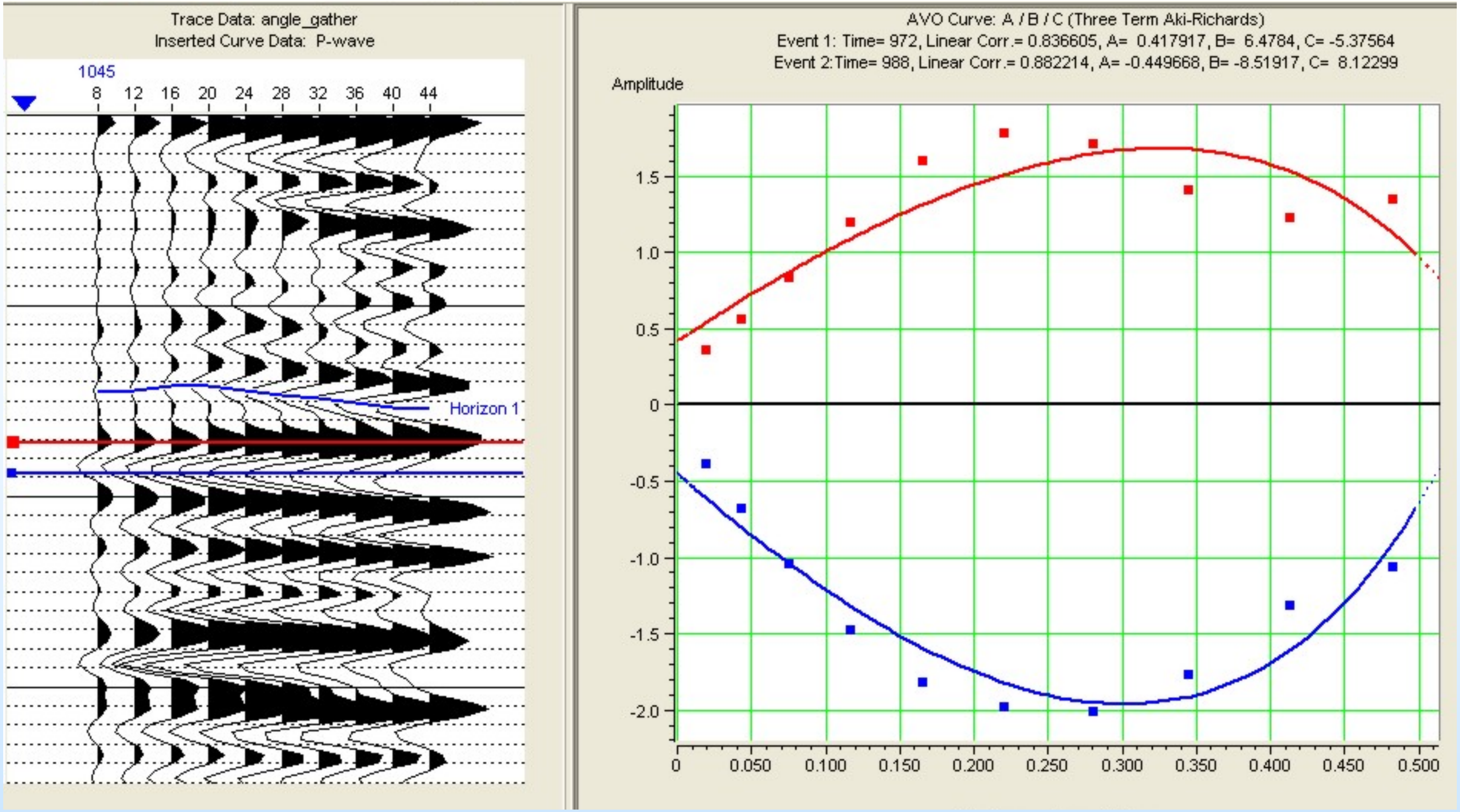
Tezuka et al., 2006

Workflow of seismic fluid substitution modeling

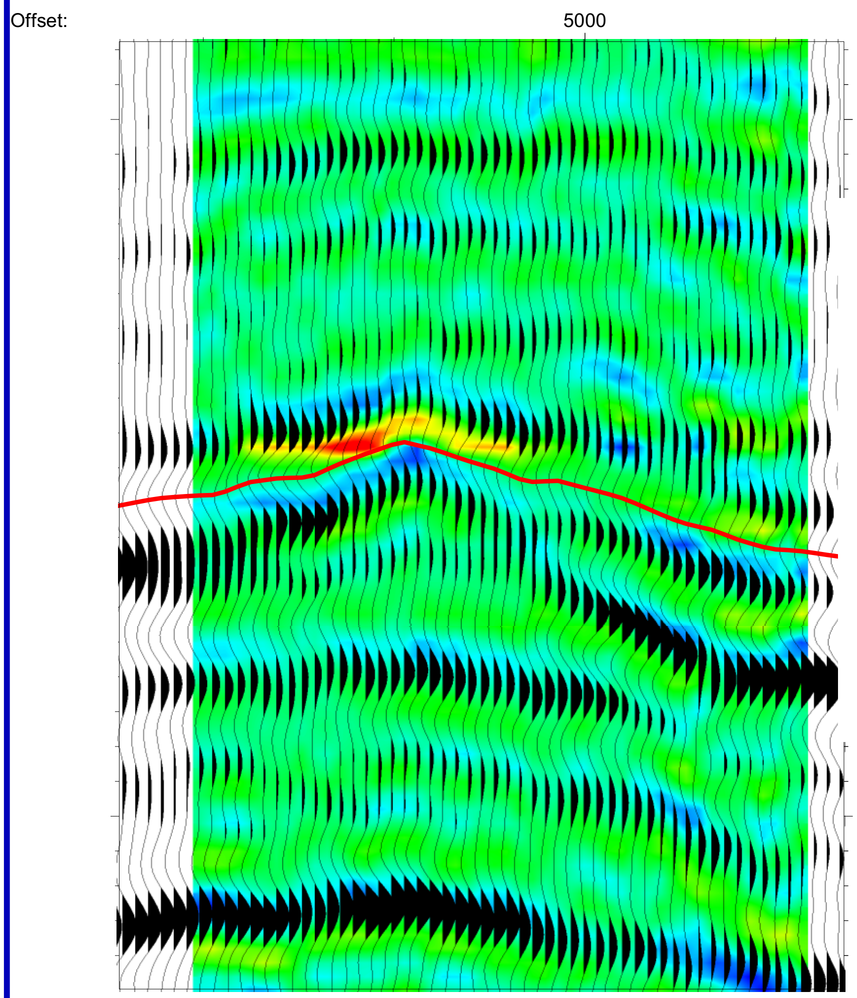


This slide courtesy Dr. Alan Mur, IKON Science

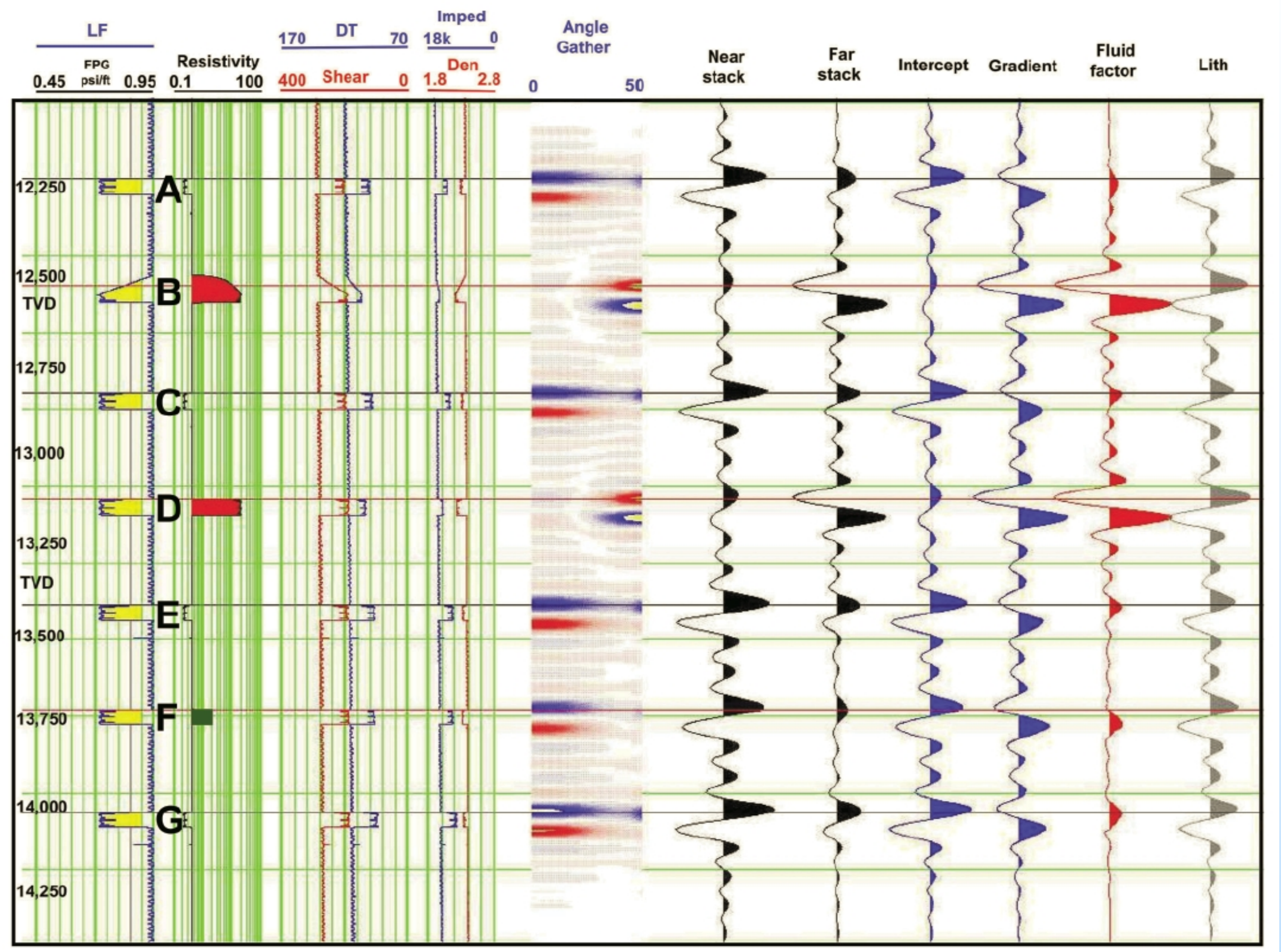
Aki and Richards 3 term AVO curve fit



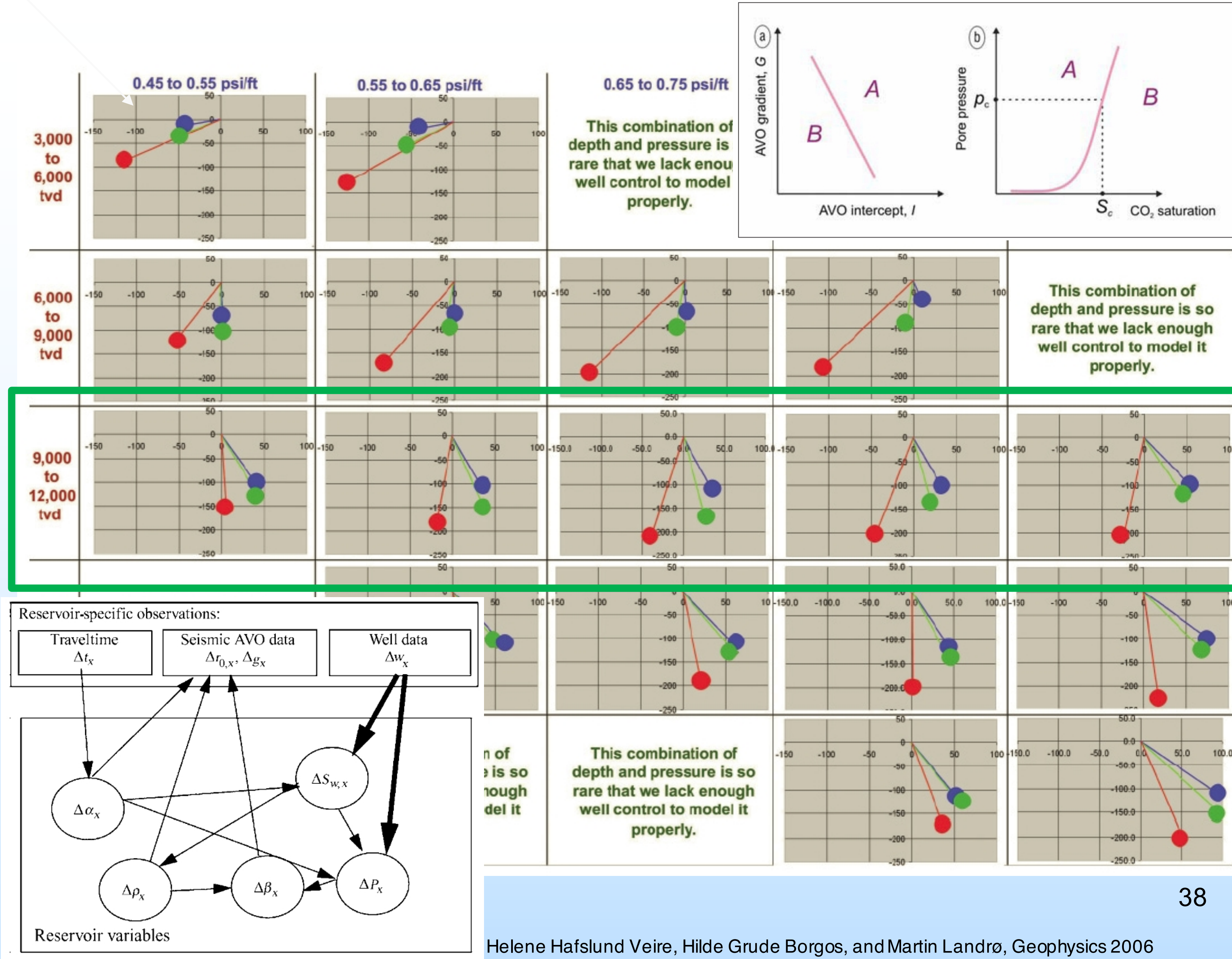
AVO anomaly
Described by
Purcell et al (2011)



Fluid and pressure variation used in AVO modeling



FROM: TLE, RICK BOX and ERIC DOSS, Hunt Petroleum, Houston, USA

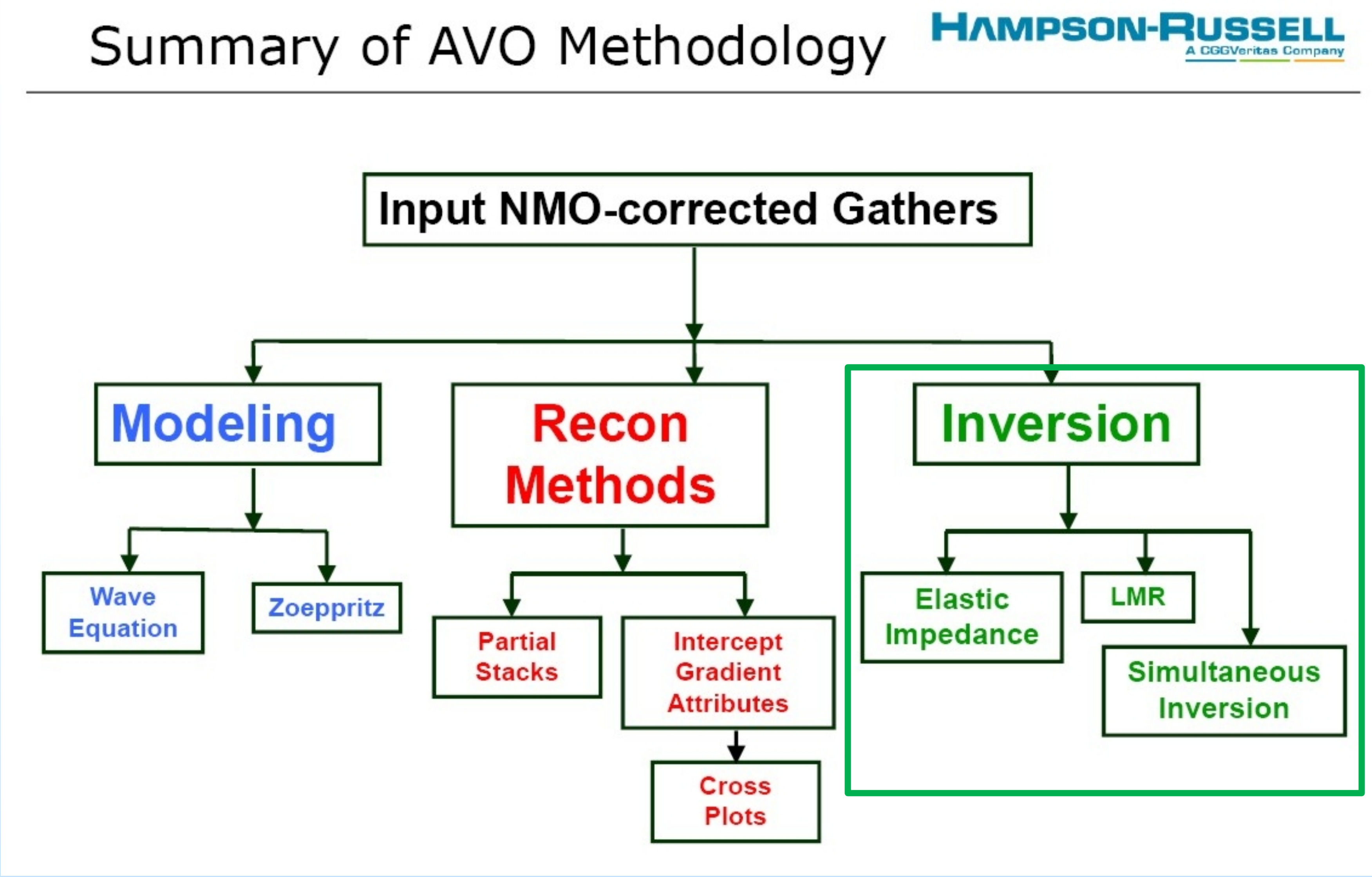


Ma and Morozov, TLE, 2010

Helene Hafslund Veire, Hilde Grude Borgos, and Martin Landrø, Geophysics 2006

FROM: TLE, RICK BOX and ERIC DOSS, Hunt Petroleum, Houston, USA

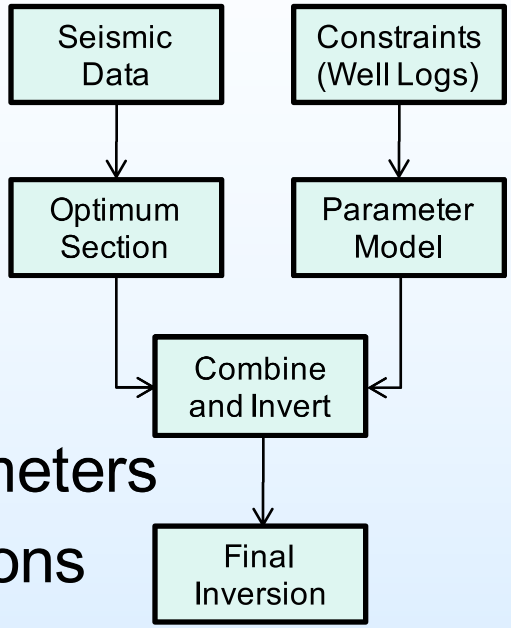
Overall Project Workflow



From Dan Hampson, Hampson-Russell

Inversion Based Modeling

- Create Model
  - Select Wells
  - Correlate each well
  - Extract Wavelet
  - Pick seismic horizons
- Perform Inversion
  - Select Inversion Type and Parameters
  - QC Inversion result at well locations
- Interpret Results
  - Create data slices
  - Create cross plots



From Dan Hampson, STRATA Course, Houston, Texas

Seismic methods

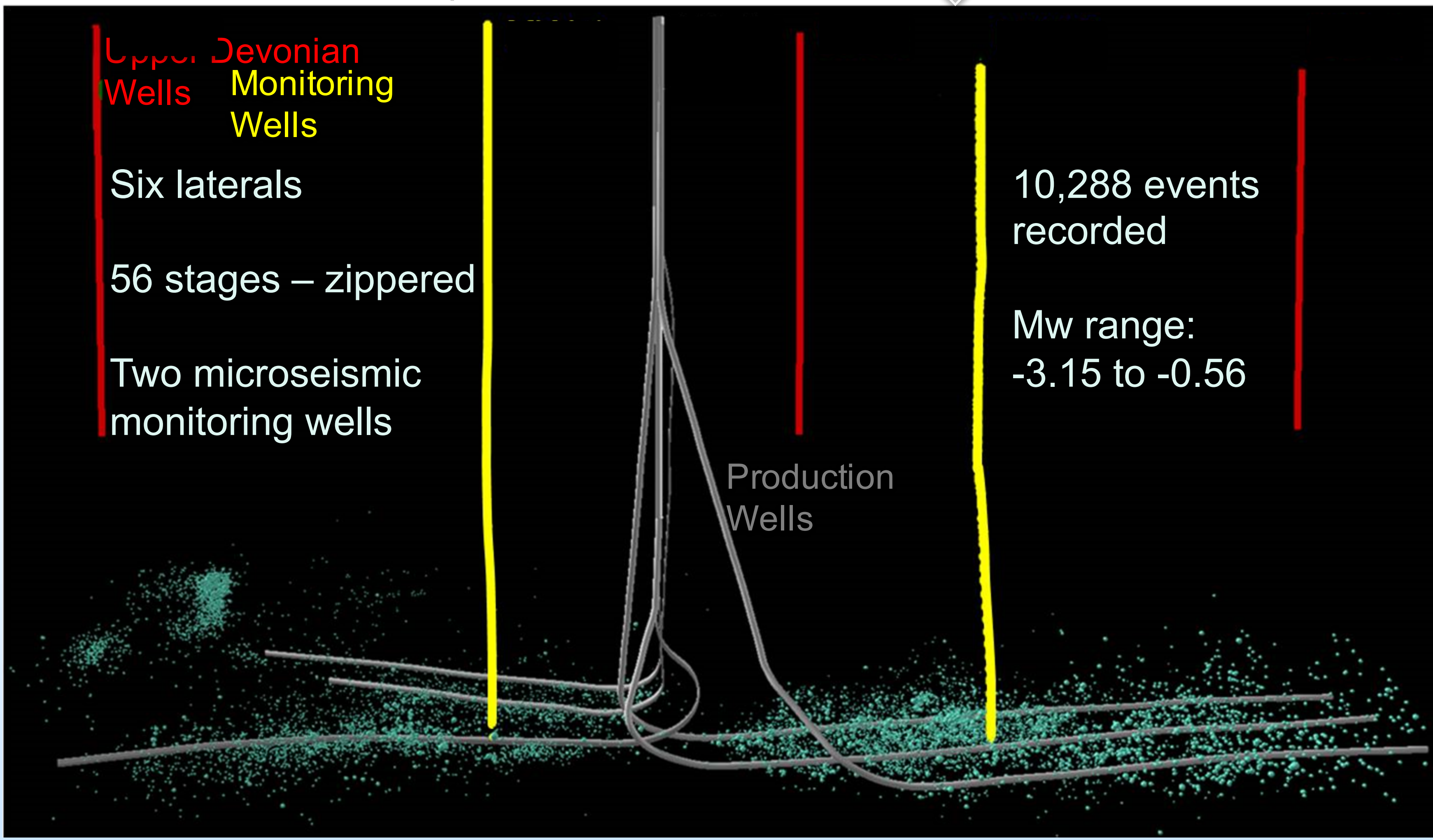
- Complete analysis of existing datasets focusing on gradient intercept and AVO parameter variation.
- Forward model expected pressure and fluid trends using well log data to determine expected trends.
- Analysis of seismic inversion results calibrated with core laboratory measurements

Presentation Outline

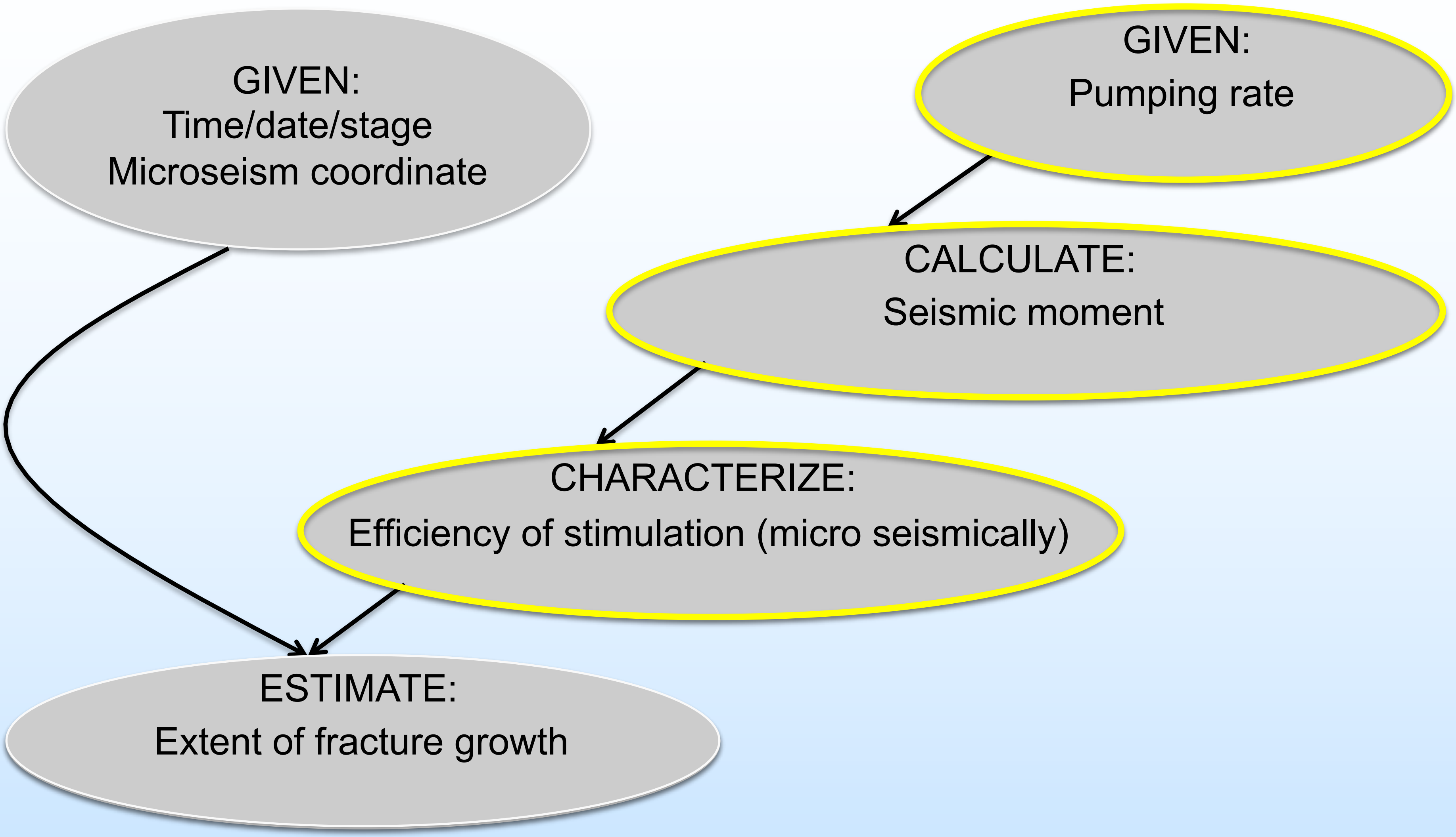
- Core based petrophysical measurements, analysis and interpretation.
- Reflection seismic based reservoir monitoring and surveillance.
- Microseismic monitoring and surveillance.
- Electromagnetic methods.

Site details

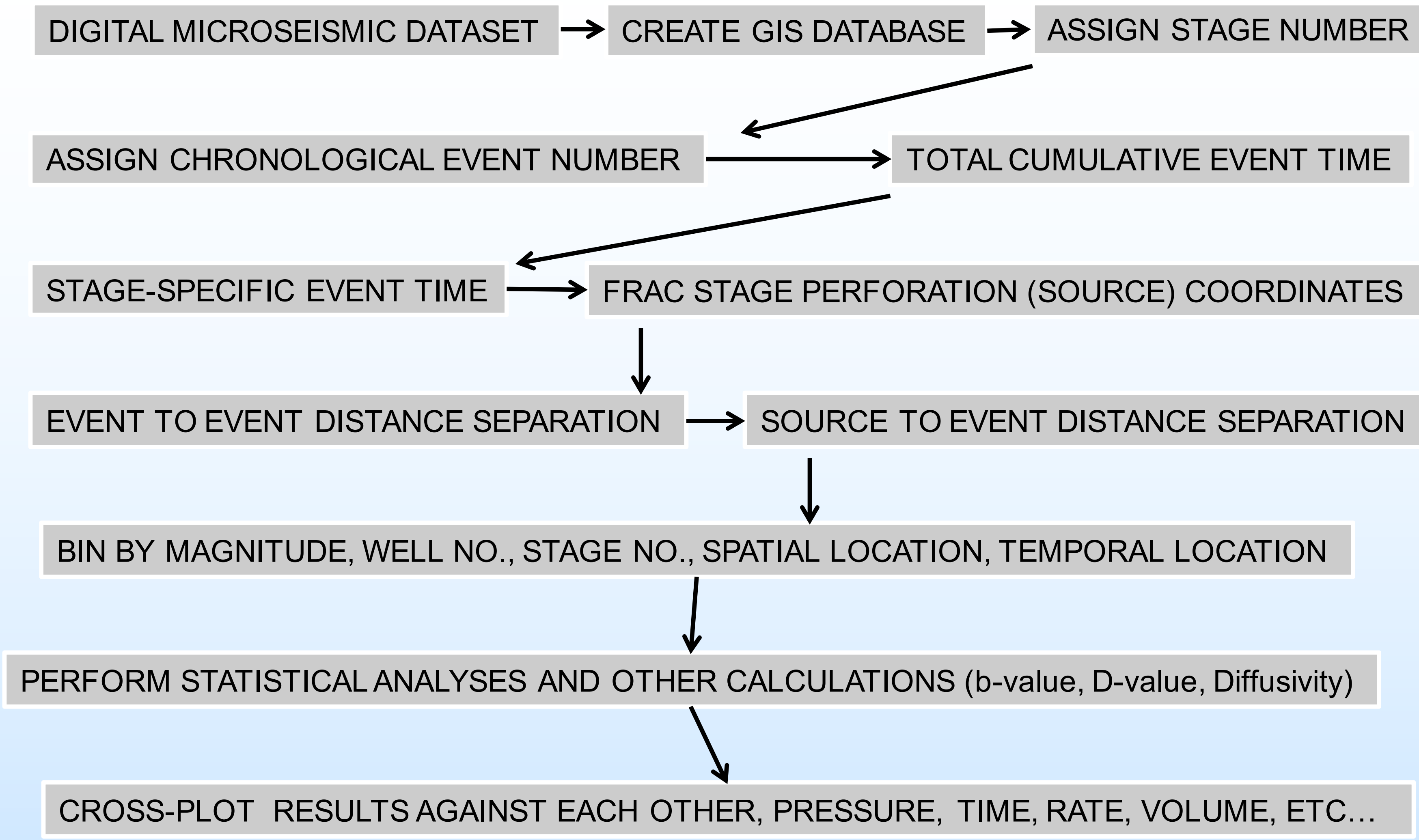
3-component, 2Hz seismometer

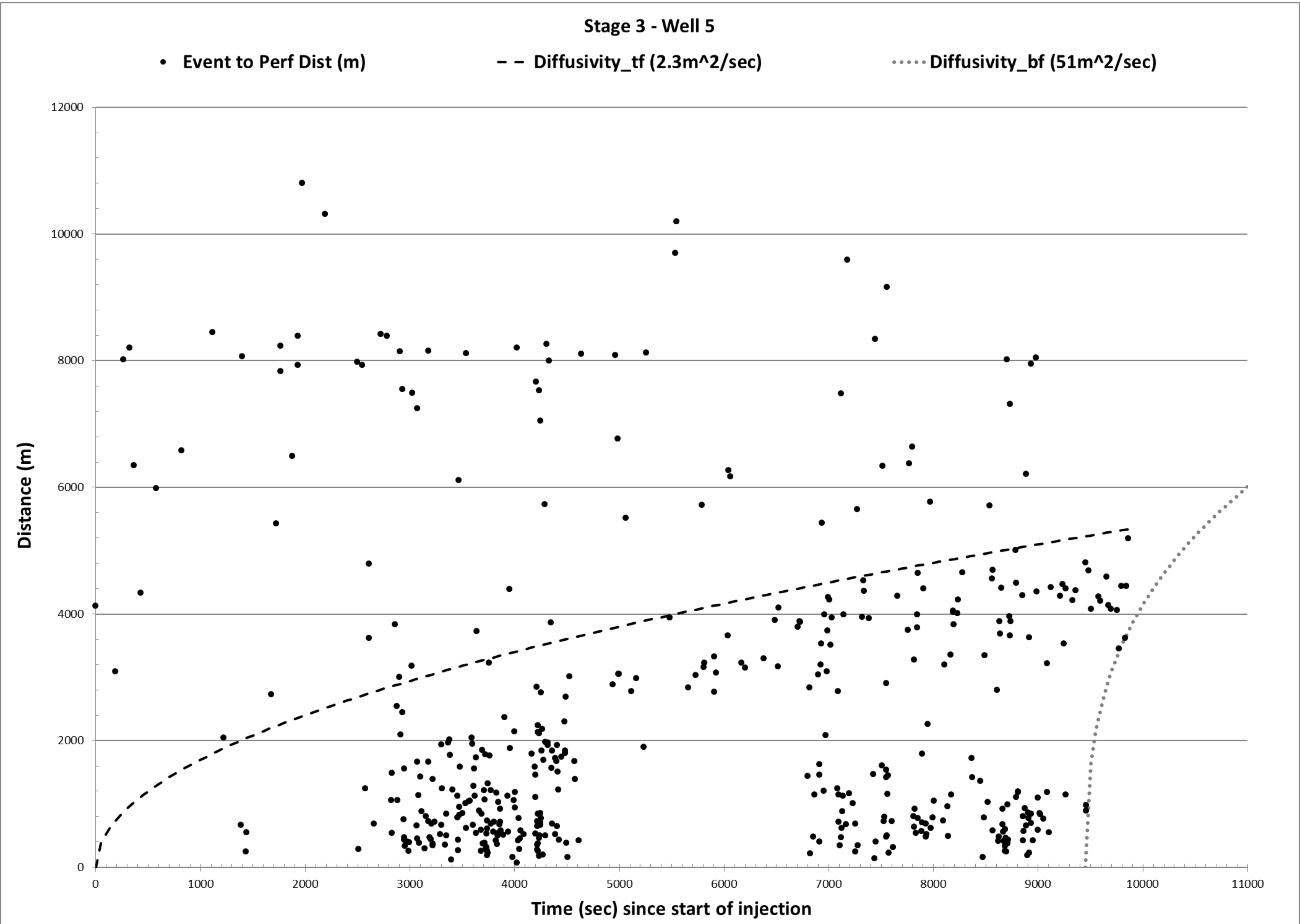


Motivation


GIVEN:
Time/date/stage
Microseism coordinate
GIVEN:
Pumping rate
CALCULATE:
Seismic moment
CHARACTERIZE:
Efficiency of stimulation (micro seismically)
ESTIMATE:
Extent of fracture growth

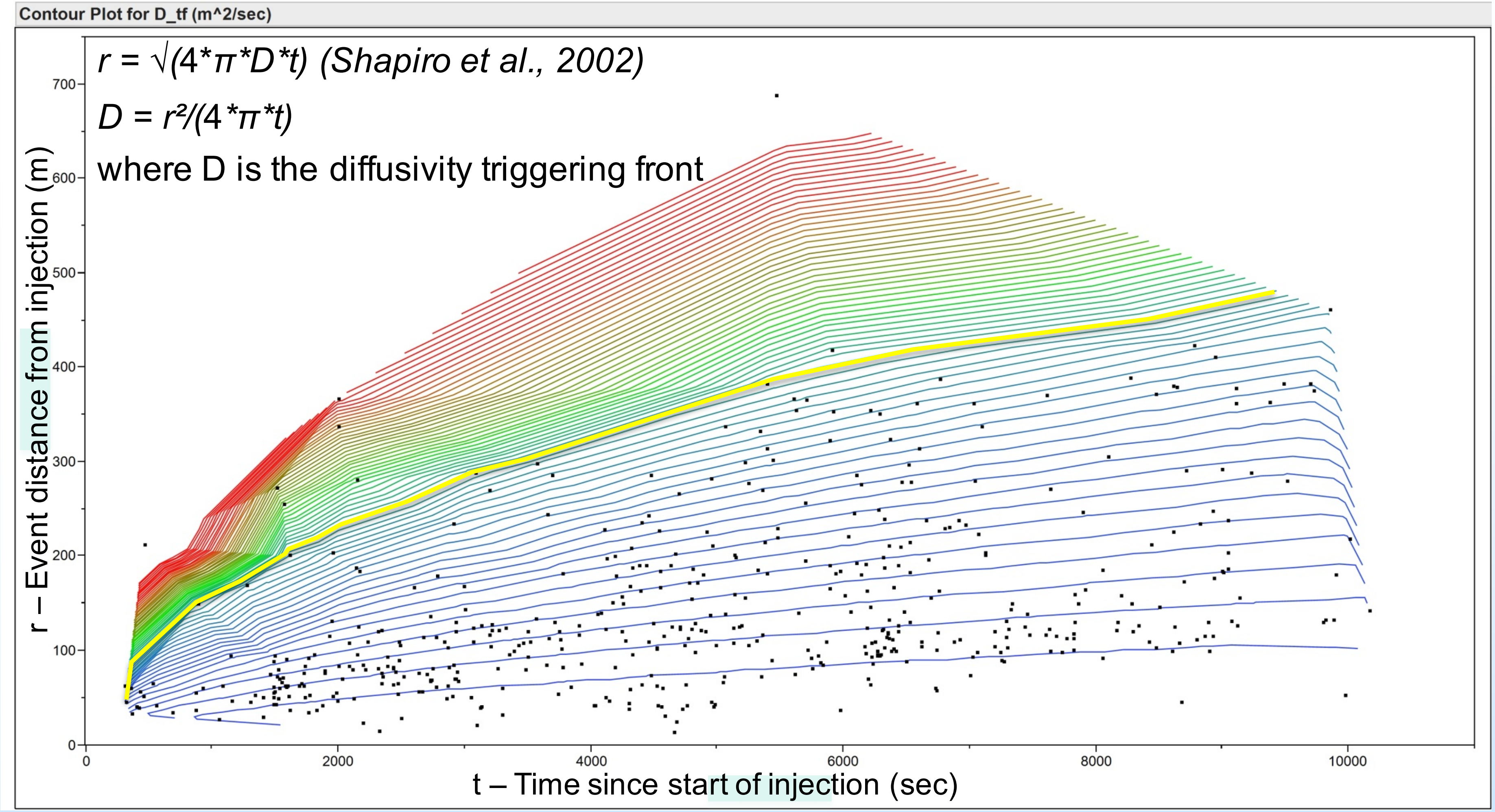
Workflow


DIGITAL MICROSEISMIC DATASET
CREATE GIS DATABASE
ASSIGN STAGE NUMBER
ASSIGN CHRONOLOGICAL EVENT NUMBER
TOTAL CUMULATIVE EVENT TIME
STAGE-SPECIFIC EVENT TIME
FRAC STAGE PERFORATION (SOURCE) COORDINATES
EVENT TO EVENT DISTANCE SEPARATION
SOURCE TO EVENT DISTANCE SEPARATION
BIN BY MAGNITUDE, WELL NO., STAGE NO., SPATIAL LOCATION, TEMPORAL LOCATION
PERFORM STATISTICAL ANALYSES AND OTHER CALCULATIONS (b-value, D-value, Diffusivity)
CROSS-PLOT RESULTS AGAINST EACH OTHER, PRESSURE, TIME, RATE, VOLUME, ETC…

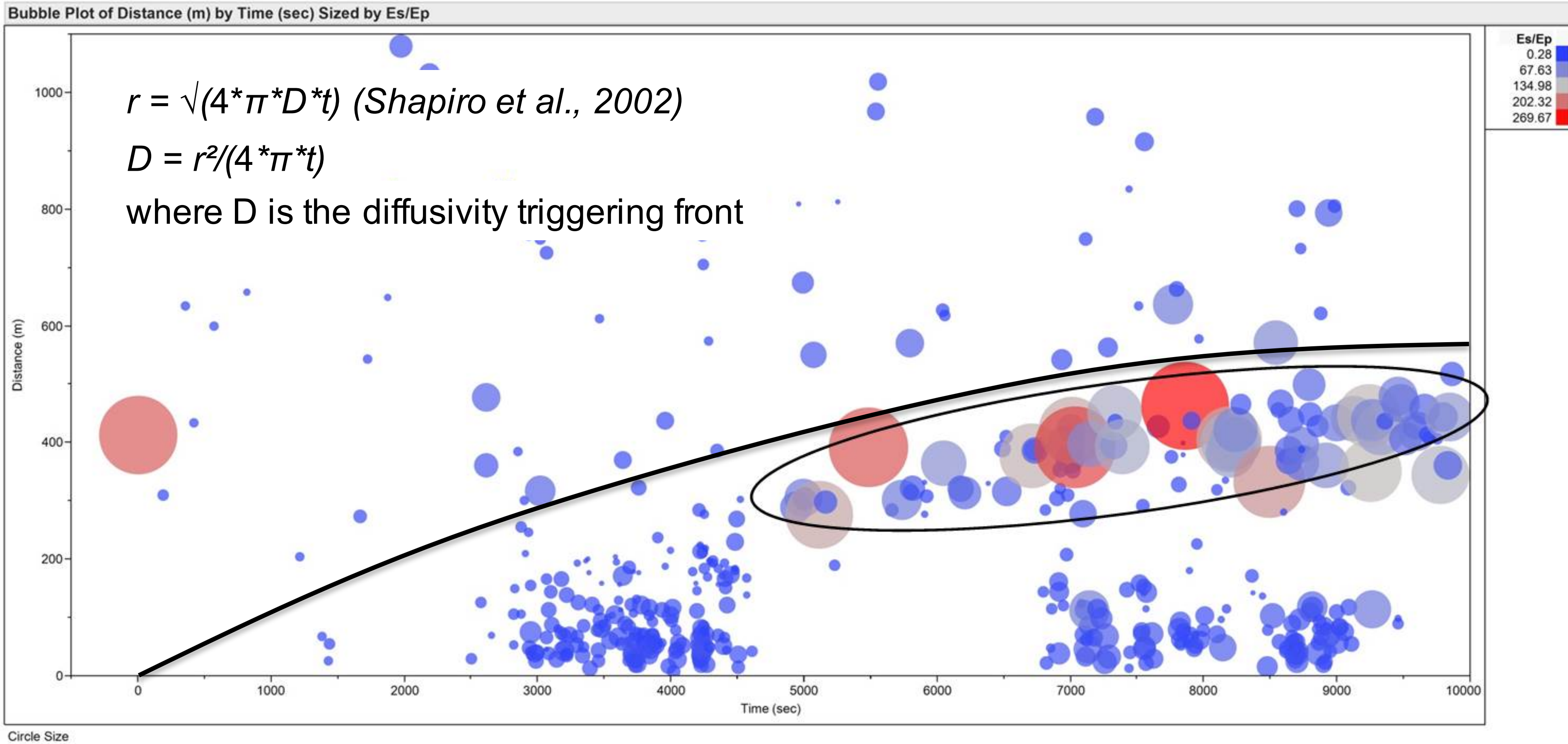


Stage 3 - Well 5
Event to Perf Dist (m)
Diffusivity_tf (2.3m^2/sec)
Diffusivity_bf (51m^2/sec)
Distance (m)
Time (sec) since start of injection
0
2000
4000
6000
8000
10000
12000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000

Hydraulic Diffusivity: The triggering front

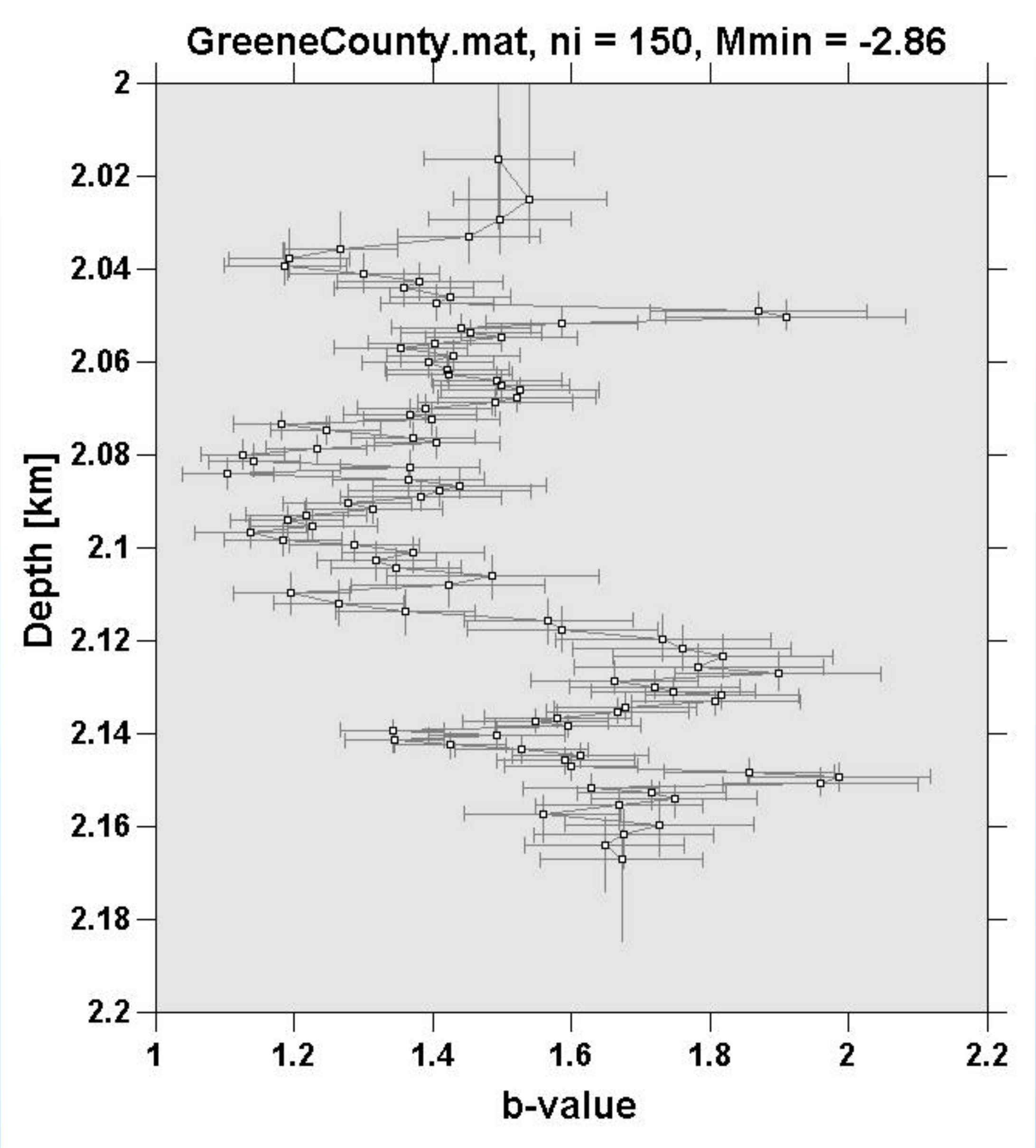


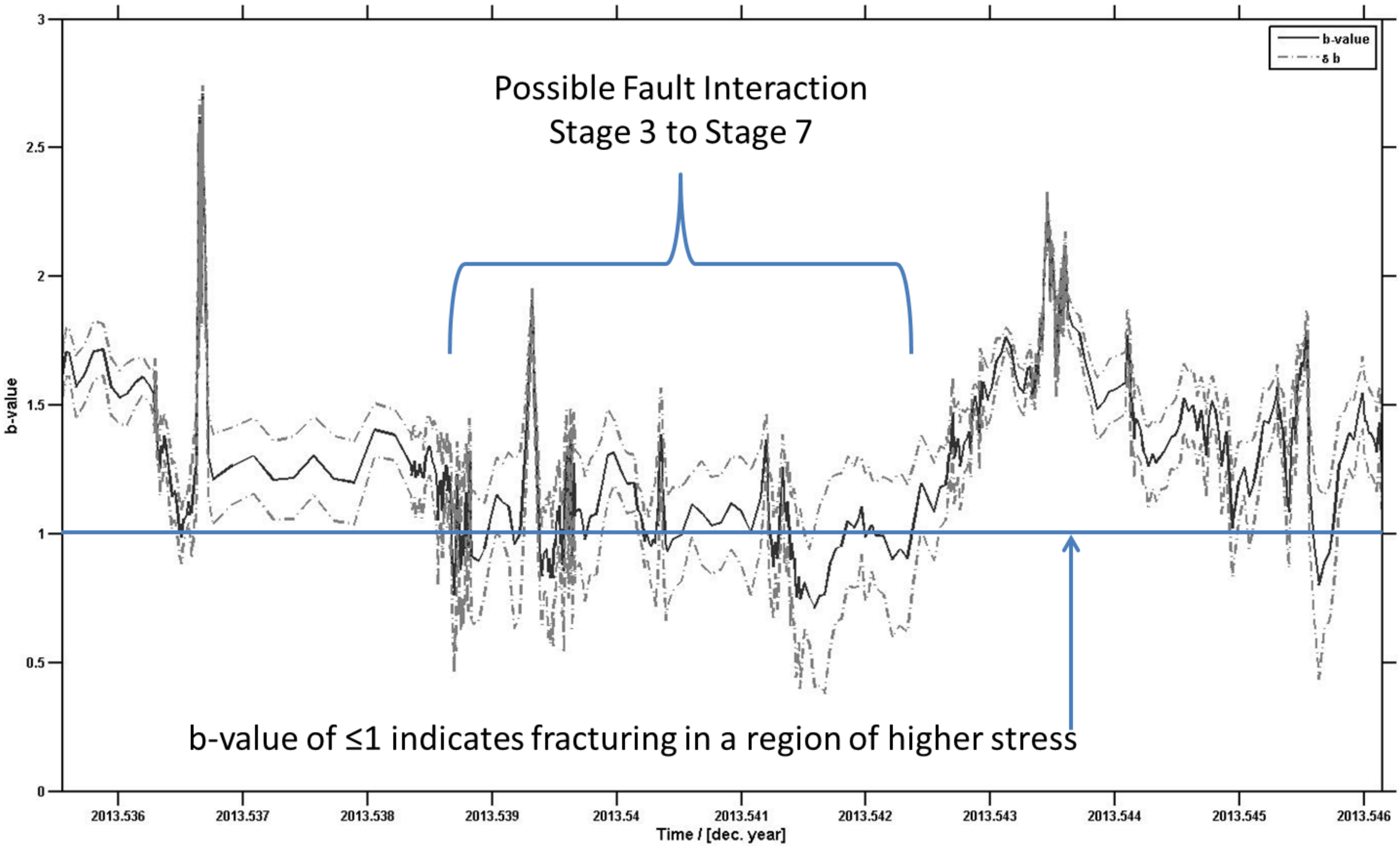
r-t plot with points scaled by Es/Ep ratio



Presently completing calculation of Coulomb Yield Stress (CYS) perturbation with time Rozkho (2010)

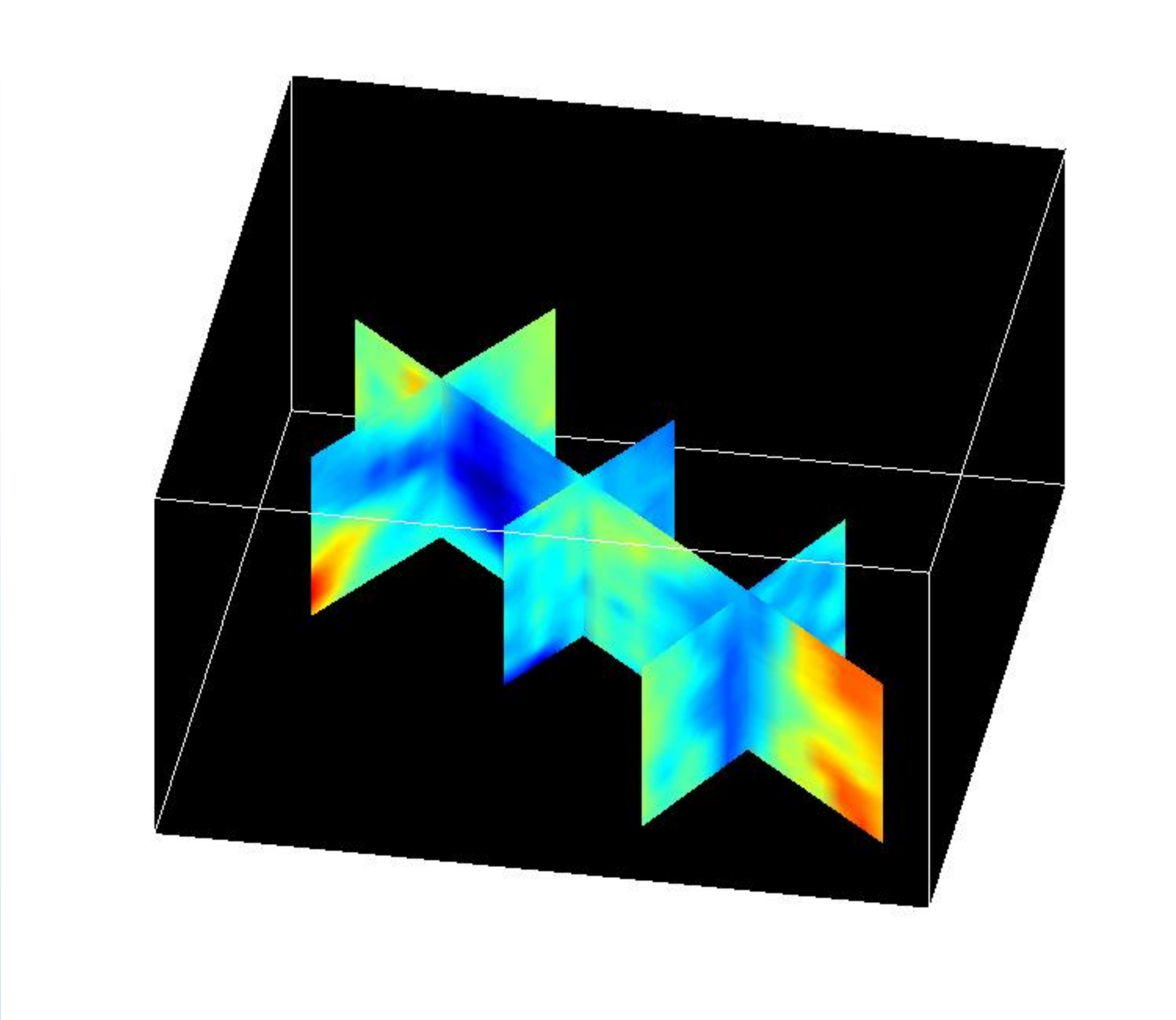
Variation in b-value with depth



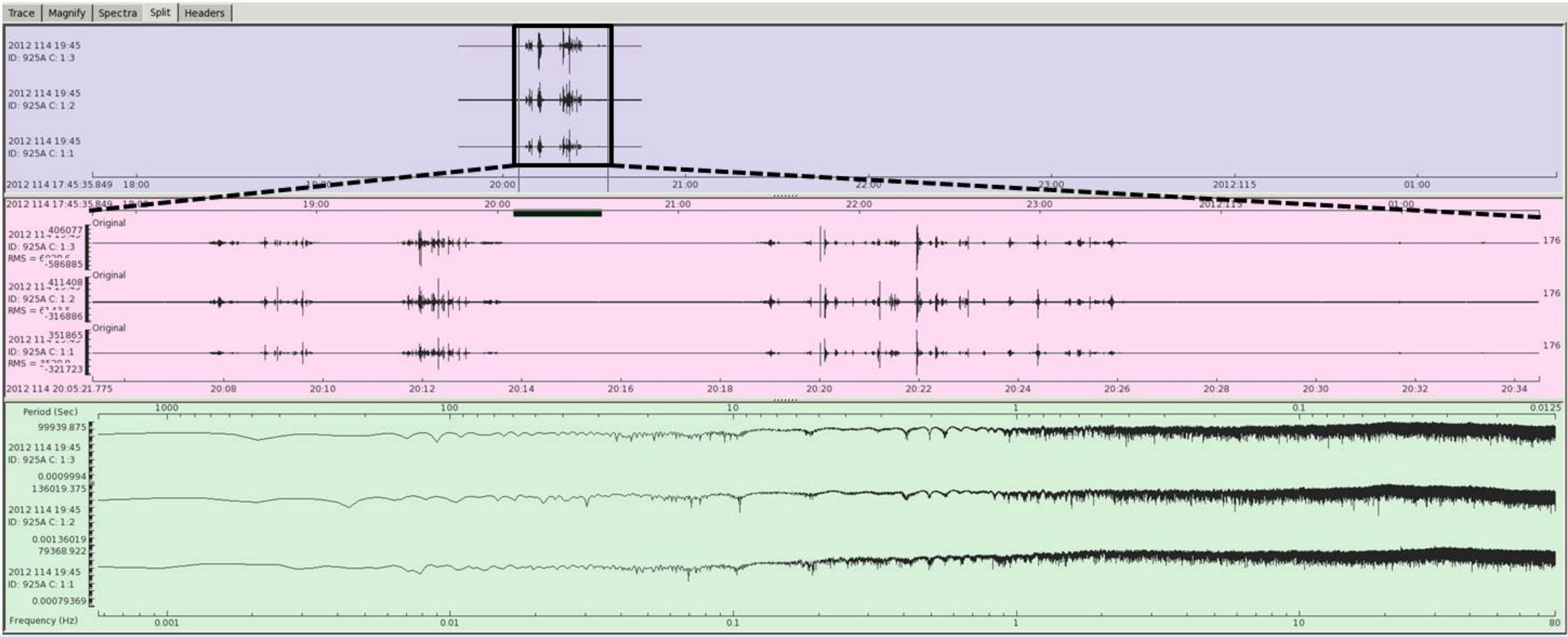


Possible Fault Interaction
Stage 3 to Stage 7
b-value of ≤1 indicates fracturing in a region of higher stress
b-value
δ b
b-value
Time / [dec. year]
0
0.5
1
1.5
2
2.5
3
2013.536
2013.537
2013.538
2013.539
2013.54
2013.541
2013.542
2013.543
2013.544
2013.545
2013.546

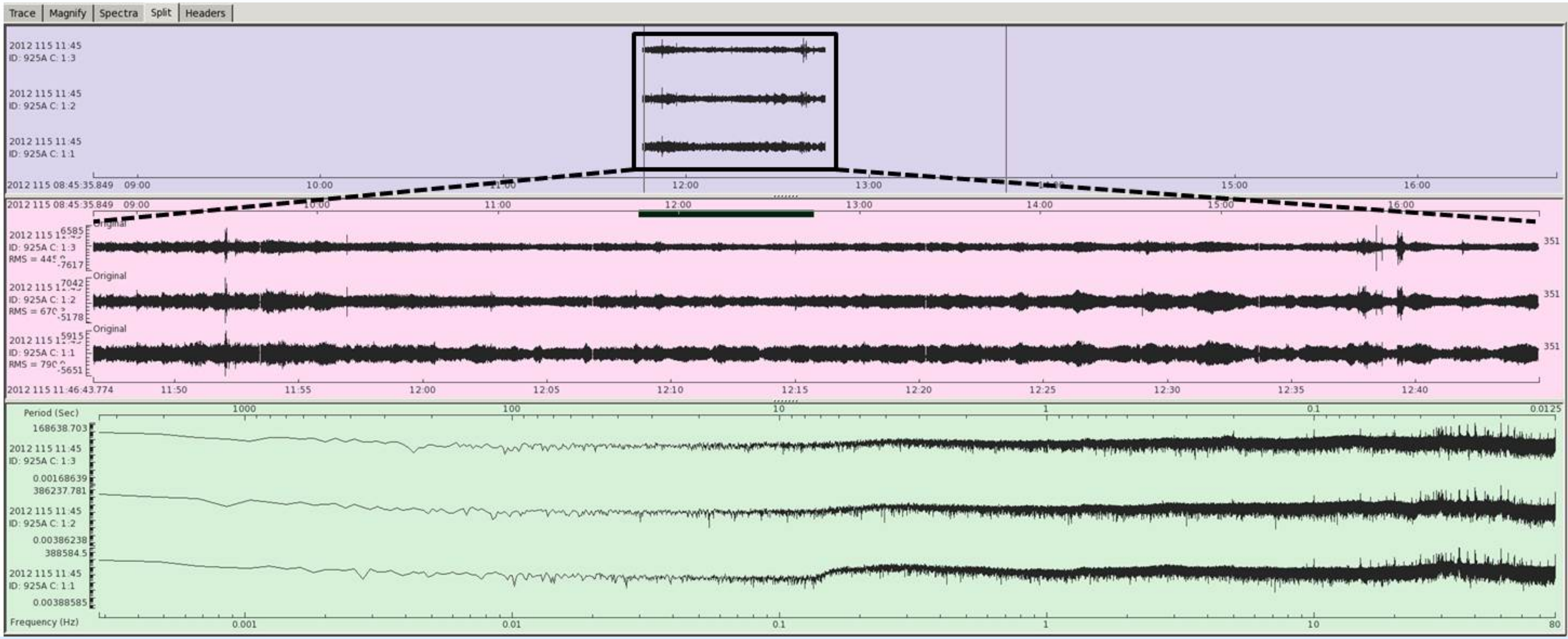
Volumetric b-value fence diagram



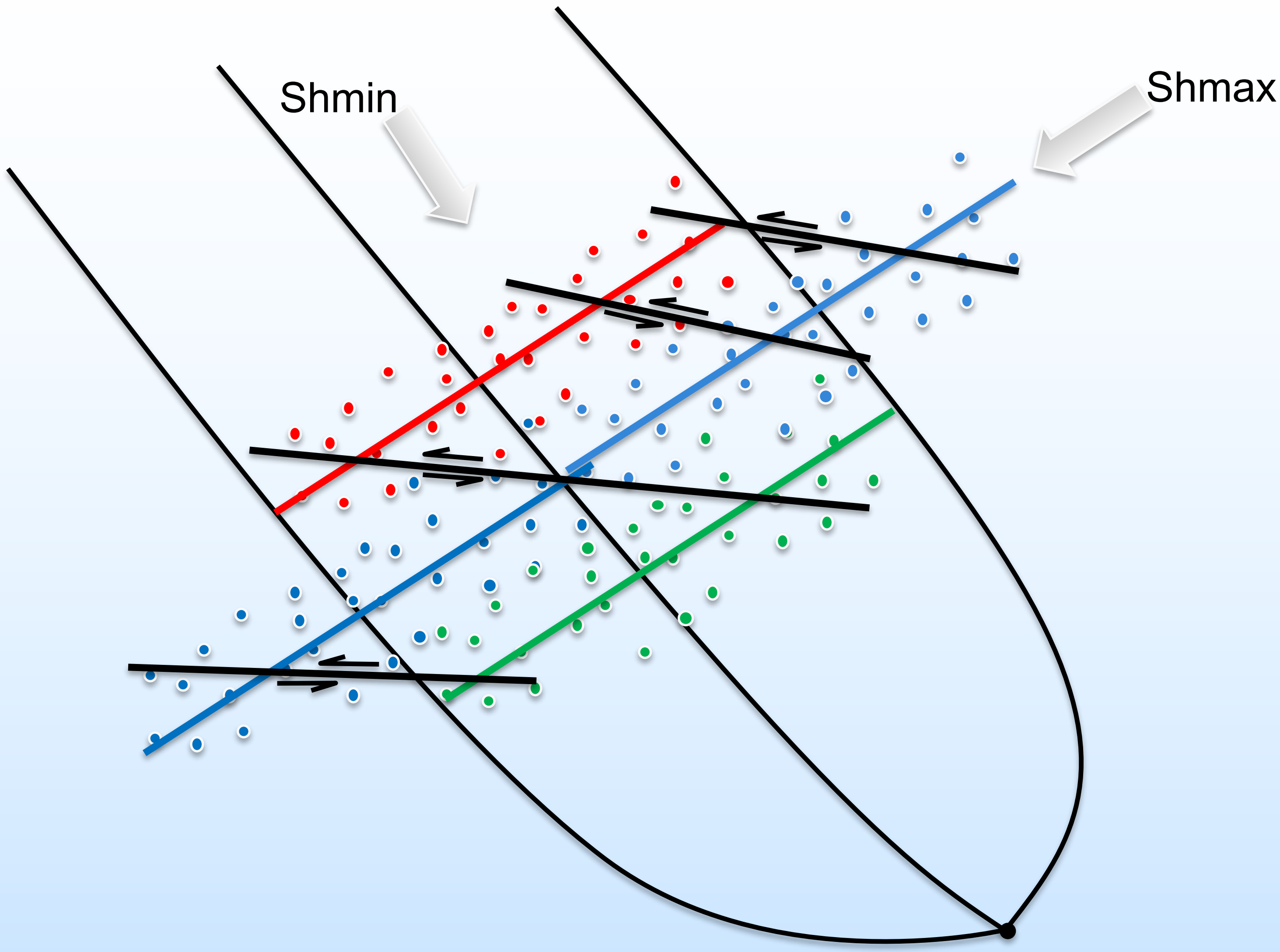
Seismogram and frequency spectrum: Pre-frac

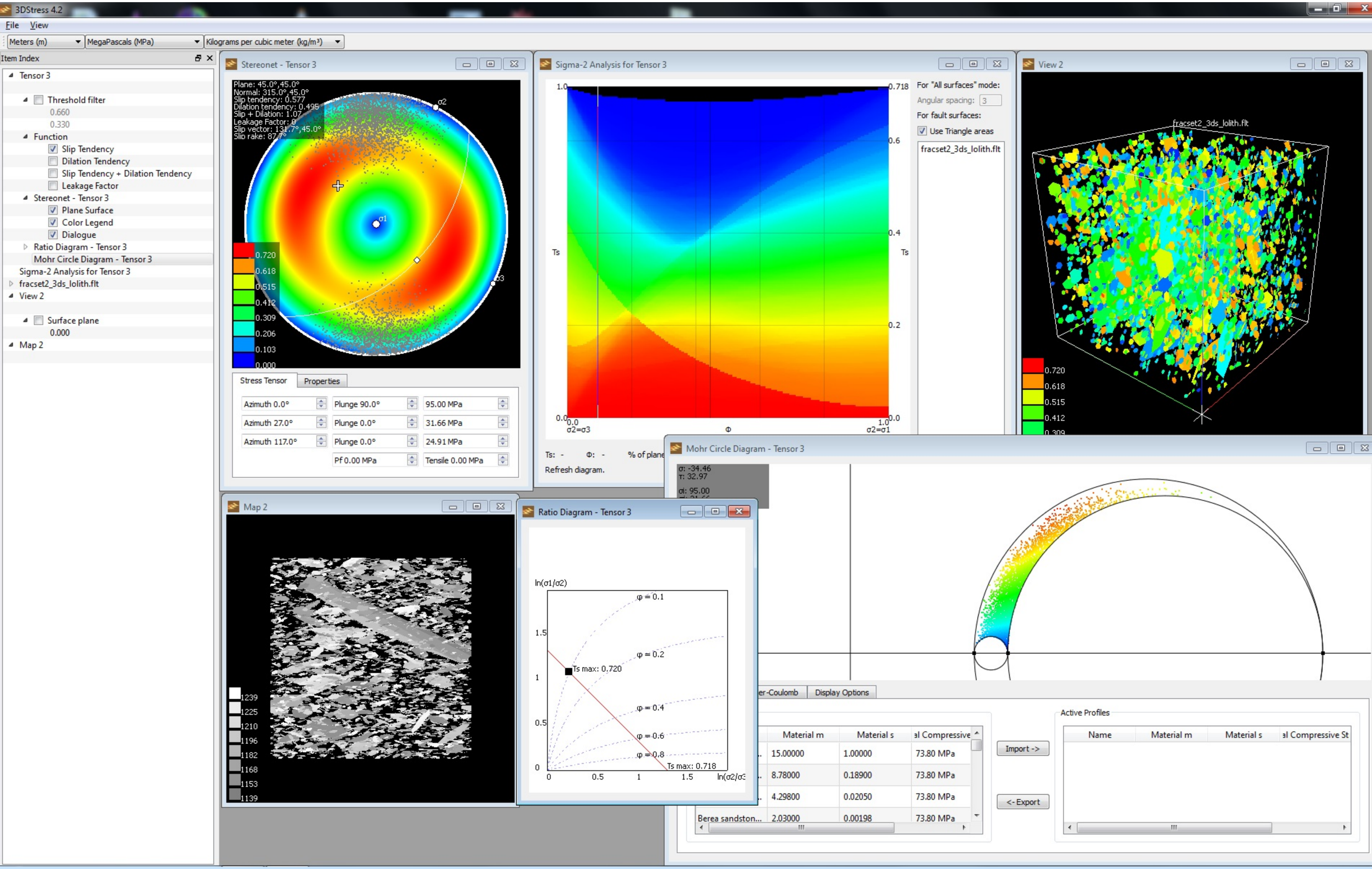


Seismogram and frequency spectrum: During hydrofracturing



Overview of slow-slip mechanics





Combine with rock property and stress data to estimate slip and dilation tendencies

Micro seismic methods

- Determination of b-values with depth, time and voxel element.
- Determination of triggering front and propagation of Coulomb yielding stress (CYS).
- Discrimination between “wet” and “dry” micro seismic events (Maxwell et al.,)
- Correlate variation with well log derived properties, 3D seismic, ant tracking and attribute volumes.

Presentation Outline

- Core based petrophysical measurements, analysis and interpretation.
- Reflection seismic based reservoir monitoring and surveillance.
- Microseismic monitoring and surveillance.
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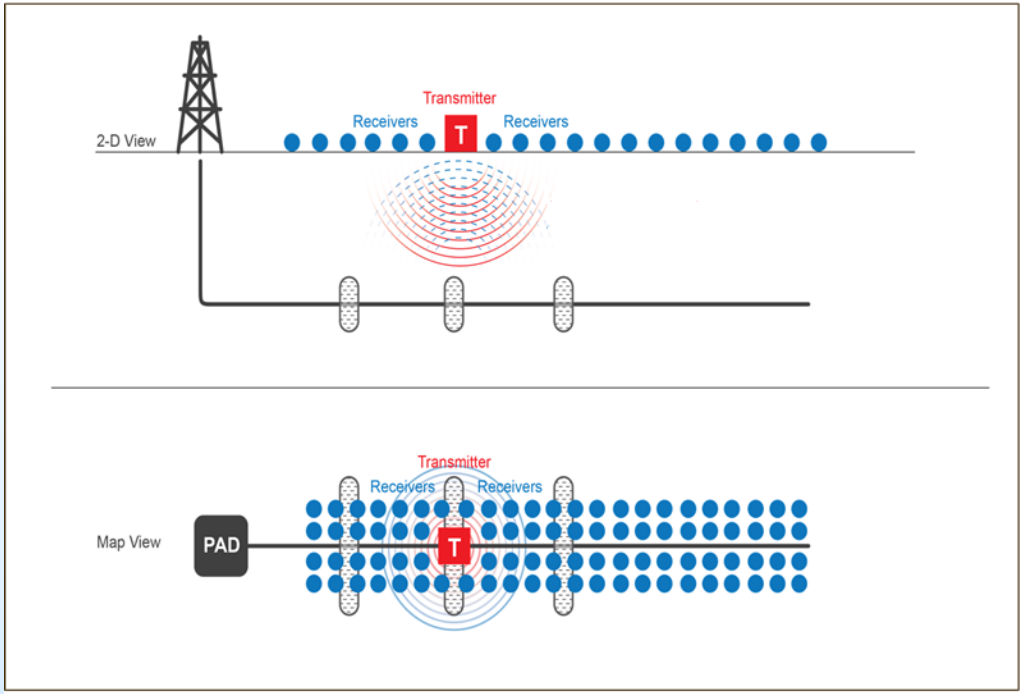
Controlled Source Electromagnetics

- Transmitter
  - Grounded Dipole
  - Broadband
    - PRN
    - 64 freq. per 1 Hz
  - High Power
    - 30 kW
- Receivers
  - High Sample Rate
  - Nanosecond timing
  - -140 dB S/N

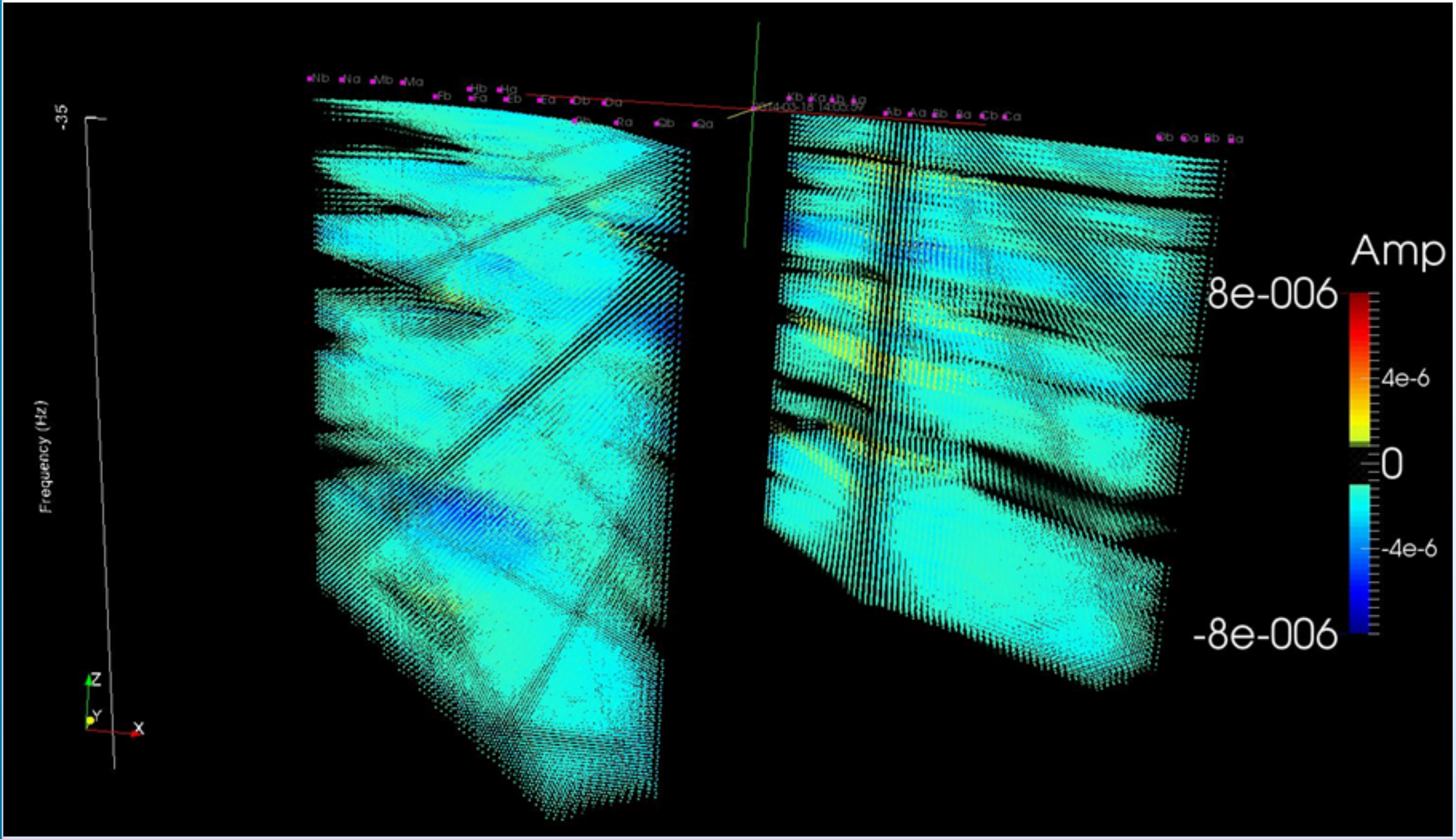


URTeC: 2172634: *This slide courtesy of Mark S. Hickey, Deep Imaging Technologies Inc.*

Atascosa County: Monitoring geometry

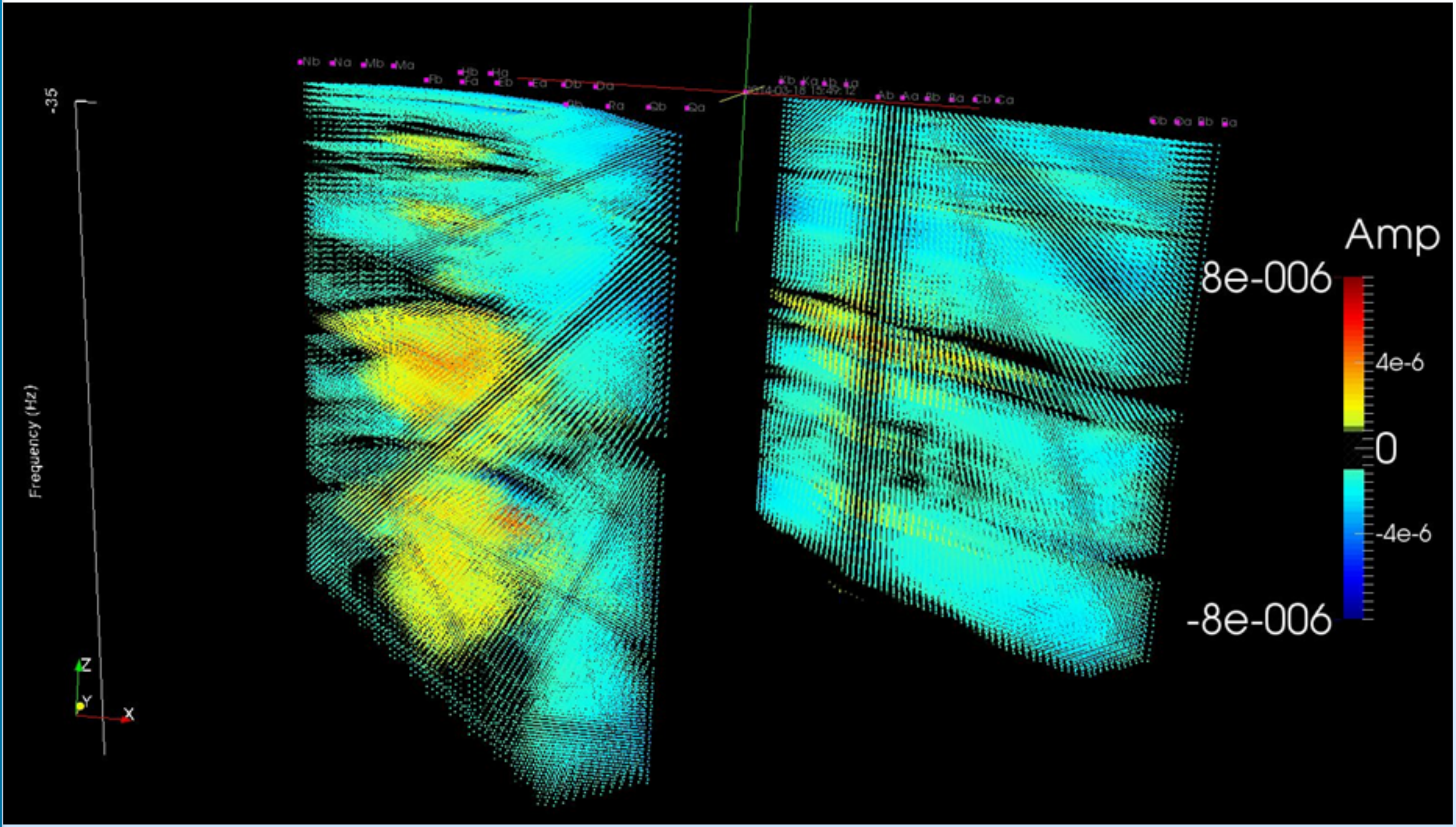
URTeC: 2172634: *This slide courtesy of Mark S. Hickey, Deep Imaging Technologies Inc.*

Atascosa County : Frac Stg 5 Start



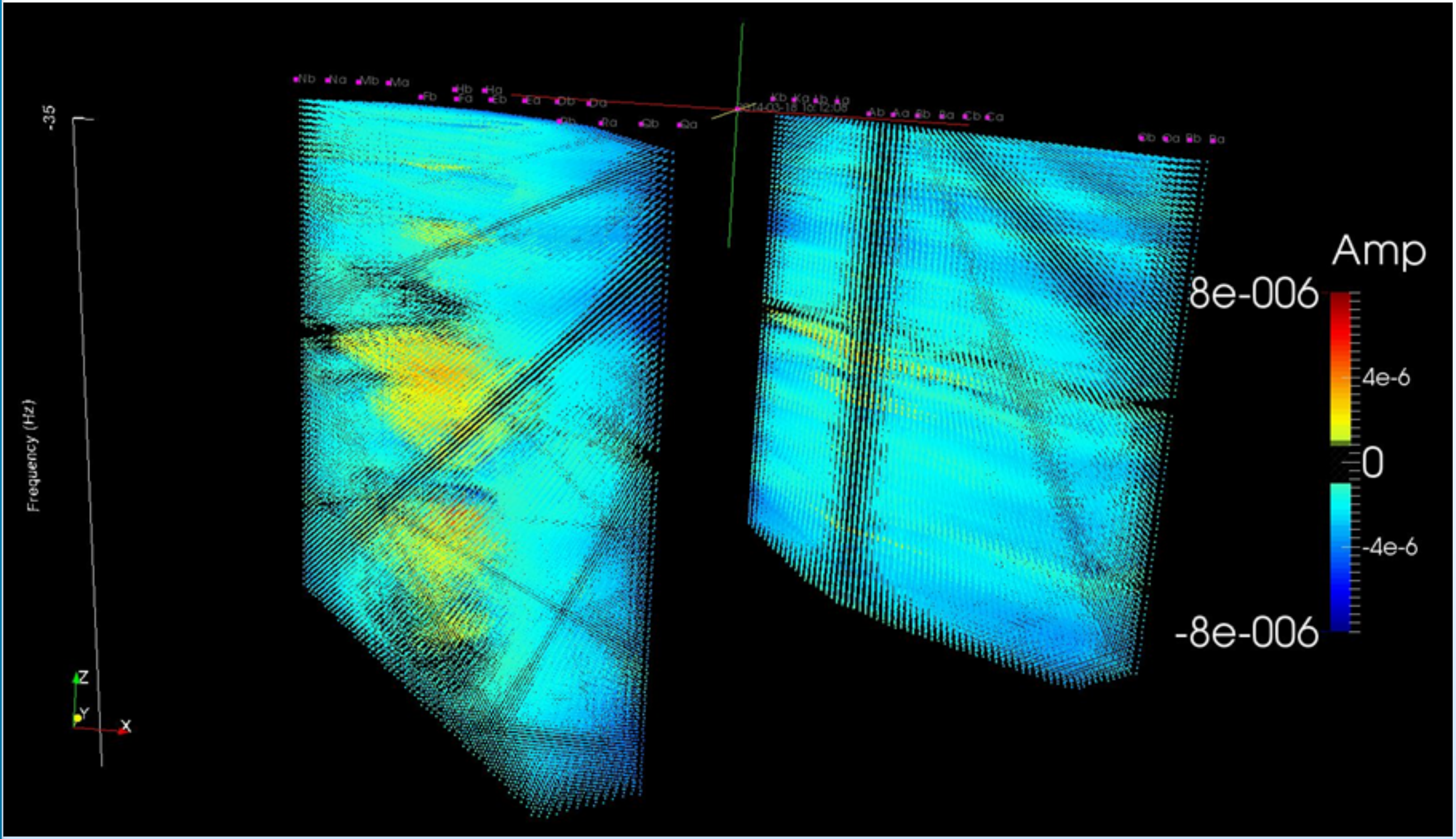
URTeC: 2172634: *This slide courtesy of Mark S. Hickey, Deep Imaging Technologies Inc.*

Atascosa County : Frac Stg 5 End



URTeC: 2172634: *This slide courtesy of Mark S. Hickey, Deep Imaging Technologies Inc.*

Atascosa County : Frac Stg 5 End & Pumps Off



URTeC: 2172634: *This slide courtesy of Mark S. Hickey, Deep Imaging Technologies Inc.*

Accomplishments to Date

- Suitable infrastructure and teaming arrangements established.
- Selected well log, microseismic, and geological data in process of establishment.
- Technology assessment of Triaxial Gravity Gradiometry, Broad-Band Seismicity, Controlled Source or Magnetotellurics, and Dual-Moment Time Domain EM has begun.

Synergy Opportunities

– All workflows and methodologies will be presented to regional Carbon Sequestration Partnerships, field experts and peer reviewed.
– Combination of experimental, core-calibrated geophysical pressure and fluid surveillance with relevant field datasets.
– We are keen to collaborate in the areas of petrophysics, well log interpretation, and advanced seismic analysis and interpretation.

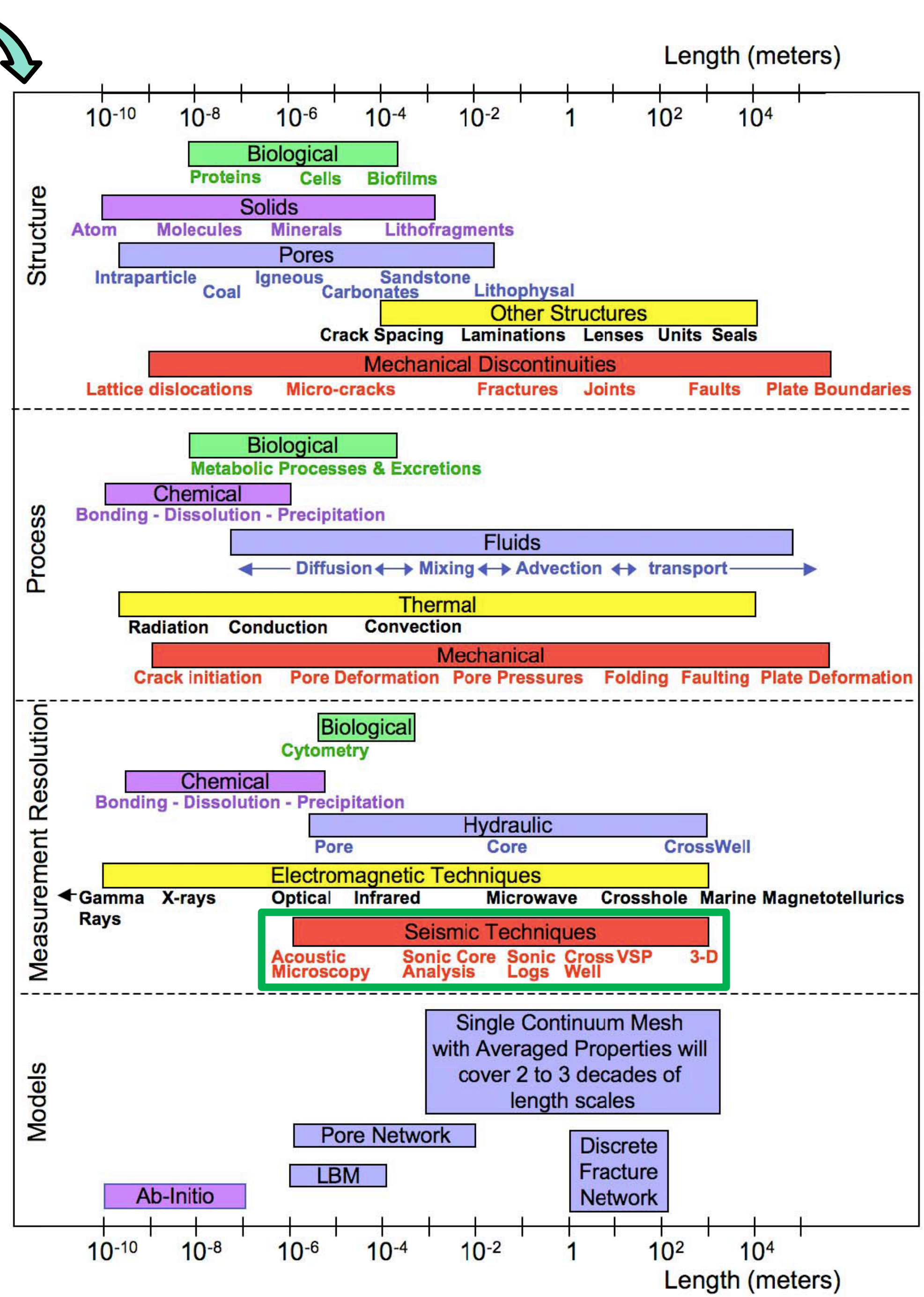
Summary

- Inelastic pressure cycling related changes in Lame properties and permeability appear to be potentially minor in expected reservoir units.
- 3D reflection seismic pre-stack wide offset datasets ideally suited for pressure and fluid monitoring. Seismic attribute spaces developed from those proposed by Landrø (2001) differentiate between fluid and pressure.
- Baseline data is critical to success: Core calibration is important.
- We hope to apply these laboratory activities and proposed workflows to partnership activities.

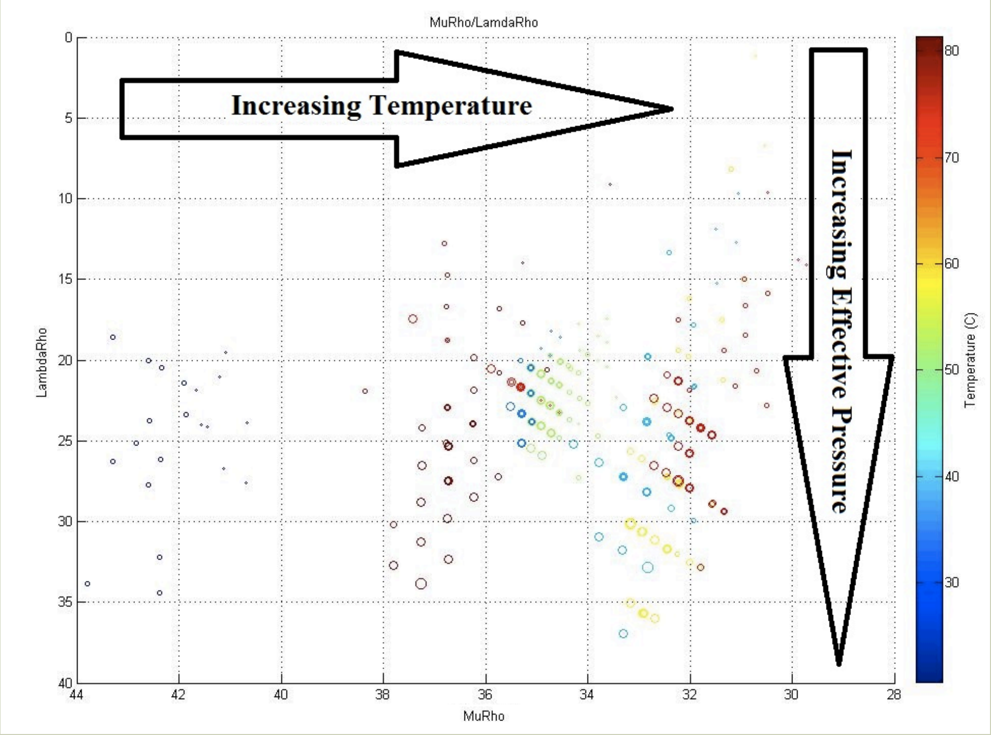
Appendix

Length scales associated with observational methods, structure and physical processes in geological systems.

From DePaolo et al., (2007)



PRESSURE AND TEMPERATURE EFFECTS ON λρ-μρ



- Tested two rhyolite cores, one high and one low porosity
- Varied temperatures between 0 to 80 C
- Increasing Temperature decreases μρ
- Increasing effective pressure primarily increases λρ

This slide courtesy Mr. Daniel Delaney

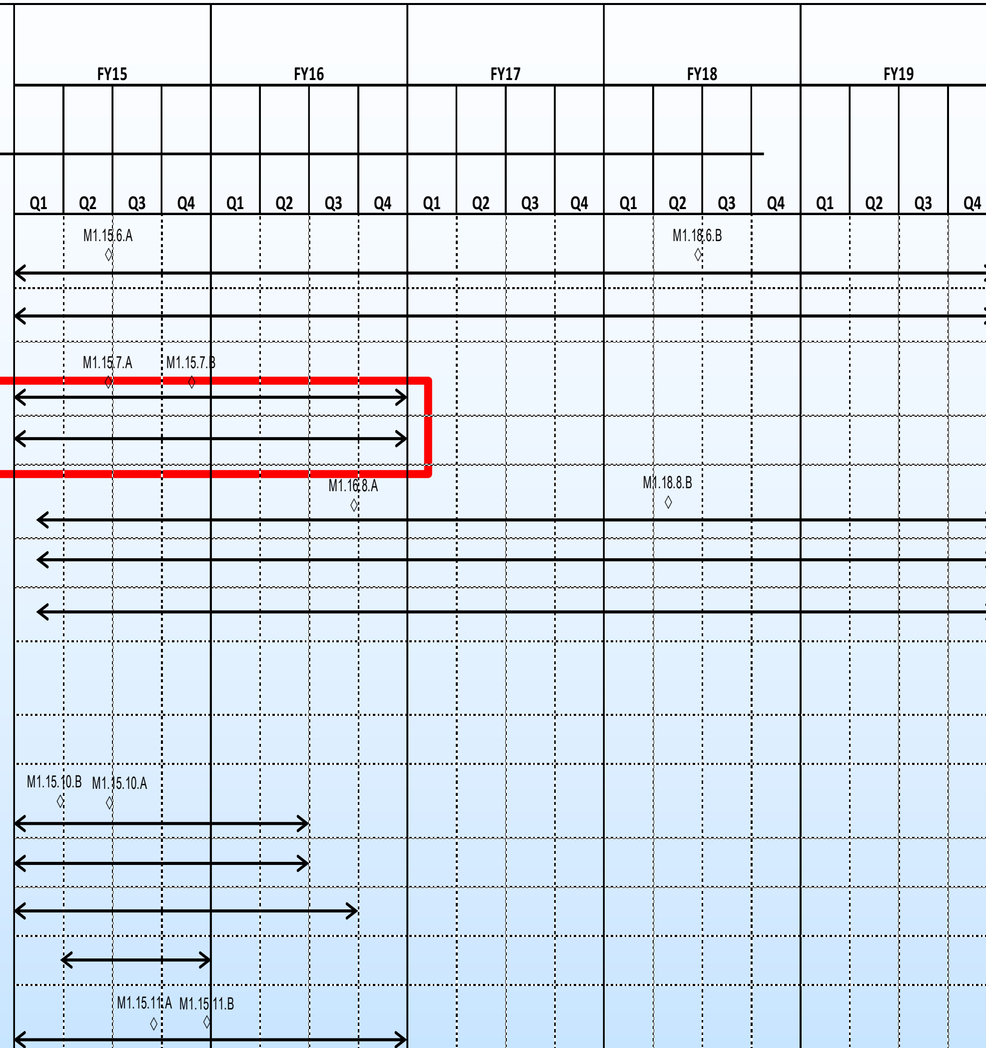
Organization Chart

Task 7.0 Monitoring the Extent of CO_2 Plume and Pressure Perturbation (TTT: Rick Hammack)

- **Subtask 7.1 Knowledge and Technology Gap Identification (Rick Hammack)**

Gantt Chart

FY15 Carbon Storage (Project Period: 10/01/14 – 09/30/19)	Project Dates For each Task, Subtask, Sub-subtask of your WBS — Start: Reflects the date the work is scheduled to begin	Finish: Reflects the date the work is scheduled for completion
6. Energy Data eXchange/National Carbon Sequestration Database and Geographic Information System Geospatial Resources	**10/1/2014**	**9/30/2019**
6.1 Energy Data eXchange/National Carbon Sequestration Database and Geographic Information System	10/1/2014	9/30/2019
7. Monitoring the Extent of CO_2 Plume and Pressure Perturbation	**10/1/2014**	**9/30/2016**
7.1 Knowledge and Technology Gap Identification	10/1/2014	9/30/2016
8. Catalytic Conversion of CO_2 to Industrial Chemicals	**11/15/2014**	**11/14/2020**
8.1 Novel Reaction Chemistries and Reactor Development for Scalability Assessments	11/15/2014	11/14/2020
8.2 Design, Discovery, Synthesis, and Characterization of Novel Catalyst Systems for Catalytic CO_2 Conversion	11/15/2014	11/14/2020
9. Evaluation of CO_2 Use and Re-Use Strategies	**TBD**	**TBD**
9.1 CO_2 Use and Re-Use Strategy Evaluation		
10. SubTER - Induced Seismicity with Big Data	**10/1/2014**	**3/30/2015**
10.1 Data Gathering	10/1/2014	3/30/2015
10.2 Development of Data Mining Techniques	10/1/2014	6/30/2015
10.3 Data Mining	1/1/2015	9/30/2015
11. Perfluorocarbon Tracers (PFT) Analysis to Support SW Partnership	**10/1/2014**	**9/30/2016**



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- Want, Pengyun, Small, M., Harbert, W., and Pozzi, M., 2015, A Bayesian approach for assessing seismic transitions associated with wastewater injections, Bulletin of the Seismological Society of America, (in review).

Acknowledgements

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Thank you