Seismic Reservoir Characterization and Pre-stack Inversion in Resource Shale Plays*

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Abstract

Over the last few years, a multitude of new and different AVO (Amplitude Variations with Offset) and pre-stack inversion techniques have been developed, all of which put a slightly different spin on the way we extract lithological and fluid information from pre-stack seismic data. These methods are as diverse as intercept versus gradient cross-plotting, lambda-mu-rho (LMR), simultaneous pre-stack inversion and Extended Elastic Impedance (EEI). For the working interpreter, keeping track of all of these different methods and how they relate to each other has become an almost impossible task. This talk will review a range of AVO and pre-stack inversion methods, describe their strengths and weaknesses, and discuss how they are related. The talk will show that the fundamental concept behind AVO is the reflectivity derived from a physical earth parameter, and that the fundamental concept behind pre-stack inversion is the earth parameter itself, which is usually some type of impedance. The presentation will stress the fundamental geology and geo-physics behind each method, and case histories from various basins around the world will be used to illustrate the methods. In particular, one of the case histories will focus on how pre-stack inversion can help in the delineation of sweet spots in the Haynesville shale play. This case study will focus on some of the newer inversion techniques that can estimate anisotropic earth parameters.

References Cited

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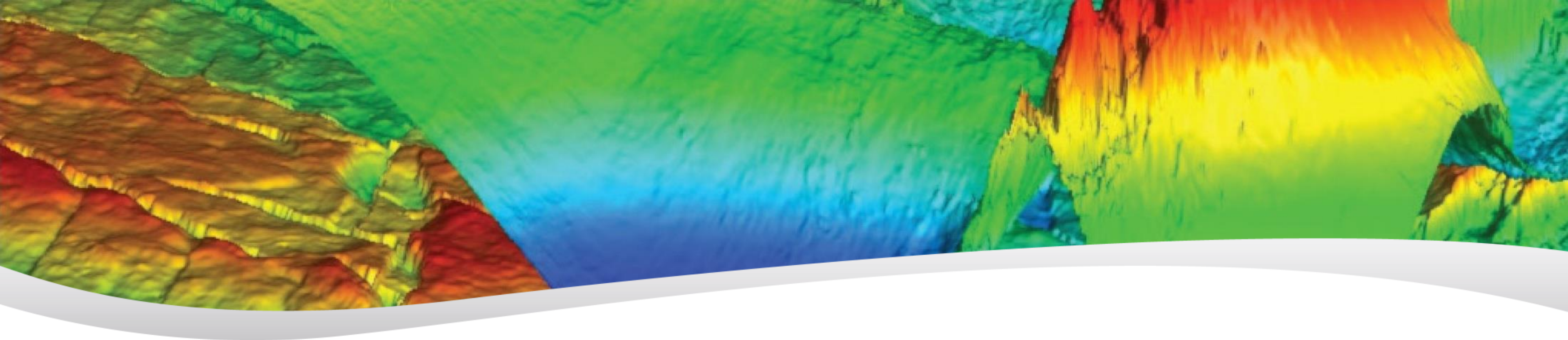
Rickman, R., M. Mullen, E. Petre, B. Bill Grieser, and D. Kundert, 2008, A practical use of shale petrophysics for stimulation design optimization: All shale plays are not clones of the Barnett shale: SPE 115258.

Rüger, A., 2002, Reflection coefficients and azimuthal AVO analysis in anisotropic media: Society of Exploration Geophysicists, Geophysical monograph series no. 10, xi, 189 p.

Sena, A., G. Castillo, K. Chesser, S. Voisey, J. Estrada, J. Carcuz, E. Carmona, and P. Hodgkins, 2011, Seismic reservoir characterization in resource shale plays: stress analysis and sweet spot discrimination: The Leading Edge, v. 30 (July, 2011) p. 758-764.



Seismic Reservoir Characterization and Pre-stack inversion in Resource Shale Plays

Brian Russell

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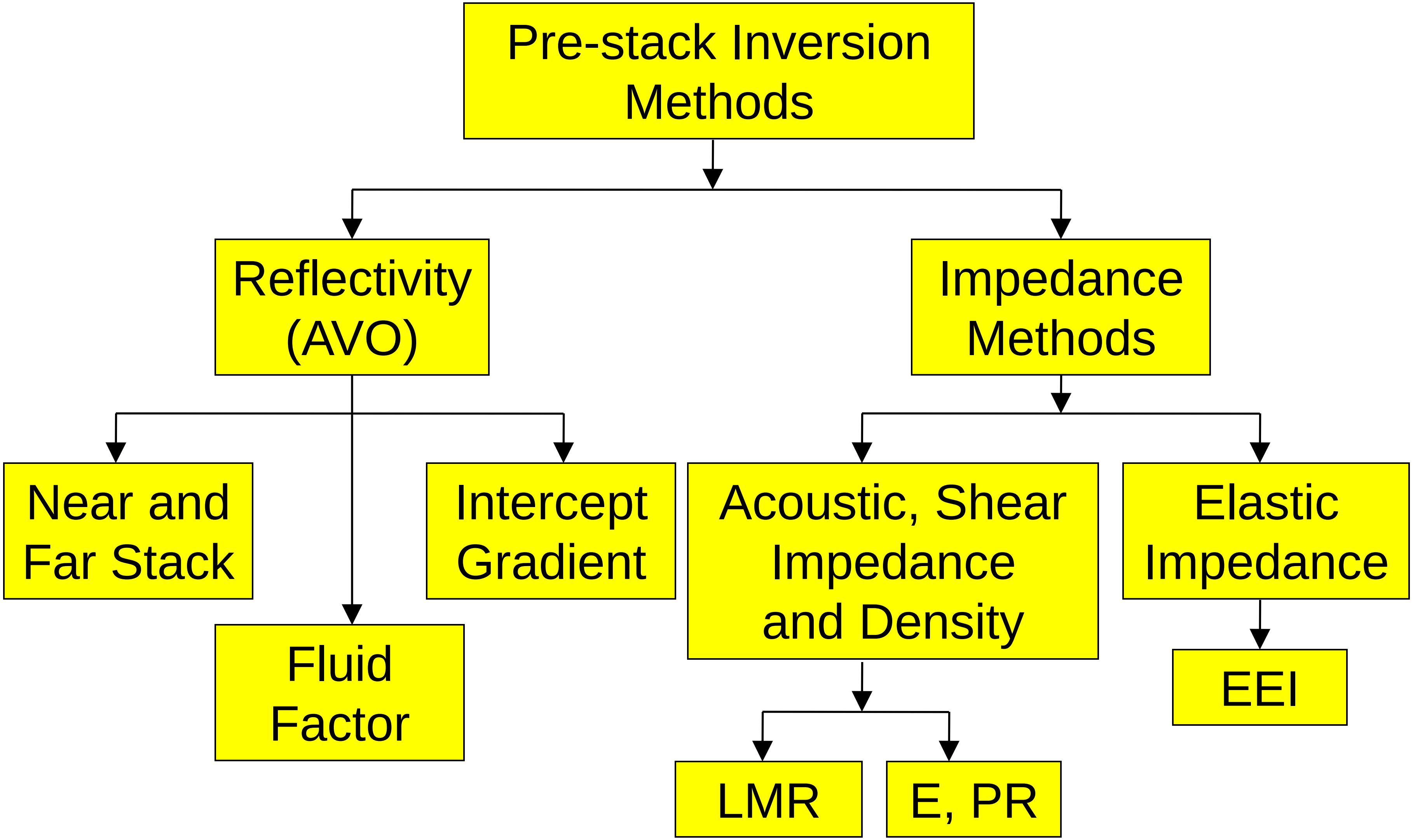
Introduction

In this talk, I will give a brief overview of pre-stack seismic inversion and then show how it can help in unconventional plays by:

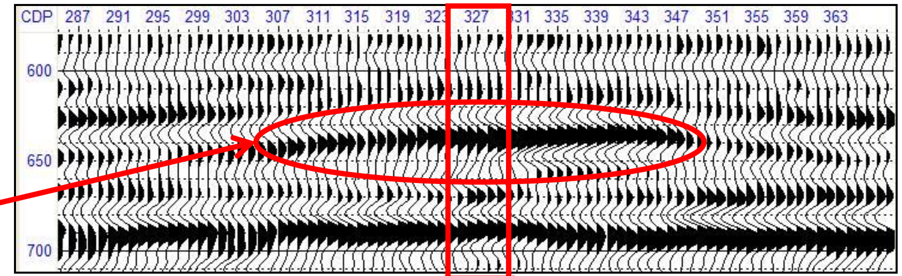
- Prioritizing wells on 'sweet spots‘.
- Using seismic azimuthal anisotropy to identify fracture density and orientation with a success rate of upwards of 80% in unconventional gas plays.
- Identifiying the best areas for inducing hydraulic fractures by calculating the stress state.
- Maximizing the potential of the shale gas reservoirs by integrating all the disciplines: engineering, geology and geophysics.

Summary of pre-stack inversion and AVO

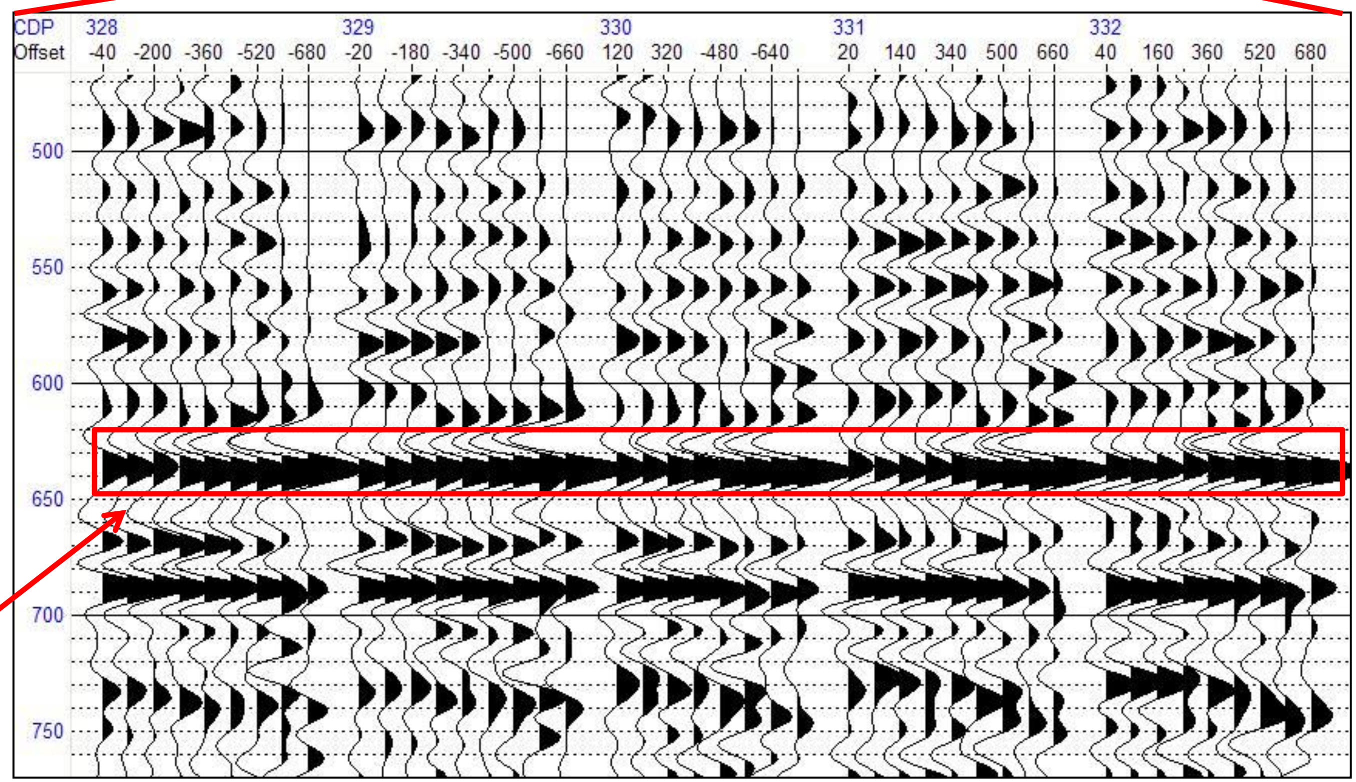


Gas sand example

Here is a portion of a seismic line showing a gas sand “bright-spot”.



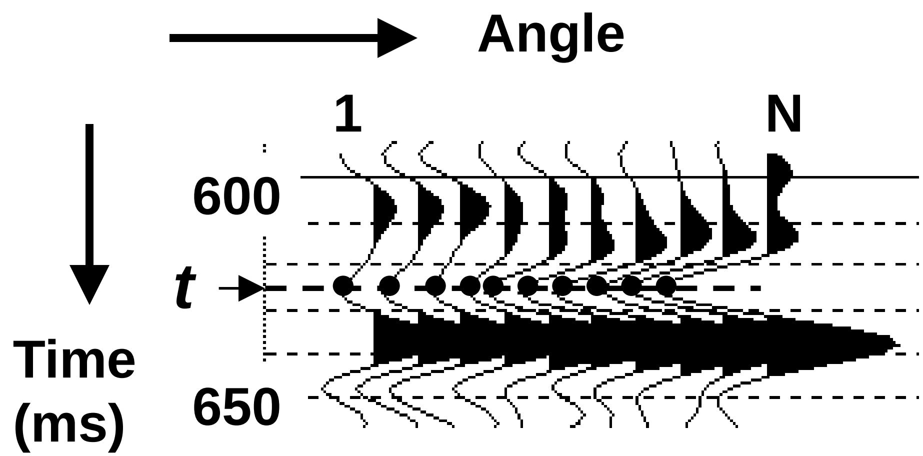
The seismic line is the “stack” of a series of CMP gathers, as shown here.



The gas sand is a typical Class 3 AVO anomaly.

Estimating the reflectivities

To estimate the reflectivities, the amplitudes at each time ***t*** in an *N*-trace angle gather are picked as shown here.



We can solve for the reflectivities at each time sample using least-squares:

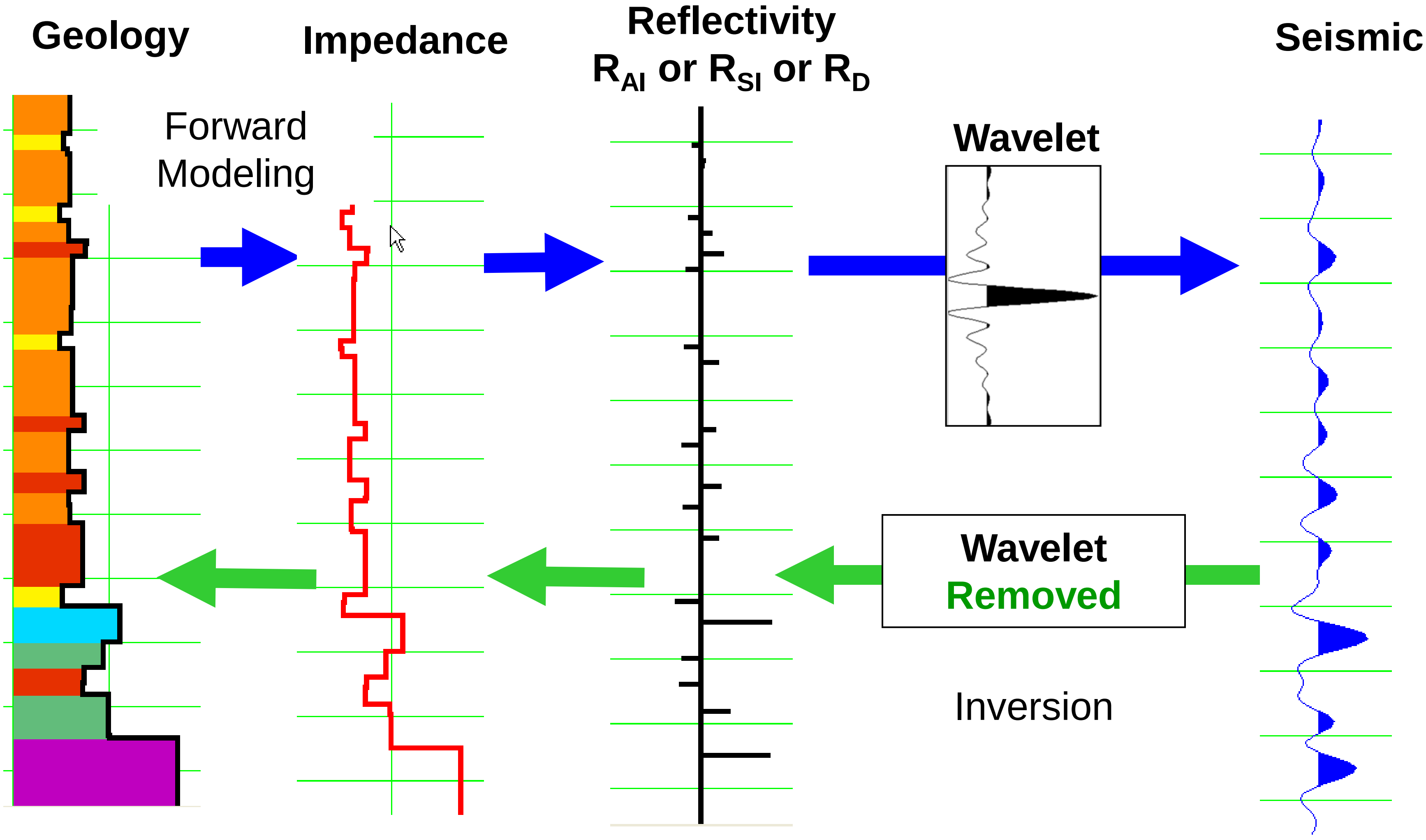
Generalized inverse of weight matrix

$$\begin{bmatrix} R_{AI} \\ R_{SI} \\ R_{D} \end{bmatrix} = \begin{bmatrix} weight \\ matrix \end{bmatrix}^{-1} \begin{bmatrix} R_P(\theta_1) \\ \vdots \\ R_P(\theta_N) \end{bmatrix}$$

Reflectivities

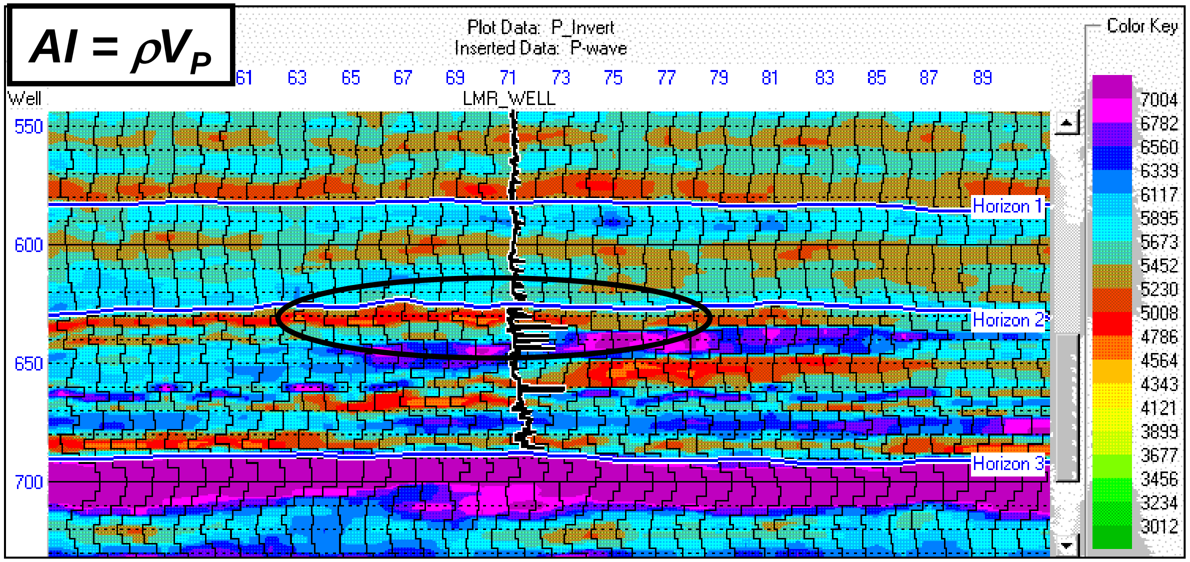
Observations

Forward Modeling and Inversion

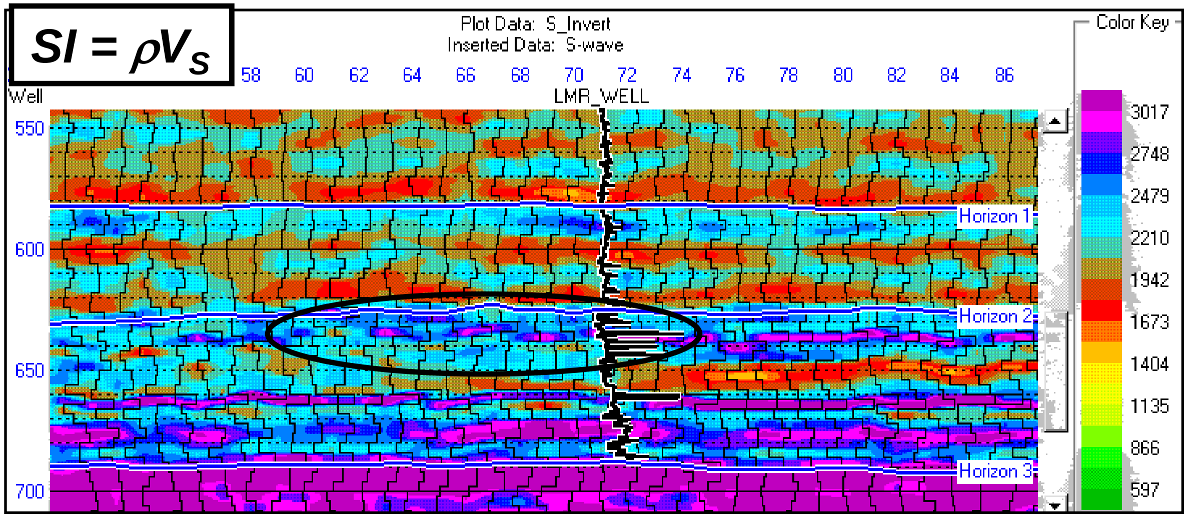


P-wave and S-wave Inversions

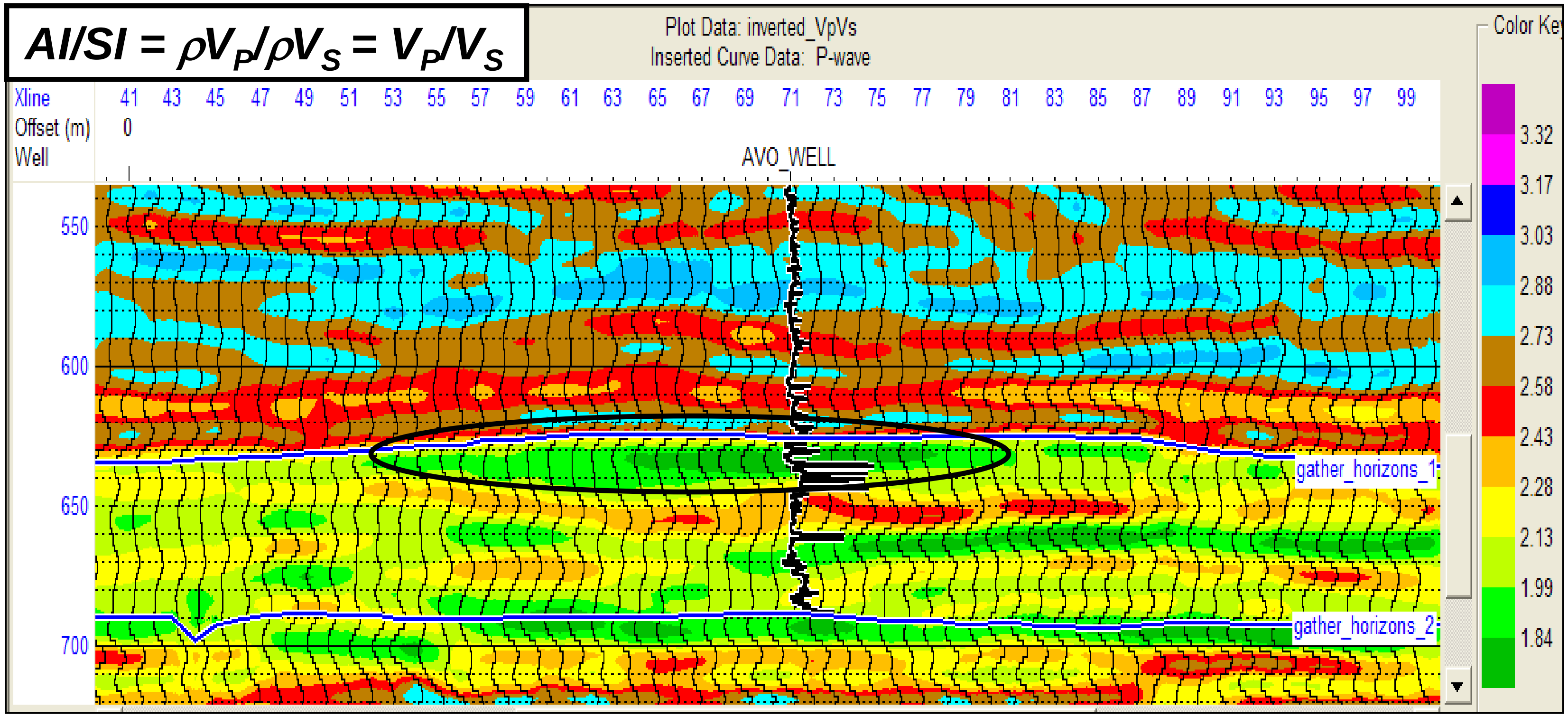
Here is the P-wave inversion result. The low acoustic impedance below Horizon 2 represents the gas sand.



Here is the S-wave inversion result. The gas sand is now an increase, since S-waves respond to the matrix.

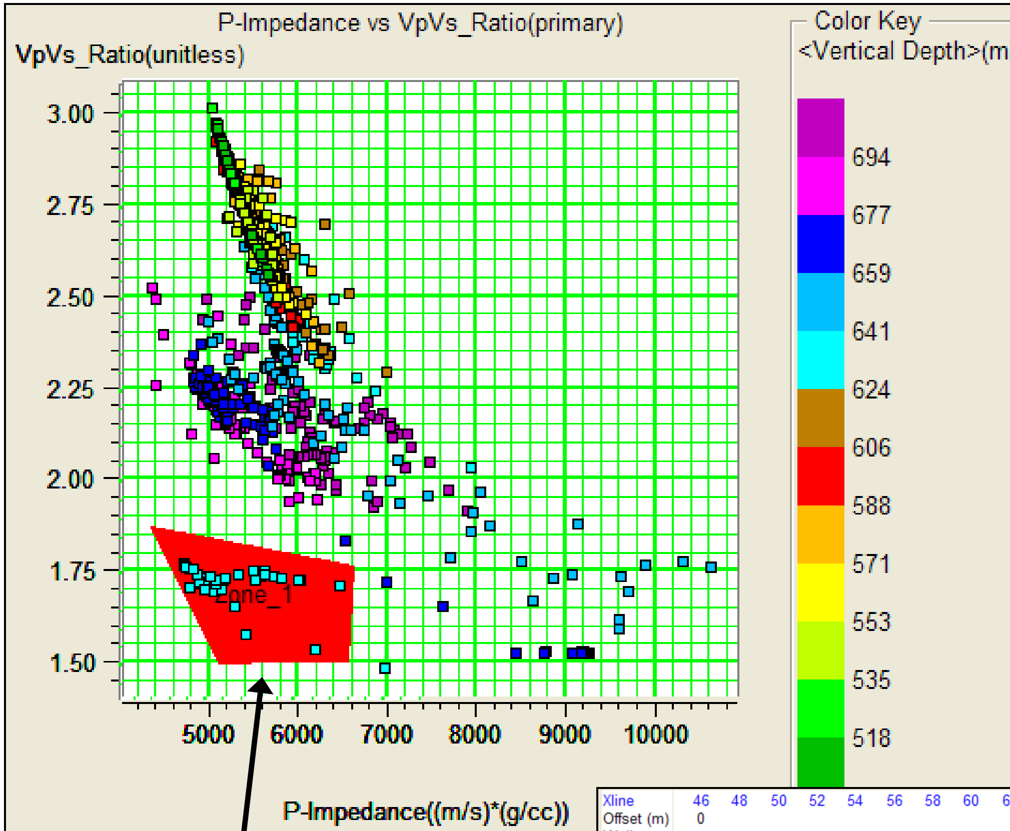


V_P/V_S Ratio

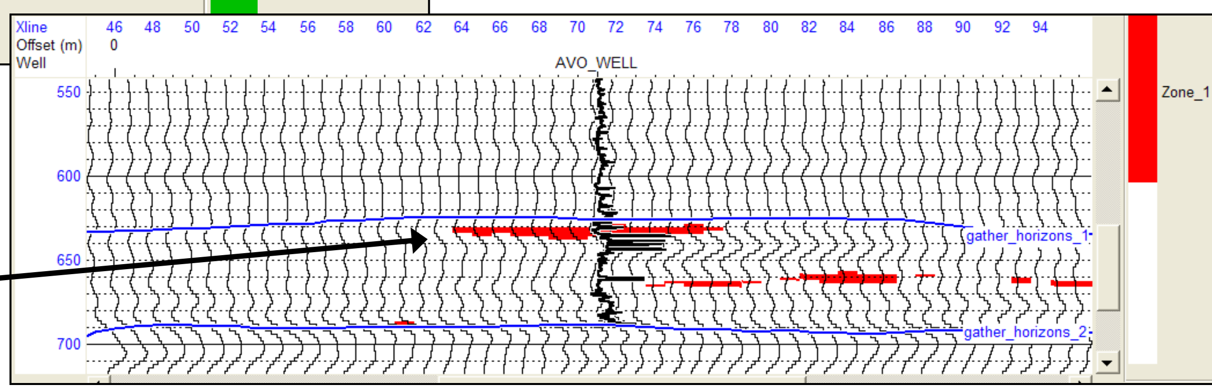


Here is the ratio of *P* to *S* impedance, which is equal to the ratio of *P* to *S* velocity. Notice the low ratio at the gas sand.

Cross-plotting V_P/V_S Ratio vs P-impedance



When we crossplot V_P/V_S ratio against P-impedance, the zone of low values of each parameter should correspond to gas, as shown.



This zone should correspond to gas:

Poisson’s Ratio and Young’s Modulus

- Two parameters that are important in unconventional resource plays are Poisson’s ratio, ν, and Young’s Modulus E.
- The Poisson’s ratio from impedances obtained from the simultaneous inversion is found by:

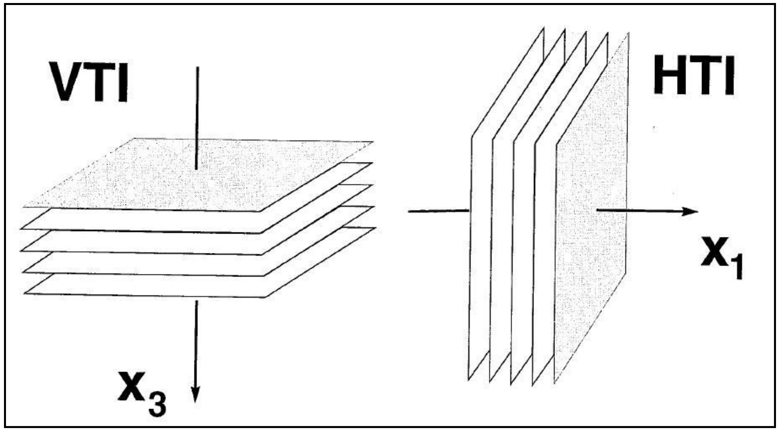
$$\nu = \frac{\left(I_p / I_S\right)^2 - 2}{2\left(I_p / I_S\right)^2 - 2}, \text{ where } I_P = \rho V_P \text{ and } I_S = \rho V_S.$$

- Young’s modulus is found from the Shear Impedance, Poisson’s ratio and density:

$$E = 2\frac{I_S^2}{\rho}\left(1 + \nu\right)$$

Pre-stack inversion and Anisotropy

- More recently, seismic inversion and has been expanded by the use of anisotropic methods, especially the analysis of Vertical and Horizontal Transverse Isotropy (VTI/HTI).
  - VTI consists of horizontal layers and can be caused by fine layering of the earth or by particle alignment in a shale.
  - HTI consists of vertical layers and is caused by vertical fractures or steeply dipping shales.



Rüger, 2002

- To estimate HTI anisotropy, fracture orientation and fracture density the seismic data needs to be rich in azimuths.
- This is done with AVAz (Amplitude versus Azimuth) reflectivity and Azimuthal Inversion.

North American Basins

The major unconventional basins in Canada are shown here. I will show an example from the Montney.

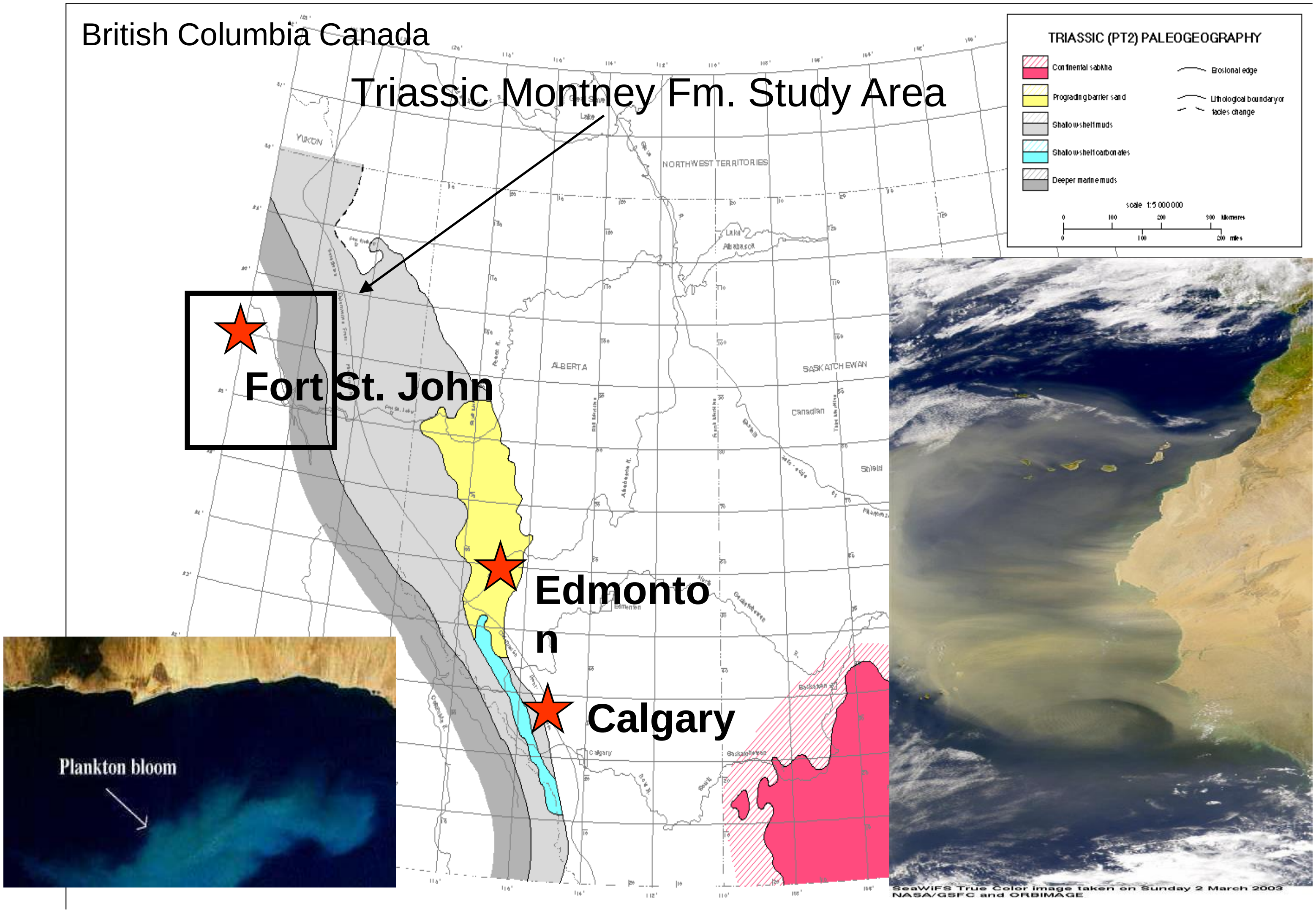
The main unconventional basins are in the U.S. are shown here. I will show an example from the Haynesville.

Courtesy: Microseismic Inc.

The key drivers in shale plays

- The key drivers for the explosion of activity in shale plays has been the development of horizontal drilling and hydraulic fracturing.
- However, Rickman et al. (2008) show examples from the Barnett shale and point out that, for optimum production, it is important to know:
  - The mineralogical and TOC properties of the shale.
  - The geomechanical properties of the shale.
- I will use examples from the Montney and Haynesville plays to how pre-stack seismic inversion can play a role in the understanding of these properties.

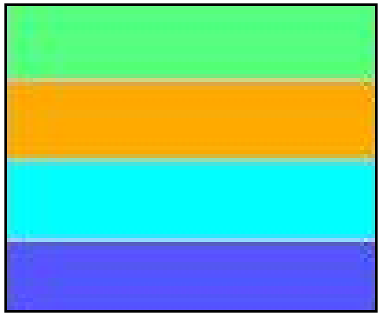
Montney lithofacies example



Nieto et al., CSEG Recorder, February 2013)

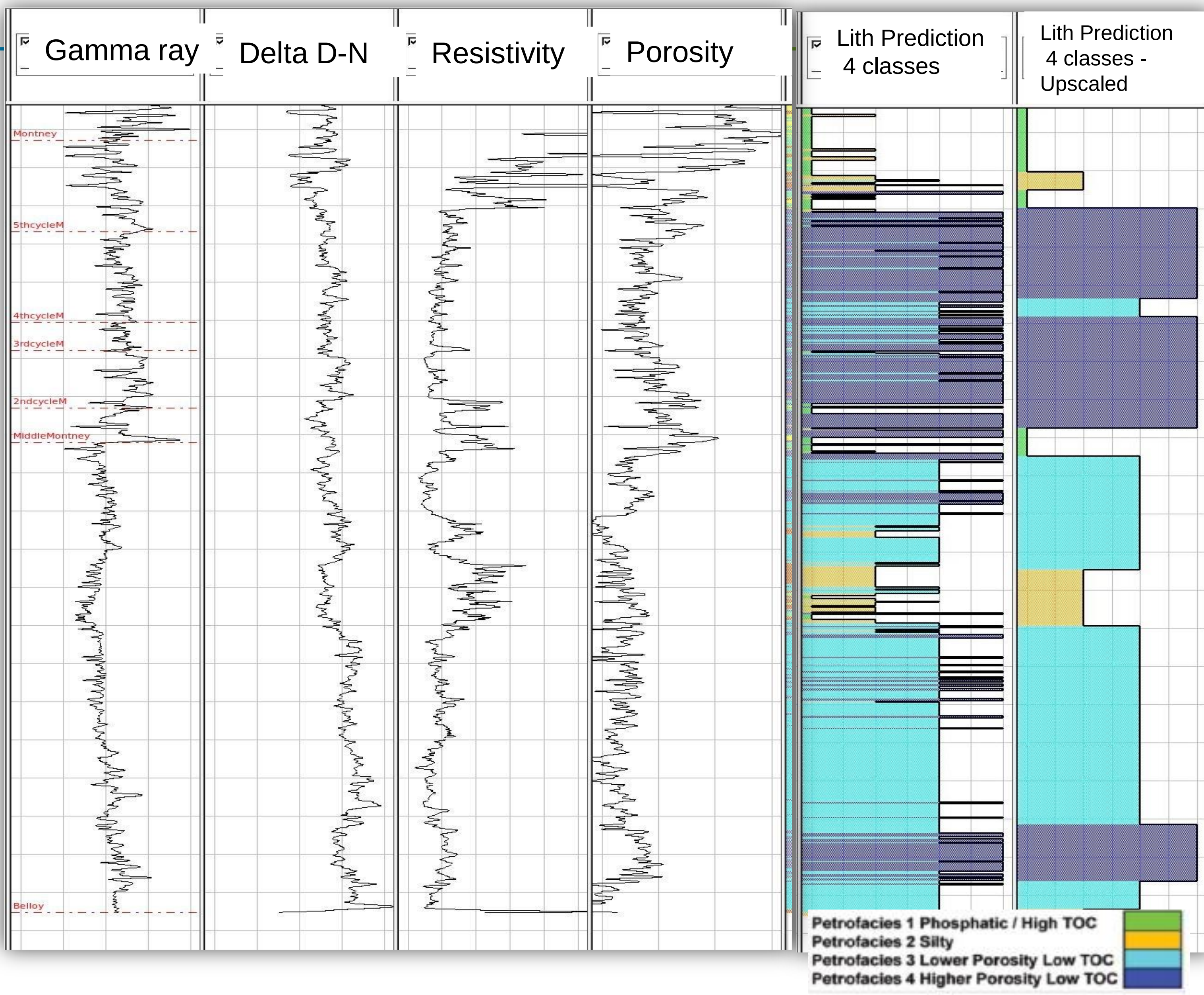
Montney Lithofacies

Petrofacies 1 Phosphatic / High TOC
Petrofacies 2 Silty
Petrofacies 3 Lower Porosity Low TOC
Petrofacies 4 Higher Porosity Low TOC

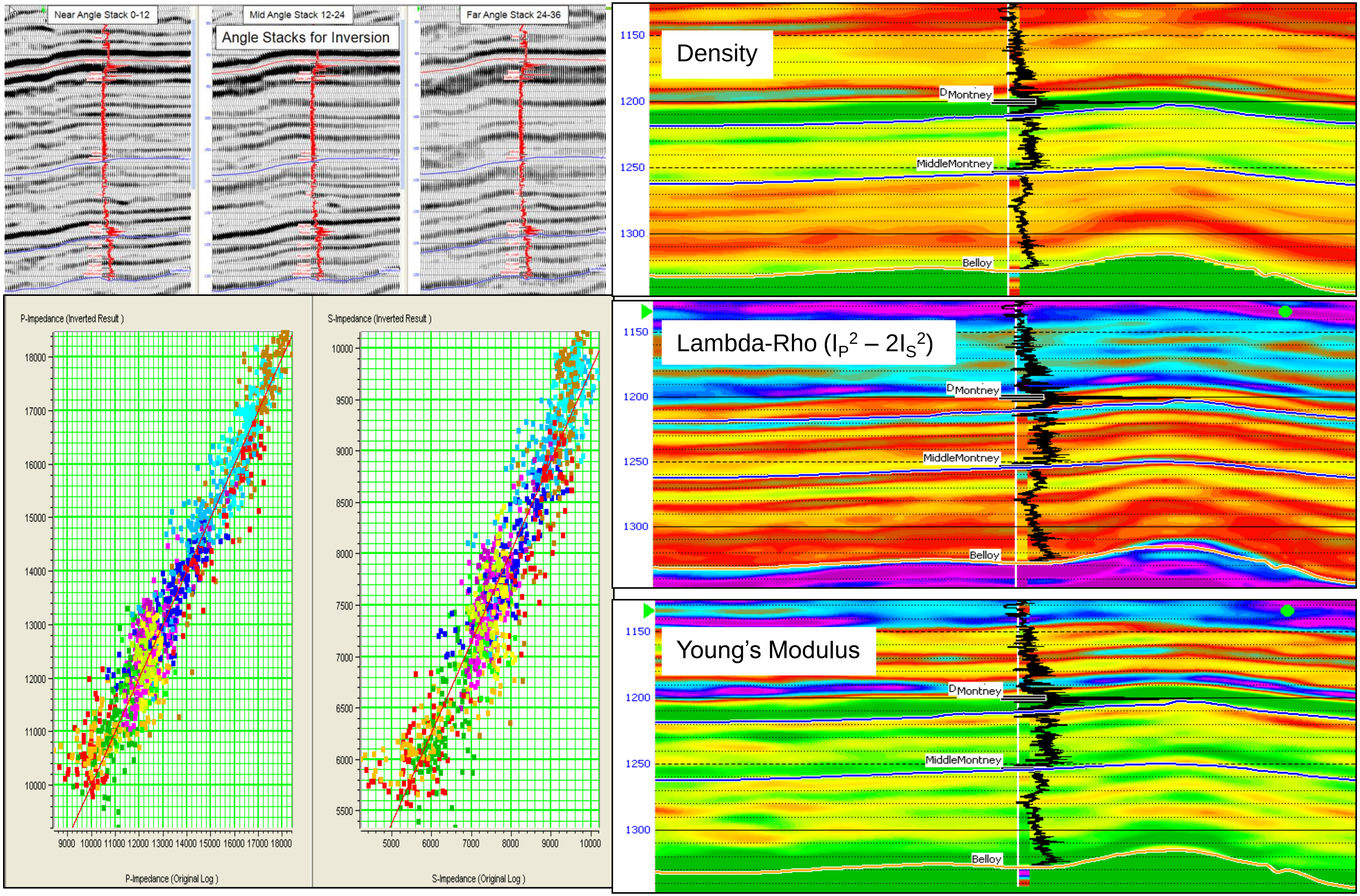


Petrofacies 1: Phosphatic / High TOC	Gamma Ray > 105 API and Resistivity >100 ohm and Density Porosity ≥ 4% Or Gamma Ray ≥ 80 API and Density Porosity ≥ 3% and (Neutron Porosity – Density Porosity) ≥ 0.07
Petrofacies 2: Silty	Resistivity >= 80 ohm and (Neutron Porosity – Density Porosity) < 0.08
Petrofacies 3: Lower Porosity, Low TOC	Resistivity < 80 ohm and Density Porosity < 3%
Petrofacies 4: Higher Porosity, Low TOC	Resistivity < 80 ohm and Density Porosity ≥3%

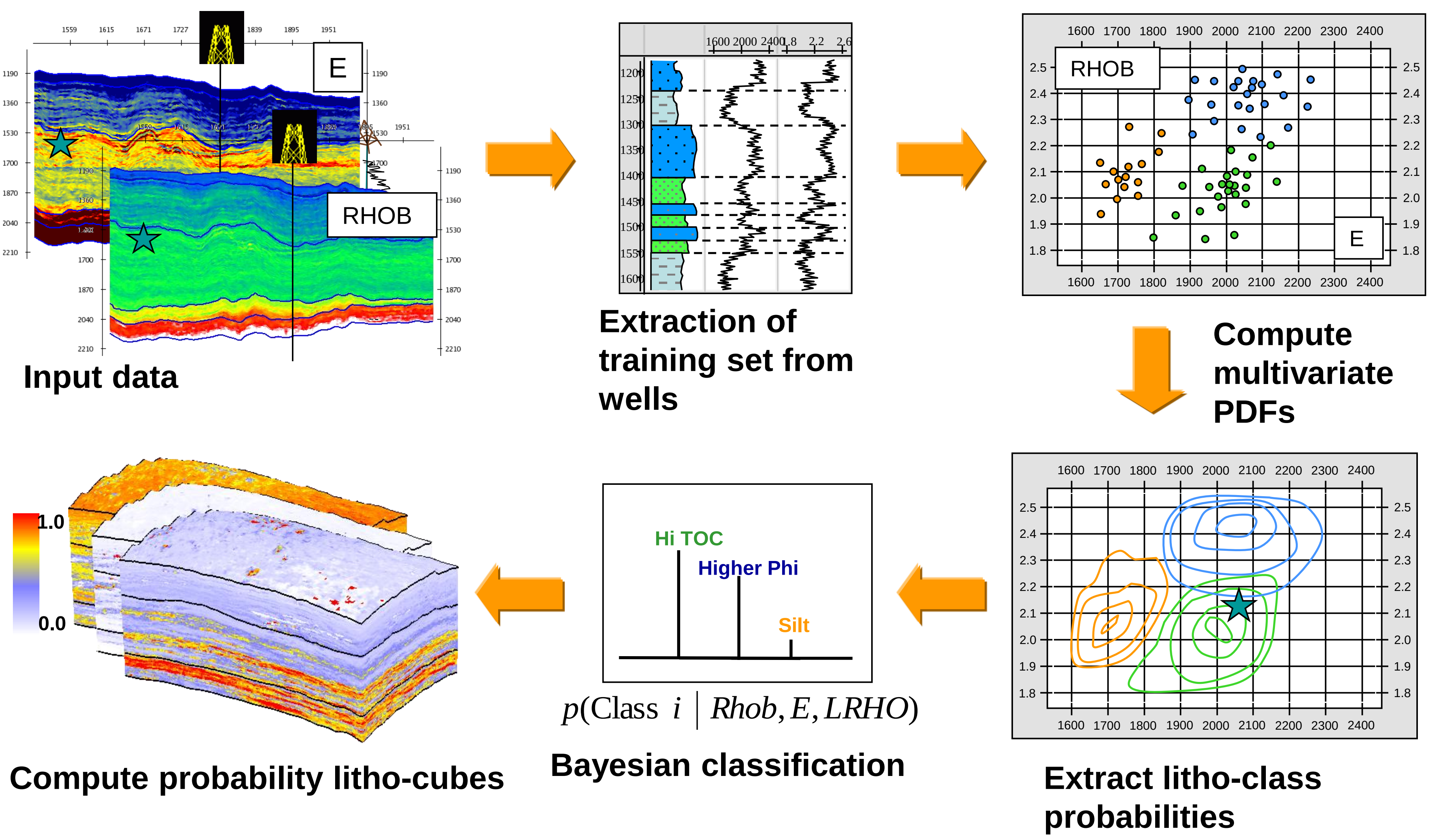
Well 1 Lithology Prediction from Logs



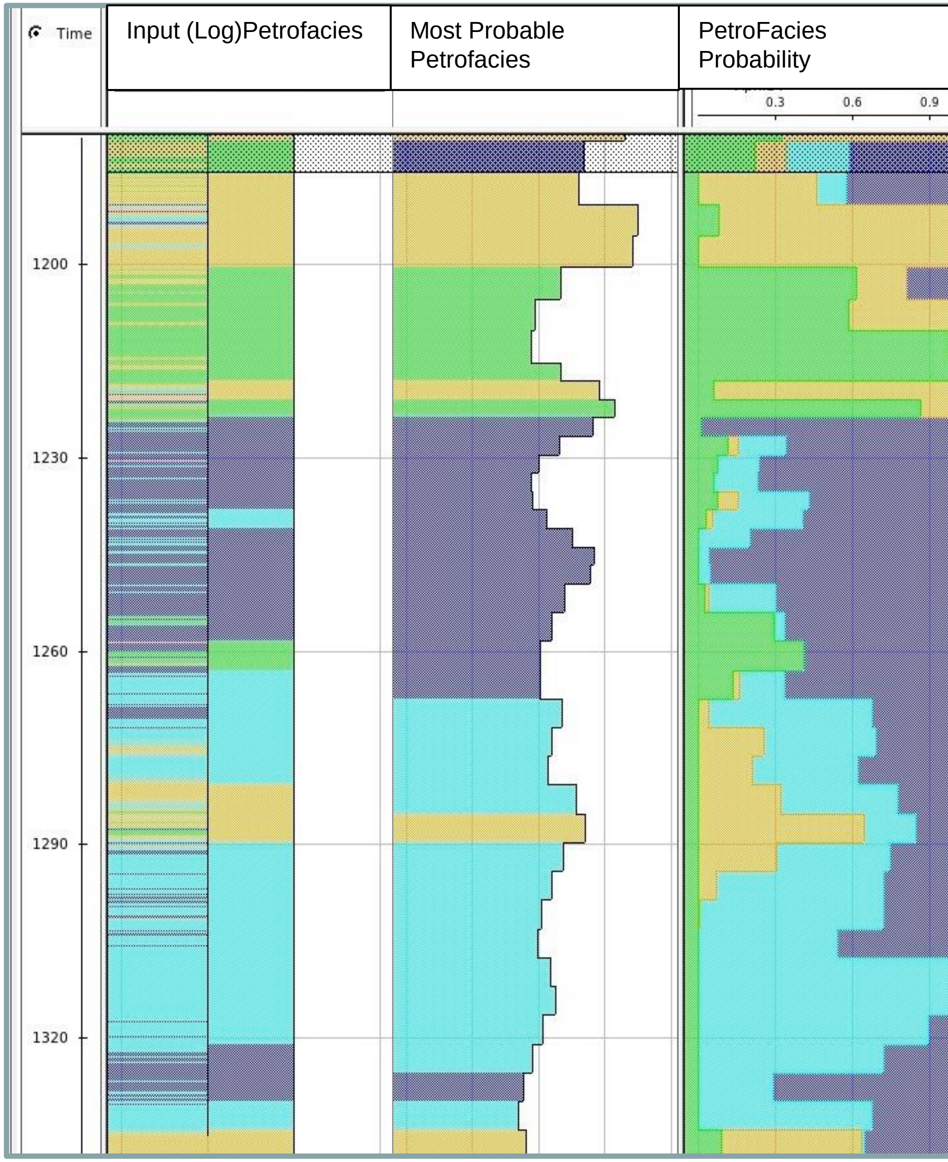
Seismic inversion results



Lithology Prediction Workflow



Well 1 Petrofacies Prediction QC



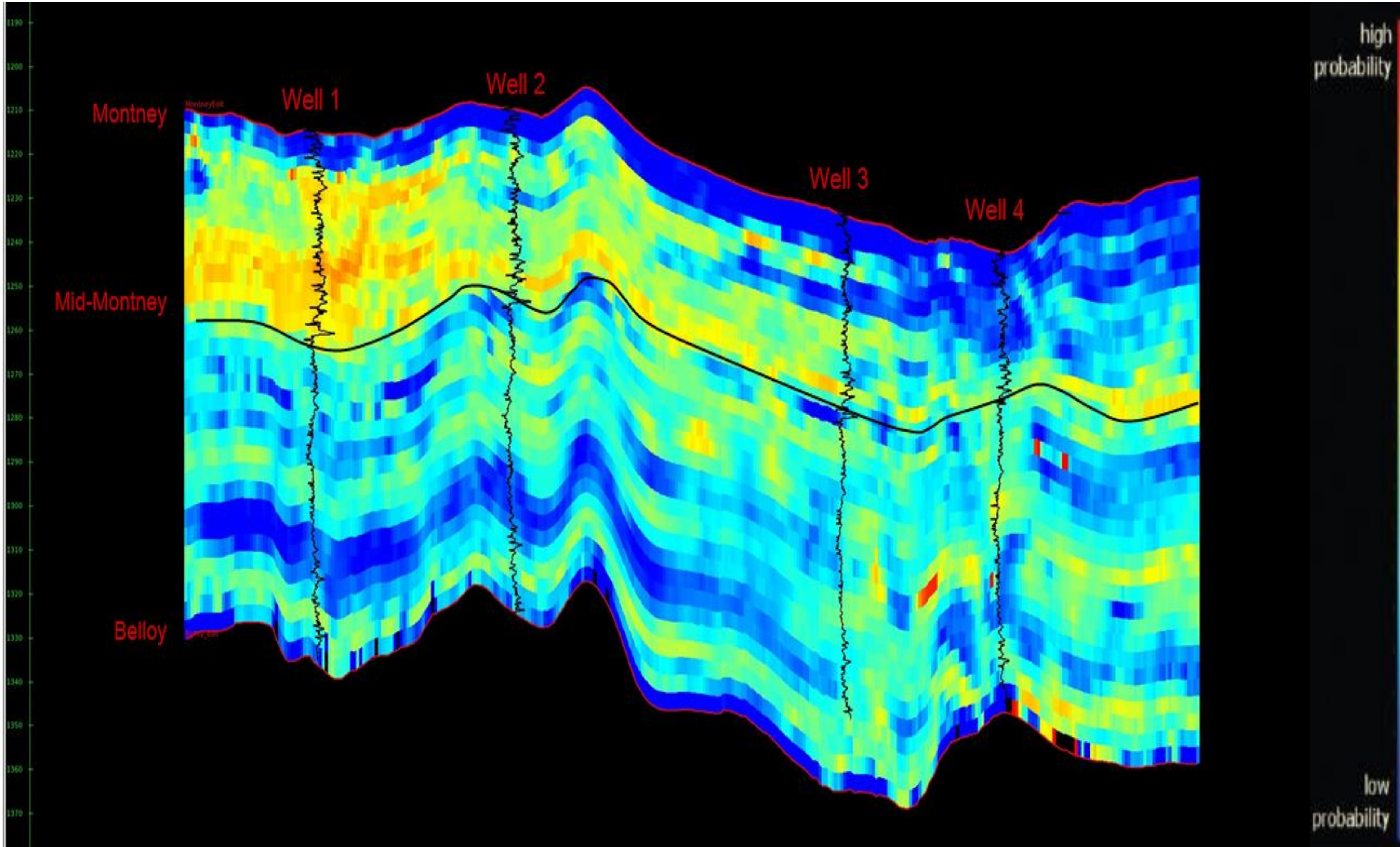
Classified log

Litho-log	HighTOC/Phosphatic	Silt	LowTOC-LowPhi	LowTOC-HighPhi
HighTOC/Phosphatic	83.33%	0.00%	0.00%	16.67%
Silt	0.00%	85.71%	14.29%	0.00%
LowTOC-LowPhi	0.00%	0.00%	84.62%	15.38%
LowTOC-HighPhi	0.00%	0.00%	8.33%	91.67%

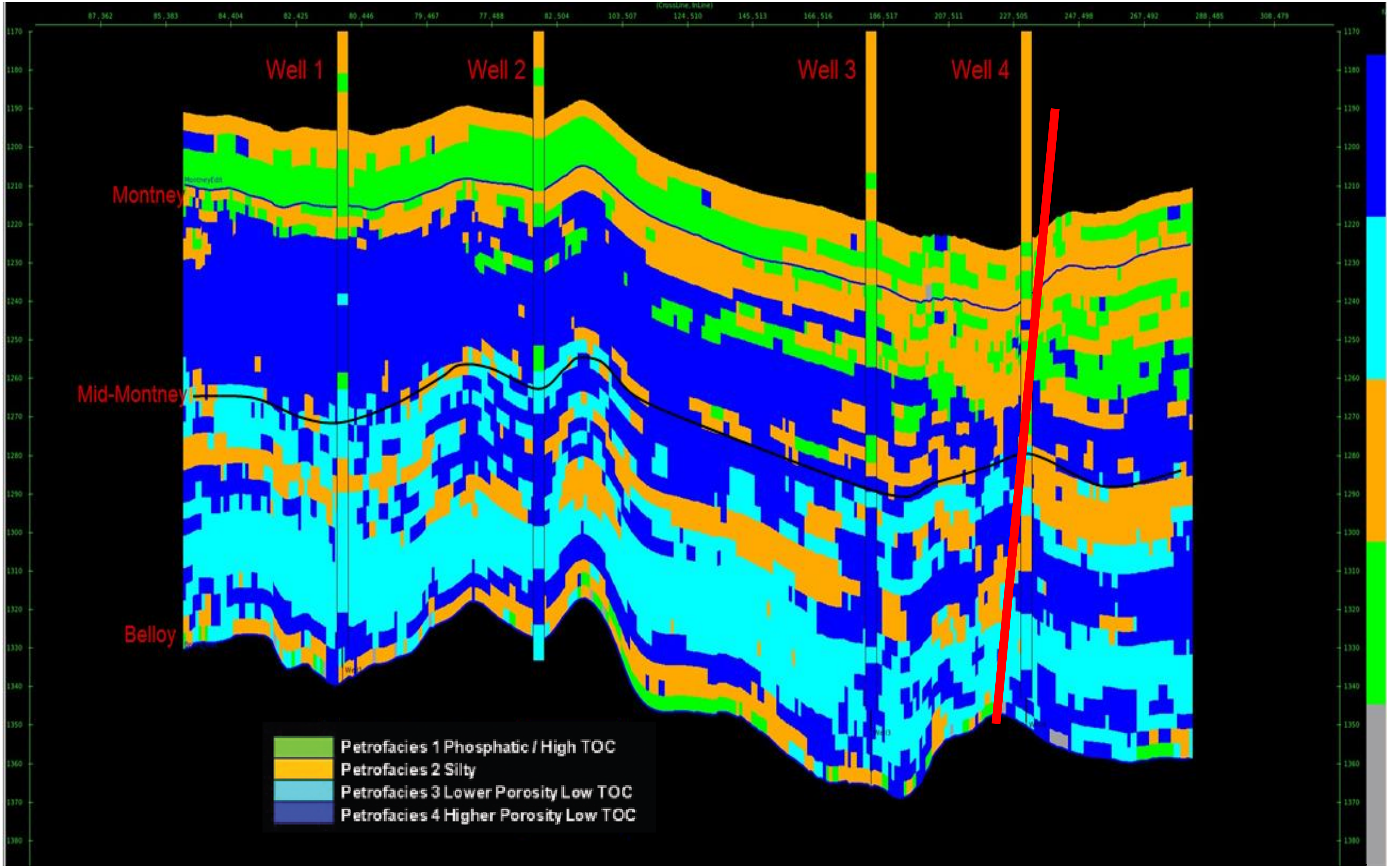
Number of samples	Misclassified samples
6	16.67%
7	14.29%
13	15.38%
12	8.33%

Petrofacies 1 Phosphatic / High TOC
Petrofacies 2 Silty
Petrofacies 3 Lower Porosity Low TOC
Petrofacies 4 Higher Porosity Low TOC

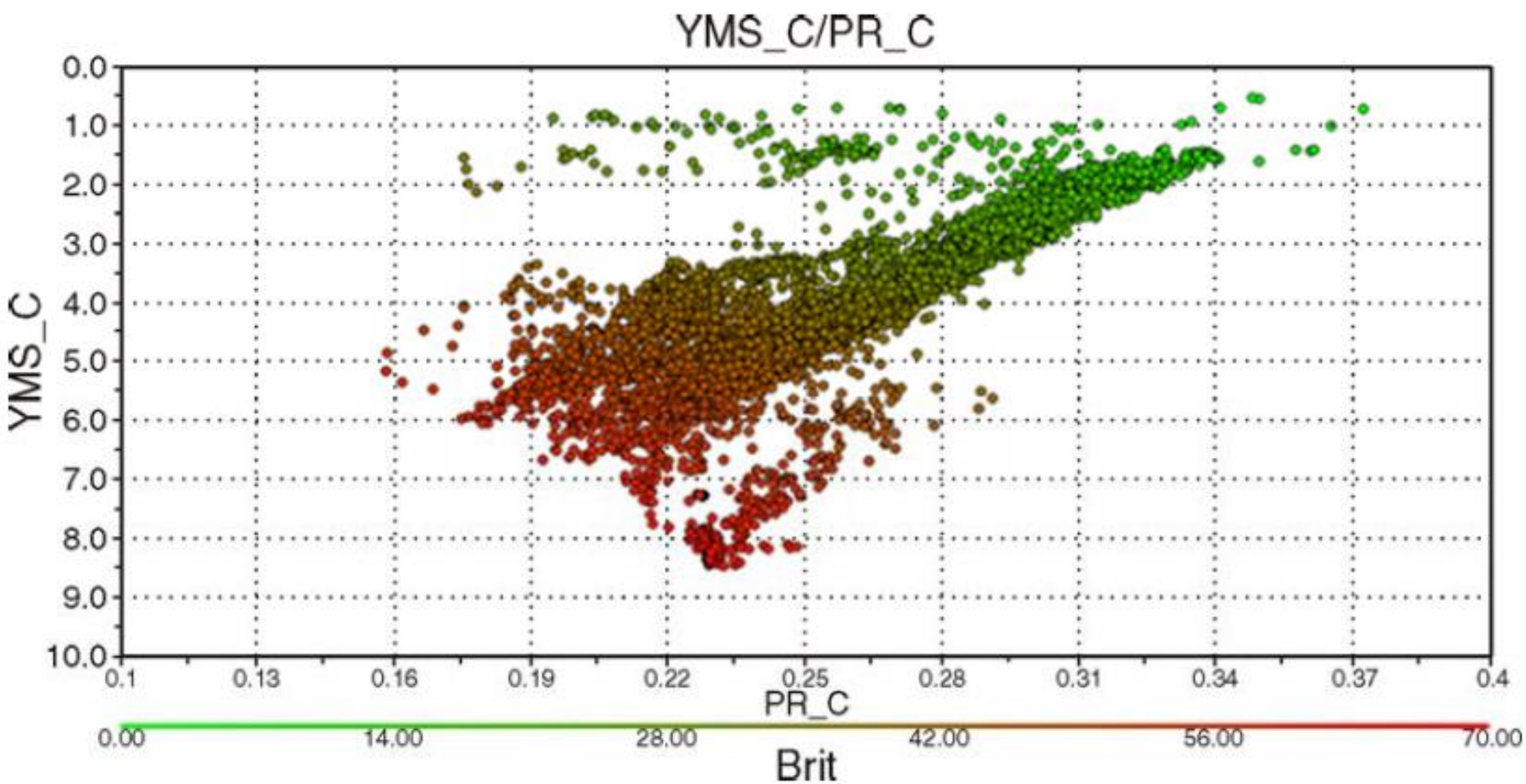
Montney Section: Probability of Petrofacies 4



Section QC – Most Probable Petrofacies

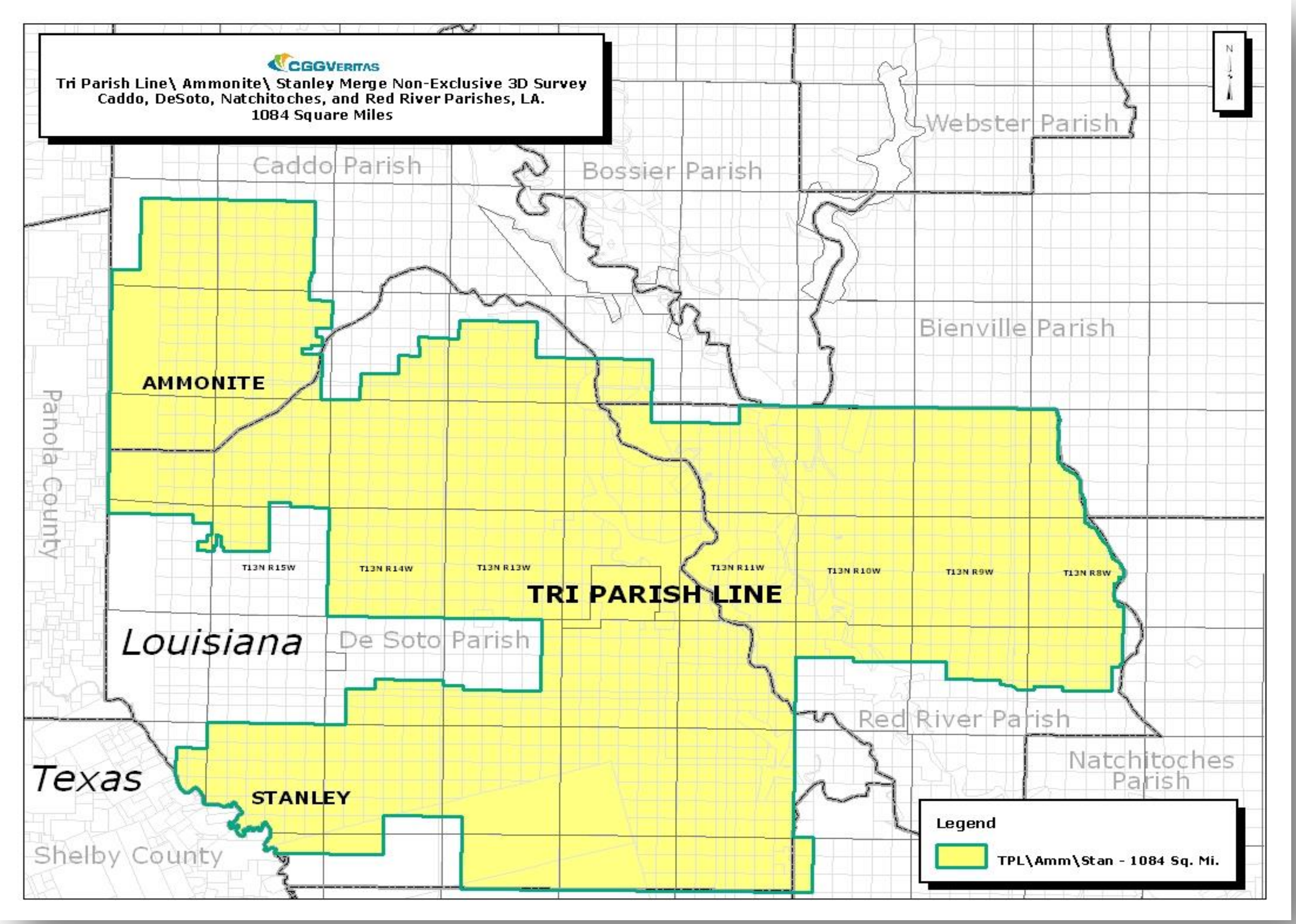


Geomechanical Properties



Next, let's discuss how to determine geomechanical properties. The figure above, from Rickman et al. (2008) crossplots static Young's modulus (YMS) vs static Poisson's ratio (PR) and calibrates the result to brittleness (Brit).

Case study: Haynesville Shale



Sena et al. (2011) applied seismic reservoir characterization to the Haynesville shale play.

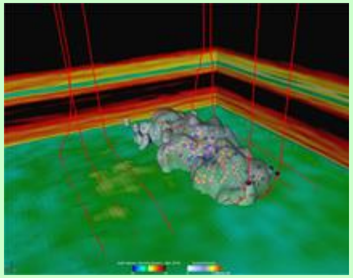
Seismic Reservoir Characterization Workflow

Seismic Rock Properties

Azimuthal Processing (HTI-VTI Anisotropy)
- Orthorhombic Migration

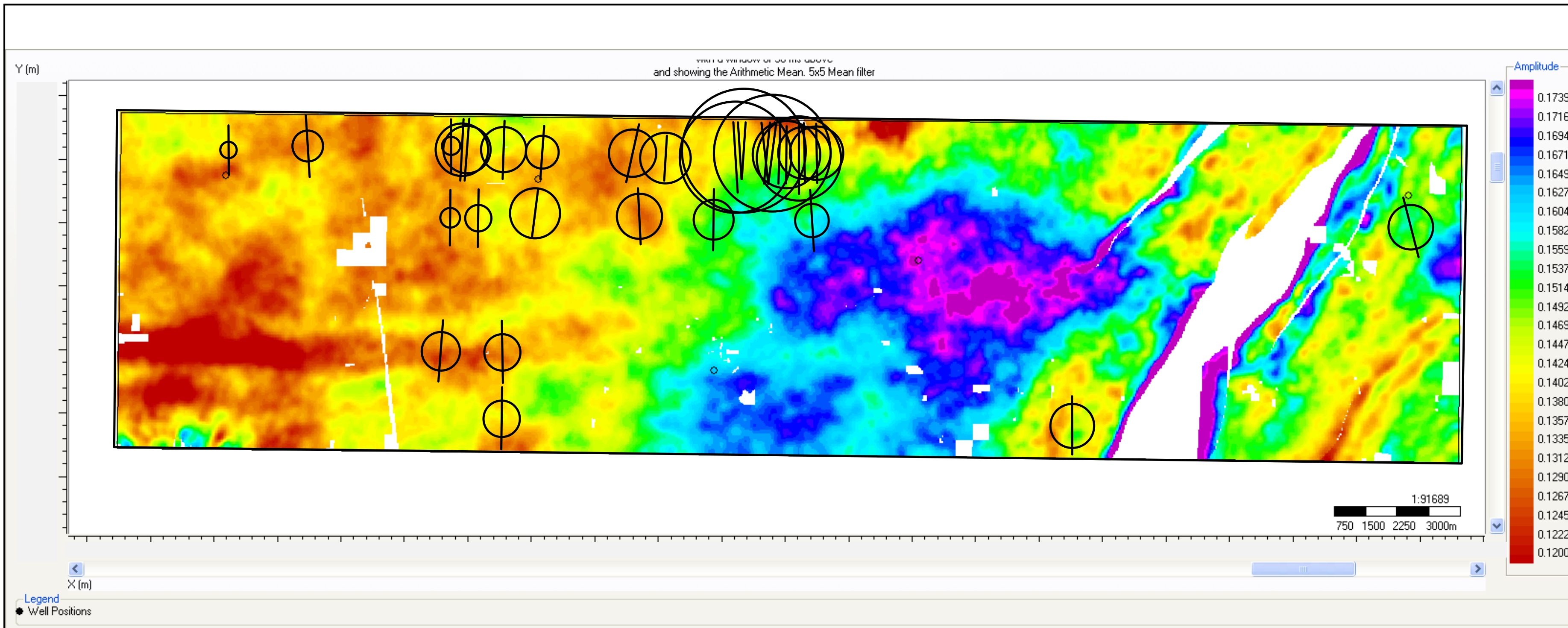
Seismic Analysis
- Pre Stack Inversion
- Pre Stack Azimuthal Inversion
- Pore Pressure Prediction
- Stress Analysis

Multi Attribute / Integration



Haynesville: Poisson's Ratio

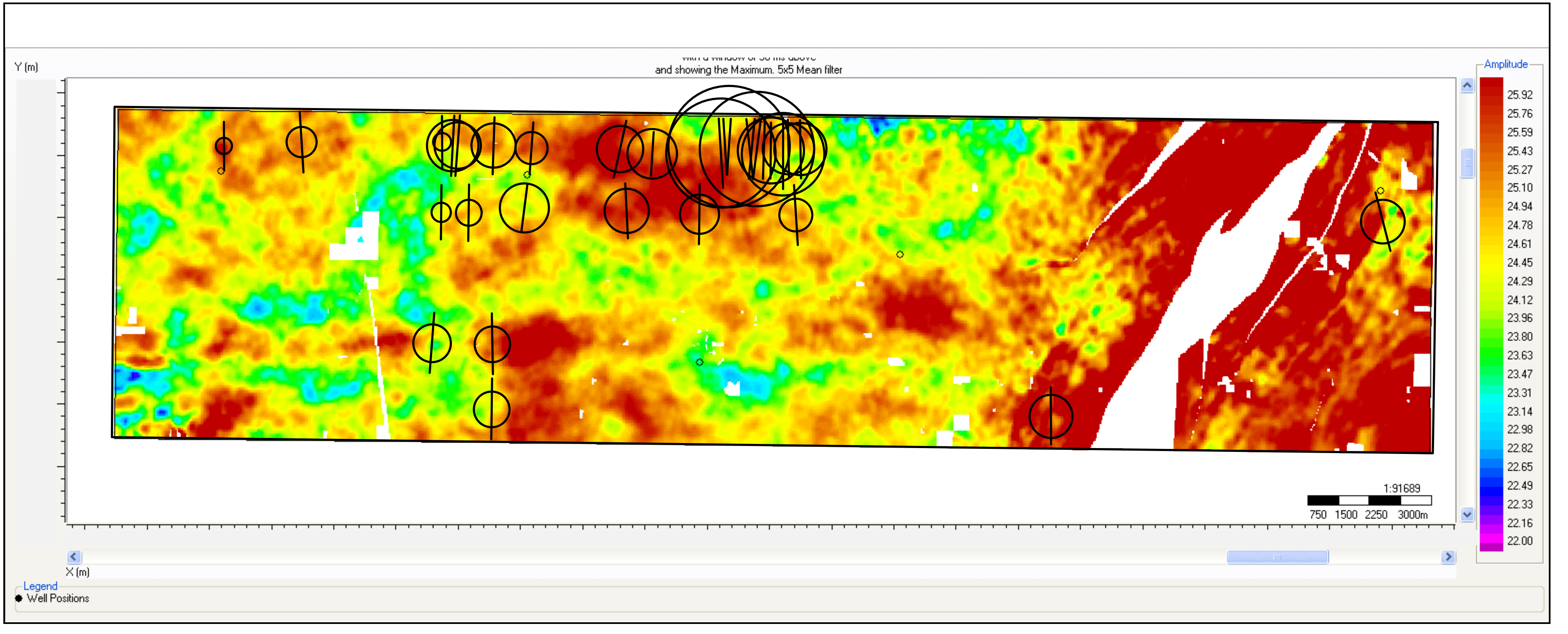
Pre-stack seismic inversion was used to invert for P and S impedance and transform to Poisson's ratio. This is the result after calibration from the dynamic to static case.



Bubble map: 6 month cumulative production / horizontal well length (Mcfpd)

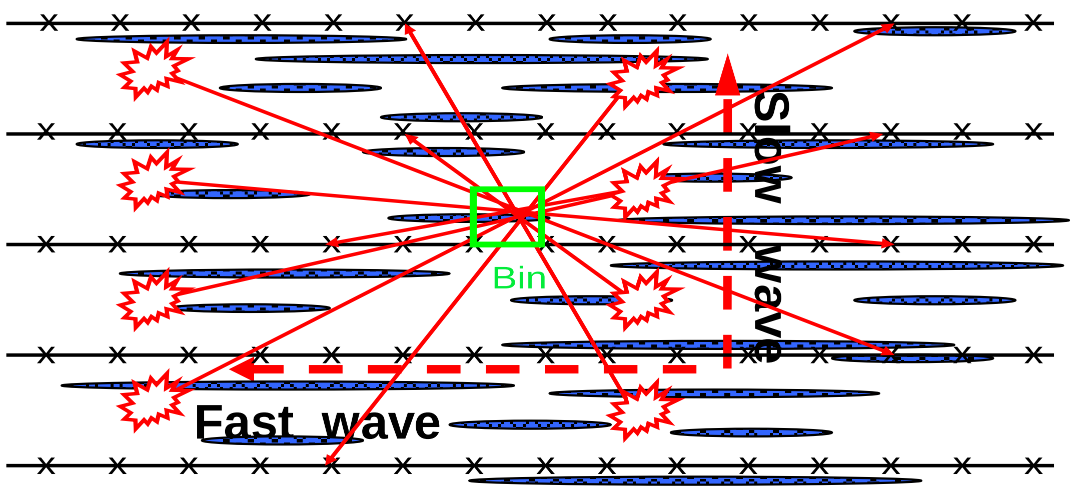
Young's Modulus

Pre-stack seismic inversion was used to invert for P and S impedance and density and transform to Young's modulus. This result is after calibration from the dynamic to static case.



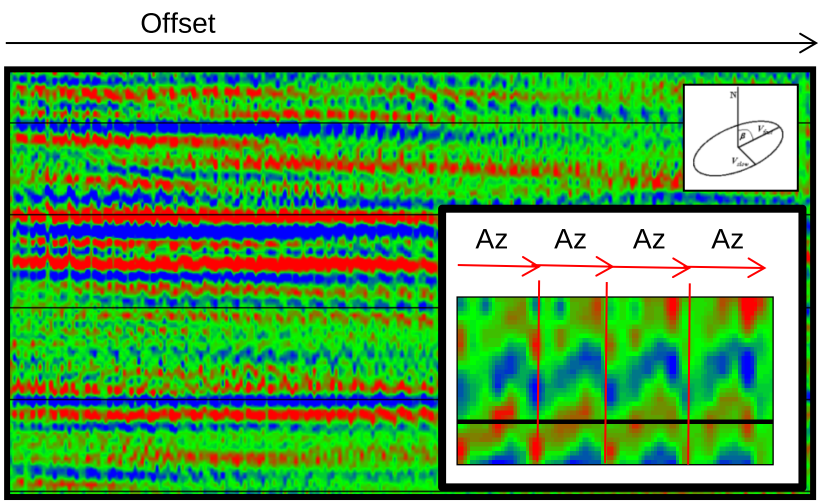
Bubble map: 6 month cumulative production / horizontal well length (Mcfpd)

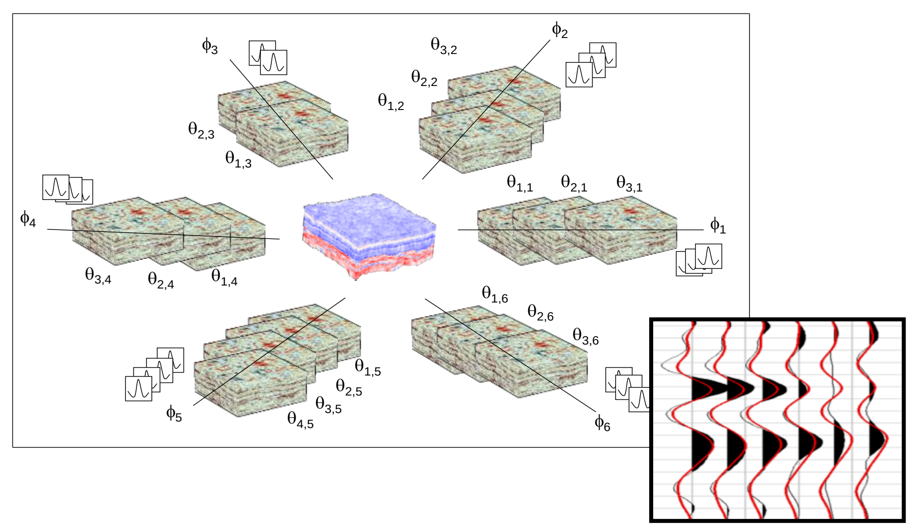
Using HTI Anisotropy



Azimuthal Velocity Analysis

Azimuthal AVO Analysis
Simultaneous Azimuthal Inversion





Differential Horizontal Stress Ratio (DHSR)

- An important parameter used in the extraction of fracture information about the reservoir is the Differential Horizontal Stress Ratio, or *DHSR*, where:

$$DHSR = \frac{\sigma_{H\max} - \sigma_{h\min}}{\sigma_{H\max}}, \text{ where:}$$

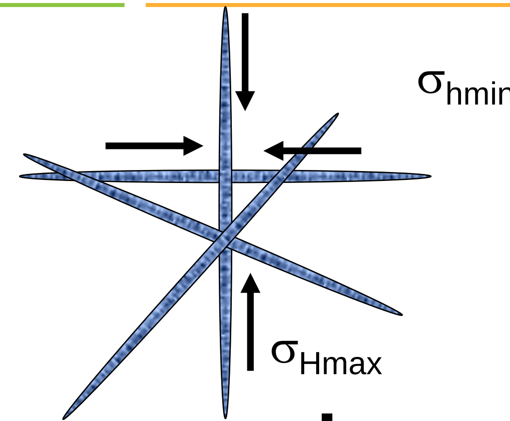
$$\sigma_{H\max} = \text{maximum horizontal stress, and}$$

$$\sigma_{h\min} = \text{minimum horizontal stress.}$$

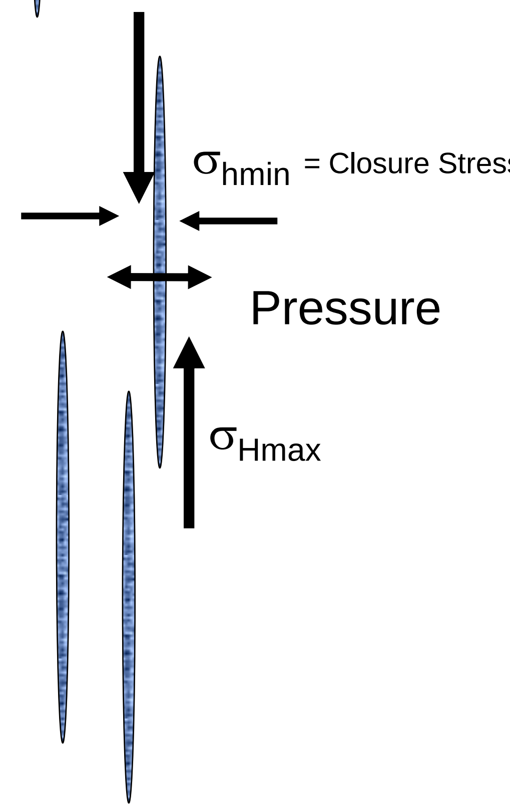
- Using inverted density (which gives the vertical stress) and normal fracture compliance estimated from azimuthal inversion, *DHSR* can be computed.
- The next slide shows how it is interpreted.

Using DHSR for production information

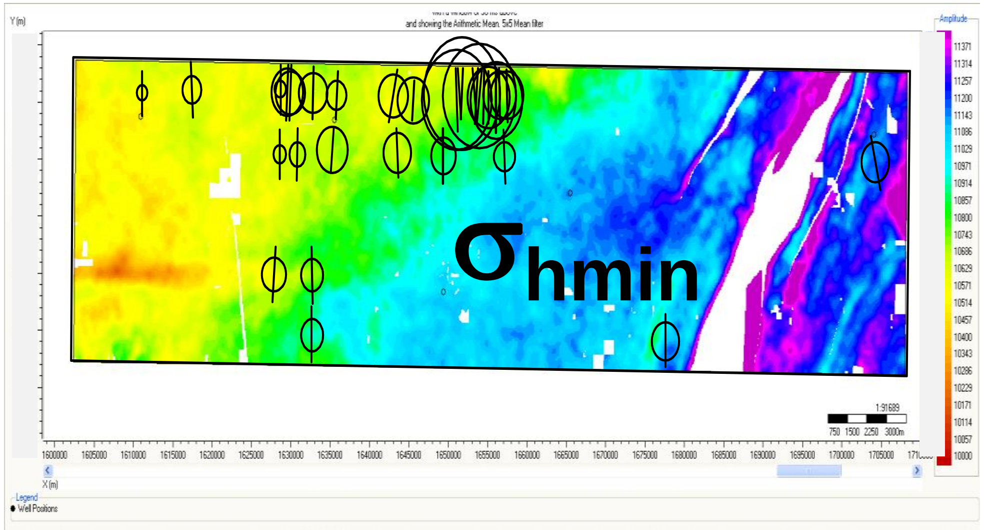
- If $\sigma_{Hmax} \approx \sigma_{hmin}$ (DHSR ≈ 0)
  - Tensile cracks any direction
    - || rock weakness
    - Fracture network



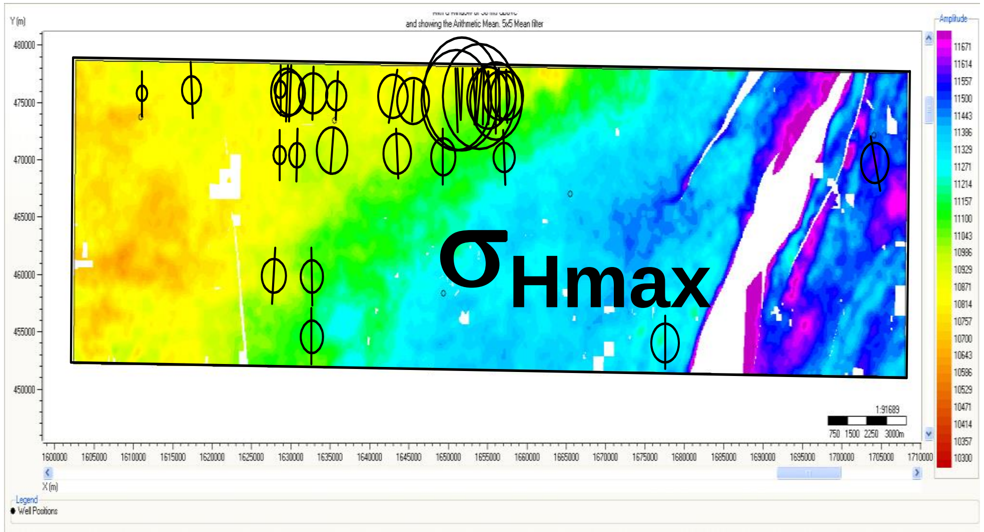
- If $\sigma_{Hmax} >> \sigma_{hmin}$ (DHSR > 3-5%)
  - Fractures || σ_{Hmax}
    - Shear Fractures
    - Tensile Fractures
  - Connect to existing fracture network for production



Stress Analysis Results



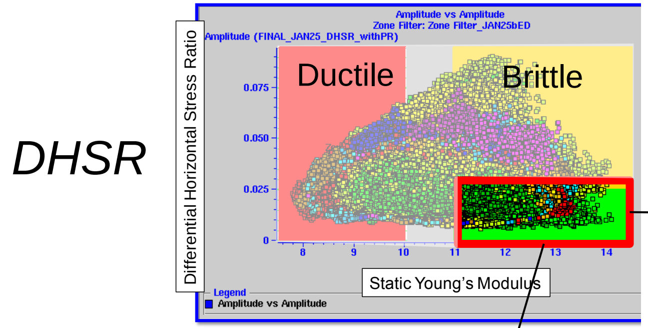
Here are the results for the minimum horizontal stress.

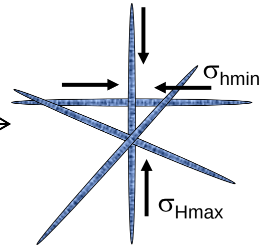


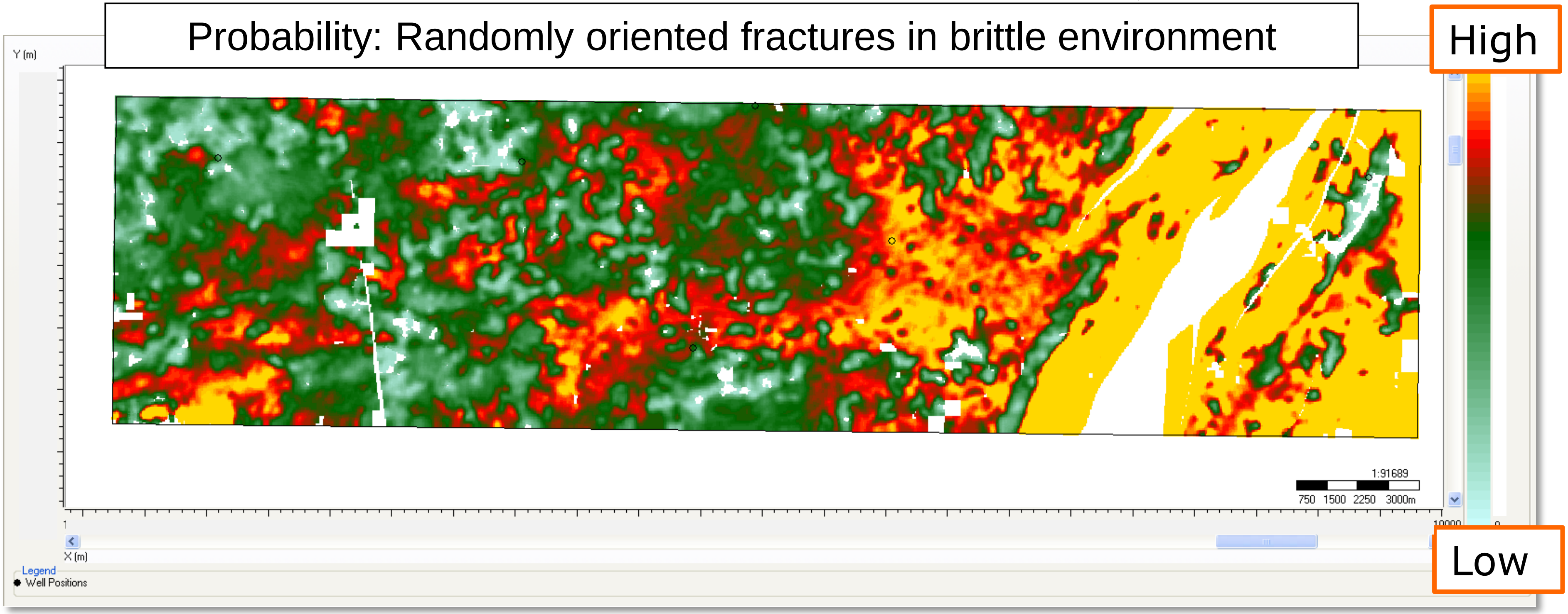
Here are the results for the maximum horizontal stress.

Randomly oriented fractures in brittle environment

A cross-plot of DHSR versus Young's Modulus gives us information about fractures.







Multi-Attribute Analysis

- Finally, reservoir parameters were computed using multi-attribute analysis:

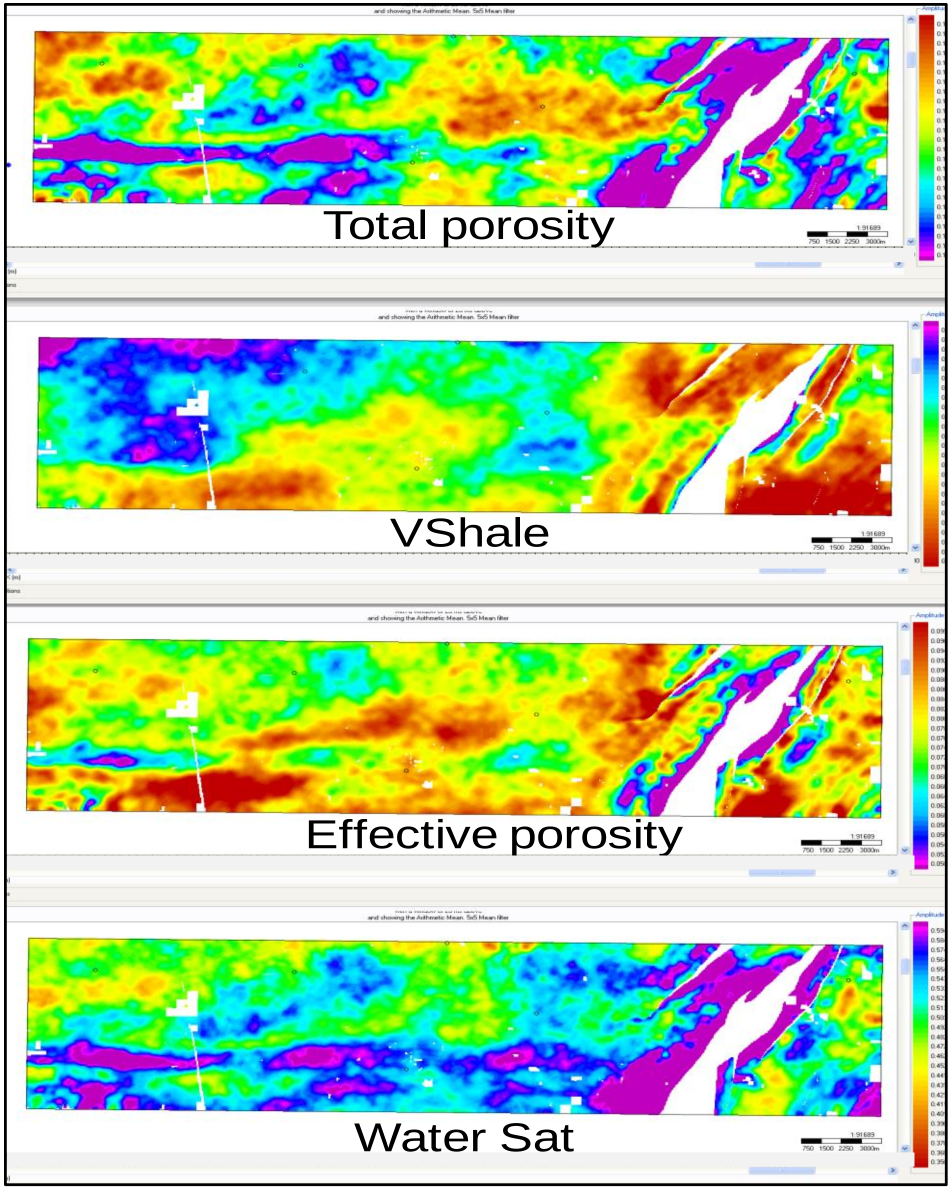
$$P = w_0 + w_1 A_1 + \ldots + w_n A_n, \text{ where:}$$

$$P = \text{parameter}, \; A_i = i^{th} \text{ attribute.}$$

- The following reservoir parameters were predicted:
  - Porosity (Total and Effective Porosity)
  - Volume of Carbonate/Clay
  - Water Saturation
  - Bulk Gas Volume
- The multiple seismic attribute maps were then integrated to highlight good production areas.

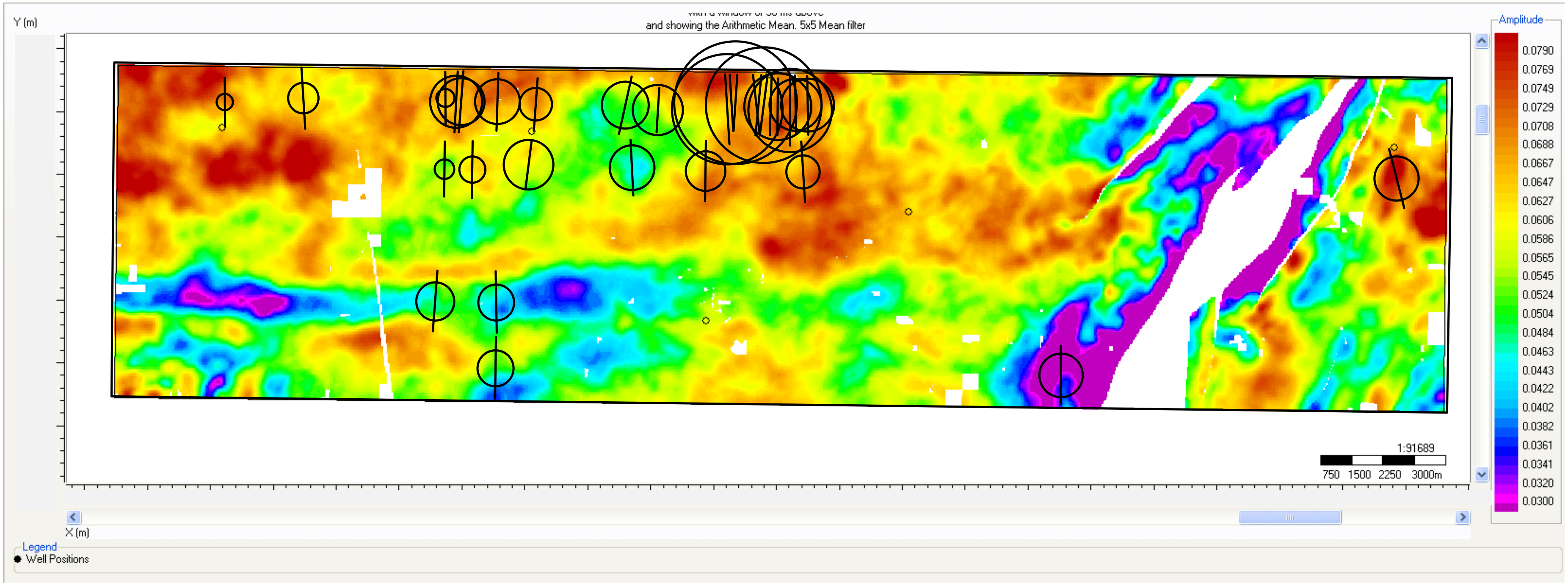
Multi-Attribute Analysis

Here are some of the results that were found from the multi-attribute analysis.



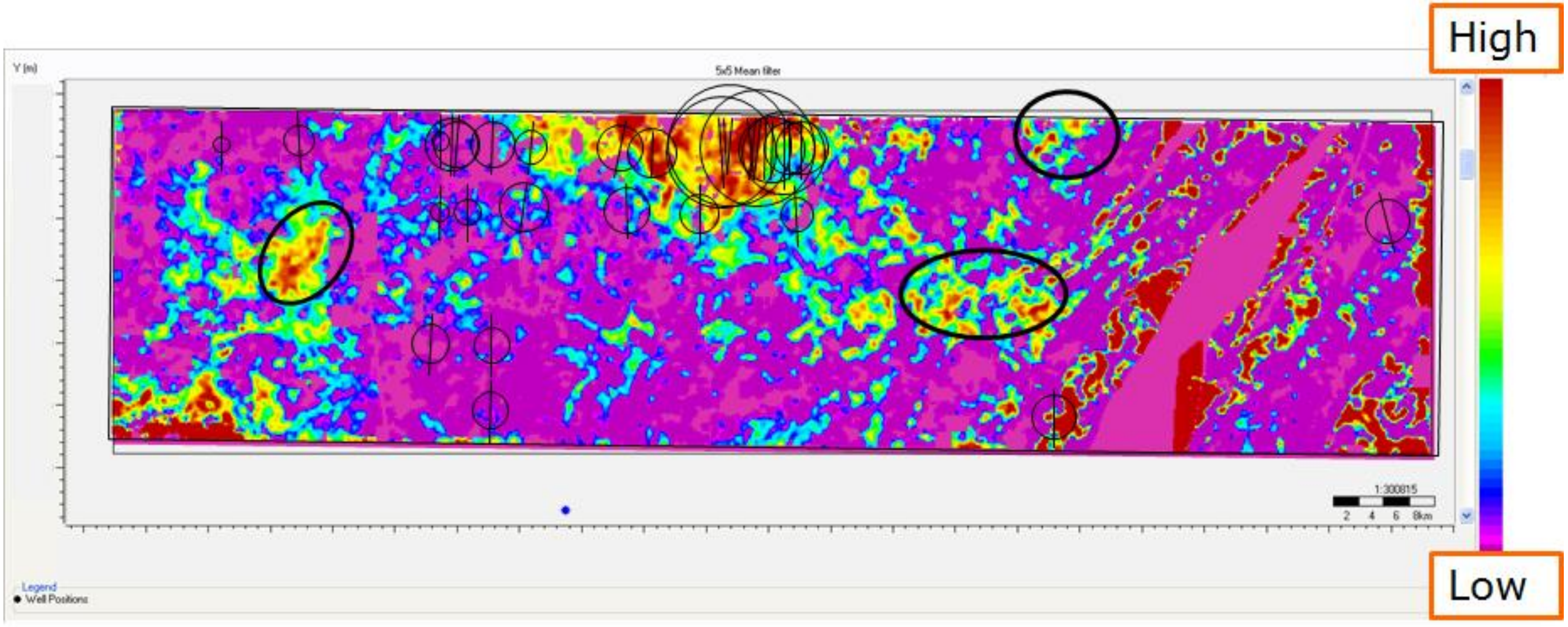
Haynesville: Bulk Volume Gas

The figure below shows the Bulk Volume of Gas, equal to Total Porosity x (1–Water Saturation), where the bubble map shows the 6 month cumulative production / horizontal well length (Mcfpd):



Haynesville: Production predicition

The final result integrated multiple seismic attribute maps to highlight good production areas:



Conclusions

- In this talk I showed how pre-stack seismic inversion can be used in reservoir characterization for unconventional resource plays.
- The two key properties derived from seismic are Young's modulus and Poisson's ratio.
- In addition, azimuthal inversion and AVO can be used to determine:
    - Principal stresses
    - Differential horizontal stress ratio
- The benefits include:
    - Sweet spot identification
    - Well location optimization
    - Completions optimization