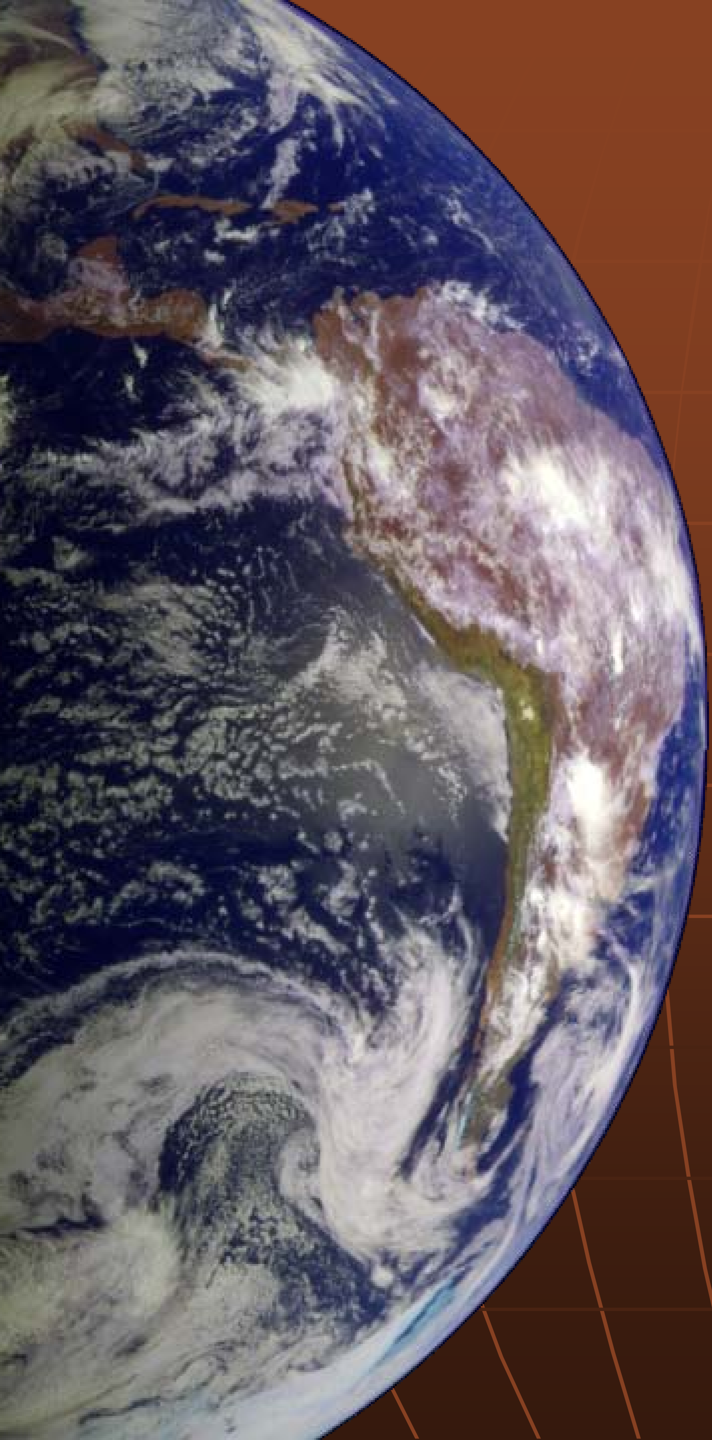

Analytic Tools for Quantitative Interpretation

Mrinal K.Sen

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Tools

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- Modeling of fractures – static, dynamic, numerical
- Modeling seismic wave propagation in anisotropic media
- Travel time an amplitude based methods for estimating anisotropy parameters
- Data integration using geostatistical tools
- Seismic inversion

Geochemistry

- The Barnett Shale has been such a productive reservoir due to high proportion of **total organic carbon** (TOC) despite having likely leaked much of its gas to surrounding formations/reservoirs over time.
- The TOC of the Barnett averages ~4.5% (immature outcroppings indicate it was as high as 11-13%). This is important because there is a linear relationship between TOC values and gas content. A high TOC value suggests a large potential to generate hydrocarbons.

Natural Fractures

- Gas production from the Barnett Shale relies on hydraulic fracture stimulation.
- Natural opening-mode fractures reactivate during stimulation and enhance efficiency by widening the treatment zone.
- Knowledge of both the present-day maximum horizontal stress, which controls the direction of hydraulic fracture propagation, and the geometry of the natural fracture system, necessary for effective hydraulic fracture treatment design.

Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments
Julia F. W. Gale, Robert M. Reed, and Jon Holder

Fractures

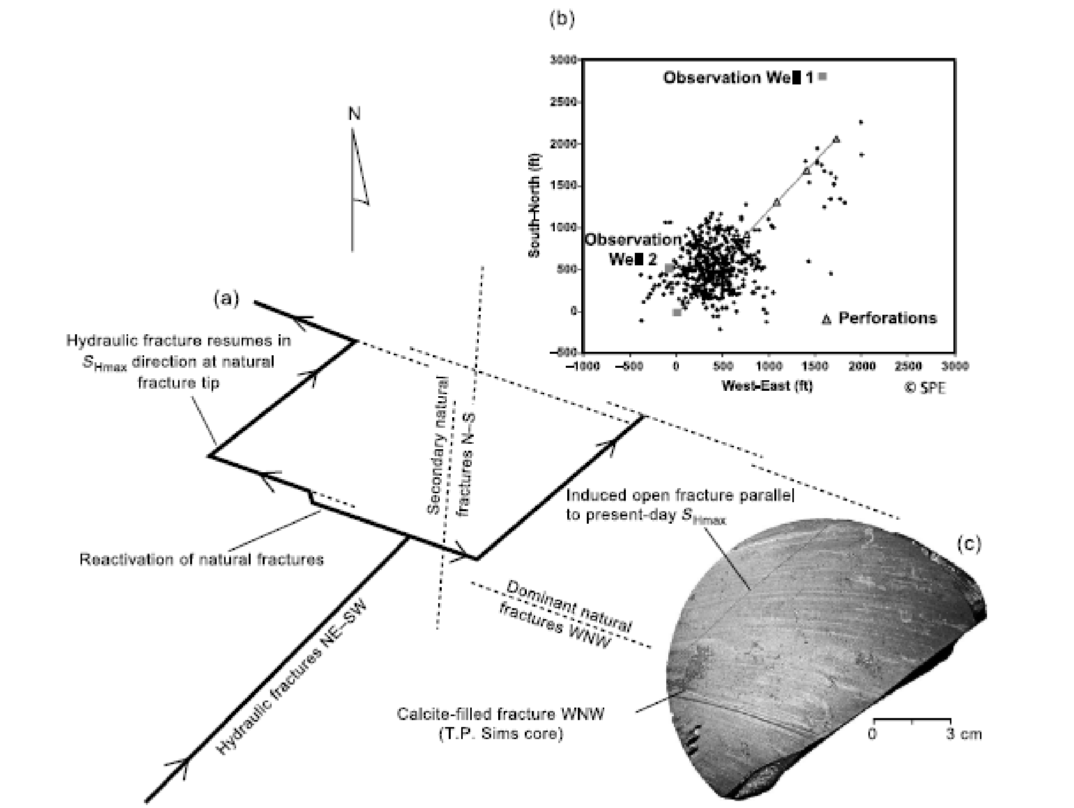

Figure 2. Diagrammatic representation of hydraulic fracture growth showing why natural fracture systems are important for optimal stimulation. (a) Hydraulic fracture growth proceeds northeast-southwest and reactivates natural fractures (dashed lines) trending west-northwest–east-southeast and north-south. Arrows indicate the propagation direction of hydraulic fractures. (b) Map of microseismic data from Warpinski et al. (2005, reprinted with permission from the Society of Petroleum Engineers). (c) A sealed west-northwest–trending fracture and an open, unmineralized, northeast-trending, induced fracture in a disc from the T. P. Sims core.

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Fractures

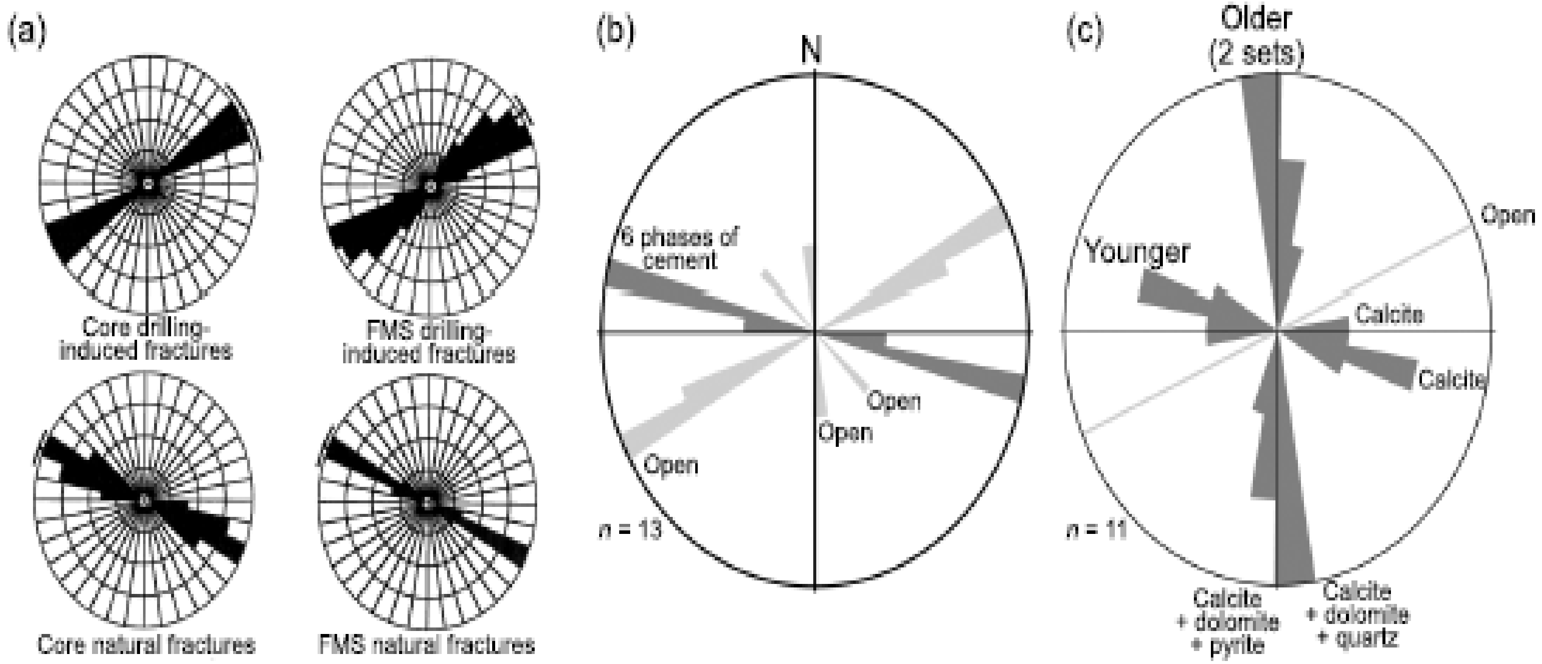

Figure 5. Rose diagrams showing fracture trends in the T. P. Sims core (a) from Hill (1992), used with permission from the Gas Technology Institute; (b) in the mudrock sample from this study; and (c) in the dolomitic sample from this study.

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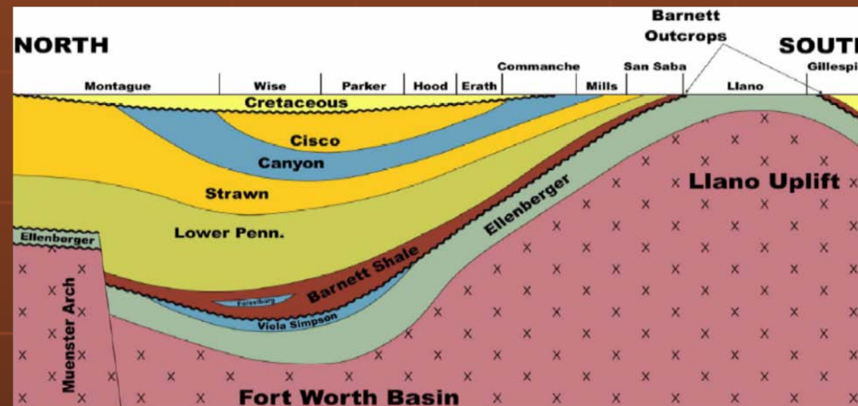
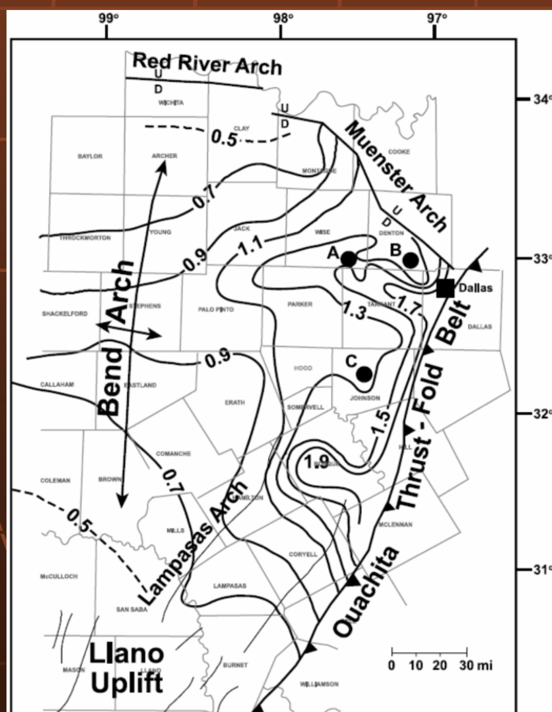
Reservoir characterization issues

Natural fractures associated with thrust faults





Spatially variable TOC and thermal maturation levels

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Tools

- Modeling of fractures – static, dynamic, numerical
- Modeling seismic wave propagation in anisotropic media
- Travel time based methods for estimating anisotropy parameters
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Waveform Modeling of fractured reservoirs—Failure of AVOA? Overburden Effect

Sen, Lane and Foster 2007

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Working Hypothesis

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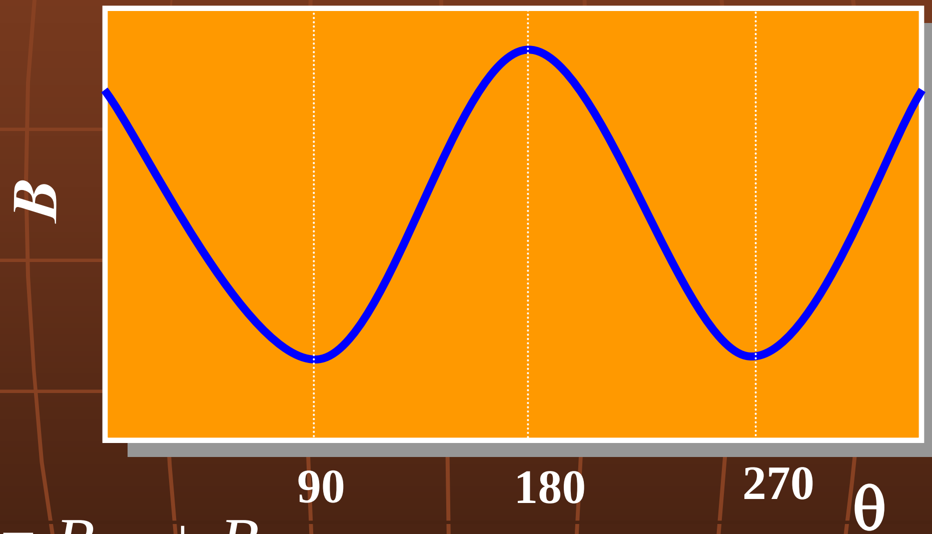
1. Assume an HTI medium so that the gradient, B, is described by $B = B_{iso} + B_{ani}\cos(\theta)$ for a fixed angle of incidence.



At $\theta = 0$ $B = B_{iso} + B_{ani}$

At $\theta = 90$ $B = B_{iso}$

Where θ represents azimuth from fractures.

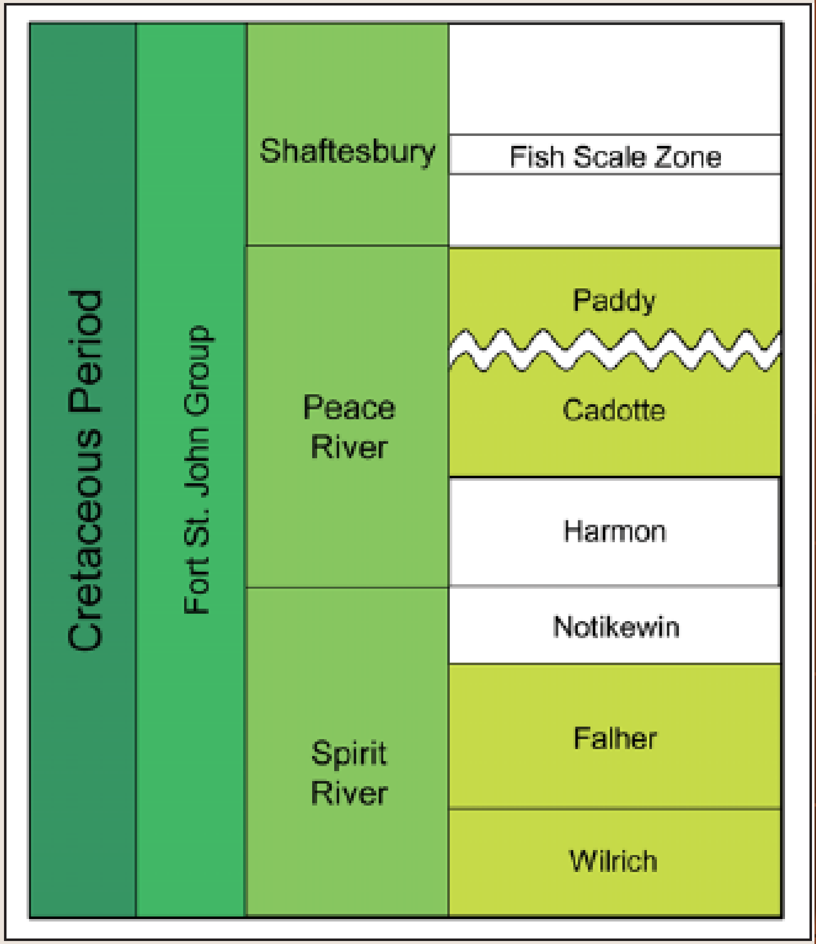


Figure 1. Stratigraphic correlation chart for the Lynx prospect area. The objective interval for this study is the Cadotte member of the Lower Cretaceous Peace River Formation, Fort St. John Group. It rests conformably on interbedded-silts and shales of the Harmon member, and is unconformably overlain by other silts and shales of the Paddy member. The contact between the Paddy and Cadotte has been interpreted to be an erosional surface resulting from fluvial erosion and valley mass wasting (Leickie et al., 1990). The Paddy is conformably overlain by a thick shale succession belonging to the Shaftesbury Formation.

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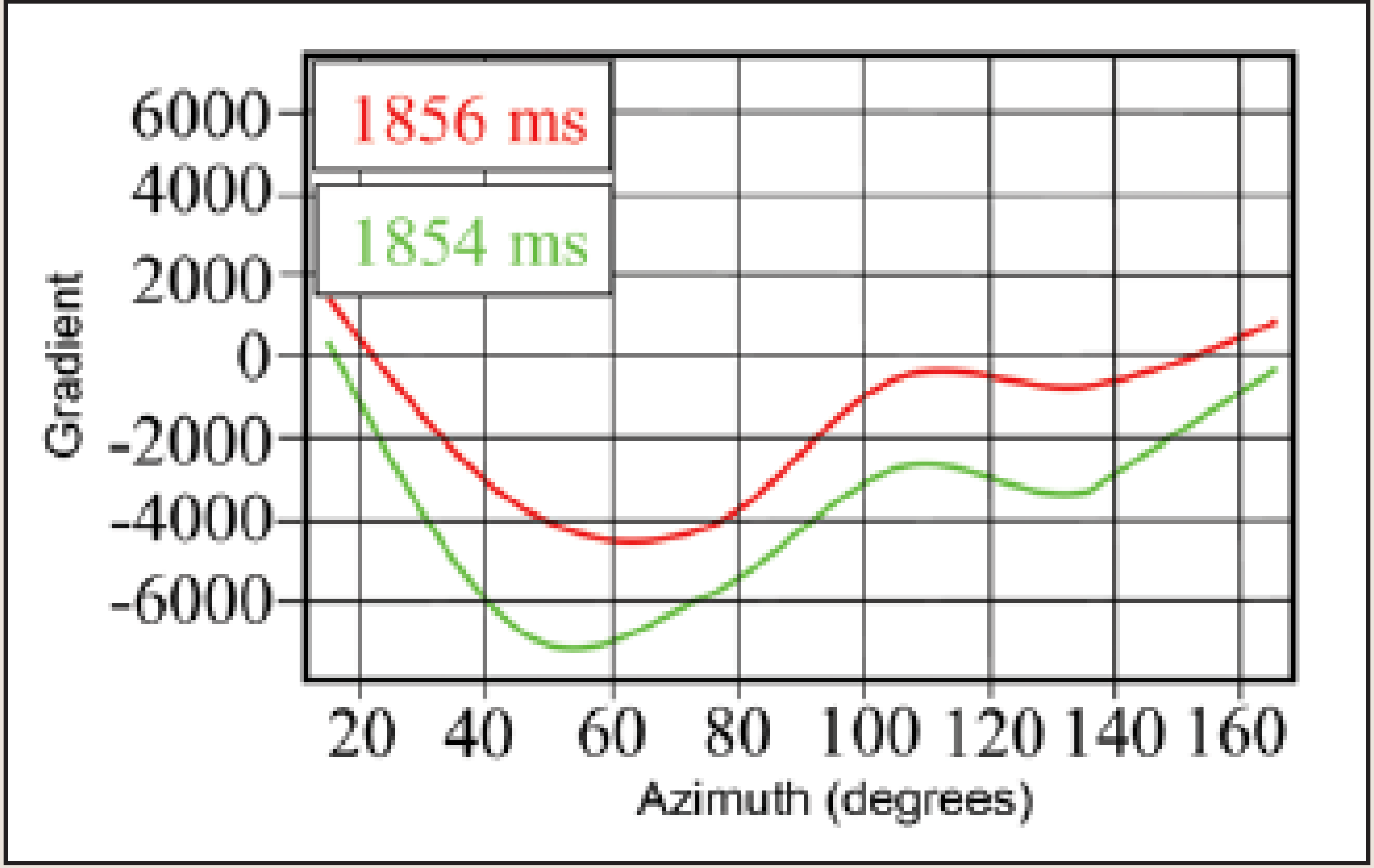


Figure 4. Amplitude of the AVO gradient versus azimuth observed for a reflection from the top of the Falher Formation. The red curve was extracted at 1856 ms, and the green curve at 1854 ms. For an isotropic half-space overlying an HTI medium, the curves should exhibit a $\cos^2(\phi)$ variation. The fact that they don't suggests a more complex fracture pattern.

Objectives

- Can we explain the near-isotropic AVOA from the Cadotte and anisotropic AVOA from the Falher?
- Can we explain the asymmetric AVOA observed over the Falher?

Approach

- Generate full wave synthetic seismograms for different ‘what if’ scena

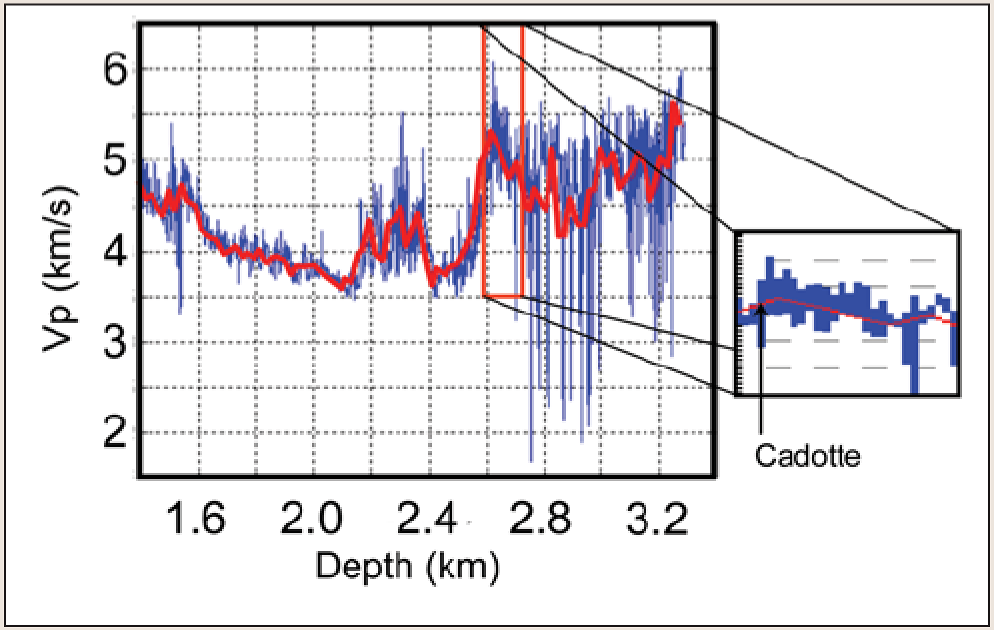
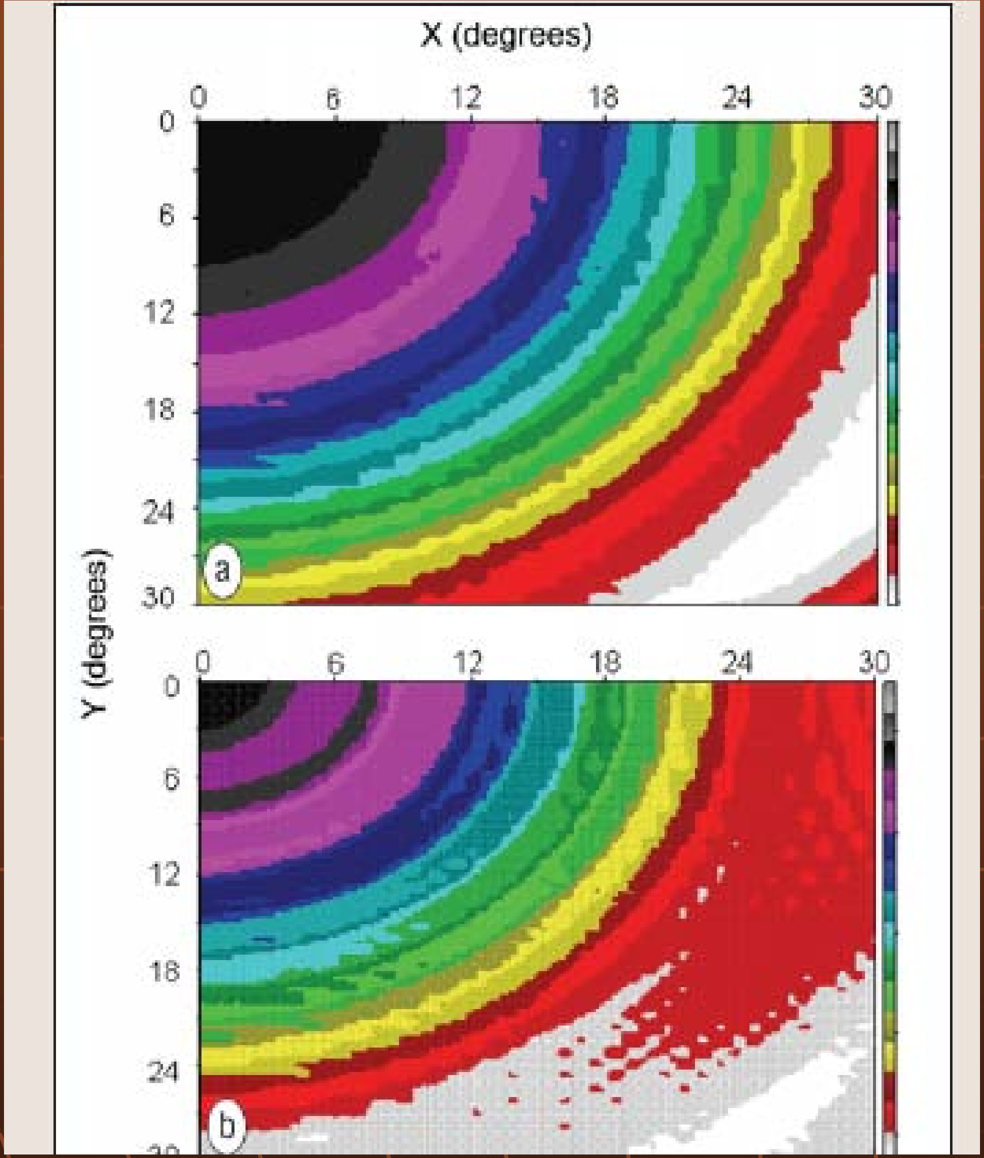
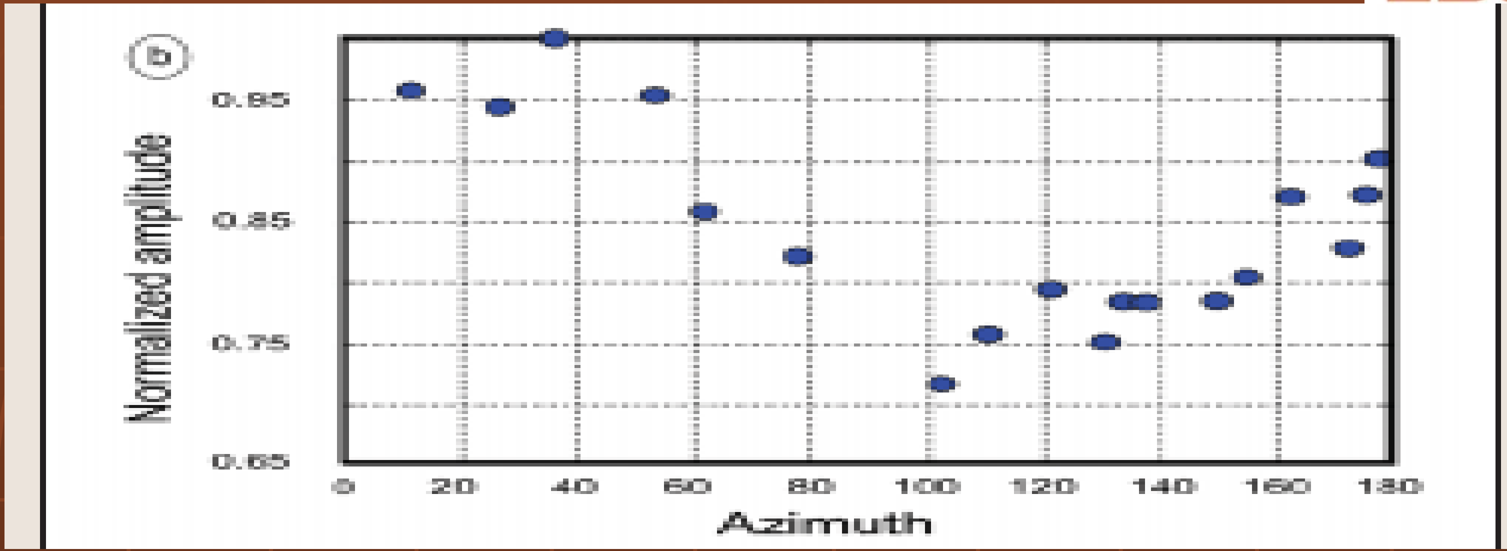
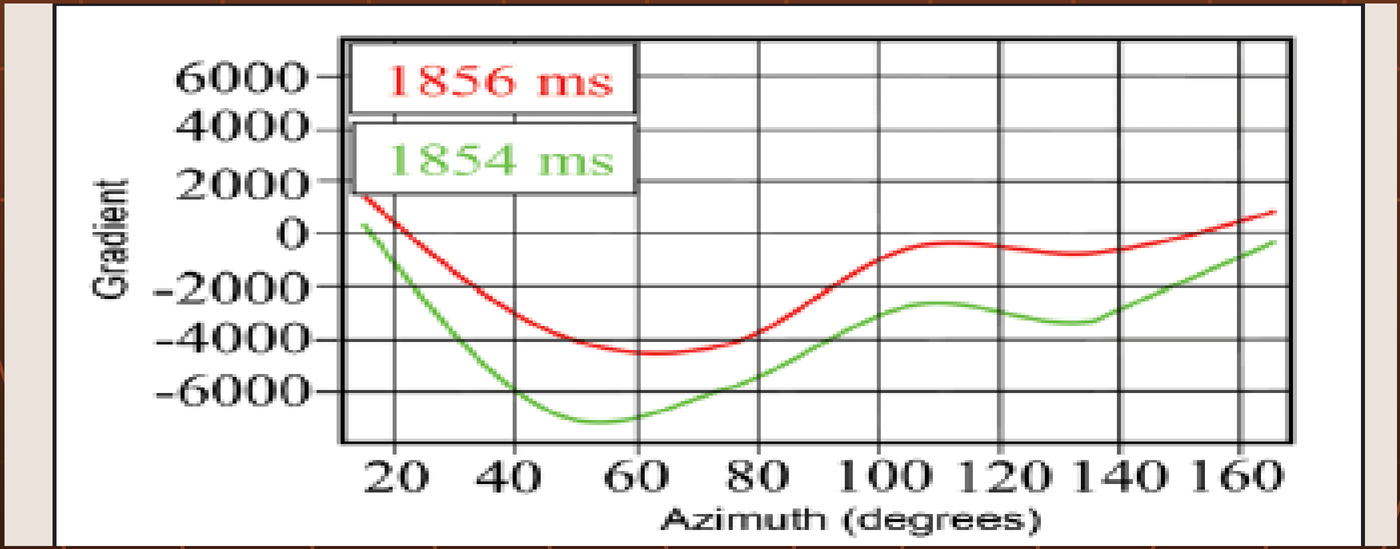


Figure 5. *Compressional-wave velocity log used for generating synthetic seismograms. The blue curve represents the recorded data, and the red curve the data used for generating synthetic seismograms. The actual location of the Cadotte Formation is shown on the inset.*



Fractured Cadotte
(10m)
Isotropic Falher





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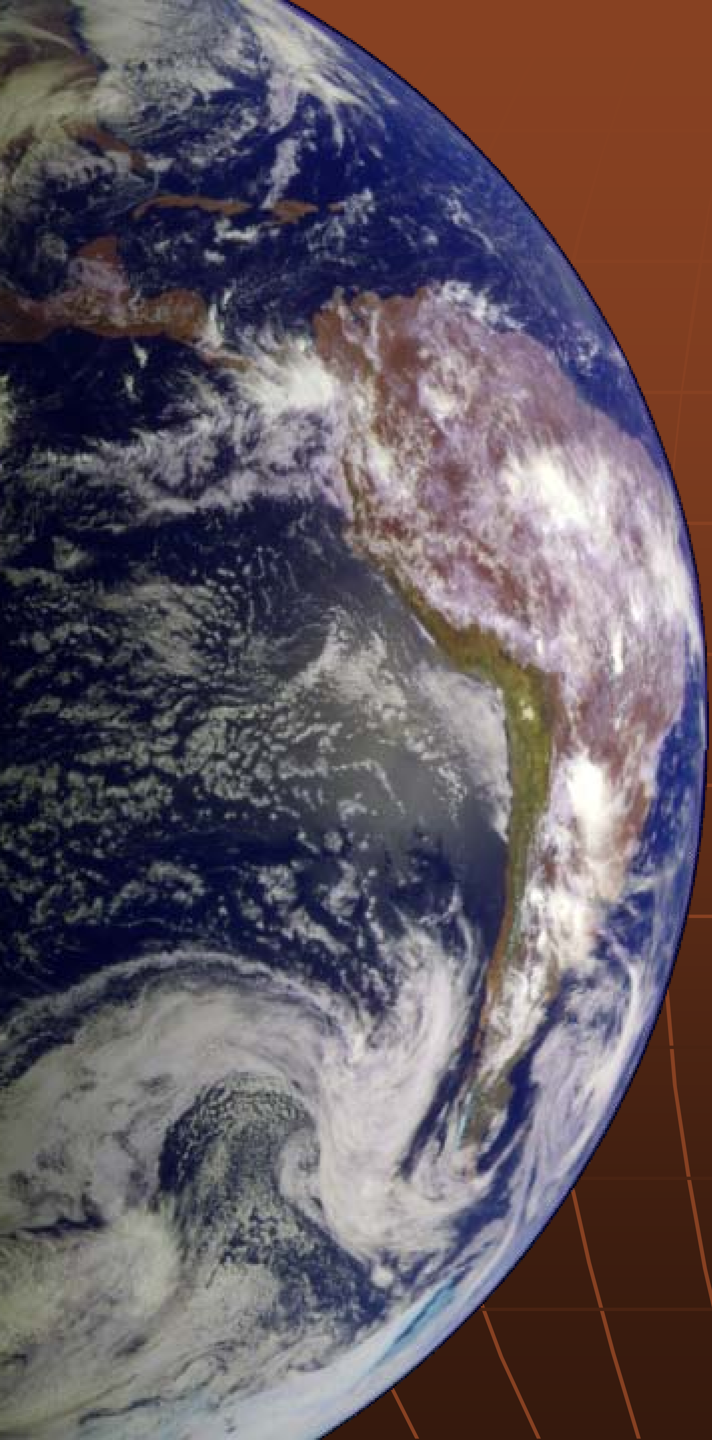
Summary

- Dry intersecting vertical fractures give rise to strong anisotropic effects
- This results in a breakdown of the symmetry of AVOA typical of single HTI model
- This is the likely cause of the unusual AVOA observation



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Fracture Mapping from seismic P-wave arrival time

Samik Sil, Sanjay Srinivasan & Mrinal Sen

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Travel time based method

- A fractured medium shows azimuthal velocity variation. Even along a given azimuth, travel time cannot be predicted by a single isotropic velocity.
- One can estimate anisotropy parameters (or the fracture parameters) from the measurement of velocity along different azimuths.

Travel time based method (New Method)

- Our approach is based on analyzing the data in plane-wave or tau-p domain.
- The tau-p domain allows for estimating individual layer parameters rather than an average over depth.
- It is based on a layer-stripping approach and thus, corrects for effects due to shallow layers.

New azimuthal tau-p equation for HTI medium

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So we have developed the following 2 parameter equation for HTI media (vertical fractures):

$$\tau(p_r,\phi) = \sum_{i=1}^{nl} \tau_0^i (1 - p^2 \alpha_{el}^{i2})^{1/2} [1 - \frac{2p^4 \alpha_{el}^{i4} \kappa^i}{1 - p^2 \alpha_{el}^{i2}}]^{1/2}$$

(Sil and Sen 2008; 2009a; 2009b)

Velocity uncertainty from prestack

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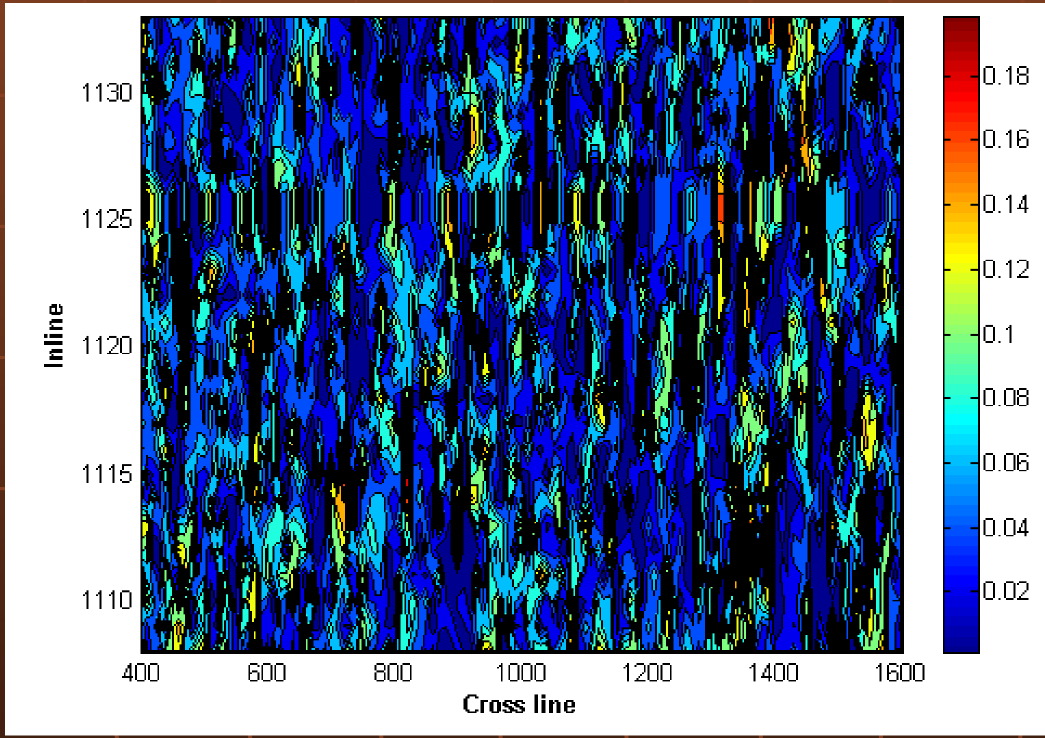

Percentage velocity uncertainty (dv / v) is calculated using the described method.

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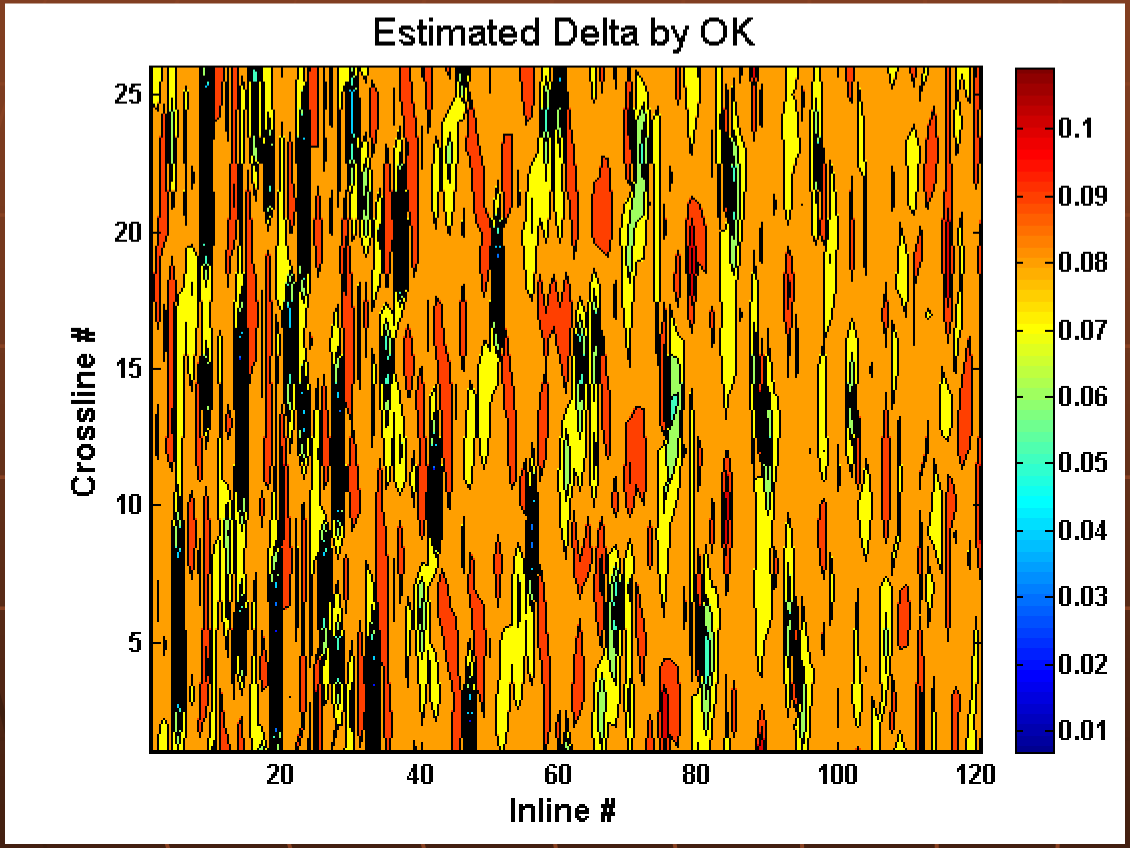
Estimation of δ^h

- Value of δ is available at sparse locations.
- An exhaustive map of δ is required to prepare a fracture orientation map from the velocity uncertainty.
- Exhaustive δ value map can only be prepared using geostatistical estimation.
- Ordinary Kriging is performed to estimate δ for the study area.

Estimated δ map



Using OK δ value map is prepared from the well log data. Value of δ is ranging from 0 to -0.1 (in the map absolute values are plotted). Using this map and velocity uncertainty map fracture map can be prepared.

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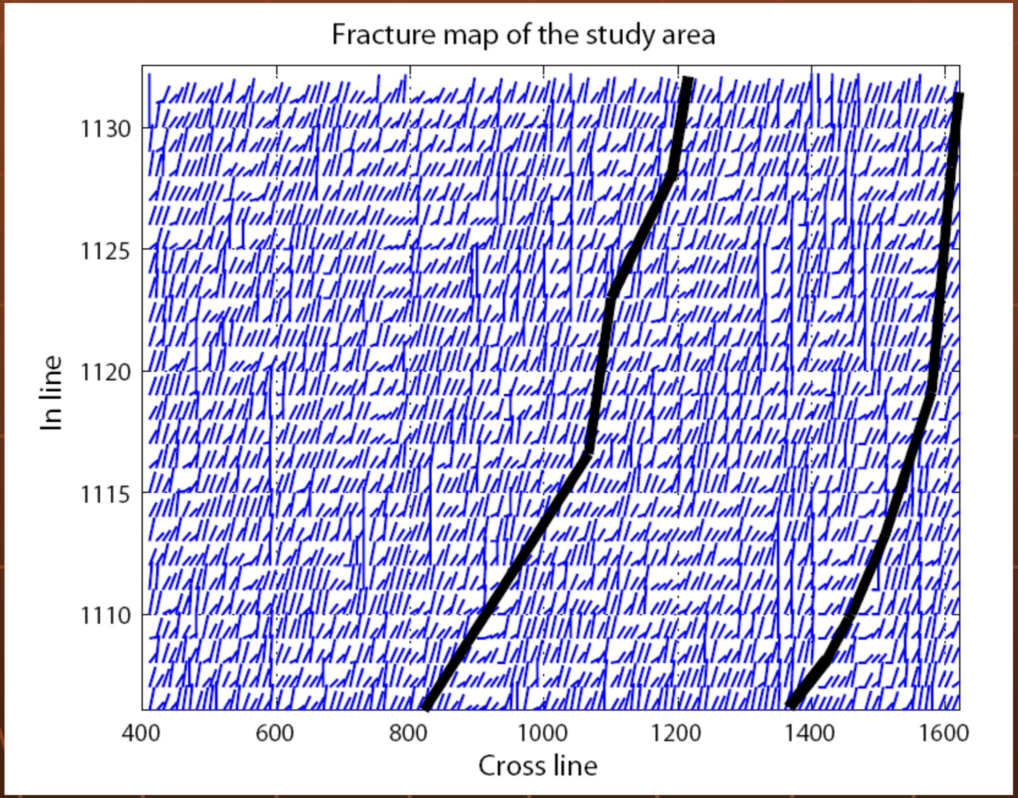
Azimuth from velocity uncertainty



Fracture map of the study area with major faults obtained from velocity uncertainty and estimated δ value maps.

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Rose plot

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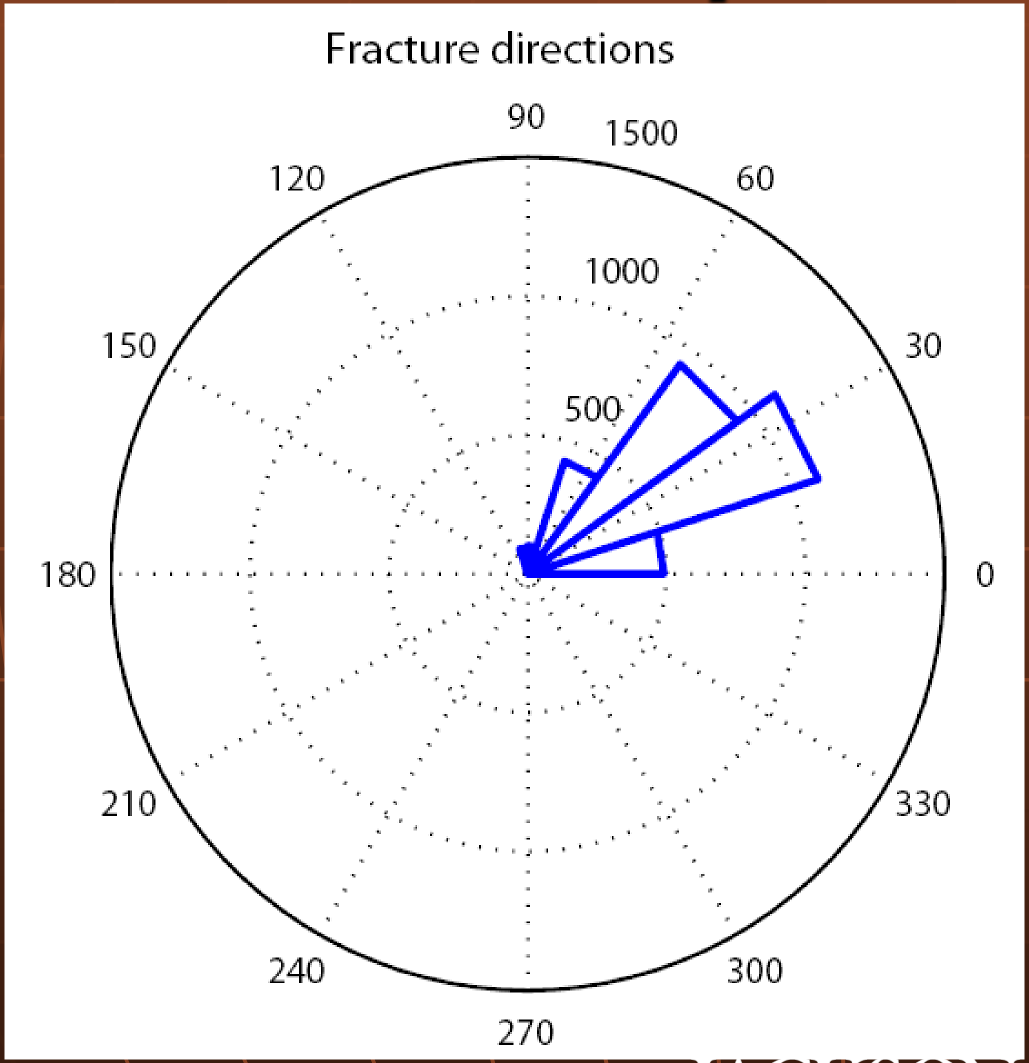

Rose plot indicates fractures incorporating the effect of anisotropy are oriented mostly around 30-60 degree from the inline. There is a group of fractures presents in 0 degree with the inline direction. That could be the result of dv=0.

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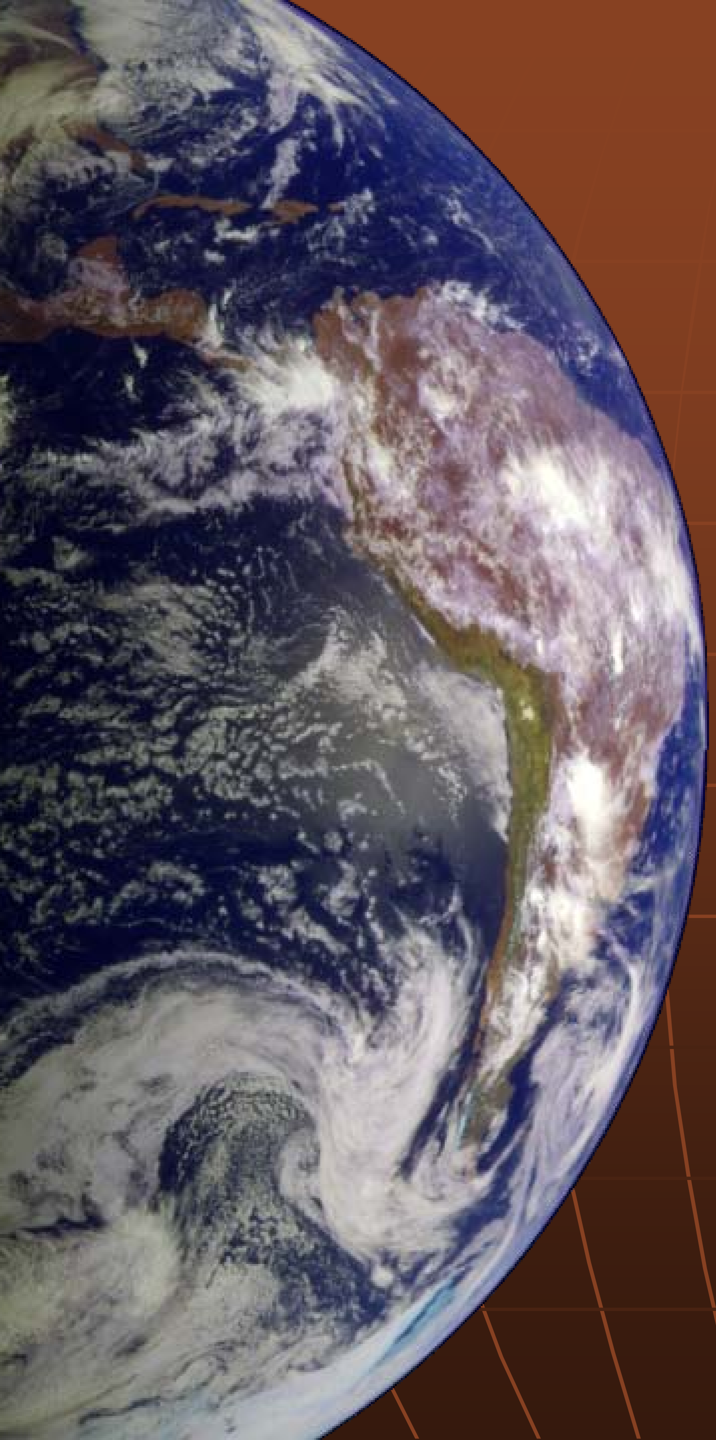

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Seismic Inversion for Acoustic Impedance , Poisson's ratio, and density

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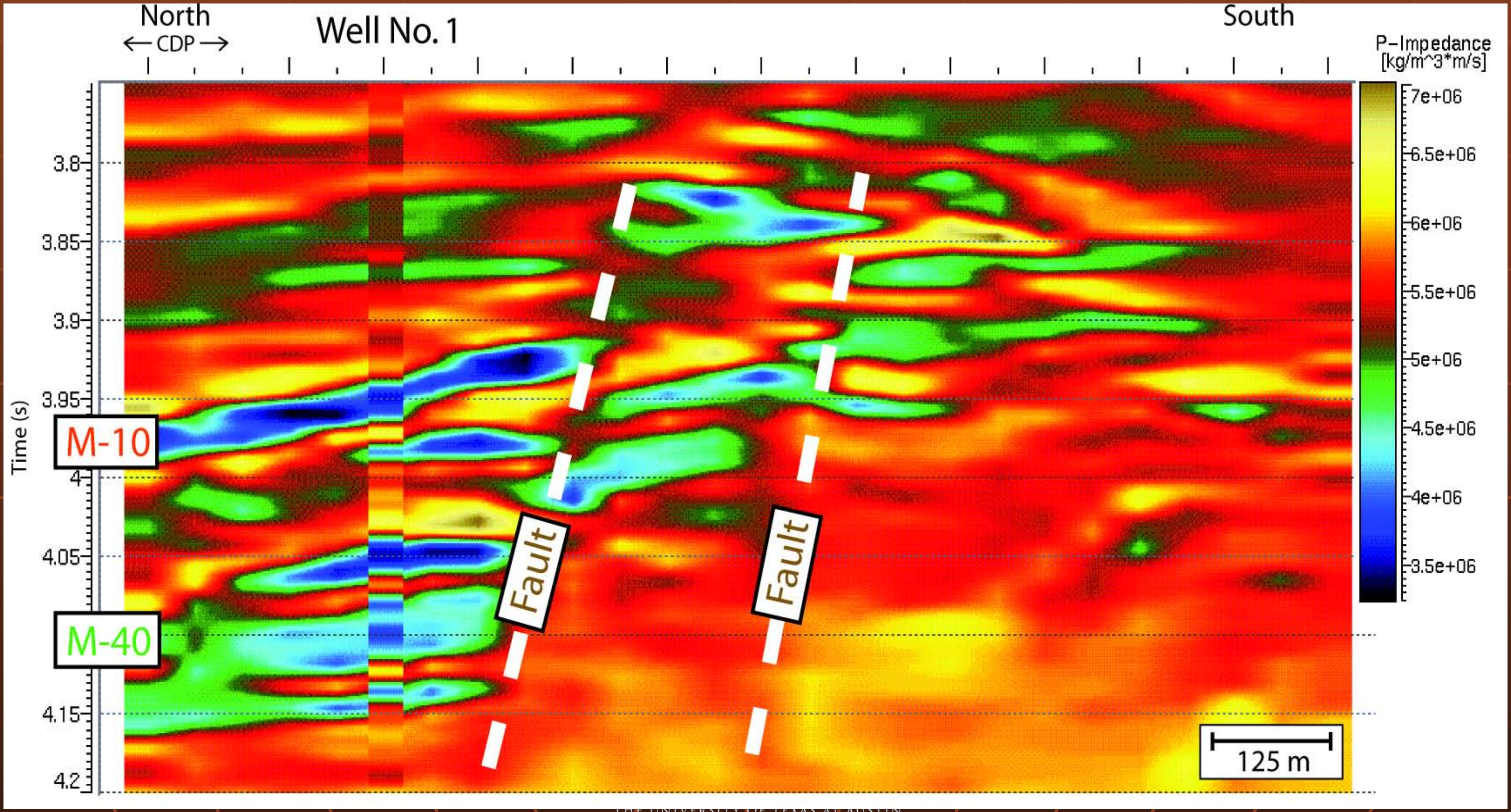
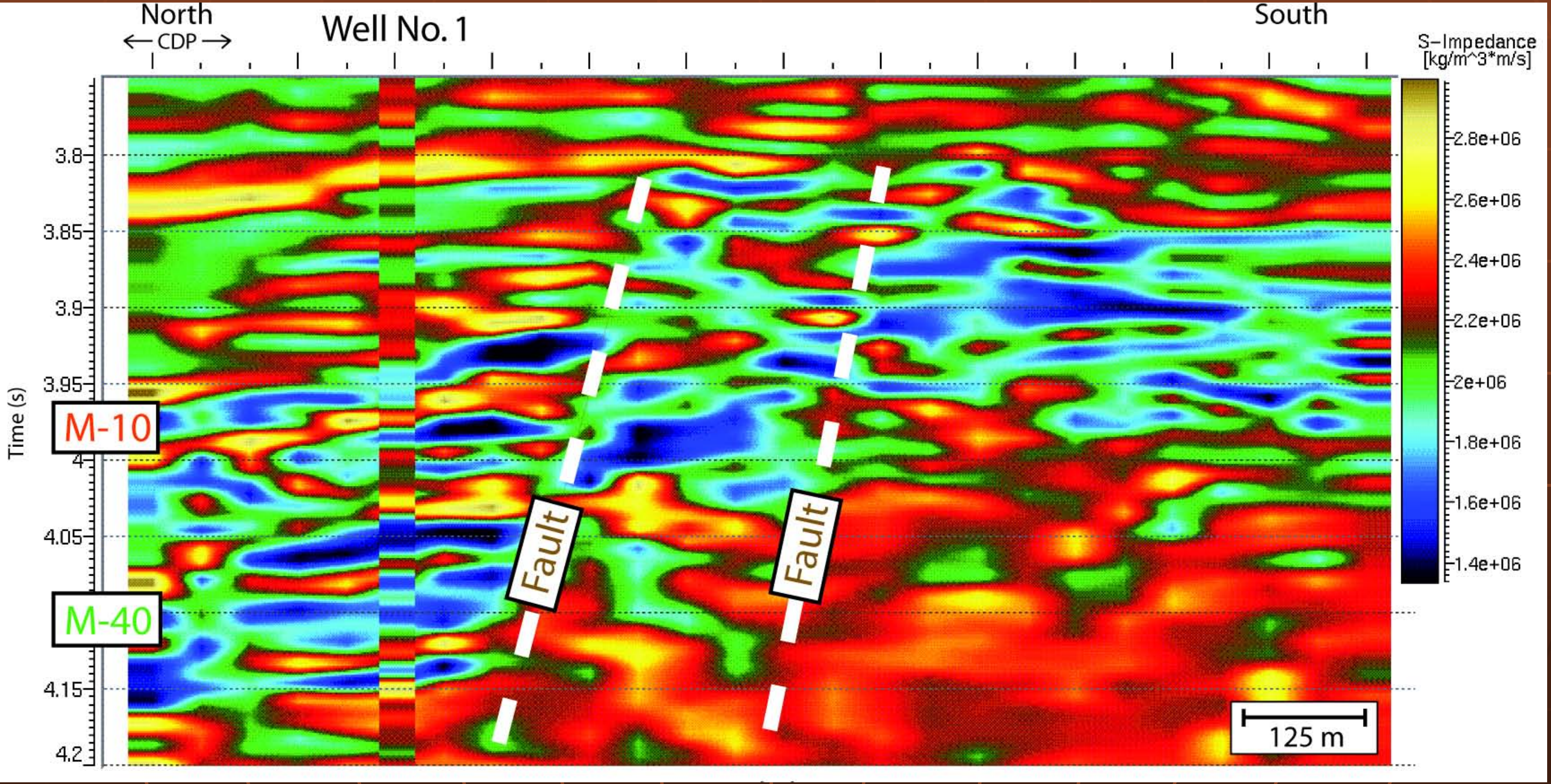
Estimated P-Impedance



Estimated S-Impedance



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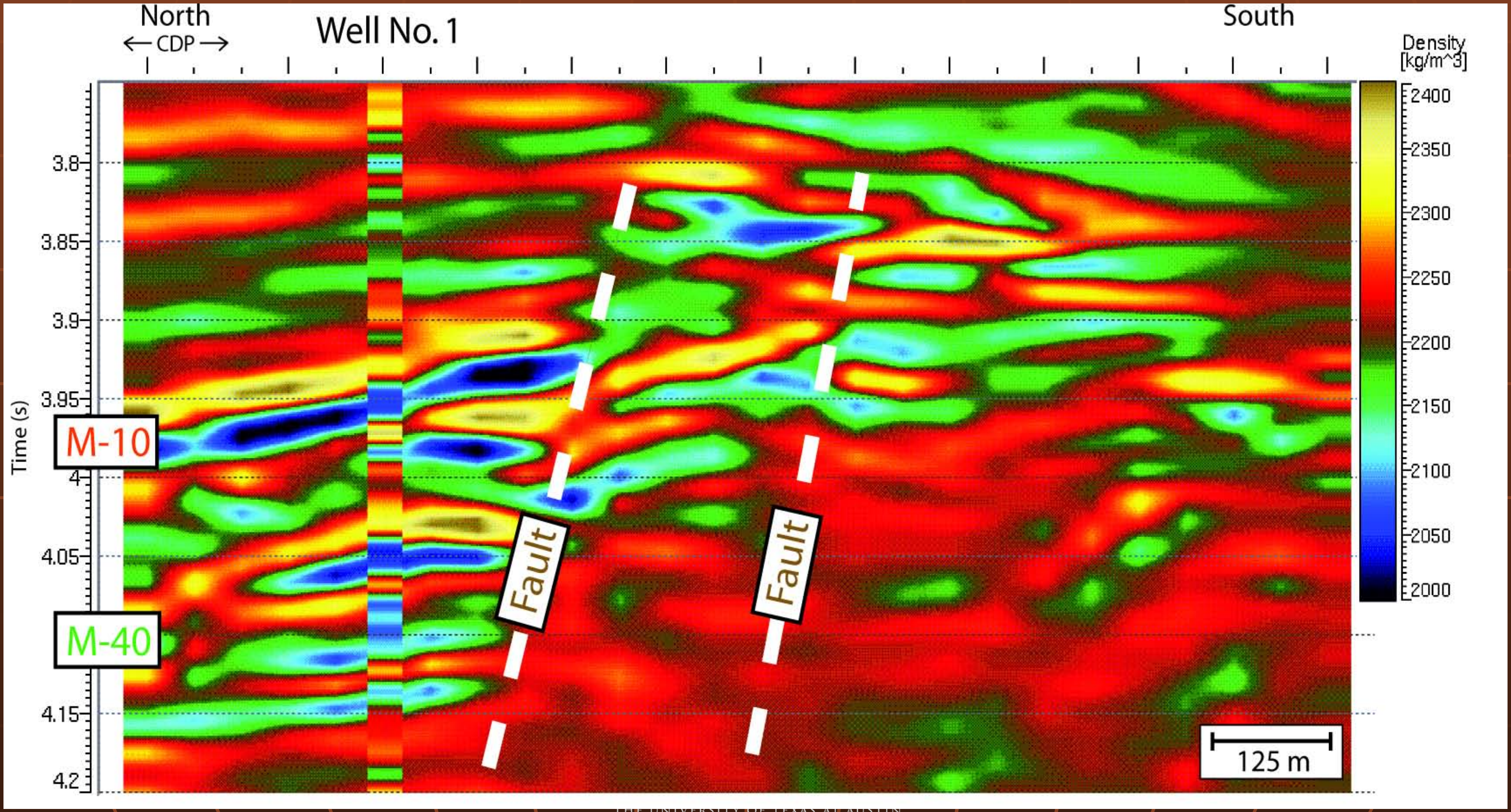
Pre-Stack Full waveform Inversion Estimated Density



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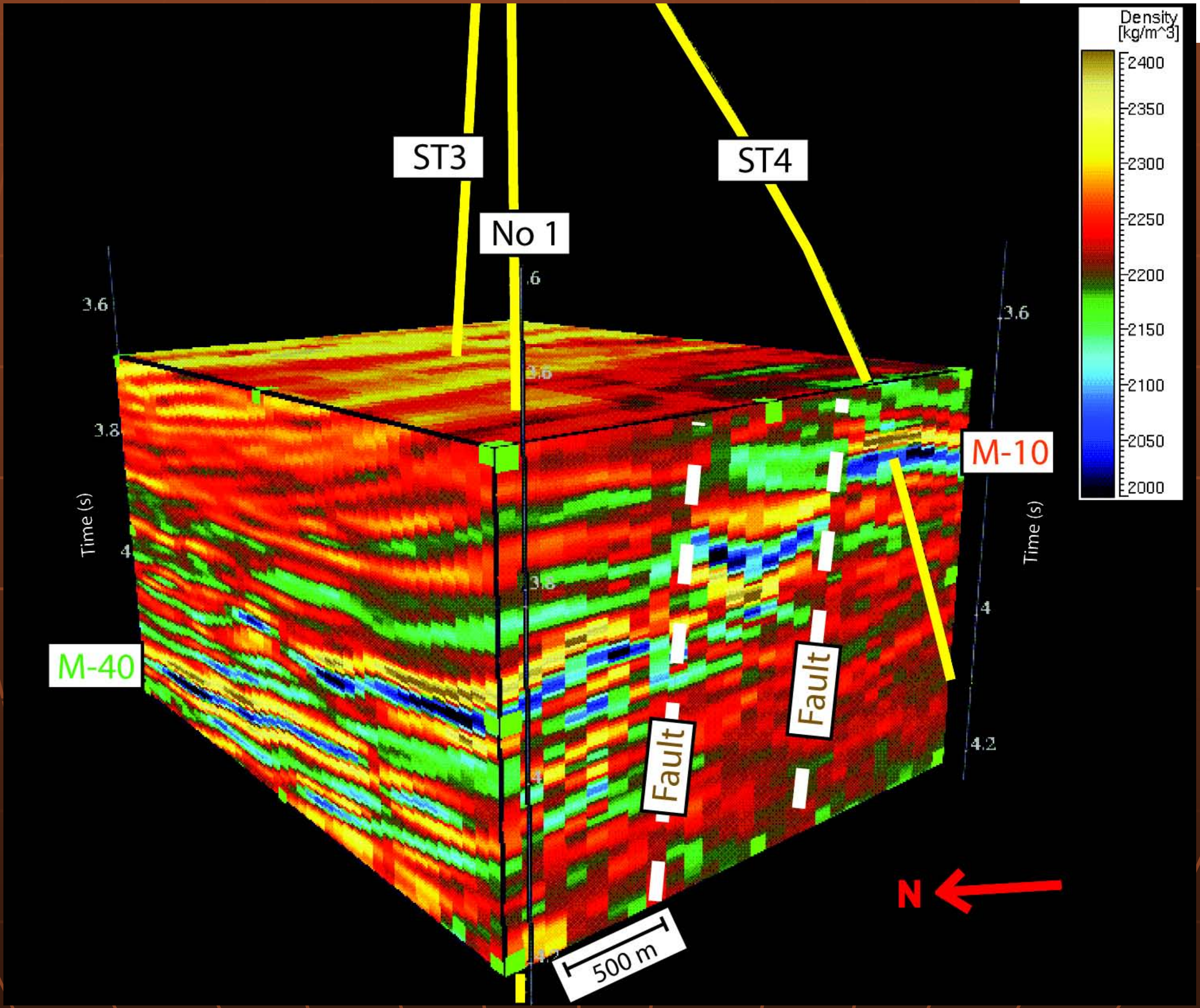
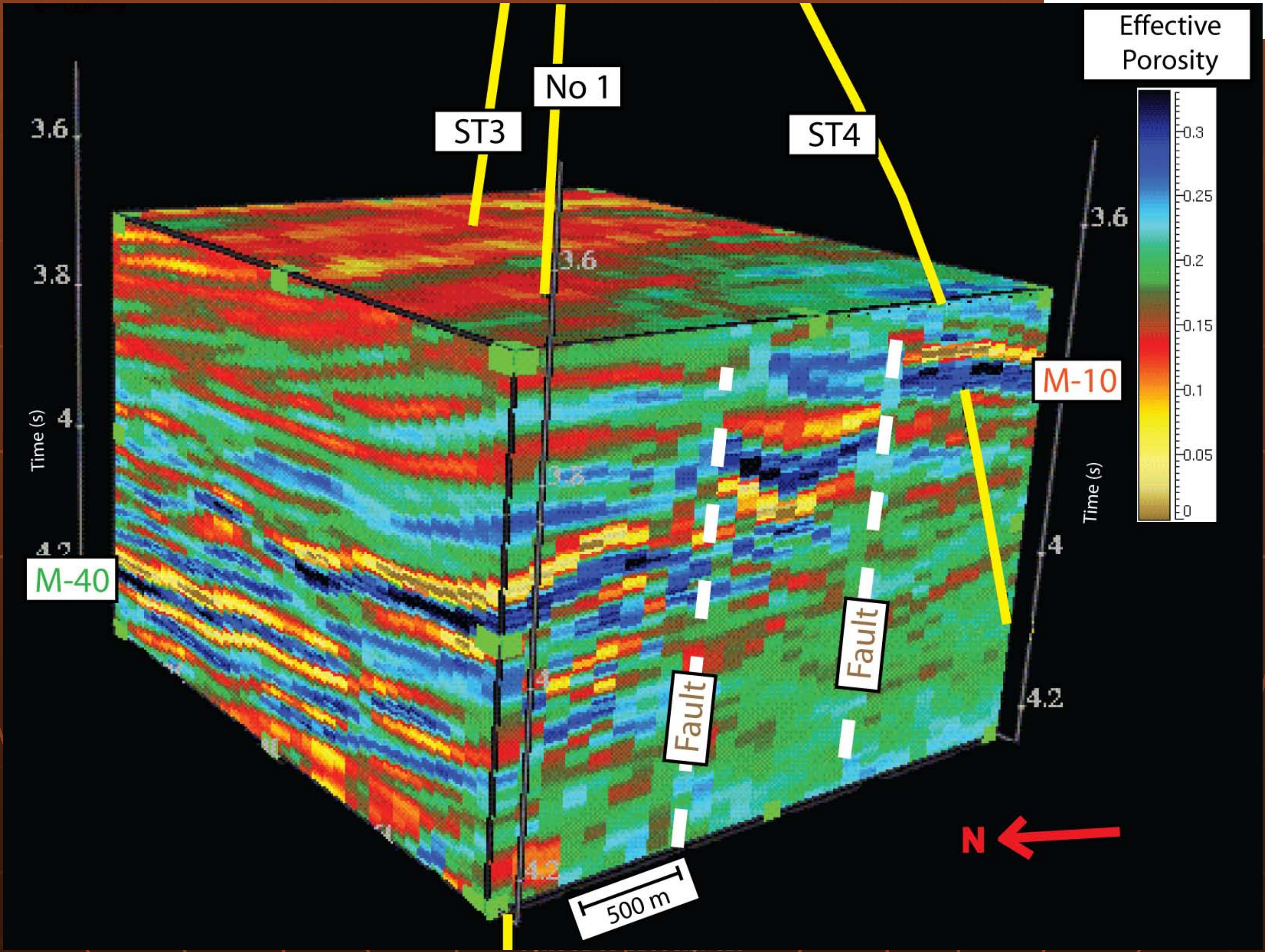
Pre-Stack Estimated Density



Pre-Stack Estimated Porosity



Acoustic Impedance and Poisson's ratio map derived from seismic inversion (Roy and Sen)

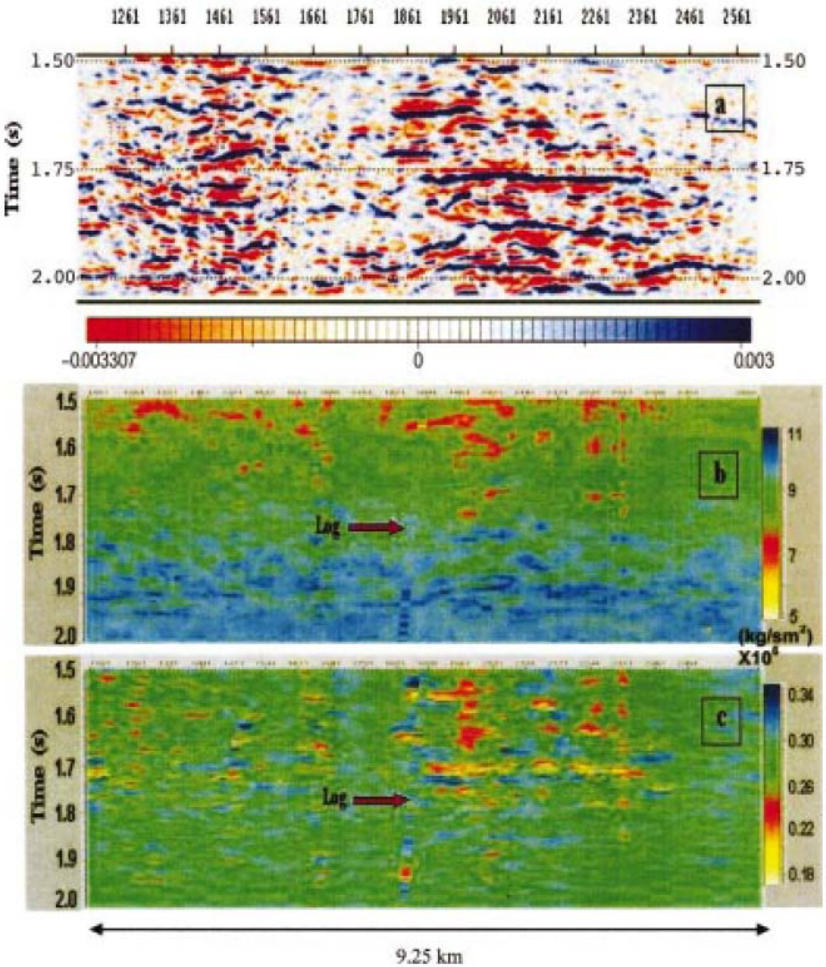


Figure 8. (a) Stacked seismic section for entire seismic line (CMP 1161 to CMP 2601) within a time window of 1.5–2.0 s. Blue color denotes positive amplitude, red denotes negative amplitude. Several anomalous zones are identified in (b) the acoustic impedance and (c) the Poisson's ratio.

These methods will be extended to fractured media

Integrate of seismic derived sweet spots with well data