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Distinguished Lecturer Program

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Shale Sweet Spot Detection with Surface Seismic

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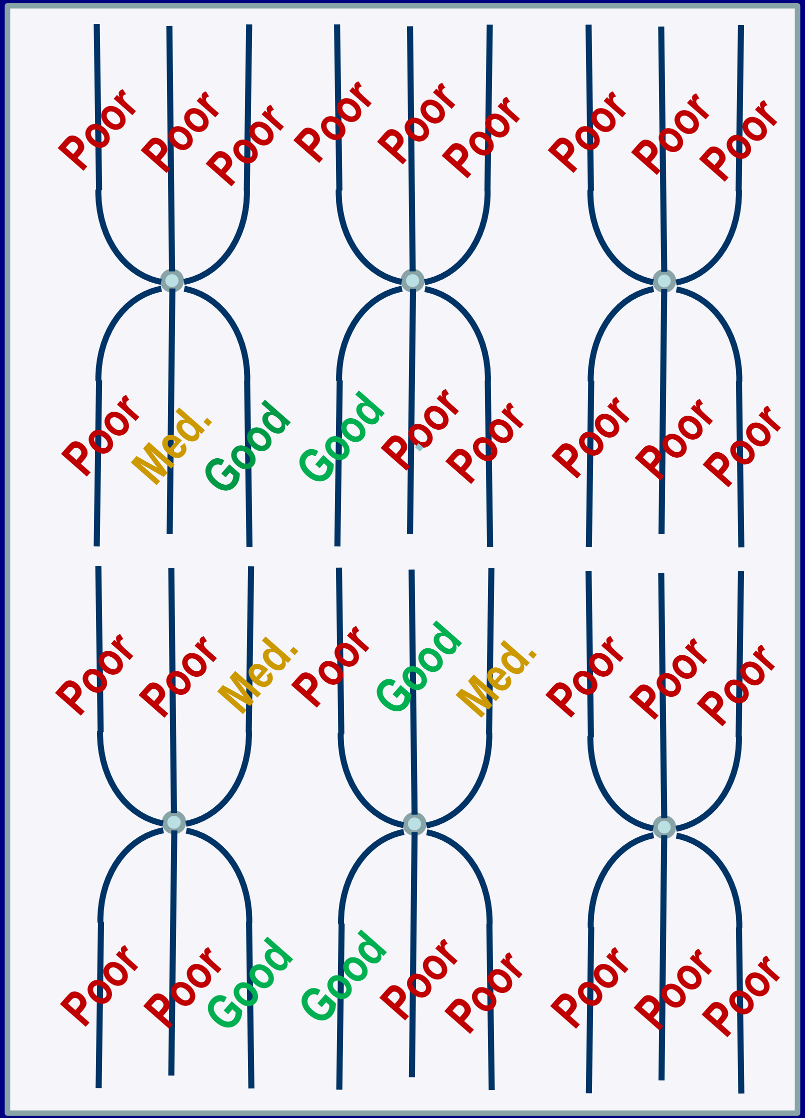
Presentation Outline

- Shale Production Sweet Spots - Do They Exist?
- Statistical Drilling Versus Sweet Spot Drilling
- “Basin Scale Sweet Spots” in Shale Plays
- “Local Reservoir Quality Sweet Spots”
  - High TOC and Porosity
  - Open Natural Fractures Systems
- Effects of Reservoir Quality Sweet Spots on Seismic
- “Completion Sweet Spots”
- Summary

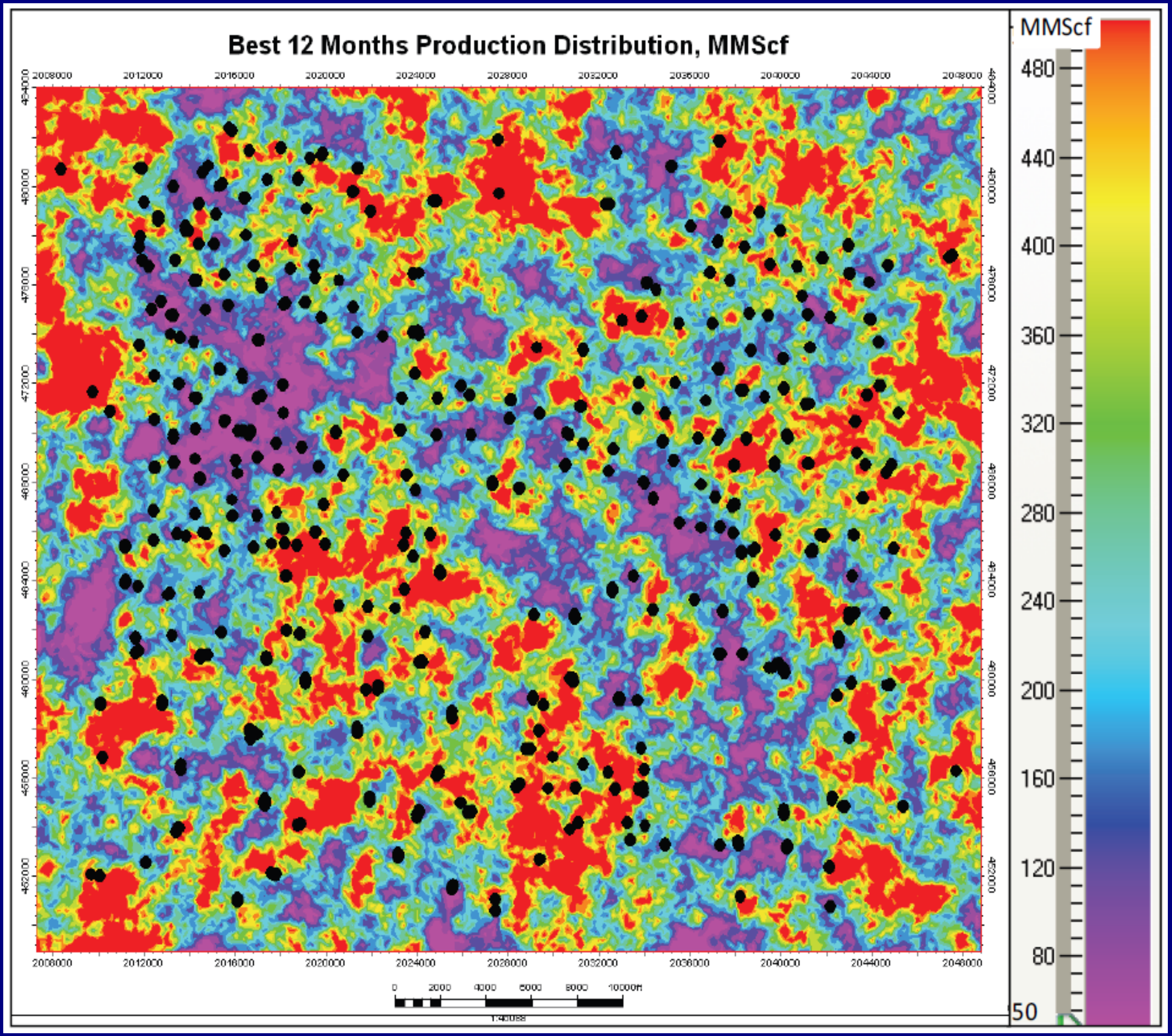
"Sweet Spots" in Shale Reservoirs

- Early in the modern "shale boom" many shales were drilled "Statistical Drilling".
- For this a large number of horizontal boreholes are drilled across an area using same pattern and completion methods.
- This often results in a many poor producers and only few good producers.



Example of Production Sweet Spots – Barnett Shale

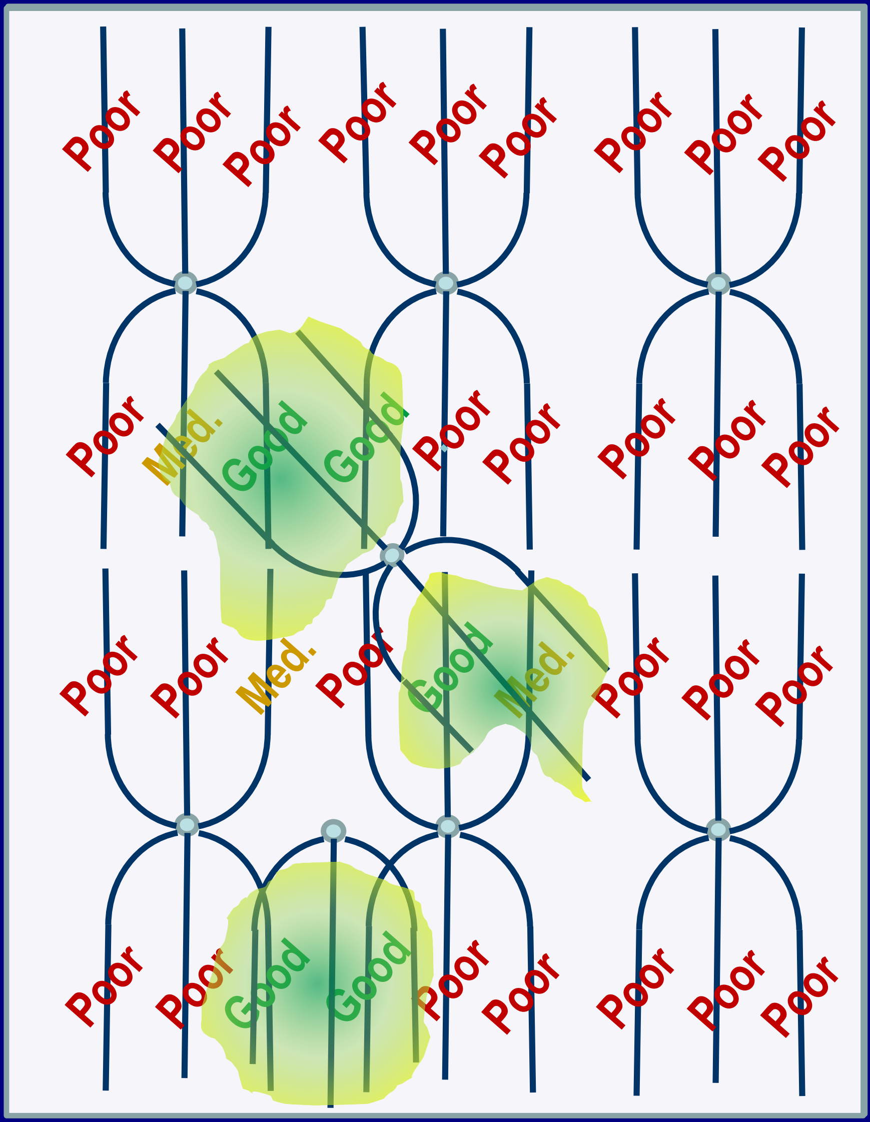
- Scale = 50 to 500 MMcf
- In many cases the extremes are as close as only 1 well location away!
- Ten fold variance observed in production.
- Clearly "sweet spots" do exist.



Source: Baihly, 2010, SPE paper 138427

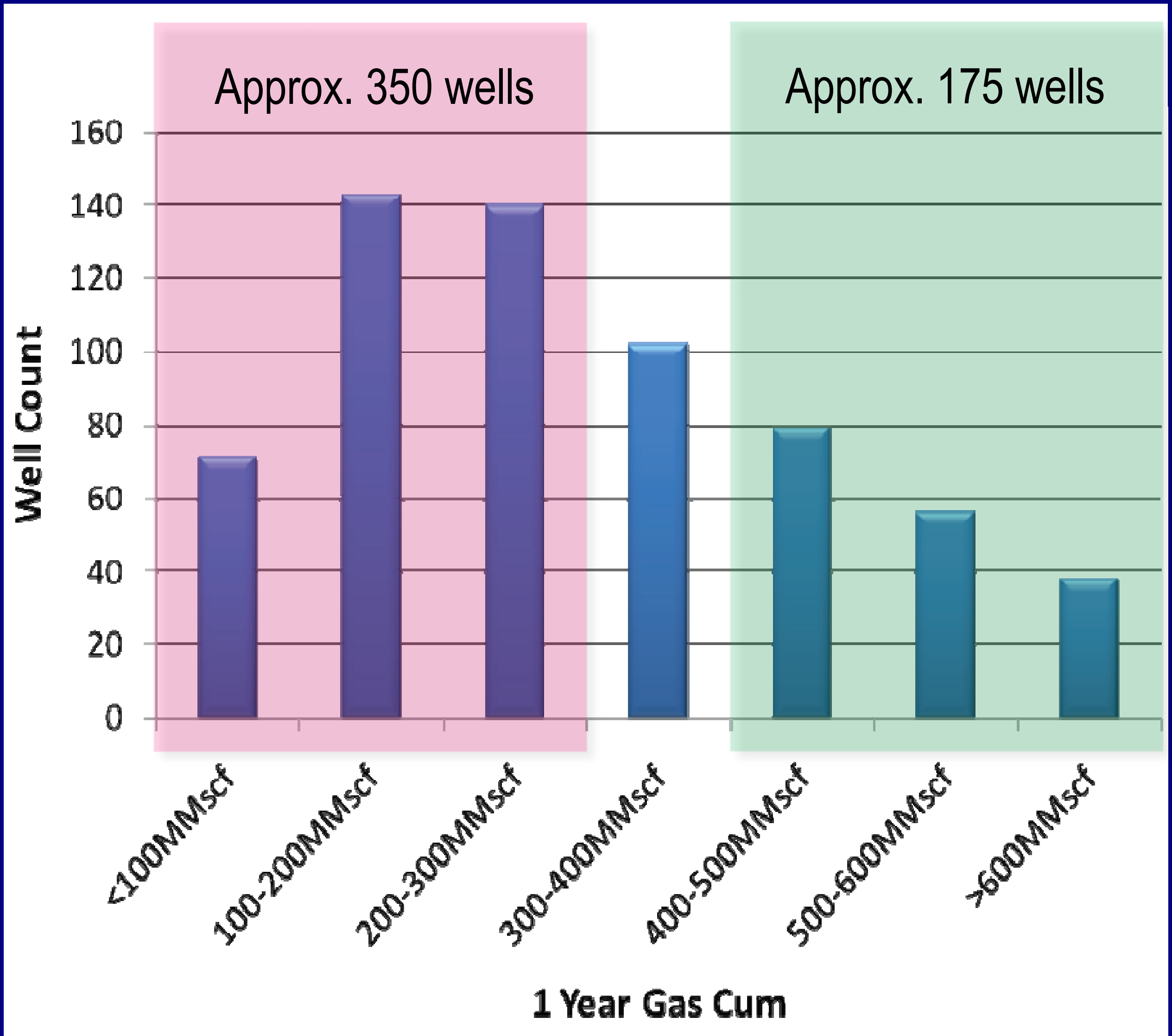
“Sweet Spot” Detection and Drilling

- In “statistical drilling” wells are often drilled without considering geology.
- Years of production showed that “Sweet Spots” existed in these reservoirs.
- If these can be found prior to drilling they can be specifically targeted.
- This would dramatically increase the play’s profitability.



Example of Production Sweet Spots – Barnett Shale

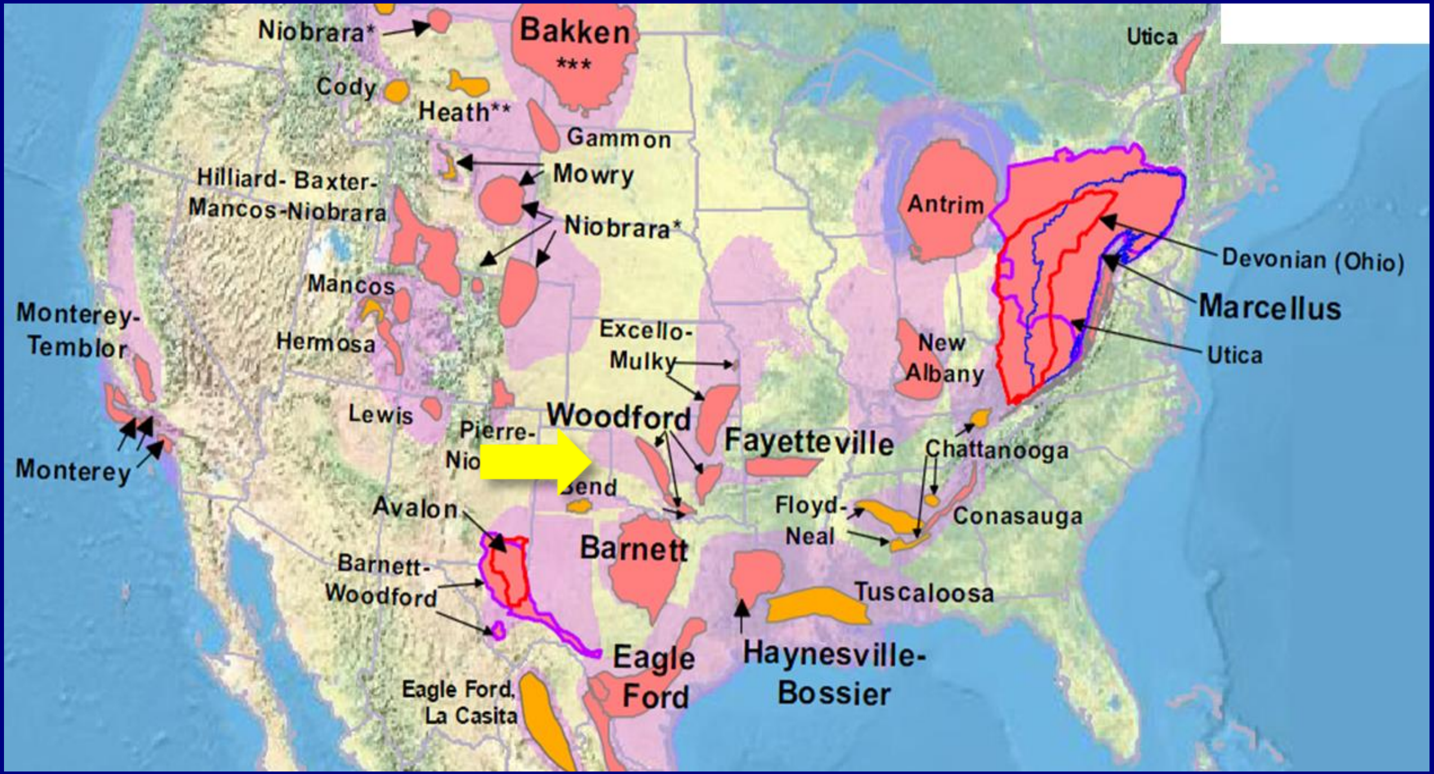
- A significant number of wells drilled in the lower performing portion of the reservoir.
- Smaller group of wells drilled in the higher performing portion of the reservoir.



Source: Baihly, 2010, SPE paper 138427

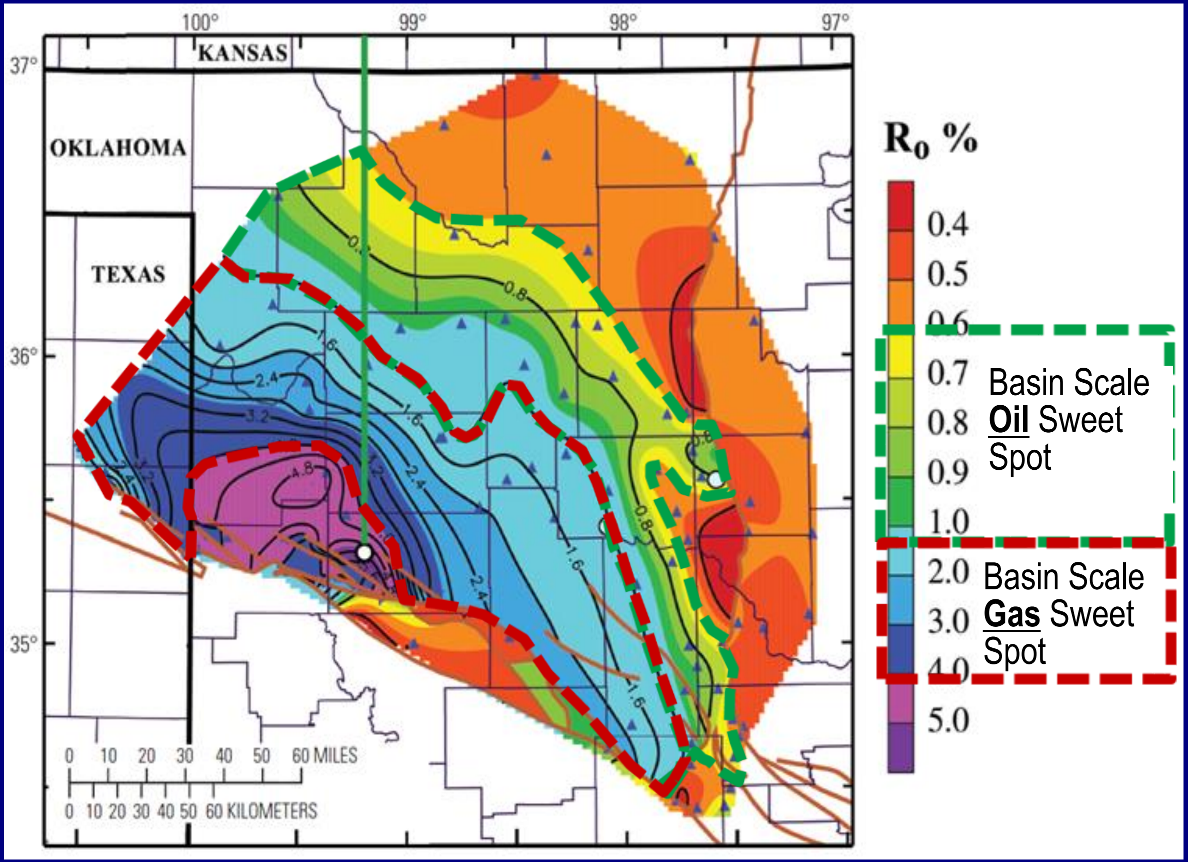
“Basin Scales Sweet Spots”

- Shale formations may cover an entire basin, however, the shale may be thermal mature only in a portion of that basin.



“Basin-Scales Sweet Spots” in Shale Plays

- Shale formations may cover an entire basin, however, the shale may be thermal mature only in a portion of that basin.
- Before drilling throughout the basin these “Basin scale sweet spots” can only be found with basin modeling.
- 2D seismic interpretation supports this.

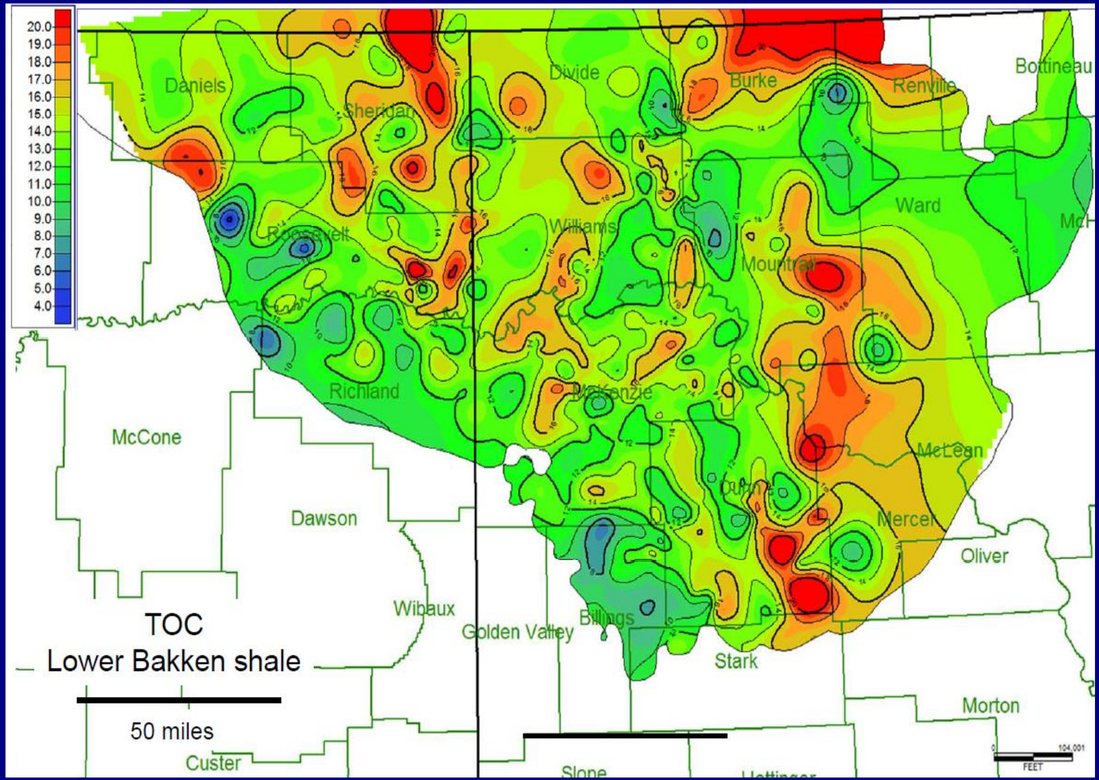


Source: Higley, 2011, USGS Open-File Report 2011–1242

"Local Sweet Spots" in Shale Reservoirs

- "Local Sweet Spots are locations within shale formations containing high amounts of TOC and system porosity and permeability.

Bakken example of TOC mapping

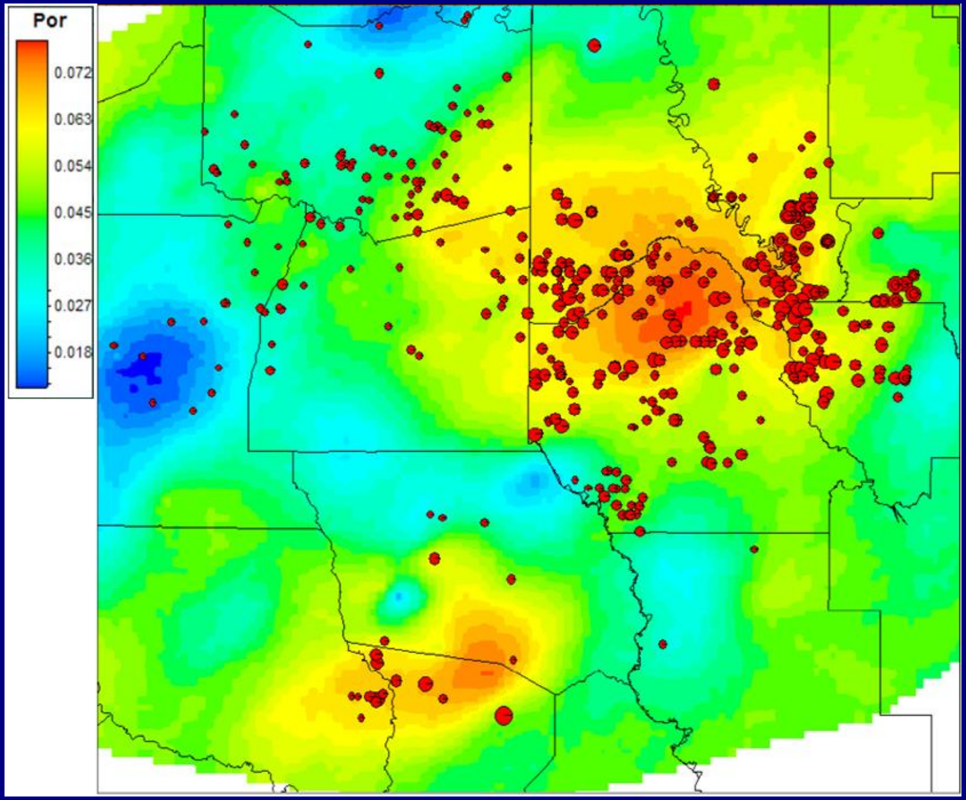


Source: Hui Jin, 2012, Search and Discovery Article #20156

"Local Sweet Spots" in Shale Reservoirs

- "Local Sweet Spots are locations within shale formations containing high amounts of TOC and system porosity and permeability.
- Haynesville shale porosity map indicates the best producers occur where the shale has high porosity.
- However, matrix porosity and permeability are only part of system porosity.
- Open, natural fractures are also part of the reservoir's system permeability.

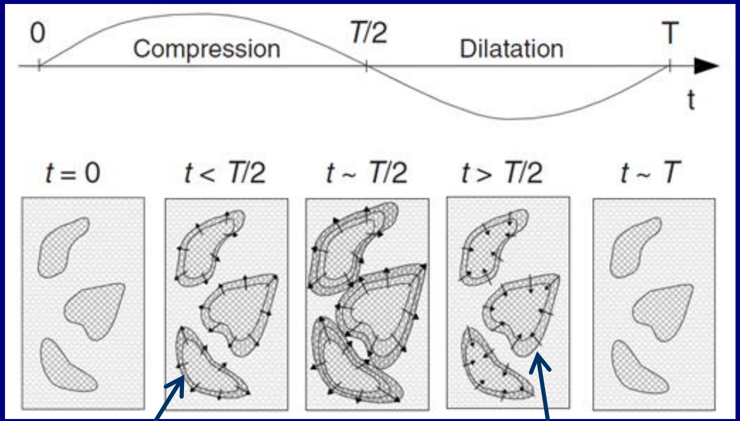
Haynesville example of porosity mapping



Source: Thompson, 2010, CSUG/SPE 136875

Seismic Compressional Wavelet Induced Fluid Flow

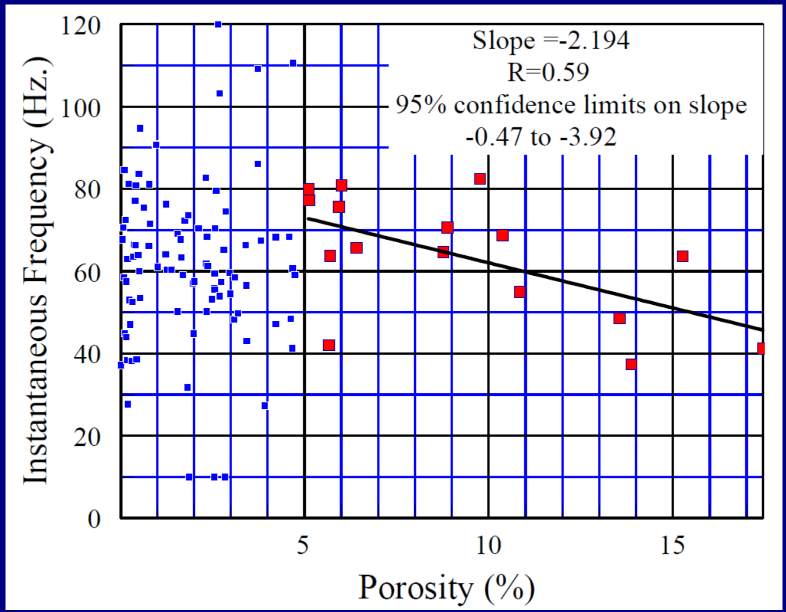
- In the mid-1950s Biot established that frequency attenuation could be caused by fluid movement in permeable systems.
- High porous / permeable rocks can attenuate higher seismic frequencies.
- This leaves a strong low frequency component in the seismic signal.



Fluid movement out elastically soft zones during compression.

Fluid movement back into these zones during relaxation.

Source: Müller, 2010

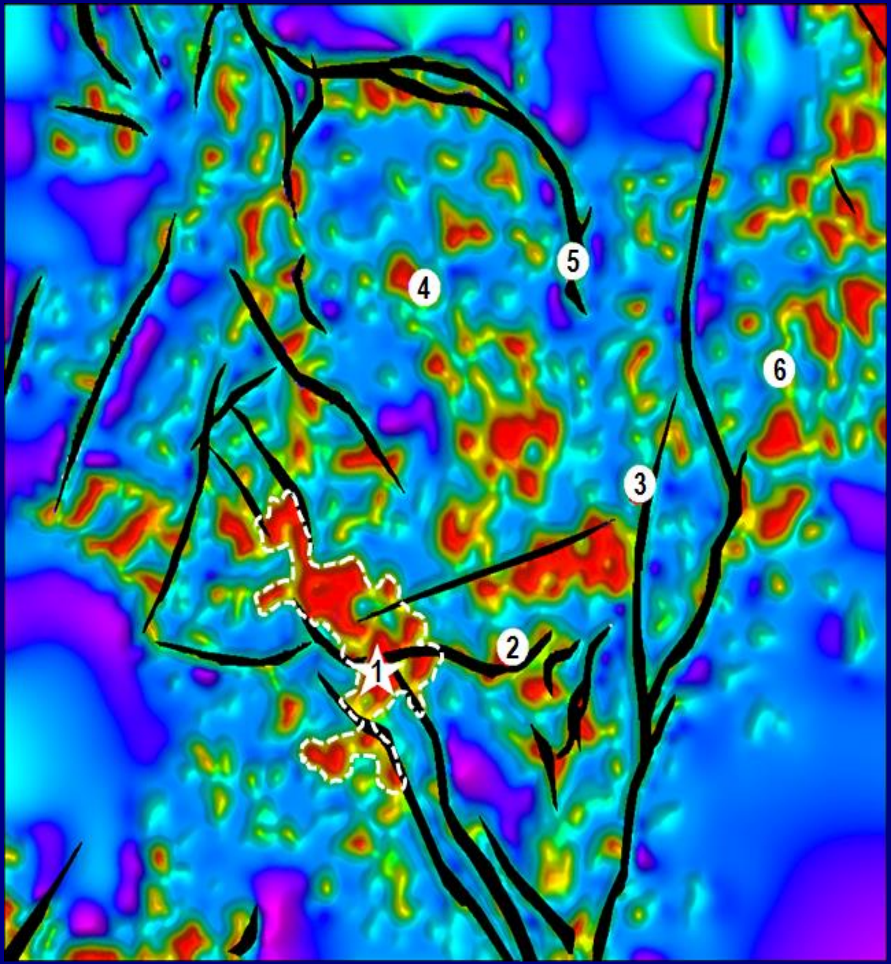


Source: Toelle, 2012., Ph.D Dissertation

Early Application in Shale Reservoirs

- 6 vertical producers from the Woodford Shale, Arkoma Basin.

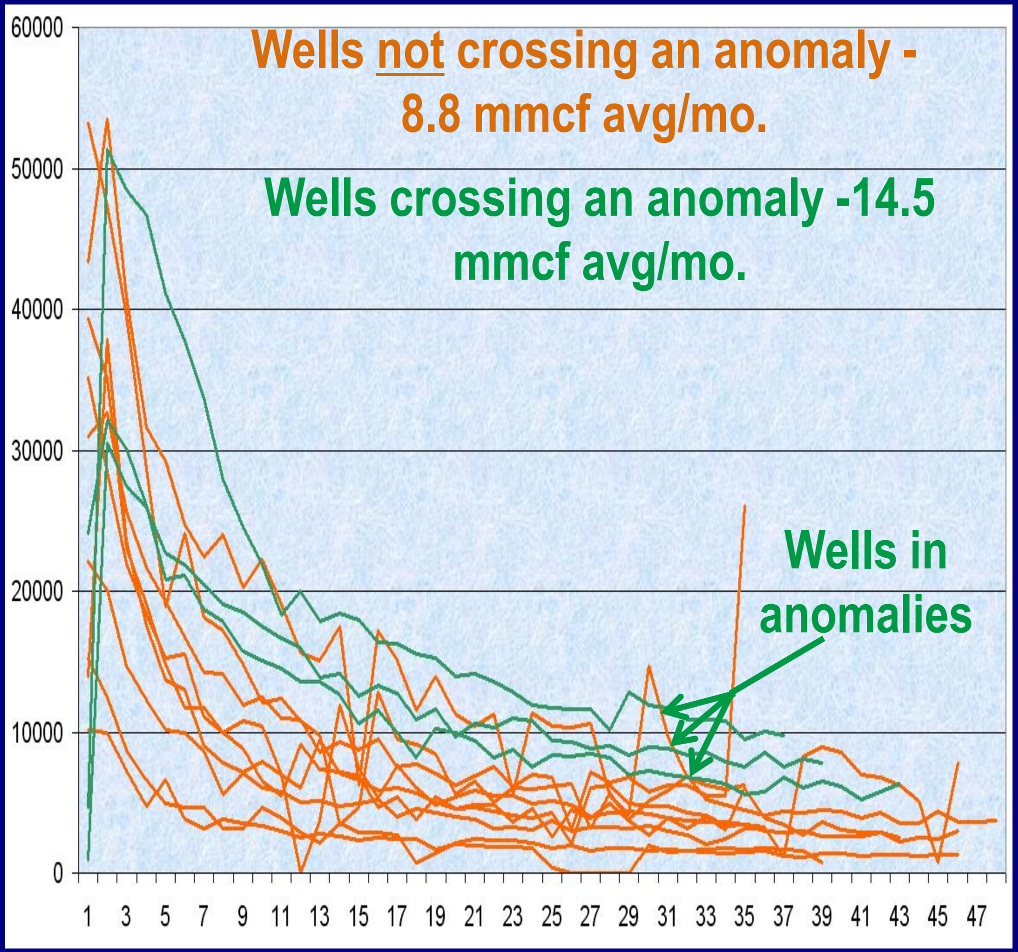
- All wells came "on-line" at approximately the same time.
- The poorest producers are outside of the frequency anomalies.
- The best well (1) inside a frequency anomaly, produced approximately 9 times average of the other 5 wells.



Source: Toelle, 2008, West Virginia IOGA

Early Application in Shale Reservoirs

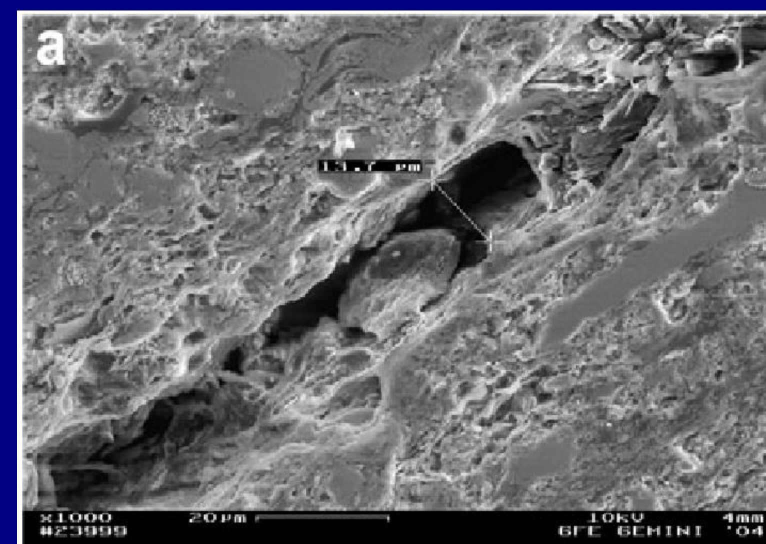
- 6 frequency attenuation anomalies were detected.
- Wells with significantly more fractures on image logs occur in association with frequency anomalies.
- Horizontal boreholes crossing frequency anomalies have the best production.



Source: Toelle, 2009, New York IOGA

Generation of Natural Fractures

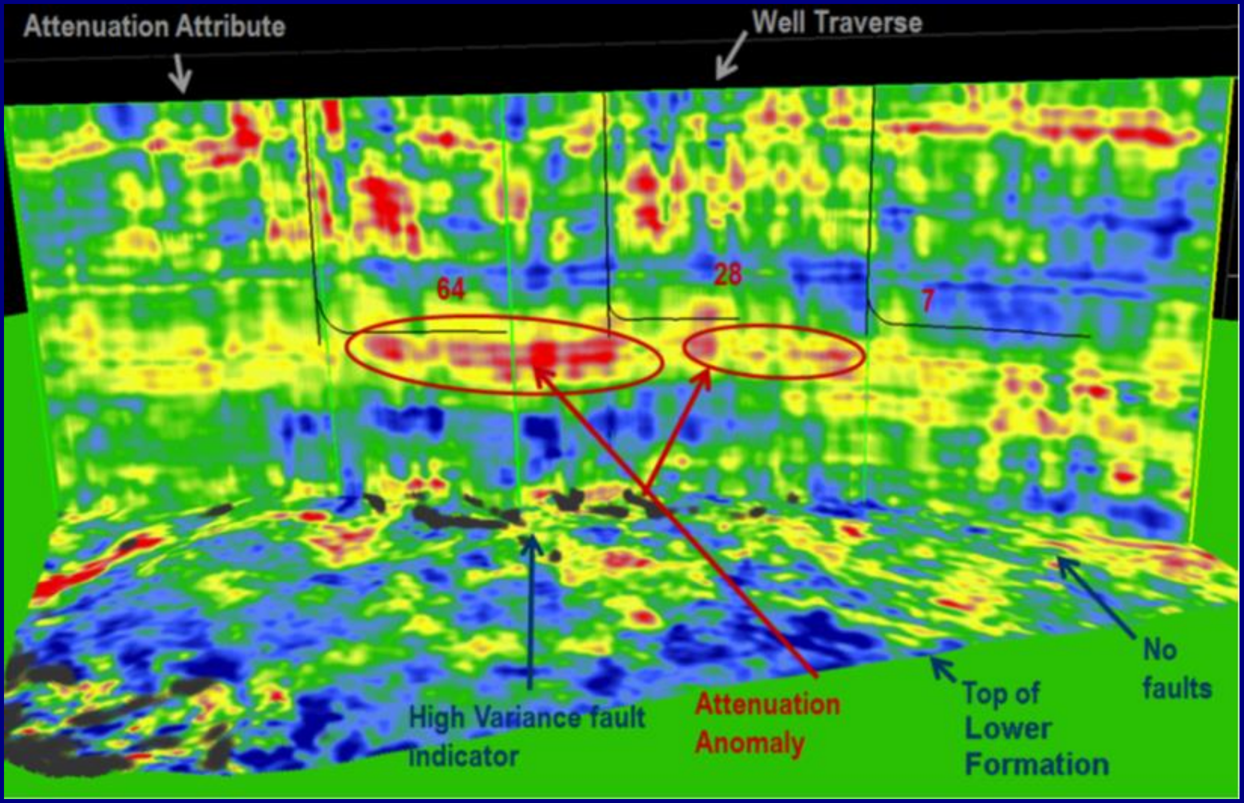
- Tectonics
- Dehydration
- Devolatilization
- Exhumation
- Natural hydraulic fracturing
- Posidonia Shale - “Based on flow rates, flux, optical evidence, porosity in the oil window, capillary displacement of water-saturated pores and the existence of transport porosity in mudstones, primary migration dominantly occurs through fracture porosity”.



Source: Eseme , Marine and Petroleum Geology 31 (2012) 110-124

Shale Reservoir Quality Sweet Spot

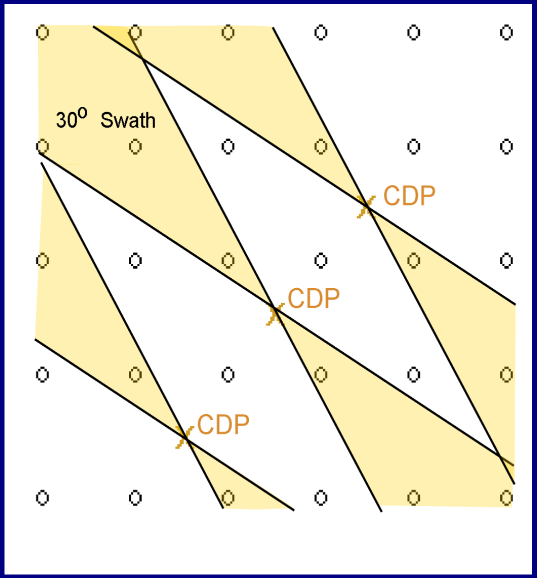
- Shale formation in Delaware Basin being developed.
- Random line through 3D surface seismic attribute – frequency attenuation.
- 3 wells along random line.
- Monthly avg. production shown in red text.
- Best prod. where attenuation anomalies occur.

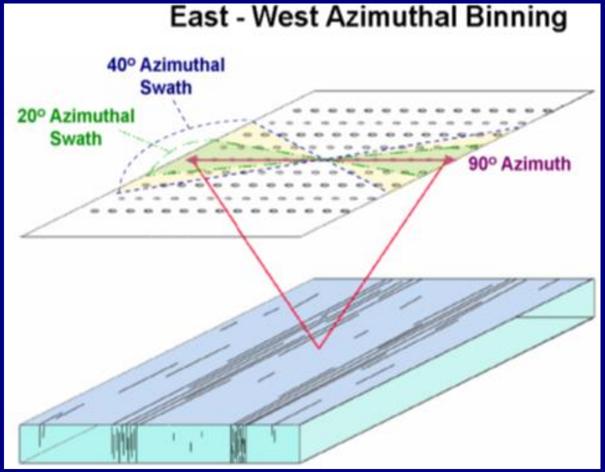


Monthly avg. gas production (red text) in mmcf..

Azimuthal Seismic-Based Fracture Detection Methods

- 3D azimuthal seismic volumes are created by "stacking" the data directionally.
- These can be used to identify anisotropy produced by open fracture trends.
- A number of azimuthal seismic interpretation methods have been demonstrated detect open natural fractures.
    - Amplitude versus Azimuth (AVAZ)
    - Azimuthal Velocity (VVAZ)
    - AVOaz Inversion (Azimuthal Prestack Inversion)

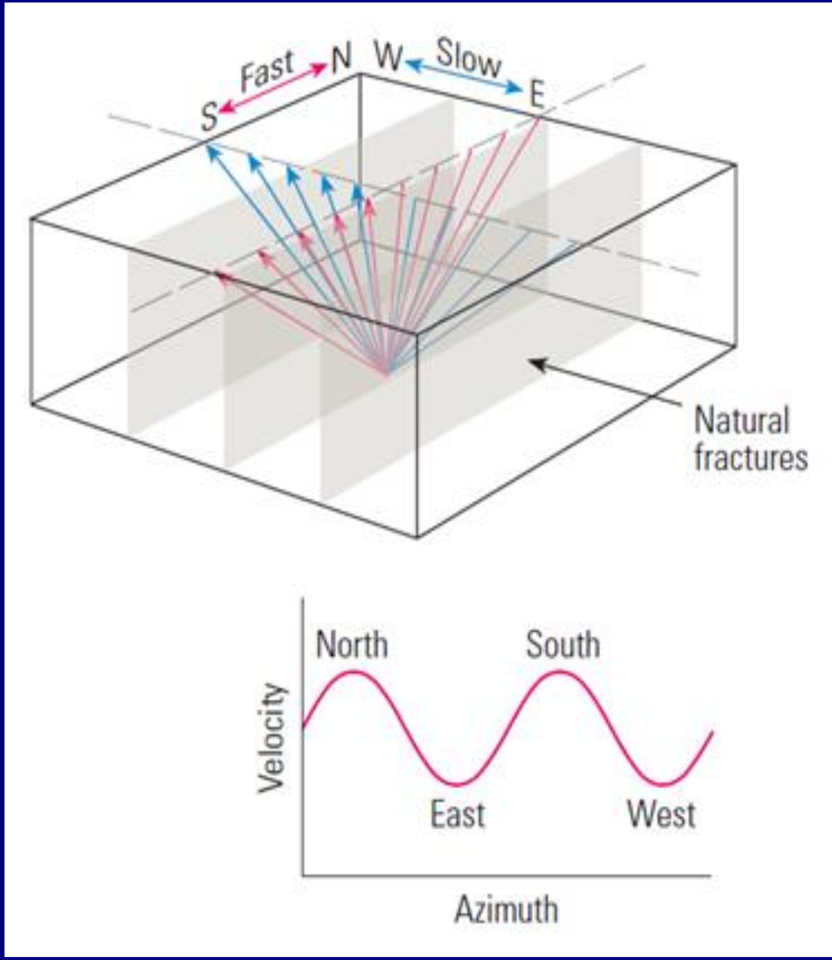




Source: Toelle, 2012, PhD research

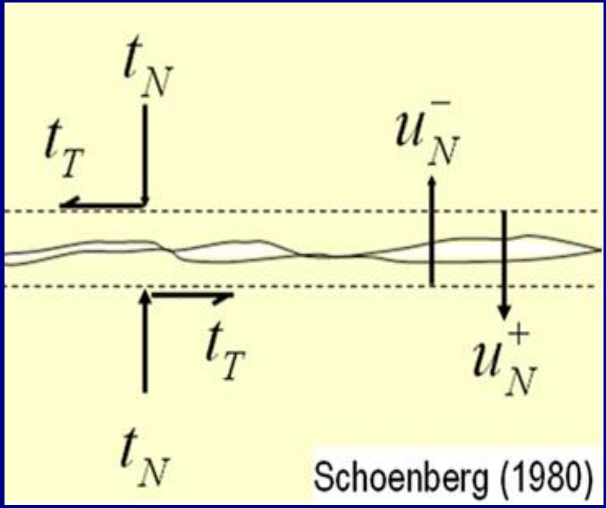
Shear Wave Birefringence

- Linear, open fracture trends cause shear wave birefringence.
- This is detectable with azimuthal P-wave seismic volumes.
- These are inverted and used to determine the amount of shear wave anisotropy.
- The slow shear direction is perpendicular to the open fracture trends.



Type of Reservoir Quality Sweet Spot and Their Effect of Natural Fractures on Seismic

- Three types of Reservoir Quality Sweet Spots can be located with surface seismic.
  - Zones of high porosity (increased Free Gas) – indicated by decrease in amplitude and velocity and increased attenuation of high frequencies.
  - Zones of higher TOC (increased Adsorbed Gas) – Same affects but to a lesser degree.
  - Zone of increased microfractures – Same affects as high porosity but directional in nature.
  - Note only microfractures increase system permeability.

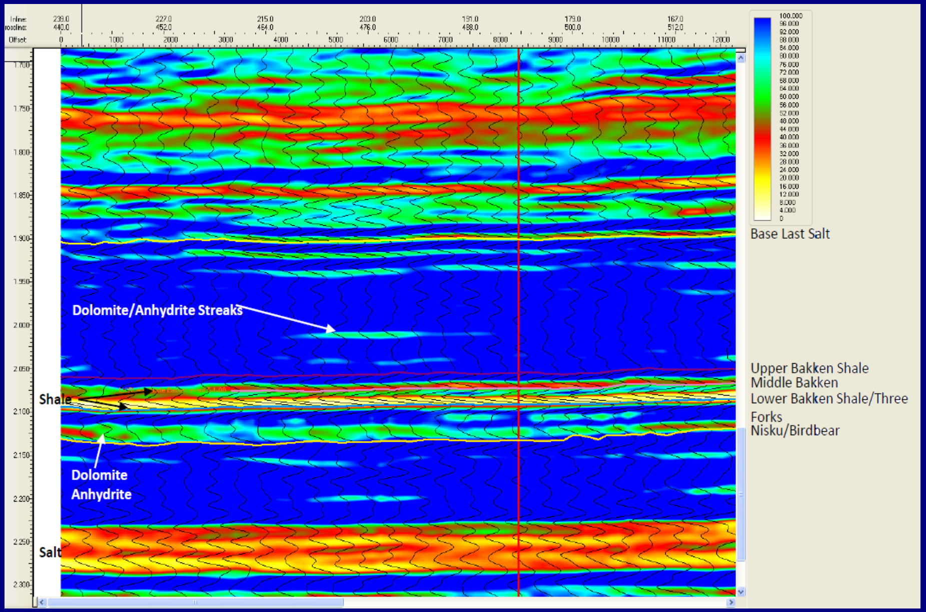


Pre-Stack (AVO) Inversion

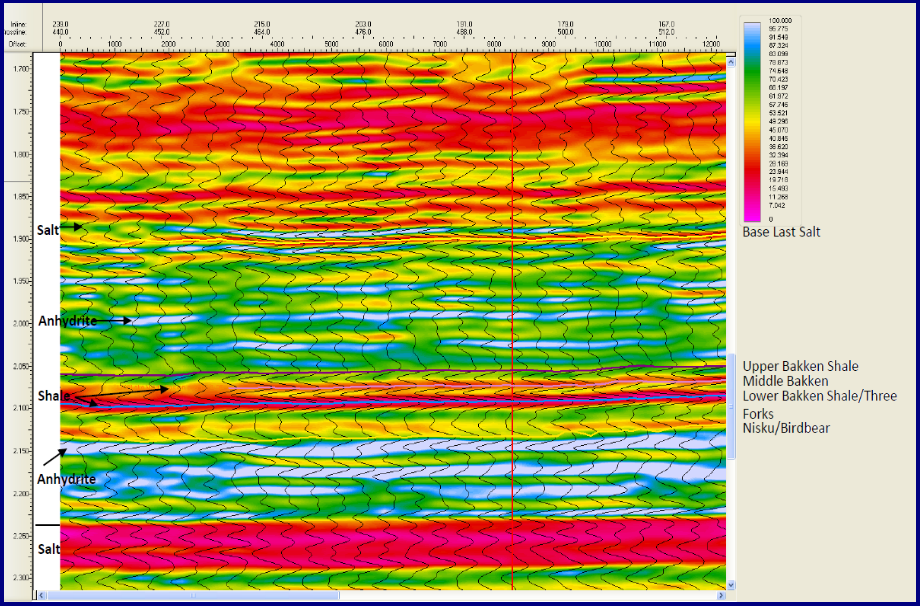
- In 1997, Goodway, et al. published a paper on an AVO inversion method based on Lamé's parameters (rock physics descriptors). This method is known as Lambda-Mu-Rho, or simply "LMR".
- Lame's parameters can be viewed as
  - Lambda (λ) = incompressibility
  - Mu (μ) = rigidity
  - Rho = Density
- P-wave and S-wave reflectivities are compute from pre-stack data and are then inverted, using standard inversion techniques.
- P-impedance and S-impedance are then derived and estimates of the Lamé parameters made.

Pre-stack (AVO) Inversions

- Lambda-Rho (λ-ρ) Inversions are believed to be sensitive to rock "compressibility".

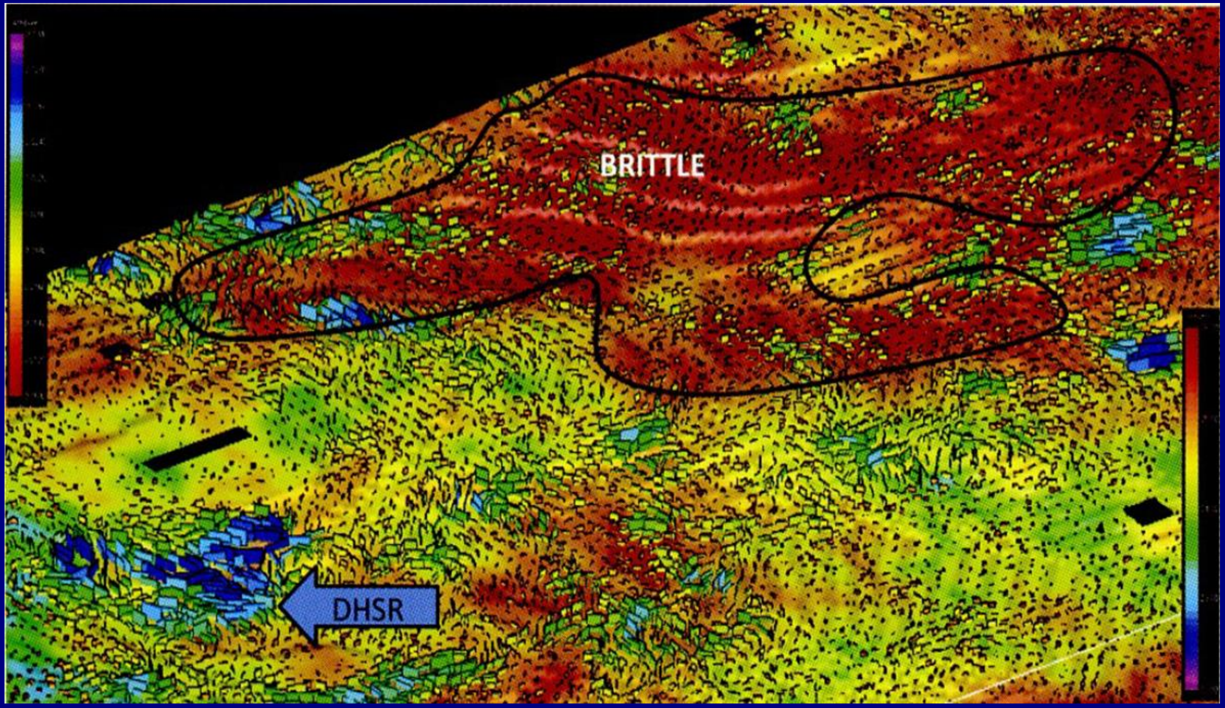


- Mu-Rho (μ-ρ) Inversions are believed to be sensitive to rock "rigidity".
- Rigidity in shale reservoirs has been shown to be related to completion quality.



Acoustic Impedance Inversions

- “Brittleness map” (in color) with stress direction shown as texture.
- Using these advanced inversion techniques the location of “completion sweet spots” can be detected.



DHSR = Differential Horizontal Stress Ratio

Young’s Modulus

Source: Castillo (2010)

Shale Sweet Spot Detection with Surface Seismic

- Two classes of Sweet Spots exist; “Basin-Scale” and “Local”.
- 2D seismic ➔ basin’s structural framework ➔ basin modeling ➔ Basin-Scale Sweet Spots.
- Local Sweet Spots occur in two types; “Reservoir-Quality” and “Completion Quality”.
- Local Reservoir Quality Sweet Spots are zones of greater TOC, porosity or microfractures.
- Only open natural fractures enhance a shale’s system permeability.
- Local Reservoir and Completion Quality Sweet Spots can be located with various 3D seismic analyses.

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