

Acoustics for Overburden Characterization: A North Sea Case Study

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Overburden Characterization in the Eldfisk Field

- Overview of the area
- Motivation
- Theory
- North Sea Case Study
- Conclusions

Case study presented at SPWLA 2011, 52nd Annual Symposium, Paper II:

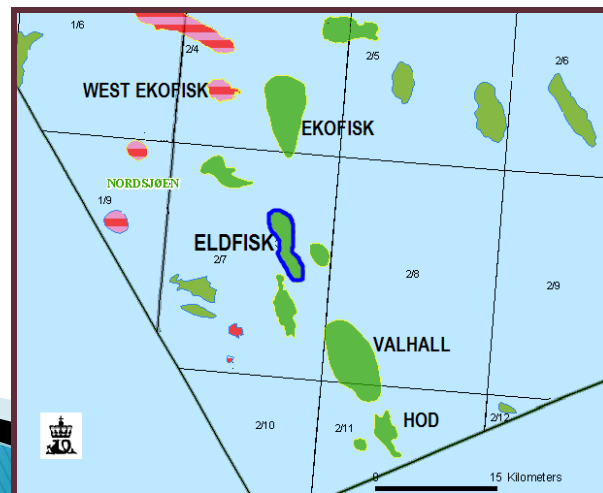
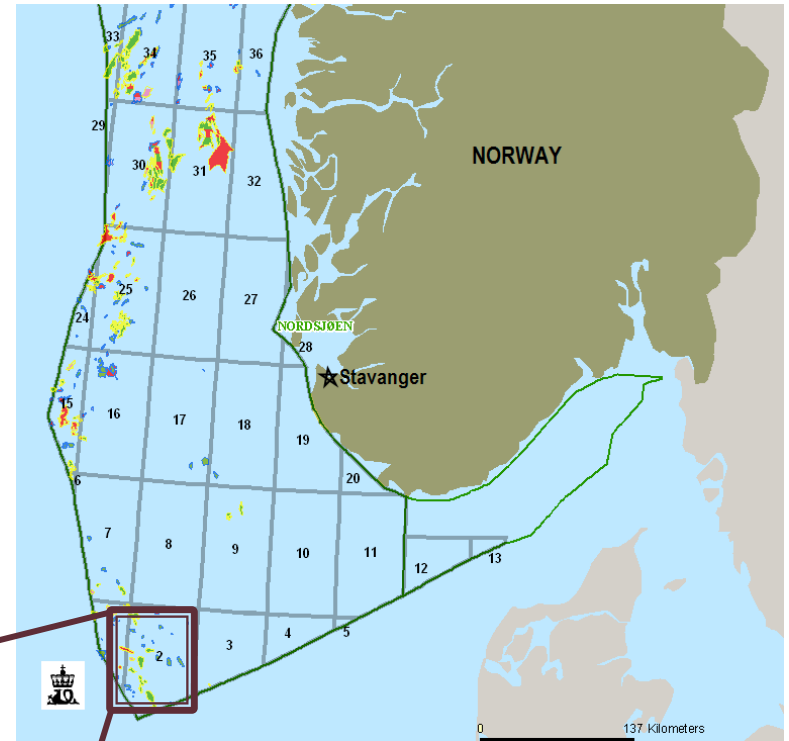
Overburden Characterization for Geomechanics and Geophysical Applications in the Eldfisk Field: A North Sea Case Study

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¹Schlumberger, ²ConocoPhillips

Introduction to the Eldfisk Field

- Overburden logging
- Traditional techniques
- Challenges
- Anisotropic techniques



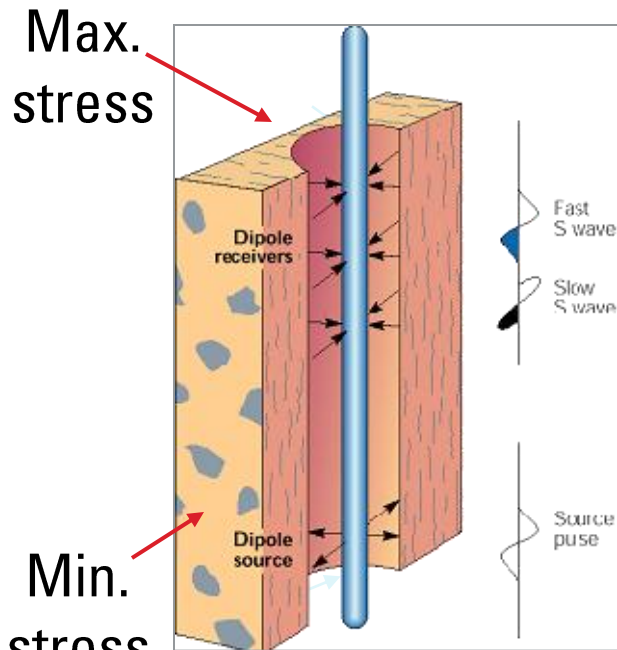
From Norwegian Petroleum Directorate

Motivation

- Obtain general geomechanical understanding of overburden
 - Mud weights, drilling speed
- Drilling challenges
 - High overburden pore pressure, low reservoir pore pressure
 - Small wellbore stability window in overburden
- Deviated wells
 - Need more than a robust model
- Developing predictive tools

Cross-Dipole Shear Anisotropy Mechanisms

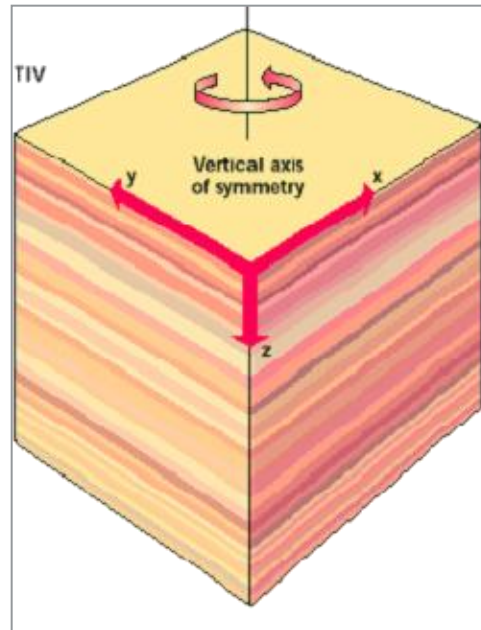
Stress-Induced



Stress

$$V_S(r, \theta)$$

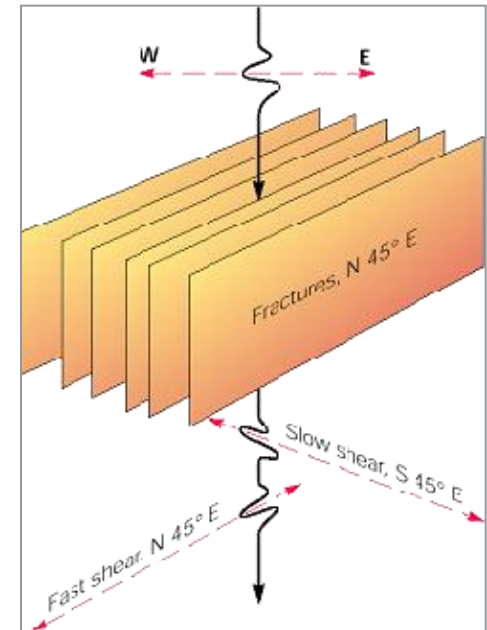
Intrinsic



Shales, bedding
(transverse isotropic vertical)

$$V_S(\theta)$$

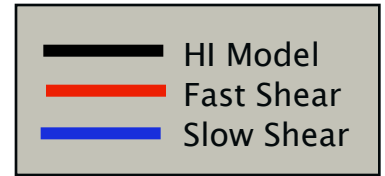
Intrinsic



Fractures
(transverse isotropic horizontal)

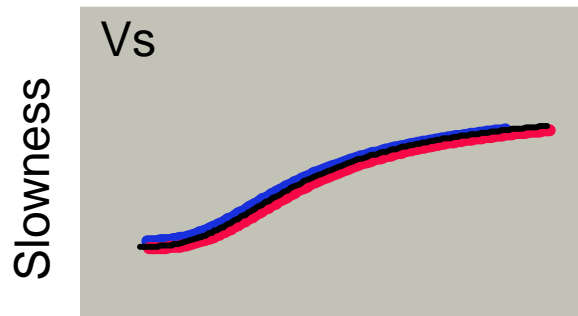
$$V_S(\theta)$$

Slowness Dispersion Analysis



Homogeneous Isotropic

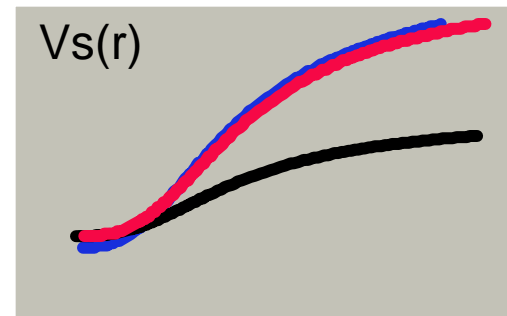
No Failure



Frequency

Inhomogeneous Isotropic

Slowness

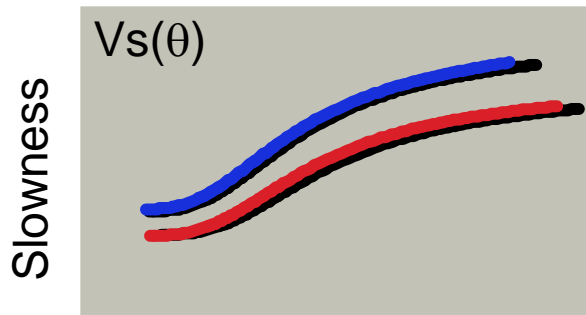


Altered,
Near
Failure

Frequency

Homogeneous Anisotropic

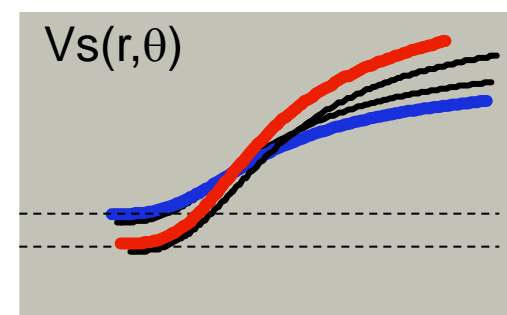
Intrinsic Fractures or Bedding



Frequency

Inhomogeneous Anisotropic

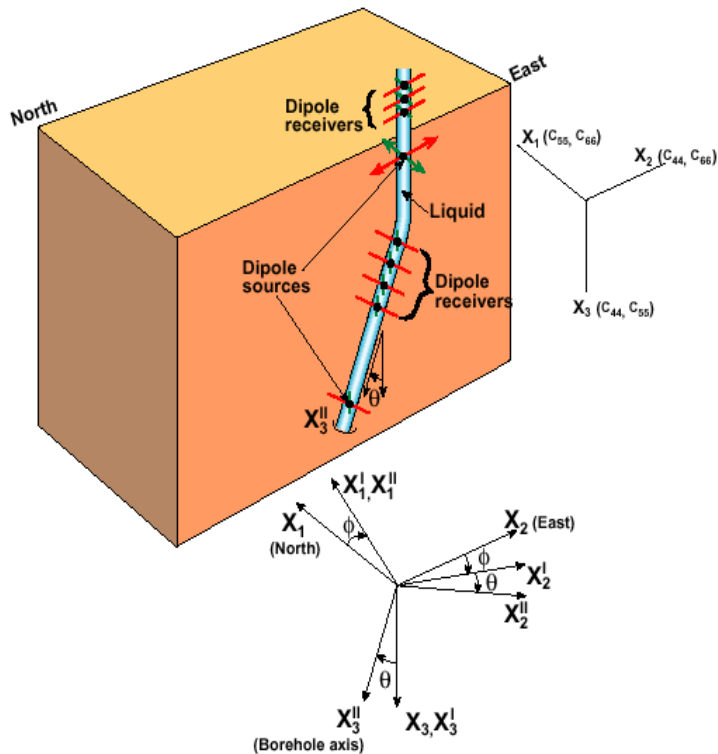
Slowness



Stress Induced

Frequency

3D Anisotropy for Deviated Wells



Compressional
Radial Profile

Two Shear
Radial Profile

3D Anisotropy to
convert from well
reference to Earth
reference

Stoneley
Radial Profile

Well
Geometry

Traditional Modeling Techniques

■ Fracture Gradient

- Matthews & Kelly:

$$FG = p_p + K_0(\sigma_v - p_p)$$

- Eaton Gulf Coast Method:

$$FG = p_p + \frac{K_0}{1 - K_0}(\sigma_v - p_p)$$

$$K_0 = A1 * TVDSS * TVDSS + A2 * TVDSS + A3$$

■ Isotropic Minimum Horizontal Stress

$$\sigma_h - p_p = \frac{\nu}{1 - \nu}(\sigma_v - p_p) + tectonics$$

Using Calibration
Coefficients

Using Tectonic
Strains

Stress Modeling Including Anisotropy

- Anisotropic minimum horizontal stress equation, Thiercelin & Plumb (1994):

$$\sigma_h - \alpha_h p_p = \frac{C_{13}}{C_{33}} (\sigma_v - \alpha_v p_p) + \left(C_{11} - \frac{C_{13}^2}{C_{33}} \right) \varepsilon_h + \left(C_{12} - \frac{C_{13}^2}{C_{33}} \right) \varepsilon_H$$

- Hooke's Law:

$$\sigma_i = C_{ij} \varepsilon_j$$

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

Valid in Horizontal Beds

Elastic stiffnesses:

Relation to geophysical and geomechanical parameters

A Transverse-Isotropic (TI) system with density ρ is fully described by five independent stiffnesses: C_{11} , C_{33} , C_{44} , C_{66} , and C_{13} . Assuming horizontal layering:

Thomsen parameters (geophysics)		Mechanical properties (geomechanics)	
$V_{P0} = \sqrt{C_{33} / \rho}$	Vertical P-wave velocity	$E_V = C_{33} - 2 \frac{C_{13}^2}{C_{11} + C_{12}^*}$	Vertical Young's modulus
$V_{S0} = \sqrt{C_{44} / \rho}$	Vertical S-wave velocity	$E_H = \frac{(C_{11} - C_{12}^*)(C_{11}C_{33} - 2C_{13}^2 + C_{12}^*C_{33})}{C_{11}C_{33} - C_{13}^2}$	Horizontal Young's modulus
$\varepsilon = (C_{11} - C_{33}) / (2C_{33})$	P-wave anisotropy	$\mu_V = C_{44}$	Vertical plane shear modulus
$\gamma = (C_{66} - C_{44}) / (2C_{44})$	S-wave anisotropy	$\mu_H = C_{66}$	Horizontal plane shear modulus
$\delta = \frac{(C_{13} + C_{44})^2 - (C_{33} - C_{44})^2}{2C_{33}(C_{33} - C_{44})}$	Small-offset NMO factor	$\nu_V = \frac{C_{13}}{C_{11} + C_{12}^*}$	Vertical Poisson's ratio (vertical loading, horizontal expansion)

$$*C_{12} = C_{11} - 2C_{66}$$

Input Data

- Vertical boreholes
- Deviated boreholes
- Sonic measurements provide the input:

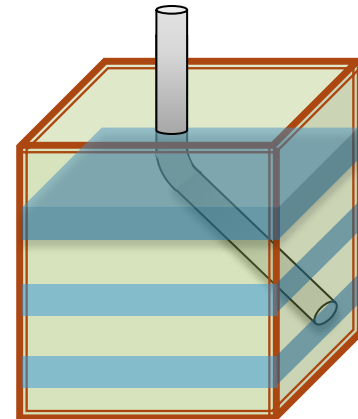
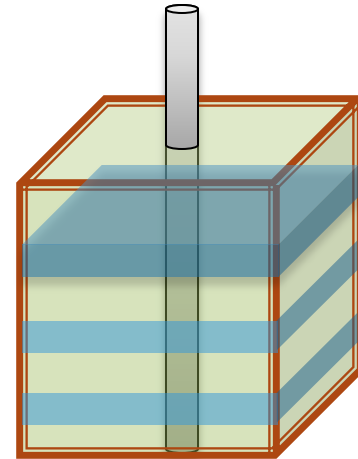
$$\rho v_{qP}^2 = C_{33} \left(1 + 2\varepsilon \sin^4 \theta + 2\eta \sin^2 \theta \cos^2 \theta \right)$$

$$\rho v_{SH}^2 = C_{44} \left(1 + 2\gamma \sin^2 \theta \right)$$

$$\rho v_{qSV}^2 = C_{44} \left(1 + 2 \frac{C_{33}}{C_{44}} (\varepsilon - \eta) \sin^2 \theta \cos^2 \theta \right)$$

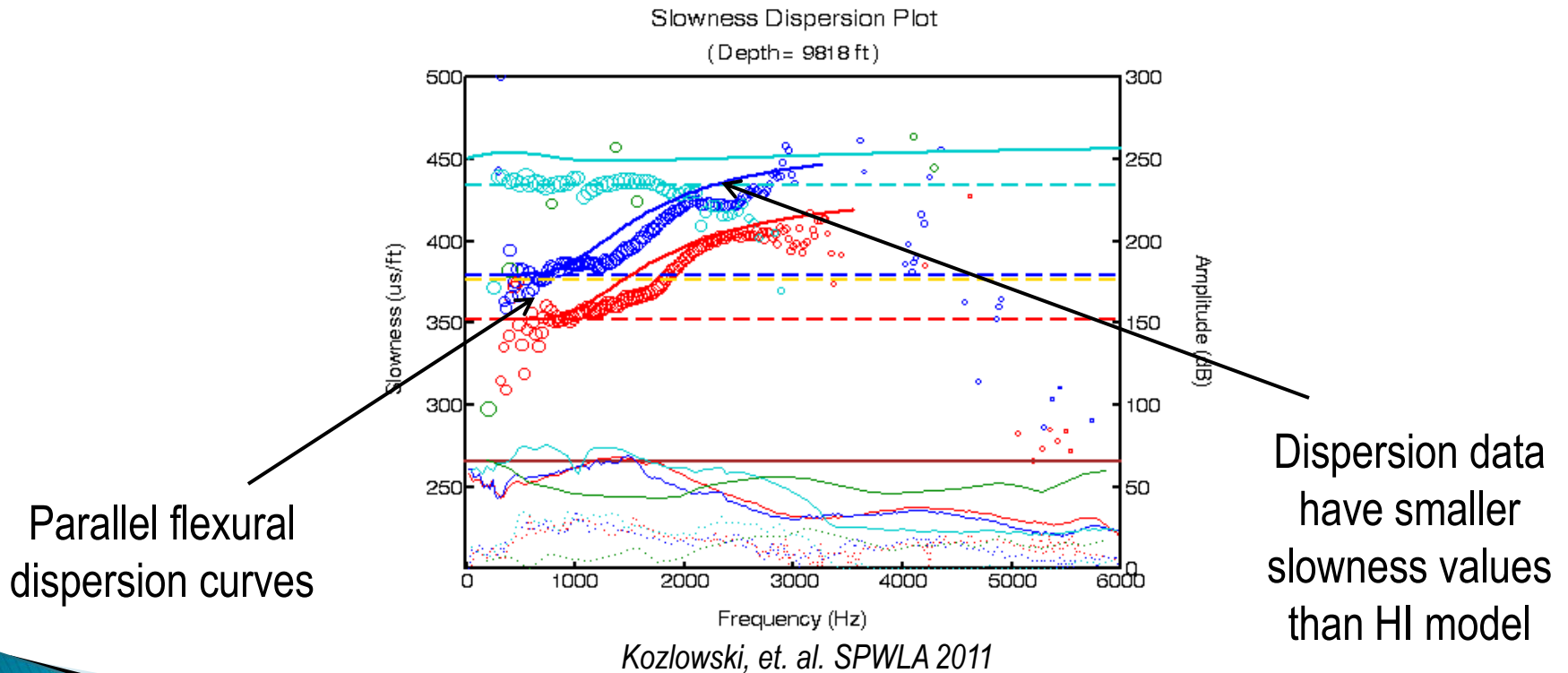
$$\rho v_{St}^2 = C_{44} + 2\gamma C_{44} \cos^2 \theta + \frac{1}{4} (\varepsilon - \eta) C_{33} \sin^4 \theta$$

- TI assumption

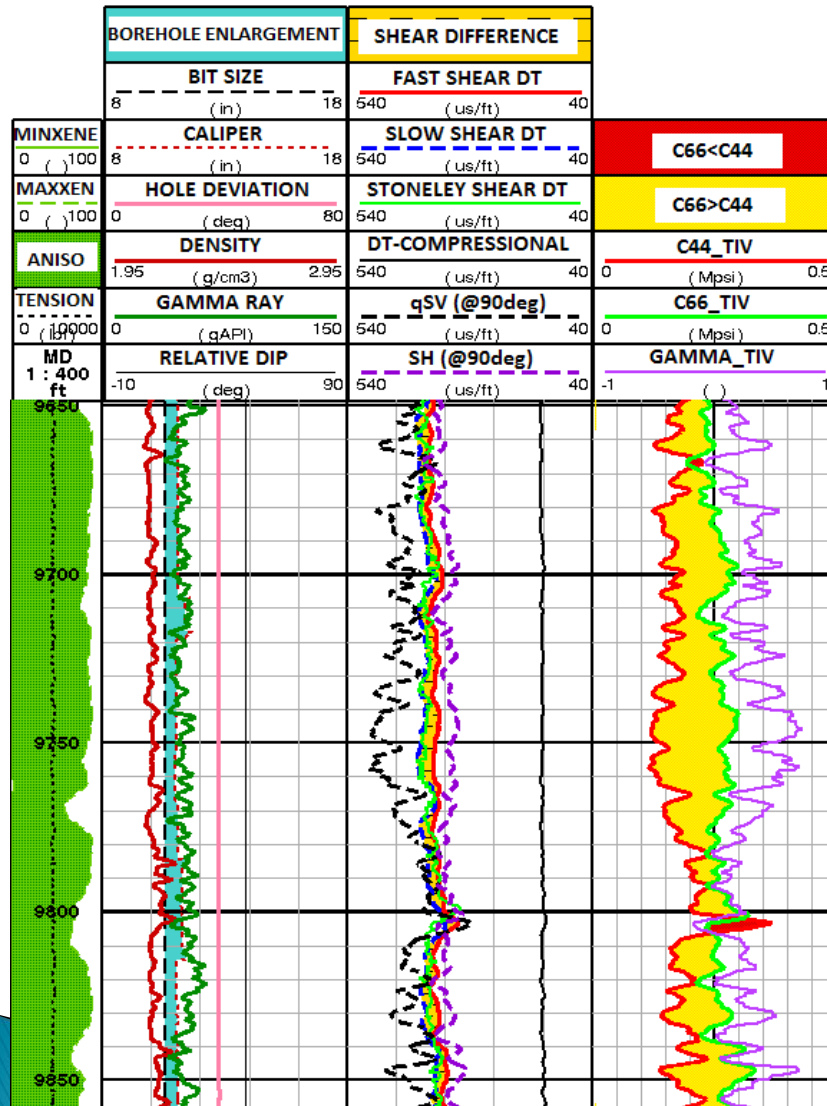


TI Assumption

- Dispersion analysis in the overburden used for validation of the TI assumption:



Interpretation of Shear Slownesses



- Stoneley shear slowness
- Monopole data to obtain qP slowness
- Waveform rotation to obtain SH and qSV slownesses



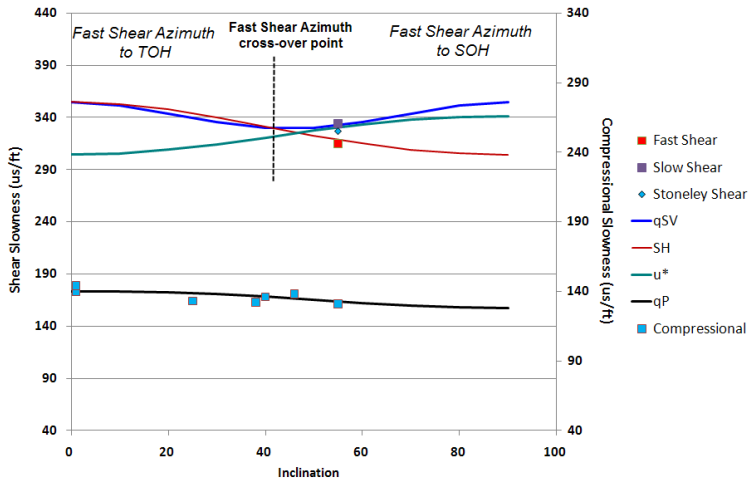
Inversion for C_{44} and C_{66}



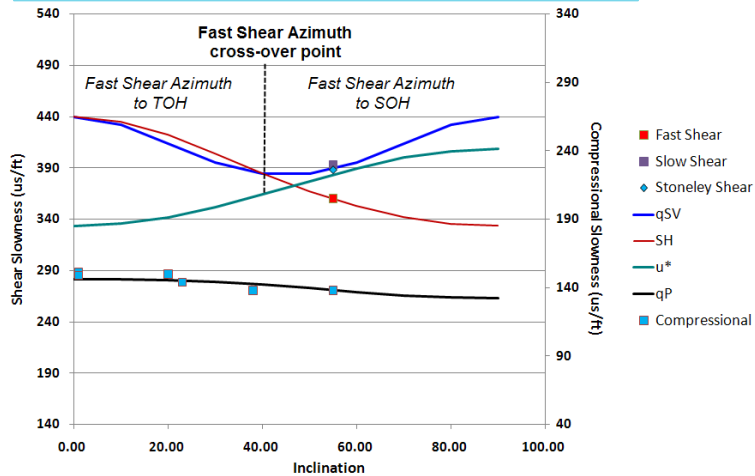
Interpretation of C_{44} and C_{66}

Offset Well Integration

Eocene Formation:



Oligocene Formation:

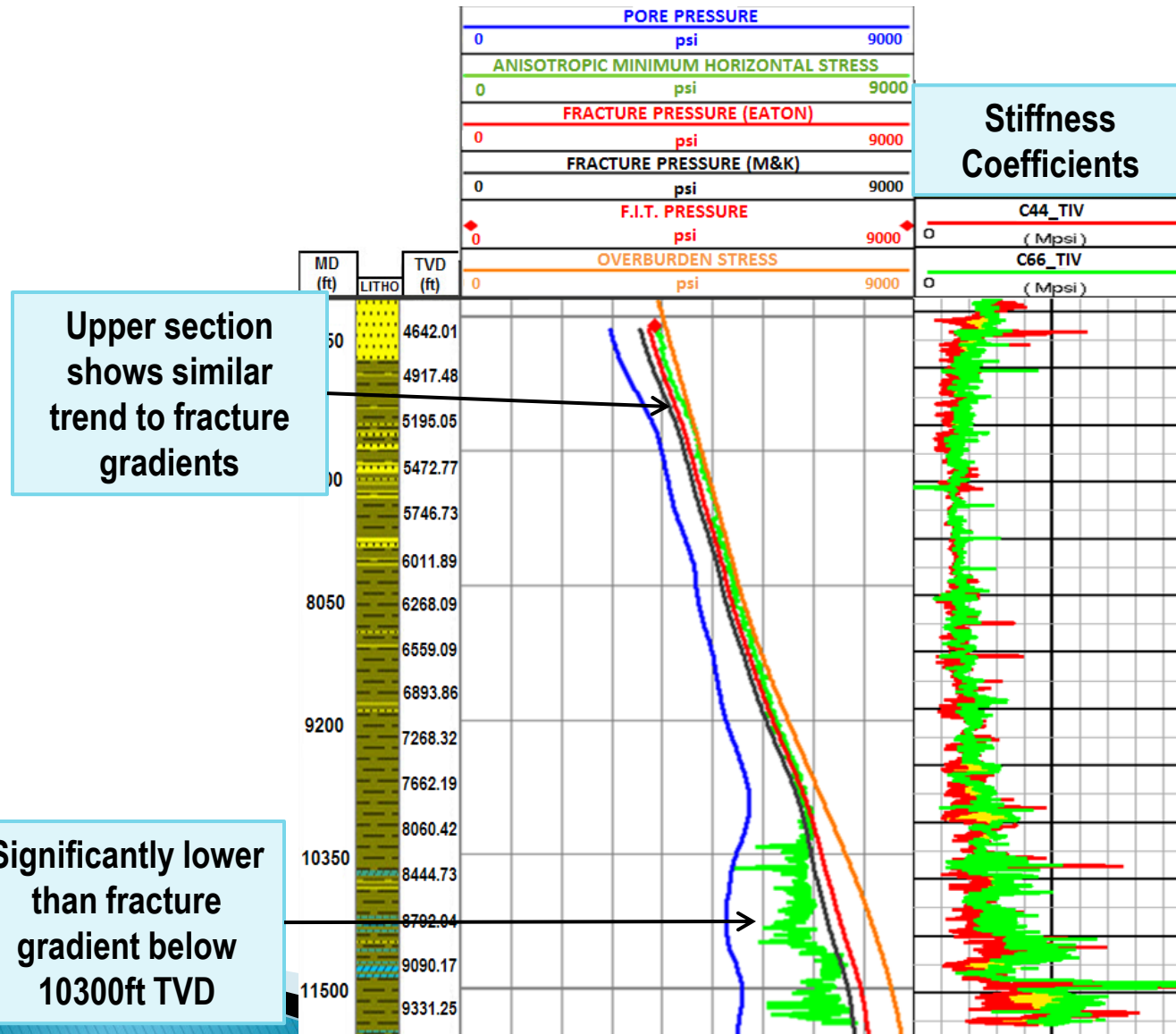


Thomsen's Parameters:

Formation	δ	ϵ	γ
Upper Oligocene	0.04	0.08	0.17
Eocene	0.05	0.10	0.18
Balder	0.08	0.17	0.42

Kozlowski, et. al. SPWLA 2011

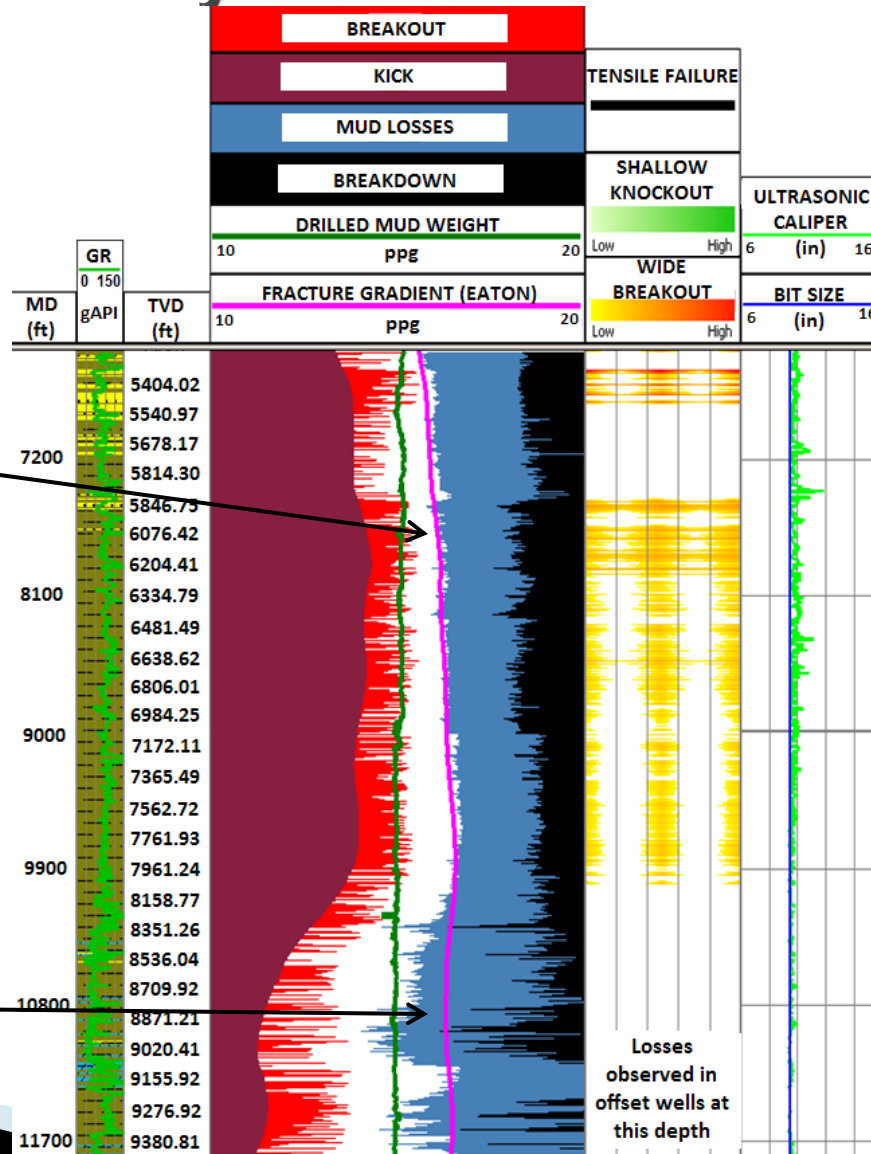
Minimum Horizontal Stress Estimation



Upper section shows similar trend to fracture gradients

Significantly lower than fracture gradient below 10300ft TVD

Wellbore Stability Model



Fracture gradient under estimated at shallow depths

Fracture gradient over estimated at deeper depths – higher likelihood of losses

Isotropic vs Anisotropic:

Upper Overburden
200 to 300 psi difference

Lower Overburden
500 to 600 psi difference

Overburden Characterization: Case Study Summary

- Four slownesses measurements from single well are integrated with offset well compressional slowness data
- Outputs are five independent TI constants
 - Thomsen parameters
- Continuous minimum horizontal stress profile derived
- TIV anisotropy
 - Sonic measurements provide most direct method for determining anisotropic elastic properties
- Eliminated need for tectonic strains and boost factors