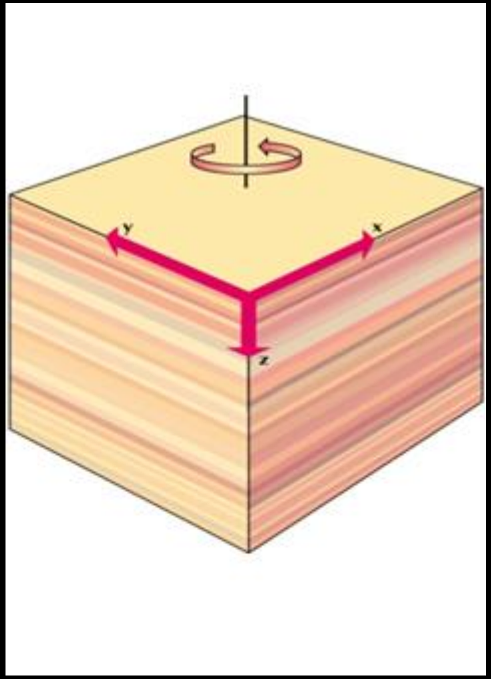
GPC workshop
October 2022

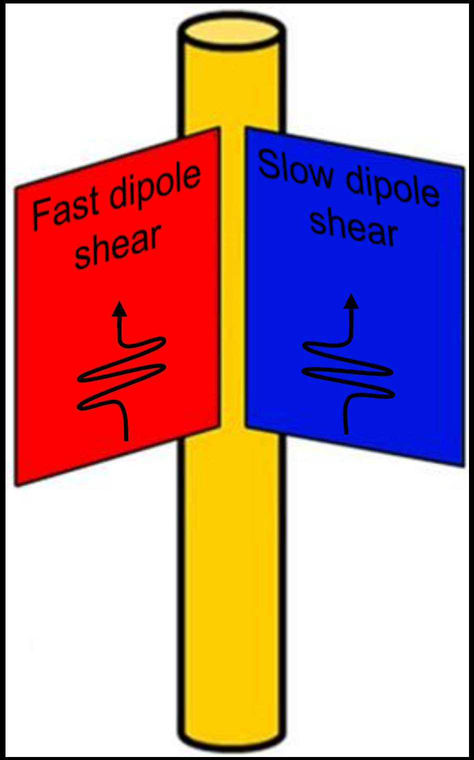
Anisotropic mechanical properties and effect of neglecting anisotropy in deviated wells

IRINA MIKHALTSEVA

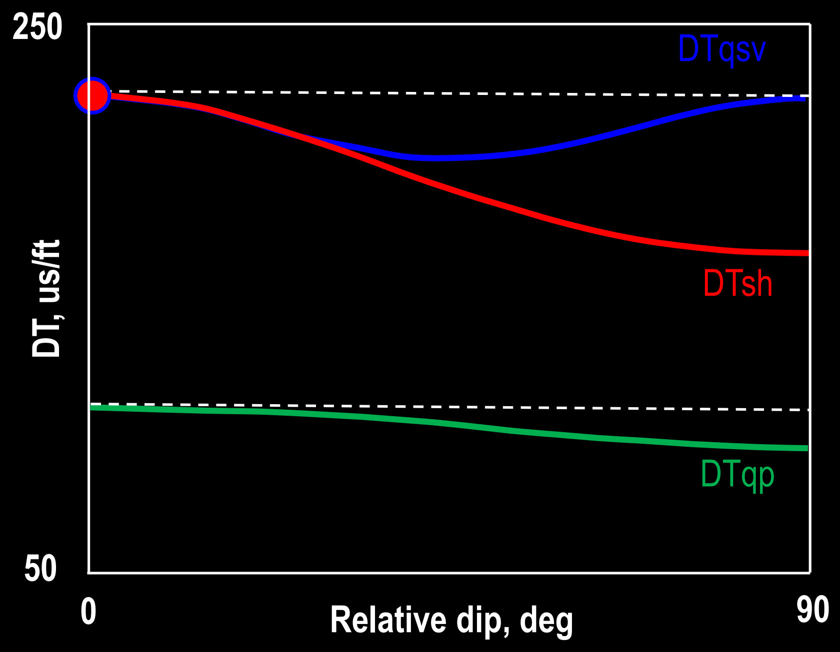
What is TI anisotropy?



Intrinsic anisotropy

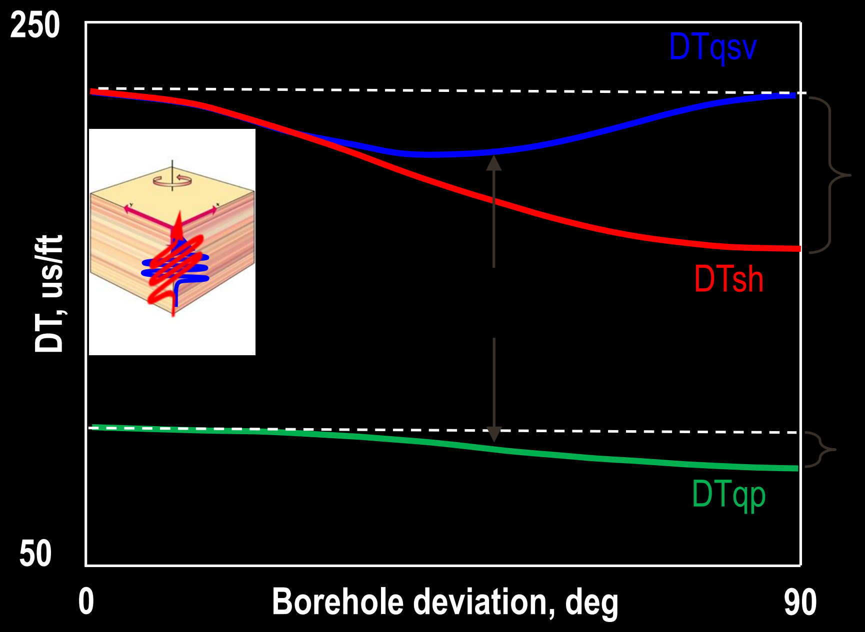


Dipole sonic tool

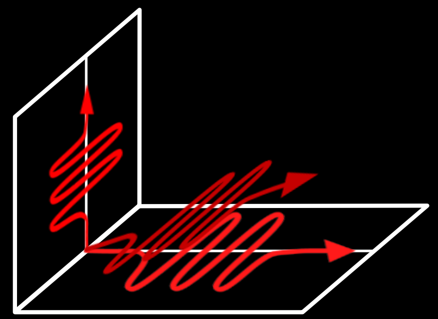


Variation in measured DT with borehole deviation in sub-horizontal bedding environment

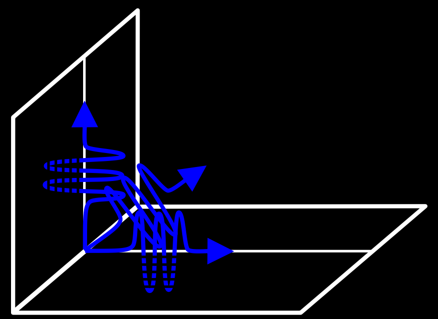
What is TI anisotropy?



DTsh – horizontally polarized shear



DTqsv – vertically polarized shear



Mechanical properties

$$E_x = \frac{(C_{11} - C_{12})C}{C_{11}C_{33} - C_{13}^2} \qquad E_z = \frac{C}{C_{11} + C_{12}}$$

$$\nu_{xy} = \frac{C_{12}C_{33} - C_{13}^2}{C_{11}C_{33} - C_{13}^2} \qquad \nu_{zx} = \frac{C_{13}}{C_{11} + C_{12}}$$

$$\mu_V = C_{55}$$

where $C = C_{33}(C_{11} + C_{12}) - 2C_{13}^2$

Stiffness tensor

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{55} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

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

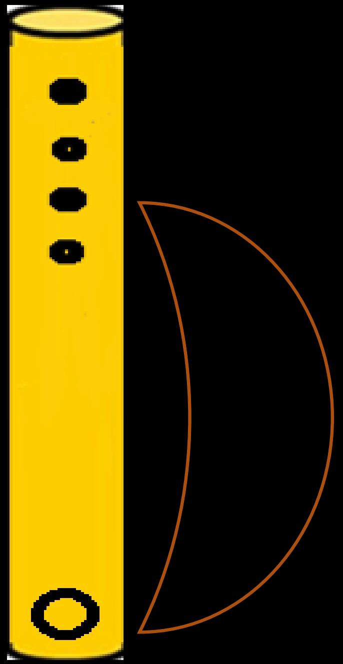
Thomsen parameters

$$V_{P0} = \sqrt{\frac{C_{33}}{\rho}} \qquad \varepsilon = \frac{C_{11} - C_{33}}{2C_{33}} = \frac{DTP_V^2 - DTP_H^2}{2 \cdot DTP_H^2}$$

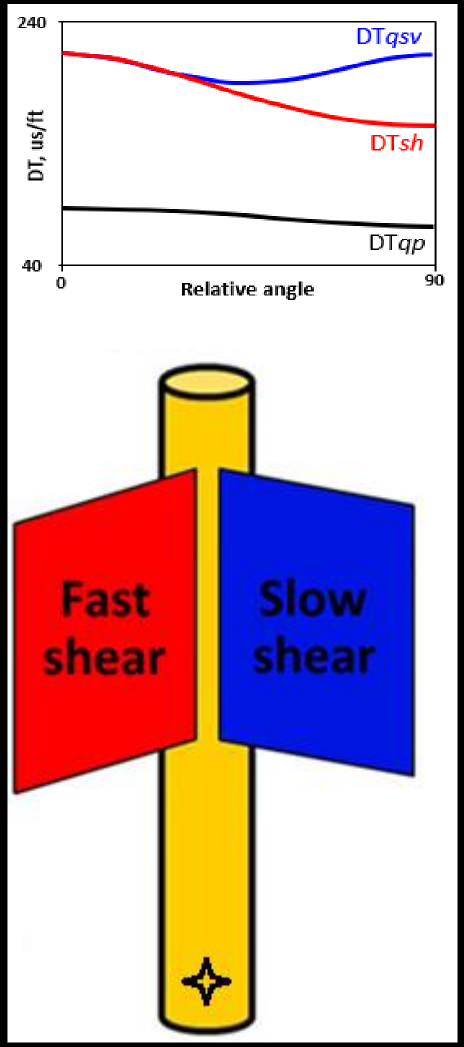
$$V_{S0} = \sqrt{\frac{C_{55}}{\rho}} \qquad \gamma = \frac{C_{66} - C_{55}}{2C_{55}} = \frac{DTS_V^2 - DTS_H^2}{2 \cdot DTS_H^2}$$

$$\delta = \frac{(C_{13} + C_{55})^2 - (C_{33} - C_{55})^2}{2C_{33}(C_{33} - C_{55})}$$

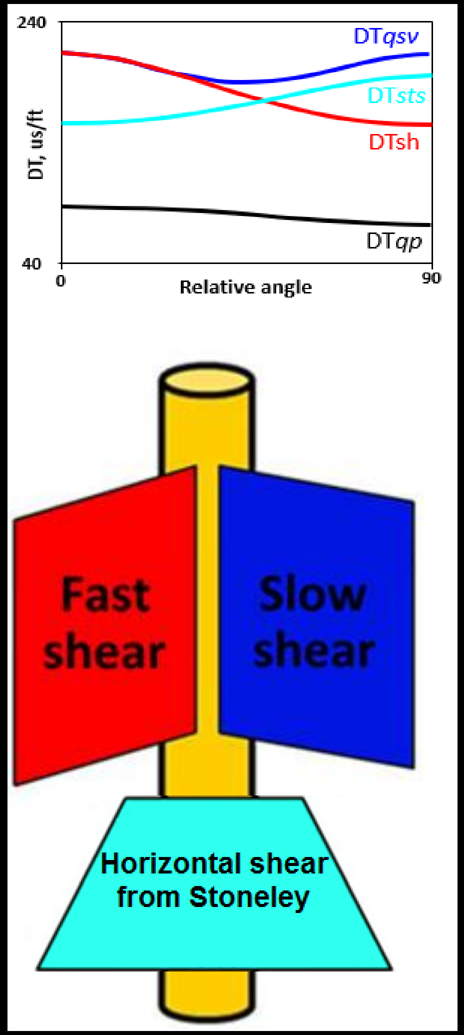
Array sonic logging



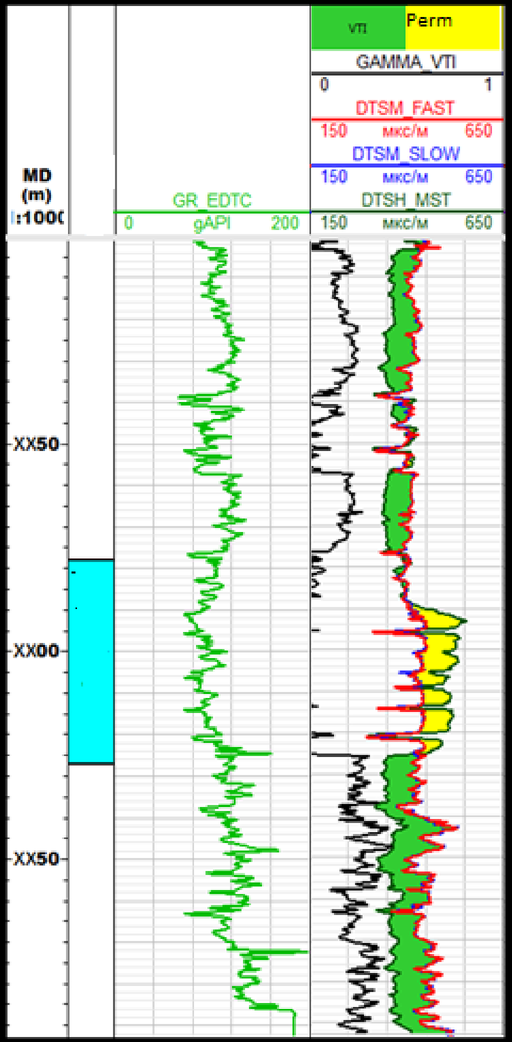
DTCO, DTSH
Vertical



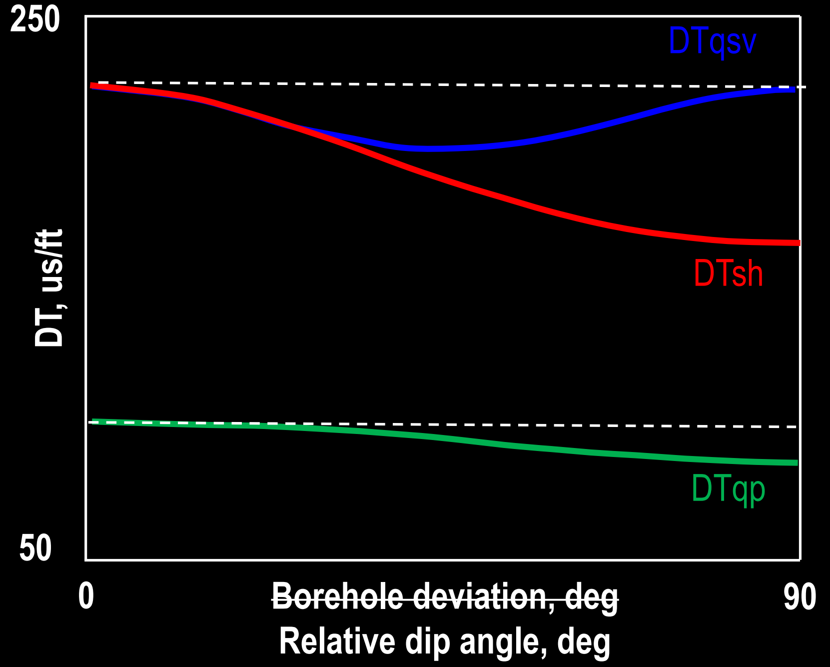
DTSH_FAST, DTSH_SLOW



DTSH
Horizontal:
(Shear from Stoneley)
Polar anisotropy



Relative dip angle – angle between borehole axis and TI-axis



Borehole deviation & azimuth

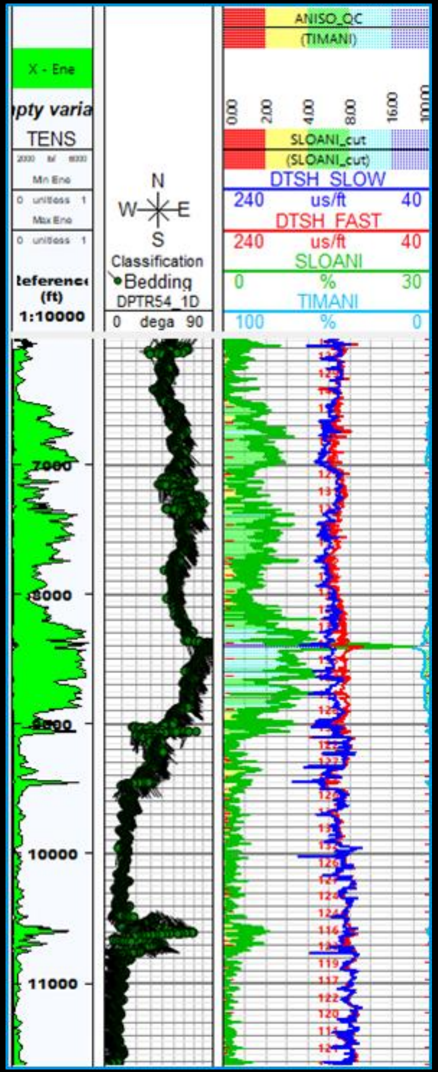
Bedding dip inclination & azimuth

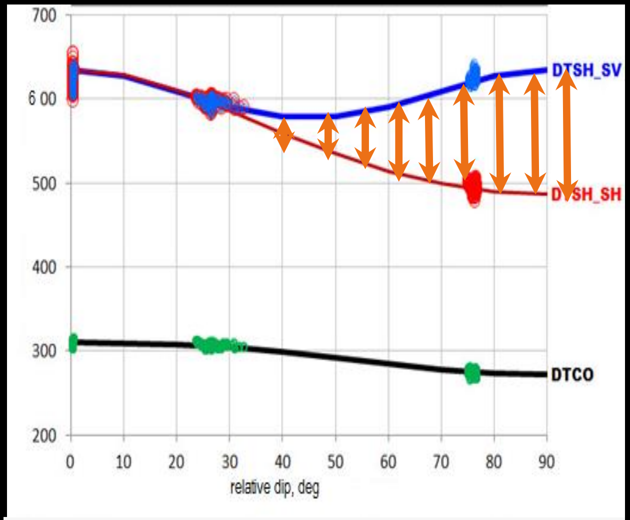
Relative dip angle

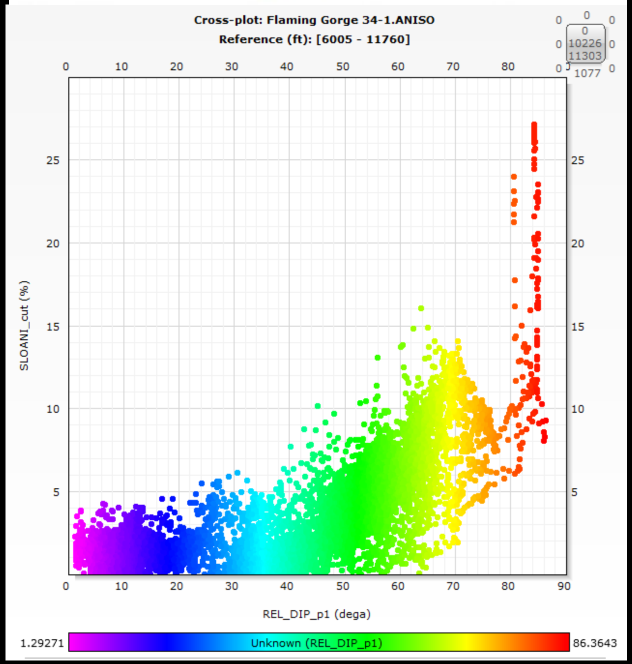
30 deg in both cases

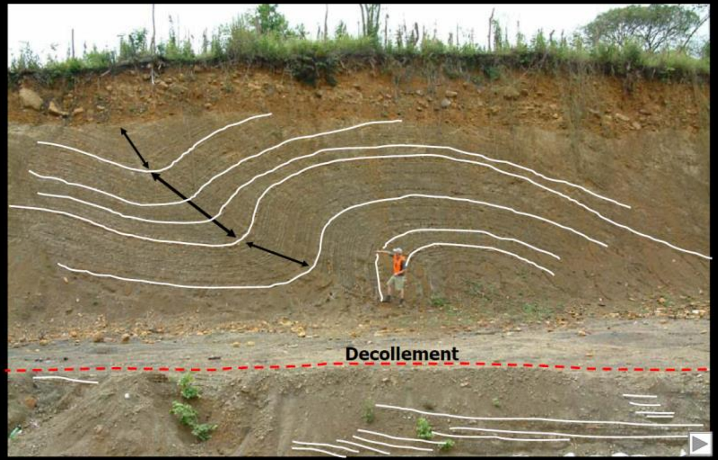
The relative dip is defined as the angle between the wellbore and the unit vector normal to bedding. The relative dip is calculated on basis of the wellbore orientation and bedding orientation

Variable bedding dips in a single well

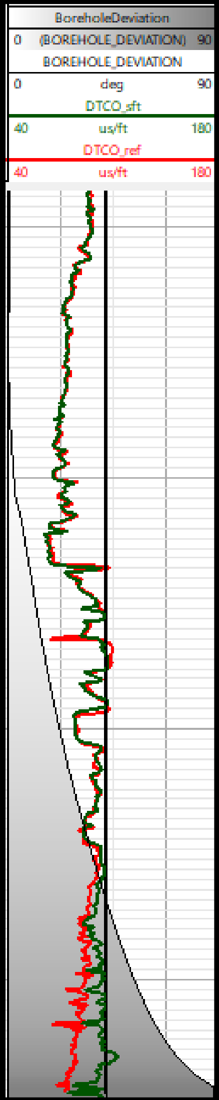


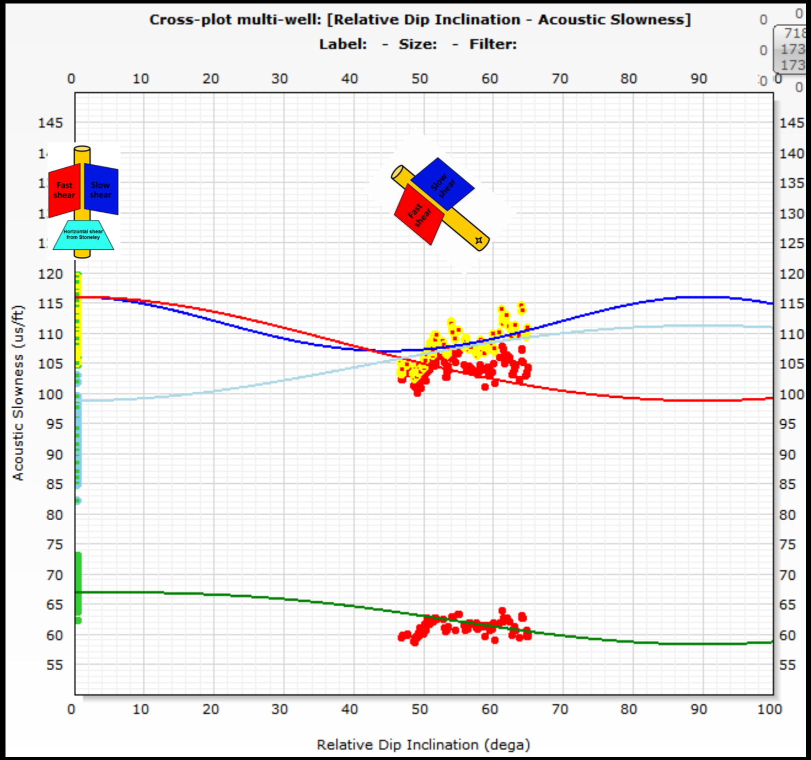






Pilot and deviated wells: measured acoustic slowness





Far-Field Stress Model

$$\sigma_{Hmin} = \frac{E_h}{E_v}\frac{\mu_v}{1-\mu_h}\left[\sigma_v - \alpha(1-\xi)p_p\right] + \alpha p_p + \frac{E_h}{1-\mu_h^2}\epsilon_{Hmax} + \frac{E_h\mu_h}{1-\mu_h^2}\epsilon_{Hmin}$$

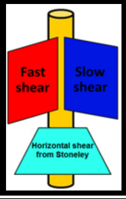
$$E_h = \frac{(C_{11}-C_{12})C}{C_{11}C_{33}-C_{13}^2} \qquad E_v = \frac{C}{C_{11}+C_{12}}$$

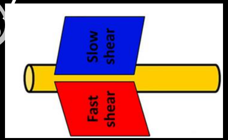
$$\boldsymbol{\mu}_h = \frac{C_{12}C_{33}-C_{13}^2}{C_{11}C_{33}-C_{13}^2} \qquad \boldsymbol{\mu}_v = \frac{C_{13}}{C_{11}+C_{12}}$$

Theircelin, M., and R. A. Plumb, 1994, Core-based prediction of lithologic stress contrasts in east Texas formations: Society of Petroleum Engineers, Paper 21847.

Measurement vs. model

$$C_{ij} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}$$





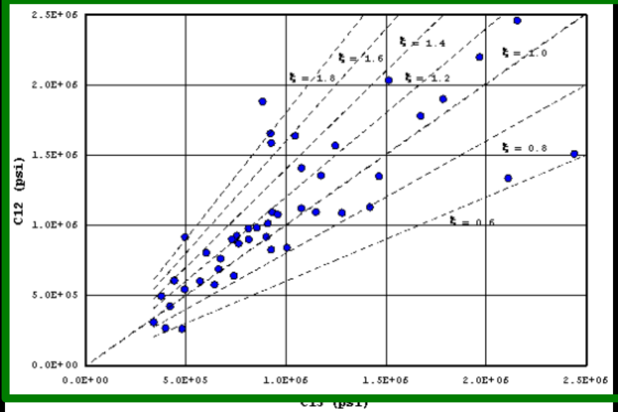
Vertical Well	Stiffness	Horizontal Well
Modeled	C_{11}	$= \rho V_p{}^2$
Modeled	C_{13}	Modeled
$= \rho V_p{}^2$	C_{33}	Modeled
$= \rho V^2{}_{slow} = \rho V^2{}_{fast}$	C_{44}	$= \rho V^2{}_{slow}$
	C_{66}	$= \rho V^2{}_{fast}$

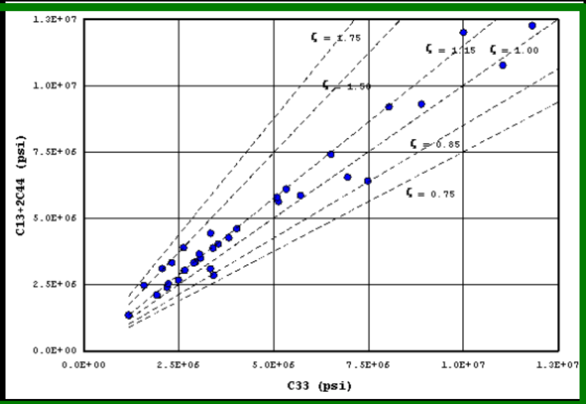
$$c_{12} = c_{11} - 2 * c_{66}$$

Model assumptions

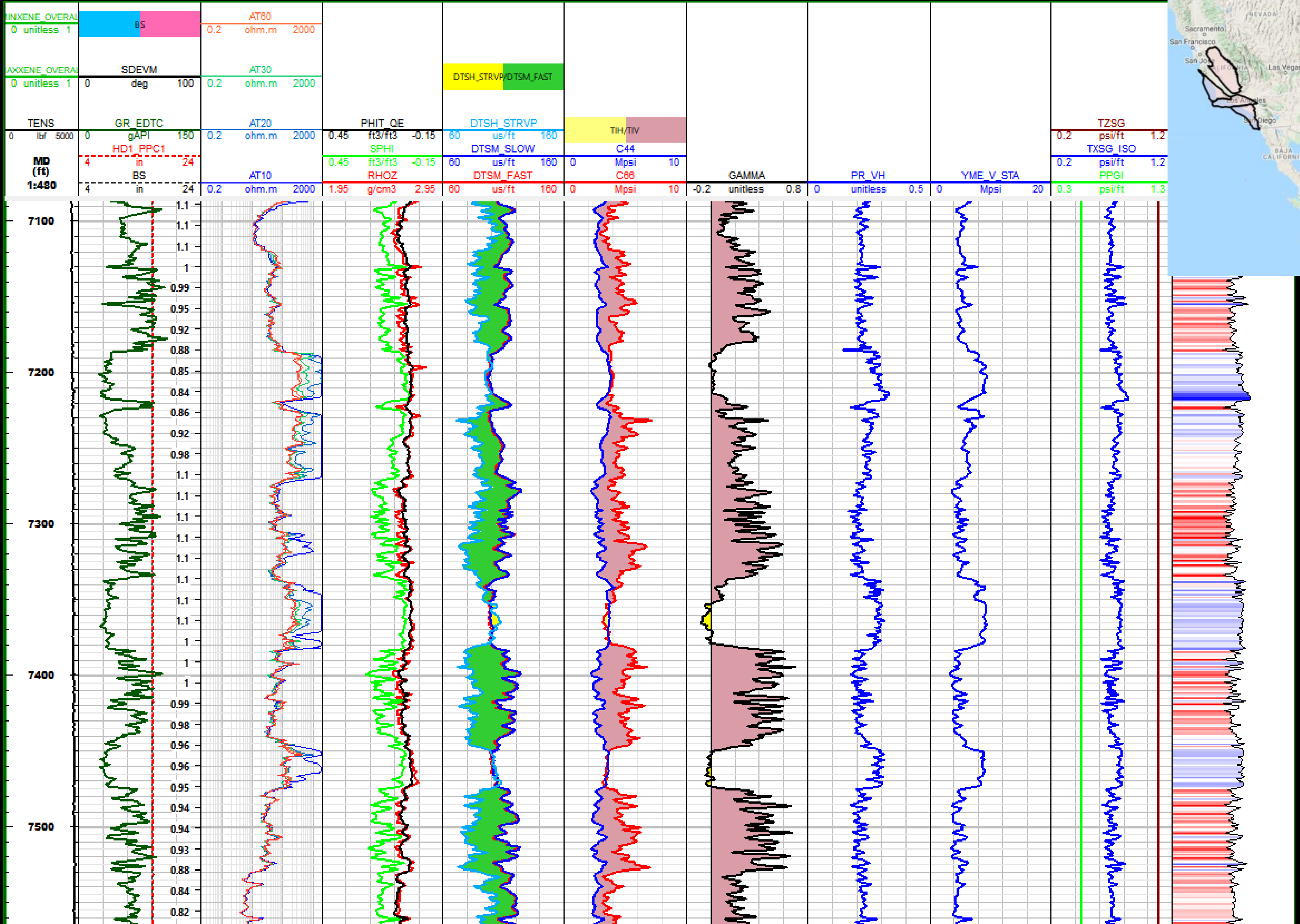
$$c_{12} = c_{11} - 2 * c_{66}$$

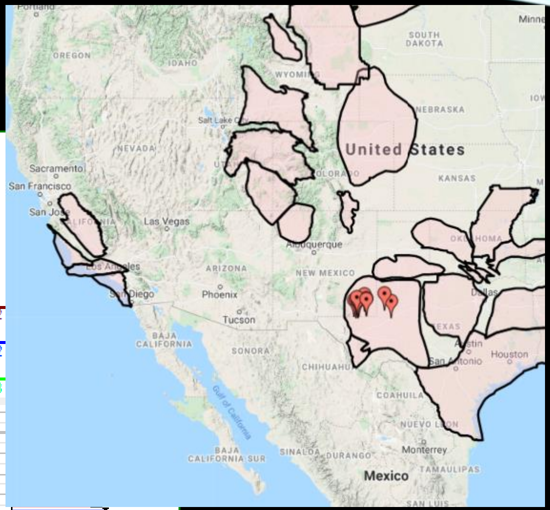
Model	**Model assumption**		
ANNIE	c_{12}=c_{13}	c_{13}=$c_{33} - 2c_{44}$	
MANNIE core	c_{12}=$mult_{13}\ c_{13}$	c_{13}=$mult_{33} c_{33} - 2c_{44}$	Multiplier from core
Epsilon linear gamma	c_{12}=c_{13}	c_{11}=mult($c_{66} - c_{44}$) $*$ c_{33}/c_{44}+c_{33}	ε= mult γ



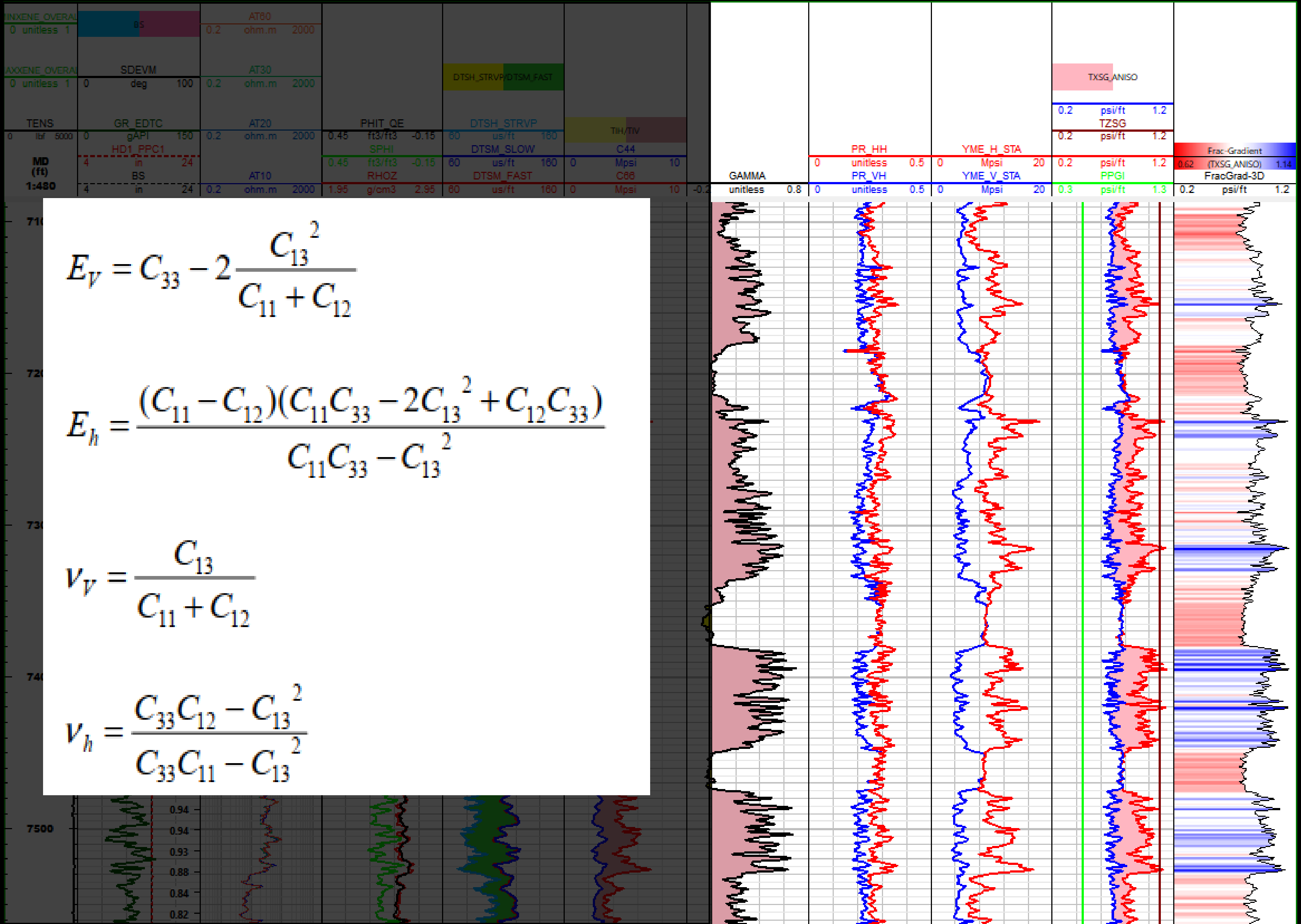


Isotropic Stress gradient





Anisotropic Stress gradient



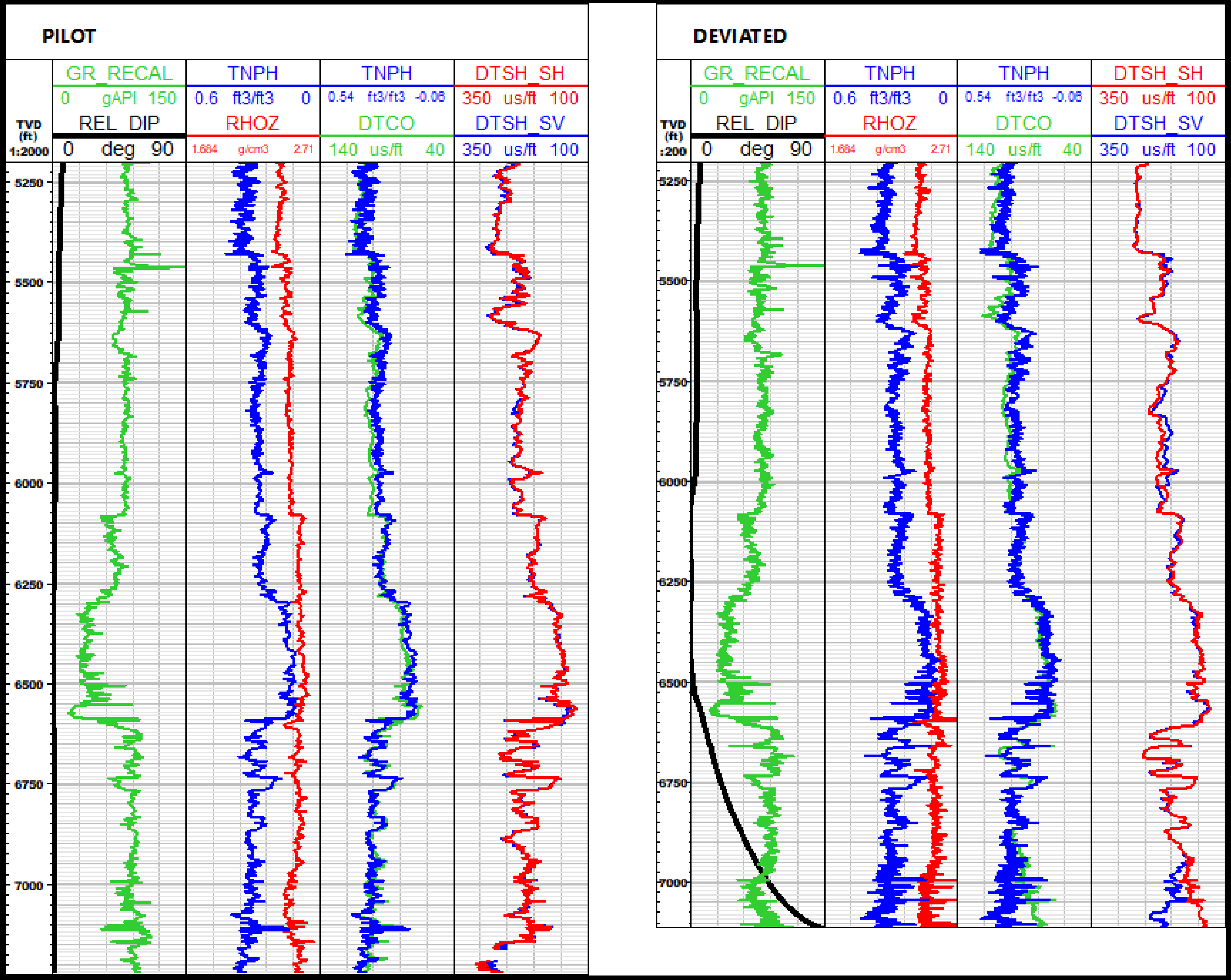
$$E_V = C_{33} - 2\frac{C_{13}^{\ 2}}{C_{11} + C_{12}}$$

$$E_h = \frac{(C_{11} - C_{12})(C_{11}C_{33} - 2C_{13}^{\ 2} + C_{12}C_{33})}{C_{11}C_{33} - C_{13}^{\ 2}}$$

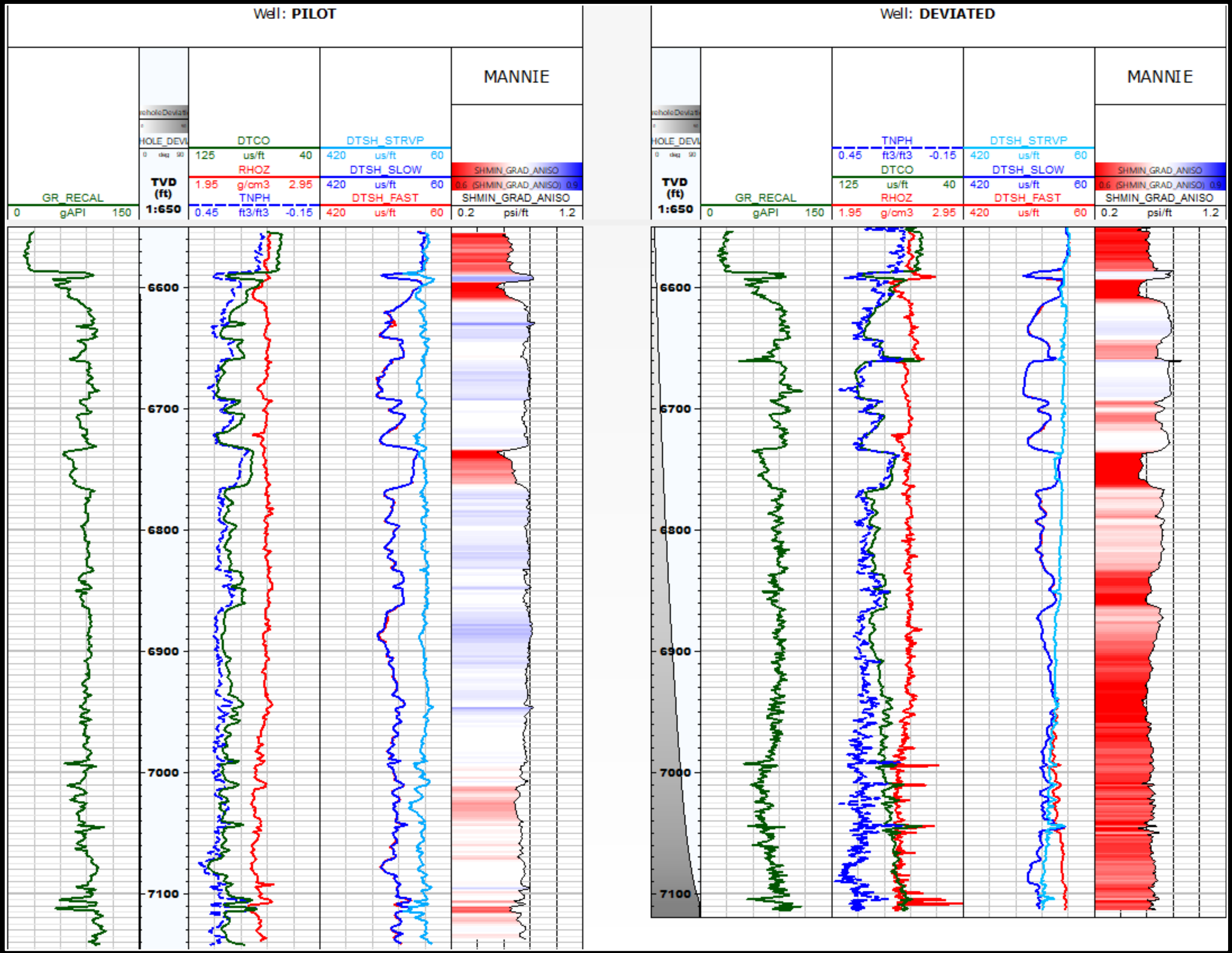
$$\nu_V = \frac{C_{13}}{C_{11} + C_{12}}$$

$$\nu_h = \frac{C_{33}C_{12} - C_{13}^{\ 2}}{C_{33}C_{11} - C_{13}^{\ 2}}$$

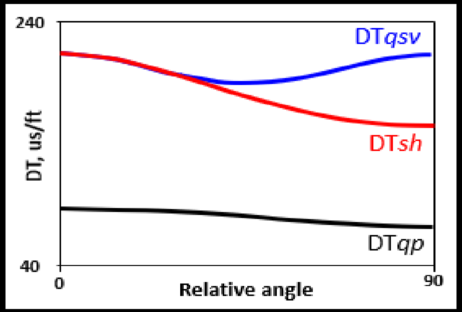
Multi-well Case Study



MANNIE in vertical and Deviated wells



Assumption-based methods don't work in deviated wells, because they based on the fact that we are measuring C33 (C11), C44 and C66. In deviated wells measured slownesses no longer can represent these stiffnesses

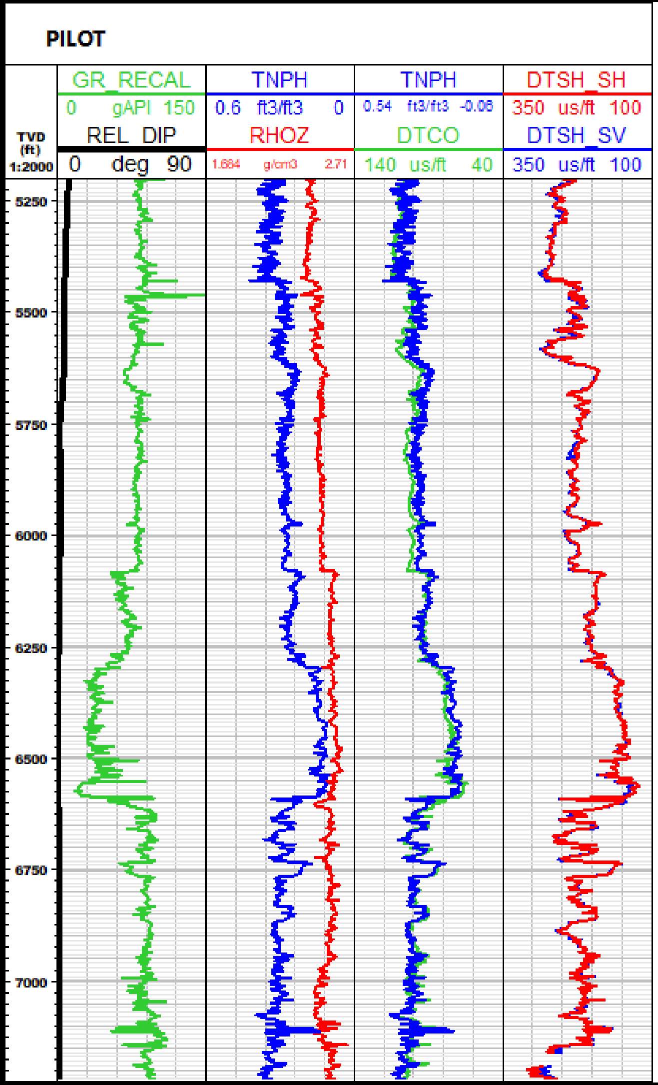


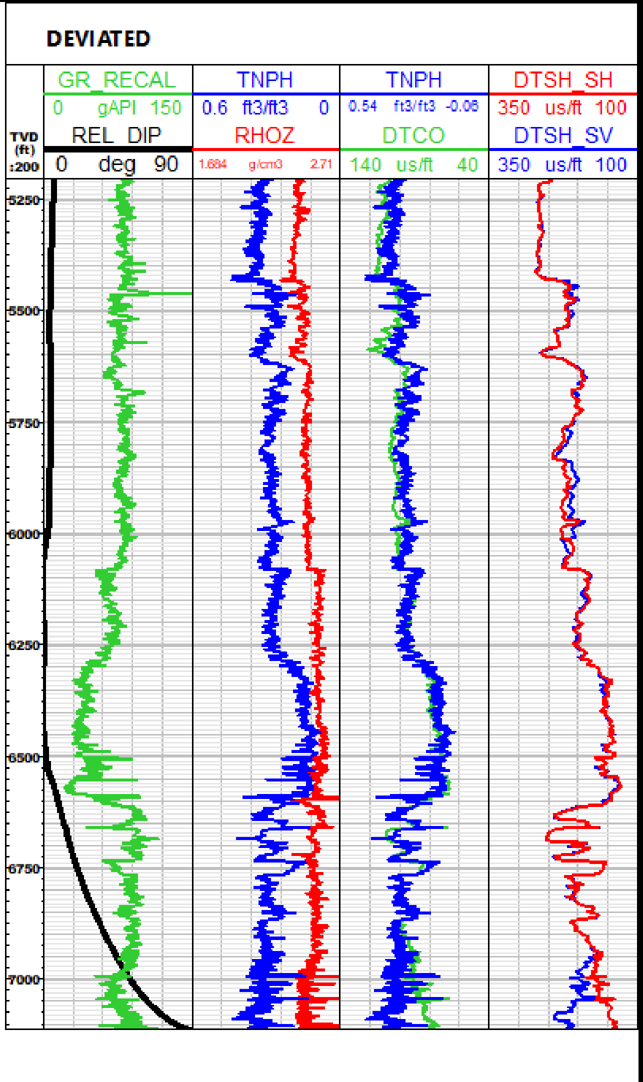
Model assumptions

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

Model	Model assumption		
ANNIE	c_{12}=c_{13}	c_{13}=$c_{33} - 2c_{44}$	
MANNIE core	c_{12}=$mult_{13}\ c_{13}$	c_{13}=$mult_{33}c_{33} - 2c_{44}$	Multiplier from core
Epsilon linear gamma	c_{12}=c_{13}	c_{11}=mult($c_{66} - c_{44}$) $*$ c_{33}/c_{44}+c_{33}	ε= mult γ
Single well Anisotropy (SWA)	Bayesian-type inversion of DTs for TI properties		Requires Prior information
Multi well Anisotropy (MWA)	Simplex inversion of DTs across multiple relative angles		Generates Prior information for SWA

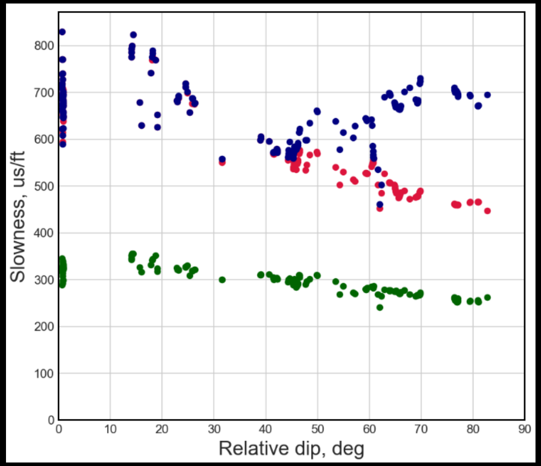
Multi-well Case Study Overview

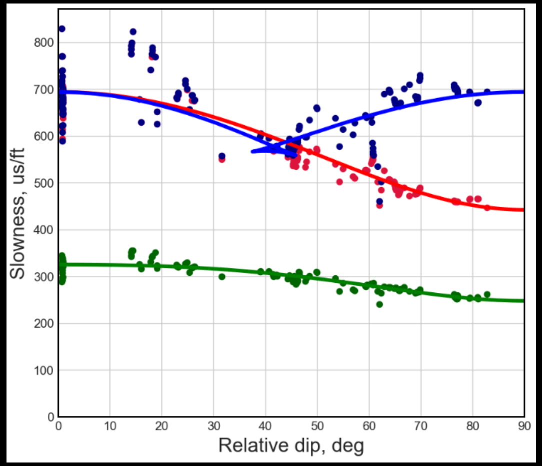




TI anisotropy – How we can find it?

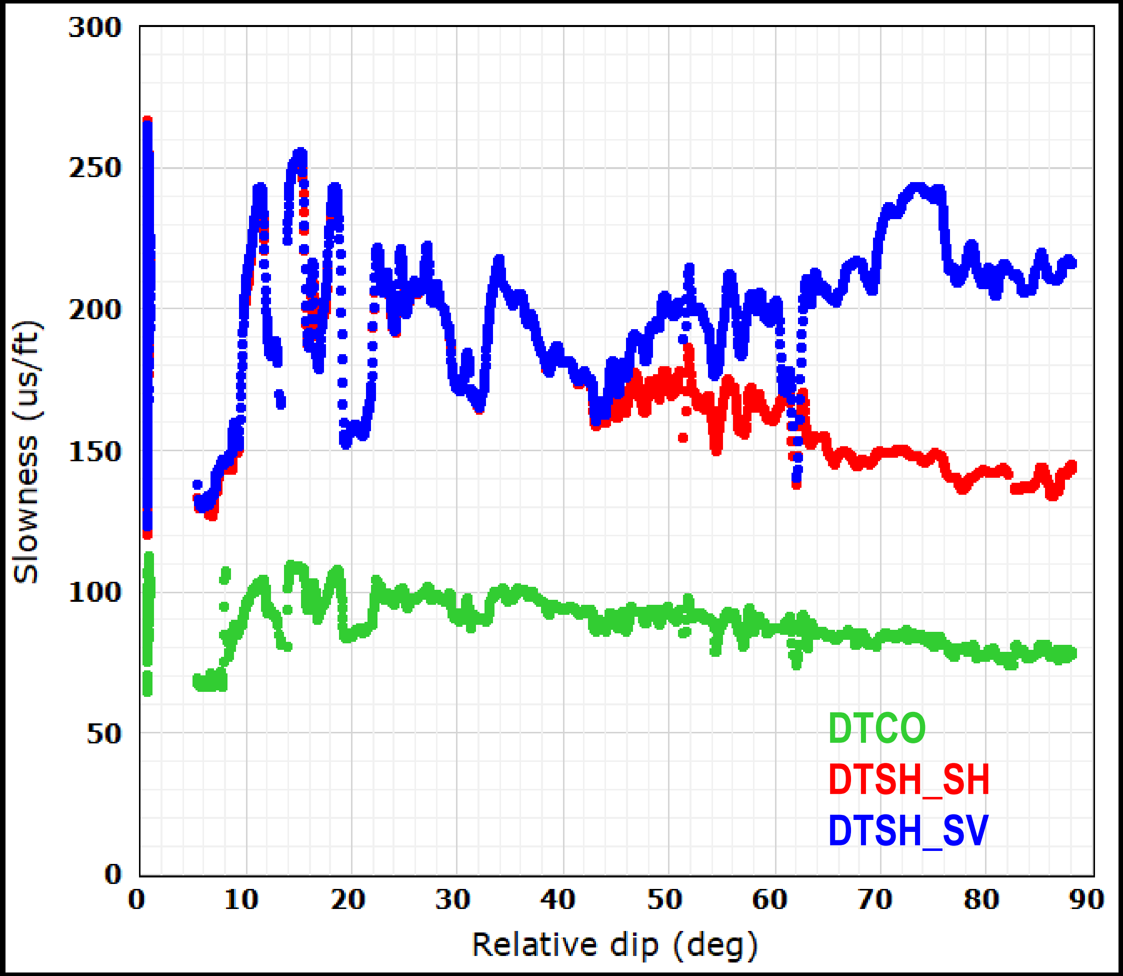
In principle, if we have enough measurements at different relative angles, we can invert TI parameters:





- Thomsen parameters
- Mechanical properties
- Stiffness tensor (Cij)

Why do we need clustering?



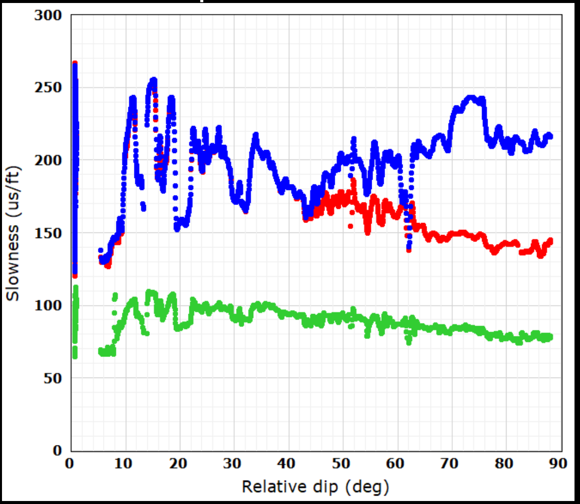
Looking at the data from both wells, we observe some variations of slowness vs. relative dip, but no unique relationship.

To find it, we need to exclude all other parameters that affect measured velocities:

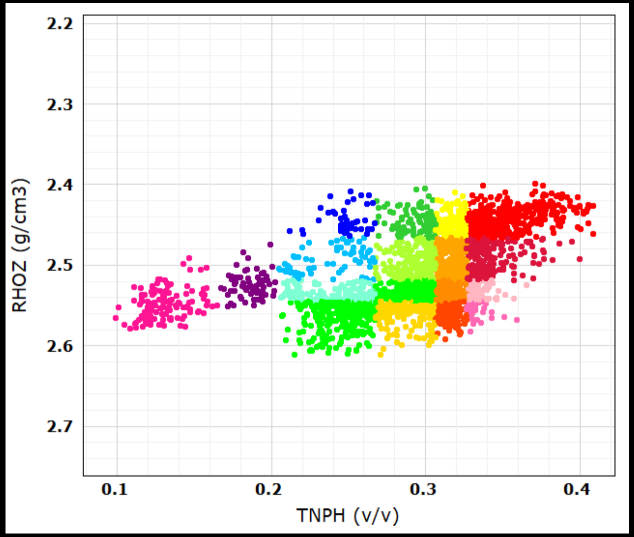
- lithology
- porosity
- saturation
- fractures
- measurement uncertainty
- etc.

Why do we need clustering?

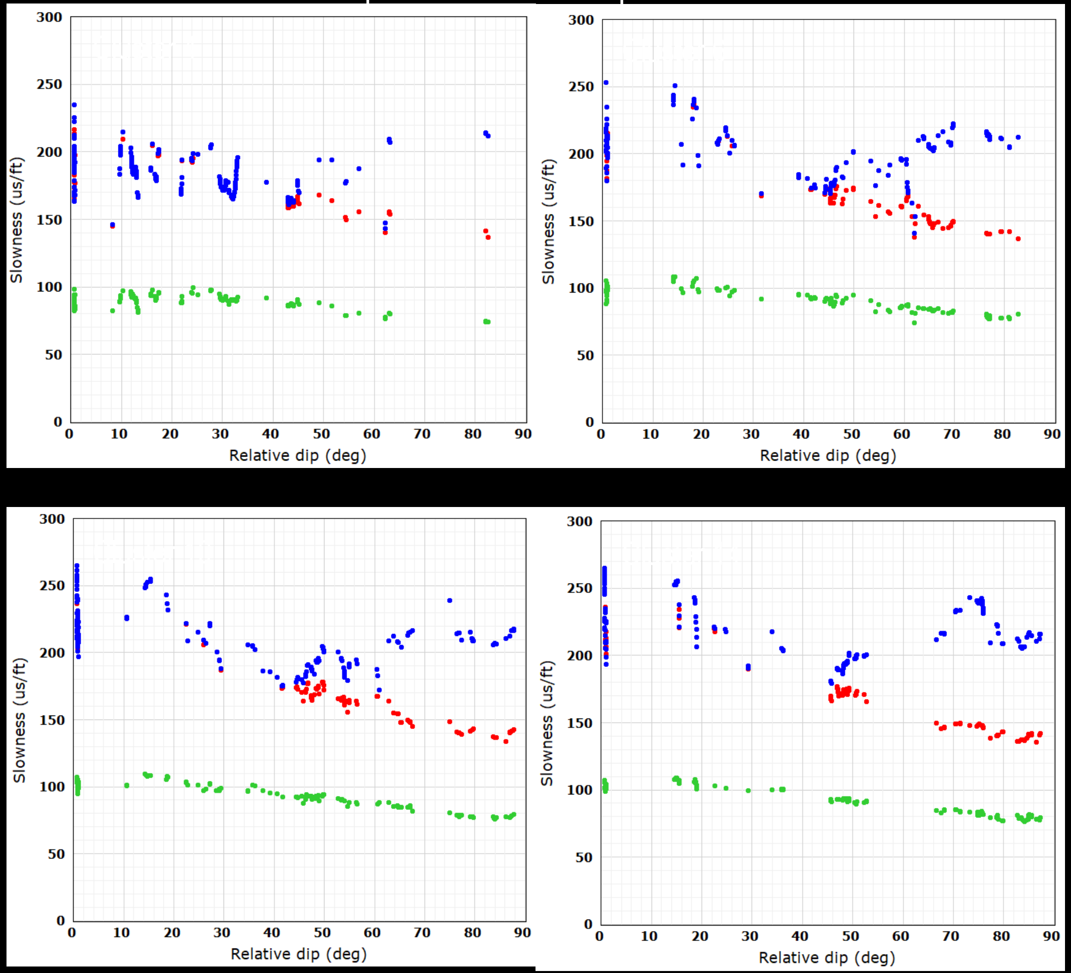
Input slowness data



Clusters of similar data points



Input slowness data per cluster

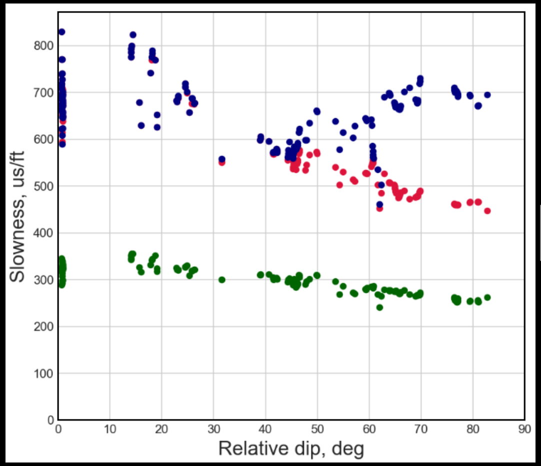


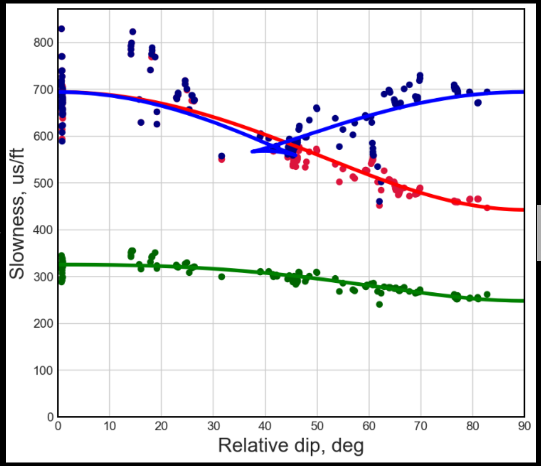
Now we eliminated (significantly reduced) the effects of all the parameters affecting measured slowness and can invert a set of TI parameters from slowness variation with relative dip for each cluster

Multi-well Case Study – Inversion

At this step synthetic (model) velocities are fitted with measured velocities for each cluster.

Model velocities are calculated on basis of a given set of TI elastic parameters, so it is in fact these sets of parameters that are changed between successive iterations in order to find the set that yields synthetic velocities that fit best with the measured velocities.



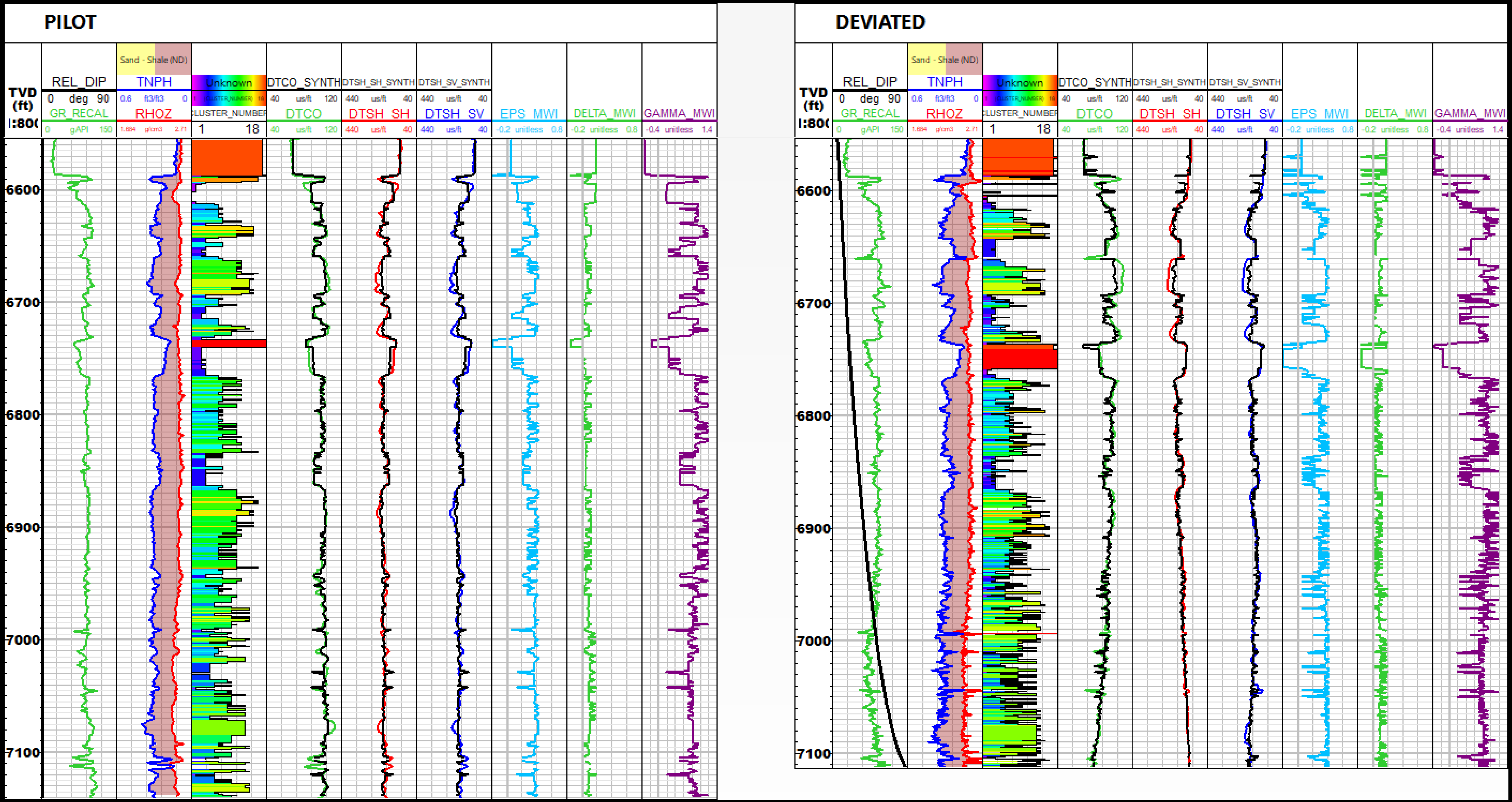


- Thomsen parameters
- Mechanical properties
- Stiffness tensor (Cij)

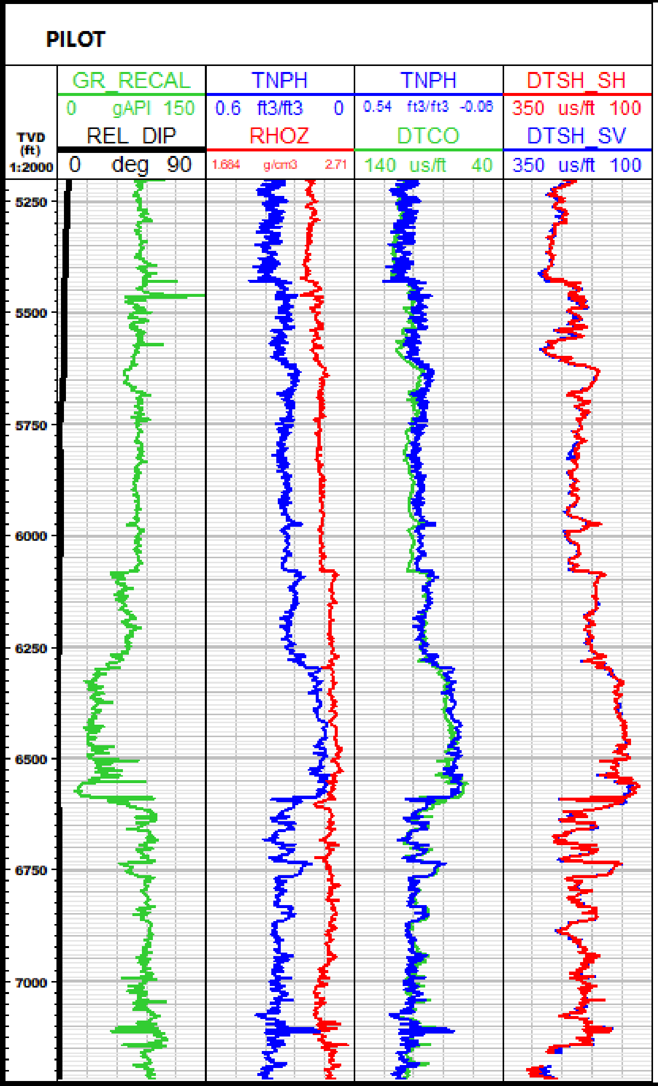
TI anisotropy characterization on basis of sonic datasets from multiple wells: A Norwegian Sea case study

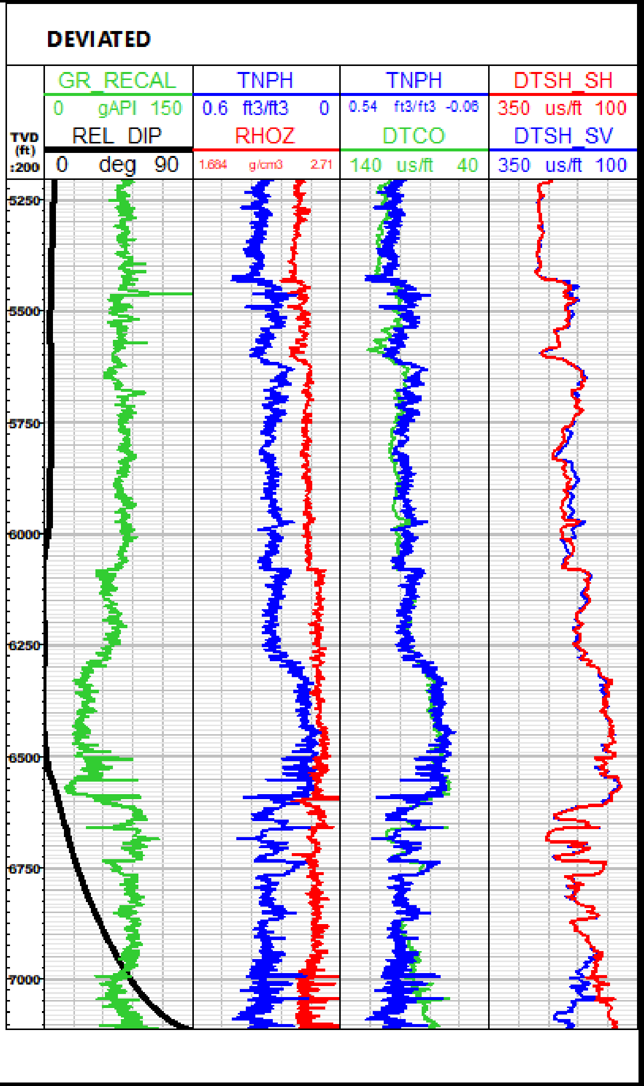
Jeroen Jocker, Schlumberger and Jan Ove Hansen, Equinor*

Multi-well Case Study – Inversion

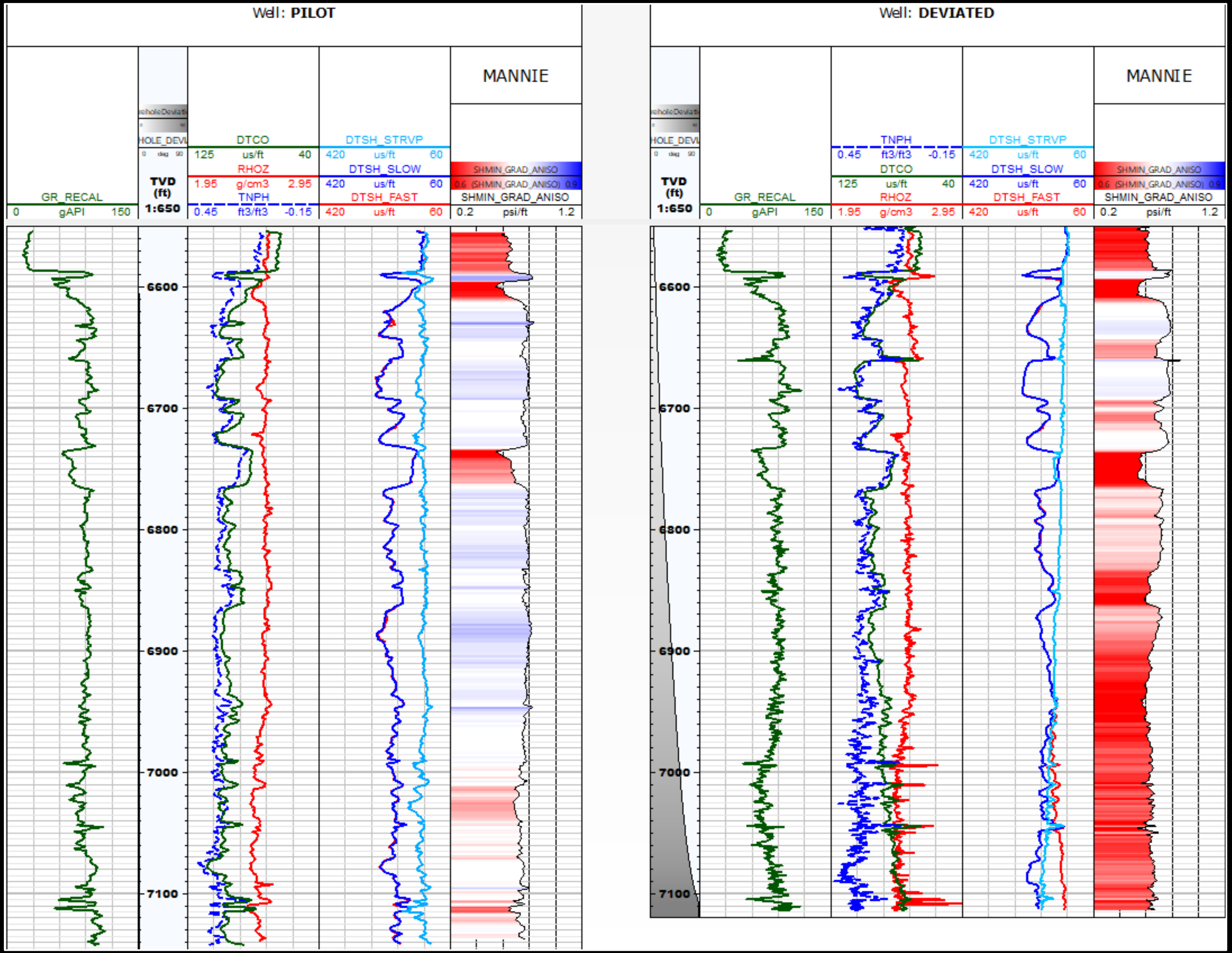


Multi-well Case Study

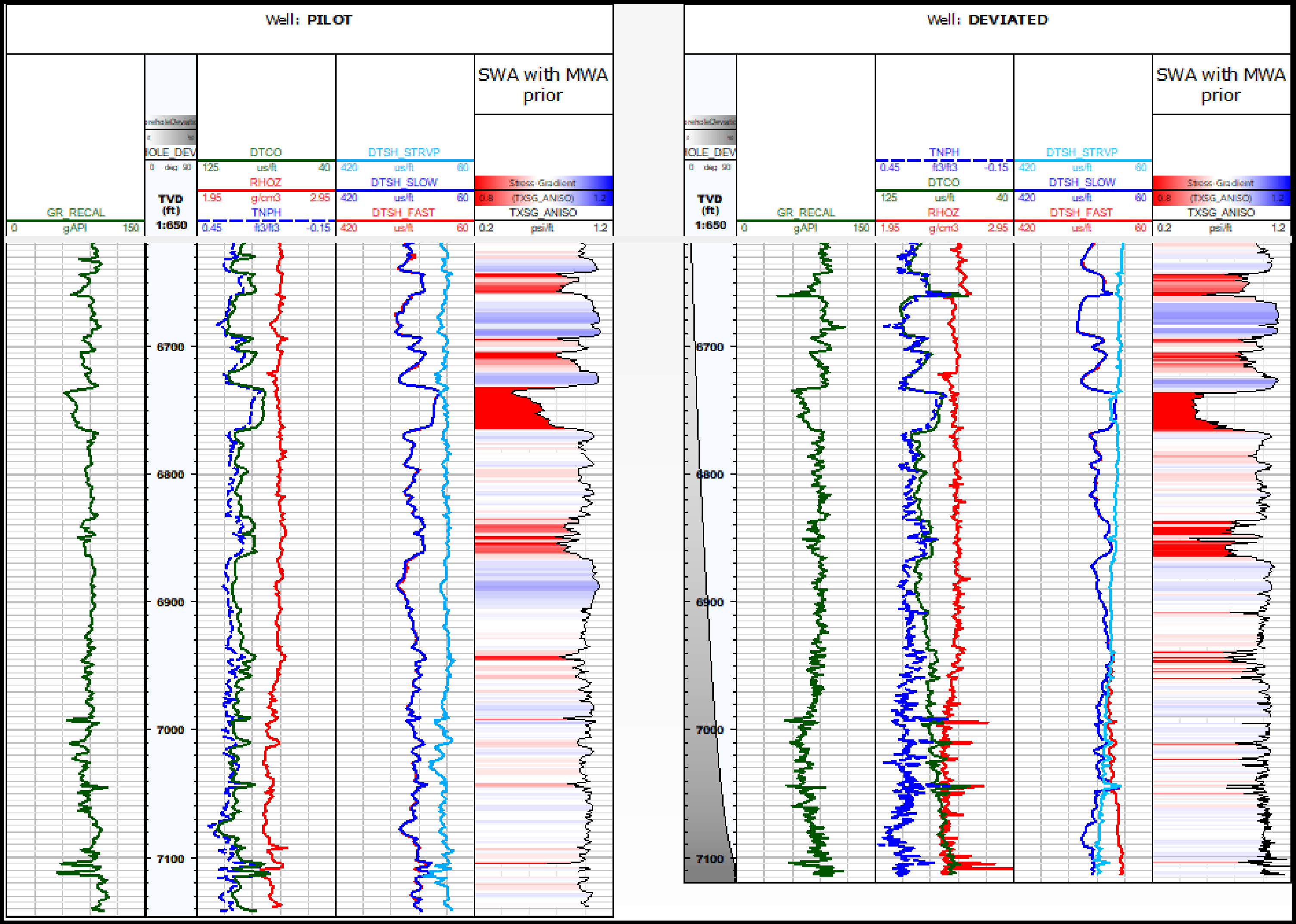




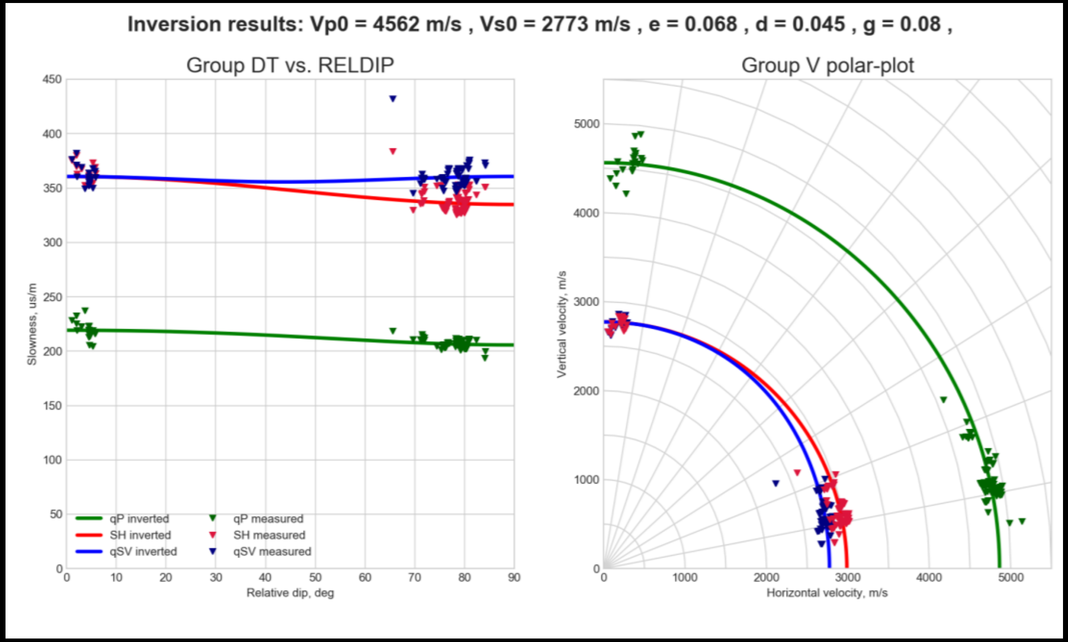
MANNIE in vertical and Deviated wells

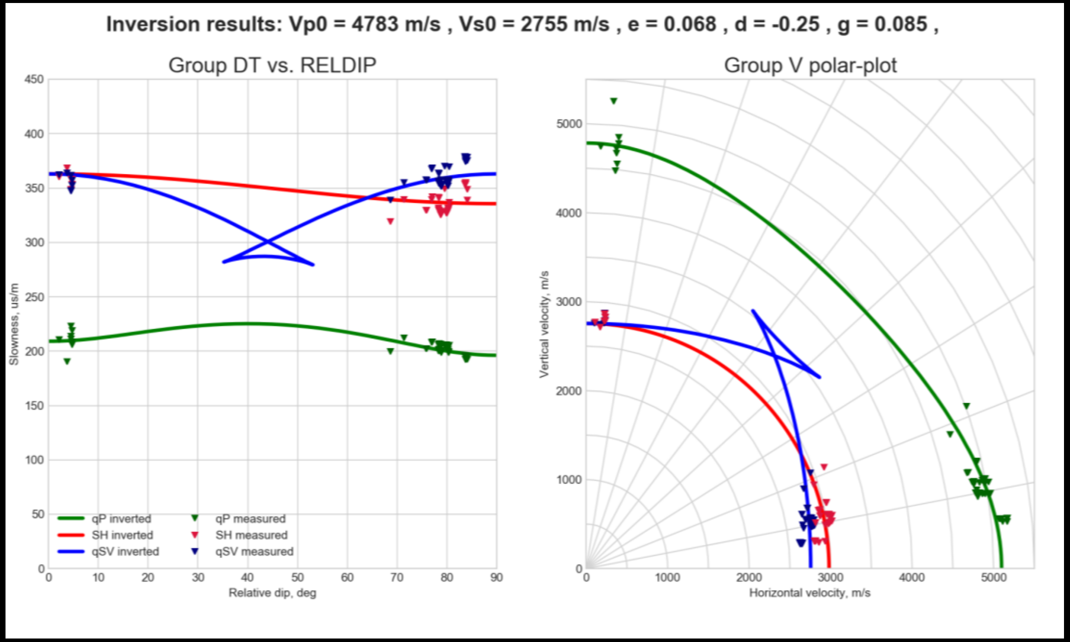


SWA (with MW prior) in vertical and Deviated wells



Messenger XTO





Thank you

Referenced publications:

- TI anisotropy characterization on basis of sonic datasets from multiple wells: A Norwegian Sea case study Jeroen Jocker*, Schlumberger and Jan Ove Hansen, Equinor
- Bayesian-type TI anisotropy characterization using depth-dependent prior information Jeroen Jocker*, Schlumberger and Jan Ove Hansen, Equinor