TI anisotropy characterization on basis of sonic datasets from multiple wells

A Norwegian Sea case study

Jeroen Jocker, Schlumberger
Jan Ove Hansen, Equinor

September 28, 2021
SEG paper ID 3594232

SEG | AAPG
image
International Meeting for Applied Geoscience & Energy

Outline

Background principles and workflow overview

- Characterization of TI anisotropic formations
  on basis of sonic datasets acquired in multiple wells

Case study

- Cape Vulture field, Norwegian Sea

Summary

Outline

Background principles and workflow overview

- Characterization of TI anisotropic formations
  on basis of sonic datasets acquired in multiple wells

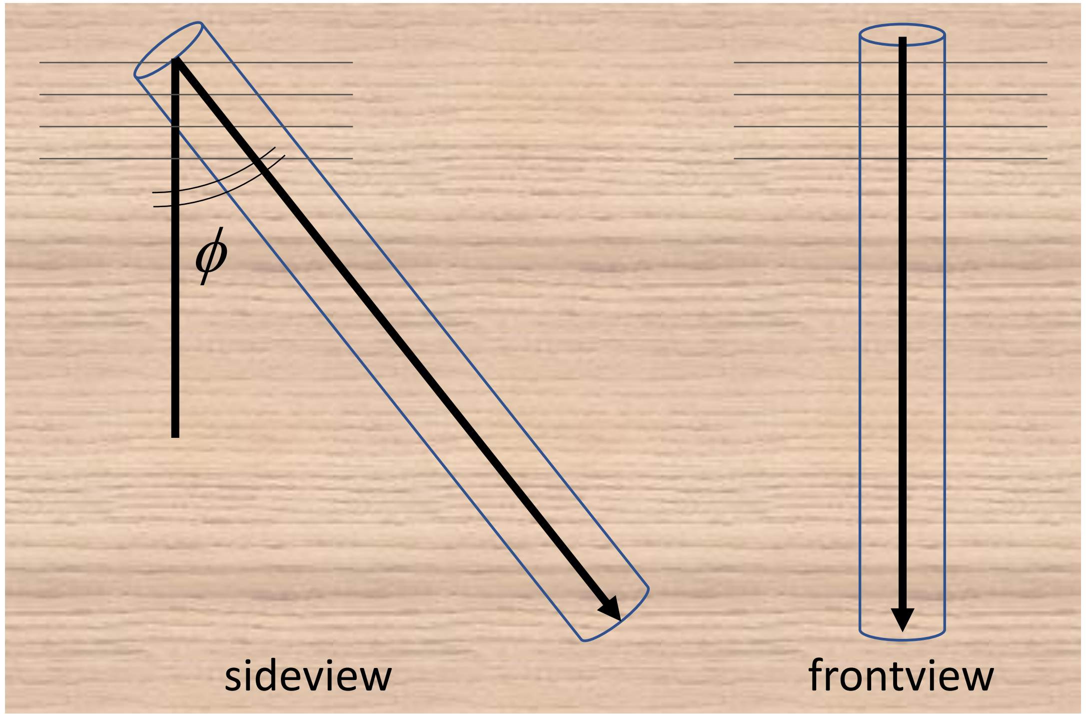
Case study

- Cape Vulture field, Norwegian Sea

Summary

Wave velocities measured by sonic

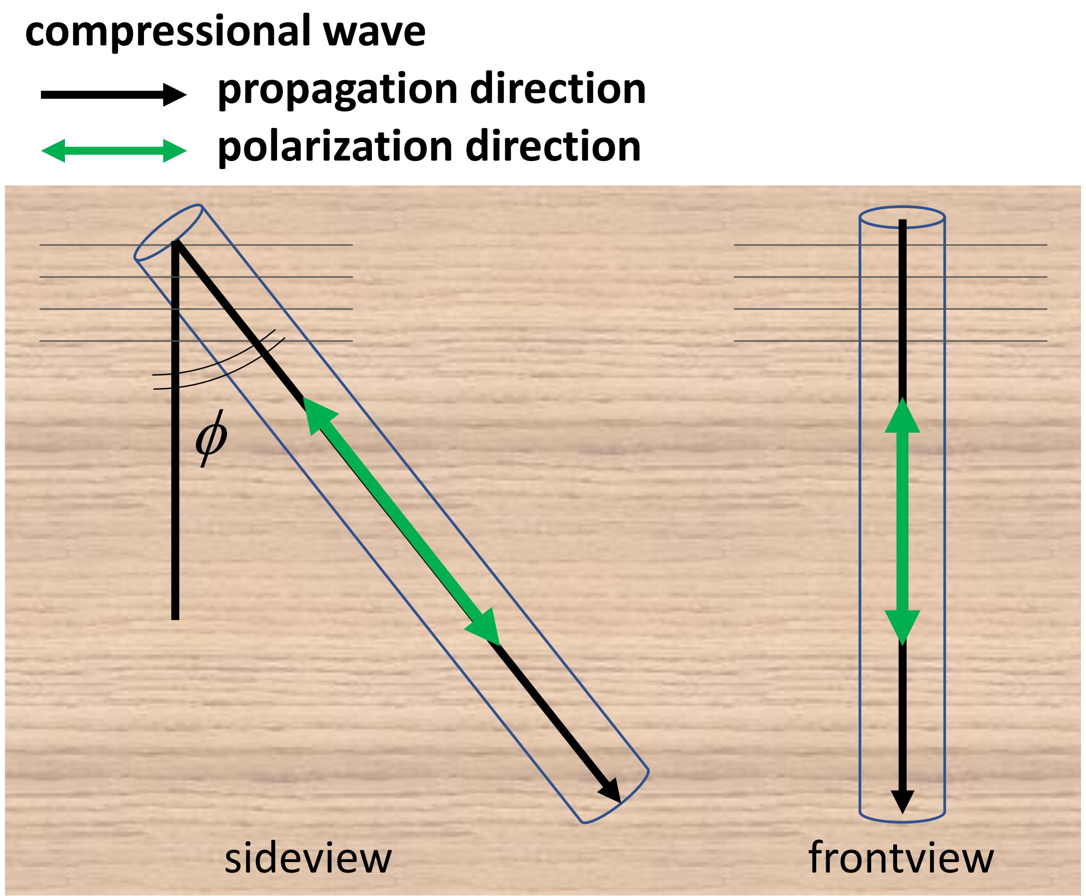
- Wellbore with deviation ϕ
- Sonic tool measures velocities of three different wavetypes traveling in the direction of the borehole
  - [assuming tool is equipped with monopole and dipole sources]
  - $Vp(\phi)$: Compressional velocity
  - $Vsv(\phi)$: SV shear velocity
  - $Vsh(\phi)$: SH shear velocity



SEG | AAPG image
International Meeting for Applied Geoscience & Energy

Wave velocities measured by sonic

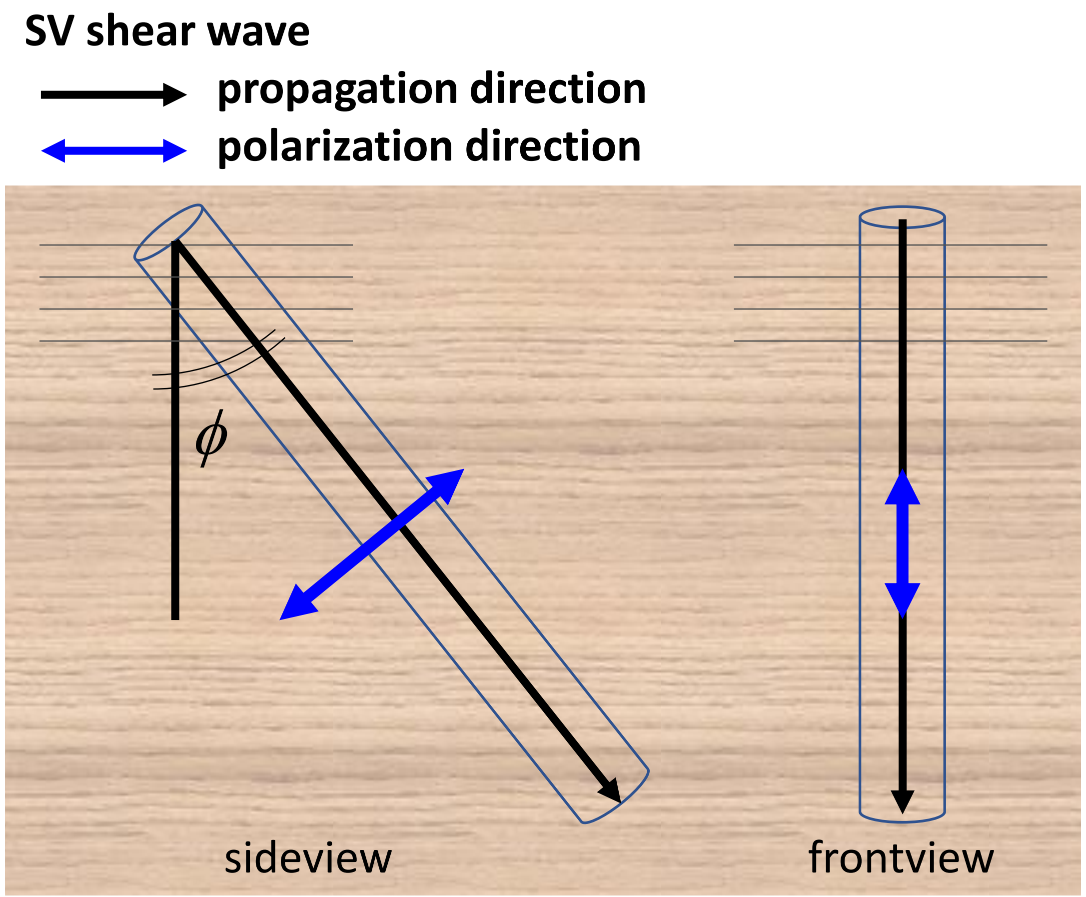
- Wellbore with deviation ϕ
- Sonic tool measures velocities of three different wavetypes traveling in the direction of the borehole
  - [assuming tool is equipped with monopole and dipole sources]
  - $Vp(\phi)$: Compressional velocity
  - $Vsv(\phi)$: SV shear velocity
  - $Vsh(\phi)$: SH shear velocity



International Meeting for Applied Geoscience & Energy

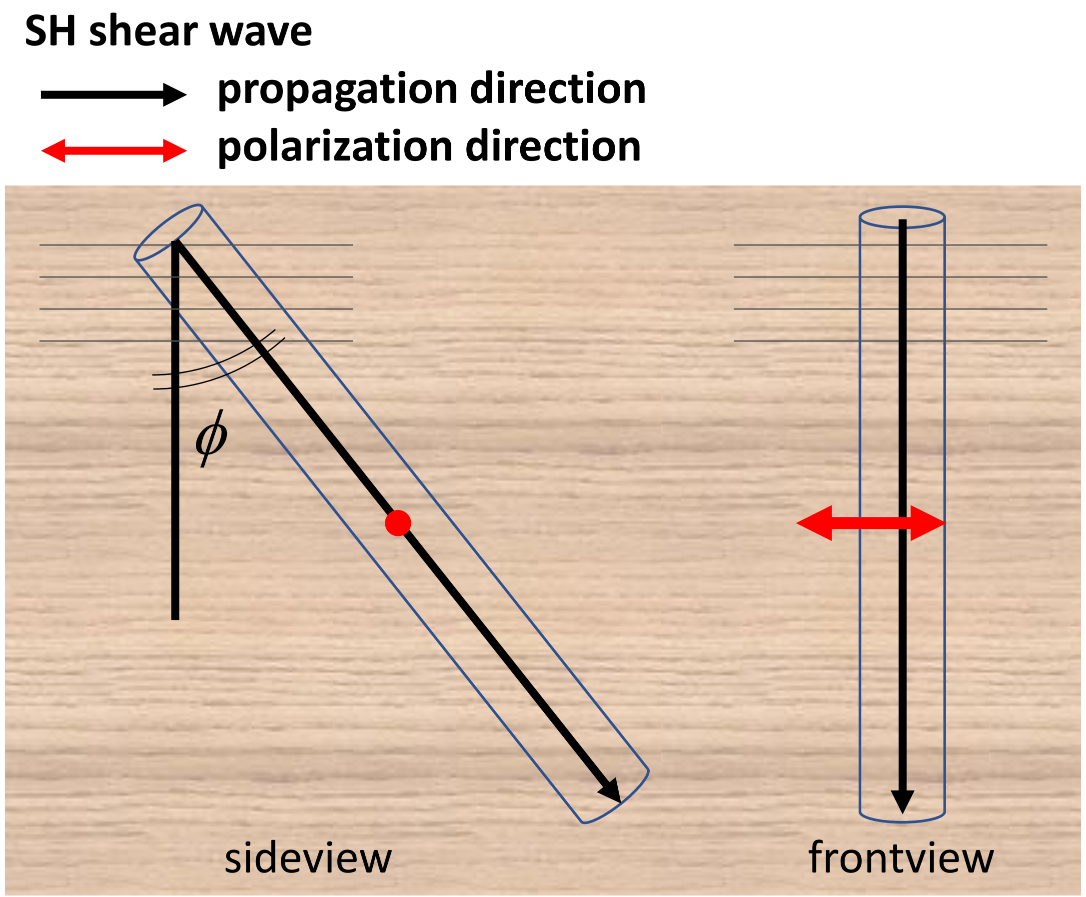
Wave velocities measured by sonic

- Wellbore with deviation ϕ
- Sonic tool measures velocities of three different wavetypes traveling in the direction of the borehole
  - [assuming tool is equipped with monopole and dipole sources]
  - $Vp(\phi)$: Compressional velocity
  - $Vsv(\phi)$: SV shear velocity
  - $Vsh(\phi)$: SH shear velocity



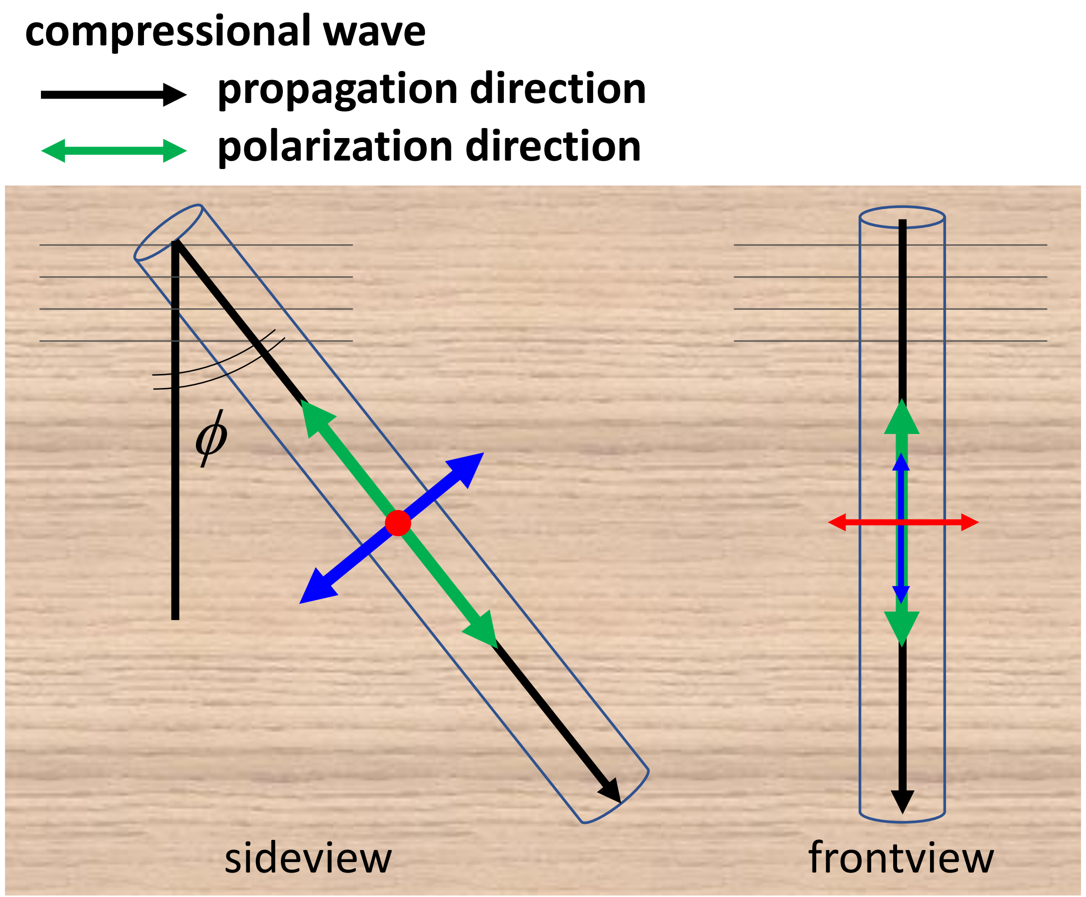
Wave velocities measured by sonic

- Wellbore with deviation ϕ
- Sonic tool measures velocities of three different wavetypes traveling in the direction of the borehole
  - [assuming tool is equipped with monopole and dipole sources]
  - Vp(ϕ): Compressional velocity
  - Vsv(ϕ): SV shear velocity
  - Vsh(ϕ): SH shear velocity



Wave velocities measured by sonic

- Wellbore with deviation ϕ
- Sonic tool measures velocities of three different wavetypes traveling in the direction of the borehole
  - [assuming tool is equipped with monopole and dipole sources]
  - Vp(ϕ): Compressional velocity
  - Vsv(ϕ): SV shear velocity
  - Vsh(ϕ): SH shear velocity
- Some tools (Sonic Scanner) can measure a fourth velocity, based on the Stoneley
  - Crucial input in vertical well datasets



Isotropic formations

Relationships between velocities and elastic stiffness

Compressional velocity V_P

$$V_P = \sqrt{\frac{M}{\rho}}$$

Shear velocity V_S

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

where M is compressional modulus, μ is shear modulus, and ρ is bulk density

Isotropic formation:

- No dependency of velocity on propagation direction ϕ
- Only two independent elastic parameters: M and μ
- Identical shear velocities: $V_{SV} = V_{SH} = V_S$

Transversely Isotropic formations

qP-Compressional velocity

Compressional phase velocity $v_{qP}(\theta)$

$$2\rho v_{qP}^2(\theta) = (C_{11} + C_{44})\sin^2\theta + (C_{33} + C_{44})\cos^2\theta + \sqrt{[(C_{11} - C_{44})\sin^2\theta - (C_{33} - C_{44})\cos^2\theta]^2 + 4(C_{13} + C_{44})^2\sin^2\theta\cos^2\theta}$$

Compressional group velocity $V_{qP}(\phi)$

$$V_{qP}\big(\phi(\theta)\big) = \sqrt{v_{qP}^2(\theta) + \left[\frac{dv_{qP}(\theta)}{d\theta}\right]^2}$$

Group angle $\phi(\theta)$ corresponding to phase angle θ

$$\tan\phi(\theta) = \left(\tan\theta + \frac{1}{v_{qP}(\theta)}\frac{dv_{qP}(\theta)}{d\theta}\right) \Big/ \left(1 - \frac{\tan\theta}{v_{qP}(\theta)}\frac{dv_{qP}(\theta)}{d\theta}\right)$$

Transversely Isotropic formations

qSV-Shear velocity

qSV shear phase velocity $v_{qSV}(\theta)$

$$2\rho v_{qSV}^2(\theta) = (C_{11} + C_{44})\sin^2\theta + (C_{33} + C_{44})\cos^2\theta$$
$$-\sqrt{[(C_{11} - C_{44})\sin^2\theta - (C_{33} - C_{44})\cos^2\theta]^2 + 4(C_{13} + C_{44})^2\sin^2\theta\cos^2\theta}$$

qSV group velocity $V_{qSV}(\phi)$

$$V_{qSV}\big(\phi(\theta)\big) = \sqrt{v_{qSV}^2(\theta) + \left[\frac{dv_{qSV}(\theta)}{d\theta}\right]^2}$$

Group angle $\phi(\theta)$ corresponding to phase angle θ

$$\tan\phi(\theta) = \left(\tan\theta + \frac{1}{v_{qSV}(\theta)}\frac{dv_{qSV}(\theta)}{d\theta}\right) \Big/ \left(1 - \frac{\tan\theta}{v_{qSV}(\theta)}\frac{dv_{qSV}(\theta)}{d\theta}\right)$$

SEG | AAPG image
International Meeting for Applied Geoscience & Energy

Transversely Isotropic formations

SH-Shear velocity

SH group velocity $V_{SH}(\phi)$

$$V_{SH}(\phi) = \sqrt{\frac{C_{44}C_{66}}{\rho(C_{44}\sin^2\phi + C_{66}\cos^2\phi)}}$$

Elastic anisotropy

Number of independent parameters

Isotropic formations

- Velocities do not vary with propagation direction ϕ
- Only 2 independent elastic parameters: M and μ

Transversely Isotropic [TI] formations

- Velocities vary with propagation direction ϕ
- 5 independent elastic parameters:
  - $C_{11}, C_{13}, C_{33}, C_{44}, C_{66}$ [Cij notation]
  - $V_{P0}, V_{S0}, \varepsilon, \delta, \gamma$ [Thomsen notation]
  - $E_V, E_H, \nu_{VH}, \nu_{HH}, C_{44}$ [Mechanical properties]

Cubic formations

- 3 independent elastic parameters

Orthorhombic formations

- 9 independent elastic parameters

Monoclinic formations

- 13 independent elastic parameters

Triclinic formations

- 21 independent elastic parameters

SEG | AAPG image
International Meeting for Applied Geoscience & Energy

Elastic anisotropy

Number of independent parameters

Isotropic formations

- Velocities do not vary with propagation direction ϕ
- Only 2 independent elastic parameters: M and μ

Transversely Isotropic [TI] formations

- Velocities vary with propagation direction ϕ
- 5 independent elastic parameters:
  - $C_{11}, C_{13}, C_{33}, C_{44}, C_{66}$ [Cij notation]
  - $V_{P0}, V_{S0}, \varepsilon, \delta, \gamma$ [Thomsen notation]
  - $E_V, E_H, \nu_{VH}, \nu_{HH}, C_{44}$ [Mechanical properties]

Case study assumption

- Formations behave, to first-order, as transversely isotropic systems
  - This includes isotropy as a special case

Not all formations behave as TI systems

- But many do, including most shales

More complex formations require more complex characterizations

- In practice this may often not be feasible

Sonic-based TI anisotropy characterization

TI Anisotropic parameters from sonic

- Sonic can provide 3 independent measurements for a single angle ϕ
  - $V_{qP}(\phi), V_{qSV}(\phi), V_{SH}(\phi)$
- TI formations have 5 independent elastic parameters
  - $C_{11}, C_{13}, C_{33}, C_{44}, C_{66}$
- Under-determined inversion problem

Approach 1 – Models

- Reduction of number of independent parameters from 5 to 3
- e.g. ANNIE
  - $\delta = 0$
  - $C_{13} = C_{11} - 2C_{66}$

Approach 2 - Multi-well analysis

Combine data from different wells acquired in the same formation but at different angles

Sonic-based TI anisotropy characterization

TI Anisotropic parameters from sonic

- Sonic can provide 3 independent measurements for a single angle ϕ
  - $V_{qP}(\phi), V_{qSV}(\phi), V_{SH}(\phi)$
- TI formations have 5 independent elastic parameters
  - $C_{11}, C_{13}, C_{33}, C_{44}, C_{66}$
- Under-determined inversion problem

Approach 1 – Models

- Reduction of number of independent parameters from 5 to 3
- e.g. ANNIE
  - $\delta = 0$
  - $C_{13} = C_{11} - 2C_{66}$

Approach 2 - Multi-well analysis

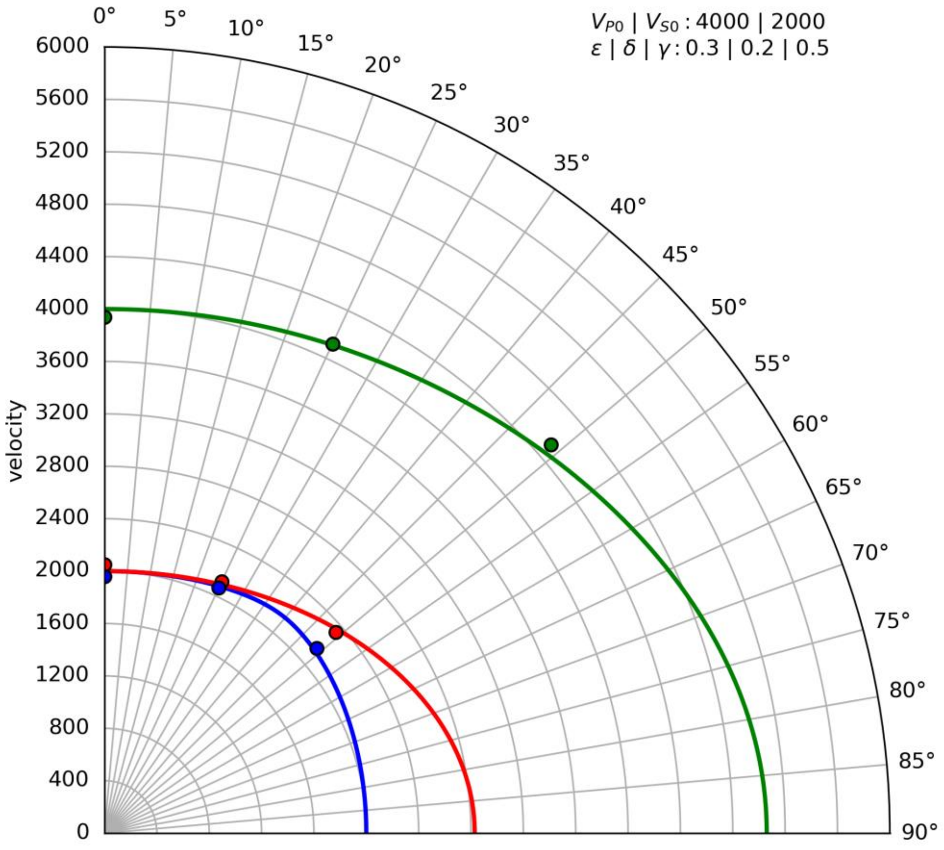
Combine data from different wells acquired in the same formation but at different angles

this study

Multi-well sonic data

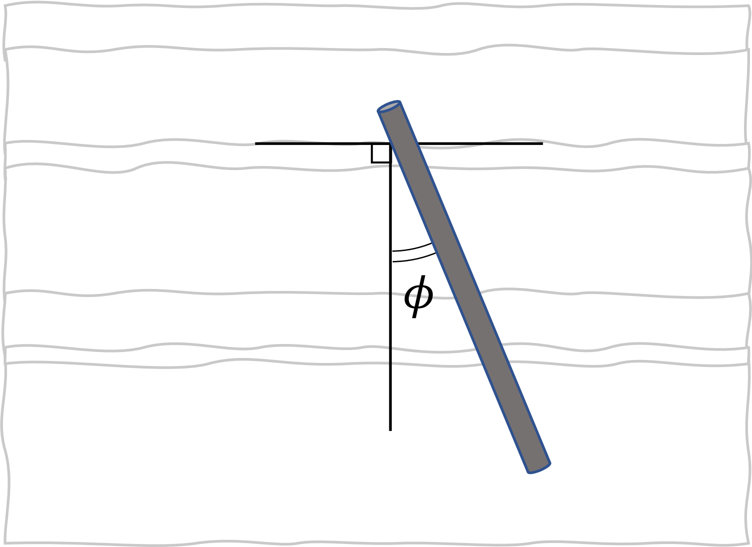
Display on a polar velocity plot

- Polar plot of velocities acquired in 3 different wells
  - Vertical well
  - Well at 25 degrees deviation
  - Well at 49 degrees deviation
- Sonic velocities available in all three wells
  - 3x3 = 9 velocity measurements
- 9 measurements versus
  5 unknown TI parameters: problem is constrained

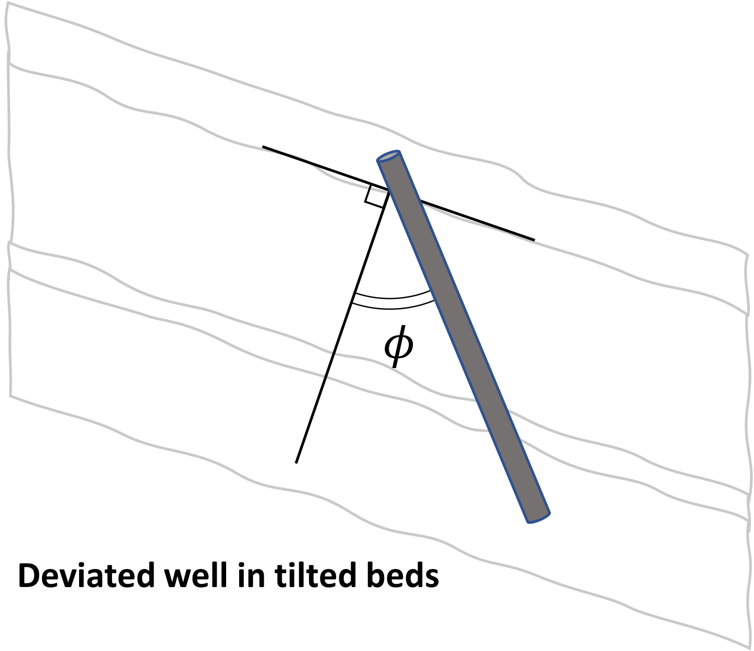


Definition of angle ϕ

- Angle ϕ corresponds to angle between wellbore and TI symmetry axis
  - Also referred to as relative dip or apparent dip
- Examples
  - A well drilled perpendicular to shale bedding: $\phi = 0$ degrees
  - A well drilled parallel to shale bedding: $\phi = 90$ degrees
- Bedding orientation data
  - Borehole images
  - Triaxial induction tool (case study)
  - Assumptions



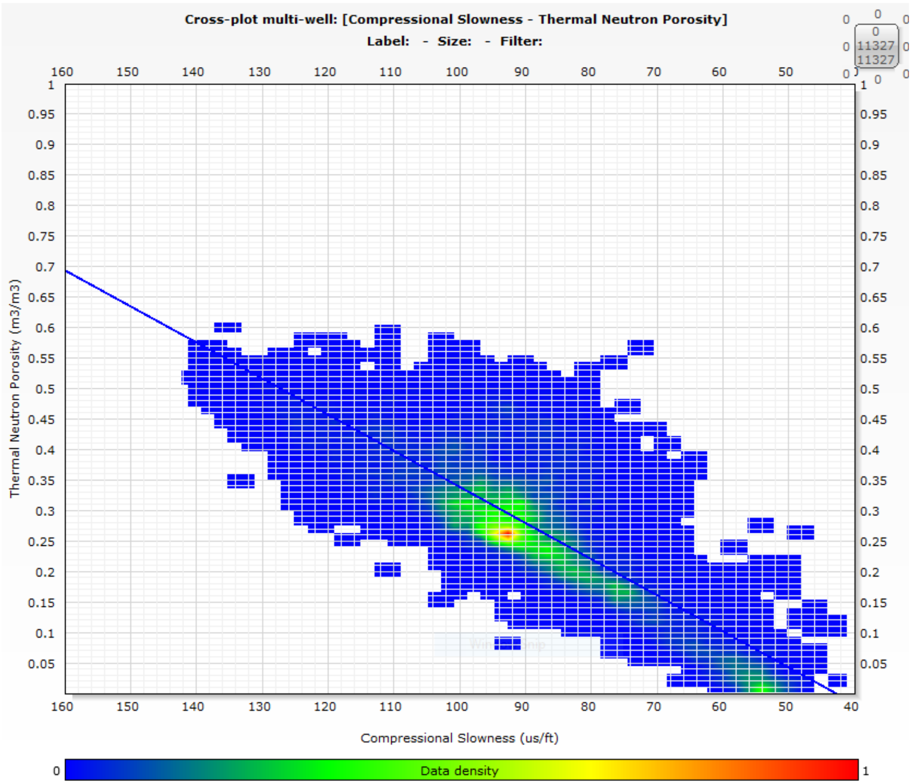
Deviated well in horizontal beds



Deviated well in tilted beds

Formation heterogeneity

- Multi-well workflow built on principle of combining velocity data from different wells and different depths
- Formations are usually not homogeneous
    - Velocity variation due to formation changes often more significant than variation due to anisotropy

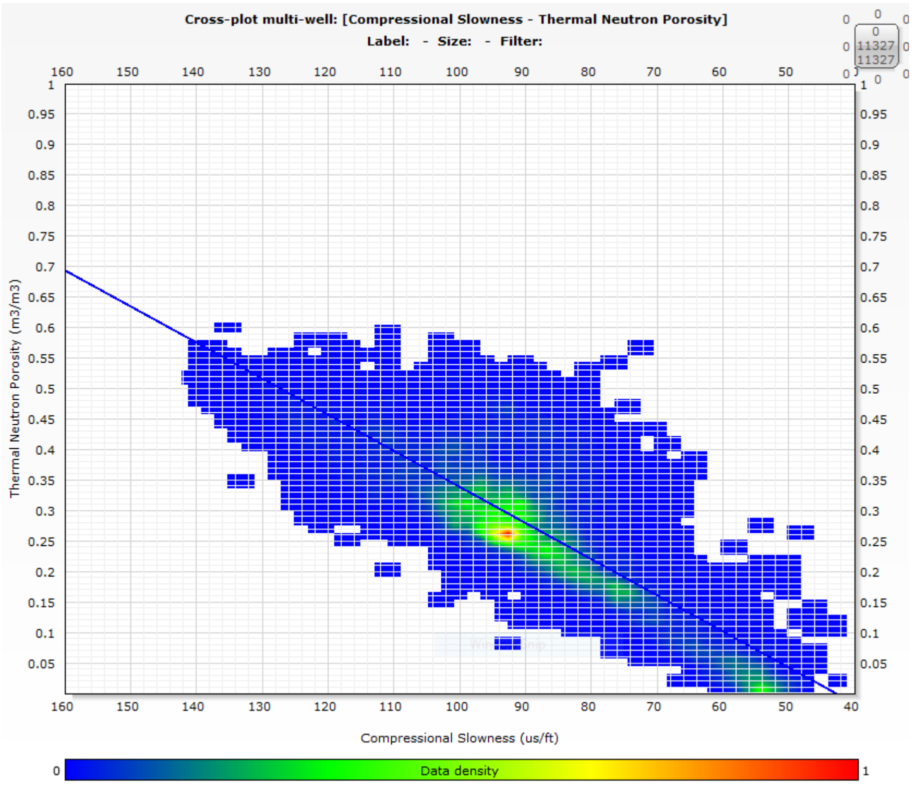


Correlation between compressional slowness and neutron porosity

Clustering

Goal: Reduce velocity variations resulting from formation heterogeneity

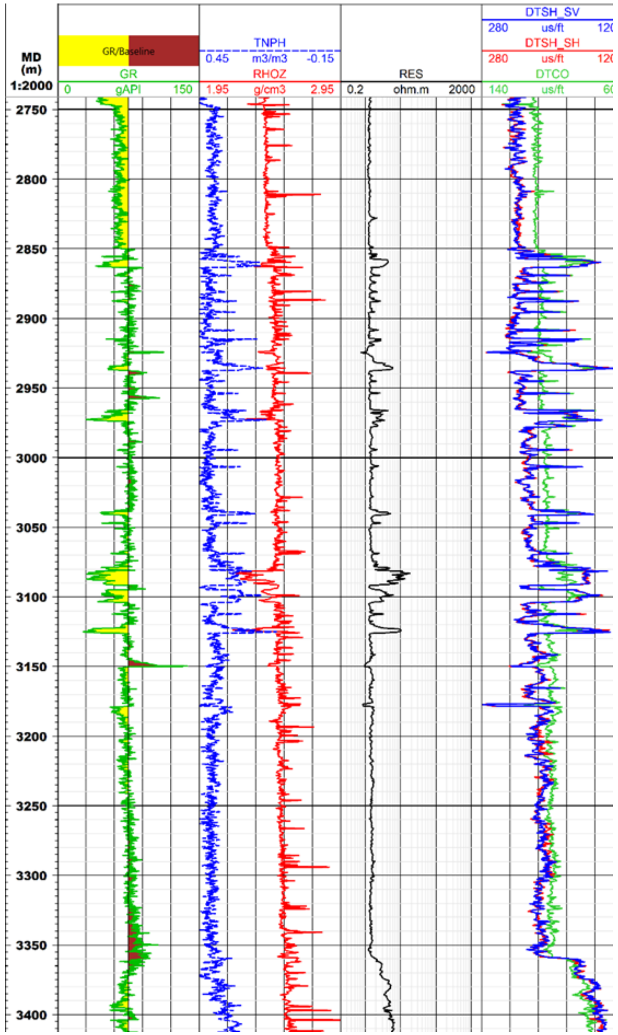
- What?
  - Prior to multi-well analysis, remove velocity variations due to formation changes
- How?
  - Clustering of sonic velocities on basis of independent data such as density and neutron porosity (so-called “cluster parameters”)



Correlation between compressional slowness and neutron porosity

Cluster parameter requirements

- Sonic data commonly acquired in combination with other measurement types
- Velocities are clustered using curves that meet the following criteria:
  - available in all datasets in the study scope
  - measured independently from the sonic data
  - scalar properties without sensitivity to measurement direction
  - good correlation with sonic velocities



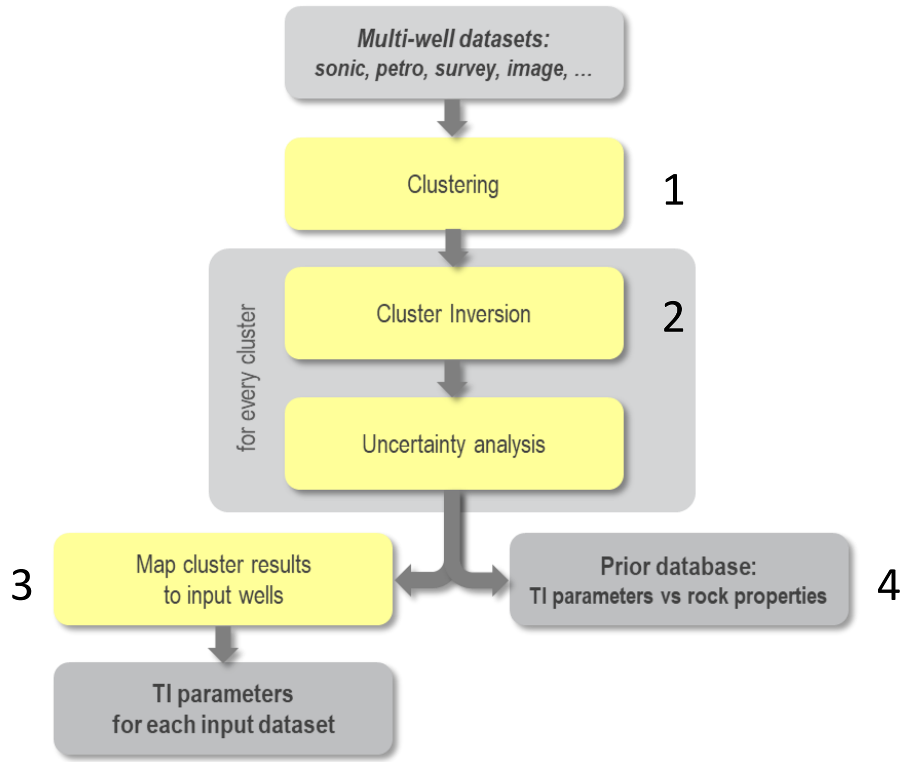
Sonic data are commonly acquired in combination with other types of logs such as gamma ray, density, neutron porosity, and resistivity

SEG | AAPG image International Meeting for Applied Geoscience & Energy

Workflow overview

TI characterization on basis of sonic datasets from multiple wells

1. Definition of clusters
   - Result: Sets of velocity data from depths with similar values for (for example) density and neutron porosity
2. Cluster inversion
   - Result: A set of (five) independent TI parameters for each cluster
3. Mapping of cluster inversion results to input wells
   - Continuous TI parameters along each input well/section
4. Create table of TI parameter sets versus cluster parameter values
   - Multiple purposes, for example for use as prior information in single-well type anisotropy inversions



Workflow for characterization of TI anisotropic formations on basis of sonic datasets acquired in multiple wells

Outline

Background principles and workflow overview

- Characterization of TI anisotropic formations on basis of sonic datasets acquired in multiple wells

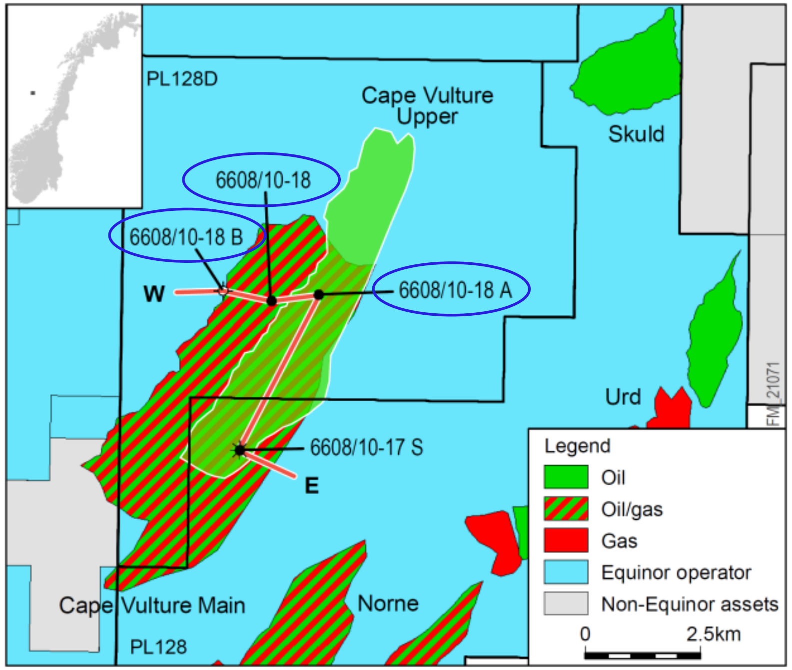
Case study

- Cape Vulture field, Norwegian Sea

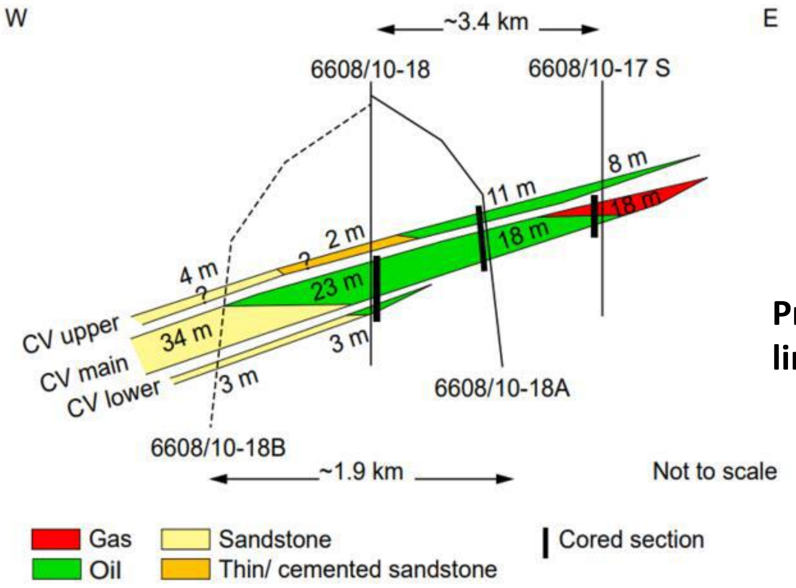
Summary

Cape Vulture

- Cape Vulture discovery located in Norwegian Sea
  - Extensive data acquisition program
- Dipole sonic logs in all wells
  - One vertical well
    - 6608/10-18
  - Two deviated wells (30-40 deg)
    - 6608/10-18A
    - 6608/10-18B



Cape Vulture map with study well locations



Profile along red contour line on map above

Khan, M. I., Datir, H., Sarkar, S., and Rafaelsen, B., 2021: Deciphering a low resistivity pay to derisk a discovery – Case study from the Norwegian Sea: SPWLA 62nd Annual Logging Symposium.

SEG | AAPG image International Meeting for Applied Geoscience & Energy

Sonic vs deviation

Larger velocities in deviated wells

Cape Vulture velocity data for:

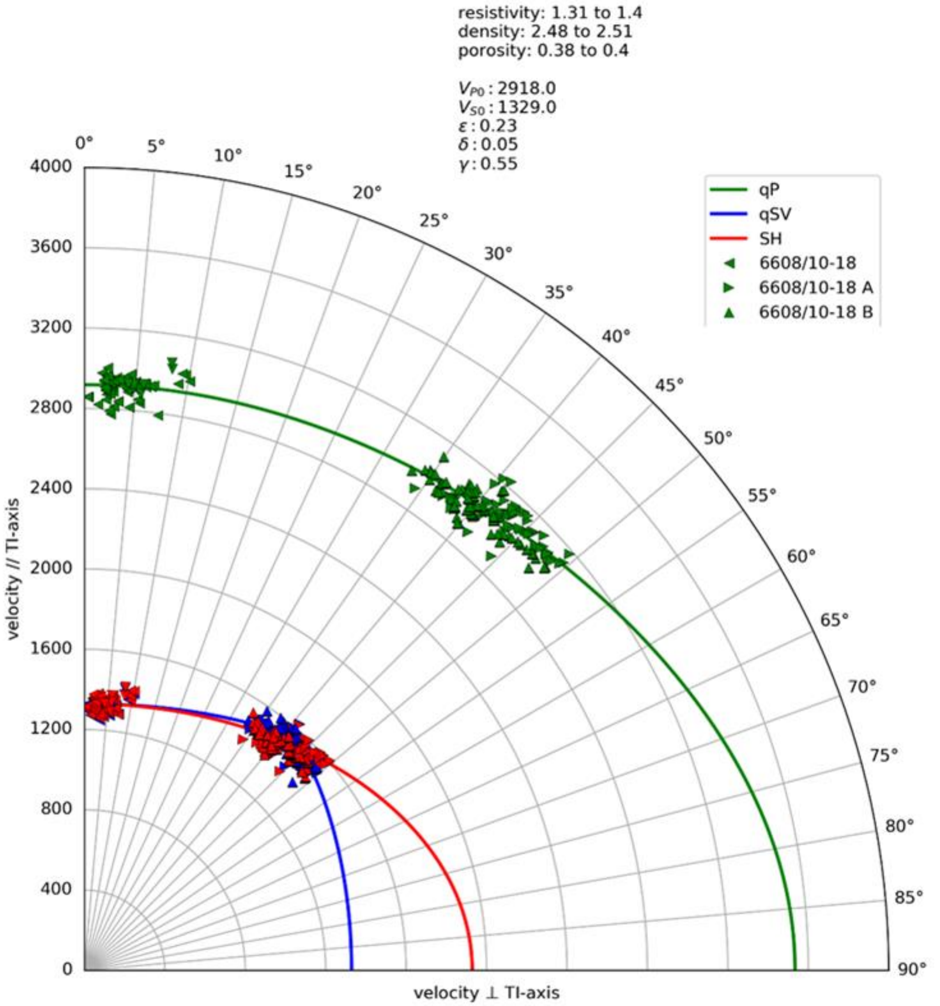
- 1.31 < resistivity < 1.4
- 2.48 < density < 2.51
- 0.38 < neutron porosity < 0.4

Observation

- Velocities larger in deviated wells

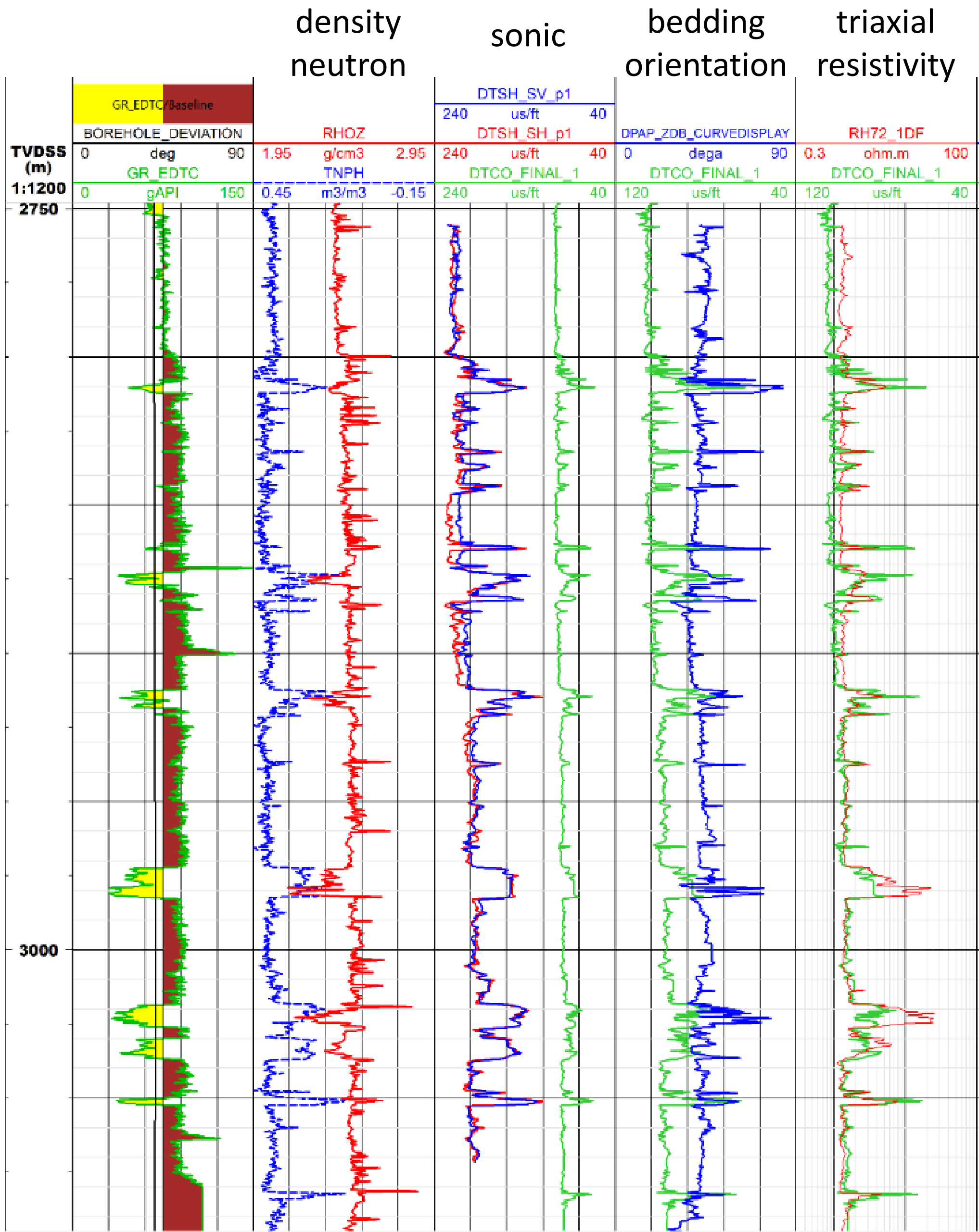
Study objective

- Obtain consistency between logs from different wells
- What can the logs tell us about the anisotropic properties of these rocks?



Types of data acquisition

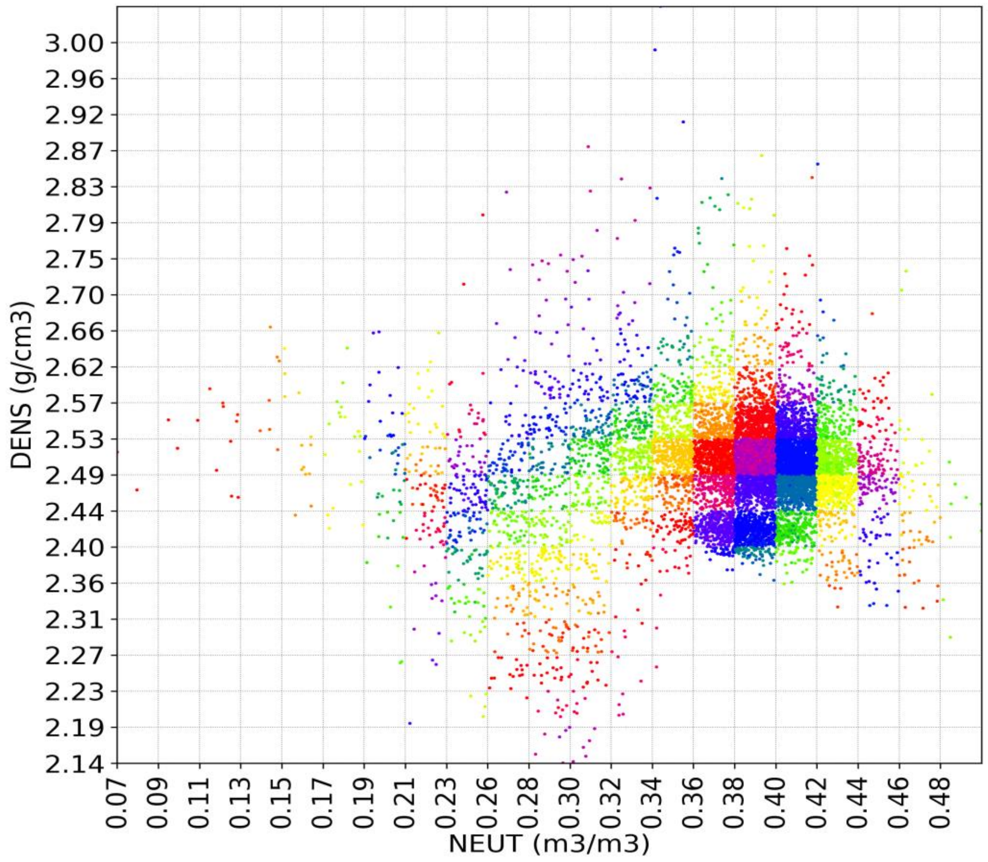
- High-quality open hole datasets acquired in multiple wells drilled at different deviations
  - Dipole sonic data to provide:
    - Compressional slowness
    - SH and SV (dipole) shear slowness
  - Triaxial resistivity data to provide:
    - Resistivity parallel and perpendicular to bedding
    - Orientation of the resistivity tensor
      - Assumption: Elastic tensor is aligned with resistivity tensor
  - Neutron porosity and density to provide:
    - Ability to cluster data into bins with similar petrophysical properties
      - In combination with horizontal resistivity
    - Statistical relationships with anisotropic elastic properties



Composite of study input data for well 6608/10-18 A

Definition of clusters

- Combined datasets from 3 wells clustered on basis of density, neutron porosity and (horizontal) resistivity
  - Total of 975 clusters defined
  - Each point originates from one of 3 wells, acquired in very similar rocks but at different orientation
- Grid-based approach

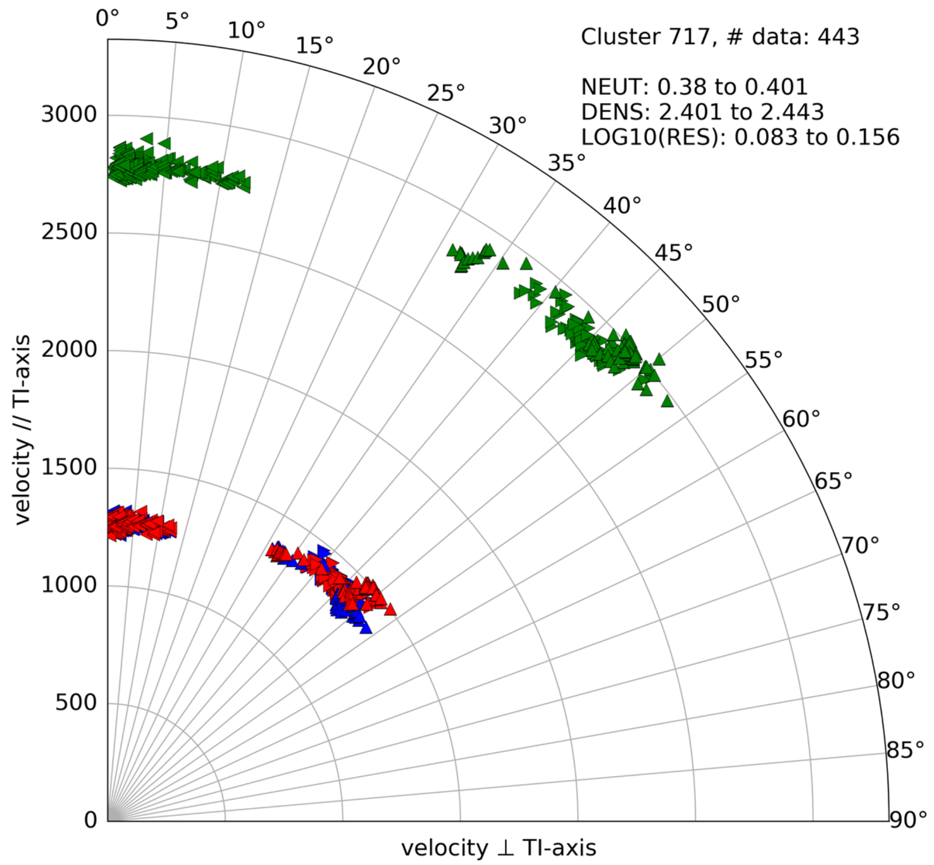


A grid-based approach is used to jointly cluster the datasets from the three input wells. In the crossplot, each cluster has a unique color. Similar crossplots can be made for porosity vs resistivity and density vs resistivity.

Cluster example

- Polar plot of velocity data contained in one of the clusters
  - 0.083 < log10(res) < 0.156
  - 2.401 < density < 2.443
  - 0.380 < neutron porosity < 0.401

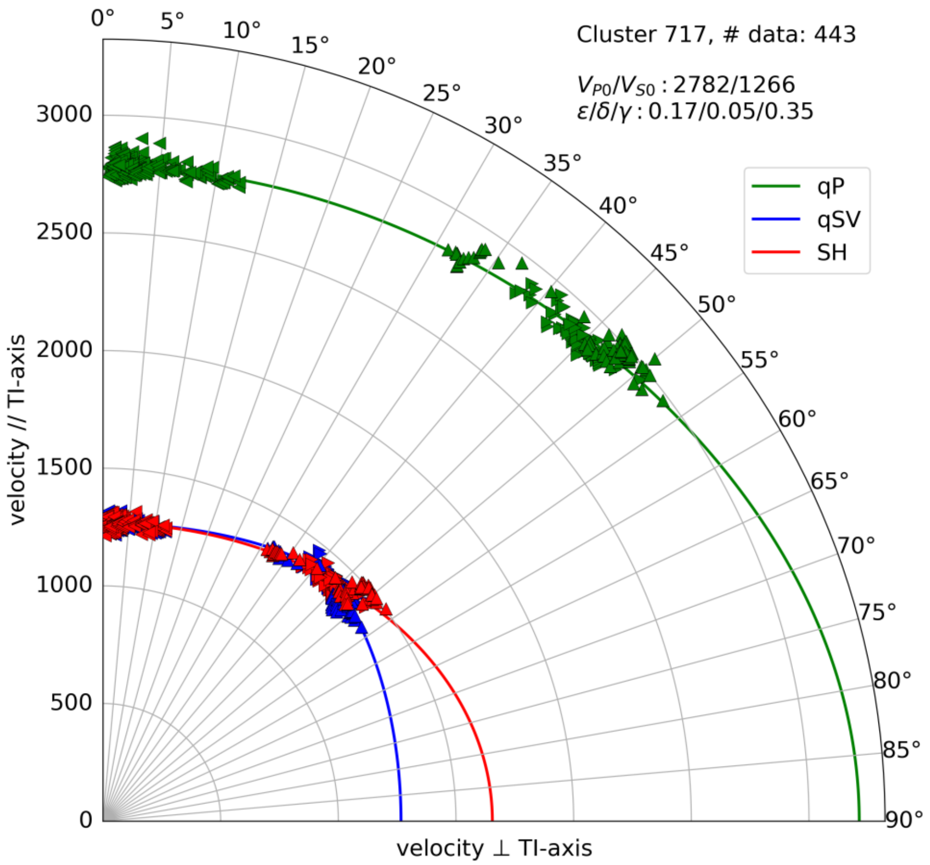
- TI properties obtained by fitting synthetic velocity curves through the measurements
  - Iterative inversion using downhill simplex method



Cluster example - This specific cluster contains data from a total of 443 depths from the 3 wells combined

Cluster example

- Solid lines drawn through the velocity data correspond to a medium with TI properties:
  - V_{P0}, V_{S0}: 2782, 1266
  - ε, δ, γ: 0.17, 0.05, 0.35

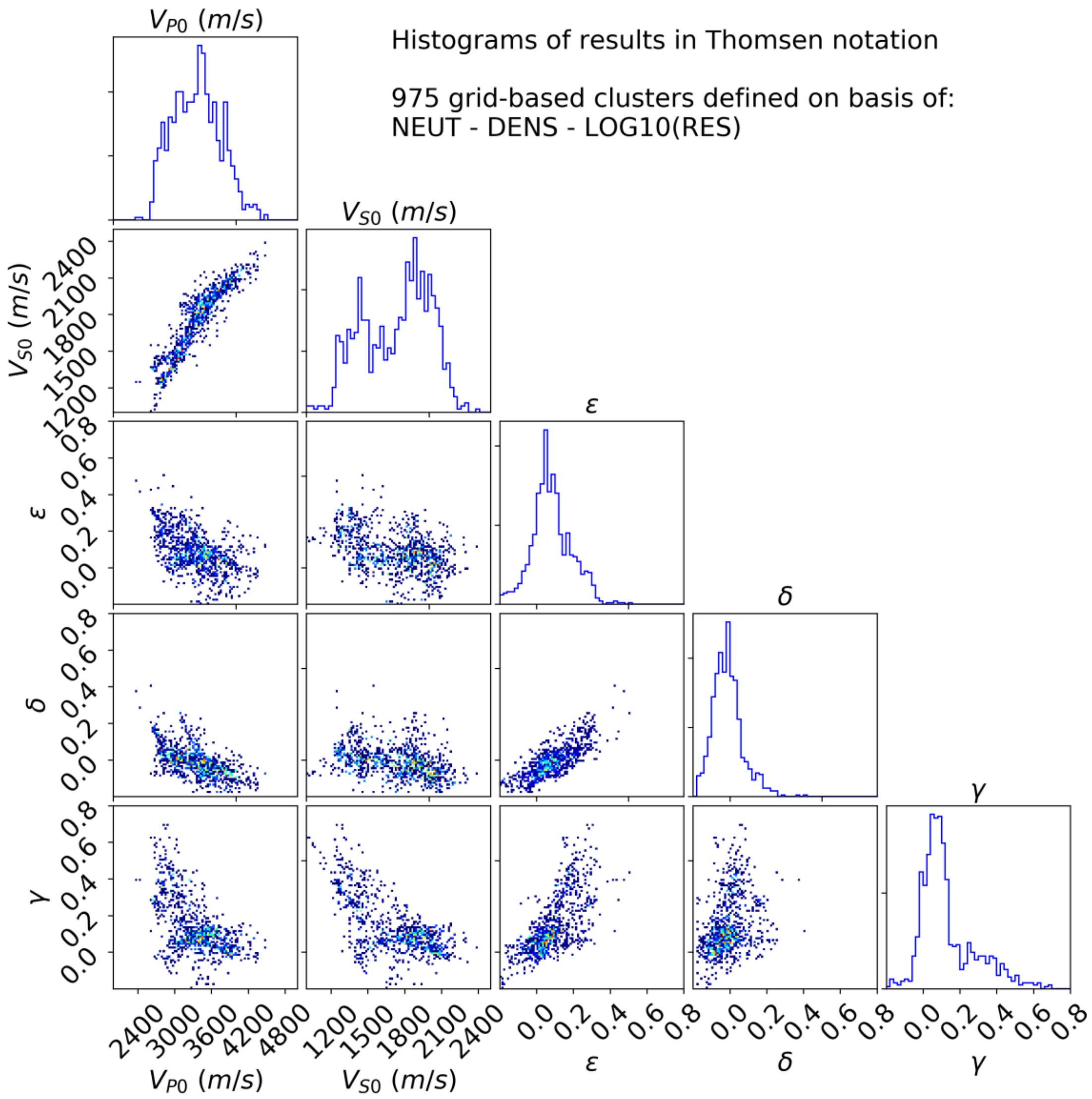


Cluster example - This specific cluster contains data from a total of 443 depths from the 3 wells combined

Cluster inversion results

Crossplots

- Each cluster inversion yields a set of 5 independent TI elastic constants
- 975 clusters: 975 sets of TI constants

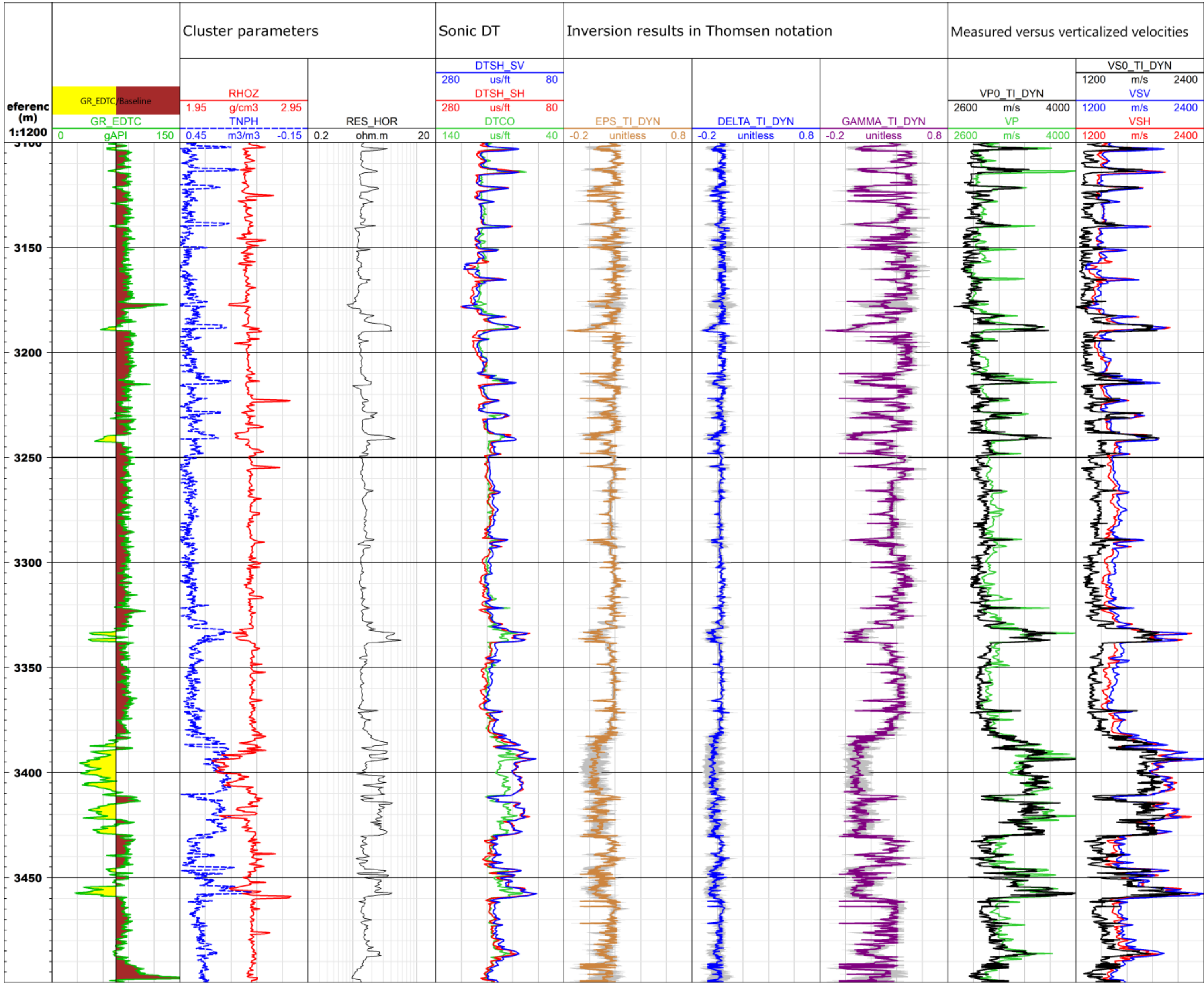


Crossplots of cluster inversion results in Thomsen notation

Inversion results

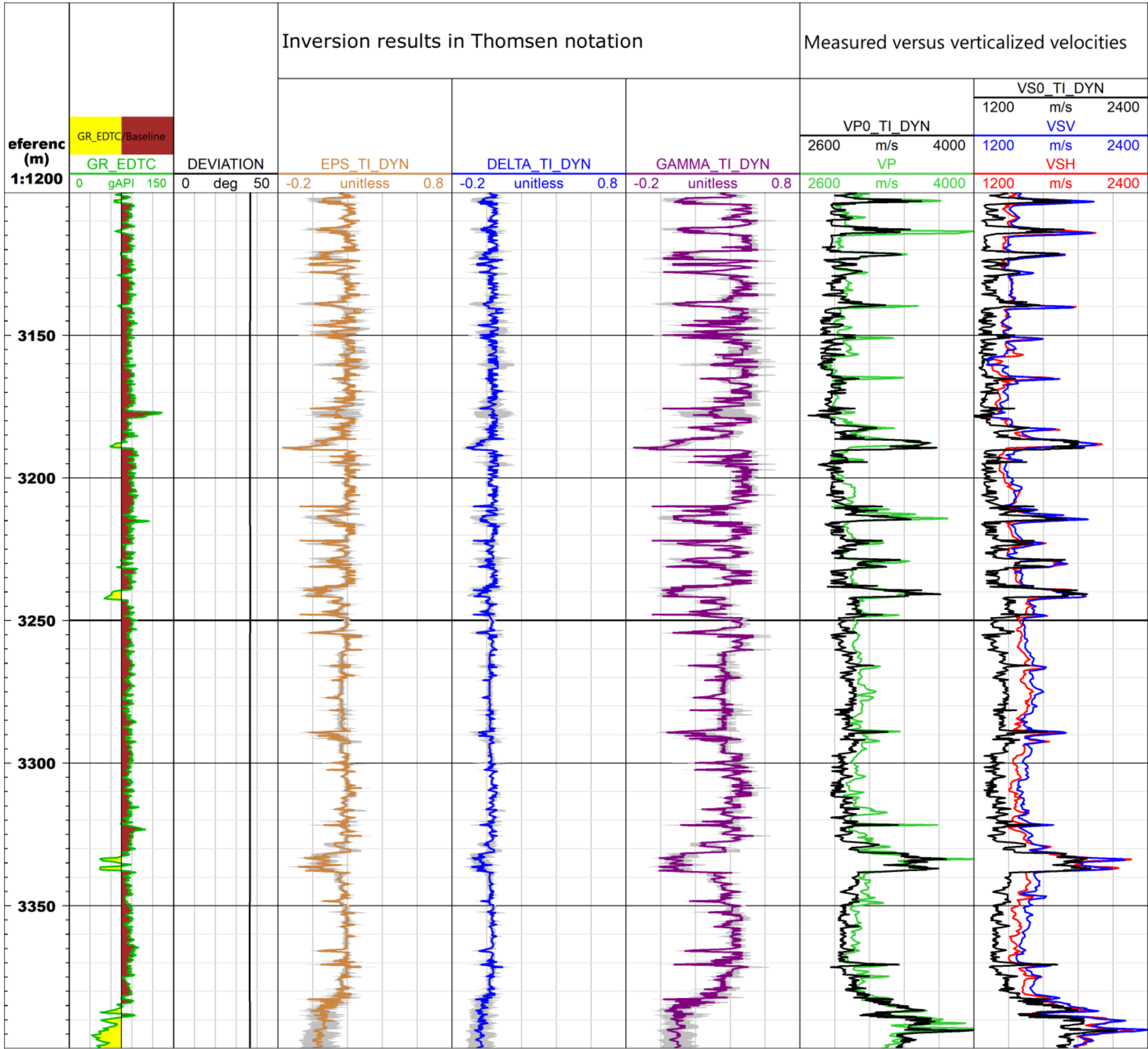
Mapped back to input wells

- Cluster inversion inputs and results for well 6608/10-18B
- Independent TI elastic properties as function of depth
- Uncertainties estimated using MCMC analysis
  - shaded areas in Thomsen parameter tracks



Vertical velocities

- Two tracks on the right:
  - Verticalized velocities in black
    - Thomsen V_{P0} and V_{S0}
  - Measured velocities in color
- Interval is 37 degrees deviated



Vertical velocities

- Significant differences between vertical and deviated velocities
  - Large correction across shales
    - 100m/s for compressional, 200m/s for shear
  - No correction across sands
- Note: Verticalization changes impedance contrasts
- Cluster approach ensures consistency between wells

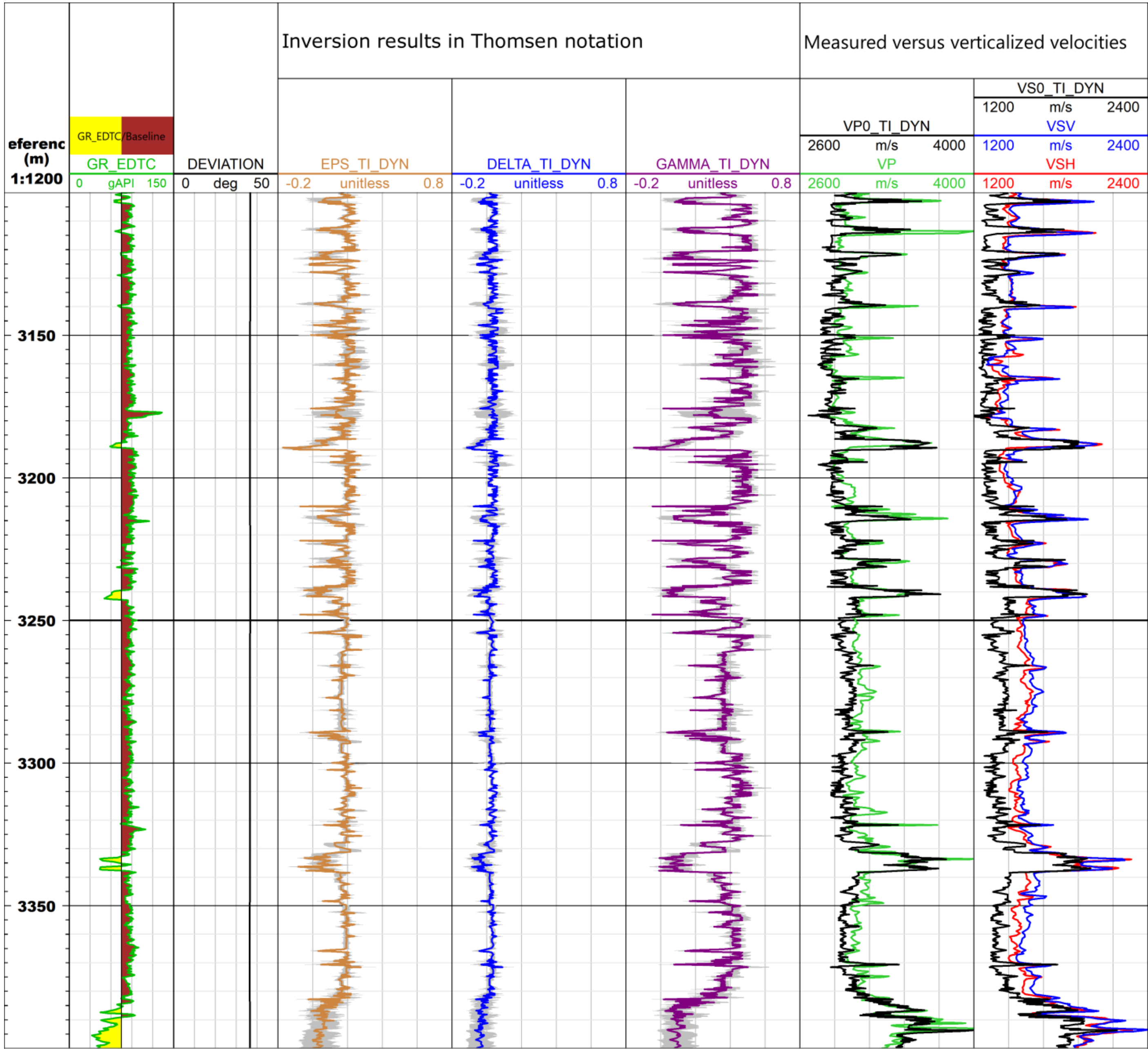


Table of TI constants

- Each cluster inversion yields a set of 5 independent TI elastic constants
- 975 clusters: 975 sets of TI constants
- For each set: corresponding neutron porosity, density and (horizontal) resistivity

cluster number	<NEUT> (m3/m3)	<RHOZ> (g/cm3)	<RES> (ohm.m)	VP0 (m/s)	VS0 (m/s)	eps (-)	delta (-)	gamma (-)
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
103	0.233	2.456	3.518	3450.1	1859.9	0.092	0.006	0.084
104	0.222	2.468	4.46	3449	1951	0.105	-0.009	0.072
105	0.227	2.47	5.437	3532.6	1893.4	0.086	-0.015	0.098
106	0.229	2.465	5.812	3439.6	2037.7	0.139	0.131	0.037
107	0.218	2.471	9.618	3891.1	2063.6	0.093	-0.055	0.107
109	0.221	2.496	1.298	2987.9	1476.7	0.013	0.009	-0.007
110	0.222	2.504	1.624	3514.2	1899.7	0.053	0.015	0.075
111	0.223	2.488	2.187	3573.1	1950.9	0.088	0.001	0.103
112	0.22	2.492	2.772	3725	2002.3	0.047	0.023	0.097
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Cluster inversion results table where each row corresponds to a single cluster, relating the means of the clustering parameters to the TI parameter inversion results

Outline

Background principles and workflow overview

- Characterization of TI anisotropic formations
  on basis of sonic datasets acquired in multiple wells

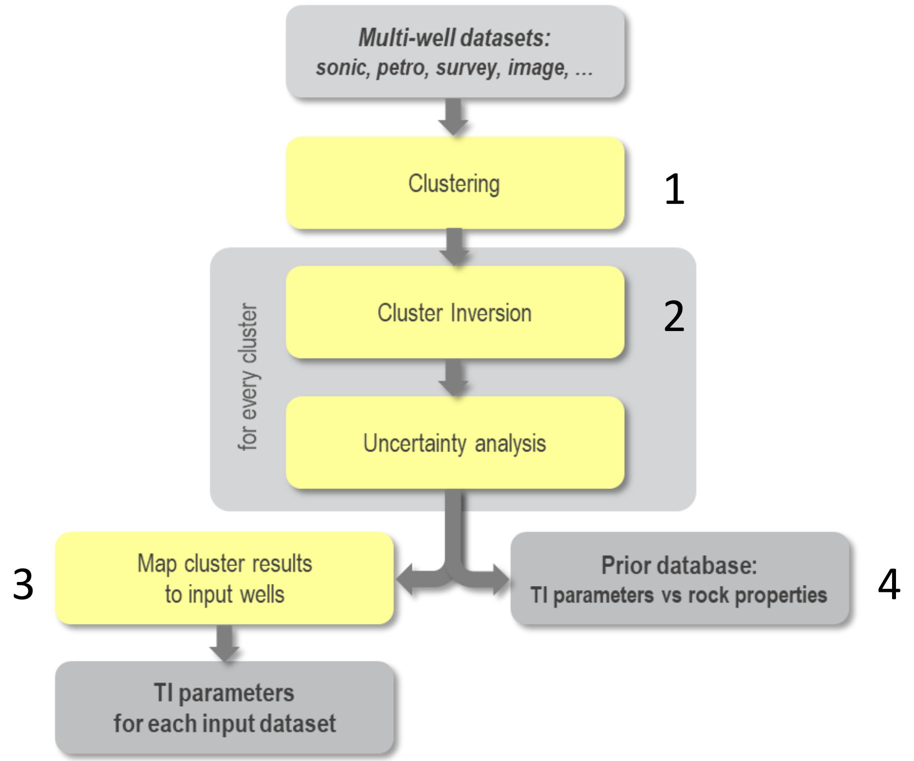
Case study

- Cape Vulture field, Norwegian Sea

Summary

Summary

- Cape Vulture observation: Sonic data in deviated wells faster than in vertical wells
- Workflow applied to characterize in-situ elastic TI anisotropy and to obtain consistency between multi-well datasets regardless of wellbore orientation
  1. Cluster sonic velocities on basis of independent measurements (the “cluster parameters”)
  2. Invert each cluster to obtain a set of independent TI parameters per cluster
  3. Map inversion results back to input wells
  4. Create table of TI results and cluster parameters



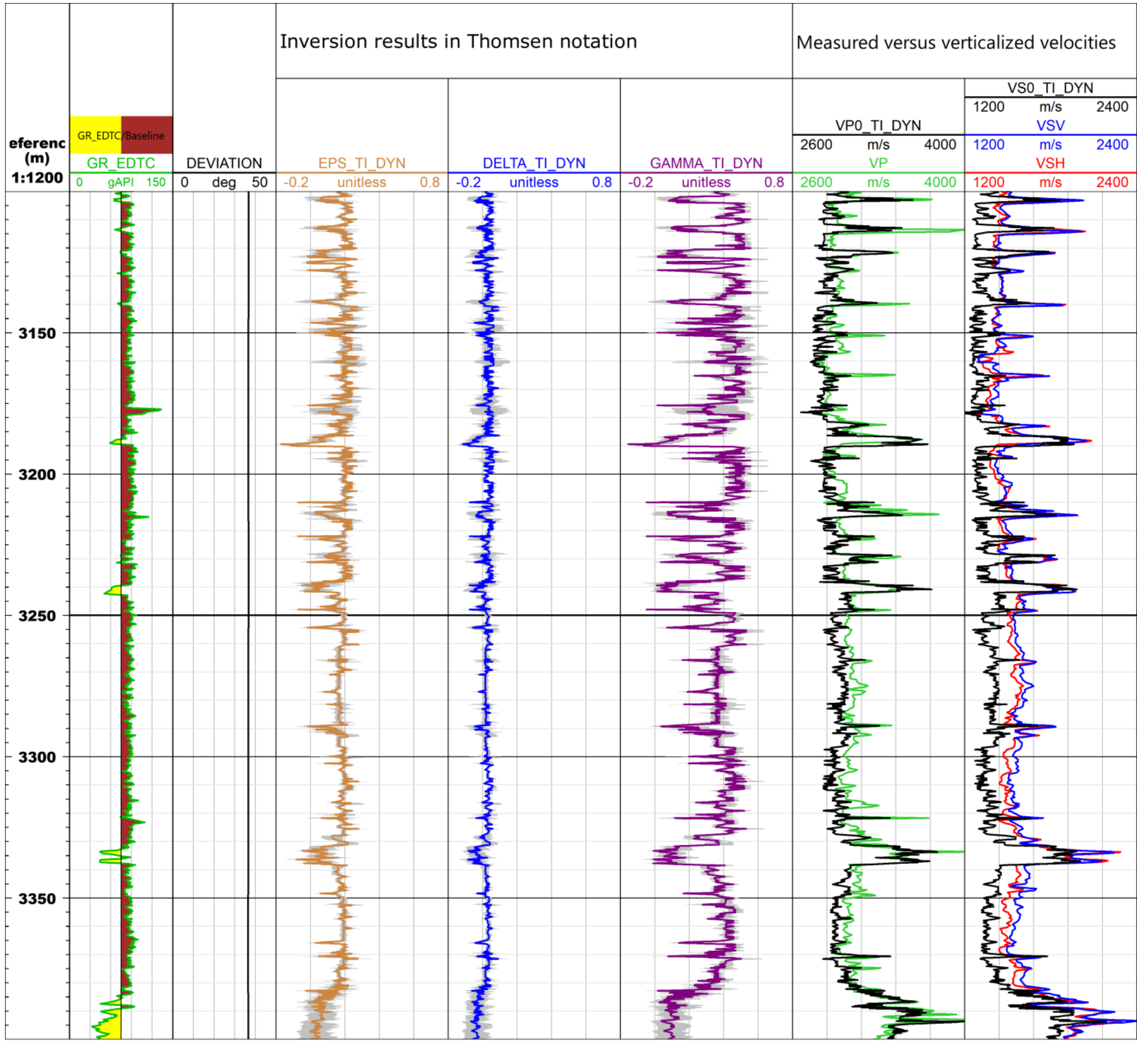
Workflow for characterization of TI anisotropic formations on basis of sonic datasets acquired in multiple wells

Summary

Anisotropy effect compared to vertical data

- Up to 100m/s for deviated compressional log
- Up to 200m/s for deviated shear log

Verticalization makes shales slower compared to sands: Impedance contrasts changed



SEG | AAPG image
International Meeting for Applied Geoscience & Energy

Thank you

Multi-well Anisotropy Characterization

Upscaling

Sonic anisotropy results upscaled to seismic wavelength

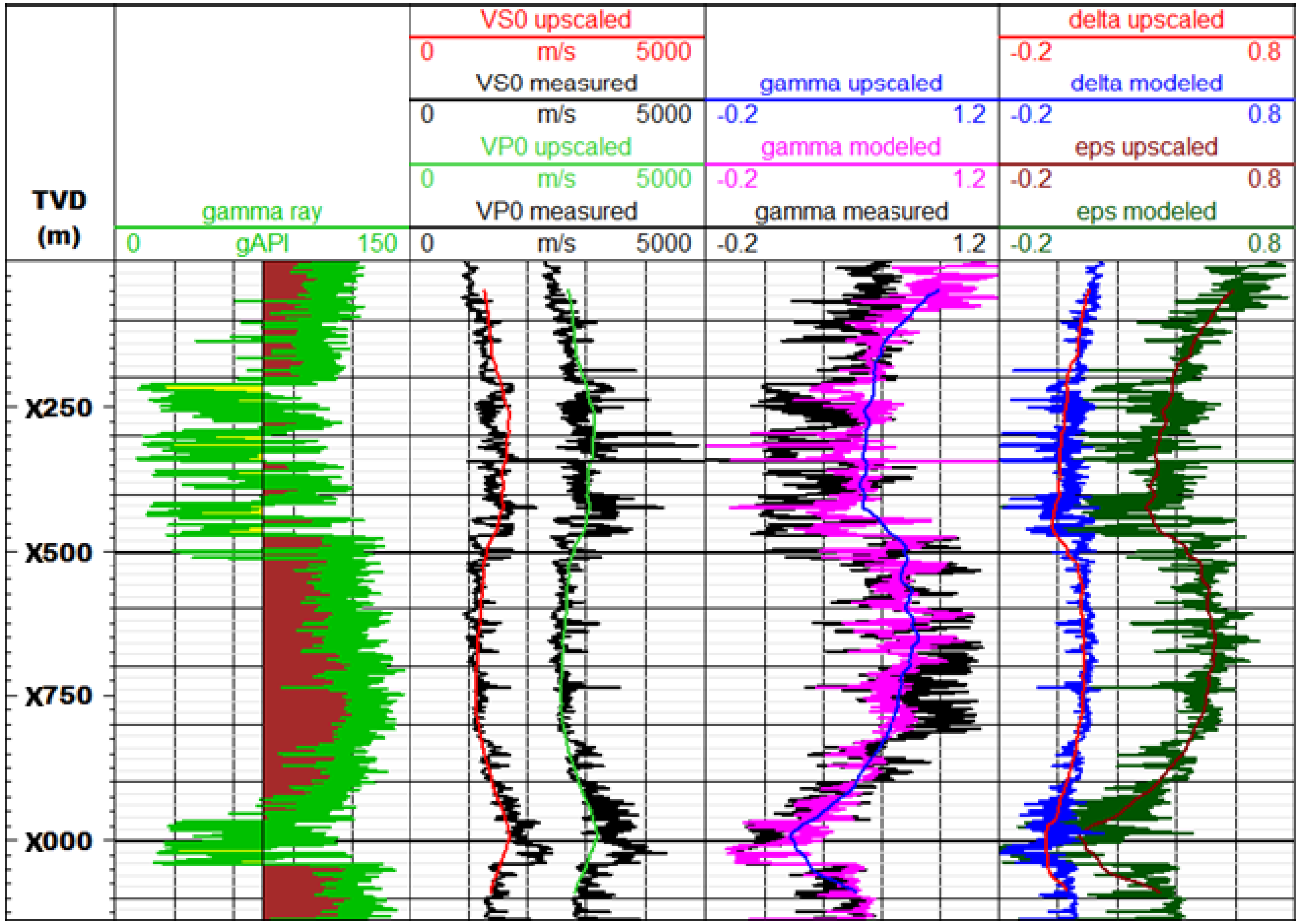


Figure ref.: Jocker et al., TI anisotropic model building using borehole sonic logs acquired in heterogeneous formations, SEG 2013

Multi-well Anisotropy Characterization

Guide for seismic anisotropic velocity model building

Sonic anisotropy parameters flatten seismic CMP gathers at large offsets

- Seismic anisotropic velocity model calibration at well location

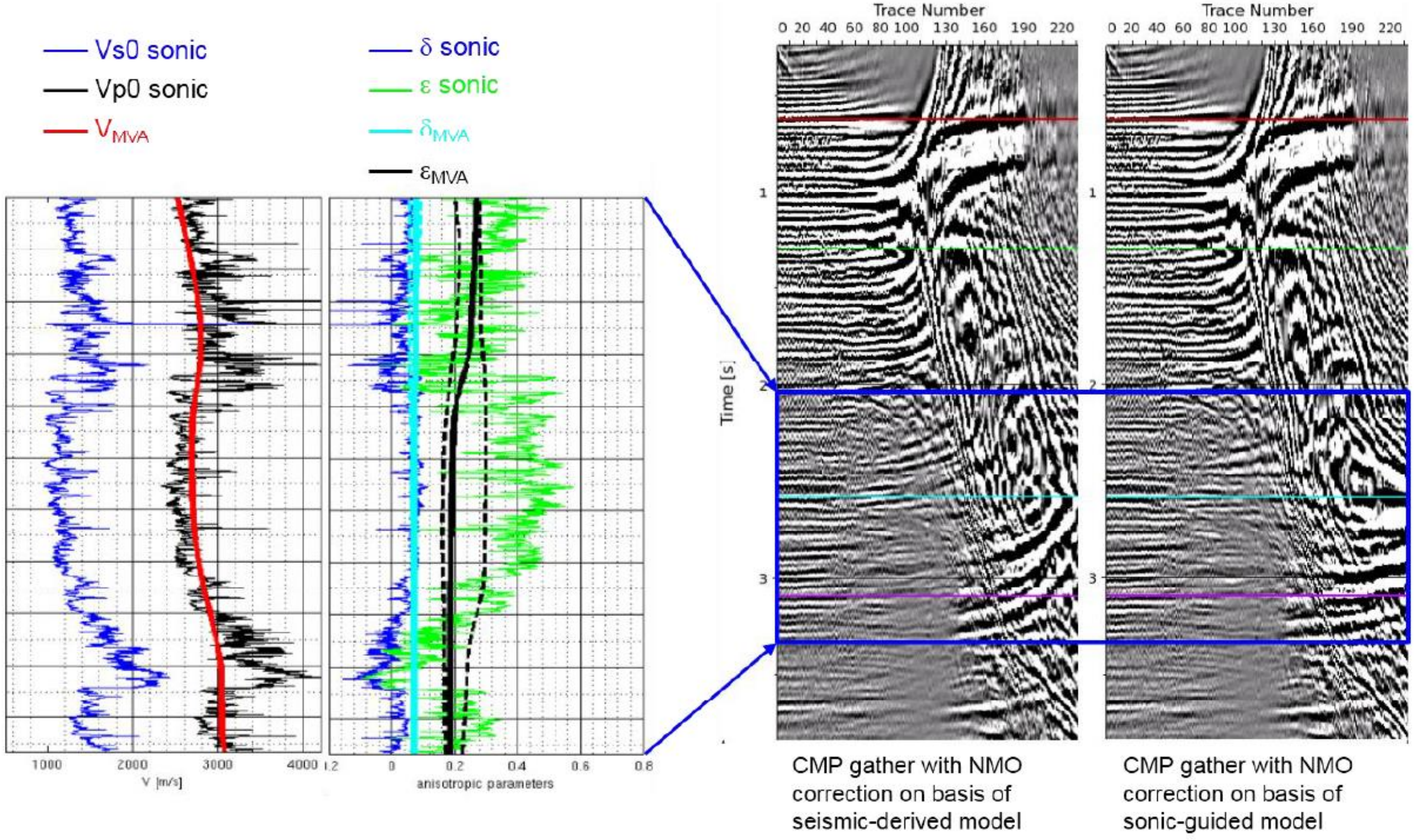


Figure ref.: Ferla et al., Sonic-derived TI anisotropy as a guide for seismic velocity model building, SEG 2015

Single-well Application of Multi-well results

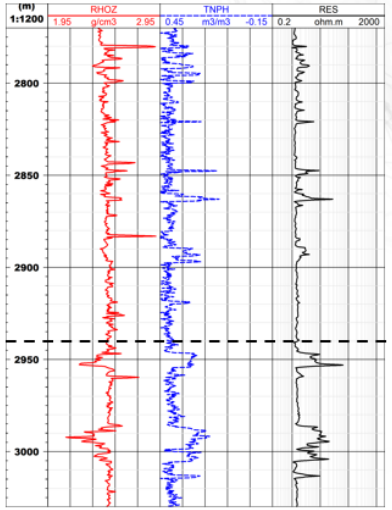
Application of multi-well study results on new well data

Use multi-well study results as prior information for new single-well anisotropy applications

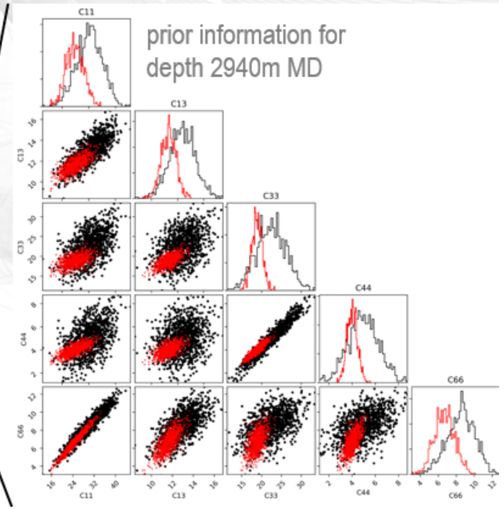
EAGE 2021: Formation-specific prior information for Bayesian-type inversion

cluster number	<NEUT> (m3/m3)	<RHOZ> (g/cm3)	<RES> (ohm.m)	VP0 (m/s)	VS0 (m/s)	eps (-)	delta (-)	gamma (-)
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
103	0.233	2.456	3.518	3450.1	1859.9	0.092	0.006	0.084
104	0.222	2.468	4.46	3449	1951	0.105	-0.009	0.072
105	0.227	2.47	5.437	3532.6	1893.4	0.086	-0.015	0.098
106	0.229	2.465	5.812	3439.6	2037.7	0.139	0.131	0.037
107	0.218	2.471	9.618	3891.1	2063.6	0.093	-0.055	0.107
109	0.221	2.496	1.298	2987.9	1476.7	0.013	0.009	-0.007
110	0.222	2.504	1.624	3514.2	1899.7	0.053	0.015	0.075
111	0.223	2.488	2.187	3573.1	1950.9	0.088	0.001	0.103
112	0.22	2.492	2.772	3725	2002.3	0.047	0.023	0.097
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

+



=



1. multi-well table of TI parameters is combined with…
2. logs of bulk density, neutron porosity and horizontal resistivity to define…
3. depth-dependent prior information

Figure ref.: Jocker and Hansen, Bayesian-type TI anisotropy characterization using depth-dependent prior information, EAGE 2021

Single-well Application of Multi-well results

Application of multi-well study results on new well data

Use multi-well study results as prior information for new single-well anisotropy applications

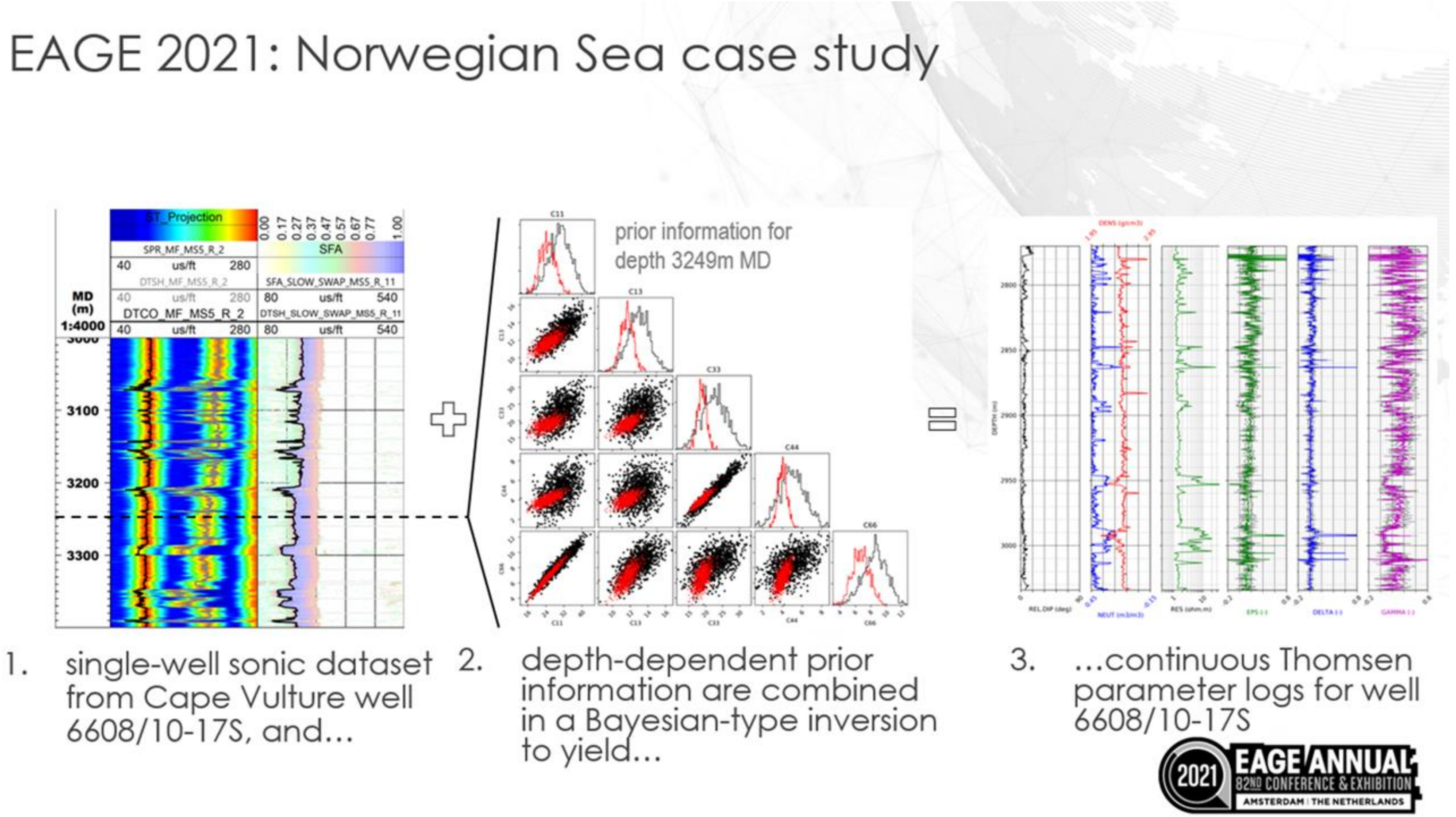


Figure ref.: Jocker and Hansen, Bayesian-type TI anisotropy characterization using depth-dependent prior information, EAGE 2021