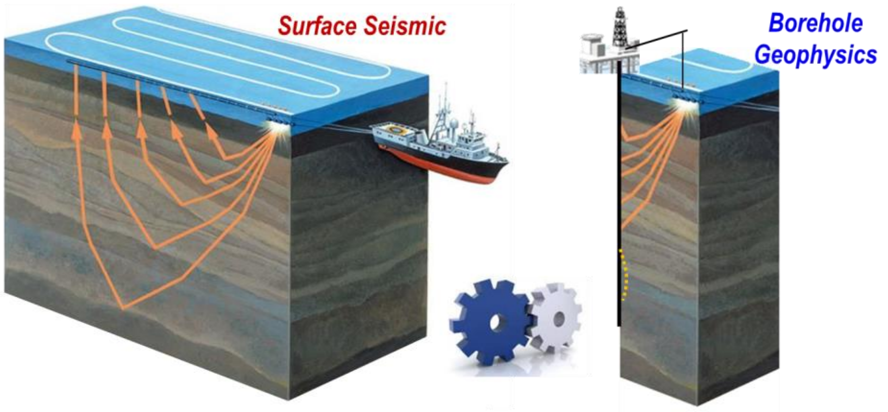
Calibration of Anisotropic Velocity Models using Innovative Borehole Geophysical Measurements



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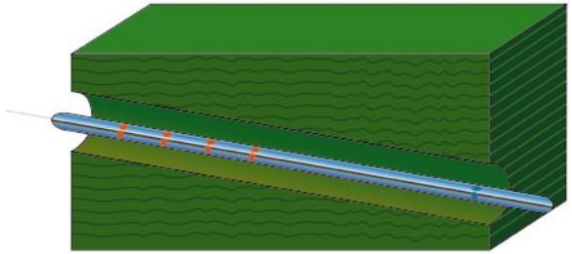
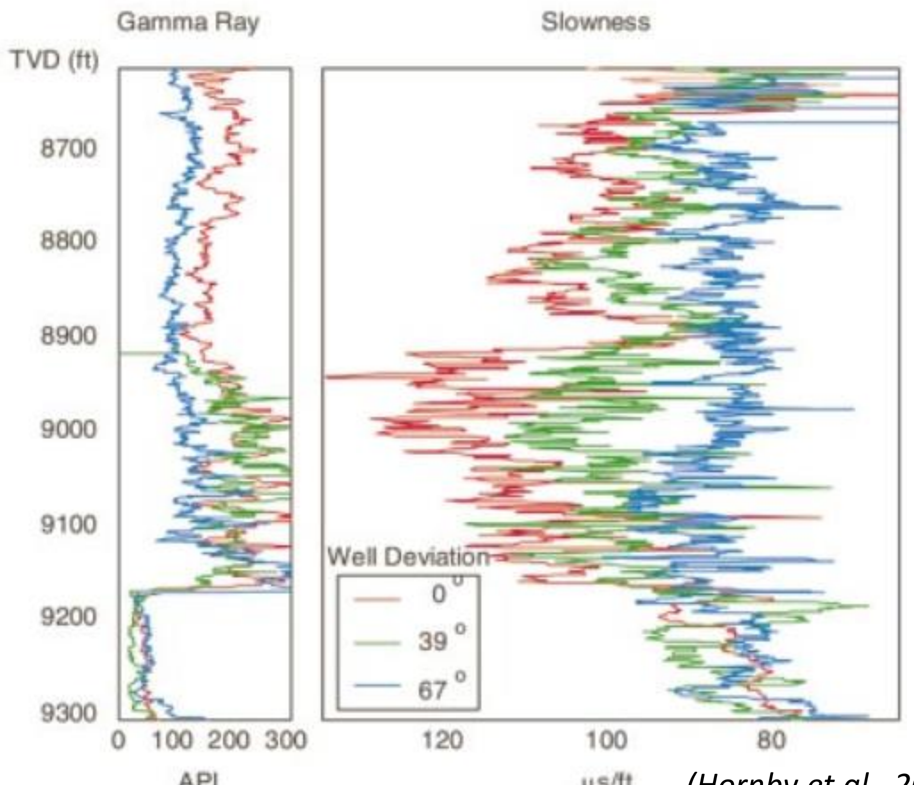
05-April-2017

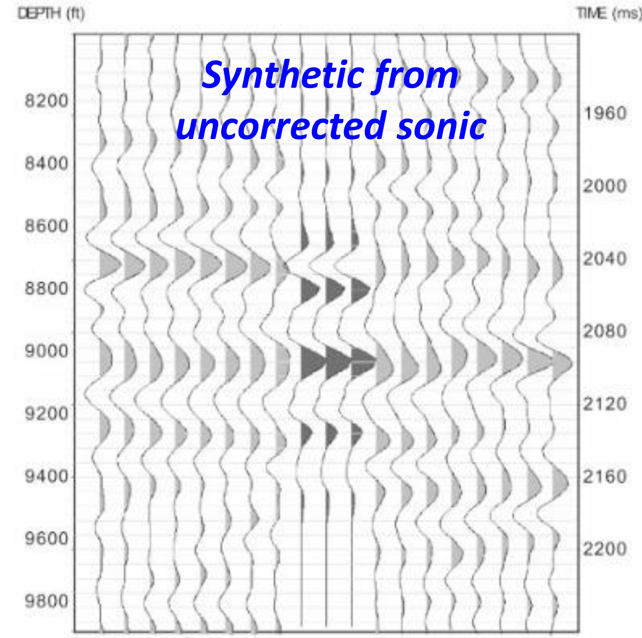
Preliminaries *(1/2)*

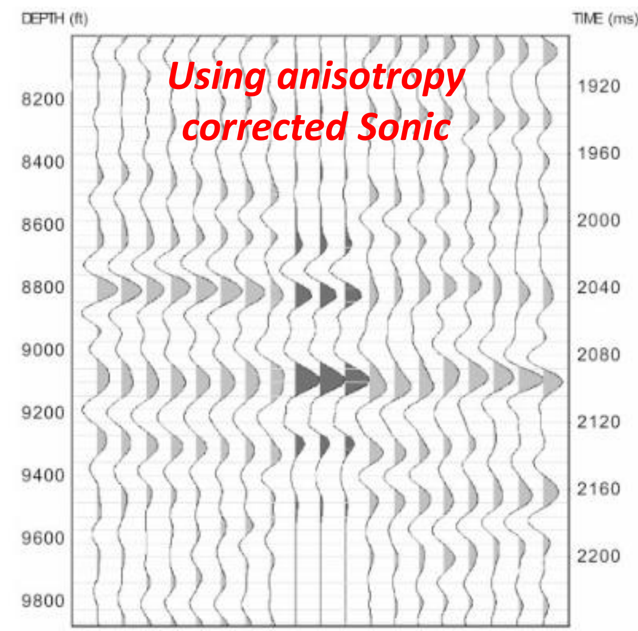
- **Compressional sonic logs in same field at different well deviations**





(Hornby et al., 2003)





Preliminaries *(2a/2)*

- Legacy surface seismic processed without borehole calibration of anisotropy

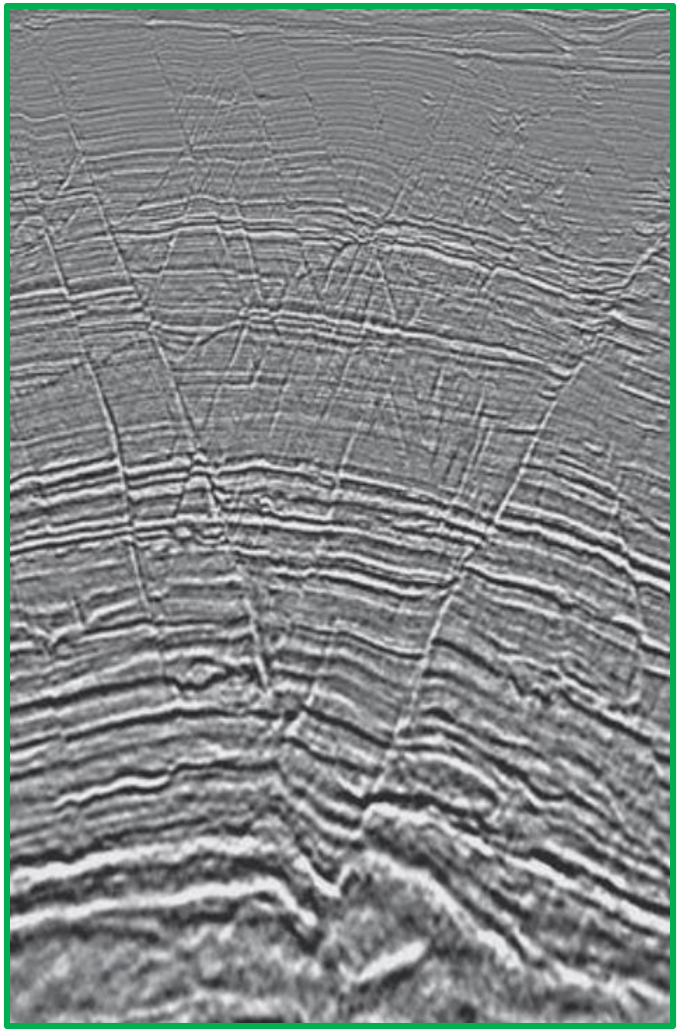
(Zhu et al, 2013)

Legacy PSDM seismic

Preliminaries *(2b/2)*

- New surface seismic processed including borehole calibration of anisotropy *(multi-Walkaway Checkshots)*
- Resulting in structural repositioning and better definition of faults

(Zhu et al, 2013)

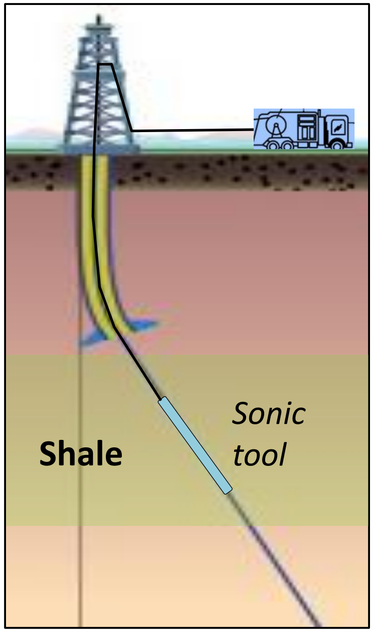


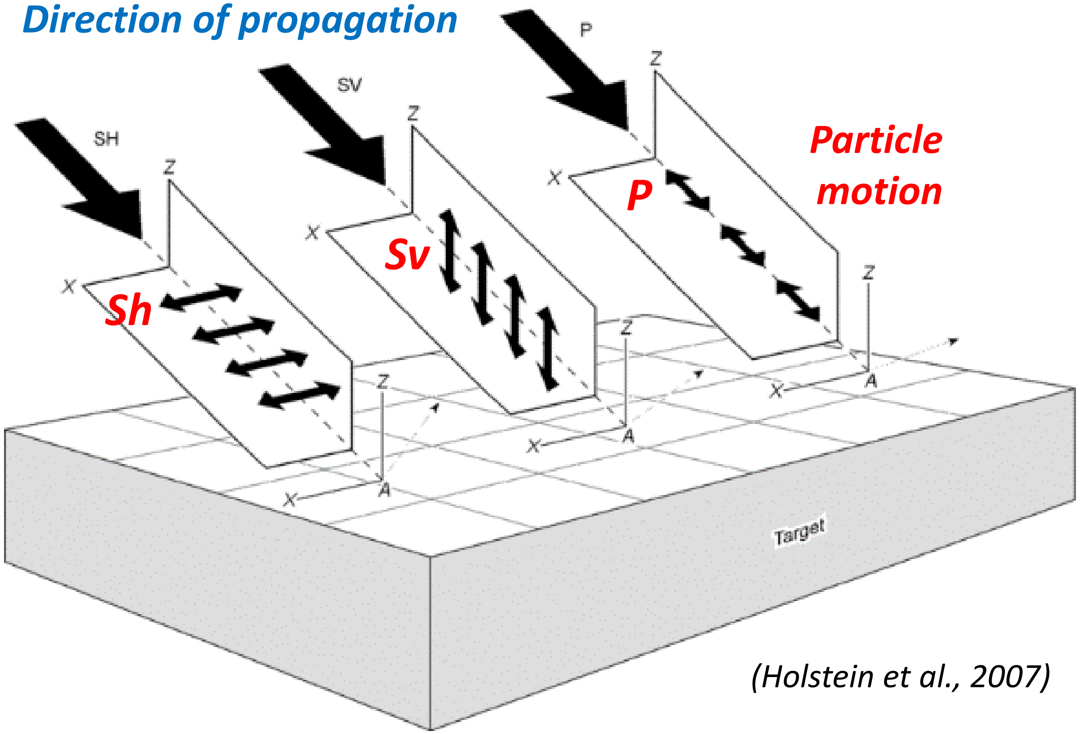
Calibrated anisotropic PSDM seismic

Road Map to Anisotropy

What is it? → Why it matters? → How to measure it? → Case studies → What next?

First a note on P- and S-waves

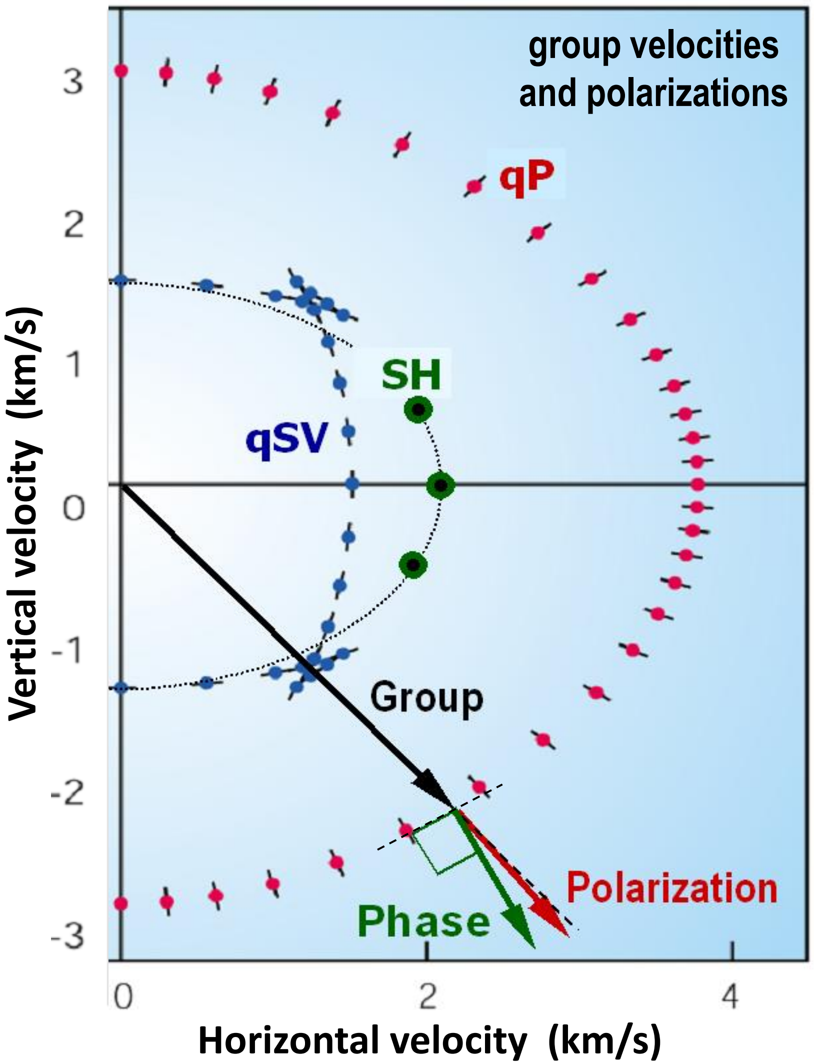




- For sonic/seismic wave propagation at an angle with layers, we observe three distinct body waves *(P, Sv, Sh)*
- They have all different speeds for different angles of incidence, and are related to the rock compressibility and rigidity

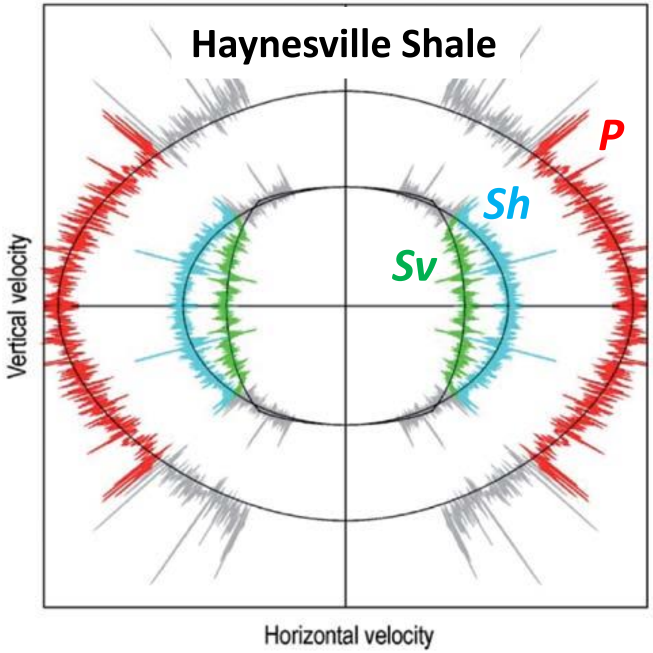
Polar Anisotropy (VTI) – What it is?

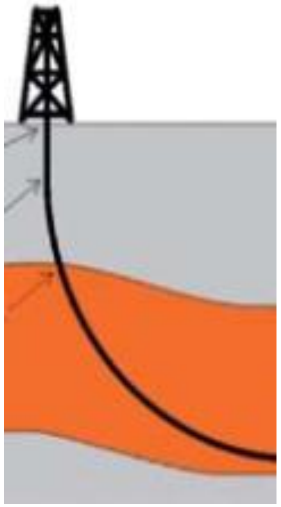
(Adapted from Oilfield Review, 1994)



"The wave velocity varies with the propagation angle from vertical"

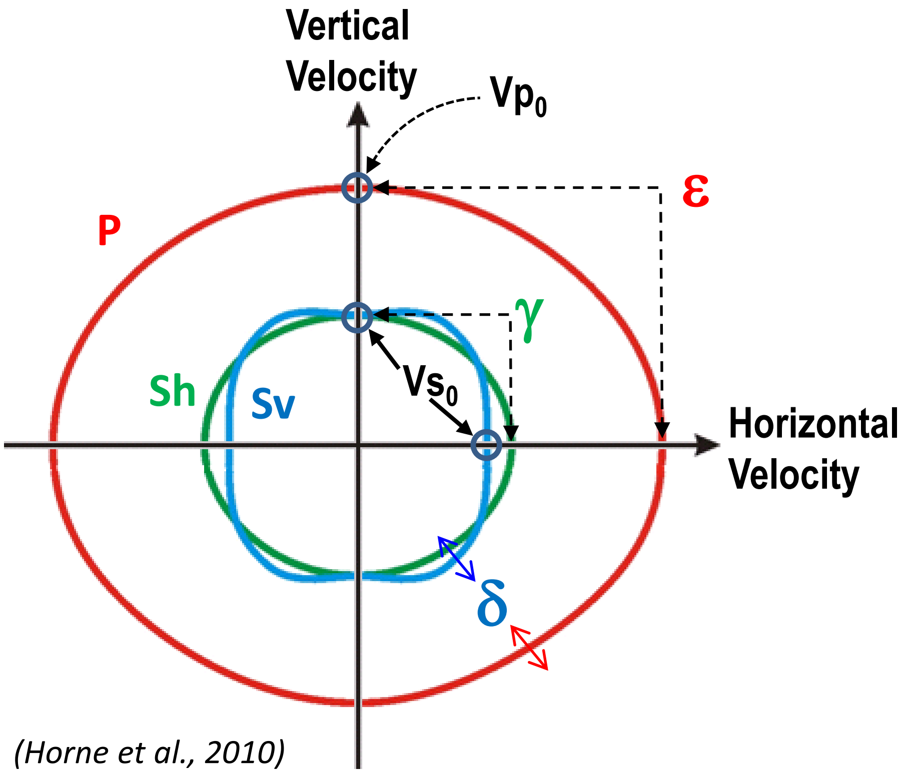
- Shales exhibit polar anisotropy
- This talk only covers polar anisotropy





(Horne et al., 2012)

Polar Anisotropy - *Thomsen parameters (ε, δ, γ)*



(Horne et al., 2010)

Isotropic seismic analyses:

- *Vp, Vs, density*

Anisotropic seismic analyses:

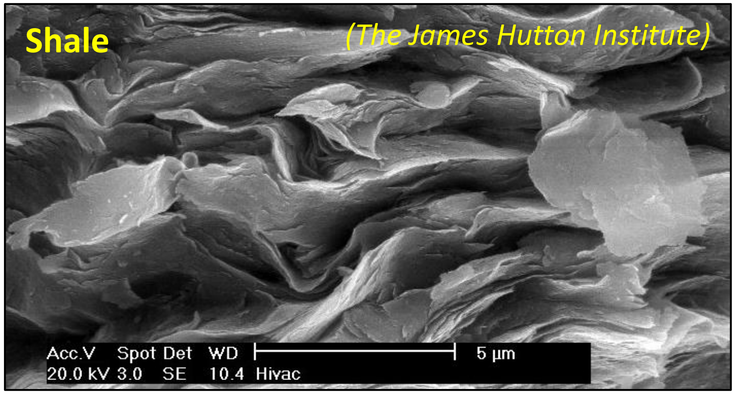
- *Vp0, Vs0, density*
- *ε, δ*
- *γ (microseismic, multi-component seismic, etc …)*
- *Tilt of symmetry axis → TTI*

- ❑ Vp_0 *Vertical P-wave velocity*
- ❑ Vs_0 *Vertical S-wave velocity*
- ❑ ε *~ "%" of P-wave anisotropy (horizontal vs vertical velocity)*
- ❑ γ *~ "%" of SH-wave anisotropy (horizontal vs vertical velocity)*
- ❑ δ *Anisotropy curve 'Shape' parameter (P- and Sv-waves)*

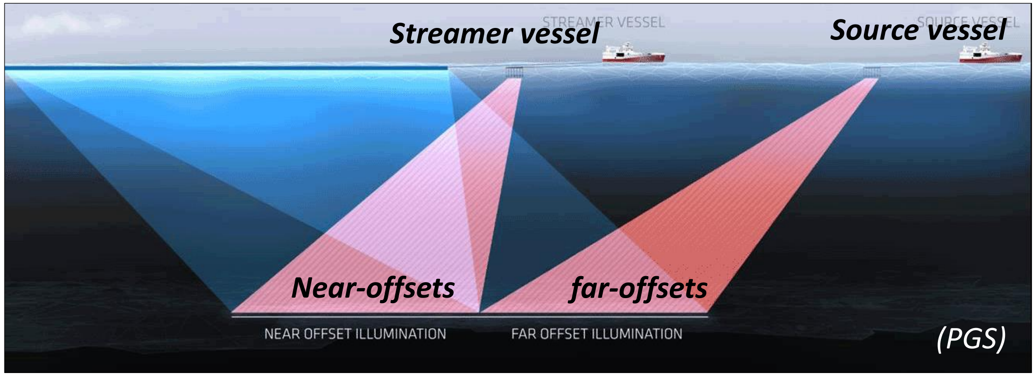
Why it matters? *(1/3)*

- **Most formations are layered,** and at the seismic scale exhibit polar seismic anisotropy

- **Shales/clay-rich rocks are abundant,** and they often show strong polar anisotropy



- **Long-offset seismic data acquisition and anisotropic data processing are common**

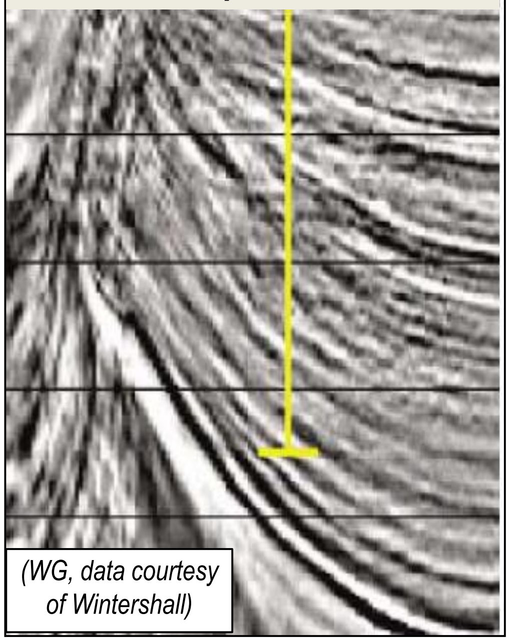


Why it matters? *(2/3)*

Including anisotropy in seismic data processing can result in:

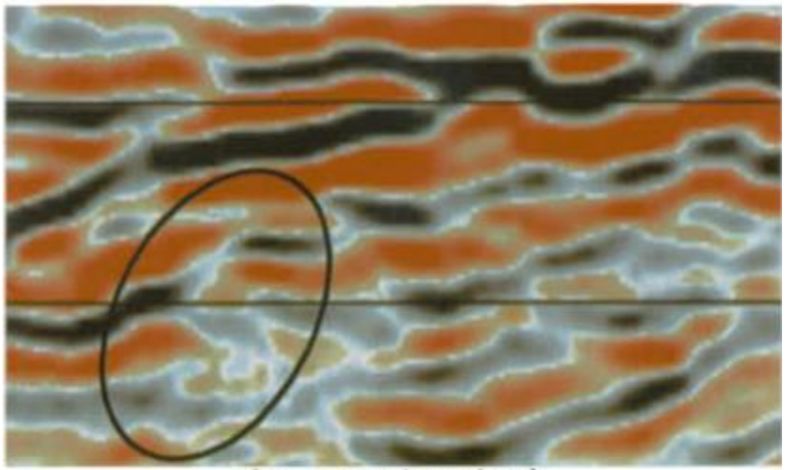
- *Sharper images*
- *More accurate structures*
- *Improved well ties*
- *Improved amplitude analyses*

Isotropic PSDM

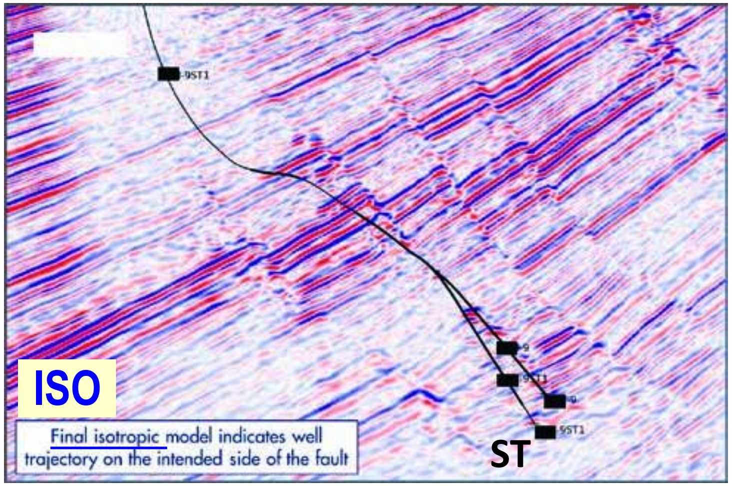


(WG, data courtesy of Wintershall)

Isotropic 3D preSDM



(converted to time) *(Jones et al., 2003)*

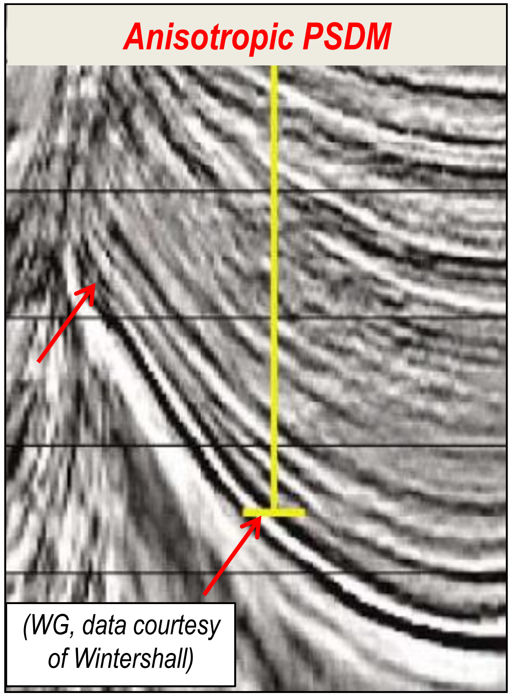


(Gerritsen et al., 2016)

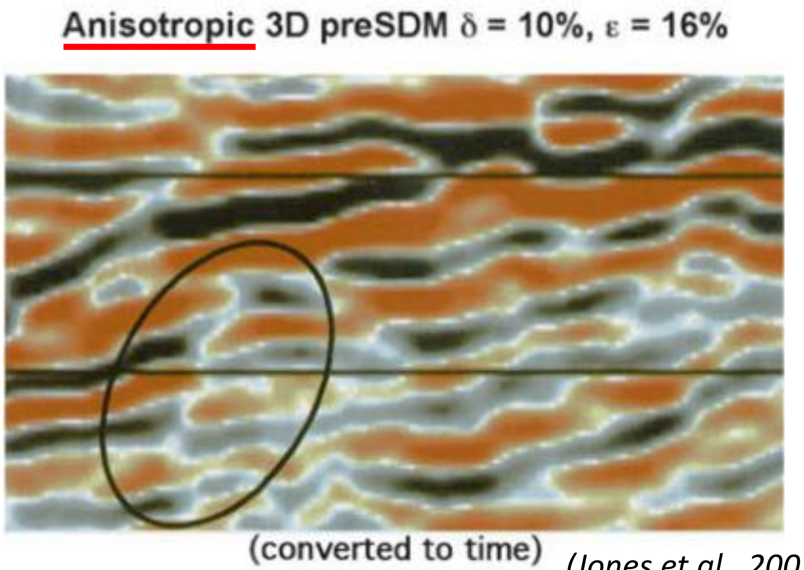
Why it matters? *(3/3)*

Including anisotropy in seismic data processing can result in:

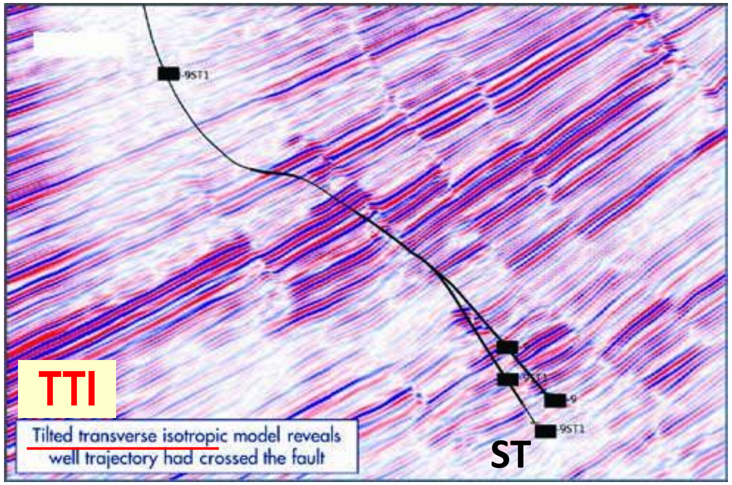
- *Sharper images*
- *More accurate structures*
- *Improved well ties*
- *Improved amplitude analyses*



(WG, data courtesy of Wintershall)

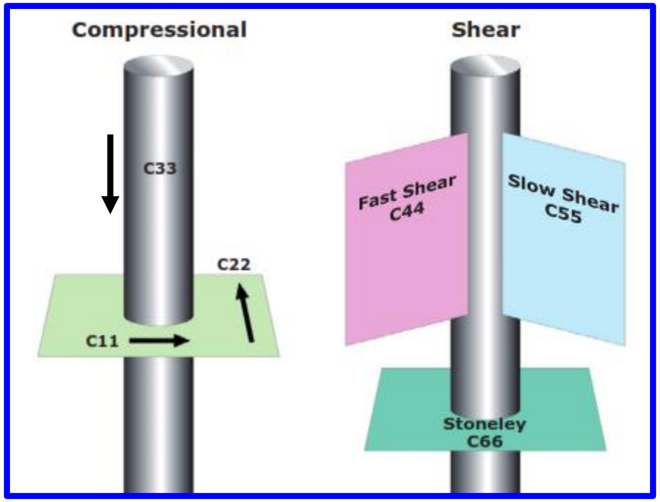


(Jones et al., 2003)



(Gerritsen et al., 2016)

How to measure it? *Sonic logs*



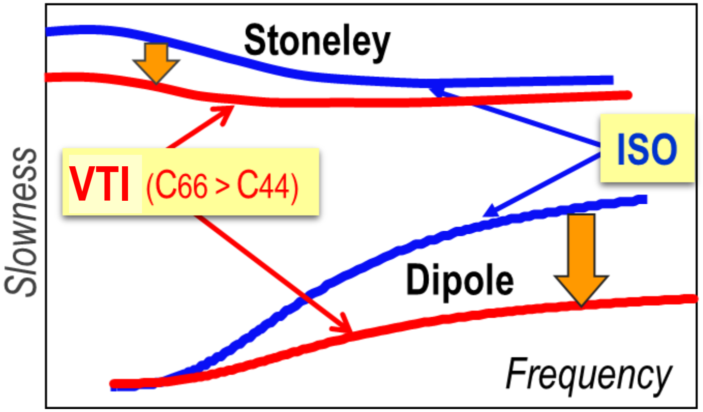
Vertical wells drilled through flat shales:

- LWD and wireline sonic measure vertical shear (C44=C55) and also horizontal shear (C66) from Stoneley mode → *Thomsen* γ

Deviated wells drilled through shales:

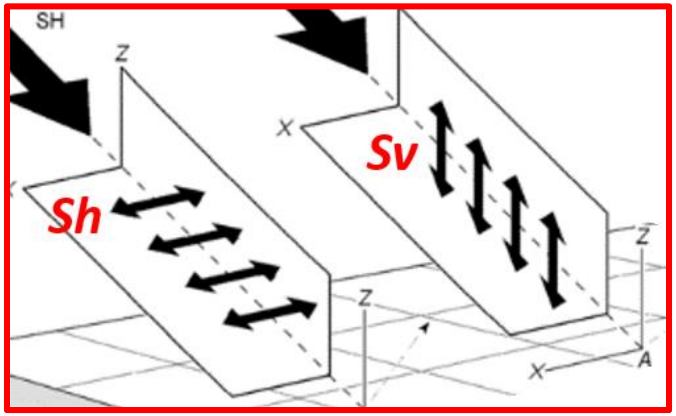
- Wireline sonic required to discriminate SV & SH shears
- Monopole compressional and Stoneley are used
- *A priori* anisotropy database, VSP or multi-well sonic measurements → Thomsen $\varepsilon, \delta, \gamma$

Polar anisotropy signature of sonic recorded in vertical well flat layers



~ similar VTI effect on LWD Quadrupole

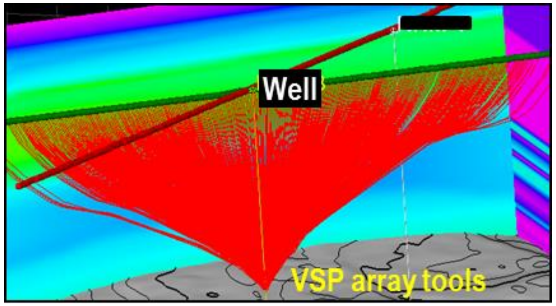
(Valero et al., 2009)



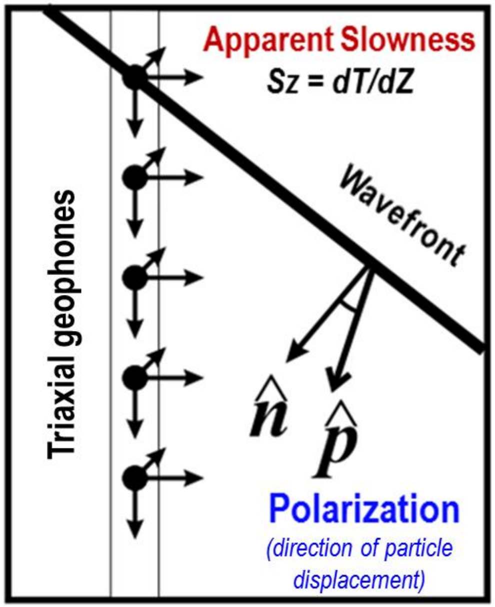
(Holstein et al., 2007)

NOTE: *dipmeter required to know relative dips*

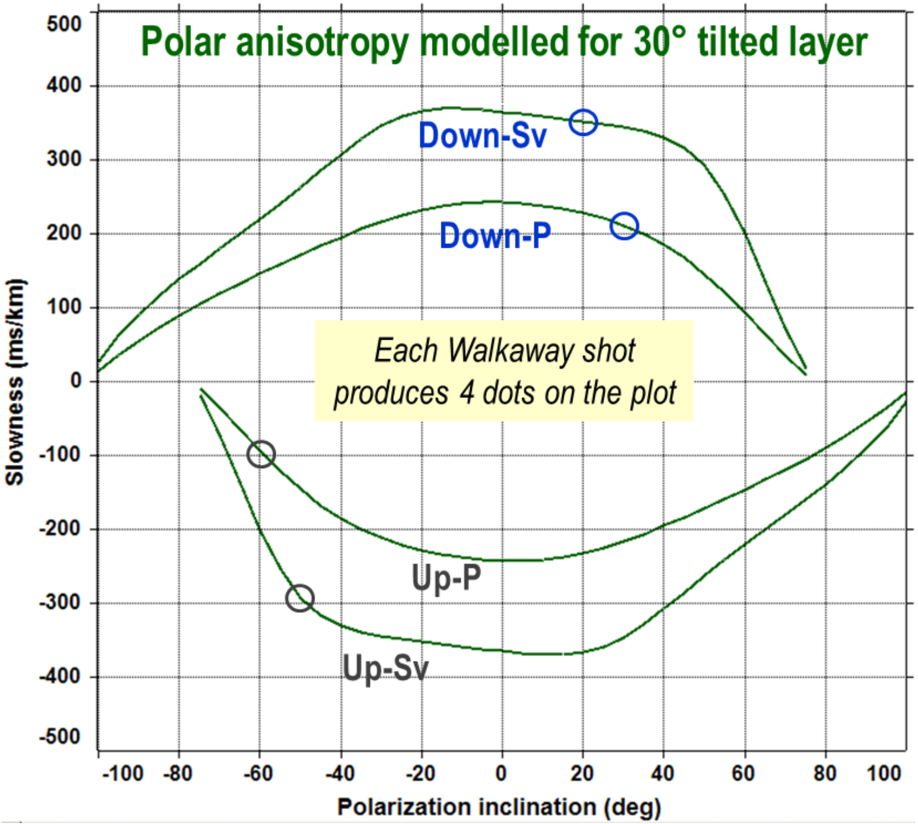
How to measure it? *Wireline Walkaway VSPs*



Slowness Polarization Method*



Local method to estimate polar anisotropy



Each Walkaway shotpoint produces 4 points in plot above

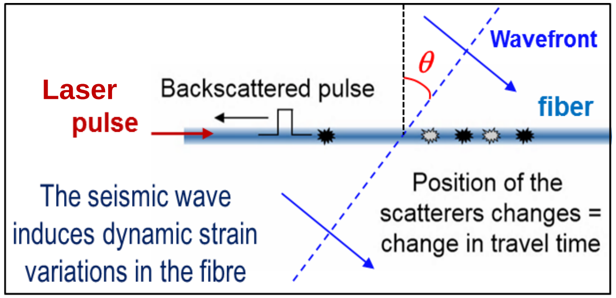
*** References:**
- *Parscau & Nicoletis, 1990*
- *Leaney & Esmersoy, 1989*
- *Horne & Leaney, 2000*
- *Leaney & Hornby, 2007*

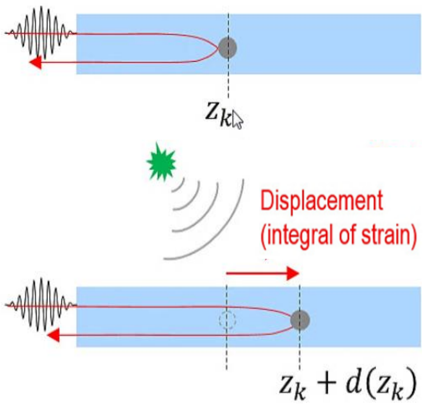
→ **Delivers locally:** *Thomsen ε, δ and tilted axis*

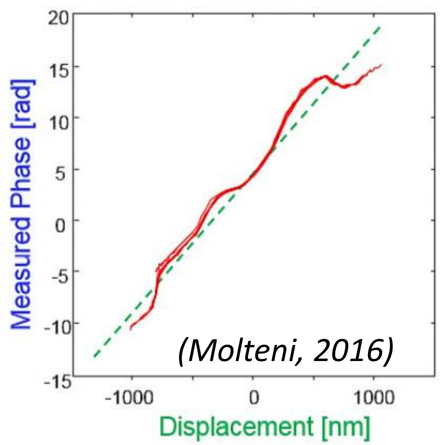
How to measure it?

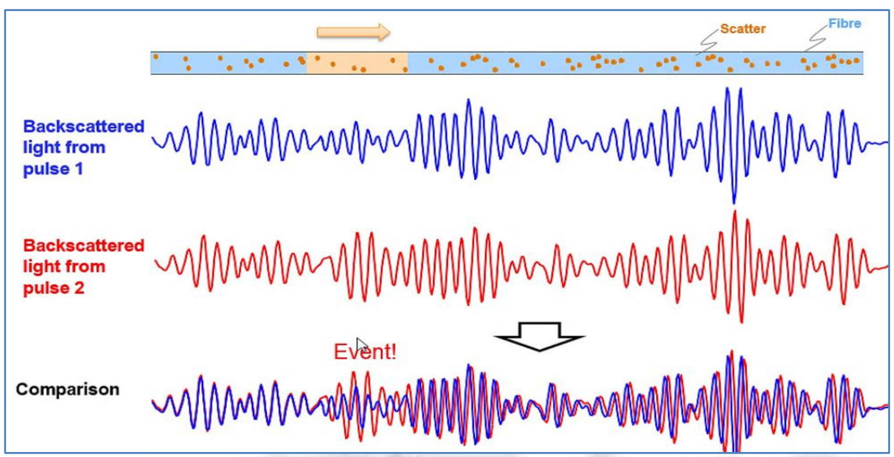
DAS Walkaway/3D-Checkshots

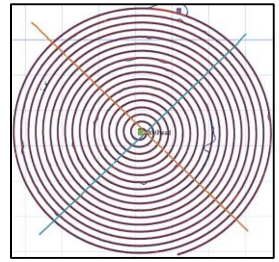
DAS interrogator

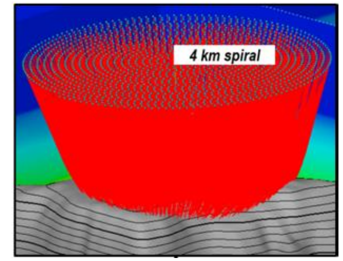




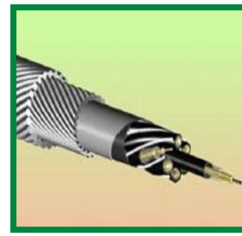






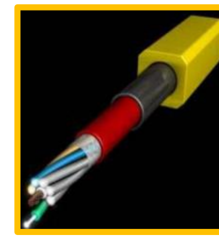


Seismic vessel or supply boat



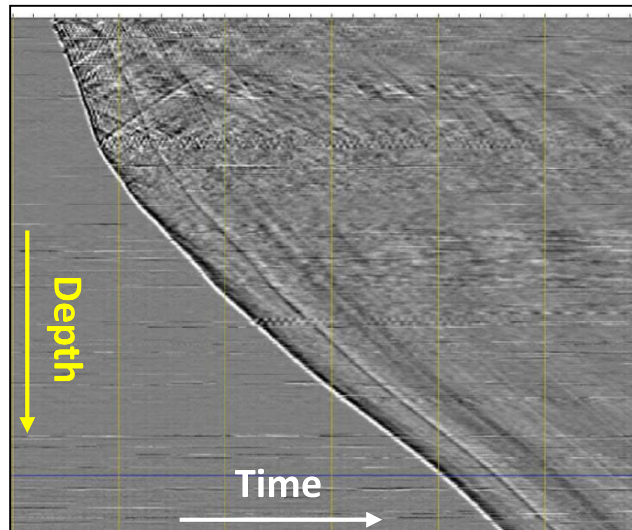
WL hybrid cable

Drilling rig



Permanent fibre

Platforms



NEON hybrid optoelectric monitoring system

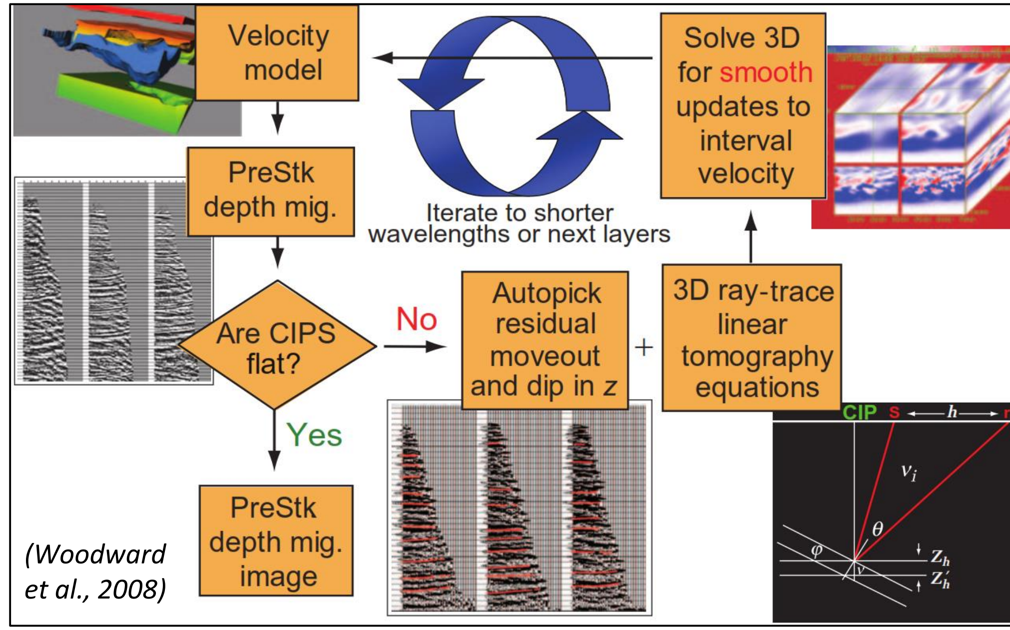
- 182 shots
- 3 hours

Thanks to ConocoPhillips-Skandinavia AS and the PL018 Partnership (Total E&P Norge AS, ENI Norge AS, Statoil Petroleum AS and Petoro AS) for allowing to show Ekofisk data

How to measure it?

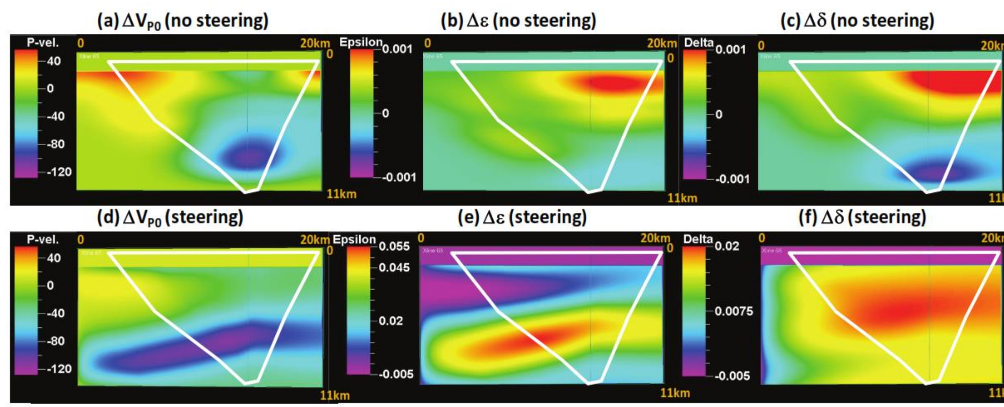
Surface seismic

- Grid tomography workflow updates Vp0, ε, δ
- Borehole data constraints *(usually markers & vertical velocities)*



Limitations: opening angles and data quality decrease with depth and uncertainty in **Vp**0, **ε**, **δ** increases

→ *More robust results if combined with borehole anisotropy measurements*



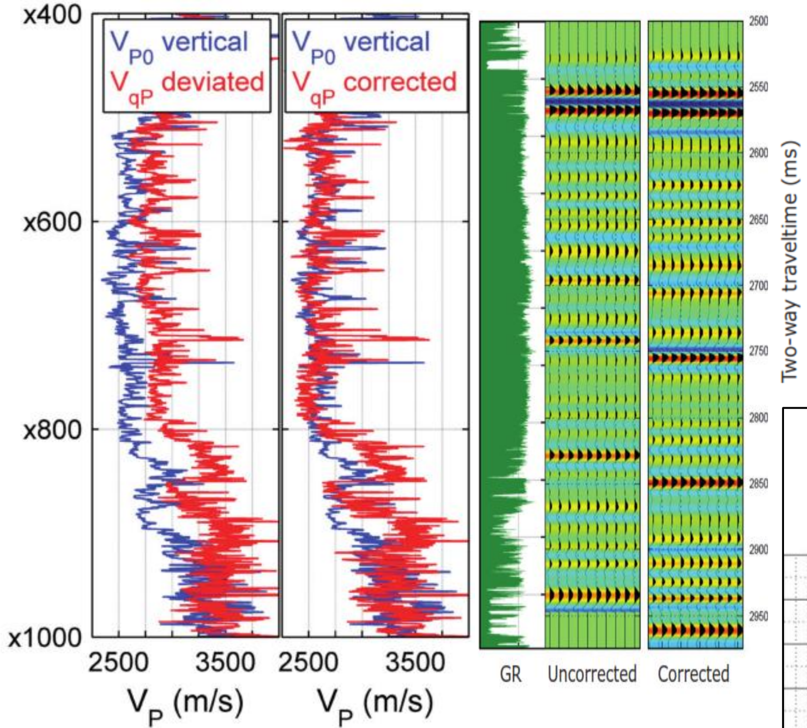
Model updates without and with steering filter by joint tomography of seismic and checkshots

(Bakulin et al., 2010)

Case Study#1

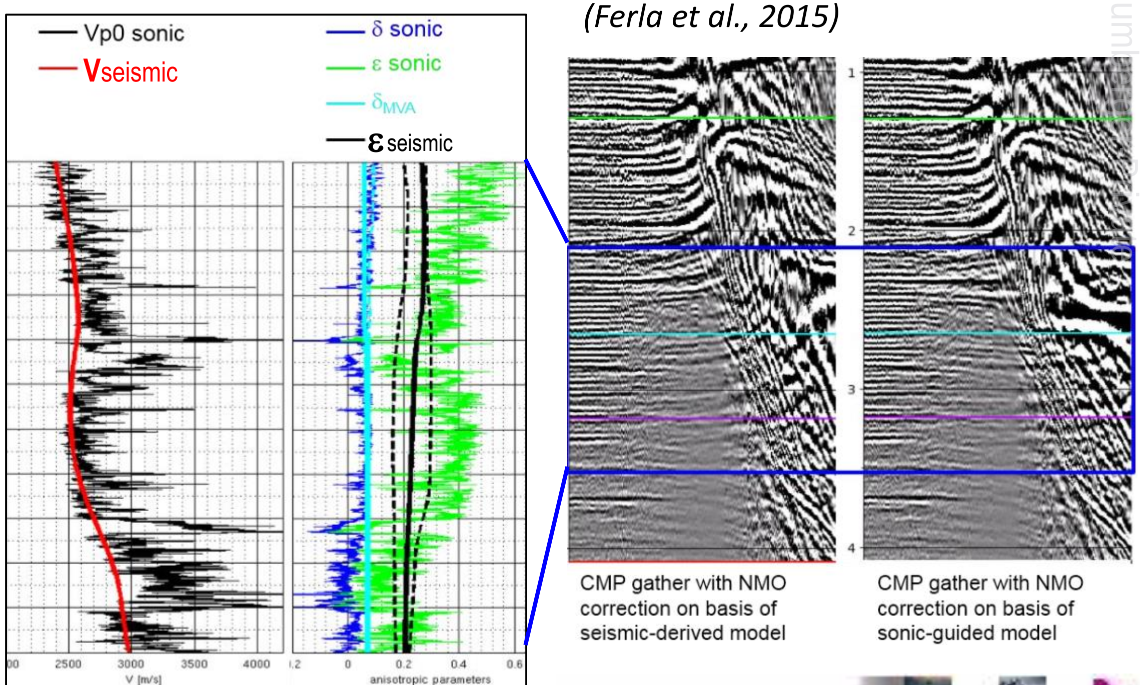
Eni wells, sonic anisotropy effects & input to surface seismic

- Deviated well sonic reads to fast and syntethic seismogram is squeezed
- Anisotropy in seismic velocity model had to be greatly increased as suggested by sonic to flatten gathers



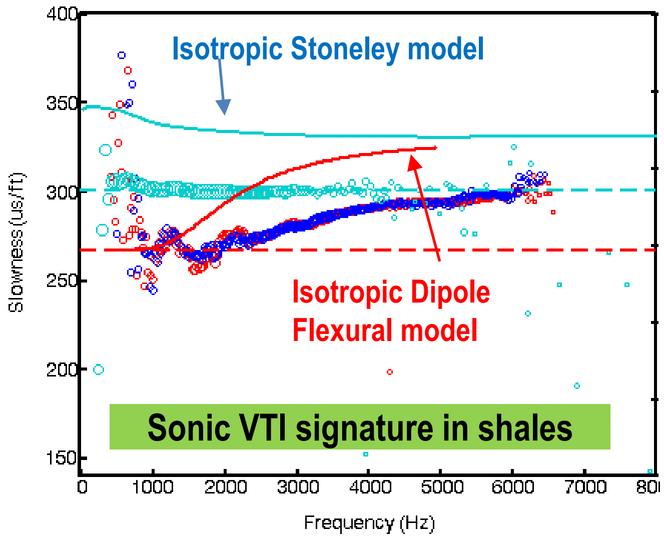
(Ferla et al., 2013)

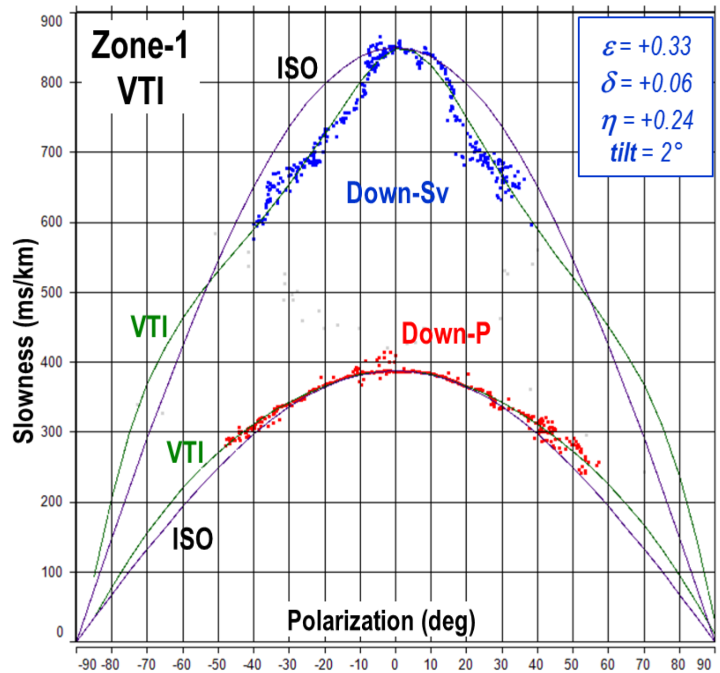
(Ferla et al., 2015)

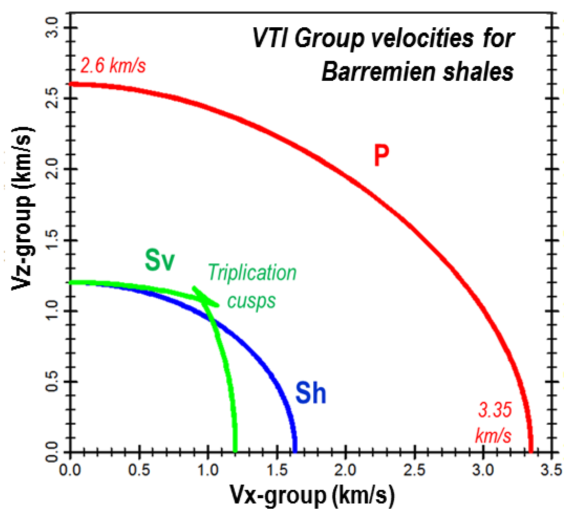


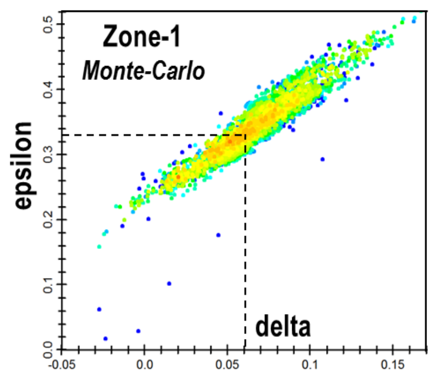
Case Study#2

Eni sonic & VSP anisotropy calibration presalt West Africa







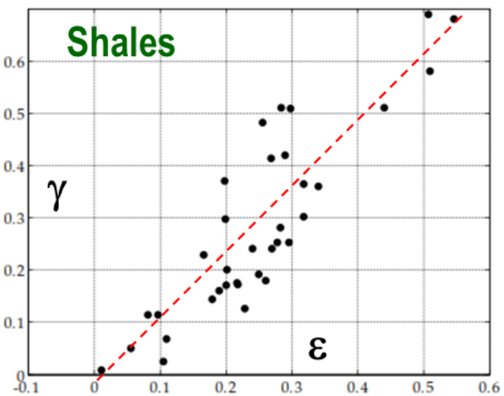


Walkaway VTI signature in shales and Thomsen parameters computed

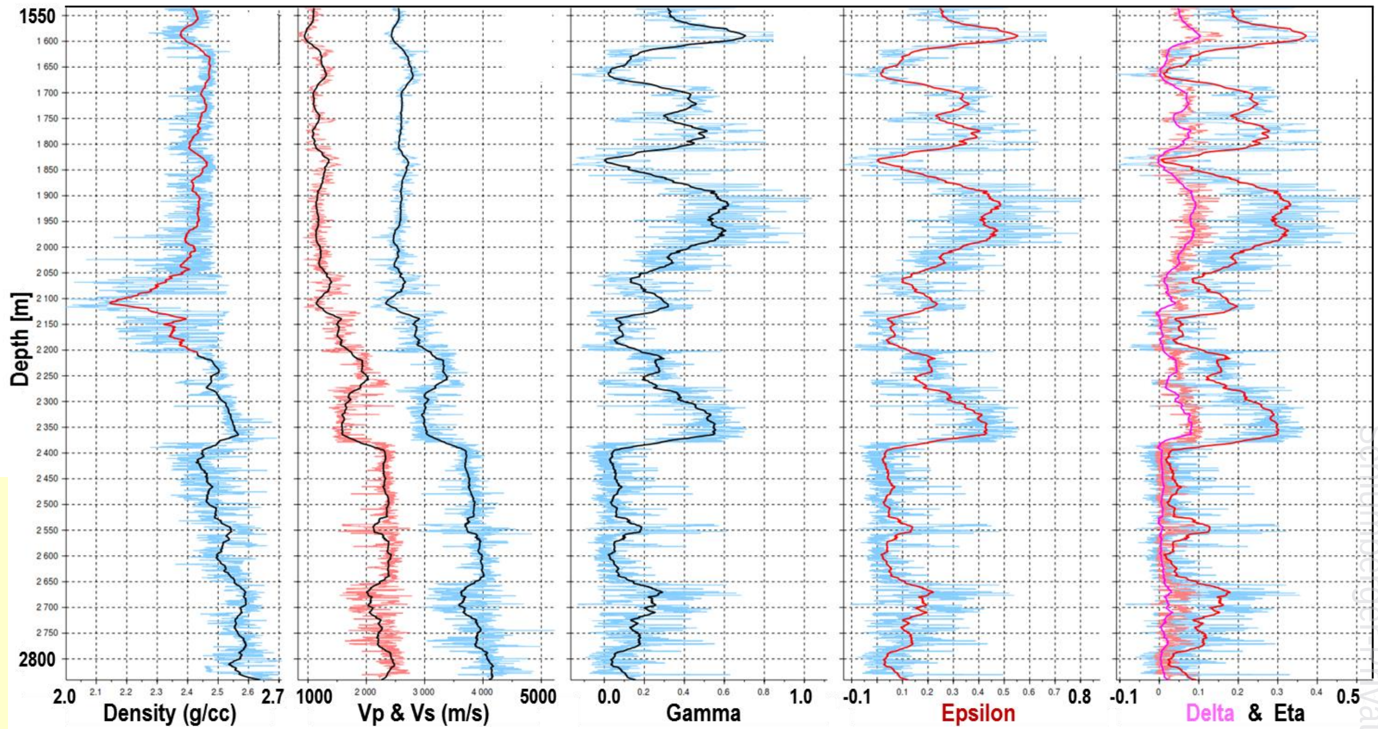
(Guerra et al., 2016)

Case Study#2 *(continued)*

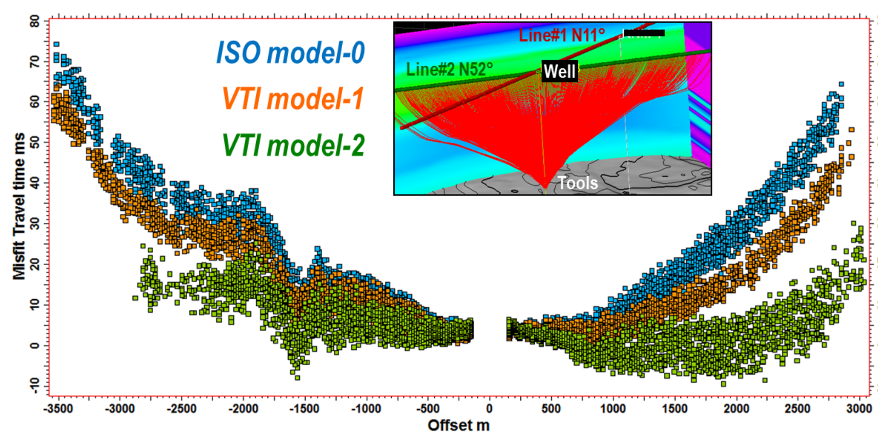
(Sayers, 2005)



Correlation between ε and **γ** seen in cores *(above)* was estimated *in-situ* from collocated Walkaway & Sonic measurements and used to extend the anisotropy logs



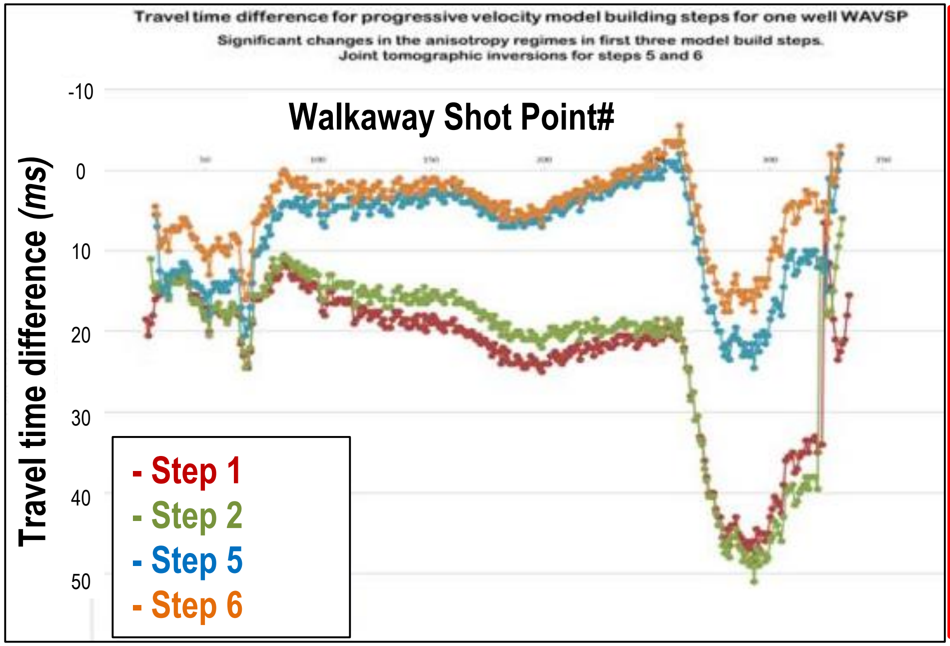
(Guerra et al., 2016)

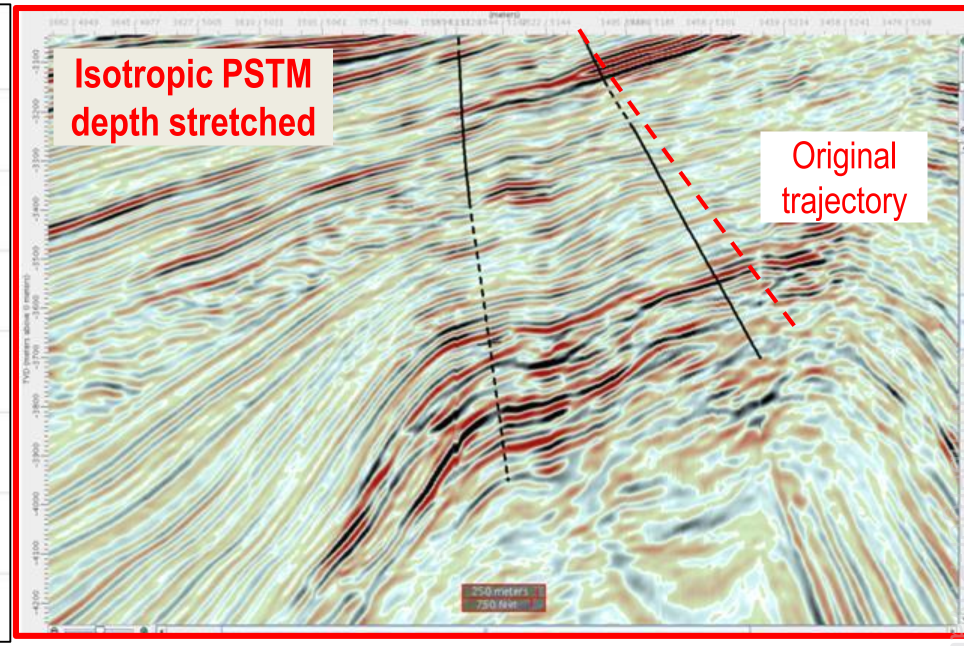


Borehole anisotropy measurements improved velocity model and minimized Walkaway travel time residuals

Case Study#3

BP Angola deep-water Block-31 (2014)



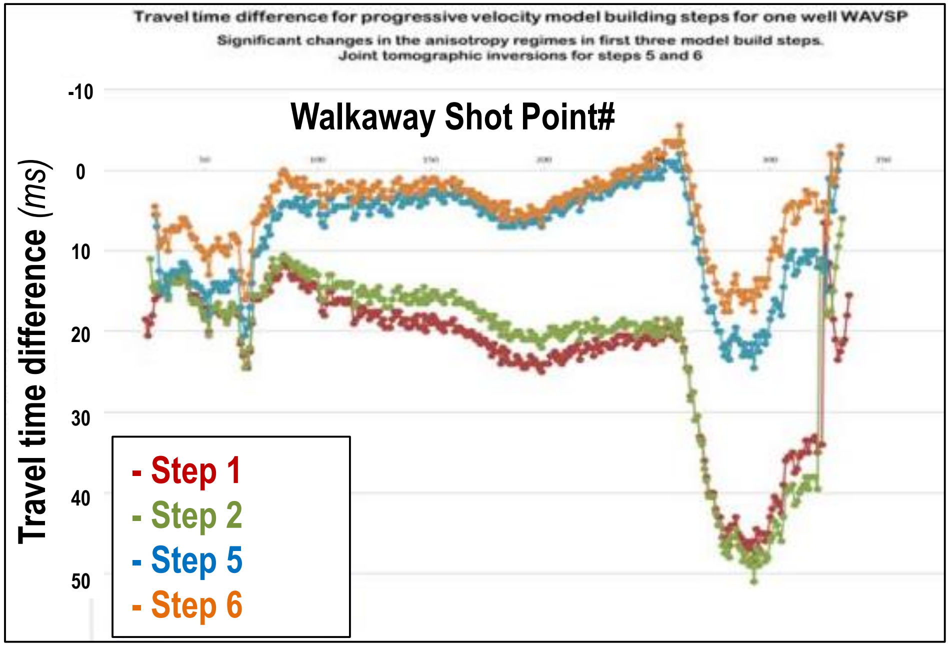


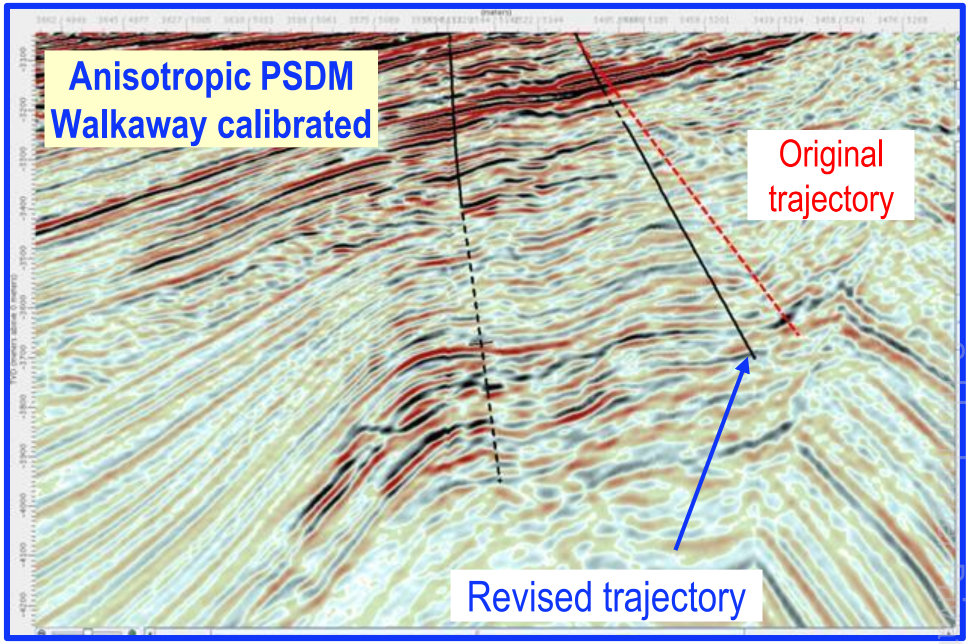
(Soulas et al., 2015)

Significant changes in the anisotropic model after joint travel time and RMO tomographic inversions *(model building steps 5 and 6)*

- Walkaways recorded in 4 wells with VSI wireline VSP tools
- Improvement of surface seismic resolution, focusing & spatial positioning
- De-risking drilling locations for new development wells

Case Study#3 *(continued)*





(Soulas et al., 2015)

Significant changes in the anisotropic model after joint travel time and RMO tomographic inversions *(model building steps 5 and 6)*

- Walkaways recorded in 4 wells with wireline VSP tools → ***could have used DAS***
- Improvement of surface seismic resolution, focusing & spatial positioning
- De-risking drilling locations for new development wells

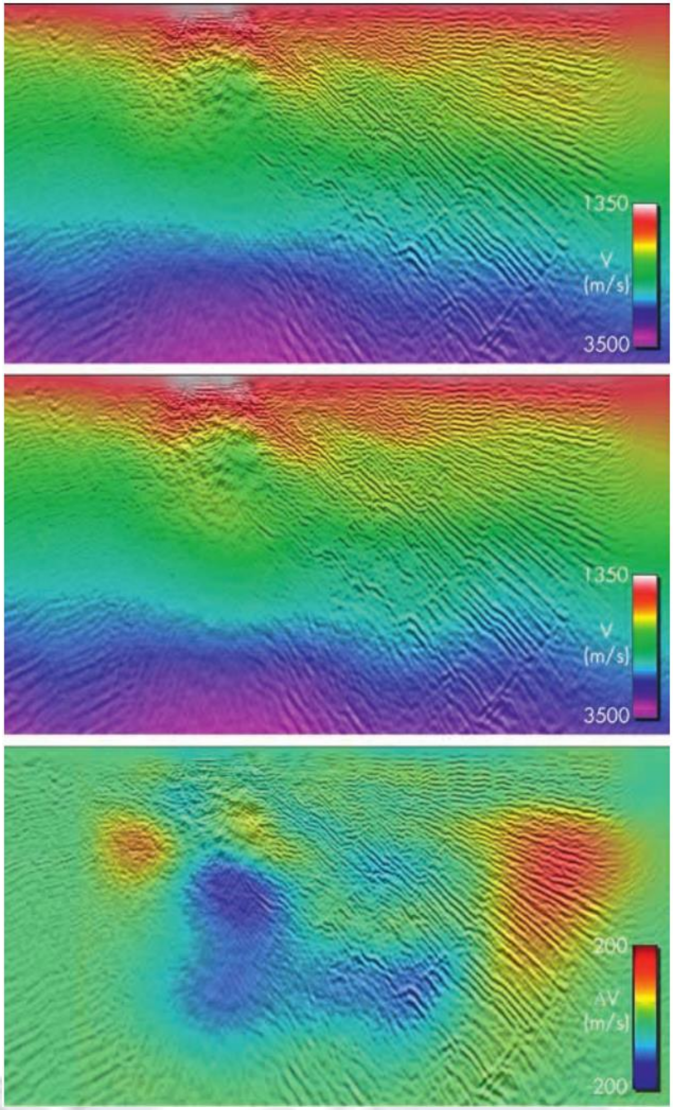
Case Study#4

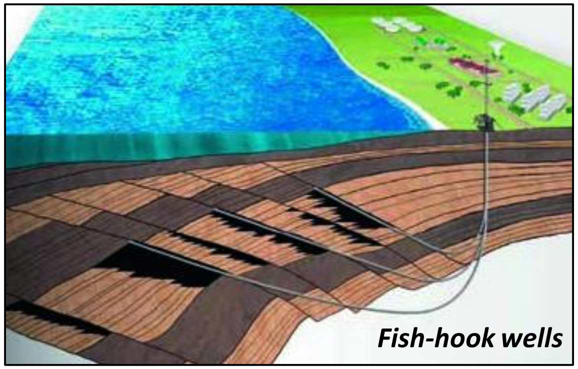
Shell Brunei multi-well DAS 3D-Checkshot survey (2014)

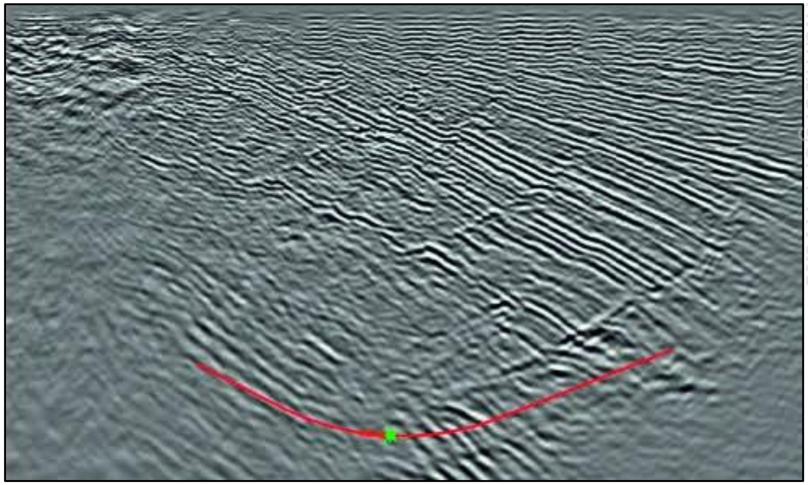
Initial velocity model

After joint inversion of DAS and diving wave first breaks

Velocity updates







(Gerritsen et al., 2016)

→ 6 wells had permanent optical fibers installed for temperature

Case Study#4 *(continued)*

Travel time residuals reduced after model calibration with DAS-VSP and diving seismic wave first breaks

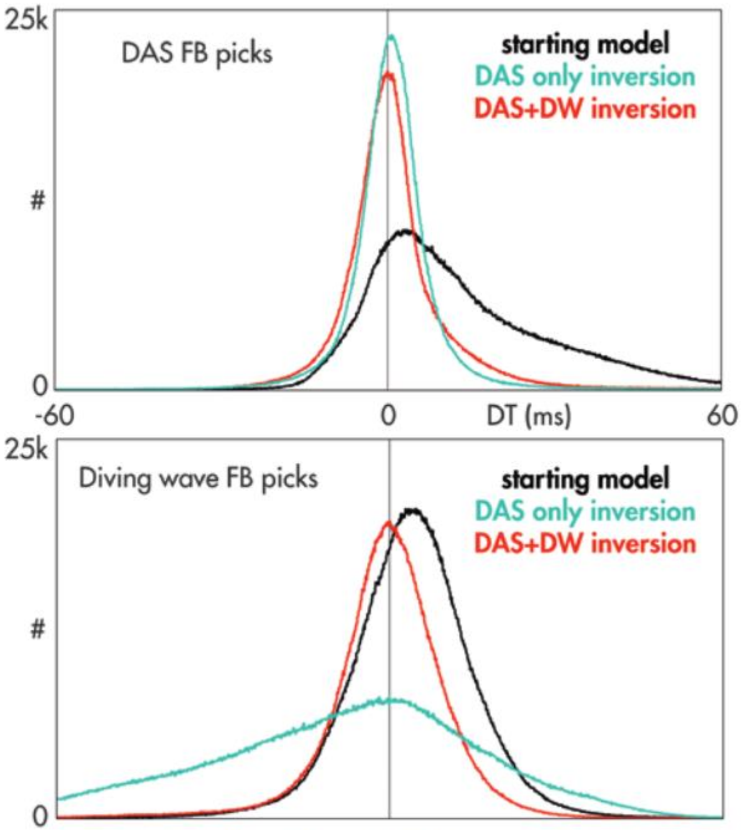
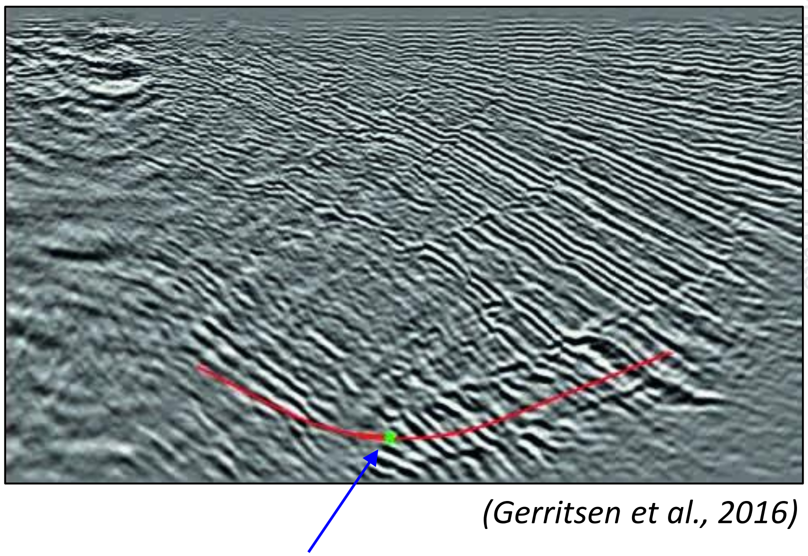


Figure 11 *Travel time residuals of the DAS first break picks (top) and the diving wave first break picks (bottom) in the starting model (black histogram), the model after inversion with DAS picks only (cyan histogram) and the model after simultaneous inversion for DAS and diving wave picks (red histogram).*

> *"… a step change in velocity model quality by using… guided-wave inversion, FWI, and joint inversion of seismic and DAS-VSP first breaks … led to demonstrable improvements in velocity model for imaging and depth conversion with direct impact on the business"*
> *Gerritsen et al. (2016)*



(Gerritsen et al., 2016)

Improved well markers tie and better focussed seismic images in depth

What Next?

- **Improve the data acquisition:**
  - Earlier diagnostic of anisotropy *(during exploration & appraisal)*
  - Plan the borehole and surface seismic measurements required
- **Improve the velocity model:**
  - It should honour all borehole and surface seismic data
  - Integrate sonic and VSP measurements with surface seismic
  - Seismic model can feed geomechanics & reservoir simulation models

Thank you.

Any Questions?

References

Ferla, M., Jocker, J., Pampuri, F. and E. Wielemaker [2013] Seismic Anisotropy Characterization in Heterogeneous Formations Using Borehole Sonic Data: 75th EAGE Conference & Exhibition

de Parscau, J. and Nicoletis, L. [1990] Transverse isotropy estimation from multioffset VSPs. SEG Technical Program Expanded Abstracts 1990.

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