Calibration of anisotropic velocity models using sonic and Walkaway VSP measurements

Rafael Guerra and Erik Wielemaker

Schlumberger Wireline

Contact authors at:
JGuerra5@slb.com
EWielemaker@slb.com

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Agenda

• Introduction
  • *Elastic Anisotropy principles*
  • *Key applications in oil industry*

• How do we measure elastic anisotropy *in-situ*?
  • *Case studies*

• Conclusion
Elastic anisotropy – *geophysics & geomechanics*

**Simple definition:**
- Elastic wave velocity depends on propagation direction (*geophysics*)
- Rock mechanical properties depend on measurement direction (*geomechanics*)

**Simple connection between geophysics and geomechanics:**

**P-waves**

F = normal stress  
$\Delta V/V = \text{Volumetric strain}$  
k = Bulk Modulus  
$V_p = \left[\frac{k + 4\mu/3}{\rho}\right]^{1/2}$ 

**Z_p = V_p \cdot \rho**

**S-waves**

F = Shear stress  
e = $\tan \theta = \text{Shear strain}$  
$\mu = \text{Shear Modulus}$  

$V_s = \left[\frac{\mu}{\rho}\right]^{1/2}$

**Z_s = V_s \cdot \rho**
Simple Example (rocks)

Fractured rock \((HTI, FVTI, \ldots)\)

Laminated shale \((VTI)\)

The arrows indicate direction of maximum rock compressibility & minimum rigidity

It coincides with the direction with the lowest velocities:

- \(P\)-wave velocity \((V_p)\) and \(S\)-wave* velocity \((V_s)\)

*In anisotropic media there are two \(S\)-waves \((S_v/S_h\) or \(S_1/S_2)\) with \(<>\) polarizations & speeds
Simple Example (sonic logs)

- Compressional sonic logs in same field for different well deviations

(Hornby et al., 2003)
Polar anisotropy (VTI) – what it is?

“The wave velocity varies with the propagation angle from vertical”

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

(Adapted from Oilfield Review, 1994)

(Horne et al., 2012)
Polar Anisotropy (VTI) - *Thomsen parameters* $\varepsilon$, $\delta$, $\gamma$

- **Isotropic seismic analyses:**
  - $Vp$, $Vs$, density

- **Anisotropic seismic analyses:**
  - $Vp_0$, $Vs_0$, density
  - $\varepsilon$, $\delta$
  - $\gamma$ (*microseismic, multicomponent seismic*)
  - *Tilt* of symmetry axis $\rightarrow$ TTI

- $Vp_0$ vertical $P$-wave velocity
- $Vs_0$ vertical $S$-wave velocity
- $\varepsilon$ $\sim$ “%” of $P$-wave anisotropy (horizontal vs vertical velocity)
- $\gamma$ $\sim$ “%” of $SH$-wave anisotropy (horizontal vs vertical velocity)
- $\delta$ anisotropy curve ‘Shape’ parameter ($P$- and $Sv$-waves)

(Horne et al., 2010)
The **elastic tensor** relates stress to strain (*Hooke’s law*)

The elastic tensor has \(\leq 21\) independent parameters

- **Isotropy (ISO):** 2 parameters \((V_p, V_s)\)
- **Tilted TI (TTI):** 5 parameters \((V_{p_0}, V_{s_0}, \varepsilon, \delta, \gamma)\) + tilt
  - **VTI:** 5 parameters (*Vertical axis / polar*)
  - **HTI:** 5 parameters (*Horizontal axis / azimuthal*)
- **Orthorhombic (ORT):** 9 parameters (2 sym. planes)
  - **FVTI = Fractured VTI**
    - 8 parameters (*1 sym. plane*)
**VTI-anisotropy impact on Geomechanics**

**Key applications:** wellbore stability, well design and hydraulic fracturing

Minimum horizontal stress is computed from vertical stress, elasticity, closure stress data and a poroelastic model

**Barnett shale:**
- Low stress in high-clay volumes using isotropic model
- Higher stress predicted using anisotropic model

(Waters et al., 2011)
Key applications: seismic depth imaging, amplitude vs angle (AVA), AVA vs azimuth in fractured reservoirs (AVAz), Full-waveform Inversion (FWI), etc.

(WG, data courtesy of Wintershall)

(Isotropic PSDM)

(ISO, data courtesy of Wintershall)

(Jones et al., 2003)

(Gerritsen et al., 2016)
Anisotropic seismic imaging results in:

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

Anisotropic 3D preSDM $\delta = 10\%$, $\varepsilon = 16\%$

Anisotropic PSDM

Anisotropic models reveal:

- Tilted transverse isotropic model reveals well trajectory had crossed the fault

(WG, data courtesy of Wintershall)

(Jones et al., 2003)

(Gerritsen et al., 2016)
How to measure TTI? Surface seismic

- Grid tomography workflow updates $Vp_0$, $\varepsilon$, $\delta$
- Borehole data constraints (usually markers & vertical velocities)

**Limitations:** opening angles and data quality decrease with depth and uncertainty in $Vp_0$, $\varepsilon$, $\delta$ increases

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

→ **Upscaling** borehole data and joint tomography are key processes

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

(Woodward et al., 2008)

(Bakulin et al., 2010)
How to measure TTI? **Sonic logs**

**Vertical wells drilled through flat shales:**
- Advanced LWD and wireline sonic measure vertical shear ($C44=C55$) and also horizontal shear ($C66$) from Stoneley mode $\rightarrow$ Thomsen $\gamma$

**Deviated wells drilled through shales:**
- Wireline dipole required to discriminate $Sv$ & $Sh$ shears
- Monopole compressional and Stoneley are used

*Constraints from a priori* anisotropy database, VSP or multi-well sonic data $\rightarrow$ Thomsen $\epsilon$, $\delta$, $\gamma$

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**Polar anisotropy signature of sonic recorded in vertical well flat layers**

- **VTI** ($C66 > C44$)
- **Stokey**
- **Dipole**
- **ISO**
- ~ similar VTI effect on LWD Quadrupole

*(Valero et al., 2009)*

*(Holstein et al., 2007)*

**NOTE:** dipmeter required to know relative dips
How to measure TTI? **Wireline Walkaway VSPs**

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

**Delivers locally:** Thomsen $\varepsilon$, $\delta$ and tilted axis
Thomsen parameters:
\[ \varepsilon \sim 0.6, \quad \delta \sim 0.1 \text{ (Walkaway), } \gamma \sim 1 \text{ (Sonic)} \]  

(Waqaq et al., 2017)
Calibration of Anisotropic Models using Sonic & Walkaway VSP

**Sonic VTI signature in shales**

**Isotropic Stoneley model**

**Isotropic Dipole Flexural model**

**Sonic VTI signature in shales**

**Zone-1 VTI**

**ISO**

**Down-Sv**

**Down-P**

**Walkaway VTI signature in shales and Thomsen parameters computed**

\( \varepsilon = +0.33 \)

\( \delta = +0.06 \)

\( \eta = +0.24 \)

**tilt = 2°**

(Guerra et al., 2016)
Correlation between $\varepsilon$ and $\gamma$ seen in cores (above) was estimated \textit{in-situ} from collocated Walkaway & Sonic measurements and used to extend the anisotropy logs.

Borehole anisotropy improved velocity model and minimized Walkaway travel time residuals.
Calibration of Anisotropic Models using Sonic & Walkaway VSP

Walkaway & Sonic TI-anisotropy – North Sea (1/2)

Slowness-
Polarization
TI-anisotropy
Inversion

\[
\varepsilon = 0, \delta = 0 \quad \text{(isotropic)}
\]
\[
\varepsilon = +0.20, \delta = +0.10
\]
\[
\varepsilon = +0.41, \delta = +0.10 \quad \text{(solution)}
\]
\[
\varepsilon = +0.40, \delta = +0.10 \quad \text{(strongly VTI)}
\]

Quality S-wave data points were key to constrain solution

Simplex method for Line-2

Simplex method for Line-1

(Mogensen et al., 2018)
Walkaway & Sonic TI-anisotropy – North Sea (2/2)

Calibration of Anisotropic Models using Sonic & Walkaway VSP

(Mogensen et al., 2018)
The Reservoir (at this location) is orthorhombic, with $\varepsilon = 0.12$, $\delta_V = 0.10$, $\delta_N = 0.13$

- Average fast azimuth from sonic shear is N60E, ortho upscaling requires Schoenberg and Muir (1989)
- Upscaled model used as background for AVAZ inversion

The sonic method relies on core database and advanced wireline sonic measurement to deliver in vertical wells 7 FVTI parameters:

- **Vp0, Vs0, $\varepsilon$, $\delta$, $\gamma$, $\delta_N$, $\delta_V$**
- **Missing**: $\delta_H$

Two ortho-walkaways give 6 FVTI parameters:

- **Vp0, Vs0, $\varepsilon$, $\delta$, $\delta_N$, $\delta_V$**

(Mizuno et al, 2015)
Conclusions

• We have reviewed elastic anisotropy and its importance in:
  • *Seismic data analyses*
  • *Geomechanical studies*

• *In-situ* borehole measurements of anisotropy from sonic & VSP are crucial to calibrate earth models and minimize uncertainties

• *New advances still needed in the integration of the different measurement scales, from core to field scale, and in handling lower anisotropy symmetries*
References


Leaney, W.S. and Jocker, J. [2018] Sonic tensor completion, GeoConvention, CSEG

Mogensen, C., Khaitan, M., Guerra, R., Dahlhaus, L., Leaney, S., Jocker, J. and E. Wielemaker [2018] Elastic Anisotropy from Walkaway VSP and Sonic Data Recorded in the North Sea: 80th EAGE Conference and Exhibition, Copenhagen, Extended Abstracts


