Attenuation anisotropy: Analysis and Estimation

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Acknowledgements

- Ilya Tsvankin (CSM)
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What is attenuation?
Attenuation mechanisms

- intrinsic attenuation
- fluid flow
- stress
- friction
Attenuation in volcanoes

Gori et al., 2011
Attenuation in gas-hydrates

Priest et al., 2006
Attenuation in heavy-oils

Hedlin et al., 2001
Attenuation in oil & gas fields

Rapoport et al., 2004
Anisotropic attenuation mechanisms

- interbedding of thin layers
- preferential fluid flow
- directionally-dependent stress
- friction
Attenuation anisotropy in subduction zone

\[ Q_{NS} = 116 \pm 6 \]

\[ Q_{EW} = 89 \pm 7 \]

Hiramitsu & Ando, 1995
Attenuation anisotropy in the lab

Best et al., 2007
Attenuation anisotropy from VSP

Maultzsch et al., 2005
Take-home message

- attenuation anisotropy exists
- ...and can be strong
Topics covered

- influence of the inhomogeneity angle
- parameterization
- AVO
- estimation
- case studies
Mystery of the inhomogeneity angle

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Inhomogeneity angle $\xi$

\[ A(\xi) = \frac{k^I}{k^R} \text{ (attn. per wavelength)} \]
Reflection from attenuative reservoir

Elastic cap rock

Attenuative reservoir

\[ \xi = \theta_T \]

\[ k^R \]

\[ k^{I,refl} \]

\[ k^{R,refl} \]
Estimated vs exact interval attenuation

Behura & Tsvankin, 2009
Estimated vs exact interval attenuation

Behura & Tsvankin, 2009
Group attenuation (isotropy)
Group attenuation (isotropy)

\[ A_g = \frac{1}{\omega} (\vec{k}^I \cdot \vec{V}_g) \]
Group attenuation (isotropy)

\[ A_g = \frac{1}{\omega} (\vec{k}^I \cdot \vec{V}_g) \]

\[ = \frac{k^I \cos \xi}{k^R} \]
Group attenuation (isotropy)

\[ A_g = \frac{1}{\omega} \left( \vec{k}^I \cdot \vec{V}_g \right) \]

\[ = \frac{k^I \cos \xi}{k^R} \]

\[ = A|_{\xi=0^\circ} = \frac{1}{2Q} \]
Isotropic medium \((Q_P = Q_S = 5)\) (as function of \(\xi\))

**P-wave**

**S-wave**

\[
\begin{align*}
A_\parallel |_{\xi=0}^\circ & \\
A_g & \\
\end{align*}
\]
Anisotropic media
Group attenuation (anisotropy)
Group attenuation (anisotropy)

\[ A_g = \frac{1}{\omega} \left( \vec{k}^I \cdot \vec{V}_g \right) \]
Group attenuation (anisotropy)

\[ A_g = \frac{1}{\omega} \left( \vec{k}^I \cdot \vec{V}_g \right) \]

\[ = \frac{k^I \cos(\xi - \psi)}{k^R \cos \psi} \]
Group attenuation for $\xi = 0^\circ$

$$A_g(\xi = 0^\circ) = \left. \frac{k^I}{k^R} \right|_{\xi=0^\circ} = A|_{\xi=0^\circ}$$
\[ \xi = 0^\circ: \quad Q_{P0} = Q_{S0} = 10 \]
\[ \epsilon_Q = 0.6, \quad \delta_Q = 0.4, \quad \gamma_Q = 0.5 \]
Group attenuation for $\xi \neq 0^\circ$

$$A_g \approx A_{|\xi=0^\circ}$$
\[ \xi = 60°: Q_{P0} = Q_{S0} = 10 \]
\[ \epsilon_Q = 0.6, \delta_Q = 0.4, \gamma_Q = 0.5 \]
\[ A_g \neq A \bigg|_{\xi=0^\circ} \]
ξ approaching forbidden directions

\( Q_P = 5 \)
**Take-home message**

- wide range of $\xi$: $A_g = A|_{\xi=0^\circ}$
- near forbidden directions: $A_g \neq A|_{\xi=0^\circ}$
- $A_g$ controlled by attenuation anisotropy
- velocity field needed for inversion
Declercq et al., 2005, *The history and properties of ultrasonic inhomogeneous waves*, IEEE transactions on ultrasonics, ferroelectrics, and frequency control.


Backup slides
VTI: $Q_{S0} = 5$, $\gamma_Q = 0.5$

\[ \theta = 0^\circ \quad \theta = 45^\circ \]
Background: Isotropic attenuative
Perturbed: Anisotropic attenuative
Perturbation of complex wave vector

\[
\frac{\Delta k^R}{k^R,0} \approx f_1(\Delta c_{ij}^R)
\]

\[
\frac{\Delta k^I}{k^I,0} \approx f_2(\Delta c_{ij}^R, \Delta c_{ij}^I, \xi)
\]
Perturbation of complex wave vector

- $\Delta k^R$: velocity anisotropy
- $\Delta k^I$: velocity + attenuation anisotropy
- only $\Delta k^I$ influenced by $\xi$
\[ A_{g,P} \approx A\big|_{\xi=0^\circ,P} \]

\[ = \frac{1}{2Q_{P0}} \left( 1 + \delta_Q \sin^2 \theta \cos^2 \theta + \epsilon_Q \sin^4 \theta \right) \]
Attenuation anisotropy: analytic description

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- Yaping Zhu (ExxonMobil)
- Ilya Tsvankin
Transverse isotropy (TI)
TI velocity and attenuation: SH-wave

\[ V_{SH} = V_{S0} (1 + \gamma \sin^2 \theta) \]

\[ \gamma = \frac{c_{66} - c_{55}}{2c_{55}} \]
TI velocity and attenuation: SH-wave

velocity

\[ V_{SH} = V_S(1 + \gamma \sin^2 \theta) \]

\[ V_x \]

\[ V_{z} \]

\[ V_{S0} \]

\[ \gamma = \frac{c_{66} - c_{55}}{2c_{55}} \]

attenuation

\[ A_{SH} = A_S(1 + \gamma_Q \sin^2 \theta) \]

\[ A_x \]

\[ A_z \]

\[ A_{S0} \]

\[ \gamma_Q = \frac{Q_{55} - Q_{66}}{Q_{66}} \]
TI velocity and attenuation parameters

\begin{align*}
\text{isotropy} & \quad \begin{array}{c}
\text{velocity} \\
V_{P0} \\
V_{S0}
\end{array} & \quad \begin{array}{c}
\text{attenuation} \\
A_{P0} \\
A_{S0}
\end{array} \\
\text{anisotropy} & \quad \begin{array}{c}
\varepsilon \\
\delta \\
\gamma
\end{array} & \quad \begin{array}{c}
\varepsilon_Q \\
\delta_Q \\
\gamma_Q
\end{array}
\end{align*}
\[ \delta_Q \equiv \frac{1}{2A_{P0}} \left. \frac{d^2 A_P}{d\theta^2} \right|_{\theta=0^\circ} = f(\delta, V_{P0}/V_{S0}; Q_{33}, Q_{55}, Q_{13}) \]
Approximate P-wave attenuation

\[ A_P = A_{P0}(1 + \delta_Q \sin^2 \theta \cos^2 \theta + \epsilon_Q \sin^4 \theta) \]

\[ V_P = V_{P0}(1 + \delta \sin^2 \theta \cos^2 \theta + \epsilon \sin^4 \theta) \]
VTI velocity and attenuation

\[
\begin{align*}
V_{P0} &= 2.42 \text{ km/s} \\
V_{S0} &= 1.40 \text{ km/s} \\
\delta &= 0.15, \ \epsilon = 0.40
\end{align*}
\]

\[
\begin{align*}
A_{P0} &= 0.015 \\
\delta_Q &= 0.94 \\
\epsilon_Q &= -0.13
\end{align*}
\]
Physical model

Dewangan et al., 2005
Data acquisition

- Source: 10.8 cm
- Receptors: 60 cm
- Symmetry axis: 70°
Data analysis

Zhu et al., 2007

Receiver coordinate (cm)

Time (ms)

Frequency (kHz)

0.05
0.10
20

0
20
0
400
600
200

P
Attenuation anisotropy

Zhu et al., 2007

10.8 cm

receivers

70° sym. axis

X_3

X_1

Zhu et al., 2007
Orthorhombic media
Phase-velocity surfaces

Tsvankin, 2005

\[
\begin{bmatrix}
\varepsilon^{(2)} \\
\delta^{(2)} \\
\gamma^{(2)}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\varepsilon^{(1)} \\
\delta^{(1)} \\
\gamma^{(1)}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\delta^{(3)}
\end{bmatrix}
\]

Tsvankin, 2005
### Anisotropy parameters

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{P0}$</td>
<td>$A_{P0}$</td>
</tr>
<tr>
<td>$V_{S0}$</td>
<td>$A_{S0}$</td>
</tr>
<tr>
<td>$\epsilon^{(1,2)}$</td>
<td>$\epsilon^{(1,2)}_Q$</td>
</tr>
<tr>
<td>$\delta^{(1,2,3)}$</td>
<td>$\delta^{(1,2,3)}_Q$</td>
</tr>
<tr>
<td>$\gamma^{(1,2)}$</td>
<td>$\gamma^{(1,2)}_Q$</td>
</tr>
</tbody>
</table>

*Zhu & Tsvankin, 2007*
Take-home message

- Thomsen-style parameters
- linearized attenuation coefficients
References


• Zhu et al., 2007, *Physical modeling and analysis of P-wave attenuation anisotropy in transversely isotropic media*, Geophysics.
Reflection coefficients in attenuative anisotropic media

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Isotropic media

![Graph showing the relationship between $|R_{PP}^H|$ and $\theta$ for different values of $Q$.]
Inhomogeneity angle

\[ \xi = 0^\circ \]

\[ \xi \neq 0^\circ \]
Incident P-wave with $\xi = 0^\circ$
TI medium parameters

\[ V_{P0}, V_{S0}, \delta, \varepsilon, \gamma \]
TI medium parameters

\[ V_{P0}, V_{S0}, \delta, \epsilon, \gamma \]

\[ A_{P0}, A_{S0}, \delta_Q, \epsilon_Q, \gamma_Q \]

\[ Q_{P0} \approx \frac{1}{2A_{P0}} \]
VTI PP-wave reflection coefficient

\[ R_{PP}^H = R_{PP}^H(0) + G_{PP}^H \sin^2 \theta \]
\[ + C_{PP}^H \sin^2 \theta \tan^2 \theta \]
VTI PP-wave reflection coefficient

\[ R_{PP}^H = R_{PP}^H(0) + G_{PP}^H \sin^2 \theta \]
\[ + C_{PP}^H \sin^2 \theta \tan^2 \theta \]

\[ R_{PP}^H(0) = \frac{\Delta \rho}{2 \rho_0} + \frac{\Delta V_{P0}}{2 V_{P0}} + \frac{\Delta A_{P0}}{2} \left( i + \frac{1}{Q_{P0}} \right) \]
shale/oil-sand reflection

\[ |R^H_{PP}| \]

\[ Q = 2.5 \]

\[ \theta \]

\[ 0^\circ \quad 10^\circ \quad 20^\circ \quad 30^\circ \]
Influence of $Q$-anisotropy

\[ G_{PP}^H \]

\[ \delta_{Q,2} \]

Graph showing the relationship between $G_{PP}^H$ and $\delta_{Q,2}$ for different values of $Q$: $Q = 50$, $Q = 10$, $Q = 5$.
Influence of inhomogeneity angle

\[ \xi \neq 0^\circ \]
Incident P-wave with $\xi \neq 0^\circ$

$$R_{PP}^{\text{IH}} = R_{PP}^{\text{IH}}(0) + B_{PP}^{\text{IH}} \sin \theta + G_{PP}^{\text{IH}} \sin^2 \theta$$
\[ R_{PP}^{IH}(0) = R_{PP}^{H}(0) + \frac{\sin^2 \xi}{4Q_{P0}} f_1(\Delta) \]

\[ B_{PP}^{IH} = \frac{-i \sin \xi}{Q_{P0}} f_2(\Delta) \]

\[ G_{PP}^{IH} = G_{PP}^{H} + \frac{i \sin^2 \xi}{8Q_{P0}} f_3(\Delta) \]
$Q = 50$

\[ |R_{pp}^{HH}| \]

\[ \theta \]

- \[ \xi = 0^\circ \]
- \[ \xi = 25^\circ \]
- \[ \xi = 50^\circ \]
$Q = 10$
\( Q = 5 \)

\[ |R_{PP}^{HH}| \]

\( \xi = 0^\circ \)
\( \xi = 25^\circ \)
\( \xi = 50^\circ \)

\( \theta \)

-20\(^\circ\), 0\(^\circ\), 20\(^\circ\)
Asymmetric ref. coef.
\[ R_{PS}^{IH} = R_{PS}^{IH}(0) + B_{PS}^{IH} \sin \theta + G_{PS}^{IH} \sin^2 \theta \]
PS-wave ref. coef. \((\xi = 50^\circ)\)
Take-home message

- only low $Q$ influences ref. coef.
- inhomogeneity angle:
  - additional terms
  - non-zero PS-wave energy at normal incidence


Backup slides
Reflection from attenuative reservoir

Elastic cap rock

Attenuative reservoir

$\xi = \theta_T$

$\theta_T$

$\mathbf{k}^{R,\text{refl}}$

$\mathbf{k}^I_{\text{refl}}$

$\mathbf{k}^R$

$\mathbf{k}^I$
Incident P-wave with $\xi = 0^\circ$

$$R_{PP}^H = \frac{\Delta \rho}{2 \rho_0} + \frac{\Delta \tilde{a}_{33}}{4 \tilde{V}_{P0}^2}$$

$$+ \left( \frac{\Delta \tilde{a}_{13}}{2 \tilde{V}_{P0}^2} - \frac{\Delta \tilde{a}_{33}}{4 \tilde{V}_{P0}^2} - \frac{\Delta \tilde{a}_{55}}{\tilde{V}_{P0}^2} - \frac{2 \tilde{V}_{S0}^2}{\tilde{V}_{P0}^2} \frac{\Delta \rho}{\rho_0} \right) \sin^2 \theta$$

$$+ \frac{\Delta \tilde{a}_{11}}{4 \tilde{V}_{P0}^2} \sin^2 \theta \tan^2 \theta$$
Estimating \textit{interval} anisotropic attenuation from reflection data

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Interval attenuation

- sonic log
- VSP
- crosswell techniques
Interval attenuation

- sonic log
- VSP
- crosswell techniques
- reflection data
Layer stripping for $Q$
Layer stripping for $Q$
Layer stripping for $Q$
Layer stripping for $Q$
Layer stripping for $Q$

Interval attenuation
Layer stripping for $Q$
Layer stripping for $Q$
Layer stripping for $Q$

Overburden

Target

$A$ $B$ $C$ $D$ $E$ $F$ $G$
Layer stripping for $Q$
Frequency-domain amplitude

\[ |U_{ABCEG}(\omega)| = S(\omega) G_{ABCEG} \]

\[ \ast e^{-k_{g,O}^I (l_{AB} + l_{EG})} e^{-k_{g,T}^I (l_{BC} + l_{CE})} \]
Layer stripping for $Q$
Modified spectral-ratio

\[ U_{ratio} = \frac{\left| U_{ABCEG}(\omega) \right|^2}{\left| U_{ABD}(\omega) \right| \left| U_{GEF}(\omega) \right|} \]
Modified spectral-ratio

\[ \ln \left( U_{ratio} \right) = \ln(G) - 2 k_{g,T}^I (l_{BC} + l_{CE}) \]
\[ \ln \left( U_{ratio} \right) = \ln(G) - 2 k_{g,T}^I (l_{BC} + l_{CE}) \]
\[ \ln (U_{ratio}) = \ln (g) - 2 k_{g,T}^I (l_{BC} + l_{CE}) \]
\[ \ln (U_{ratio}) = \ln (G) - 2 k^{I}_{g,T} V_g t_{BCE} \]
Interval $A = \frac{k^I}{k^R}$

\[
\ln (U_{\text{ratio}}) = \ln(G) - 2 \omega A t_{BCE}
\]
\[ \ln \left( \frac{U_{ratio}}{G} \right) = \ln(G) - \omega \frac{1}{Q} t_{BCE} \]
**Synthetic example**

<table>
<thead>
<tr>
<th>Material</th>
<th>$Q_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>$Q = \infty$</td>
</tr>
<tr>
<td>VTI</td>
<td>$Q_0 = 10$</td>
</tr>
<tr>
<td>VTI halfspace</td>
<td>$Q_0 = 200$</td>
</tr>
<tr>
<td>VTI halfspace</td>
<td>$Q_0 = 100$</td>
</tr>
</tbody>
</table>
Shot gather

Offset (km)

Time (s)

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Interval attenuation
Shot gather

Interval attenuation

J. Behura (CSM)
Shot gather

J. Behura (CSM)

Interval attenuation
A – 2nd layer

\[ \xi \approx 40^\circ \]

\[ \xi = 0^\circ \]
Shot gather

Interval attenuation
A – 3rd layer
## 3D synthetic example

<table>
<thead>
<tr>
<th>Material</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>$Q = \infty$</td>
</tr>
<tr>
<td>Orthorhombic</td>
<td>$Q_{33} = 50$</td>
</tr>
<tr>
<td>VTI</td>
<td>$Q_0 = 100$</td>
</tr>
<tr>
<td>Orth. halfspace</td>
<td>$Q_{33} = 100$</td>
</tr>
</tbody>
</table>
A – 2nd layer

Estimated

True

Interval attenuation
A – 3rd layer

Estimated

True
Take-home message

- \( Q \) from reflection data – requires clean data
- accurate results even for low \( Q \) and strong anisotropy
- fracture characterization
References


Backup slides
3D synthetic example

\[ \rho, V_{P0}, V_{S0}, \epsilon^{(1)}, \epsilon^{(2)}, \delta^{(1)}, \delta^{(2)}, \delta^{(3)}, Q_{P0}, Q_{S0}, \epsilon^{(1)}_Q, \epsilon^{(2)}_Q, \delta^{(1)}_Q, \delta^{(2)}_Q, \delta^{(3)}_Q, \phi \]
Estimation of interval attenuation and velocity anisotropy from reflection data at Coronation Field

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Questions in unconventional plays:

- Where to drill?
- How to orient the well?
Why velocity anisotropy?

- imaging
- reservoir characterization
Why attenuation?

- lithology
- fluid presence
- physical properties of rocks
- permeability, fluid mobility & saturation
Interval velocity from reflection seismic data (Dewangan & Tsvankin, 2006)
Interval attenuation from reflection seismic data (*Behura & Tsvankin, 2009*)
Layer stripping

A

B

C

D

E

F

G

Overburden

Target

J. Behura (CSM)  Coronation field study
Layer stripping

Dewangan & Tsvankin, 2006
Layer stripping

Dewangan & Tsvankin, 2006
Interval quantities

\[ t_{int} = t_{total} - \frac{t_{o1} + t_{o2}}{2} \]

Dewangan & Tsvankin, 2006
Interval quantities

\[ t_{\text{int}} = t_{\text{total}} - \frac{t_{o1} + t_{o2}}{2} \]

Dewangan & Tsvankin, 2006

\[ \ln \left( \frac{|U_{\text{total}}|^2}{|U_{o1}| \cdot |U_{o2}|} \right) = \ln(G) - \frac{\omega t_{\text{int}}}{Q} \]

Behura & Tsvankin, 2009
Products

- interval velocity anisotropy
- interval attenuation anisotropy
Stratigraphy

Jackson, 1984
Acquisition

sources
receivers
### Acquisition

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey type</td>
<td>3D 3-C</td>
</tr>
<tr>
<td>Shot interval (single hole dynamite)</td>
<td>42.43 m</td>
</tr>
<tr>
<td>Shot line interval</td>
<td>240 m</td>
</tr>
<tr>
<td>Receiver interval</td>
<td>30 m</td>
</tr>
<tr>
<td>Receiver line interval</td>
<td>210 m</td>
</tr>
<tr>
<td>Receiver patch</td>
<td>12 × 94</td>
</tr>
<tr>
<td>Nominal fold (30 m × 30 m bins)</td>
<td>140</td>
</tr>
<tr>
<td>Maximum offset</td>
<td>2060 m</td>
</tr>
</tbody>
</table>

*Monk et al., 2006*
refraction statics corrections
- despiking
- residual statics
- ground-roll suppression
- dynamite source strength compensation
Determine interval velocity and attenuation using layer-stripping (assuming orthorhombic symmetry)

- nonhyperbolic semblance analysis
- layer-stripping for traveltimes
- estimation of interval $V_{\text{nmo}}^{(1,2)}$, $\eta^{(1,2,3)}$ and symmetry-plane azimuths
- attenuation layer stripping
Azimuthal velocity anisotropy
Attenuation coefficient $1/(2\psi)$
Independent data (Monk et al., 2006)
Attenuation anisotropy parameter $\delta_Q^{(1)}$
Summary

- processing for orthorhombic media
- velocity-independent layer-stripping
- interval velocity and attenuation anisotropy
- large attenuation $\rightarrow$ gas-producing wells
- can be used to plan horizontal wells
velocity $+$ attenuation $=$
References


- Behura et al., 2012, *Estimation of interval velocity and attenuation anisotropy from reflection data at Coronation Field*, TLE.
Backup slides
Velocity anisotropy parameter $\delta^{(3)}$
Independent data (*Monk et al., 2006*)

![Graph showing data distribution with grid marks for X (km) and Y (km). The color scale ranges from 6 to 26. Symbols are present in the lower right quadrant.]

J. Behura (CSM)
Coronation field study
Attenuation anisotropy from cross-hole data

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- Bharath Shekar
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3D Acquisition geometry

- Receivers
- Sources

Stage 3
Stage 4
Stage 5
Stage 6
Stage 7
...plan view in polar coordinates
Azimuthal attenuation

\[ A_P \]

\[ \phi (\text{deg}) \]

- Stage 3
- Stage 4
- Stage 5
- Stage 6
- Stage 7
Q change with frac-stage

![Graph showing Q change with frac-stage](image-url)
Take-home message

- polar anisotropy $>\,$ azimuthal anisotropy
- time-lapse measurement of attenuation