# Azimuthal AVO and Curvature

Jesse Kolb*
David Cho
Kris Innanen

UNIVERSITY OF CALGARY

NSERC CRSNG

CREWES

# Azimuthal AVO

What is azimuthal AVO?:

- Analysis of incidence angle and azimuthal amplitude variations of reflection coefficients;
- Measures change in elastic properties at an interface.

Why is azimuthal AVO used?:

- Better vertical resolution than propagation methods (e.g. VVAZ, S-wave splitting);
- Usually used to attempt to characterize natural fractures or differential stress in a reservoir.

# Motivation

Want an azimuthal AVO technique that

- Works for general anisotropy (no rock physics assumptions in the initial stage);
- Has no ambiguities (solutions are unique);
- Is easy to understand.

# Voigt notation

Hooke's Law:

$$\sigma_{ij} = C_{ijkl}\epsilon_{kl}$$

# Voigt notation

Hooke's Law:

$$\sigma_{ij} = C_{ijkl}\epsilon_{kl}$$

General Anisotropy

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46}\\ C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56}\\ C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66}\end{bmatrix}\begin{bmatrix}\epsilon_1\\ \epsilon_2\\ \epsilon_3\\ \epsilon_4\\ \epsilon_5\\ \epsilon_6\end{bmatrix}$$

# Voigt notation

Hooke's Law:

$$\sigma_{ij} = C_{ijkl}\epsilon_{kl}$$

General Anisotropy

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\ C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\ C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix}$$

Orthotropy

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix}$$

# Voigt notation

Hooke's Law:

$$\sigma_{ij} = C_{ijkl}\epsilon_{kl}$$

General Anisotropy

$$\begin{bmatrix}\sigma_1\\\sigma_2\\\sigma_3\\\sigma_4\\\sigma_5\\\sigma_6\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\ C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\ C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66} \end{bmatrix} \begin{bmatrix}\epsilon_1\\\epsilon_2\\\epsilon_3\\\epsilon_4\\\epsilon_5\\\epsilon_6\end{bmatrix}$$

Orthotropy

$$\begin{bmatrix}\sigma_1\\\sigma_2\\\sigma_3\\\sigma_4\\\sigma_5\\\sigma_6\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix}\epsilon_1\\\epsilon_2\\\epsilon_3\\\epsilon_4\\\epsilon_5\\\epsilon_6\end{bmatrix}$$

A = C/ρ

$$\begin{bmatrix} (V_{P_1})^2 & A_{12} & A_{13} & 0 & 0 & 0 \\ A_{12} & (V_{P_2})^2 & A_{23} & 0 & 0 & 0 \\ A_{13} & A_{32} & (V_{P_3})^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & (V_{S_{23}})^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & (V_{S_{13}})^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & (V_{S_{12}})^2 \end{bmatrix}$$

# Isotropic AVO

Shuey (1985) wrote the linearized weak contrast PP reflection coefficient in the form

$$R_{PP}^{iso}(\theta) = A + B\sin^2\theta + C\tan^2\theta\sin^2\theta$$

And Thomsen (1990) used this form to describe the effect of common seismic parameters $V_P$, $V_S$, ρ, and μ on the reflection coefficient:

$$R_{PP}^{iso}(\theta) = \frac{1}{2}\left[\frac{\Delta V_P}{\overline{V}_P} + \frac{\Delta\rho}{\overline{\rho}}\right] + \frac{1}{2}\left[\frac{\Delta V_P}{\overline{V}_P} - \left(\frac{2\overline{V}_S}{\overline{V}_P}\right)\frac{\Delta\mu}{\overline{\mu}}\right]\sin^2\theta + \frac{1}{2}\frac{\Delta V_P}{\overline{V}_P}\tan^2\theta\sin^2\theta$$

# Isotropic AVO

Shuey (1985) wrote the linearized PP reflection coefficient in the form

$$R_{PP}^{iso}(\theta) = \overbrace{\boxed{A}}^{\text{Intercept}} + \overbrace{\boxed{B}}^{\text{Gradient}} \sin^2\theta + \overbrace{\boxed{C}}^{\text{Curvature}} \tan^2\theta \sin^2\theta$$

And Thomsen (1990) used this form to describe the effect of common seismic parameters $V_P$, $V_S$, $\rho$, and $\mu$ on the reflection coefficient:

$$R_{PP}^{iso}(\theta) = \underbrace{\boxed{\frac{1}{2}\left[\frac{\Delta V_P}{\overline{V}_P} + \frac{\Delta\rho}{\overline{\rho}}\right]}}_{\text{Intercept}} + \underbrace{\boxed{\frac{1}{2}\left[\frac{\Delta V_P}{\overline{V}_P} - \left(\frac{2\overline{V}_S}{\overline{V}_P}\right)\frac{\Delta\mu}{\overline{\mu}}\right]}}_{\text{Gradient}} \sin^2\theta + \underbrace{\boxed{\frac{1}{2}\frac{\Delta V_P}{\overline{V}_P}}}_{\text{Curvature}} \tan^2\theta \sin^2\theta$$

# Anisotropic reflection coefficient

Thomsen (1993) derived the linearized PP reflection coefficient for small contrast weak anisotropy along a vertical plane:

$$
\begin{aligned}
R_{PP}(\theta) =& \frac{1}{2}\left[\frac{\Delta Z_0}{\overline{Z}_0}\right] \\
&+ \frac{1}{2}\left[\frac{\Delta V_{P_0}}{\overline{V}_{P_0}} - \left(\frac{2\overline{V}_{S_0}}{\overline{V}_{P_0}}\right)\frac{\Delta\mu_0}{\overline{\mu}_0} + (\delta_2 - \delta_1)\right]\sin^2\theta \\
&+ \frac{1}{2}\left[\frac{\Delta V_{P_0}}{\overline{V}_{P_0}} - (\delta_2 - \delta_1 - \epsilon_2 + \epsilon_1)\right]\tan^2\theta\sin^2\theta
\end{aligned}
$$

as did Vavryčuk and Pšenčík (1998) using perturbations from background P-wave velocities, α, and S-wave velocities β:

$$
\begin{aligned}
R_{PP}(\theta_P) =& \frac{\rho\Delta A'_{33} + 2\alpha^2\Delta\rho}{4\rho\alpha^2} \\
&+ \frac{1}{2}\left[\frac{\Delta A'_{33}}{2\alpha^2} - \frac{4(\rho\Delta A'_{55} + \beta^2\Delta\rho)}{\rho\alpha^2} + \Delta\delta^{*\prime}\right]\sin^2\theta_P \\
&+ \frac{1}{2}\left(\frac{\Delta A'_{33}}{2\alpha^2} + \Delta\epsilon^{*\prime}\right)\sin^2\theta_P\tan^2\theta_P
\end{aligned}
$$

Where

$$
\delta^{*(I)\prime} = \frac{A^{(I)\prime}_{13} + 2A^{(I)\prime}_{55} - A^{(I)\prime}_{33}}{\alpha^2}, \epsilon^{*(I)\prime} = \frac{A^{(I)\prime}_{11} - A^{(I)\prime}_{33}}{2\alpha^2}
$$

# Anisotropic reflection coefficient

Thomsen (1993) derived the linearized PP reflection coefficient for small contrast weak anisotropy along a vertical plane:

$$
\begin{aligned}
R_{PP}(\theta) =& \frac{1}{2}\left[\frac{\Delta Z_0}{\overline{Z}_0}\right] \\
&+ \frac{1}{2}\left[\frac{\Delta V_{P_0}}{\overline{V}_{P_0}} - \left(\frac{2\overline{V}_{S_0}}{\overline{V}_{P_0}}\right)\frac{\Delta\mu_0}{\overline{\mu}_0} + (\delta_2 - \delta_1)\right]\sin^2\theta \\
&+ \frac{1}{2}\left[\frac{\Delta V_{P_0}}{\overline{V}_{P_0}} - (\delta_2 - \delta_1 - \epsilon_2 + \epsilon_1)\right]\tan^2\theta\sin^2\theta
\end{aligned}
$$

as did Vavryčuk and Pšenčík (1998) using perturbations from background P-wave velocities, α, and S-wave velocities β:

$$
\begin{aligned}
R_{PP}(\theta_P) =& \frac{\rho\Delta A'_{33} + 2\alpha^2\Delta\rho}{4\rho\alpha^2} \\
&+ \frac{1}{2}\left[\frac{\Delta A'_{33}}{2\alpha^2} - \frac{4(\rho\Delta A'_{55} + \beta^2\Delta\rho)}{\rho\alpha^2} + \Delta\delta^{*\prime}\right]\sin^2\theta_P \\
&+ \boxed{\frac{1}{2}\left(\frac{\Delta A'_{33}}{2\alpha^2} + \Delta\epsilon^{*\prime}\right)}\sin^2\theta_P\tan^2\theta_P
\end{aligned}
$$

Where

$$
\delta^{*(I)\prime} = \frac{A_{13}^{(I)\prime} + 2A_{55}^{(I)\prime} - A_{33}^{(I)\prime}}{\alpha^2}, \boxed{\epsilon^{*(I)\prime} = \frac{A_{11}^{(I)\prime} - A_{33}^{(I)\prime}}{2\alpha^2}}
$$

# Curvature term

Substituting $\Delta\varepsilon^{*\prime}$ into the equation for a reflection coefficient from Vavryčuk and Pšenčík (1998) results in a curvature of

$$\frac{1}{2}\left(\frac{\Delta A'_{33}}{2\alpha^2}+\frac{\Delta A'_{11}-\Delta A'_{33}}{2\alpha^2}\right)=\frac{\Delta A'_{11}}{4\alpha^2}\approx\frac{1}{2}\frac{\Delta {V_P}'_H}{{V_P}'_H}$$

This term

- Is only influenced by a single stiffness coefficient
- Easily relates to the isotropic AVO equations
- Is simple to understand

# Curvature compared to Rüger's equation

The coordinate transformation (Bond, 1943) for $A'_{11}$ along an arbitrary vertical plane at an angle $\phi$ from the original plane is

$$A'_{11} = A_{11}\cos^4\phi + 4A_{16}\cos^3\phi\sin\phi + 2(A_{12}+2A_{66})\cos^2\phi\sin^2\phi + 4A_{26}\sin^3\phi\cos\phi + A_{22}\sin^4\phi$$

Rüger's curvature is

$$\frac{1}{2}\left[\frac{\Delta\alpha}{\overline{\alpha}} + \Delta\epsilon^{(V)}\cos^4\phi + \Delta\delta^{(V)}\sin^2\phi\cos^2\phi\right]$$

and inserting the weak anisotropy parameters and assuming $\alpha^2 = A_{33}$ it becomes

$$\frac{1}{2}\left[\left(\frac{\Delta A_{33}}{2\alpha^2}\right) + \left(\frac{\Delta A_{11} - \Delta A_{33}}{2\alpha^2}\right)\cos^4\phi + \left(\frac{\Delta A_{13} + 2\Delta A_{55} - \Delta A_{33}}{\alpha^2}\right)\sin^2\phi\cos^2\phi\right] =$$

$$\frac{1}{4\alpha^2}\left[\Delta A_{11}\cos^4\phi + 2(\Delta A_{13} + 2\Delta A_{55})\cos^2\phi\sin^2\phi + \Delta A_{33}\sin^4\phi\right]$$

# Anisotropic reflection coefficient

Thomsen (1993) derived the linearized PP reflection coefficient for small contrast weak anisotropy along a vertical plane:

$$
\begin{aligned}
R_{PP}(\theta) =& \frac{1}{2}\left[\frac{\Delta Z_0}{\overline{Z}_0}\right] \\
&+ \frac{1}{2}\left[\frac{\Delta V_{P_0}}{\overline{V}_{P_0}} - \left(\frac{2\overline{V}_{S_0}}{\overline{V}_{P_0}}\right)\frac{\Delta\mu_0}{\overline{\mu}_0} + (\delta_2 - \delta_1)\right]\sin^2\theta \\
&+ \frac{1}{2}\left[\frac{\Delta V_{P_0}}{\overline{V}_{P_0}} - (\delta_2 - \delta_1 - \epsilon_2 + \epsilon_1)\right]\tan^2\theta\sin^2\theta
\end{aligned}
$$

as did Vavryčuk and Pšenčík (1998) using perturbations from background P-wave velocities, α, and S-wave velocities β:

$$
\begin{aligned}
R_{PP}(\theta_P) =& \frac{\rho\Delta A'_{33} + 2\alpha^2\Delta\rho}{4\rho\alpha^2} \\
&+ \frac{1}{2}\left[\frac{\Delta A'_{33}}{2\alpha^2} - \frac{4(\rho\Delta A'_{55} + \beta^2\Delta\rho)}{\rho\alpha^2} + \Delta\delta^{*\prime}\right]\sin^2\theta_P \\
&+ \frac{1}{2}\left(\frac{\Delta A'_{33}}{2\alpha^2} + \Delta\epsilon^{*\prime}\right)\sin^2\theta_P\tan^2\theta_P
\end{aligned}
$$

Where

$$
\delta^{*(I)\prime} = \frac{A^{(I)\prime}_{13} + 2A^{(I)\prime}_{55} - A^{(I)\prime}_{33}}{\alpha^2}, \epsilon^{*(I)\prime} = \frac{A^{(I)\prime}_{11} - A^{(I)\prime}_{33}}{2\alpha^2}
$$

# Anisotropic reflection coefficient

Thomsen (1993) derived the linearized PP reflection coefficient for small contrast weak anisotropy along a vertical plane:

$$R_{PP}(\theta) = \frac{1}{2}\left[\frac{\Delta Z_0}{\overline{Z}_0}\right] + \frac{1}{2}\left[\frac{\Delta V_{P_0}}{\overline{V}_{P_0}} - \left(\frac{2\overline{V}_{S_0}}{\overline{V}_{P_0}}\right)\frac{\Delta \mu_0}{\overline{\mu}_0} + (\delta_2 - \delta_1)\right]\sin^2\theta + \frac{1}{2}\left[\frac{\Delta V_{P_0}}{\overline{V}_{P_0}} - (\delta_2 - \delta_1 - \epsilon_2 + \epsilon_1)\right]\tan^2\theta \sin^2\theta$$

as did Vavryčuk and Pšenčík (1998) using perturbations from background P-wave velocities, α, and S-wave velocities β:

$$R_{PP}(\theta_P) = \frac{\rho \Delta A'_{33} + 2\alpha^2 \Delta \rho}{4\rho\alpha^2} + \boxed{\frac{1}{2}\left[\frac{\Delta A'_{33}}{2\alpha^2} - \frac{4(\rho \Delta A'_{55} + \beta^2 \Delta \rho)}{\rho \alpha^2} + \Delta \delta^{*\prime}\right]}\sin^2\theta_P + \frac{1}{2}\left(\frac{\Delta A'_{33}}{2\alpha^2} + \Delta \epsilon^{*\prime}\right)\sin^2\theta_P \tan^2\theta_P$$

Where

$$\boxed{\delta^{*(I)\prime} = \frac{A_{13}^{(I)\prime} + 2A_{55}^{(I)\prime} - A_{33}^{(I)\prime}}{\alpha^2}}, \quad \epsilon^{*(I)\prime} = \frac{A_{11}^{(I)\prime} - A_{33}^{(I)\prime}}{2\alpha^2}$$

# Gradient along a plane

Substituting the weak anisotropy parameters into Vavryčuk and Pšenčík's gradient along a vertical plane results in

$$\frac{1}{2\alpha^2}\left[-2\Delta A'_{55} - 4\beta^2\frac{\Delta\rho}{\rho} + \Delta A'_{13} - \frac{\Delta A'_{33}}{2}\right]$$

The only terms in this gradient that change with azimuth are $\Delta A'_{55}$ and $\Delta A'_{13}$ under the following relations:

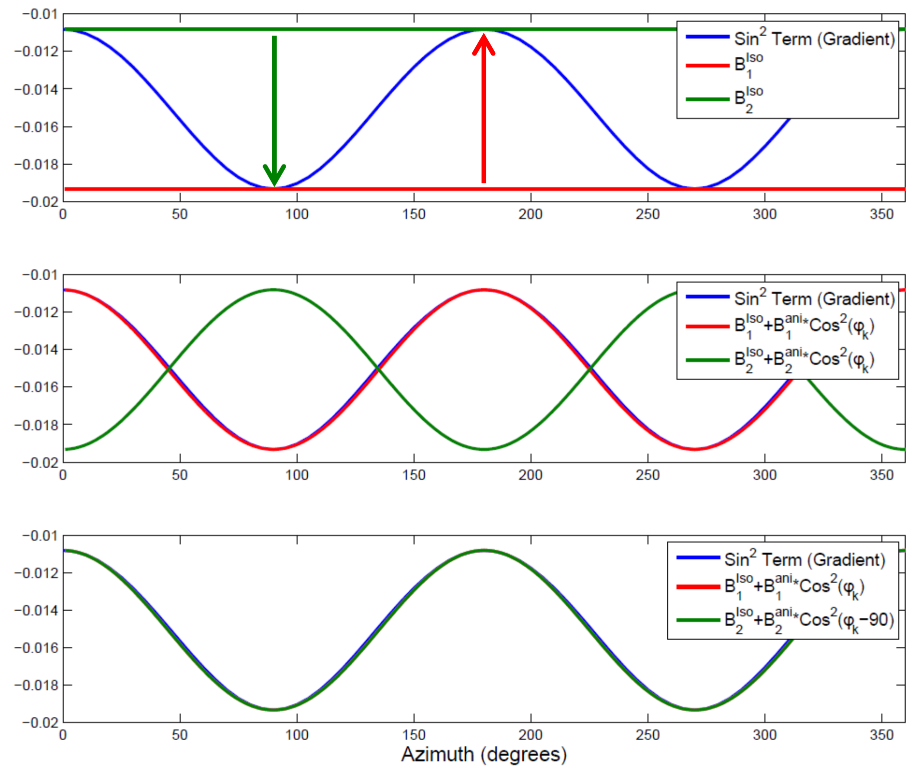
$$A'_{55} = A_{55}\cos^2\phi + 2A_{45}\cos\phi\sin\phi + A_{44}\sin^2\phi,$$
$$A'_{13} = A_{13}\cos^2\phi + 2A_{36}\cos\phi\sin\phi + A_{23}\sin^2\phi.$$

# 90-degree ambiguity

Rüger writes the gradient as

$$B(\phi_k) = B^{iso} + B^{ani}\cos^2(\phi_k - \phi_{sym})$$

which has 3 variables and is nonunique with 2 solutions.

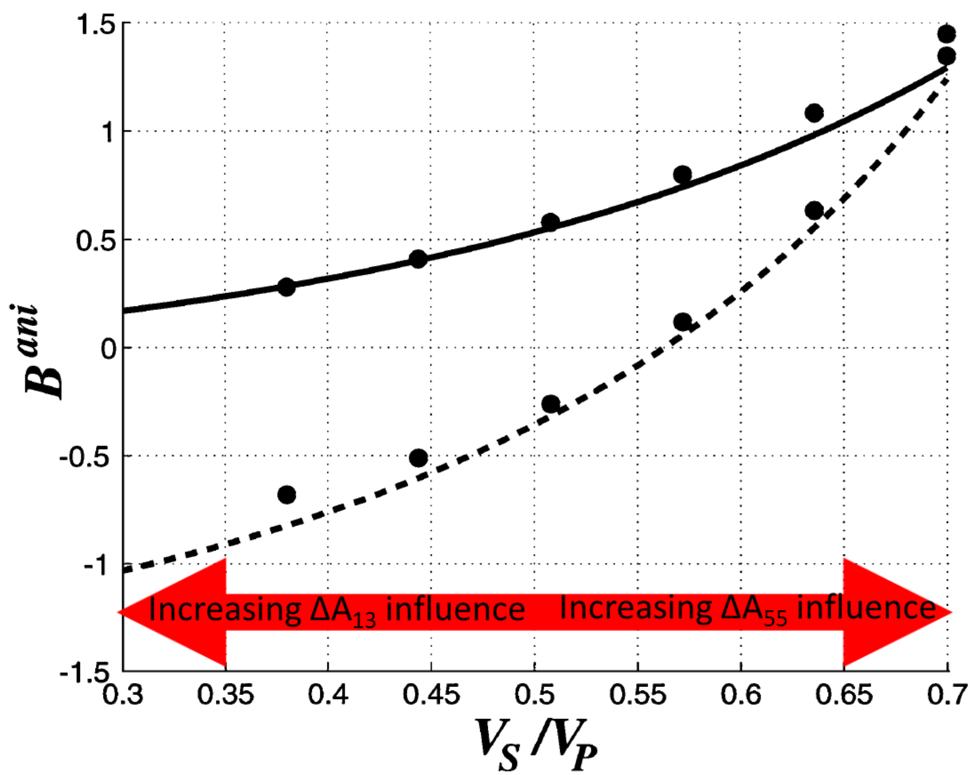



Azimuthal AVO gradient (blue) with two possible solutions (green and red). It is unclear if minima or maxima correspond to the symmetry axis.

# Ambiguity as minima/maxima

The azimuthal gradient is a combination of gradients along individual vertical planes so its minima and maxima are minima and maxima of the quantity

$$[-2\Delta A'_{55} + \Delta A'_{13}]$$

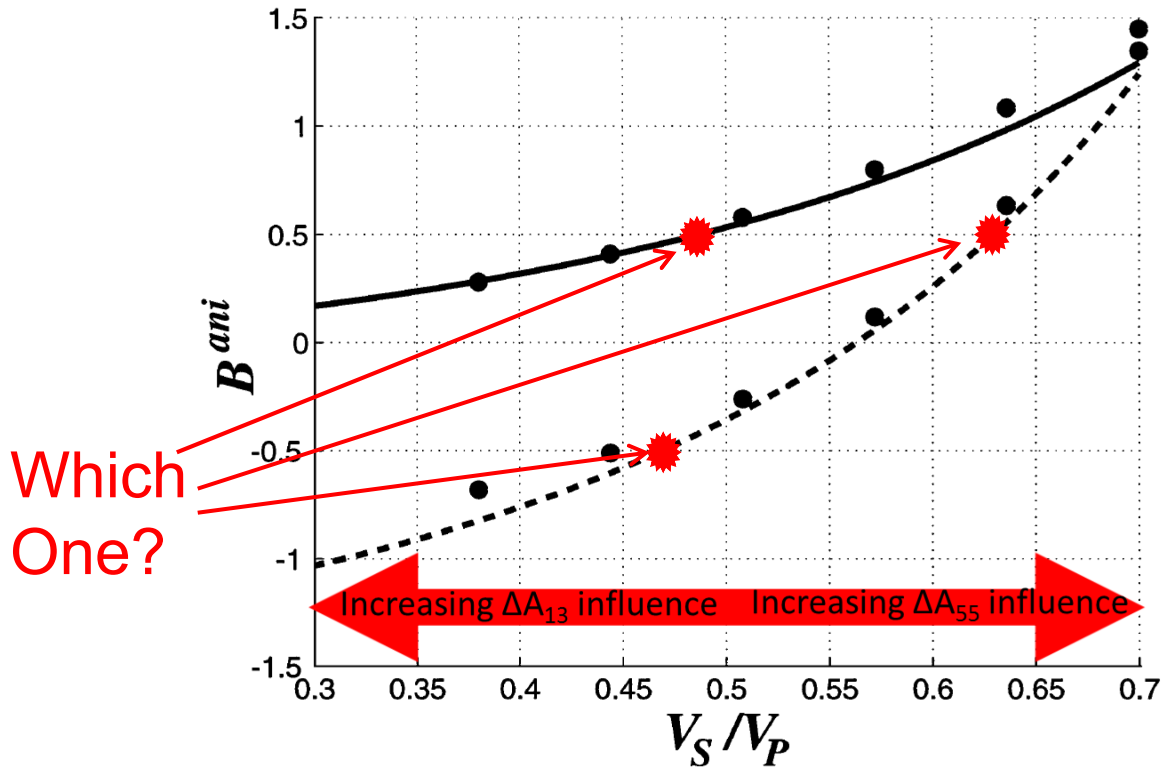



Change in anisotropic gradient with Vs/Vp ratio for aligned vertical dry (dashed line) and wet (solid line) fractures. After Bakulin et al. (2000).

# Ambiguity example

Here is an example of an ambiguity that would be caused if $B^{ani}$ had a measured magnitude of 0.5.

Values of 0.5 and -0.5 are both possibilities.




Change in anisotropic gradient with Vs/Vp ratio for aligned vertical dry (dashed line) and wet (solid line) fractures. After Bakulin et al. (2000).

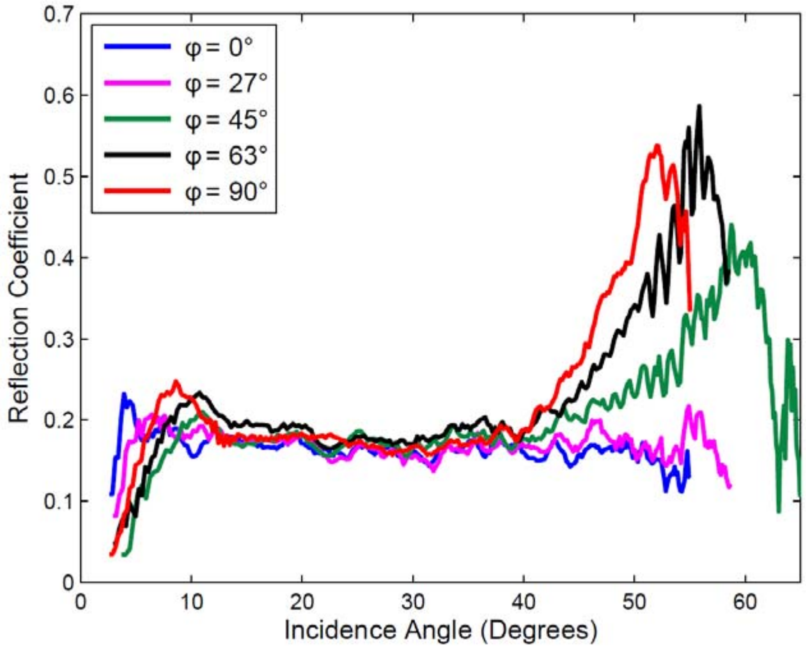
# Ways to constrain gradient

- Knowledge of liquid presence or lack of liquid presence + Vp/Vs ratio
- Approximate fracture direction from another method or from geology
- Azimuthal change in critical angle
- Azimuthal AVO curvature

# Physical modeling data

**Mahmoudian (2013)** collected and processed azimuthal reflection data using a model with the following approximate stiffnesses:

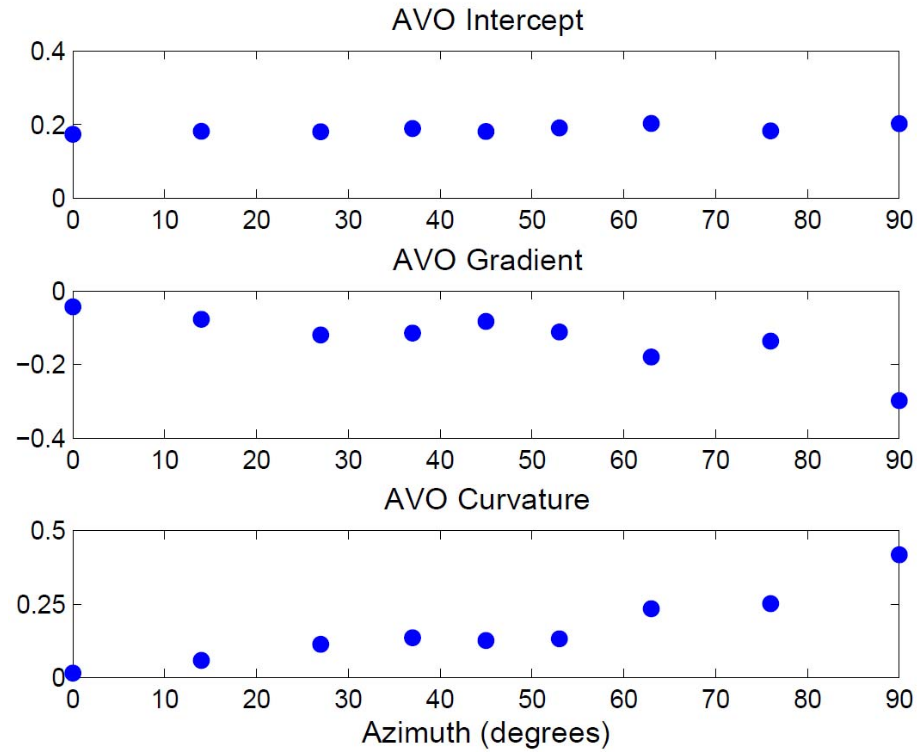
$$\begin{bmatrix} 8.70 \pm 0.49 & 4.68 \pm 0.21 & 5.07 \pm 0.21 & 0 & 0 & 0 \\ & 13.25 \pm 0.49 & 5.13 \pm 0.23 & 0 & 0 & 0 \\ & & 12.25 \pm 0.49 & 0 & 0 & 0 \\ & & & 2.89 \pm 0.12 & 0 & 0 \\ & & & & 2.34 \pm 0.12 & 0 \\ & & & & & 2.28 \pm 0.12 \end{bmatrix}$$




Azimuthal physical-modeling reflection data from Mahmoudian (2013).

# Intercept, gradient, and curvature

- Intercept, gradient, and curvature were estimated.
- Gradient is more negative at 90 degrees but this is a combination of -2$\Delta A'_{55}$ and $\Delta A'_{13}$ and does not indicate fast and slow directions.

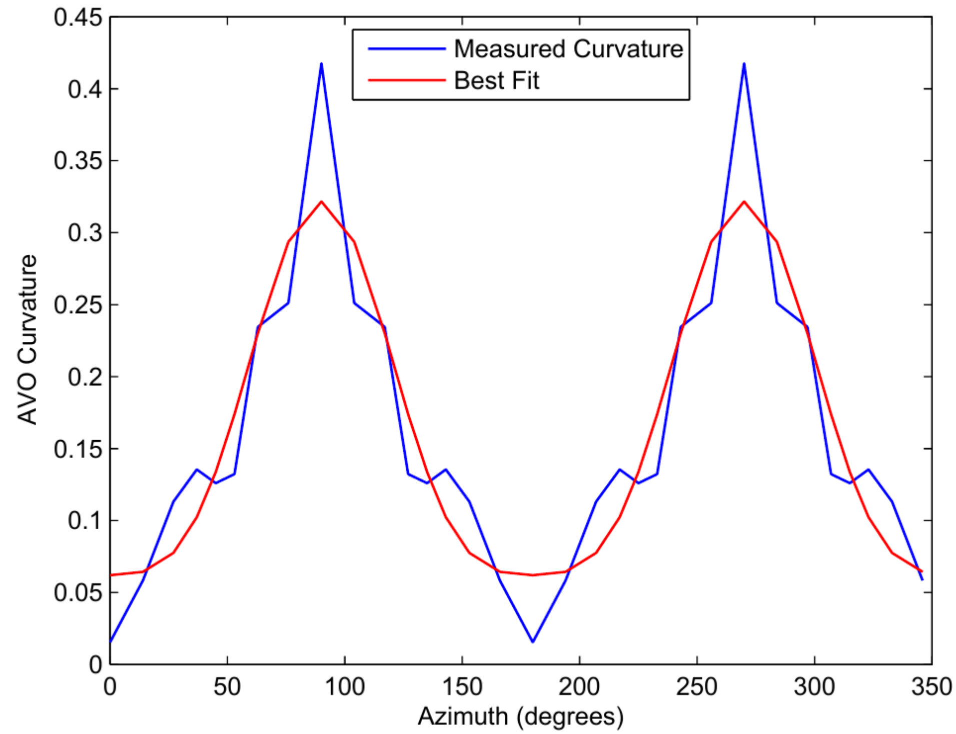



Azimuthal variations in the AVO intercept, gradient, and curvature for the physical modeling dataset.

# Fitting the curvature

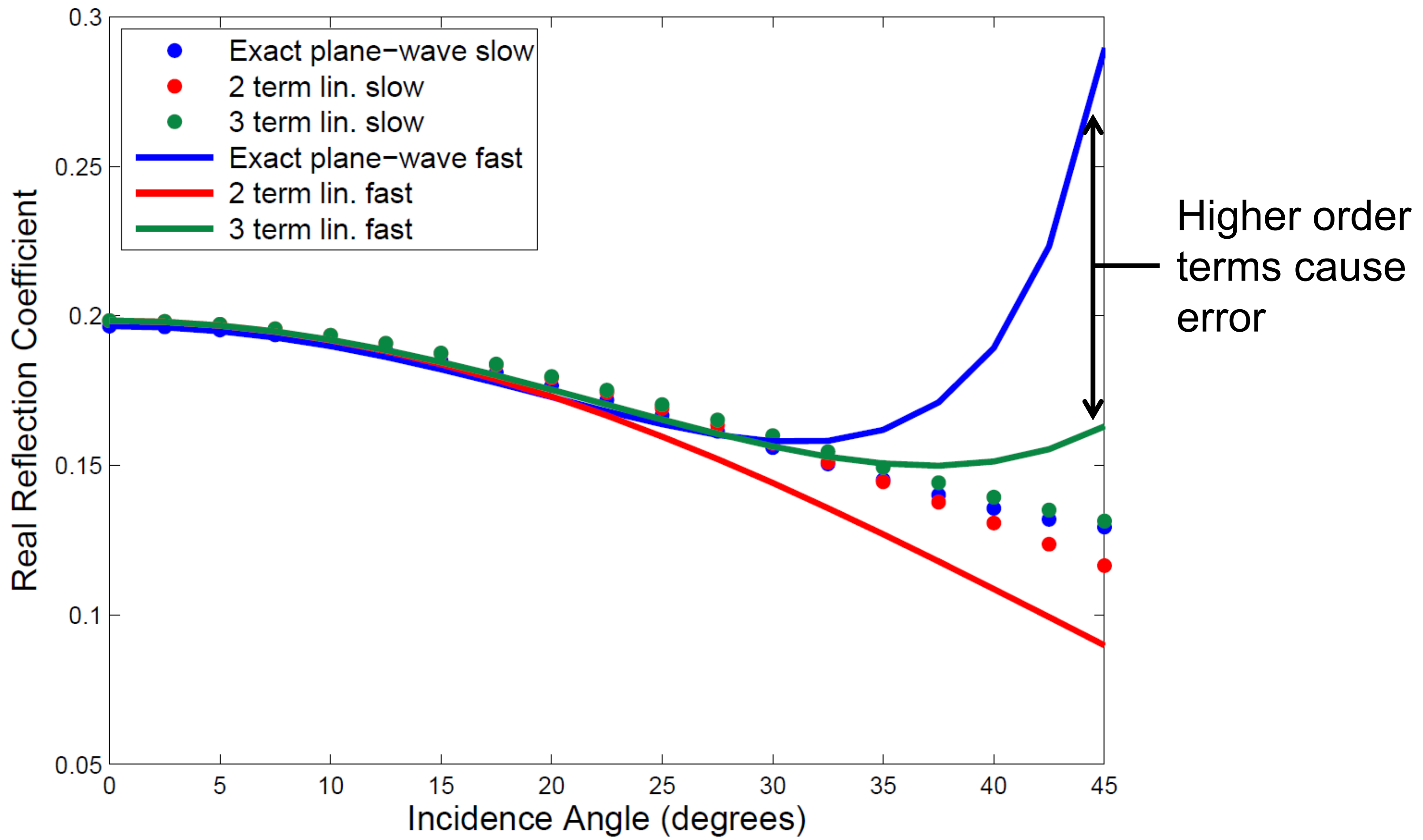
Fitting the curvature resulted in finding 0º and 90º as the azimuths having the biggest separation between $\Delta A_{11}$ and $\Delta A_{22}$.

This allows us to determine that 0º is the slow direction.

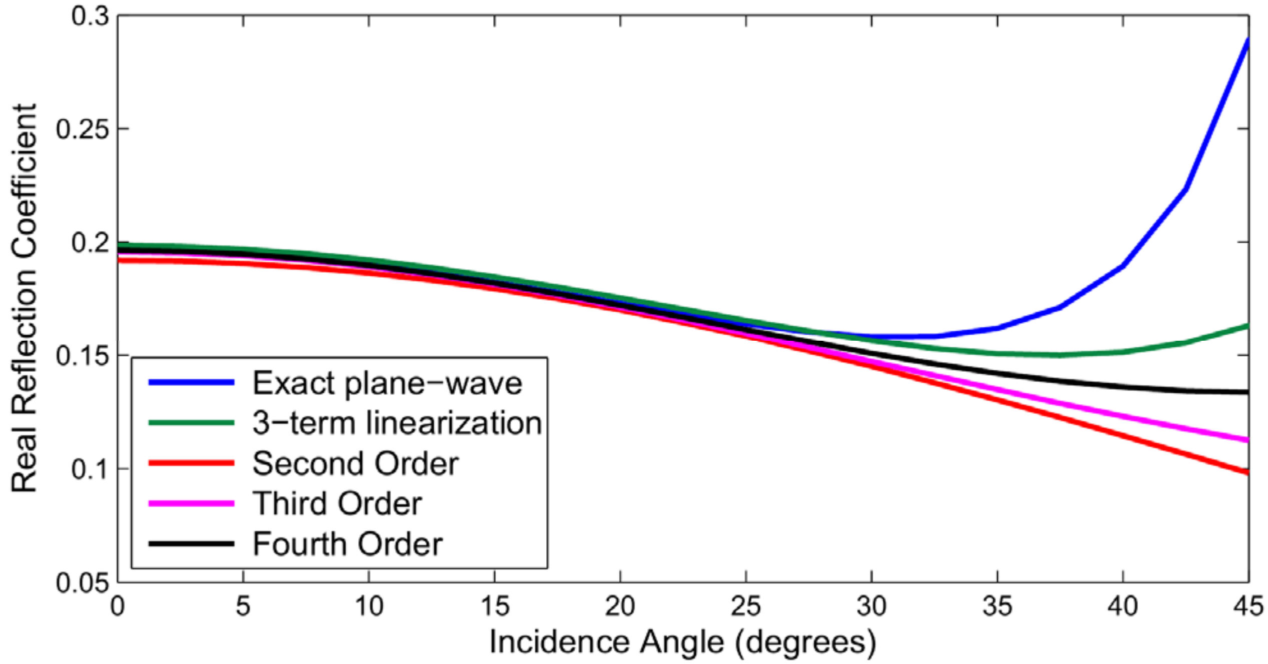



Best Fit of the coordinate transformation of $\Delta A_{11}$ to the curvature.

# Need for higher order reflection coefficients



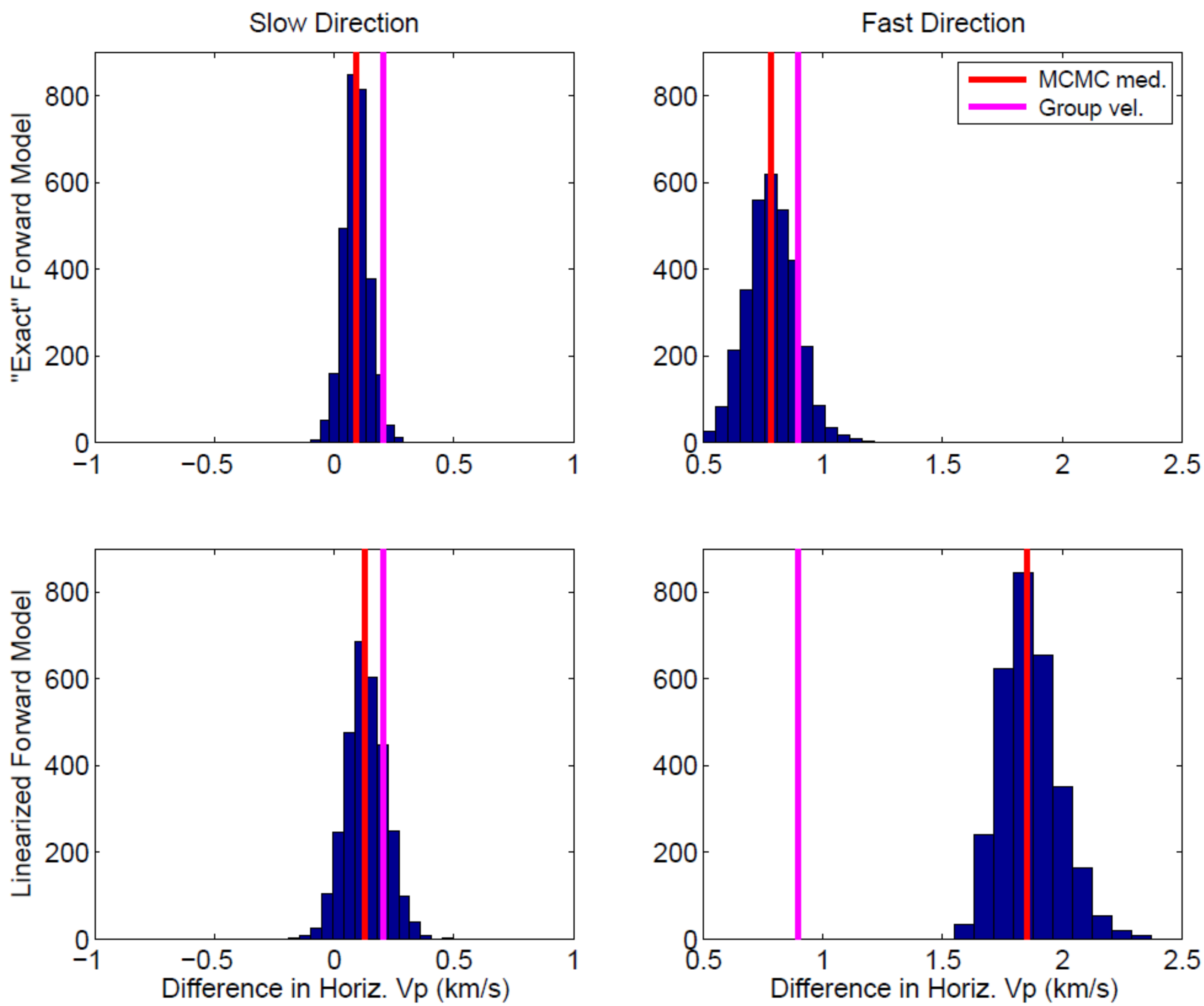
# Series expansion of reflection coefficient




- Expansion in ray parameter and small contrasts, δx, replacing second layer parameters:

$$\delta \mathbf{x} = 1 - \frac{\mathbf{x}^{(1)}}{\mathbf{x}^{(2)}} \quad \Rightarrow \quad \mathbf{x}^{(2)} = \frac{\mathbf{x}^{(1)}}{1 - \delta \mathbf{x}}$$

# MCMC results: exact vs. linearized



# Conclusions

- Individual azimuths = simple representation of theory
- Assumptions about symmetry don't need to be made to analyze certain subsurface elastic properties.
- Curvature is only dependent on a single elastic stiffness, while gradient is dependent on two, leading to ambiguity in interpretation made from the gradient.
- Curvature can be used to determine azimuthal changes in horizontal P-velocity and can be a tool to constrain anisotropy orientation estimates from the gradient.
- Higher order terms important but complicated. Use exact formulas?

# Possible Future Work

- Analyze AVO curvature / large offsets in real datasets;
- Continue testing nonlinear inversions;
- Incorporate attenuation anisotropy to determine if cracks contain liquid;
- Analyze azimuthal change in critical angles;

# Acknowledgements

Faranak Mahmoudian

Pat Daley

Khaled Al Dulaijan

CREWES

NSERC

# References


- Bakulin, A., Grechka, V., and Tsvankin, I., 2000, Estimation of fracture parameters from reflection seismic data-Part I: HTI model due to a single fracture set: Geophysics, **65**, No. 6, 1788-1802.
- Bond, W. L., 1943, The mathematics of the physical properties of crystals. *Bell system technical journal*, *22*(1), 1-72.
- Mahmoudian, F., 2013, Physical Modeling and analysis of seismic data from a simulated fractured medium: Ph.D. thesis, University of Calgary.
- Rüger, A., 1998, Variation of P-wave reflectivity with offset and azimuth in anisotropic media: Geophysics, **63**, No. 3, 935-947.
- Shuey, R., 1985, A simplification of the Zoeppritz equations: Geophysics, **50**, No. 4, 609-614.
- Thomsen, L., 1993, Weak anisotropic reflections: Offset-dependent reflectivity-Theory and practice of AVO analysis: Soc. Expl. Geophys, 103-111.
- Vavryčuk, V., and Pšenčík, I., 1998, PP-wave reflection coefficients in weakly anisotropic media: Geophysics, **63**, No. 6, 2129-2141.