Azimuthal seismic difference inversion for fracture weaknesses

Huaizhen Chen

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- Acknowledgements

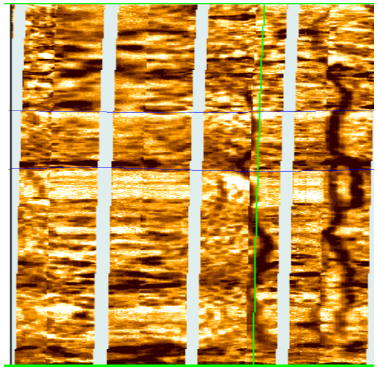
Introduction

- Fractures developed in carbonate and unconventional rocks (tight sand and shale).

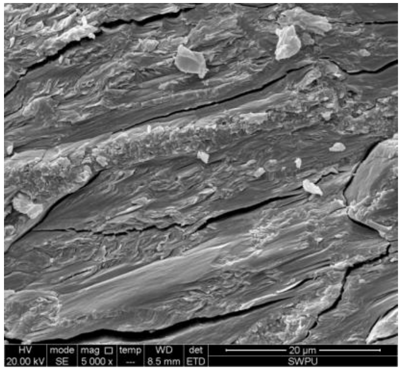
Carbonate
Source: West Texas, USA

Tight sand
Source: Europe

Shale
Source: Southern China



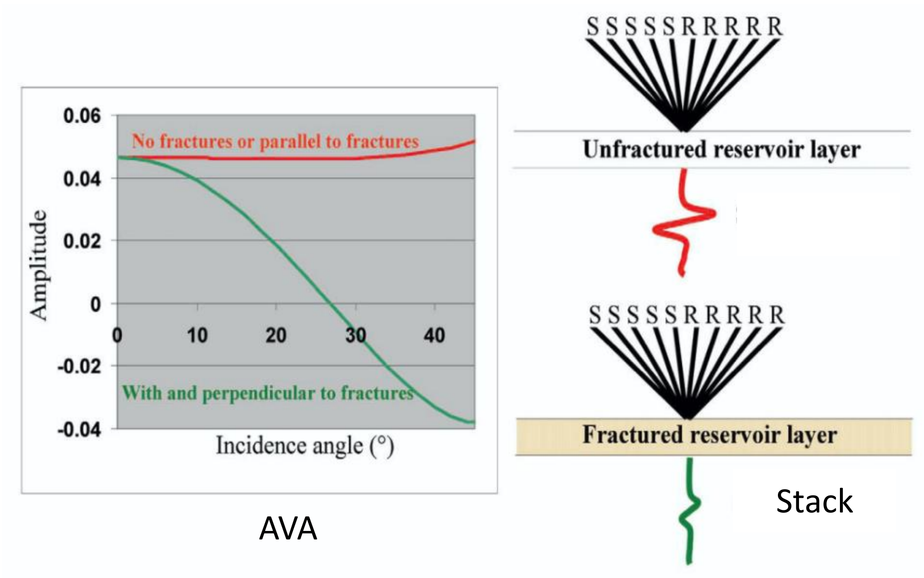
FMI



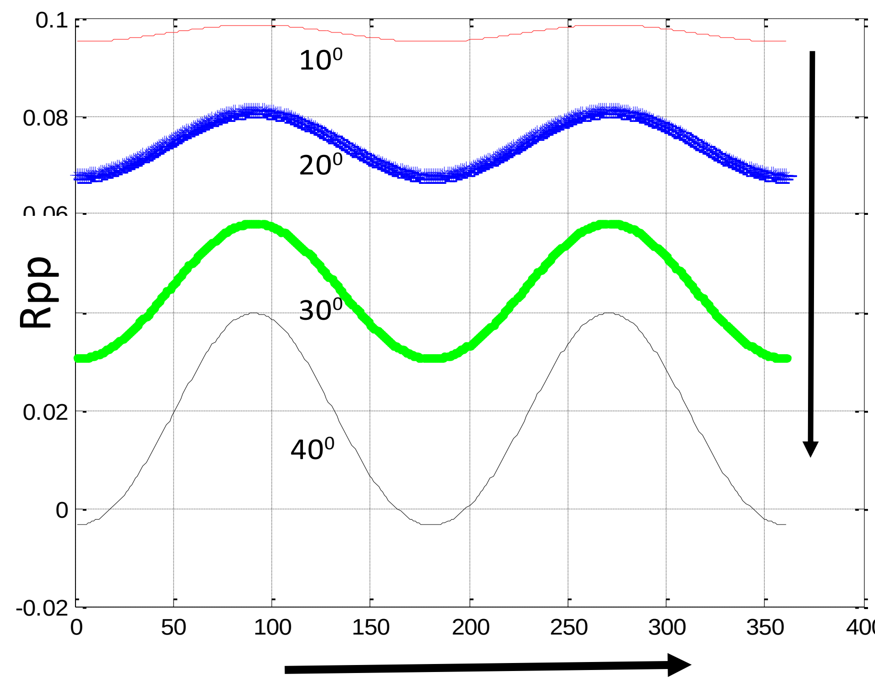
Microscope
Source: Southern China

- Fractures can connect the isolate pores to improve the porosity and permeability of reservoirs.

Seismic response

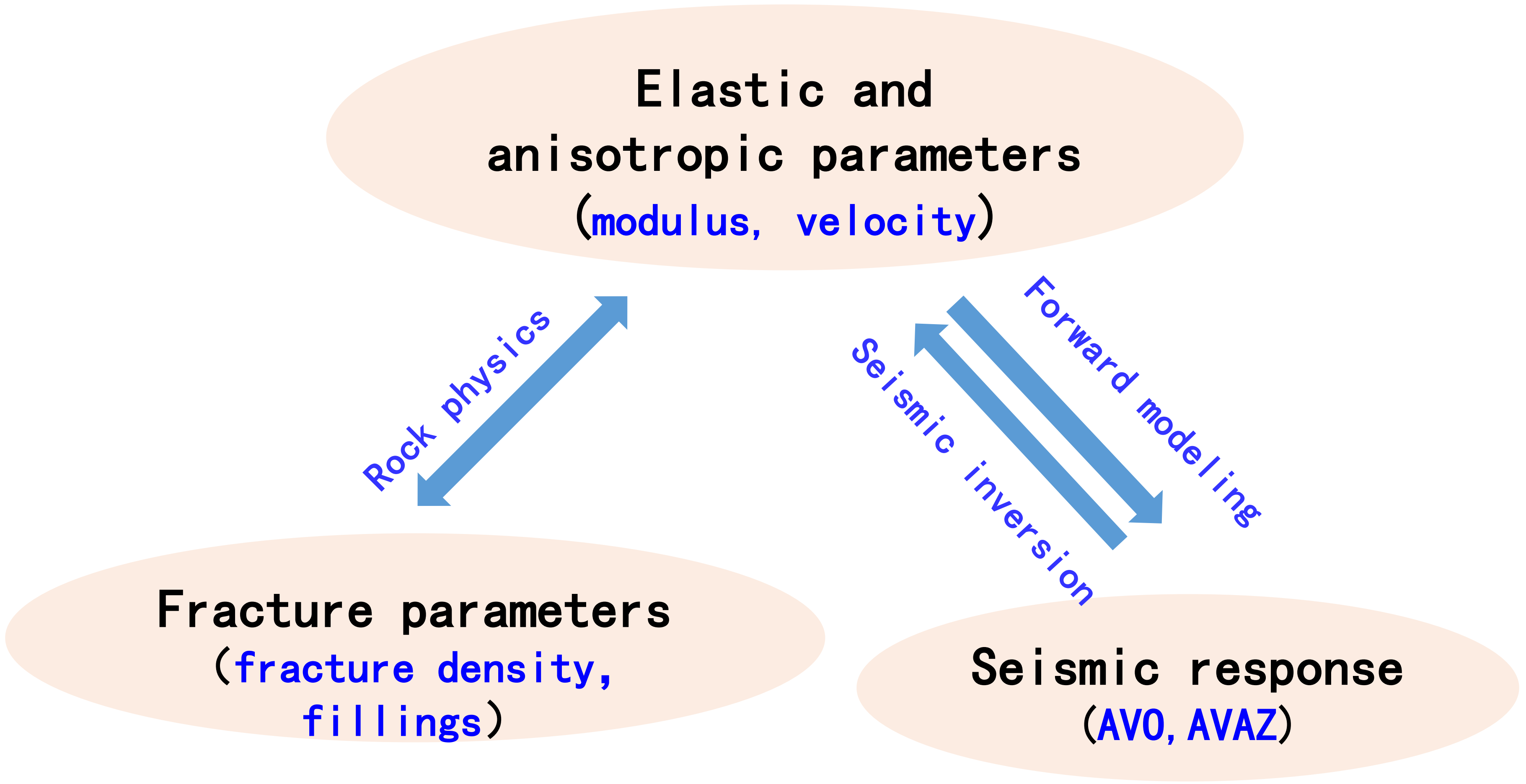


(WILLIAMS AND JENNER, 2002)



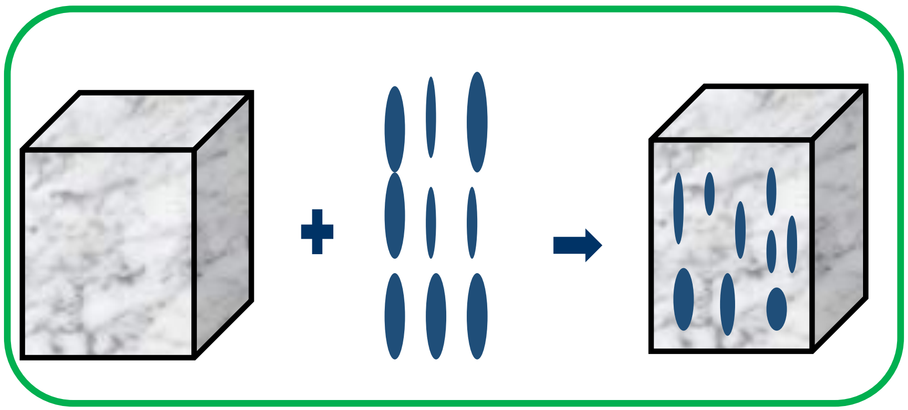
- Seismic response are different between unfractured and fractured reservoir layers.
- Seismic amplitude varies with incident angle and azimuth (AVAZ).

Research design

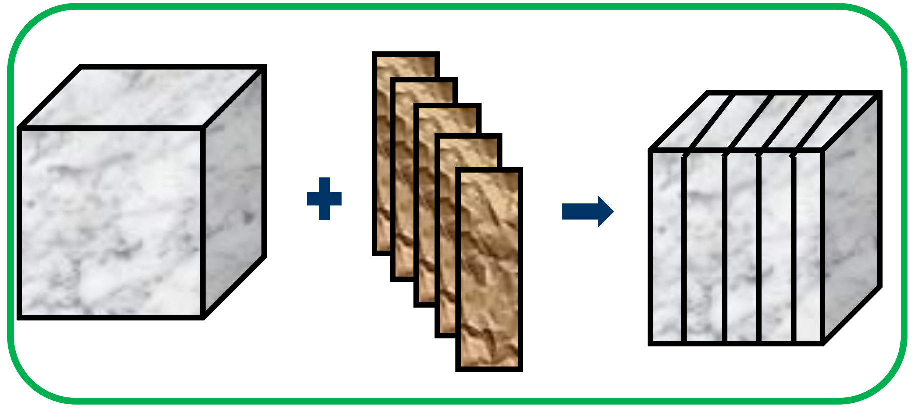


Theory and Method

- Rock physics model for crack and fracture



➢Penny-shaped crack model (Hudson, 1980)



➢Linear slip model for fracture (Schoenberg, 1980)

$$\boldsymbol{C} = \boldsymbol{C}_{iso} + \Delta\boldsymbol{C}_{ani}$$

Anisotropic term of stiffness matrix

Penny-shaped crack model

$$
\Delta C_{ani} = -\frac{e}{\mu}\begin{bmatrix}
(\lambda+2\mu)^2 U_{33} & \lambda(\lambda+2\mu)U_{33} & \lambda(\lambda+2\mu)U_{33} & 0 & 0 & 0 \\
\lambda(\lambda+2\mu)U_{33} & \lambda^2 U_{33} & \lambda^2 U_{33} & 0 & 0 & 0 \\
\lambda(\lambda+2\mu)U_{33} & \lambda^2 U_{33} & \lambda^2 U_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \mu^2 U_{11} & 0 \\
0 & 0 & 0 & 0 & 0 & \mu^2 U_{11}
\end{bmatrix}
$$

Linear slip fracture model

$$
\Delta C_{ani} = \begin{bmatrix}
-(\lambda+2\mu)\Delta_N & -\lambda\Delta_N & -\lambda\Delta_N & 0 & 0 & 0 \\
-\lambda\Delta_N & \frac{-\lambda^2}{\lambda+2\mu}\Delta_N & \frac{-\lambda^2}{\lambda+2\mu}\Delta_N & 0 & 0 & 0 \\
-\lambda\Delta_N & \frac{-\lambda^2}{\lambda+2\mu}\Delta_N & \frac{-\lambda^2}{\lambda+2\mu}\Delta_N & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\mu\Delta_T & 0 \\
0 & 0 & 0 & 0 & 0 & -\mu\Delta_T
\end{bmatrix}
$$

Assumptions

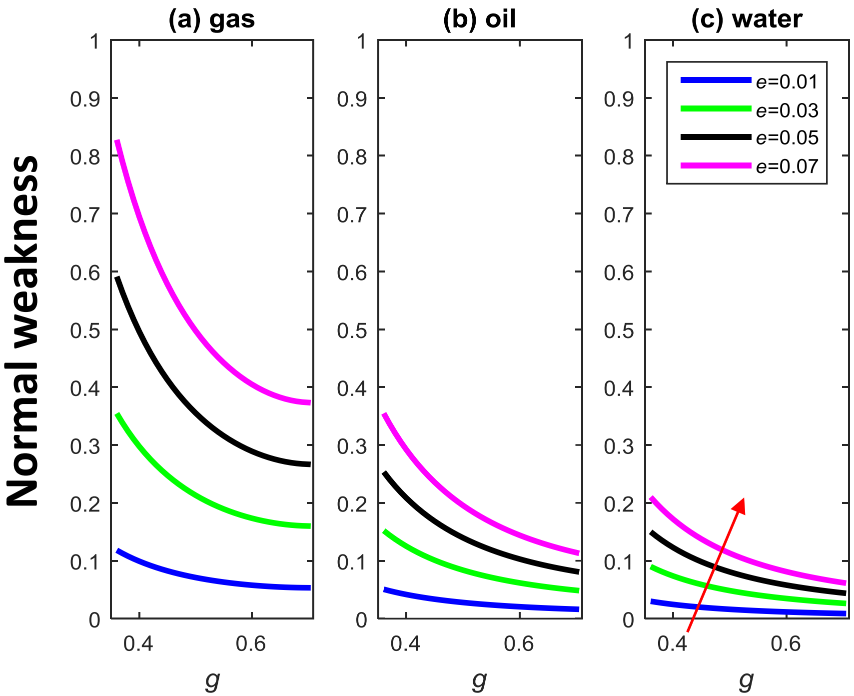
1) Smooth fracture plane
2) Weak inclusion (moduli of fillings are small)

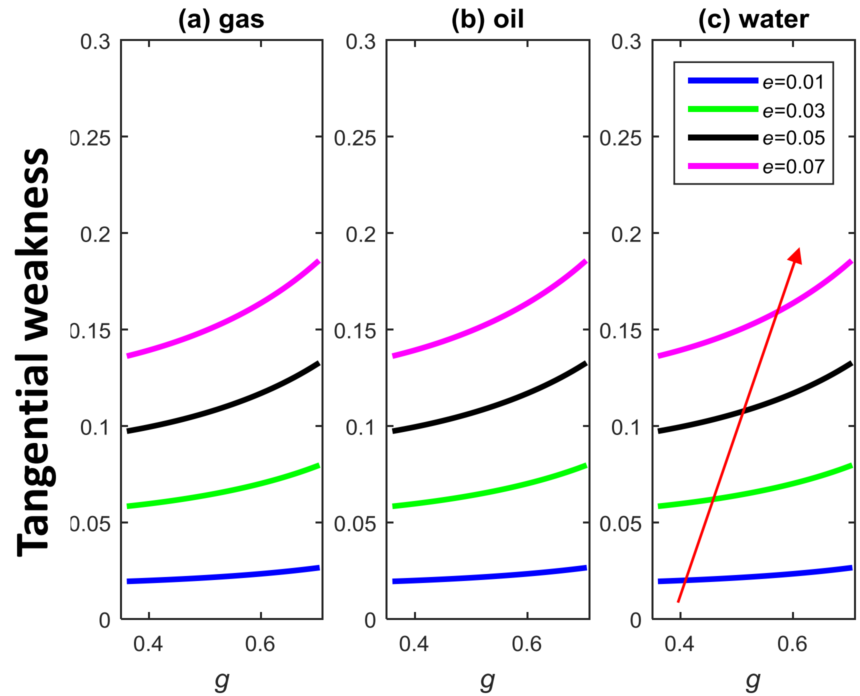
$$
\Delta_N = \frac{\lambda+2\mu}{\mu}U_{33}e = \frac{4e}{3g(1-g)\left[1+\frac{1}{\pi(1-g)}\left(\frac{K'+4/3\mu'}{\mu\alpha}\right)\right]}
$$

$$
\Delta_T = U_{11}e = \frac{16e}{3(3-2g)\left[1+\frac{4}{\pi(3-2g)}\left(\frac{\mu'}{\mu\alpha}\right)\right]}
$$

e is fracture density.
K', *μ'* are moduli of fillings.
α is fracture aspect ratio.

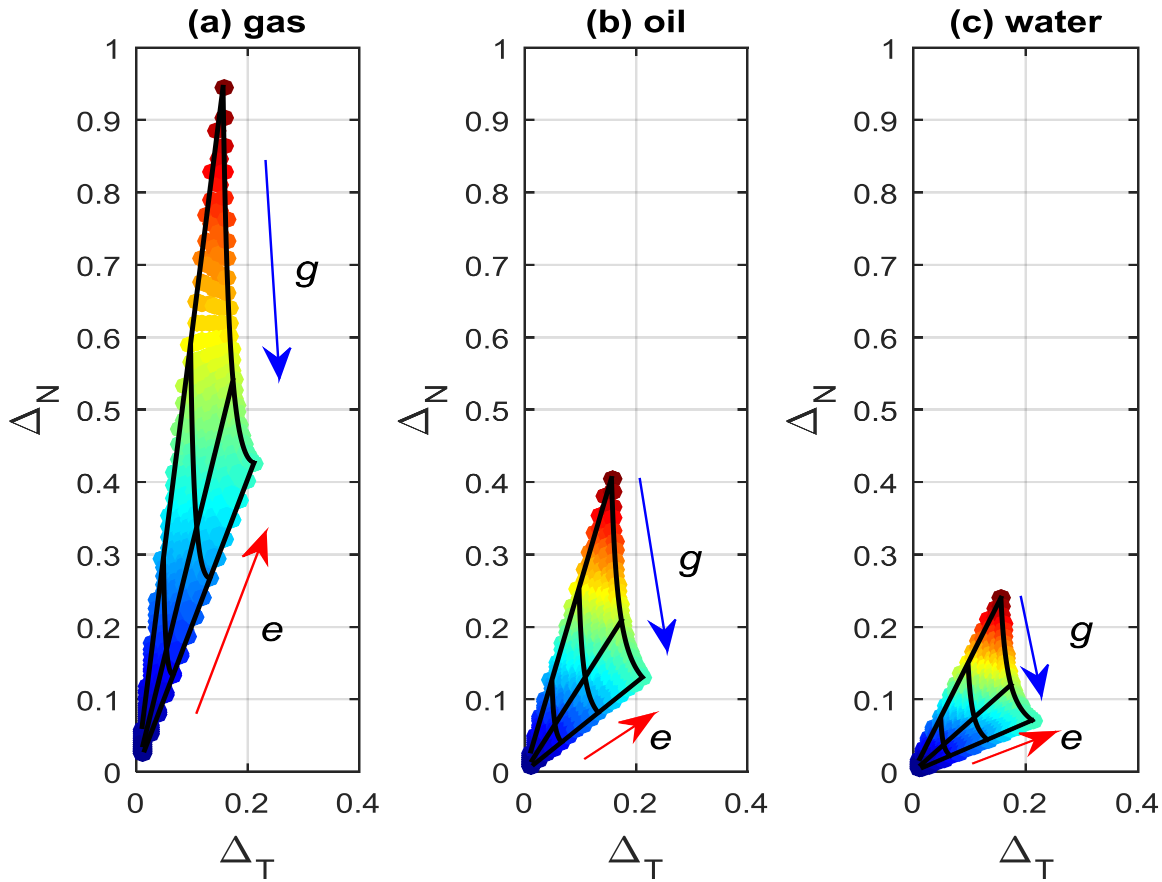
Fracture weaknesses characteristics





- The normal weakness exhibits significant dependence on fluid infill and fracture density.
- The tangential weakness does not vary with the fluid infill but with fracture density .

Relationship between weaknesses



- There is correlation between two fracture weaknesses because of fracture density.

Reflection coefficient equation of HTI medium

- Ruger(1996) equation for HTI medium

$$R_{\mathrm{PP}}(\theta,\phi)=\frac{1}{2}\frac{\Delta Z}{\bar{Z}}+\frac{1}{2}\left\{\frac{\Delta\alpha}{\bar{\alpha}}-\left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2\frac{\Delta G}{\bar{G}}+\left[\Delta\delta^{(\mathrm{V})}+2\left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2\Delta\gamma\right]\cos^2\phi\right\}\sin^2\theta+$$
$$\frac{1}{2}\left\{\frac{\Delta\alpha}{\bar{\alpha}}+\Delta\varepsilon^{(\mathrm{V})}\cos^4\phi+\Delta\delta^{(\mathrm{V})}\sin^2\phi\cos^2\phi\right\}\sin^2\theta\tan^2\theta$$

- It can be represented as the sum of two parts: isotropic background and anisotropic part

$$R_{\mathrm{PP}}(\theta,\phi)=R_{\mathrm{PP}}^{\mathrm{iso}}(\theta)+\Delta R_{\mathrm{PP}}^{\mathrm{ani}}(\theta,\phi)$$

$$\Delta R_{\mathrm{PP}}^{\mathrm{ani}}(\theta,\phi)=\frac{1}{2}\left\{\begin{aligned}&\left(\cos^2\phi\sin^2\theta+\sin^2\phi\cos^2\phi\sin^2\theta\tan^2\theta\right)\underline{\Delta\delta^{(\mathrm{V})}}\\&+\cos^4\phi\sin^2\theta\tan^2\theta\underline{\Delta\varepsilon^{(\mathrm{V})}}+2\left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2\cos^2\phi\sin^2\theta\underline{\Delta\gamma}\end{aligned}\right\}$$

The relationship between fracture weaknesses and Thomsen anisotropic parameters

- The definition of anisotropic parameters

$$\varepsilon^{(\mathrm{V})} = \frac{C_{11} - C_{33}}{2C_{33}}$$

$$\delta^{(\mathrm{V})} = \frac{\left(C_{13} + C_{55}\right)^2 - \left(C_{33} - C_{55}\right)^2}{2C_{33}\left(C_{33} - C_{55}\right)}$$

$$\gamma^{(\mathrm{V})} = \frac{C_{66} - C_{44}}{2C_{44}}$$

- The relationships between fracture weaknesses and anisotropic parameters (Based on penny-shaped crack model and linear slip fracture model)

$$\varepsilon^{(\mathrm{V})} = \frac{-2g\left(1-g\right)\Delta_{\mathrm{N}}}{1-\Delta_{\mathrm{N}}\left(1-2g\right)^2}$$

$$\delta^{(\mathrm{V})} = \frac{-2g\left[\left(1-2g\right)\Delta_{\mathrm{N}} + \Delta_{\mathrm{T}}\right]\left[1-\left(1-2g\right)\Delta_{\mathrm{N}}\right]}{\left[1-\Delta_{\mathrm{N}}\left(1-2g\right)^2\right]\left\{1+\frac{1}{1-g}\left[\Delta_{\mathrm{T}} - \Delta_{\mathrm{N}}\left(1-2g\right)^2\right]\right\}}$$

$$\gamma = \frac{\Delta_{\mathrm{T}}}{2}$$

Anisotropic part of Reflection coefficient with fracture weaknesses

$$\Delta R_{\mathrm{PP}}^{\mathrm{ani}}(\theta,\phi)=\mathrm{A}\Delta$$

- where

$$\mathrm{A}=\left[a(\theta,\phi)\quad b(\theta,\phi)\right]$$

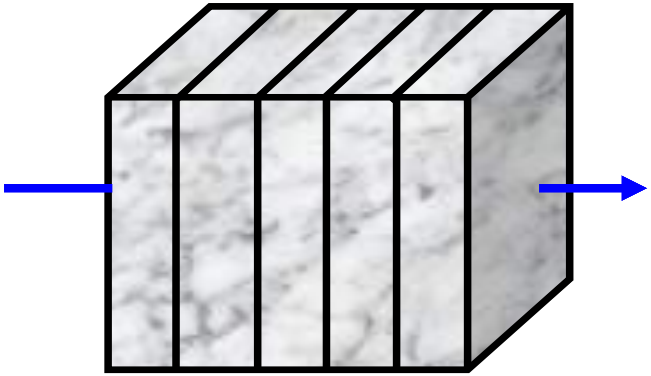
$$a(\theta,\phi)=\frac{1}{4}(1-2g)^2+\left[(1-2g)+2g(1-2g)\cos 2\phi\right]\sin^2\theta$$
$$+\frac{1}{4}\left[\left(1-2g+\frac{3}{2}g^2\right)+2g(1-g)\cos 2\phi+\frac{1}{2}g^2\cos 4\phi\right]\sin^2\theta\tan^2\theta$$

$$b(\theta,\phi)=\frac{1}{4}\left[-2g(1+\cos 2\phi)\sin^2\theta+\frac{g}{2}(1-\cos 4\phi)\sin^2\theta\tan^2\theta\right]$$

$$\Delta^{\mathrm{T}}=\left[\Delta_{\mathrm{N}}\quad \Delta_{\mathrm{T}}\right]$$

Condition

1) Fractures are invariant under rotation about the normal to the fracture faces
2) Weak anisotropy



Reflection and seismic difference

- Reflection coefficient

$$R_{\text{PP}}(\theta,\phi) = R_{\text{PP}}^{\text{iso}}(\theta) + \Delta R_{\text{PP}}^{\text{ani}}(\theta,\phi)$$

- Reflection coefficient difference between azimuthal angles (ϕ_1 and ϕ_2)

$$\Delta R_{\text{PP}}^{\text{ani}}(\theta) = \left[a(\theta,\phi_1) - a(\theta,\phi_2)\right]\Delta_{\text{N}} + \left[b(\theta,\phi_1) - b(\theta,\phi_2)\right]\Delta_{\text{T}}$$

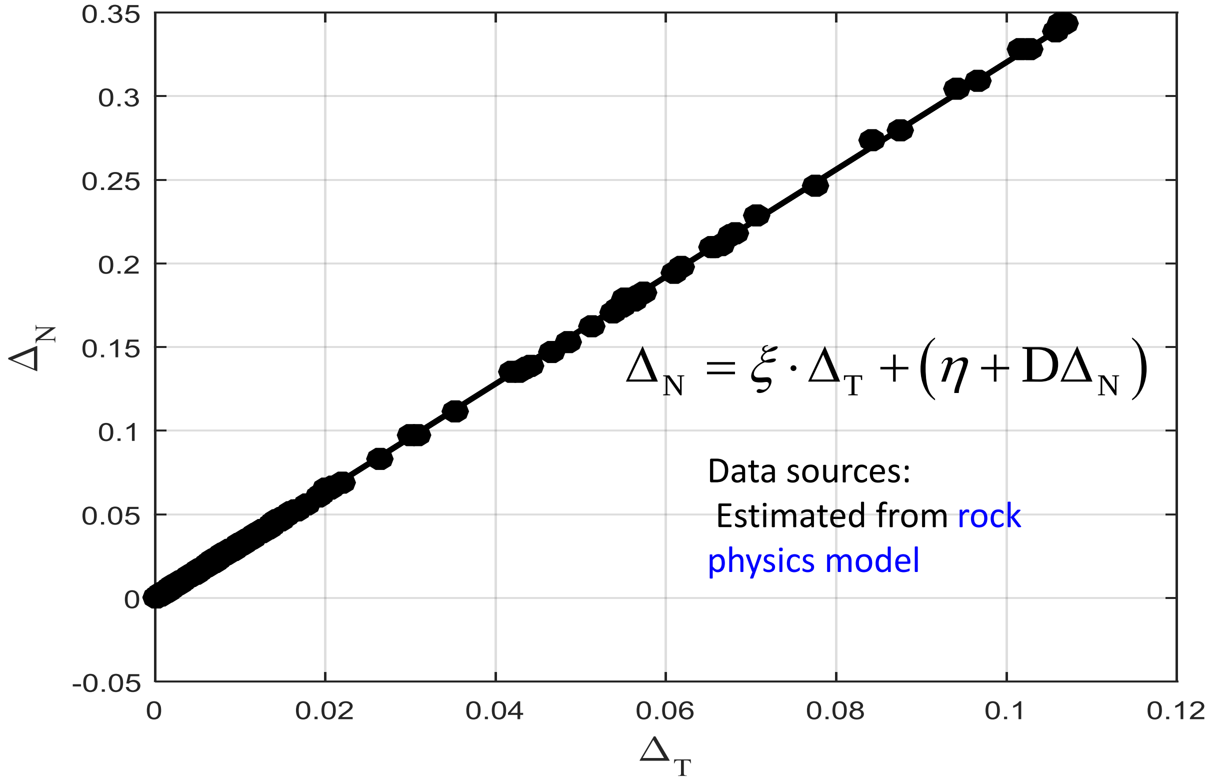
- Seismic difference between azimuthal angles (ϕ_1 and ϕ_2)

$$\Delta seis(\theta) = wvlt * \left(\Delta R_{\text{PP}}^{\text{ani}}(\theta)\right)$$
$$= \boldsymbol{W}\left[a(\theta,\phi_1) - a(\theta,\phi_2)\right]\Delta_{\text{N}} + \boldsymbol{W}\left[b(\theta,\phi_1) - b(\theta,\phi_2)\right]\Delta_{\text{T}}$$

- where, *wvlt* is wavelet, and ***W*** is wavelet matrix.

Decorrelation

- Remove the correlation between fracture weaknesses to improve the accuracy of inversion: Linear fitting



$$\Delta seis(\theta) = W\left[a(\theta,\phi_1) - a(\theta,\phi_2)\right]\Delta_N + W\left[b(\theta,\phi_1) - b(\theta,\phi_2)\right]\Delta_T$$

Seismic inversion for fracture weaknesses

- Seismic difference expression after decorrelation

$$\Delta seis(\theta) = W\left[c(\theta,\phi_1) - c(\theta,\phi_2)\right]\left(\mathrm{D}\Delta_{\mathrm{N}} + \eta\right) + W\left[d(\theta,\phi_1) - d(\theta,\phi_2)\right]\Delta_{\mathrm{T}}$$

$$c(\theta,\phi) = a(\theta,\phi)$$

$$d(\theta,\phi) = a(\theta,\phi)\cdot\xi + b(\theta,\phi)$$

- In the case of an M incident angle (seismic difference in the form of matrix)

$$\begin{bmatrix} \Delta seis(\theta_1) \\ \Delta seis(\theta_2) \\ \vdots \\ \Delta seis(\theta_{\mathrm{M}}) \end{bmatrix} = W \begin{bmatrix} c(\theta_1,\phi_1) - c(\theta_1,\phi_2) & d(\theta_1,\phi_1) - d(\theta_1,\phi_2) \\ c(\theta_2,\phi_1) - c(\theta_2,\phi_2) & d(\theta_2,\phi_1) - d(\theta_2,\phi_2) \\ \vdots & \vdots \\ c(\theta_{\mathrm{M}},\phi_1) - c(\theta_{\mathrm{M}},\phi_2) & d(\theta_{\mathrm{M}},\phi_1) - d(\theta_{\mathrm{M}},\phi_2) \end{bmatrix} \begin{bmatrix} \left(\mathrm{D}\Delta_{\mathrm{N}} + \eta\right) \\ \Delta_{\mathrm{T}} \end{bmatrix}$$

$$\mathbf{d} = \mathbf{G}\mathbf{m}$$

Inversion

- Inversion method (damped least-squares algorithm)

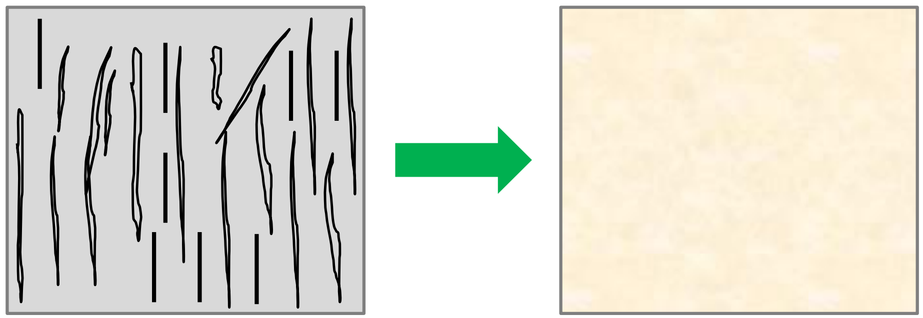
$$\mathbf{m} = \mathbf{m}_{\text{int}} + \left[\mathbf{G}^{\text{T}}\mathbf{G} + \sigma\mathbf{I}\right]^{-1}\mathbf{G}^{\text{T}}\left(\mathbf{d} - \mathbf{G}\mathbf{m}_{\text{int}}\right)$$

- where, m_{int} is initial model, σ is the damping parameter.
- The construction of initial model
- 1) Rock physics effective model
- 2) AVAZ analysis (Anisotropic AVO gradient)

Rock physics effective model

- Fractured rock physics effective media theory

Inhomogenous medium
Isotropic background with fractures



Homogeneous anisotropic medium

（Liu et al.， 2012）

- The process to construct fractured rock physics effective model

Mineral mixture → **Isotropic dry framework** → **anisotropic dry framework** → **Saturated anisotropic rock**

AVAZ analysis

- In HTI media

$$R_{\mathrm{PP}}\left(\theta,\phi\right) \approx P + G\sin^2\theta = P + \left[G_{iso} + G_{ani}\cos^2\left(\phi\right)\right]\sin^2\theta$$

- where P is AVO intercept, and Giso and Gani denote AVO isotropic gradient and anisotropic gradient respectively.

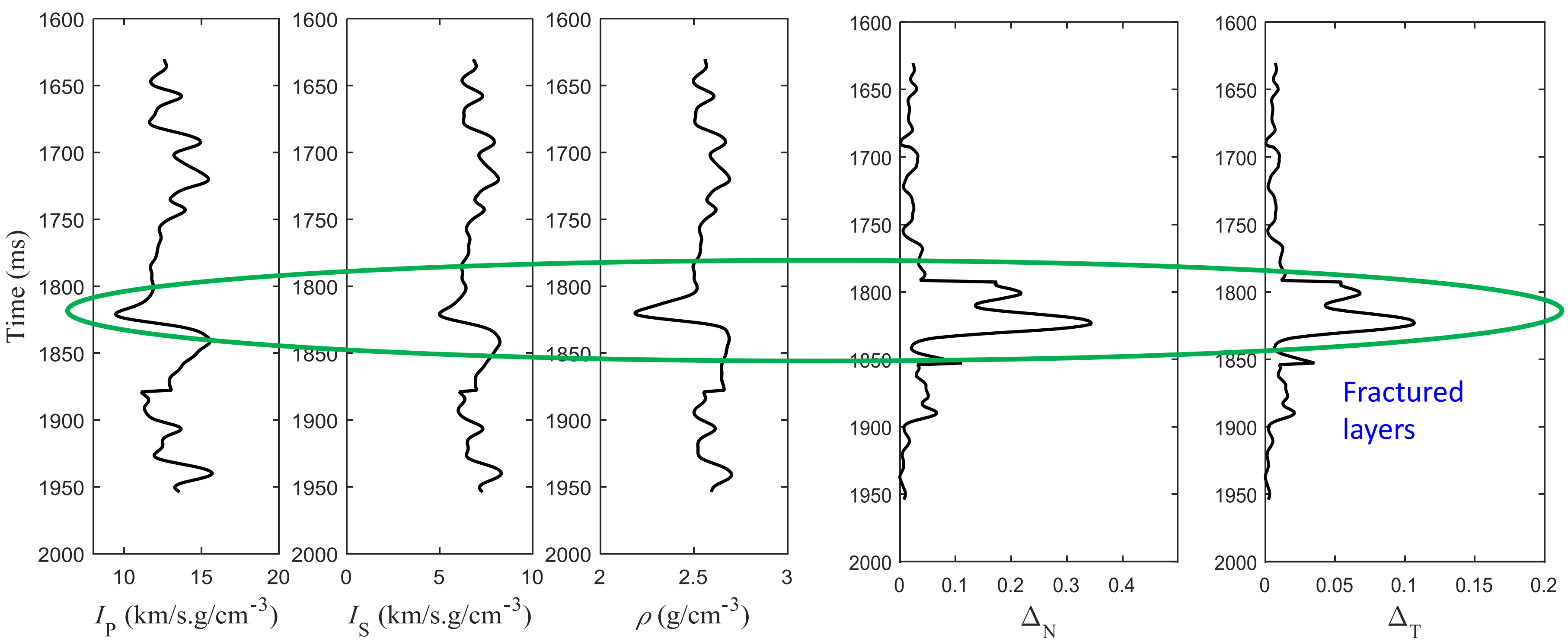
$$G_{ani} = -g\left(1-2g\right)\Delta_N + g\Delta_T$$

- If we have AVO gradients of two azimuthal angles

$$\frac{G\left(\phi_1\right)-G\left(\phi_2\right)}{\left[\cos^2\left(\phi_1\right)-\cos^2\left(\phi_2\right)\right]} = G_{ani} = -g\left(1-2g\right)\Delta_N + g\Delta_T$$

Examples

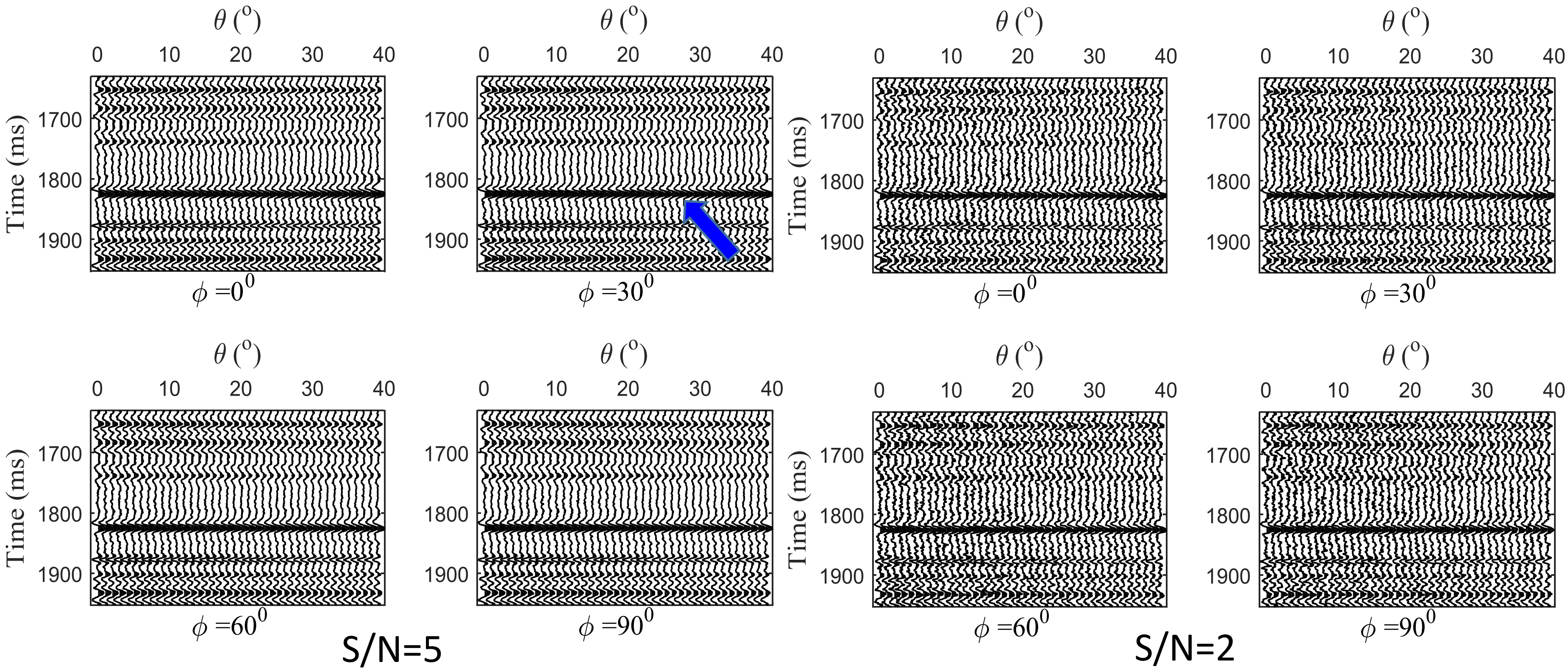
- Synthetic test



- P- and S-wave impedances show low values, and fracture weaknesses show high values.

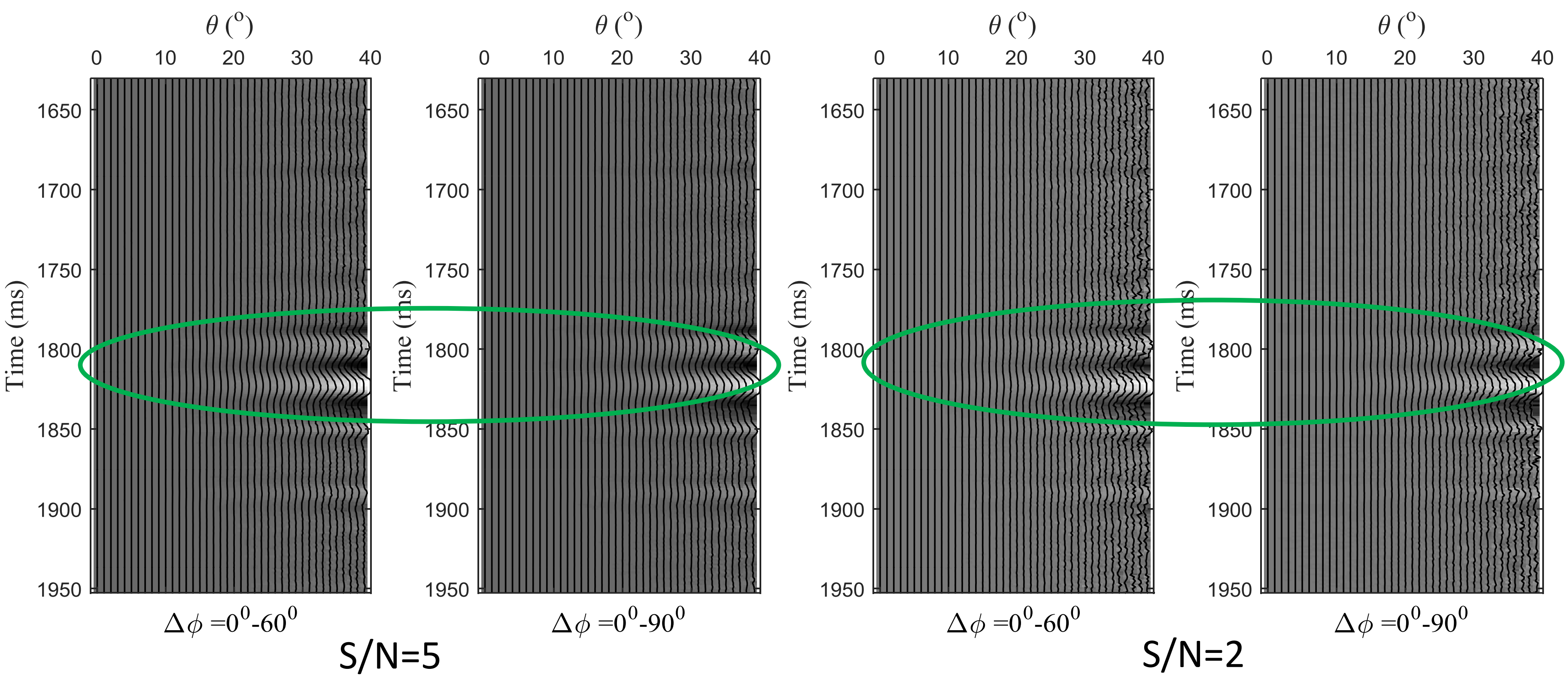
Examples

- Synthetic seismic data of different azimuthal angles (40HZ Ricker wavelet)



Examples

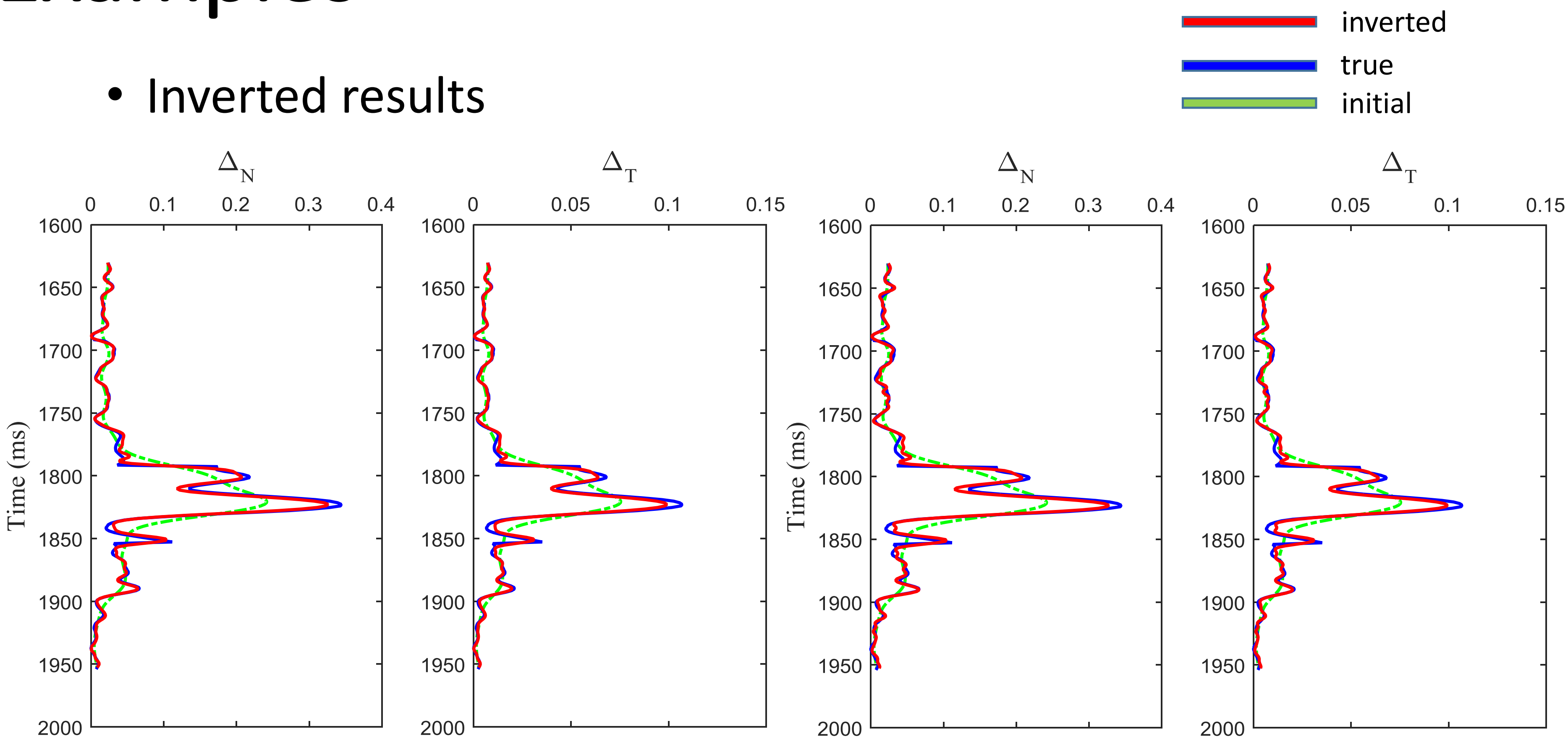
- Seismic difference between different azimuthal angles



- At fractured layers location, there are strong amplitude remains.

Examples

- Inverted results

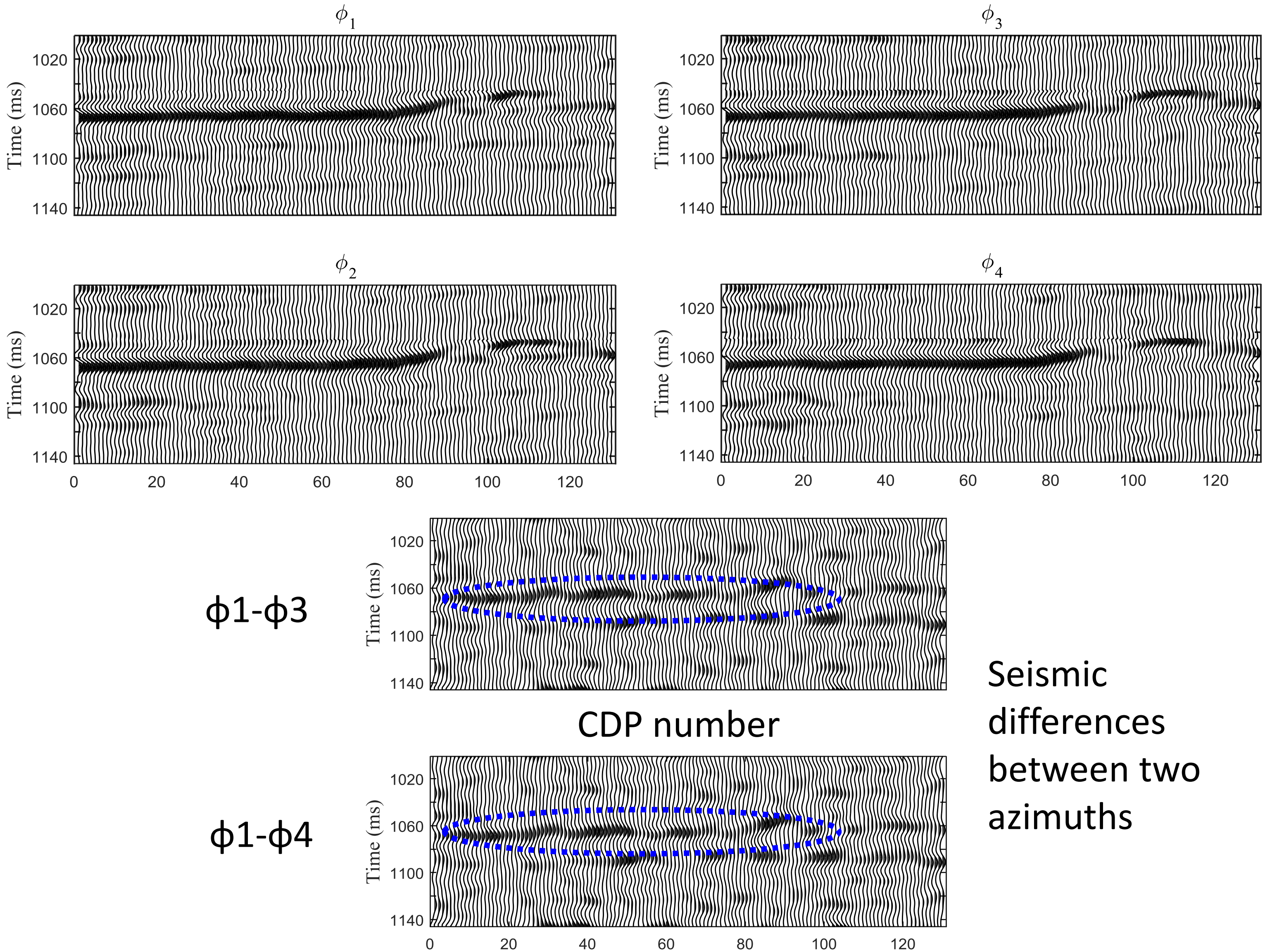


S/N=5

S/N=2

- Initial model are the smooth results of true values. Even when the S/N is 2, fracture weaknesses can be inverted reasonably.

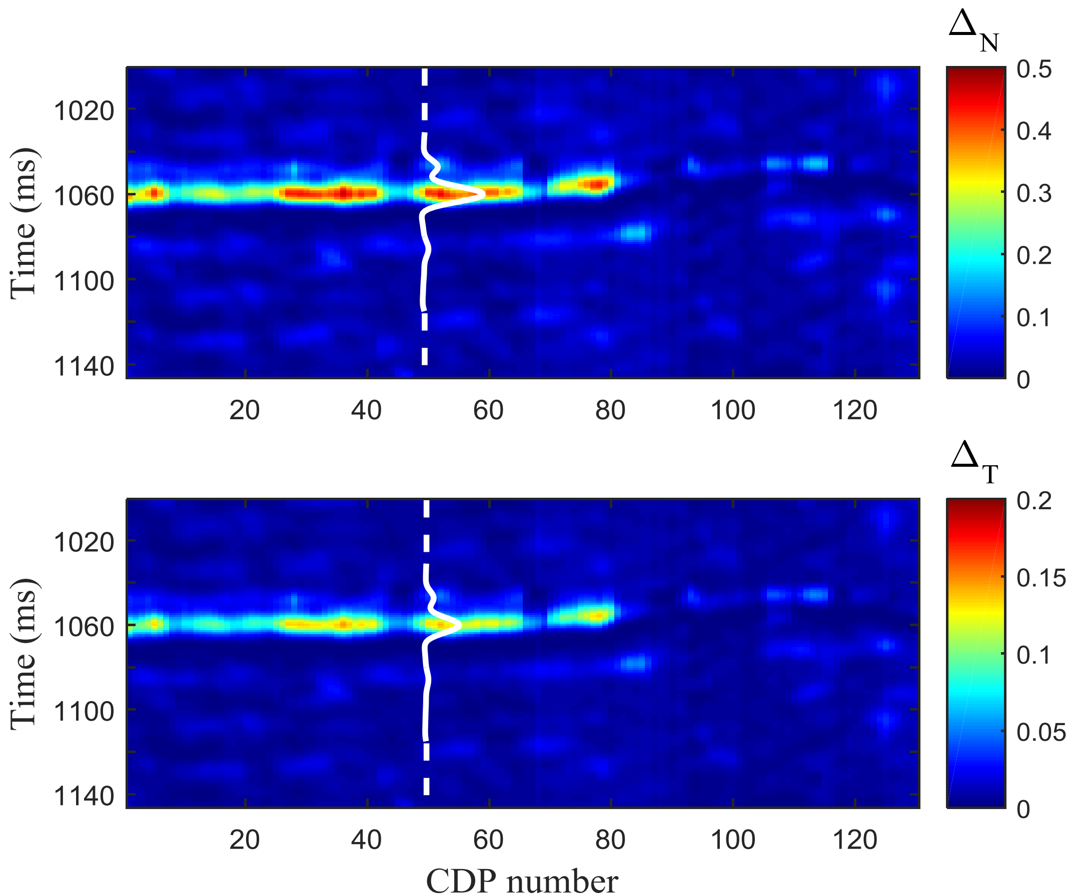
Examples: Real data



Stack seismic of four azimuths

Seismic differences between two azimuths

Examples: Real data



- The inverted results of fracture weaknesses can be used to estimate stress ratio (Gray et al , 2010), fracture fluid factor (Schoenberg and Sayers, 2009), which may be our future research work.

Conclusions

- Fracture weaknesses are important parameters which can be used to predict underground fractures, and they can be estimated by using azimuthal seismic differences.
- Decorrelation can improve the accuracy of fracture weaknesses inversion.
- Rock physics and AVAZ analysis are two tools to construct initial model of fracture weaknesses for seismic inversion.
- The azimuth of symmetry axis of fractures are ignored here, but the main direction of fractures can be estimated by AVAZ analysis.

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