Seismic modeling and inversion for reflections from fractures

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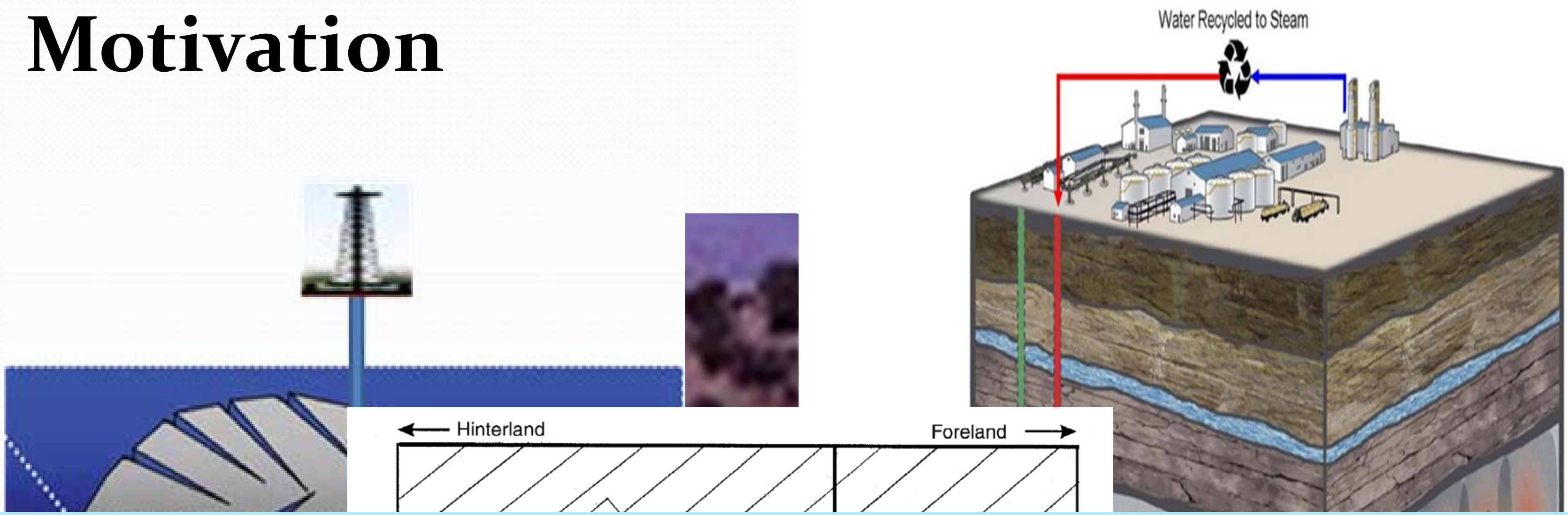
Outline

- Motivation
- Objective and values
- Background
- Theory of fractures: the linear slip interface (Non-welded contact interface)
- FD scheme of the fractures
- Inversion method for the fractures
- Applications
- Conclusions

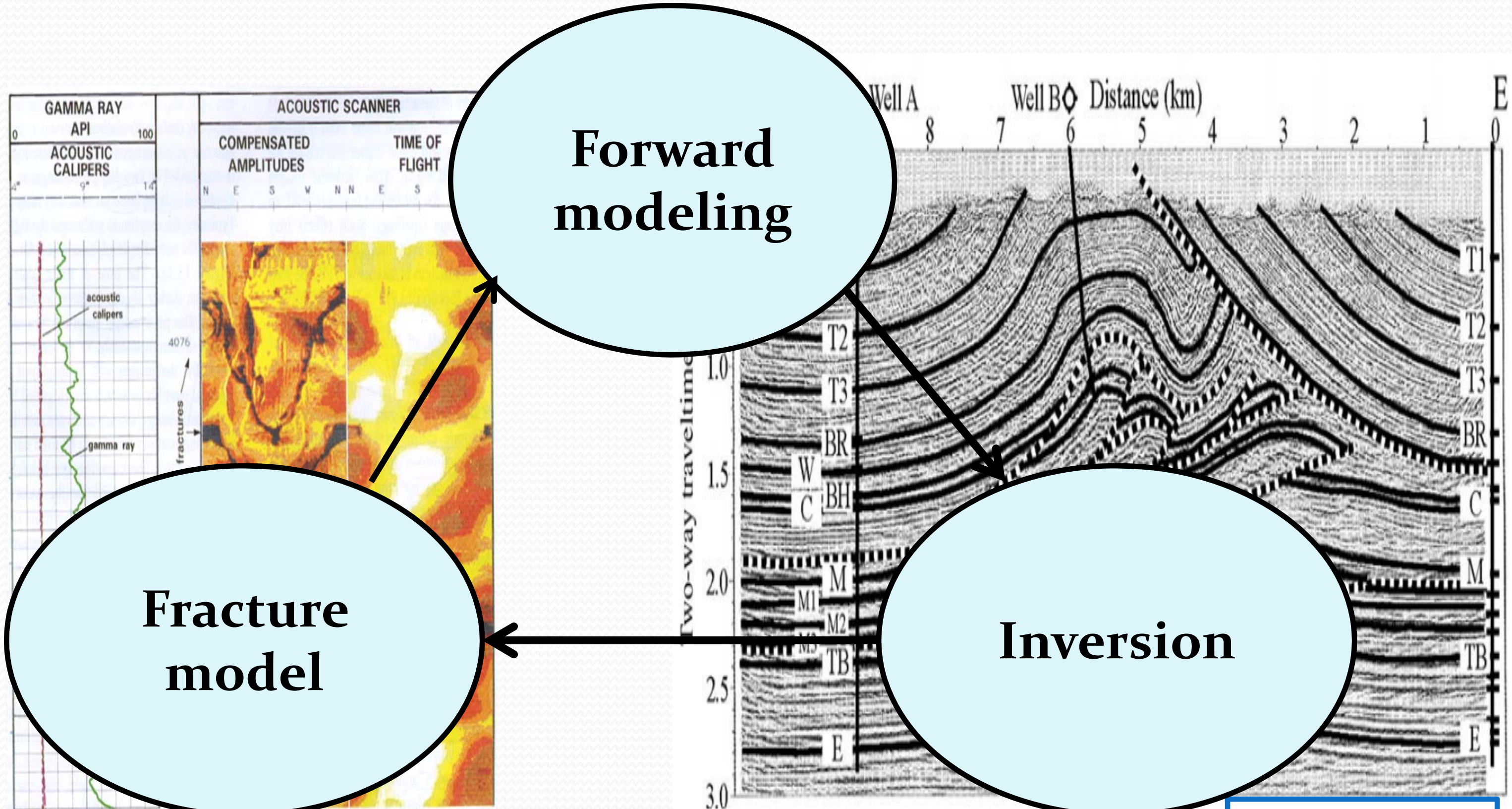
Seismic modeling and inversion for reflections from fractures

➢ Motivation



❑ Knowledge of the fracture characterization are of benefits to reservoir engineers and geoscientists to optimize reservoir and well performance.

➢ Objective and values

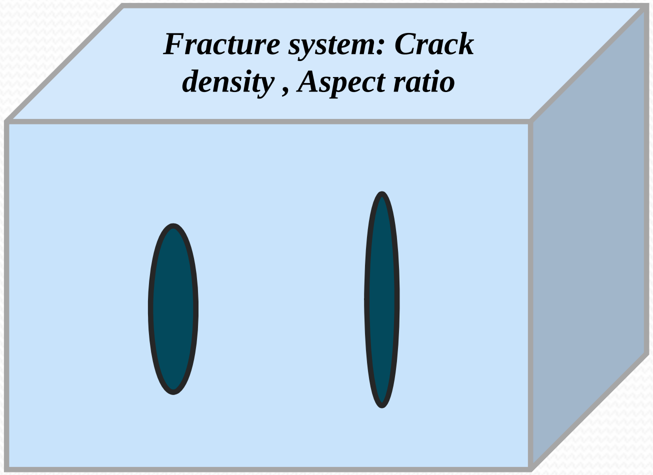


Rider, 2002

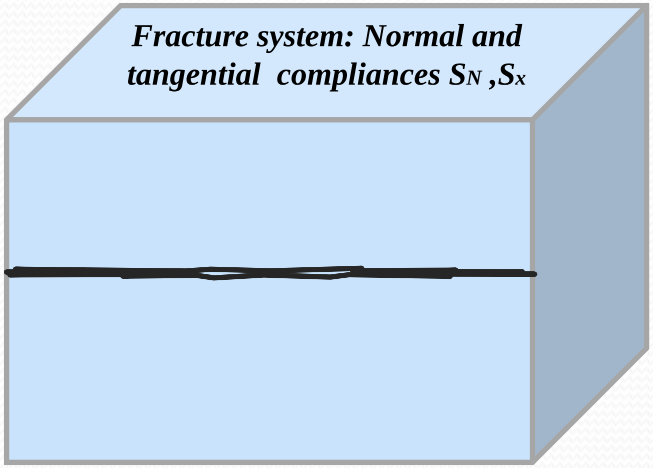
Lines, 2012

➢ Background

–Two existing fracture models



Hudson's model (1980): penny-shaped cracks



Schoenberg's model (1980): linear-slip interface

➢ Background

-Assumption of the long wavelength limit

$$\sigma_T \left\{ \begin{matrix} \\ \\ \\ \end{matrix} \right. \quad \sigma_N \left\{ \begin{matrix} \\ \\ \\ \end{matrix} \right. \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & 0 & c_{13} & 0 & 0 \\ c_{21} & c_{22} & 0 & c_{23} & 0 & 0 \\ 0 & 0 & c_{66} & 0 & 0 & 0 \\ c_{31} & c_{32} & 0 & c_{33} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{55} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_6 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \end{bmatrix} \left. \begin{matrix} \\ \\ \\ \end{matrix} \right\} \varepsilon_T \quad \left. \begin{matrix} \\ \\ \\ \end{matrix} \right\} \varepsilon_N$$

$$\sigma_N = c_{NT}\varepsilon_T + c_{NN}\varepsilon_N$$

$$\sigma_N \approx c_{NN}\varepsilon_N$$

$$\left(\begin{bmatrix} C_{33} & 0 & 0 \\ 0 & C_{44} & 0 \\ 0 & 0 & C_{55} \end{bmatrix} \right)^{-1} = \begin{bmatrix} S_N & 0 & 0 \\ 0 & S_x & 0 \\ 0 & 0 & S_x \end{bmatrix}$$

Schoenberg and Douma, 1988

Background

- Assumption of the long wavelength limit

$$E_T = C_{44b}S_x \qquad E_N = C_{33b}S_N$$

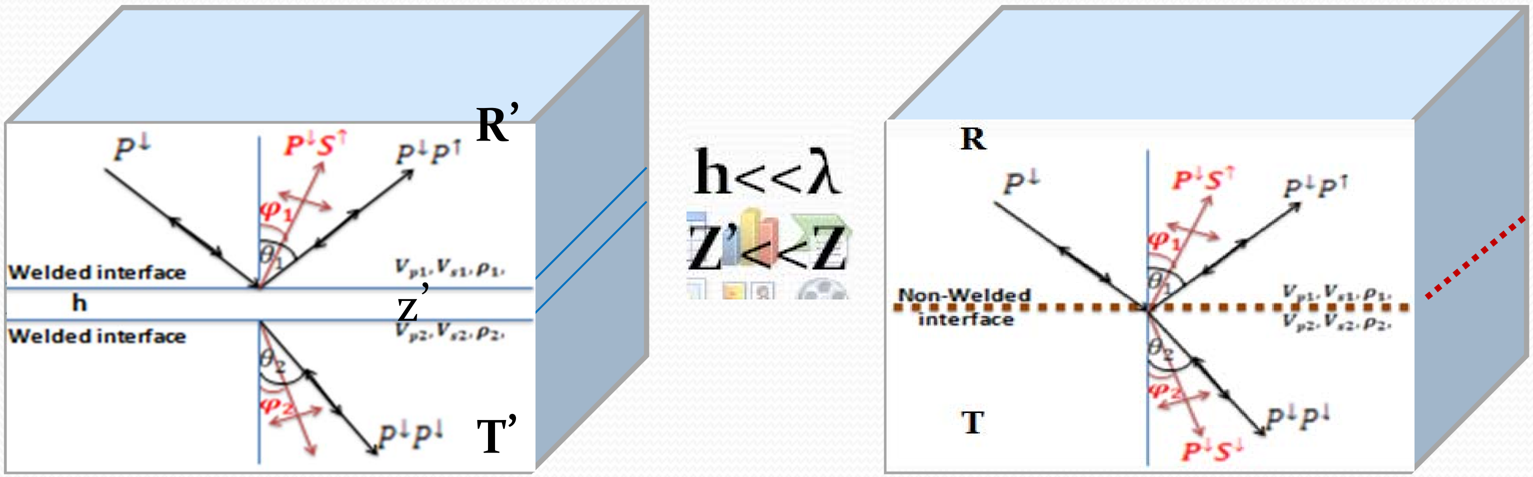
$$\frac{E_N}{1+E_N} = \frac{\lambda+2\mu}{\mu}U_{33}e$$

$$\frac{E_T}{1+E_T} = U_{11}e$$

$$\gamma_{Th} = E_T/2,\ \varepsilon_{Th} = 2\gamma_b(1-\gamma_b)E_N,\ \delta_{Th} = 2\gamma_b(E_N-E_T)$$

Schoenberg and Douma, 1988

➢ Theory of the linear slip interface

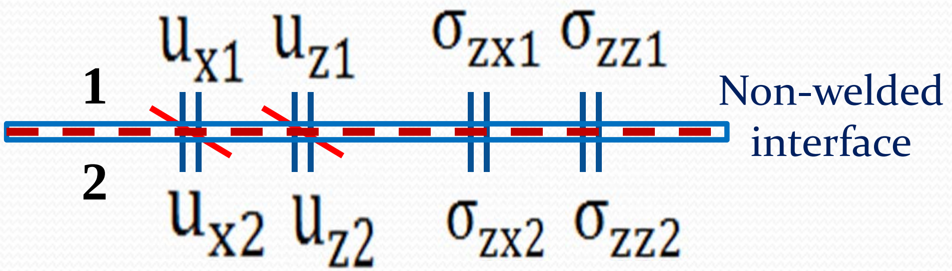


Schoenberg, 1980

➢ Theory of the linear slip interface

1) The discontinuity displacements

$$u_{x1} - u_{x2} = S_x \sigma_{zx}$$



$$u_{z1} - u_{z2} = S_z \sigma_{zz}$$

2) The continuity stresses

$$\sigma_{zx1} = \sigma_{zx2} \qquad \sigma_{zz1} = \sigma_{zz2}$$

$$\sigma_{zx} = \mu\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right) \qquad \sigma_{zz} = \lambda \frac{\partial u_x}{\partial x} + (\lambda + 2\mu)\frac{\partial u_z}{\partial z}$$

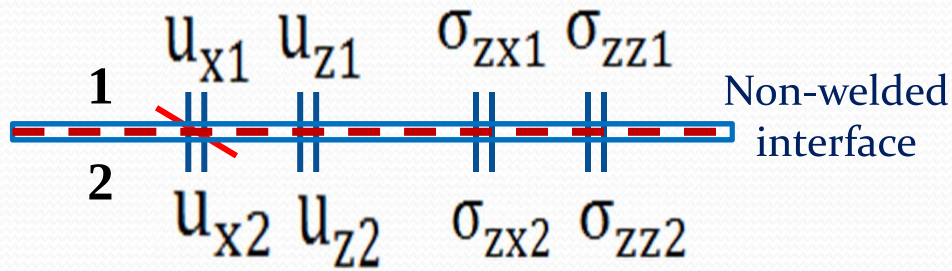
Schoenberg, 1980

Theory of the linear slip interface

1) The discontinuity displacements

$$u_{x1} - u_{x2} = S_x \sigma_{zx}$$

$$u_{z1} - u_{z2} = 0$$



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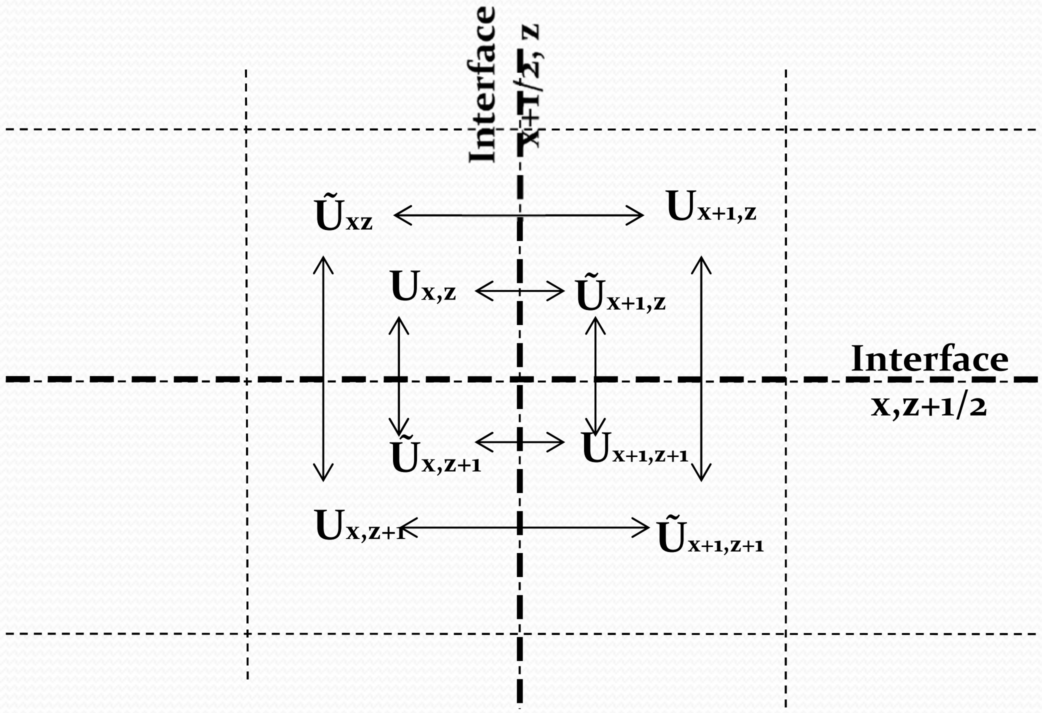
Schoenberg, 1980

➢ FD scheme of the linear slip interface



(Korn and Stolk, 1982.
Slawinski and Krebes , 2002)

FD scheme of the linear slip interface

$$U_{x,z}^{t+1} \approx -U_{x,z}^{t-1} + 2U_{x,z}^{t} + \left(\frac{\Delta t}{\Delta x}\right)^2 A\left(U_{x+1,z}^{t} - 2U_{x,z}^{t} + U_{x-1,z}^{t}\right) + \left(\frac{\Delta t^2}{\Delta x \Delta z}\right) B\left(U_{x+1,z+1}^{t} - U_{x+1,z-1}^{t} - U_{x-1,z+1}^{t} + U_{x-1,z-1}^{t}\right) + \left(\frac{\Delta t}{\Delta z}\right)^2 C\left(U_{x,z+1}^{t} - 2U_{x,z}^{t} + U_{x,z-1}^{t}\right)$$

Aki & Richards, 1980

$$U_{x,z}^{t+1} \approx -U_{x,z}^{t-1} + 2U_{x,z}^{t} + \left(\frac{\Delta t}{\Delta x}\right)^2 A\left(\tilde{U}_{x+1,z}^{t} - 2U_{x,z}^{t} + \tilde{U}_{x-1,z}^{t}\right) + \left(\frac{\Delta t^2}{\Delta x \Delta z}\right) B\left(U_{x+1,z+1}^{t} - U_{x+1,z-1}^{t} - U_{x-1,z+1}^{t} + U_{x-1,z-1}^{t}\right) + \left(\frac{\Delta t}{\Delta z}\right)^2 C\left(\tilde{U}_{x,z+1}^{t} - 2U_{x,z}^{t} + \tilde{U}_{x,z-1}^{t}\right)$$

➢ FD scheme of the linear slip interface

$$
\begin{aligned}
\mathbf{U}_{x,z}^{t+1} = & -\mathbf{U}_{x,z}^{t-1} + 2\mathbf{U}_{x,z}^{t} \\
& + \frac{1}{\rho}\left(\frac{\Delta t}{h}\right)^2 \Big(\mathbf{F}\widehat{\mathbf{N}}\mathbf{F}\big(\mathbf{U}_{x+1,z}^{t} - 2\mathbf{U}_{x,z}^{t} + \mathbf{U}_{x-1,z}^{t}\big) \\
& + \widehat{\mathbf{N}}\big(\mathbf{U}_{x,z+1}^{t} - 2\mathbf{U}_{x,z}^{t} + \mathbf{U}_{x,z-1}^{t}\big) \\
& + \frac{1}{4}\big(\mathbf{F}\widehat{\mathbf{G}}\mathbf{F} + \widehat{\mathbf{G}}\big)\big(\mathbf{U}_{x+1,z+1}^{t} - \mathbf{U}_{x+1,z-1}^{t} \\
& - \mathbf{U}_{x-1,z+1}^{t} + \mathbf{U}_{x-1,z-1}^{t}\big)\Big)
\end{aligned}
$$

$$
\mathbf{F} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \widehat{\mathbf{N}} = \begin{bmatrix} \frac{\mu}{1+\delta} & 0 \\ 0 & \frac{\lambda+2\mu}{1+\varnothing} \end{bmatrix}, \quad \widehat{\mathbf{G}} = \begin{bmatrix} 0 & \frac{\mu}{1+\delta} \\ \frac{\lambda}{1+\varnothing} & 0 \end{bmatrix}, \quad \delta = \frac{S_{xT}\mu}{h}, \quad \varnothing = \frac{S_N(\lambda+2\mu)}{h}
$$

➢ Inversion method of the linear slip interface

$$\begin{bmatrix} \alpha_1 P \\ \cos i_1 \\ x_1 \cos i_1 \\ \alpha_1 r_1 \end{bmatrix} = \begin{bmatrix} -\alpha_1 P & -\cos j_1 & \alpha_2 P - I\omega S_X x_2 \cos i_2 & \cos j_2 - I\omega S_X \beta_2 r_2 \\ \cos i_1 & -\beta_1 P & \cos i_2 - I\omega S_N \alpha_2 \gamma_2 & -\beta_2 P - I\omega S_N x_2 \cos j_2 \\ x_1 \cos i_1 & \beta_1 r_1 & x_2 \cos i_2 & \beta_2 r_2 \\ -\alpha_1 r_1 & x_1 \cos j_1 & \alpha_2 r_2 & -x_2 \cos j_2 \end{bmatrix} \begin{bmatrix} P_1^{`}P_1^{'} \\ P_1^{`}S_1^{'} \\ P_1^{`}P_2^{`} \\ P_1^{`}S_2^{`} \end{bmatrix}$$

Chaisri, 2002

$$P_1^{`}P_1^{'} = R_w + i\omega S_X R_{non\_w}^{x} + i\omega S_N R_{non\_w}^{N}$$

$$R_w \approx \frac{1}{2\cos^2 i}\frac{\Delta\alpha}{\alpha} - 4\left(\frac{\beta}{\alpha}\right)^2 \sin^2 i \frac{\Delta\beta}{\beta} + \frac{1}{2}\left(1 - 4\left(\frac{\beta}{\alpha}\right)^2 \sin^2 i\right)\frac{\Delta\rho}{\rho}$$

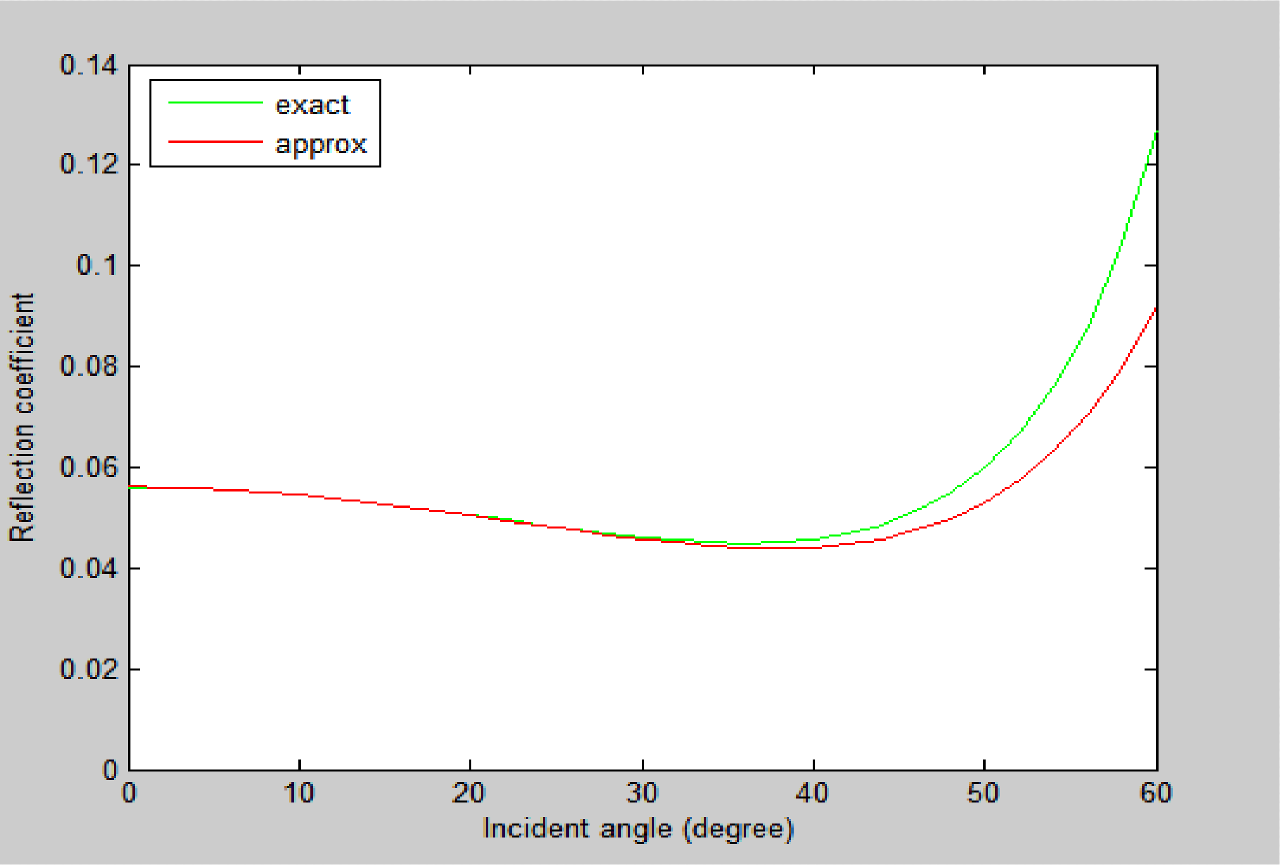
$$= A(i) r_\alpha + B(i) r_\beta + C(i) r_\rho$$

Inversion method of the linear slip interface

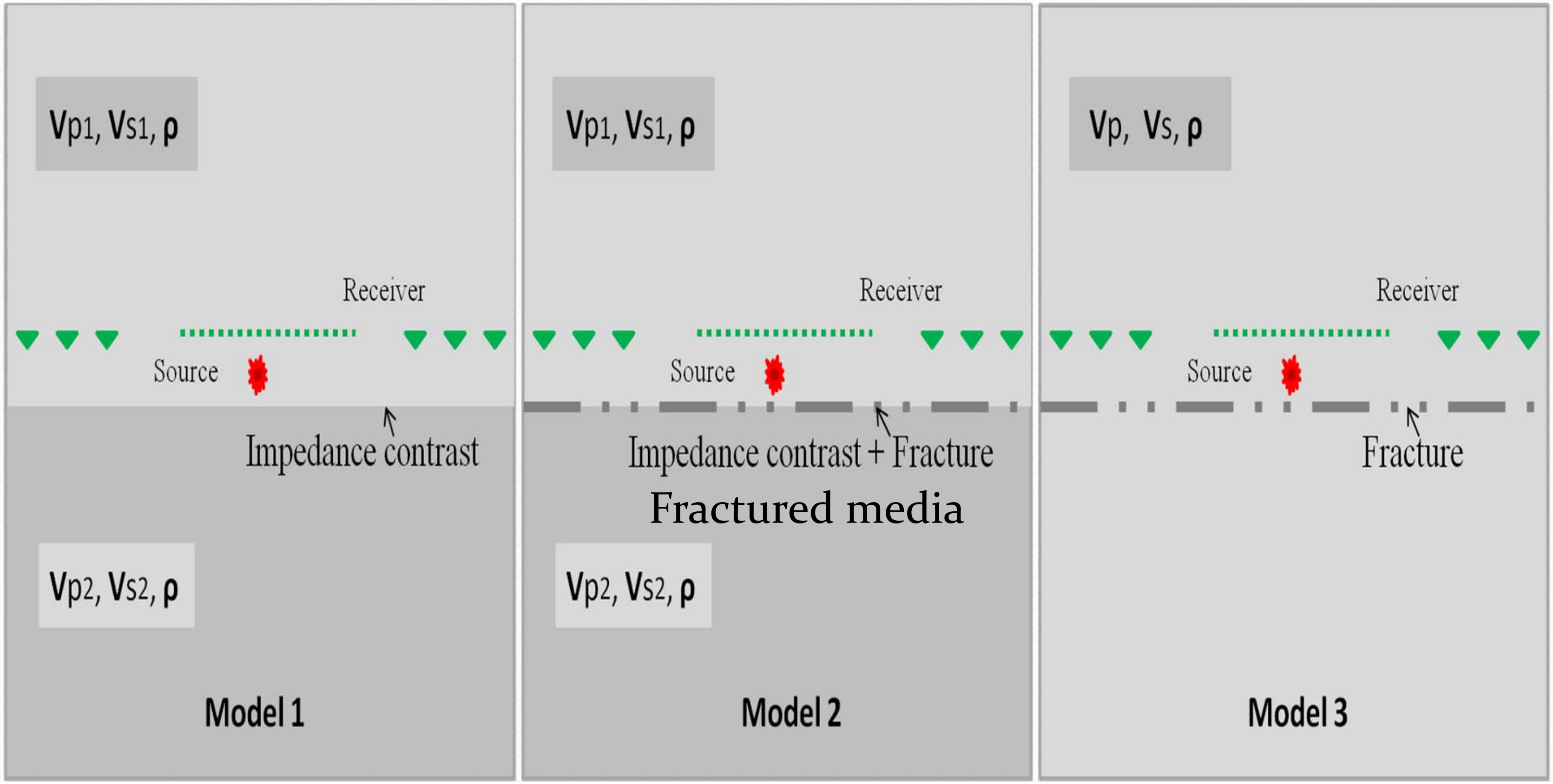
$$P_1^{`}P_1^{´} \approx \widetilde{R_w} + i\omega S_X \widetilde{R^{x}_{non_w}} + i\omega S_N \widetilde{R^{x}_{non_w}}$$

$$= (i\omega S_X X(i) + i\omega S_N N(i))$$
$$+(A(i) + i\omega S_X A^{x}(i) + i\omega S_N A^{N}(i)) r_\alpha$$
$$+(B(i) + i\omega S_X B^{x}(i) + i\omega S_N B^{N}(i)) r_\beta$$
$$+(C(i) + i\omega S_X C^{x}(i) + i\omega S_N C^{N}(i)) r_\rho$$

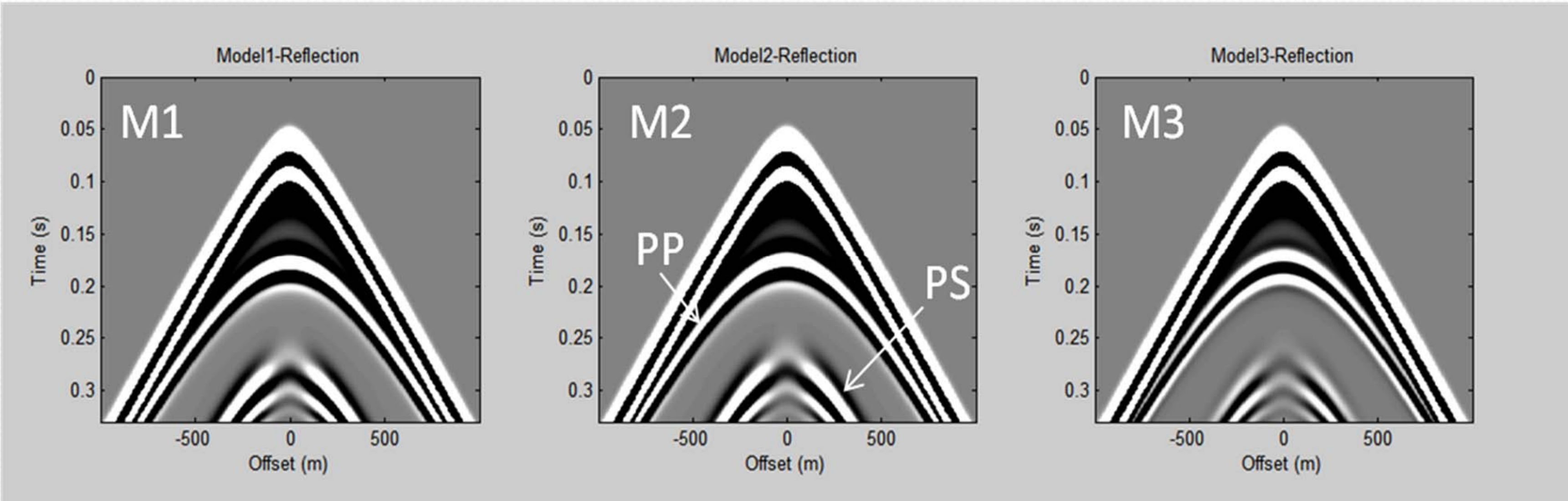
➢ Inversion method of the linear slip interface

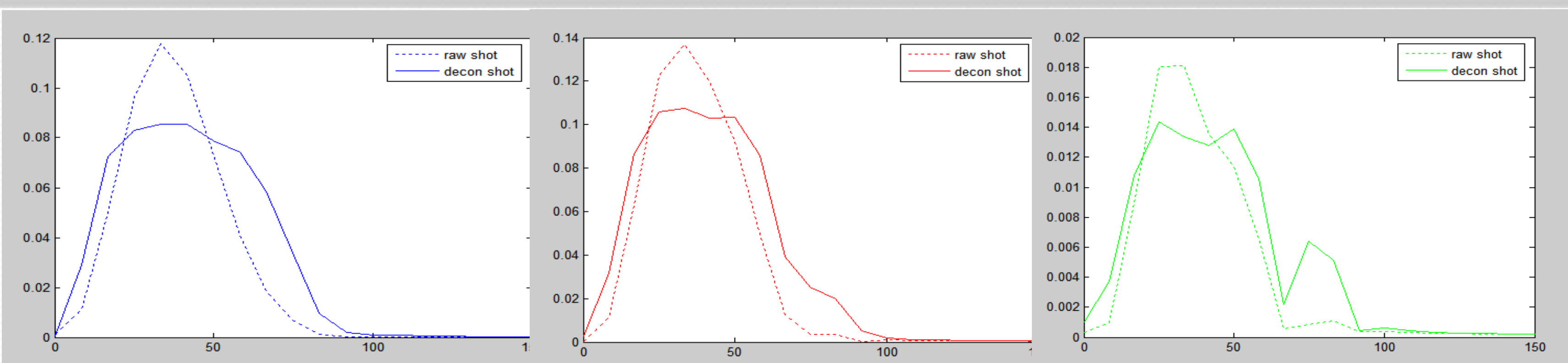


Applications

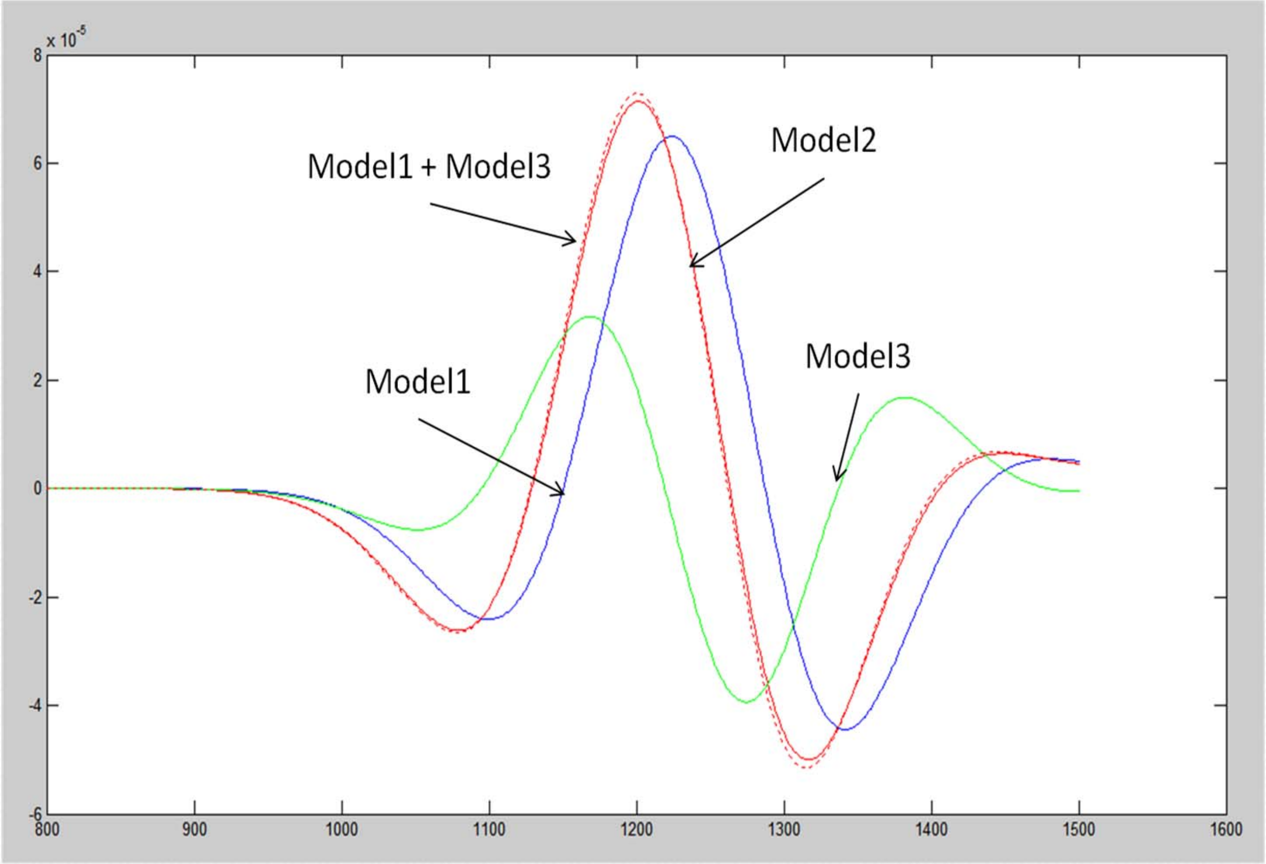


➢ Applications





➢ Applications



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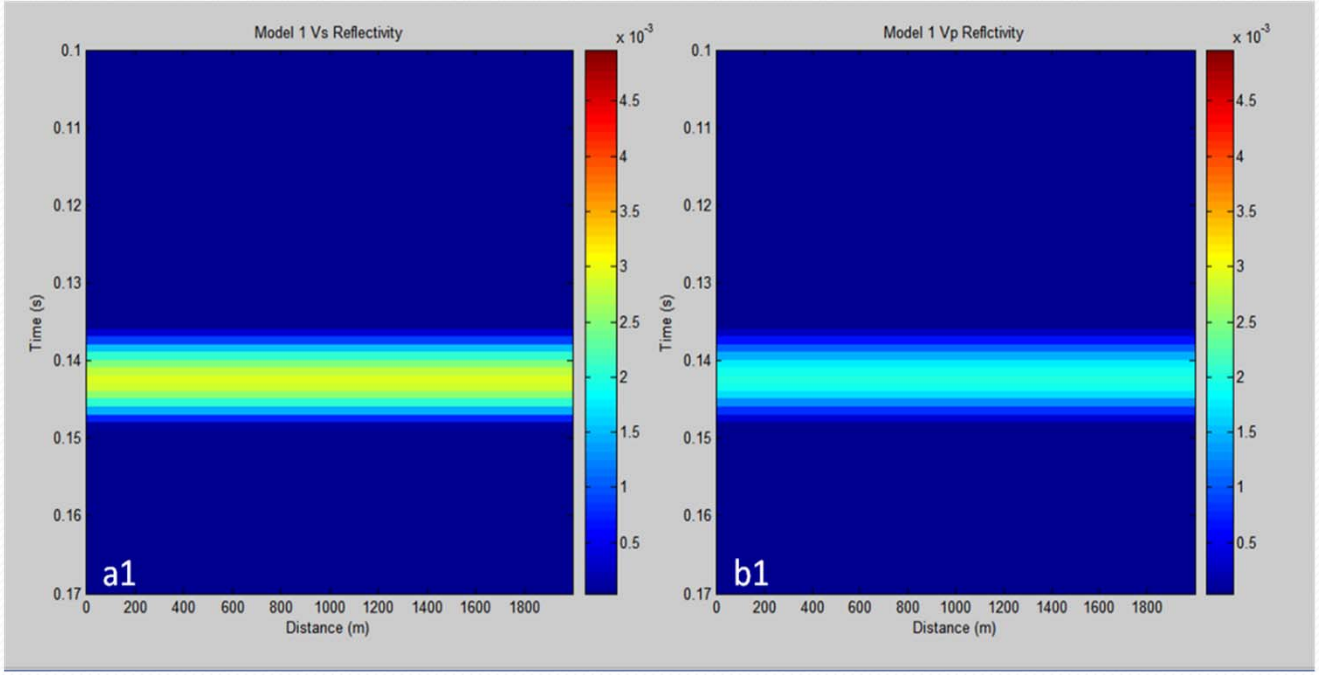
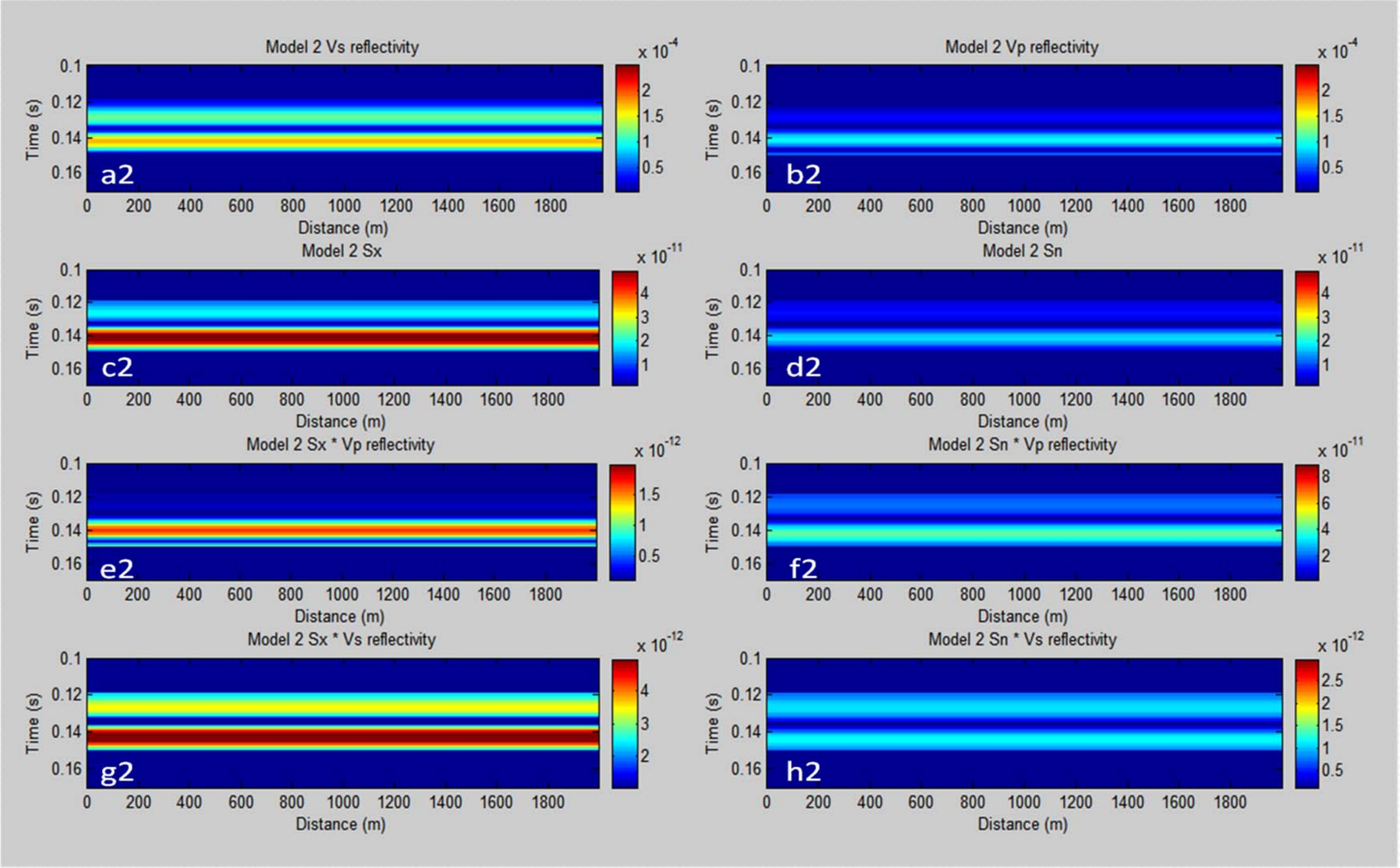


Seismic modeling and inversion for reflections from fractures

➢ Applications



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Seismic modeling and inversion for reflections from fractures

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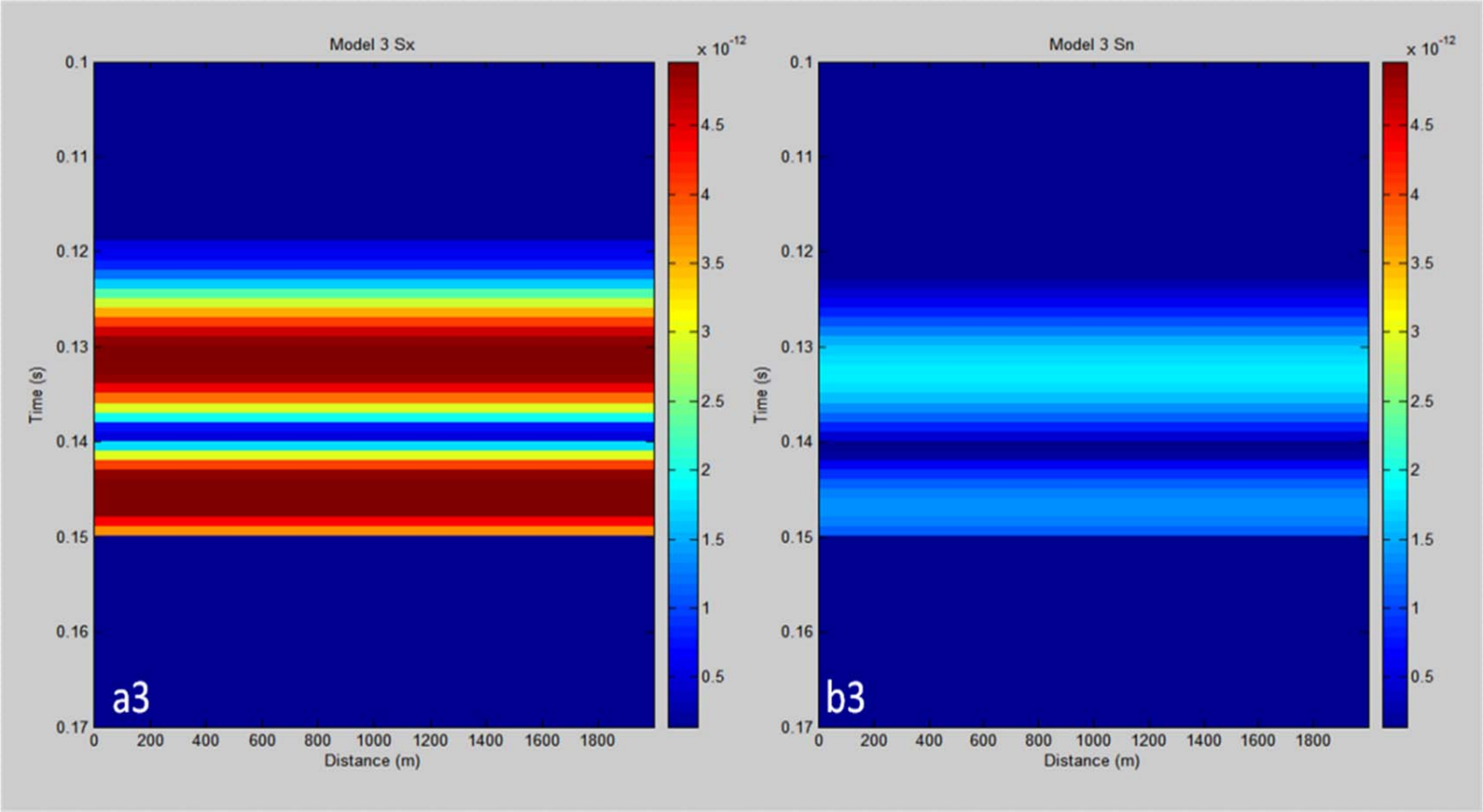

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Conclusions

The fracture as a linear slip non-welded contact interface has been studied and simulated.

The reflection of the fractured media (model 2) is considered as a combination of the reflections causing an impedance contrast and a discontinuity displacement of the fracture.

The new AVO inversion method can solve for not only the conventional elastic velocity reflectivity, but also some of elastic parameters related to the fractures.

Inverted fracture parameters contribute to the analysis of the reservoir permeability characterization and SAGD recovery.

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Thank You !!!