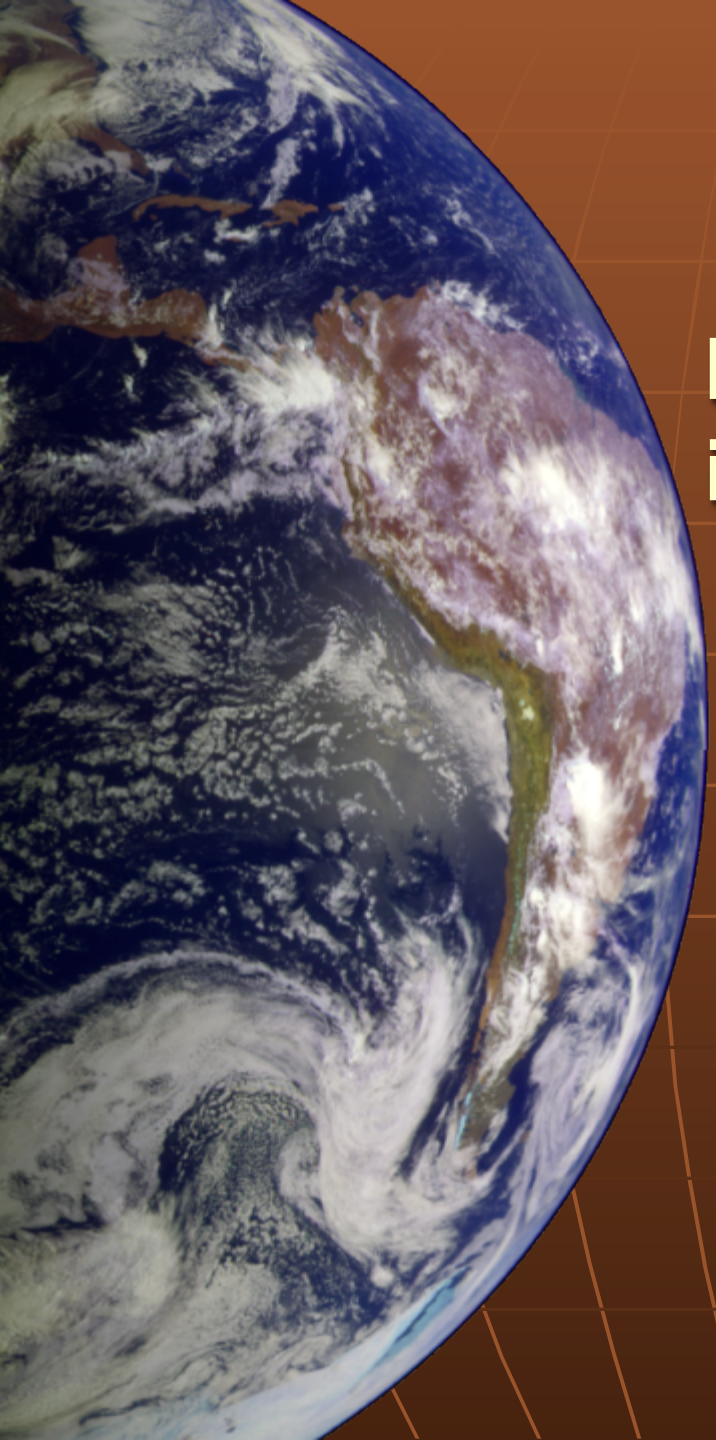

Pre-stack seismic reflection inversion with basis pursuit

Postdoc fellow: Rui Zhang

Advisor: Dr. Mrinal Sen and Dr. Sanjay Srinivasan

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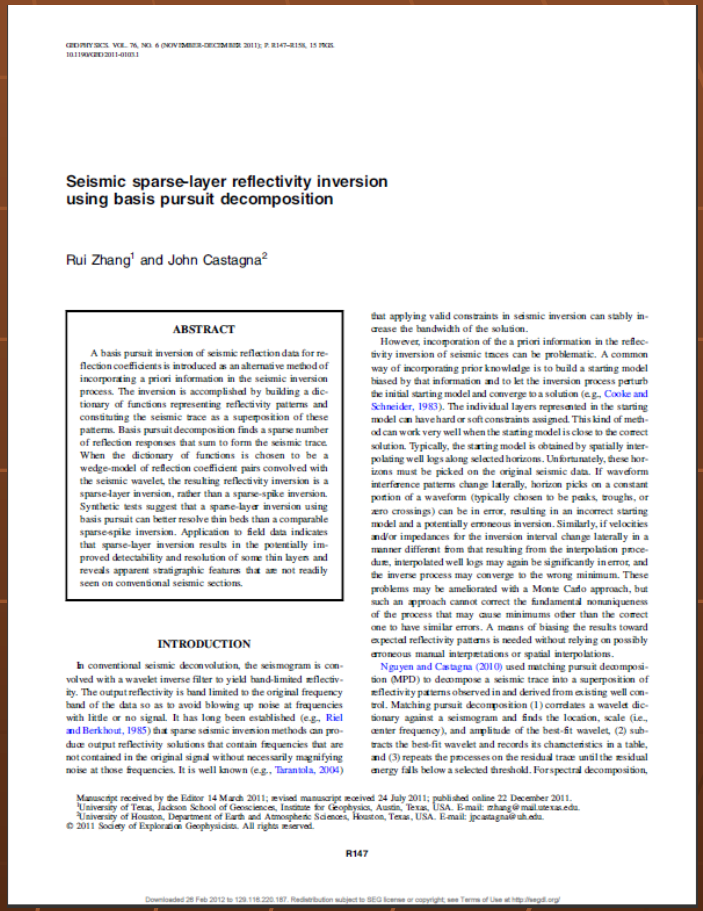
Outline

- Motivation
- Formulations
- Synthetic tests
- Field data
- Discussions
- Conclusions

Motivation

- Post-stack to pre-stack
- Acoustic to elastic
- Improved resolution



GEOPHYSICS, VOL. 76, NO. 6 (NOVEMBER-DECEMBER 2011); P. R147–R158, 15 FIGS.
10.1190/GEO2011-0103.1

Seismic sparse-layer reflectivity inversion using basis pursuit decomposition

Rui Zhang[1] and John Castagna[2]

ABSTRACT

A basis pursuit inversion of seismic reflection data for reflection coefficients is introduced as an alternative method of incorporating a priori information in the seismic inversion process. The inversion is accomplished by building a dictionary of functions representing reflectivity patterns and constituting the seismic trace as a superposition of these patterns. Basis pursuit decomposition finds a sparse number of reflection responses that sum to form the seismic trace. When the dictionary of functions is chosen to be a wedge-model of reflection coefficient pairs convolved with the seismic wavelet, the resulting reflectivity inversion is a sparse-layer inversion, rather than a sparse-spike inversion. Synthetic tests suggest that a sparse-layer inversion using basis pursuit can better resolve thin beds than a comparable sparse-spike inversion. Application to field data indicates that sparse-layer inversion results in the potentially improved detectability and resolution of some thin layers and reveals apparent stratigraphic features that are not readily seen on conventional seismic sections.

INTRODUCTION

In conventional seismic deconvolution, the seismogram is convolved with a wavelet inverse filter to yield band-limited reflectivity. The output reflectivity is band limited to the original frequency band of the data so as to avoid blowing up noise at frequencies with little or no signal. It has long been established (e.g., Riel and Berkhout, 1985) that sparse seismic invenion methods can produce output reflectivity solutions that contain frequencies that are not contained in the original signal without necessarily magnifying noise at those frequencies. It is well known (e.g., Tarantola, 2004) that applying valid constraints in seismic inversion can stably increase the bandwidth of the solution.

However, incorporation of the a priori information in the reflectivity inversion of seismic traces can be problematic. A common way of incorporating prior knowledge is to build a starting model biased by that information and to let the inversion process perturb the initial starting model and converge to a solution (e.g., Cooke and Schneider, 1983). The individual layers represented in the starting model can have hard or soft constraints assigned. This kind of method can work very well when the starting model is close to the correct solution. Typically, the starting model is obtained by spatially interpolating well logs along selected horizons. Unfortunately, these horizons must be picked on the original seismic data. If waveform interference patterns change laterally, horizon picks on a constant portion of a waveform (typically chosen to be peaks, troughs, or zero crossings) can be in error, resulting in an incorrect starting model and a potentially erroneous inversion. Similarly, if velocities and/or impedances for the inversion interval change laterally in a manner different from that resulting from the interpolation procedure, interpolated well logs may again be significantly in error, and the inverse process may converge to the wrong minimum. These problems may be ameliorated with a Monte Carlo approach, but such an approach cannot correct the fundamental nonuniqueness of the process that may cause minimums other than the correct one to have similar errors. A means of biasing the results toward expected reflectivity patterns is needed without relying on possibly erroneous manual interpretations or spatial interpolations.

Nguyen and Castagna (2010) used matching pursuit decomposition (MPD) to decompose a seismic trace into a superposition of reflectivity patterns observed in and derived from existing well control. Matching pursuit decomposition (1) correlates a wavelet dictionary against a seismogram and finds the location, scale (i.e., center frequency), and amplitude of the best-fit wavelet, (2) subtracts the best-fit wavelet and records its characteristics in a table, and (3) repeats the processes on the residual trace until the residual energy falls below a selected threshold. For spectral decomposition,

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[1]University of Texas, Jackson School of Geosciences, Institute for Geophysics, Austin, Texas, USA. E-mail: rzhang@mail.utexas.edu.
[2]University of Houston, Department of Earth and Atmospheric Sciences, Houston, Texas, USA. E-mail: jpcastagna@uh.edu.

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Formulations

Aki & Richard

$$R(\theta)=1/2\ (1+tan\uparrow 2\ \theta)\Delta V\downarrow p\ /V\downarrow p\ -4\beta\uparrow 2\ /\alpha\uparrow 2\ \ sin\uparrow 2\ \theta\Delta V\downarrow s\ /V\downarrow s\ -[1/2\ tan\uparrow 2\ \theta-2\beta\uparrow 2\ /\alpha\uparrow 2\ \ sin\uparrow 2\ \theta]\Delta\rho/\rho$$

$$R(\theta,t)=1/2\ (1+tan\uparrow 2\ \theta)\Delta V\downarrow p\ (t)/V\downarrow p\ (t)\ -4\beta\uparrow 2\ /\alpha\uparrow 2\ \ sin\uparrow 2\ \theta\Delta V\downarrow s\ (t)/V\downarrow s\ (t)\ -[1/2\ tan\uparrow 2\ \theta-2\beta\uparrow 2\ /\alpha\uparrow 2\ \ sin\uparrow 2\ \theta]\Delta\rho(t)/\rho(t)$$

$$R\downarrow p\ (t)=\Delta V\downarrow p\ (t)/V\downarrow p\ (t)$$

$$R\downarrow s\ (t)=\Delta V\downarrow s\ (t)/V\downarrow s\ (t)$$

$$R\downarrow\rho\ (t)=\Delta\rho(t)/\rho(t)$$

$$C\downarrow p\ (t)=1/2\ (1+tan\uparrow 2\ \theta)$$

$$C\downarrow s=\ -4\beta\uparrow 2\ /\alpha\uparrow 2\ \ sin\uparrow 2\ \theta$$

$$C\downarrow\rho\ =-(1/2\ tan\uparrow 2\ \theta-2\beta\uparrow 2\ /\alpha\uparrow 2\ \ sin\uparrow 2\ \theta)$$

β/α is background VsVp ratio

Formulations

$$\begin{bmatrix} R_{pp}(t,\theta_1) \\ R_{pp}(t,\theta_2) \\ \vdots \\ R_{pp}(t,\theta_N) \end{bmatrix} = \begin{bmatrix} C_p(t,\theta_1) & C_s(t,\theta_1) & C_\rho(t,\theta_1) \\ C_p(t,\theta_2) & C_s(t,\theta_2) & C_\rho(t,\theta_2) \\ \vdots & \vdots & \vdots \\ C_p(t,\theta_N) & C_s(t,\theta_N) & C_\rho(t,\theta_N) \end{bmatrix} \times \begin{bmatrix} R_p(t) \\ R_s(t) \\ R_\rho(t) \end{bmatrix},$$

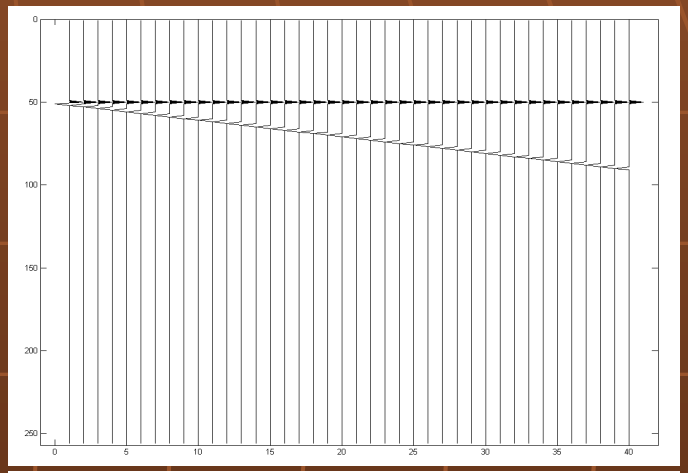
$$\begin{bmatrix} S_{pp}(t,\theta_1) \\ S_{pp}(t,\theta_2) \\ \vdots \\ S_{pp}(t,\theta_N) \end{bmatrix} = \begin{bmatrix} W_p(t,\theta_1) & W_s(t,\theta_1) & W_\rho(t,\theta_1) \\ W_p(t,\theta_2) & W_s(t,\theta_2) & W_\rho(t,\theta_2) \\ \vdots & \vdots & \vdots \\ W_p(t,\theta_N) & W_s(t,\theta_N) & W_\rho(t,\theta_N) \end{bmatrix} \times \begin{bmatrix} R_p(t) \\ R_s(t) \\ R_\rho(t) \end{bmatrix}.$$

Formulations

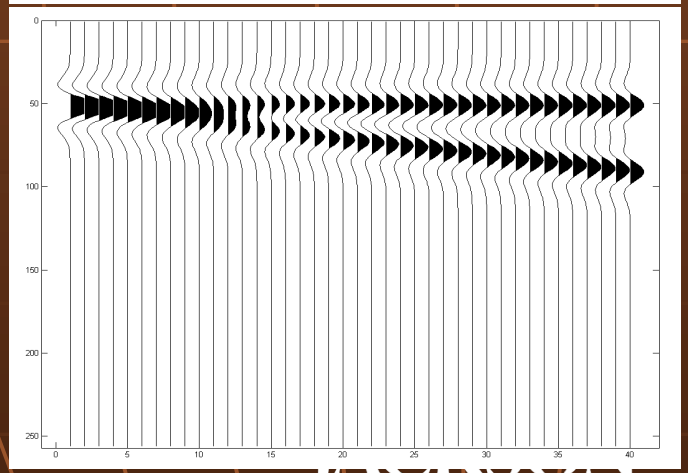
Even

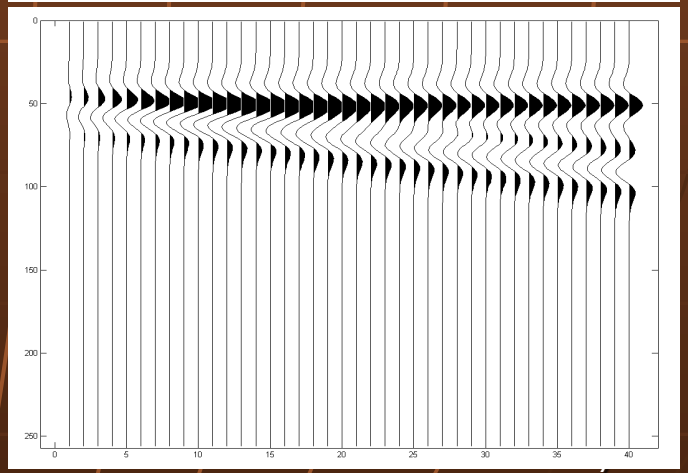
Odd

Wedge reflectivity



Wedge seismic response





Formulations

$$R_p(t) = \sum_{n=1}^{N} \sum_{m=1}^{M} (aep_{n,m} * r_e(t,m,n,\Delta t) + bop_{n,m} * r_o(t,m,n,\Delta t))$$

$$R_s(t) = \sum_{n=1}^{N} \sum_{m=1}^{M} (aes_{n,m} * r_e(t,m,n,\Delta t) + bos_{n,m} * r_o(t,m,n,\Delta t))$$

$$R_\rho(t) = \sum_{n=1}^{N} \sum_{m=1}^{M} (ae\rho_{n,m} * r_e(t,m,n,\Delta t) + bo\rho_{n,m} * r_o(t,m,n,\Delta t))$$

$$\begin{bmatrix} R_p(t) \\ R_s(t) \\ R_\rho(t) \end{bmatrix} = \begin{bmatrix} r_e & r_o & 0 & 0 & 0 & 0 \\ 0 & 0 & r_e & r_o & 0 & 0 \\ 0 & 0 & 0 & 0 & r_e & r_o \end{bmatrix} \times \begin{bmatrix} aep \\ bop \\ aes \\ bos \\ ae\rho \\ bo\rho \end{bmatrix}$$

Formulations

b A x

$$\begin{bmatrix} S_{pp}(t,\theta_1) \\ S_{pp}(t,\theta_2) \\ \vdots \\ S_{pp}(t,\theta_N) \end{bmatrix} = \begin{bmatrix} W_p(t,\theta_1) & W_s(t,\theta_1) & W_\rho(t,\theta_1) \\ W_p(t,\theta_2) & W_s(t,\theta_2) & W_\rho(t,\theta_2) \\ \vdots & \vdots & \vdots \\ W_p(t,\theta_N) & W_s(t,\theta_N) & W_\rho(t,\theta_N) \end{bmatrix} \times \begin{bmatrix} [r_e, r_o] & 0 & 0 \\ 0 & [r_e, r_o] & 0 \\ 0 & 0 & [r_e, r_o] \end{bmatrix} \times \begin{bmatrix} aep \\ bop \\ aes \\ bos \\ ae\rho \\ bo\rho \end{bmatrix}$$

Objective Function

L1 norm minimization least square solution

$\min\|x\|_{l1}$ Subject to $\min\|b - A \times x\|_2$

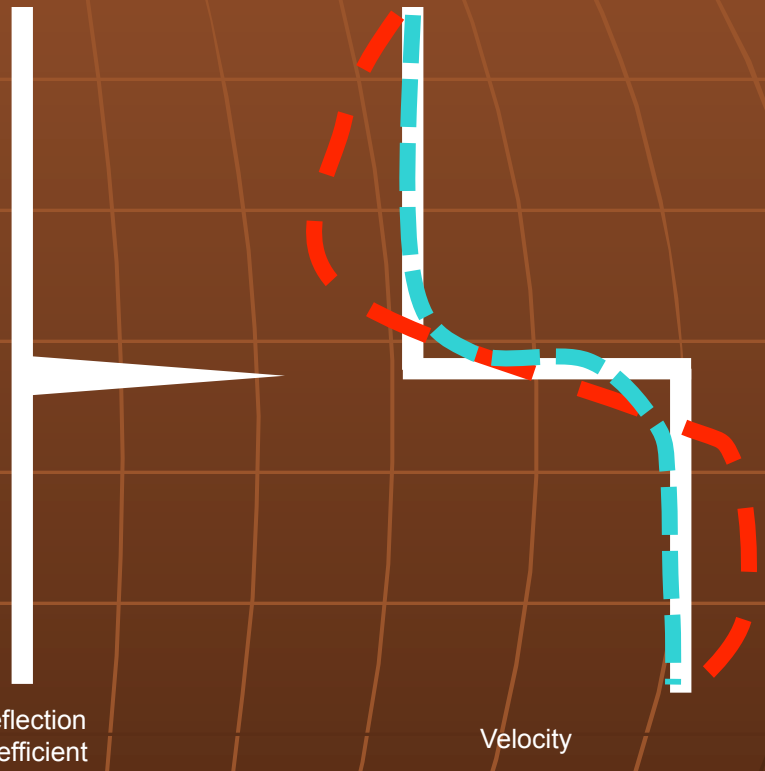
$$\min[\|b - A \times x\|_2 + \lambda\|x\|_1]$$

Velocity

$$r_t = \Delta V_t / V_t = \Delta \ln V_t$$

$$\ln V_t = \ln V_t(0) + \int_0^t r_t \, dt$$

$$V_t = V_t(0) e^{\int_0^t r_t \, dt}$$



r_t : Reflection coefficient

V_t : Velocity

Outline

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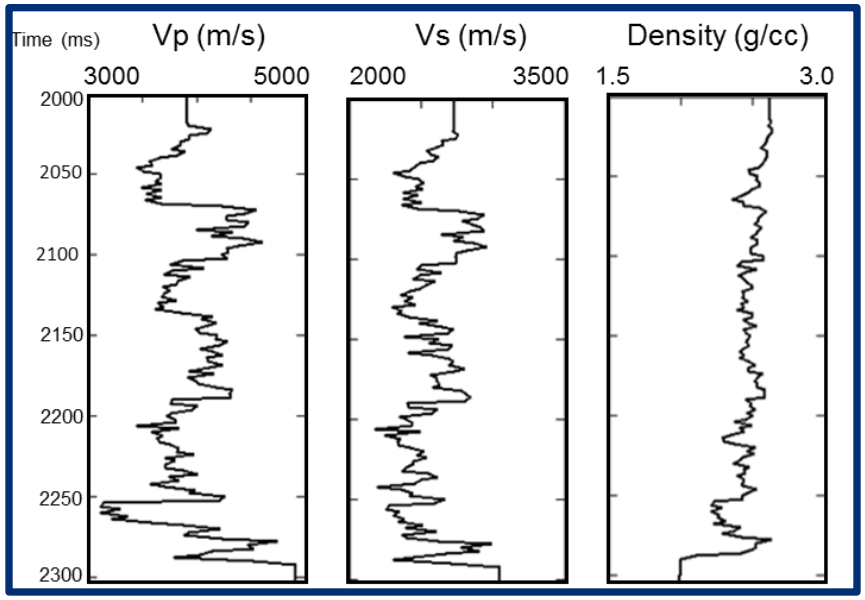
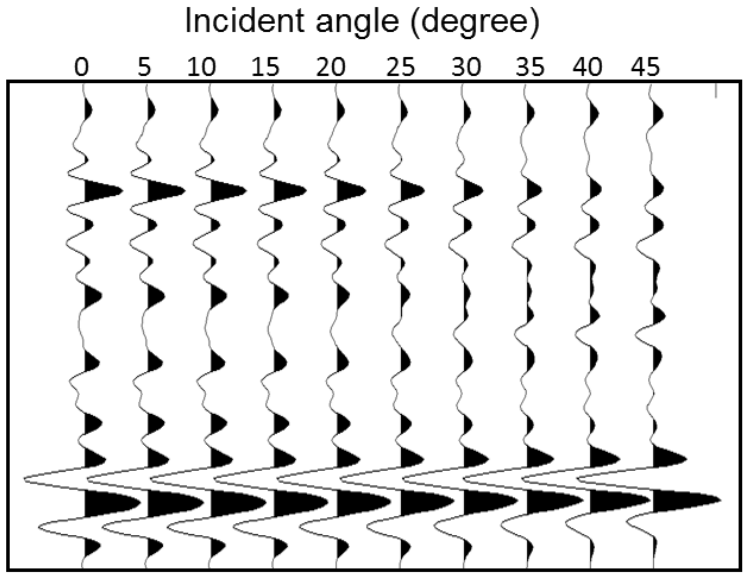
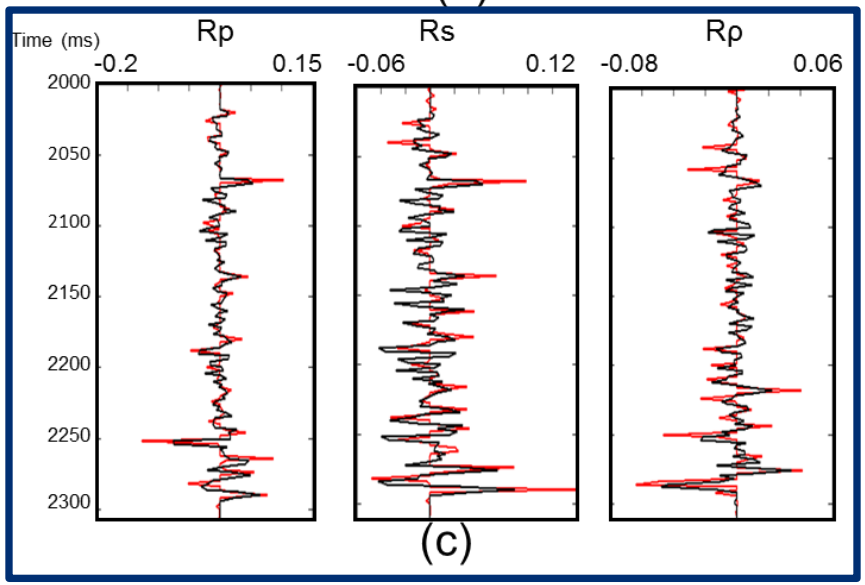
1D Synthetic tests



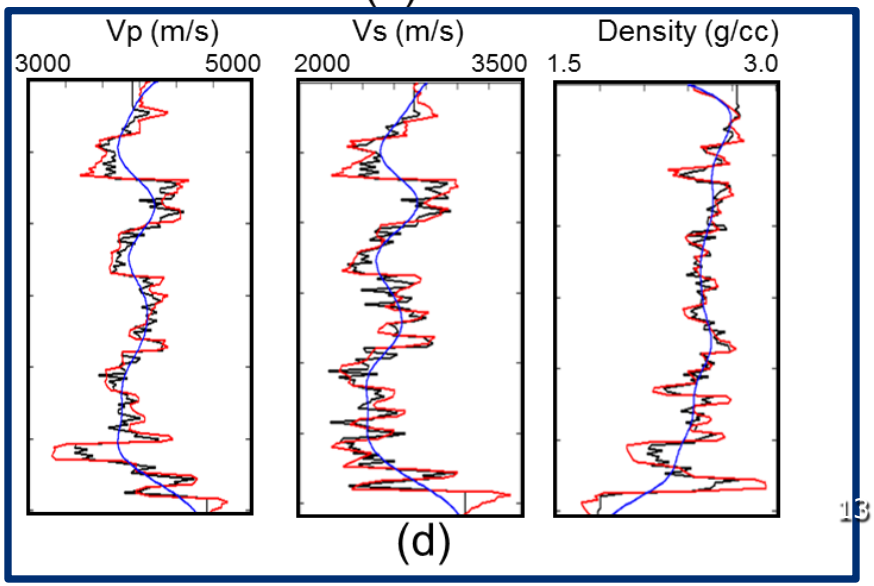
(a)



(b)

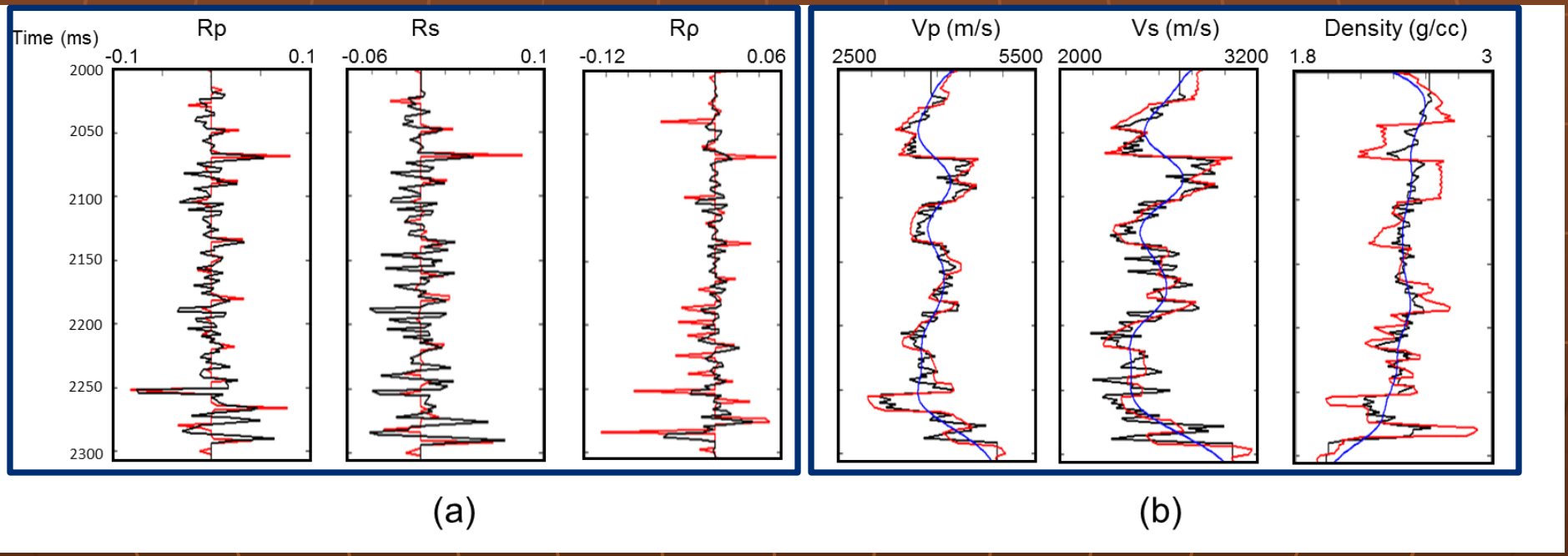


(c)

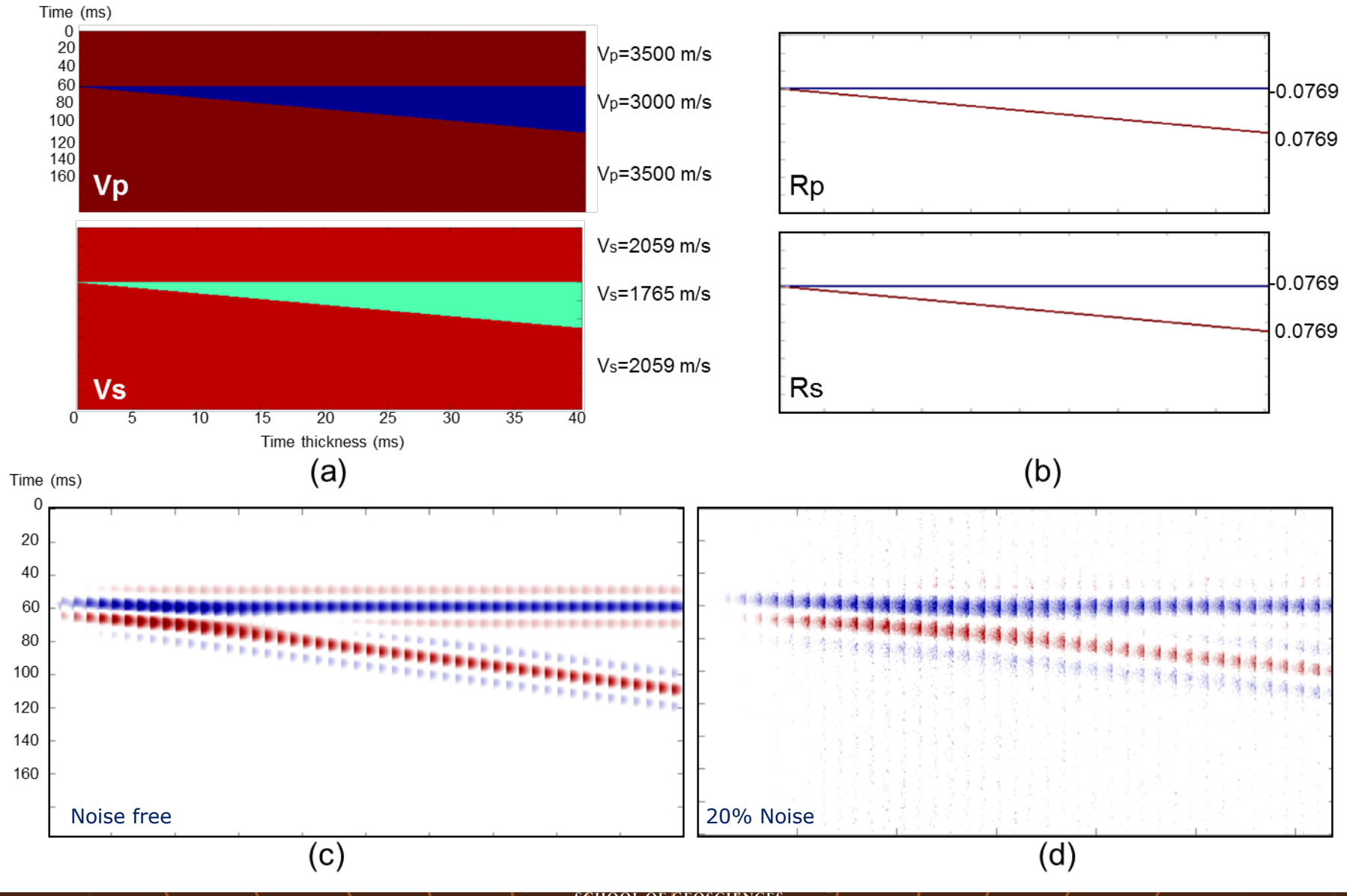


(d)

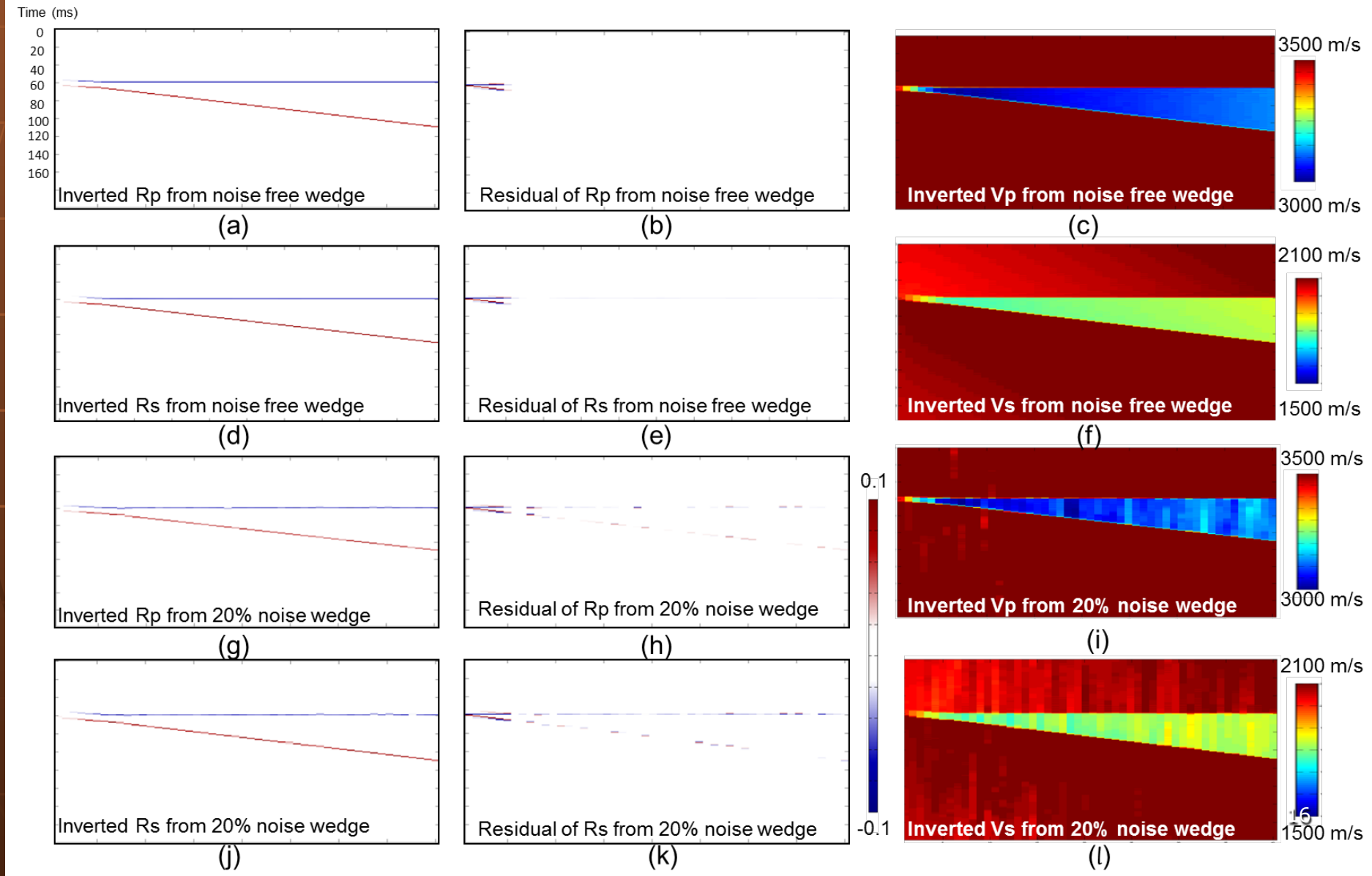
20% noise


Time (ms)
Rp
-0.1
0.1
Rs
-0.06
0.1
Rρ
-0.12
0.06
2000
2050
2100
2150
2200
2250
2300
Vp (m/s)
2500
5500
Vs (m/s)
2000
3200
Density (g/cc)
1.8
3
(a)
(b)

2D Synthetic tests



2D Synthetic tests



Outline

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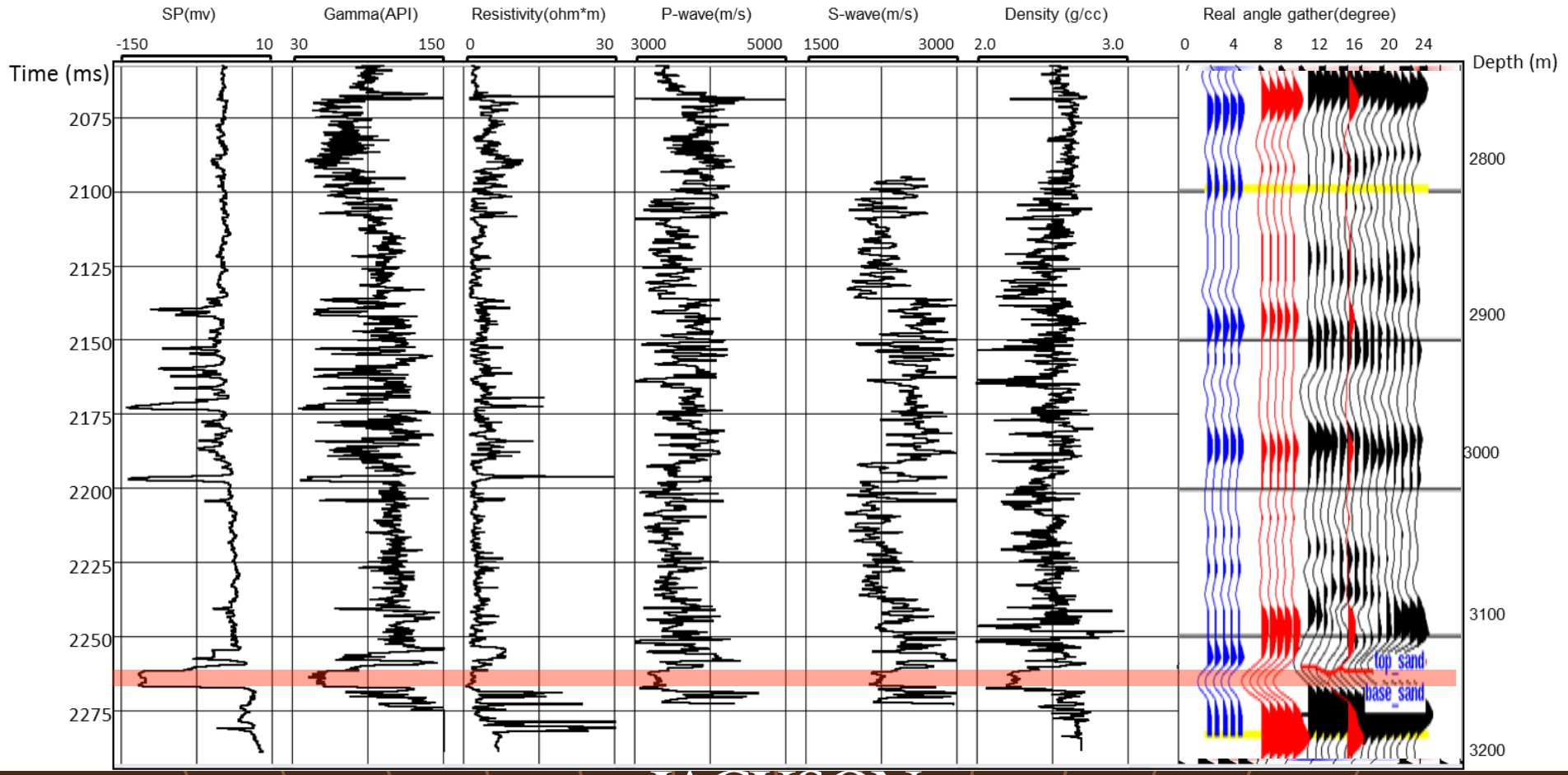
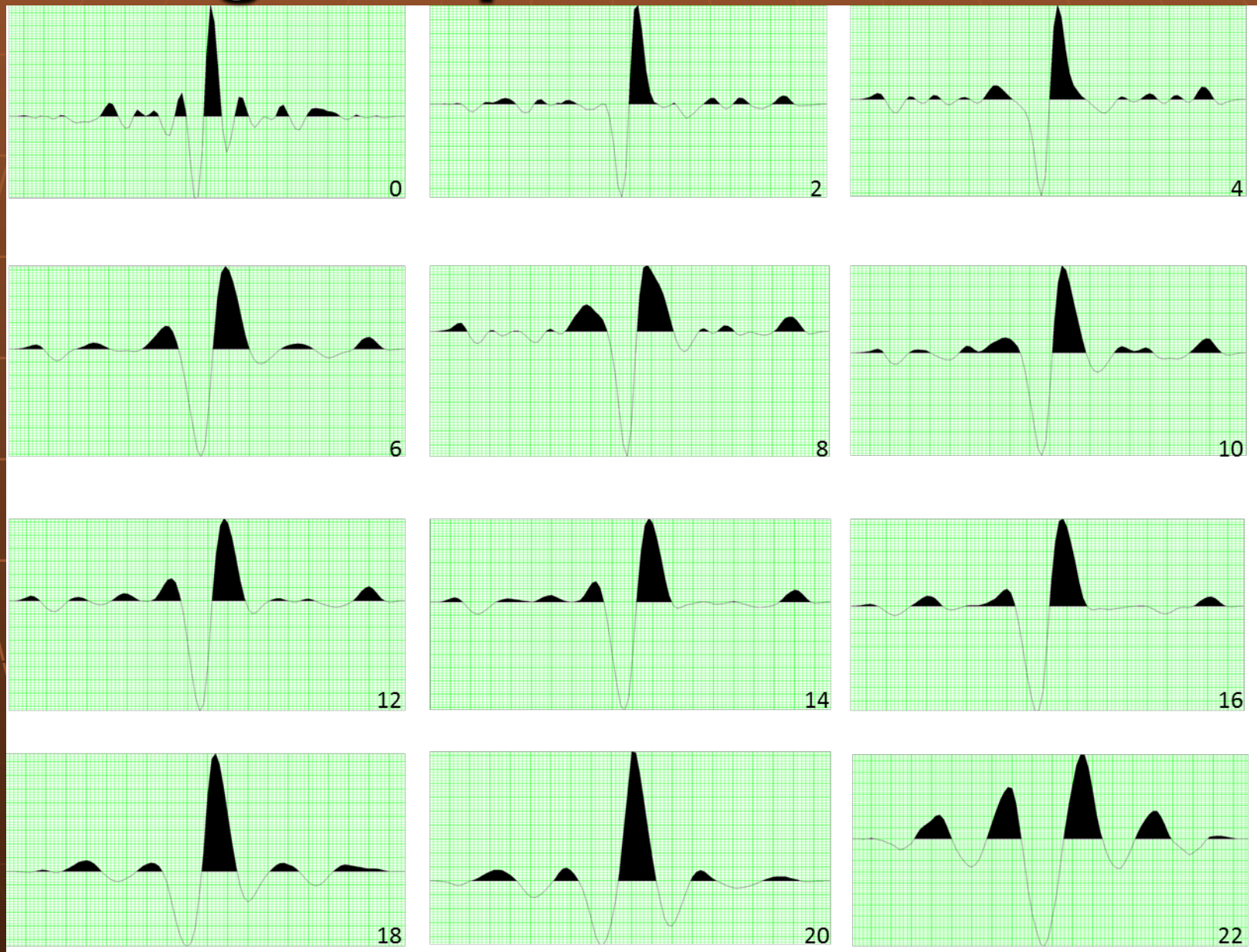
Seismic well “tie”

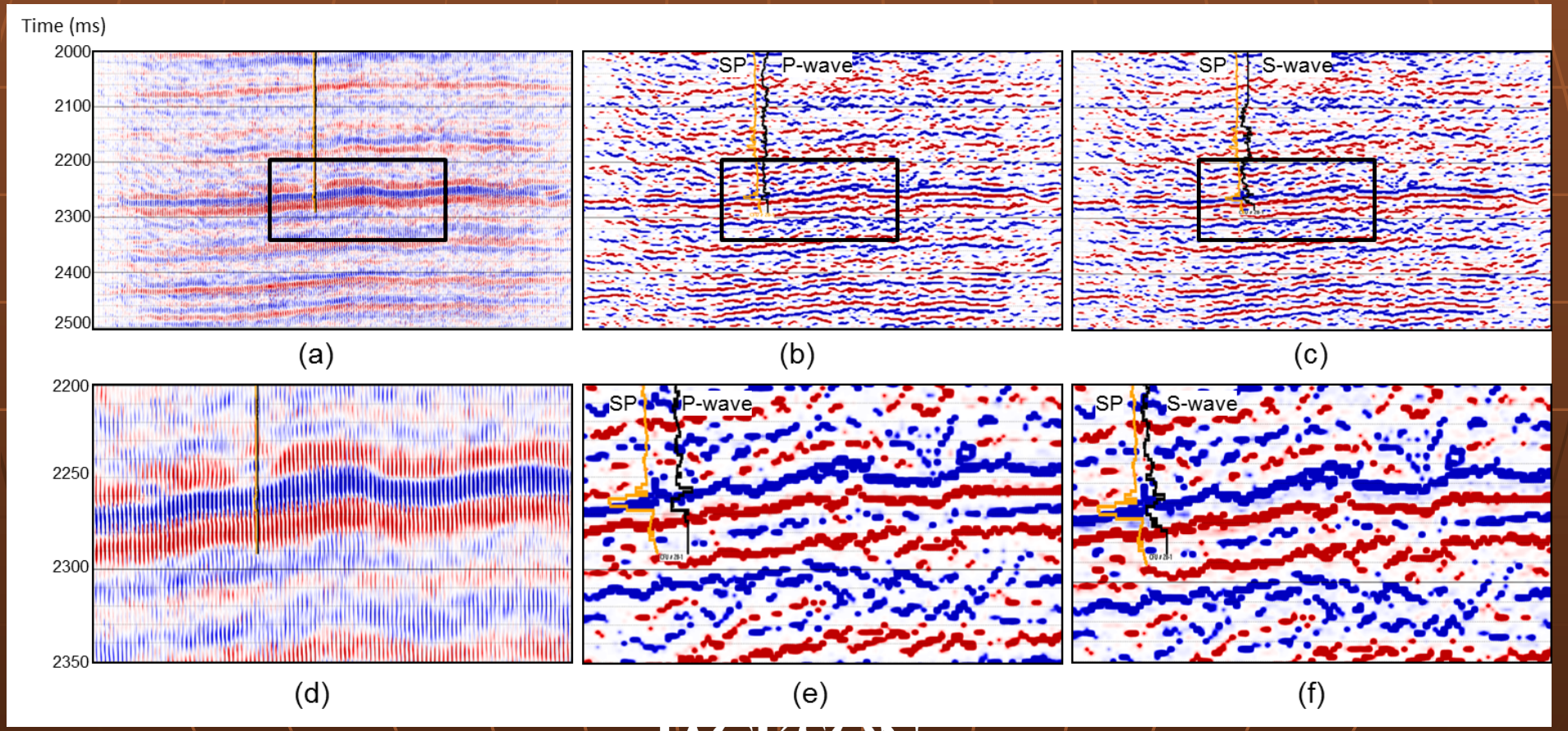


Angle dependent wavelets



Inverted Reflection Coefficients

Pre-stack seismic | Inverted Rp | Inverted Rs



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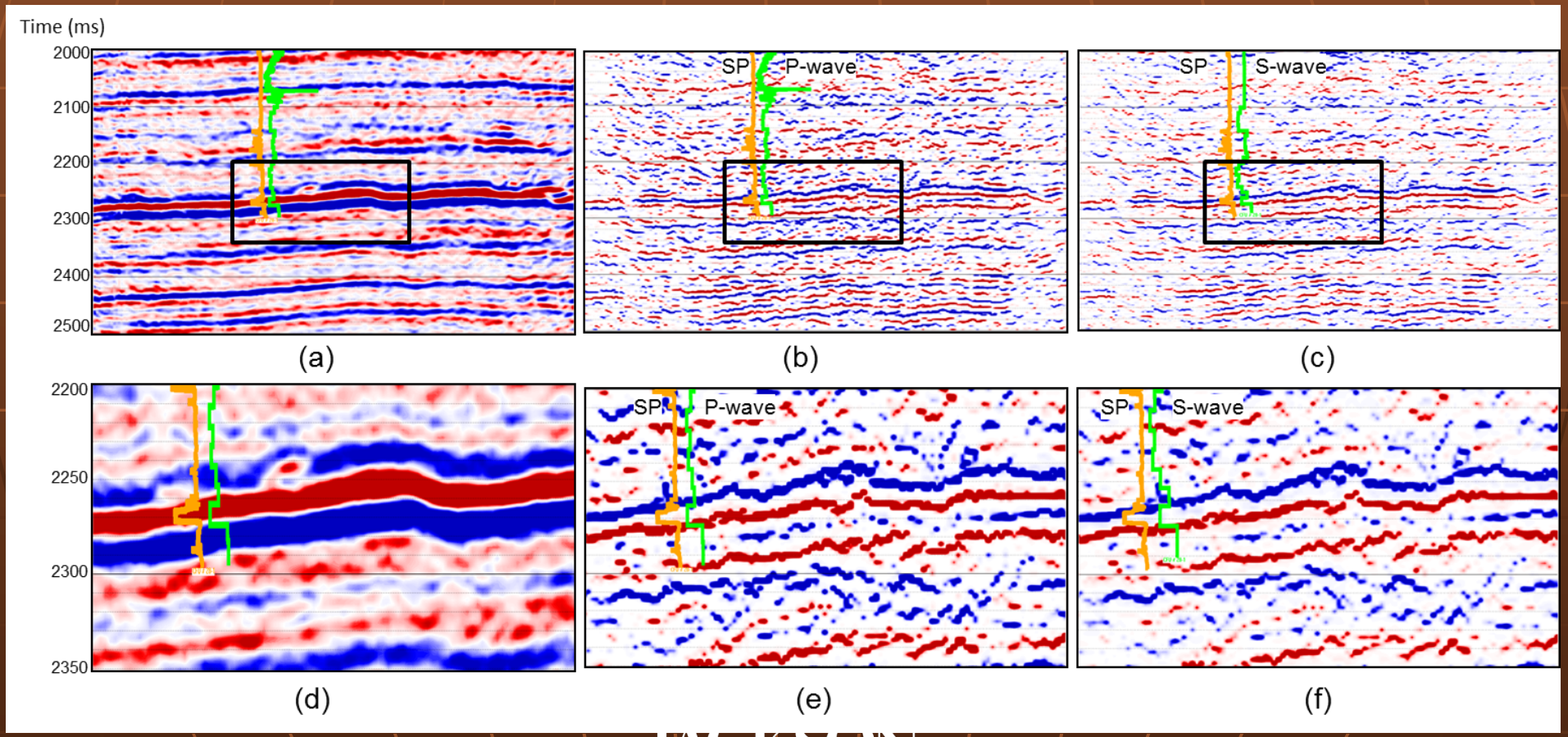
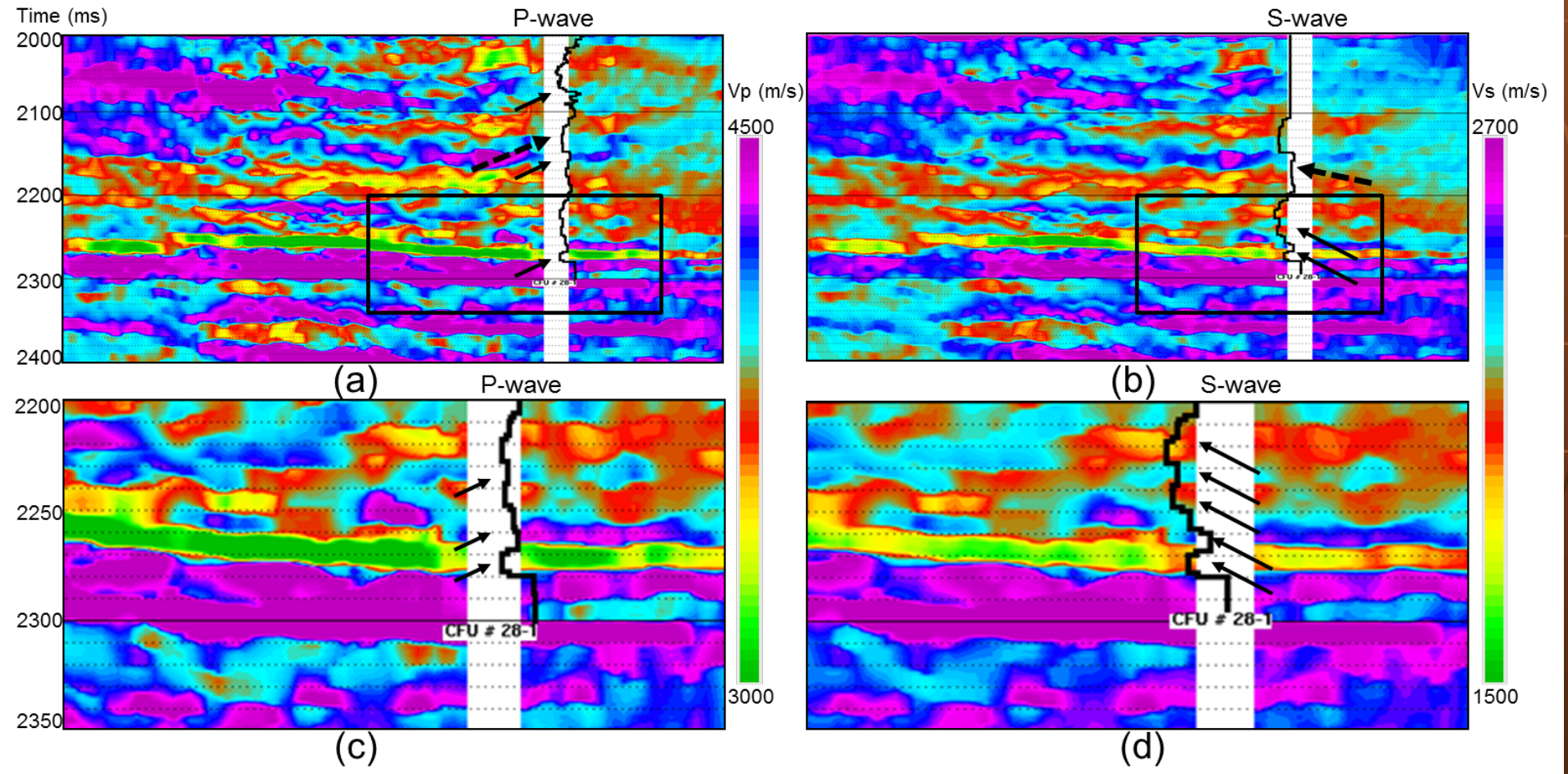
Inverted Reflection Coefficients

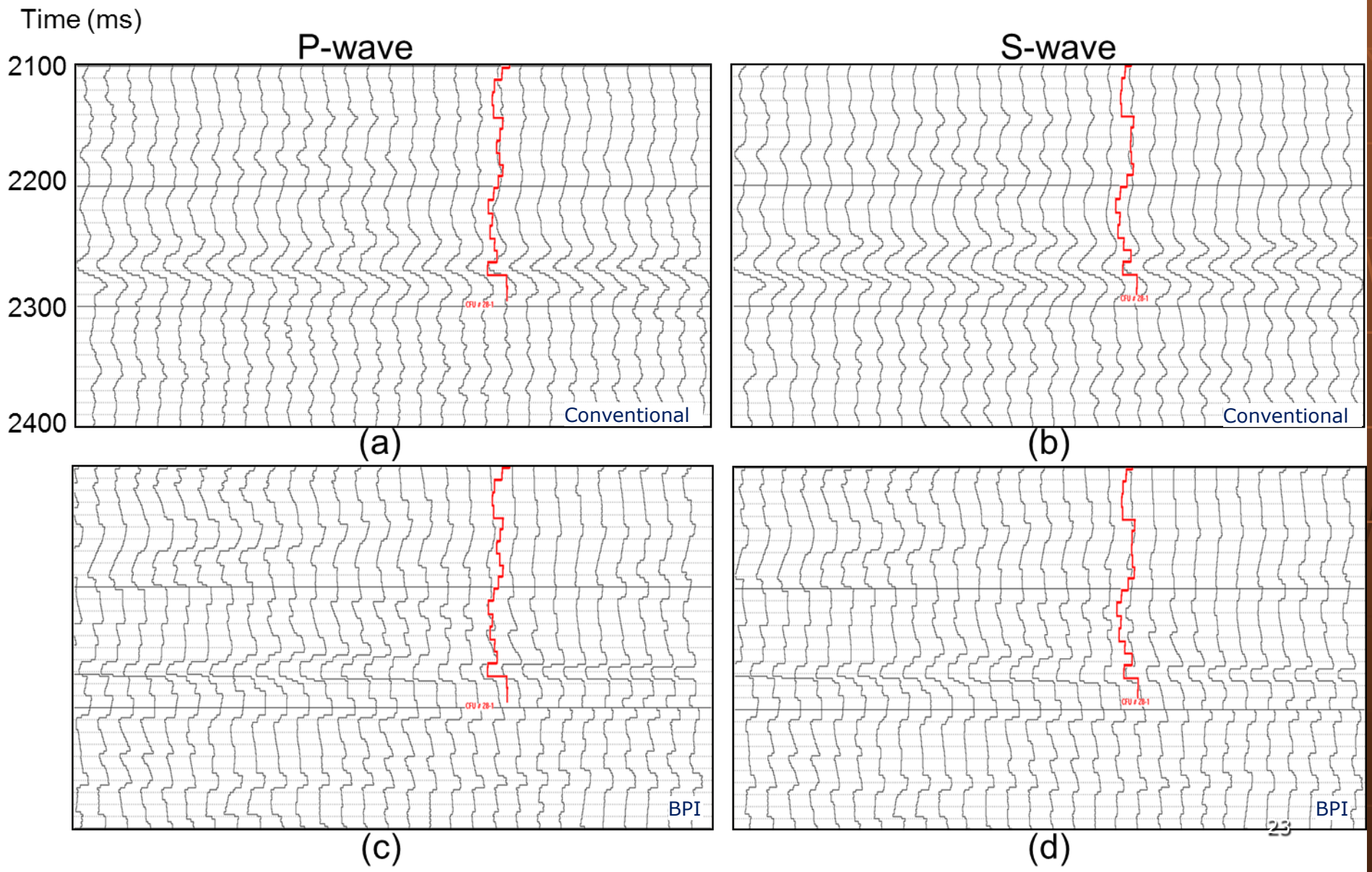
Post-stack seismic | Inverted Rp | Inverted Rs

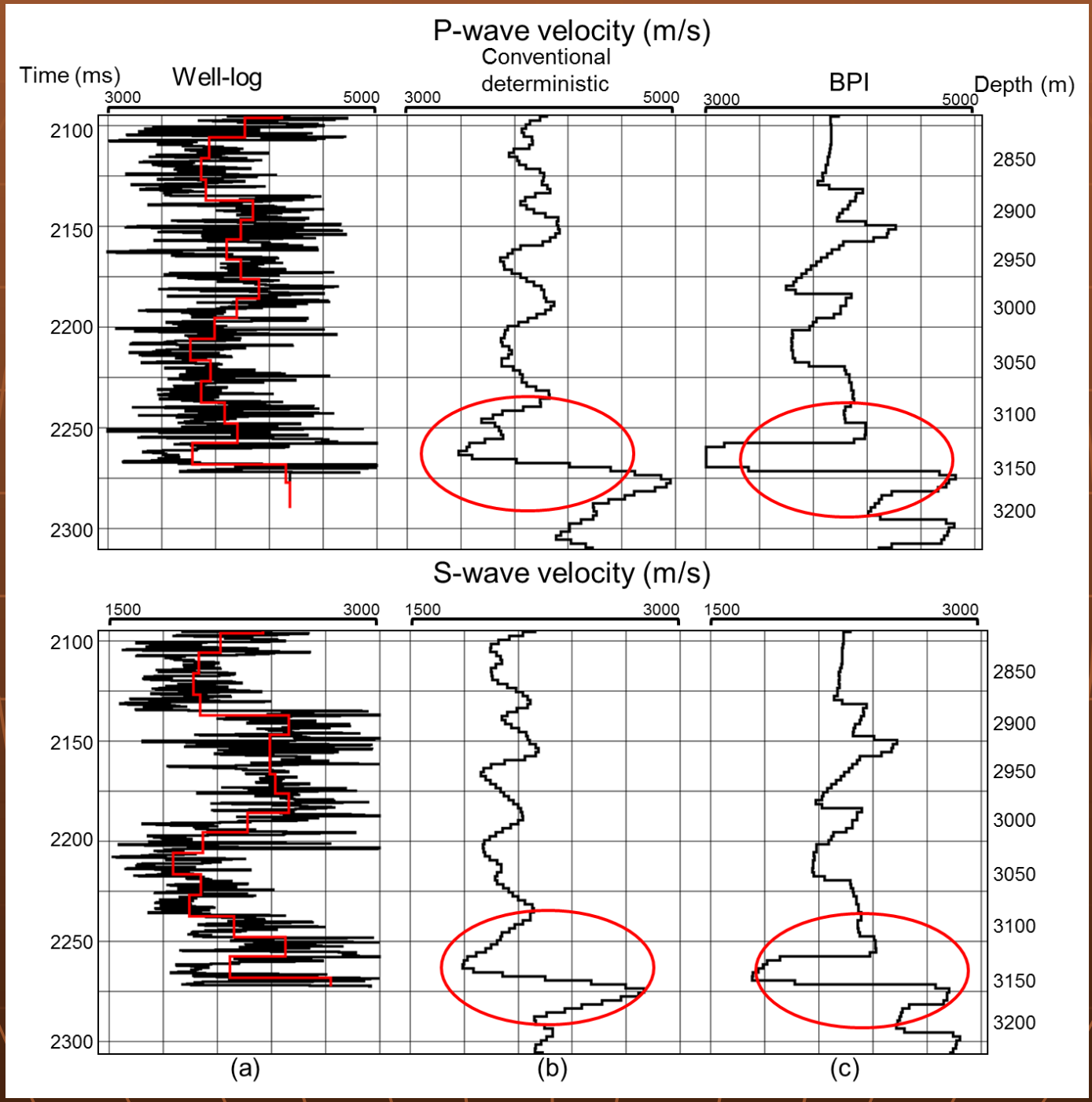


Inverted Velocity

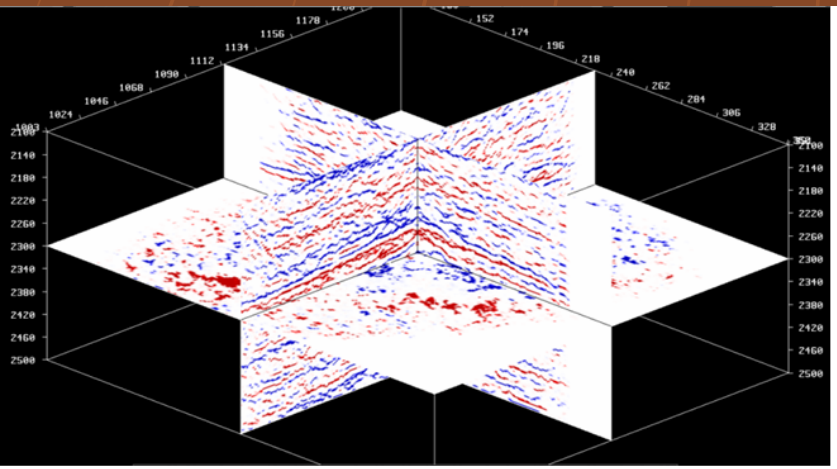


Inverted Velocity

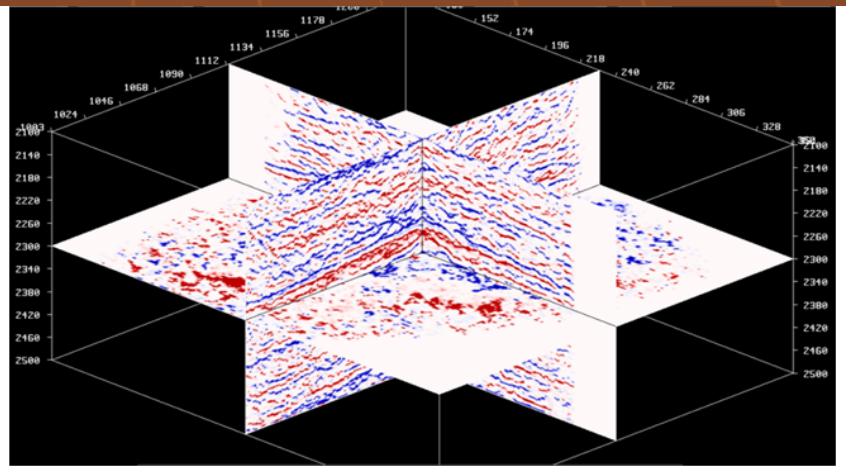



P-wave velocity (m/s)
Time (ms)
Well-log
Conventional deterministic
BPI
Depth (m)
3000
5000
2100
2150
2200
2250
2300
2850
2900
2950
3000
3050
3100
3150
3200
S-wave velocity (m/s)
1500
3000
(a)
(b)
(c)

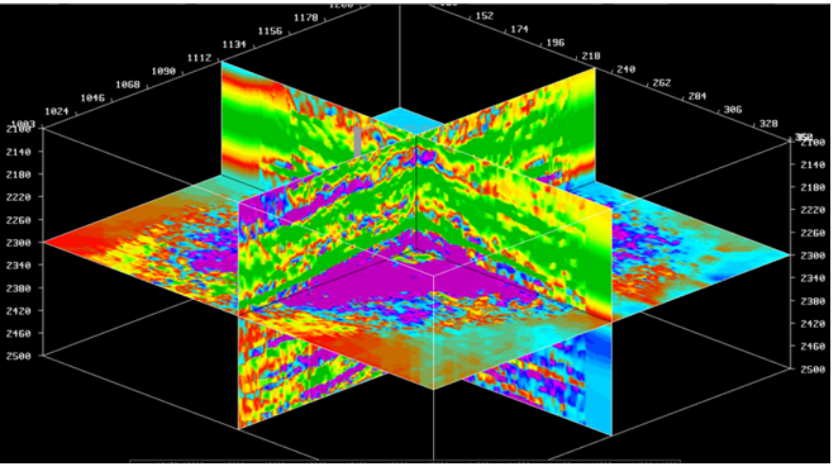
3D results



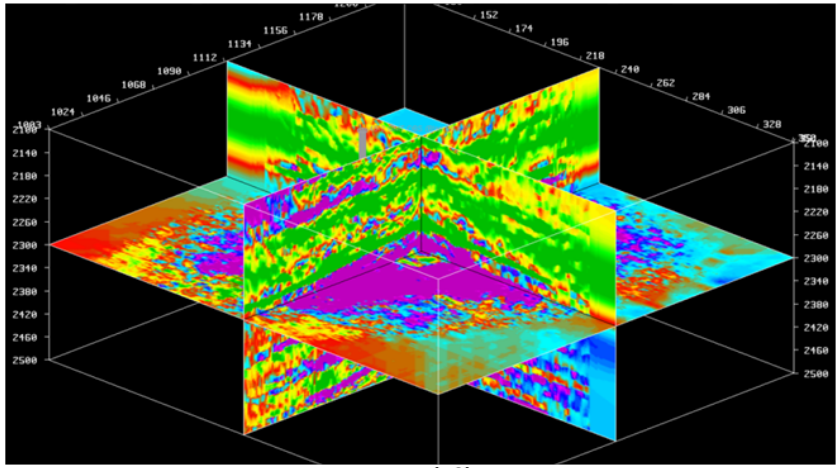
(a)



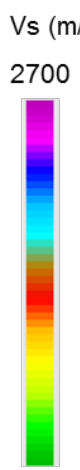
(b)



(c)



(d)



Discussions

- Perfect processing
- Offset-angle conversion
- Accommodation of non-stationary
- Angle range
- Pre-stack seismic well “tie”
- Initial model

Conclusions

- Spiky reflectivities Rp and Rs is initial model independent
- Blocky velocity Vp and Vs is initial model dependent
- Angle dependent wavelets can stabilize the results
- Two steps workflow can be QCed twice
- Blocky results enhance layer cake removing side lobes

Acknowledgements

- This work supported by Center for Frontiers of Subsurface Energy Security , an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0001114
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