Borehole reverse time migration for acoustic well logging data

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Outline

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- 3 Azimuthal detection near borehole structures by RTM
- 4 Borehole reverse time migration in VTI media

Introduction

- Great potential has been reviewed for acoustic reflection imaging logging to detect unconventional subtle reservoirs like fractures and vugs (Hornby 1989; Li et al. 2002; Tang et al,2003).
- Borehole reverse time migration is capable for delineating structures (vugs and fractures) outside well bore.
- Anisotropic borehole reverse time migration should be developed for imaging problems and positioning errors in anisotropic medium.
- For application in real acoustic data, main issue is how to determine the elastic parameters based on the well logging data.

RTM incorporating the borehole environment

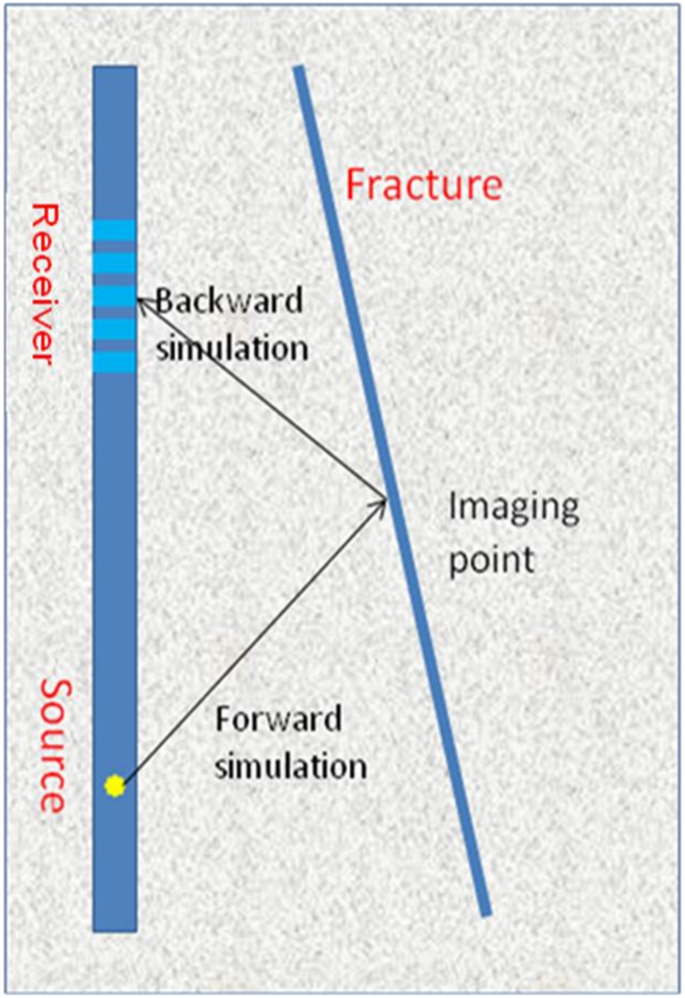
$$\frac{\partial \sigma_{xx}}{\partial t} = (\lambda + 2\mu)\frac{\partial V_x}{\partial x} + \lambda \frac{\partial V_z}{\partial z}$$

$$\frac{\partial \sigma_{zz}}{\partial t} = \lambda \frac{\partial V_x}{\partial x} + (\lambda + 2\mu)\frac{\partial V_z}{\partial z}$$

$$\frac{\partial \sigma_{xz}}{\partial t} = \mu \frac{\partial V_z}{\partial x} + \mu \frac{\partial V_x}{\partial z}$$

$$\rho \frac{\partial V_x}{\partial t} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z}$$

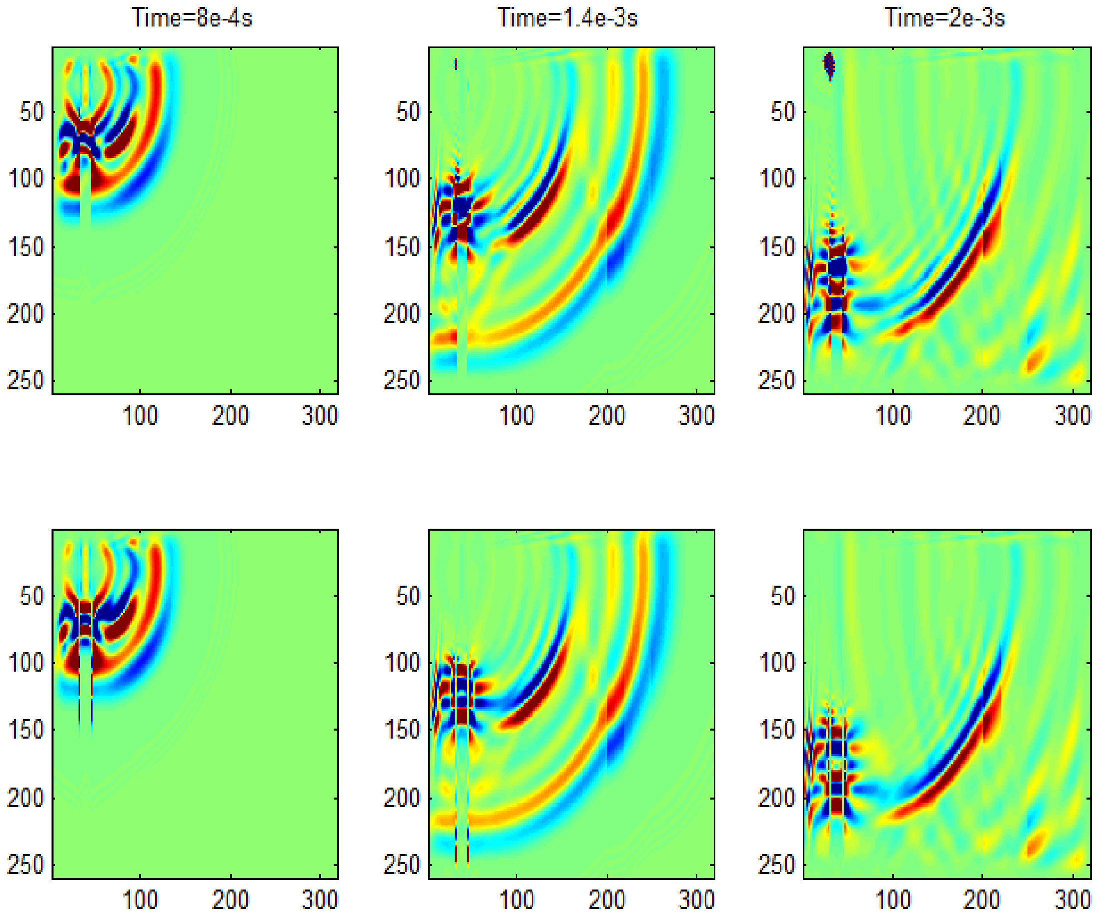
$$\rho \frac{\partial V_z}{\partial t} = \frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z}$$



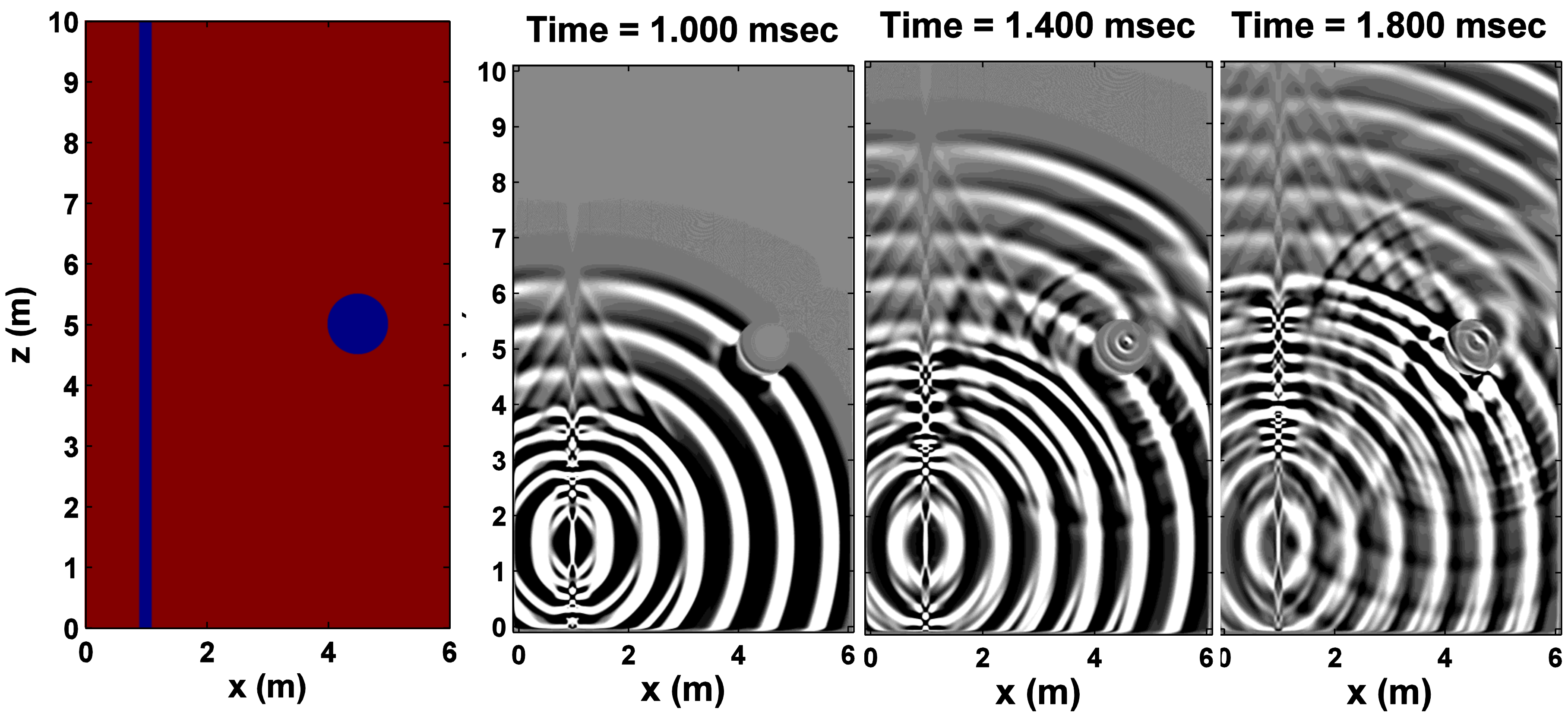
Problems: elastic parameters discontinuity between the borehole and formation

- Harmonic average
- equation:

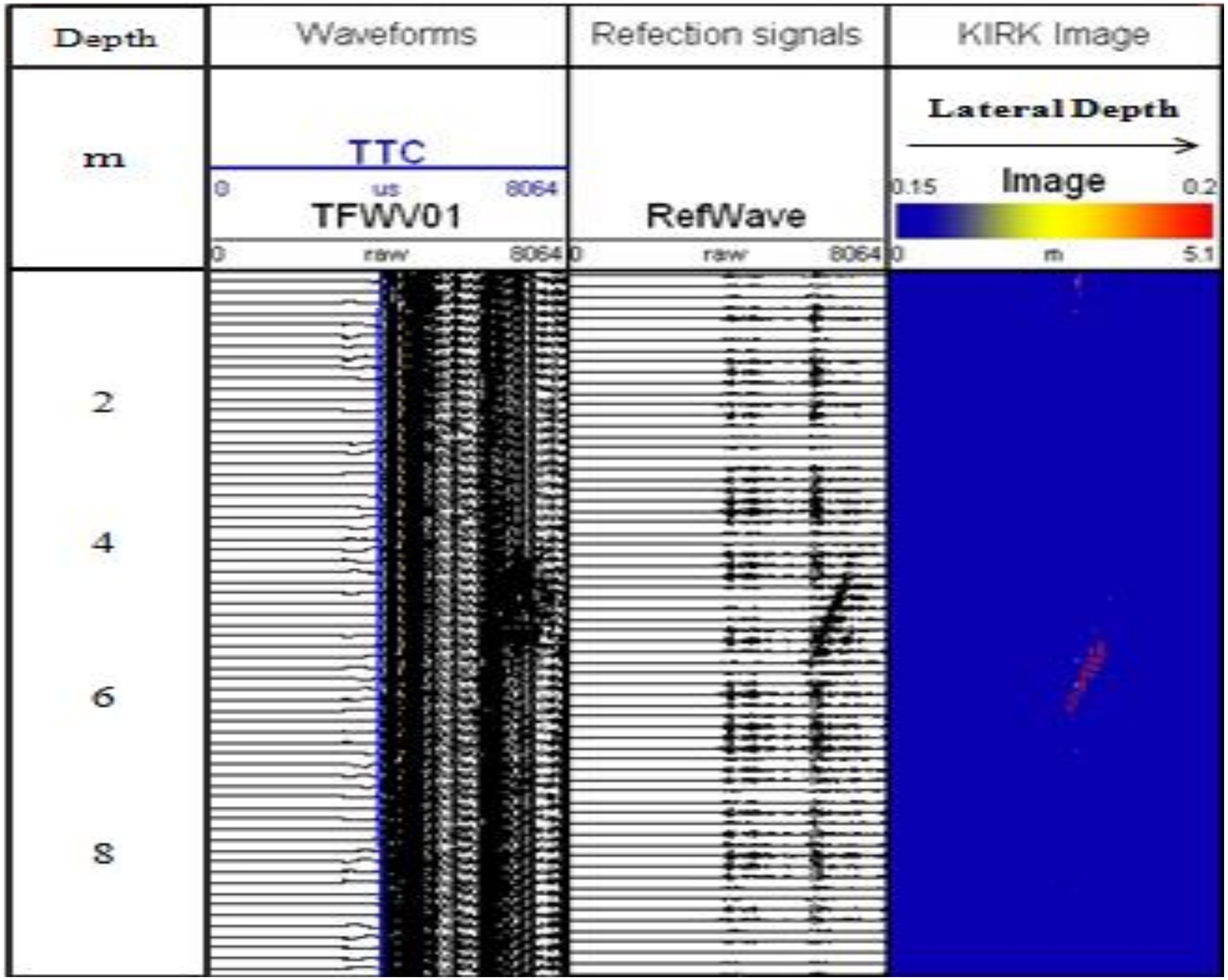
$$\frac{4}{C_{44|m,n}} = \frac{1}{C_{44|m+1/2,n+1/2}} + \frac{1}{C_{44|m-1/2,n+1/2}} + \frac{1}{C_{44|m+1/2,n-1/2}} + \frac{1}{C_{44|m-1/2,n-1/2}}$$

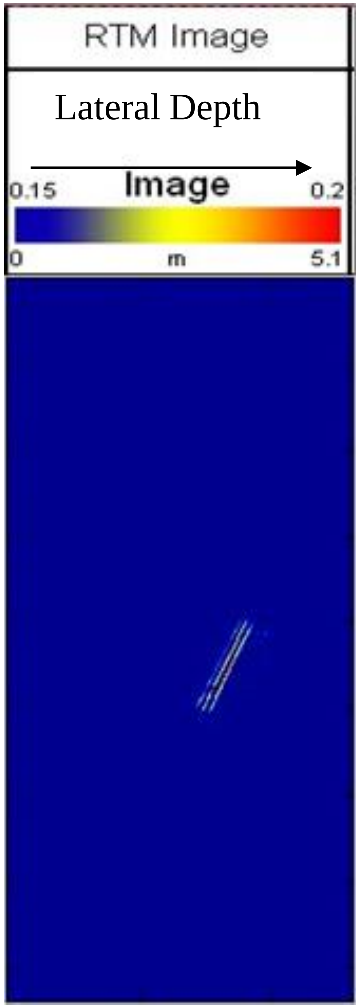


Benchmarks

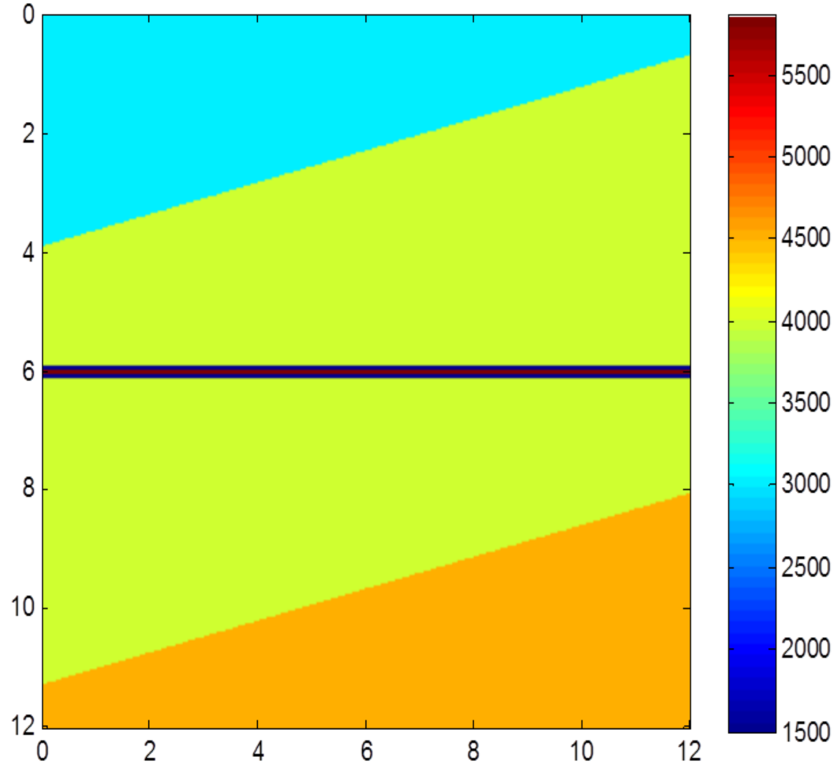

Time = 1.000 msec
Time = 1.400 msec
Time = 1.800 msec
z (m)
x (m)
x (m)
x (m)
x (m)
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6

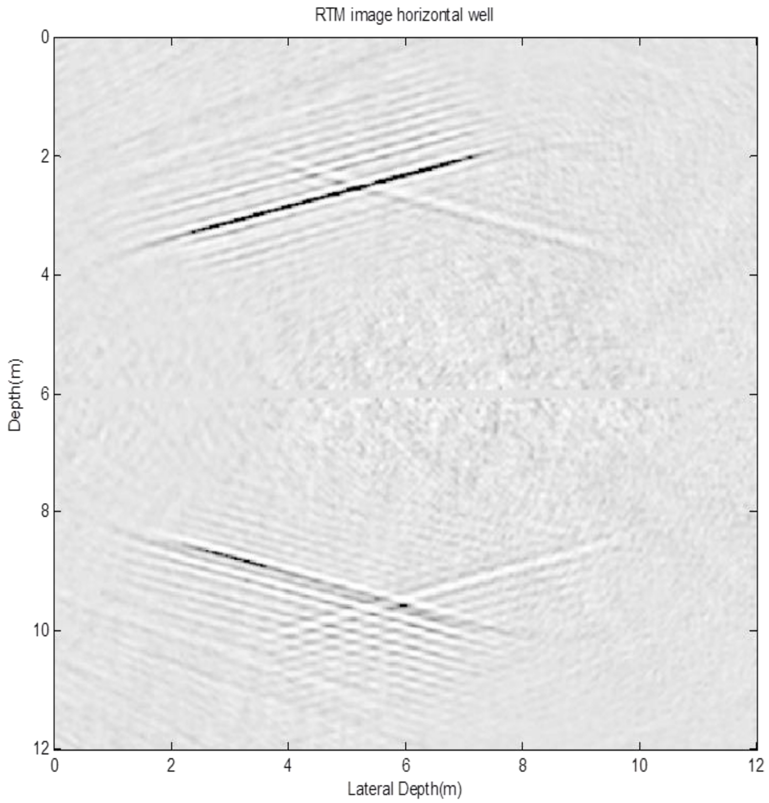
Data from laboratory water tank





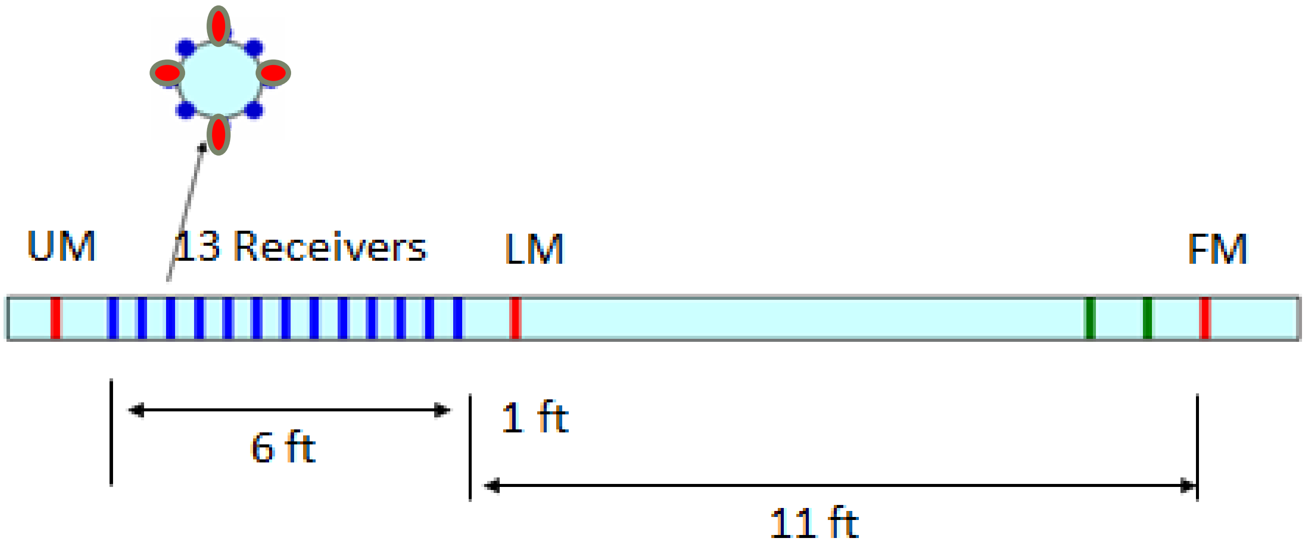
Question ?





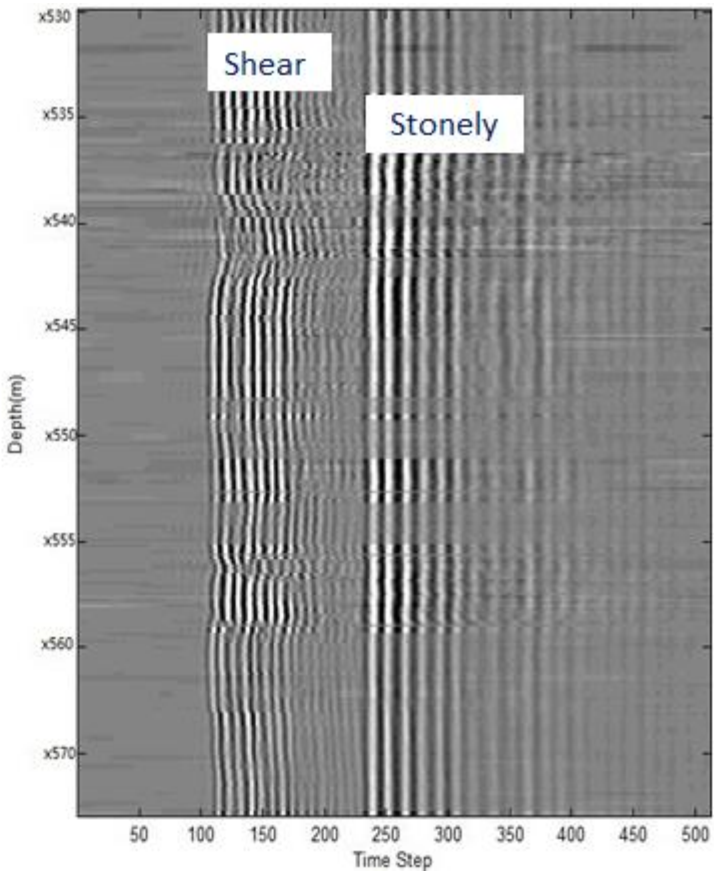
Azimuthal detection near borehole structures by RTM

Schematic of the Sonic Scanner tool



Schematic of the Sonic Scanner tool used for acquiring the data

Field data example from western China



The signal received at 0 degree in azimuth and 10.75 ft offset from the transmitter in the FM system.
The sampling interval of the system is 10 μs and the depth interval is 0.1524 m.

The primary shear and Stoneley energy can be clearly seen in this figure. The compressional energy can't be observed because its amplitude is much smaller than shear and Stoneley energy.

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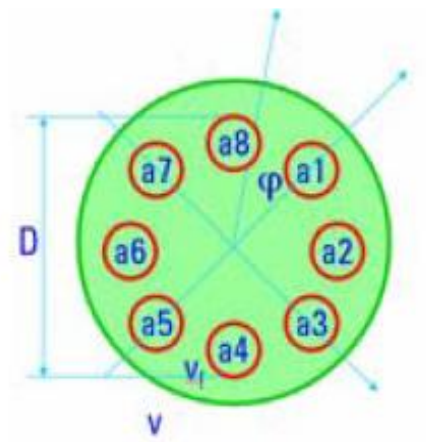
Adaptive Block-Frost beam former(Meehan et al., 1998)



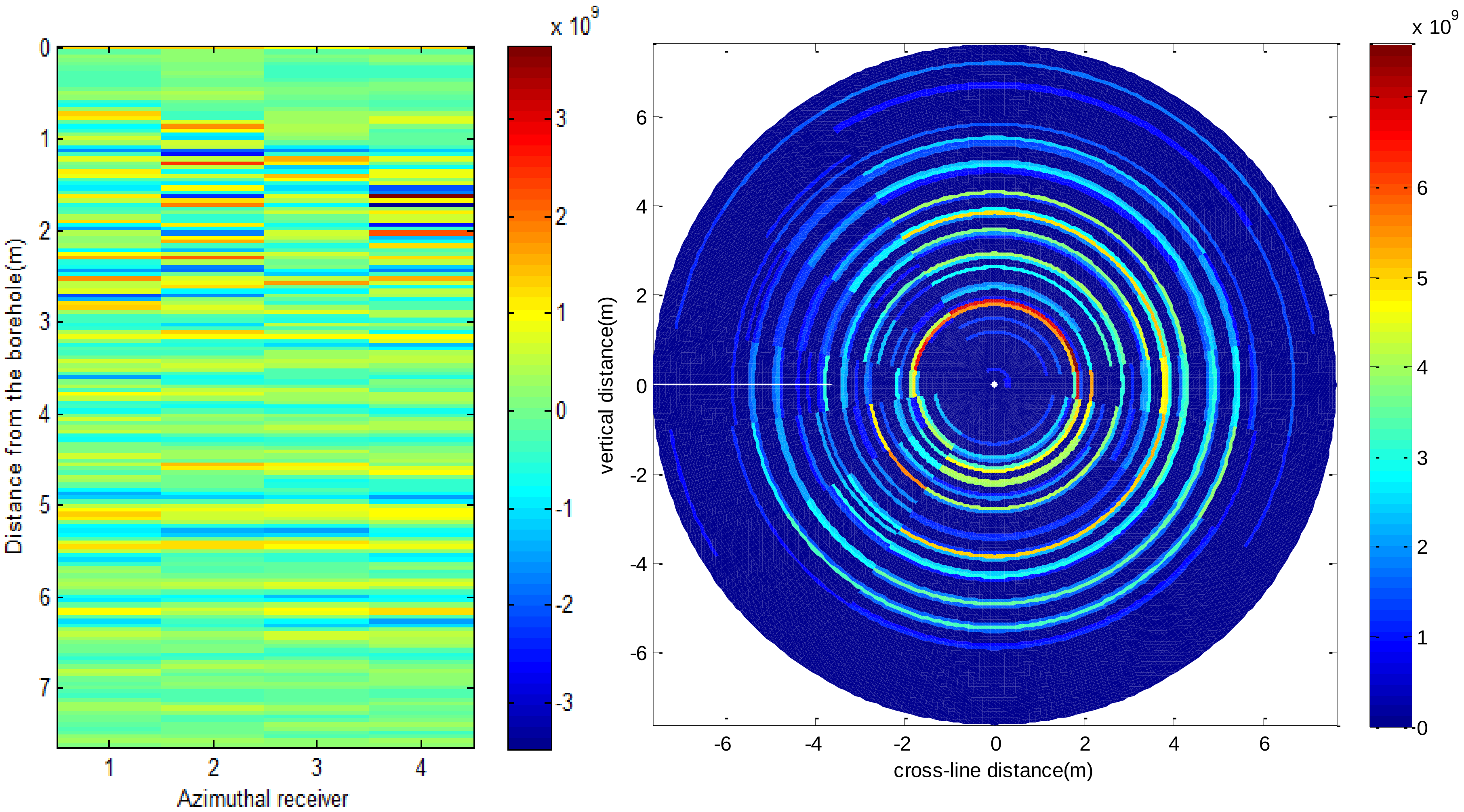
$$\Delta_{a1} = -\frac{D}{2}\cos\varphi$$
$$\Delta_{a2} = -\frac{D}{2}\cos(\varphi+\frac{\pi}{4})$$
$$\Delta_{a3} = -\frac{D}{2}\sin\varphi$$
$$\Delta_{a4} = -\frac{D}{2}\cos(\varphi+\frac{3\pi}{4})$$

$$\Delta_{a5} = \frac{D}{2}\cos\varphi$$
$$\Delta_{a6} = \frac{D}{2}\cos(\varphi+\frac{\pi}{4})$$
$$\Delta_{a7} = \frac{D}{2}\sin\varphi$$
$$\Delta_{a8} = \frac{D}{2}\cos(\varphi+\frac{3\pi}{4})$$

D: tool diameter
φ : azimuth around the borehole relative to receiver a1
Δ : Spatial shift

$$I_j(r,\varphi) = \frac{1}{N_r}\min_w \sum_{n=1}^{N_r}\left(I_{j,n}(r_n+\Delta_n(\varphi)) + \sum_{l=-L}^{+L} w_{l,n} I_{j+1,n}(r_n+\Delta_n(\varphi))\right)$$

Azimuthal Imaging around X560



Borehole RTM in VTI media

$$\rho \frac{\partial v_x}{\partial t} = \frac{\partial \tau_{xx}}{\partial \tau_x} + \frac{\partial \tau_{xz}}{\partial \tau_z}$$

$$\rho \frac{\partial v_z}{\partial t} = \frac{\partial \tau_{xz}}{\partial \tau_x} + \frac{\partial \tau_{zz}}{\partial \tau_z}$$

$$\frac{\partial \tau_{xx}}{\partial t} = C_{11} \frac{\partial v_x}{\partial x} + C_{13} \frac{\partial v_z}{\partial z}$$

$$\frac{\partial \tau_{zz}}{\partial t} = C_{13} \frac{\partial v_x}{\partial x} + C_{33} \frac{\partial v_z}{\partial z}$$

$$\frac{\partial \tau_{zx}}{\partial t} = C_{44} \frac{\partial v_x}{\partial x} + C_{44} \frac{\partial v_z}{\partial z}$$

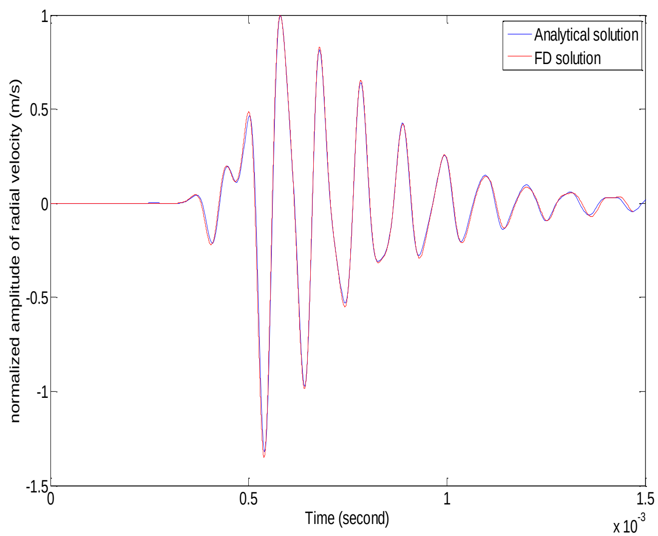
ρ : density

v_x, v_z : velocities in x and z direction

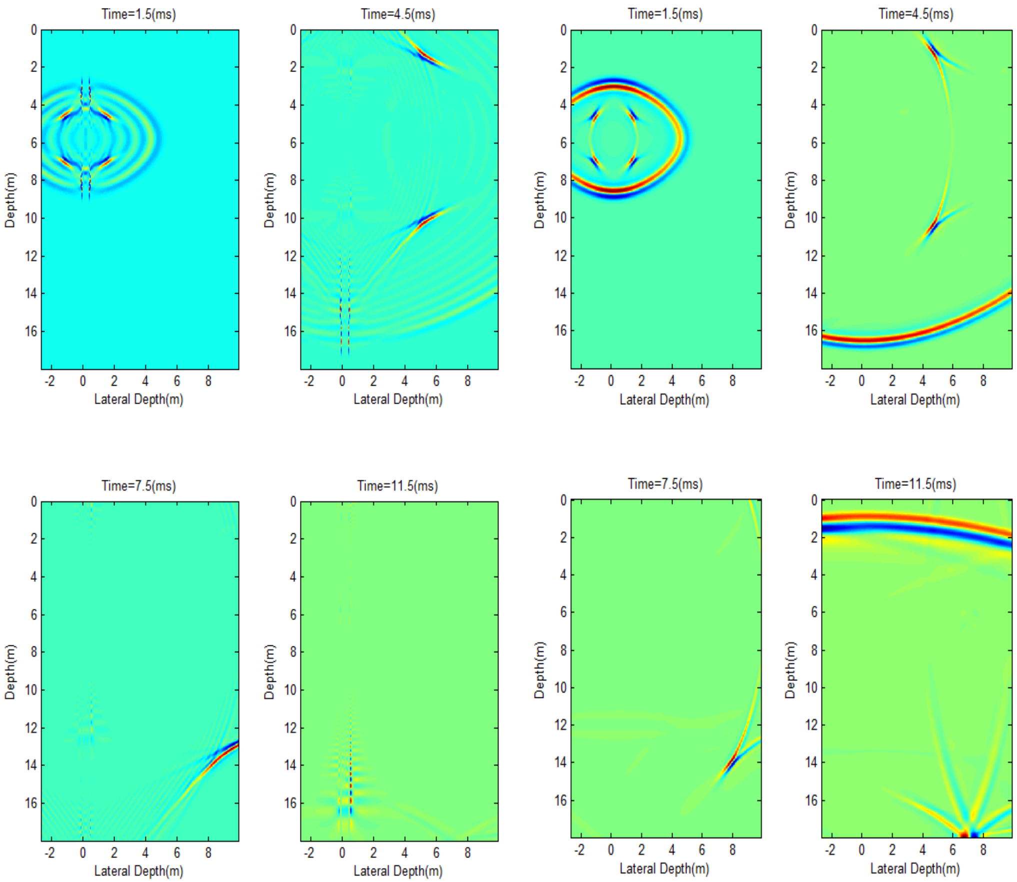
τ_{xx}, τ_{zz} : normal stress components

τ_{xz} : shear stress component

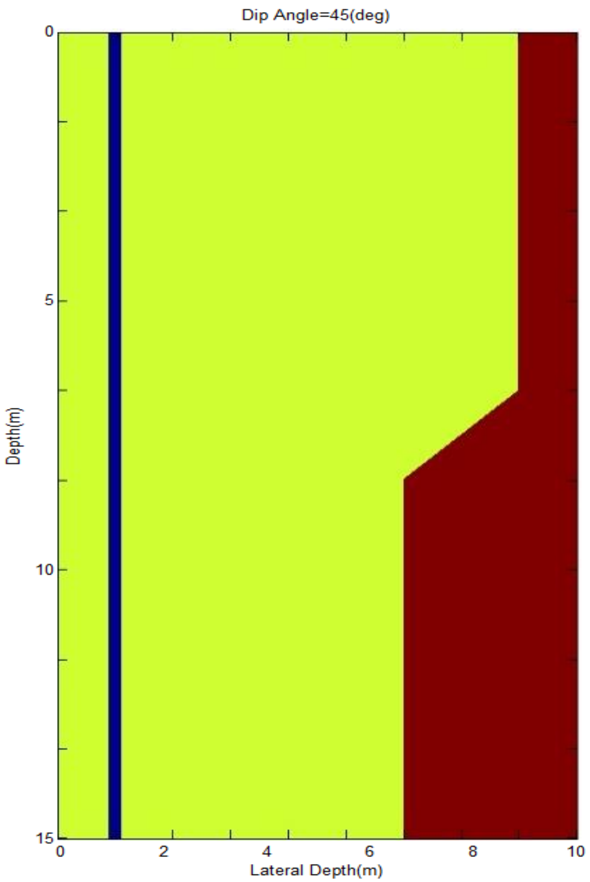
Benchmarks



Benchmark of finite difference solution with analytical solution



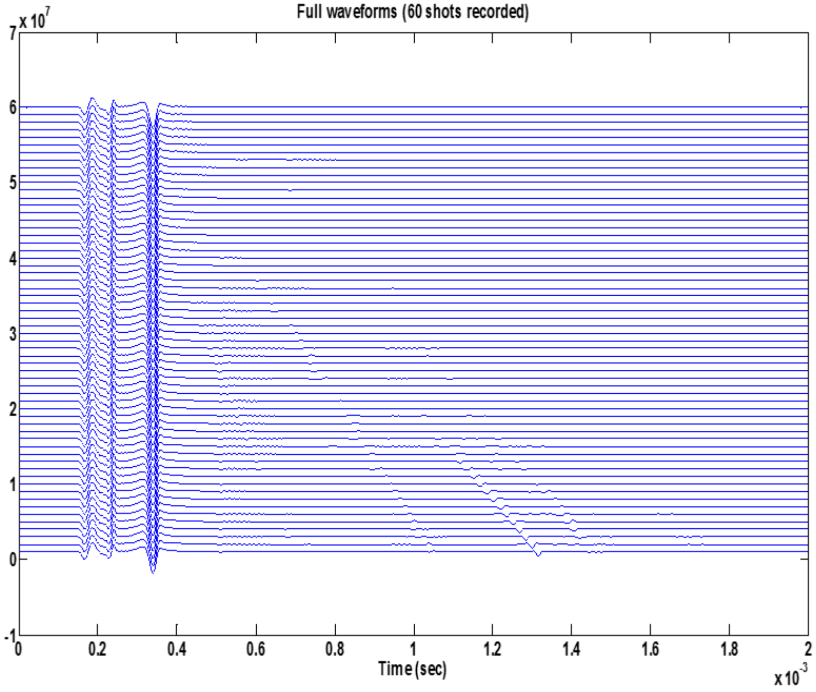
Synthetic data processing

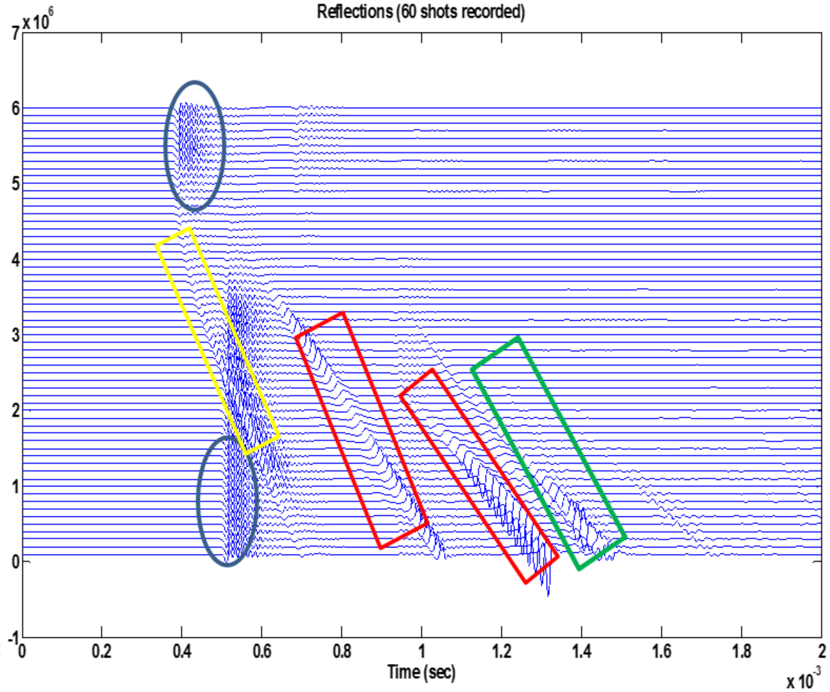


	C11	C13	C33	C44	P(g/cm^3)
Yellow	23.87	9.79	15.33	2.77	2.5
Bore hole	1.5^2	1.5^2	1.5^2	0	1
Red	40	13.55	40	13.225	2.5

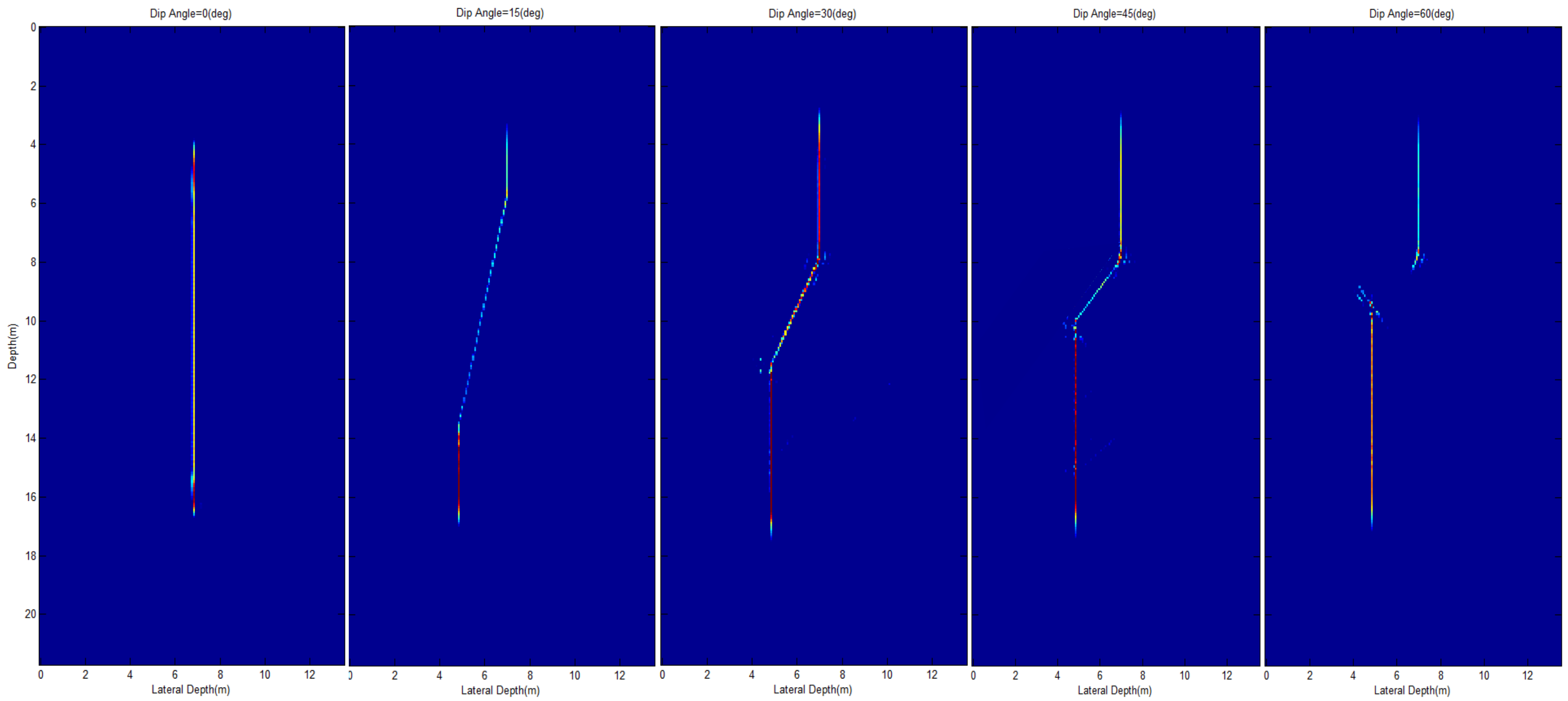
SR spacing: 3 m
RR spacing: 0.1524 m
Receiver numbers: 13
Time sample: 1e-6 sec

Recorded full waveform and correspondent reflection signals





Imaging results of Synthetic data



Long wavelength equivalent method in borehole environment

$$\gamma_i = vs_i^2 / vp_i^2$$

$$C_{44} = <\mu^{-1}>^{-1}$$

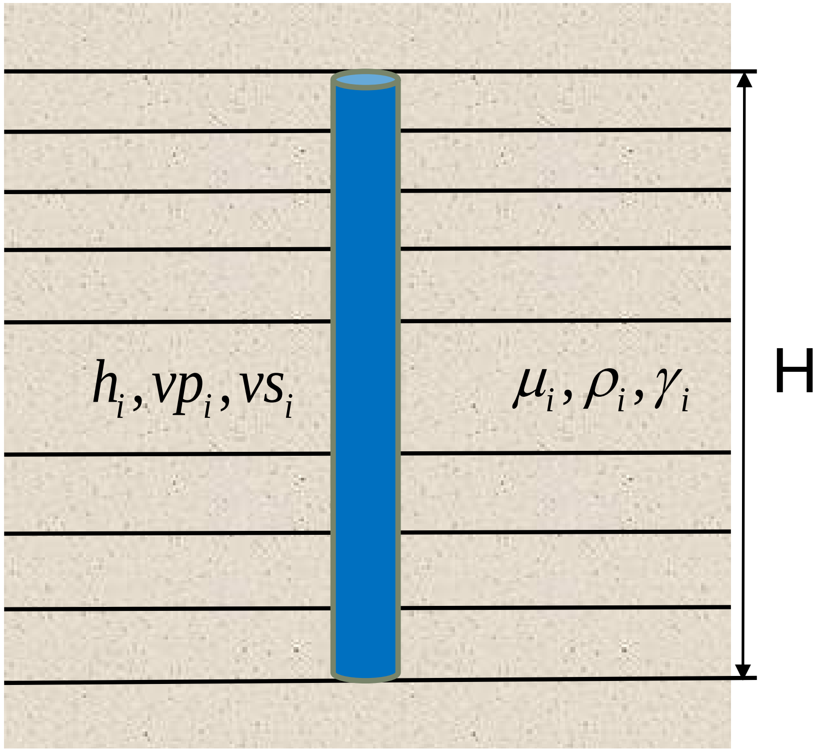
$$C_{66} = <\mu>$$

$$C_{33} = <\gamma/\mu>^{-1}$$

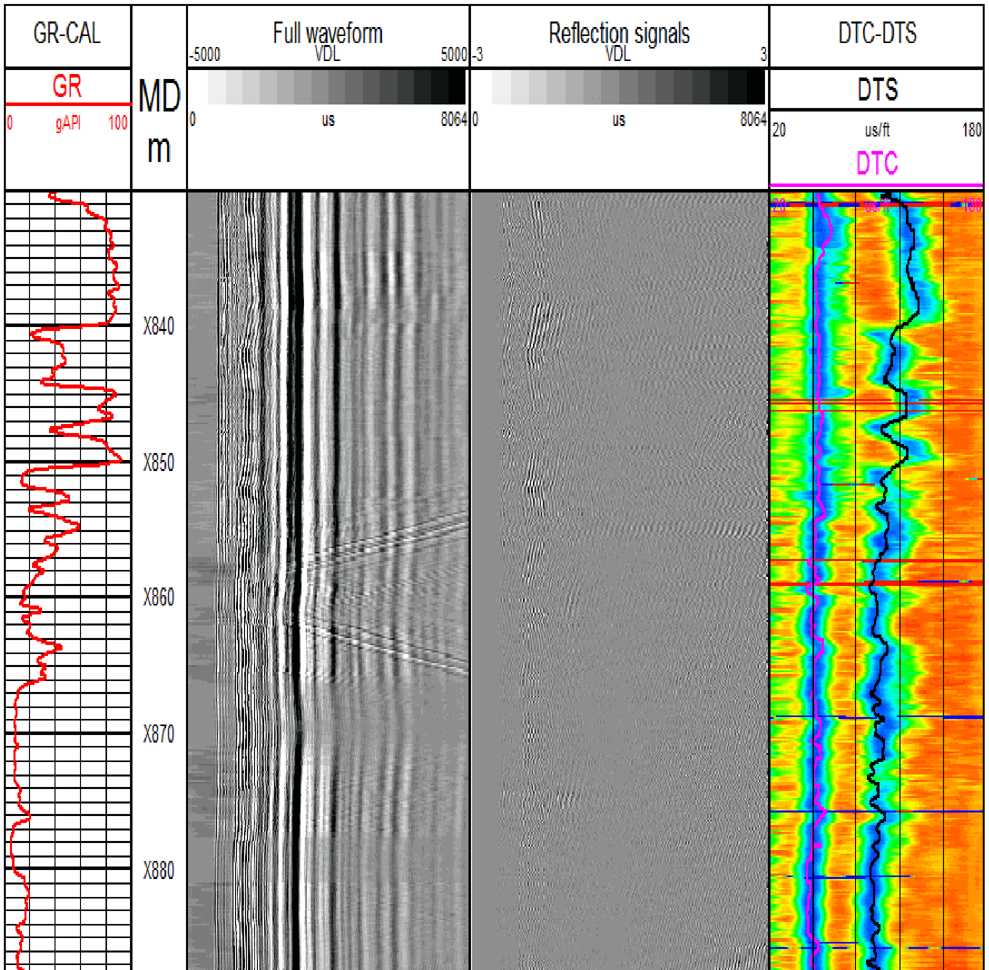
$$C_{13} = (1-2<\gamma>)<\gamma/\mu>^{-1}$$

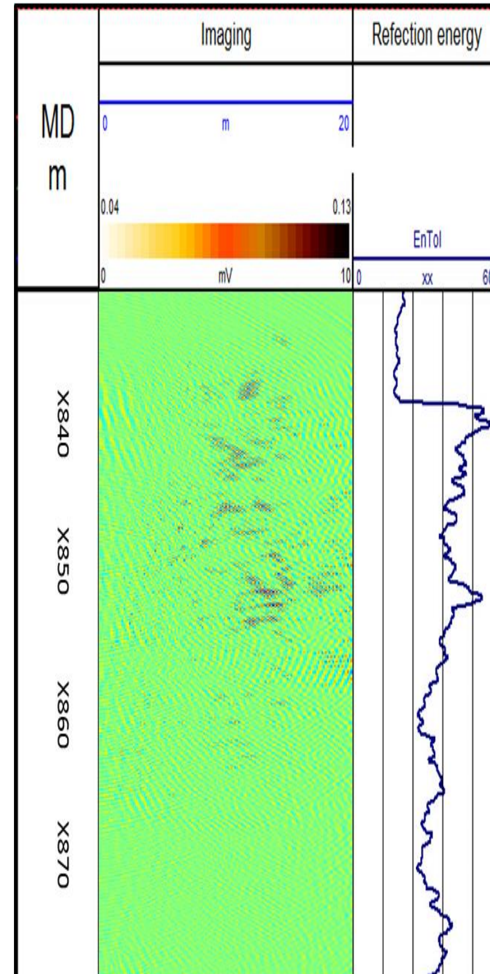
$$C_{11} = 4<\mu> - 4<\gamma\mu> + (1-2<\gamma>)^2 <\gamma/\mu>^{-1}$$

$$<\mu> = \frac{1}{H}\sum h_i H \mu_i$$



Real borehole data from East Aisa





Conclusions

- Borehole RTM is proposed to detect near borehole structures.

- Harmonic average equation is applied to solve the elastic parameters discontinuity between the borehole and formation.

- Azimuthal data received by directional receivers can be applied to get azimuthal information of near borehole structures.

- Long wavelength equivalent method is used in borehole real data to determine the elastic parameters.

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Questions & Comments