The seismic physical modelling laboratory as a tool for design and appraisal of FWI methods

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Kristopher Innanen

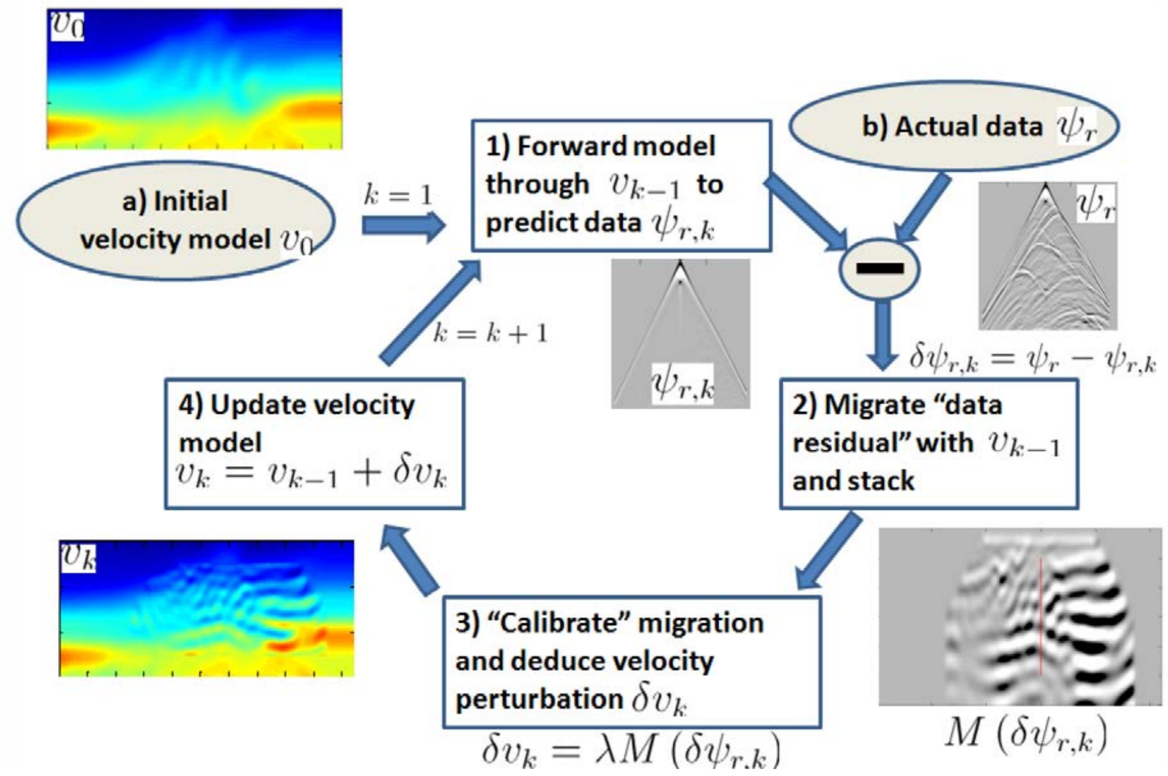
Nov - 2017

Outline

- Introduction
  - The cycle of FWI
  - FWI vs IMMI
  - CREWES physical modelling laboratory facility
- Physical modelling data
- Data conditioning
  - Directivity correction
  - Changing-waveform correction
  - Geometrical spreading
  - Low frequency noise
- Wavelet estimation
- Inversion of physical modelling data
- Conclusions

The cycle of full waveform inversion

$$\delta v(x,z) = \lambda \nabla_v \phi_k(x,z,w) = \lambda \int \sum_{s,r} \omega^2 \hat{\Psi}_s(x,z,\omega)\delta\hat{\Psi}^*_{r(s),k}(x,z,\omega)d\omega$$



Margrave et al., 2010

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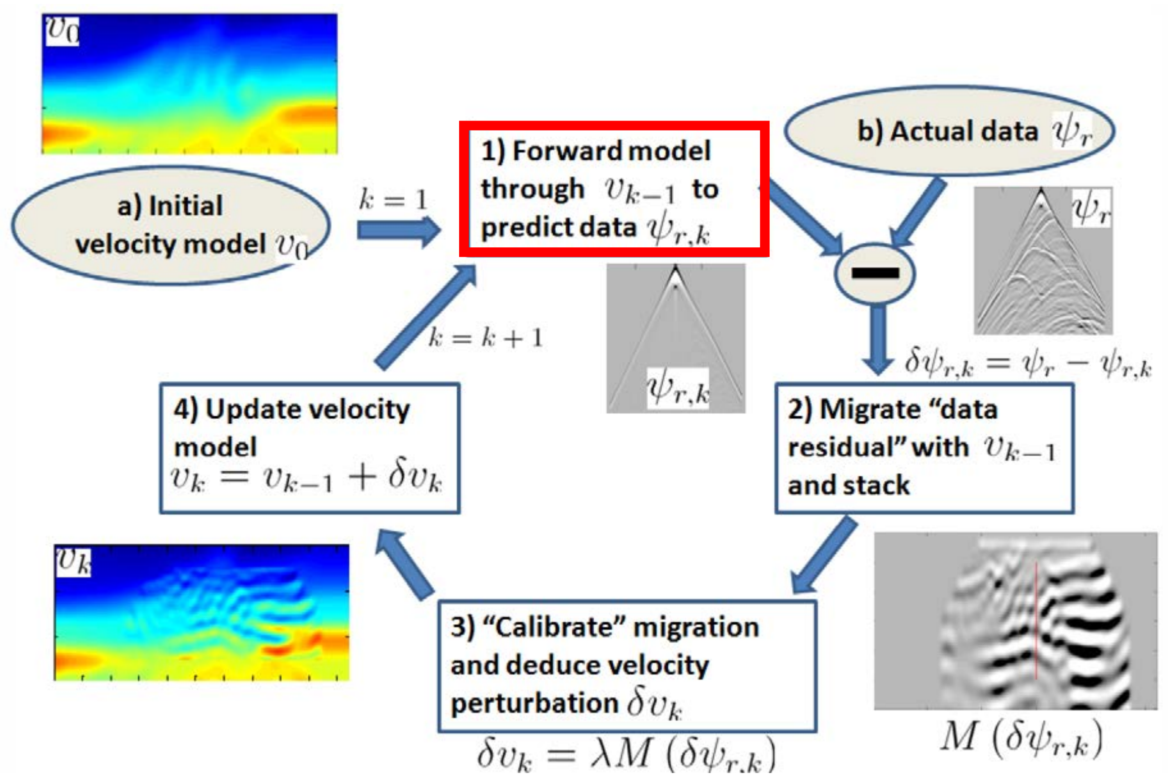

$$\phi_k = \sum_{s,r}(\Psi - \Psi_k)^2$$

Margrave et al., 2010

The cycle of full waveform inversion

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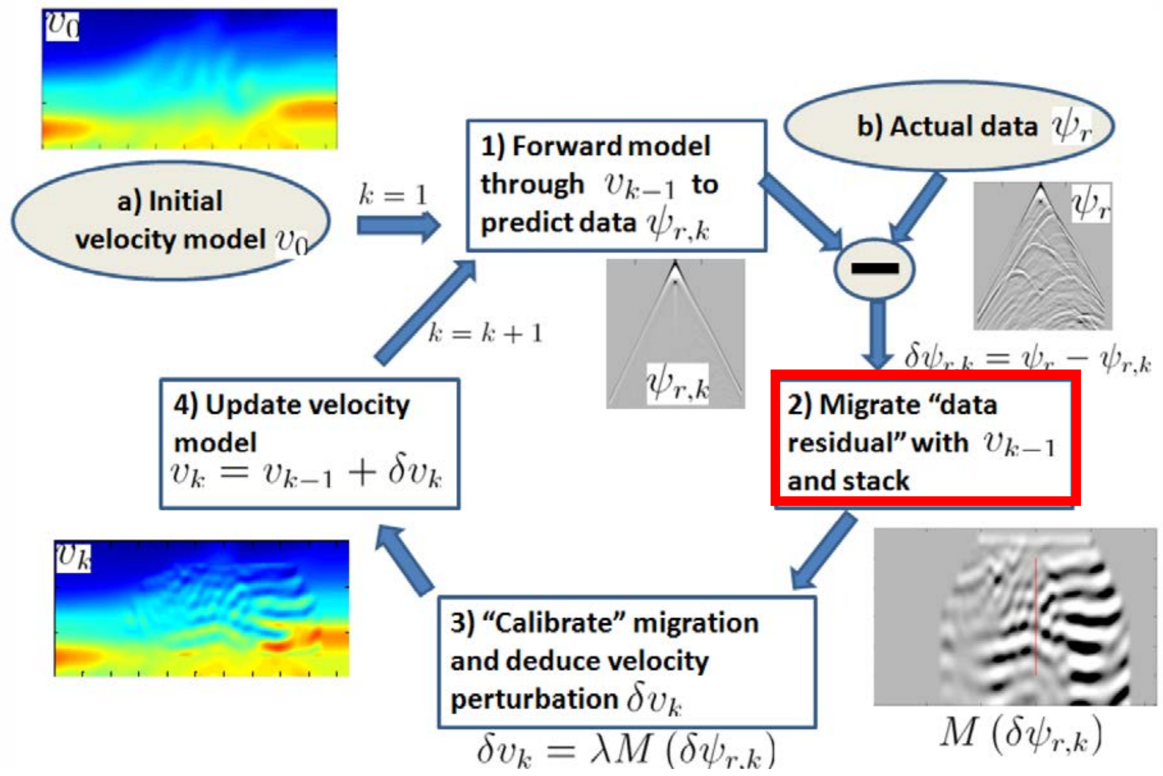

Margrave et al., 2010

The cycle of full waveform inversion

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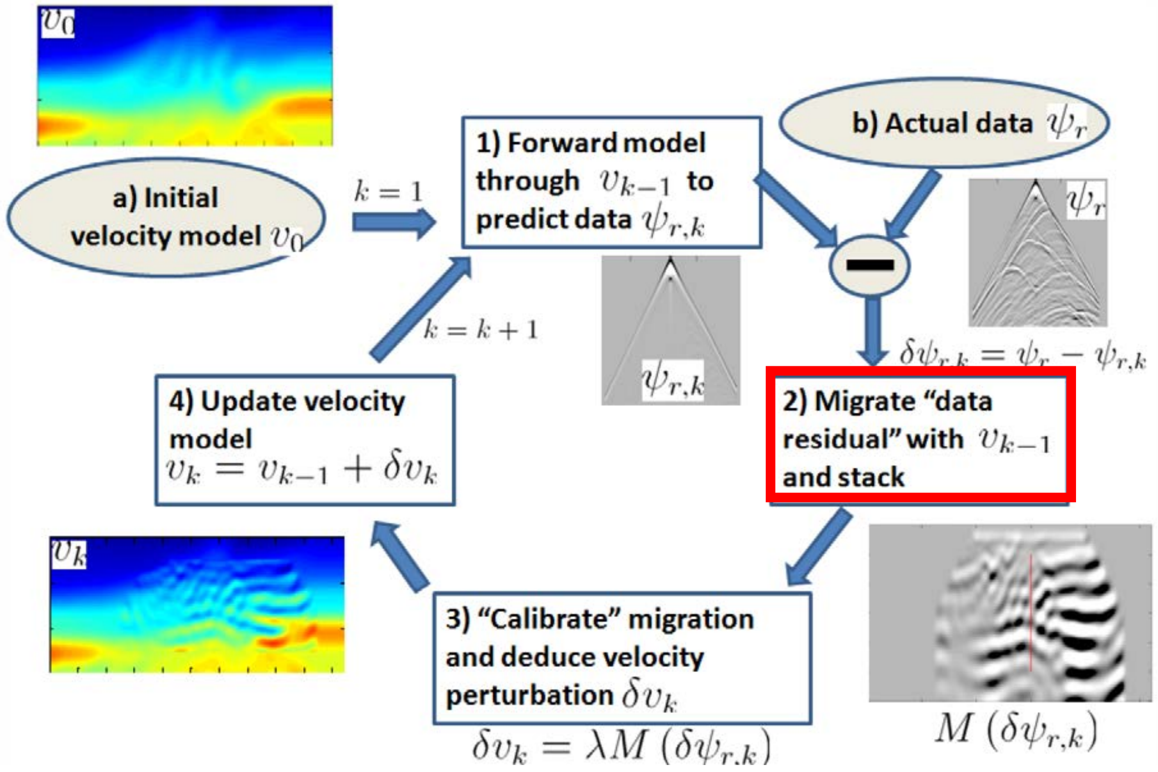
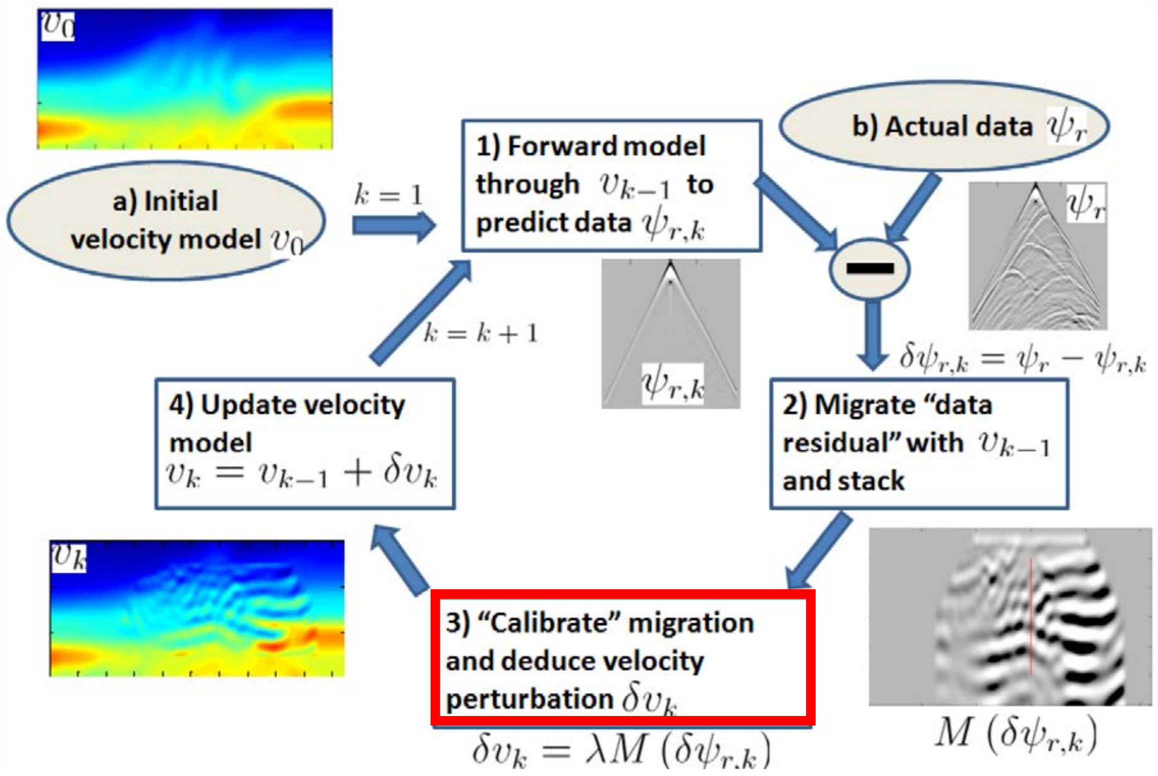


- Standard FWI uses RTM
- IMMI proposes the use of any kind of migration: PSPI

Margrave et al., 2010

The cycle of full waveform inversion

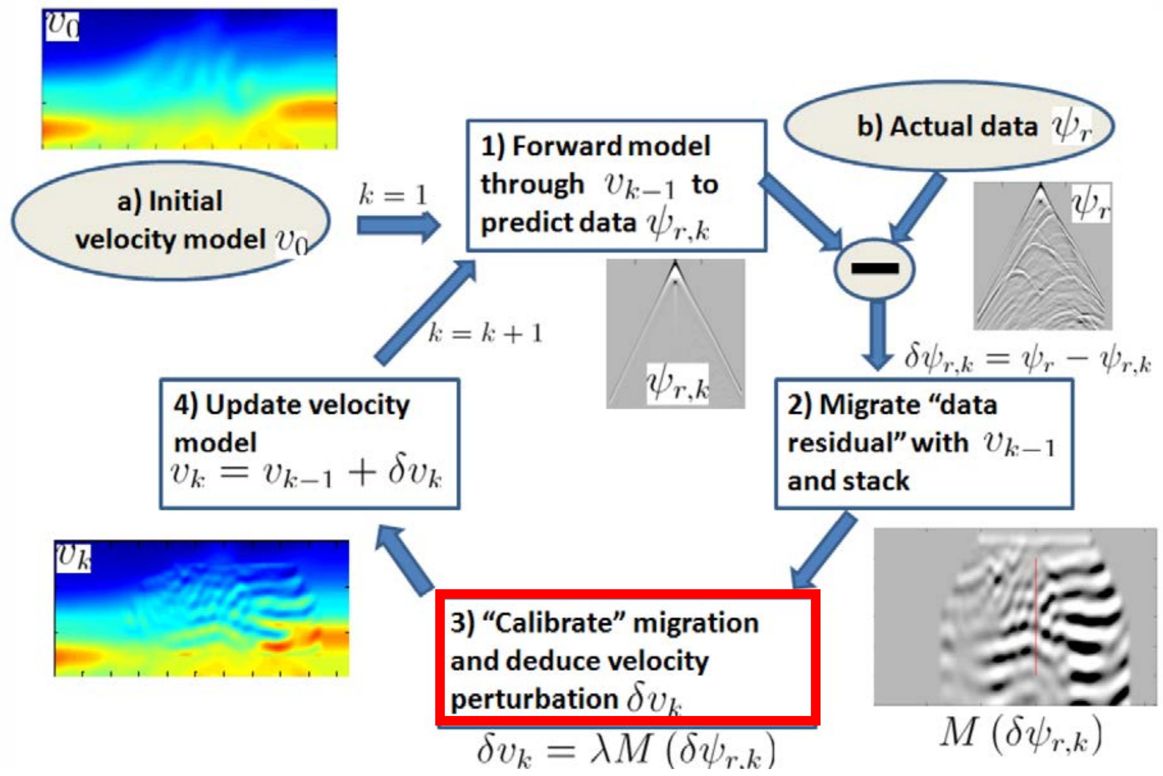
$$\delta v(x,z) = \lambda \nabla_v \phi_k(x,z,w) = \lambda \int \sum_{s,r} \omega^2 \hat{\Psi}_s(x,z,\omega) \delta \hat{\Psi}^*_{r(s),k}(x,z,\omega) d\omega$$



Margrave et al., 2010

The cycle of full waveform inversion

$$\delta v(x,z) = \lambda \nabla_v \phi_k(x,z,w) = \lambda \int \sum_{s,r} \omega^2 \hat{\Psi}_s(x,z,\omega)\,\delta\hat{\Psi}^*_{r(s),k}(x,z,\omega)\,d\omega$$



- FWI uses the inverse Hessian matrix or the step-length method
- IMMI incorporates well –log information to calibrate the gradient

Margrave et al., 2010

The cycle of full waveform inversion

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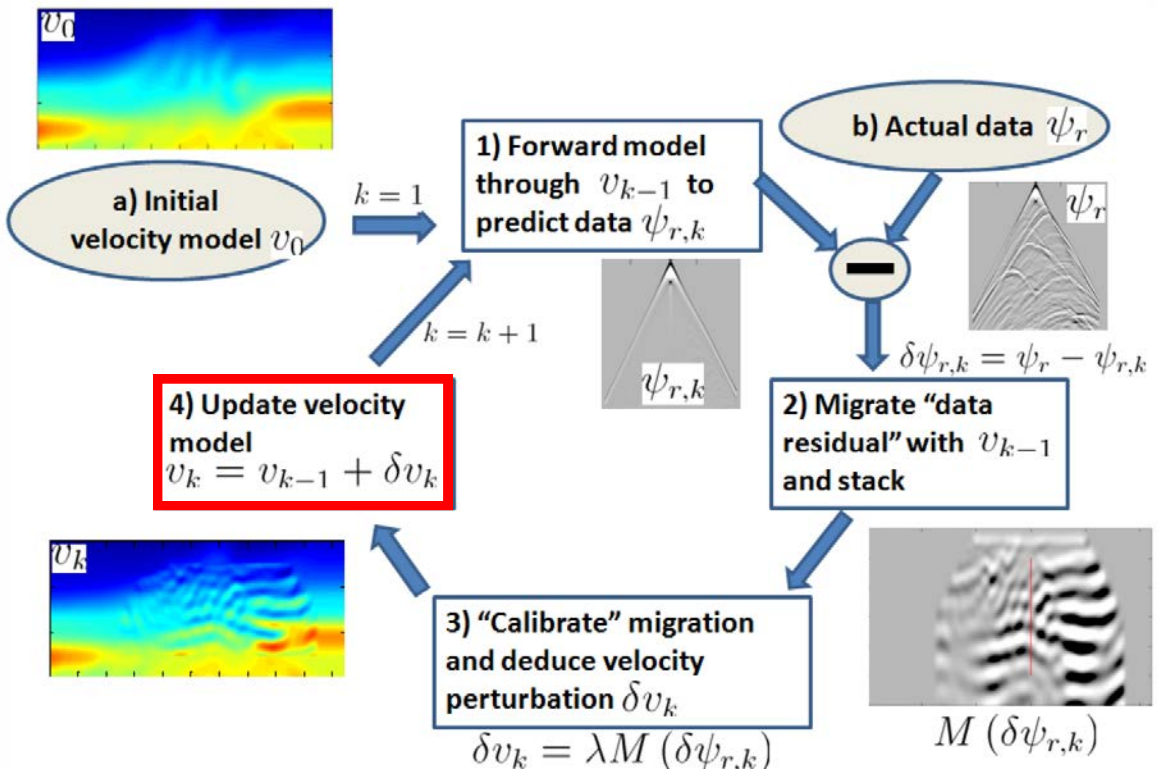
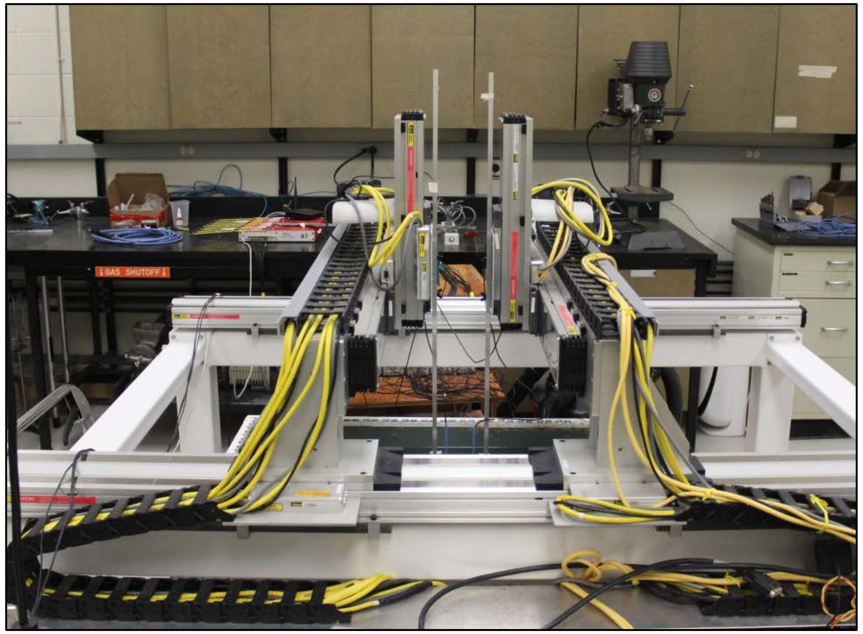


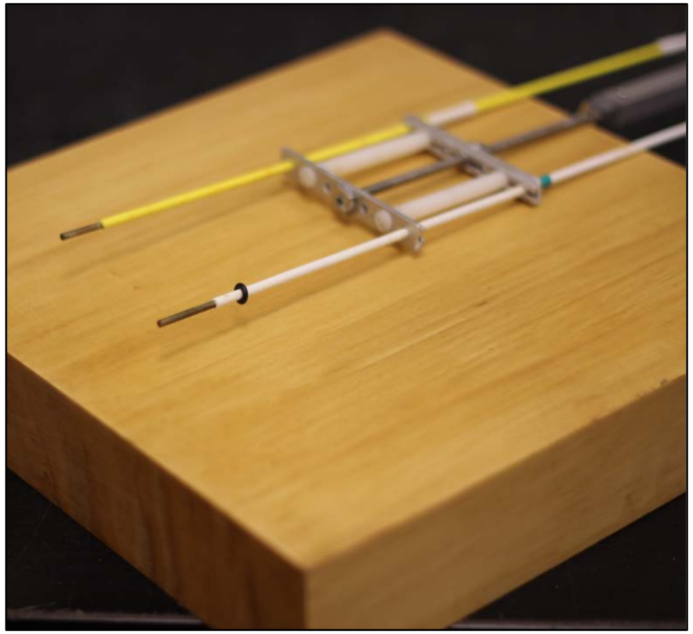
Margrave et al., 2010

Physical modelling laboratory

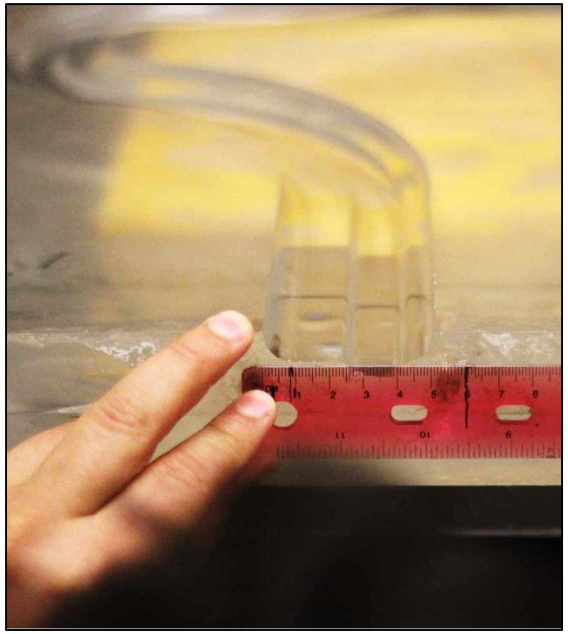
CREWES laboratory



Transducers



Acrylic slab with channel



- We can control and vary many acquisition parameters
- We know the subsurface model that we want to solve; therefore, we can monitor model errors almost exactly
- Physical modelling represents a potentially unique way of validating and appraising complex methods involving real measurements of seismic waveforms

From laboratory to real world scale

Distance	1 : 10000	1 mm = 10 m
Frequency	10000 : 1	10 kHz = 1 Hz

Photographs courtesy of Kevin Bertram.

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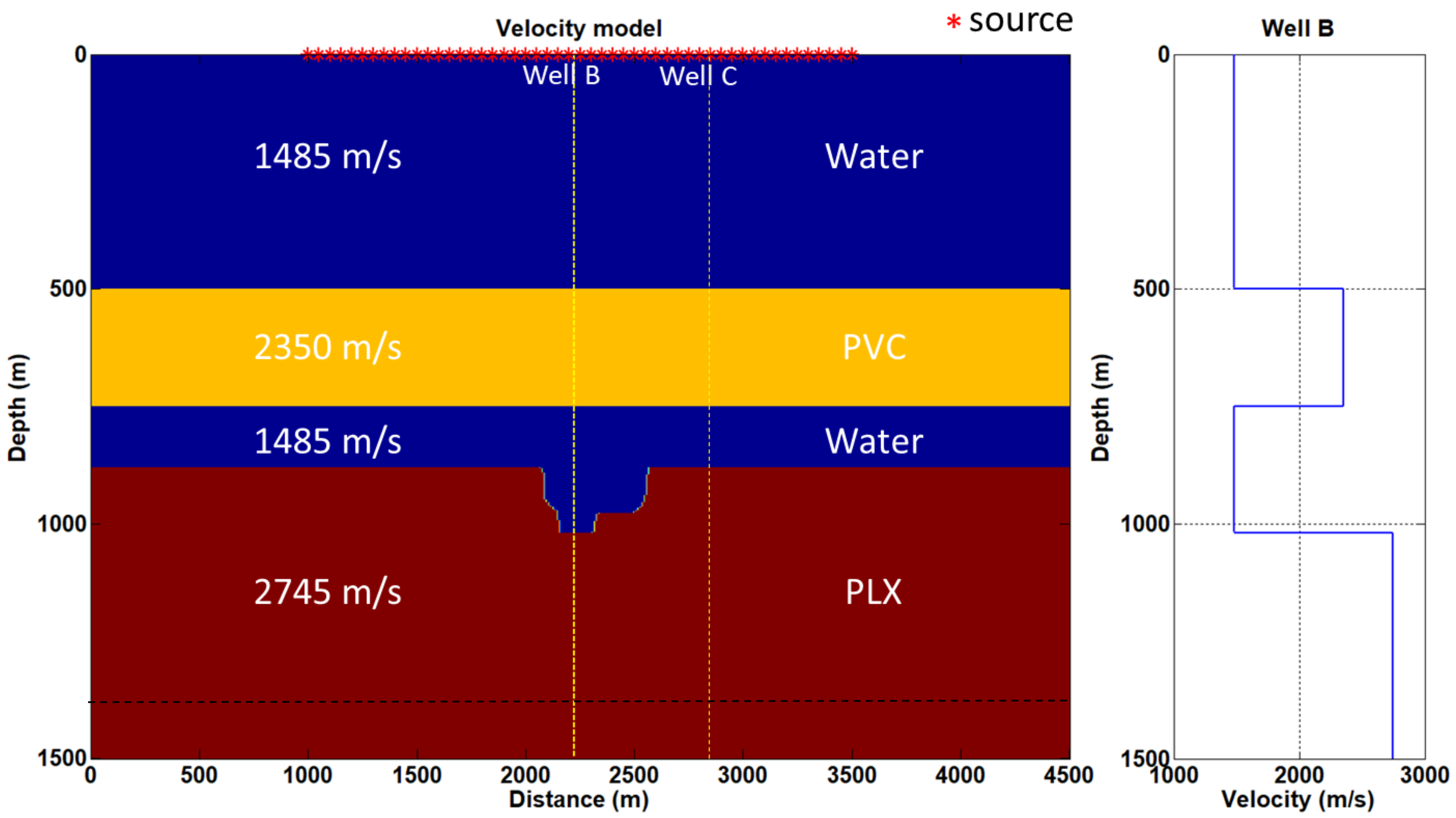
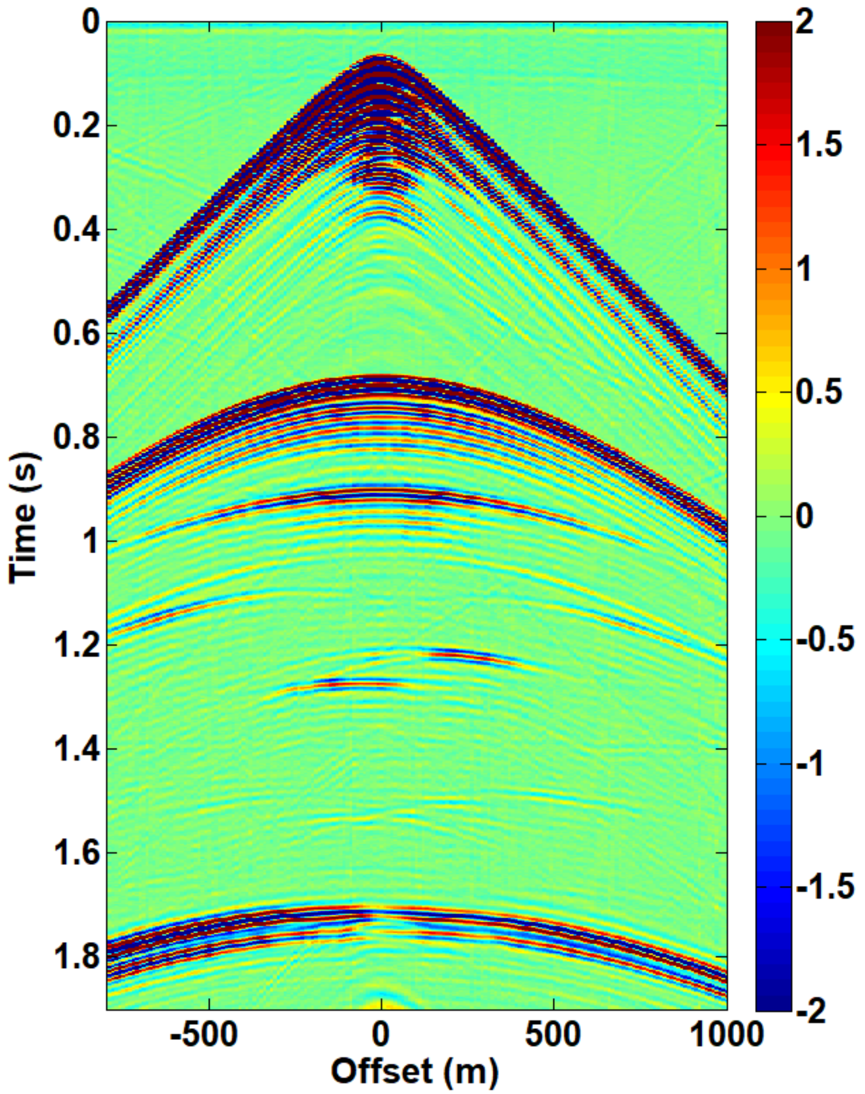
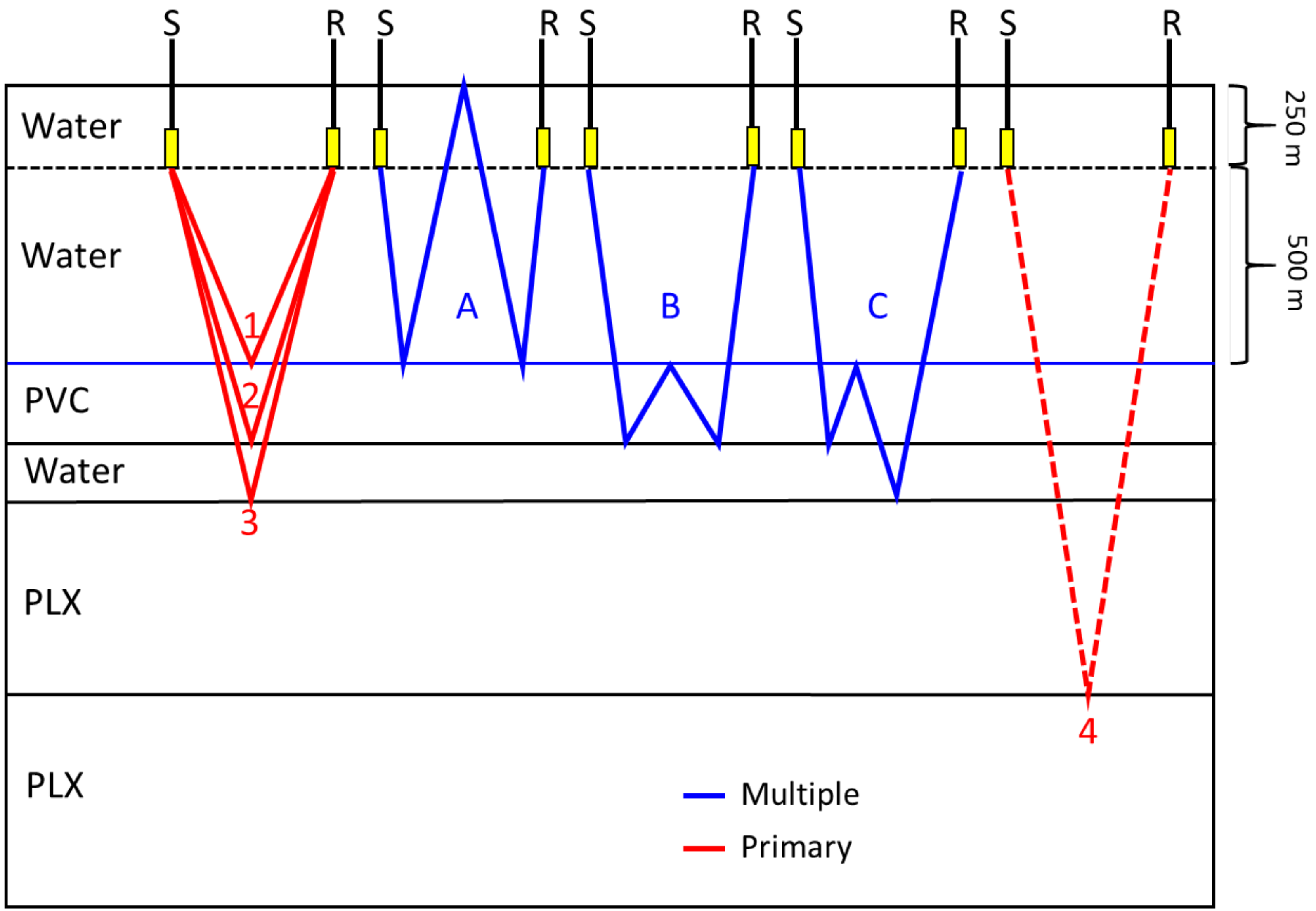
Physical model

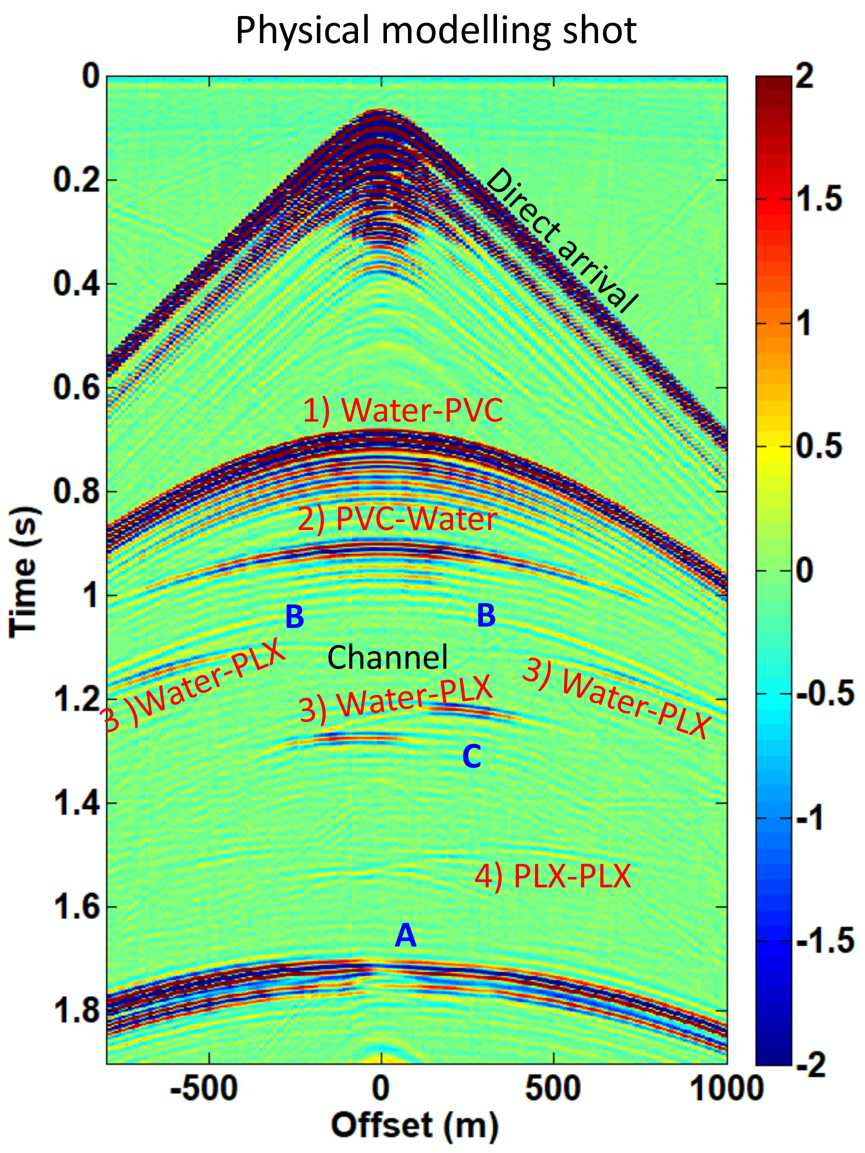
Physical modelling data



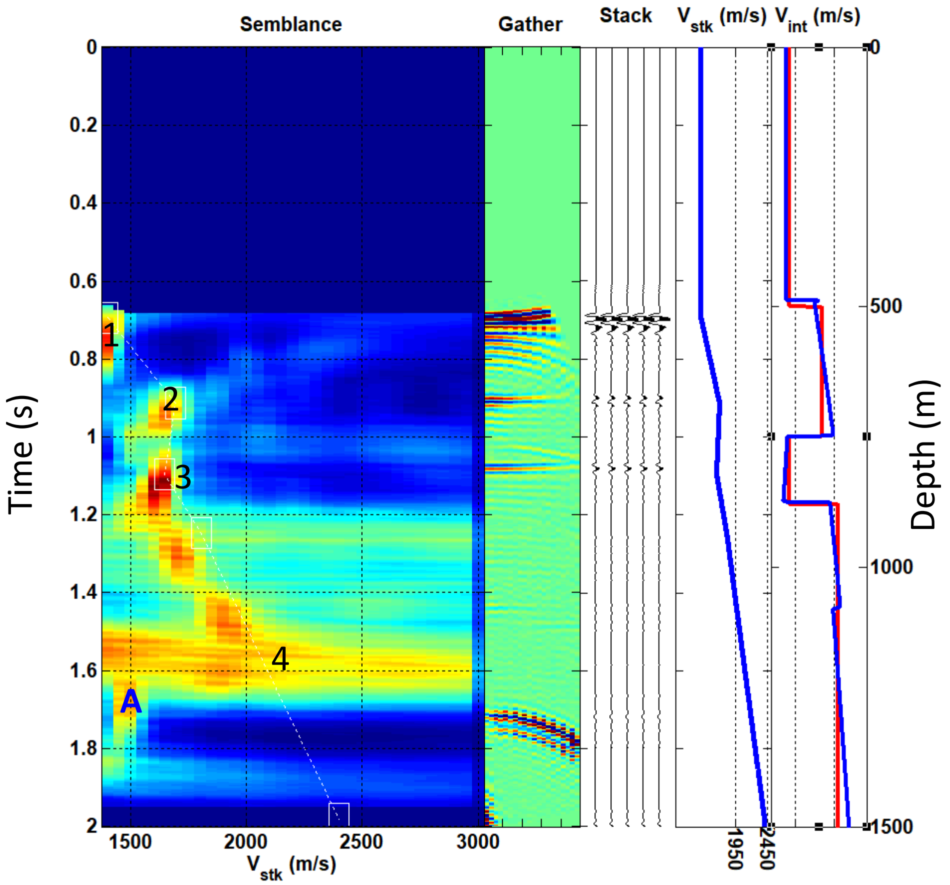
Physical modelling shot

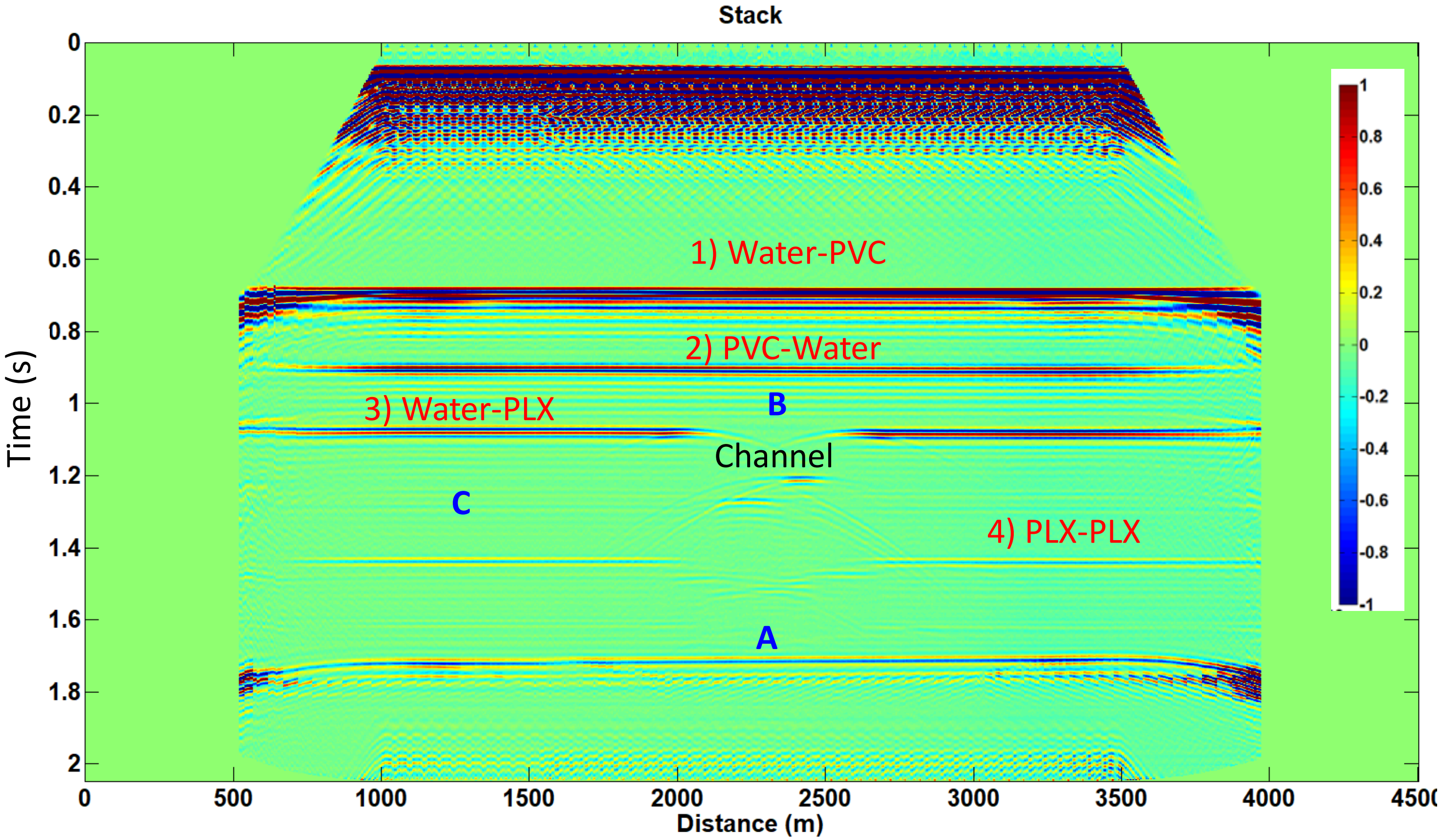



S
R
S
R
S
R
S
R
S
R
Water
Water
PVC
Water
PLX
PLX
1
2
3
4
A
B
C
250 m
500 m
Multiple
Primary


Physical modelling shot
Direct arrival
1) Water-PVC
2) PVC-Water
B
B
Channel
3)Water-PLX
3) Water-PLX
3) Water-PLX
C
4) PLX-PLX
A
Time (s)
Offset (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
-500
0
500
1000
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

Velocity analysis & stack section





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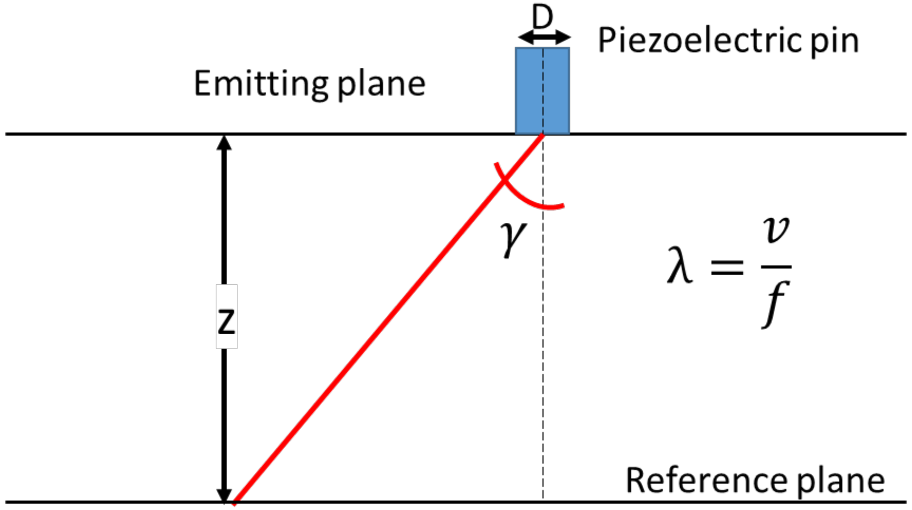
Directivity correction



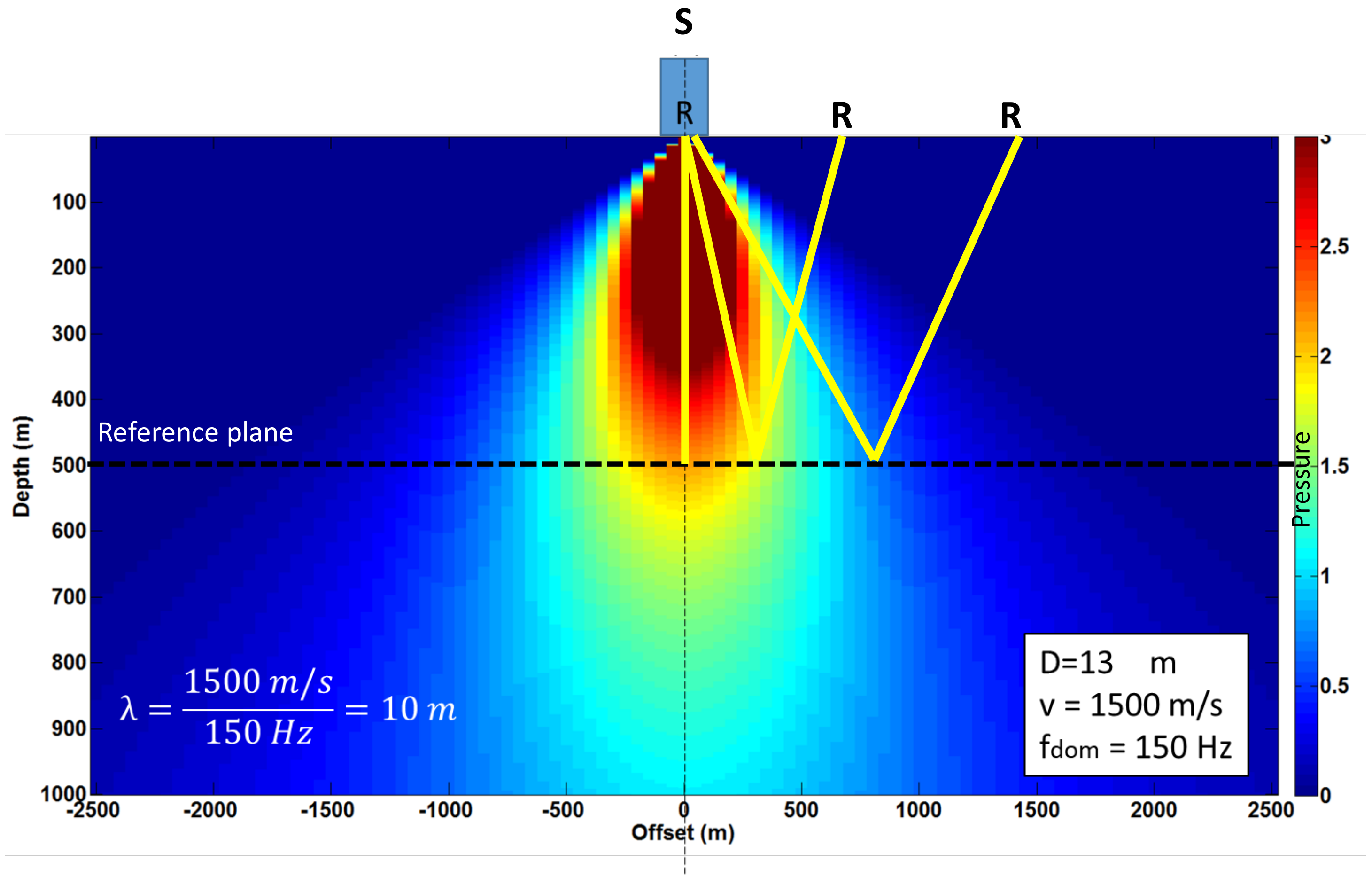
$$\lambda = \frac{v}{f}$$

$$p(p_0, D, \lambda, z, \gamma) = 4p_0 \frac{J_1(X)}{X} \sin\left(\frac{\pi D}{8\lambda z}\right)$$

$$X = \frac{\pi D}{\lambda} \sin\gamma,$$

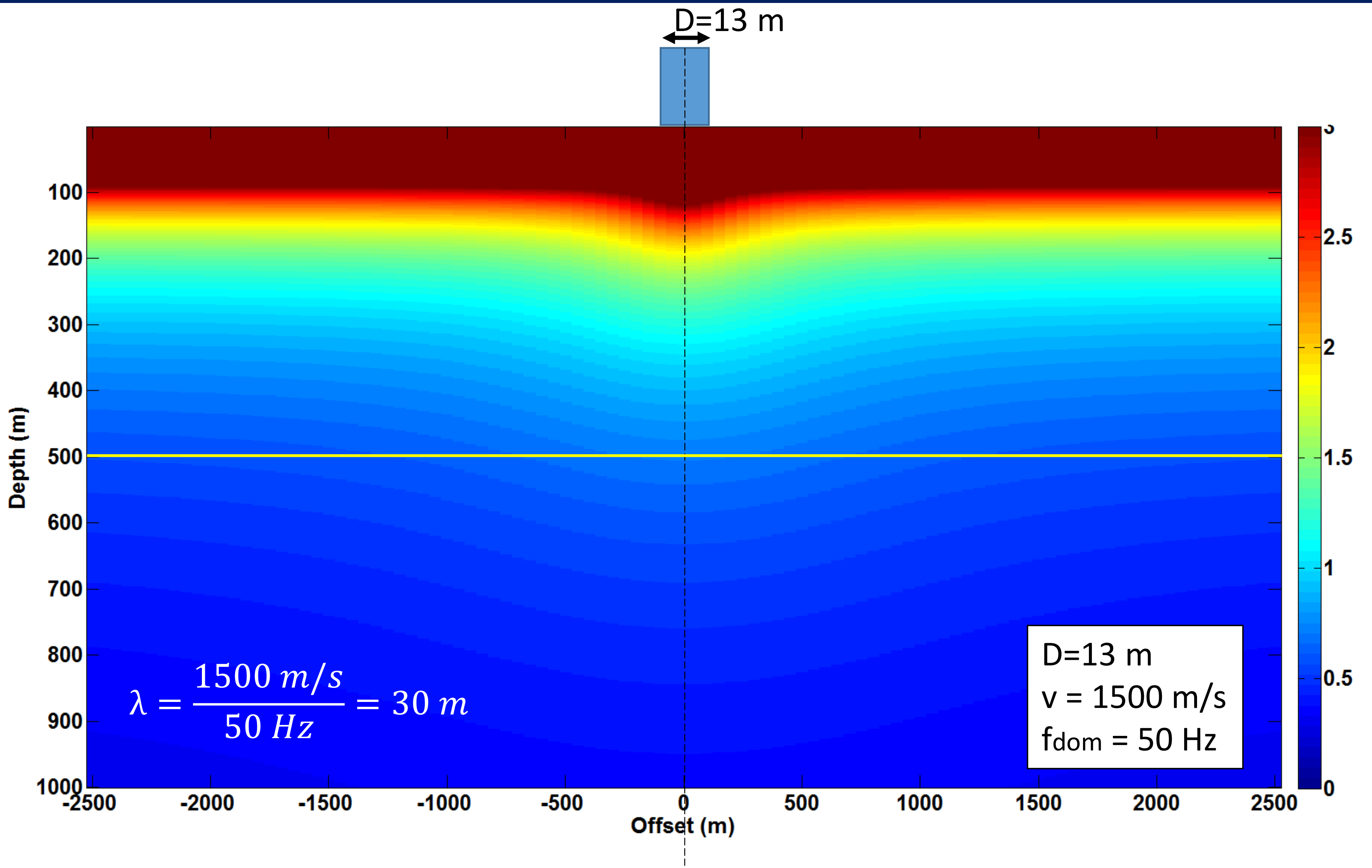
$$J_1(x) = \frac{x}{2} - \frac{x^3}{2^2 4} + \frac{x^5}{2^2 4^2 6} - \frac{x^7}{2^2 4^2 6^2 8} \cdots$$

Buddensiek et al., 2009



Amplitude abruptly decays with offset

Directivity correction



$$\lambda = \frac{1500\ m/s}{50\ Hz} = 30\ m$$

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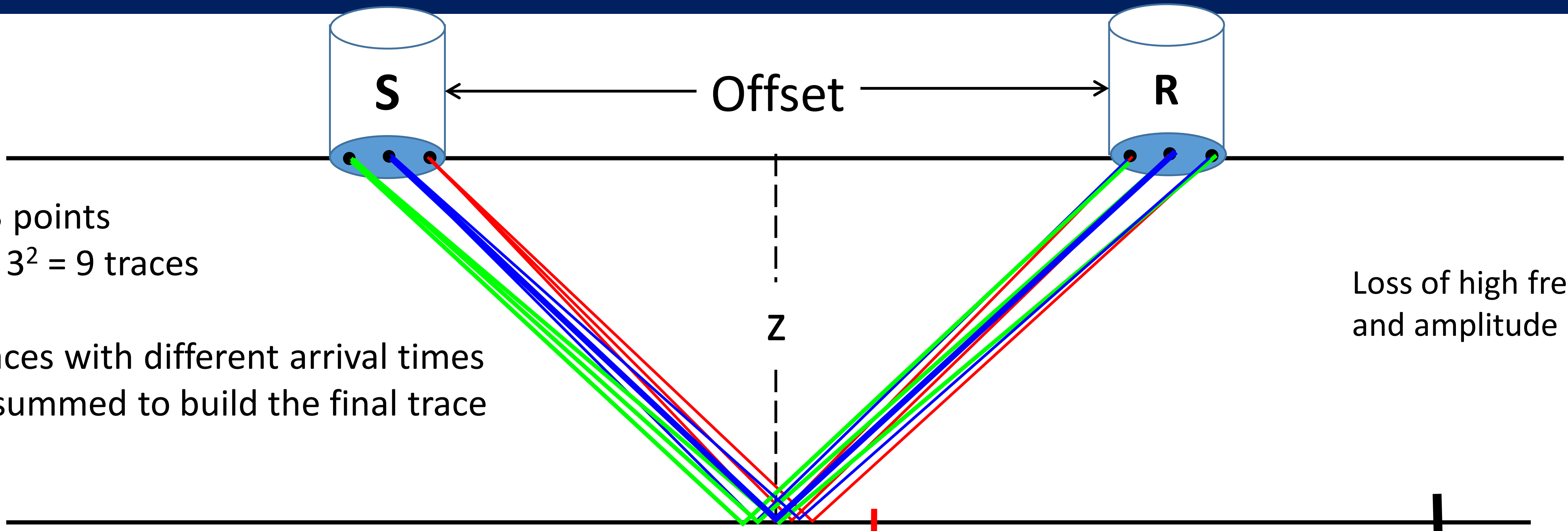
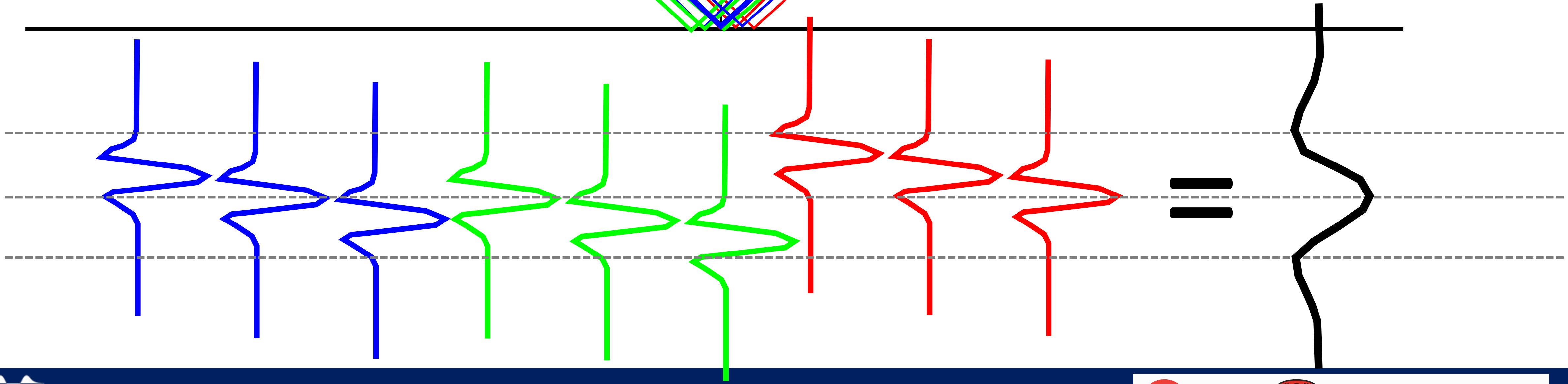
Changing waveform correction



N =3 points
$N^2 = 3^2 = 9$ traces

9 traces with different arrival times are summed to build the final trace

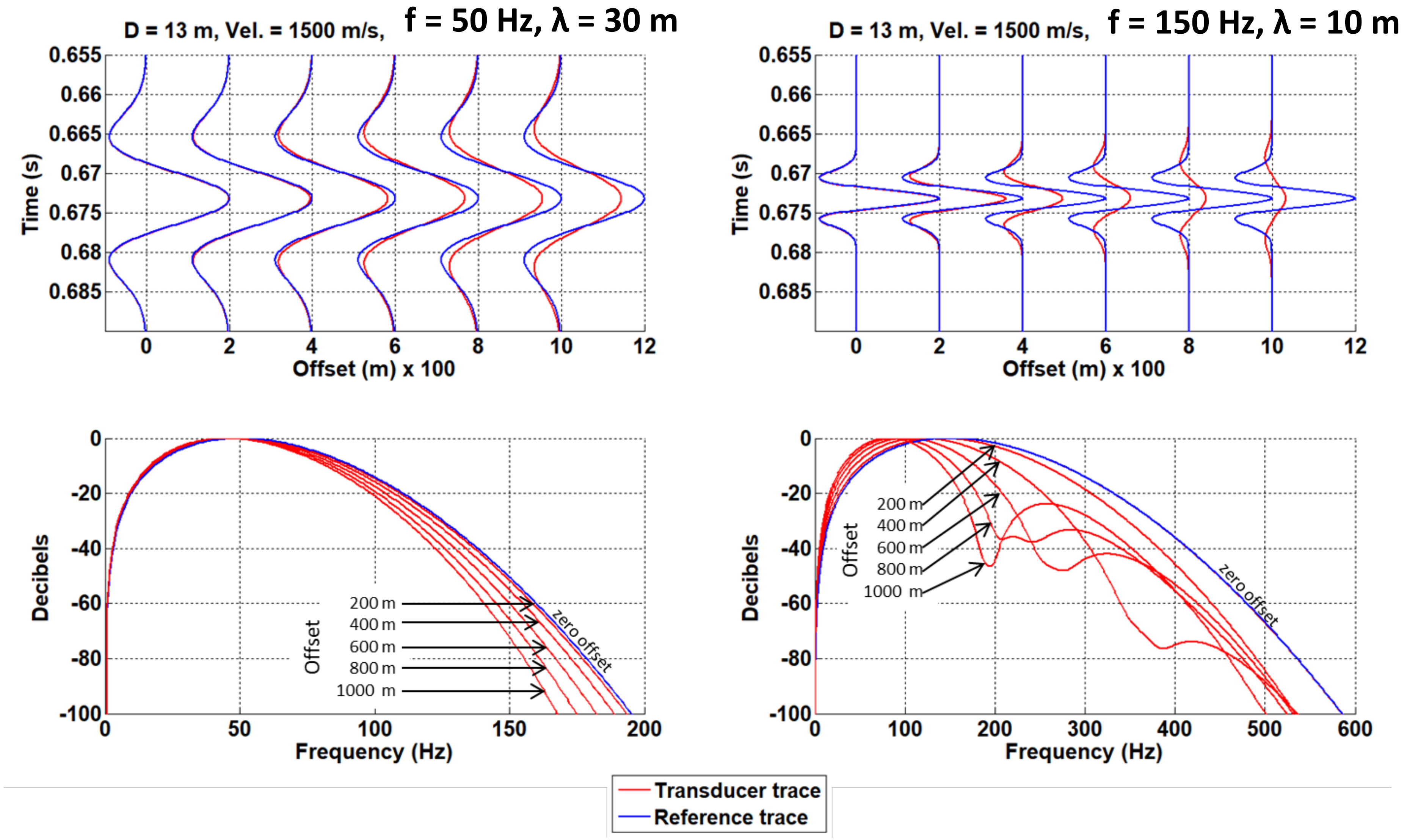
Loss of high frequencies and amplitude



Changing waveform correction

Laboratory case $\lambda > D$

Stronger effect when $\lambda < D$



Reference wavelet 1-point transducer

Wavelet for a N-point transducer

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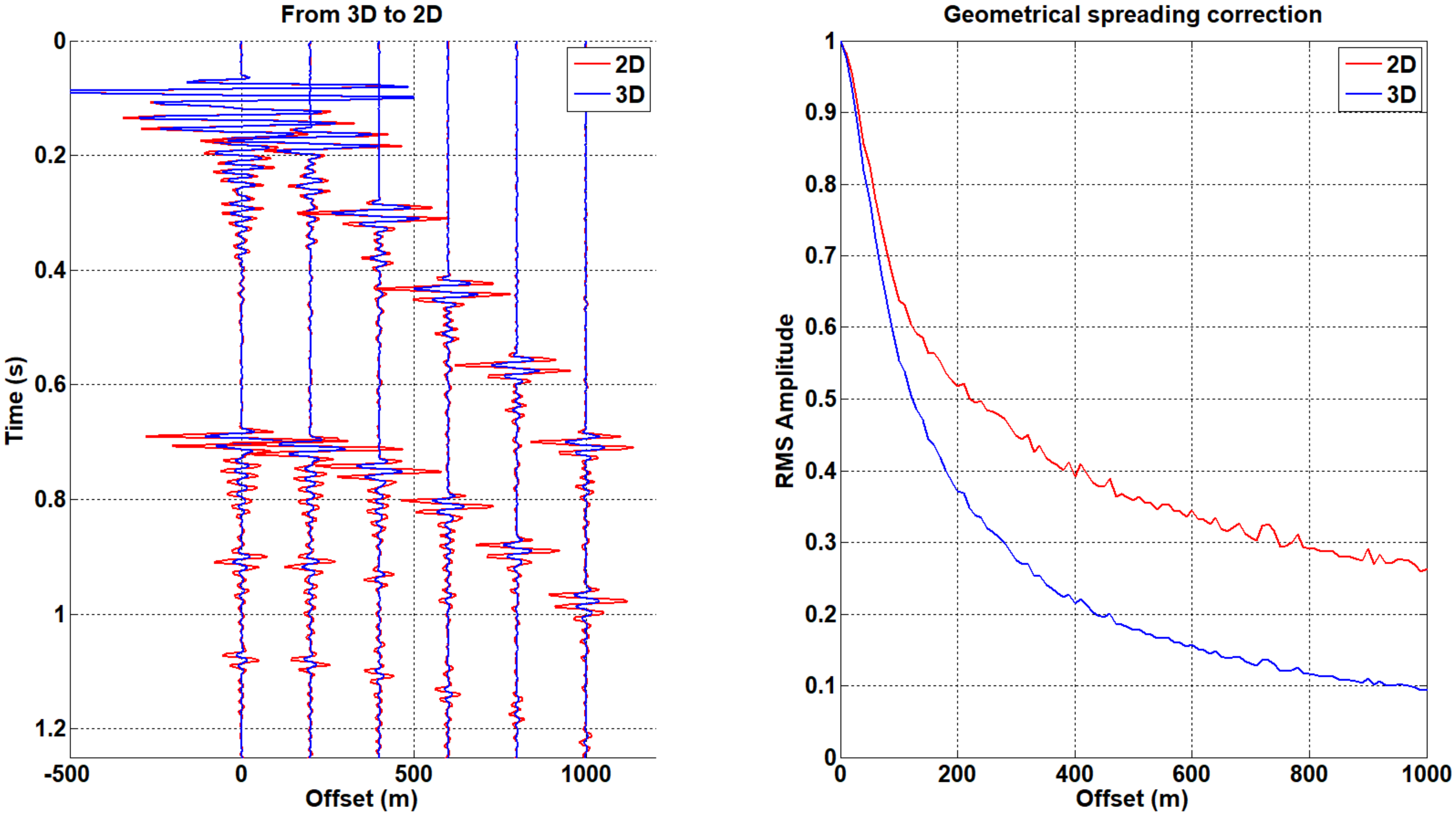
Geometrical spreading from 3D to 2D

From 3D (1/r)
to
2D (1/sqrt(r))

Multiplying by sqrt(t) and convolving by 1/ sqrt(t)
(Bleistein, 1986; Pratt, 1999)



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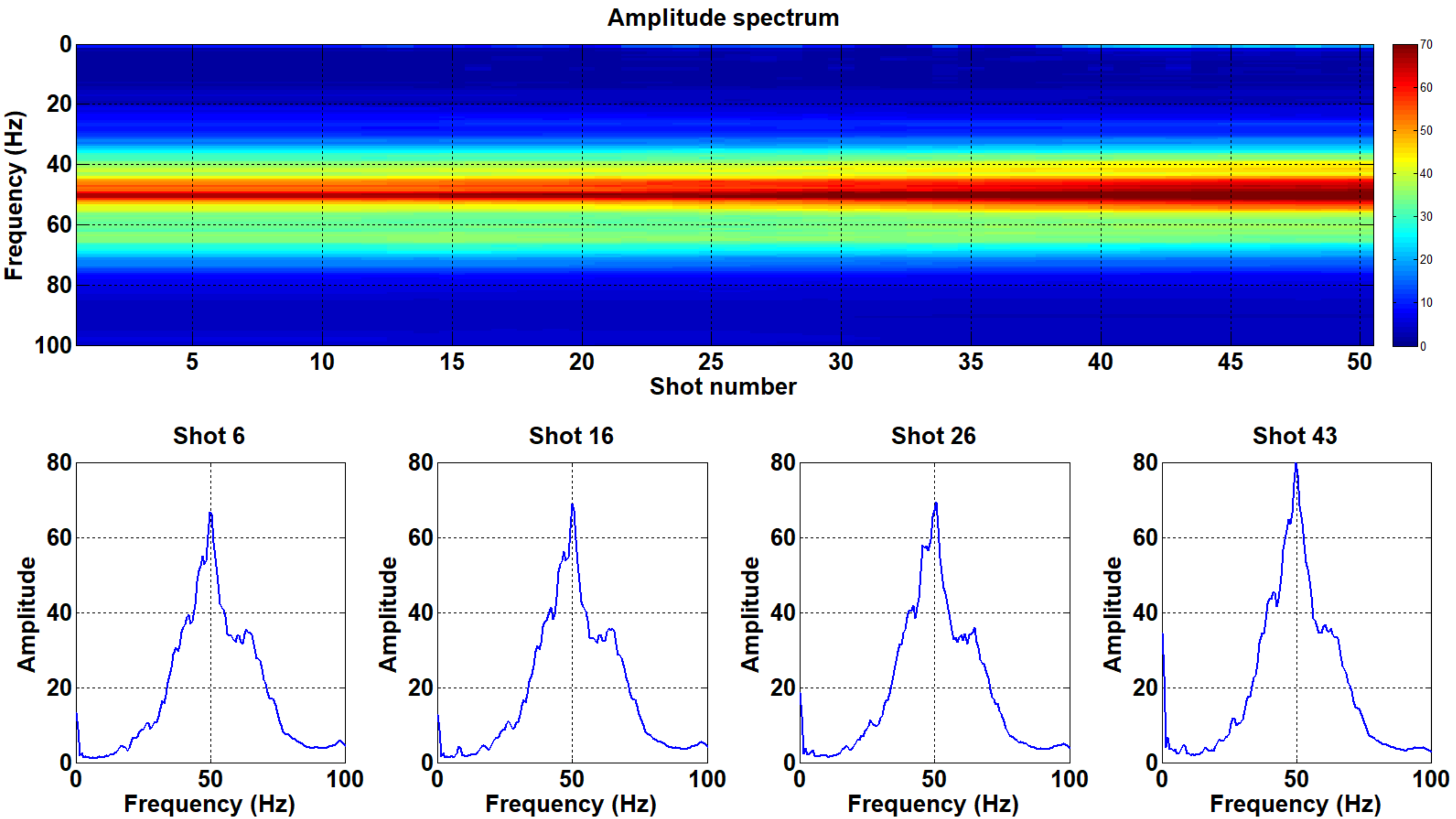
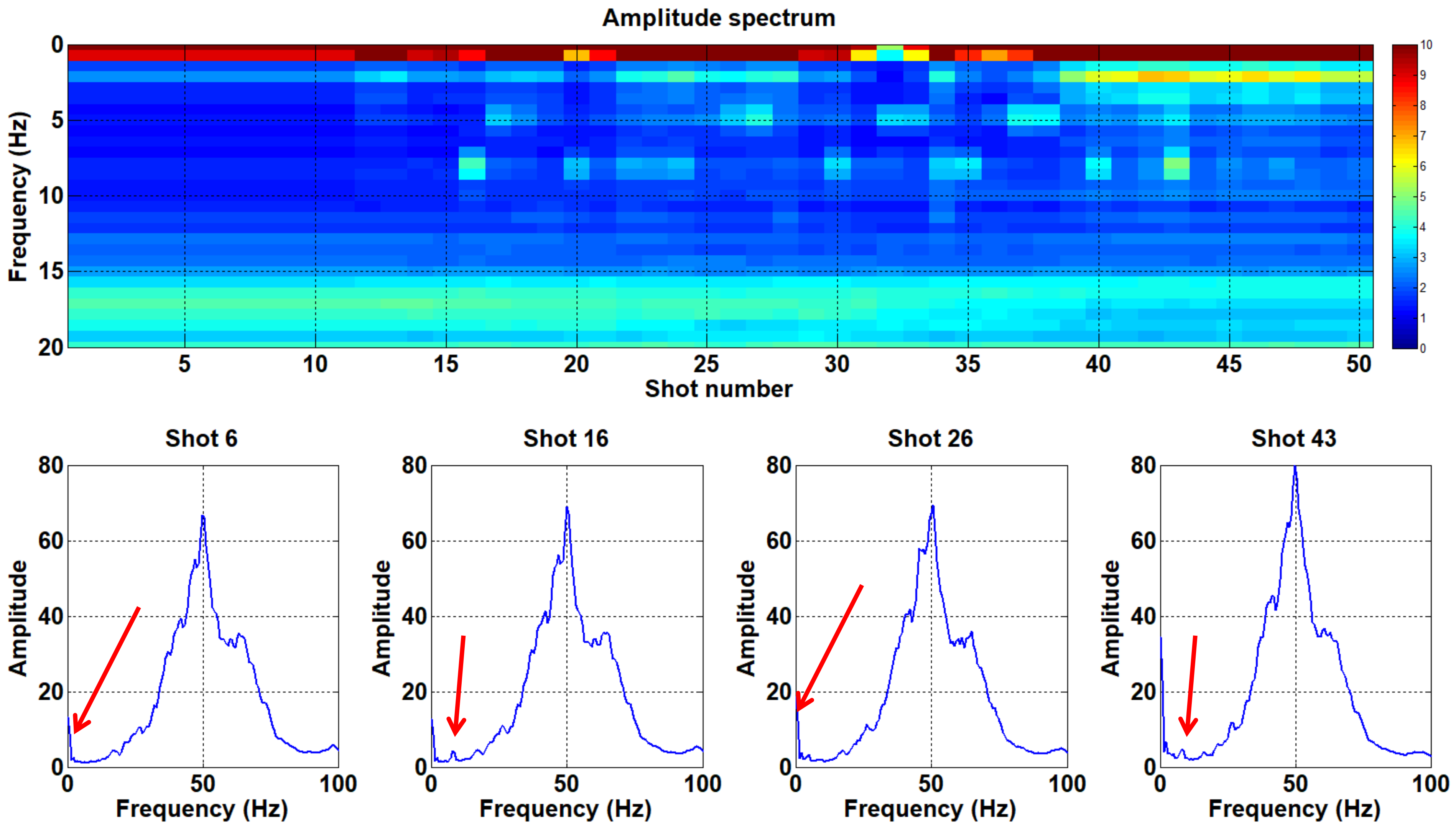
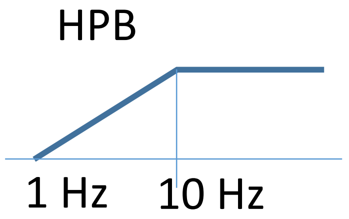
Low frequency picks

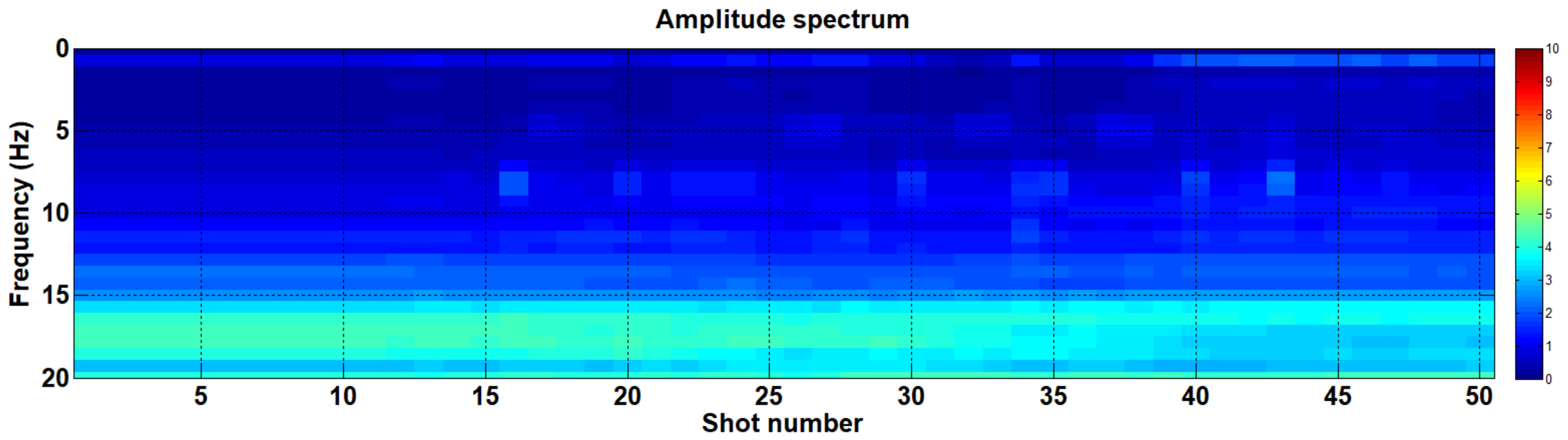


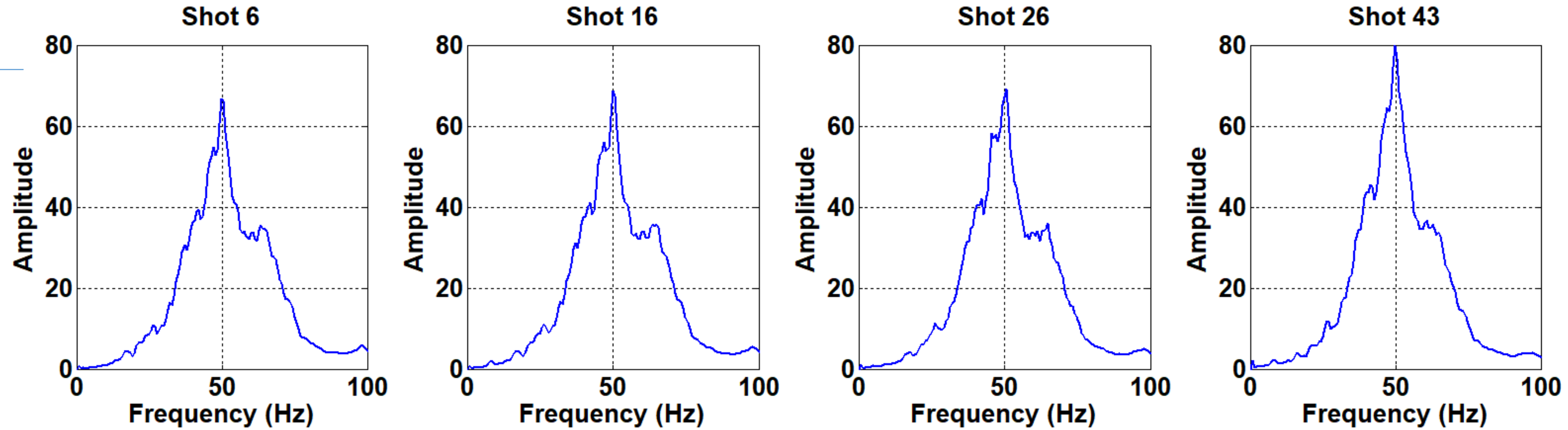
Low frequency picks



Low frequency picks







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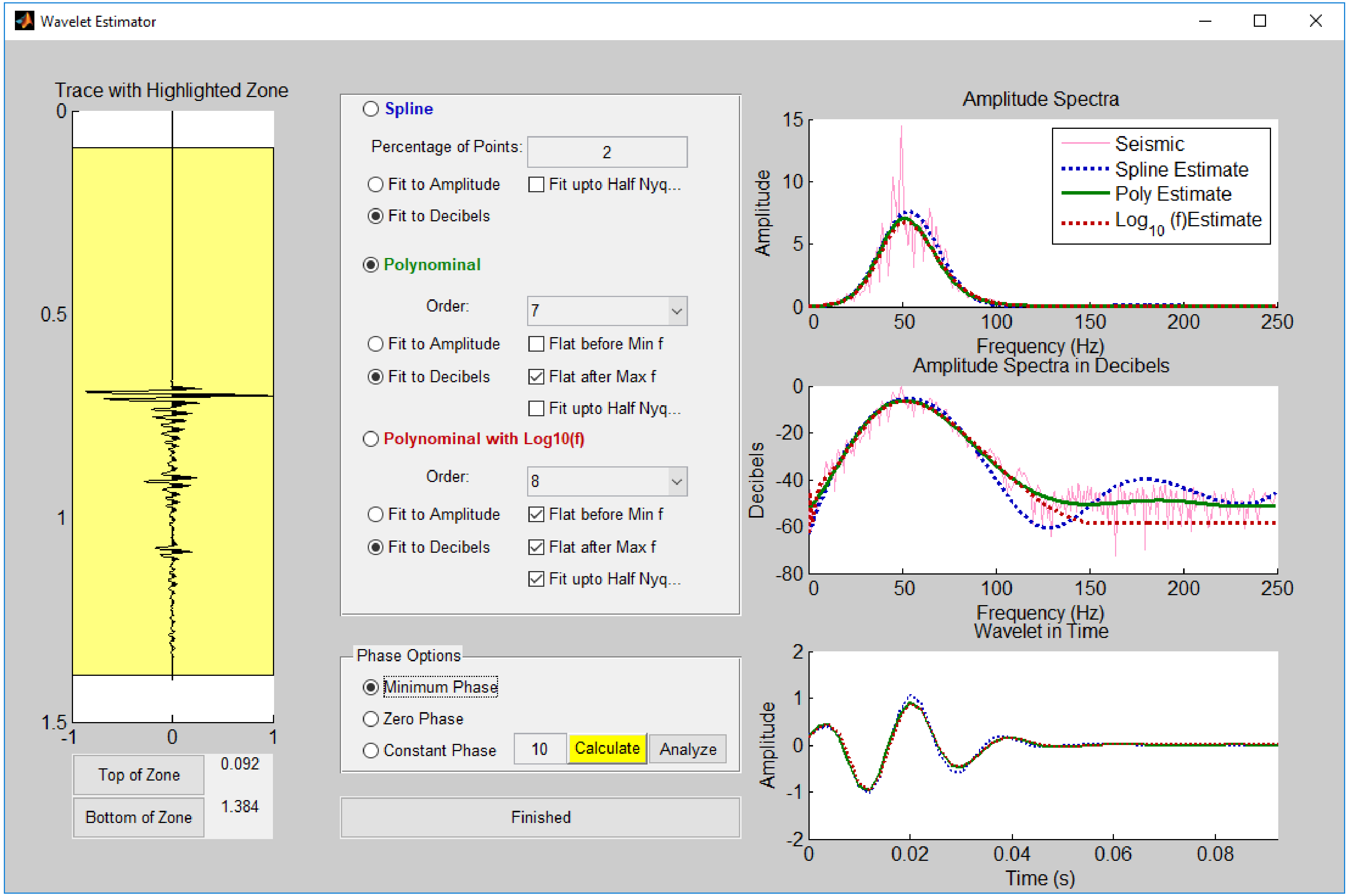
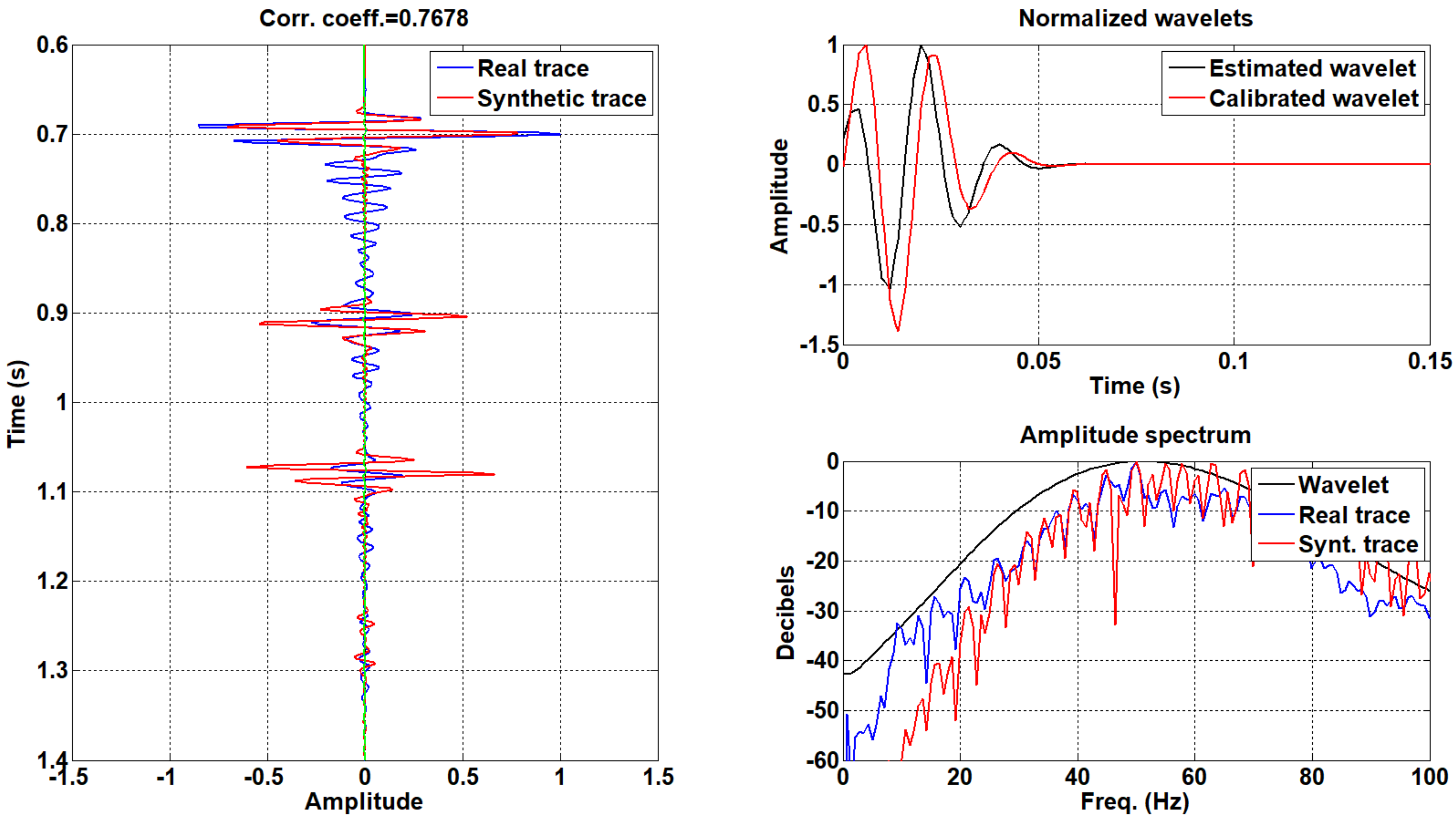
Wavelet estimation



Wavelet calibration



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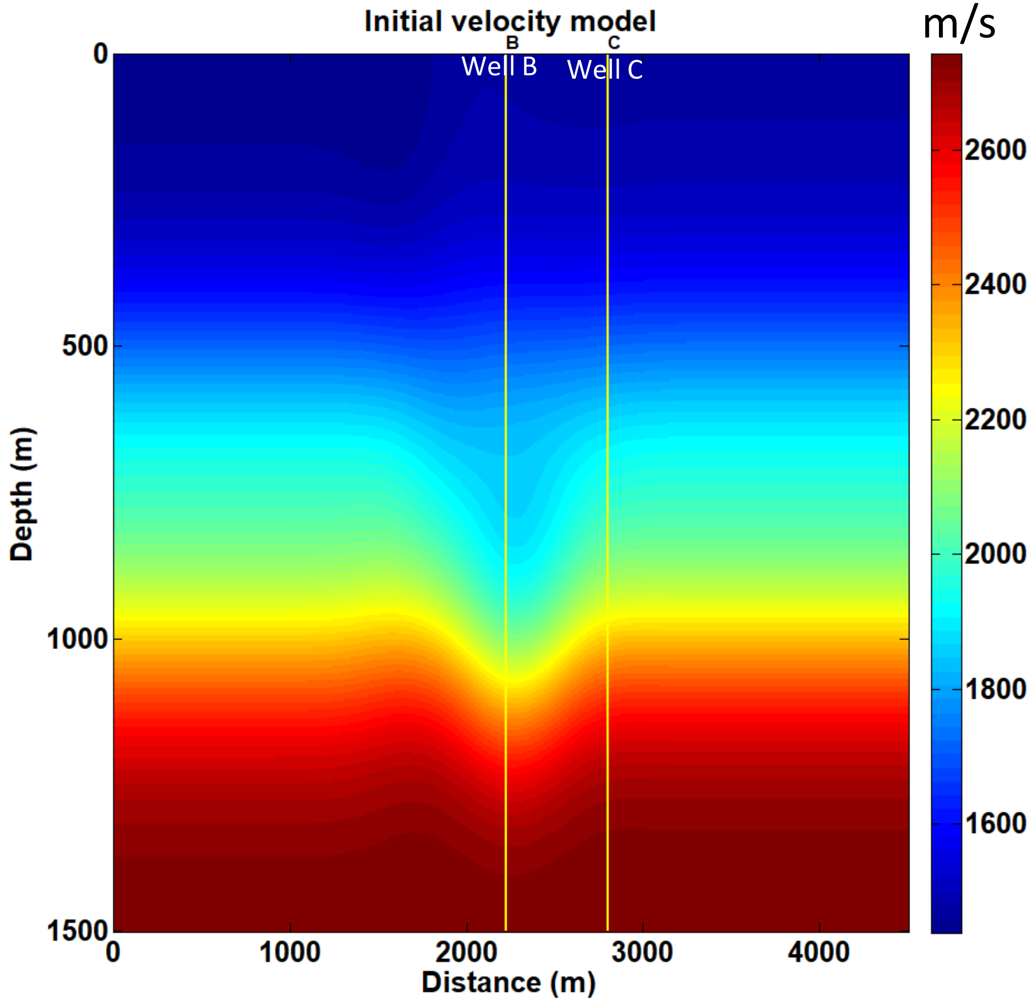
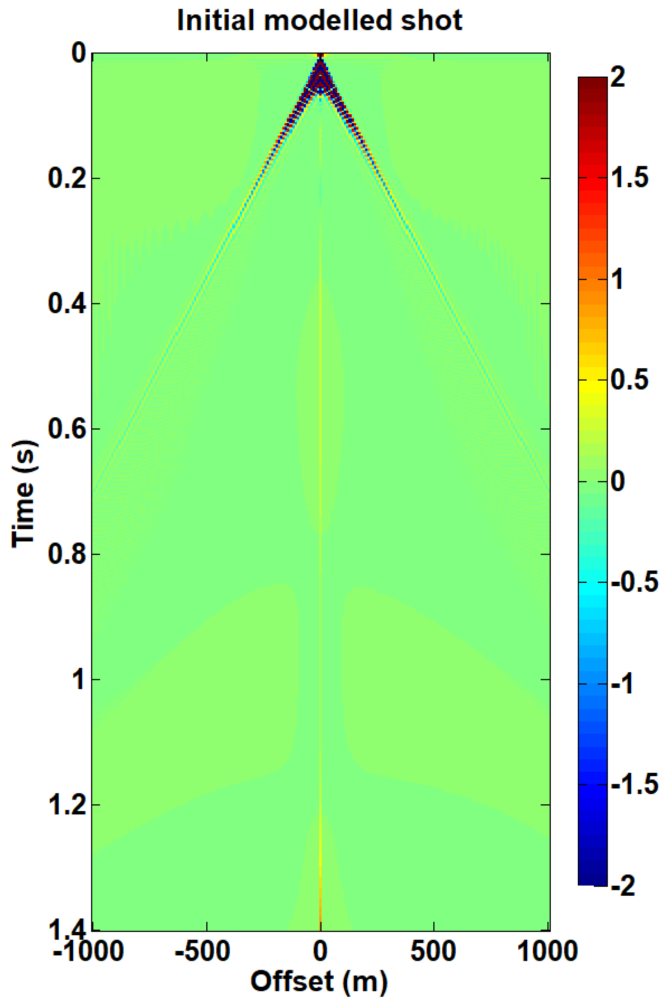
Initial velocity model

1st iteration



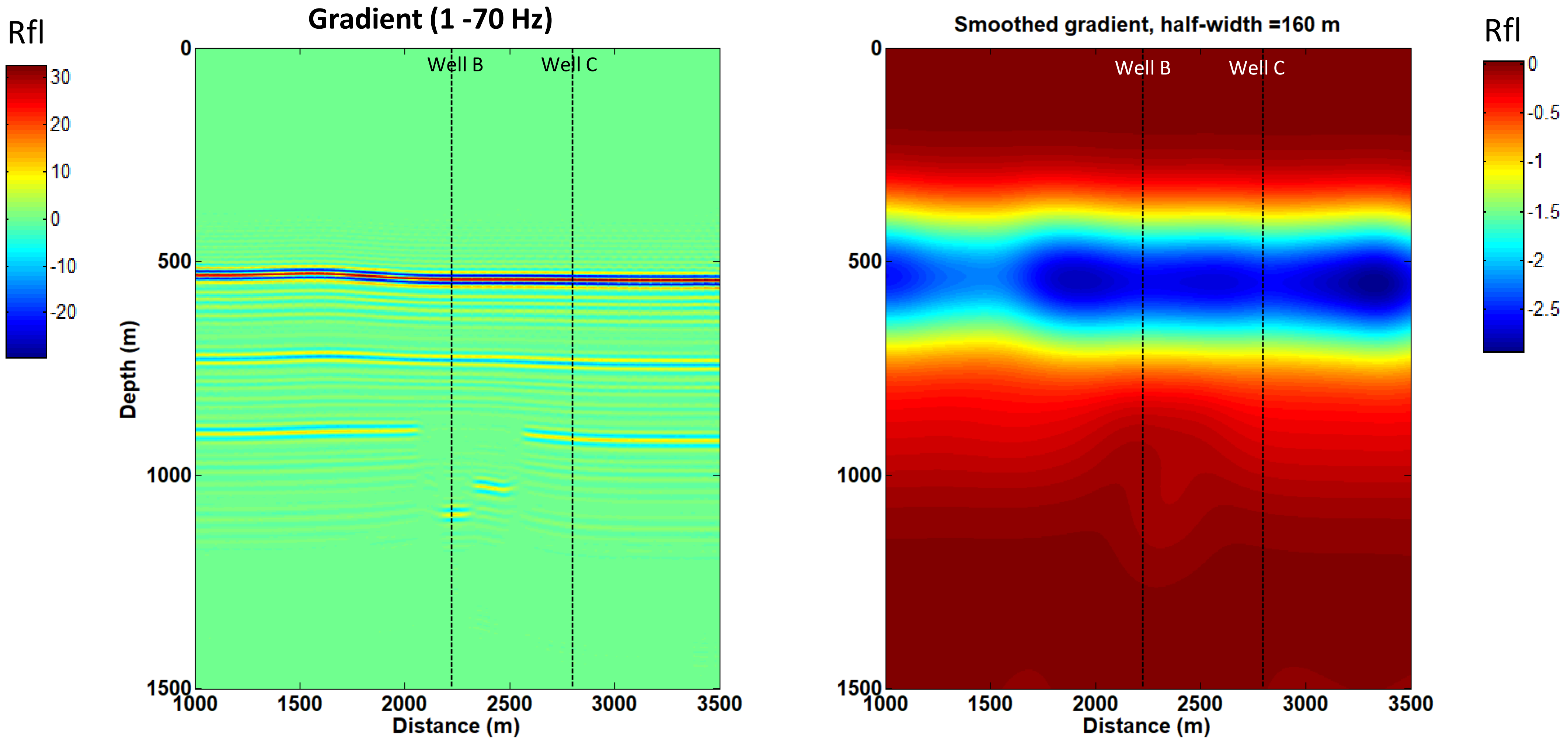


Gradient

1st iteration

Spatial multi-scale approach

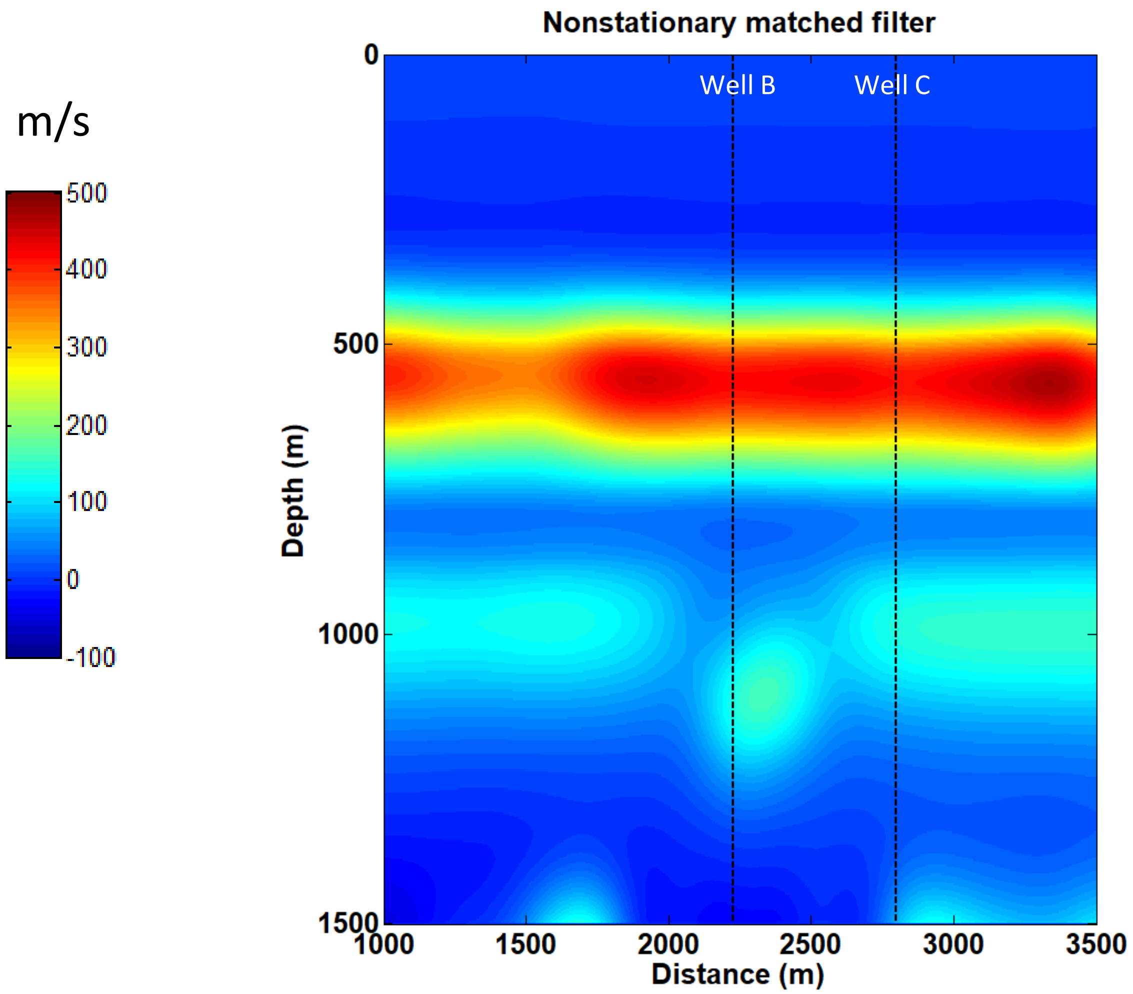
1) Migrate residuals with full-frequency band
2) Apply Gaussian smoother with a half-width of 160 m for the first iteration



Velocity update

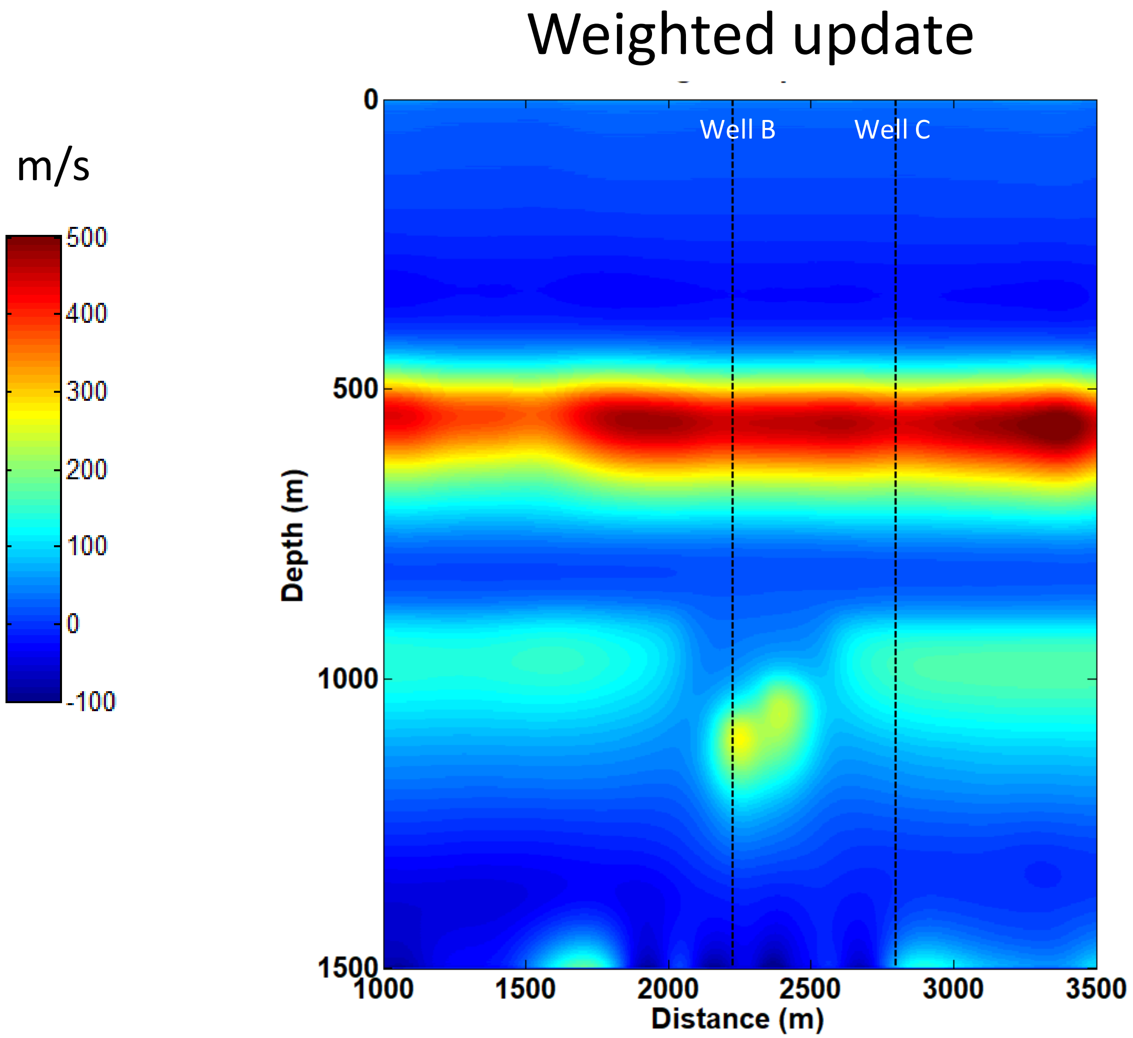
1st iteration

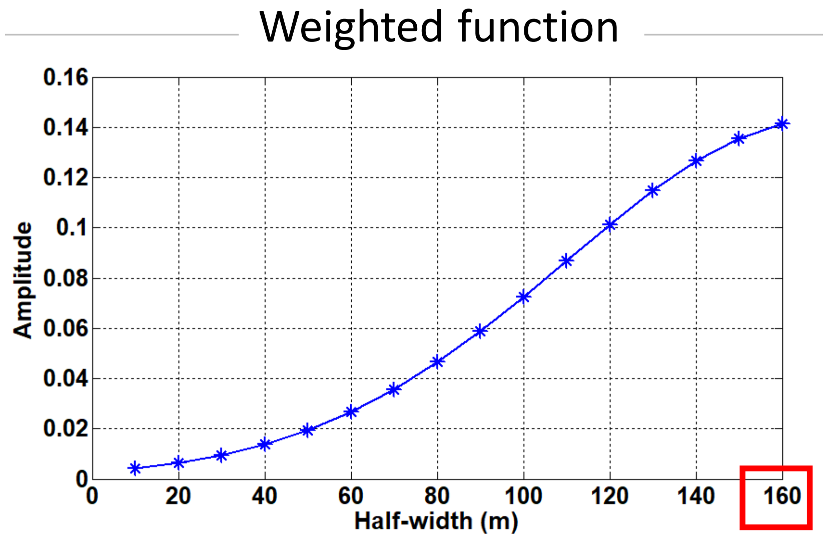
Well-calibration technique



Velocity update

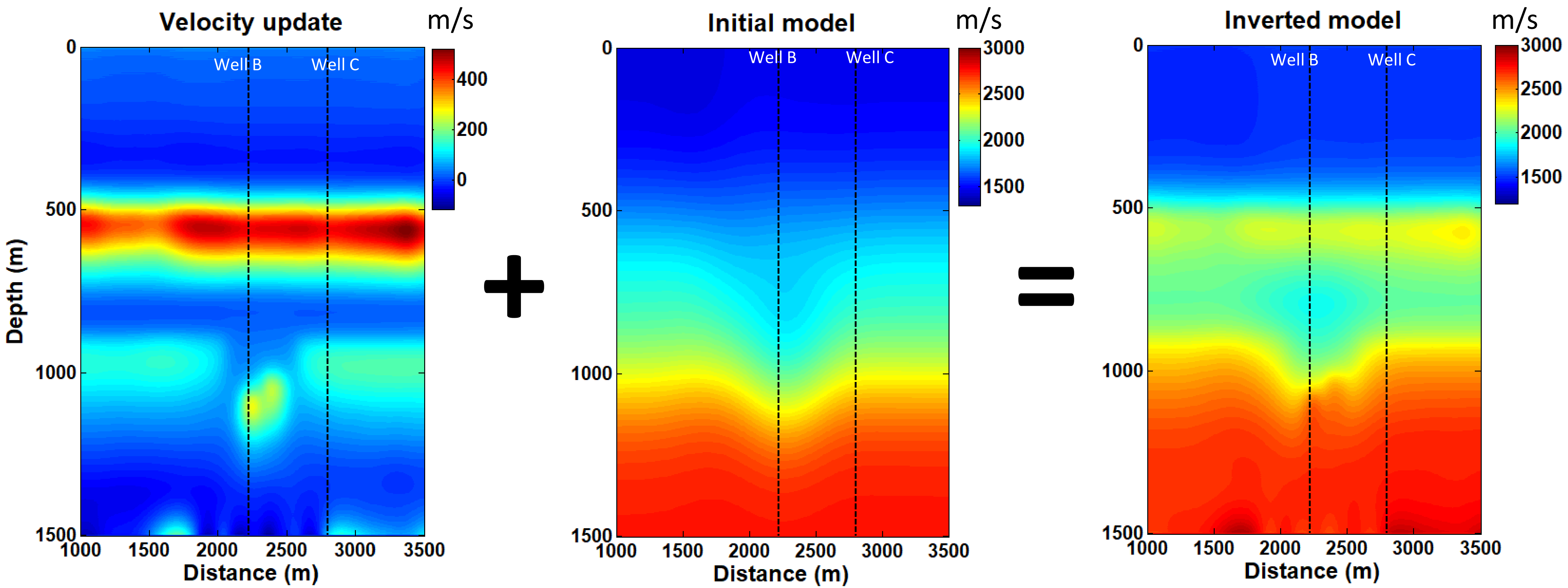
1st iteration



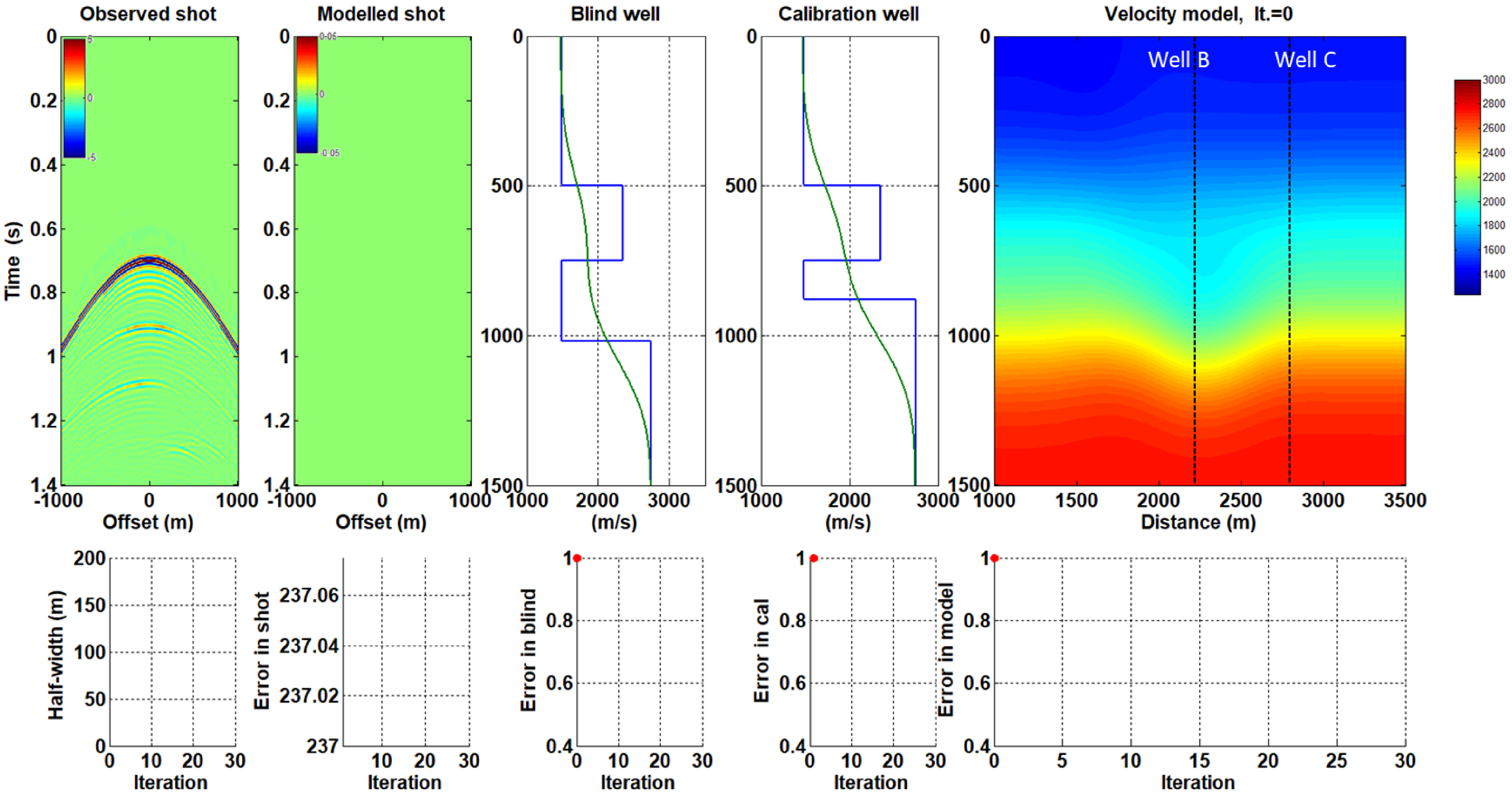


New velocity model

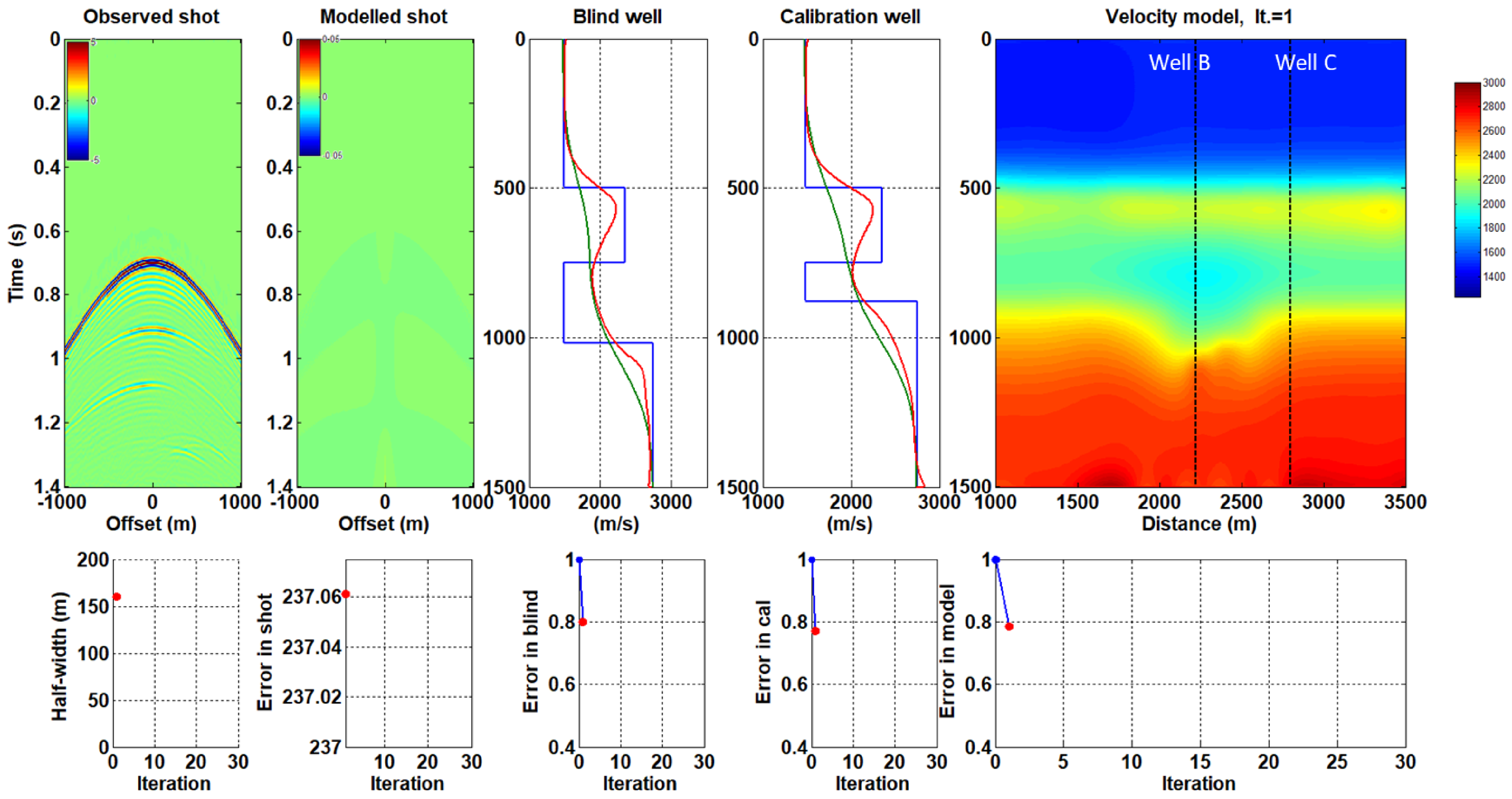
1st iteration



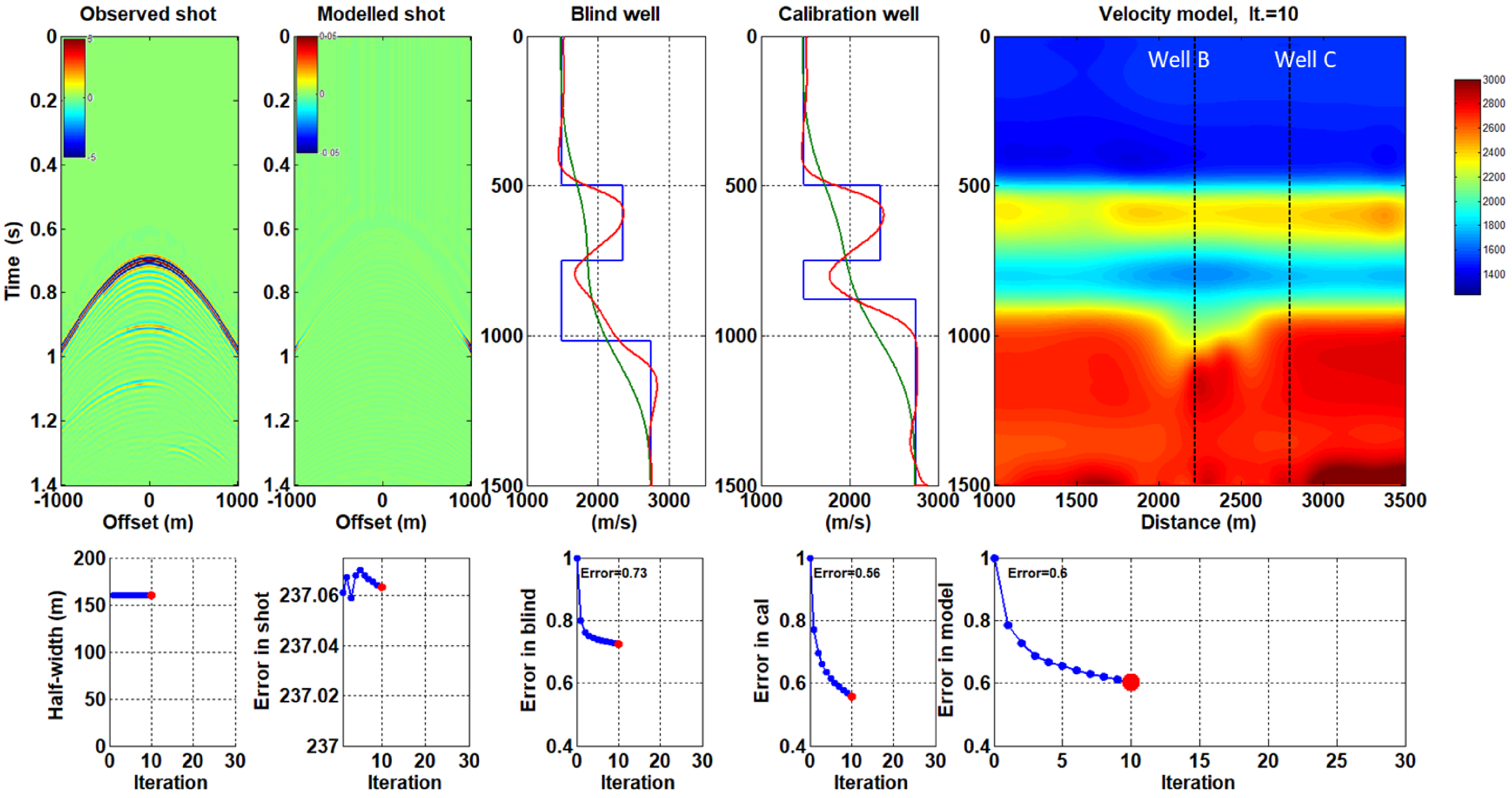
Inversion process



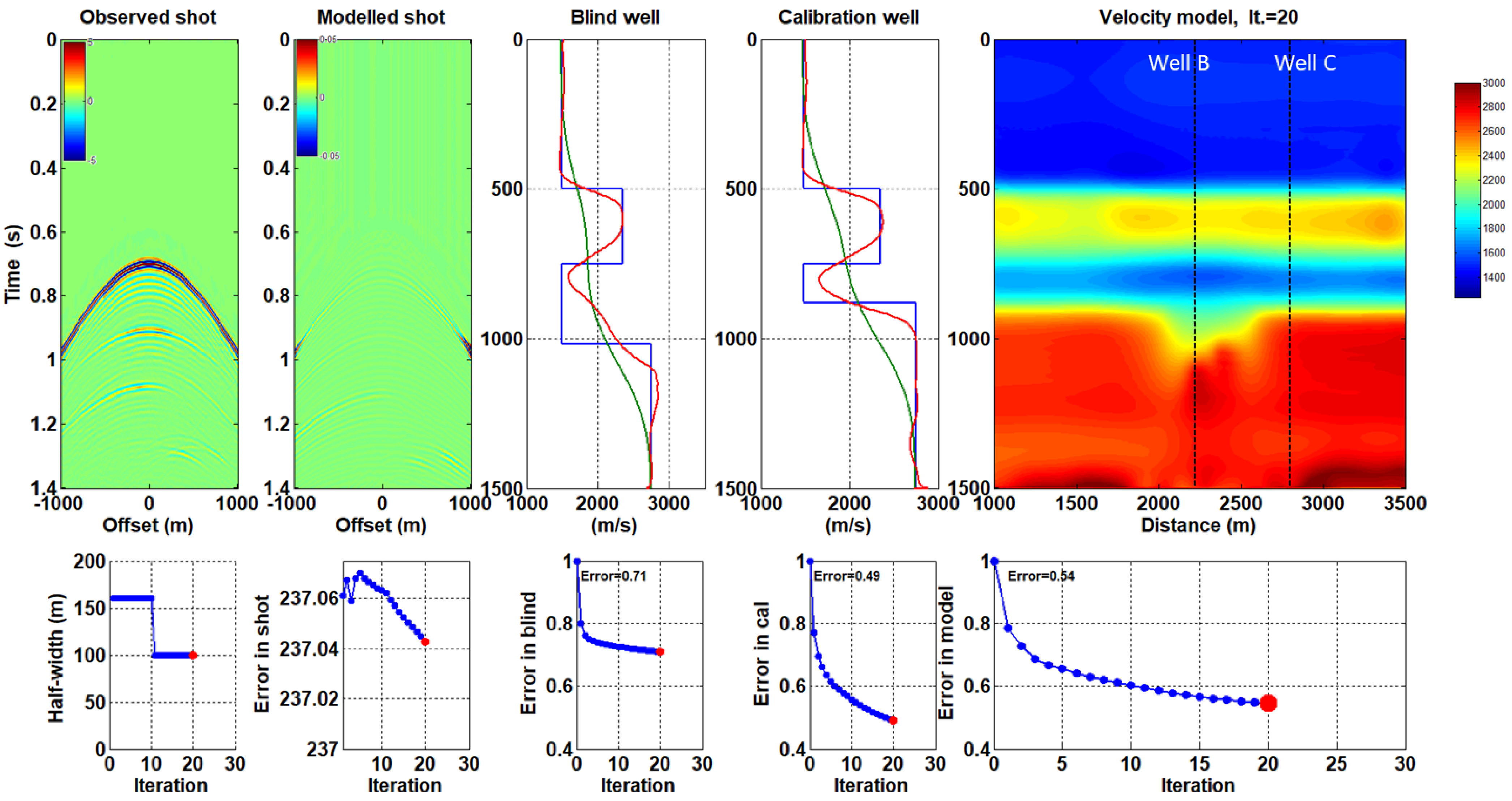
Inversion process

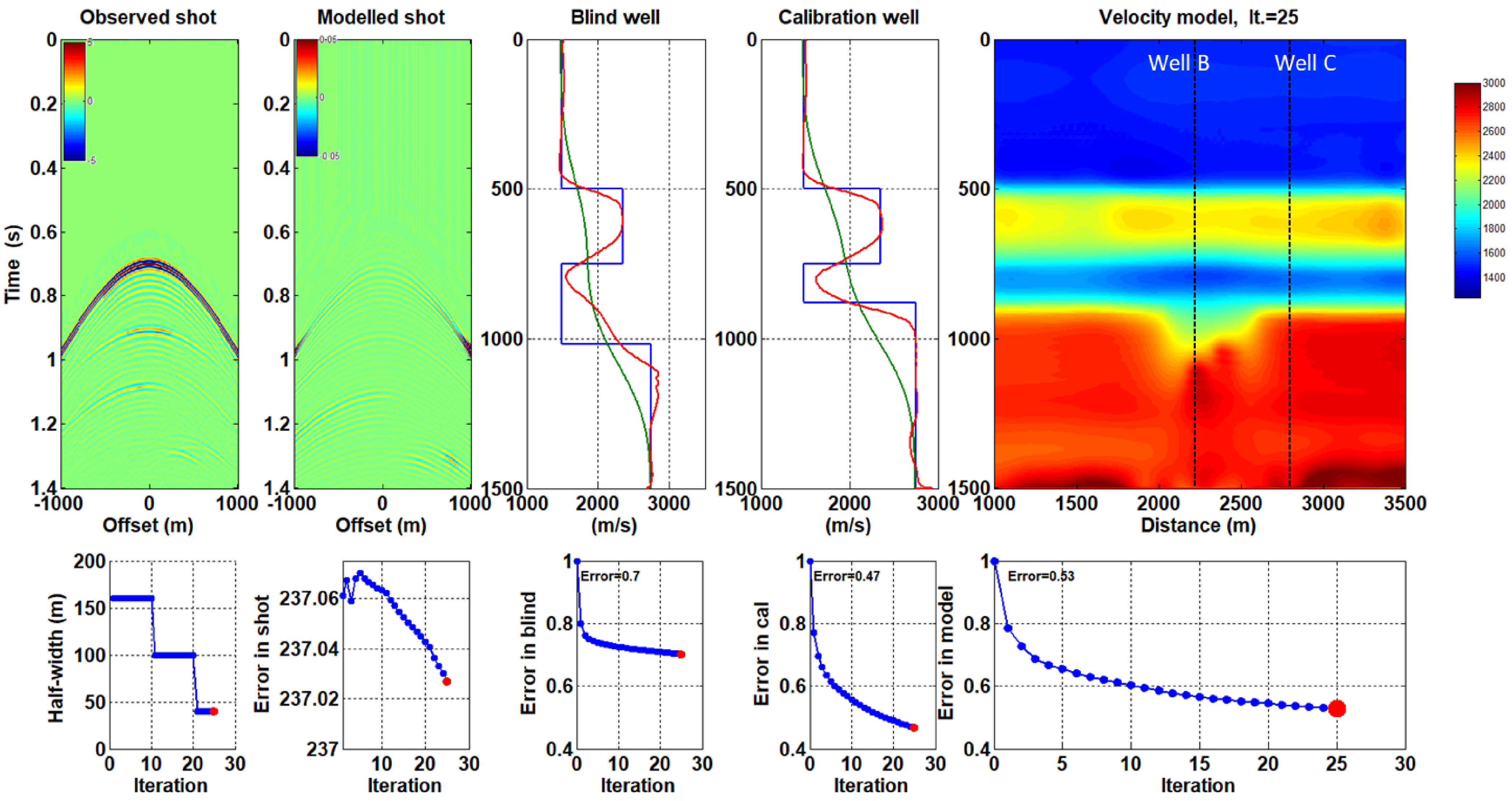


Inversion process

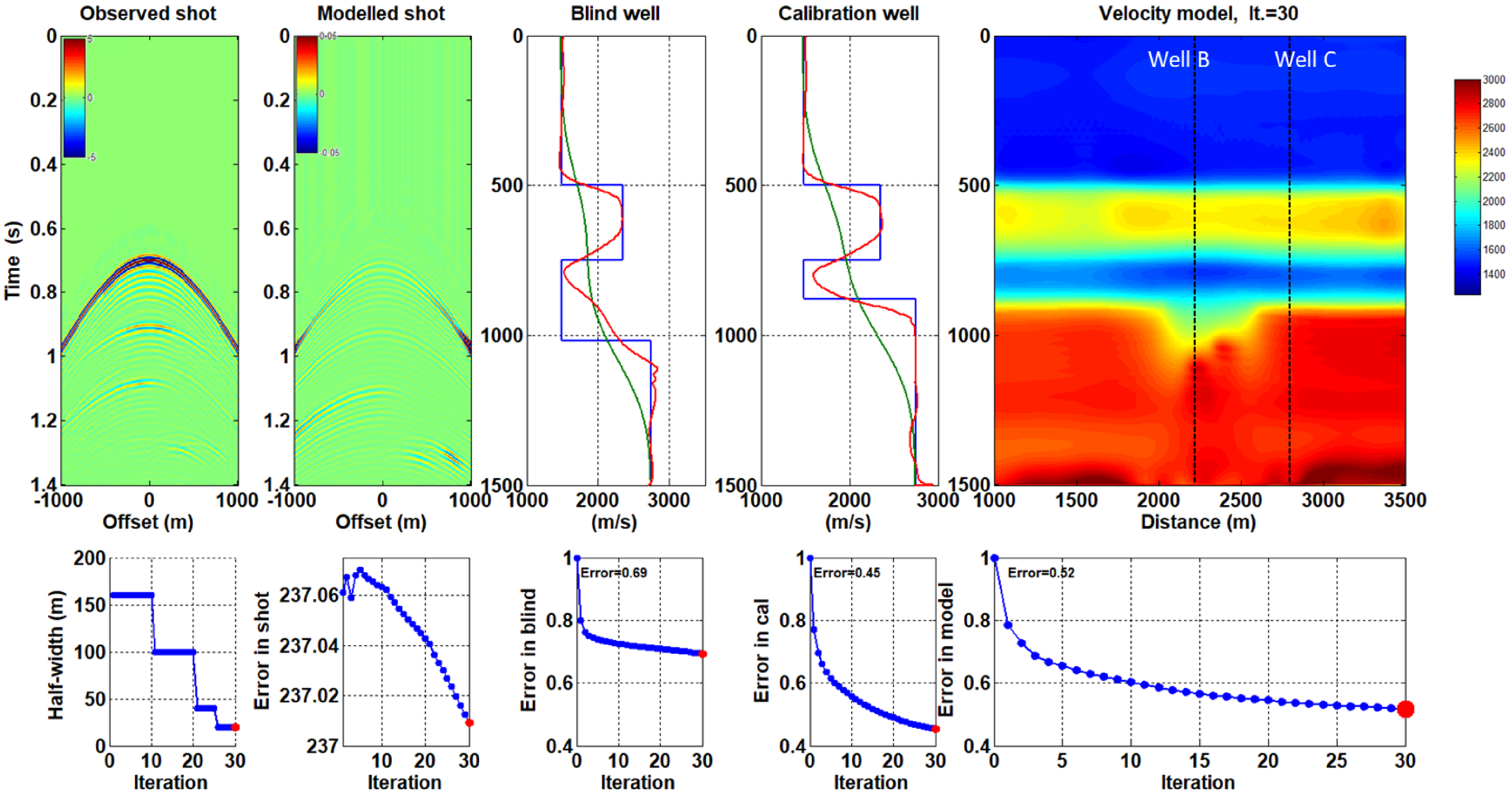


Inversion process




Observed shot
Modelled shot
Blind well
Calibration well
Velocity model, It.=25
Well B
Well C
Time (s)
Offset (m)
Offset (m)
(m/s)
(m/s)
Distance (m)
Half-width (m)
Error in shot
Error in blind
Error in cal
Error in model
Error=0.7
Error=0.47
Error=0.53
Iteration
Iteration
Iteration
Iteration
Iteration

Inversion process



Conclusions

- The CREWES seismic physical modelling laboratory facility is a valuable tool for evaluating new seismic processing and interpretation techniques outside the synthetic environment.
- Physical modelling data have to be conditioned in order to be treated as real seismic data.
- We evaluated a nonstandard FWI approach that is referred as iterative modelling, migration and inversion:
  1) PSPI migration to obtain the gradient (instead of RTM).
  2) Non-stationary matched filters from well-log velocity to calibrate the gradient (instead of the step length method).
  3) Spatial multi-scale approach. Iterative application of Gaussian smoothers to frequency-band fixed migrated data residuals (instead of the frequency multi-scale technique).
- The strategy showed great potential to recover long-wavelength information from reflection seismic data.

Acknowledgements

Thanks

Kevin Bertram and Joe Wong

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Questions?