Turning-ray tomography and tomostatics

Babatunde Arenrin*
Gary Margrave
John Bancroft

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Motivation

- My interest in this topic stems from the similarities between traveltime tomography and full waveform inversion.

- Traveltime tomography can provide good starting models for full waveform inversion.

- The IMMI approach suggests incorporating well data into FWI
  - Well data helps estimate reflectivity at the well location and for wavelet estimation.

- We know from the functional analysis approach of FWI that the gradient is a migration (RTM) of the data residuals.
    -Well data can be used for 'calibrating the migration' (Margrave et al, 2010), and/or to determine a step length. This method may be 'more practical' than the full Newton or Gauss-Newton method.
- However, wells do not start from the surface but at some depth below the Seismic Reference Datum (SRD).

- Where else can we get this missing information?

- Provided offset is large enough with very steep velocity gradient, TRT can be used to fill-in the missing information.

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Concept of seismic tomography

- Tomography is an imaging technique which generates a cross-sectional picture (a tomogram) of an object by utilizing the object's response to the nondestructive, probing energy of an external source (Lo and Inderwiesen, 1994).

- In Seismic tomography we use traveltimes and/or amplitudes responses to generate a cross-section of the subsurface properties.

- Traveltime tomography constructs estimates of the subsurface velocity distribution using traveltimes. Traveltime tomography is applicable when the target's size is much larger than the seismic wavelength. This approach is based on the high frequency assumption of ray theory (Woodward, 1989).

- Diffraction tomography on the other hand should be considered if the size of target is comparable to the seismic wavelength because the propagation of seismic waves is modelled as scattered energy using diffraction theory.

Traveltime tomography

- Based on ray theory.
- Theory is from the Eikonal equation and it's high frequency assumption.
- Can use ray tracers or finite difference for forward modelling

$$\frac{d}{ds}\left[\frac{1}{v(\mathrm{r})}\frac{dr}{ds}\right] = \nabla\left(\frac{1}{v(\mathrm{r})}\right)$$

$$\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2 = \frac{1}{v^2(x,y,z)}$$

$r, s, v, T, x, y \& z$ are the position along the ray, the path length, propagation speed, traveltime and the space coordinates respectively

The traveltime equation is given as

$$t_i = \sum_j d_{ij} / v_j = \sum_j d_{ij} s_j$$

Where t_i is the total travel time along the i^{th} ray-path, d_{ij} is the path length in the j^{th} cell of the velocity model for the i^{th} ray, v_j is the velocity of the j^{th} cell and s_j is the slowness of the j^{th} cell (Jones, 2009).

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Series expansion method

Two methods are generally used in tomography; the transform method and the Series expansion method.

- Series expansion method is used in seismic traveltime tomography; it allows for curved ray paths.

- Implemented with the ART or SIRT technique–Kaczmarz's method.

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Series expansion method- ART

- ART; Algebraic Reconstruction technique.

Involves tracing only one ray each time. Model update is given as

$$\Delta s_j = d_{ij} \frac{\left| t_i^{observed} - t_i^{predicted} \right|}{\sum_j (d_{ij})^2}$$

(Lo and Inderwiesen, 1994)

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Series expansion method- SIRT

- SIRT; Simultaneous Iterative Reconstruction technique.

Involves tracing as much rays through the model so that all corrections for all the rays are known. Model update is given as;

$$\Delta s_j = \frac{1}{W_j} \sum_{i=1}^{I} d_{ij} \frac{\left| t_i^{observed} - t_i^{predicted} \right|}{\sum_j \left(d_{ij} \right)^2}$$

(Lo and Inderwiesen, 1994)

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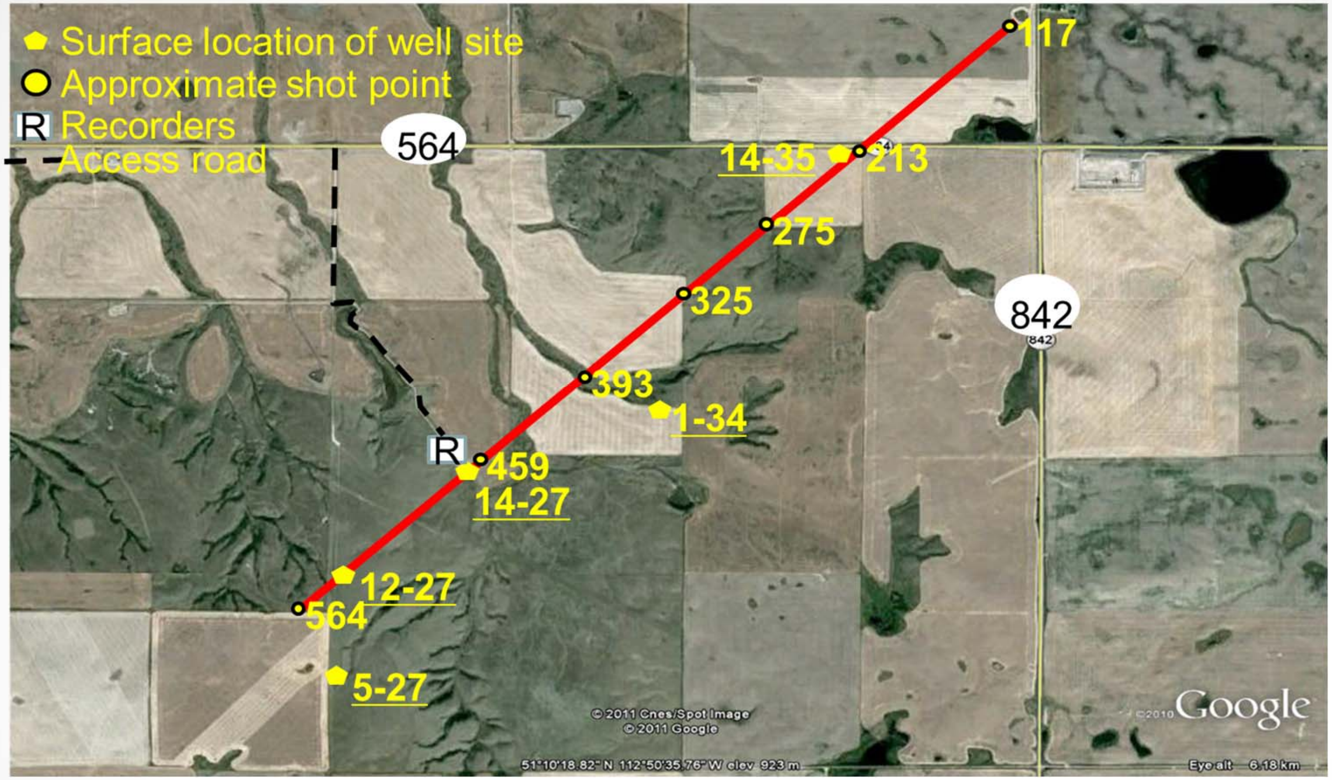
Forward Modelling/ray tracing

- Initial velocity model 4480m by 1000m, grid spacing 10m by 10m.
- Initial velocity model from firstbreaks analysis.
- Ray tracer; using Langan et al, (1985) approach of the two-point problem.
- Algorithm is Simultaneous Iterative Reconstruction Technique (SIRT).

Example with real data - Hussar Central Alberta



- 2D seismic line from Hussar, central Alberta.
- About 4.5km long running from Southwest to Northeast.
- Seismic source is dynamite, shot spacing 20m number of shots 269.
- Number of receivers is 448 with a receiver spacing of 10m.

Lloyd and Margrave, 2013

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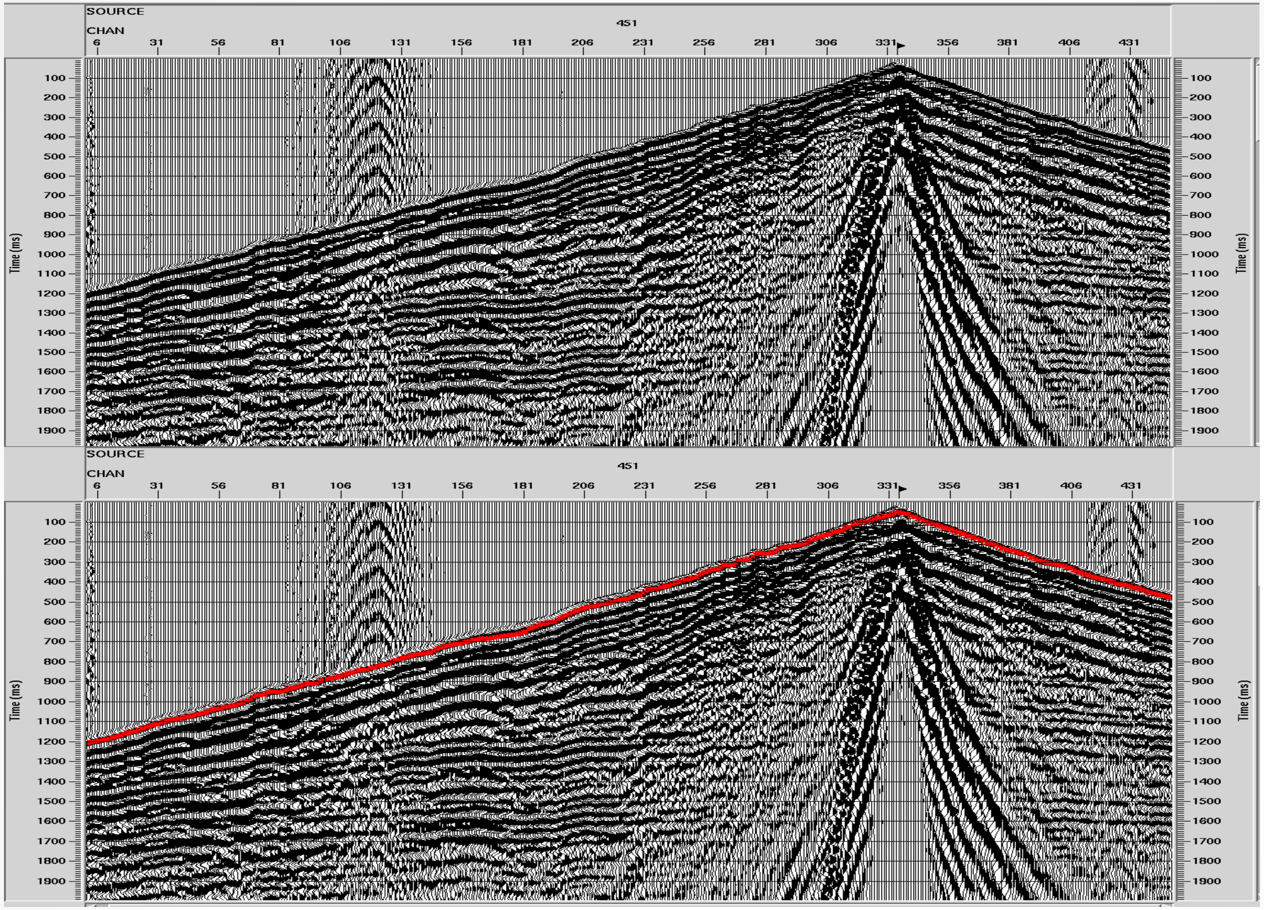
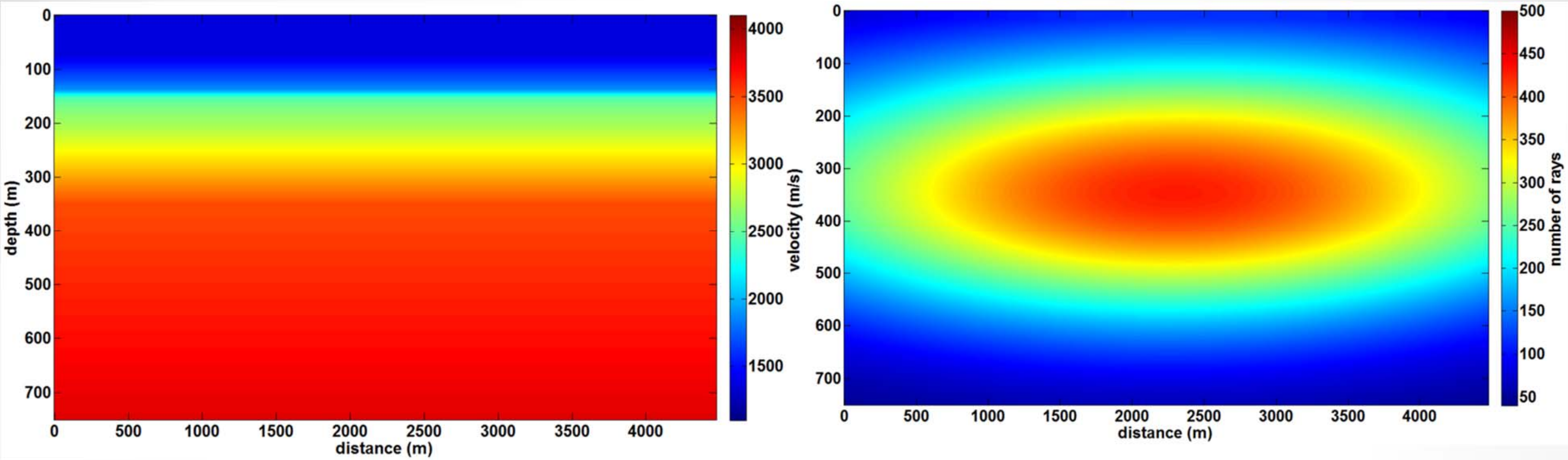
- Observed travel times is 269X448 = 120512 observed traveltimes.

- Number of unknowns are 4480X1000 /100 = 44800

- Inverse problem is over-determined



A shot gather from Hussar, showing firstbreaks picks in red.



QC Methods, Zhu (2002); ray density, first arrival fitting, and stack responses.

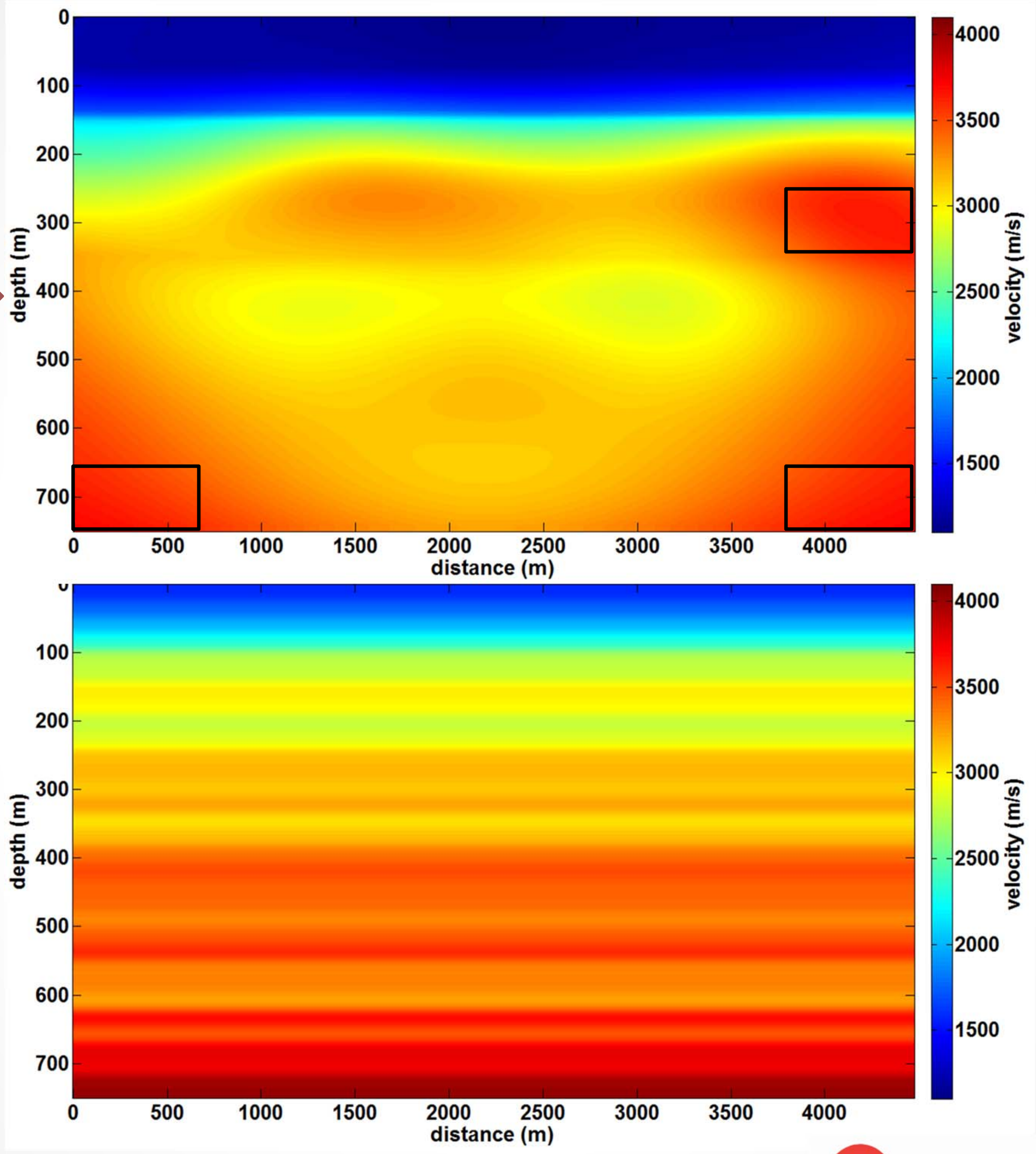
Damping

- Areas with small ray density were damped
- Minimum eigenvalue to consider during the inversion- decreasing the condition number of the matrix.

Constraints

- Could use well logs for better results.
- Maximum traveltimes to use in the inversion similar to the constrained damped SIRT-CDSIRT (Zhu et al, 1992)

Notice low velocity layer (hidden) layer between 350 and 450 meters cannot resolve with conventional refraction statics.



Final velocity model after 50 iterations. Artefacts or edge effects in the boxes

Low velocity layer between 350 and 400 meters.

Well 12-27 smoothed sonic logs. Start depth is 209 meters to 1570 meters, width of Gaussian smoother is 200 m.

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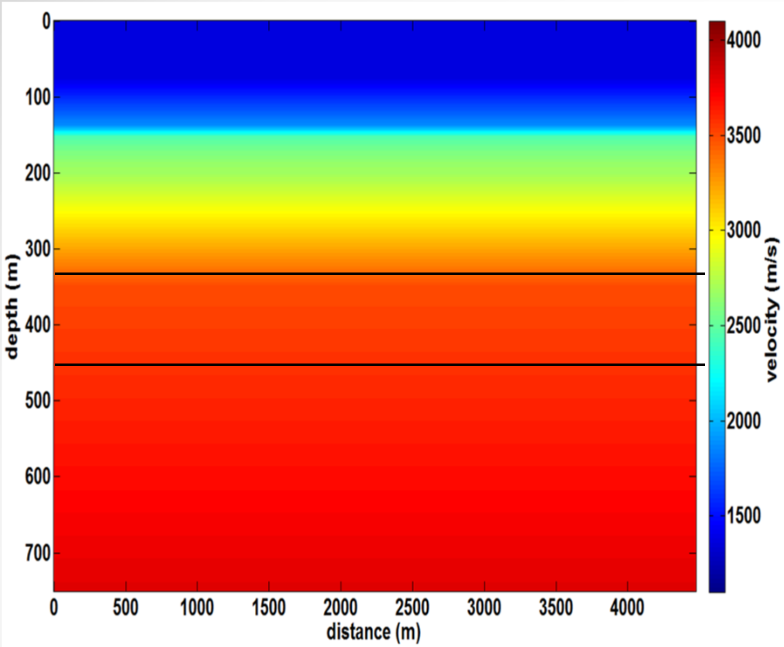

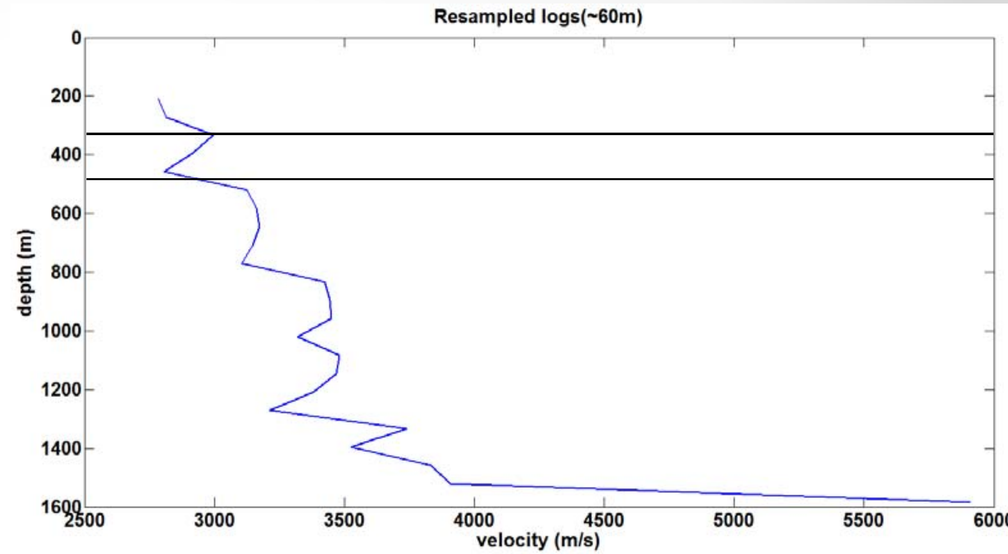

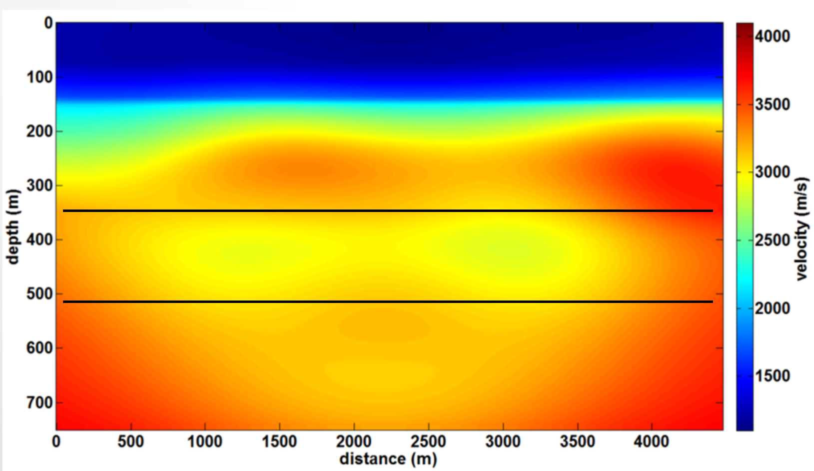

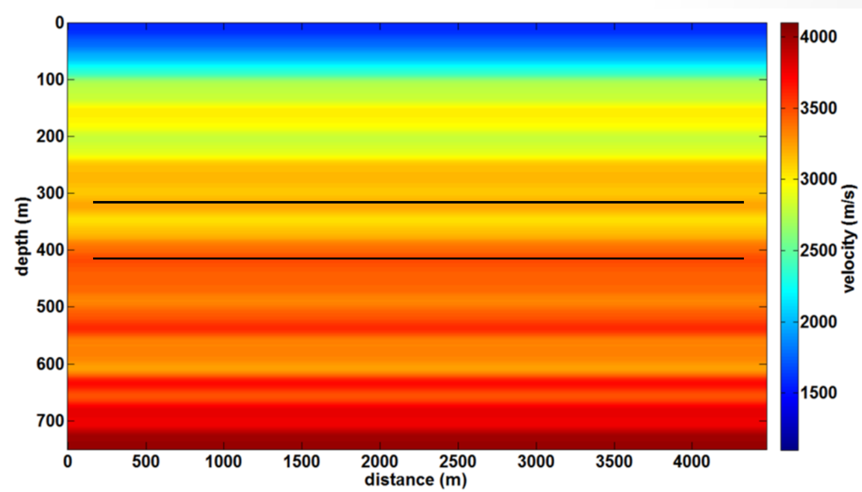

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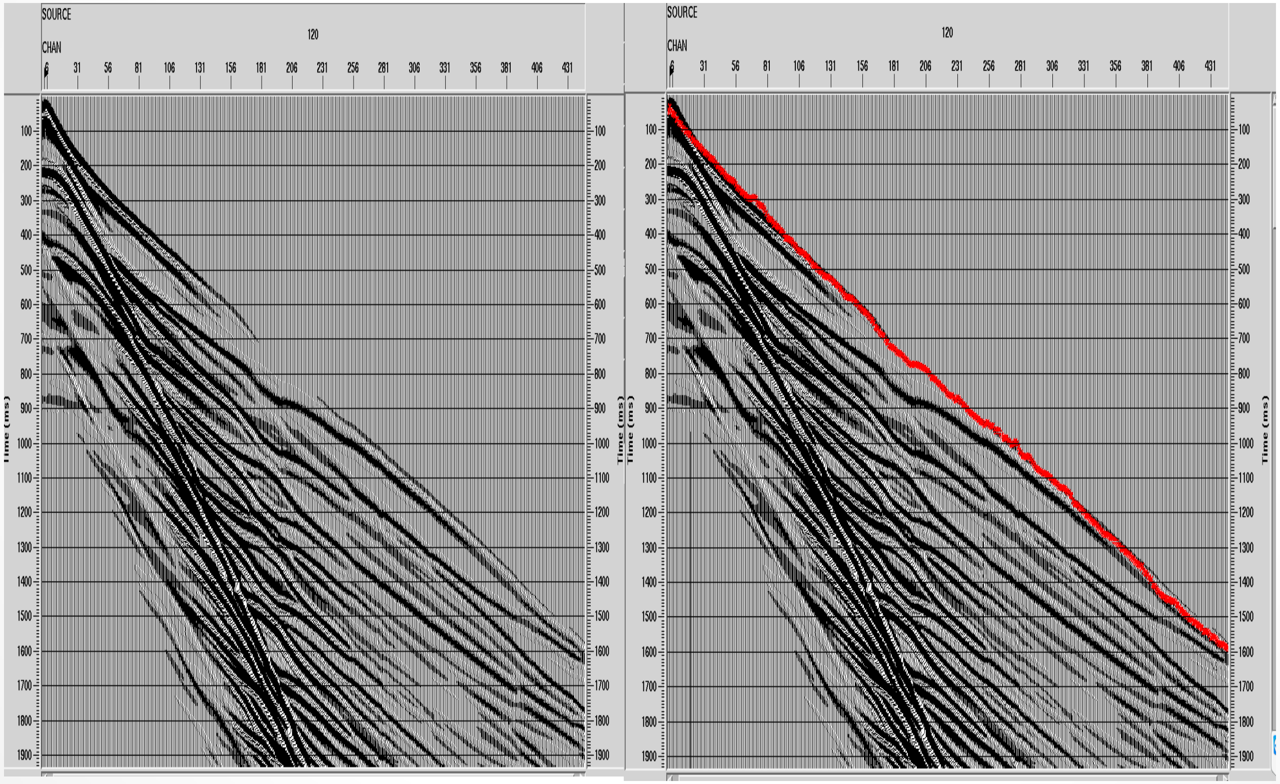
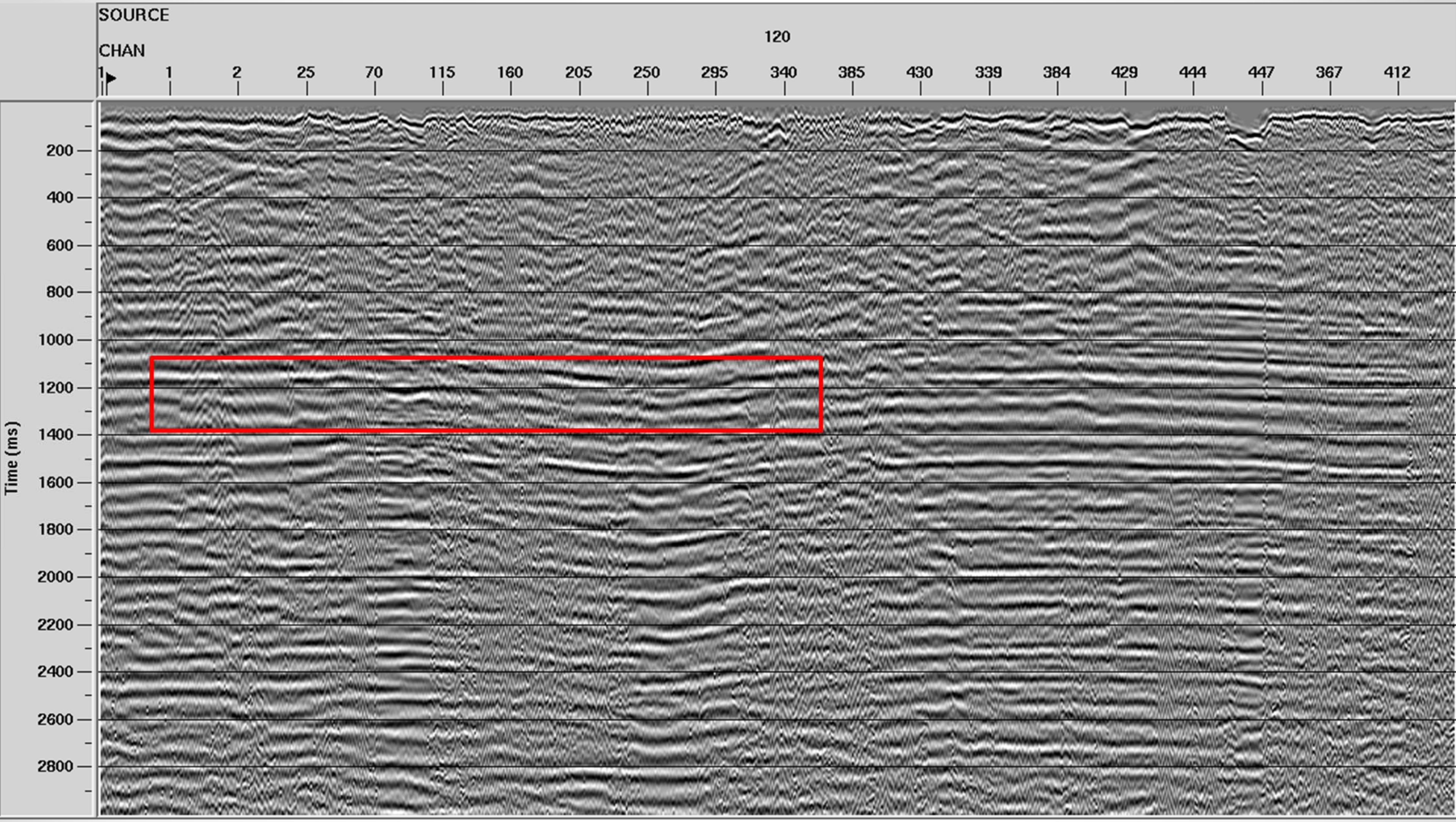
QC'ing

Synthetic data generated using acoustic finite difference. Minimum phase Ricker wavelet of 25 hertz. Observed traveltime picks superimposed on the synthetic data.



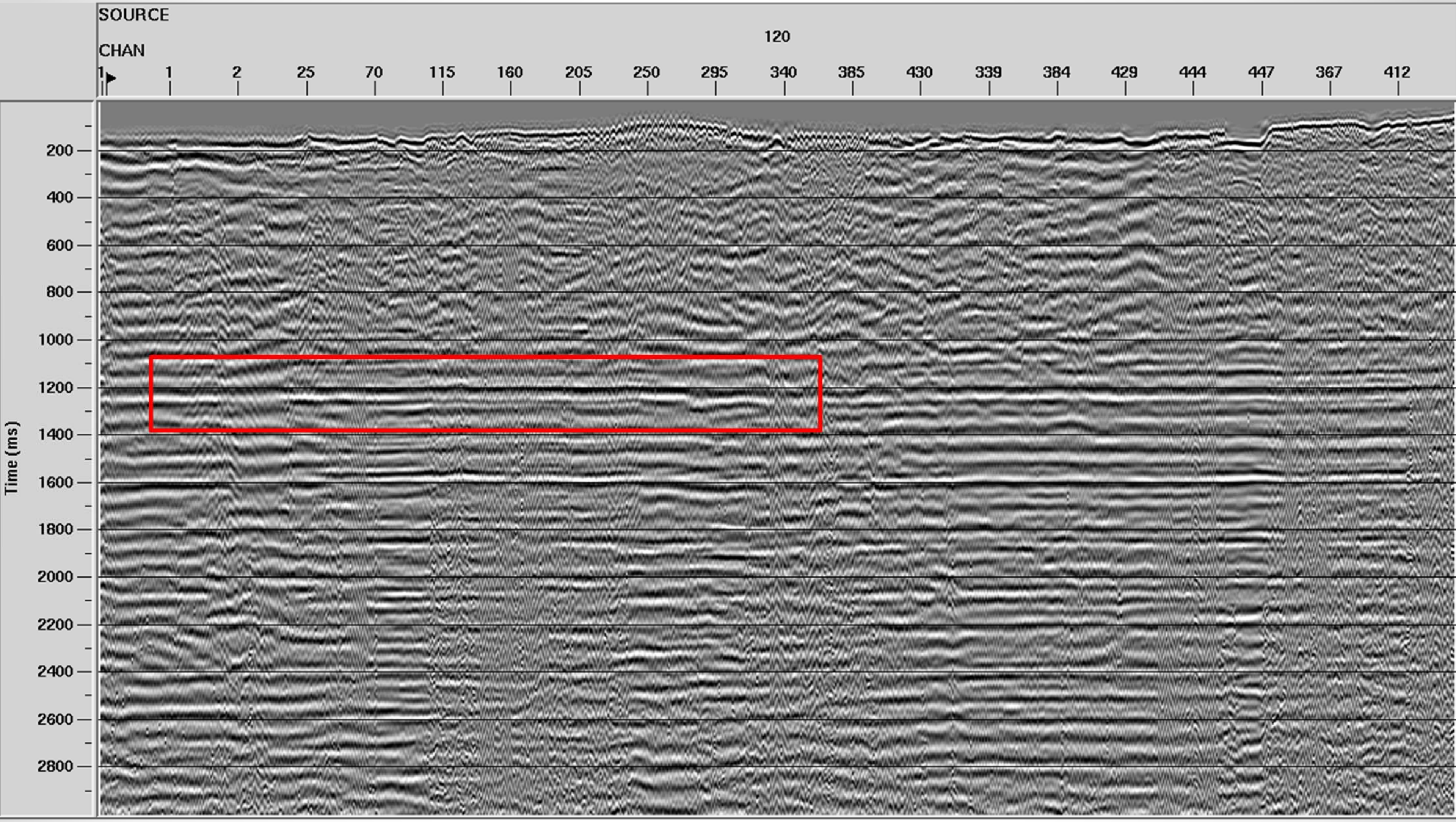
Are those the firstbreaks?

Results refraction statics



Event at 1200ms is not flattened and continuity uncertain

Results tomostatics



Event at 1200ms has been flattened and there is evidence of continuity

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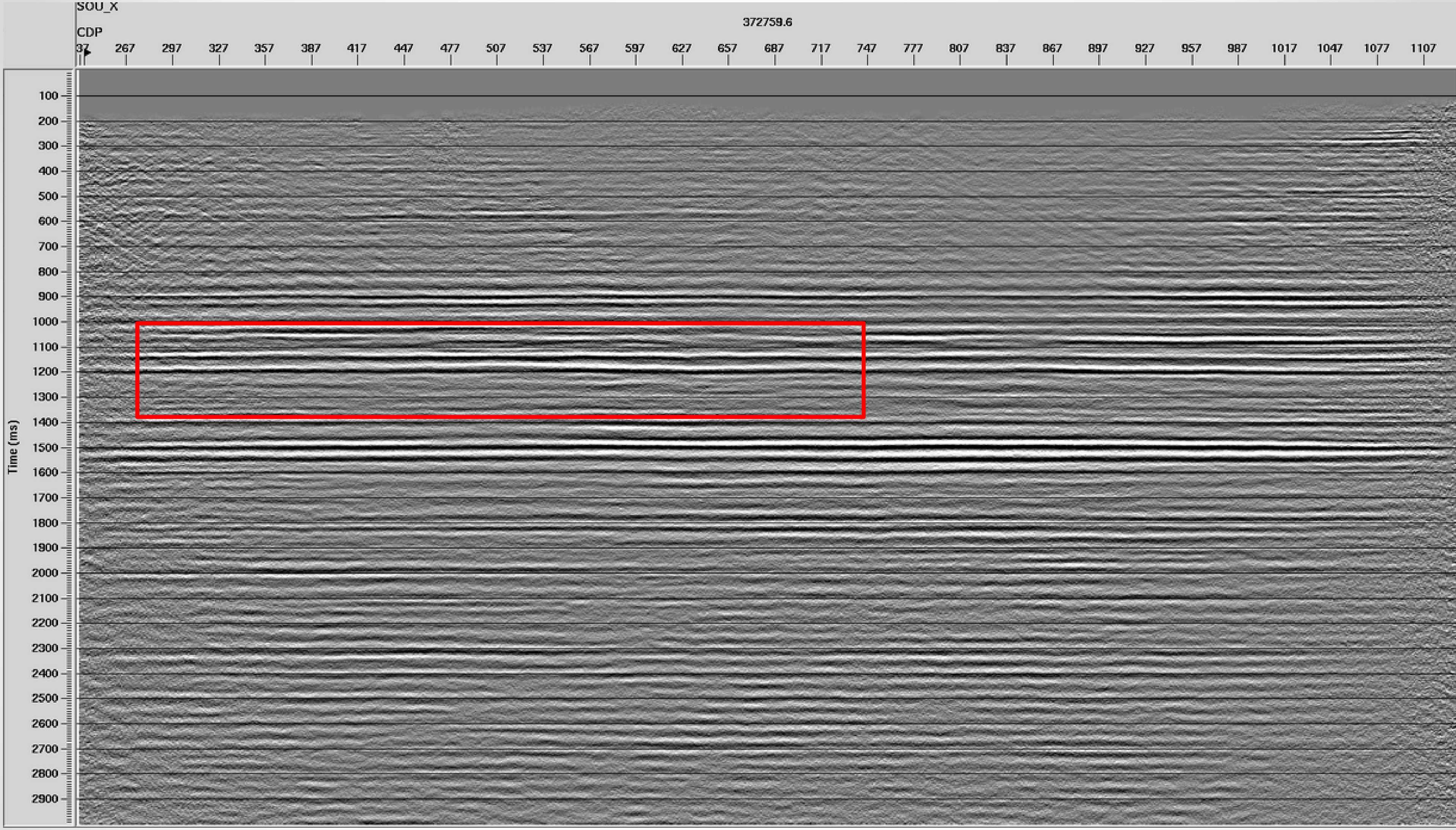


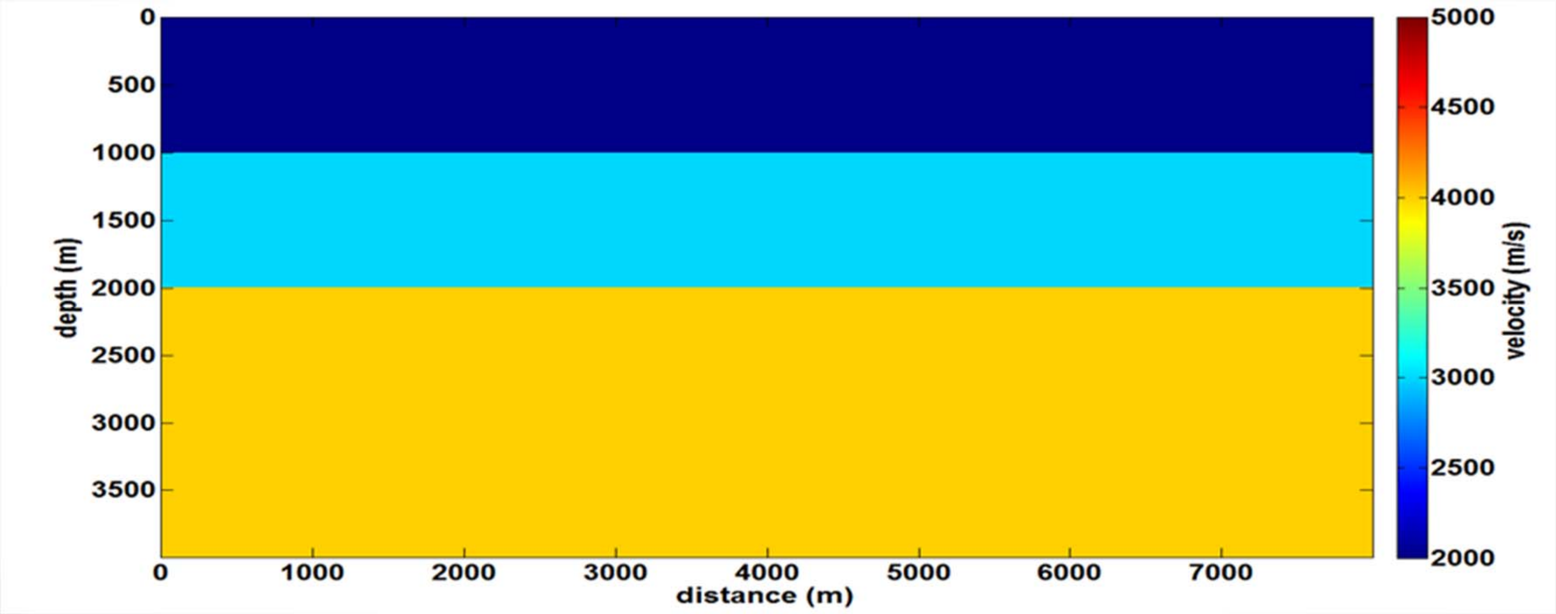
Final processed data. (Helen Isaac and Gary Margrave, 2011)

Acceleware's AxRTM…..preliminary results

Acceleware joined CREWES fairly recently. They have a forward modelling and reverse time migration package in C language.

The AxRTM API runs on GPU's and CUDA (Compute Unified Device Architecture) devices.

Can do 2D, 3D. Can do anisotropy (not tested yet). It is fast.



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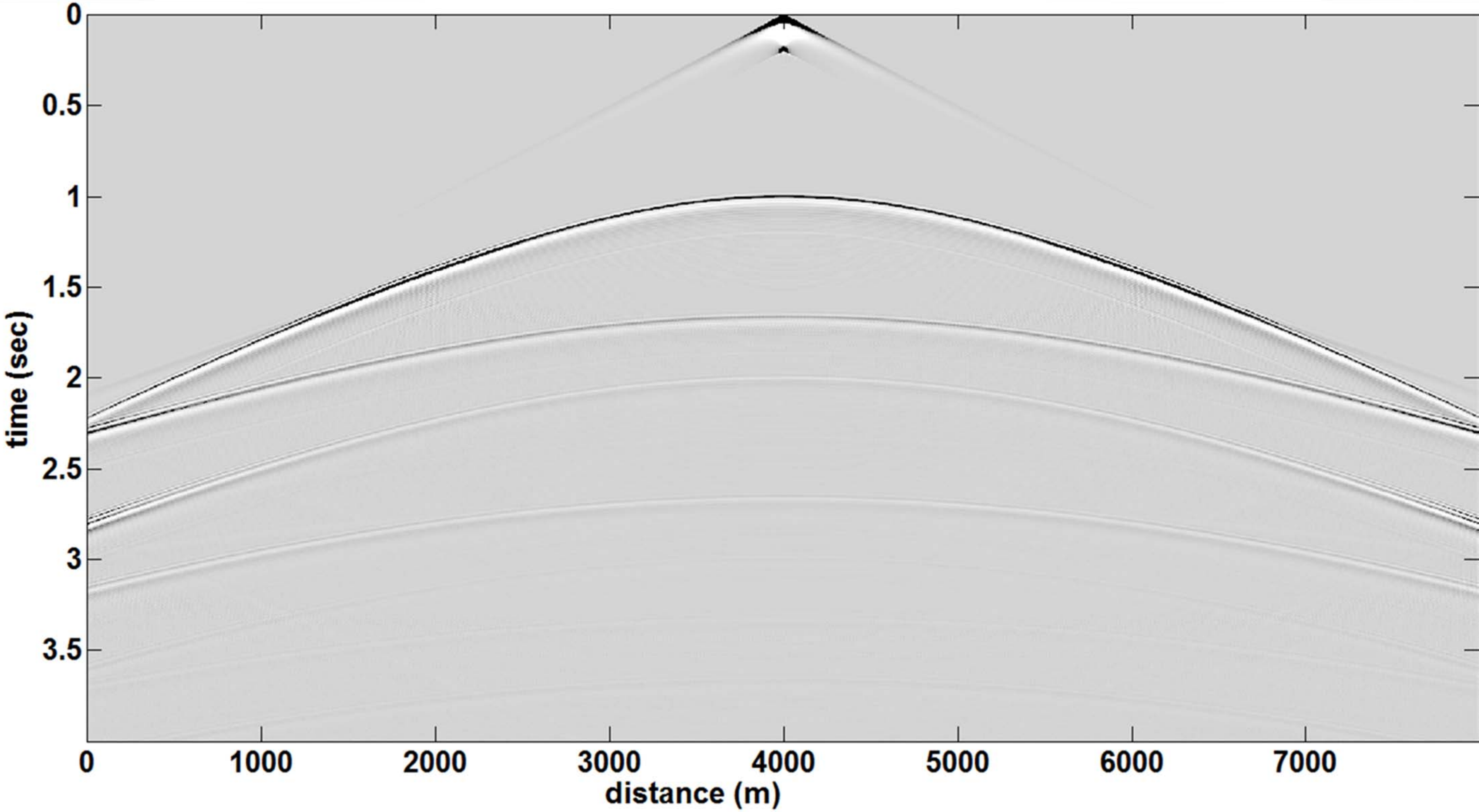
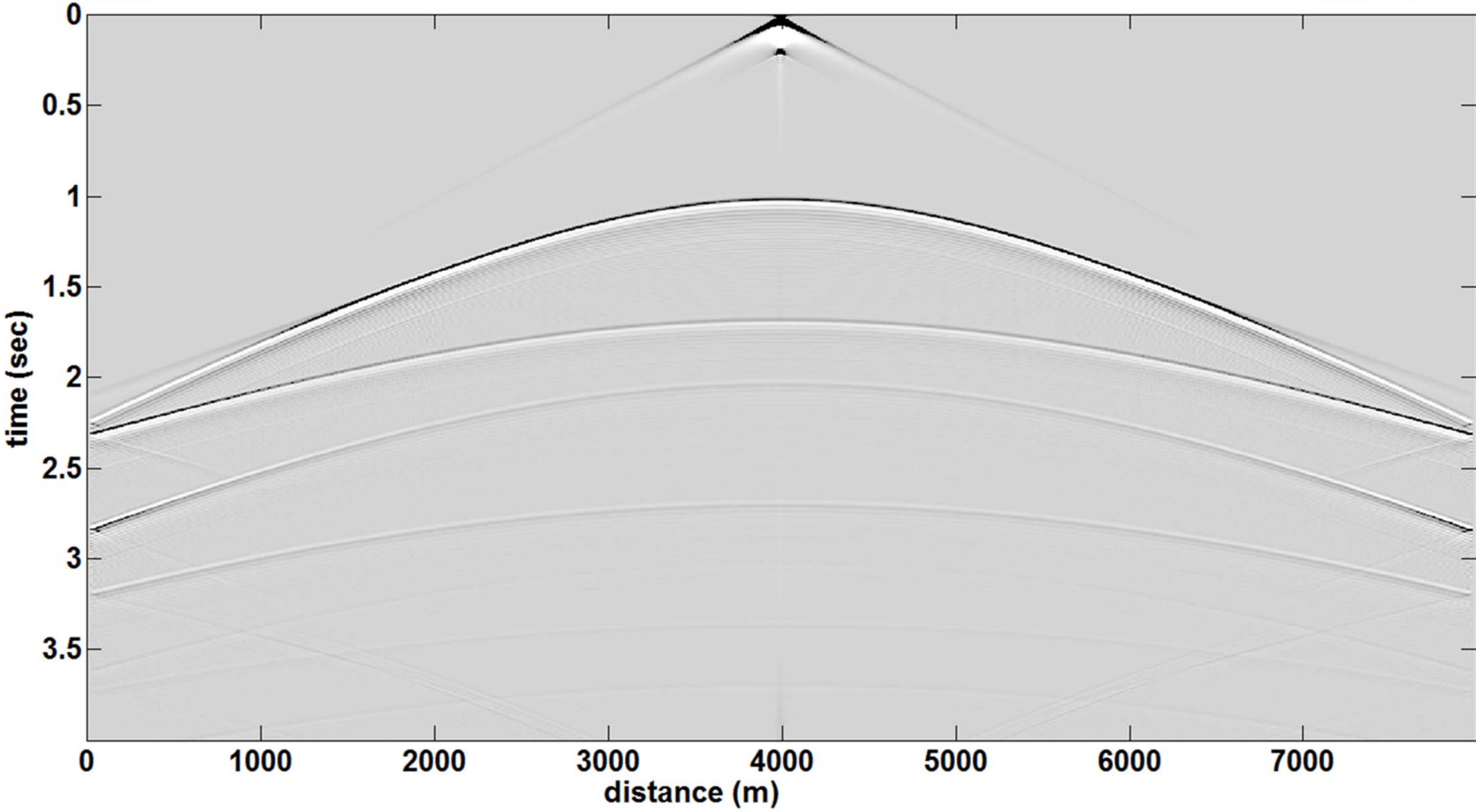
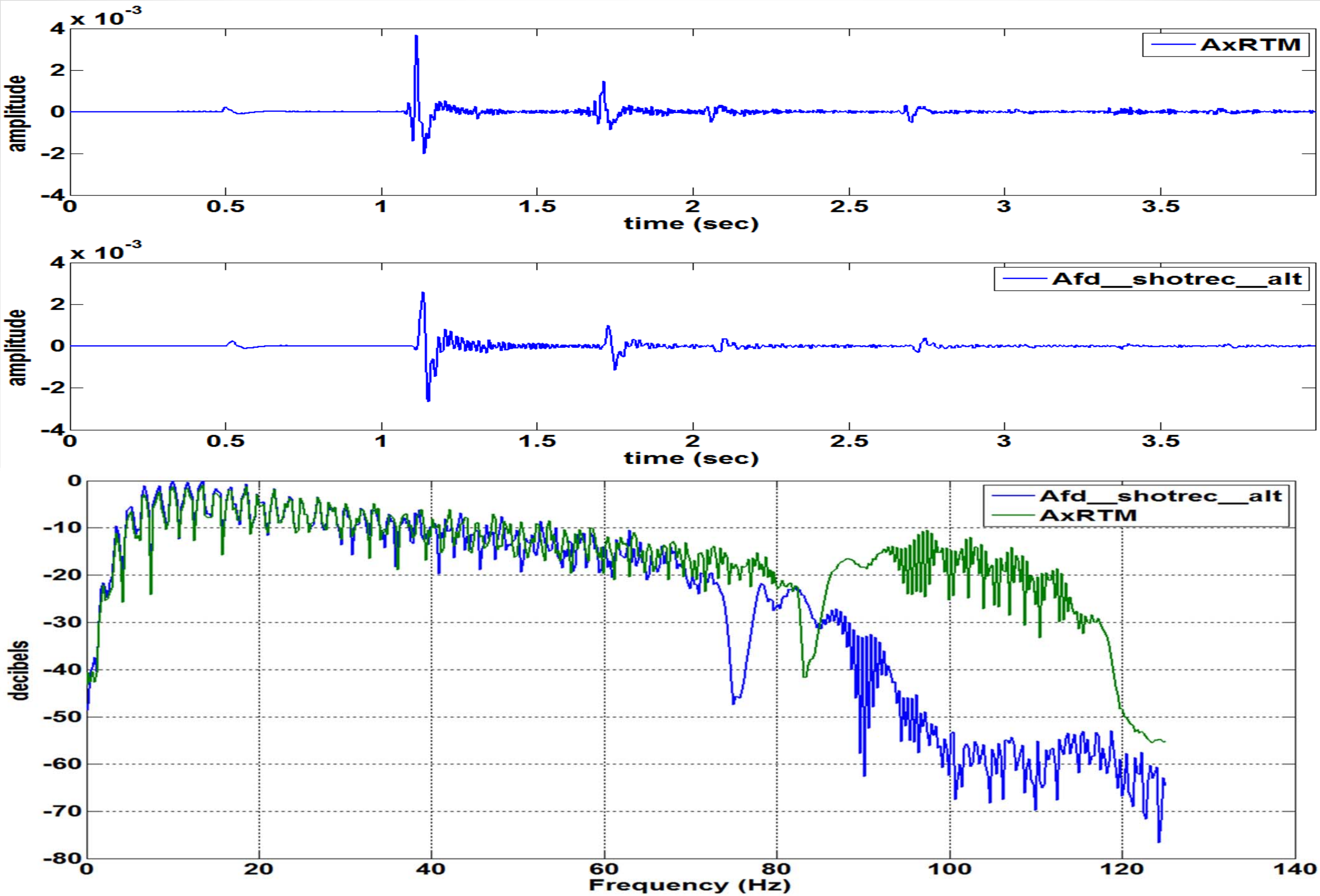
Shot record from AxRTM



Shot record using afd_shotrec_alt from CREWES toolbox





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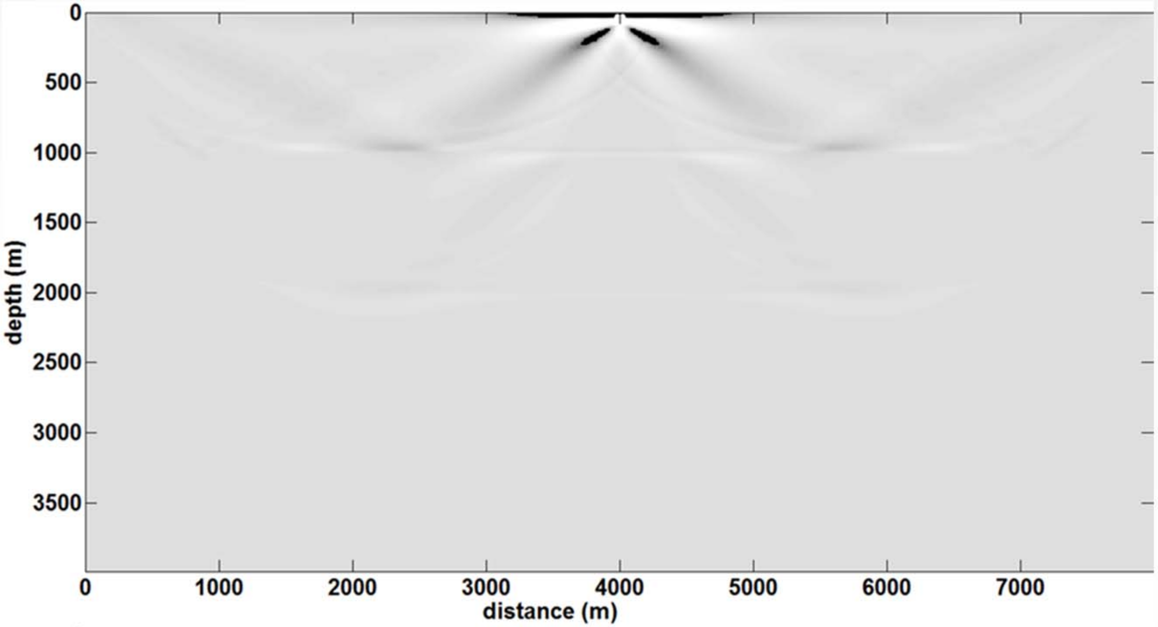
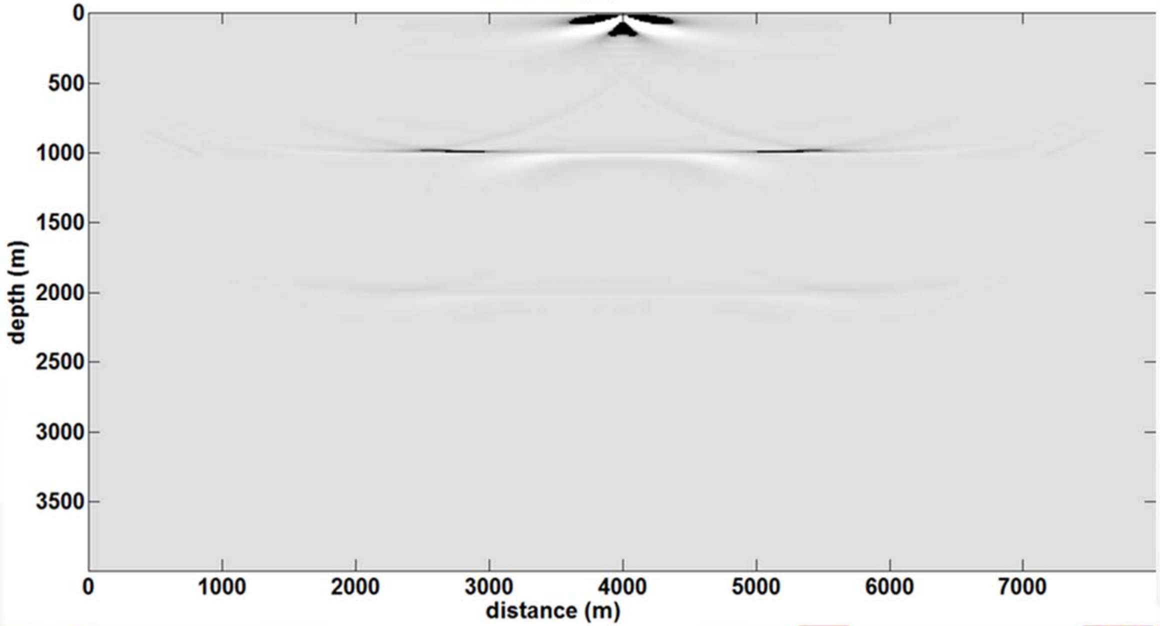
AxRTM, C-language.



PSPI, Matlab.



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Going forward we will attempt to solve the FWI problem in the time domain using RTM.

The model update in FWI can be expressed as

$$m_o(\mathrm{z})^{(n+1)} = m_o(\mathrm{z})^{(n)} + \partial m_o(z)^{(\mathrm{n})} \qquad m_o(\mathrm{z})^{(n+1)} = m_o(\mathrm{z})^{(n)} + \mu^{(n)}\,\mathrm{g}(z)^{(n)}$$

$$\mathrm{g}(z)^{(n)} = \int d\omega\omega^2 G(\mathrm{z}, \mathrm{z}_{\mathrm{S}}, \omega \mid \mathrm{m}_o{}^{(n)})[\mathrm{G}(\mathrm{z}_g, \mathrm{z}, \omega \mid \mathrm{m}_o{}^{(n)})\delta P^*(\mathrm{z}_g, \mathrm{z}_S, \omega \mid \mathrm{m}_o{}^{(n)})]$$

Conclusions

- Turning-ray tomography is a viable technique for use in statics correction especially in areas where conventional refraction statics fail such as the case of a hidden layer as we saw in the Hussar velocity model.

- The continuity and structure of the event at 1200ms has been improved by TRT.

- One important advantage of TRT is that the ambiguity between reflector depth and velocity is absent.

- The constrained SIRT algorithm increases convergence rate and improves the result.

- The result from TRT can be used for prestack depth migration and as a starting model for FWI.

- For the AxRTM test, we observed that AxRTM runs about 10 times faster than the PSPI pre-stack migration algorithm although the PSPI runs on CPU.

Future work

- Developing TRT or reflection traveltime tomography codes; ray-tracer or FD for forward modelling,

- Having a finished product for FWI, i.e. using TRT for starting models, incorporating well data, and using a RTM engine to drive the inversion.

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