Hybrid linear and non-linear full-waveform inversion application to Gulf of Mexico data

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ABSTRACT

We propose a hybrid linear and non-linear optimization method to enhance the FWI results. In this method, iterative least-squares reverse-time migration (LSRTM) is used to estimate the model update at each non-linear iteration, and the number of LSRTM iterations is progressively increased after each non-linear iteration. With this method, model updating along deep reflection wavepaths are automatically enhanced, which in turn improves imaging below the reach of diving-waves. This hybrid linear and non-linear FWI algorithm is implemented in the space-time domain to simultaneously invert the data over a range of frequencies.

TIME-DOMAIN MODEFIED GAUSS-NEWTON IMPLEMENTATION

At each non-linear iteration, this linear system of equation,

$$(\mathbf{J^T J})\mathbf{g} = \mathbf{J}^T \delta \mathbf{d}_k,$$

is solved using pre-conditioned Conjugate Gradient Solver, to calculate the step-direction. The step length is estimated using a numerical line search, and the slowness model is updated,

$$\mathbf{s}_{k+1} = \mathbf{s}_k - \alpha_k \mathbf{g}$$

The Jacobian operator and its adjoint are implemented in the time-domain, which is convenient and efficient for solving imaging problems.

The solution of the two simultaneous partial differential equations

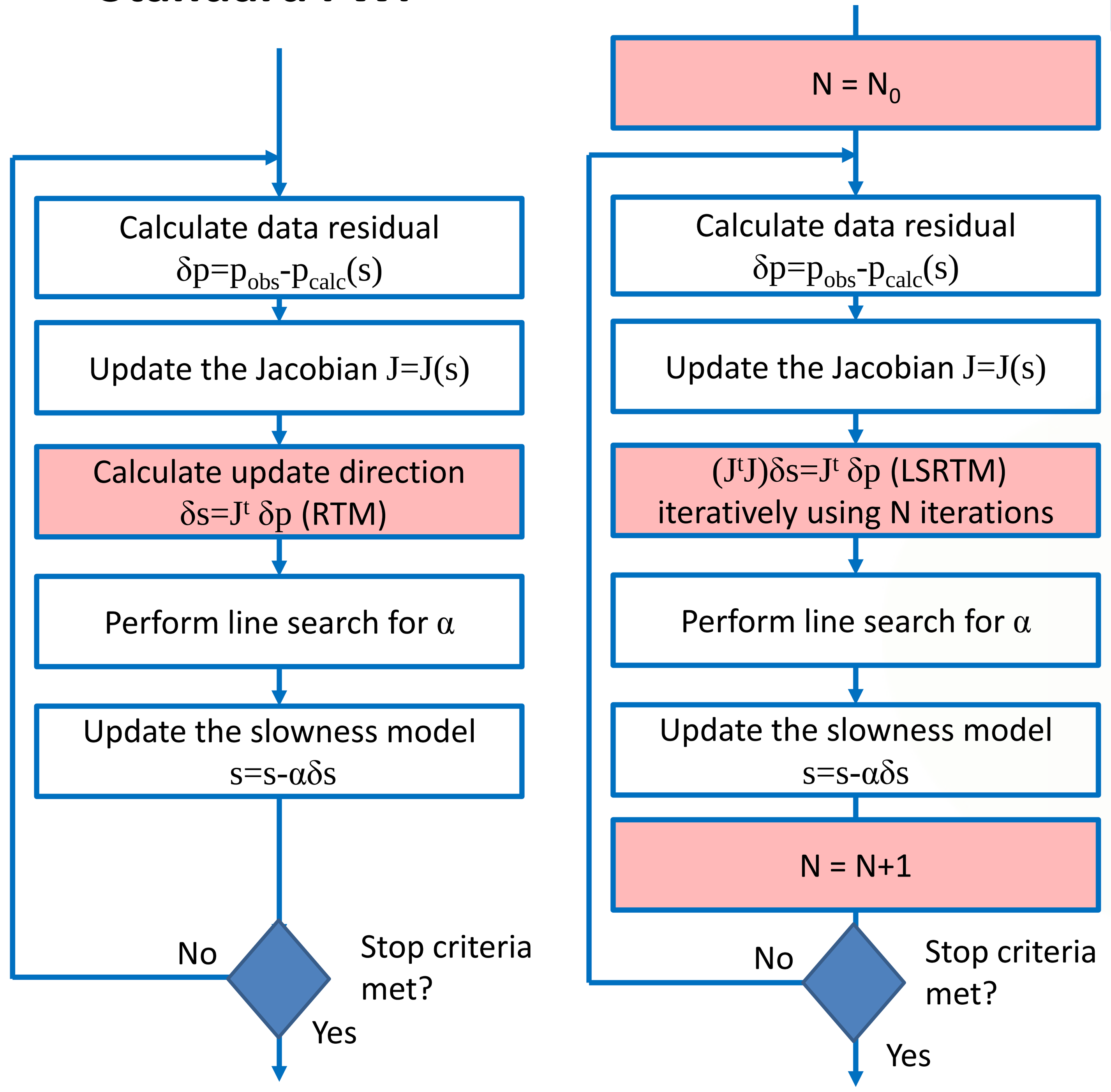
$$\begin{aligned}(\nabla^2 + \omega^2 s_0^2)\, p_0(\mathbf{x},\omega) &= -\delta(\mathbf{x}-\mathbf{x}_s)\, q(\omega),\\ (\nabla^2 + \omega^2 s_0^2)\, \delta p(\mathbf{x},\omega) &= -2\omega^2 s_0 \delta s(\mathbf{x})\, p_0(\mathbf{x},\omega)\end{aligned}$$

is the Lippmann-Schwinger equation

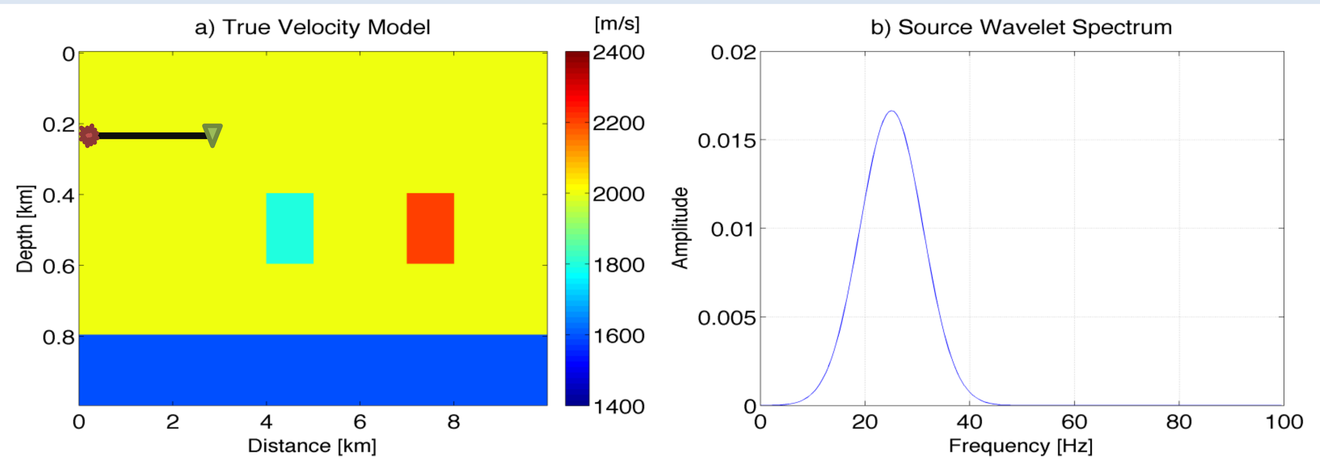
$$\delta p(\mathbf{x}_r,\omega) = 2\int \omega^2 s_0(\mathbf{x})\, \delta s(\mathbf{x})\, p_0(\mathbf{x},\omega)\, G_0(\mathbf{x}|\mathbf{x}_r,\omega)\, d\mathbf{x}$$

Similarly, we can apply the adjoint operation by numerically solving the following equations:

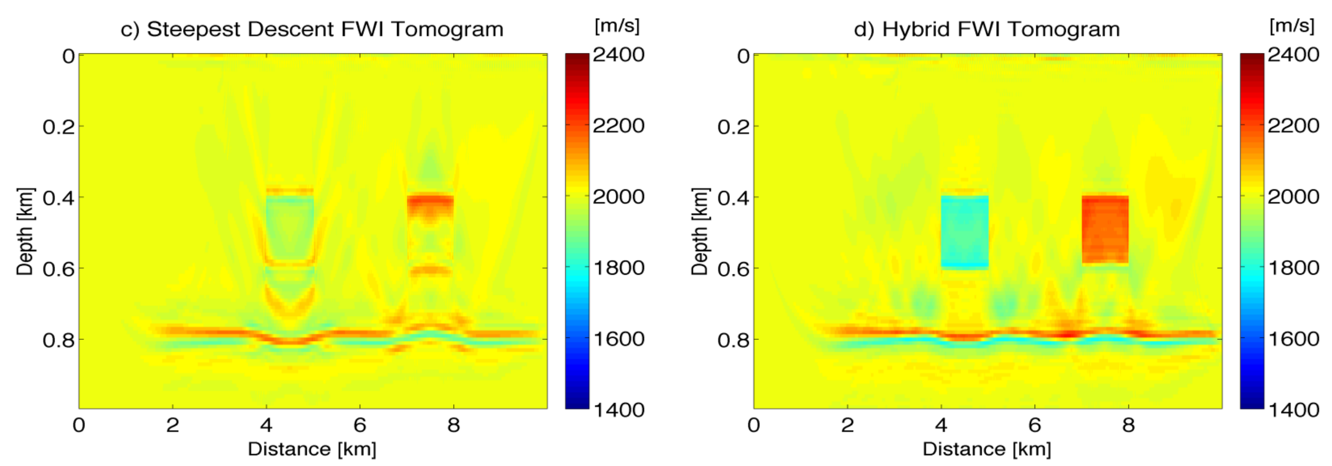
$$\begin{aligned}\left(\nabla^2 + \omega^2 s_0(\mathbf{x})^2\right) p_0(\mathbf{x},\omega) &= -\delta(\mathbf{x}-\mathbf{x}_s)\, q(\omega),\\ \left(\nabla^2 + \omega^2 s_0(\mathbf{x})^2\right) R^*(\mathbf{x},\omega) &= -\delta(\mathbf{x}-\mathbf{x}_r)\, 2\omega^2 \delta p^*(\mathbf{x}_r,\omega)\\ \delta s(\mathbf{x}) = \int s_0(\mathbf{x})\, R^*(\mathbf{x},\omega)\, p_0(\mathbf{x},\omega)\, d\omega &= \\ 2\iint \omega^2 s_0(\mathbf{x})\, p_0(\mathbf{x},\omega)\, G_0(\mathbf{x}|\mathbf{x}_r,\omega)\, \delta p^*(\mathbf{x}_r,\omega)\, d\mathbf{x}_r d\omega. &\end{aligned}$$



NUMERICAL TEST



A constant initial velocity model was used.

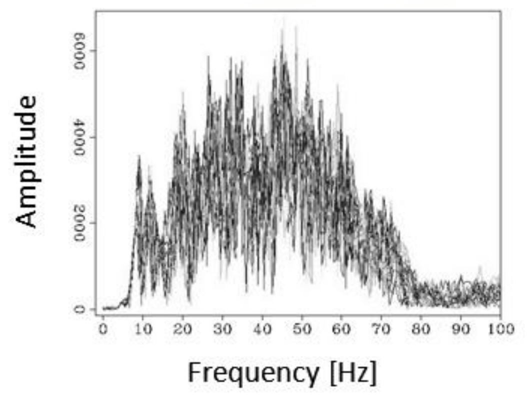


Hybrid FWI implicitly enhances reflection wavepaths which result in recovery of long wavelength features of the subsurface, even though low frequencies are not present in the data. Standard FWI fails in reconstructing shallow anomalies.

MULTISCALE INVERSION OF GOM DATA

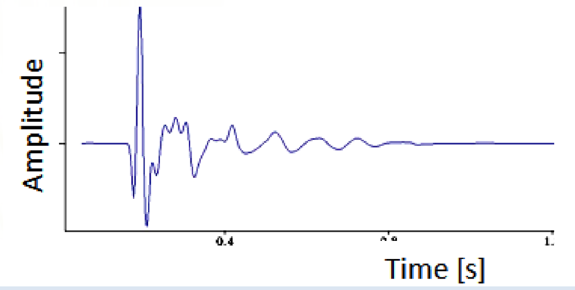
Survey Parameters:

Receiver spacing:	12.5 m
Shot spacing:	37.5 m
Number of receivers:	480
Number of shots:	515
Offset:	198 - 6,184

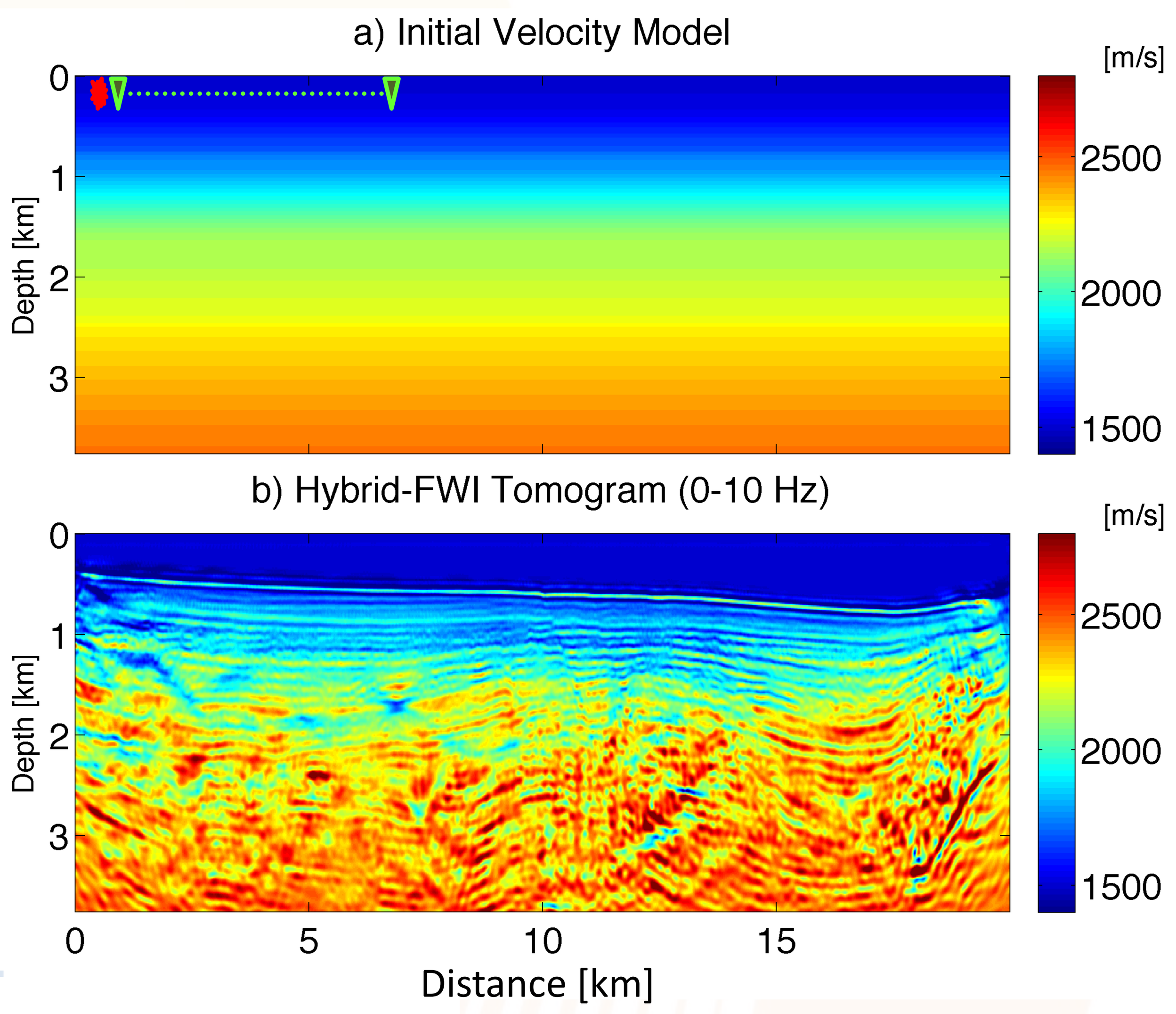


Processing:

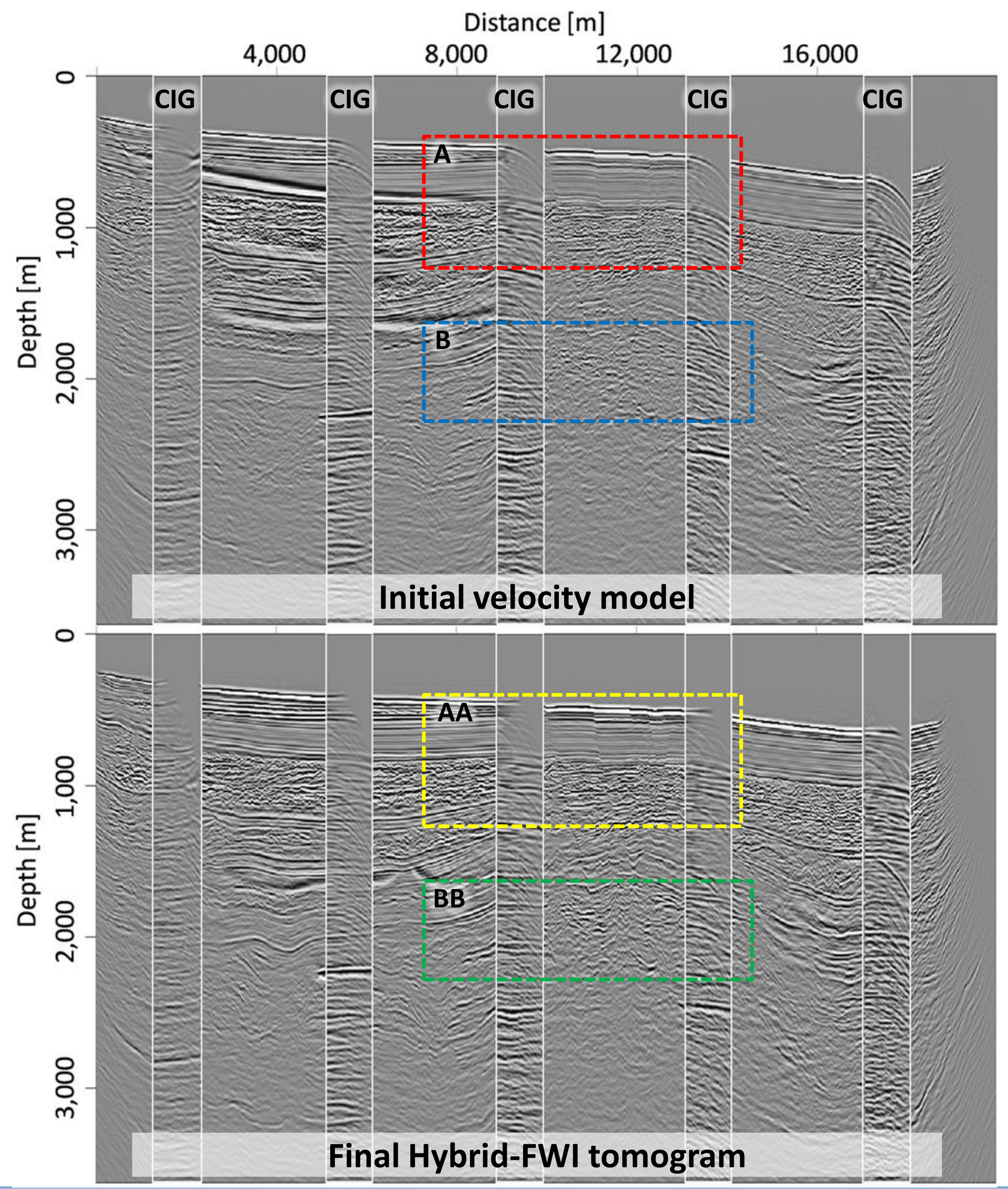
- 3D to 2D Correction.
- Wavelet estimation:

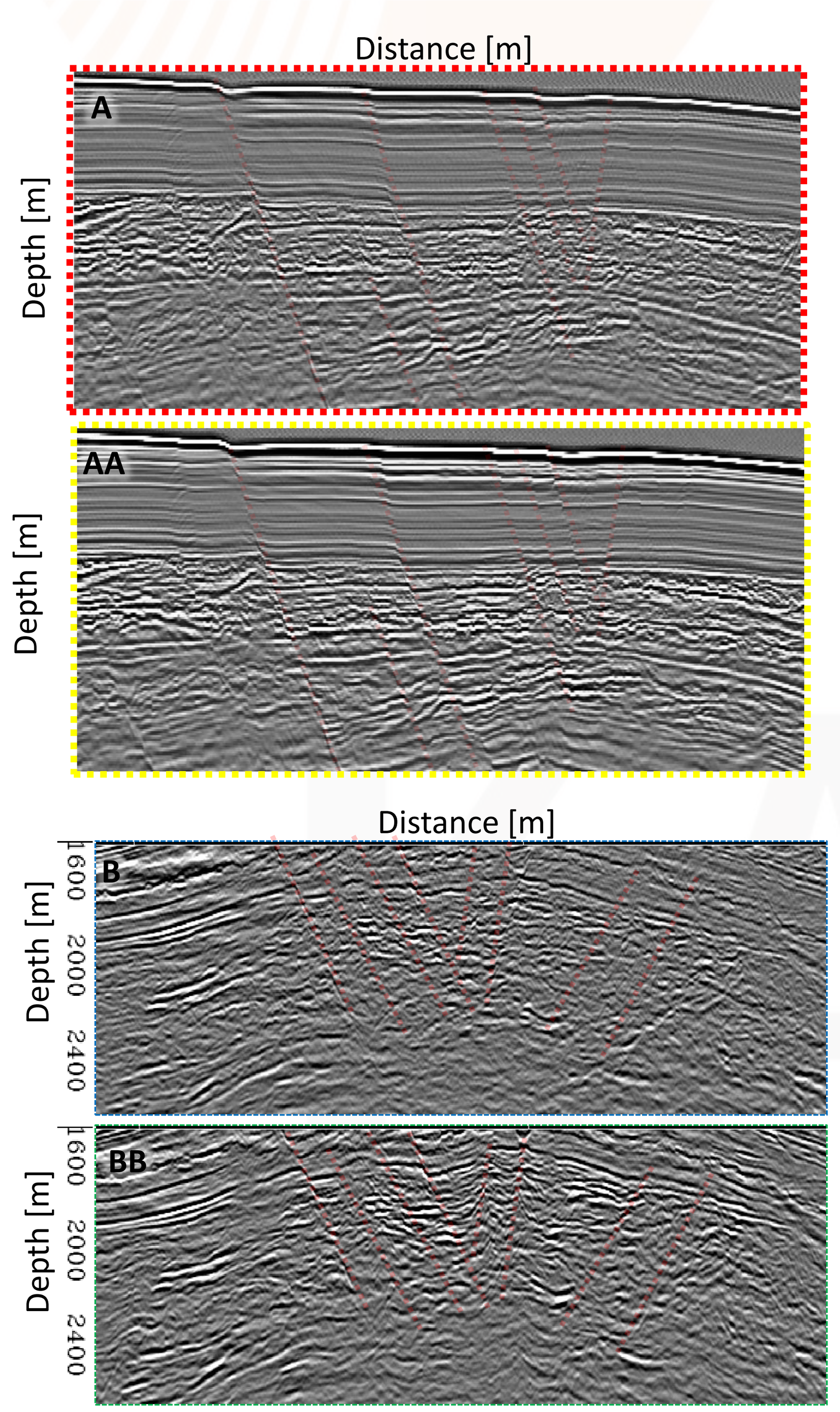


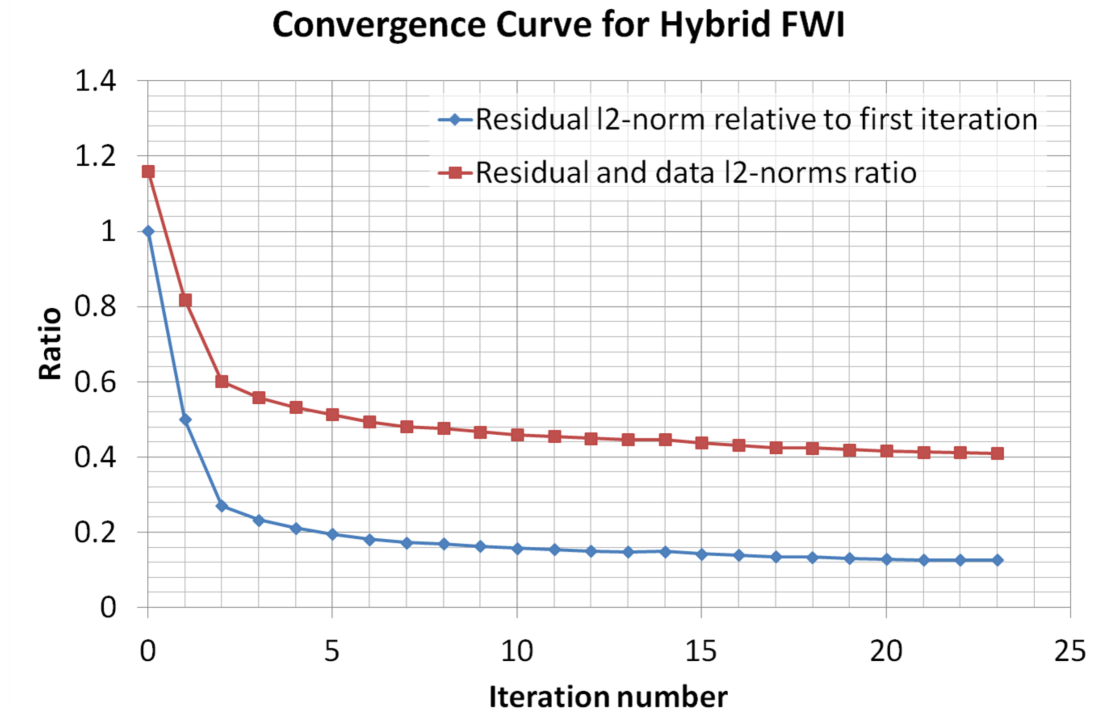
INVERSION RESULT



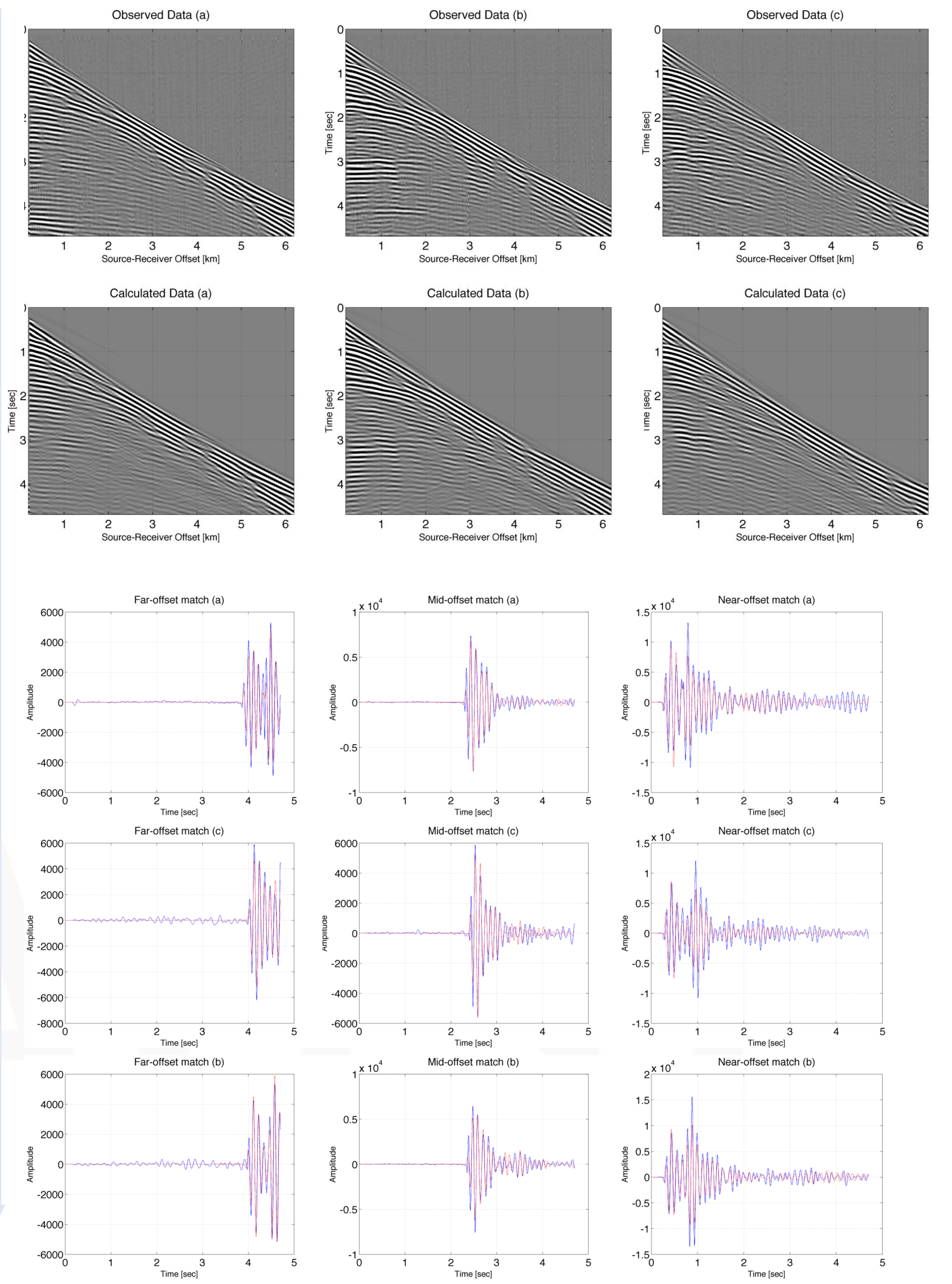
KIRCHHOFF MIGRATION IMAGES







CALCULATED & OBSERVED DATA COMPARISON



$\mathbf{J}$:Jacobian Operator, s_0 : background slowness, δs : slowness perturbation, p_0 :background wavefield, δp : scattered wavefield, q : source wavelet

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