Constrained waveform inversion of colocated VSP and surface seismic data

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Overview (1)

- Land case study:
  3D VSP + surface seismic (vibroseis acquisition)
- Combined FWI of surface (diving wave) and
  VSP (direct-wave) arrivals for joint velocity model
- Processing in 2D using multiple profiles at
  different North asimuths

Overview (2)

- Dykstra's projection algorithm and Projected Quasi-Newton (PQN) for constrained optimization
- Semi-automatic data pre-processing in Matlab from original field seismic records
- Automated workflow developed for E–W cross-section that is applied automatically to other North asimuths

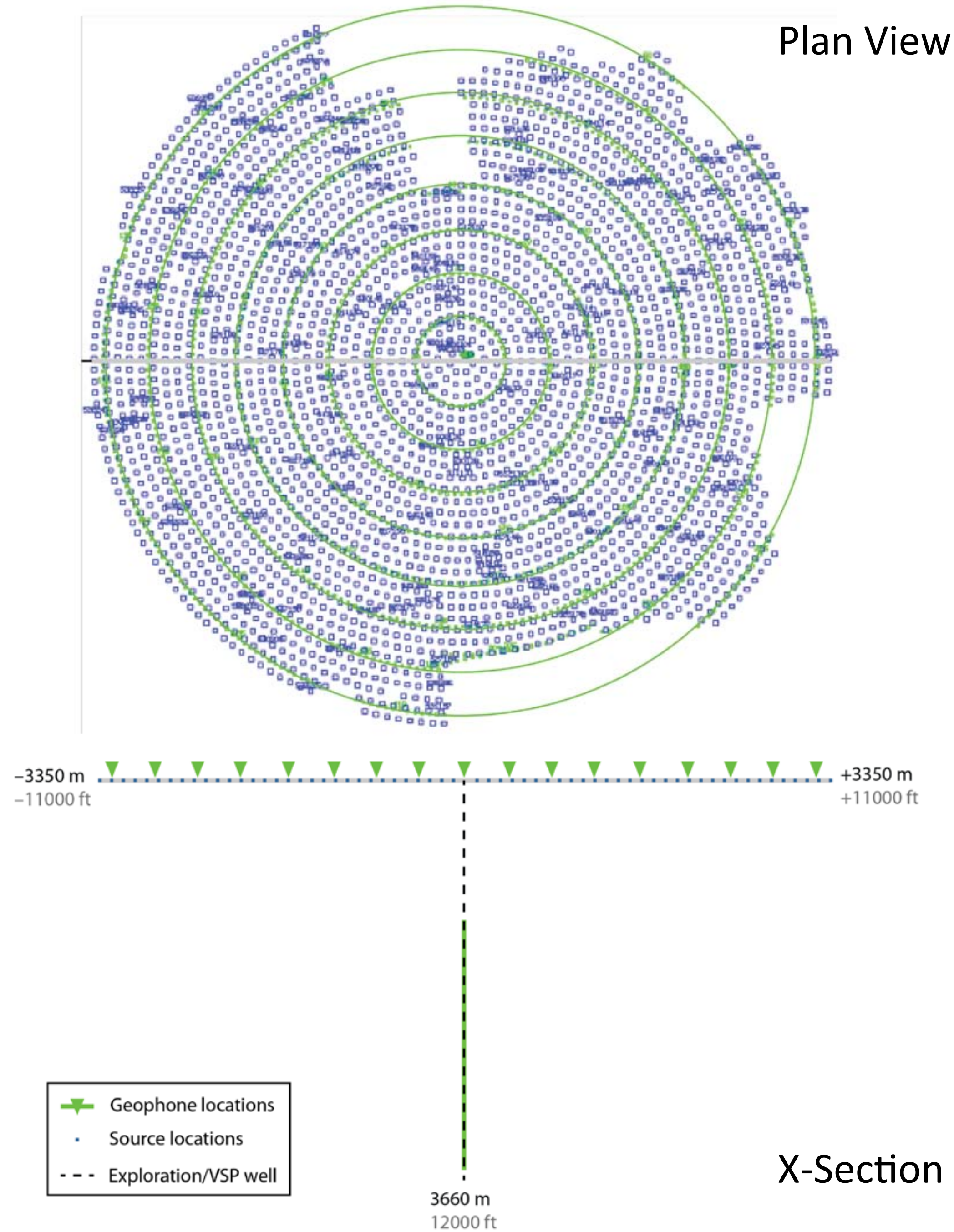
Survey Configuration

3D VSP survey + MCS

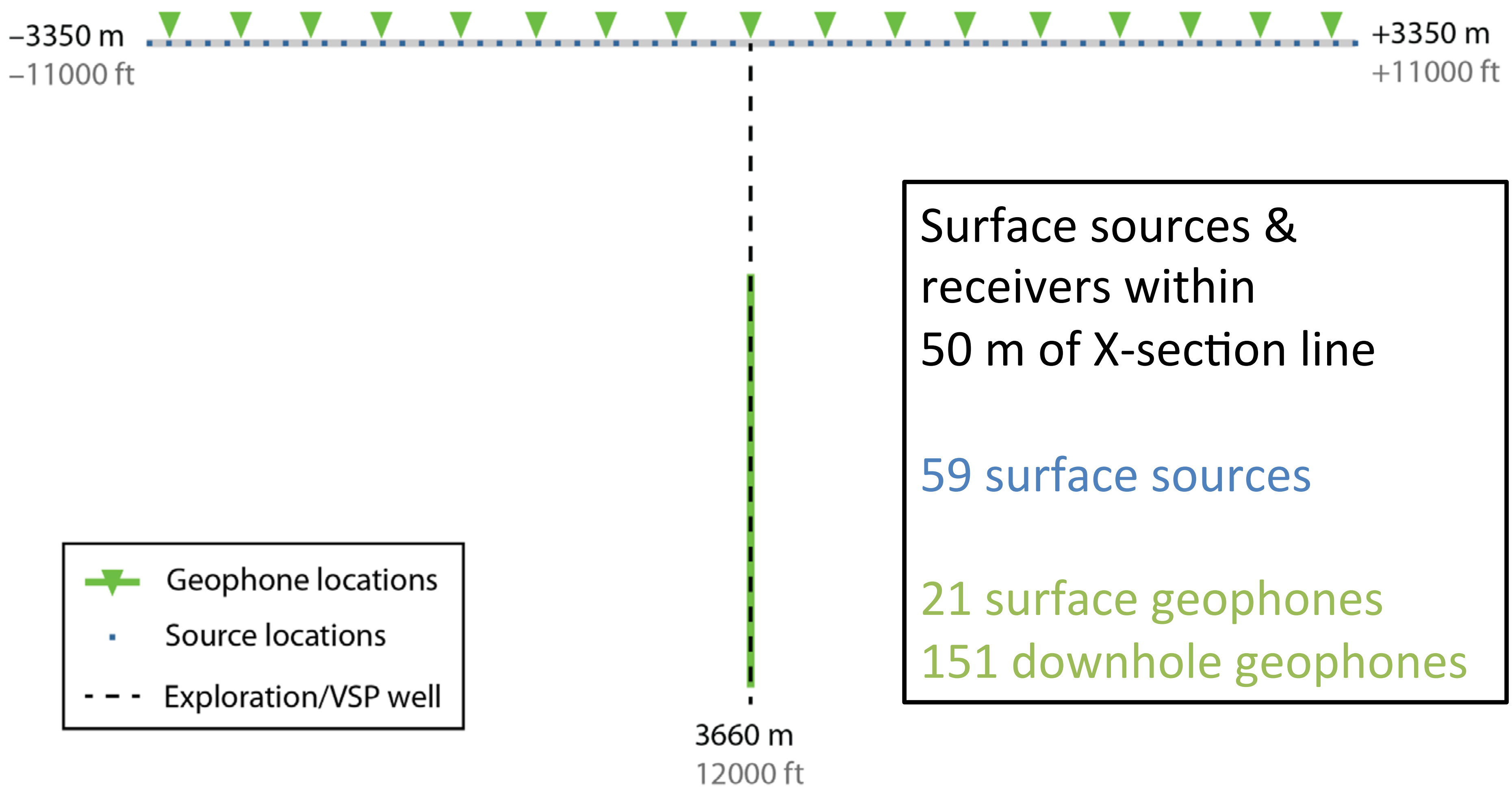
2785 shared sources (vibroseis VPs)

1649 surface recs (vertical geophones)

151 downhole recs (3C geophones)



2D X-Section Array

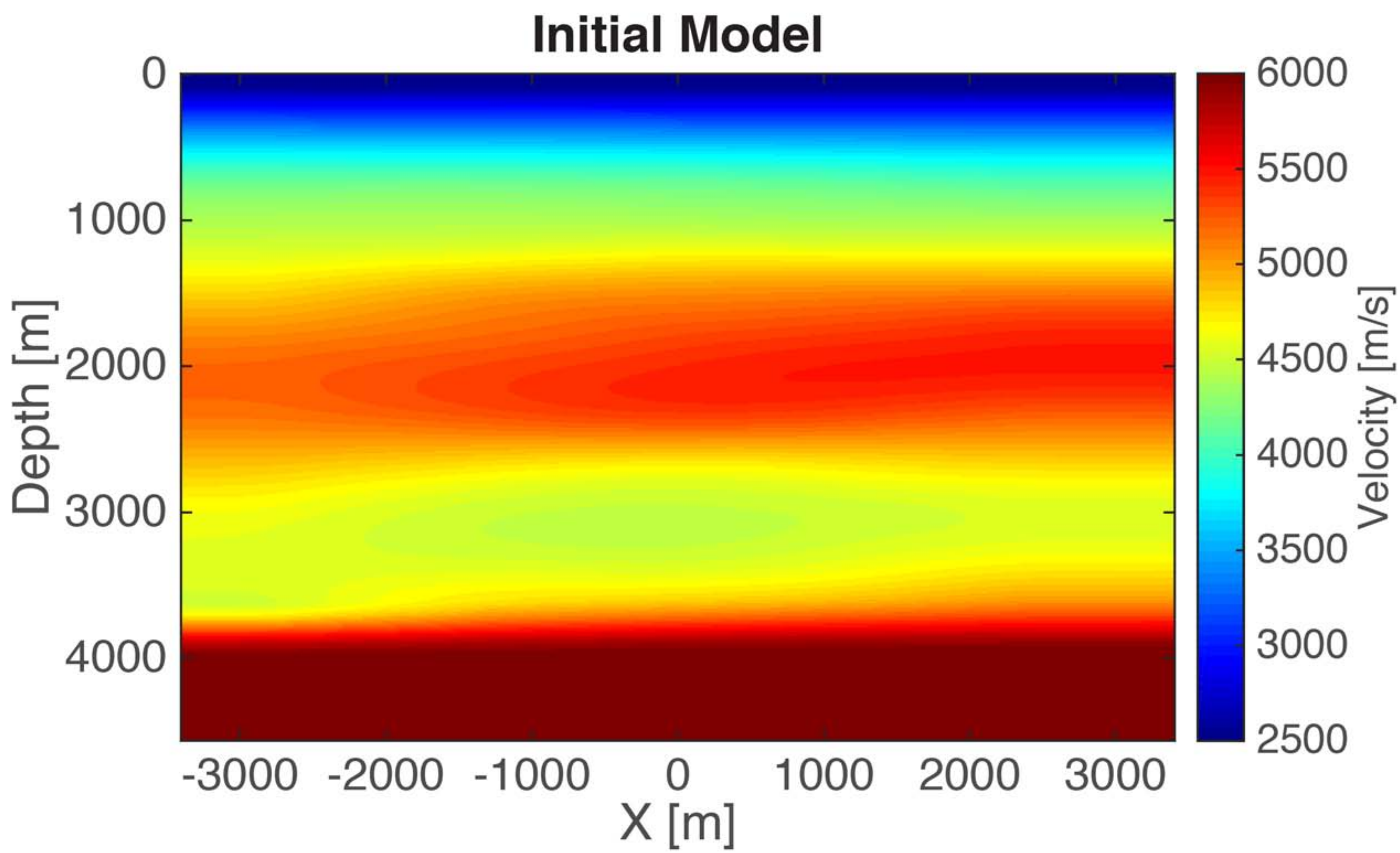


Surface sources & receivers within 50 m of X-section line

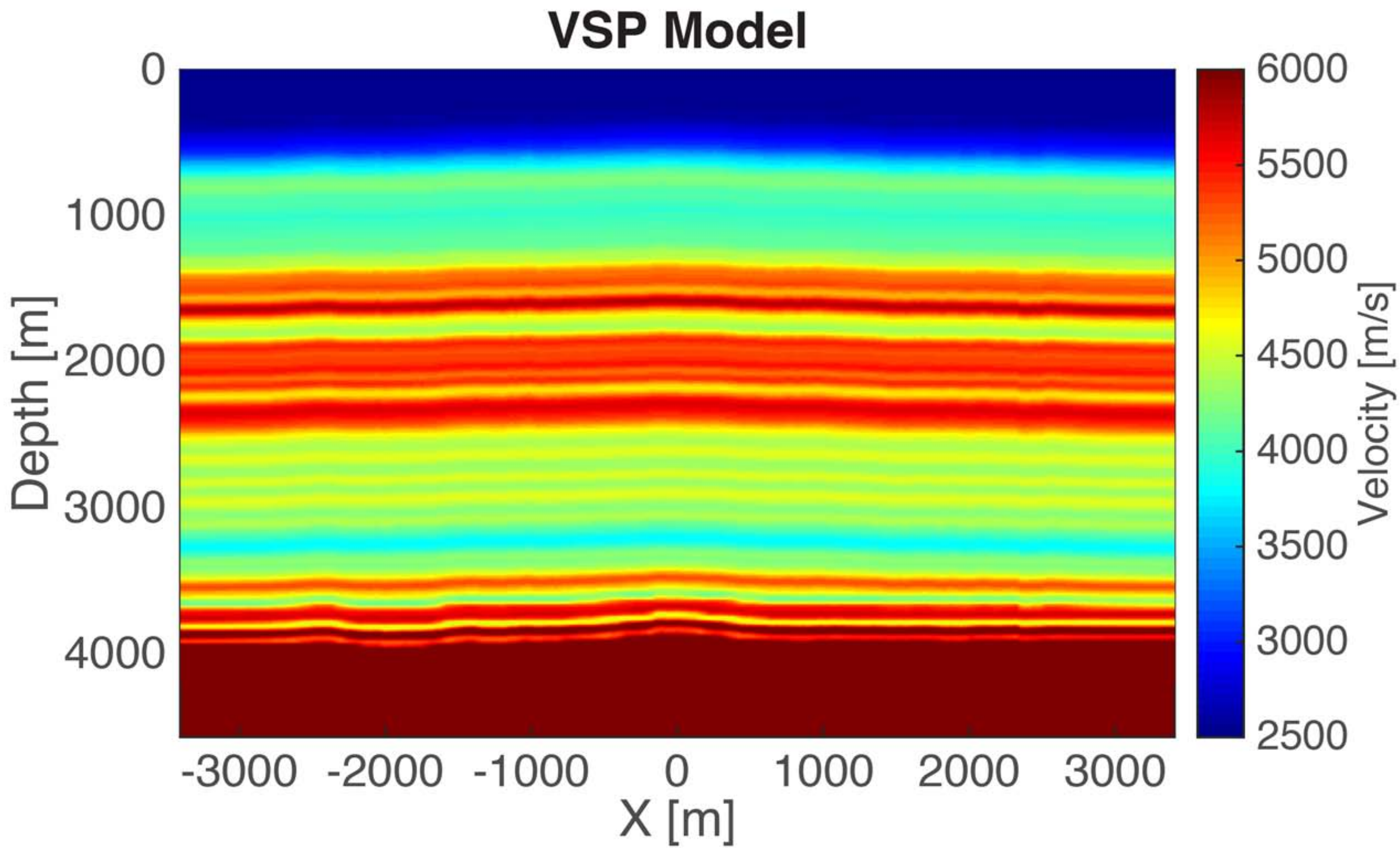
59 surface sources

21 surface geophones
151 downhole geophones

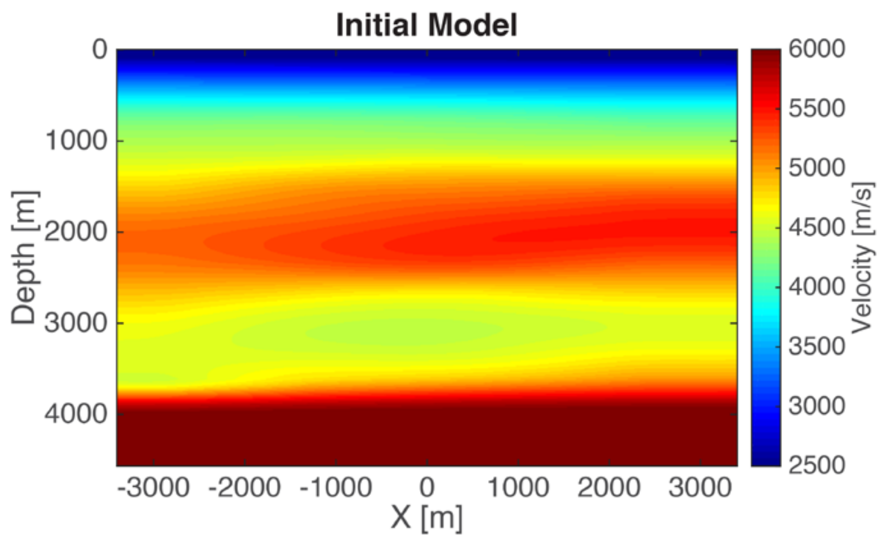
Initial PSDM Velocity Model



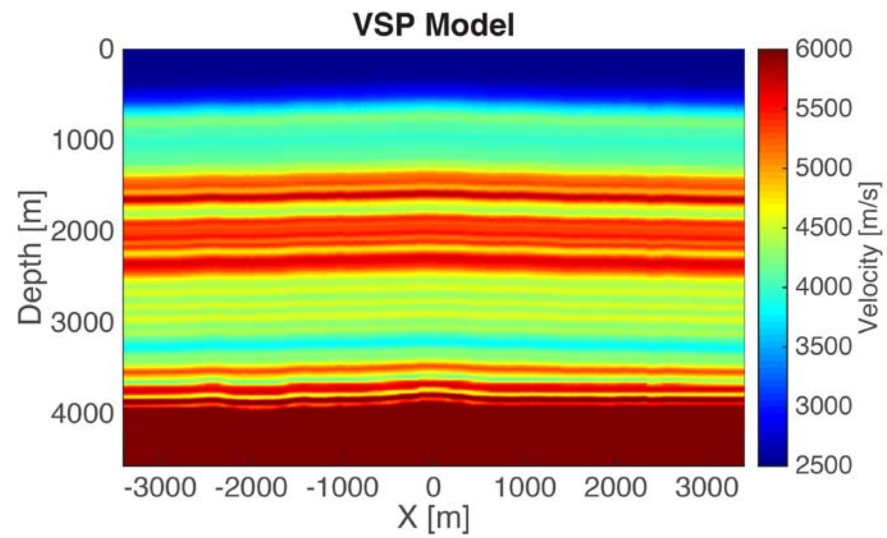
Pseudo-1D VSP Velocity



Contractor Models



Used for FWI initial model

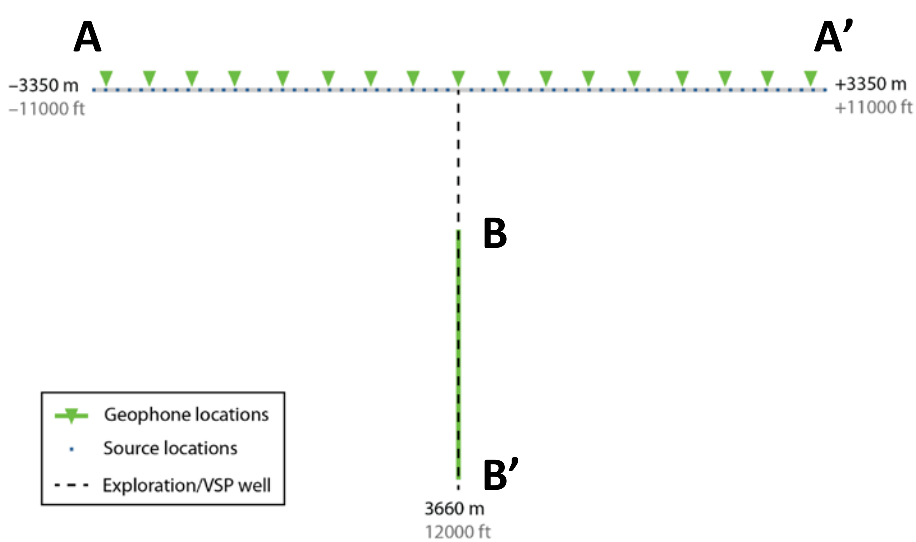


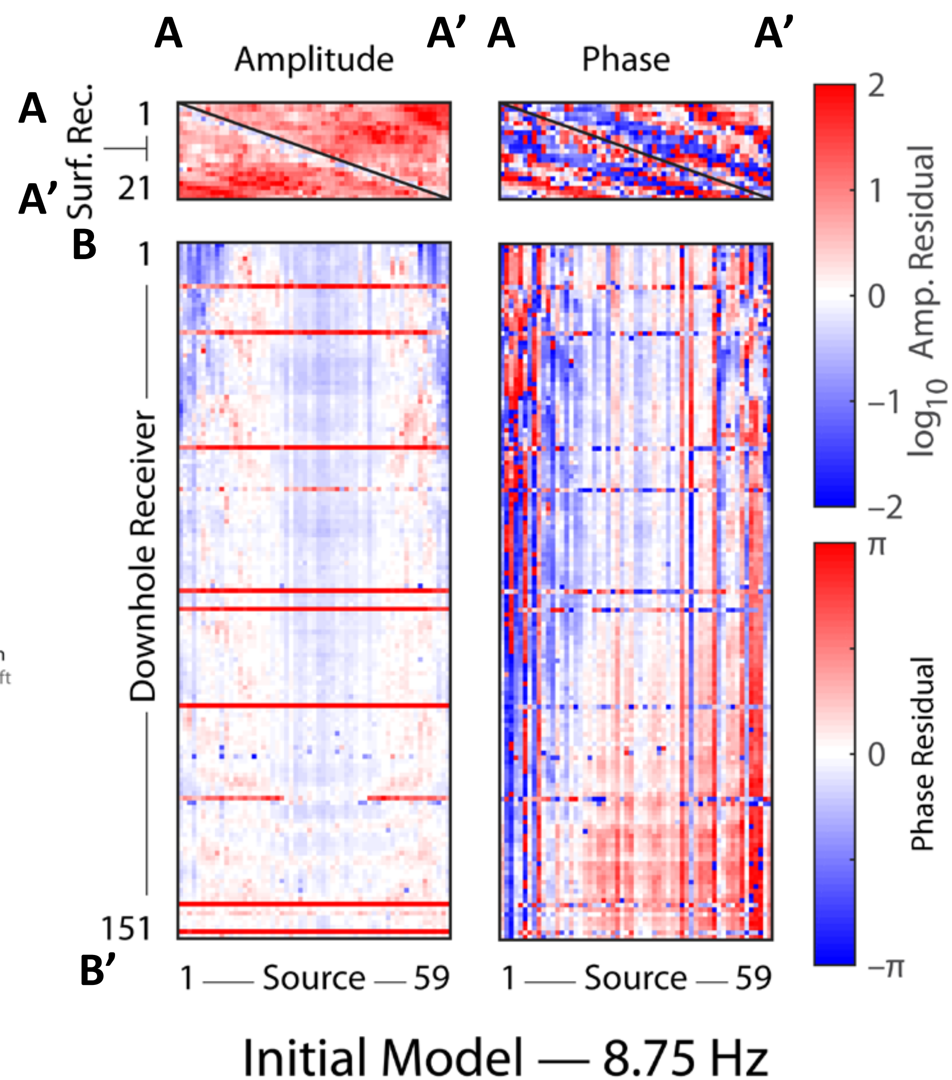
Used for QC comparison

Initial Data Fit

This plot shows information about the amplitude and phase of the data misfit at 8.75 Hz.

Each pixel represents a source/receiver pair, and the data are shown for both surface and downhole receiver arrays.





Data Preconditioning

Automatic picking (surface) via median STA/LTA + contractor picks (VSP data)

- Picks used only for data windowing (t + 200 ms; tapers: 50 ms start, 100 ms end)

- Single (best-fit) source term per array (VSP & MCS arrays differ)
- Single 2-term AVO correction per array

Modelling

- 20 m computational grid
- Bandwidth 8.00 Hz to 15.75 Hz, 32 freqs.
- PML boundary on all sides
- Sources and receivers modelled as approximate vertical dipoles
- Parallel Matlab architecture

Inversion Procedure

- Frequency-domain acoustic FWI
- Initial model from 3D MVA
- Simultaneous inversion of all freqs., spectrally whitened source
- Simultaneous inversion for (weighted) surface + VSP updates, combined objective function
- Projected Quasi-Newton inversion (M. Schmidt et al., 2009) w/ Dykstra projection

Constrained (PQN) Inversion

$$\min_{\mathbf{m}} f(\mathbf{m}) \quad \text{s.t.} \quad \mathbf{m} \in \mathcal{C}_1 \bigcap \mathcal{C}_2$$

Bound constraints: $\mathcal{C}_1 \equiv \{\mathbf{m} \mid \mathbf{b}_l \leq \mathbf{m} \leq \mathbf{b}_u\}$

2D Wavenumber filter: $\mathcal{C}_2 \equiv \{\mathbf{m} \mid E^* F^* (I - S) F E \mathbf{m} = 0\}$

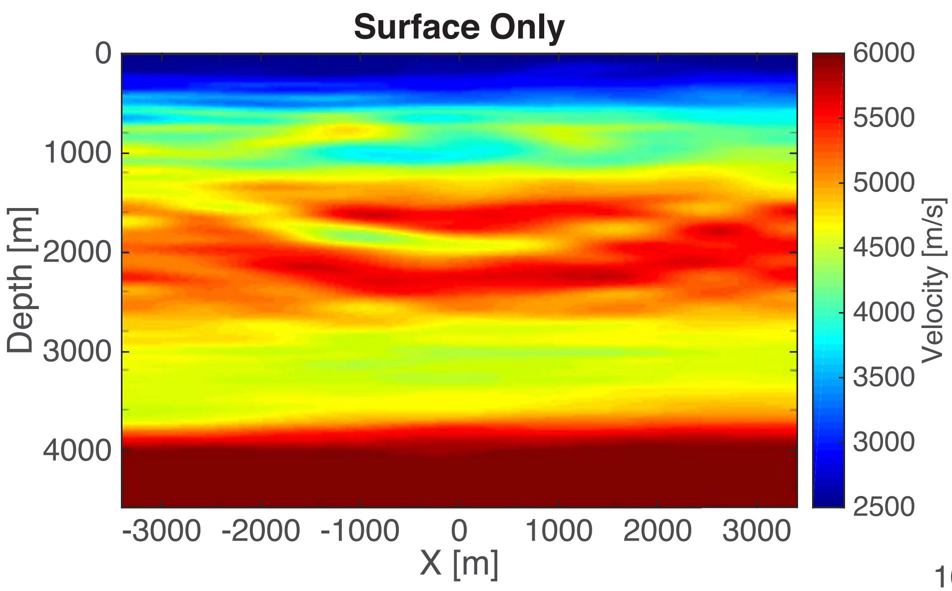
$E \in \mathbb{R}^{4N \times N}$ 2D mirror-extension

$F \in \mathbb{C}^{N \times N}$ 2D discrete Fourier transform (DFT)

$S \in \mathbb{R}^{N \times N}$ Diagonal selection matrix (filter coefficients)

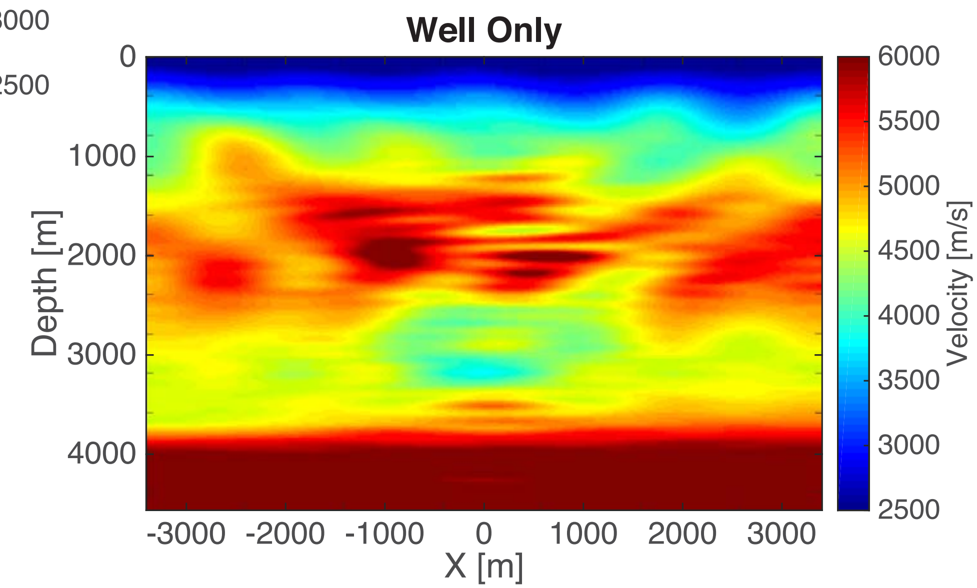
$\mathbf{m} \in \mathbb{R}^{N}$ Medium parameters (model vector)

Surface Only vs. Well Only



Better low-wavenumber recovery due to direct wavepaths; good coverage near well down to ~3 km depth ↓

↑ Delineation of layering in near-surface areas; migration-style updates at depth



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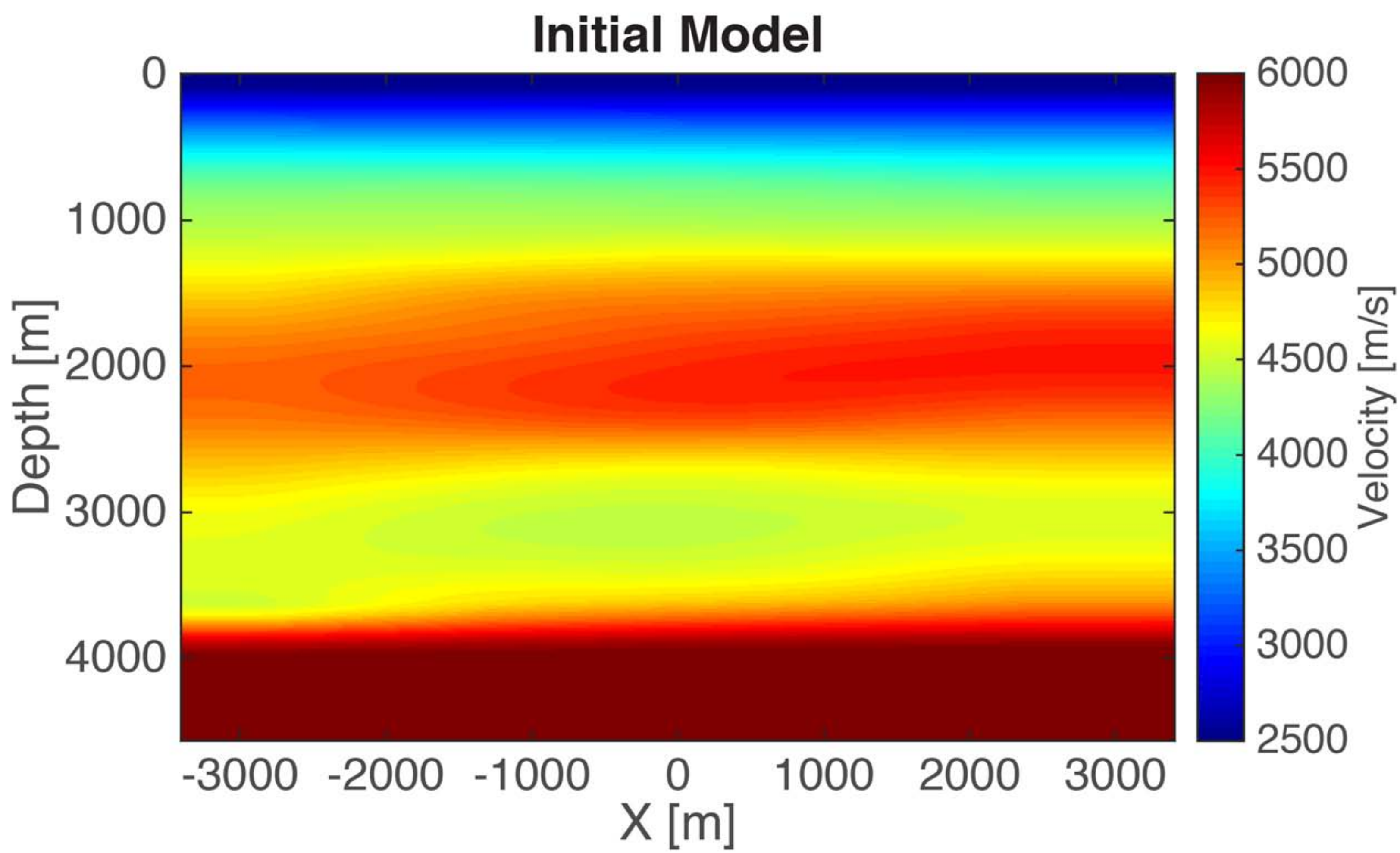
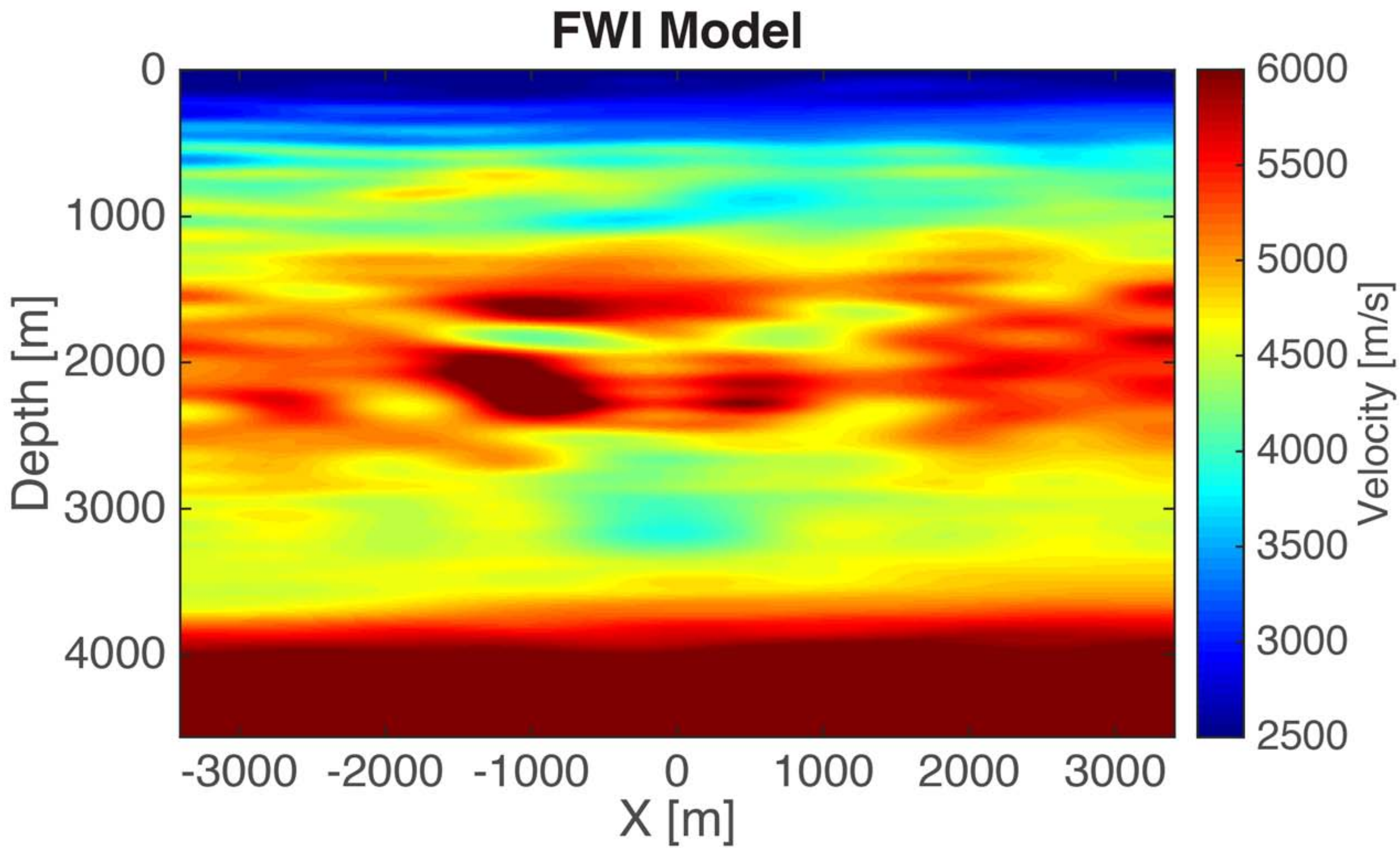
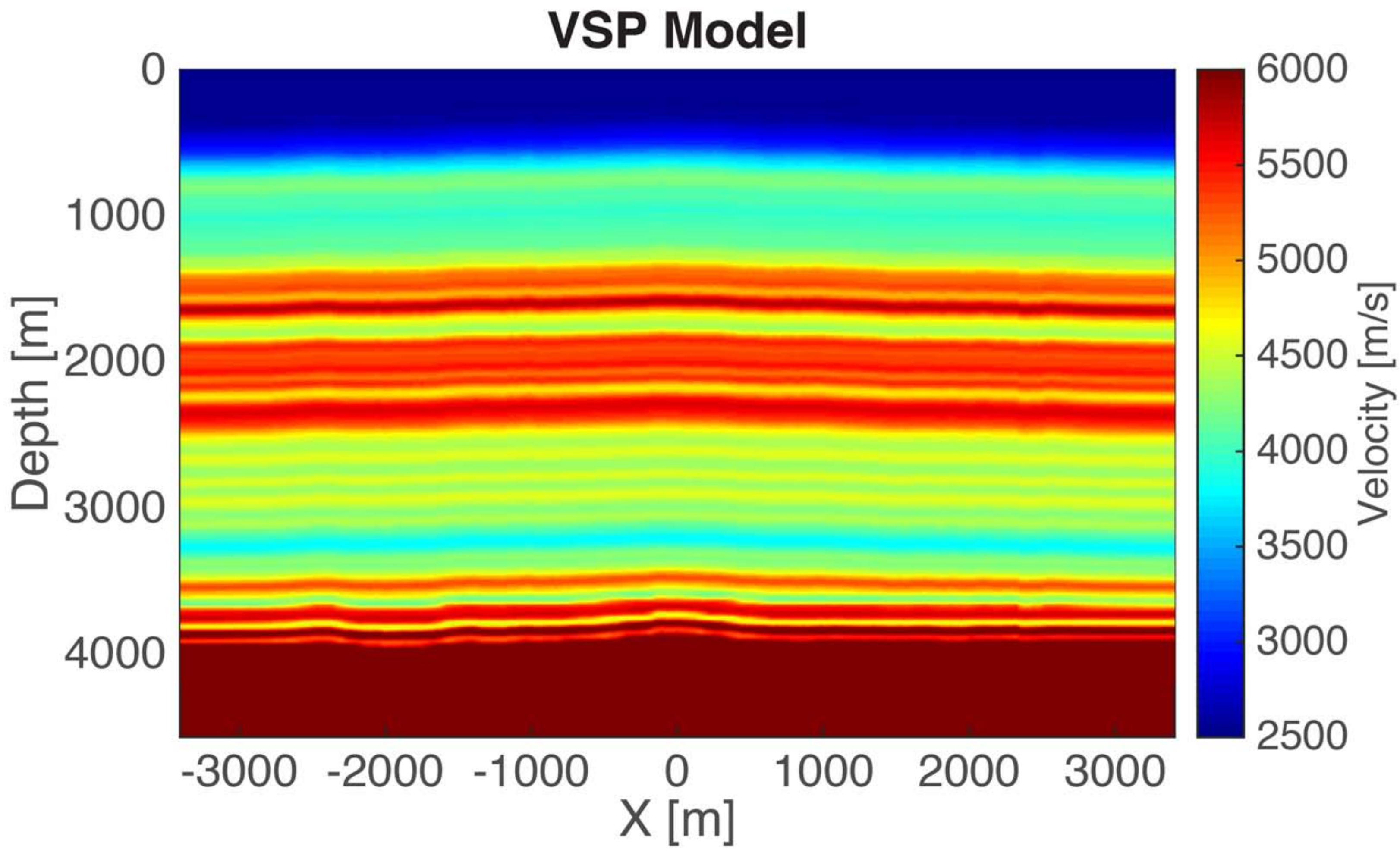


FWI Velocity Model



Pseudo-1D VSP Velocity



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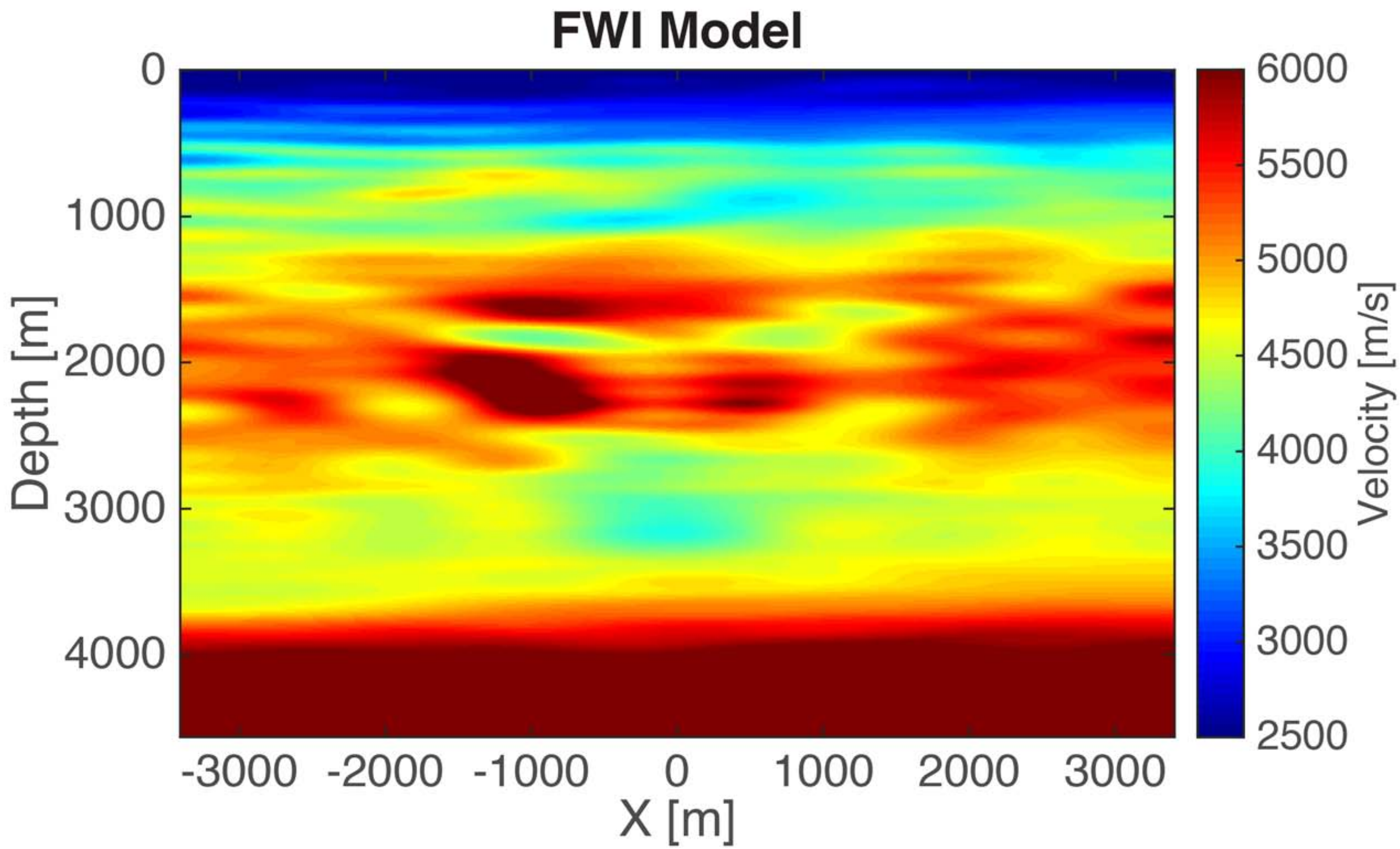
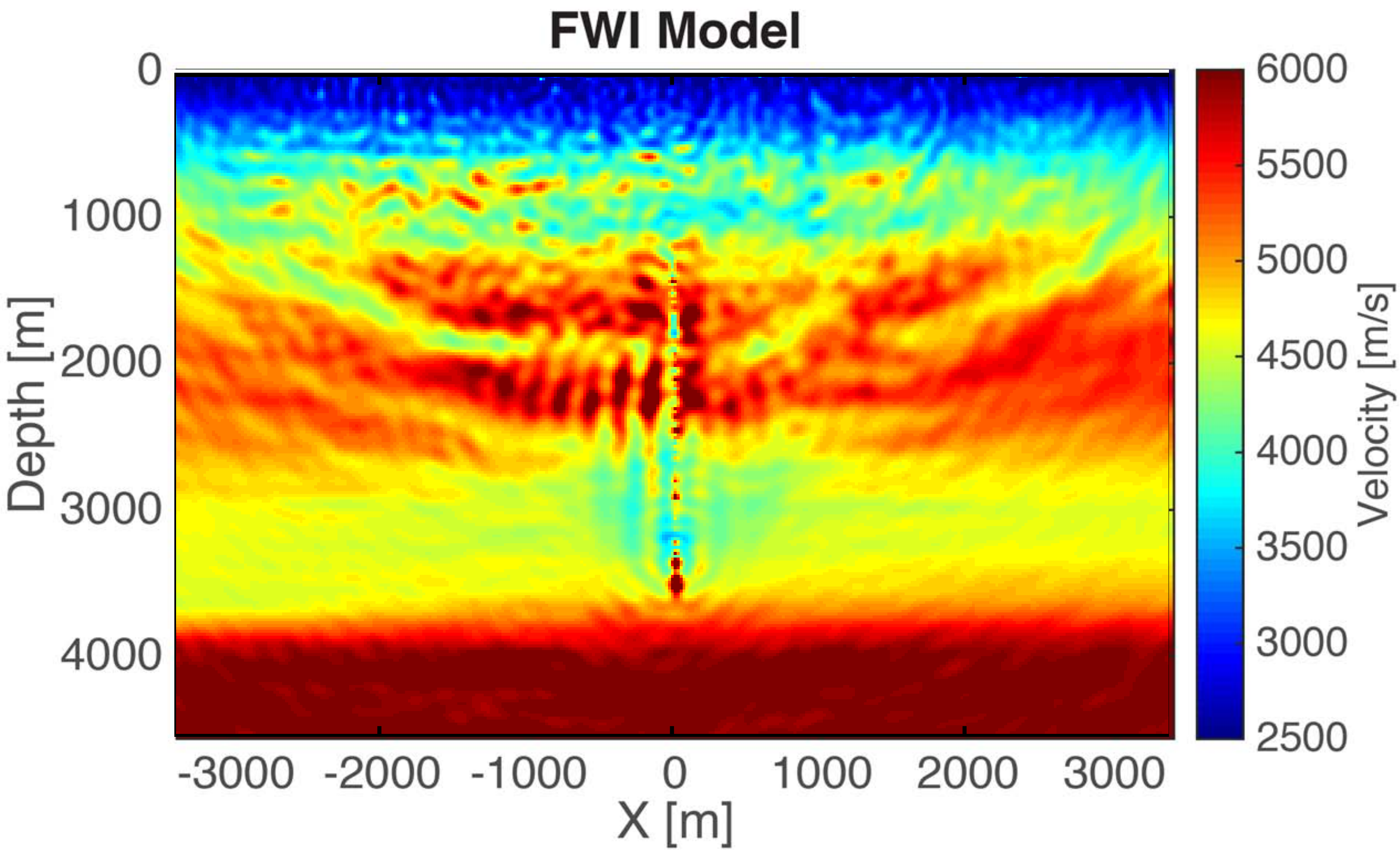
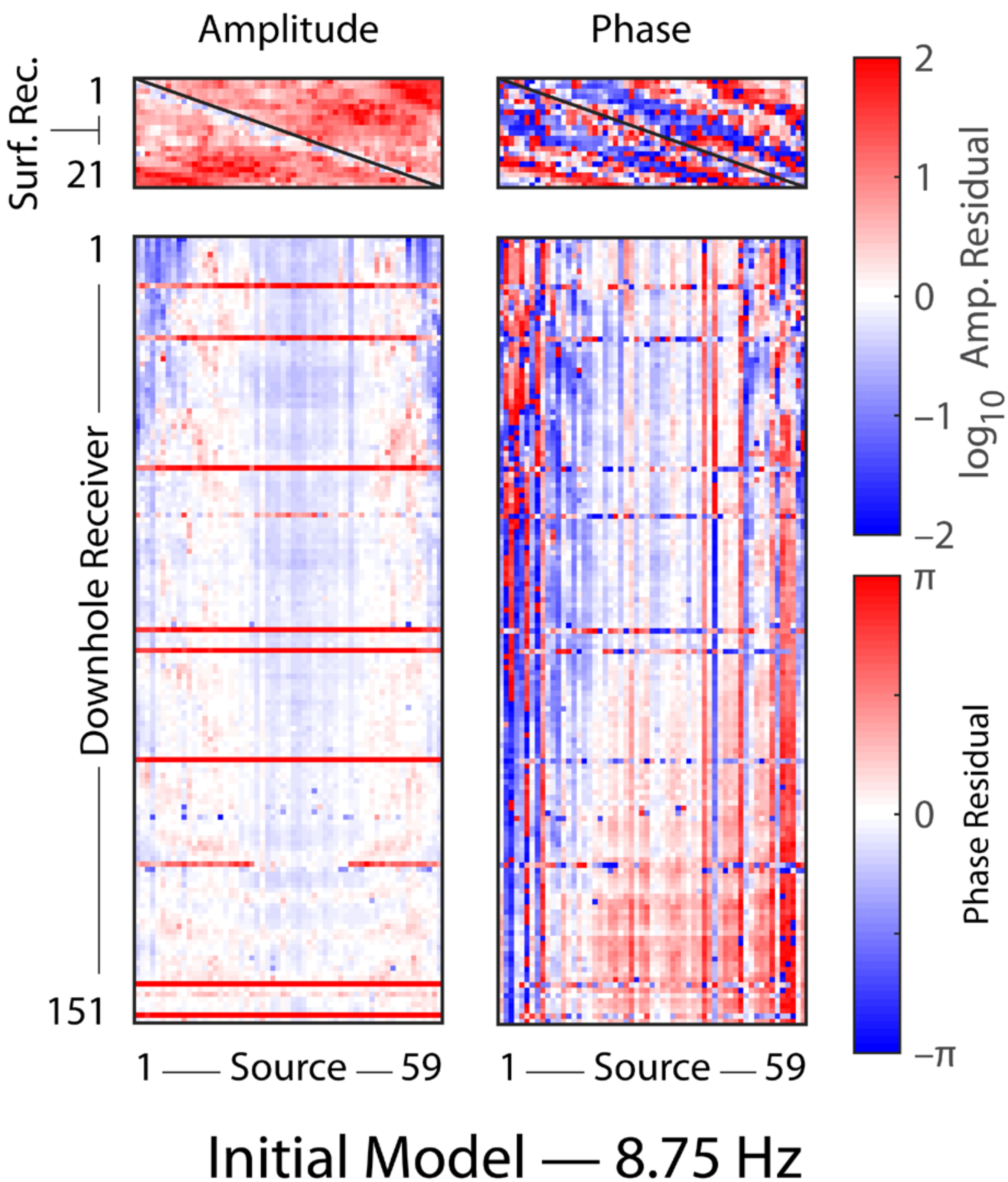


l-BFGS w/o PQN


FWI Model
Depth [m]
0
1000
2000
3000
4000
X [m]
-3000
-2000
-1000
0
1000
2000
3000
Velocity [m/s]
6000
5500
5000
4500
4000
3500
3000
2500



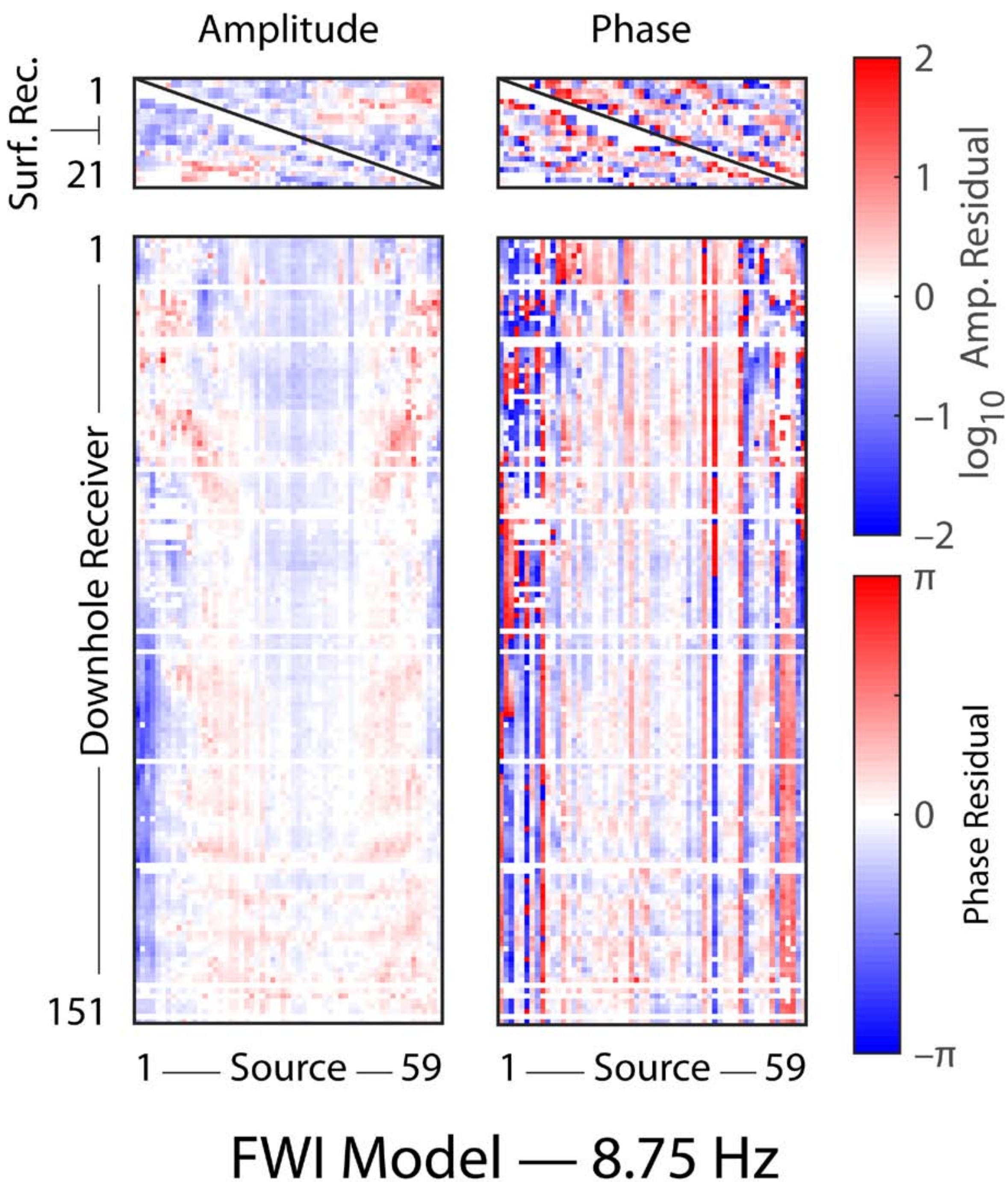
Monofrequency Data Residuals

Phase & amplitude data misfit for both *surface array* (top) and *downhole array* (bottom)

Note reduction in phase residuals throughout (remaining misfit is mainly surface-consistent)

Exception:
far left / right

Monofrequency Data Residuals



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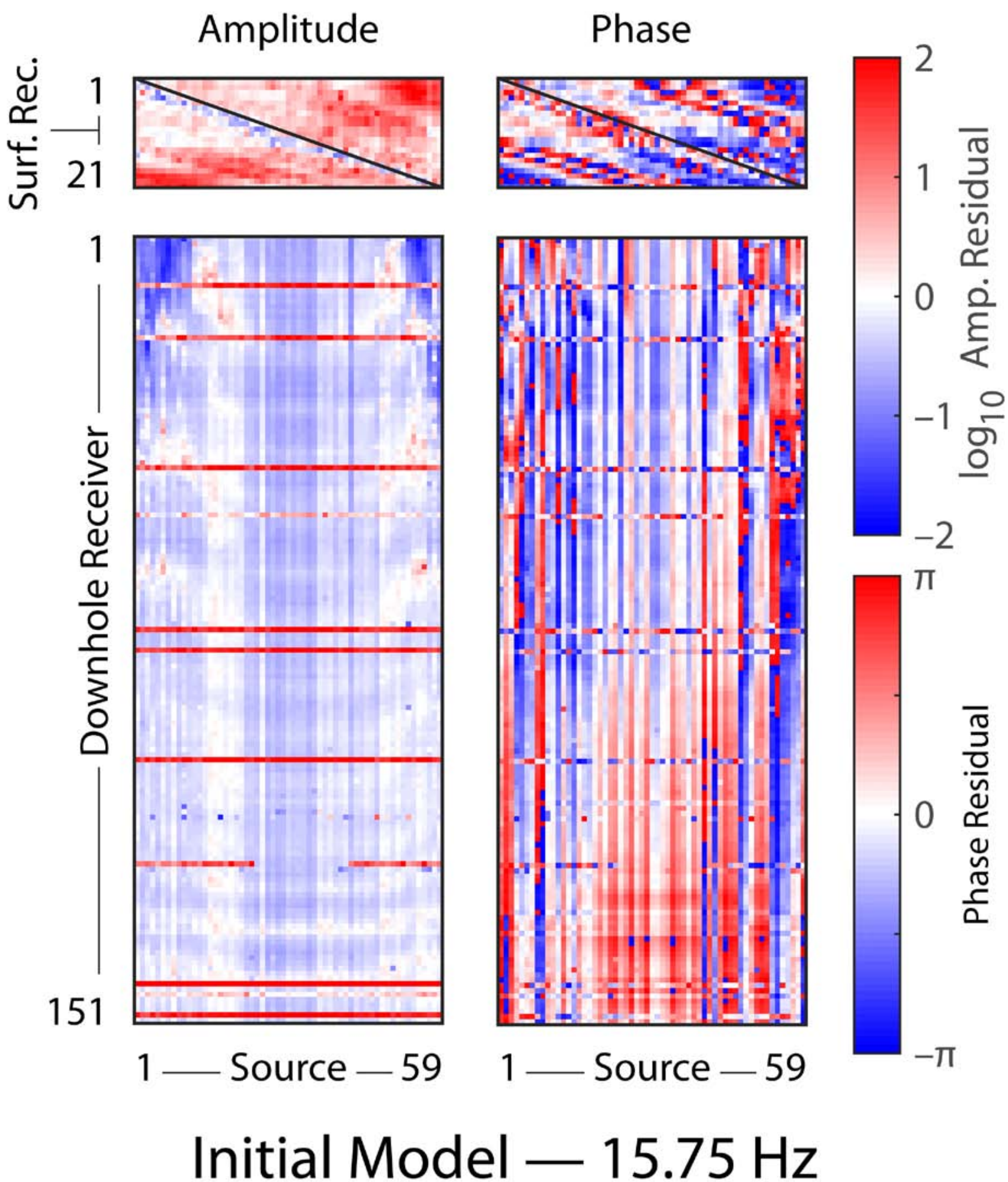

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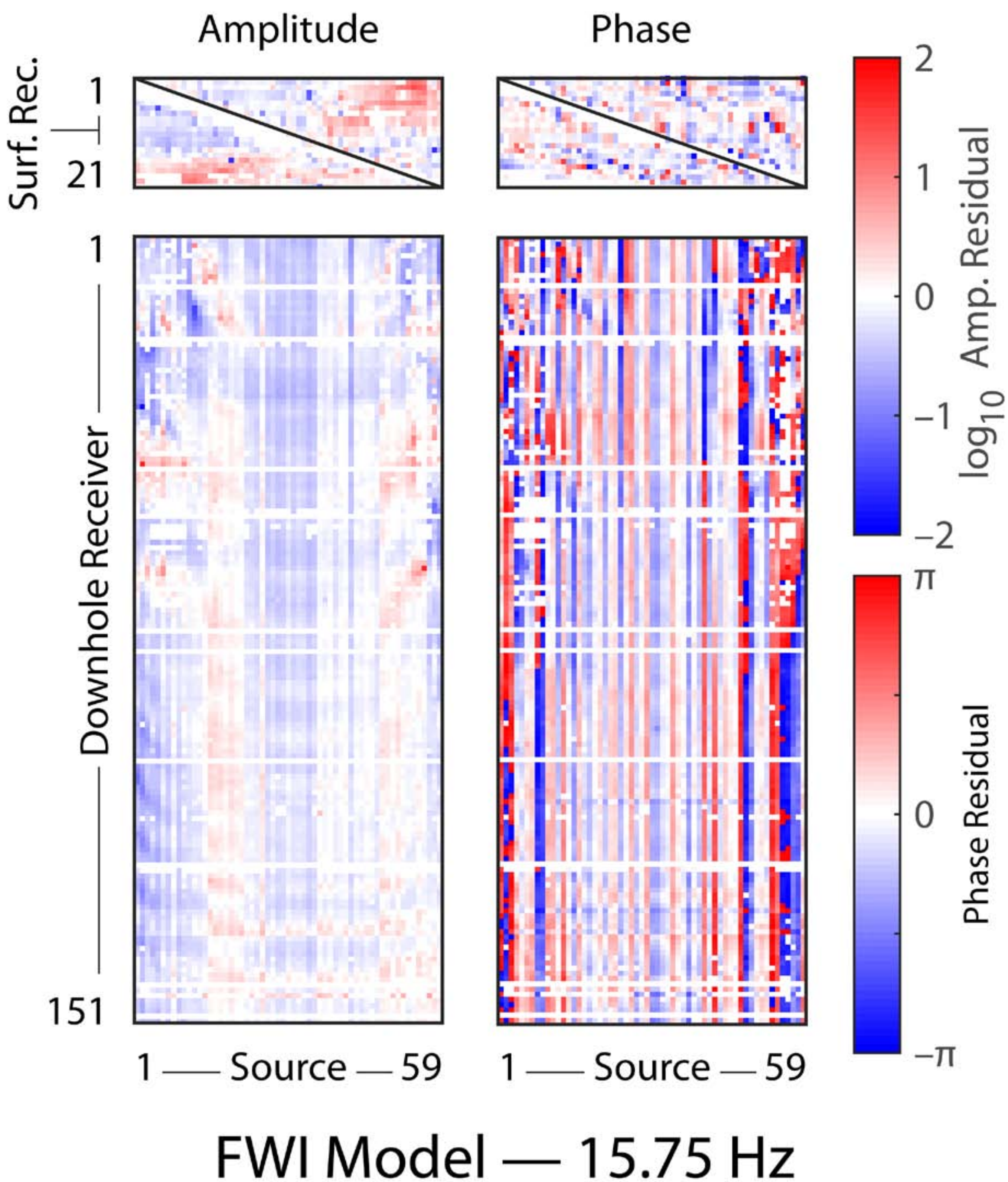

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Exception:
far left / right

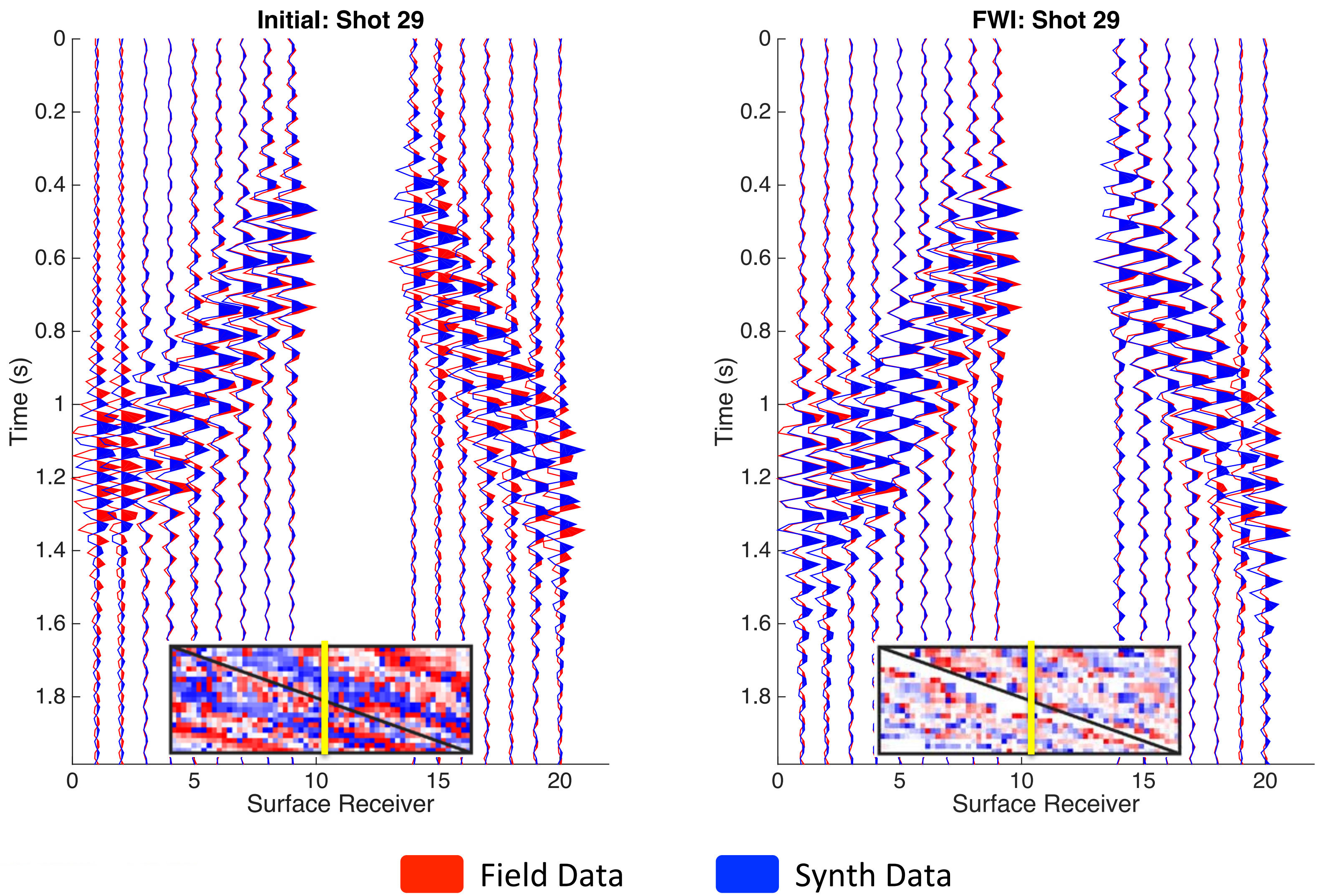
Data fit assessment

Quality of data fit improves substantially

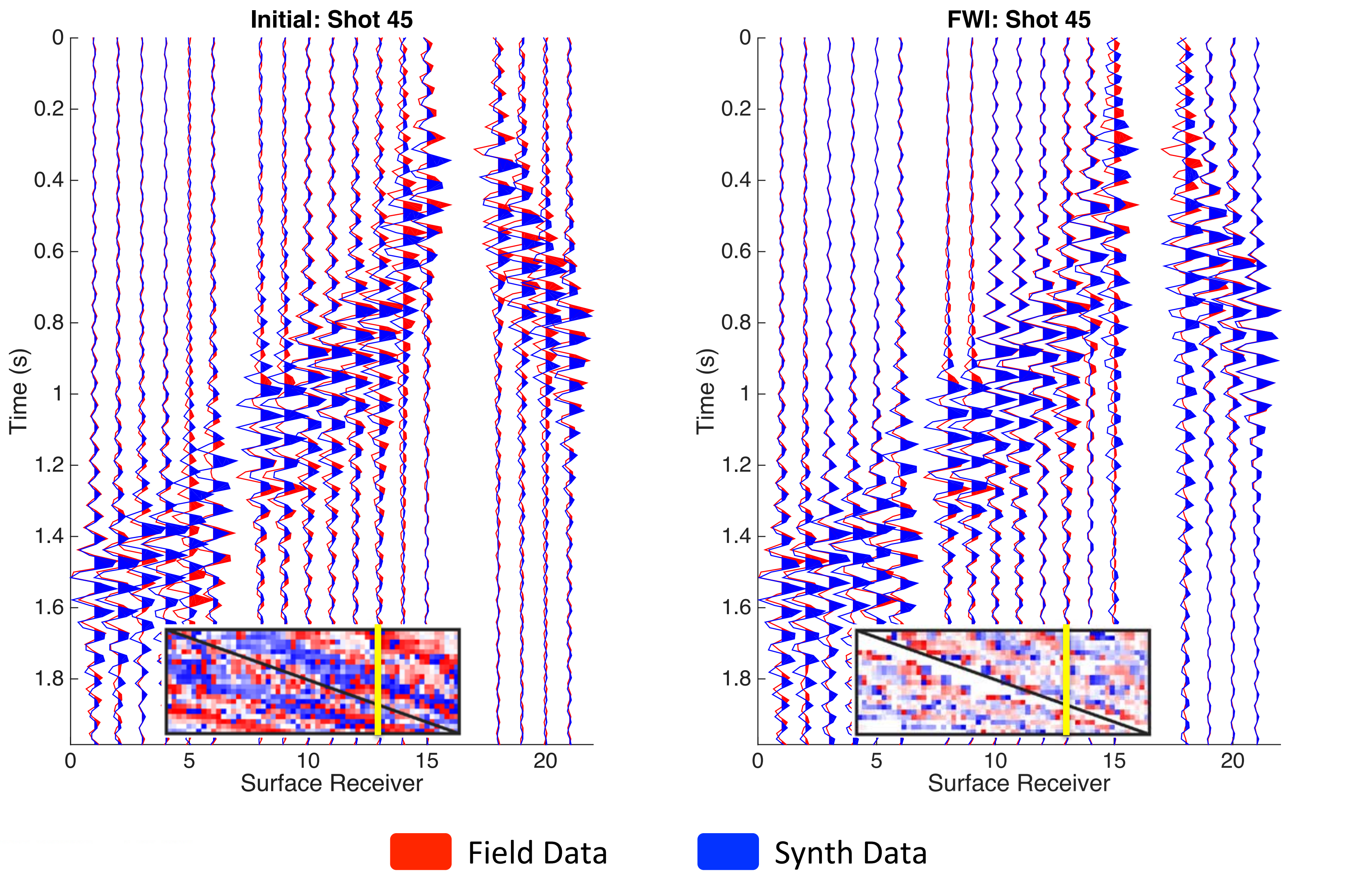
w/ exception: farthest E/W source positions show higher misfit on downhole QC plots

Next: assess time-domain data fit

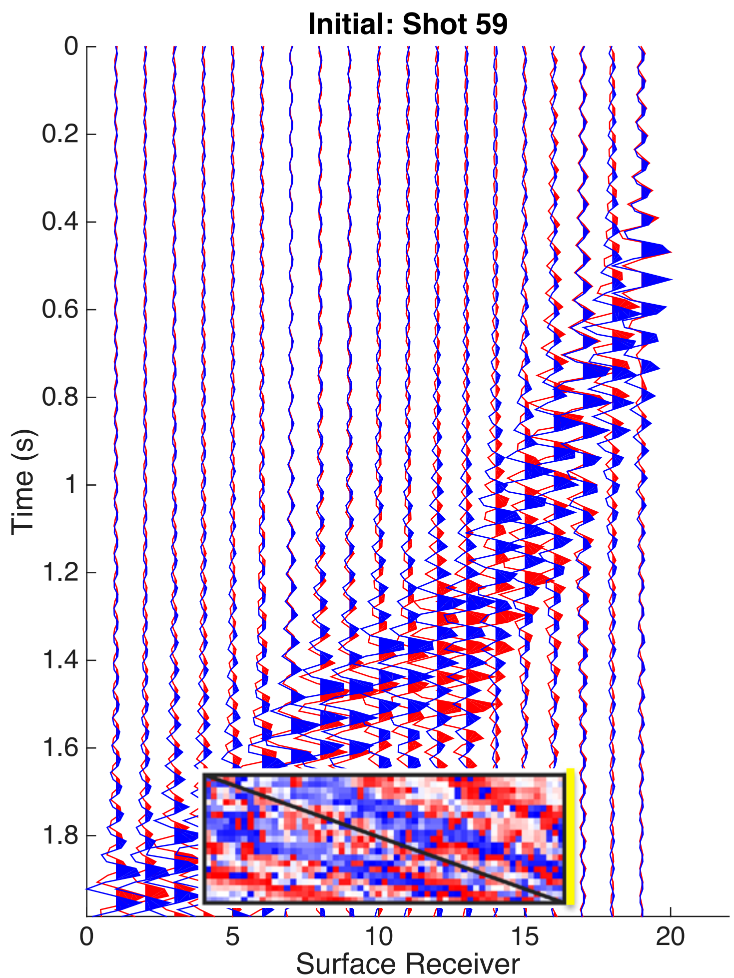
Surface / Shot 29

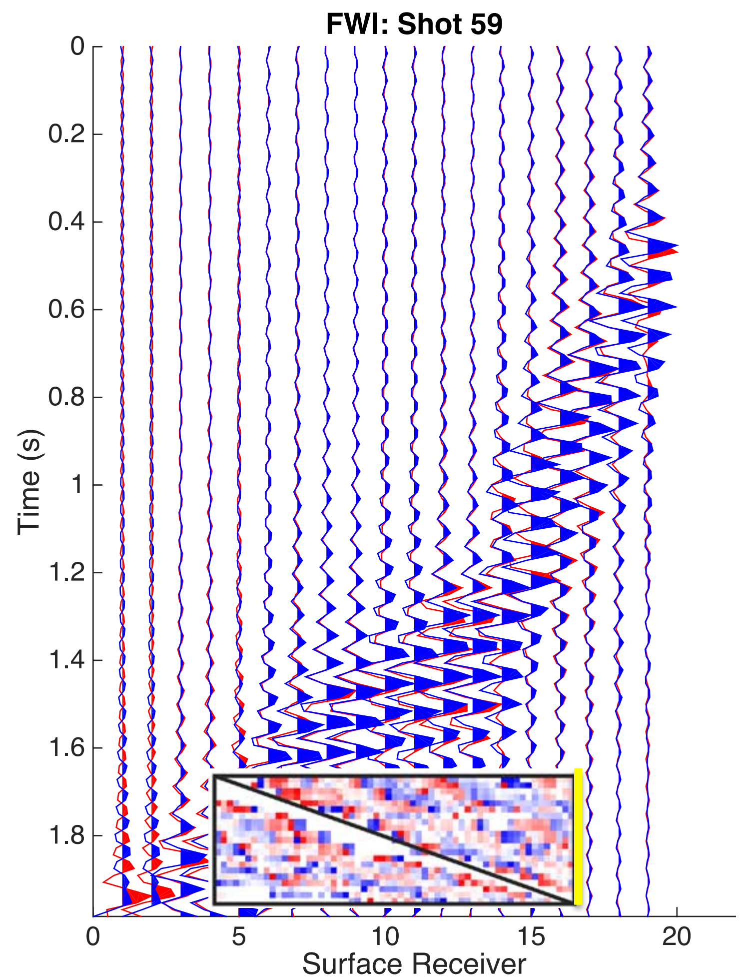


Surface / Shot 45



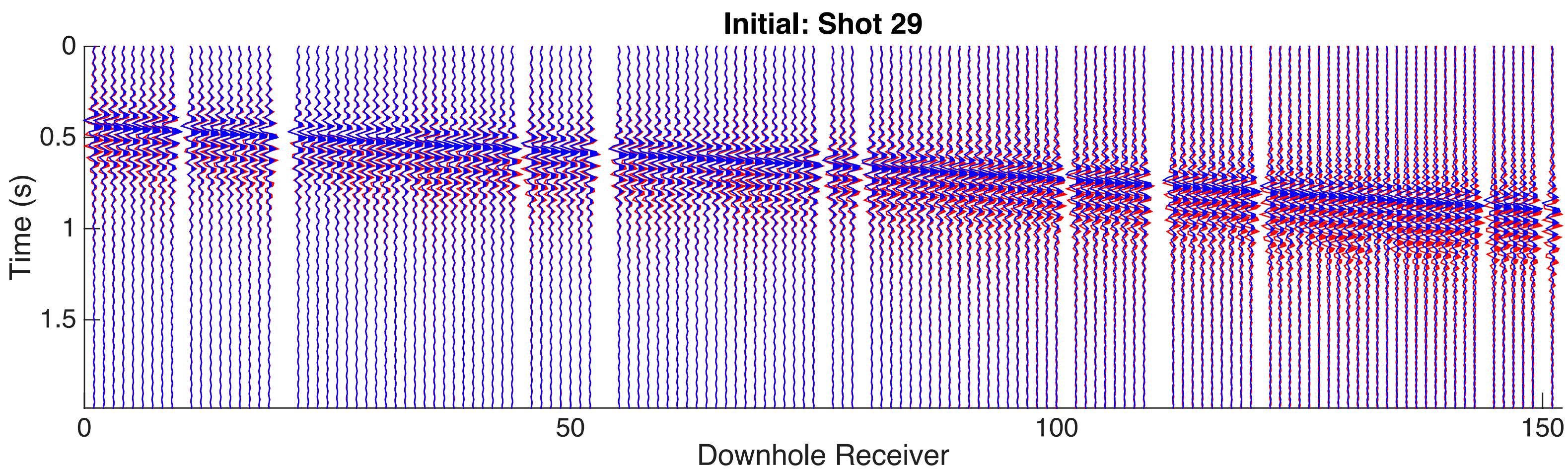
Surface / Shot 59

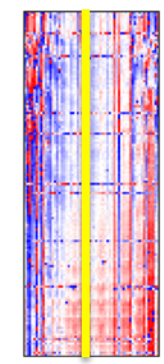


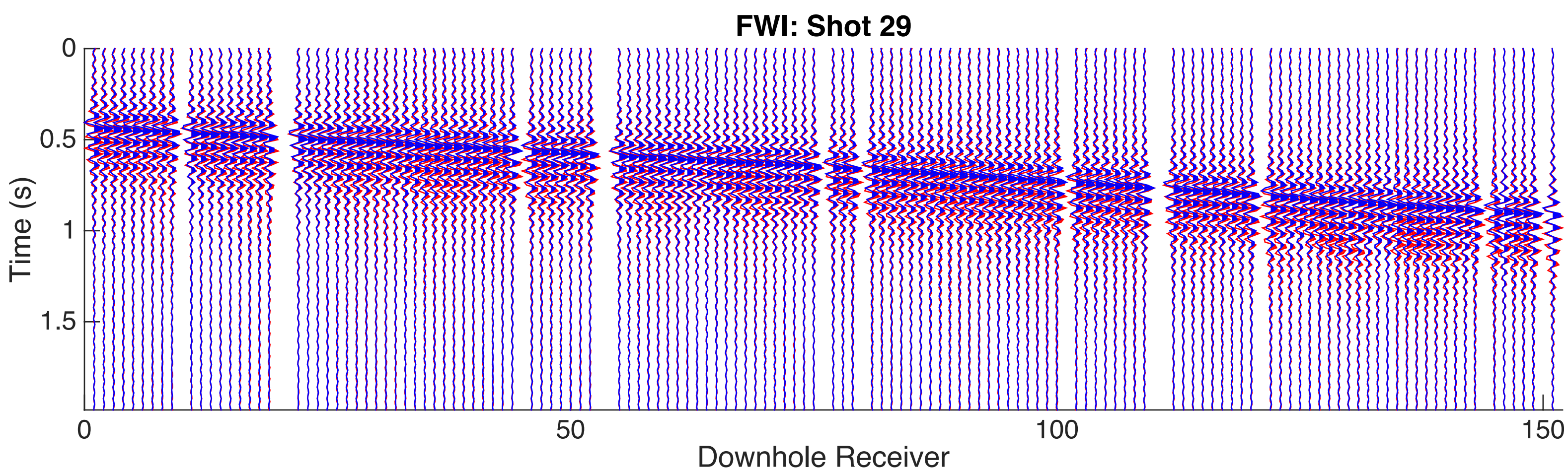


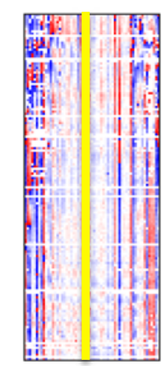
Field Data   Synth Data

Downhole / Shot 29





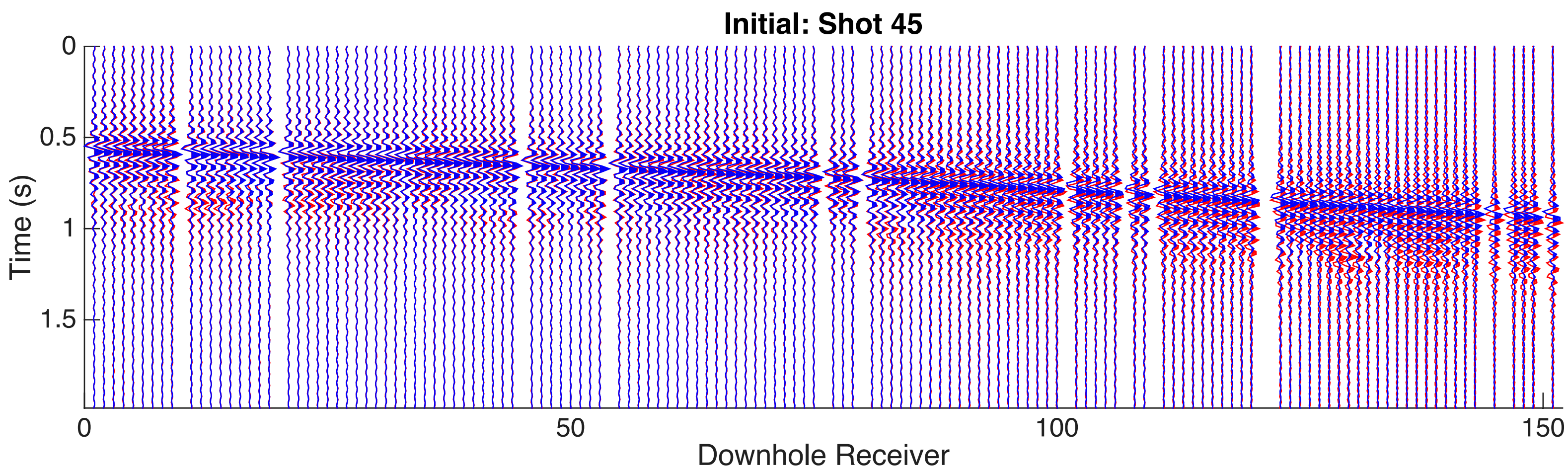


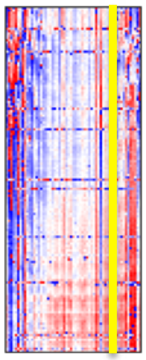


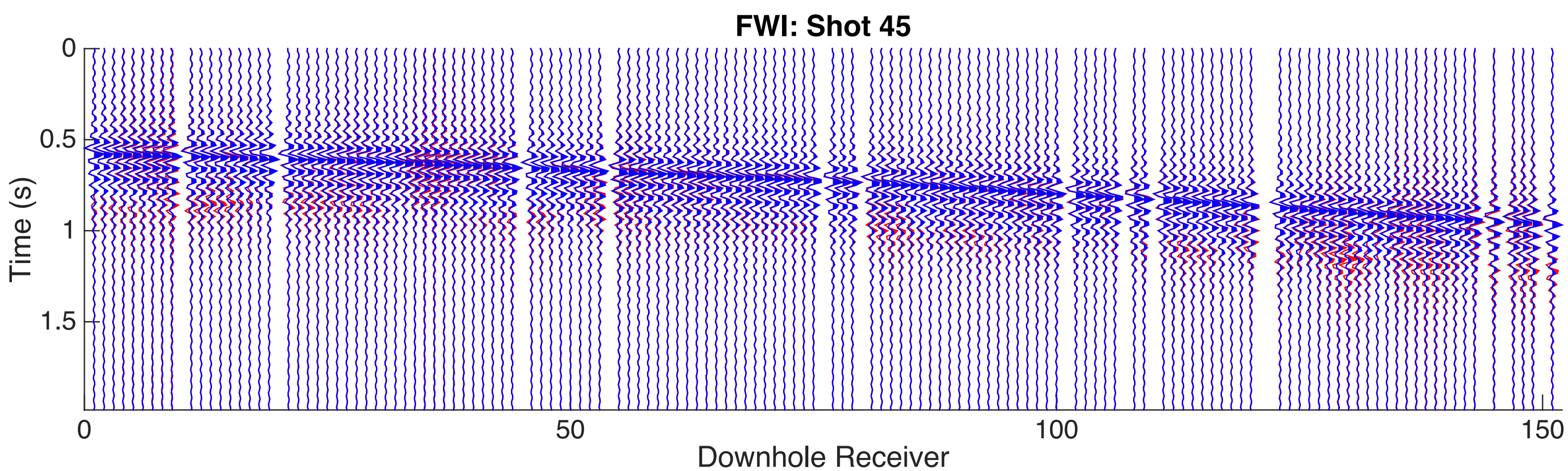
Field Data

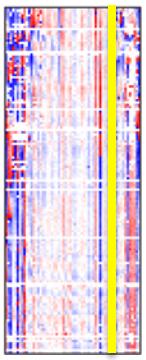
Synth Data

Downhole / Shot 45



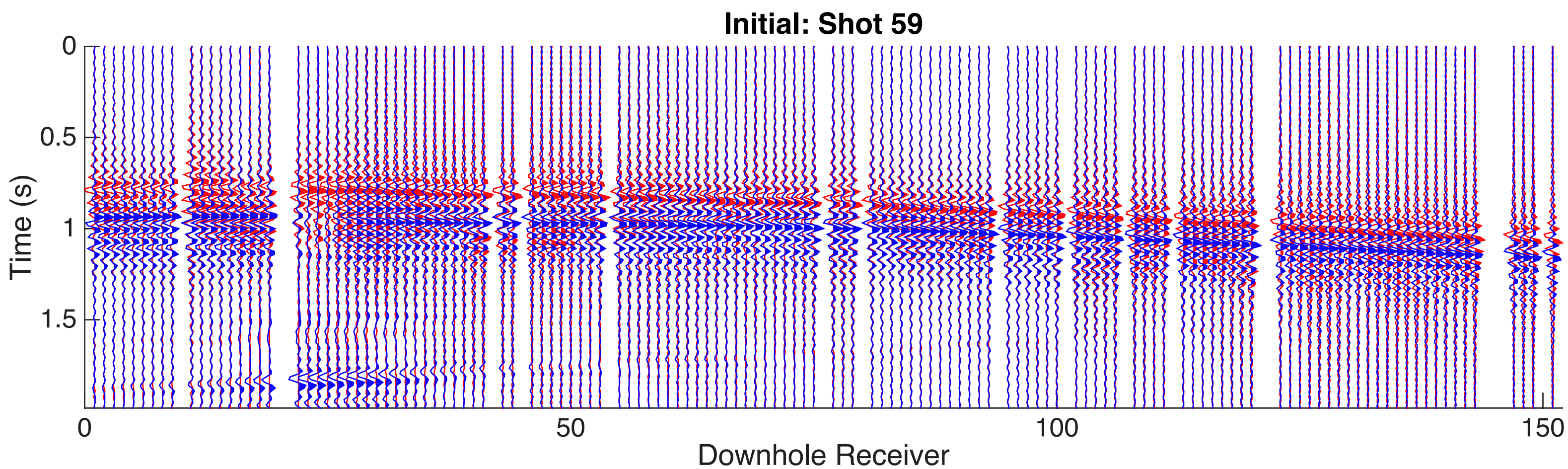


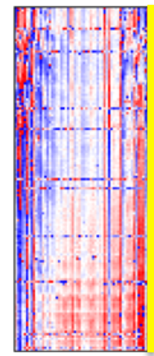


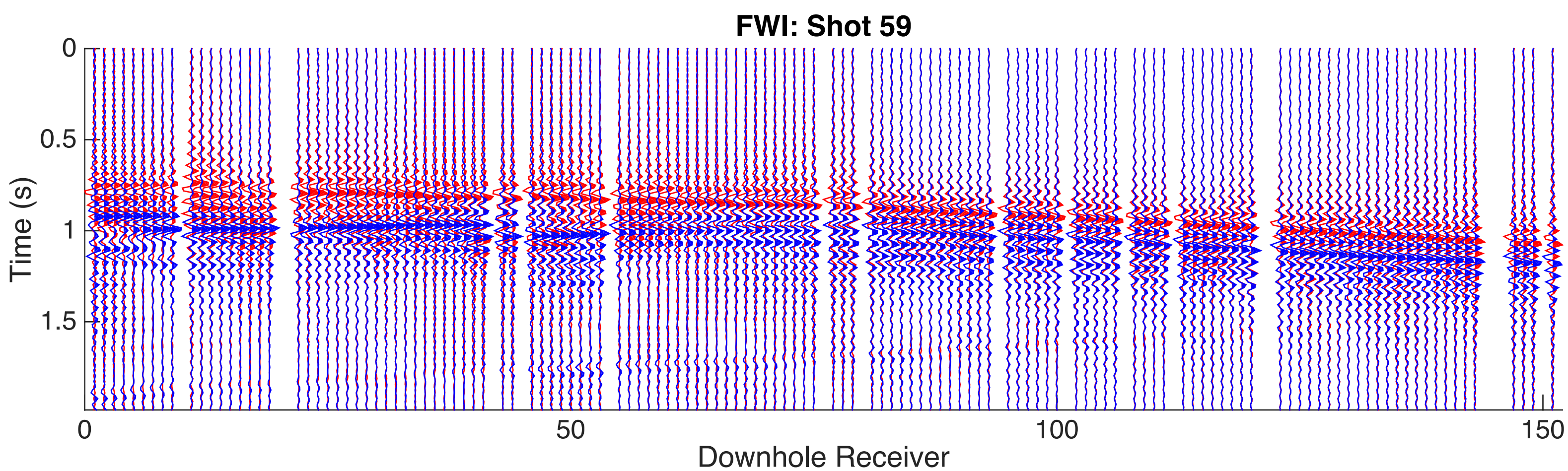


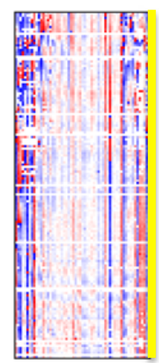
Field Data Synth Data

Downhole / Shot 59





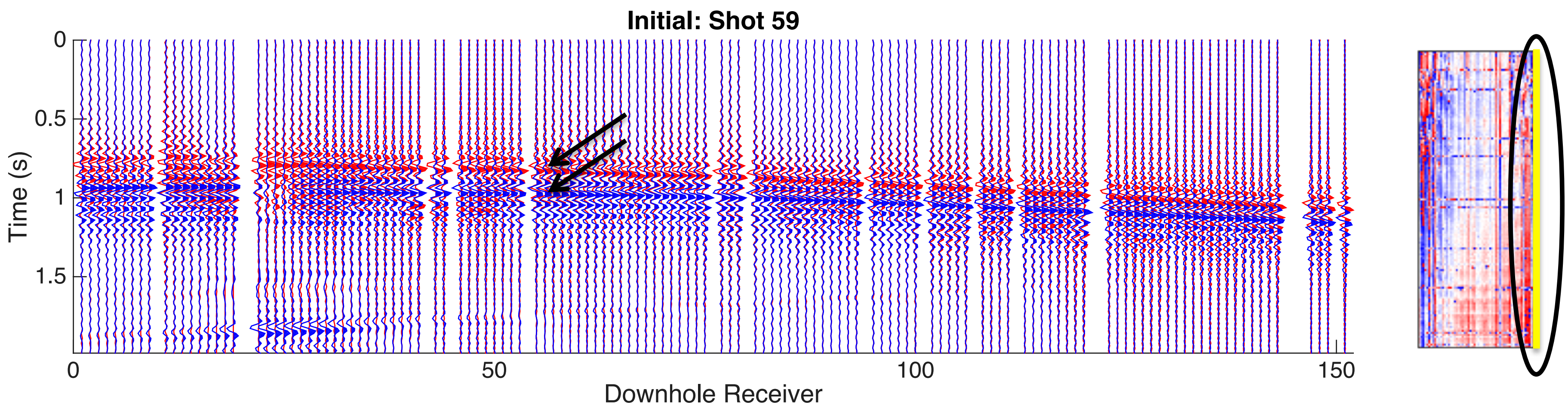


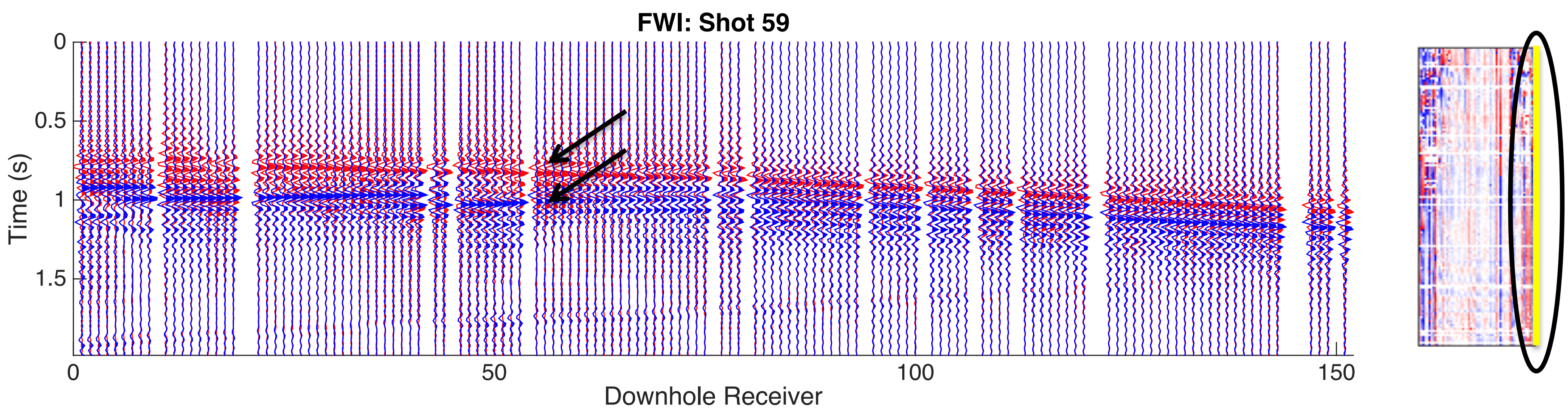


Field Data

Synth Data

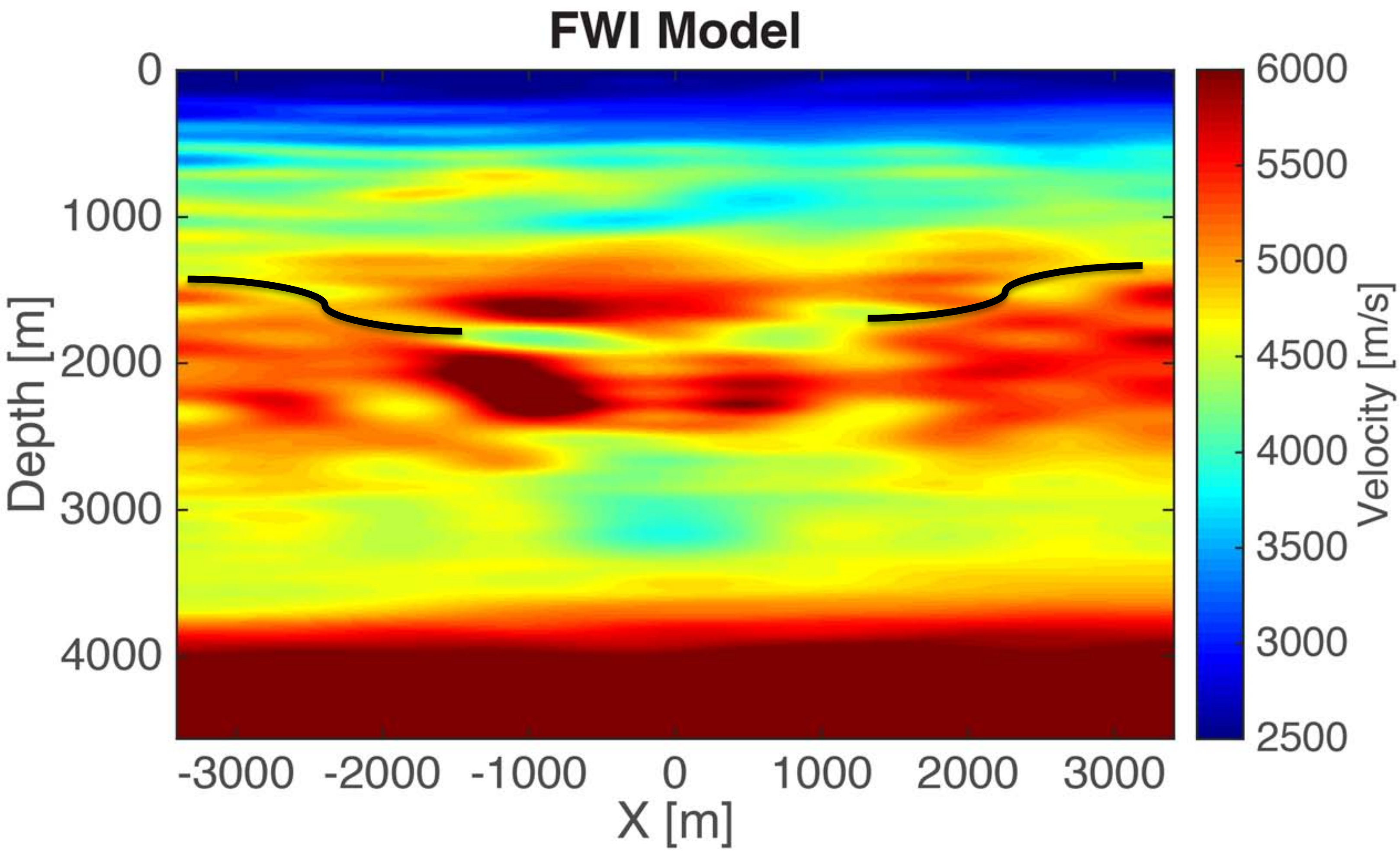
Downhole / Shot 59

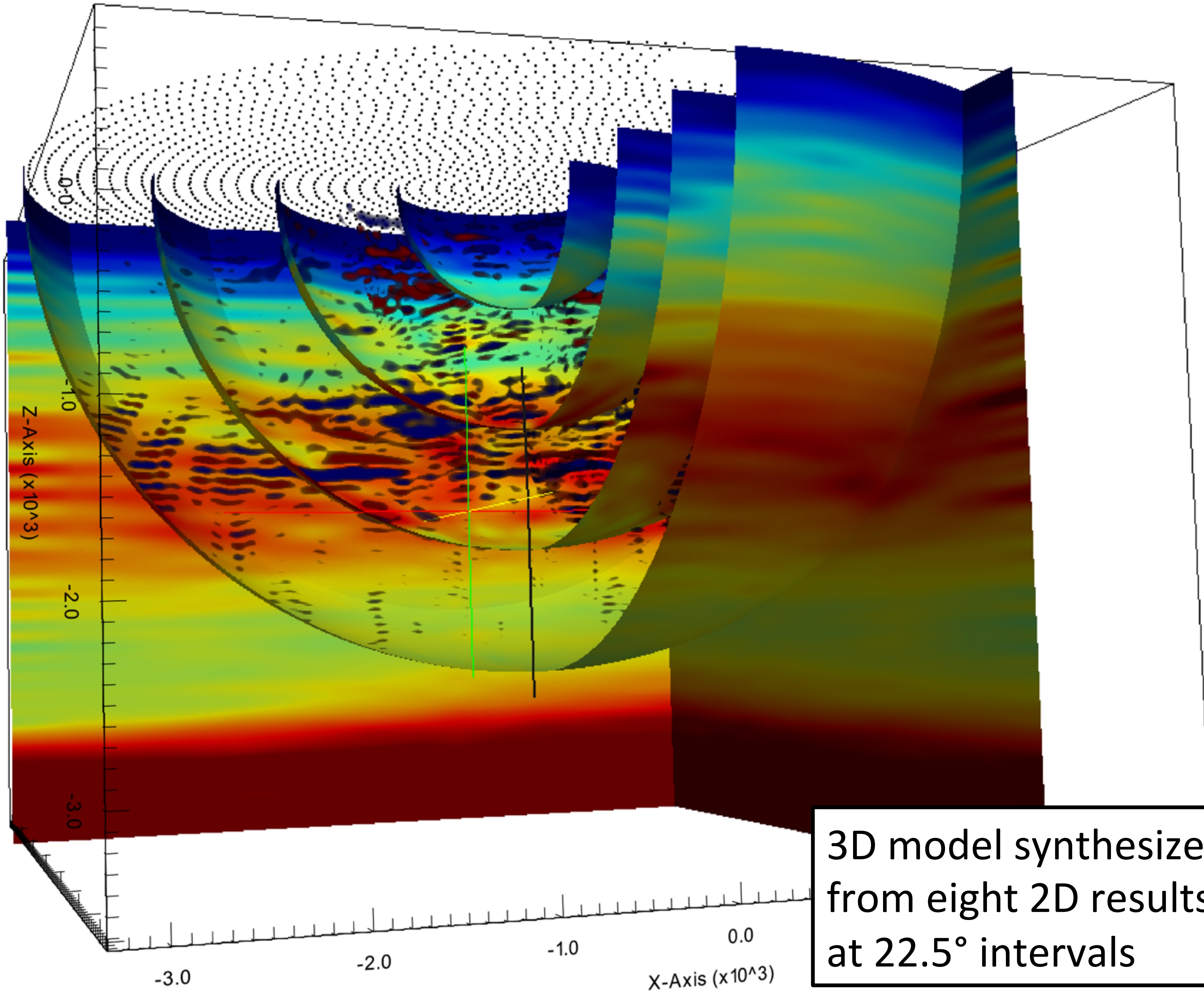




Field Data Synth Data

FWI Velocity Model





3D model synthesized from eight 2D results at 22.5° intervals

Conclusions

- Successful joint FWI result in near-surface and close to well; result suffers from cycle skipping at edges of model
- Potential to benefit from phase unwrapping
- Projected Quasi-Newton workflow helps to control model structures
- Follow-up w/ 3D workflow should substantially improve illumination & stability

Acknowledgments

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and staff at UBC / SLIM and UWO

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