Elastic Time-lapse Full Waveform Inversion

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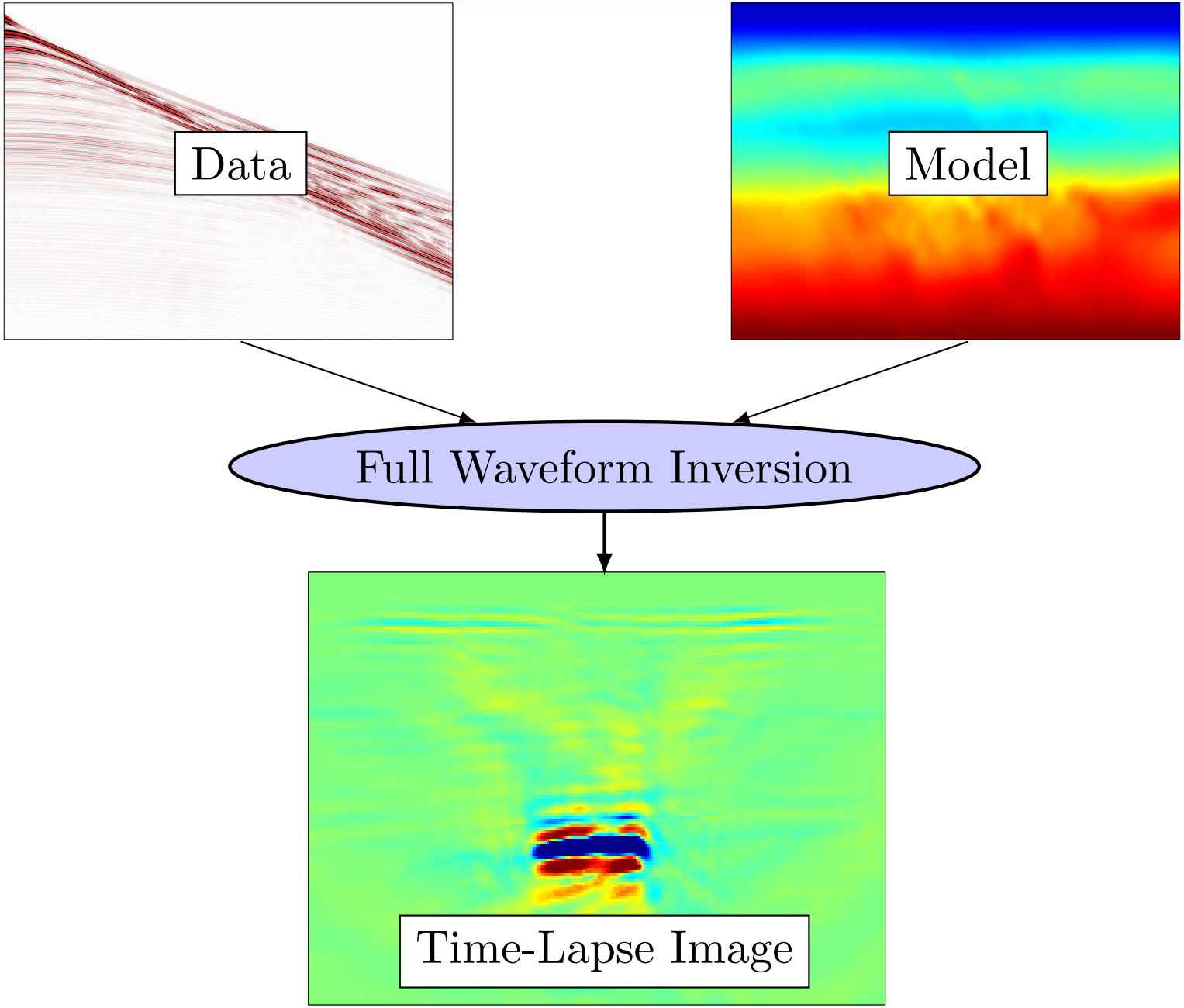

Data
Model
Full Waveform Inversion
Time-Lapse Image

Outline

A Quick Overview of Full Waveform Inversion

Overall Goal

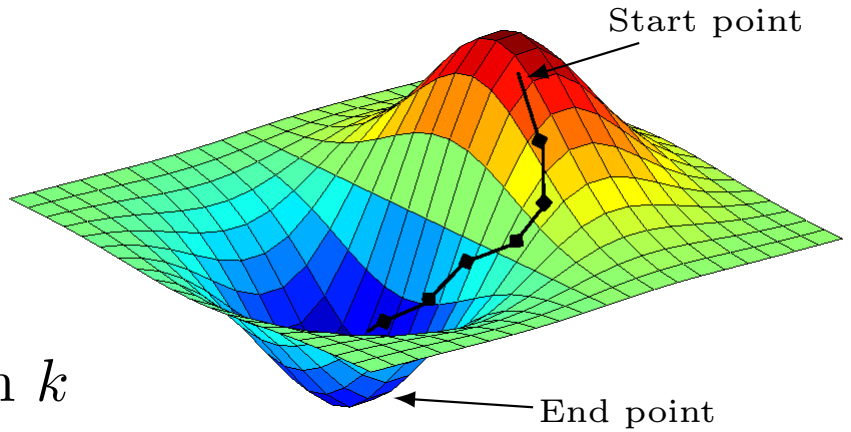
Find an Earth model from which it is possible to create synthetic data that is close to some measured data

Define $S(\mathbf{m})$ as the measure between synthetic and measured data. The FWI is then the problem

$$\arg\min_{\mathbf{m}} S(\mathbf{m})$$

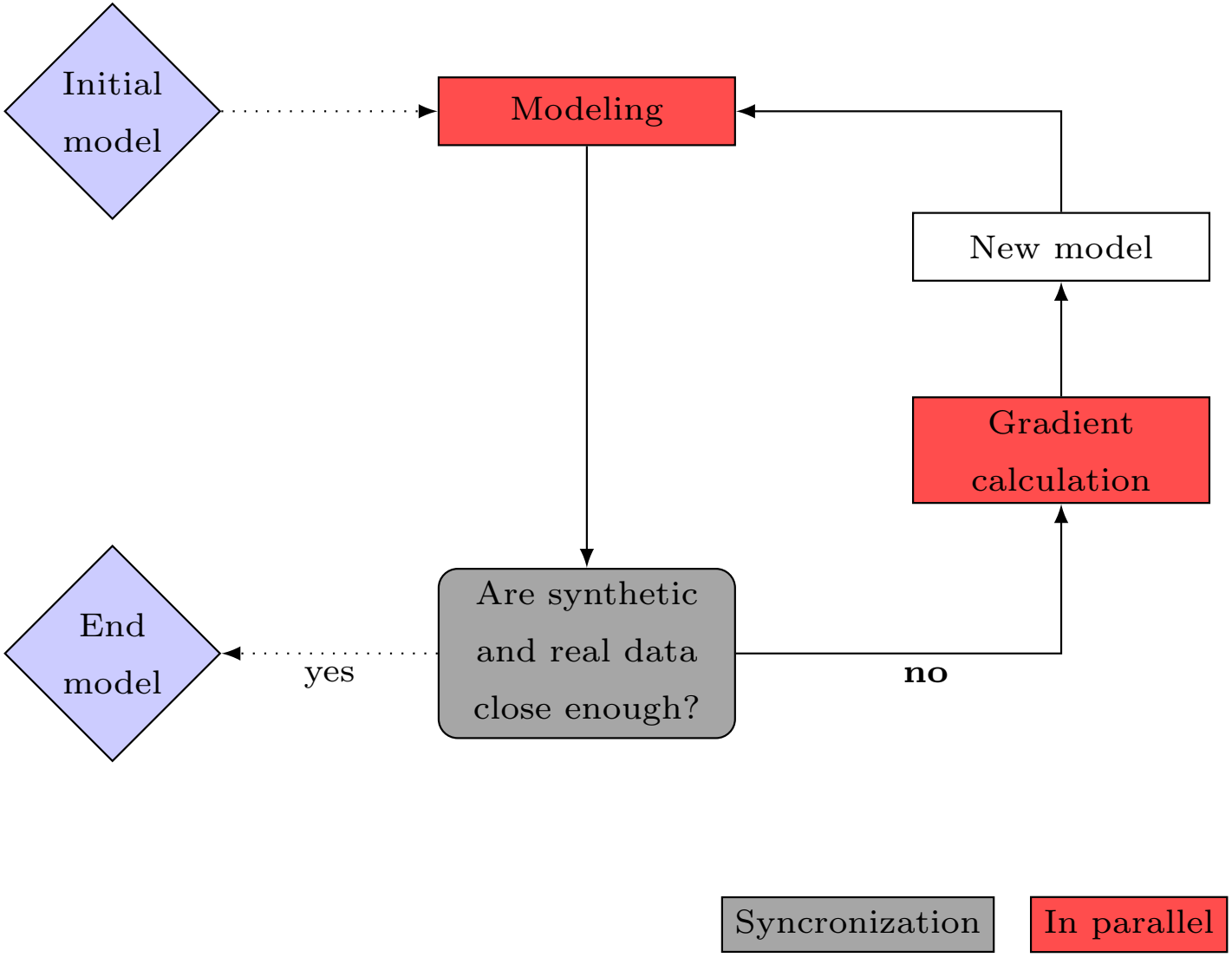
Solved using an iterative method

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



$\mathbf{m}_k$	model at iteration k
$\mathbf{g}_k$	gradient of $S(\mathbf{m})$ at iteration k
α_k	step length at iteration k

Schematic View of FWI



Time-lapse Full Waveform Inversion

Goal

Use full waveform inversion to quantify changes in time for parameters affecting wave propagation.

Different ways of doing this:

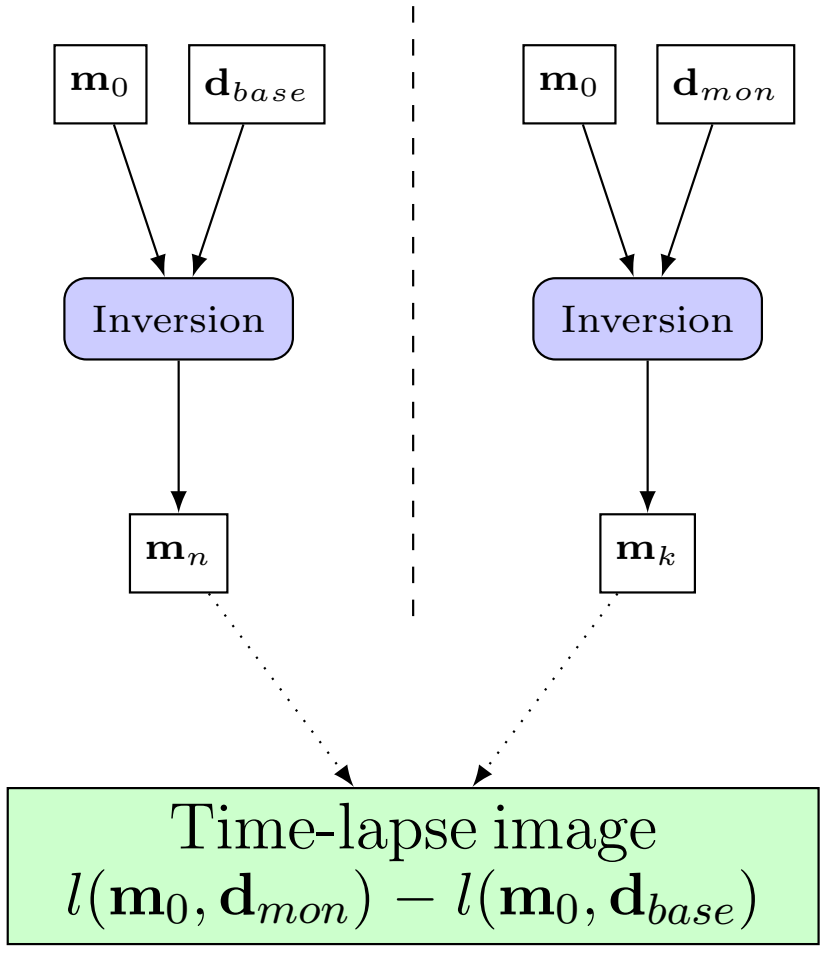
Approach 1: Two independent inversions of base and monitor

Approach 2: Invert first for base, and use the end model as input for monitor

Approach 3: Invert first for base, and use the end model in combination with a data modification as input for monitor

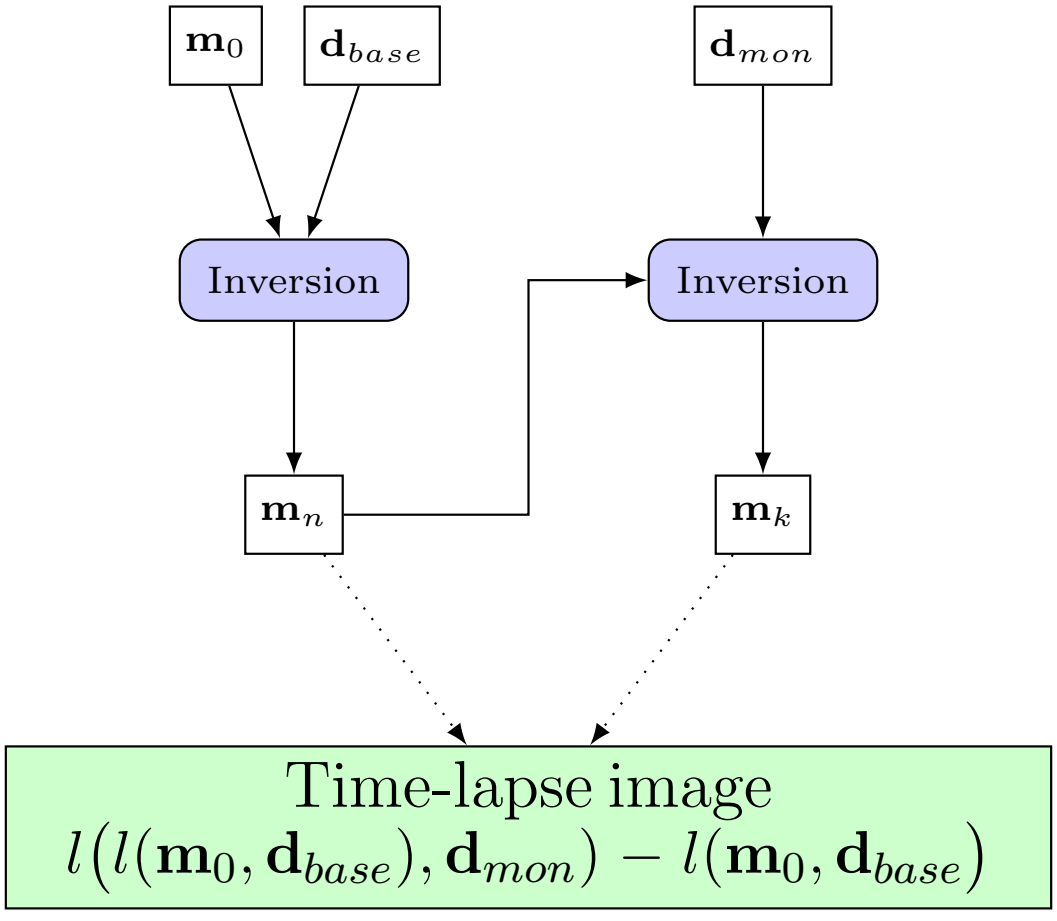
The time-lapse image is found by comparing the two end models.

Approach 1

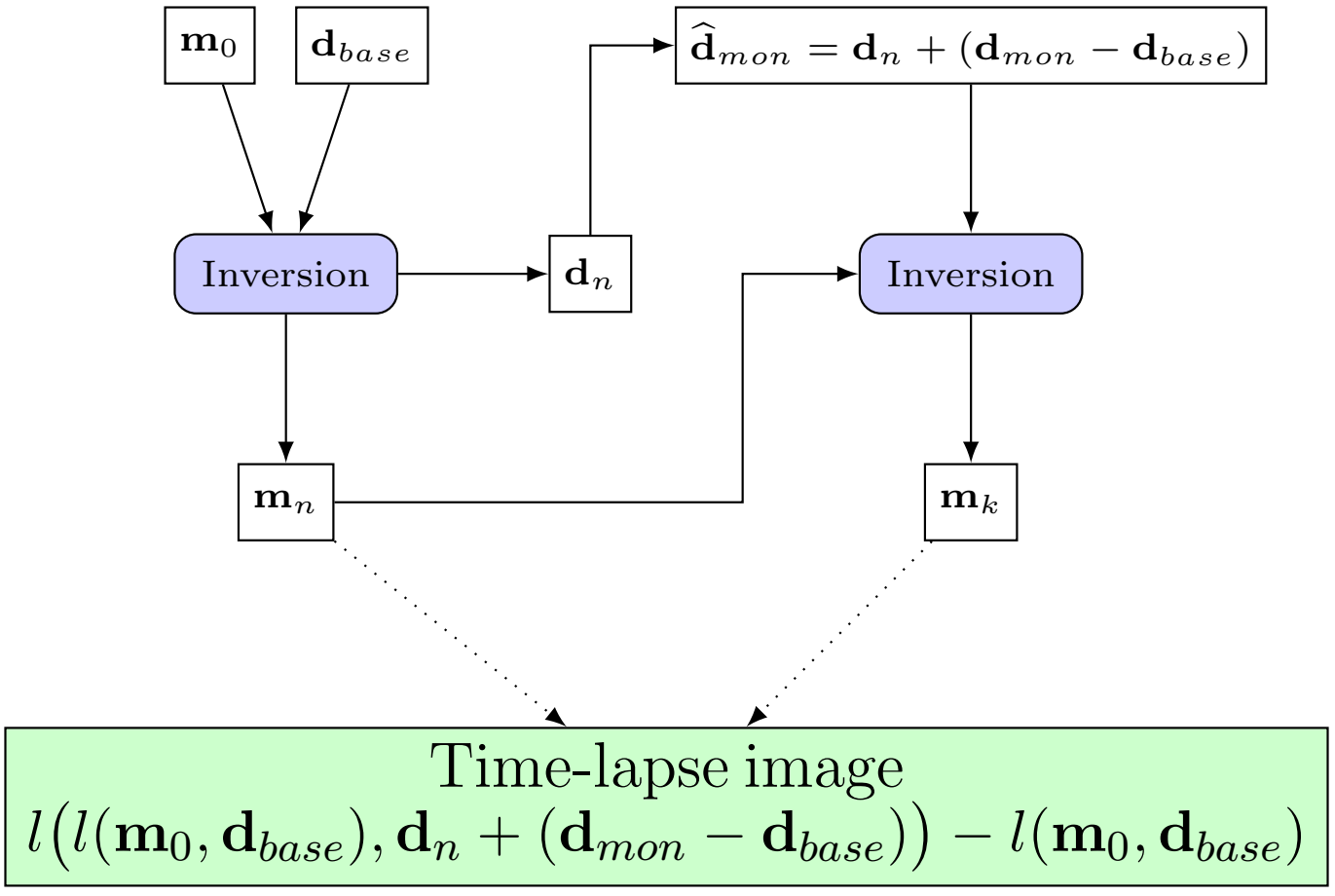


Definition: $l(\mathbf{m}, \mathbf{d})$ is the inverted model using $\mathbf{m}$ as initial model and $\mathbf{d}$ as observed data.

Approach 2


$\mathbf{m}_0$
$\mathbf{d}_{base}$
$\mathbf{d}_{mon}$
Inversion
Inversion
$\mathbf{m}_n$
$\mathbf{m}_k$
Time-lapse image
$l\big(l(\mathbf{m}_0, \mathbf{d}_{base}), \mathbf{d}_{mon}\big) - l(\mathbf{m}_0, \mathbf{d}_{base})$

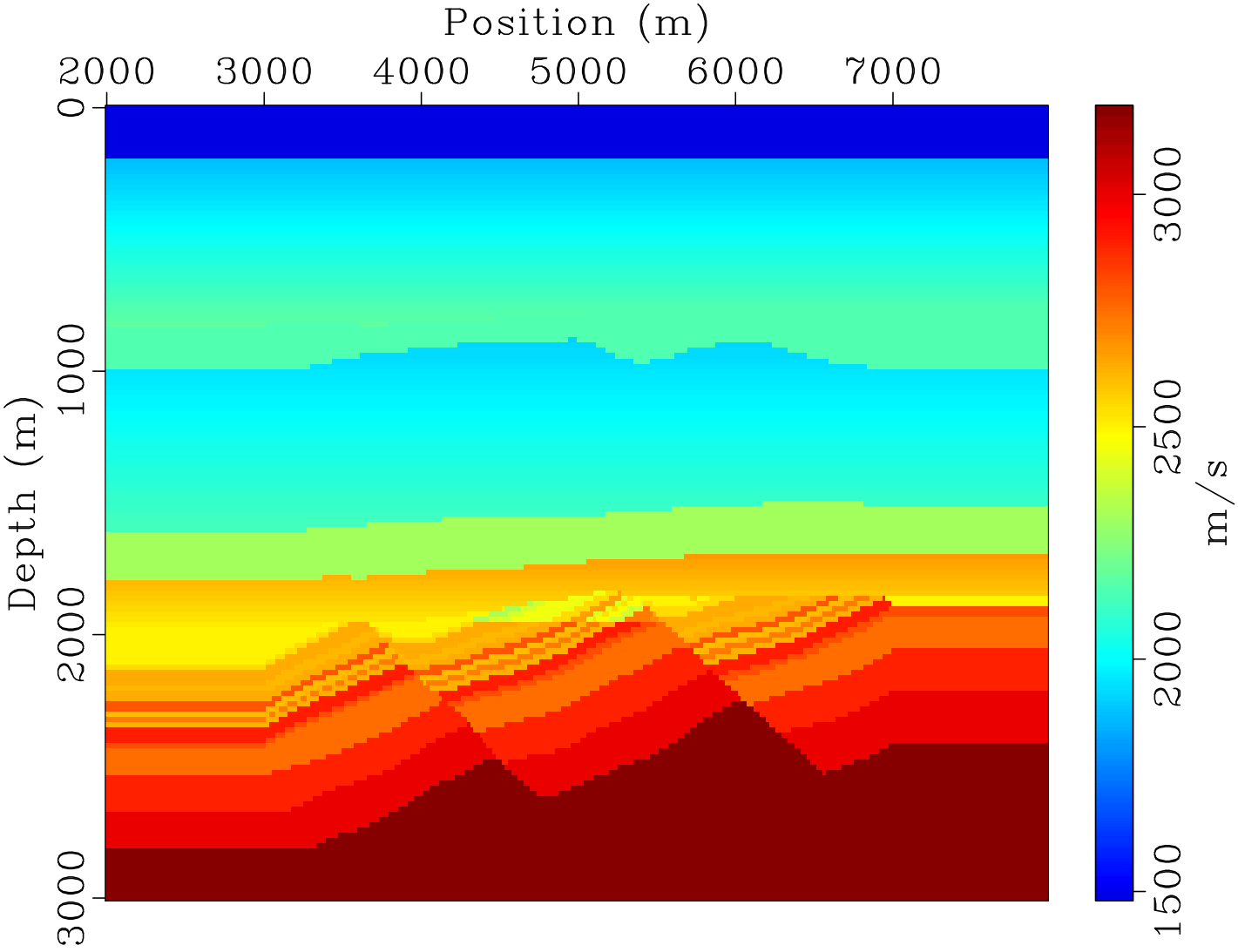
Approach 3


$\mathbf{m}_0$
$\mathbf{d}_{base}$
$\widehat{\mathbf{d}}_{mon} = \mathbf{d}_n + (\mathbf{d}_{mon} - \mathbf{d}_{base})$
Inversion
$\mathbf{d}_n$
Inversion
$\mathbf{m}_n$
$\mathbf{m}_k$
Time-lapse image
$l\big(l(\mathbf{m}_0, \mathbf{d}_{base}), \mathbf{d}_n + (\mathbf{d}_{mon} - \mathbf{d}_{base})\big) - l(\mathbf{m}_0, \mathbf{d}_{base})$

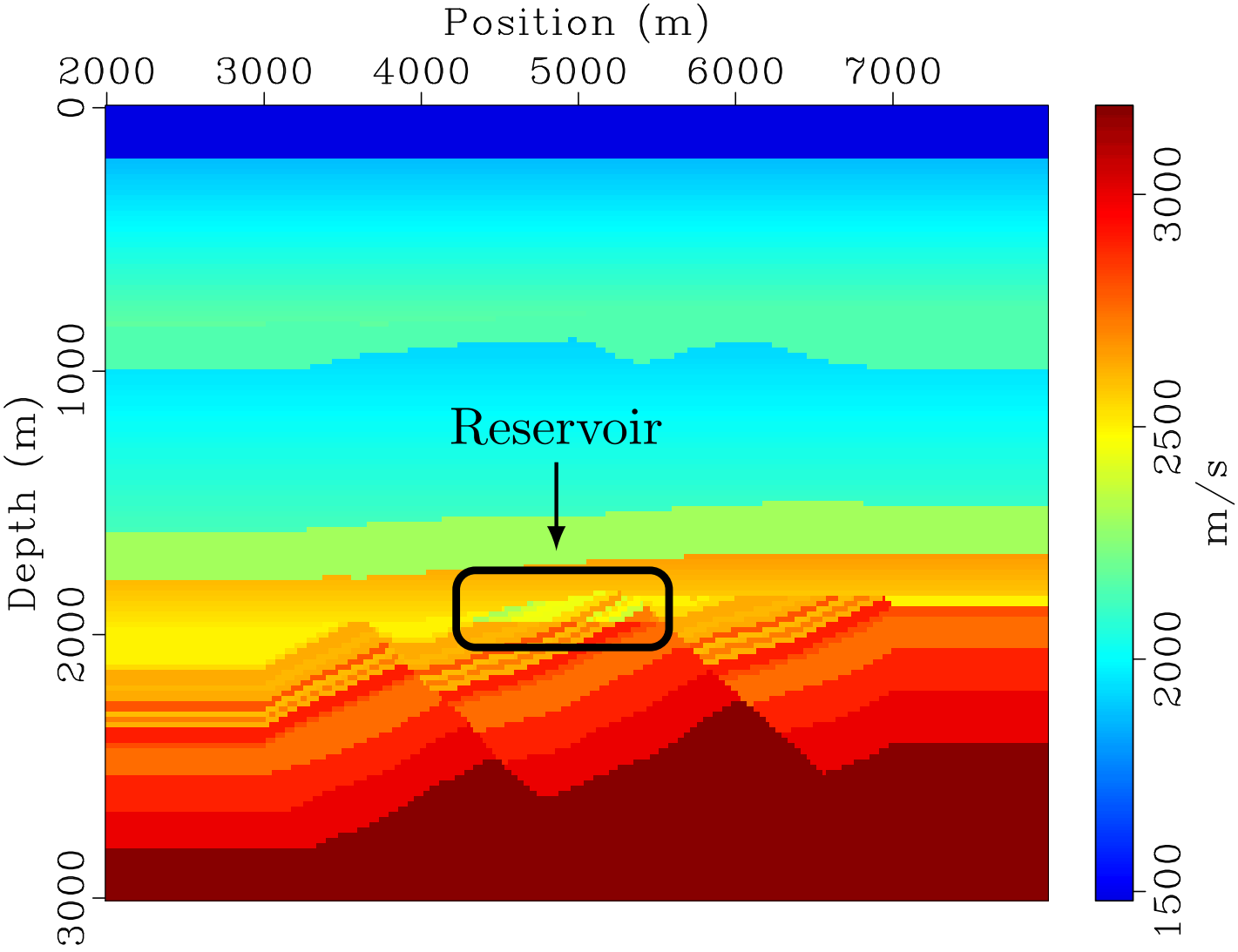
Synthetic Example

- Test model: Elastic model of the Gullfaks field.
- Base: Oil filled reservoir
- Monitor: Water filled reservoir
- P-wave velocity changes locally within reservoir: $0 - 153$ m/s
- Marine streamer survey: 370 shots and 6 km streamer length
- Streamer: 300 receivers separated by 20 m
- Shot interval: 20 m
- Source signature: Ricker wavelet with peak frequency 5.0 Hz

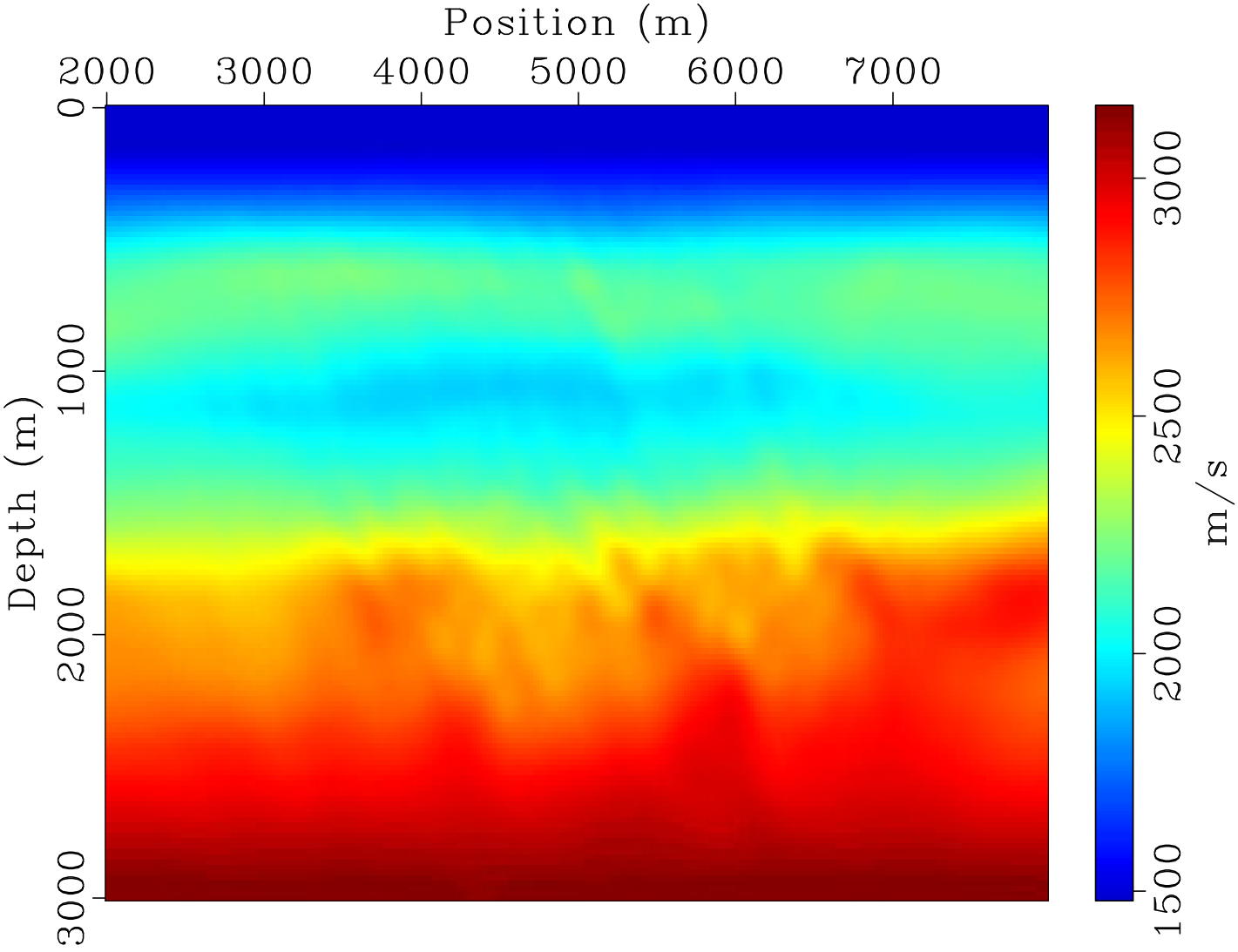
True Model


Position (m)
2000
3000
4000
5000
6000
7000
Depth (m)
0
1000
2000
3000
m/s
1500
2000
2500
3000

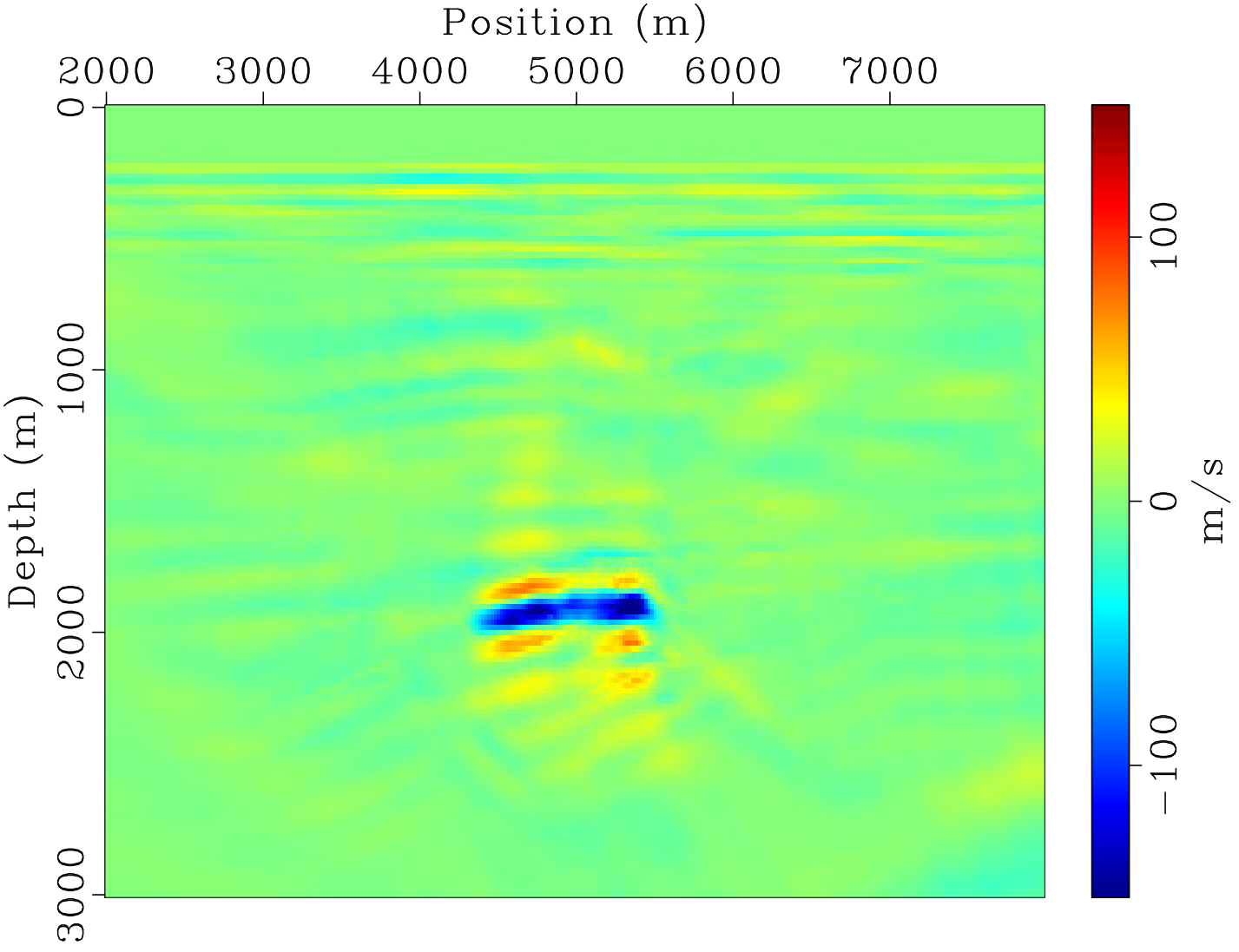
True Model


Position (m)
2000
3000
4000
5000
6000
7000
0
1000
2000
3000
Depth (m)
Reservoir
3000
2500
2000
1500
m/s

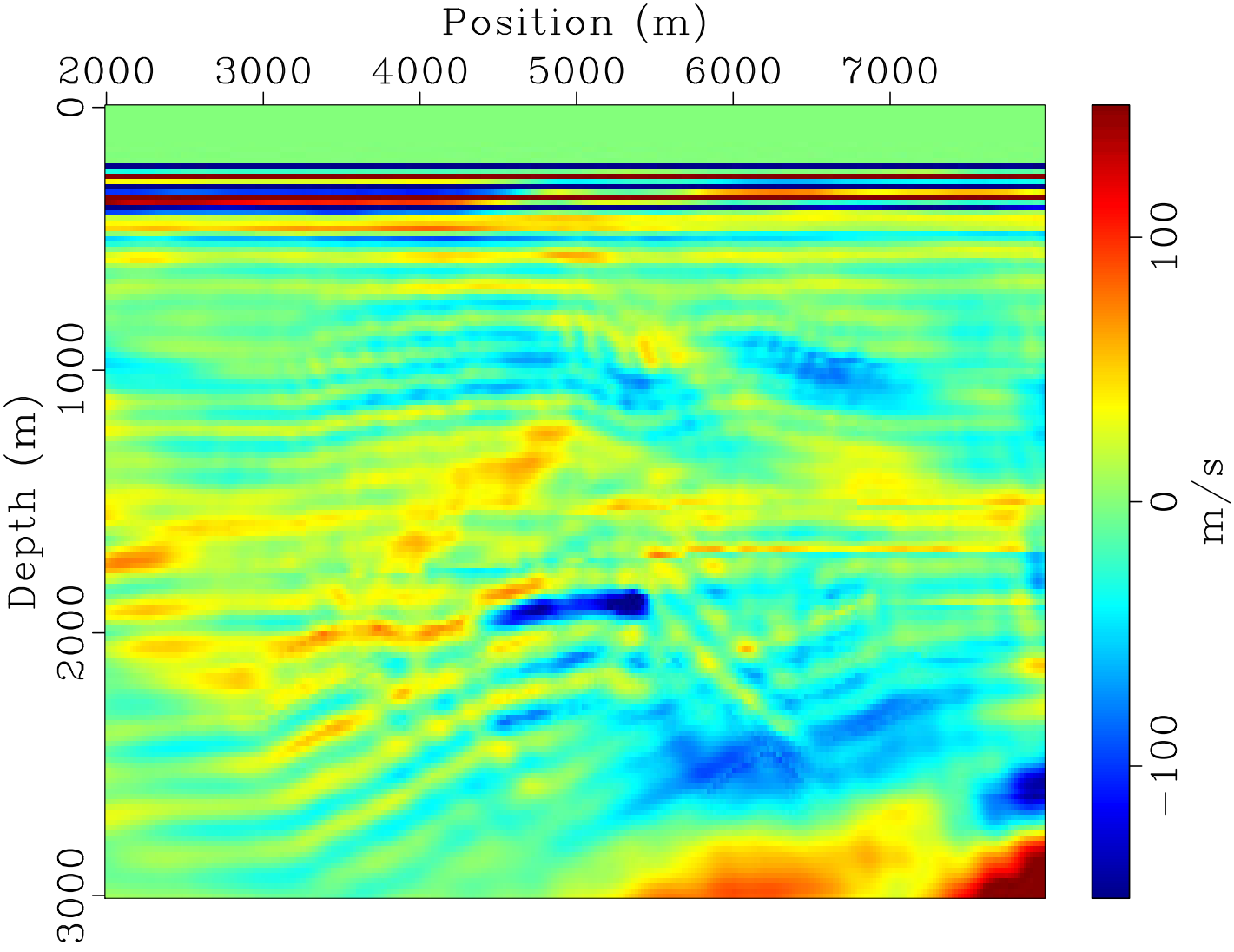
Initial Model



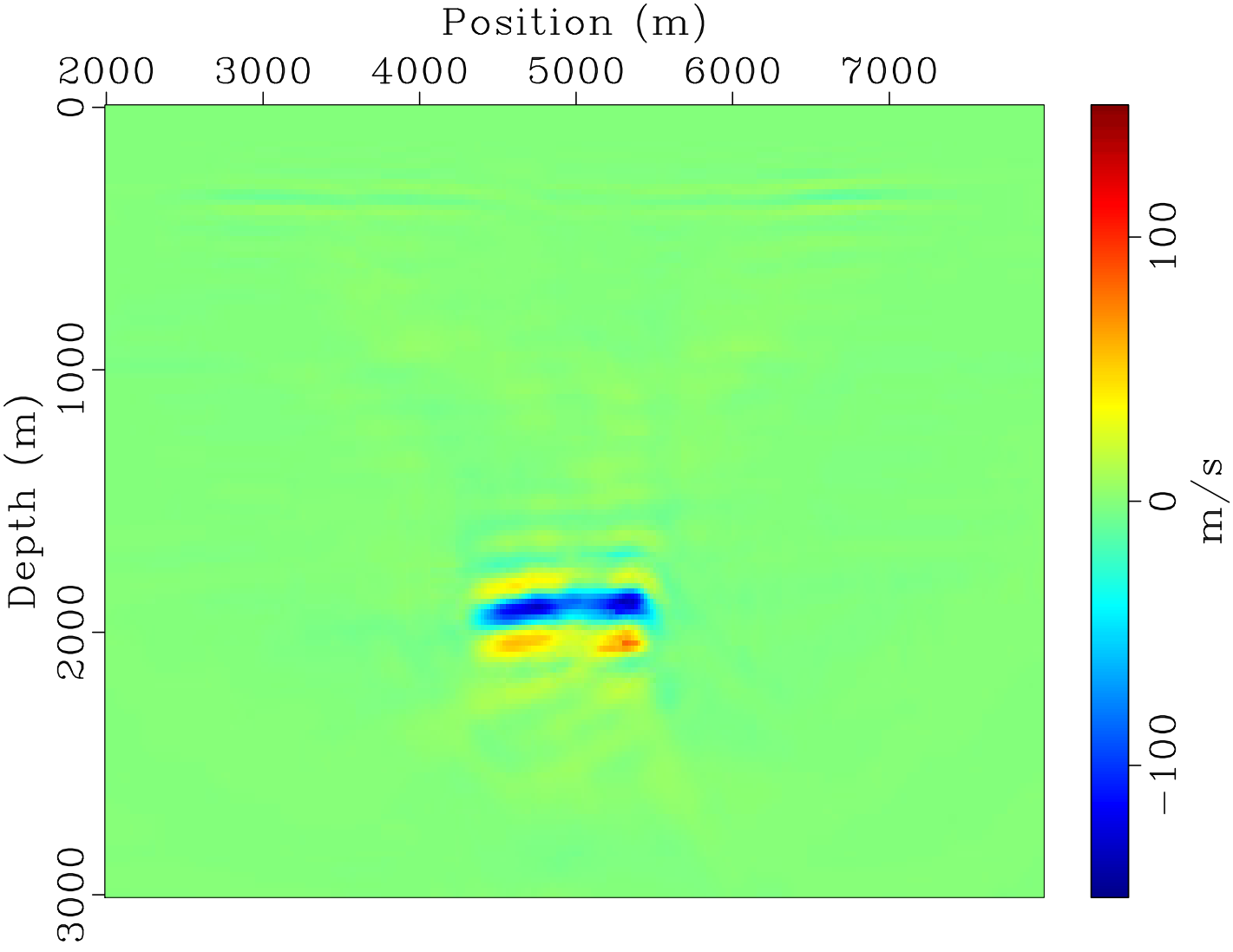
Time-Lapse Image Approach 1



Time-Lapse Image Approach 2



Time-Lapse Image Approach 3



Real Example

- Time-lapse data from the Norwegian North Sea
- Base dataset aqcuired in 1988 and monitor dataset in 1990
- Between the dataset the field was exposed to a subsurface gas leakage in one of the producing wells
- Marine streamer survey: 230 shots and 1253 m streamer length
- Streamer: 95 receivers separated by 12.5 m
- Shot intervall: 12.5 m

From Acoustic to Elastic FWI

The initial model is obtained using wave equation migration analysis (WEMVA).

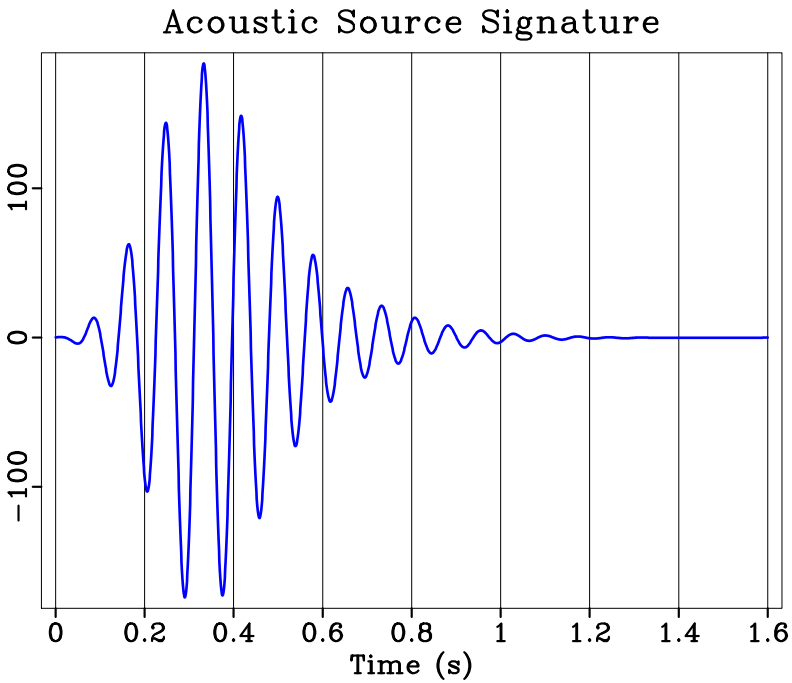
To obtain the S-wave velocity we use the following empirical V_p/V_s relation [Mavko et al., 2009]

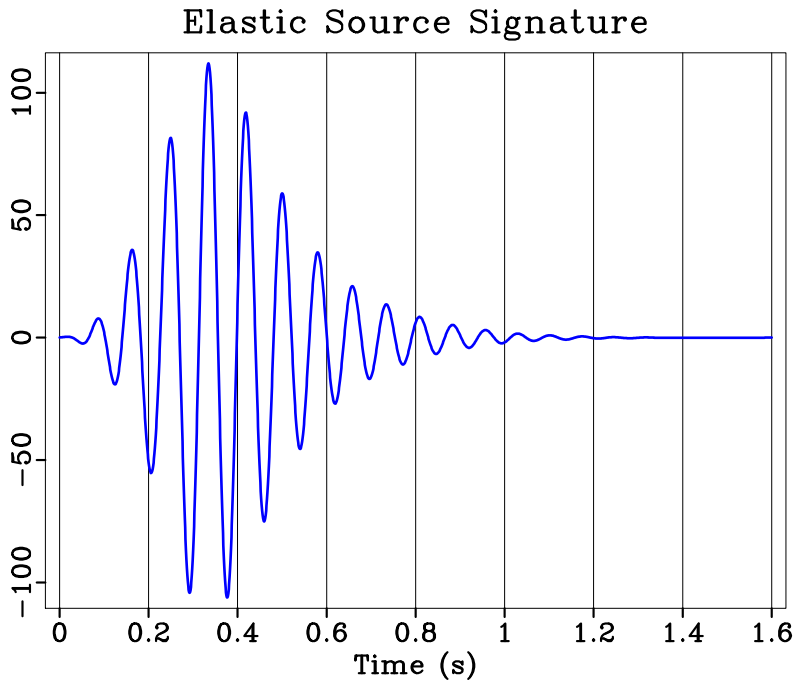
$$V_s = 0.862V_p - 1172 \text{ (m/s)}.$$

We are inverting for P-wave and S-wave velocities, and leaving the density constant during the inversion.

Source Estimation

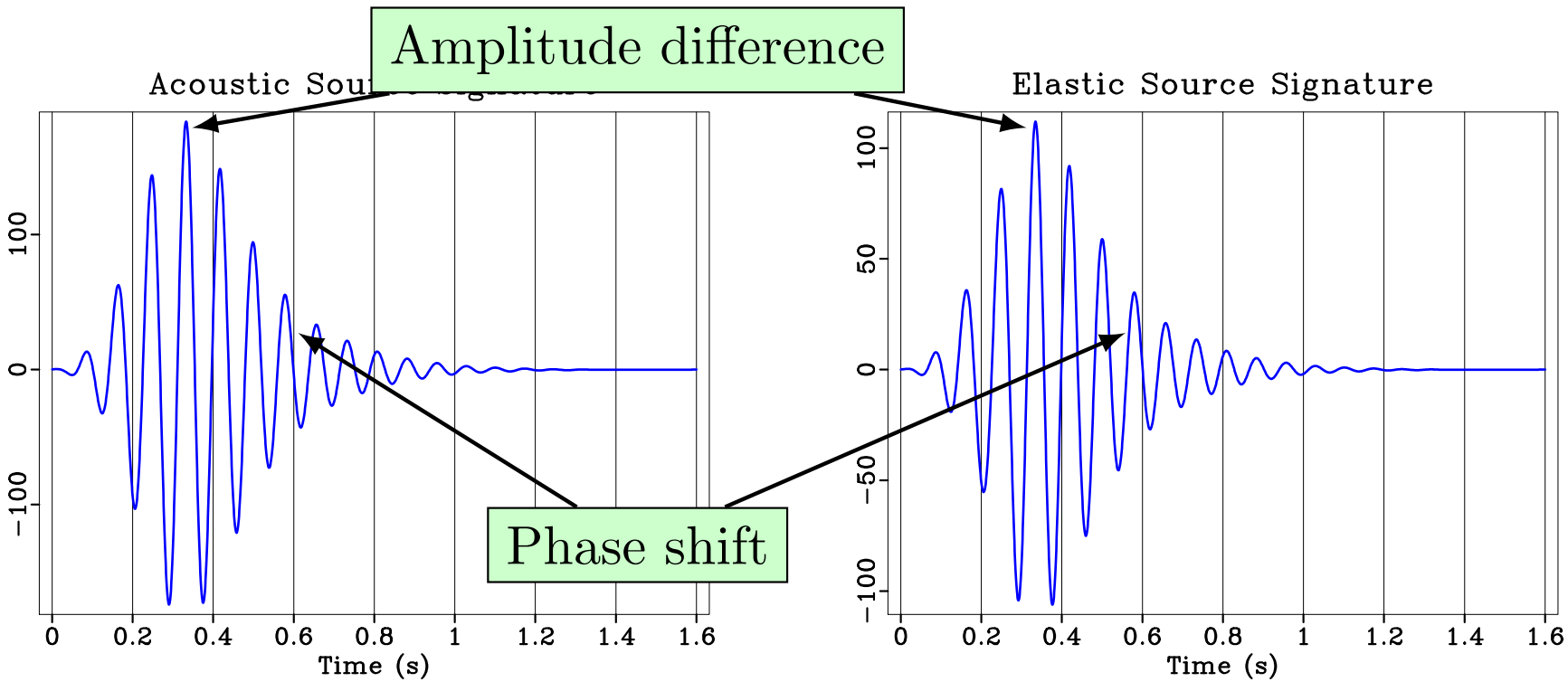
Estimated using FWI: The back propagated wave field at the source position is the gradient of the source.



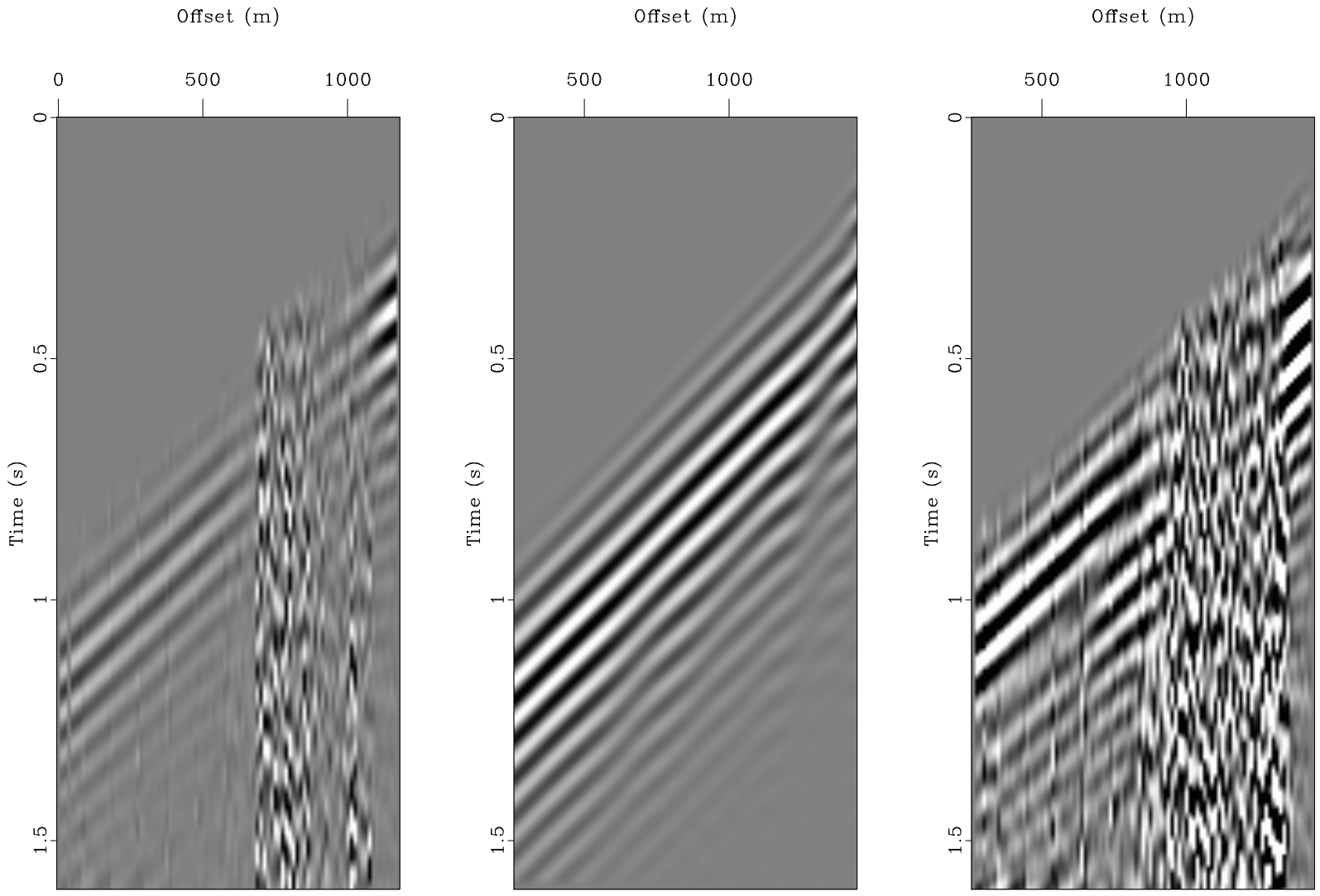


Source Estimation

Estimated using FWI: The back propagated wave field at the source position is the gradient of the source.

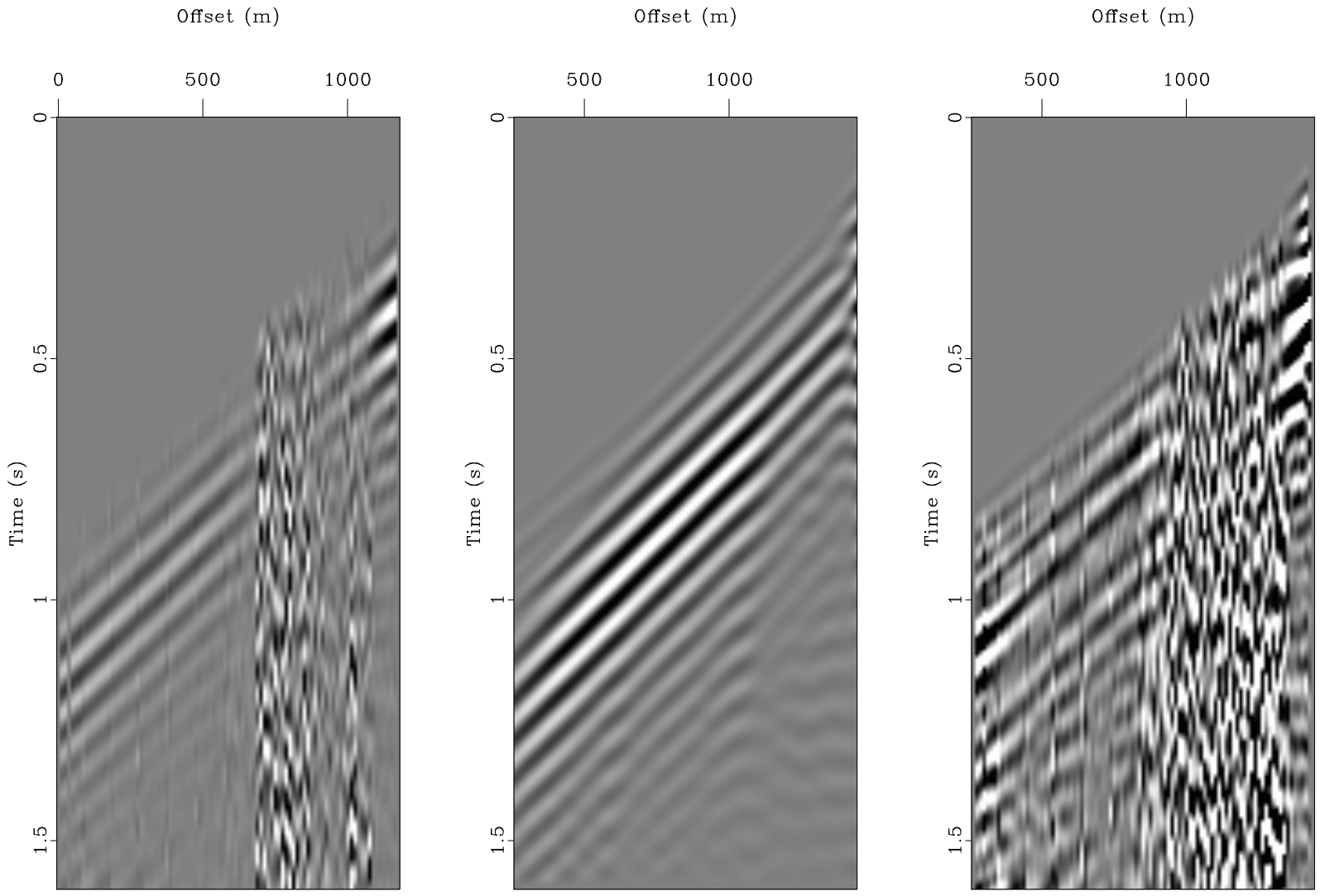


QC: Elastic Inversion - First iteration



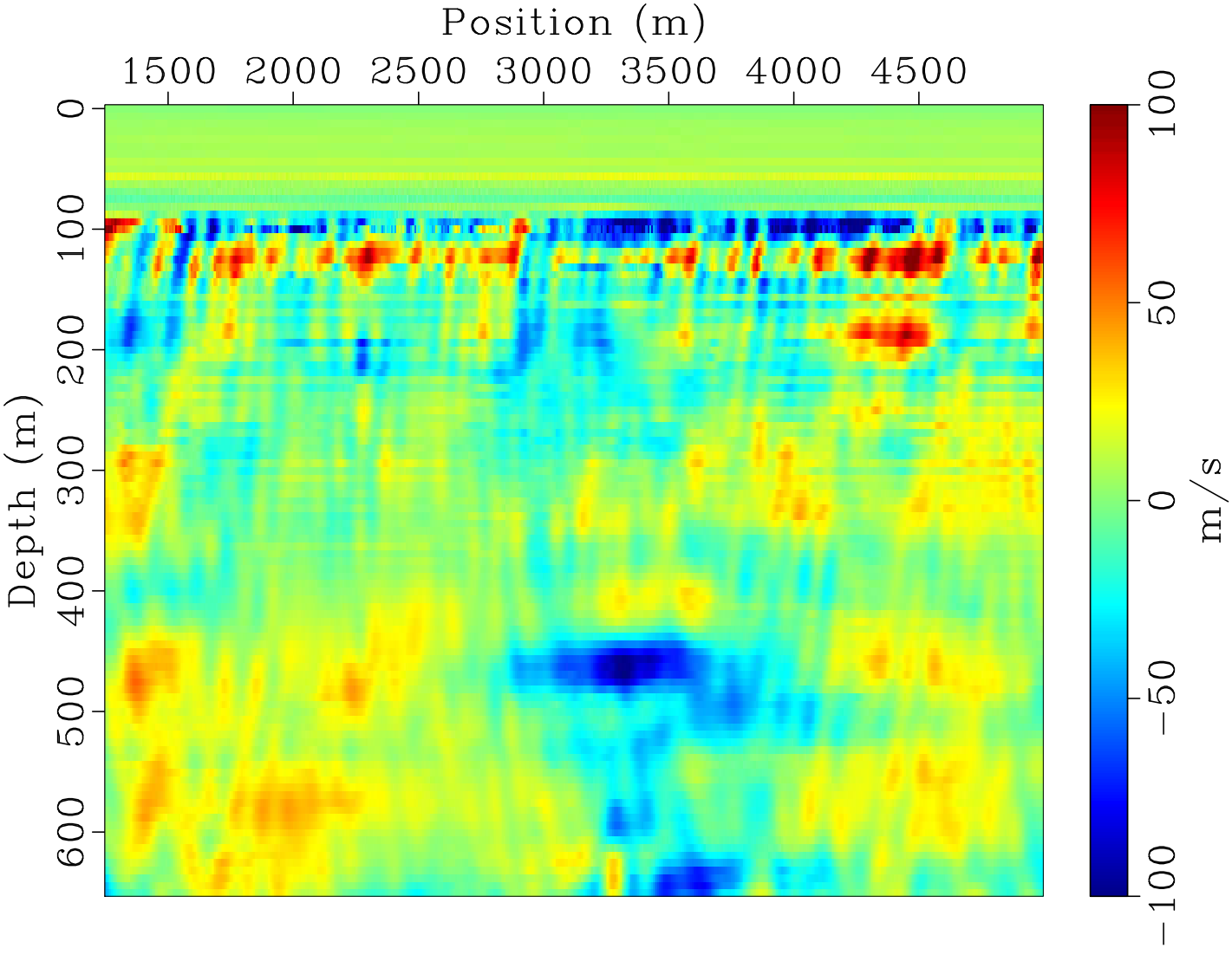
Real data Synthetic data Residual

QC: Elastic Inversion - Last iteration

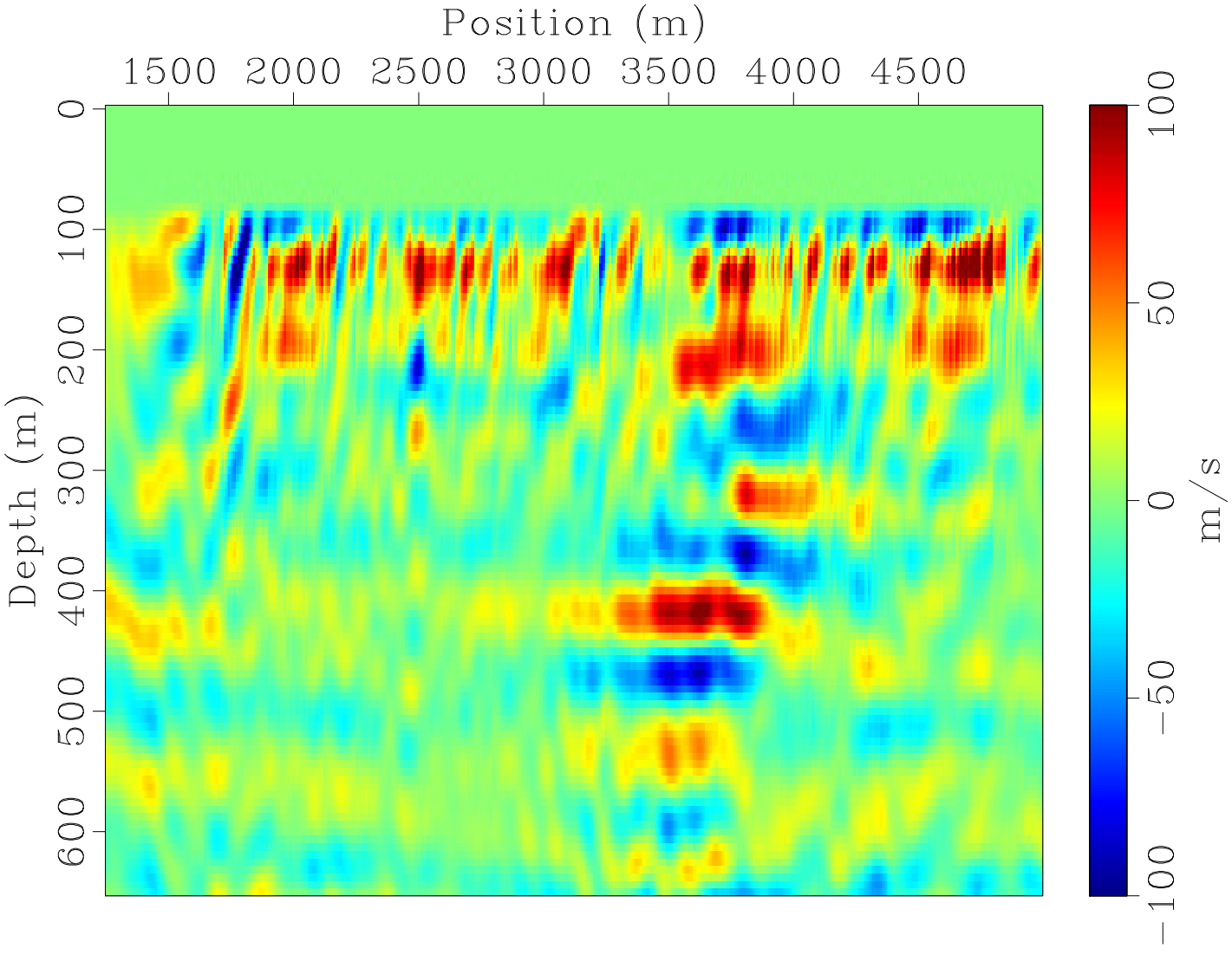


Real data Synthetic data Residual

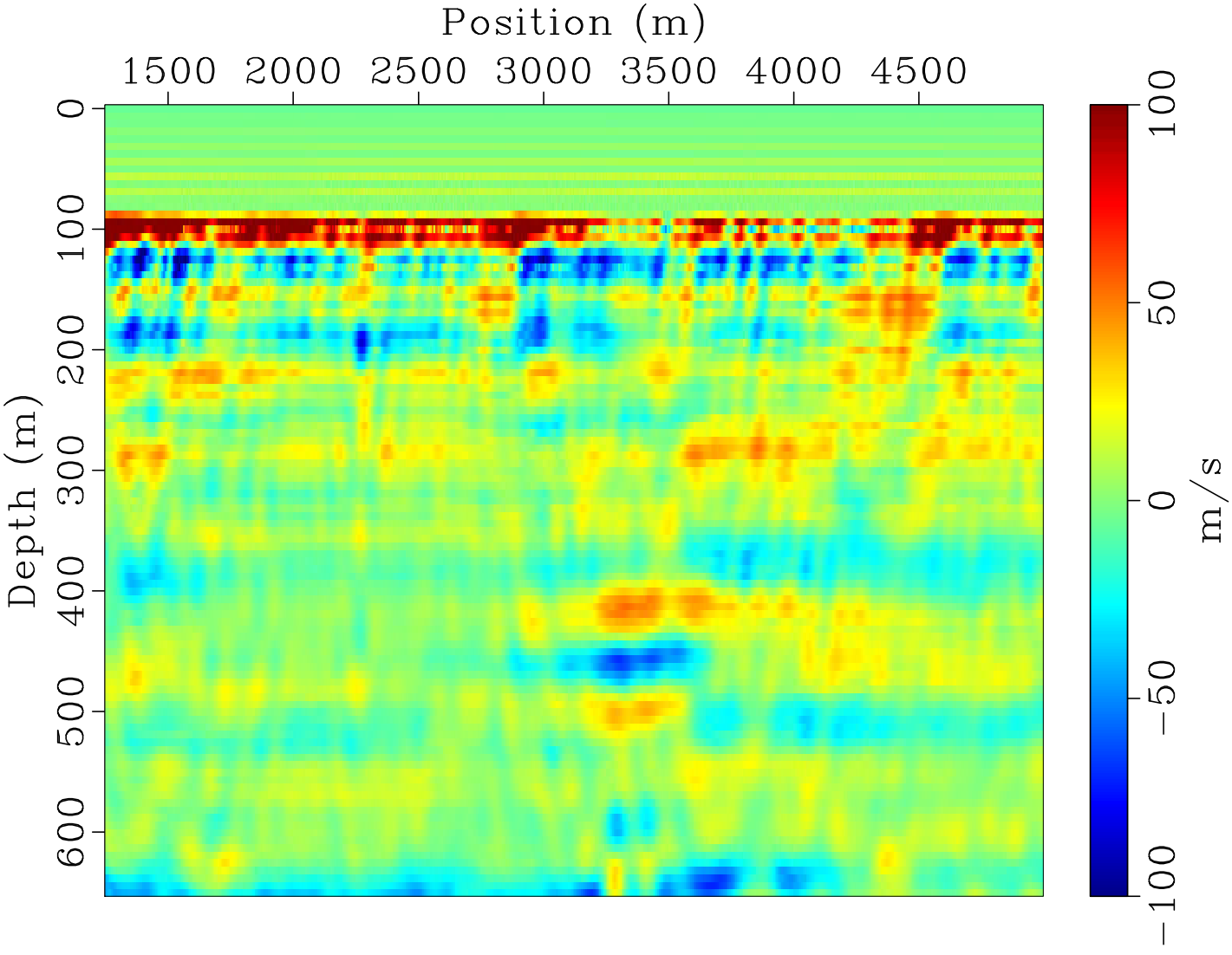
Acoustic Time-Lapse Image: Approach 1



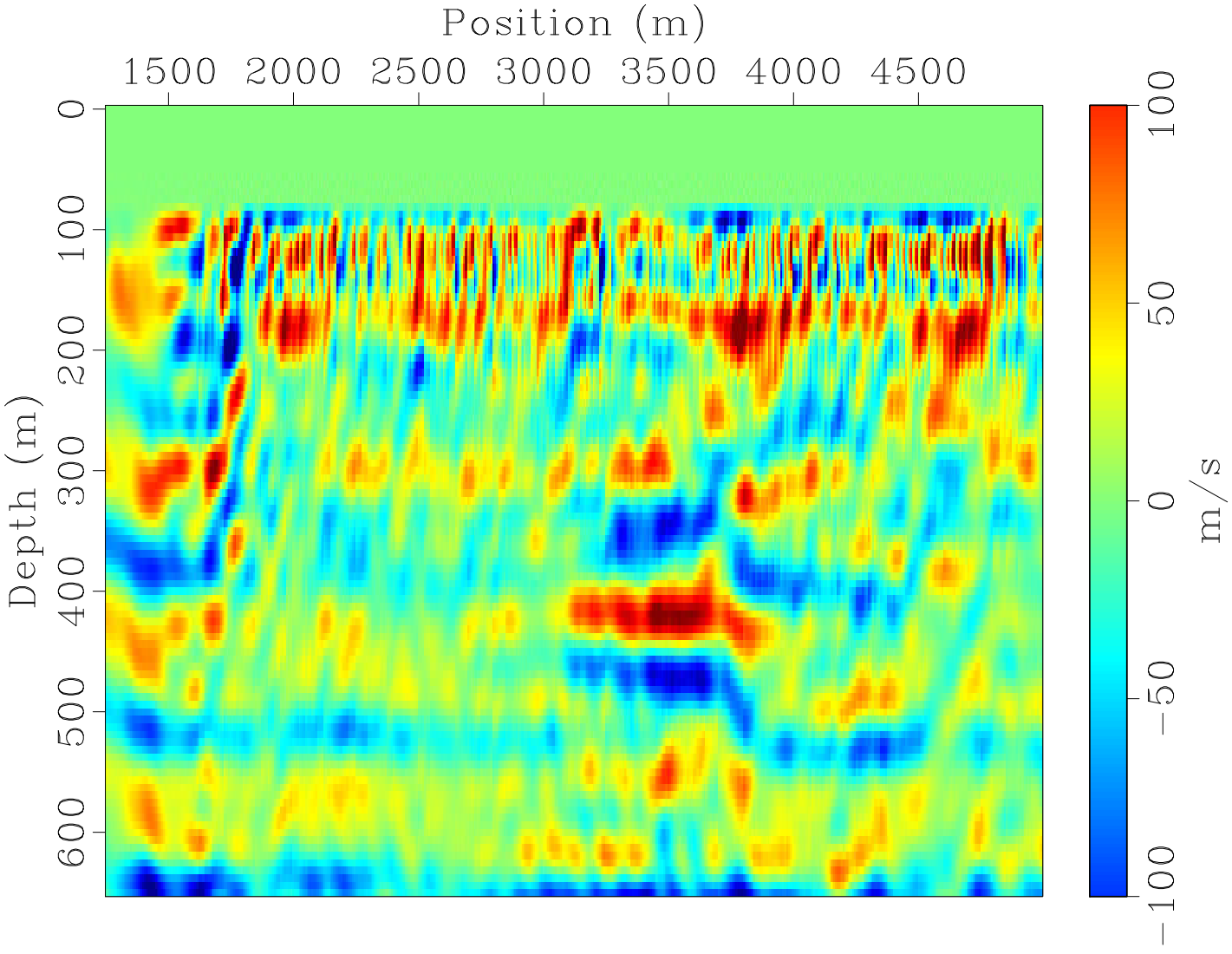
Elastic Time-Lapse Image: Approach 1



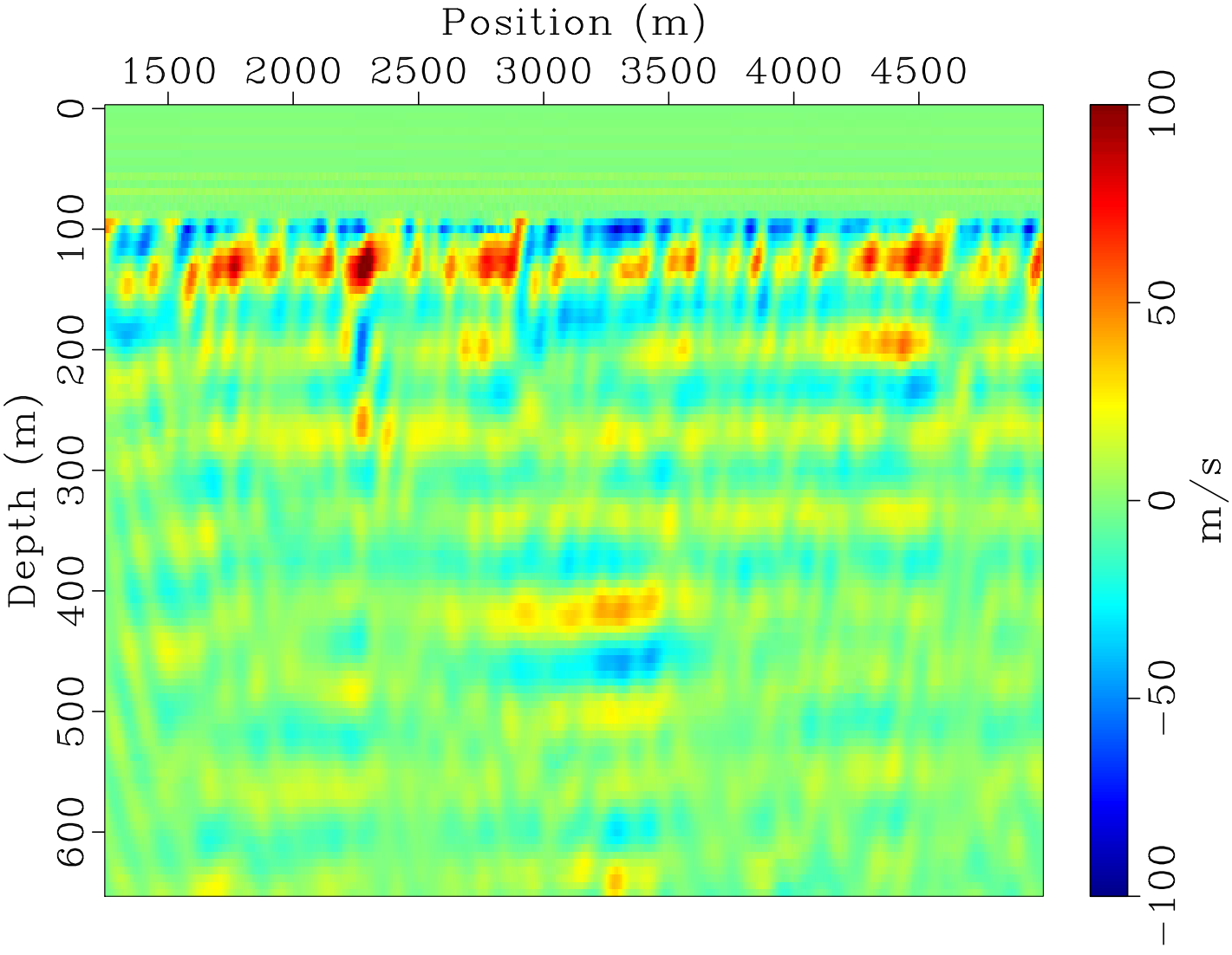
Acoustic Time-Lapse Image: Approach 2



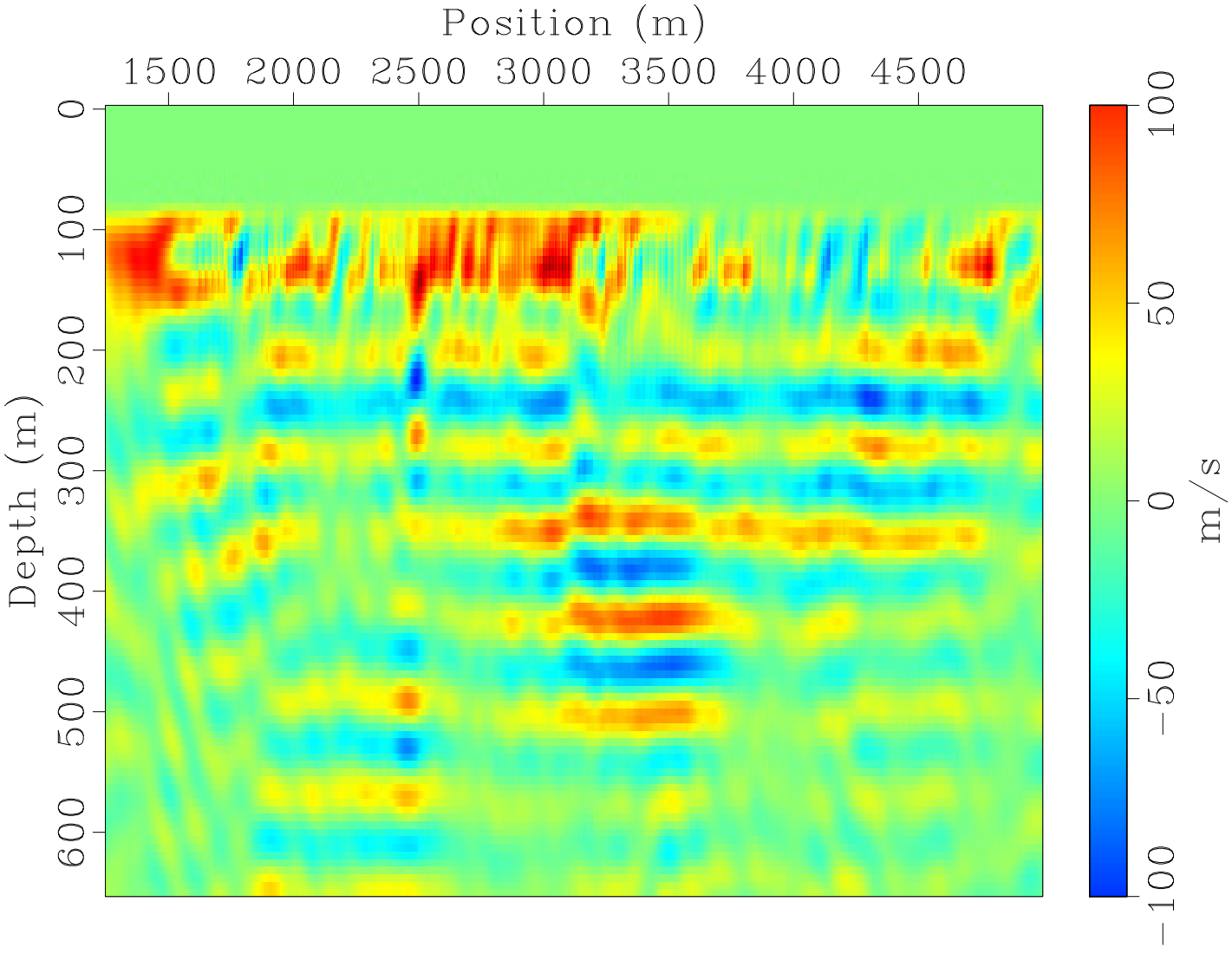
Elastic Time-Lapse Image: Approach 2



Acoustic Time-Lapse Image: Approach 3



Elastic Time-Lapse Image: Approach 3



Conclusions and Remarks

- Full waveform inversion can be used to quantify time-lapse changes in the subsurface
- Source estimation results in different source signatures for acoustic and elastic inversion
- Several artifacts appear in the time-lapse images that must be studied further. Add regularization?
- Modeling in 2D while data is 3D: No geometrical spreading. May improve results by inverting in 3D?

Acknowledgements

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References I

Biondi, B., C. Deutsch, R. Gundesø, D. Lumley, G. Mavko, T. Mukerji, J. Rickett, and M. Thiele, 1996, Reservoir monitoring: A multi-disciplinary feasibility study: SEG Technical Program Expanded Abstracts 1996, 1775–1778.

Johnston, D., R. McKenny, J. Verbeek, and J. Almond, 1998, Time-lapse seismic analysis of fulmar field: The Leading Edge, **17**, 1420–1428.

Liu, F., L. Guasch, S. A. Morton, M. Warner, A. Umpleby, Z. Meng, S. Fairhead, and S. Checkles, 2012, 3-d time-domain full waveform inversion of a valhall obc dataset: SEG Technical Program Expanded Abstracts 2012, 1–5.

Lumley, D., 2010, 4d seismic monitoring of co2 sequestration: The Leading Edge, **29**, 150–155.

Lumley, D., D. C. Adams, M. Meadows, S. Cole, and R. Wright, 2003, 4d seismic data processing issues and examples: SEG Technical Program Expanded Abstracts 2003, 1394–1397.

Mavko, G., Mukerji, T., Dvorkin, J., 2009, The Rock Physics Handbook, Cambridge University Press.

References II

Nocedal, J., and S. J. Wright, 2006, Numerical optimization, second ed.: Springer Science+ Business Media, LLC.

Routh, P., G. Palacharla, I. Chikichev, and S. Lazaratos, 2012, Full wavefield inversion of time-lapse data for improved imaging and reservoir characterization: SEG Technical Program Expanded Abstracts 2012, 1–6.

Routh, P. S., and P. D. Anno, 2008, Time-lapse noise characterization by inversion: SEG Technical Program Expanded Abstracts 2008, 3143–3147.

Tarantola, A., 1984, Inversion of seismic reflection data in the acoustic approximation: Geophysics, **49**, 1259–1266.

Virieux, J., and S. Operto, 2009, An overview of full-waveform inversion in exploration geophysics: Geophysics, **74**.

Weibull, W., B. Arntsen, and E. Nilsen, 2012, Initial velocity models for full waveform inversion: SEG Technical Program Expanded Abstracts 2012, 1–4.

Zheng, Y., P. Barton, and S. Singh, 2011, Strategies for elastic full waveform inversion of time-lapse ocean bottom cable (obc) seismic data: SEG Technical Program Expanded Abstracts 2011, 4195–4200.