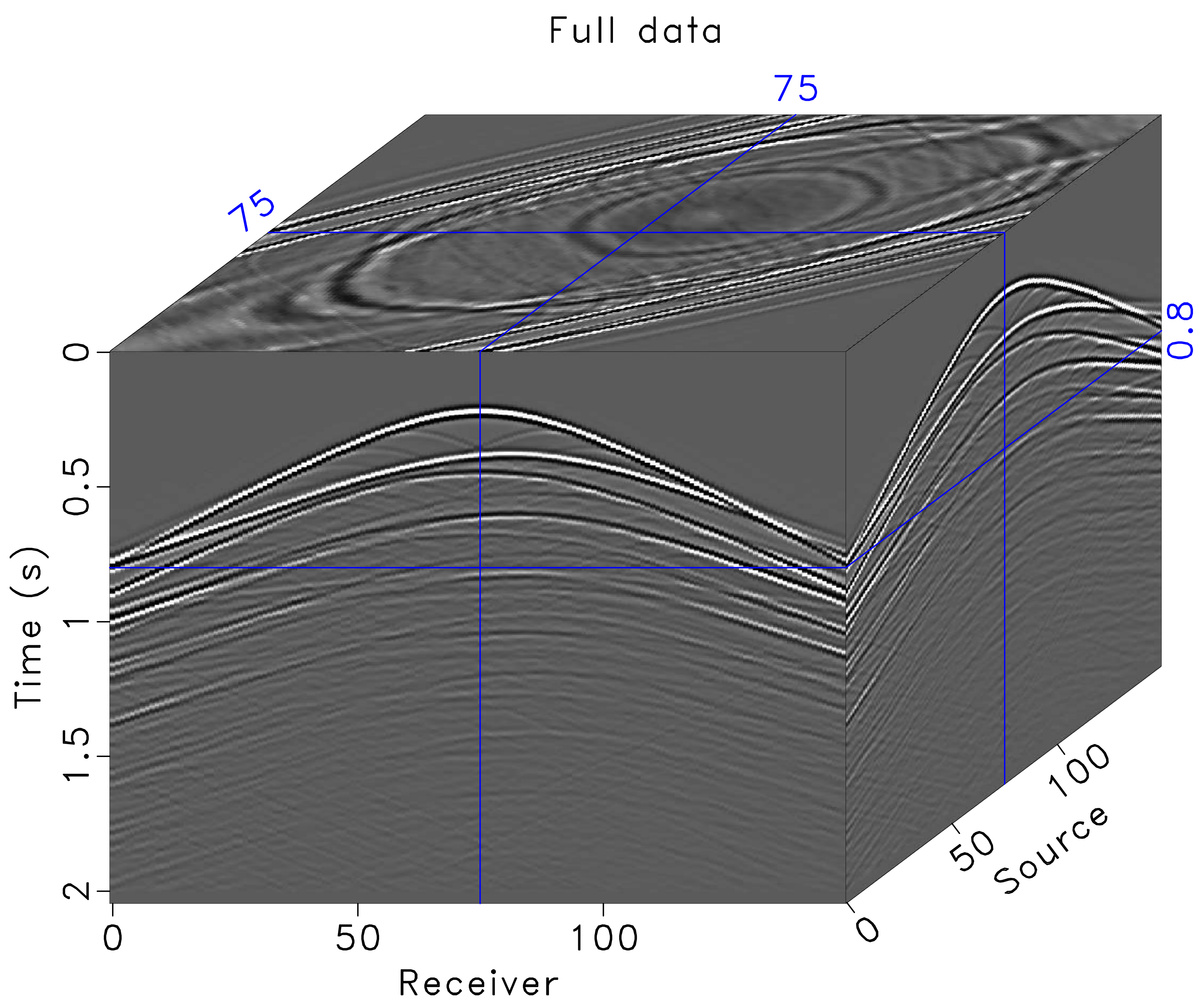
Migration with surface-related multiples from incomplete seismic data

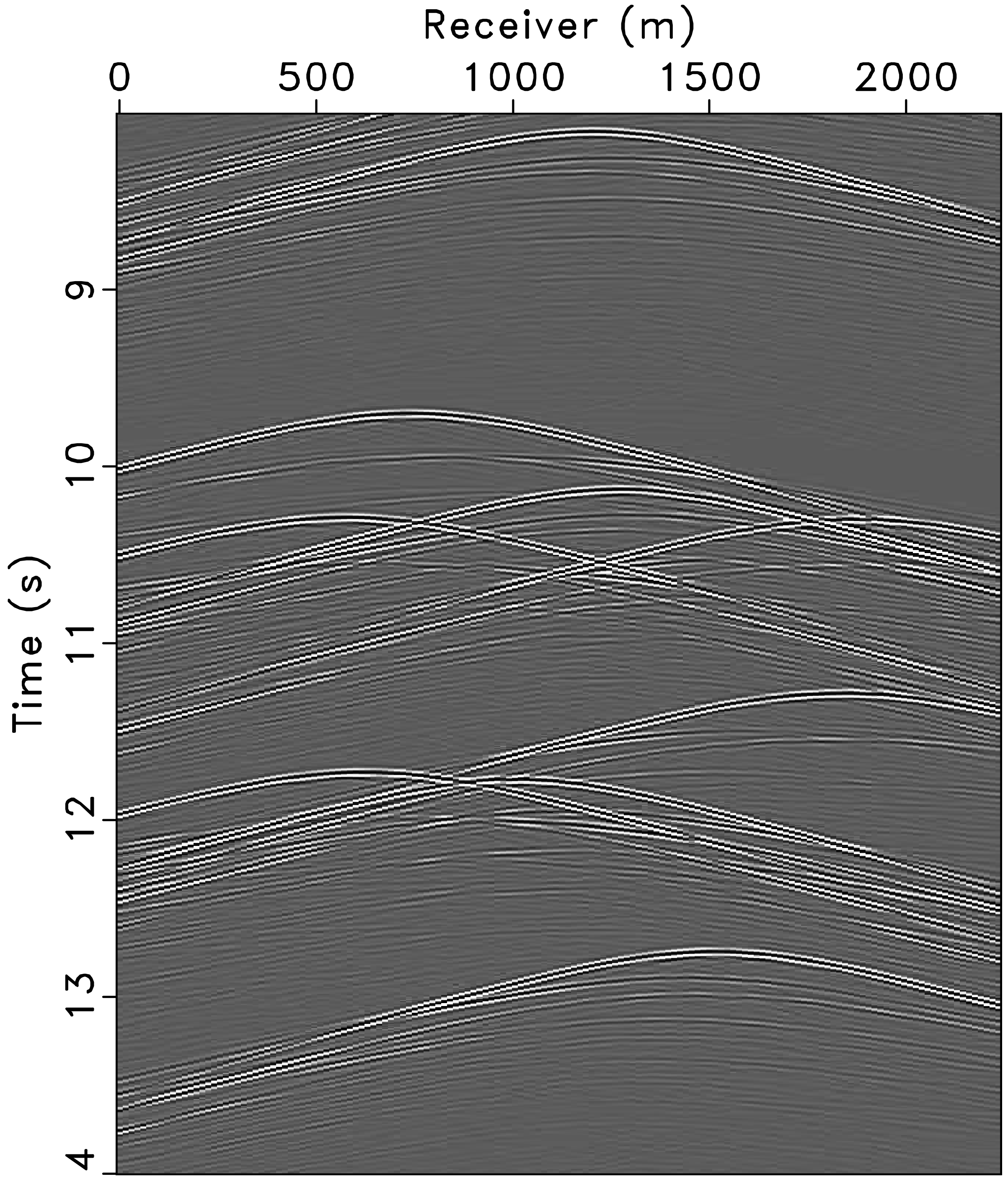
Ning Tu, Tim Lin and Felix Herrmann

SLIM
University of British Columbia

We want data like this

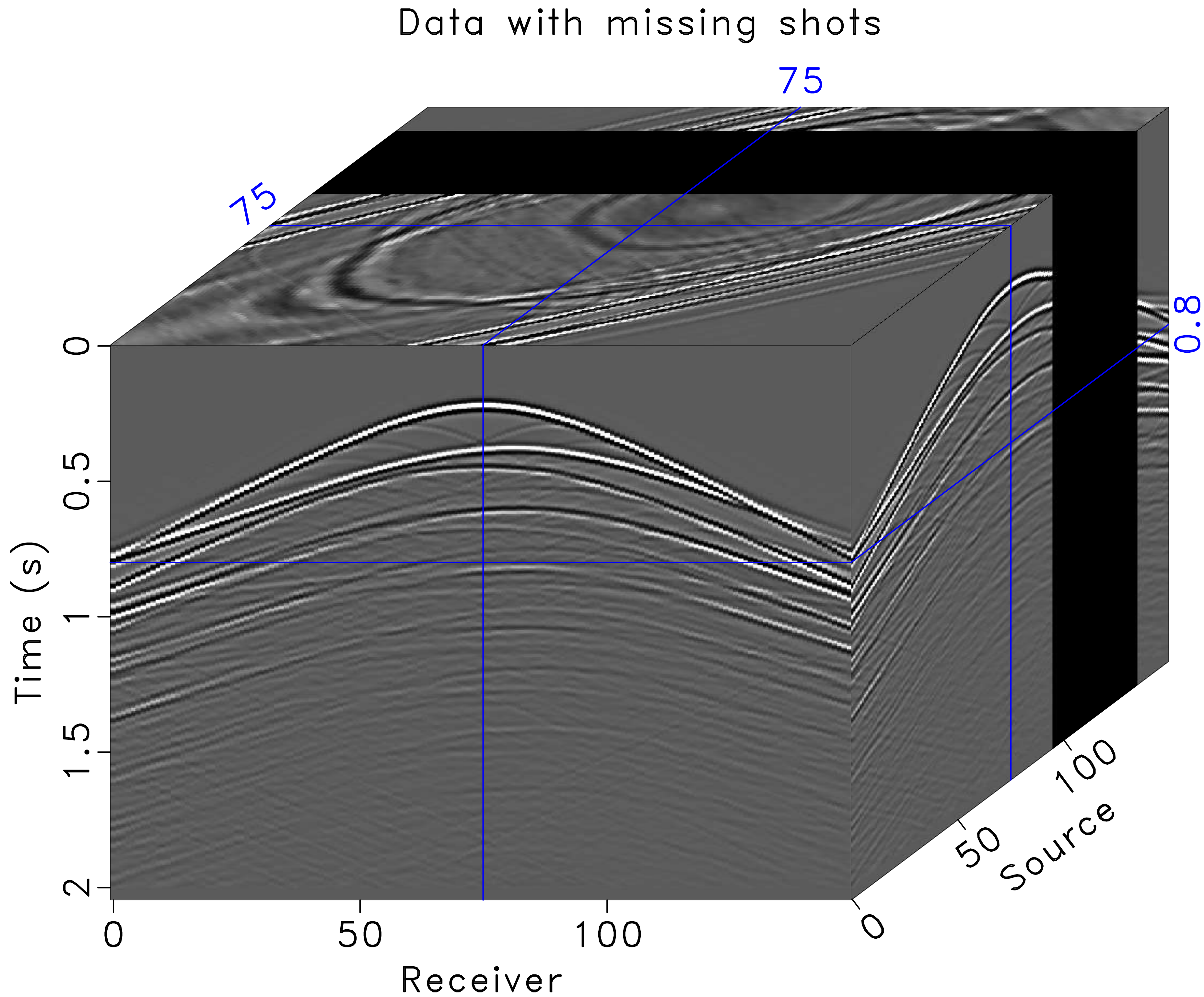


However...

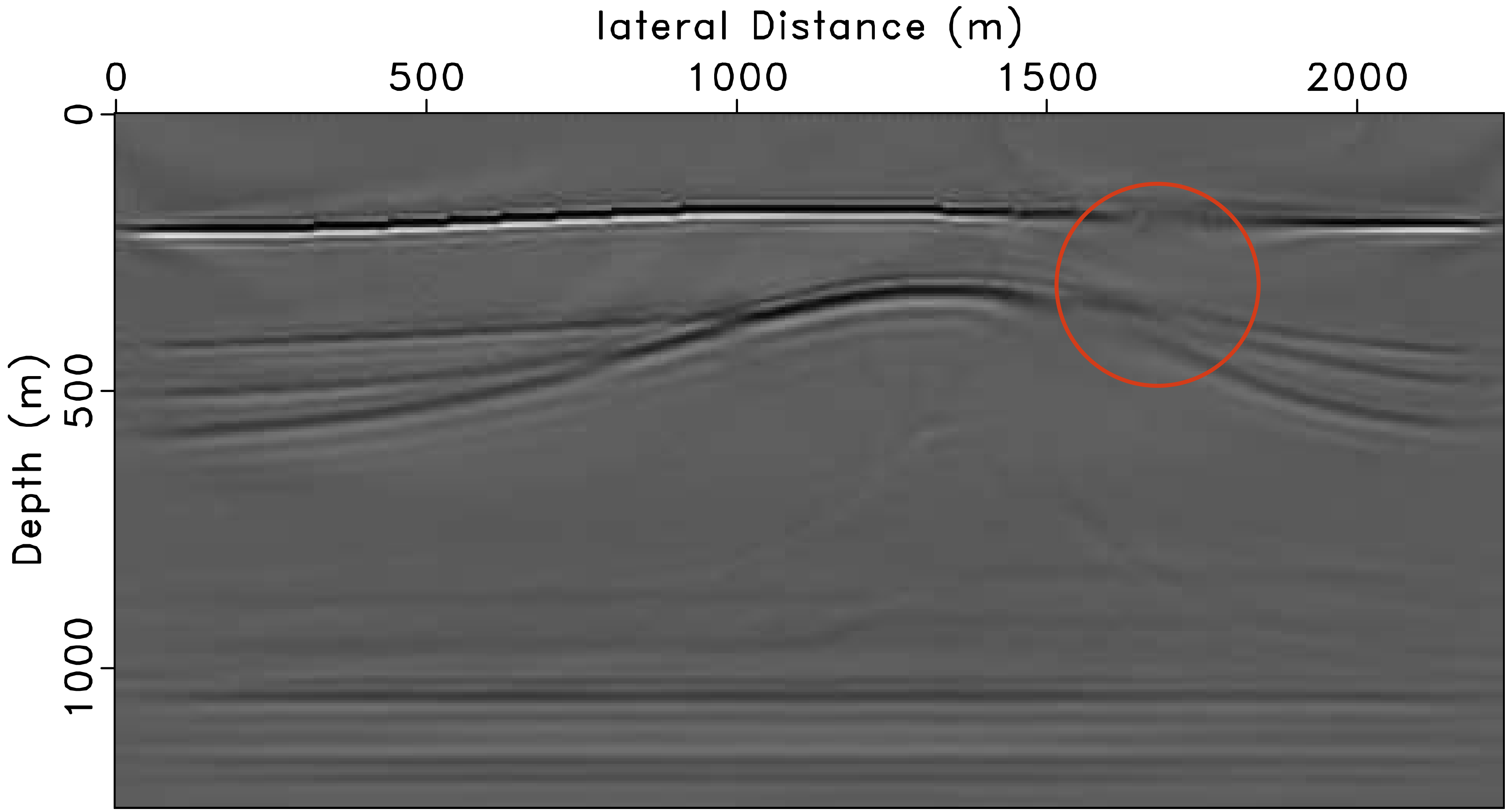


Simultaneous data: total data

Or...


Data with missing shots
75
75
0.8
Time (s)
0
0.5
1
1.5
2
0
50
100
Receiver
0
50
100
Source

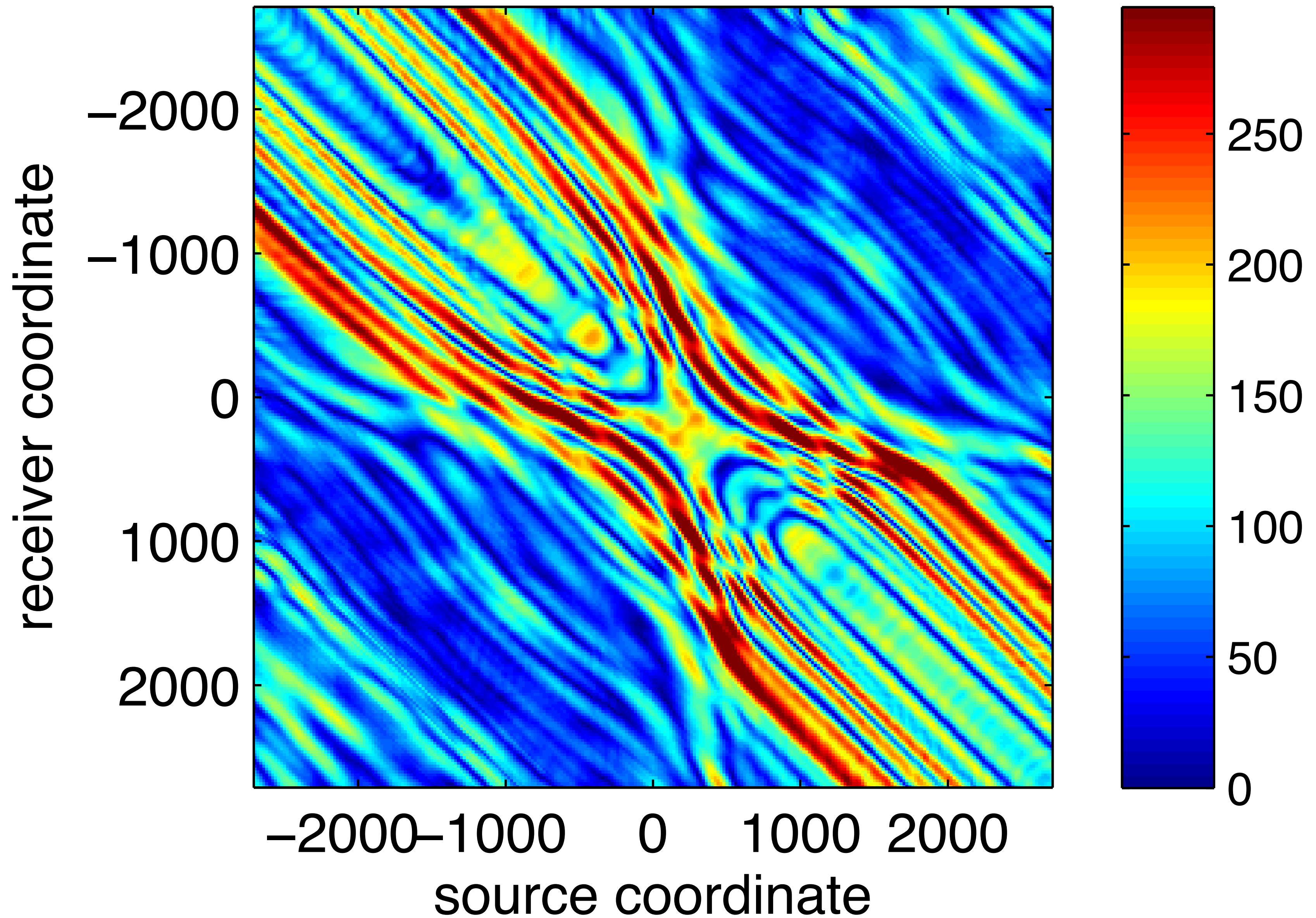
Migration with surface-free data with *missing* shots



Migration of primary impulse response

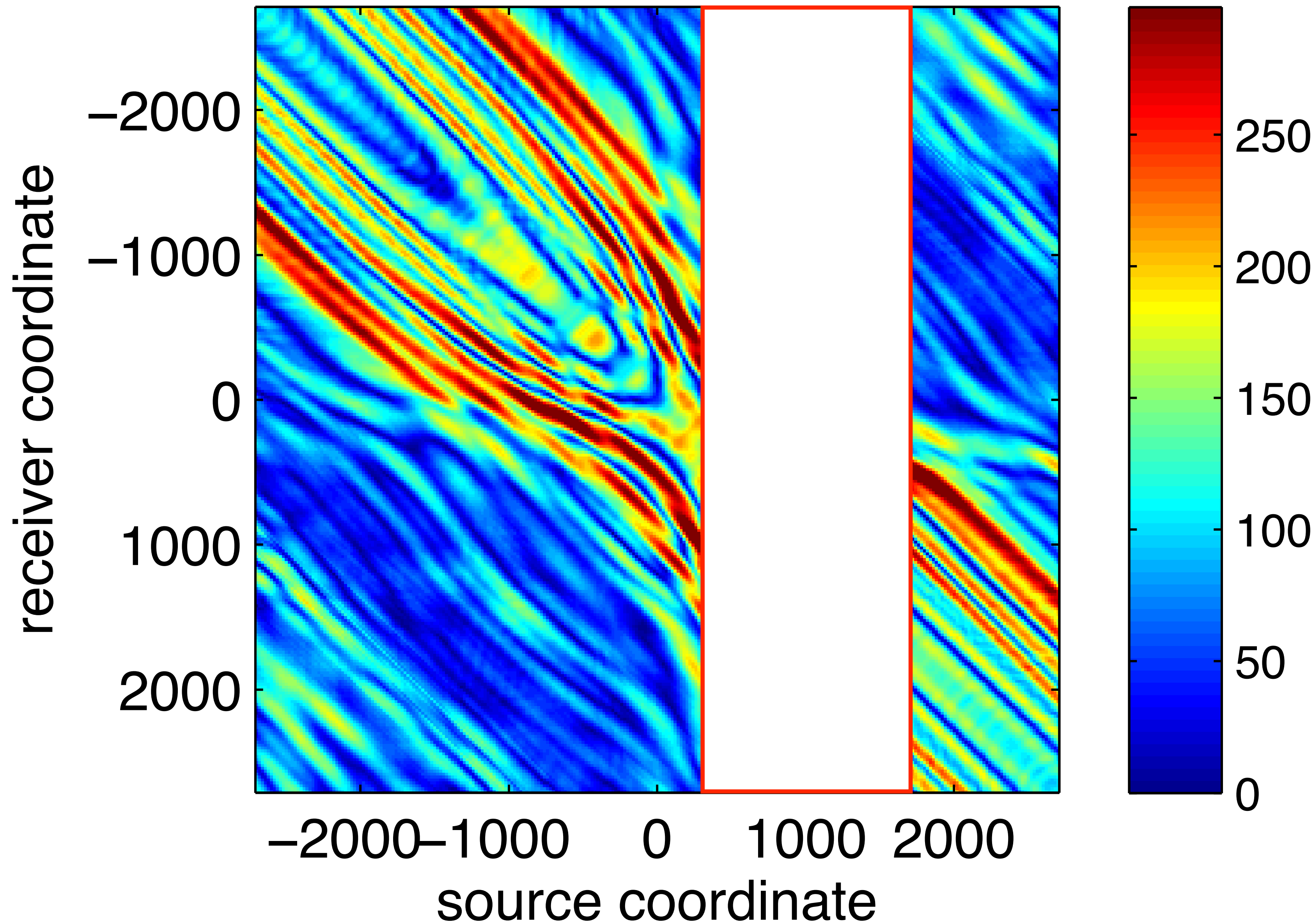
Or… with surface multiples?

Rethink multiples



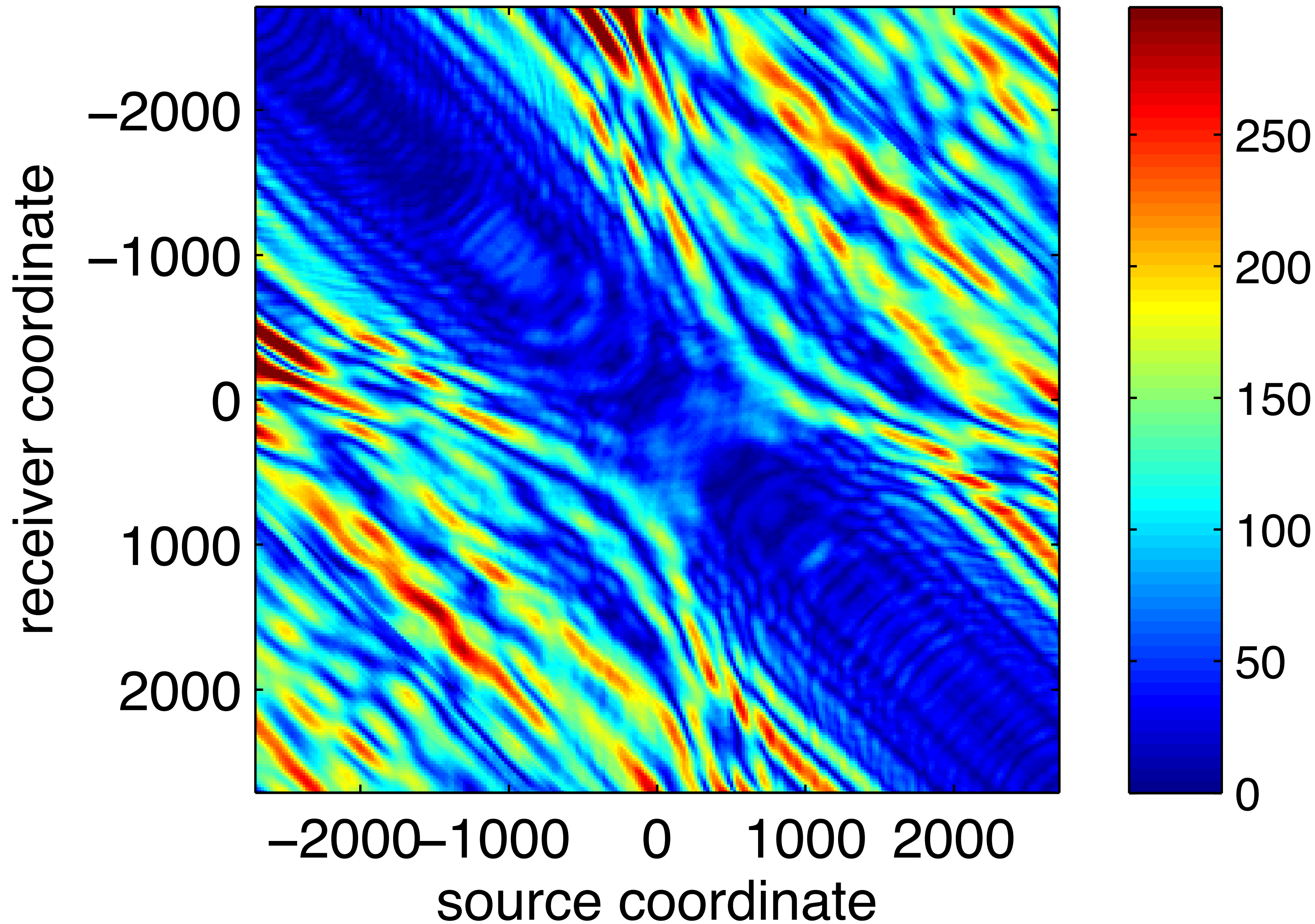
amplitude spectrum: primaries @15Hz

Rethink multiples



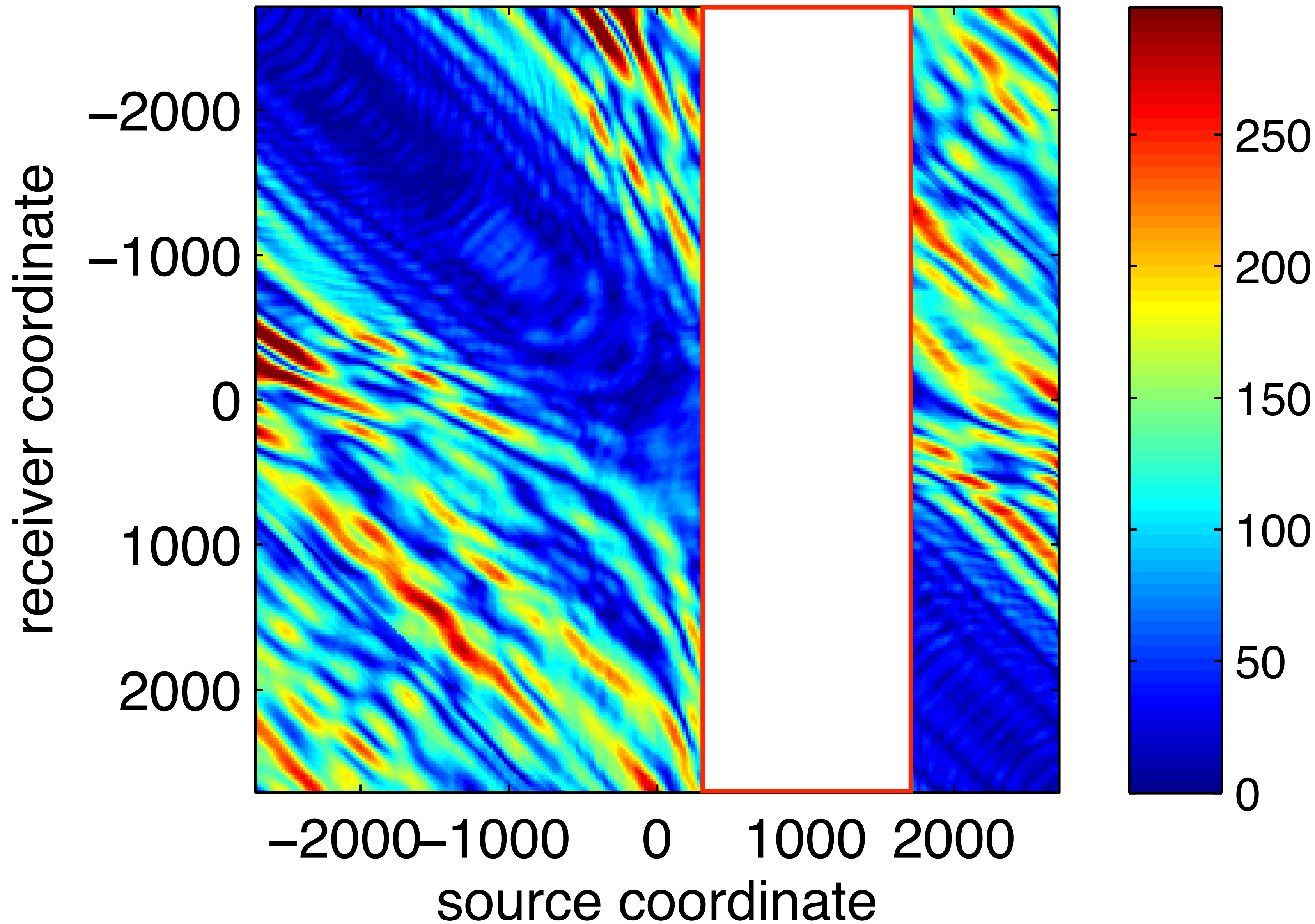
amplitude spectrum: primaries @15Hz

Rethink multiples



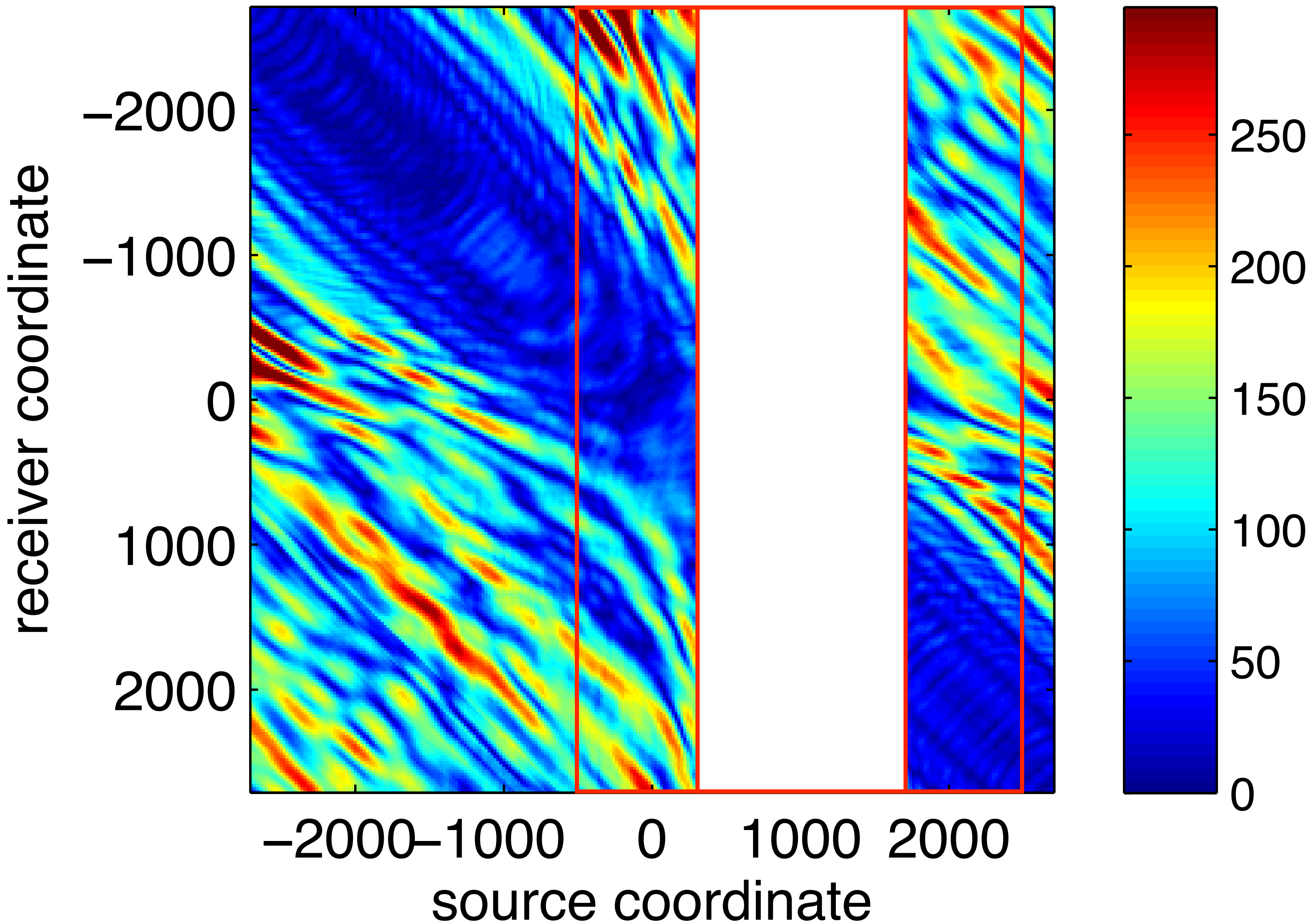
amplitude spectrum: multiples @15Hz

Rethink multiples



amplitude spectrum: multiples @15Hz

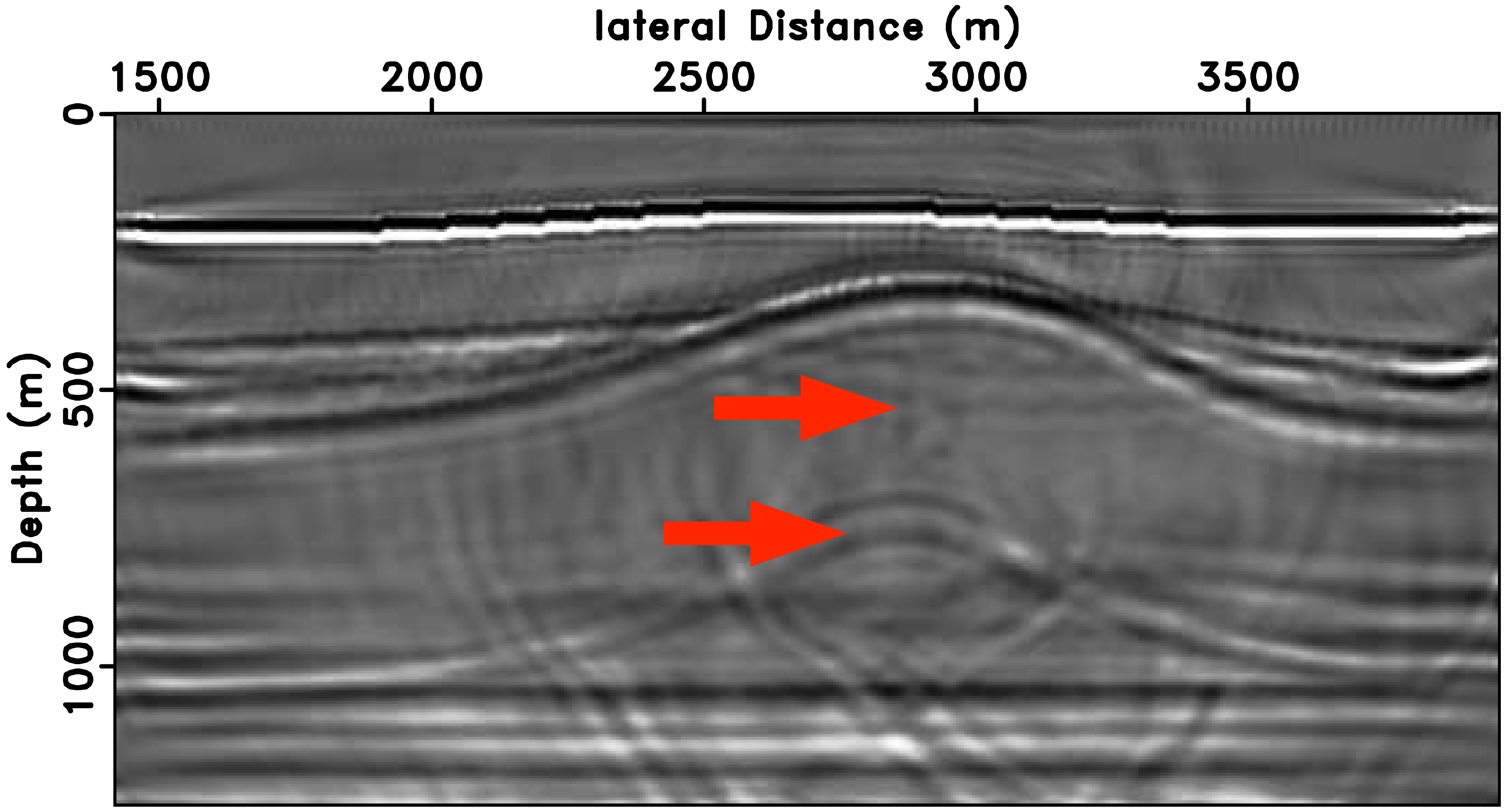
Rethink multiples



amplitude spectrum: multiples @15Hz

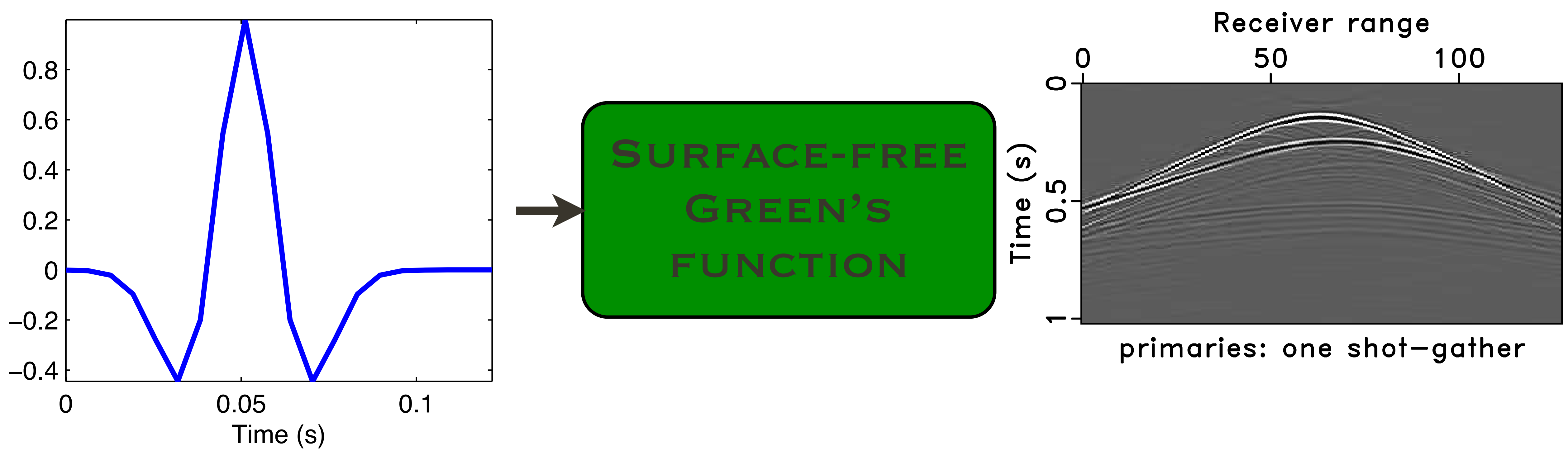
What is stopping us?

from complete data



Migration from data with surface multiples

Rethink multiples



Rethink multiples

Lin, Tu, and Herrmann, 2010

Verschuur and Berkhout, 2011

Whitmore, Valenciano, and Sollner, 2010

Extra illumination from surface multiples

Sounds reasonable, but…how?

Verschuur, 1992

SLIM

Extra illumination from surface multiples

From the formulation of SRME

$$\overbrace{\hat{\mathbf{G}}\hat{\mathbf{Q}}}^{\text{primaries}} + \overbrace{\hat{\mathbf{G}}(-\hat{\mathbf{P}})}^{\text{surface multiples}} = \hat{\mathbf{P}}$$

Groenestijn and Verschuur, 2009

Lin and Herrmann, 2010

Exploit the extra illumination with EPSI

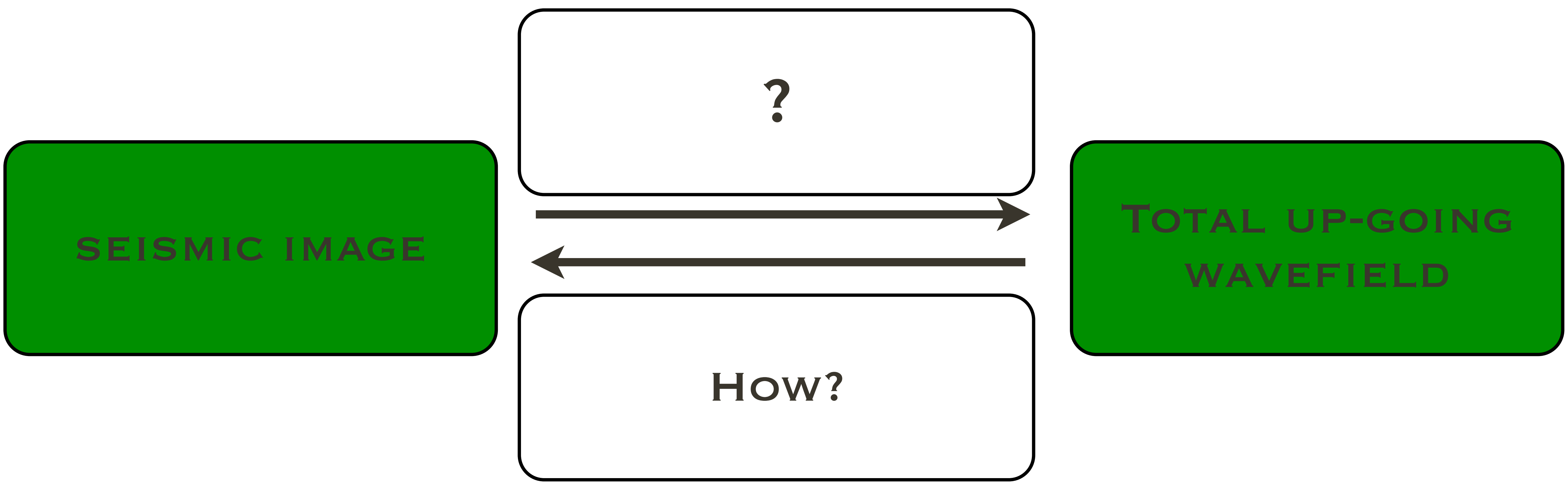
- EPSI : Estimation of Primary via Sparse Inversion
- Inverts the Green's function from the total up-going wavefield.
- Exploits the sparsity of the Green's function in data space.

SLIM

Motivation

- How to exploit this extra illumination in seismic imaging?
- How to exploit the sparsity in the image space instead of data space?

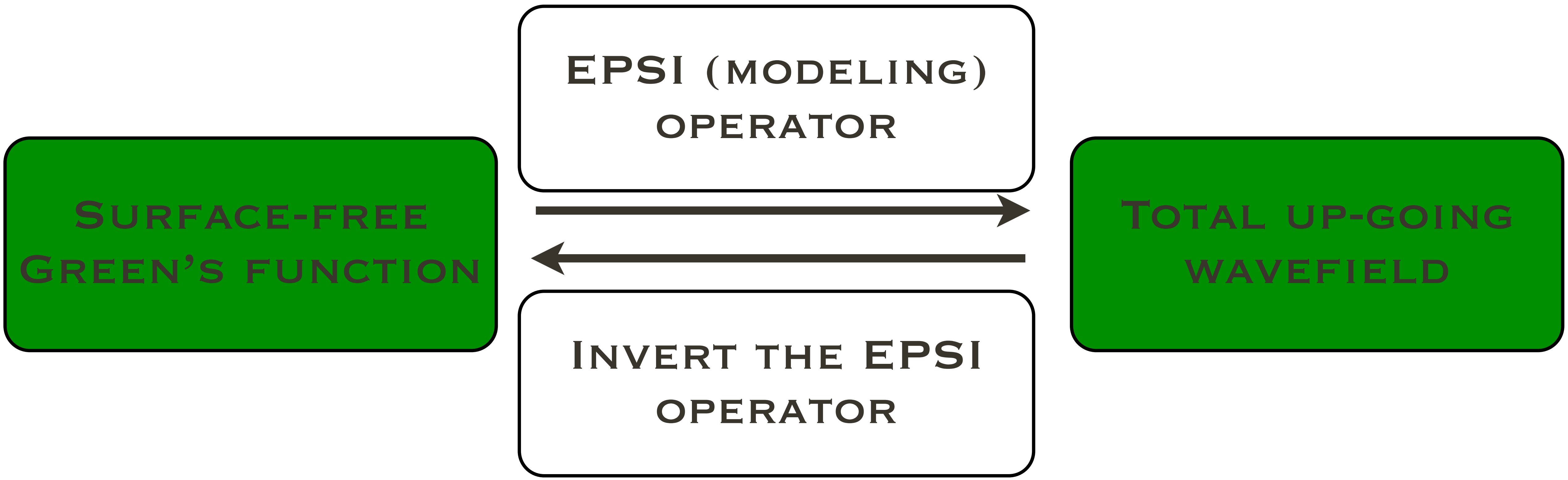
Relate data space and model space



Groenestijn and Verschuur, 2009

Lin and Herrmann, 2010

EPSI operator relates...



Verschuur, 1992

Herrmann, 2008

Lin and Herrmann, 2010

SLIM

EPSI Formulation

EPSI follows the formulation of SRME:

$$\hat{\mathbf{P}} = \hat{\mathbf{G}}(\hat{\mathbf{Q}} - \hat{\mathbf{P}})$$

Matrix-vector formulation of EPSI:

$$\underbrace{\mathcal{F}_t^* \mathrm{BlockDiag}_{1\ldots\mathrm{nf}}[(\hat{\mathbf{Q}} - \hat{\mathbf{P}})^* \otimes \mathbf{I}]\mathcal{F}_\mathbf{t}}_{\mathbf{E}}\,\mathbf{g} = \mathbf{p}$$

Lin and Herrmann, 2010

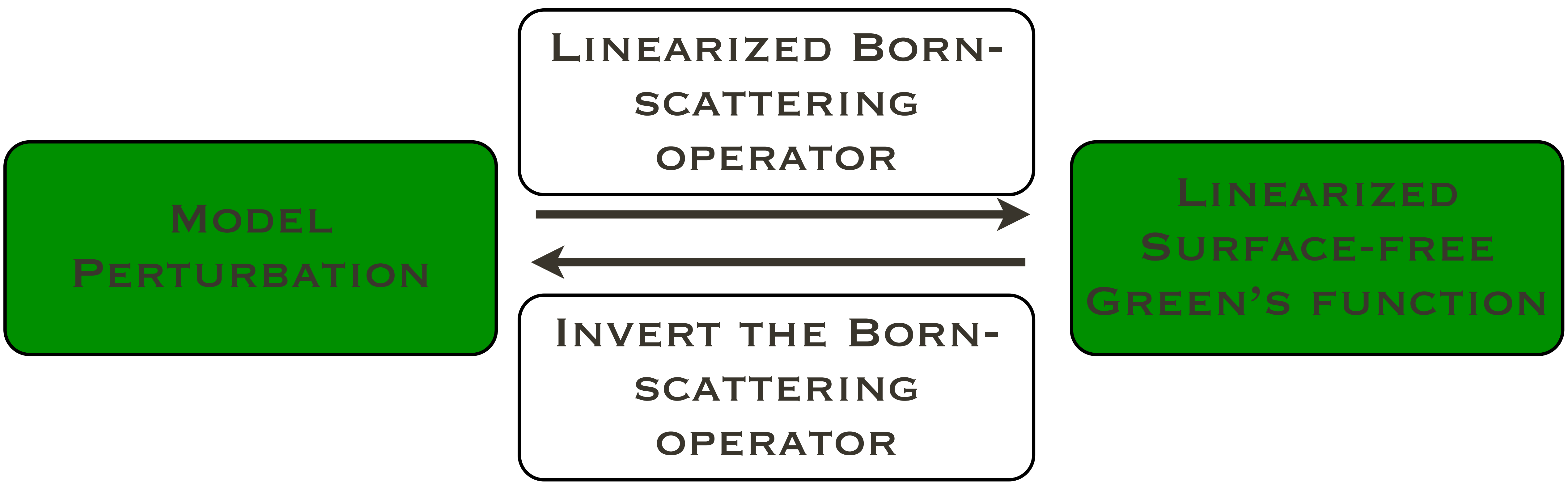
SLIM

Robust EPSI

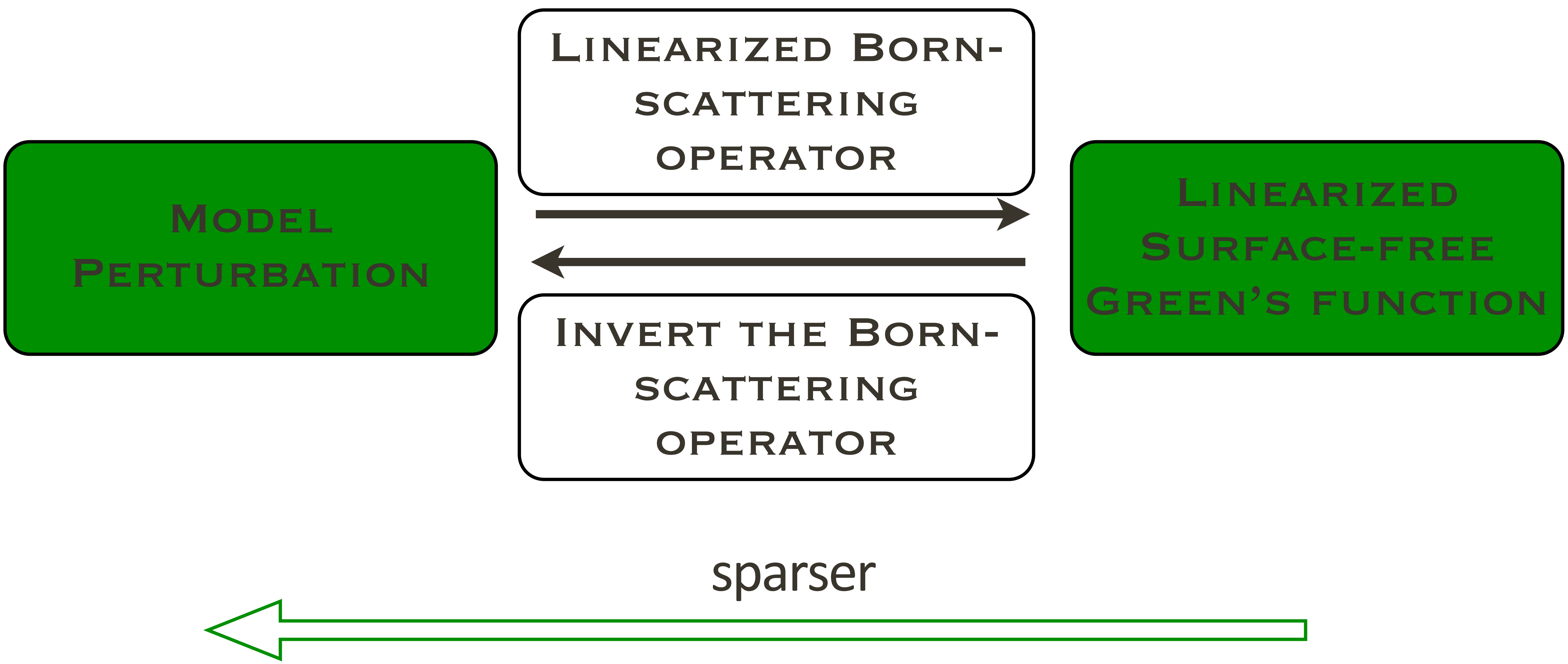
Convex sparsity-promoting formulation:

$$\underbrace{\tilde{\mathbf{g}} = \min_{\mathbf{g}} \|\mathbf{g}\|_{\mathbf{1}}}_{\text{sparsity promoting part}} \quad \text{subject to} \quad \underbrace{\|\mathbf{p} - \mathbf{E}\mathbf{g}\|_{\mathbf{2}} \leq \sigma}_{\text{data fitting part}}$$

Migration operator relates...

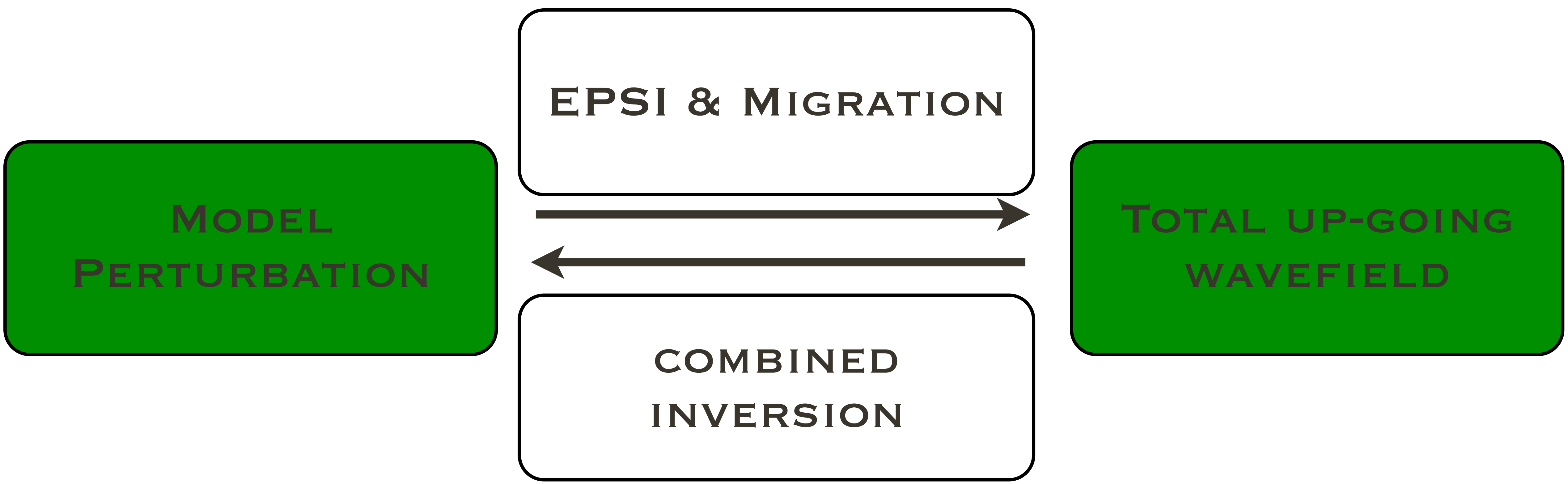


Migration operator relates...



Lin, Tu, and Herrmann, 2010

What about combine...



Approximate EPSI

Neglecting internal multiples:

$$\hat{\mathbf{P}} \approx \delta\hat{\mathbf{G}}(\hat{\mathbf{Q}} - \hat{\mathbf{P}})$$

Convex sparsity-promoting formulation:

$$\underbrace{\delta\tilde{\mathbf{g}} = \min_{\delta\mathbf{g}} ||\delta\mathbf{g}||_1}_{\text{sparsity promoting part}} \quad \text{subject to} \quad \underbrace{||\mathbf{p} - \mathbf{E}\delta\mathbf{g}||_2 \leq \sigma}_{\text{data fitting part}}$$

Lin and Herrmann, 2011

EPSI with sparsifying transform

$$\underbrace{\delta\tilde{\mathbf{g}} = \mathbf{S_3^*} \arg\min_{\mathbf{x}} \|\mathbf{x}\|_1}_{\text{sparsity promoting part}} \text{ subject to } \underbrace{\|\mathbf{p} - \mathbf{E}\mathbf{S_3^*}\mathbf{x}\|_2 \leq \sigma}_{\text{data fitting part}}$$

Migration as a sparsifying transform

$$\underbrace{\delta\tilde{\mathbf{g}} = \mathbf{K}\mathbf{S}_{\mathbf{2}}^{*} \arg\min_{\mathbf{x}} \|\mathbf{x}\|_{\mathbf{1}}}_{\text{sparsity promoting part}} \text{ subject to } \underbrace{\|\mathbf{p} - \mathbf{E}\mathbf{K}\mathbf{S}_{\mathbf{2}}^{*}\mathbf{x}\|_{\mathbf{2}} \leq \sigma}_{\text{data fitting part}}$$

SLIM

Combination of EPSI and migration

$$\underbrace{\delta\tilde{\mathbf{m}} = \mathbf{S_2^*} \arg\min_{\mathbf{x}} \|\mathbf{x}\|_\mathbf{1}}_{\text{sparsity promoting part}} \ \text{subject to} \ \underbrace{||\mathbf{p} - \mathbf{EKS_2^*x}||_\mathbf{2} \leq \sigma}_{\text{data fitting part}}$$

Linearized data examples

Linearized data

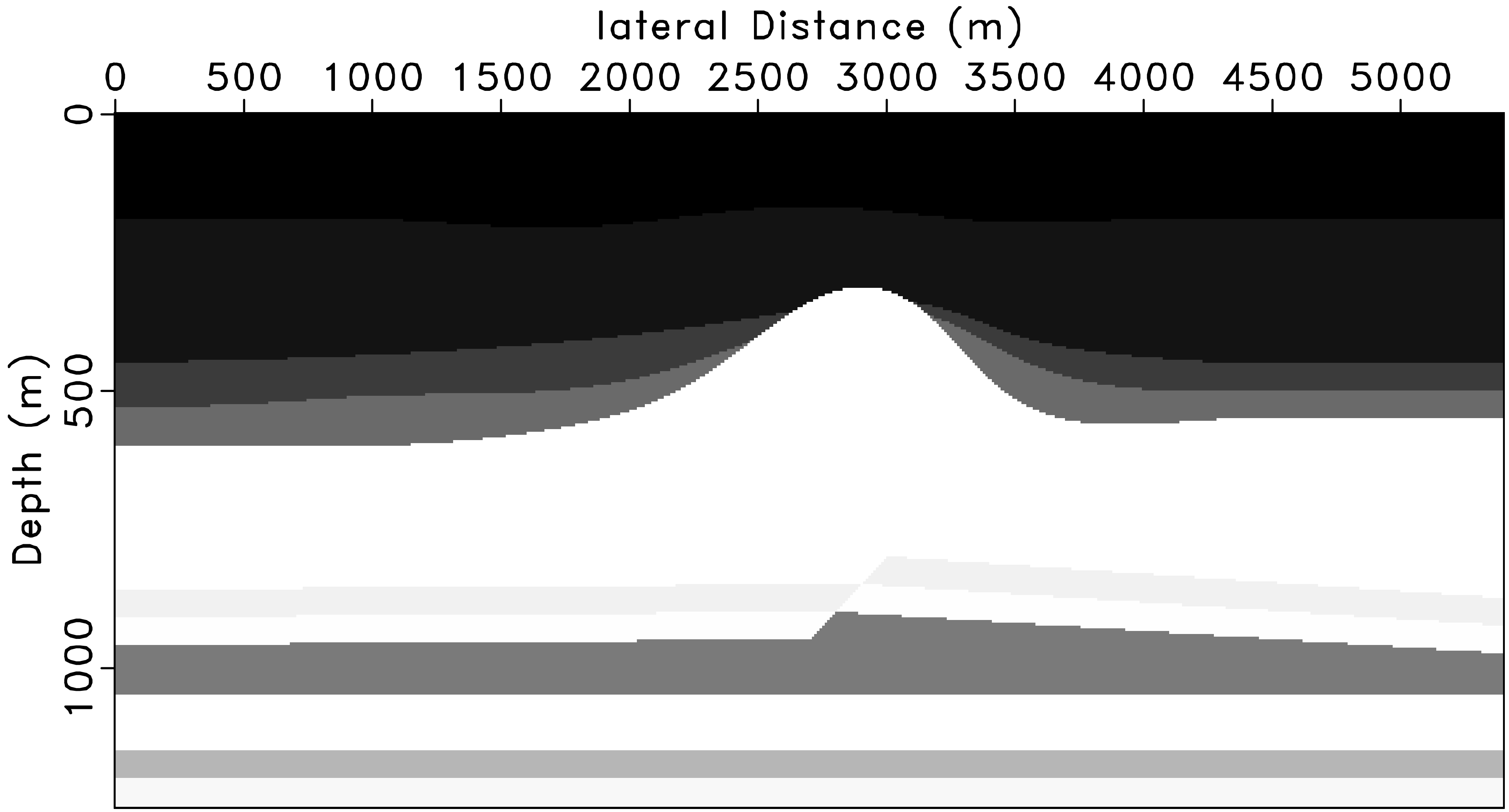
- surface-free data

$$\mathbf{p_1} = \mathbf{K}\delta\mathbf{m}$$

- total data

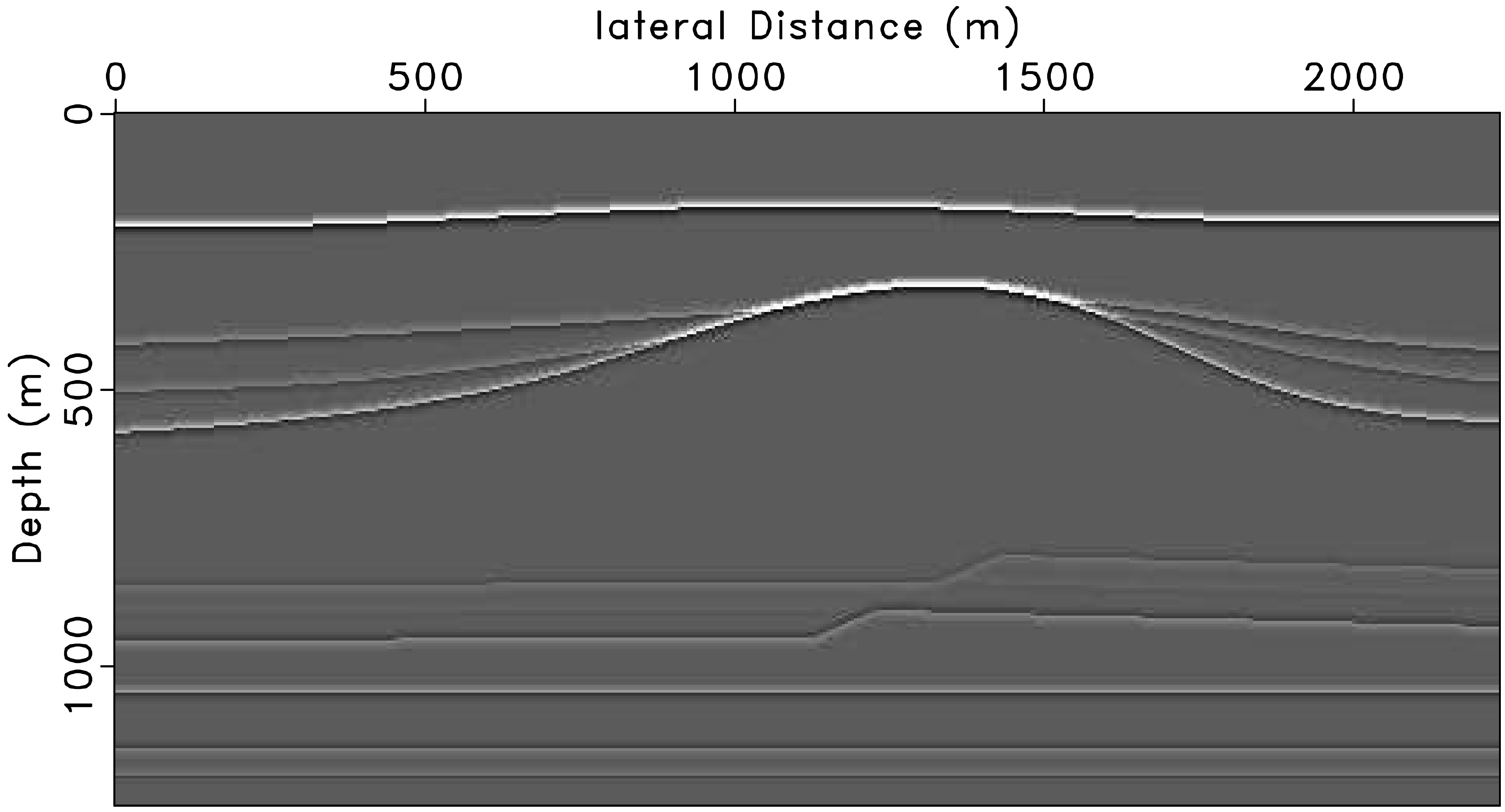
$$\mathbf{p_2} = \mathbf{E}\mathbf{K}\delta\mathbf{m}$$

True velocity



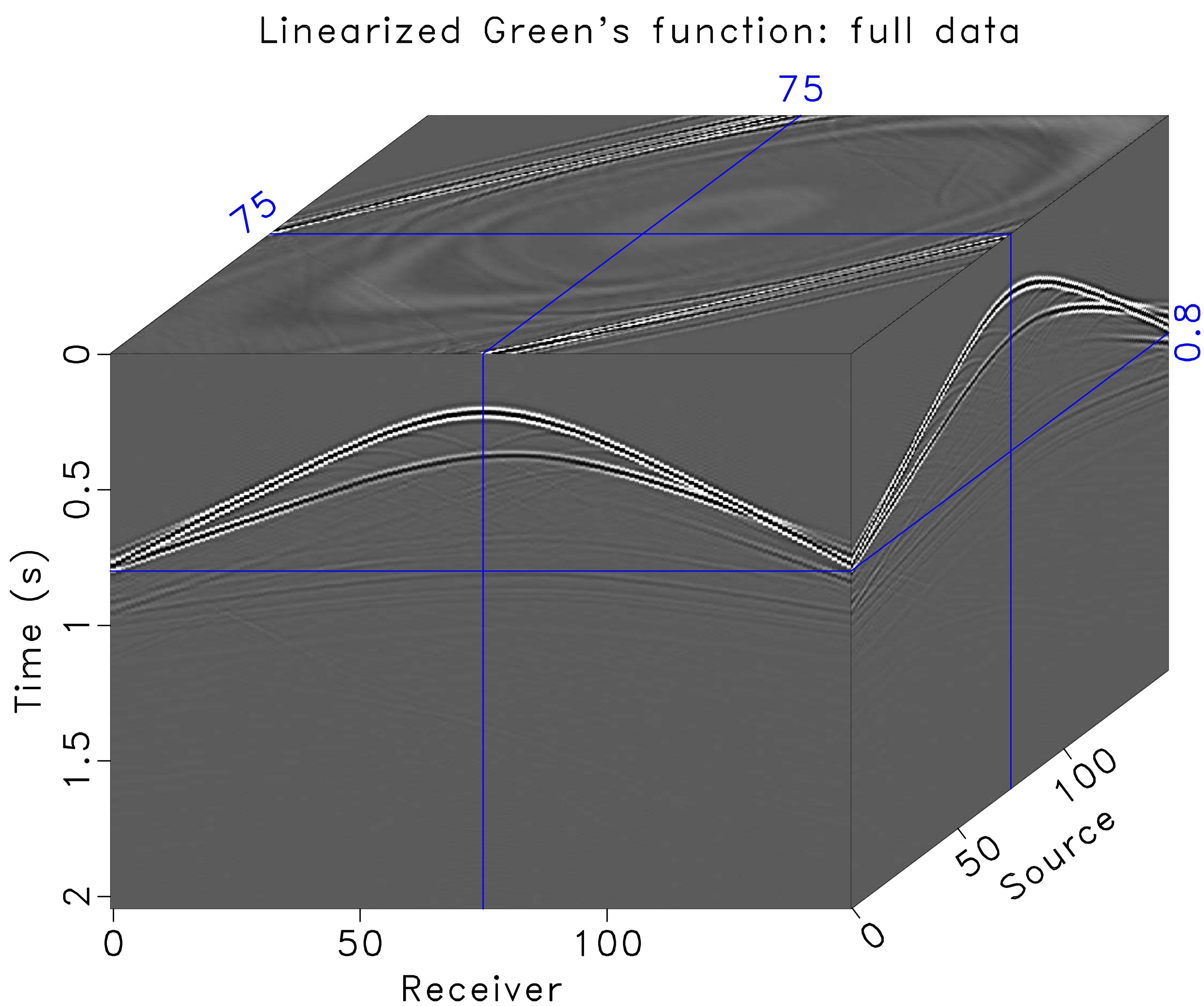
True velocity model

True velocity perturbation

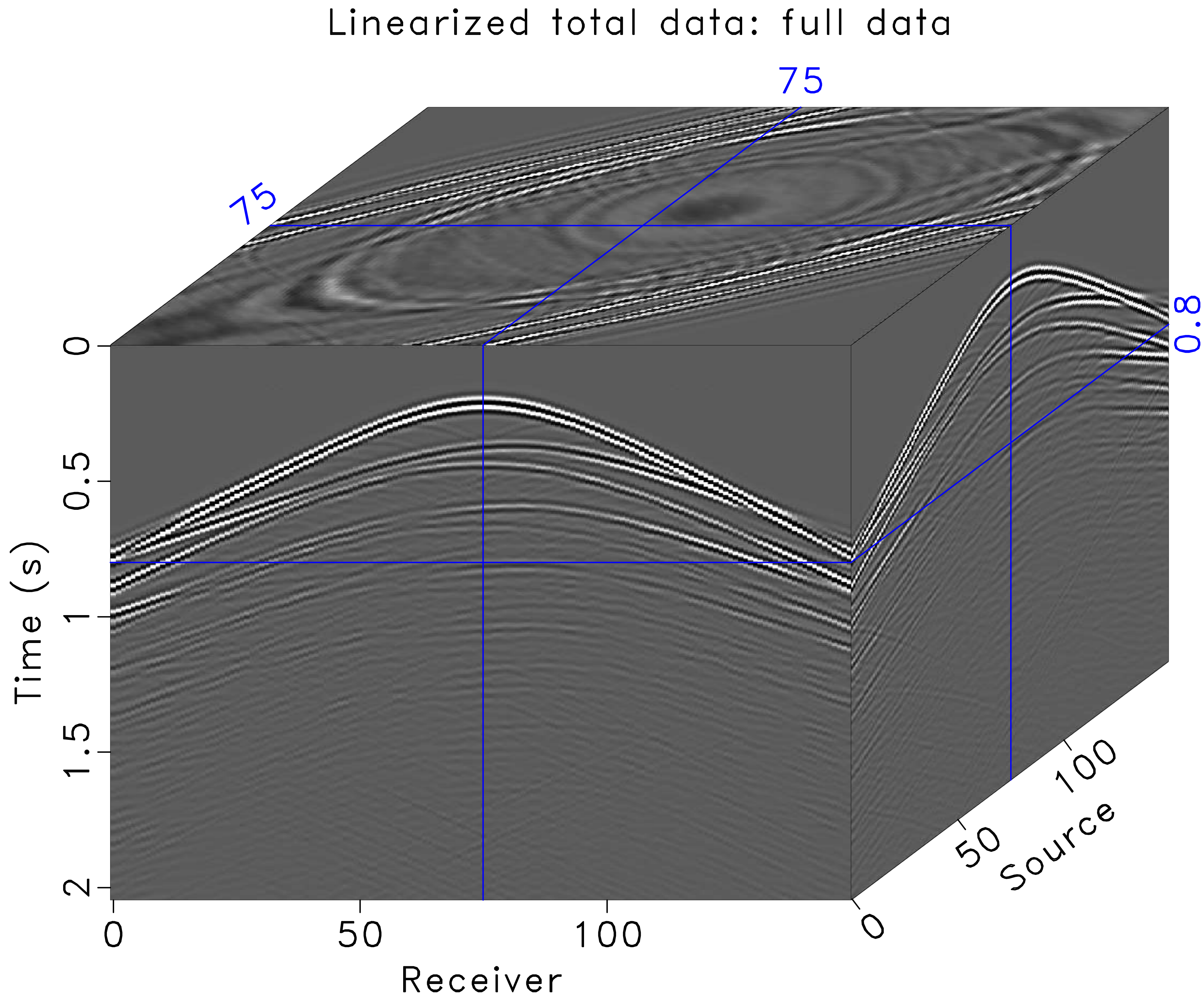


True model perturbation

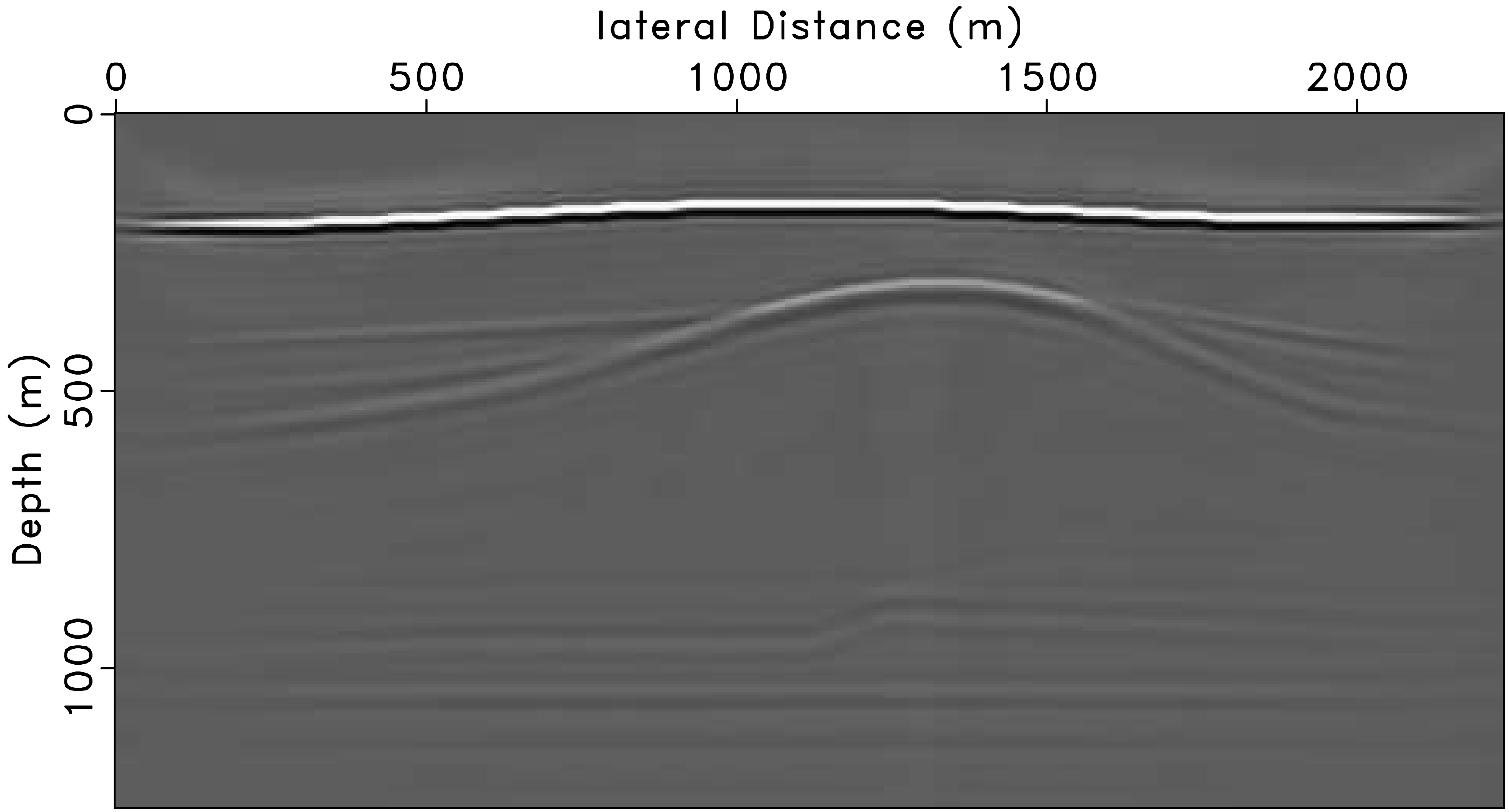
Linearized Surface-free data



Linearized total data

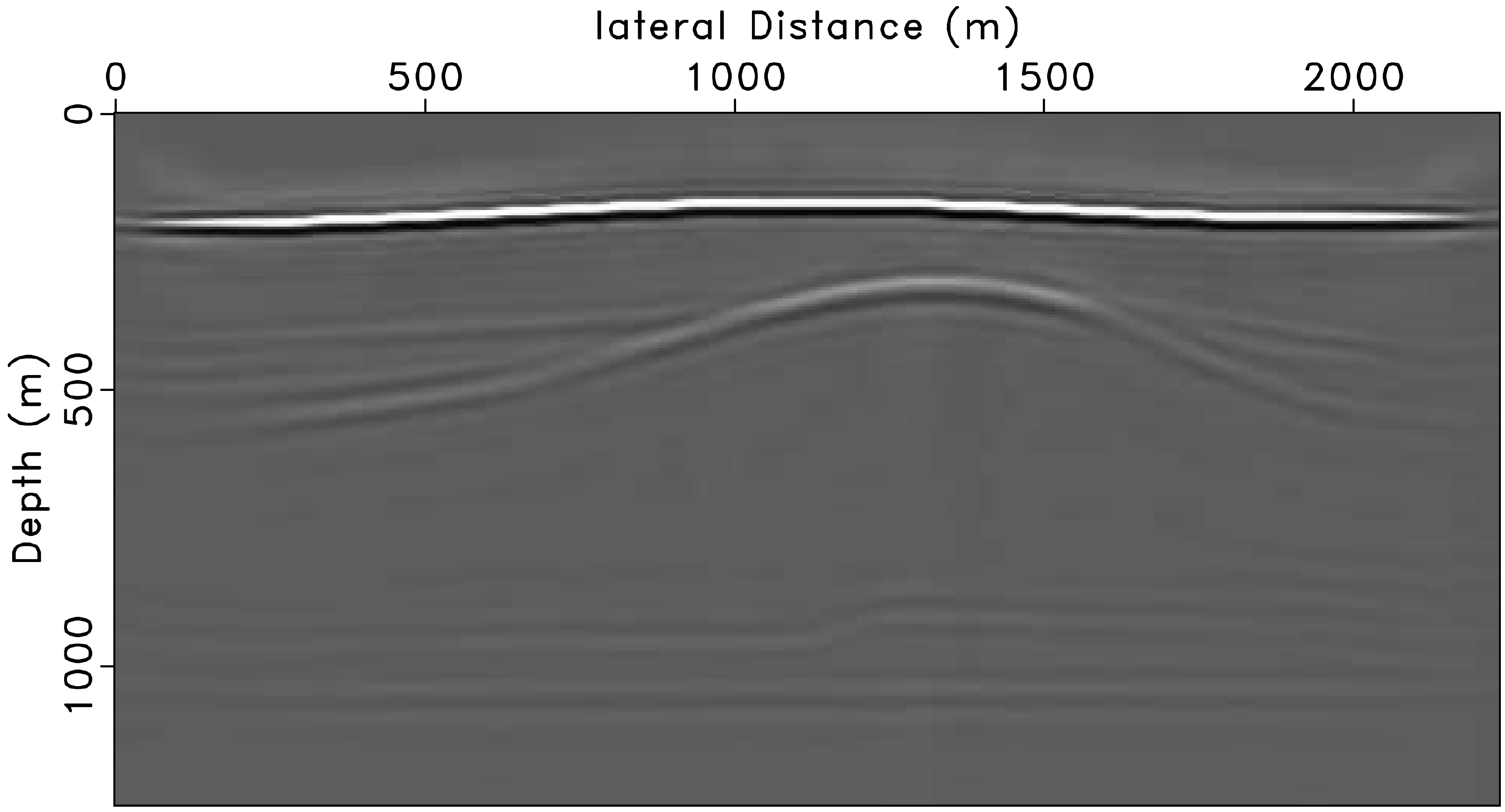


Sparse inversion of surface-free data



Migration of surface free data

Sparse inversion of total data



Migration of total data

SLIM

In case of incomplete data

surface-free case:

$$\delta\tilde{\mathbf{m}} = \mathbf{S_2^*} \underset{\mathbf{x}}{\operatorname{argmin}} \ ||\mathbf{x}||_\mathbf{1} \ \text{ subject to } ||\mathbf{RM}(\mathbf{p_1} - \mathbf{KS_2^*}\delta\mathbf{x})||_\mathbf{2} \leq \sigma$$

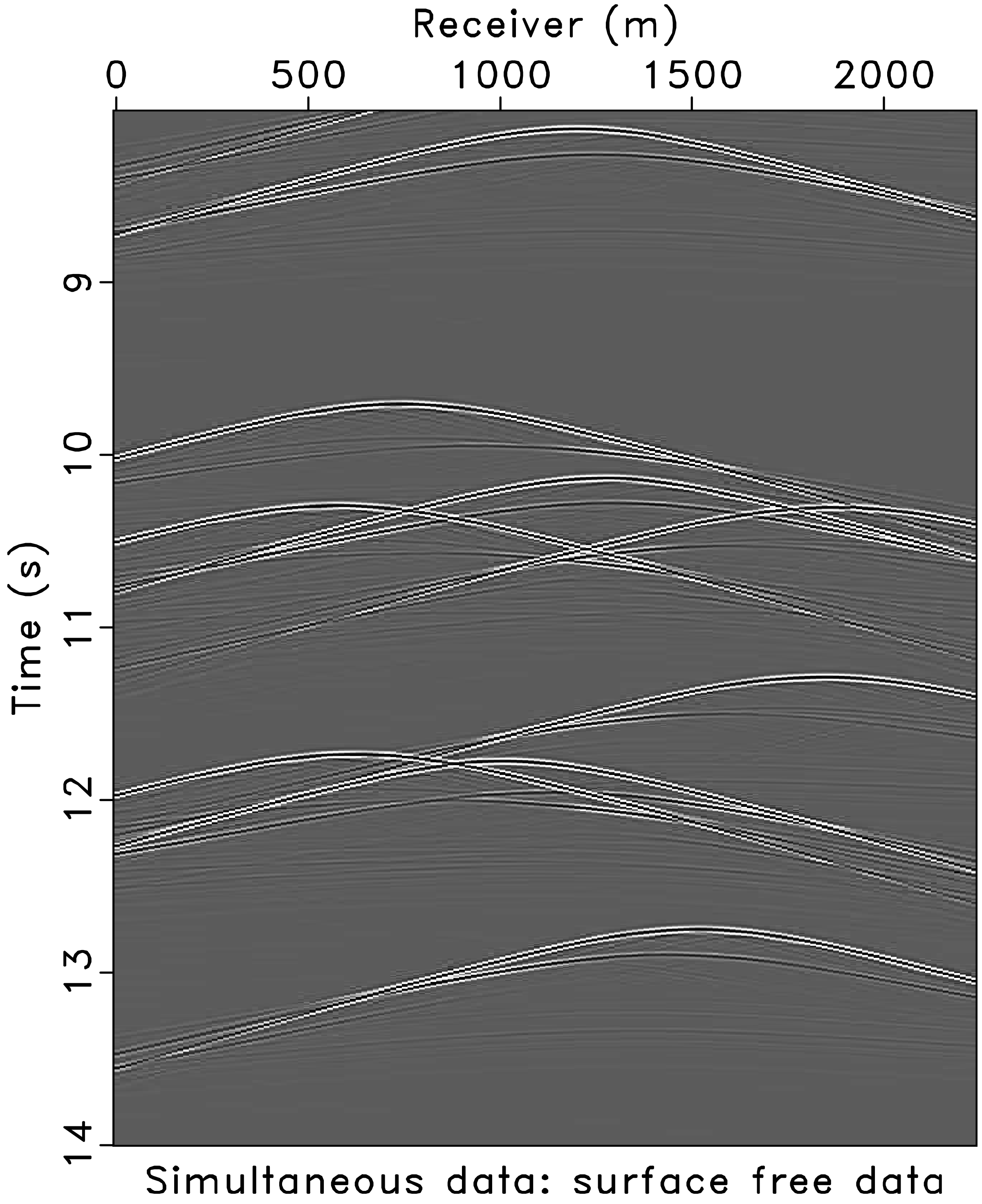
free-surface case *:

$$\delta\tilde{\mathbf{m}} = \mathbf{S_2^*} \underset{\mathbf{x}}{\operatorname{argmin}} \ ||\mathbf{x}||_\mathbf{1} \ \text{ subject to } ||\mathbf{RM}(\mathbf{p_2} - \mathbf{EKS_2^*}\mathbf{x})||_\mathbf{2} \leq \sigma$$

* we assume that full data is available to build the EPSI operator

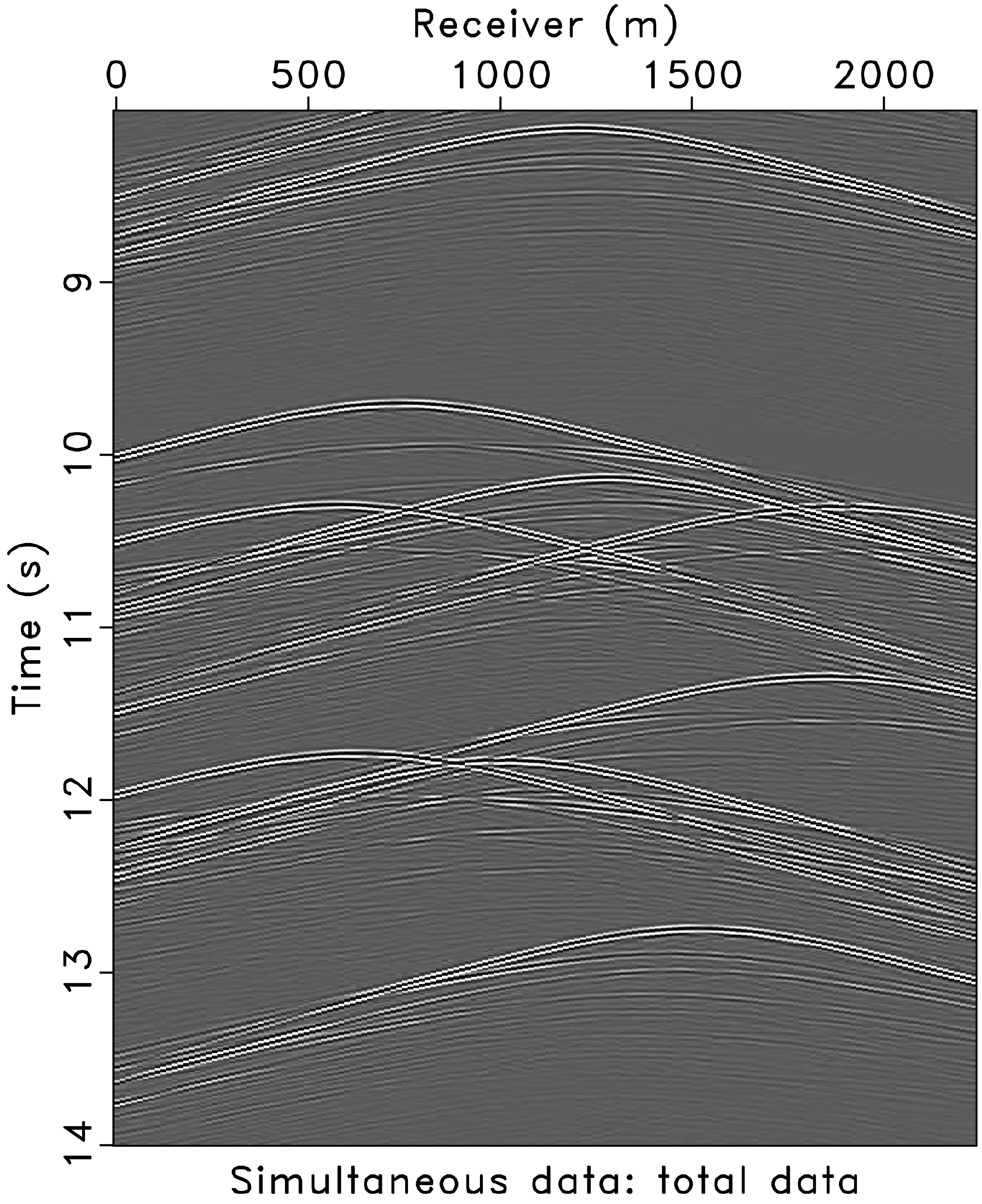
Wason and Herrmann, 2011

Simultaneous data: surface-free data



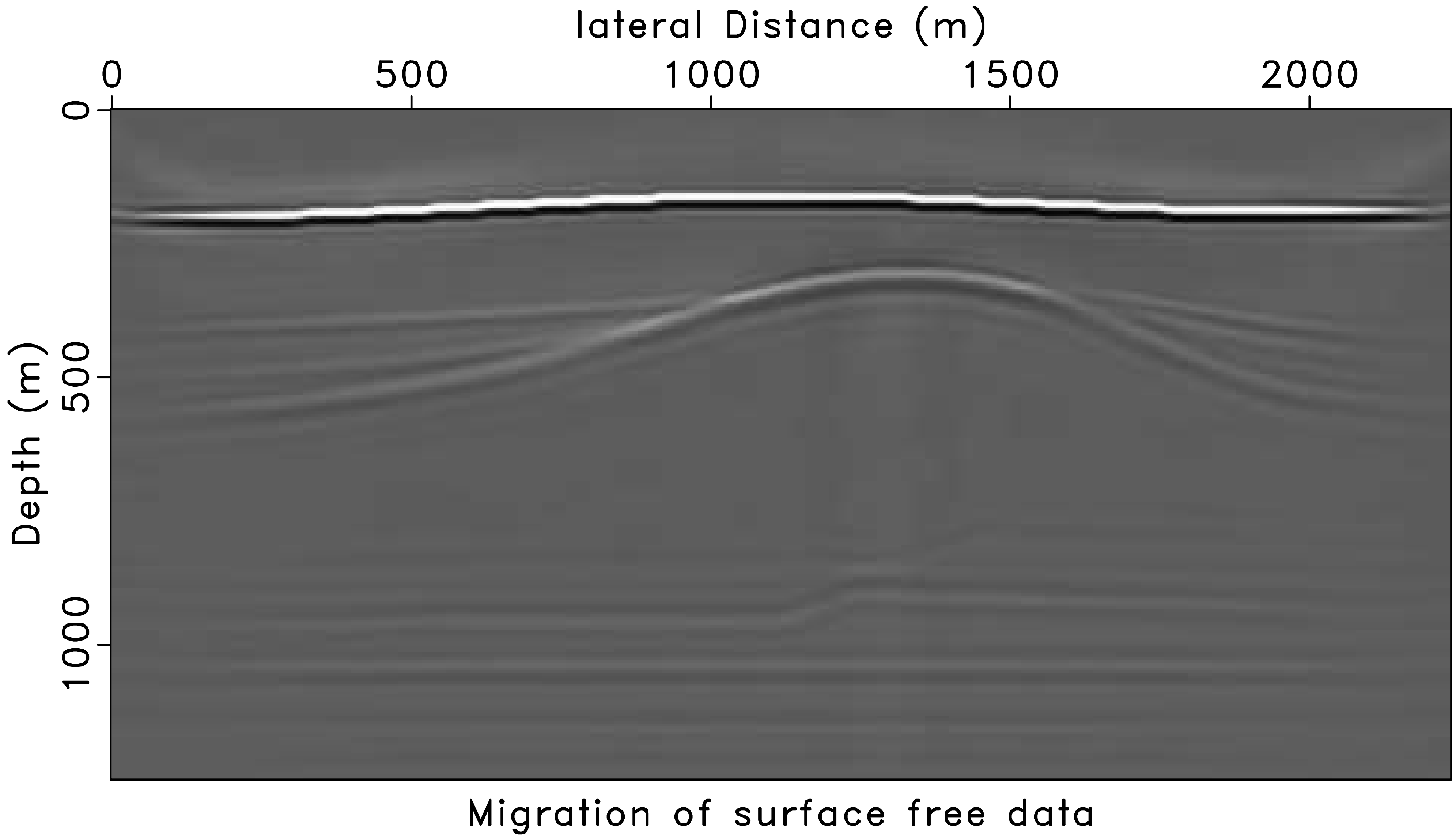
total recording time ~100s

Simultaneous data: total data

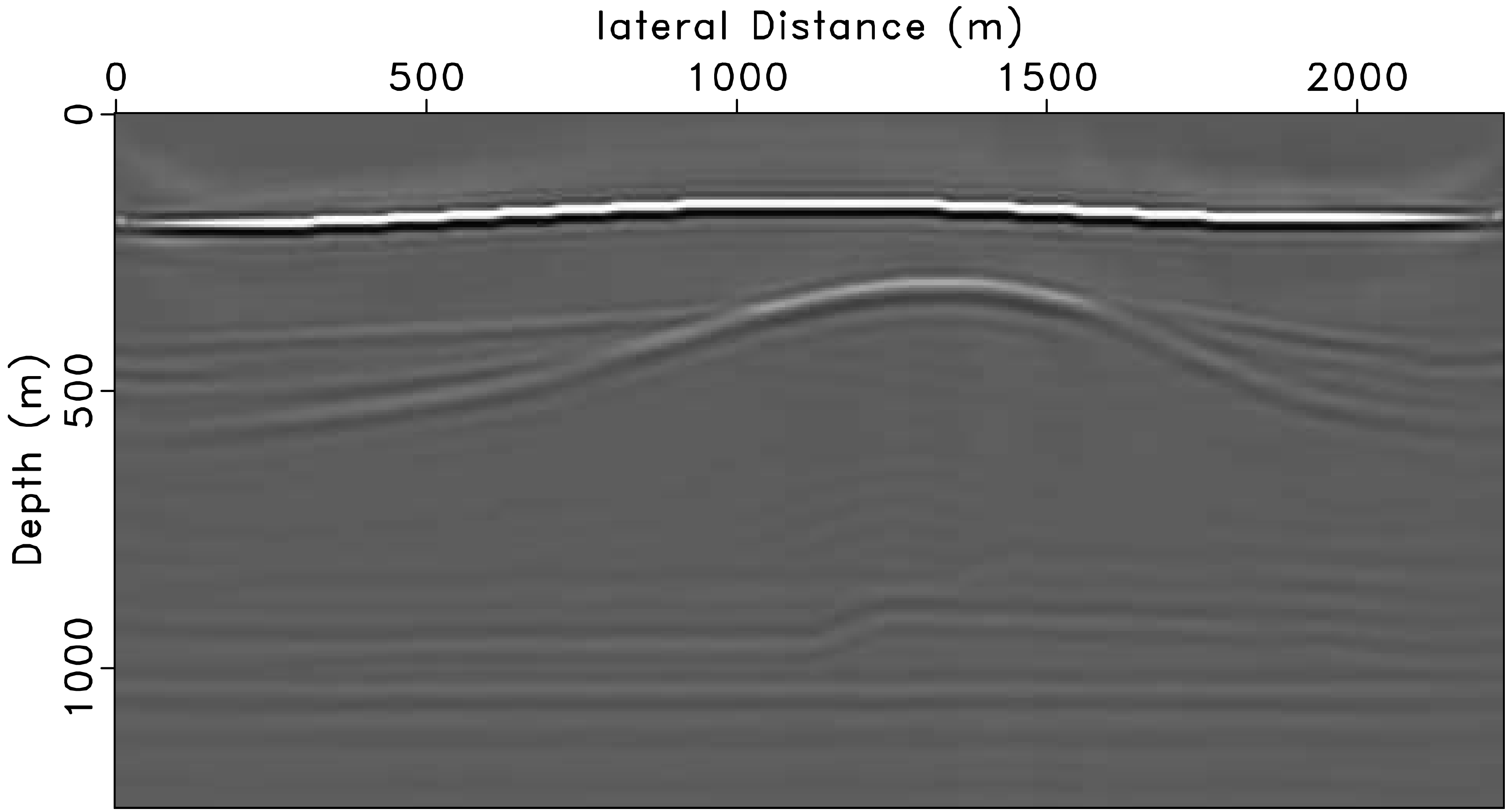


total recording time ~100s

Sparse inversion of surface-free Green's function



Sparse inversion of total data



Migration of total data

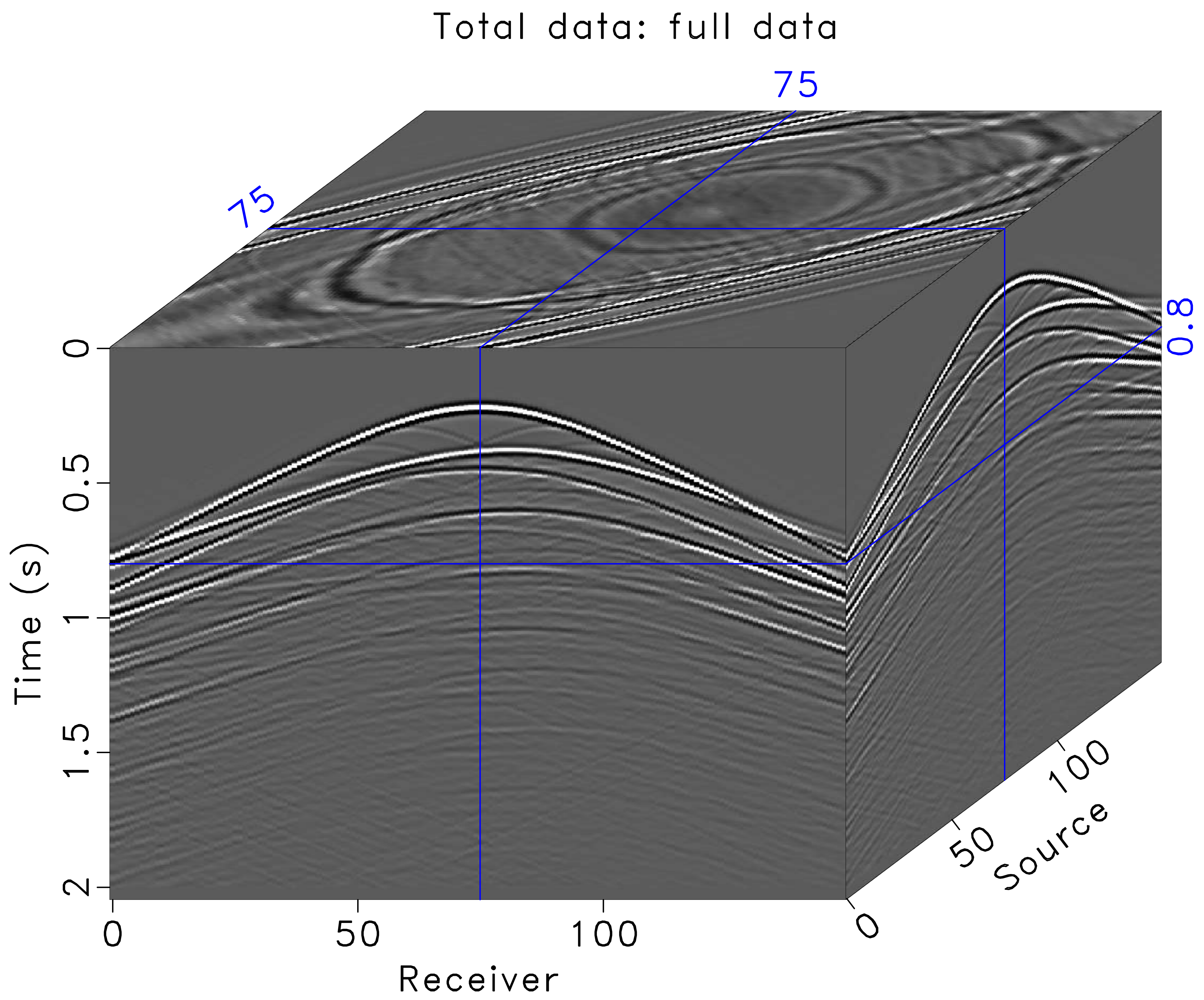
Example with finite-difference forward modelling data

SLIM

Synthetic data

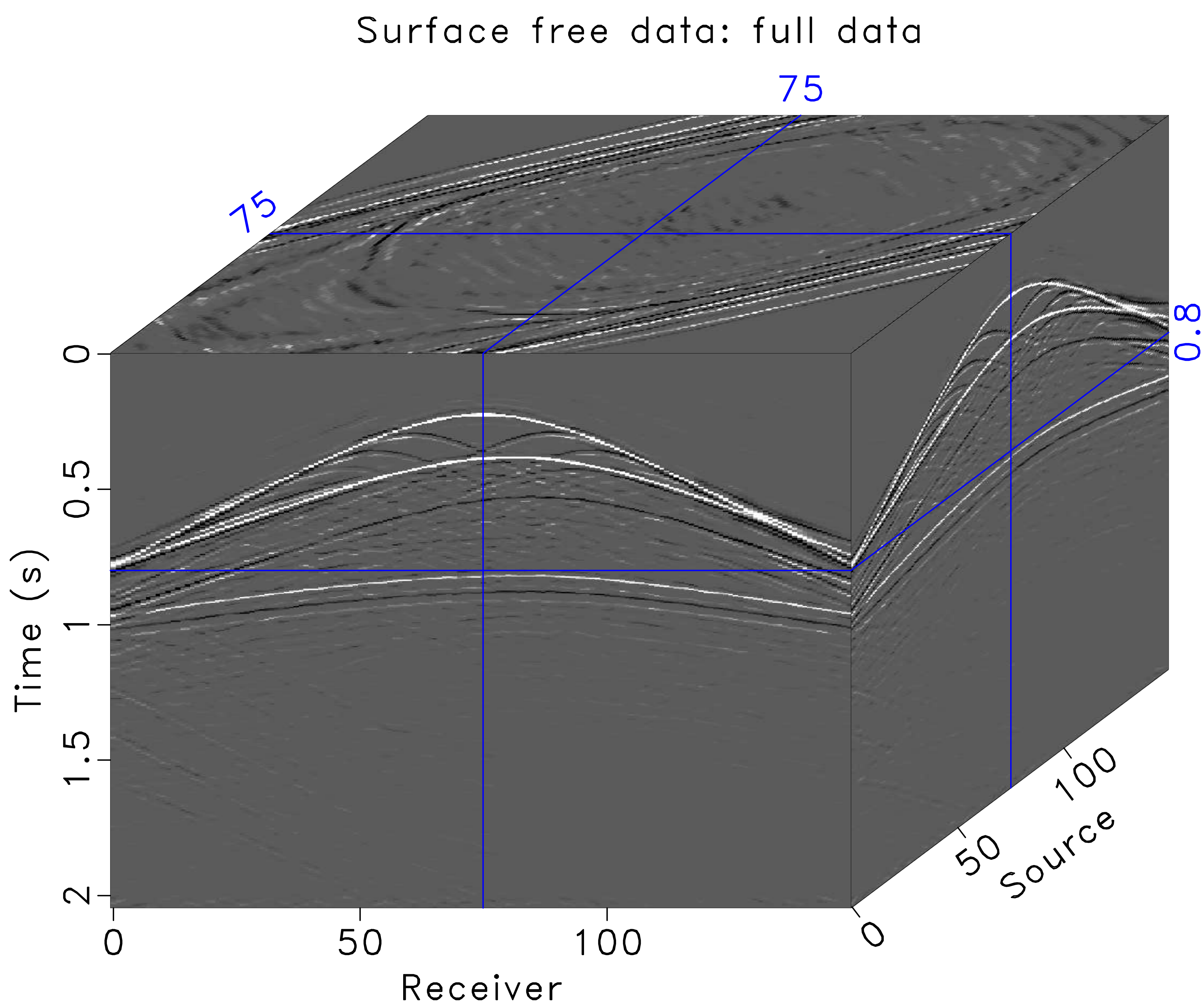
- A complete synthetic data is made first, using a time domain FD method.
- 150 sources/receivers, with 15m spacing
- Ricker wavelet up to 60Hz is used
- Run Robust EPSI to get Green's function, and separate primaries and multiples.

Total data

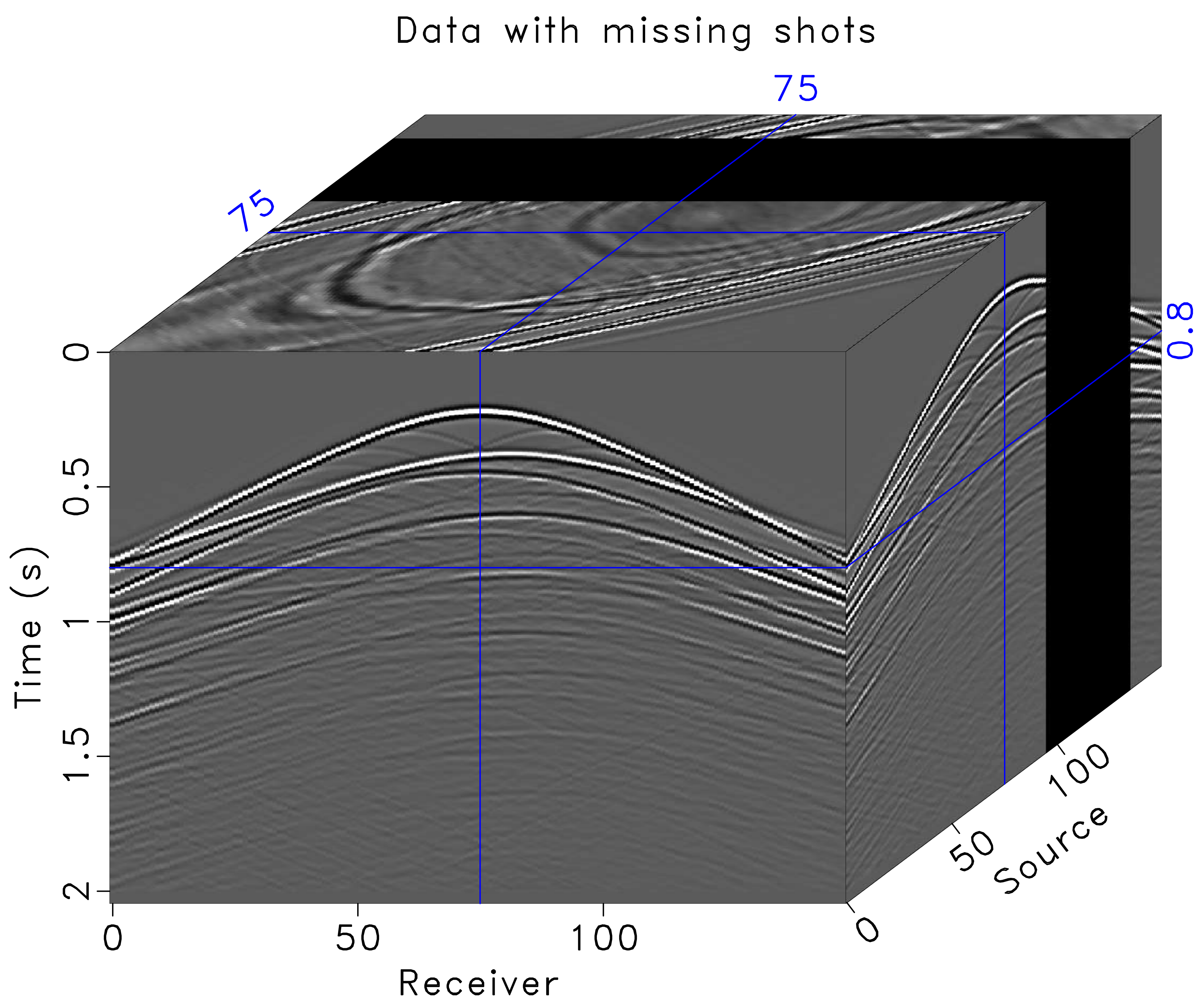


Total data: full data
75
75
0.8
0
0.5
1
1.5
2
Time (s)
0
50
100
Receiver
0
50
100
Source

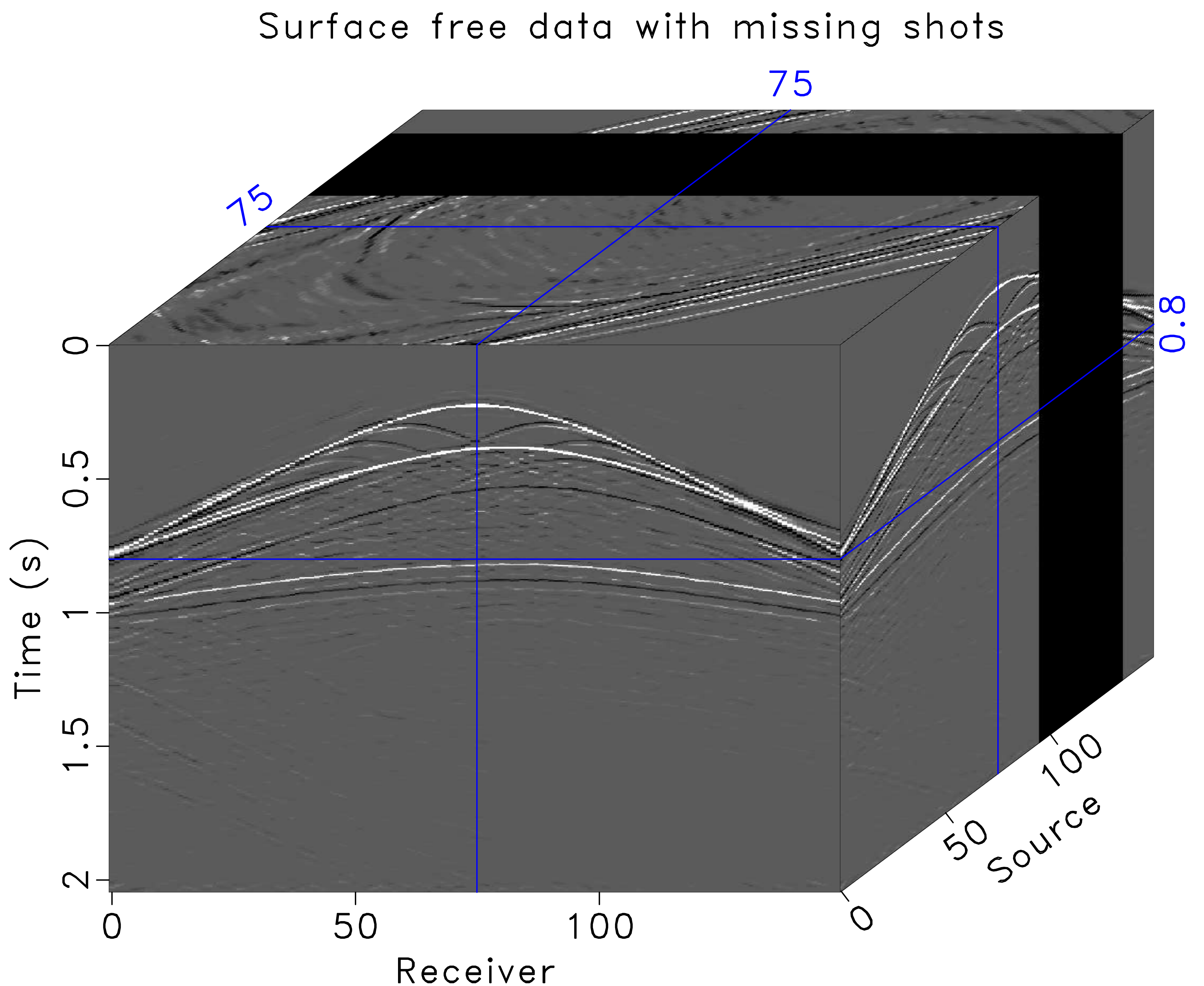
Green's function



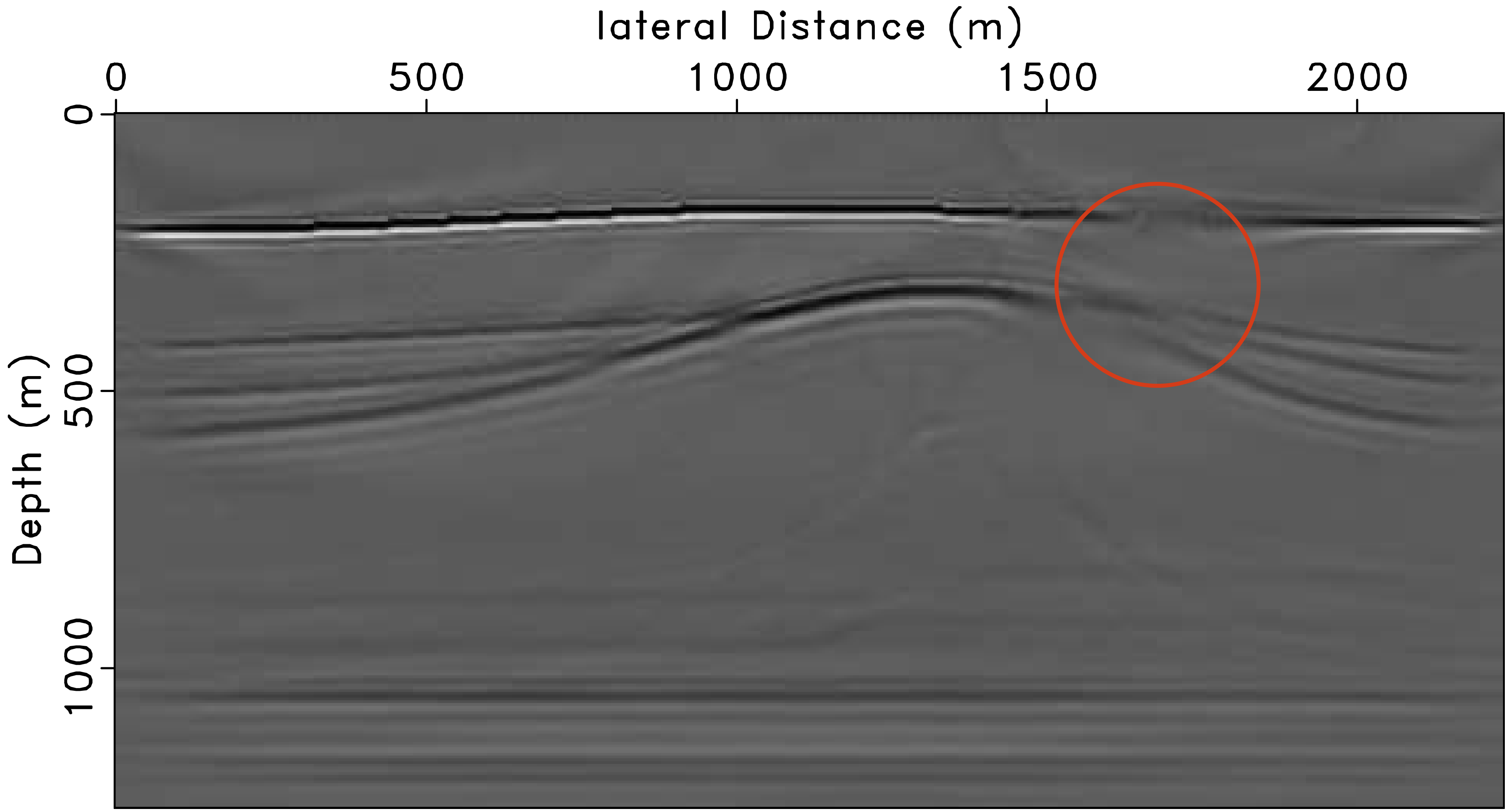
Zero out 40 shot-gathers



Zero out 40 shot-gathers

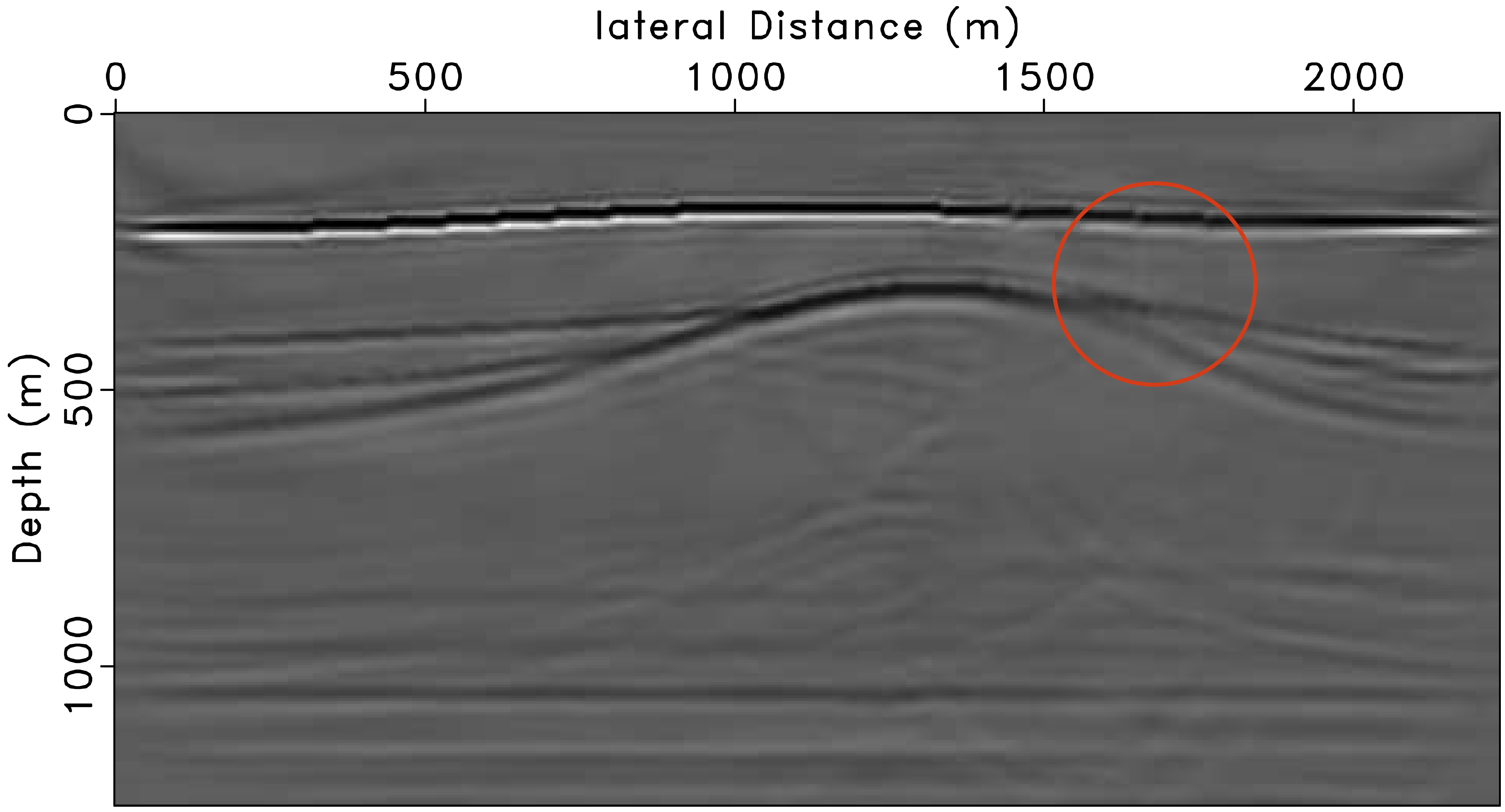


Sparse inversion of surface-free Green's function



Migration of primary impulse response

Combined inversion of total data



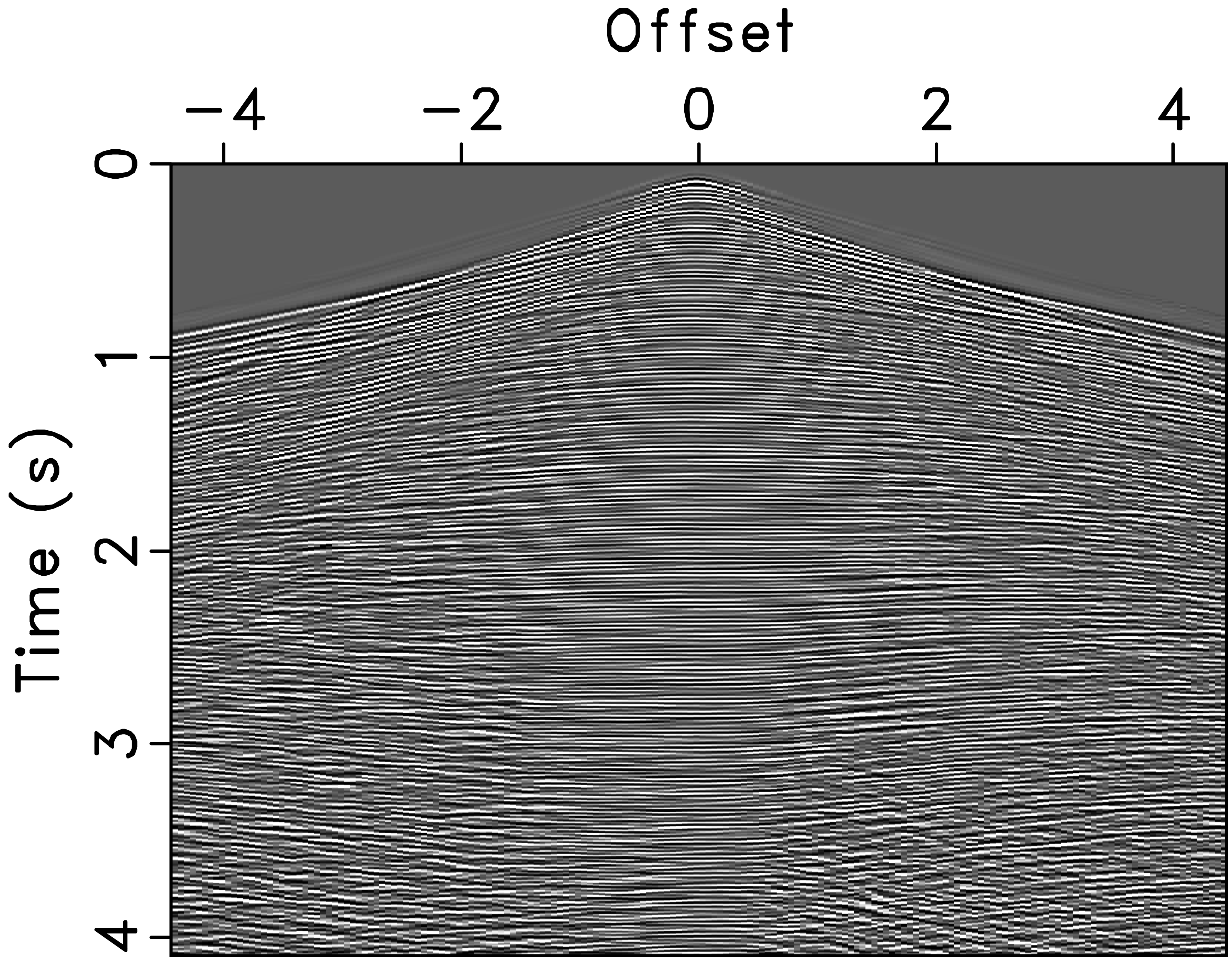
Migration of total data

Field data examples

Gulf of Suez data

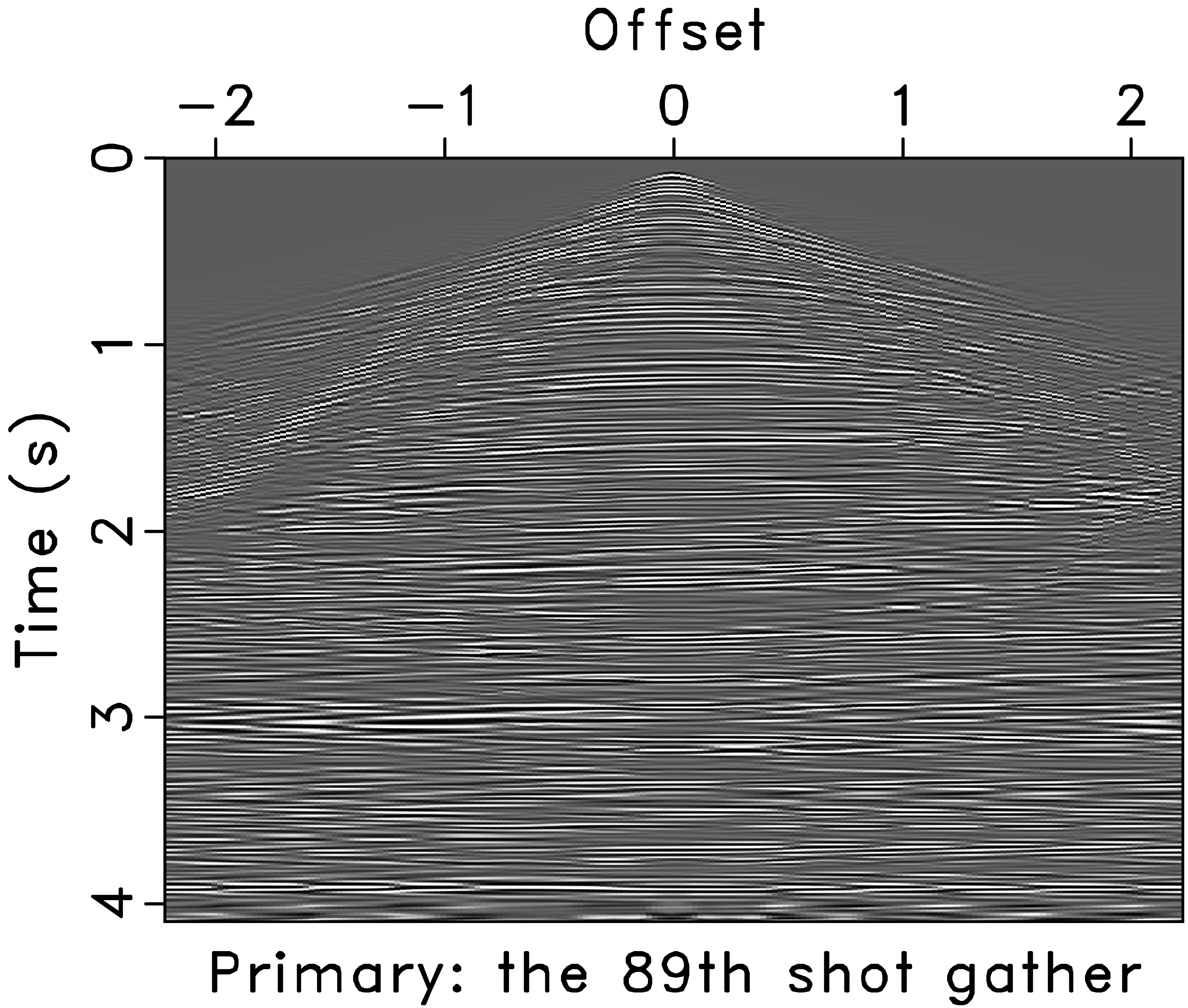
- Very shallow water, strong surface multiples
- Also contains great amount of internal multiples
- About 4s recording time
- 25m distance between two consecutive sources/receivers

Total data: one shot-gather
[shown with AGC]

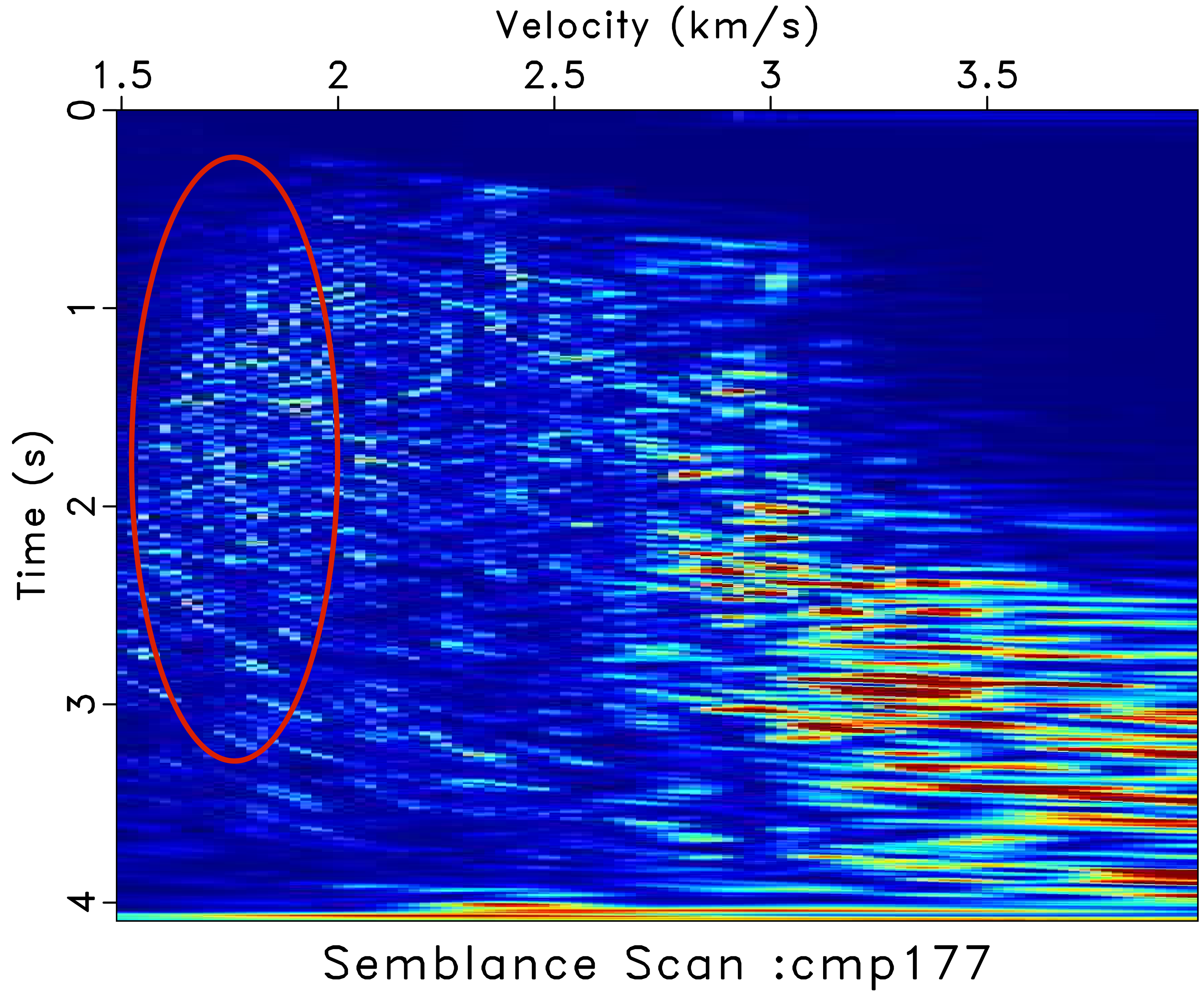


Total data: the 89th shot gather

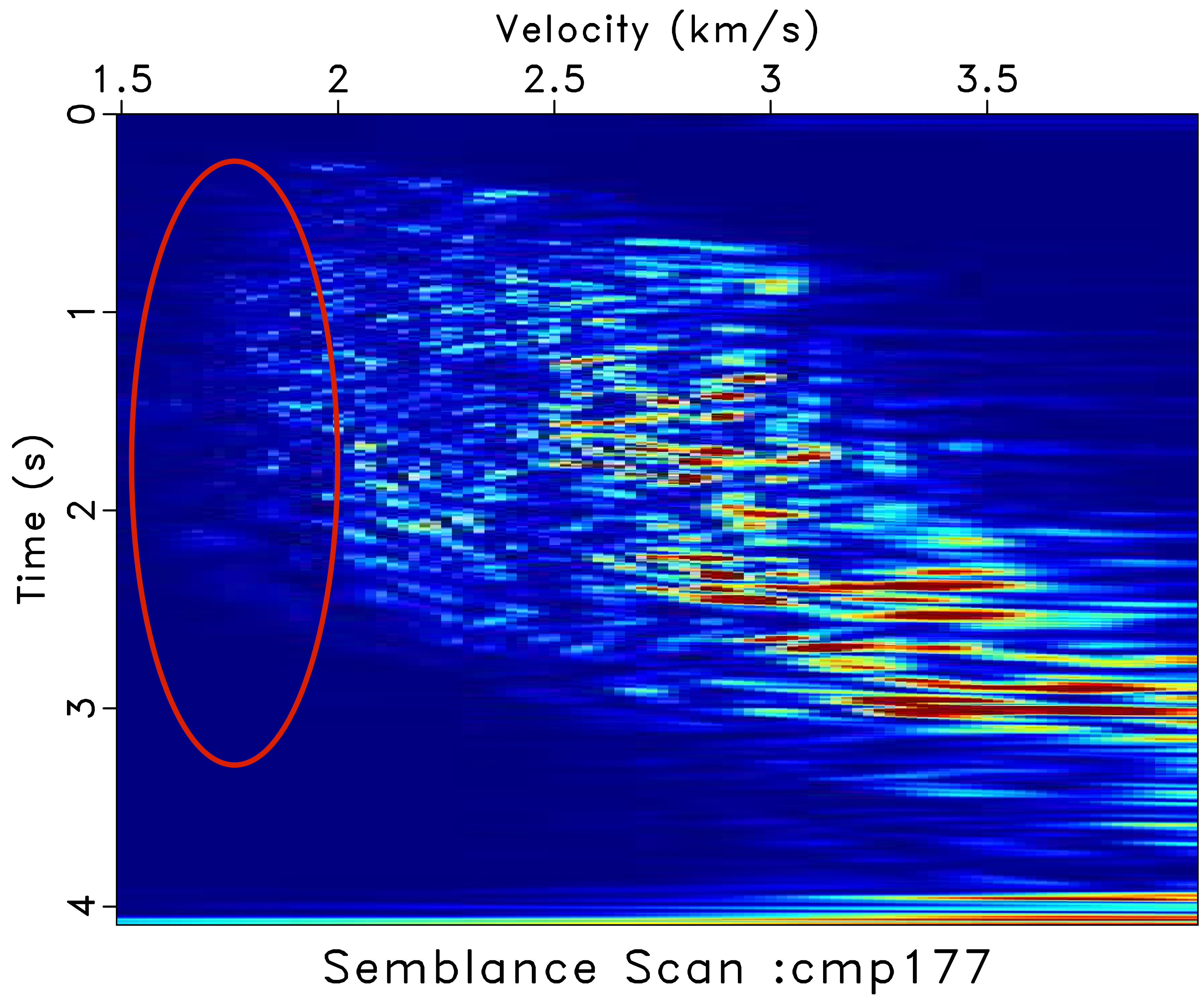
Primaries: one shot-gather
[shown with AGC and muting]



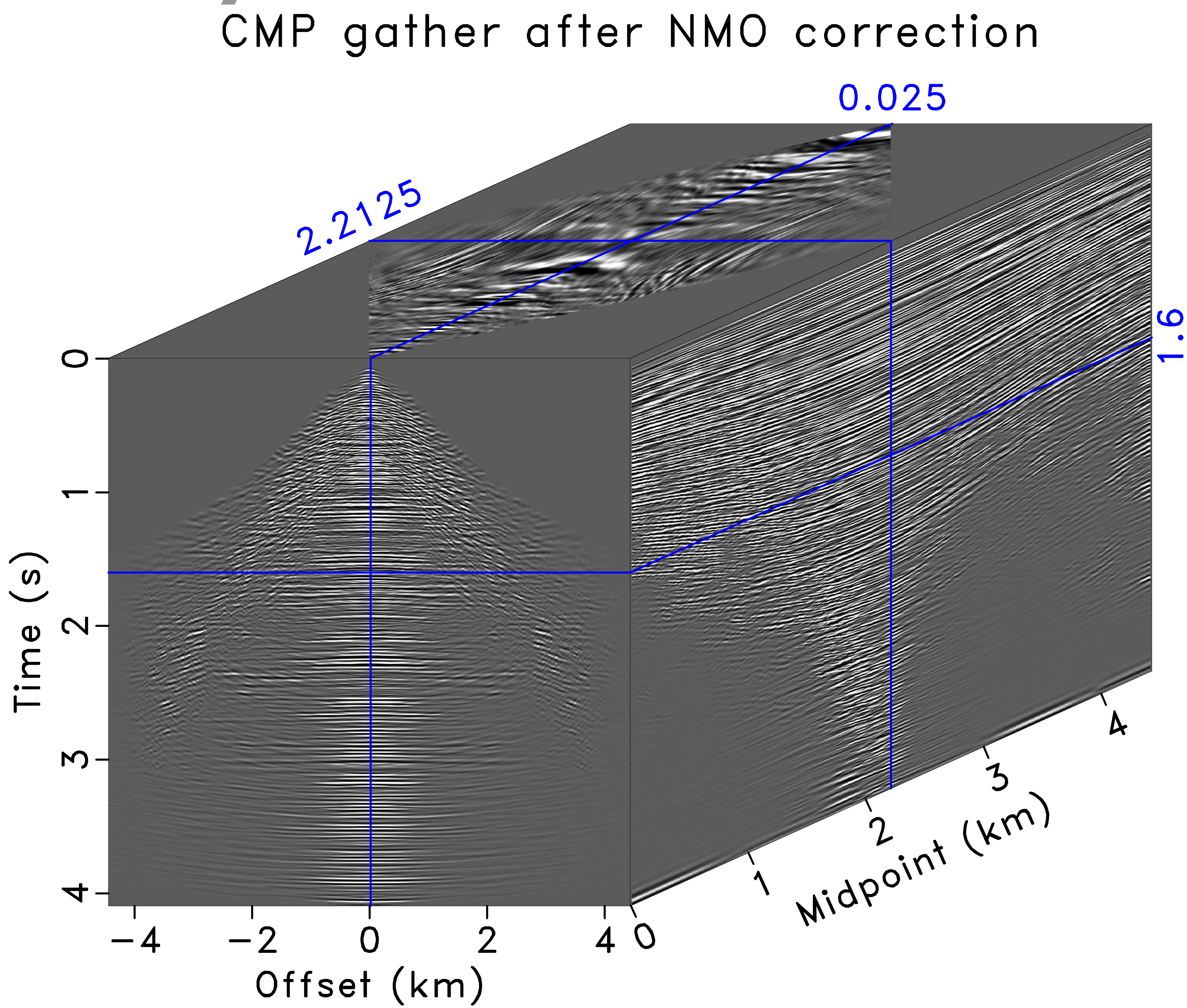
Semblance plot-total data



Semblance plot-primaries

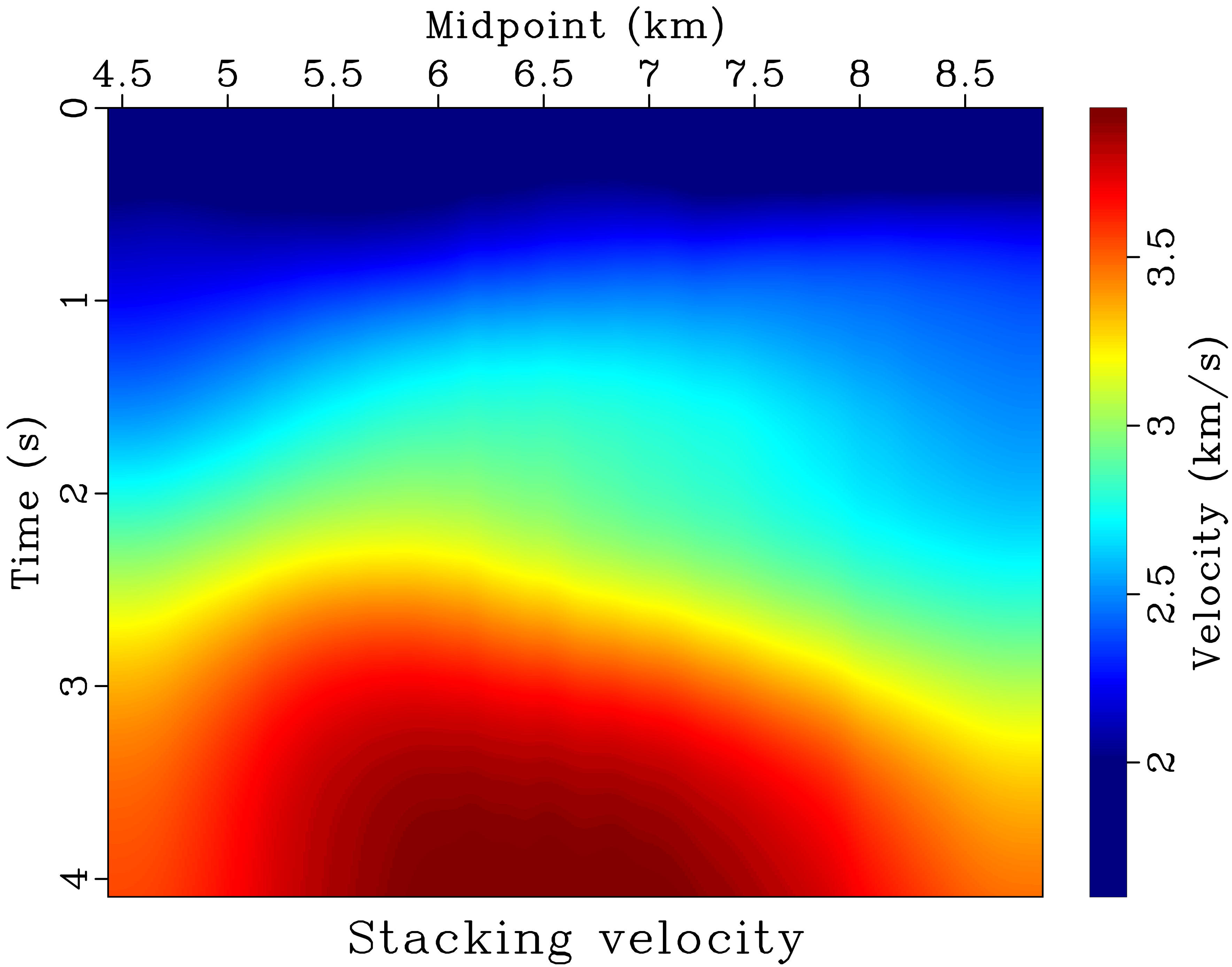


NMO correction with stacking velocity [shown with time-weighting]



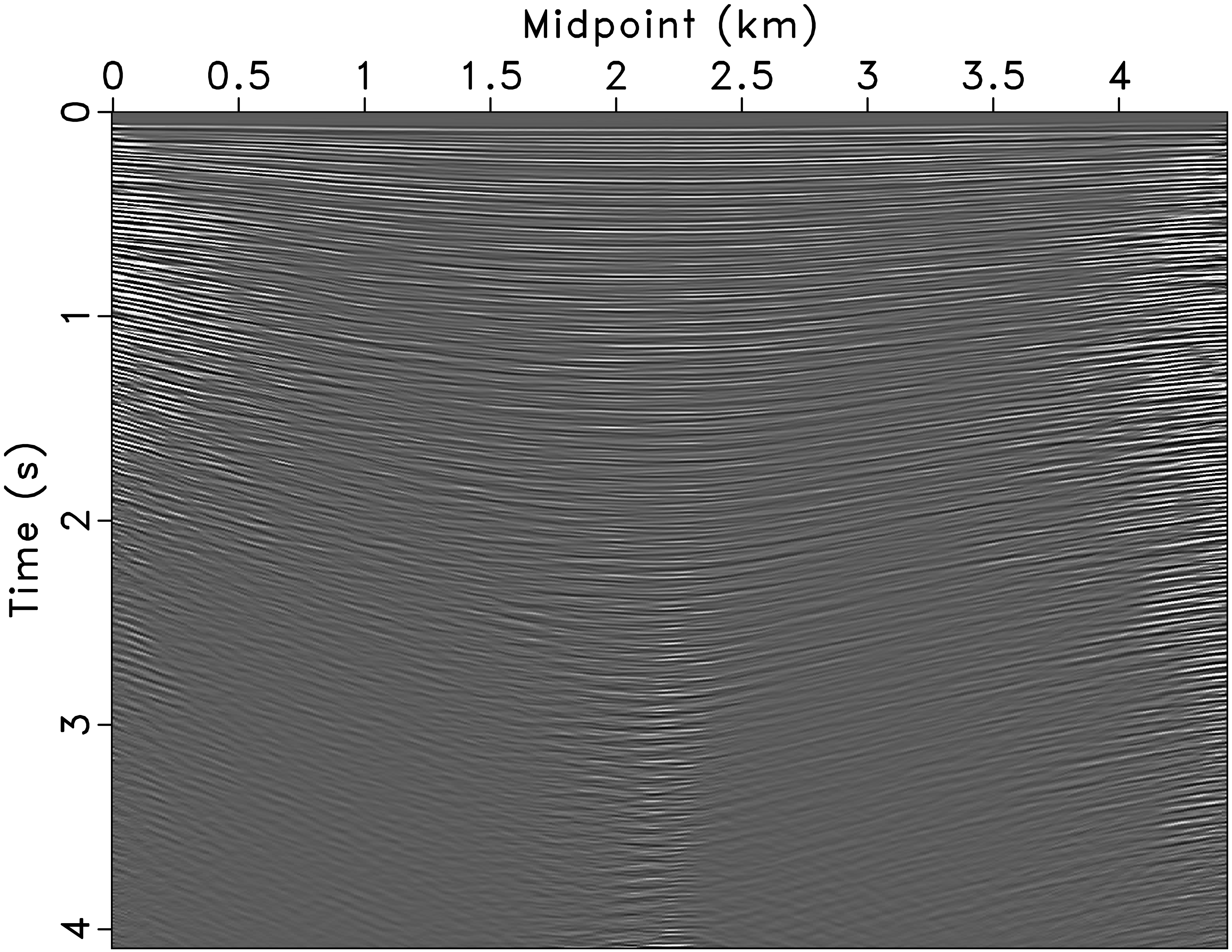
SLIM

Stacking velocity-surface free data



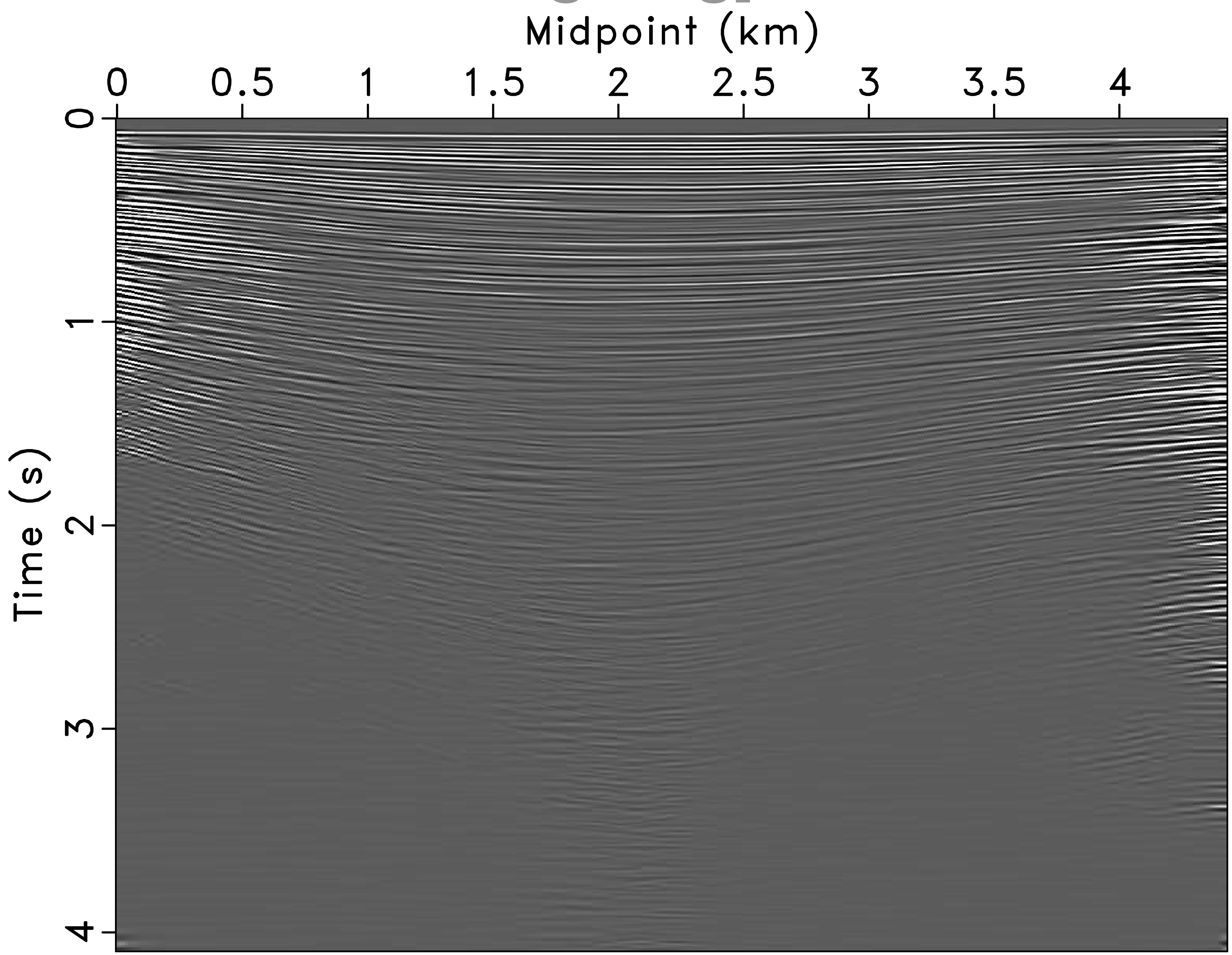
SLIM

Stacked section-total data
[shown with time-weighting]



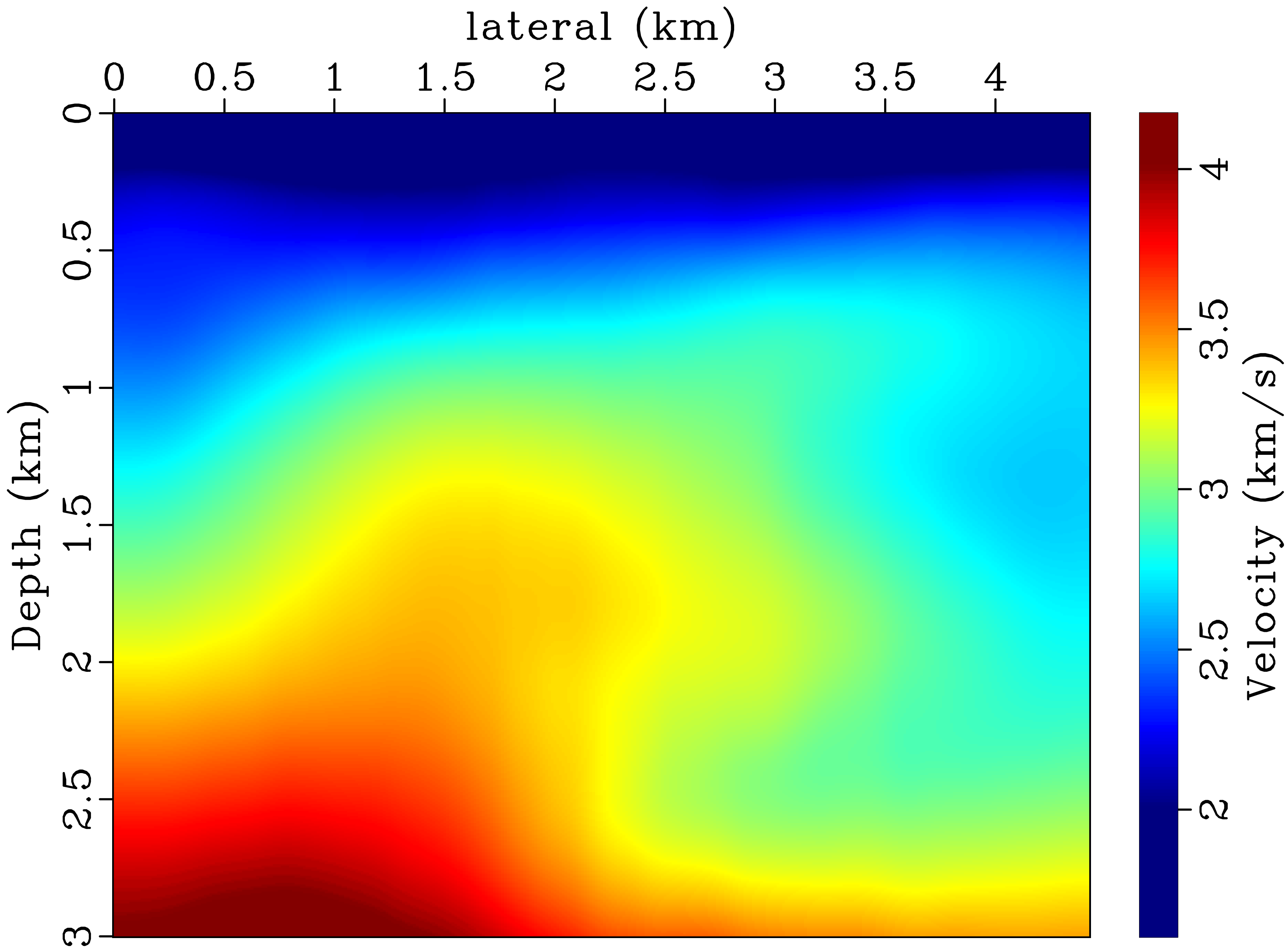
Brute stacking

Stacked section-primary
[shown with time-weighting]



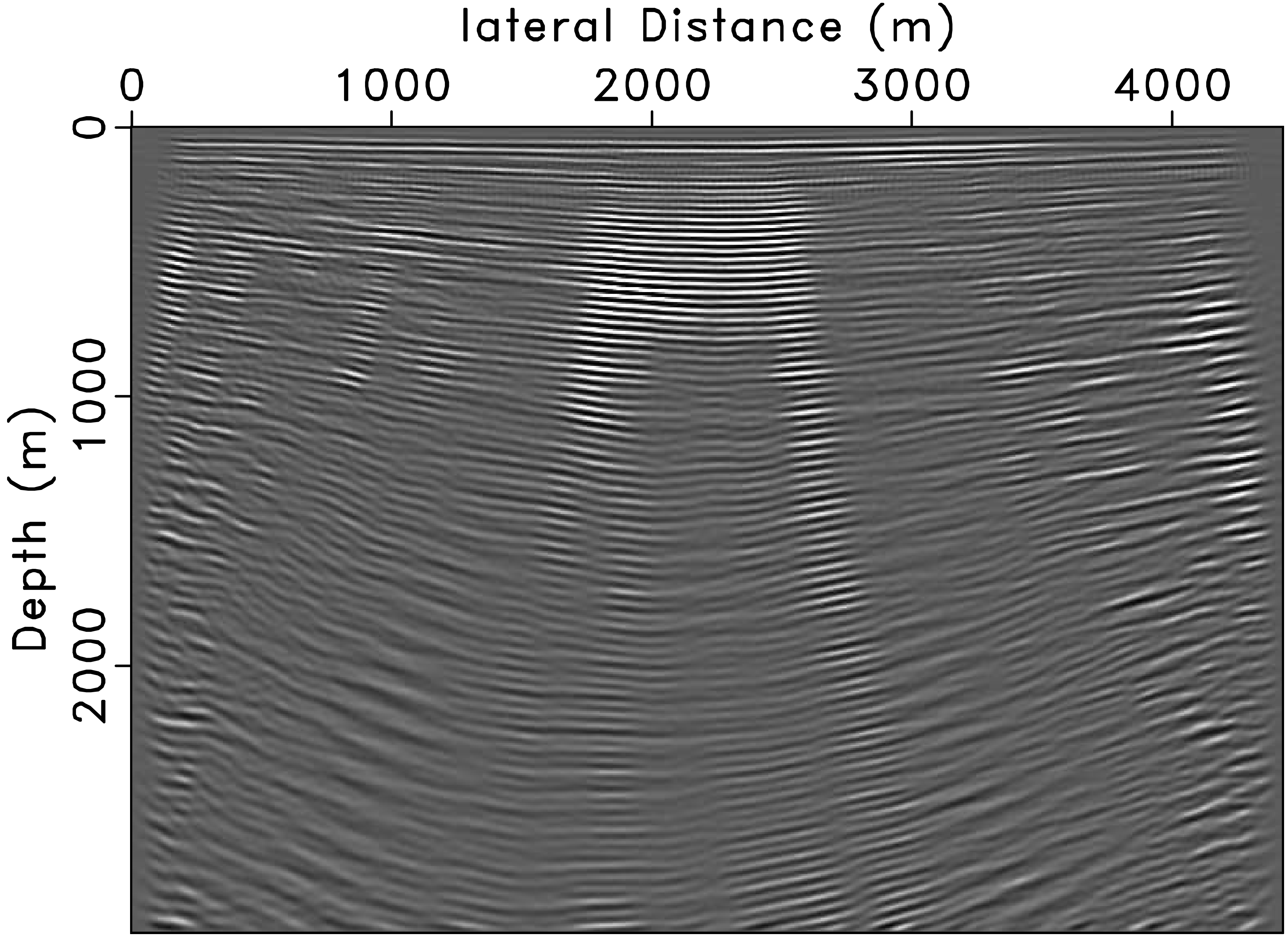
Brute stacking

Migration velocity



interval velocities

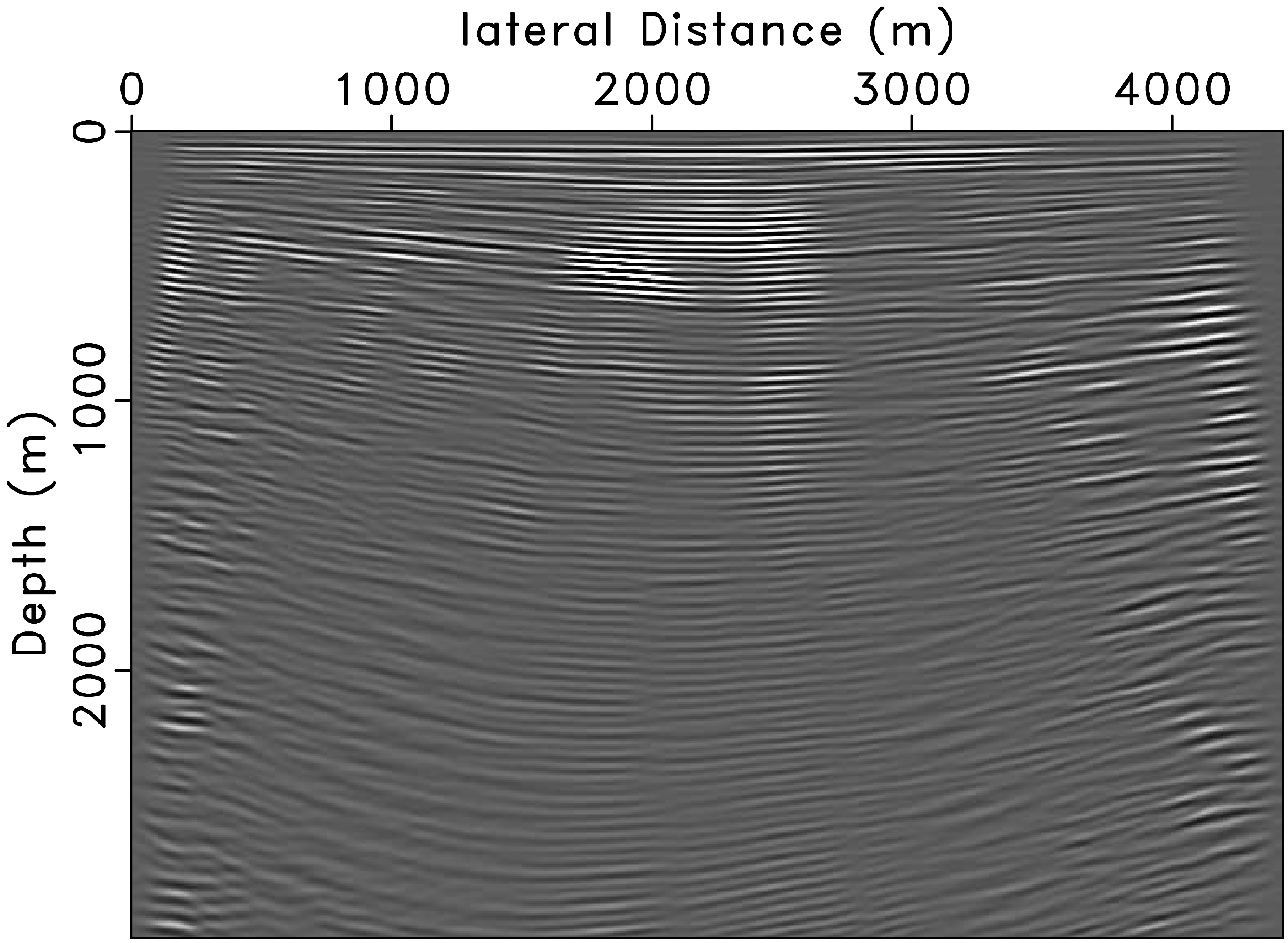
If multiples are not properly handled...



Migration of total data without EPSI

SLIM

EPSI+L1 migration of total data



Migration of total data

SLIM

Conclusions

- Multiples are well handled by combining EPSI and migration.
- For incomplete data with insufficient illumination, we do reap benefits from using multiples.

Future plans

- How to adapt EPSI for incomplete data
- Speed-up this joint inversion by introducing simultaneous sources

SLIM

References

Herrmann, F. J., 2008, Seismic wavefield inversion with curvelet-domain sparsity promotion, Presented at SEG.

Herrmann, F. J. and X. Li, Randomized dimensionality reduction for full-waveform inversion: Presented at the 72nd EAGE Conference & Exhibition.

Wason, H, F. J. Herrmann, and T. T. Y. Lin, Sparsity-promoting recovery from simultaneous data: A compressive sensing approach, Presented at SEG '11

Lin, T., and F. J. Herrmann, 2010, Stabilized estimation of primaries via sparse inversion: Presented at the 72nd EAGE Conference & Exhibition.

Lin, T., N. Tu and F. J. Herrmann, 2010, Sparsity-promoting migration from surface-related multiples: Presented at the 80th SEG Conference

Wang, J. and M. D. Sacchi, High-resolution wave-equation amplitude-variation-with-ray-parameter (AVP) imaging with sparseness constraints: Geophysics, 72, S11-S18

Symes, W., Approximate linearized inversion by optimal scaling of prestack depth migration: Geophysics, 73, R23-R35

SLIM

References

Nemeth, T, C. Wu and G. T. Schuster, Least-squares migration of incomplete reflection data: Geophysics, 64, 208-221

Whitmore, N.D., A. A. Valenciano, and W. Sollner, Imaging of primaries and multiples using a dual-sensor towed streamer, Presented at SEG '10

van den Berg, E., and M. P. Friedlander, 2008, Probing the pareto frontier for basis pursuit solutions: SIAM Journal on Scientific Computing, 31, 890–912.

van Groenestijn, G. J. A., and D. J. Verschuur, 2009, Estimation of primaries and near-offset reconstruction by sparse inversion: Marine data applications: Geophysics, 74, R119– R128.

Verschuur, D. J., 1992, Adaptive surface-related multiple elimination: Geophysics, 57, 1166.

Verschurr, D. J. and Berkhout A.J., 2011, Seismic migration of blended shot records with surface-related multiple scattering: Geophysics, 76, A7-A13

Acknowledgements

NSERC CRSNG

- Thanks to all my colleagues for the beneficial discussions
- Thanks to Eric for the advice on working with incomplete data, and for sharing with us the Gulf of Suez dataset.

SINBAD

NSERC CRSNG

This work was in part financially supported by the Natural Sciences and Engineering Research Council of Canada Discovery Grant (22R81254) and the Collaborative Research and Development Grant DNOISE II (375142-08). This research was carried out as part of the SINBAD II project with support from the following organizations: BG Group, BP, Chevron, ConocoPhillips, Petrobras, Total SA, and WesternGeco.