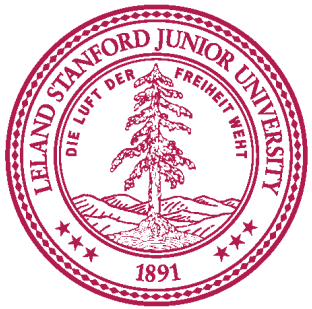
Joint-inversion of simultaneous-source time-lapse seismic data

G. Ayeni, Y. Tang & B. Biondi

SEP138: pgs.157-170



2009 SEP Annual Sponsor Meeting

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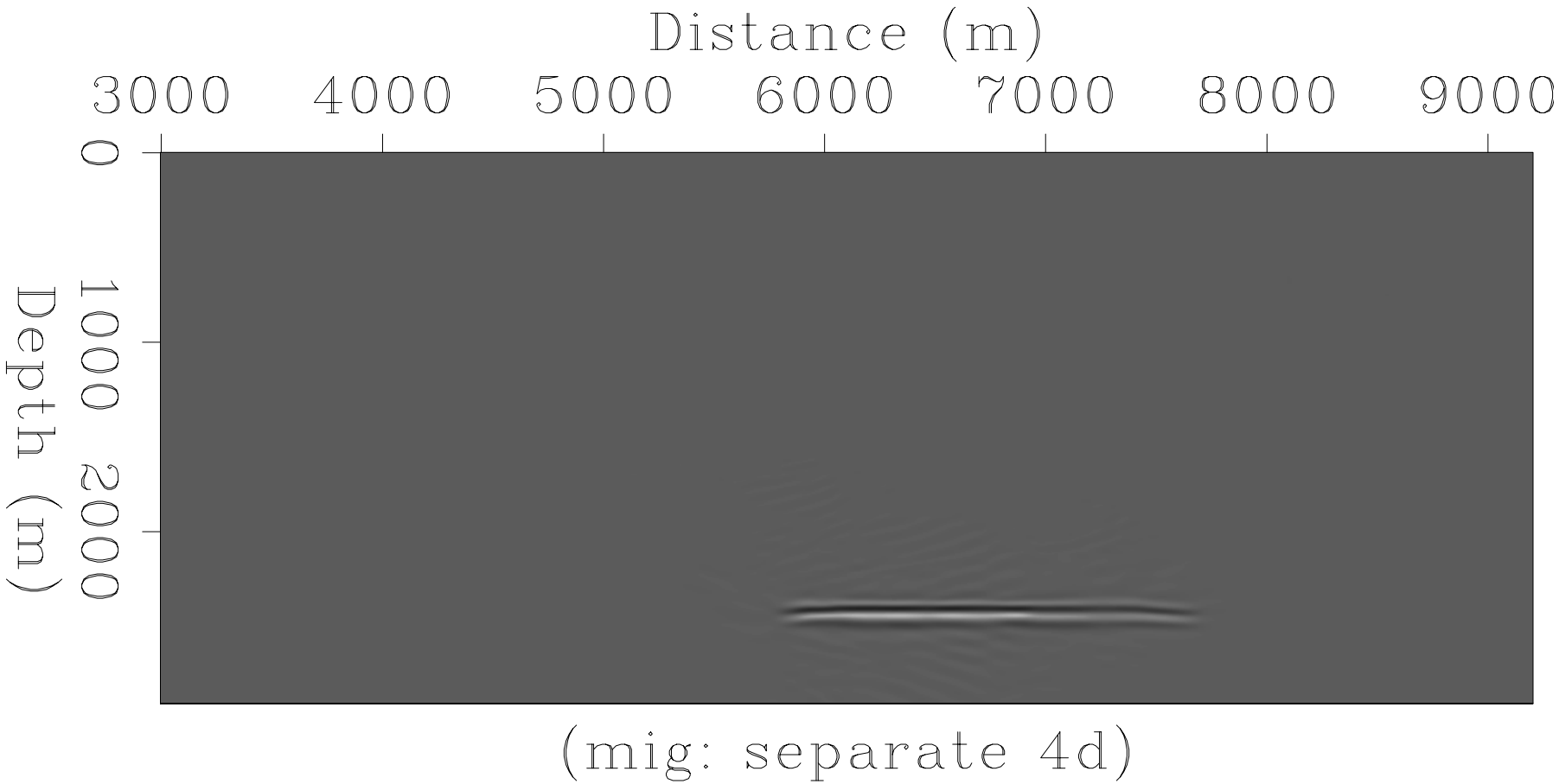
4D amplitude change: migration (separate sources)



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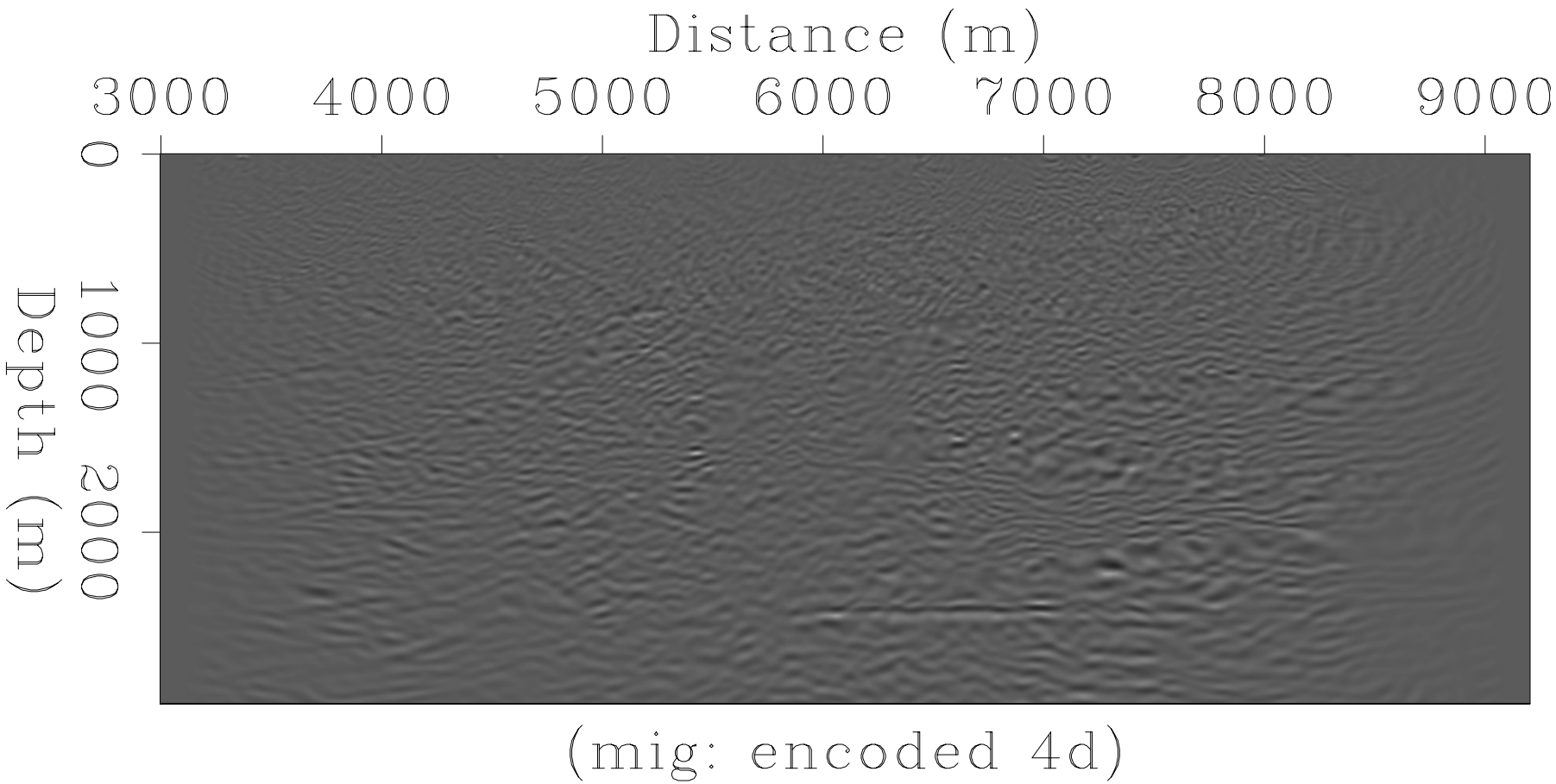

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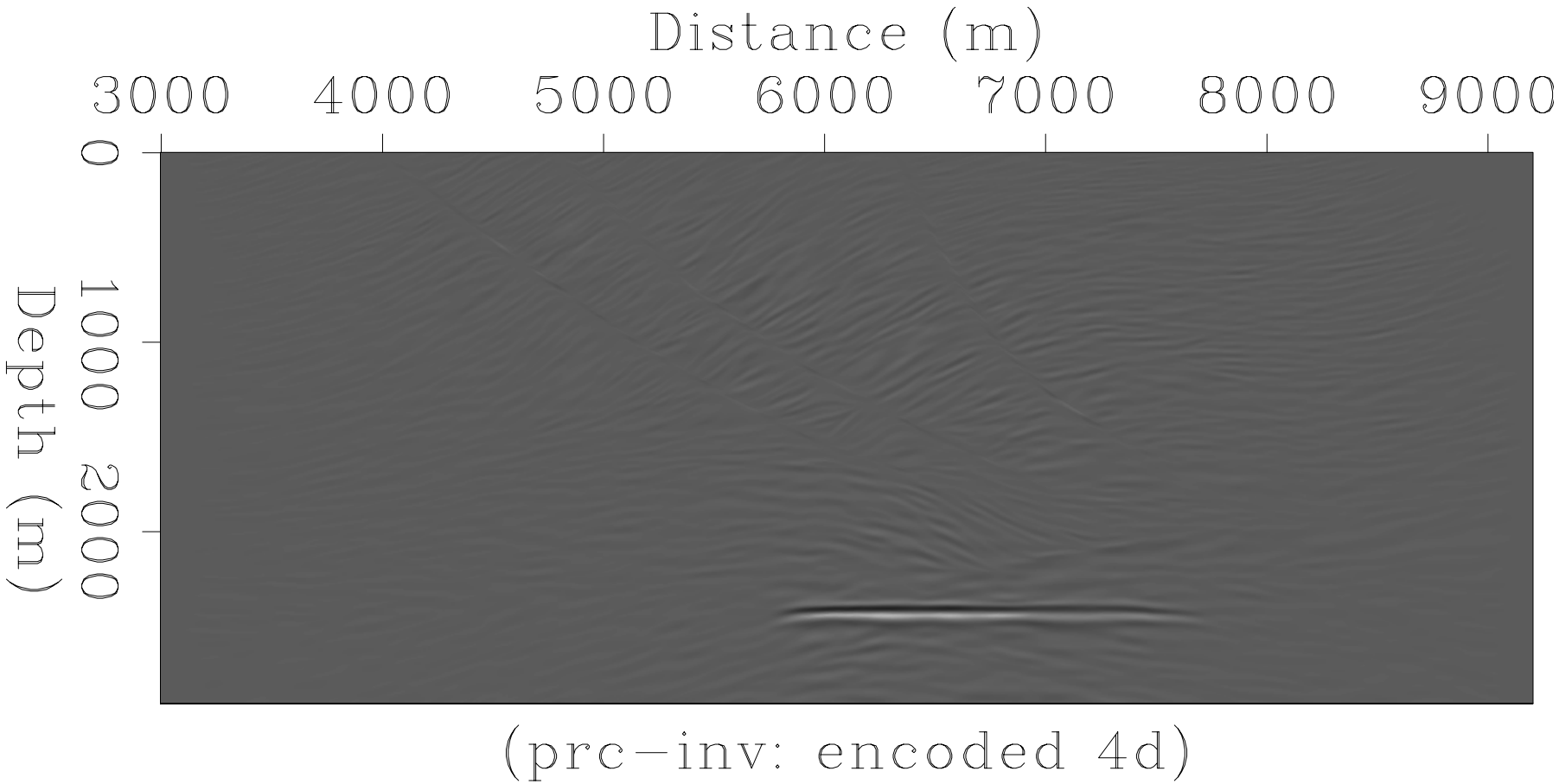

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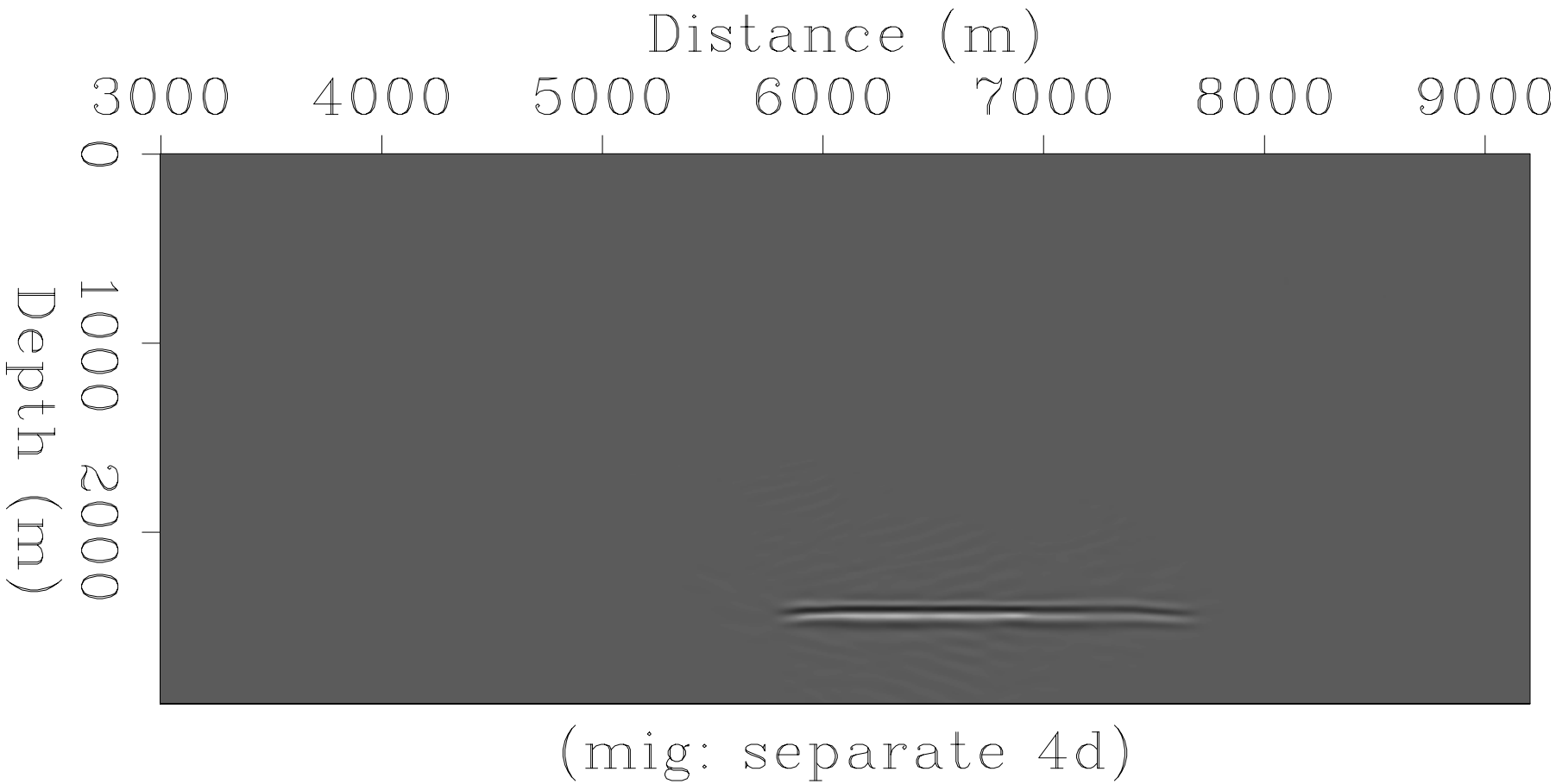

Goals

1. **Develop** a framework for processing simultaneous-source time-lapse seismic data

2. **Test** the scheme on a 2D synthetic *(Marmousi)* model

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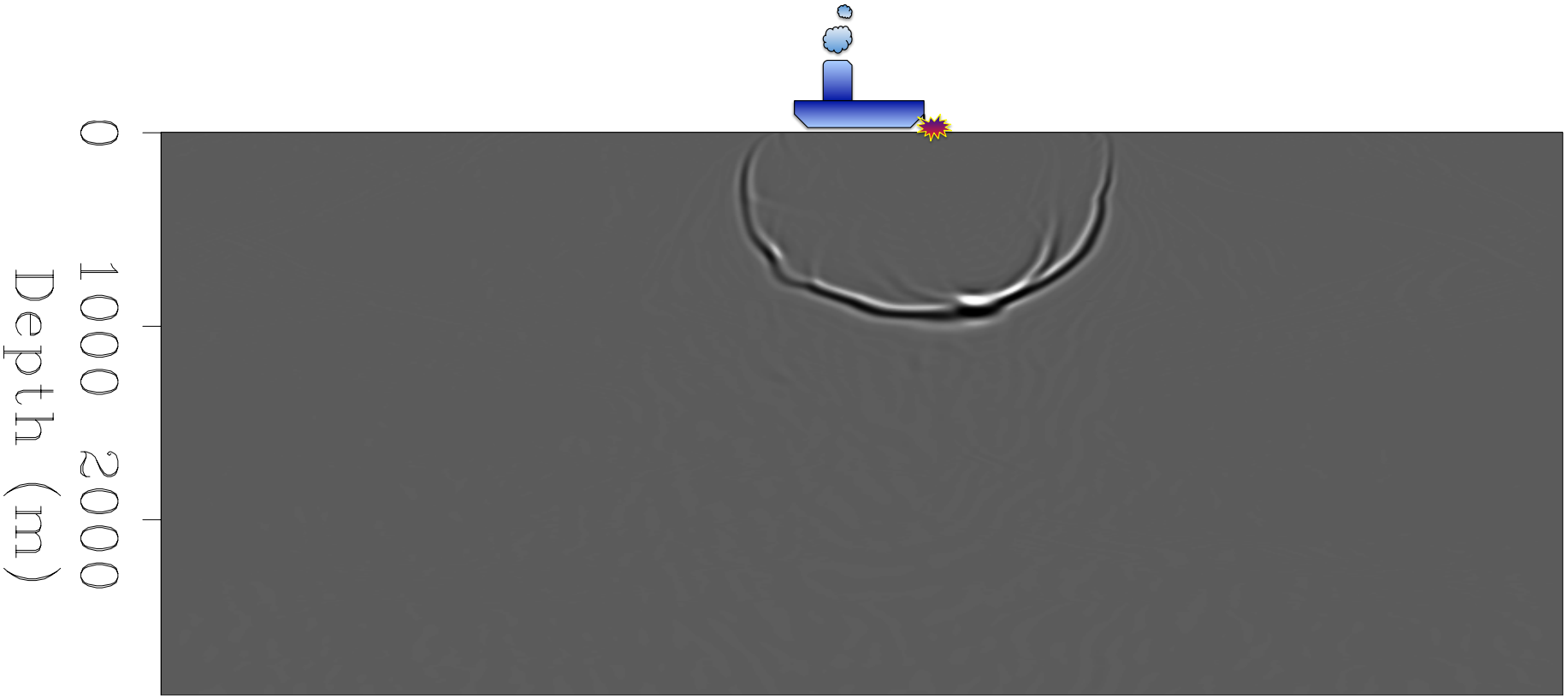
2. **Test** the scheme on a 2D synthetic *(Marmousi)* model
3. **Apply** the scheme to a complex 3D synthetic model
4. **Convince** you to give us some relevant field data

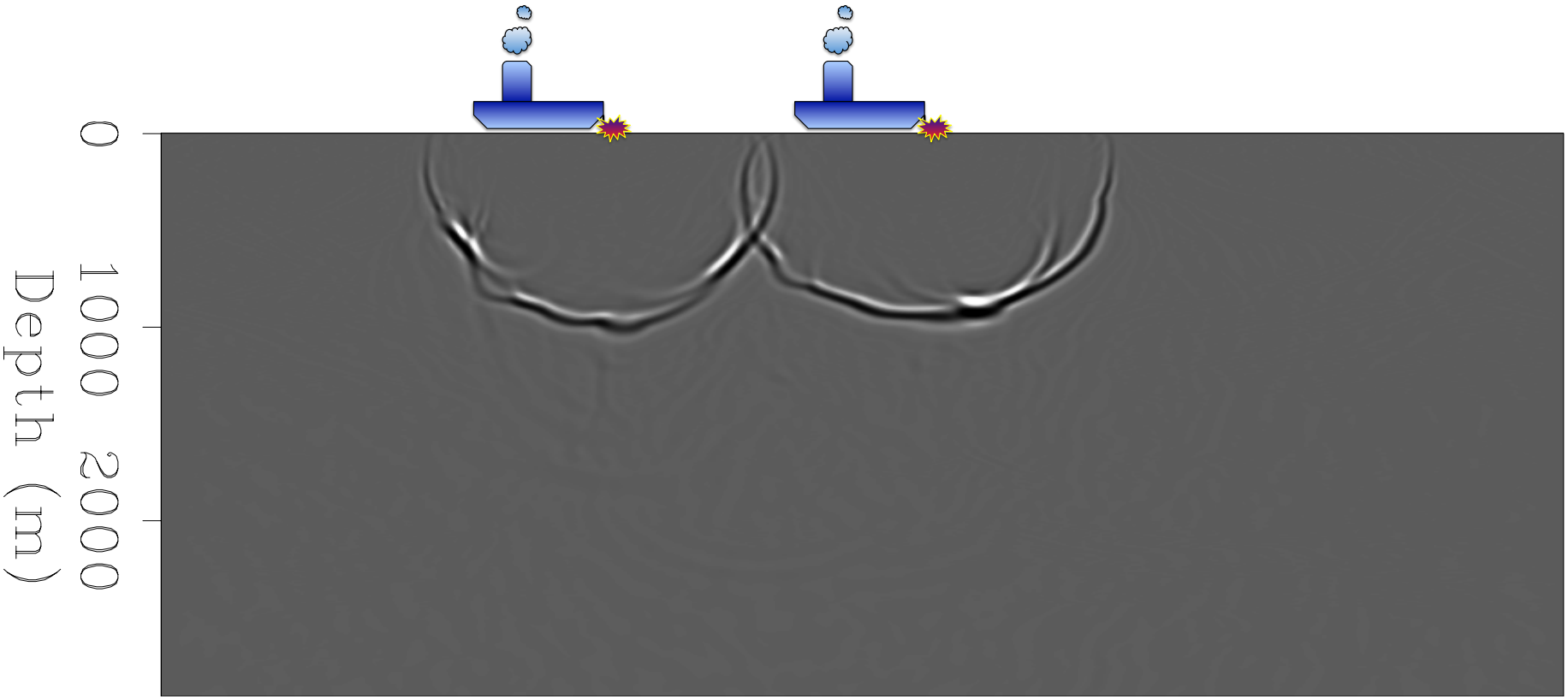
What is simultaneous shooting?

Conventional shooting (1 source)



What is simultaneous shooting?

Simultaneous shooting [2 sources]



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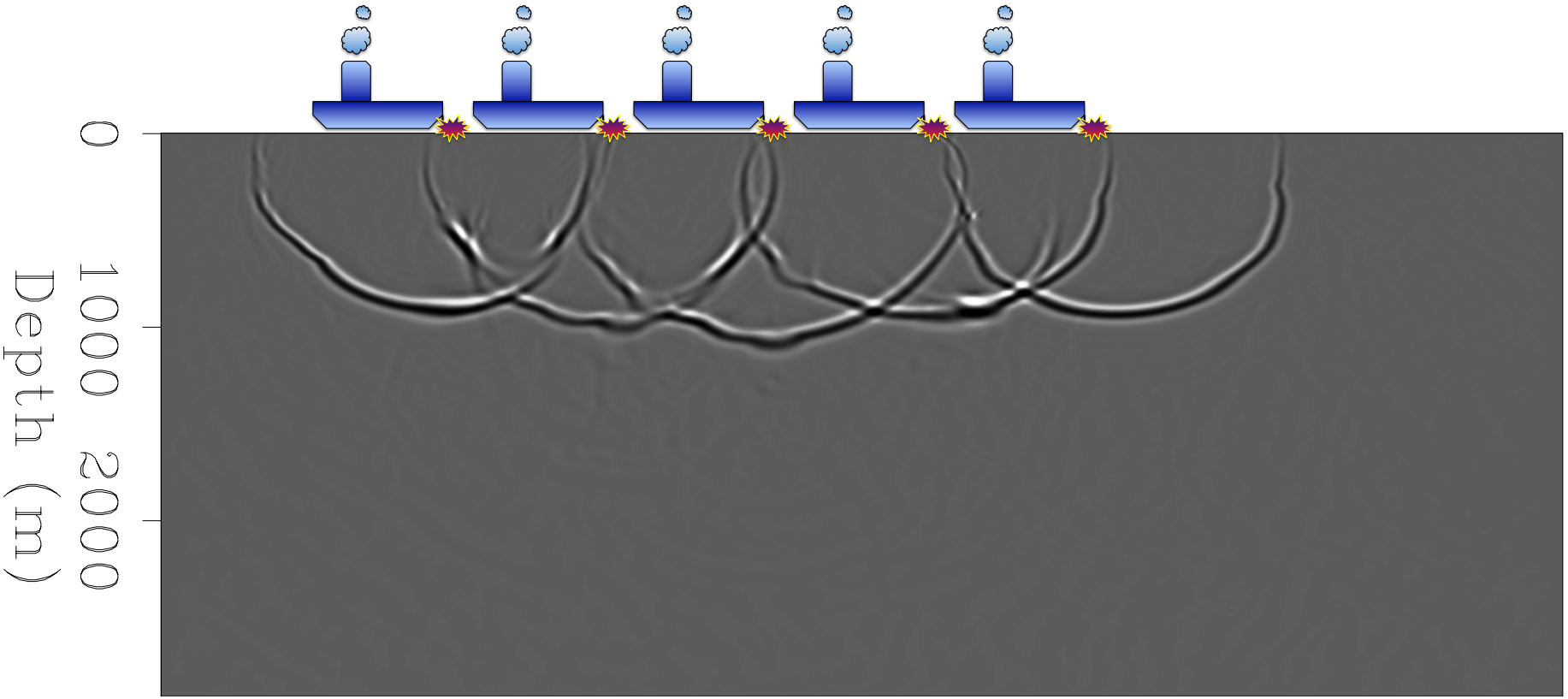
Simultaneous shooting [5 sources]



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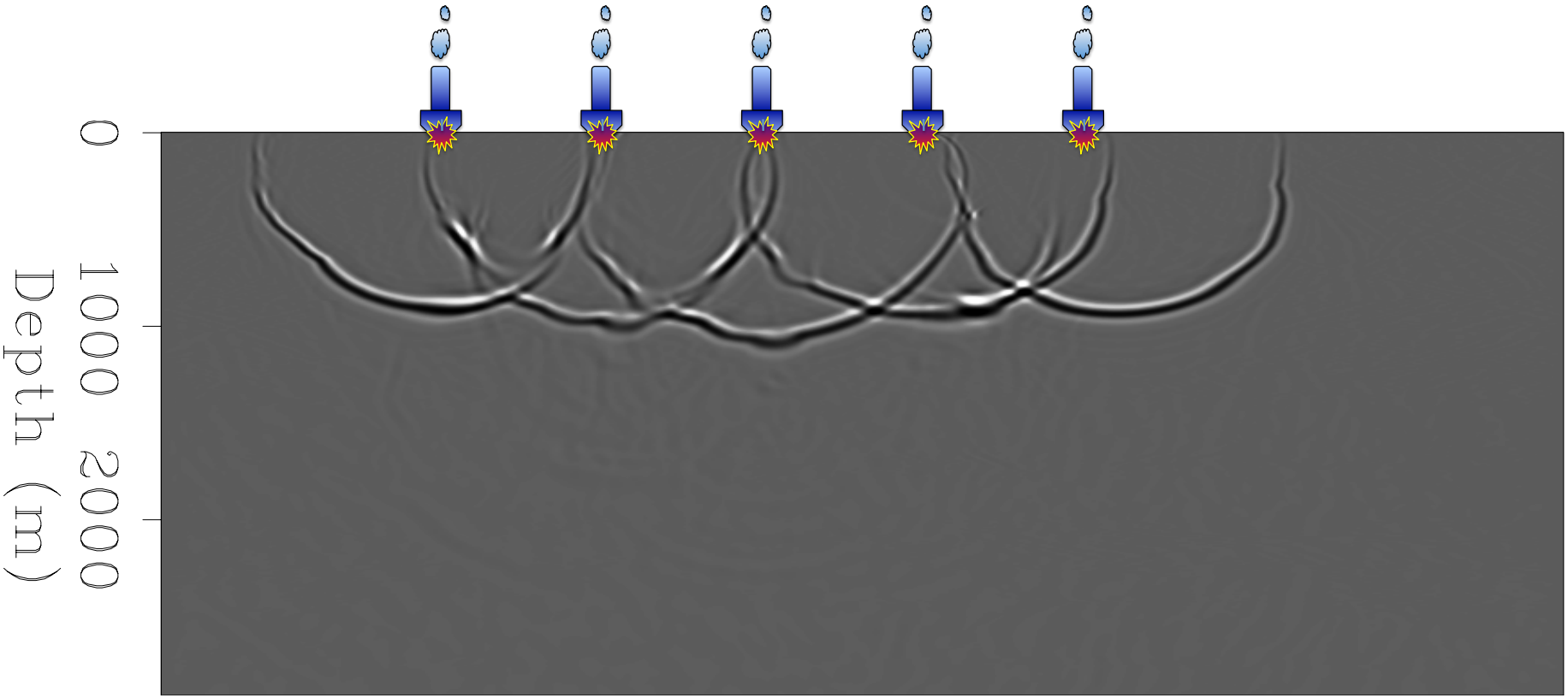

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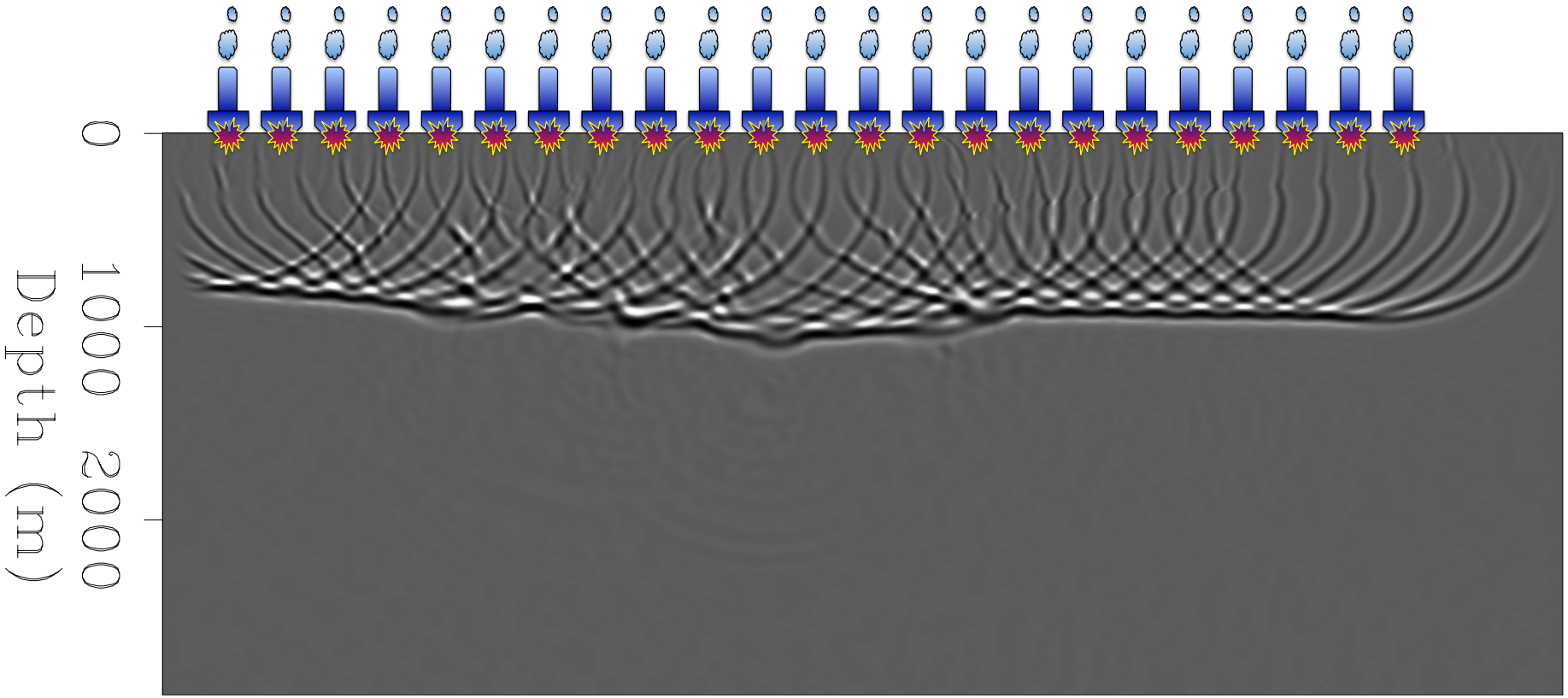
Simultaneous shooting [29 sources]



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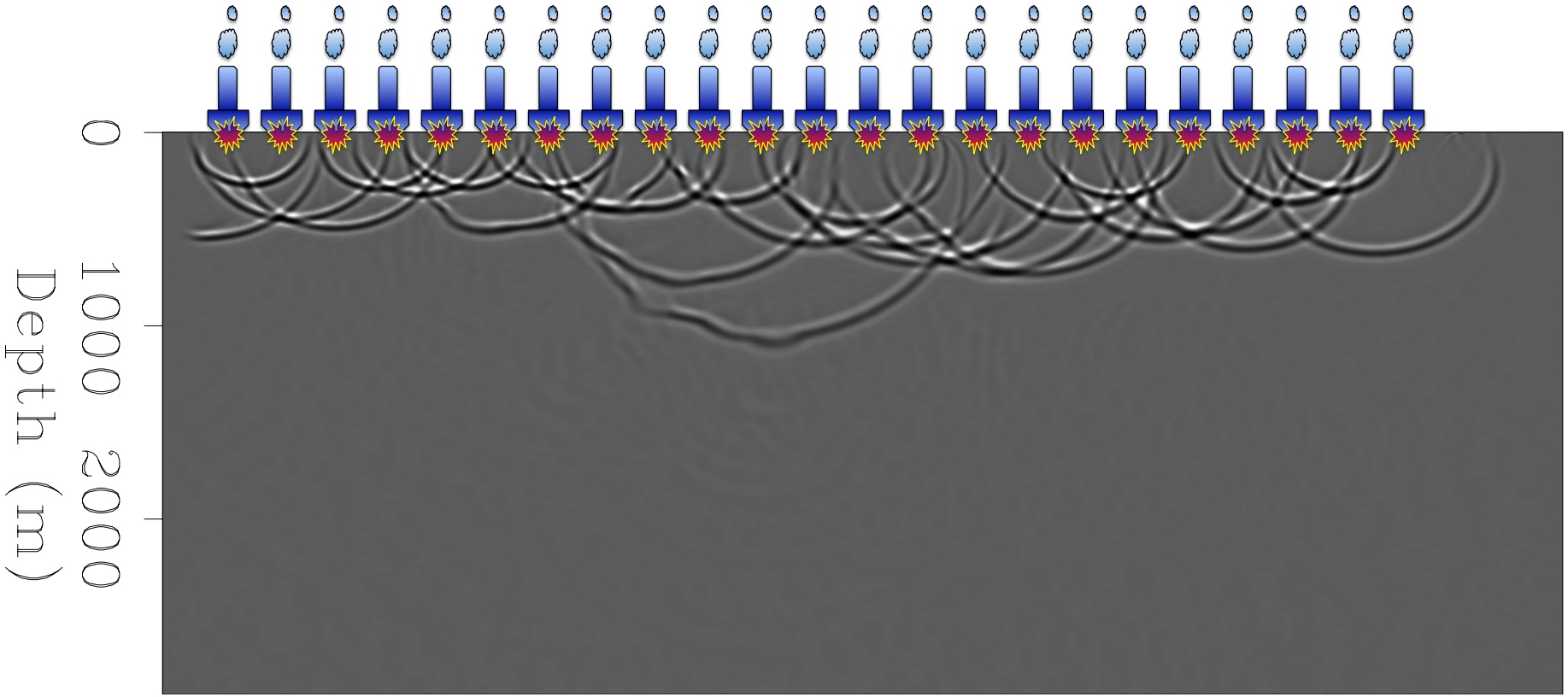
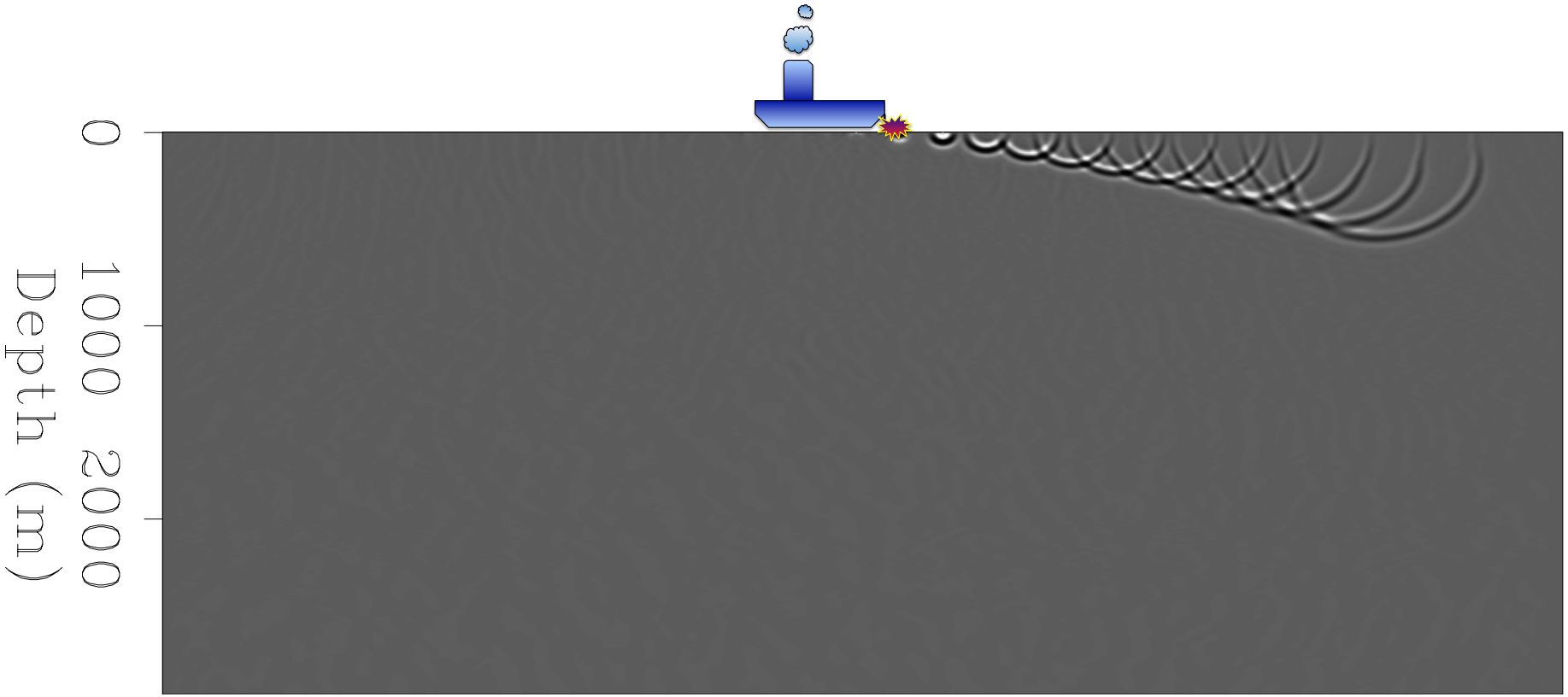
Simultaneous shooting [29 sources] (randomized)



What is simultaneous shooting?

Continuous/Blended acquisition [single boat]



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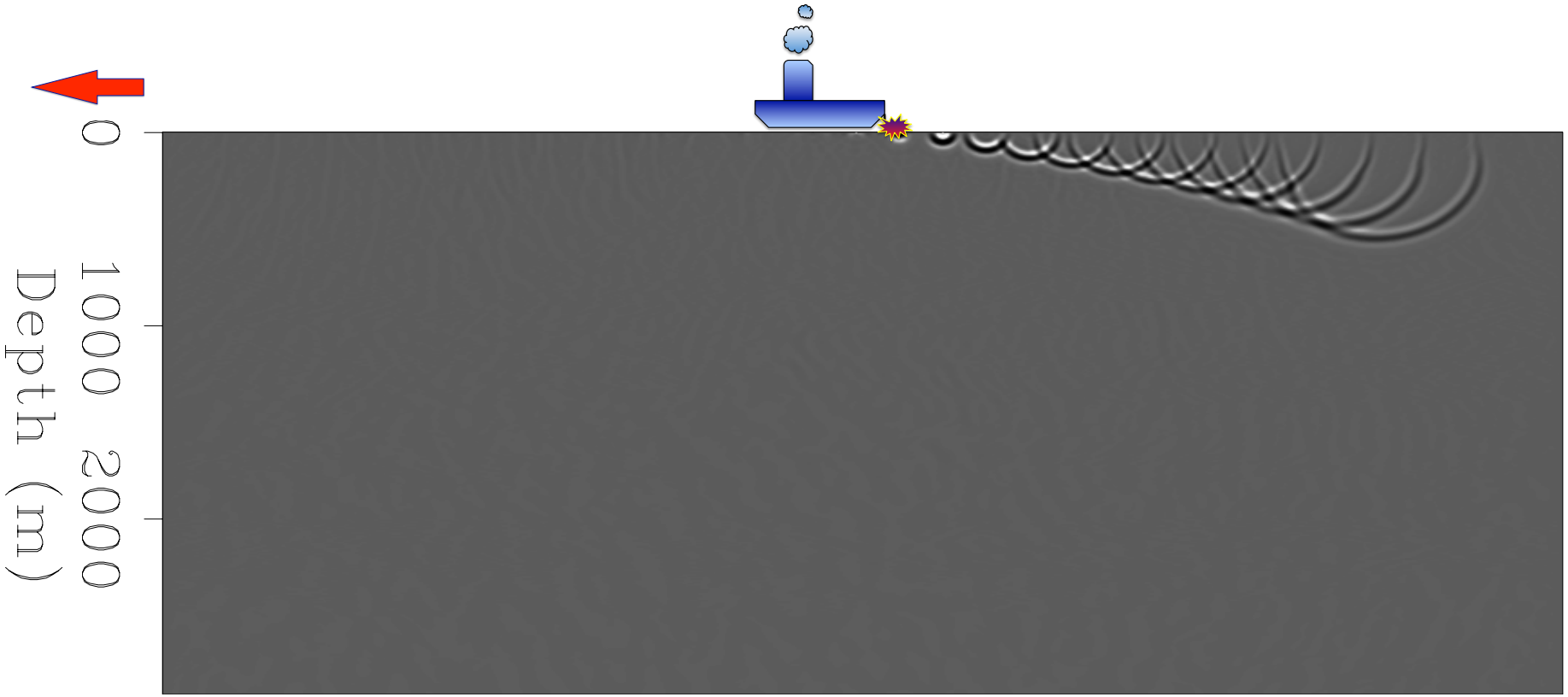

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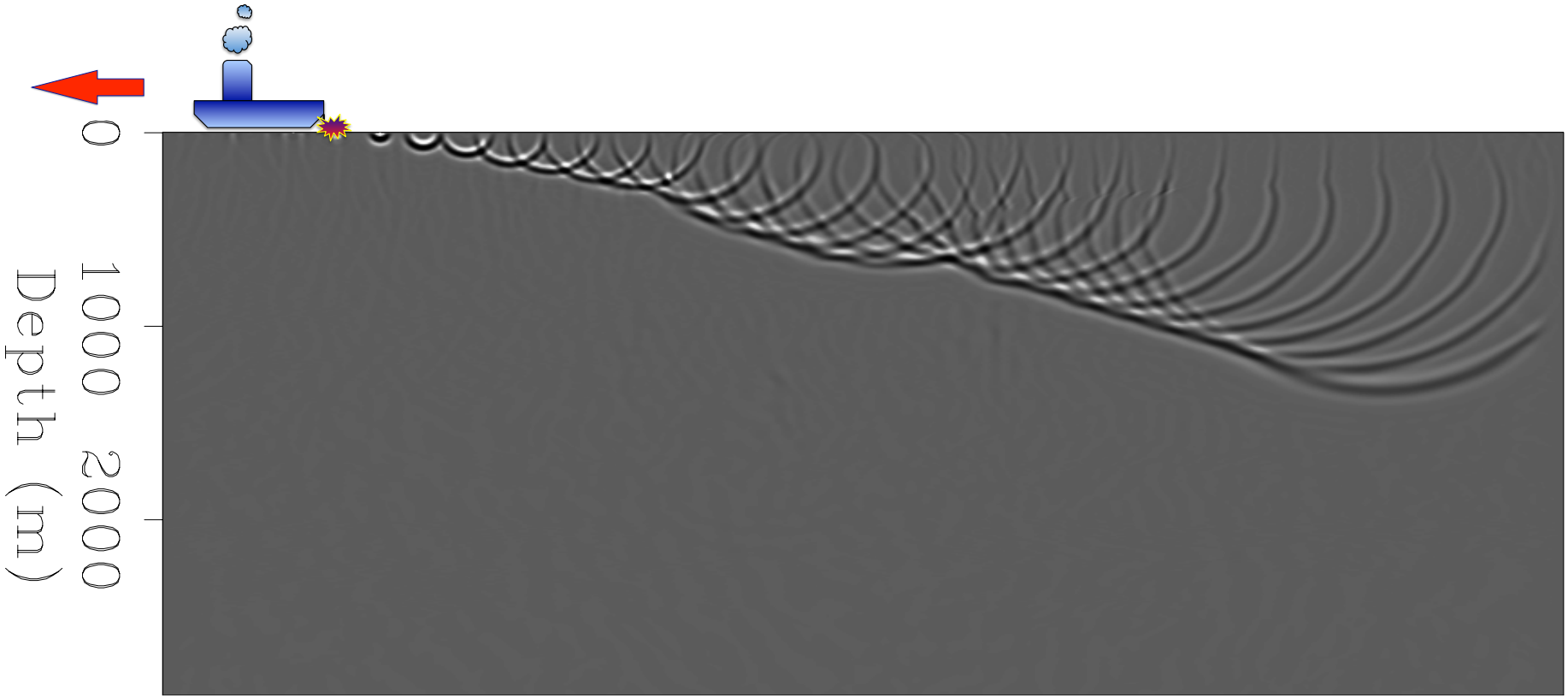

Why simultaneous shooting?

- **Improved shot-sampling**: *reduces shot-interpolation requirement in conventional 3D narrow-azimuth acquisition*
- **Lower acquisition cost**: *enables simultaneous acquisition of multiple azimuths in 3D wide- or multi- azimuth data acquisition at lower cost*
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Simultaneous-source non-repeatability hypothesis (Marine)

*"**geometry** and **relative shot-timing**, cannot be precisely repeated simultaneously for different surveys"*

$$\mathbf{\Delta X \Delta T} \geq \gamma \tag{1}$$

ΔX: RMS-error in position (geometry non-repeatability)
ΔT: RMS-error in shot-timing (shot-timing non-repeatability)

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$$\mathbf{\Delta X \Delta T} \geq \gamma \tag{2}$$

$$\gamma \propto \frac{N_s}{f_{0X} \times f_{T0}}$$

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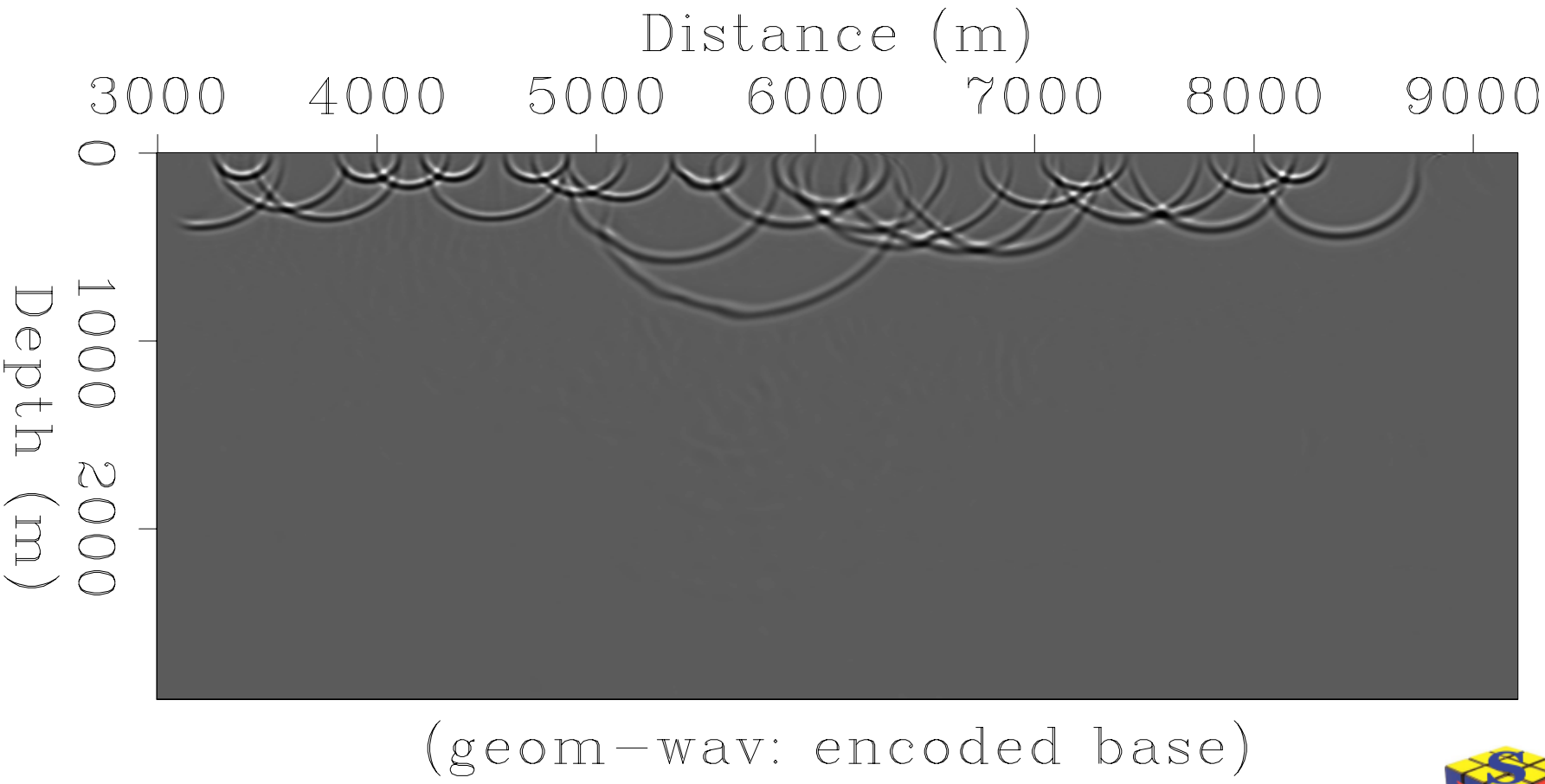
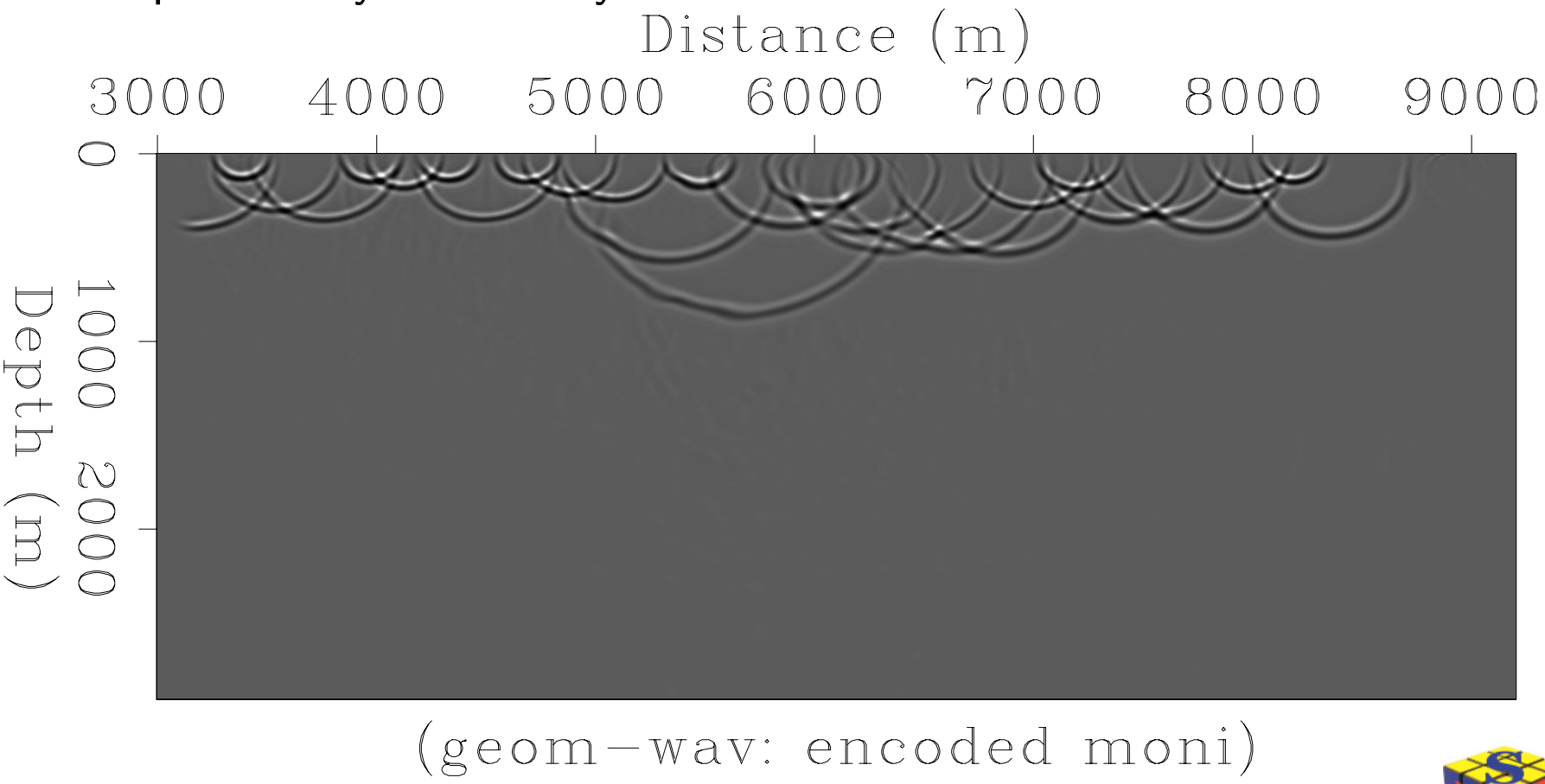
Source wavefields at 0.4 sec [Baseline]



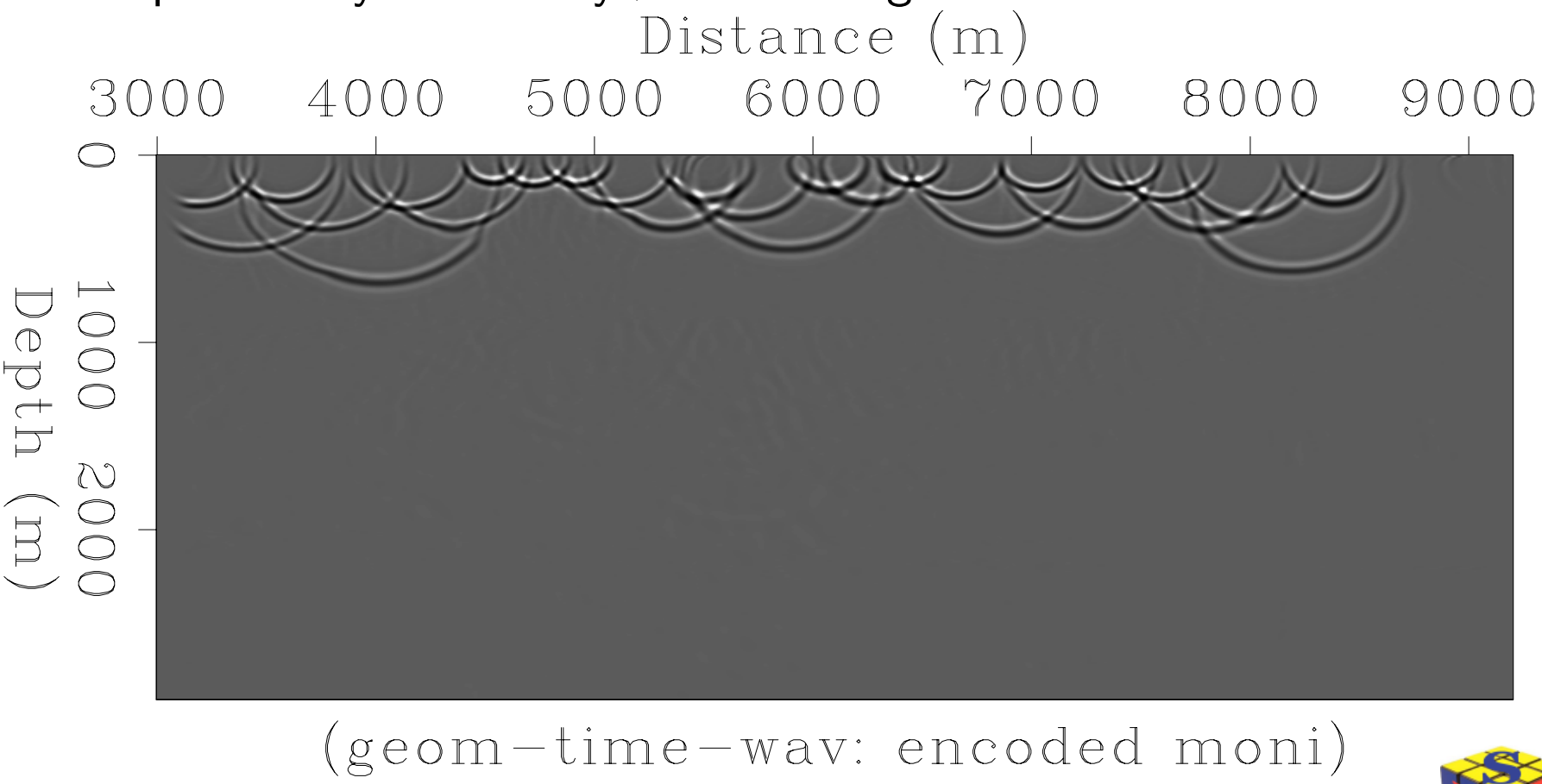
Source wavefields at 0.4 sec [Monitor]

Non-repeatability: Geometry



Source wavefields at 0.4 sec [Monitor]

Non-repeatability: Geometry+Shot-timing



Non-repeatability

How well did you repeat the
(i) geometry and
(ii) shot-timing?

$$WRMS = 2 \times \frac{\sqrt{b_{rms}} - \sqrt{m_{rms}}}{\sqrt{b_{rms}} + \sqrt{m_{rms}}} \tag{3}$$

b: baseline data
m: monitor data
$_{rms}$: root-mean-square energy

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Time-lapse (4D) imaging

$$\begin{aligned} \mathbf{L}_0\mathbf{m}_0 &= \mathbf{d}_0 \\ \mathbf{L}_1\mathbf{m}_1 &= \mathbf{d}_1 \end{aligned} \tag{4}$$

$$\Delta\mathbf{m} = \mathbf{m}_1 - \mathbf{m}_0 \tag{5}$$

$$\Delta\tilde{\mathbf{m}} = \tilde{\mathbf{m}}_1 - \tilde{\mathbf{m}}_0 \tag{6}$$

$\mathbf{L}_i$: modeling (acquisition) operator
$\mathbf{d}_i$: seismic data
$\mathbf{m}_i$: earth reflectivity model
$\tilde{\mathbf{m}}_i$: migrated image ($\mathbf{L'}_i\mathbf{d}_i$)
$\Delta\mathbf{m}$: time-lapse image
$_{i=0}$: Baseline
$_{i=1}$: Monitor

Conventional 4D processing

- **Data regularization**
- **Image alignment**
- **Match-filtering**

  E.g. [Rickett and Lumley, 2001]

We think these methods are inadequate for simultaneous source data because of the strong non-repeatability

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Recent 4D methods: inversion

- **Wave-equation velocity analysis** [Albertin et al., 2006]
- **Spatio-temporal ray-tomography** [Ajo-Franklin et al., 2007]
- **Sequential inversion** [Oldenborger et al., 2007]
- **Contrast-source waveform inversion** [Abubakar et al., 2008]
- **Joint wave-equation inversion** [Ayeni and Biondi, 2009]

LSQ migration Applications

- **Incomplete data** [Nemeth et al., 1999]
- **AVA inversion** [Kühl and Sacchi, 2003]
- **Amplitude-preserving migration** [Mulder and Plessix, 2004]
- **Sub-salt imaging** [Clapp, 2005]
- **Target-oriented imaging** [Valenciano, 2008]
- **Blended data imaging** [Tang, 2009]

Least-squares (LSQ) migration

$$\mathbf{L}\mathbf{m} = \mathbf{d} \tag{7}$$

$$\mathbf{L}'\mathbf{L}\hat{\mathbf{m}} = \mathbf{L}'\mathbf{d} \tag{9}$$

L: modeling/acquisition operator
L$'$: migration operator
d: seismic data
m: earth reflectivity model

Least-squares (LSQ) migration

$$\mathbf{Lm} = \mathbf{d} \tag{7}$$

$$S(\mathbf{m}) = \left\| \mathbf{Lm} - \mathbf{d} \right\|^2 \tag{10}$$

L: modeling/acquisition operator
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m: earth reflectivity model

S: L_2 norm

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$$\mathbf{Lm} = \mathbf{d} \tag{7}$$

$$S(\mathbf{m}) = \left\| \begin{array}{c} \mathbf{Lm} - \mathbf{d} \\ \epsilon \mathbf{Am} - \mathbf{0} \end{array} \right\|^2 \tag{11}$$

L: modeling/acquisition operator
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m: earth reflectivity model

S: L_2 norm

A: regularization
ϵ: regularization strength

Least-squares (LSQ) migration

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$$S(\mathbf{m}) = \left\| \begin{array}{c} \mathbf{LCp} - \mathbf{d} \\ \epsilon\mathbf{p} - \mathbf{0} \end{array} \right\|^2 \tag{12}$$

L: modeling/acquisition operator
L$'$: migration operator
d: seismic data
m: earth reflectivity model

S: L_2 norm

C: preconditioner
ϵ: regularization strength
p: preconditioned variable

Least-squares (LSQ) migration

$$\tilde{\mathbf{L}}\mathbf{m} = \tilde{\mathbf{d}} \tag{8}$$

$$S(\mathbf{m}) = \left\| \begin{array}{c} \tilde{\mathbf{L}}\mathbf{C}\mathbf{p} - \tilde{\mathbf{d}} \\ \epsilon\mathbf{p} - \mathbf{0} \end{array} \right\|^2 \tag{13}$$

$\tilde{\mathbf{L}}$: modeling/acquisition operator (encoded)
$\tilde{\mathbf{L}}'$: migration operator (encoded)
$\tilde{\mathbf{d}}$: seismic data (encoded)
$\mathbf{m}$: earth reflectivity model

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Least-squares (LSQ) migration

$$\tilde{\mathbf{L}}\mathbf{m} = \tilde{\mathbf{d}} \tag{8}$$

$$\tilde{\mathbf{L}}\mathbf{m} = \sum_{\mathbf{s}=\mathbf{a}}^{\mathbf{b}} a(\varphi_{\mathbf{s}})\mathbf{L}\mathbf{m} = \tilde{\mathbf{d}}_{\mathbf{s_{ab}}} \tag{14}$$

$$a(\varphi_{\mathbf{s}}) = e^{i\varphi_{\mathbf{s}}} = e^{i\omega t_{\mathbf{s}}} \tag{15}$$

s: shot

$a(\varphi_{\mathbf{s}})$: time-delay function

$t_{\mathbf{s}}$: time-delay at shot **s**.

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NOTE: *geometry non-repeatability results of differences in* $\tilde{\mathbf{L}}$

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NOTE: *shot-timing non-repeatability results of differences in* $a(\varphi_{\mathbf{s}})$

Joint least-squares (LSQ) migration

$$S(\mathbf{m}) = \left\| \begin{array}{c} \tilde{\mathbf{L}}\mathbf{C}\mathbf{p} - \tilde{\mathbf{d}} \\ \epsilon\mathbf{p} - \mathbf{0} \end{array} \right\|^2 \tag{16}$$

$$\tilde{\mathbf{L}} = \begin{bmatrix} \tilde{\mathbf{L}}_0 & \mathbf{0} \\ \mathbf{0} & \tilde{\mathbf{L}}_1 \end{bmatrix} \tag{17}$$

$$\tilde{\mathbf{d}} = \begin{bmatrix} \tilde{\mathbf{d}}_0 \\ \tilde{\mathbf{d}}_1 \end{bmatrix} \tag{18}$$

$_{i=0}$: Baseline

$_{i=1}$: Monitor

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$$\mathbf{C} = \left[\begin{pmatrix} \mathbf{C}_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_1 \end{pmatrix} \begin{pmatrix} \mathbf{I} & \mathbf{\Lambda} \\ \mathbf{\Lambda} & \mathbf{I} \end{pmatrix} \right] \tag{19}$$

$_{i=0}$: Baseline

$_{i=1}$: Monitor

$0 < \Lambda_{kk} < 1$: Diagonal leak-operator

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$$\mathbf{p} = \left[\begin{array}{c} \mathbf{C}_0^{-1}\hat{\mathbf{m}}_\mathbf{0} \\ \mathbf{C}_1^{-1}\hat{\mathbf{m}}_\mathbf{1} \end{array} \right] \tag{20}$$

$_{i=0}$: Baseline
$_{i=1}$: Monitor
$\hat{\mathbf{m}}_\mathbf{0}$: inverted baseline
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Preconditioners

- Spatial: Non-stationary dip-filters [$A^T A$ in Hale(2007)]
  - Dips estimated on *interpretable* baseline image

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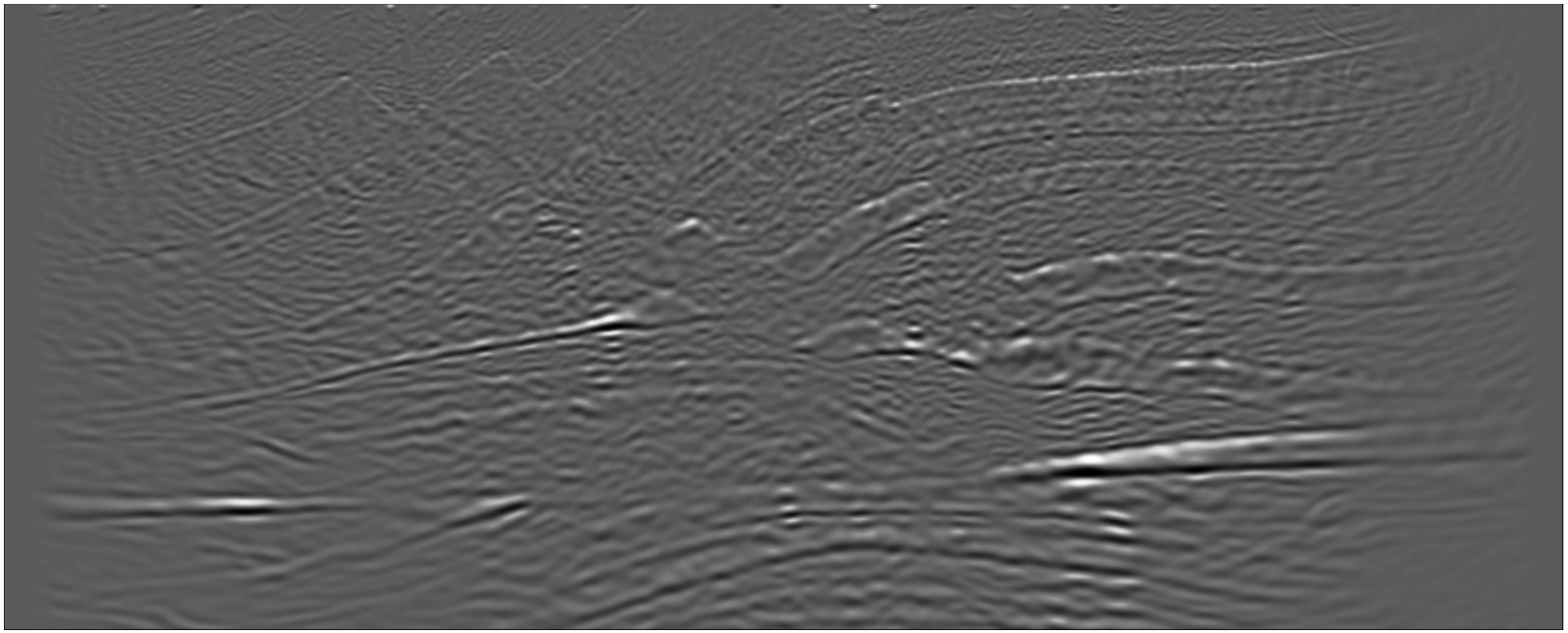

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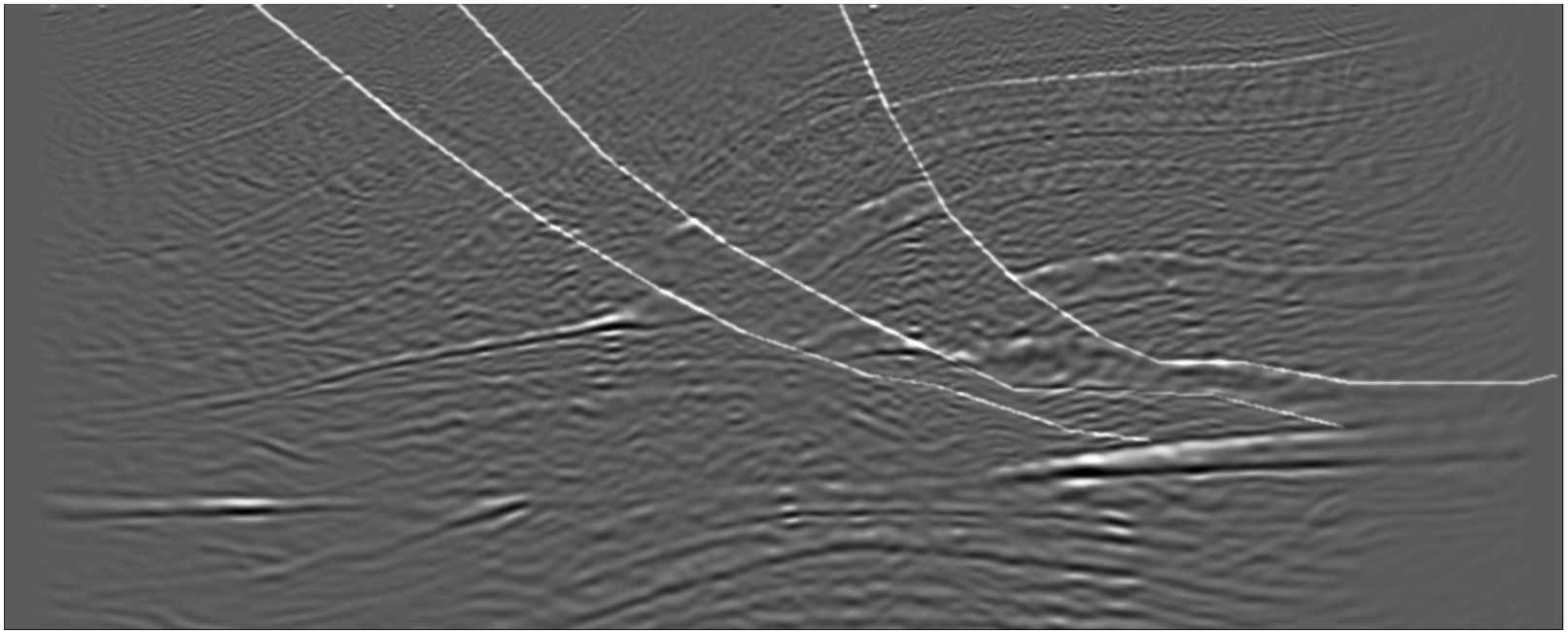

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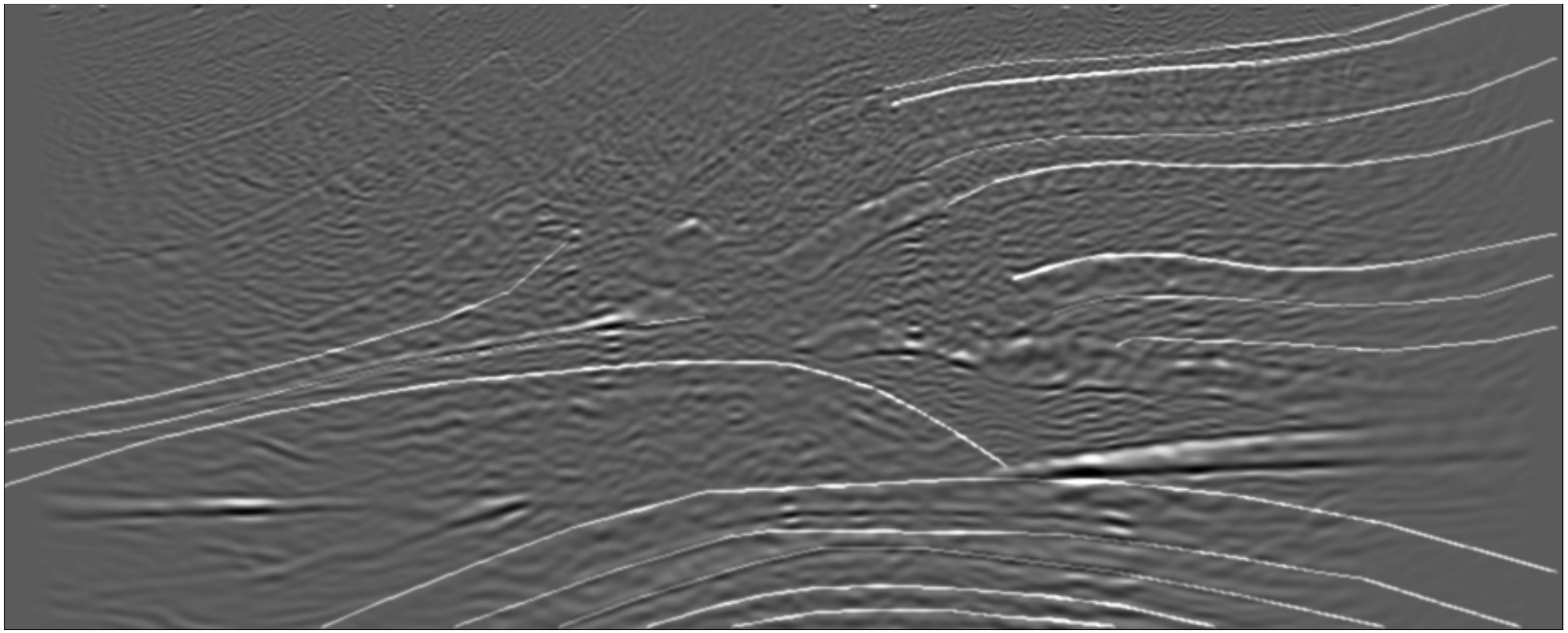

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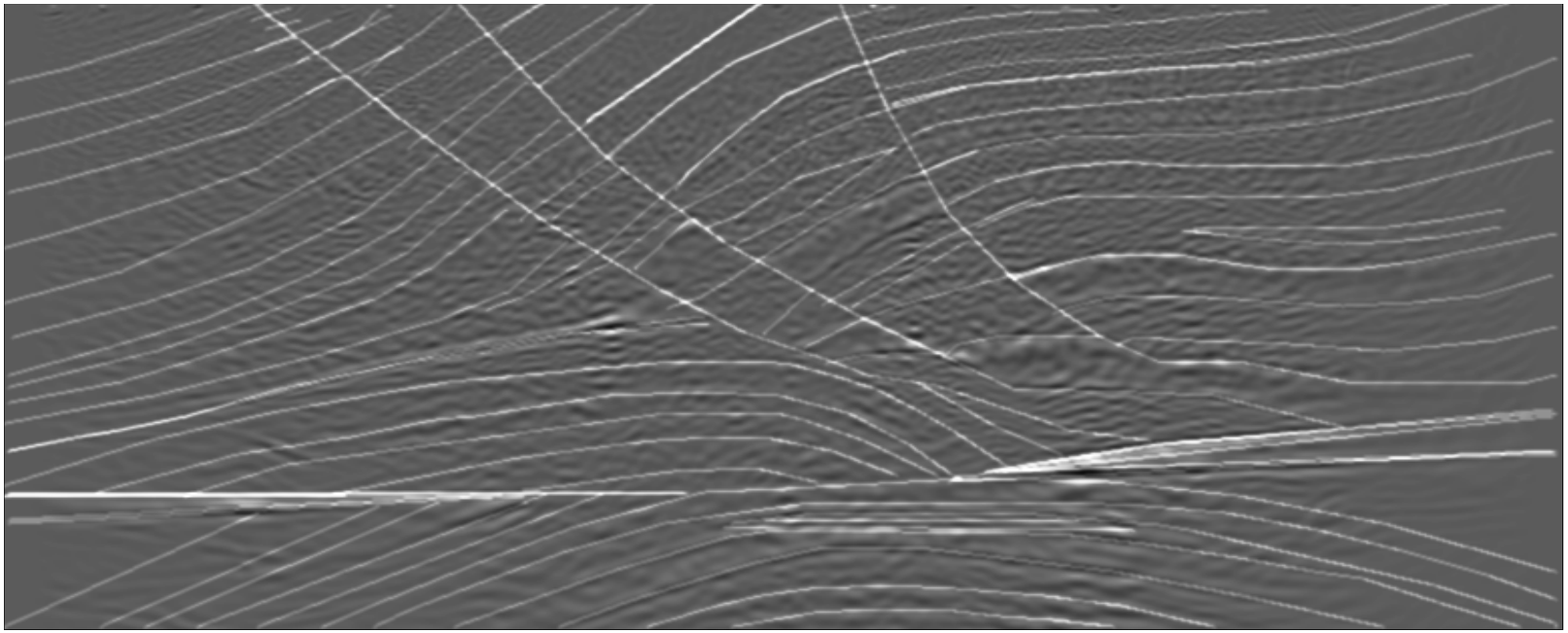

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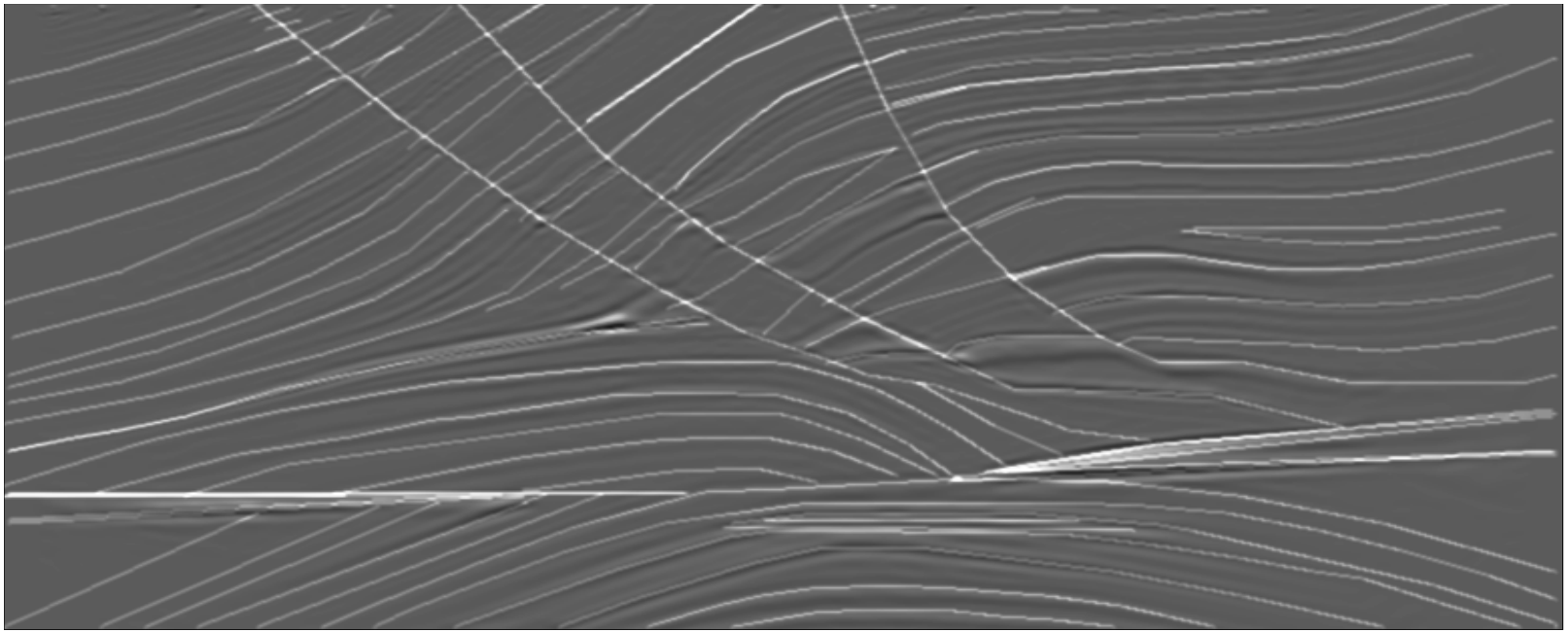

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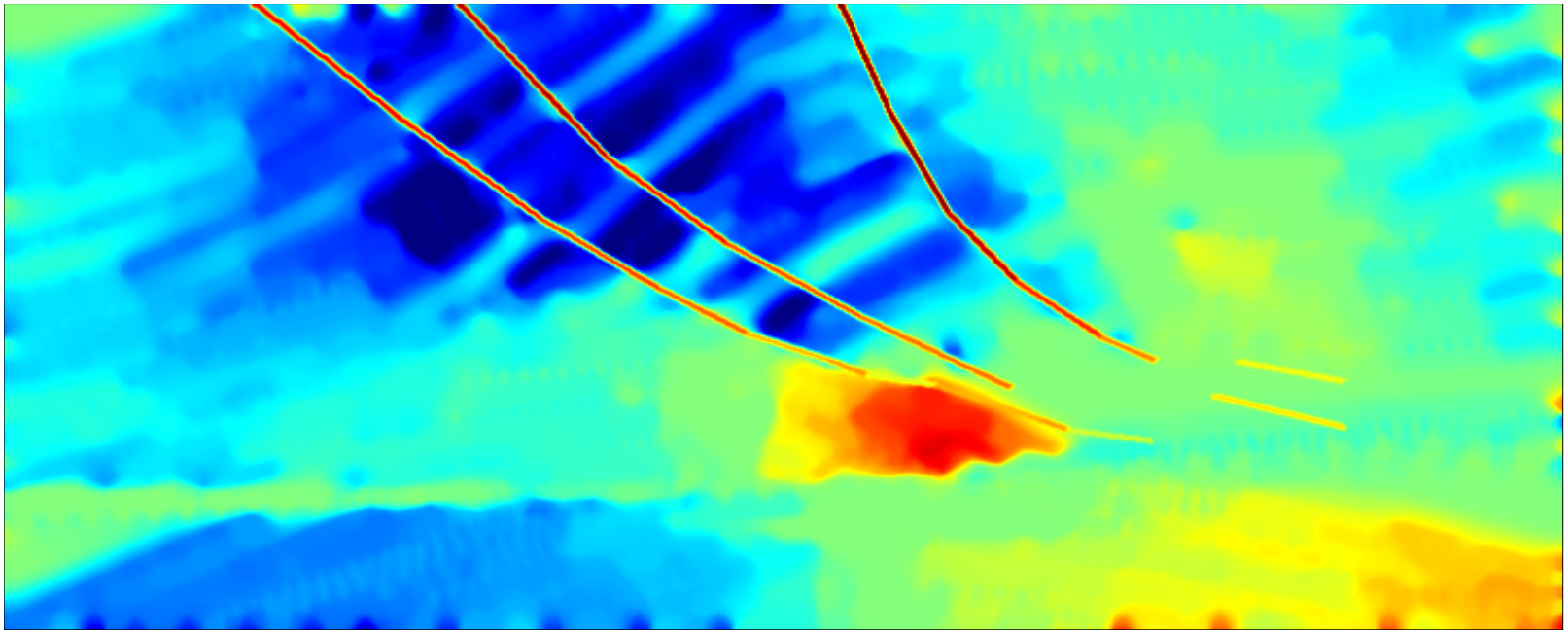

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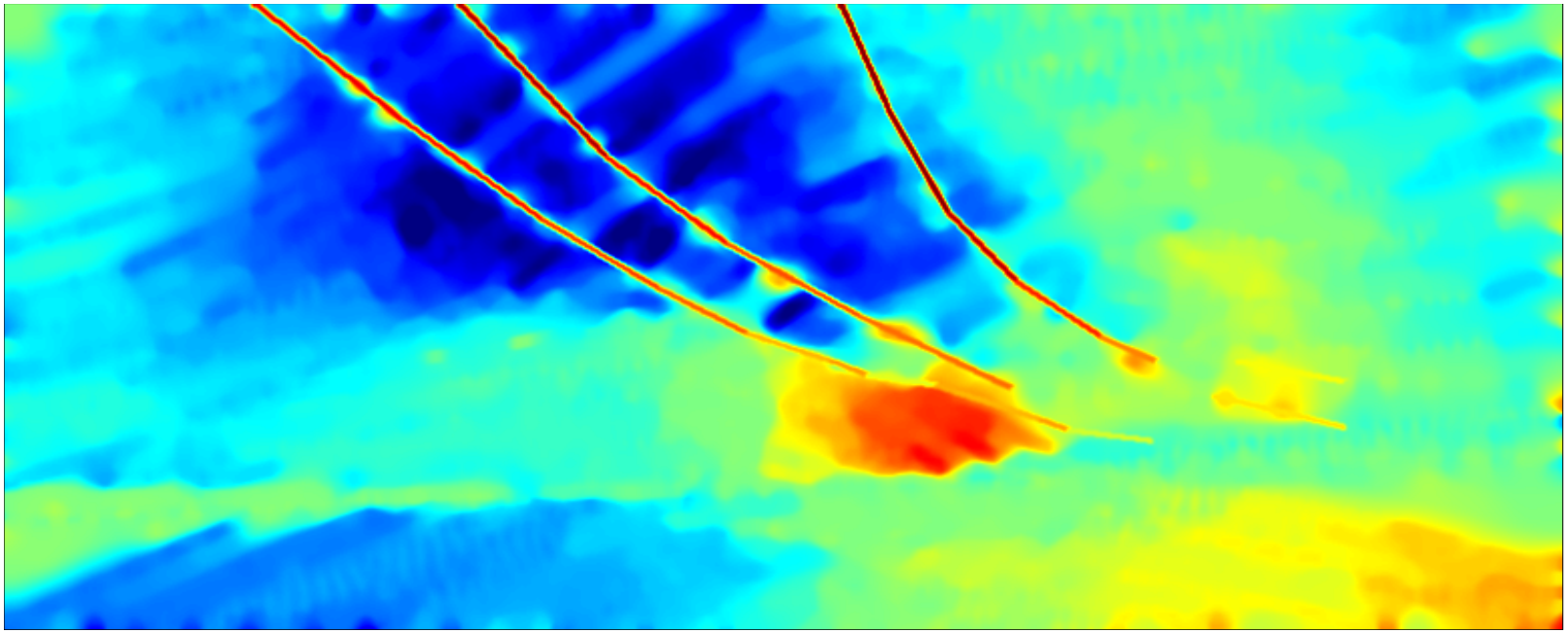

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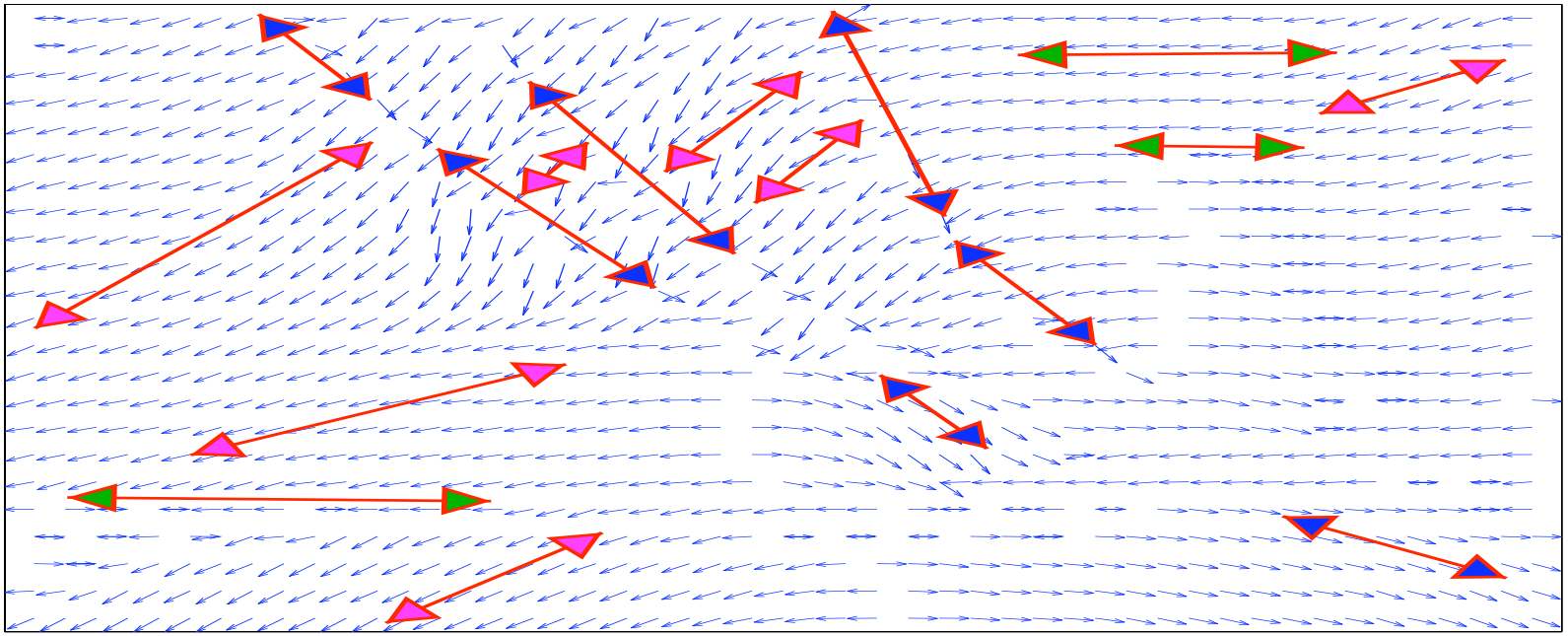

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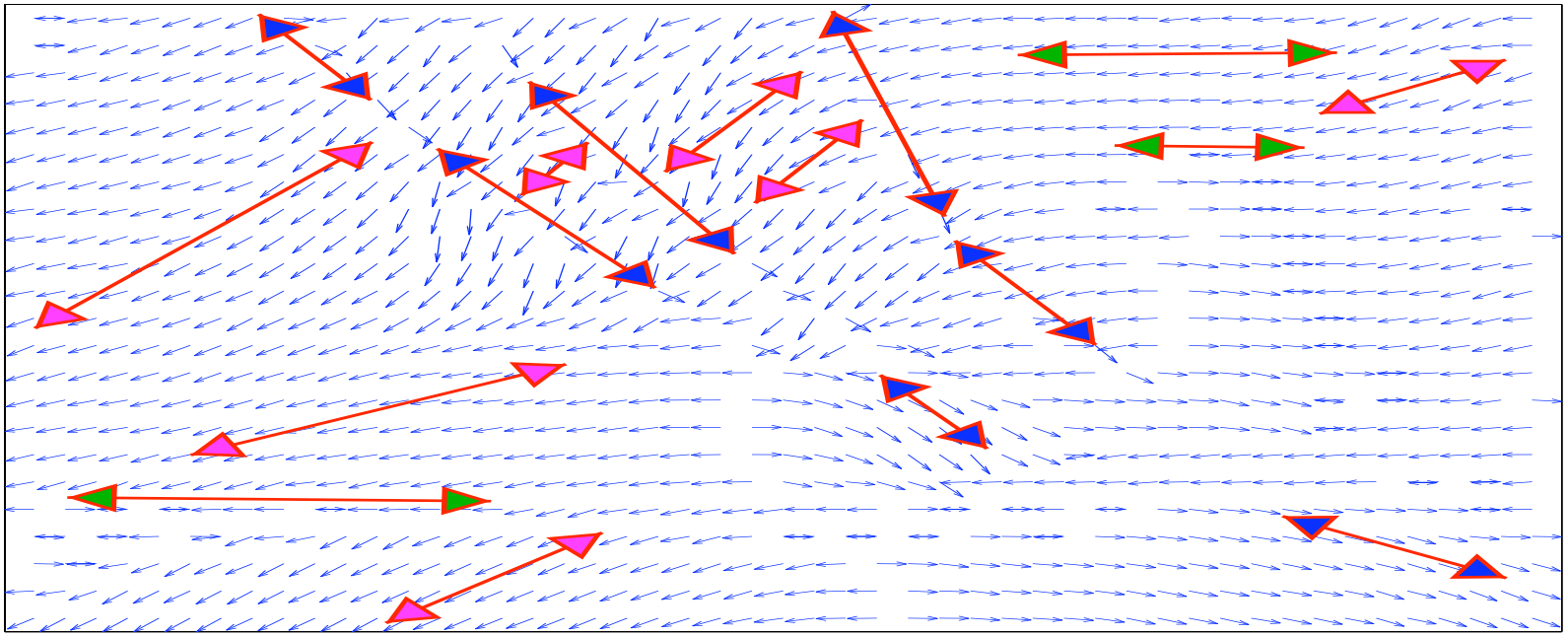

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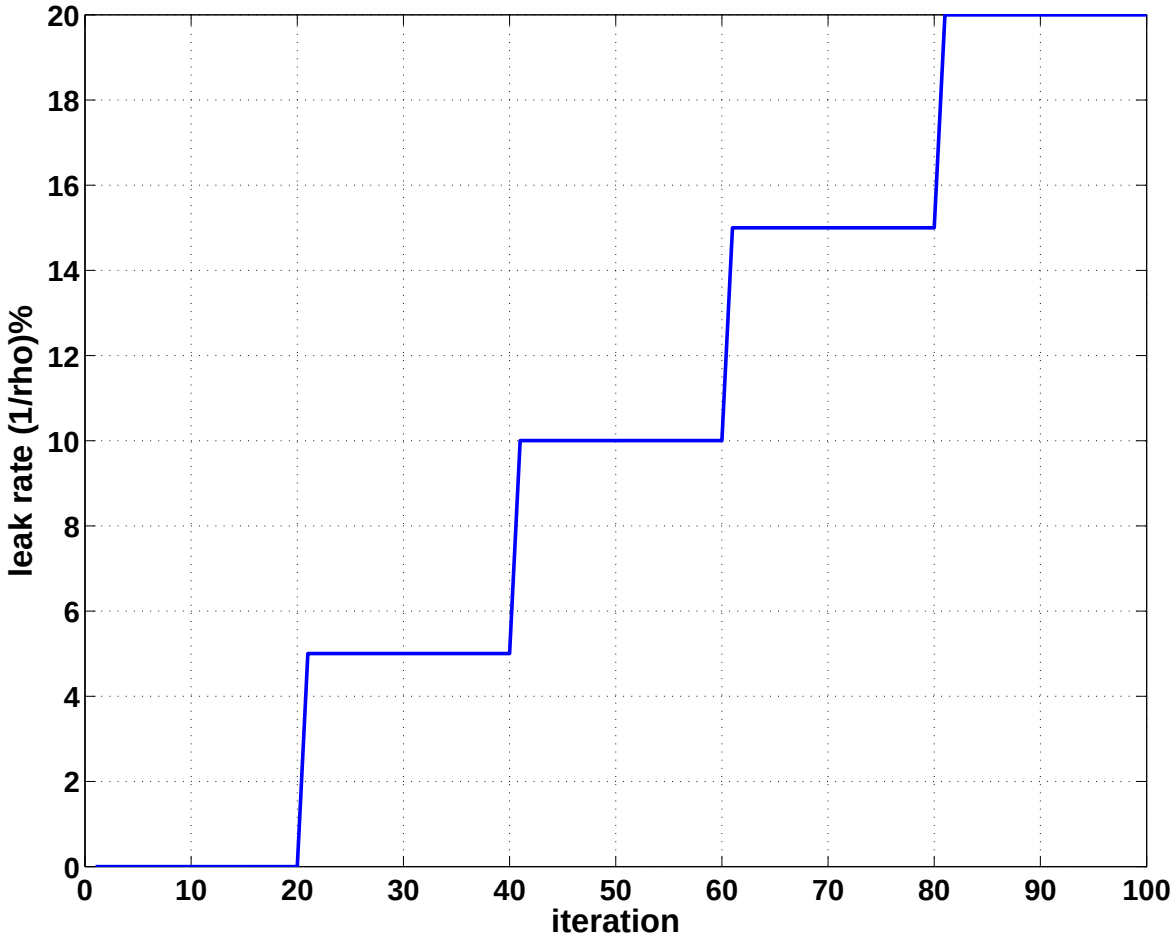
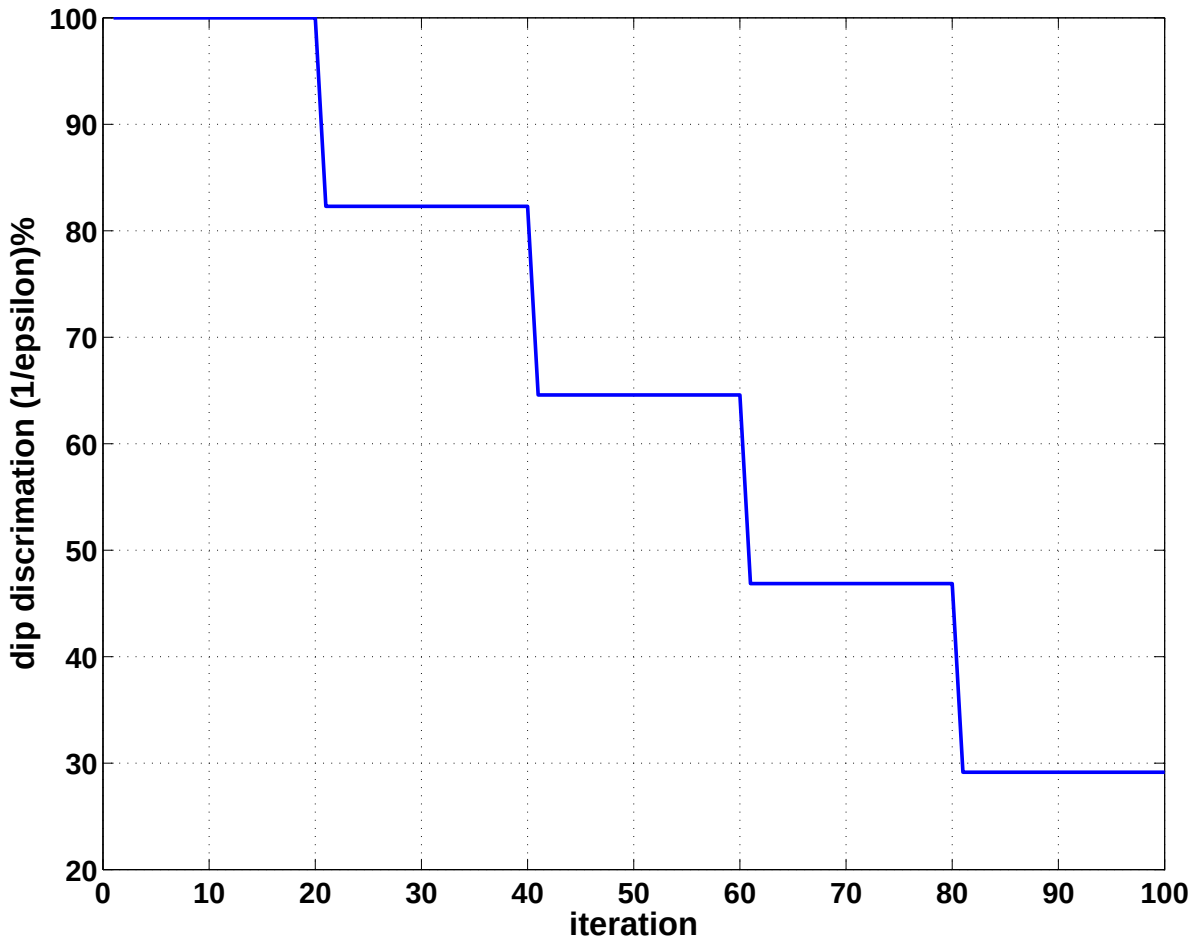
Cascaded preconditioners

Temporal leak rate

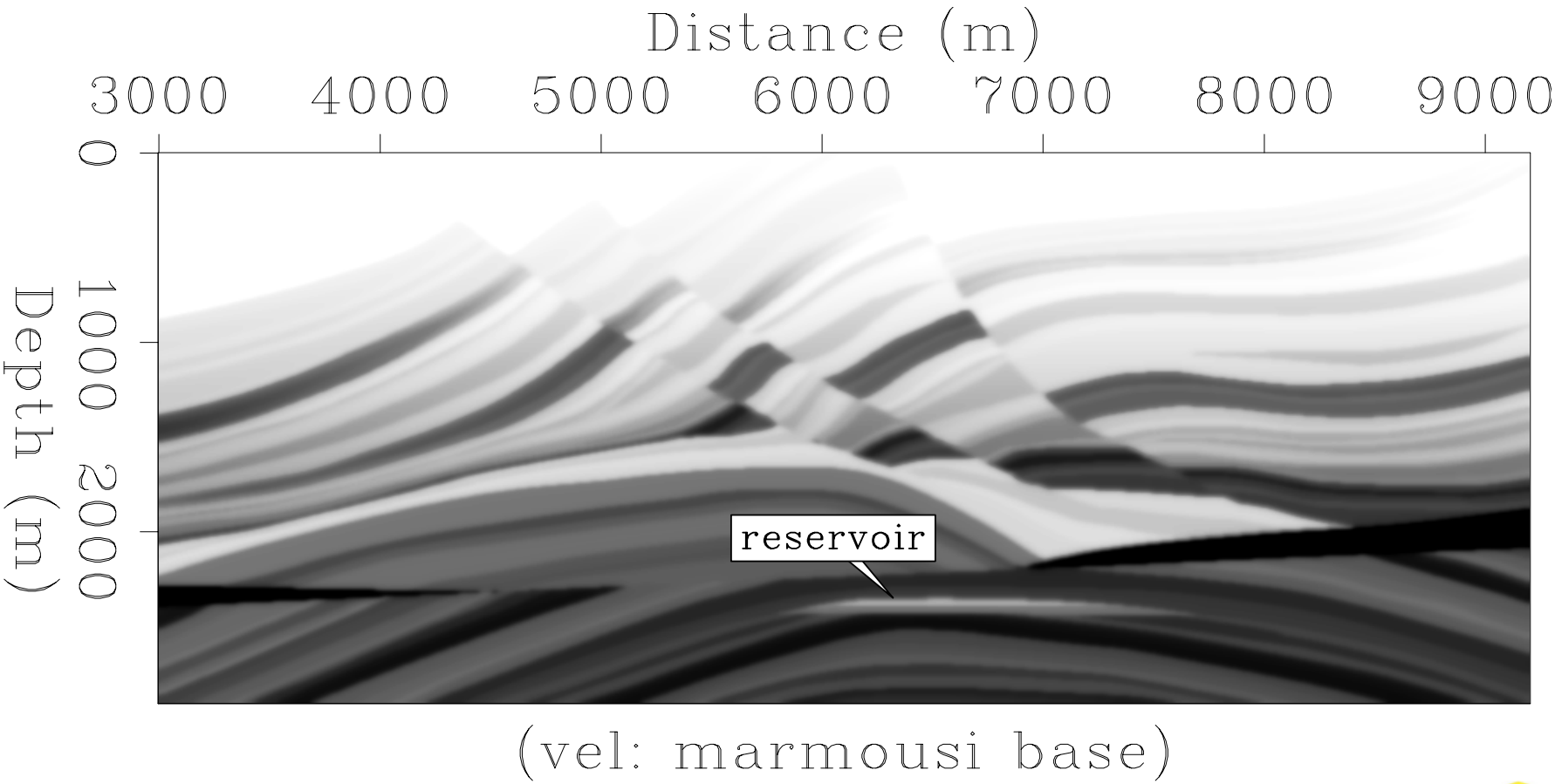


Cascaded preconditioners

Dip discrimination



2D velocity model (Baseline)



2D data summary

Table I: Modeling parameters

	Shots	Receivers
Number	29	776
spacing (m)	80	8

Maximum relative shot-time delay: 1.0 s
Maximum shot-displacement: 32 m
Model grid-size: 8x8 m

All shots encoded

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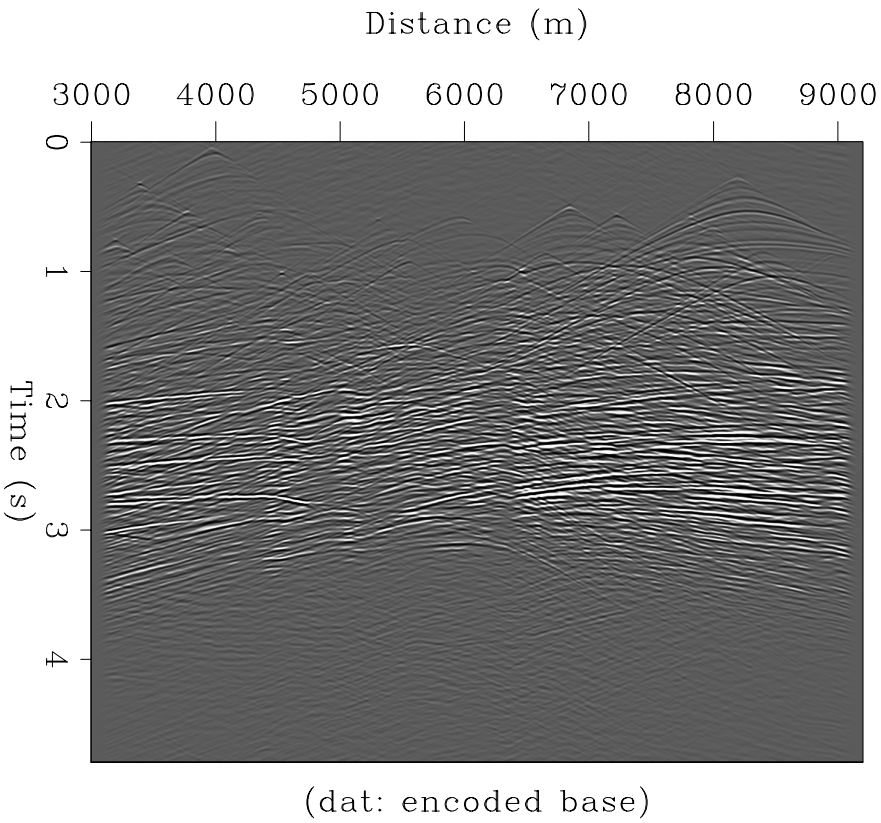
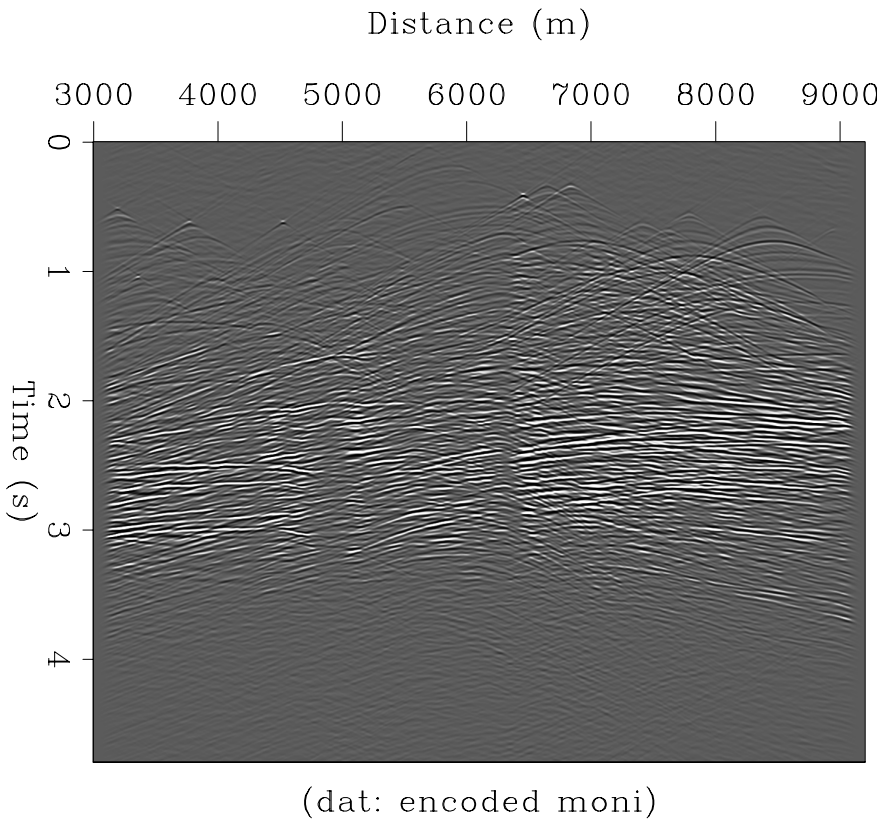
Encoded baseline (left) and monitor (right) encoded data

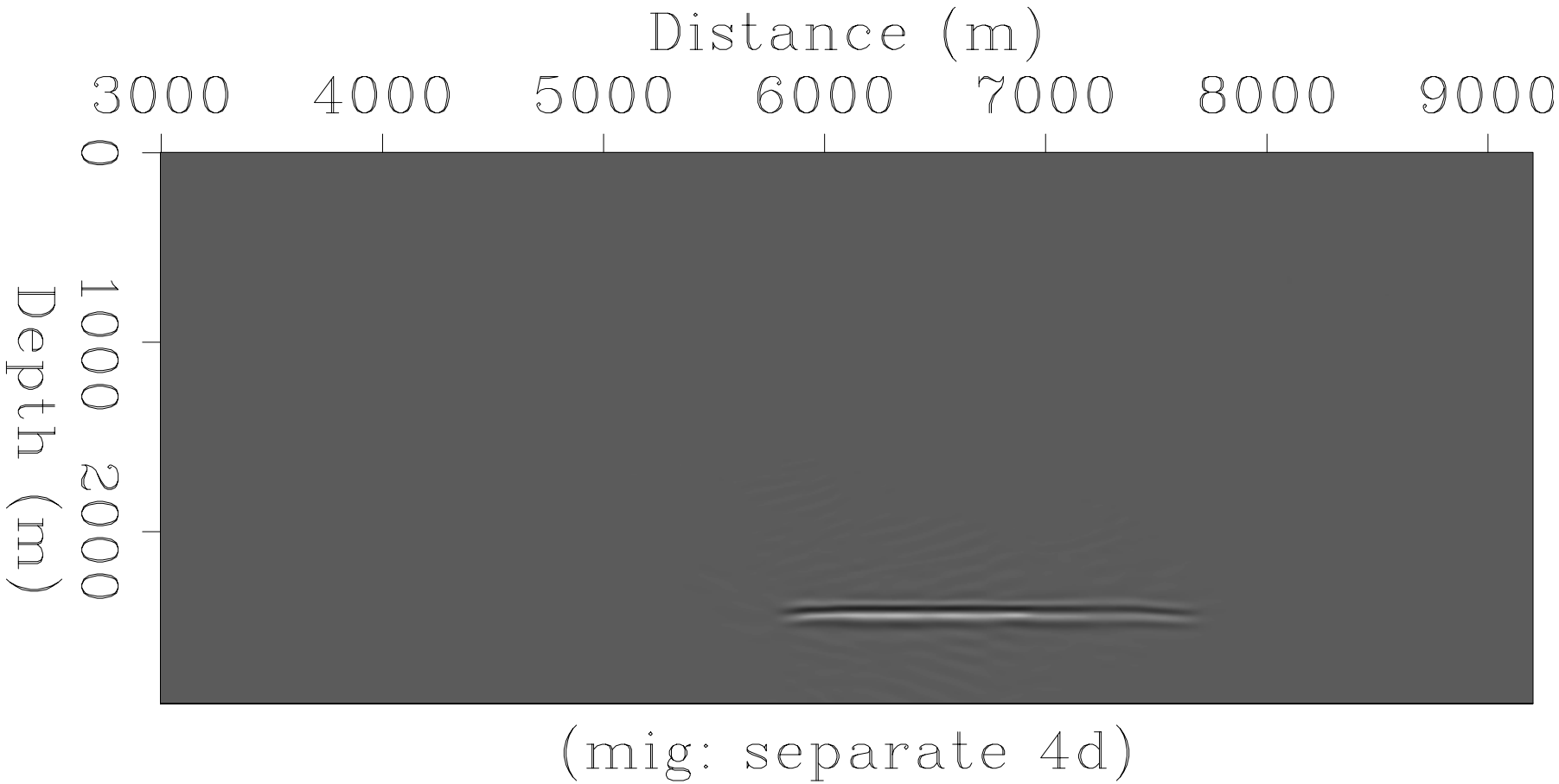


(dat: encoded base)

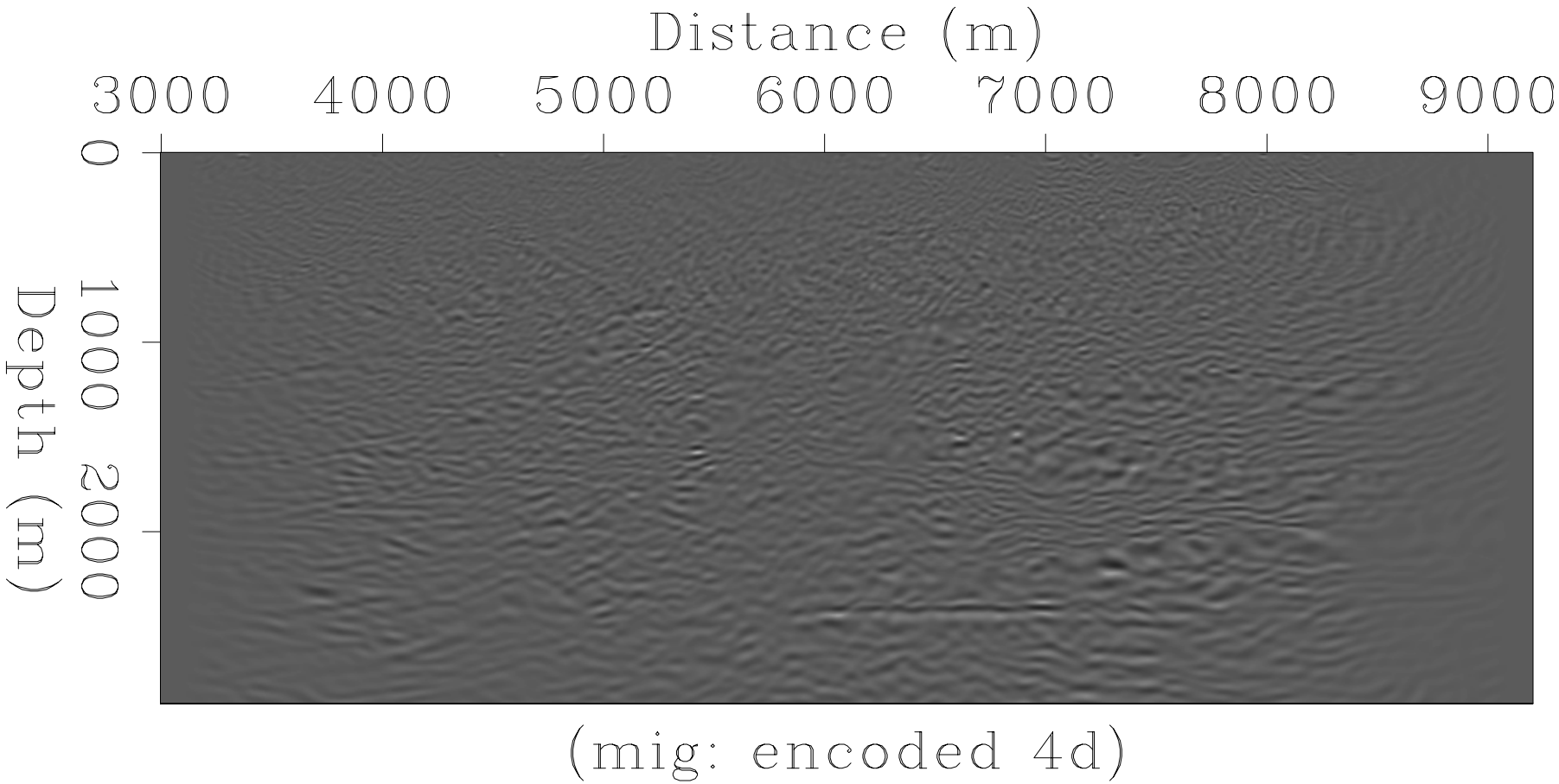


(dat: encoded moni)

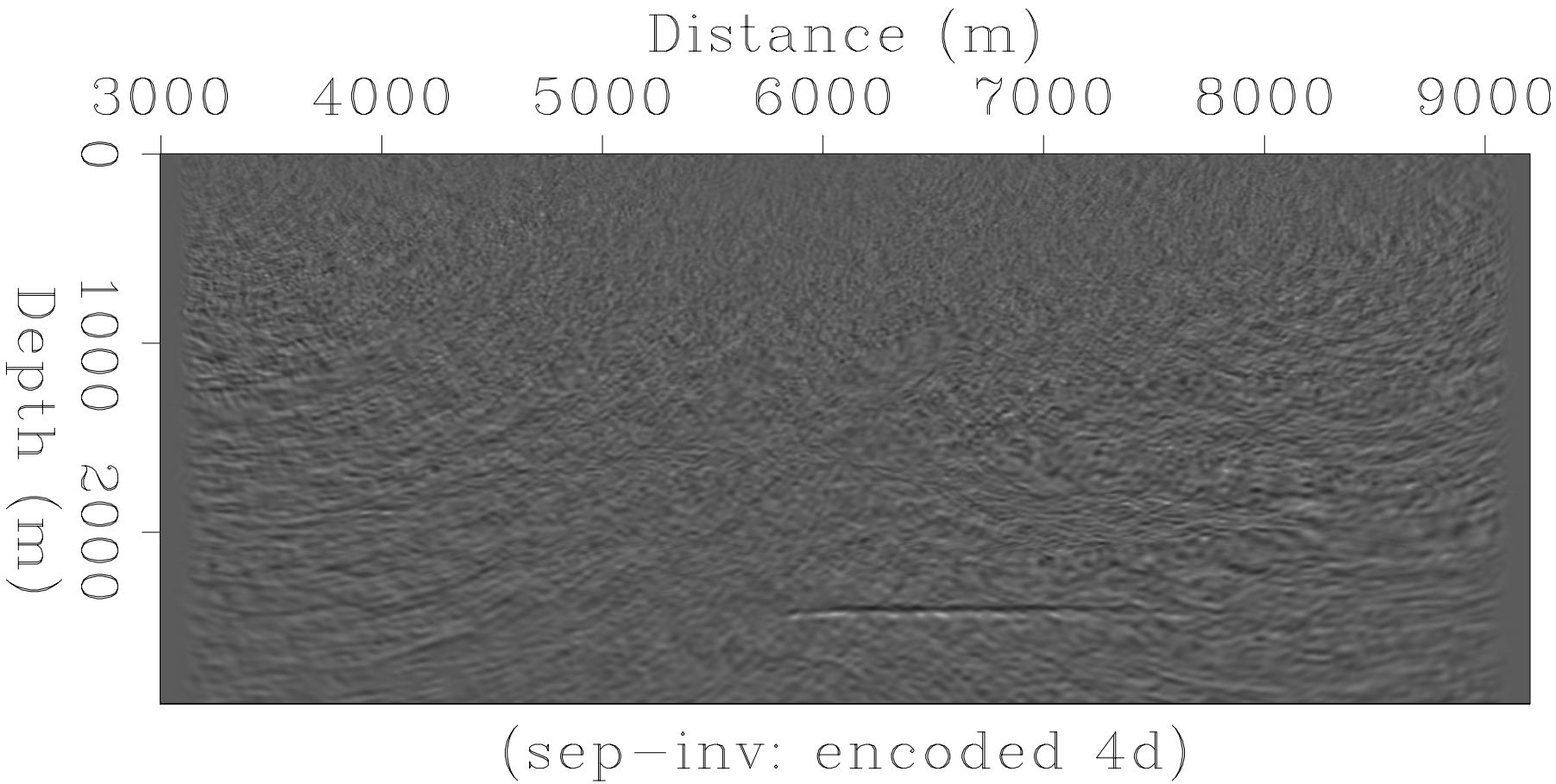
4D amplitude change: migration (separate sources)



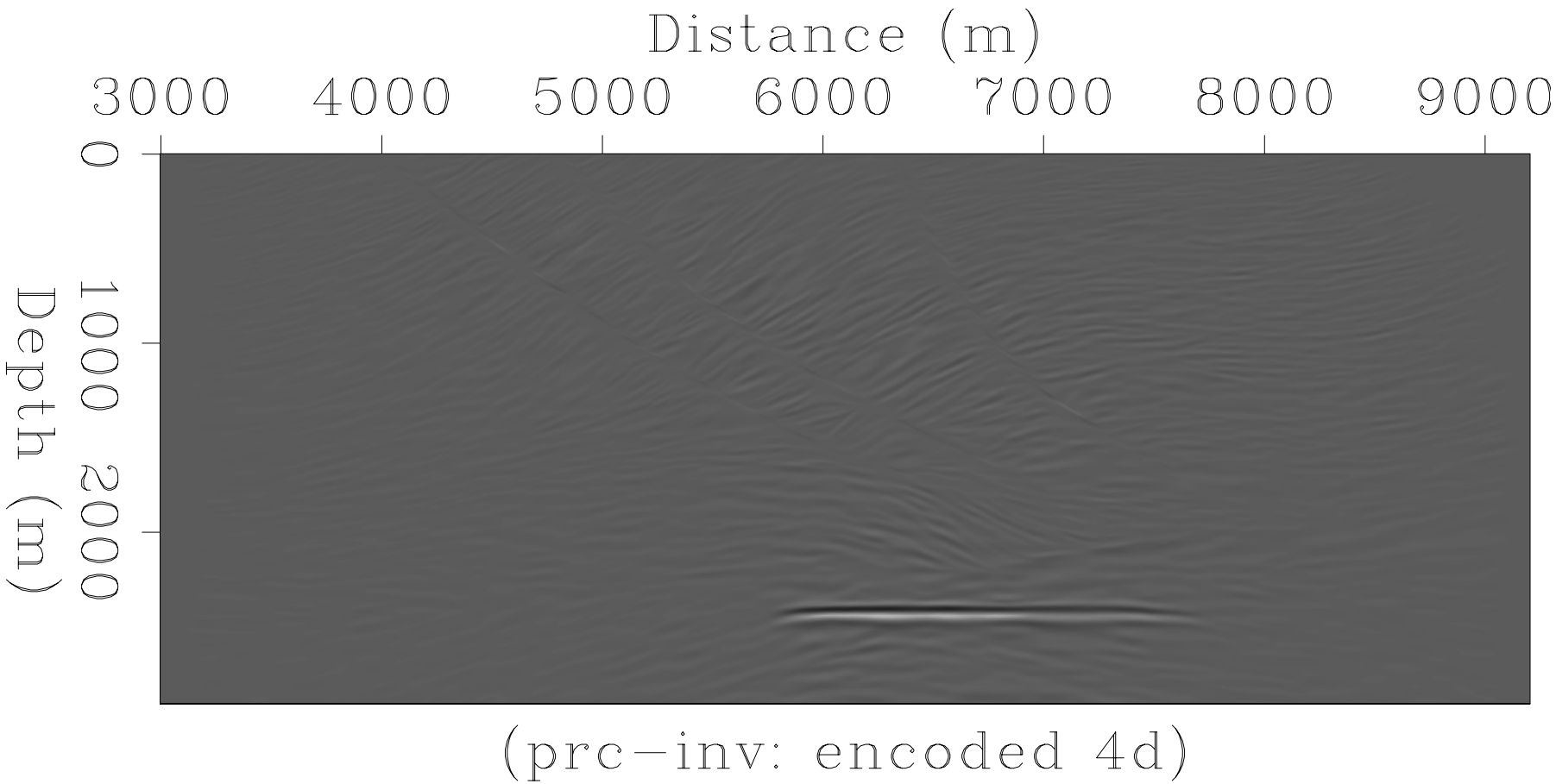
4D amplitude change: migration (simultaneous sources)



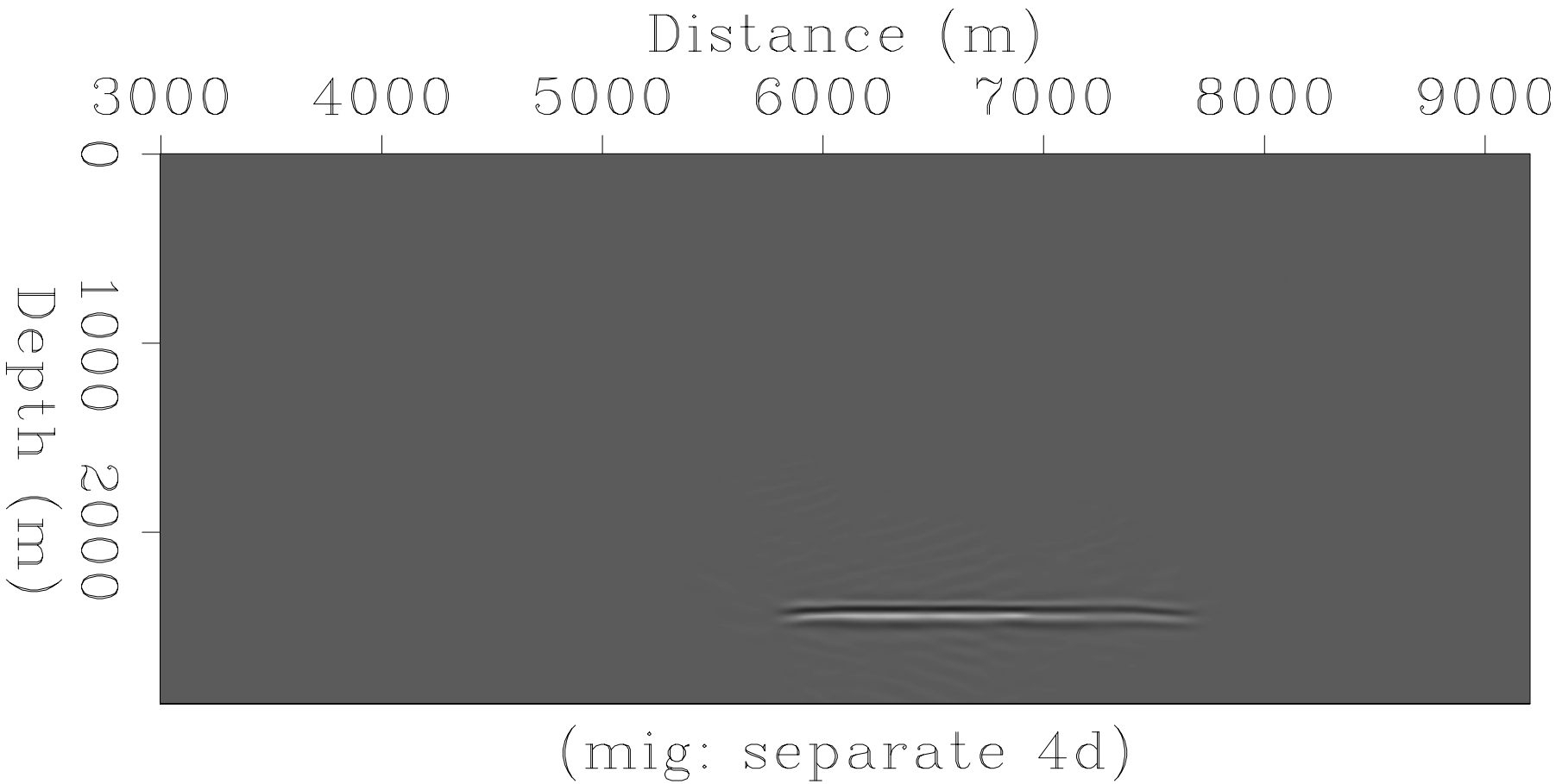
4D amplitude change: separate inversion



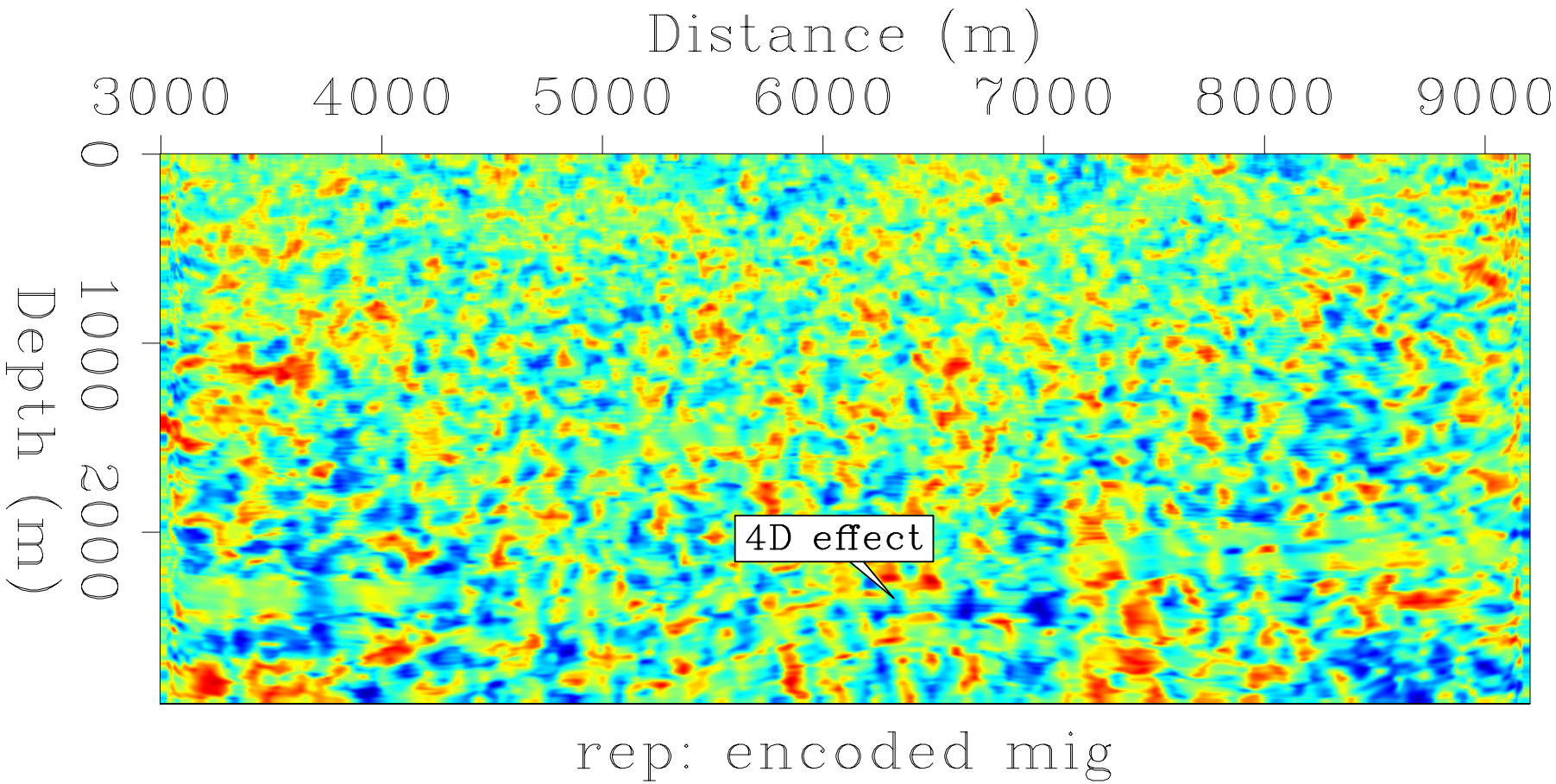
4D amplitude change: J-PLSI



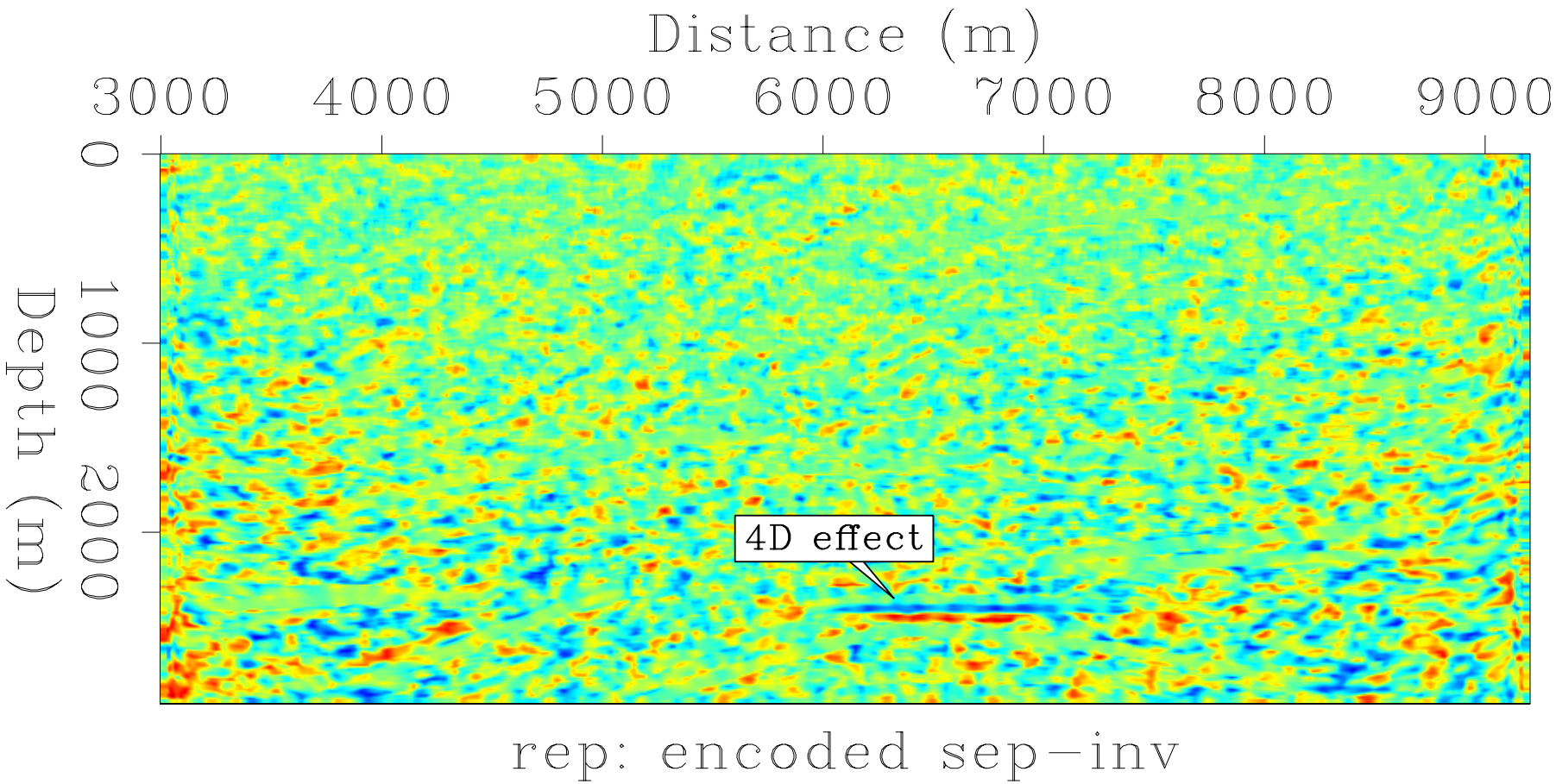
4D amplitude change: separate sources



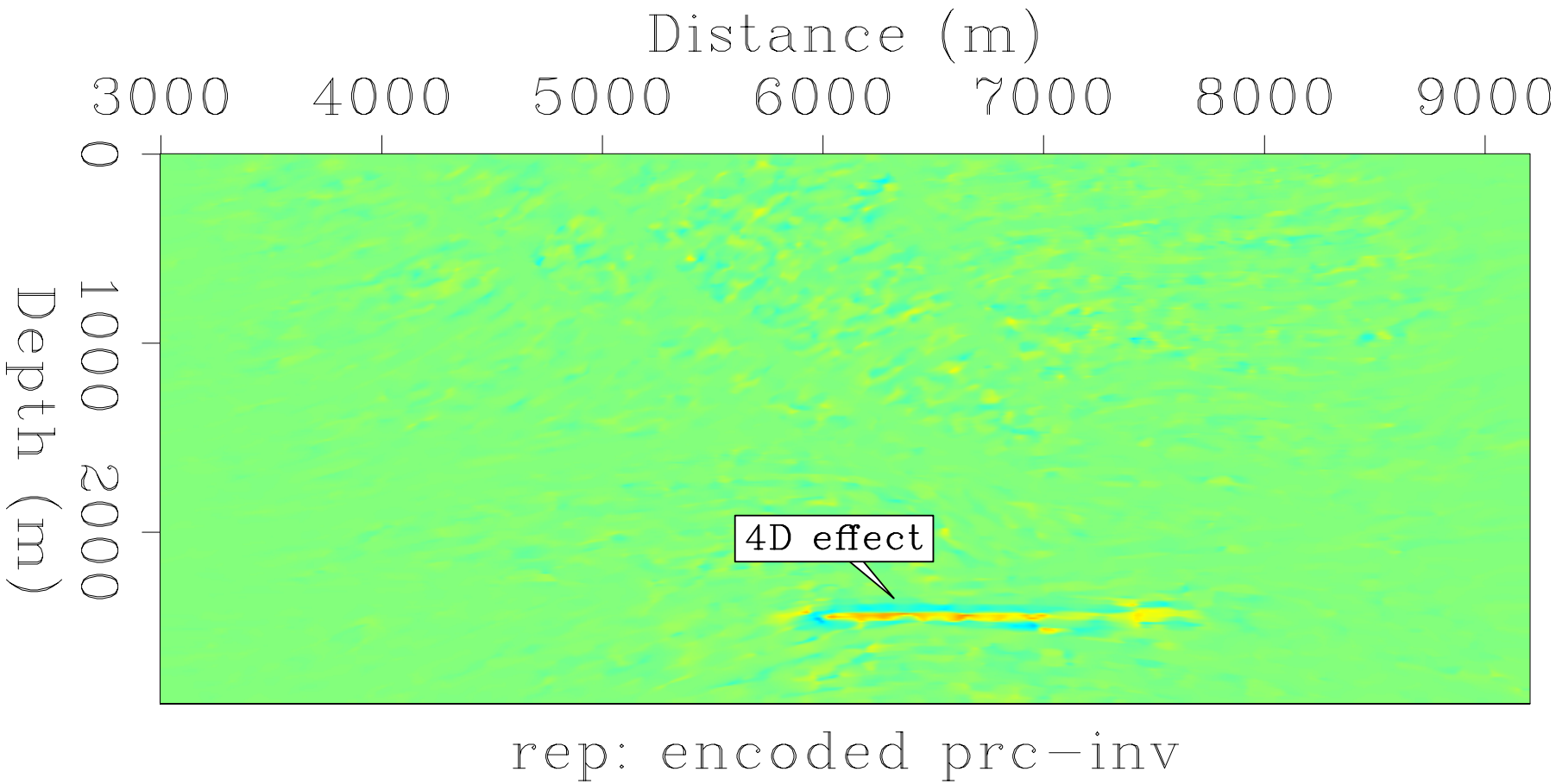
Repeatability (WRMS): migration (simultaneous sources)



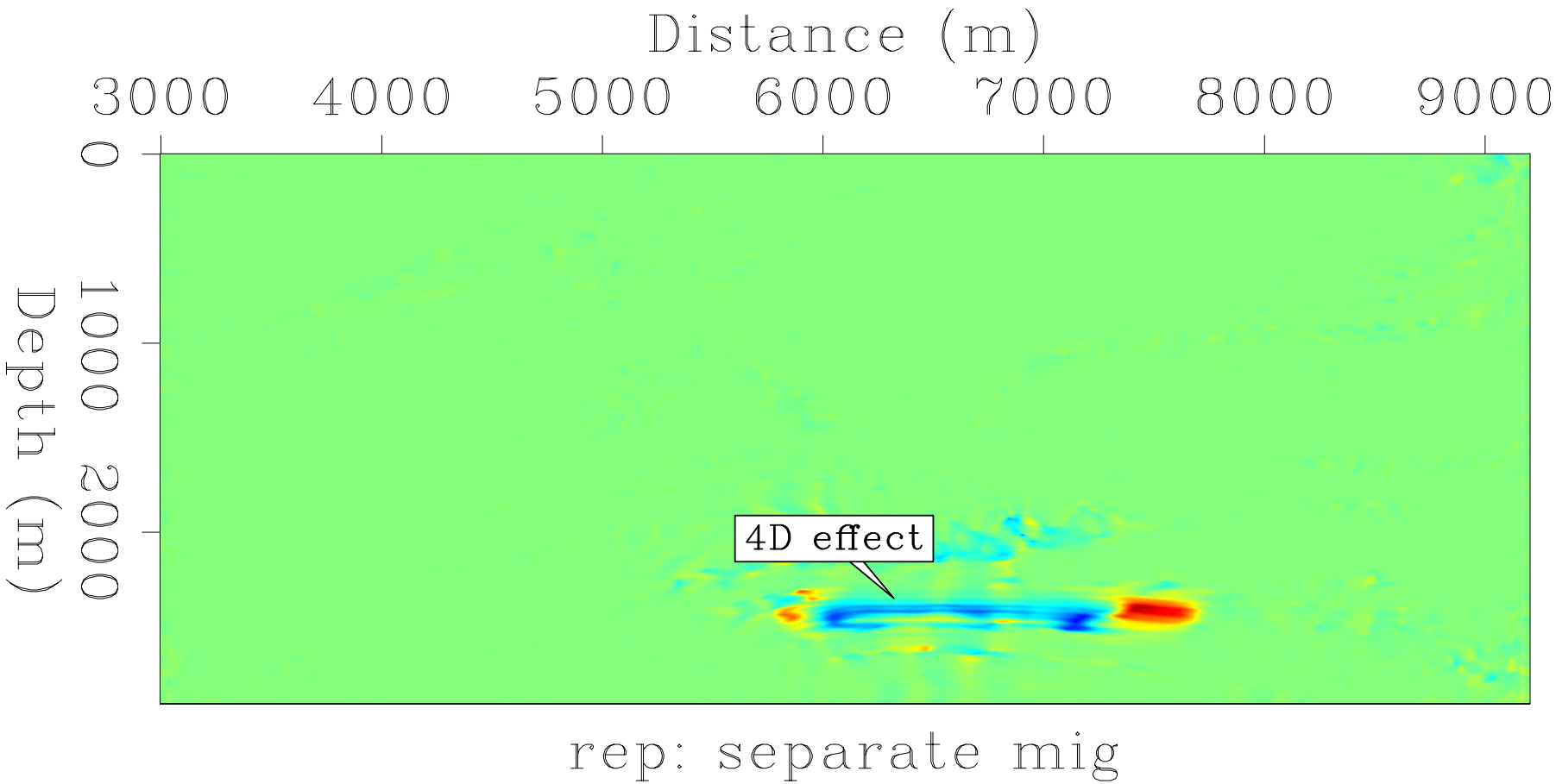
Repeatability (WRMS): separate inversion



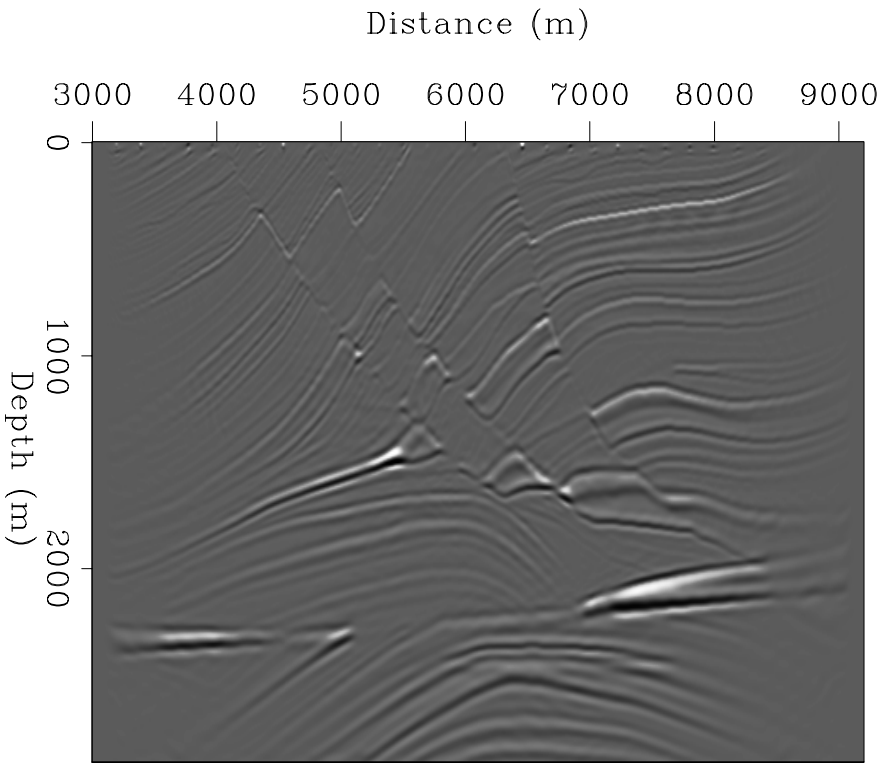
Repeatability (WRMS): J-PLSI



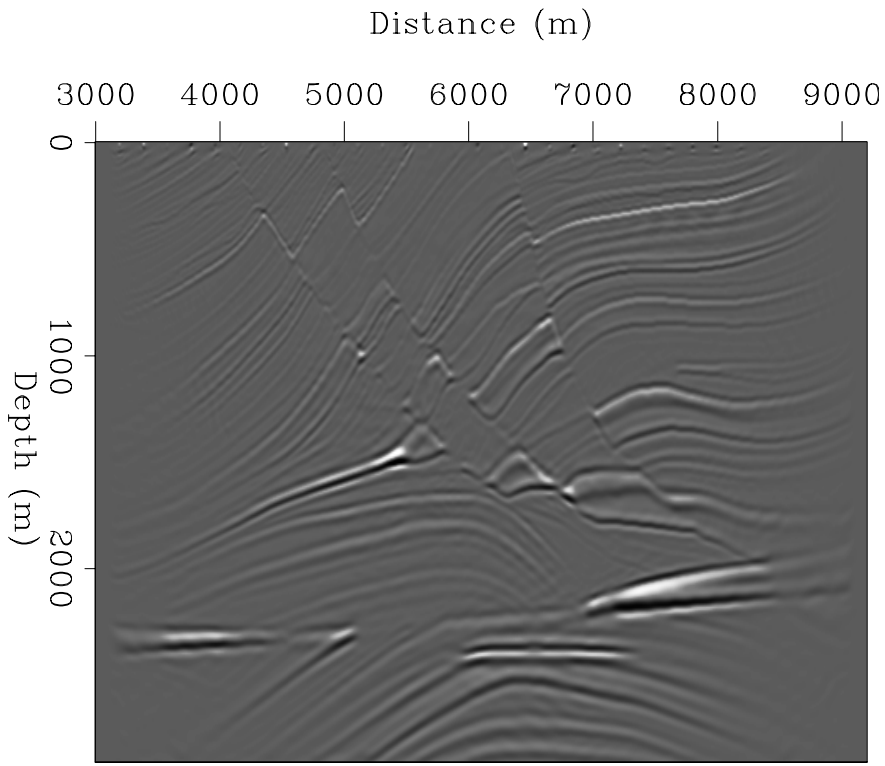
Repeatability (WRMS): migration (separate sources)



Baseline and monitor: migration (separate sources)

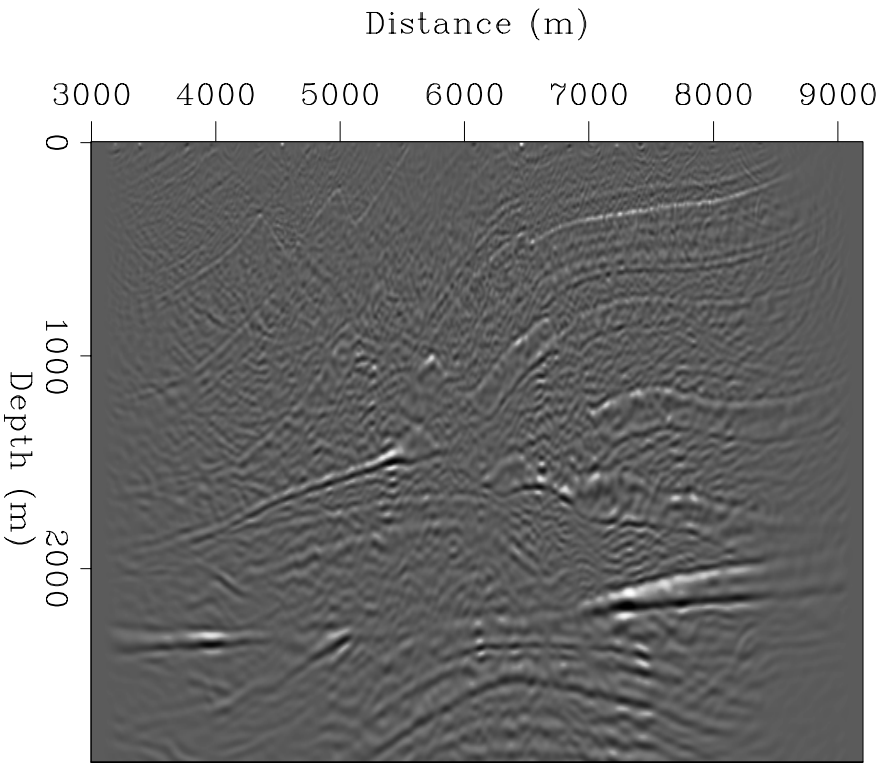


(mig: separate base)

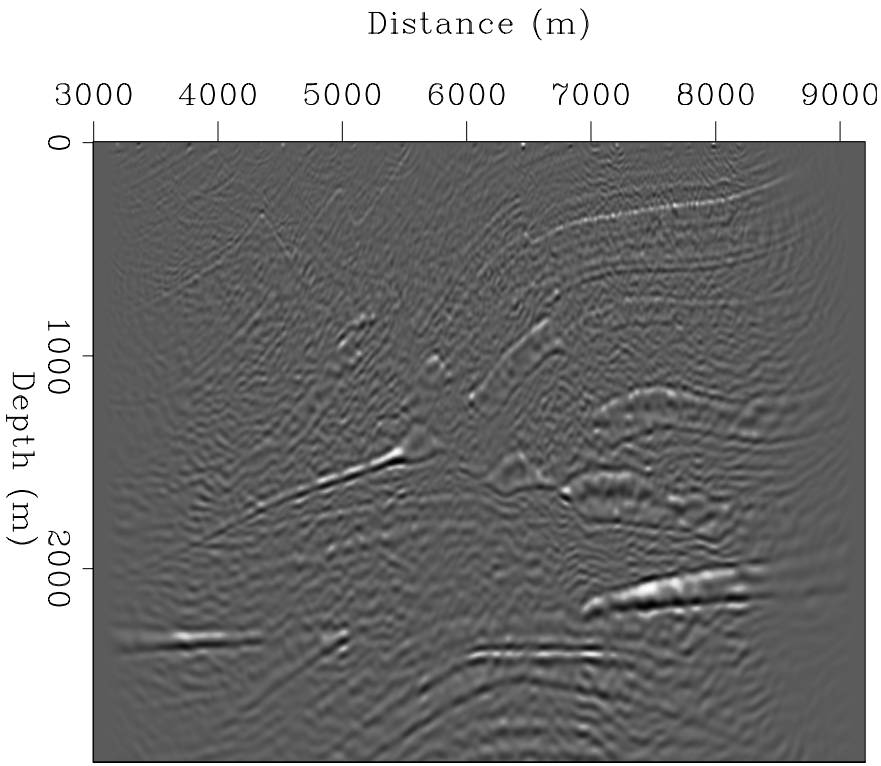


(mig: separate moni)

Baseline and monitor: migration (simultaneous sources)

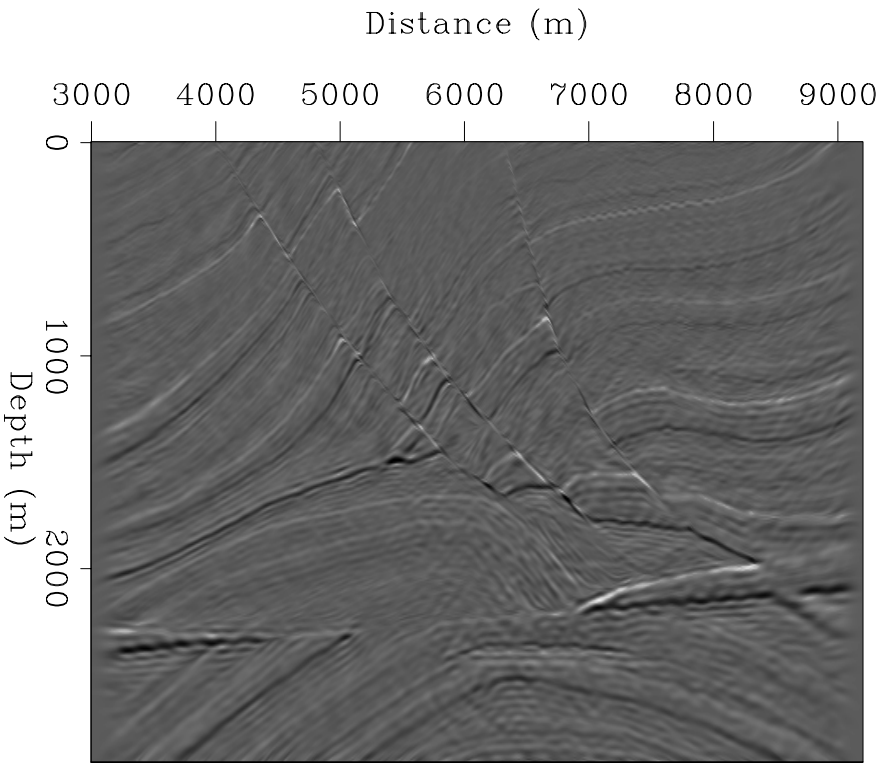


(mig: encoded base)

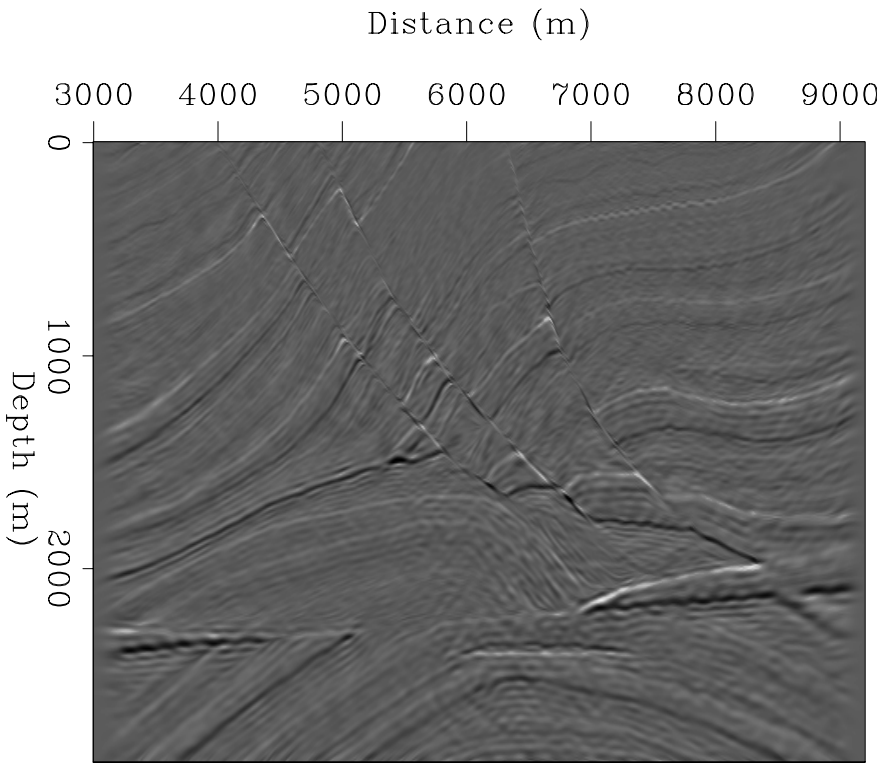


(mig: encoded moni)

Baseline and monitor: J-PLSI

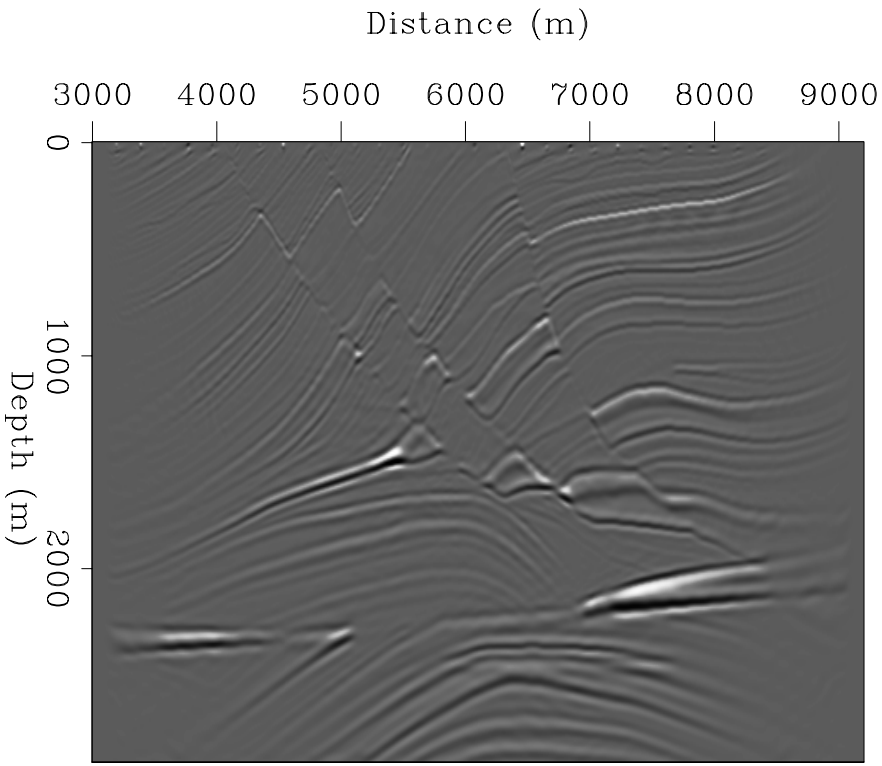


(prc−inv: encoded base)

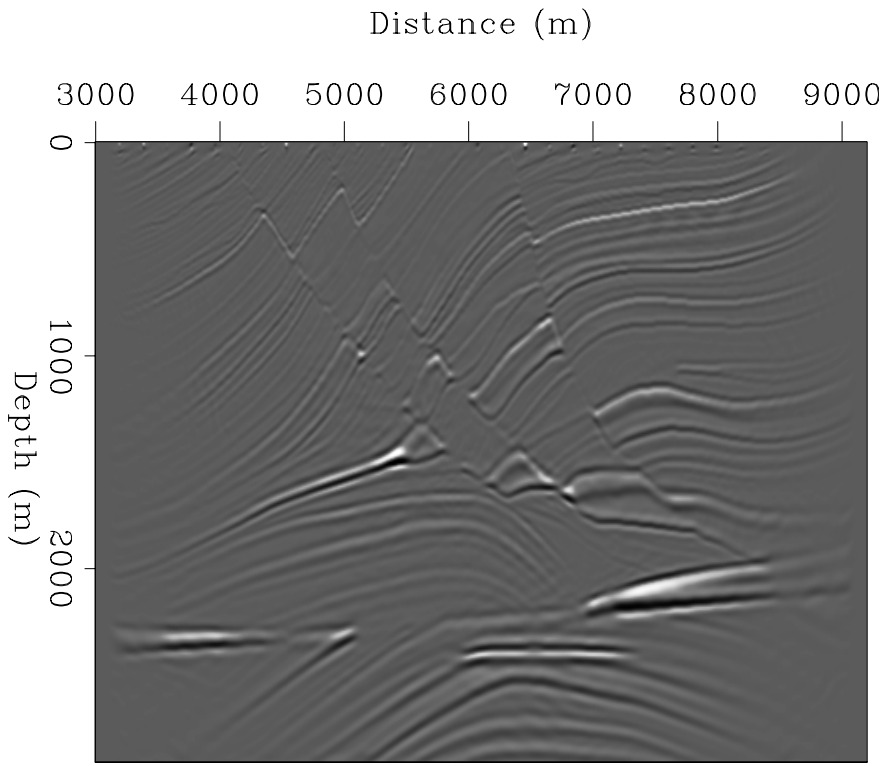


(prc−inv: encoded moni)

Baseline and monitor: migration (separate sources)



(mig: separate base)



(mig: separate moni)

Conclusions

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Acknowledgments

- Thanks to Bob Clapp for useful suggestions

Thanks for your attention

Questions?

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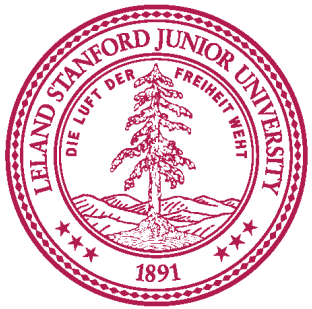
Joint-inversion of simultaneous-source time-lapse seismic data

G. Ayeni, Y. Tang & B. Biondi

SEP138: pgs.157-170



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