Seismic reservoir monitoring with simultaneous sources

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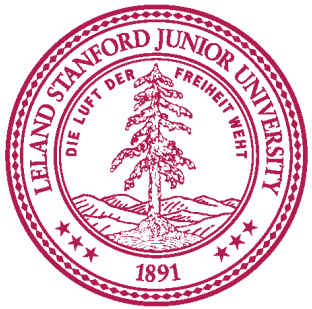
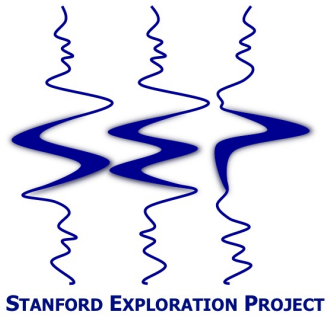
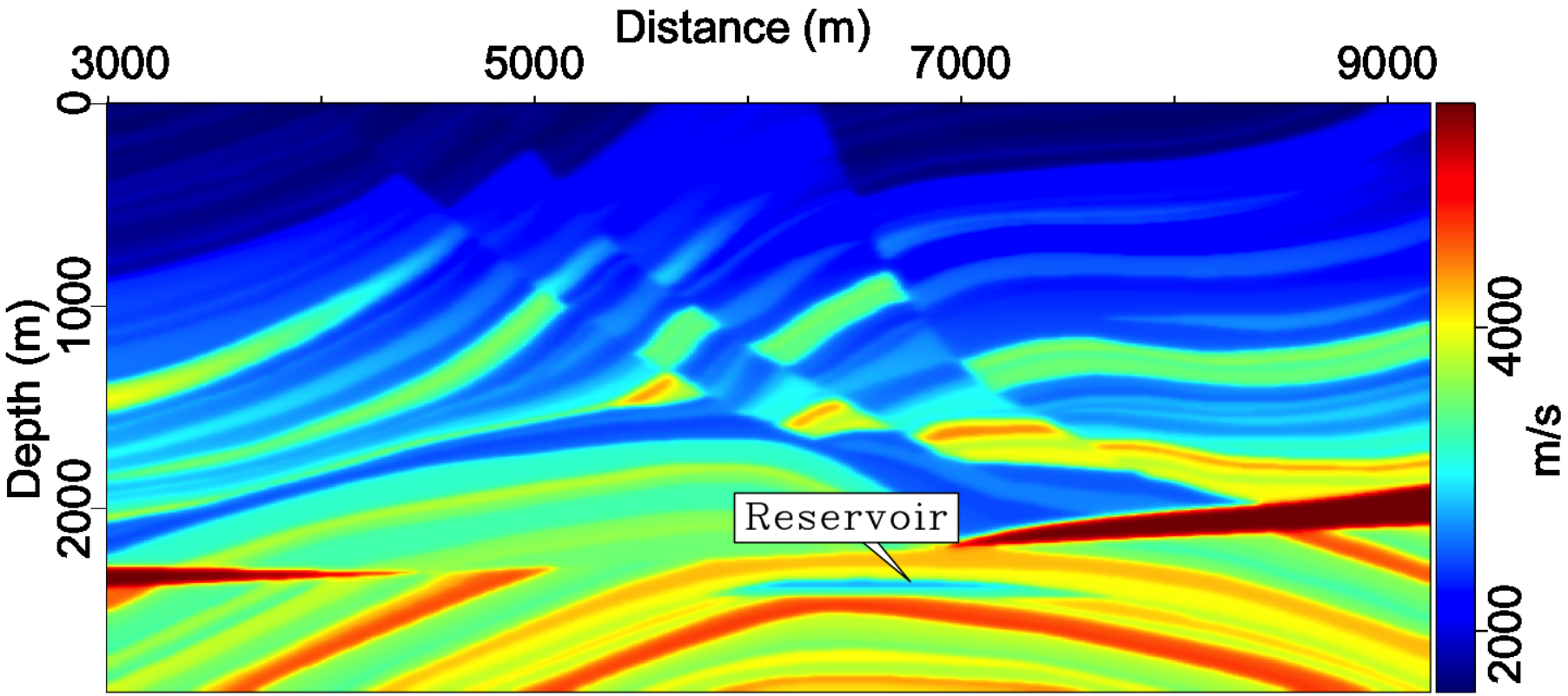


SEP Annual Meeting
May 26, 2010
(SEP140: Pg 165-180)

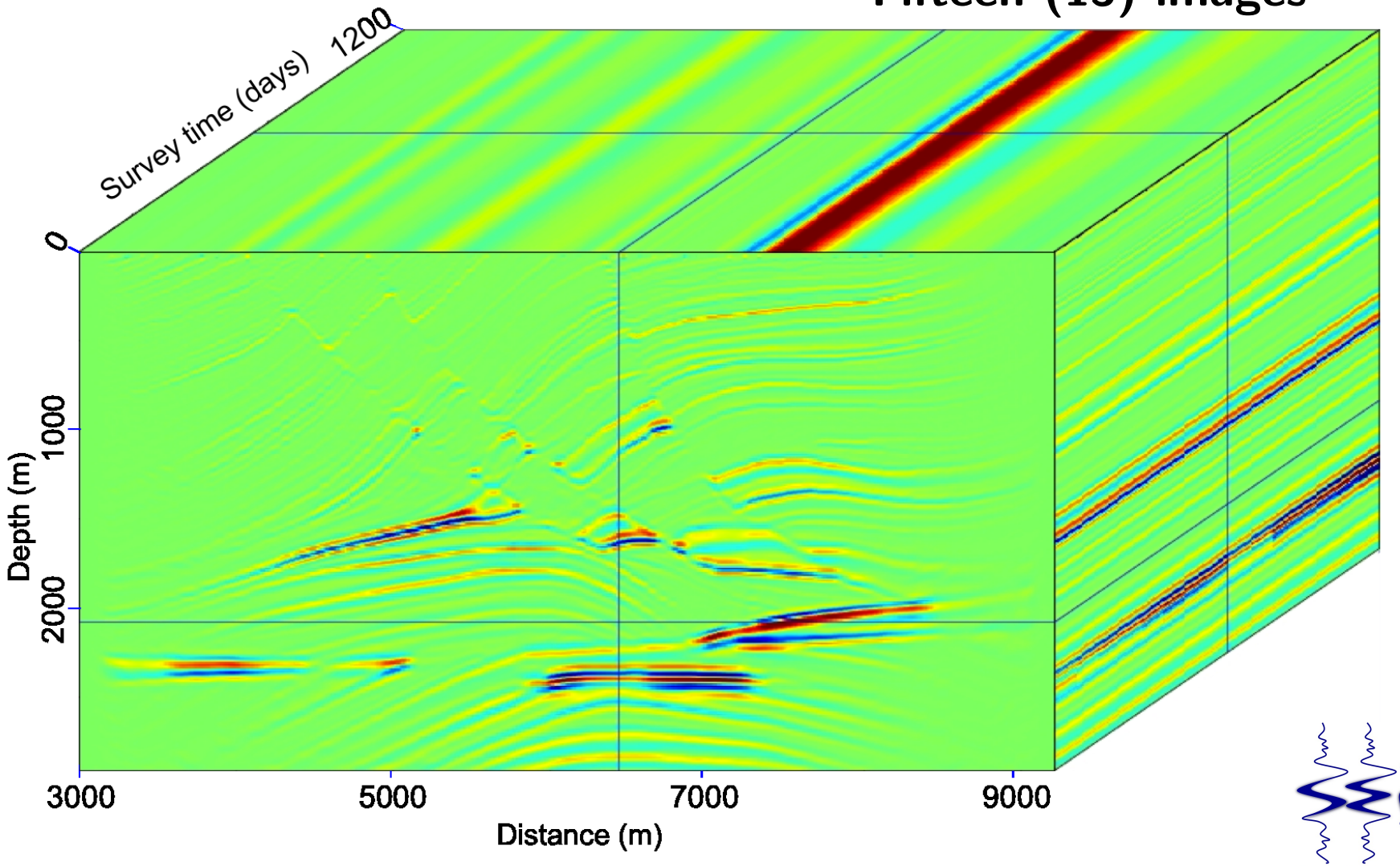


Numerical Model



Seismic image volume: Migration

Fifteen (15) images



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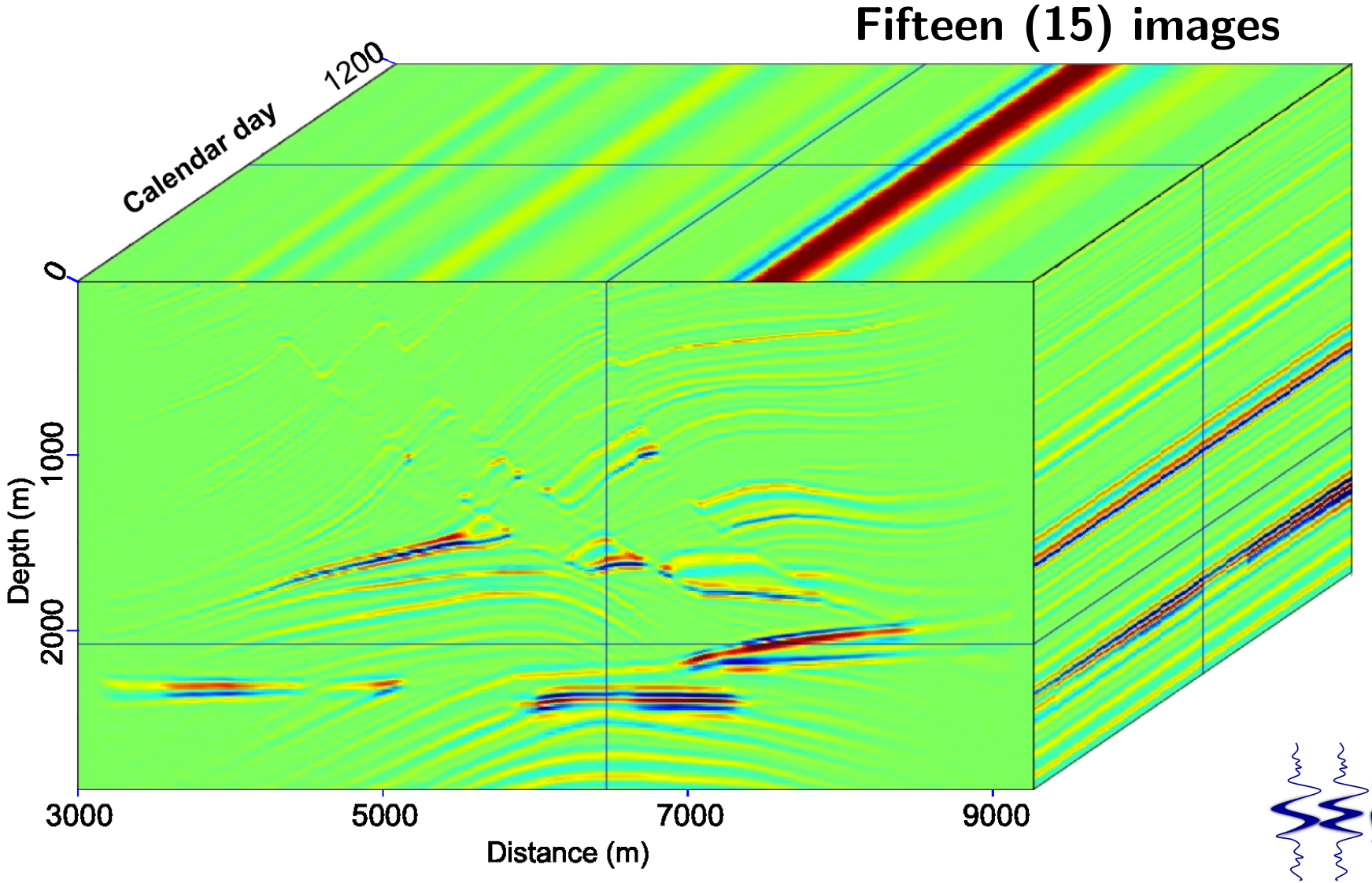
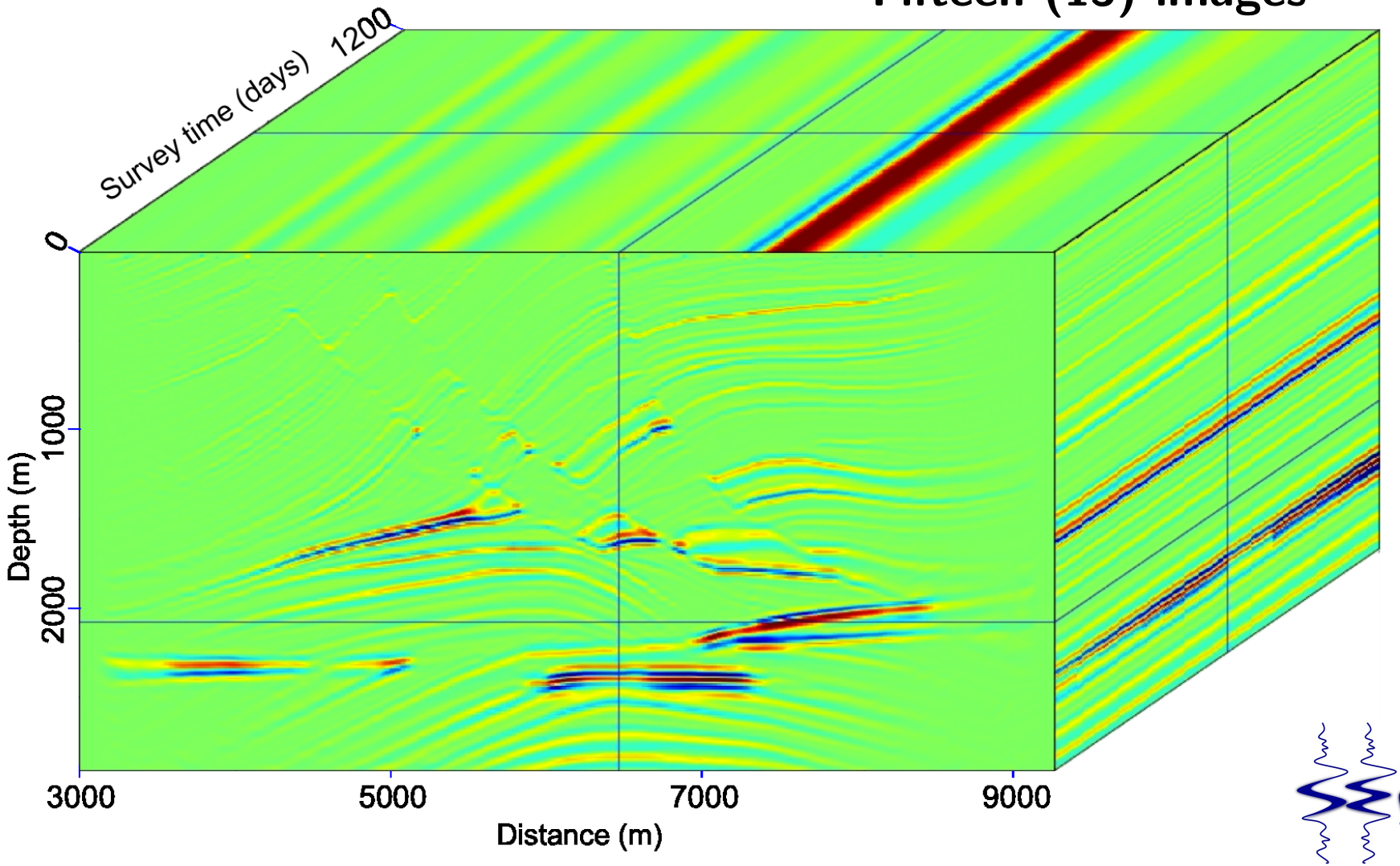


Seismic data volume: Depth slice

Fifteen (15) images



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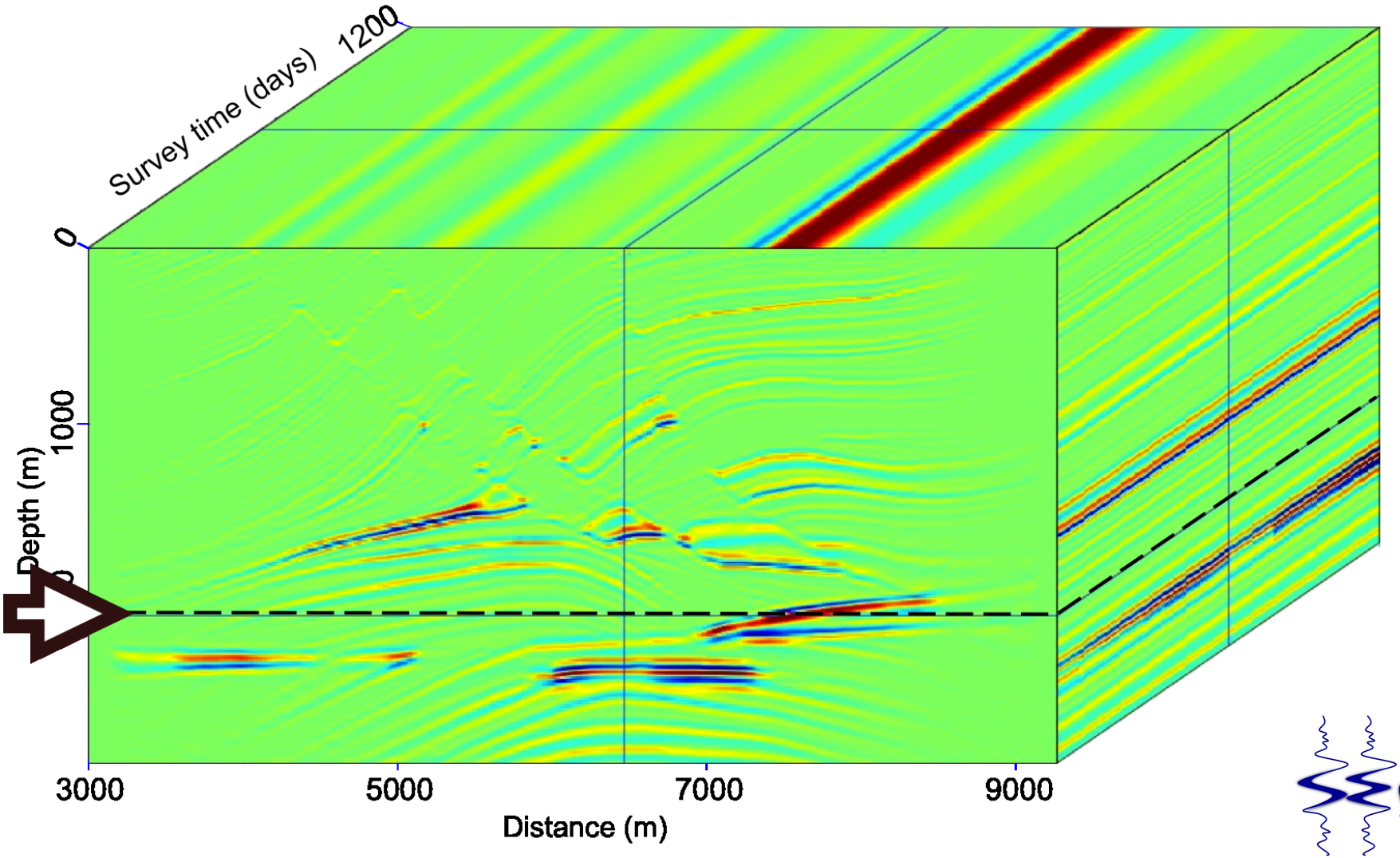

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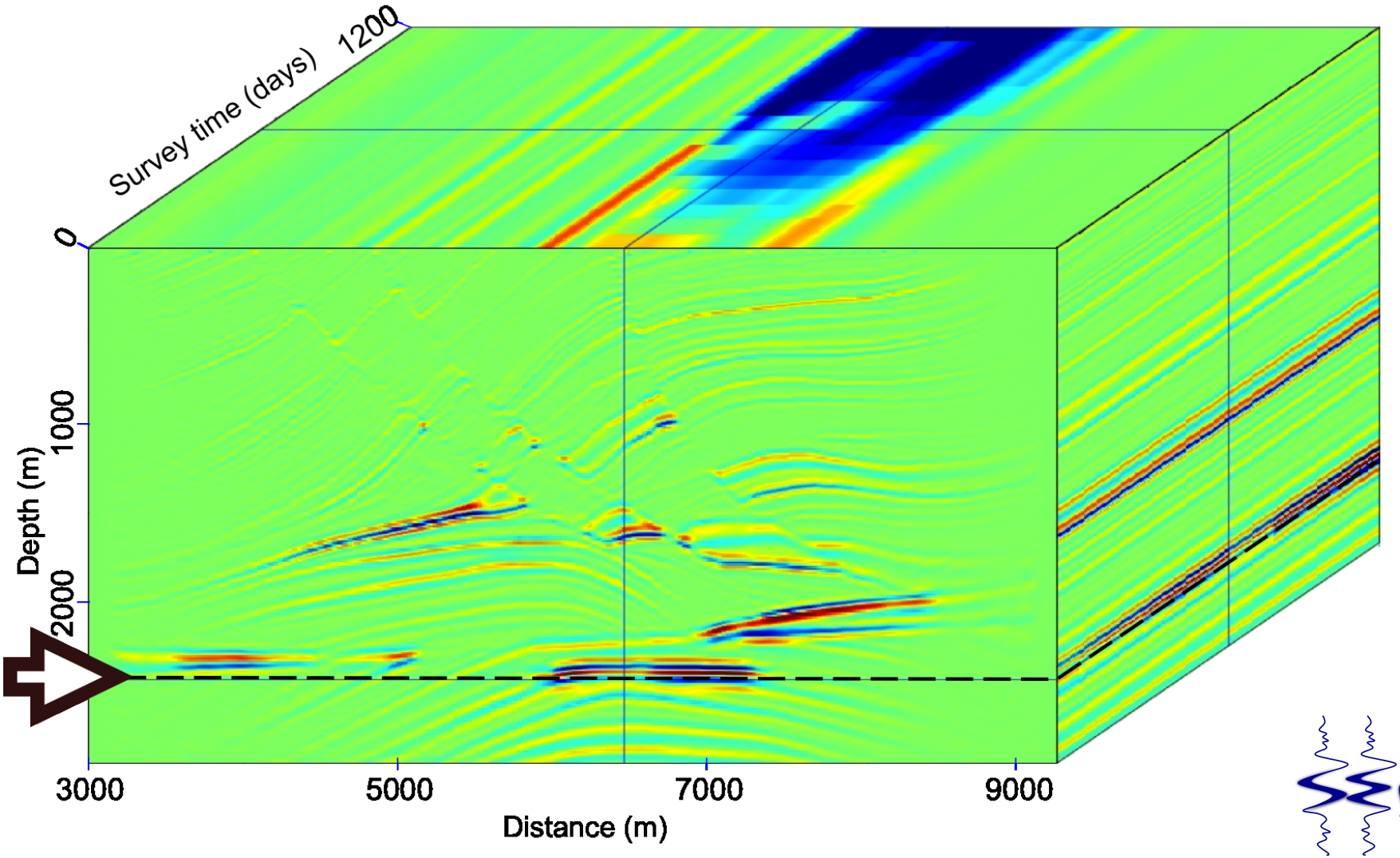

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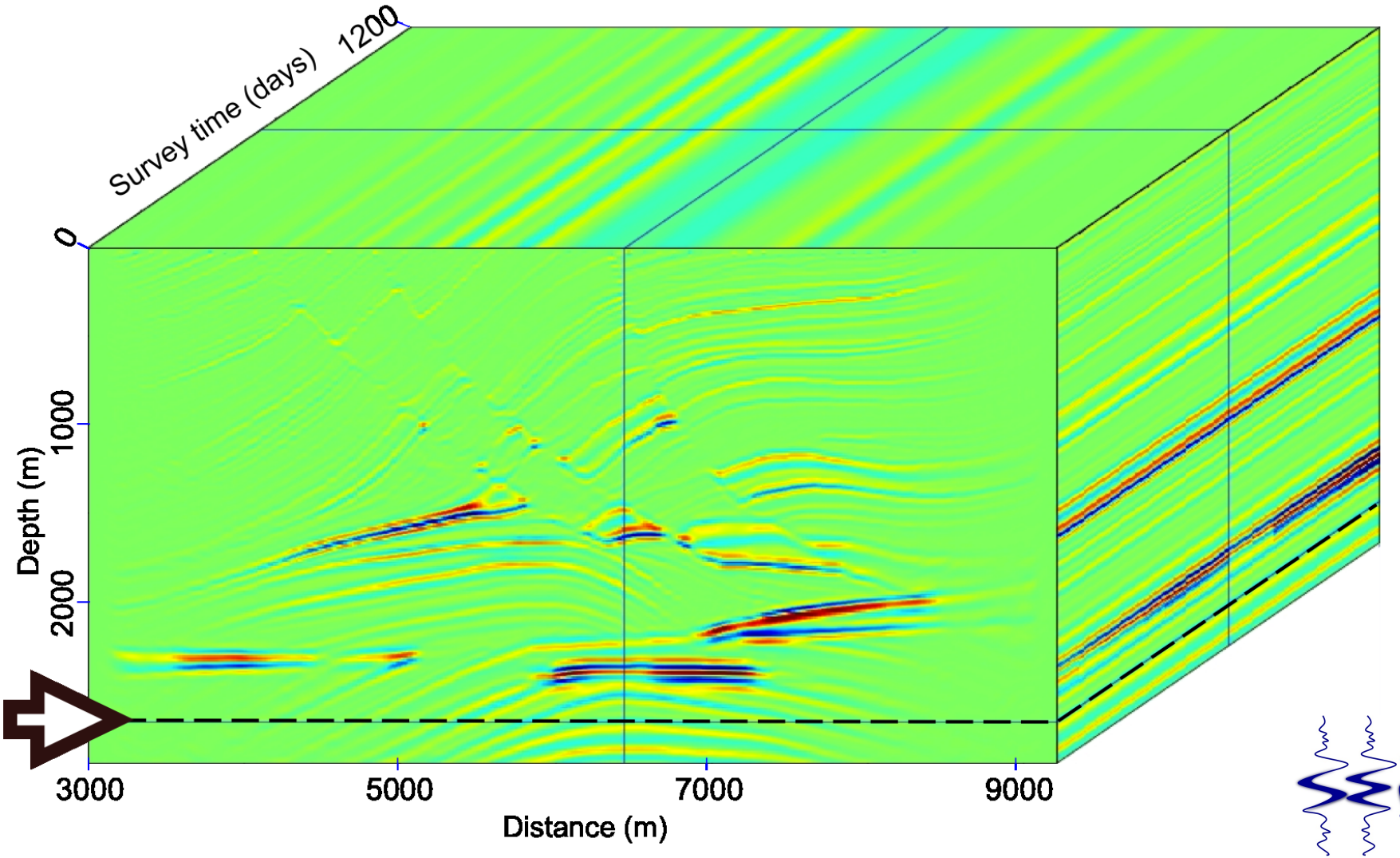
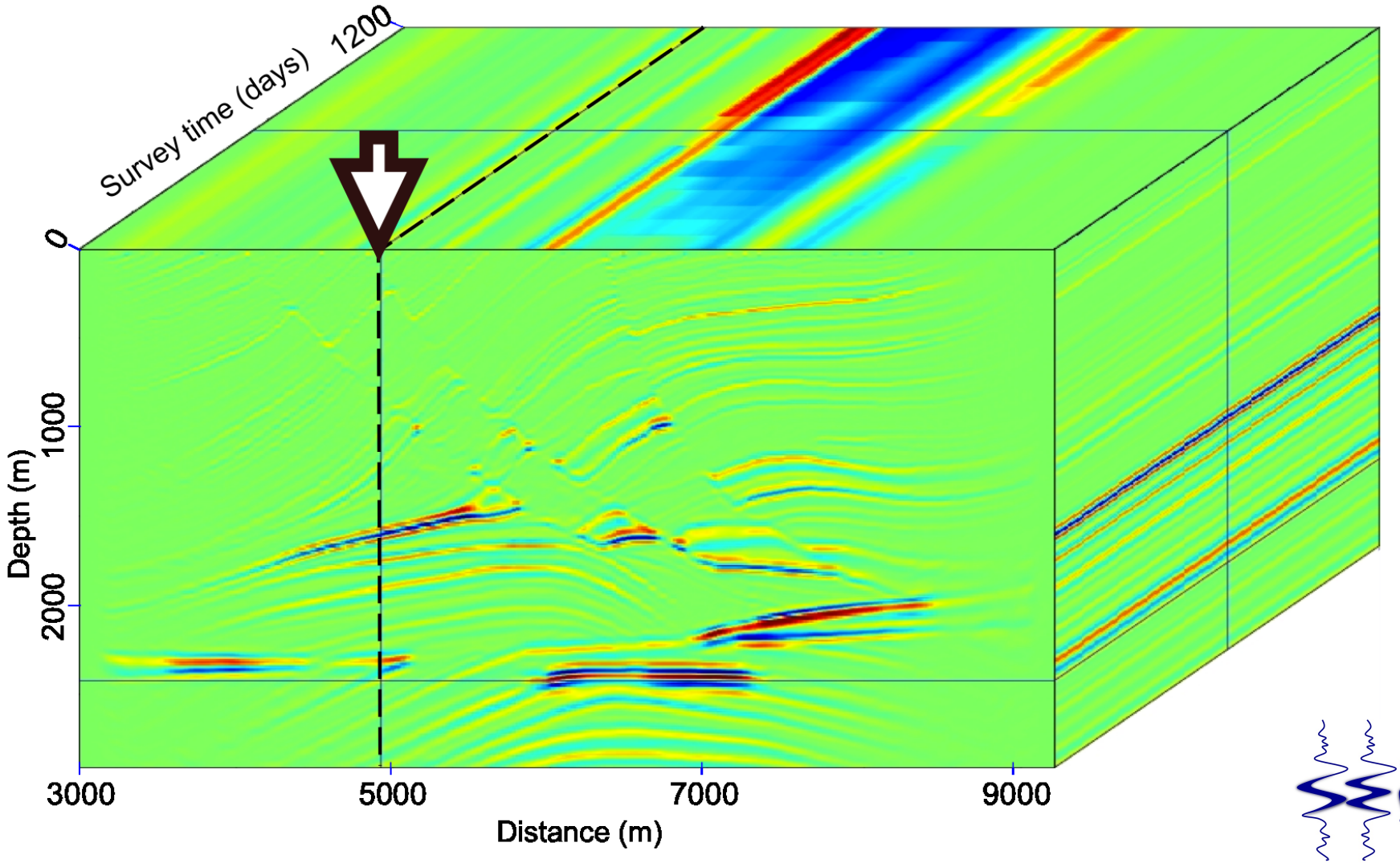
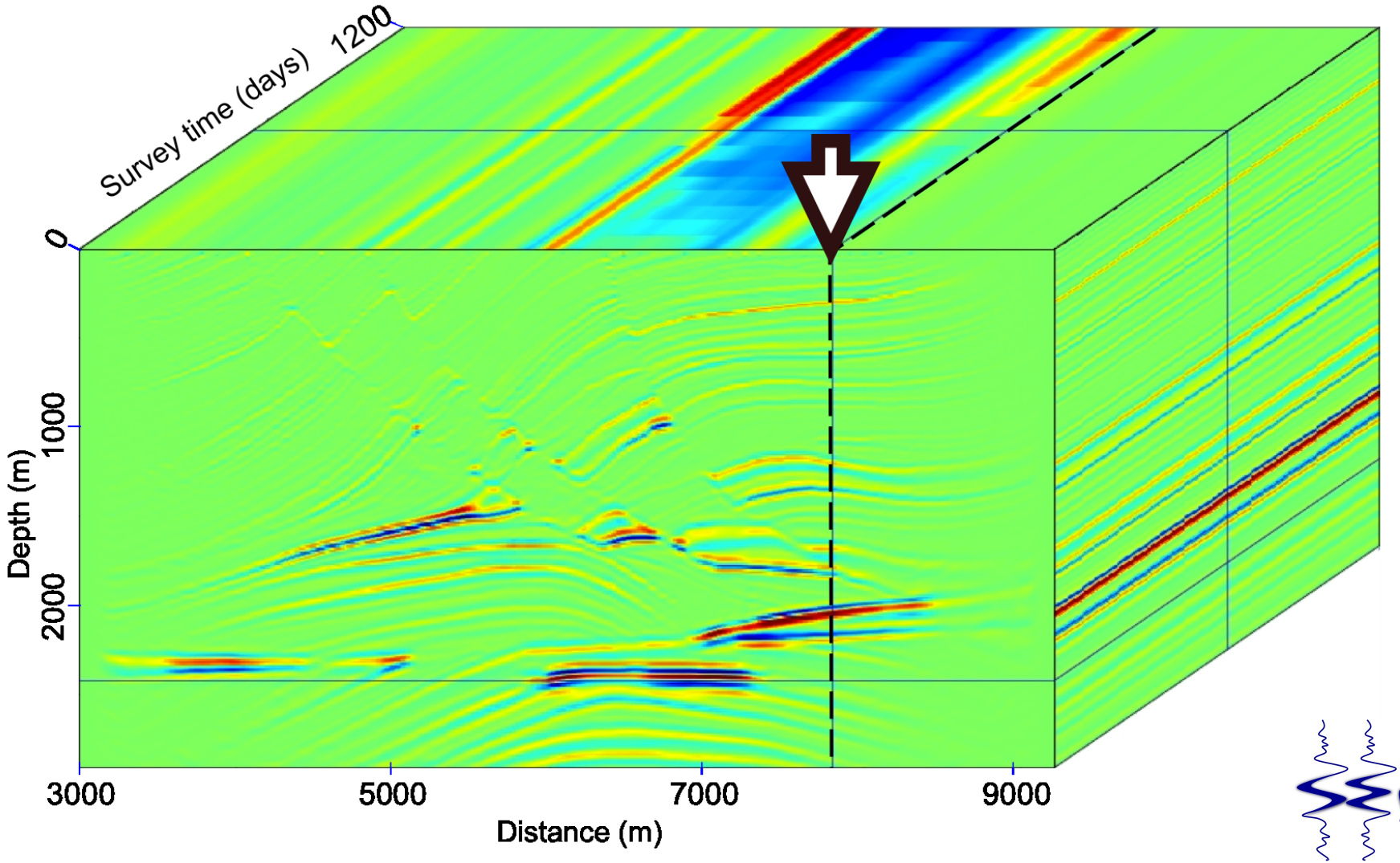


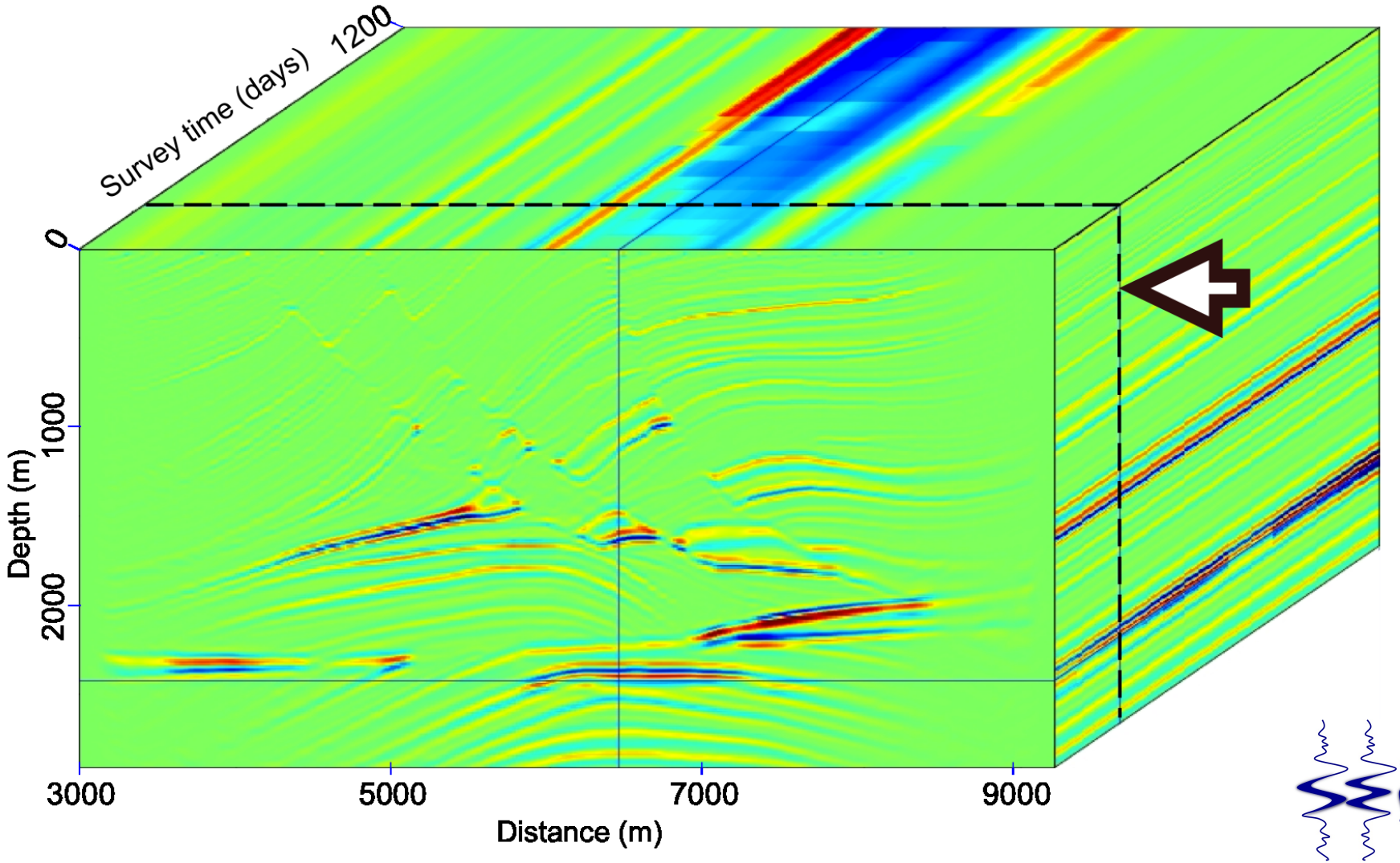
Seismic data volume: CMP slice



Seismic data volume: CMP slice



Seismic data volume: Time section



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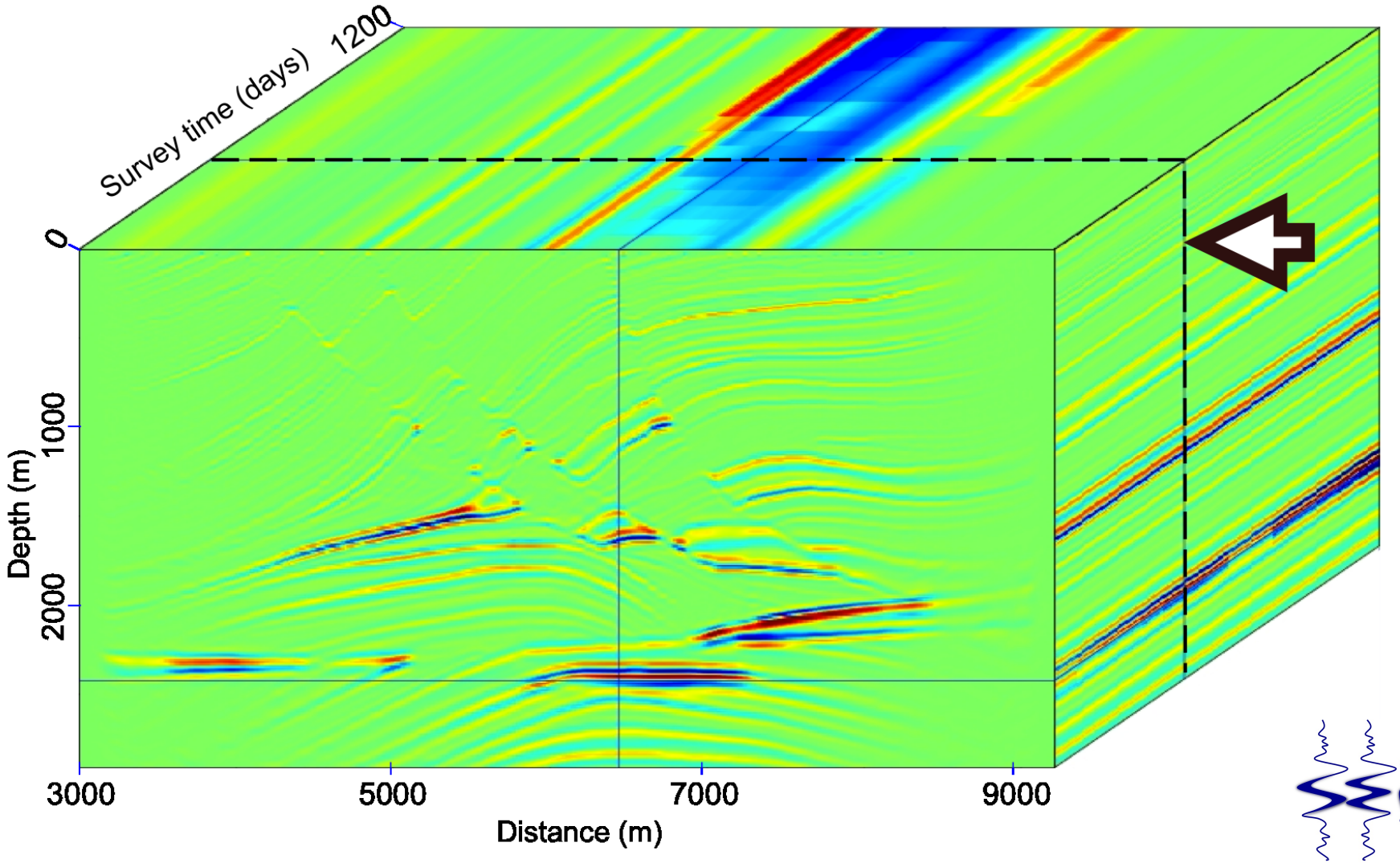

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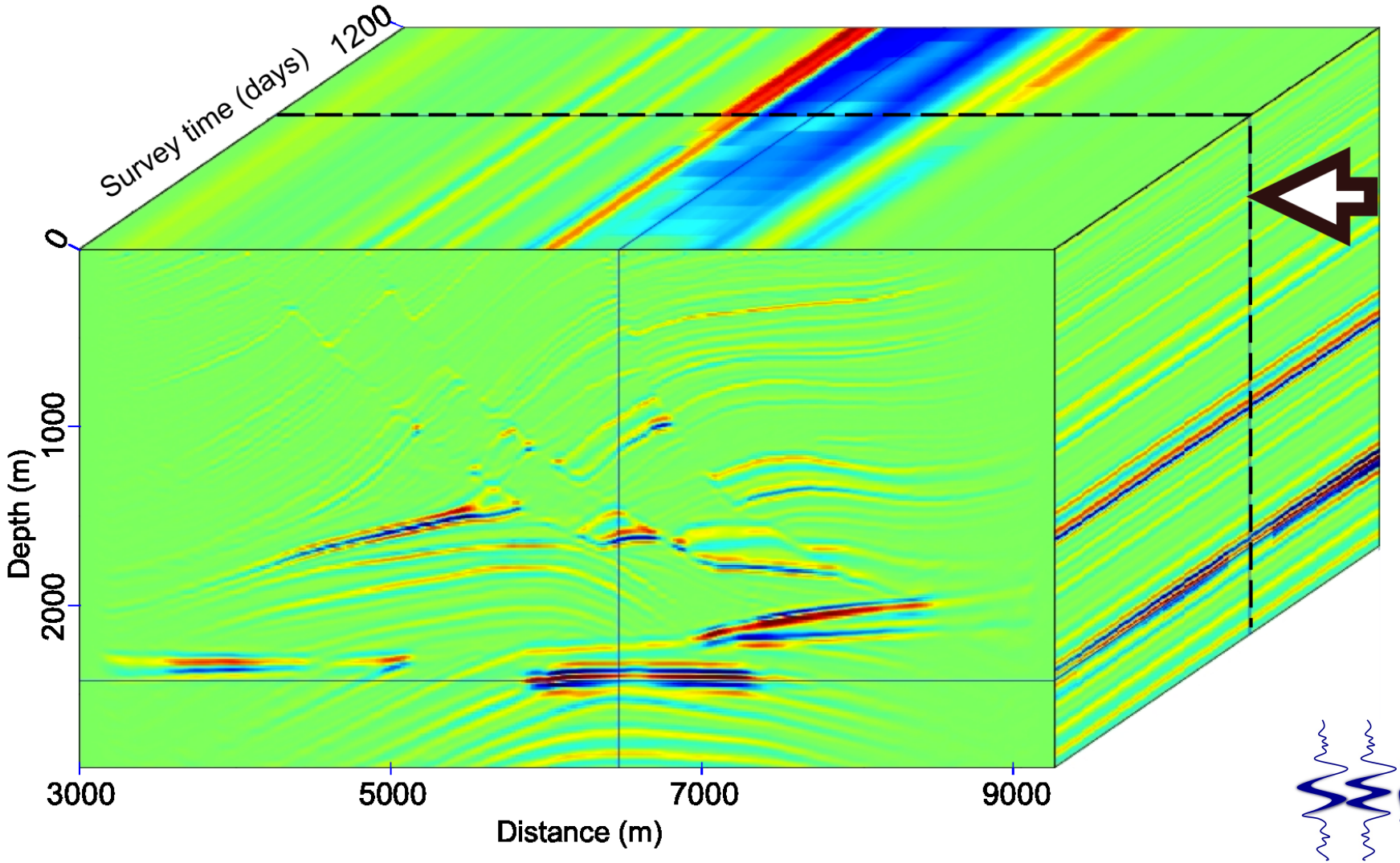

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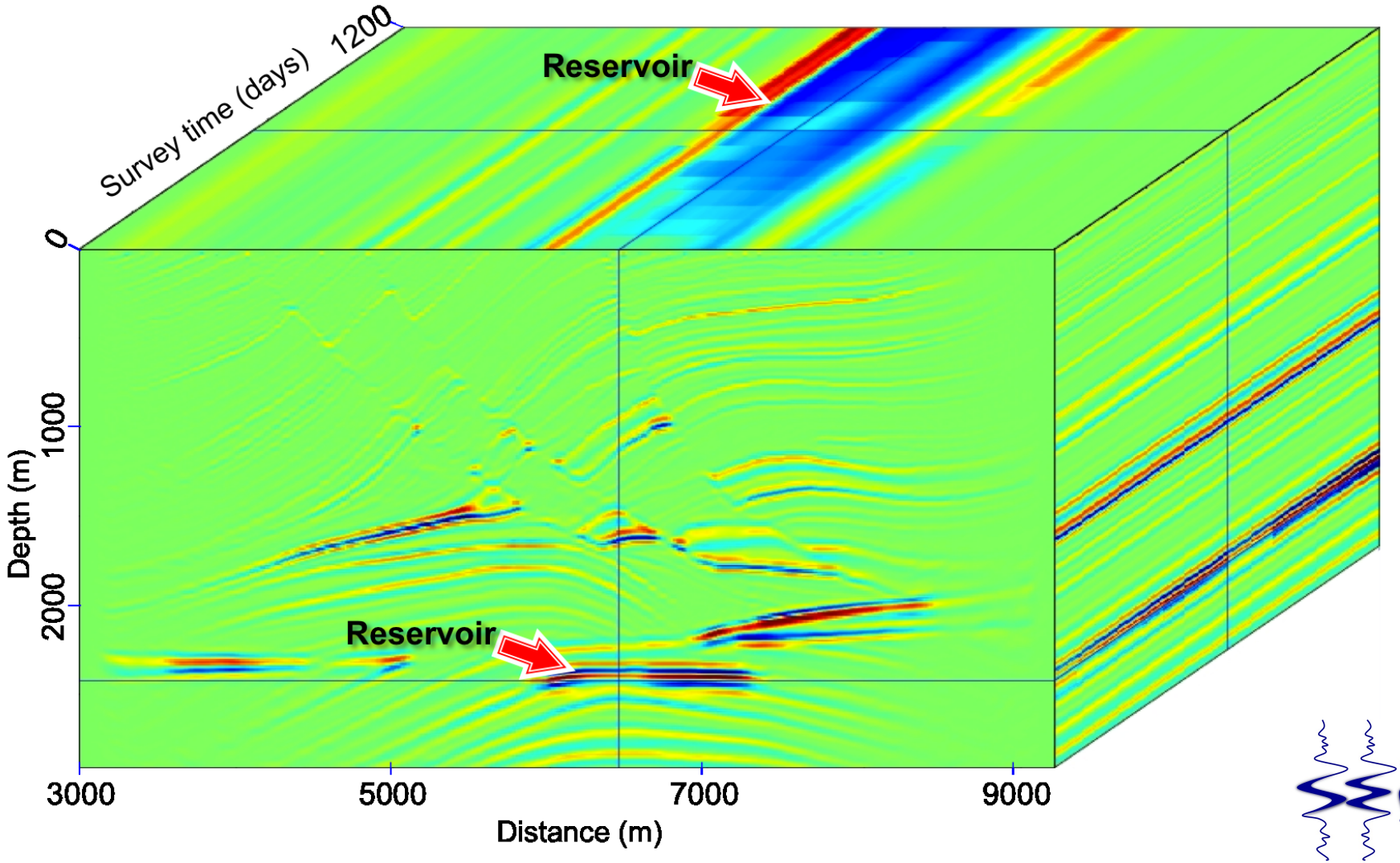
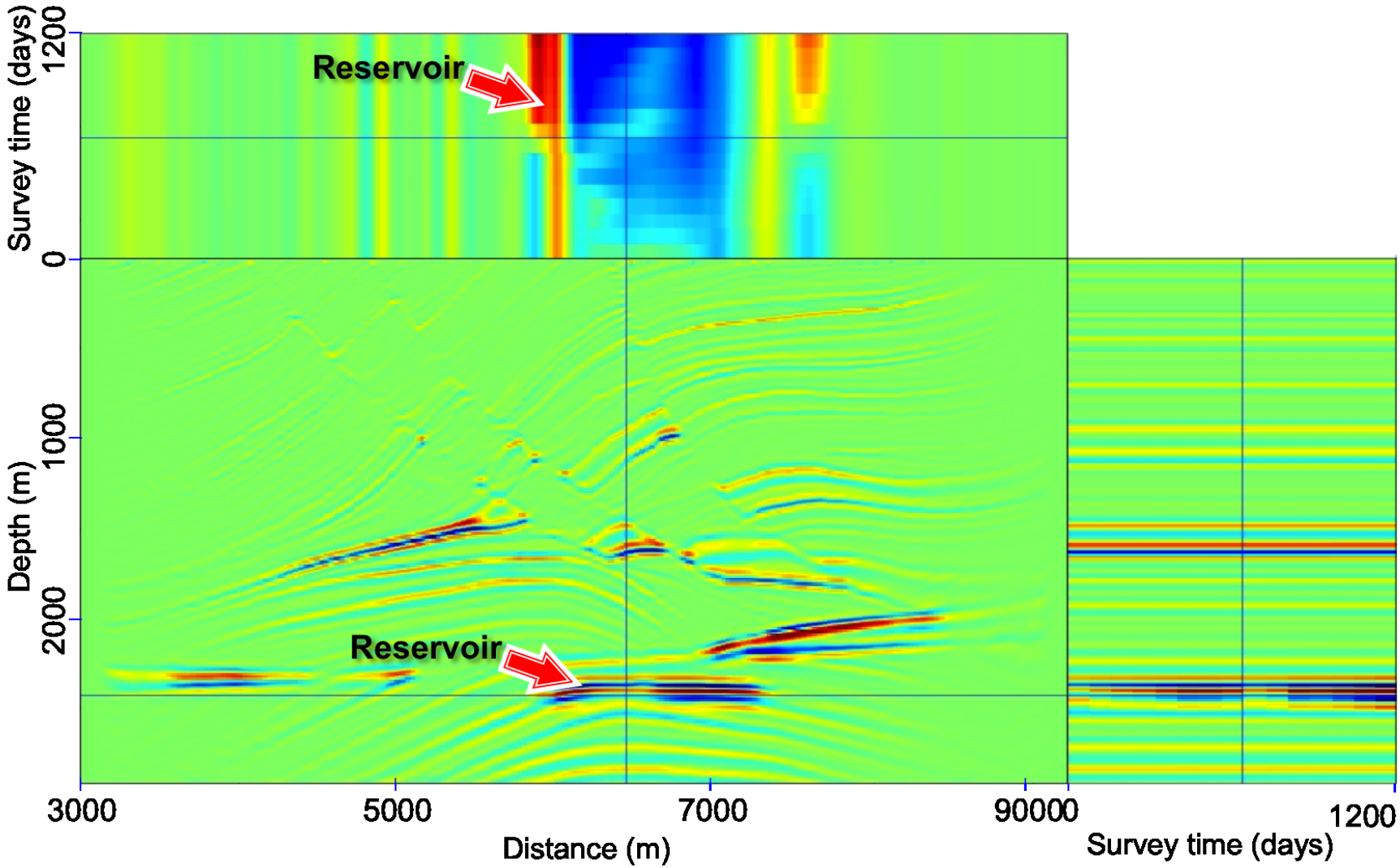


Seismic data volume



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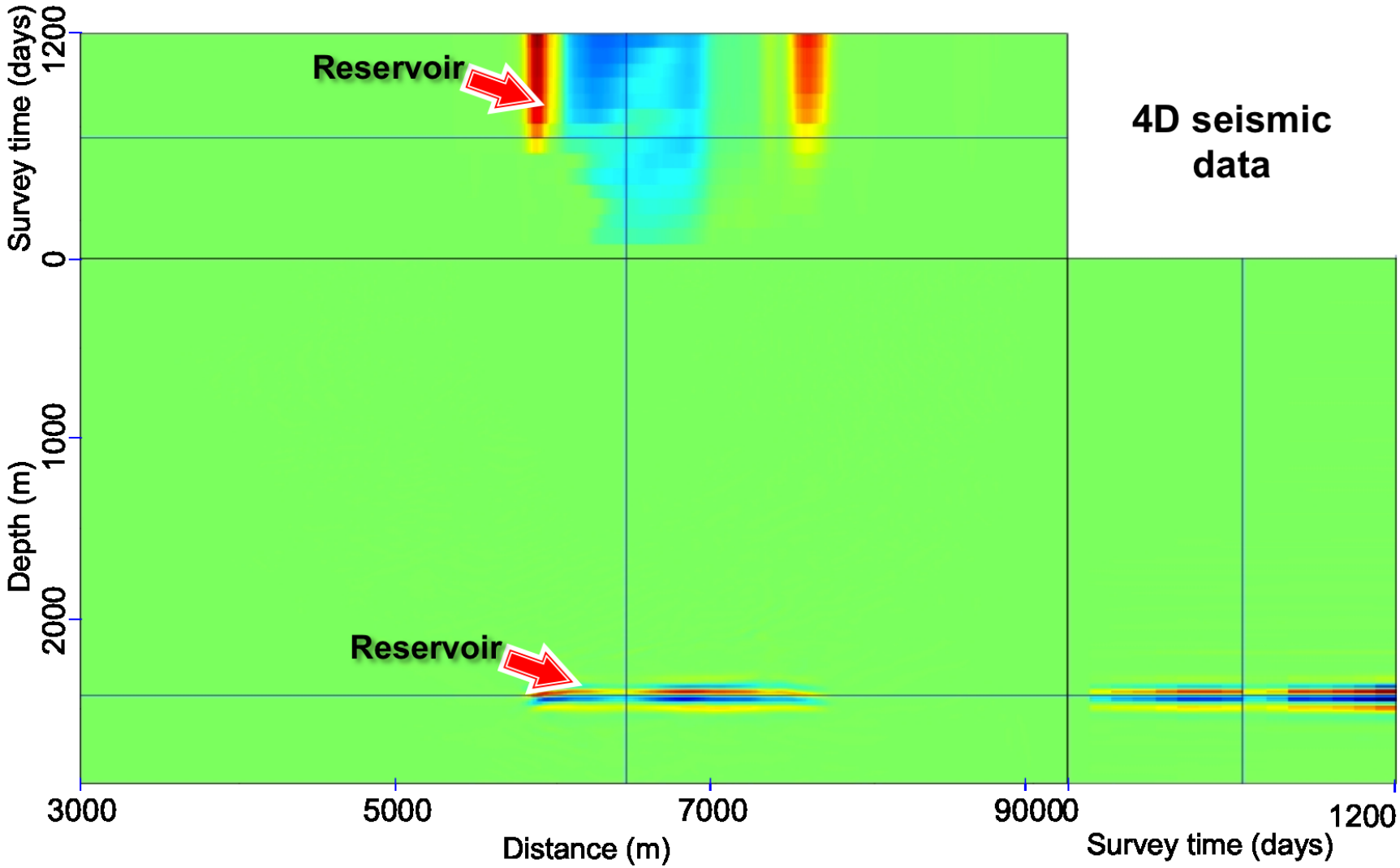
Seismic data volume



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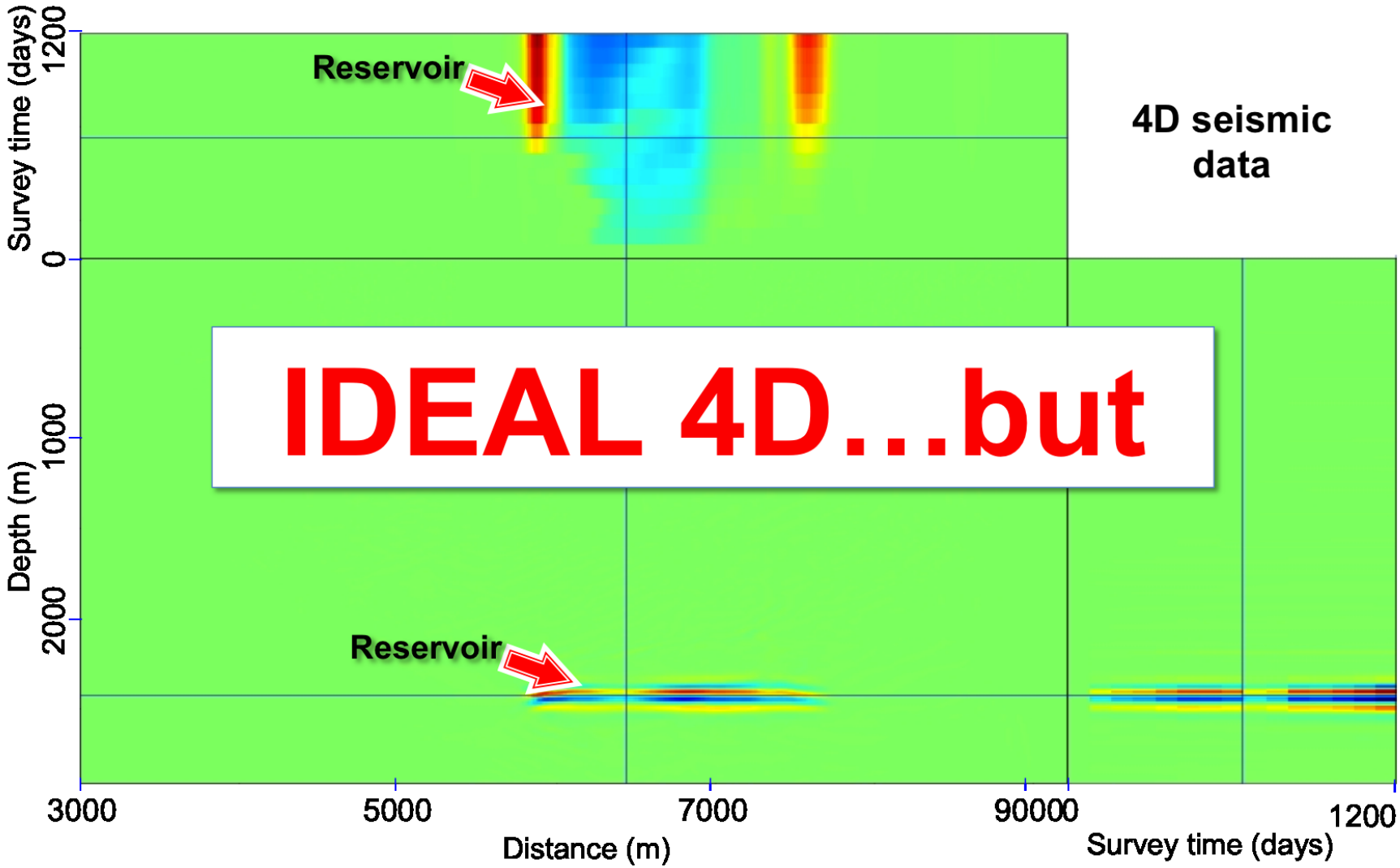
4D seismic data volume



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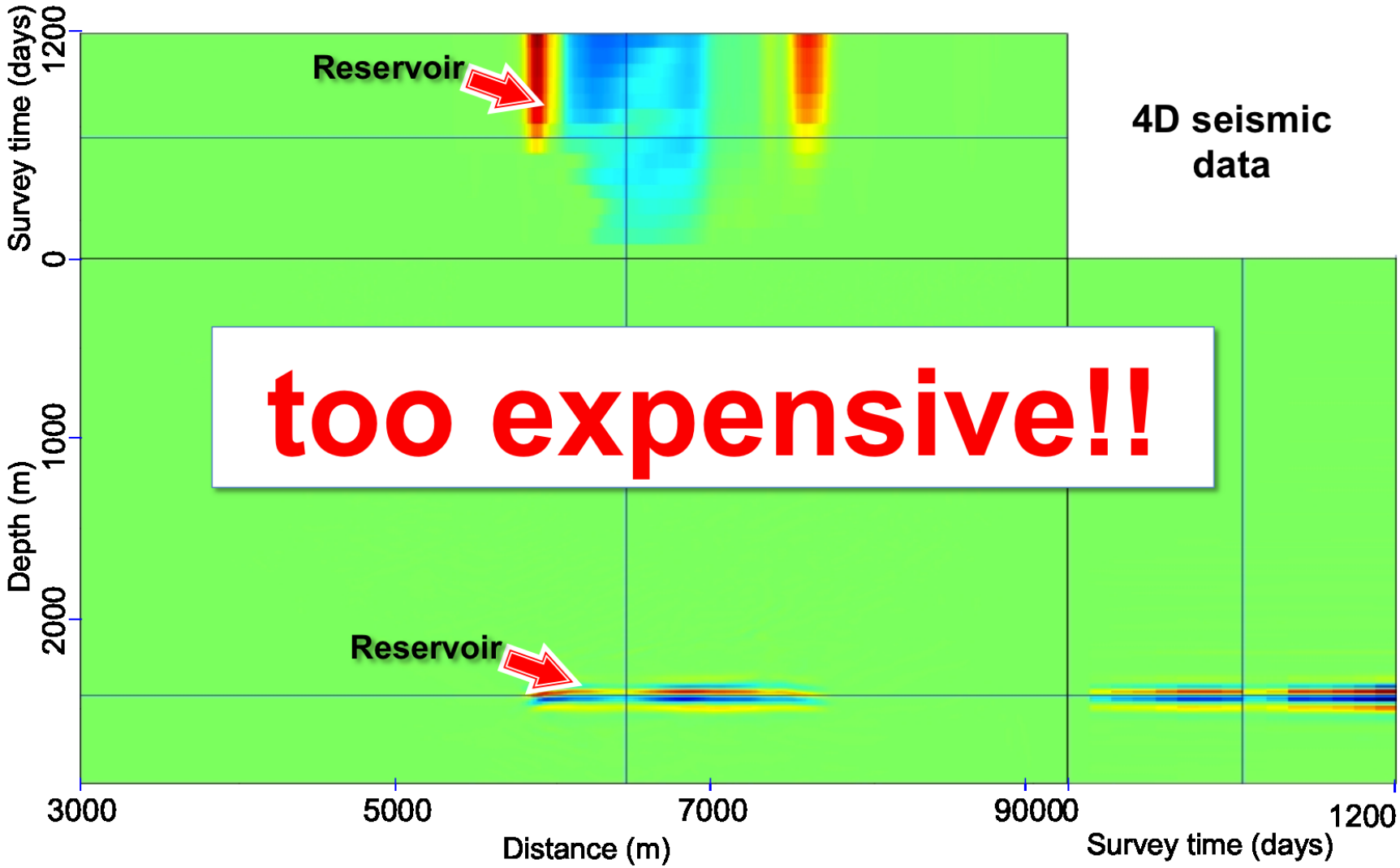

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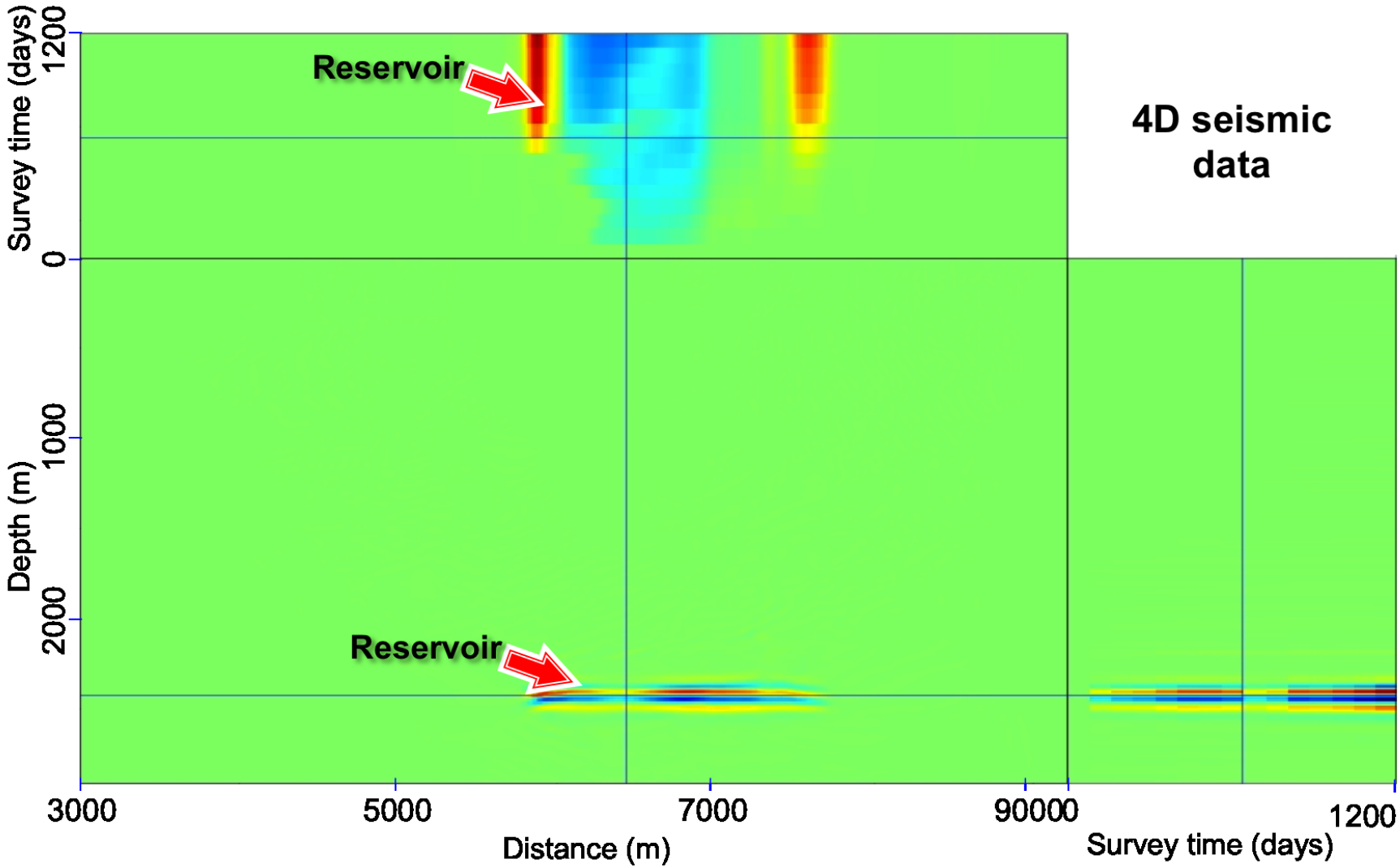

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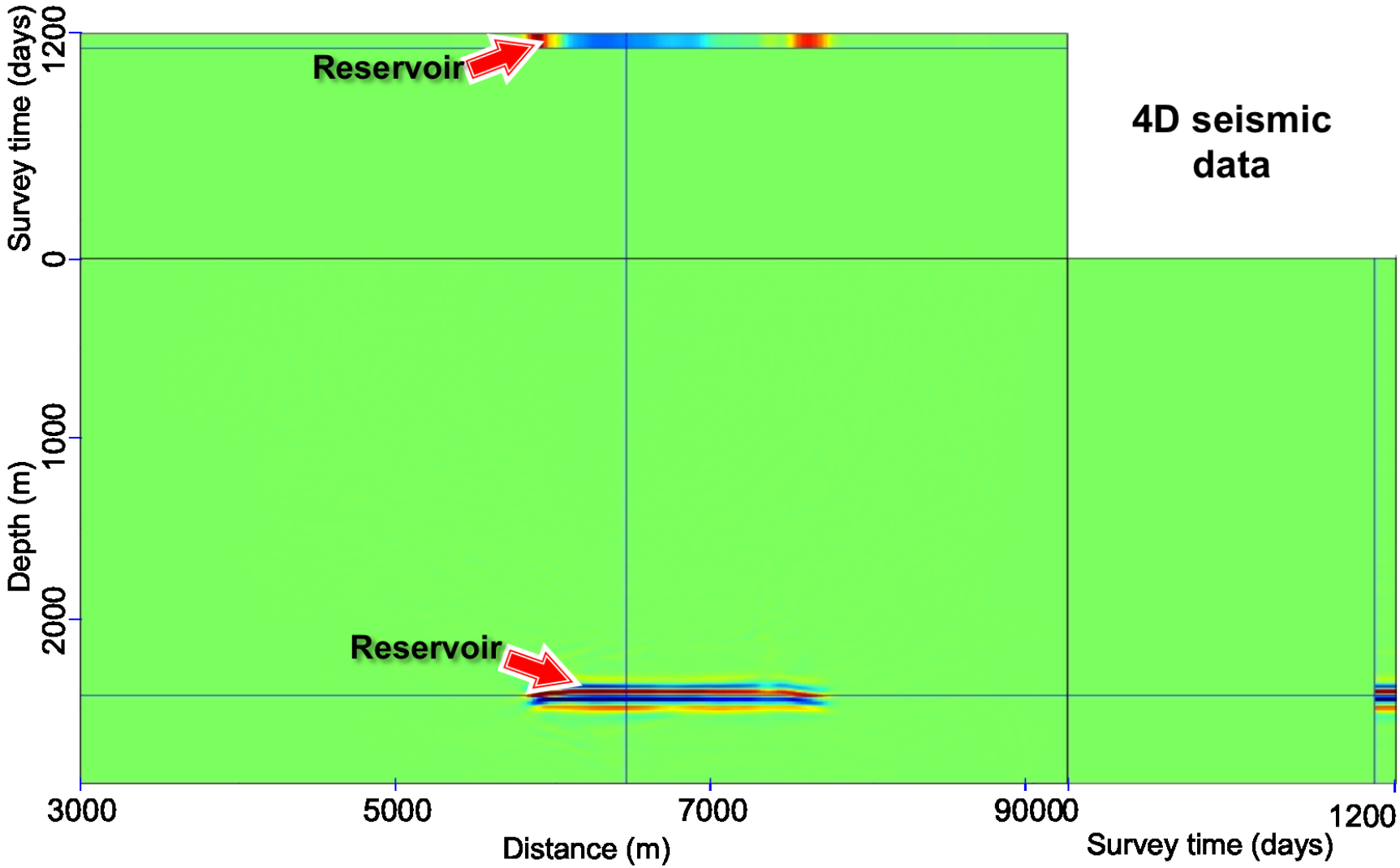
4D seismic data volume



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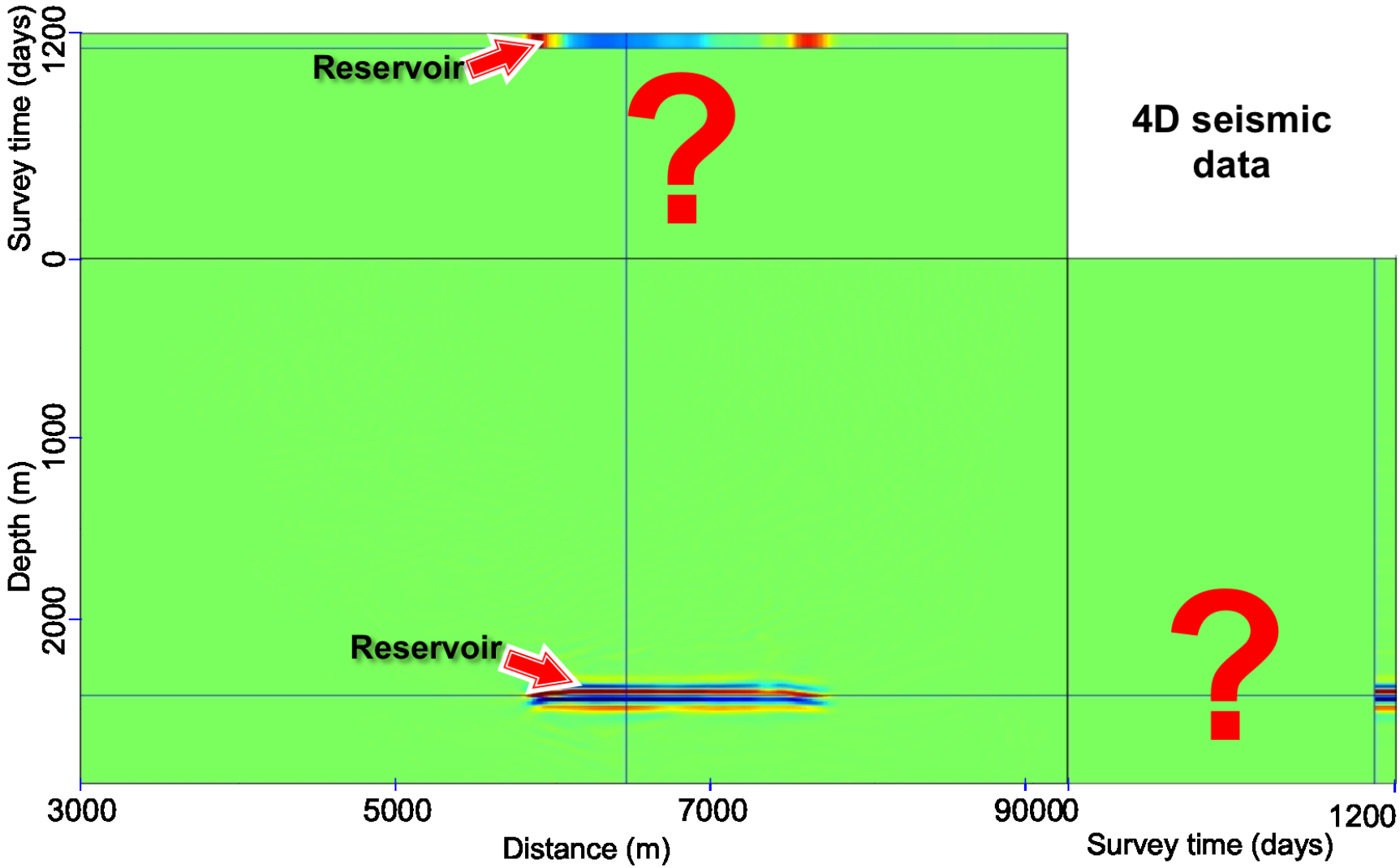
4D seismic data volume



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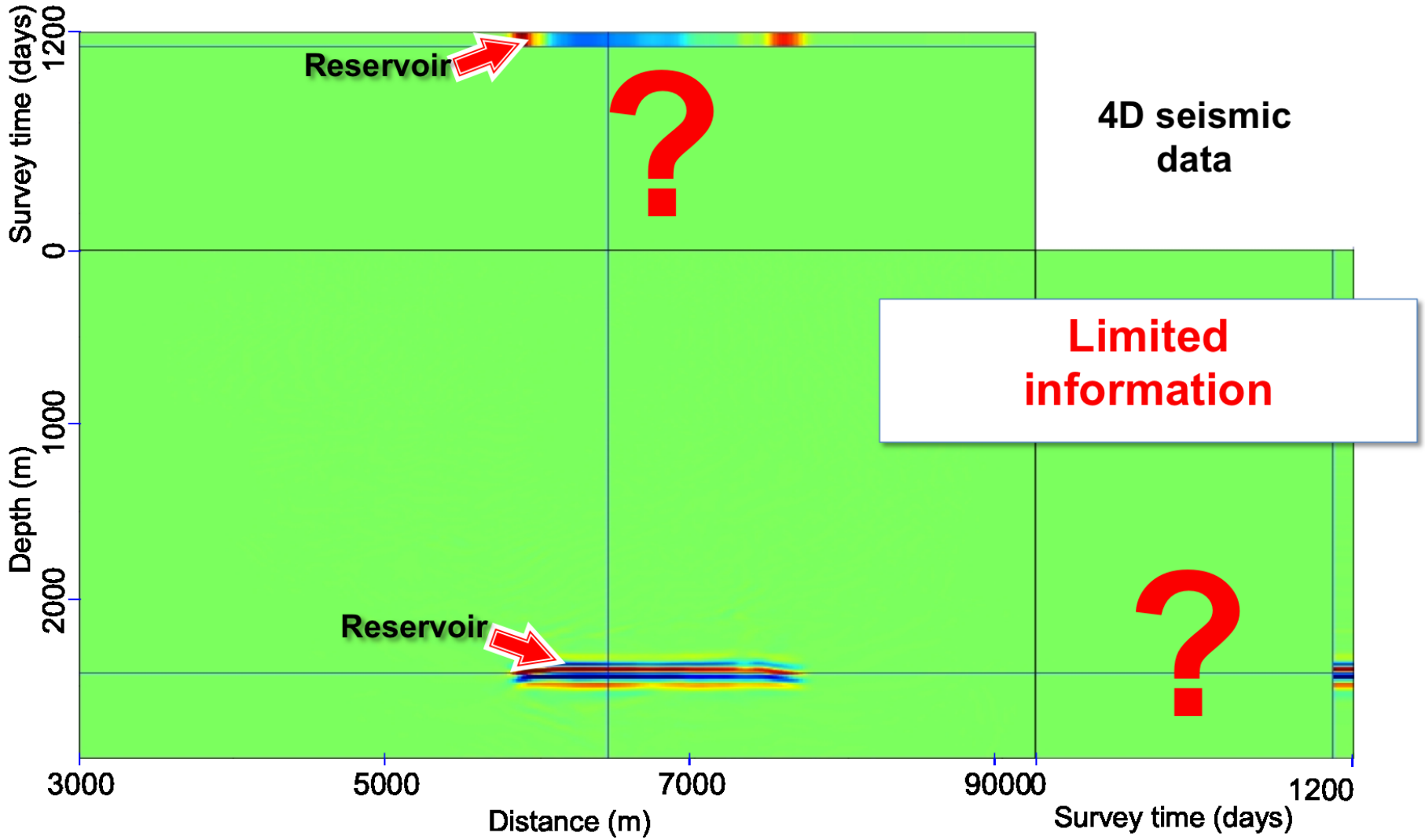
4D seismic data volume



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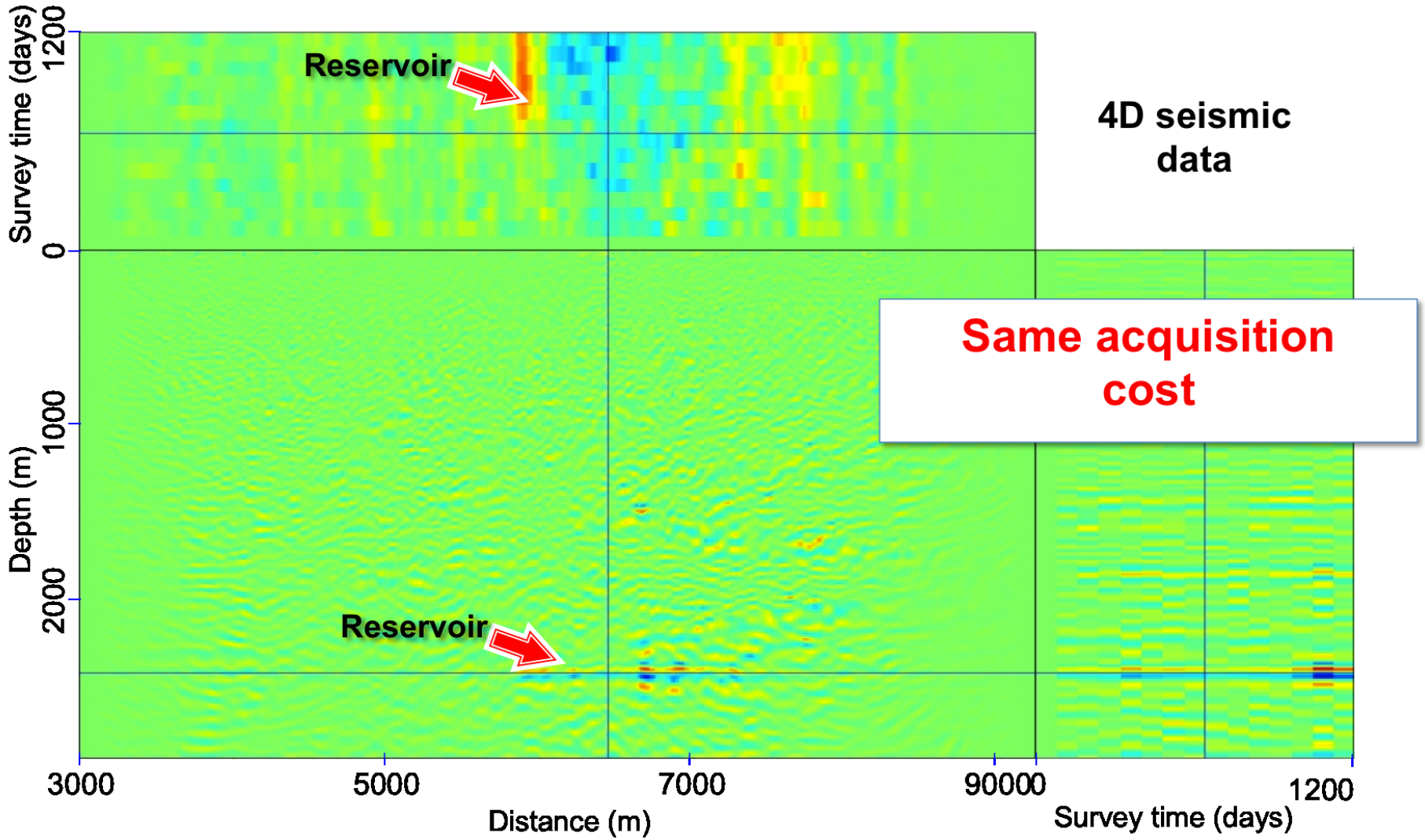
4D seismic data volume



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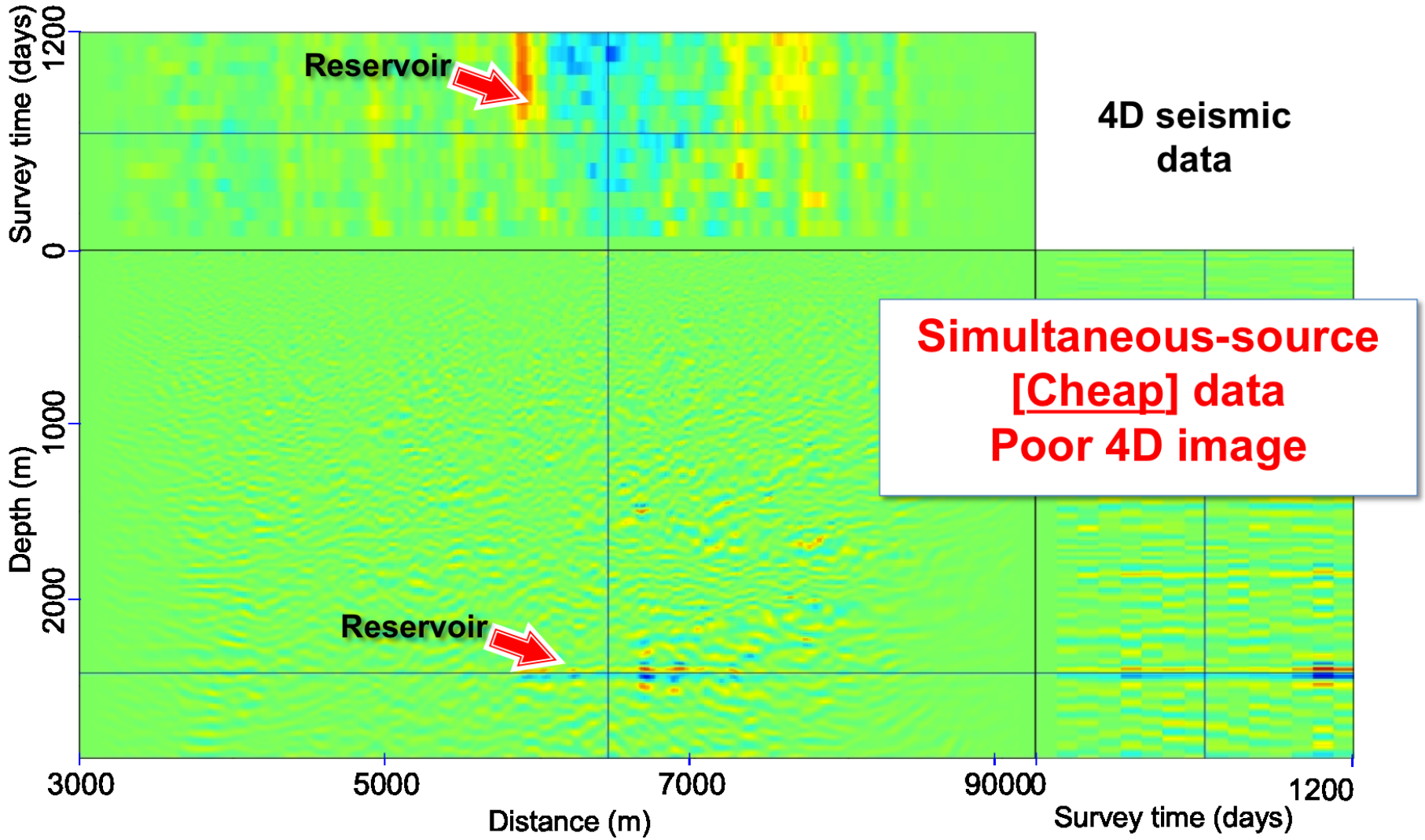
4D seismic data volume



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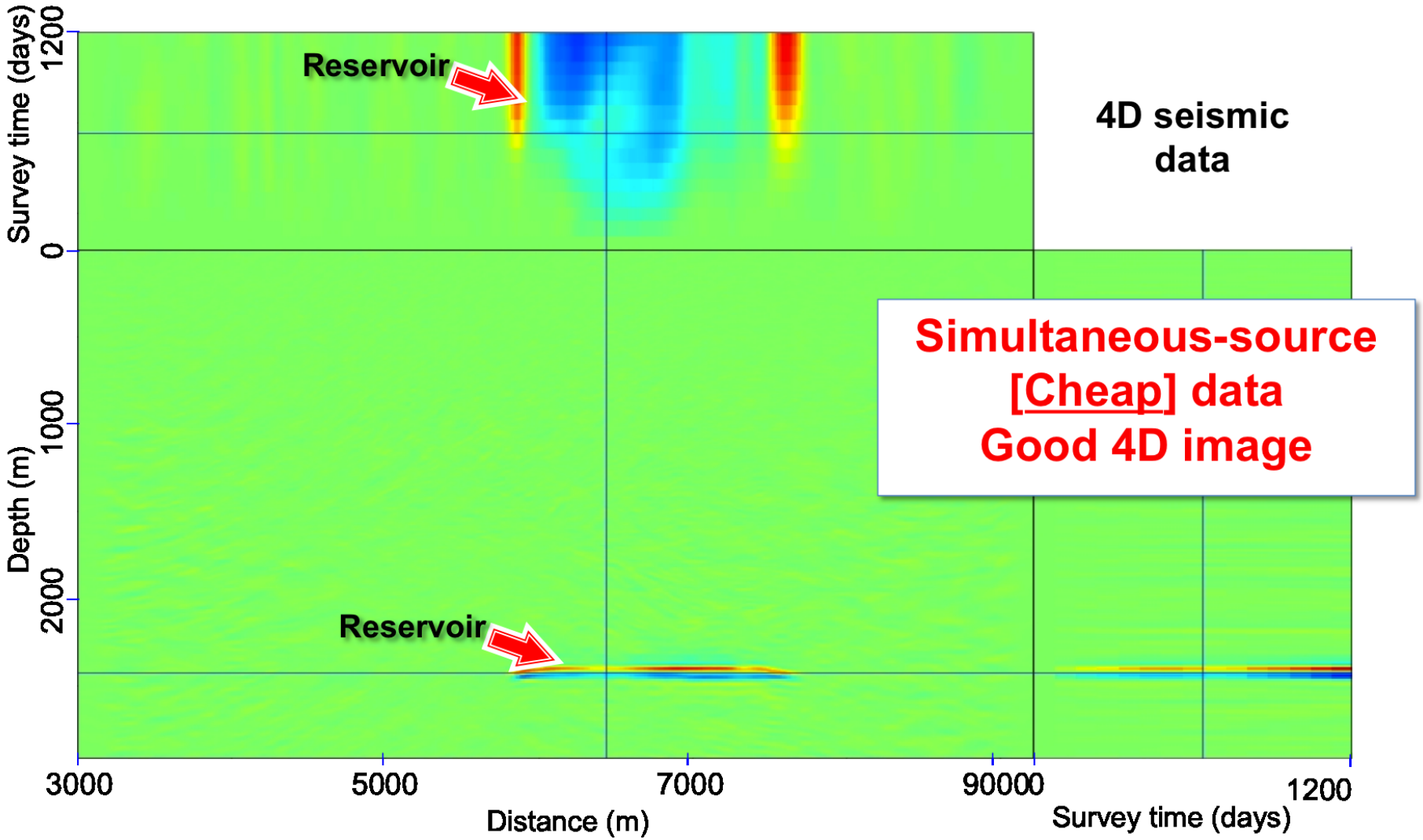
4D seismic data volume



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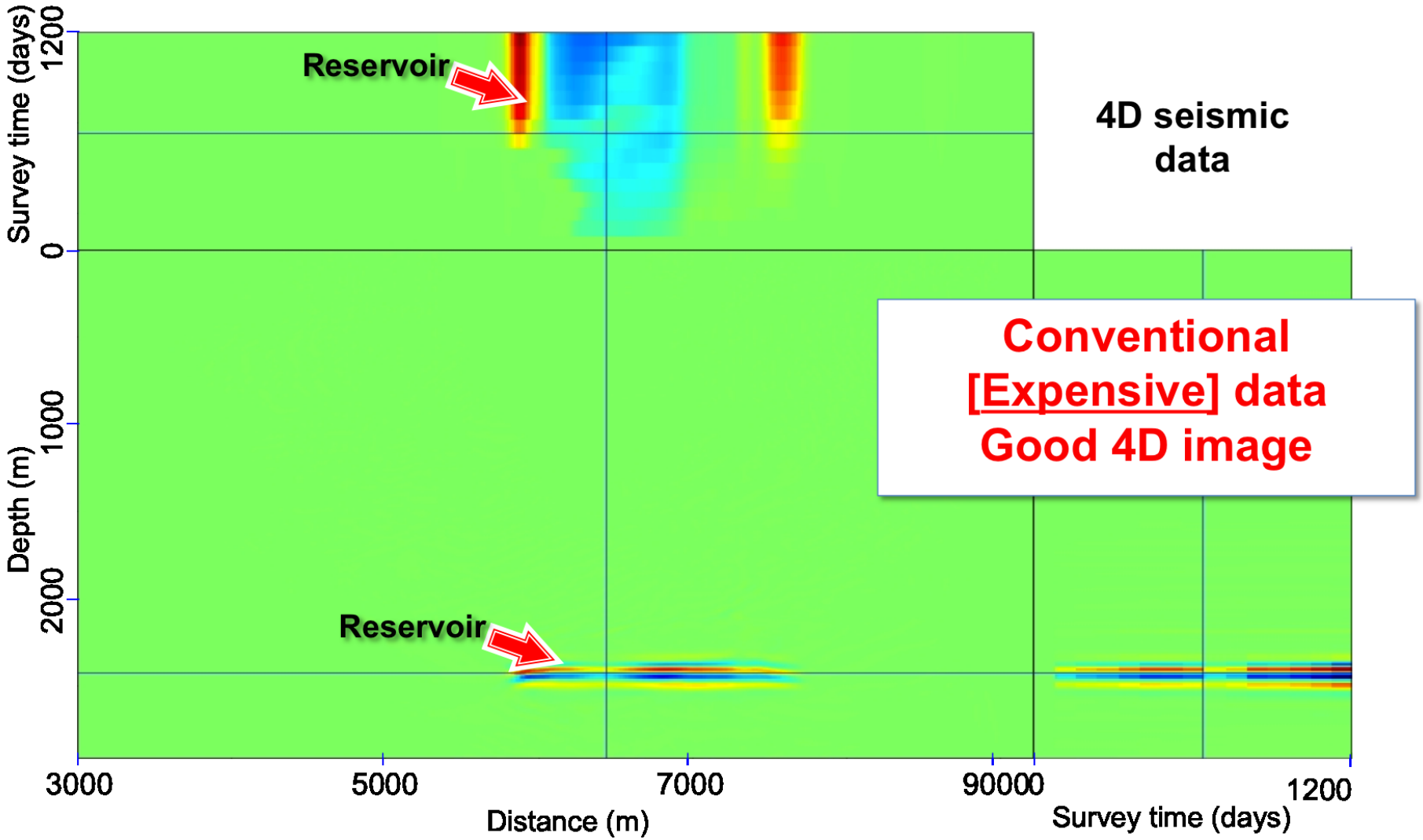

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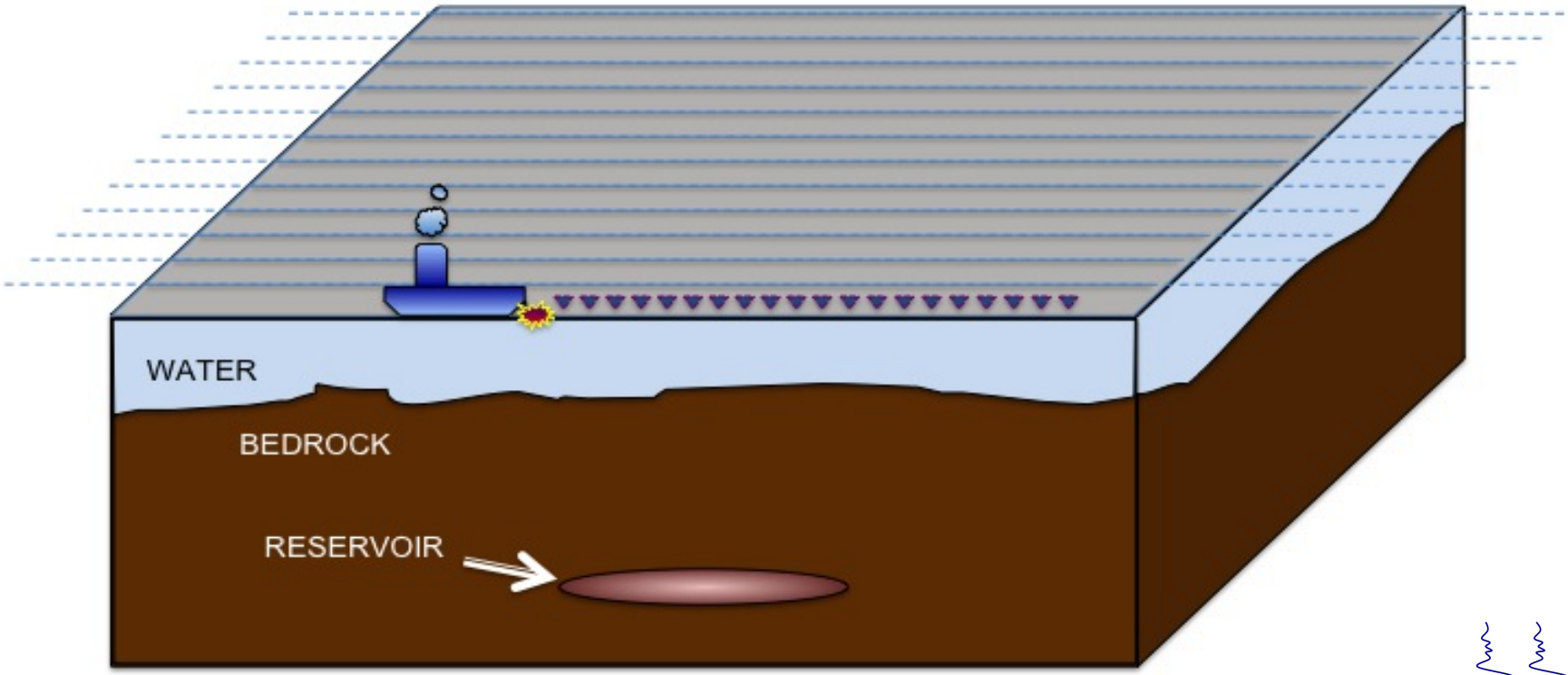
Outline

1. Background
2. Methodology
3. Numerical Example
4. Conclusions

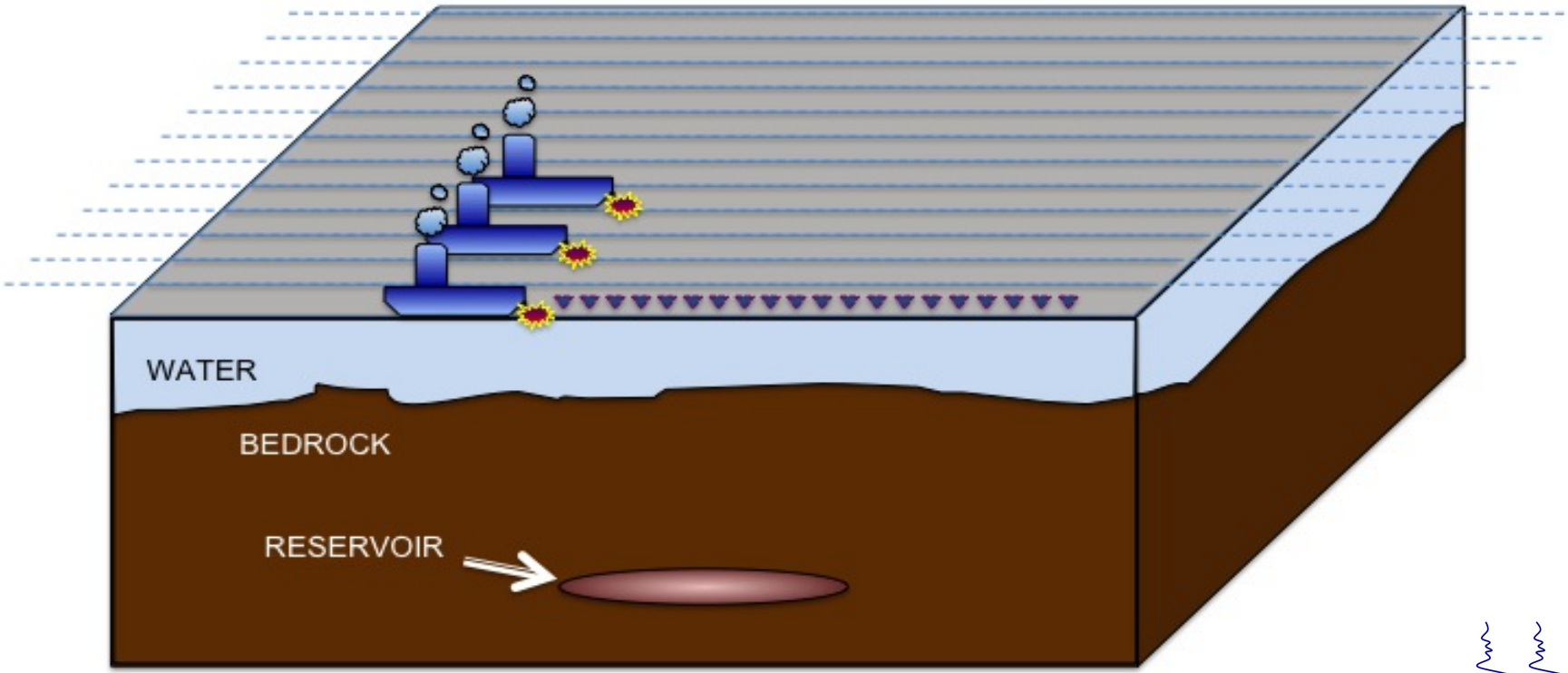
What is simultaneous shooting?

Conventional shooting (1 seismic source)



What is simultaneous shooting?

Wide-azimuth shooting (3 seismic sources)



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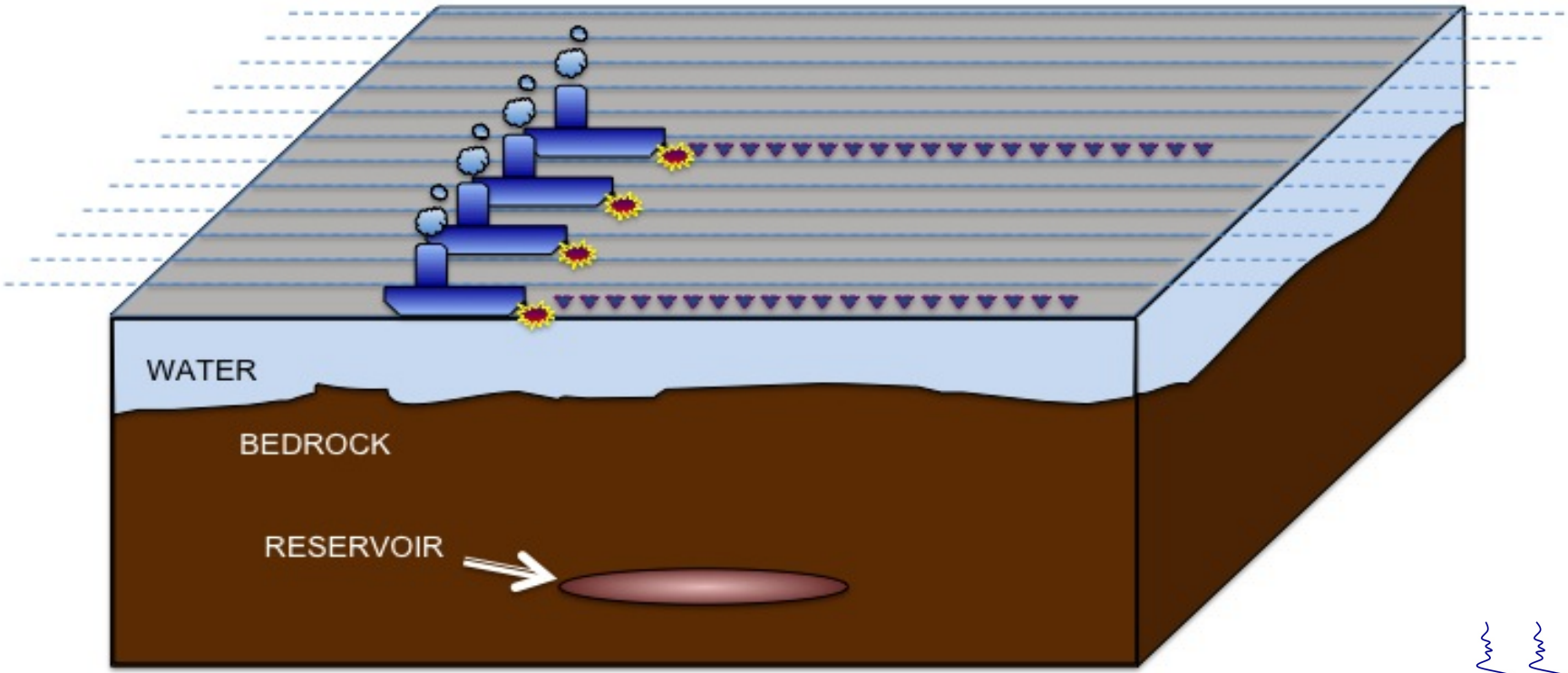
Wide-azimuth shooting (4 seismic sources)



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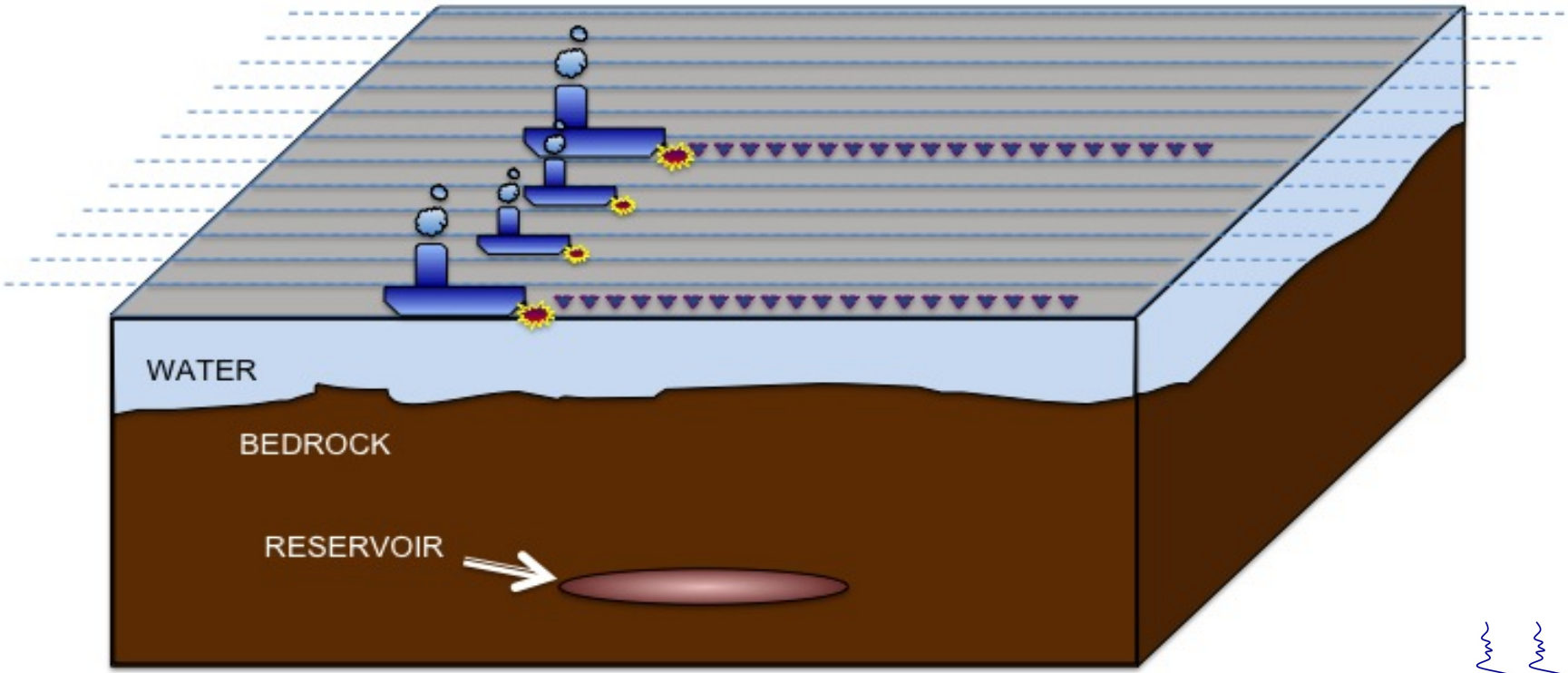
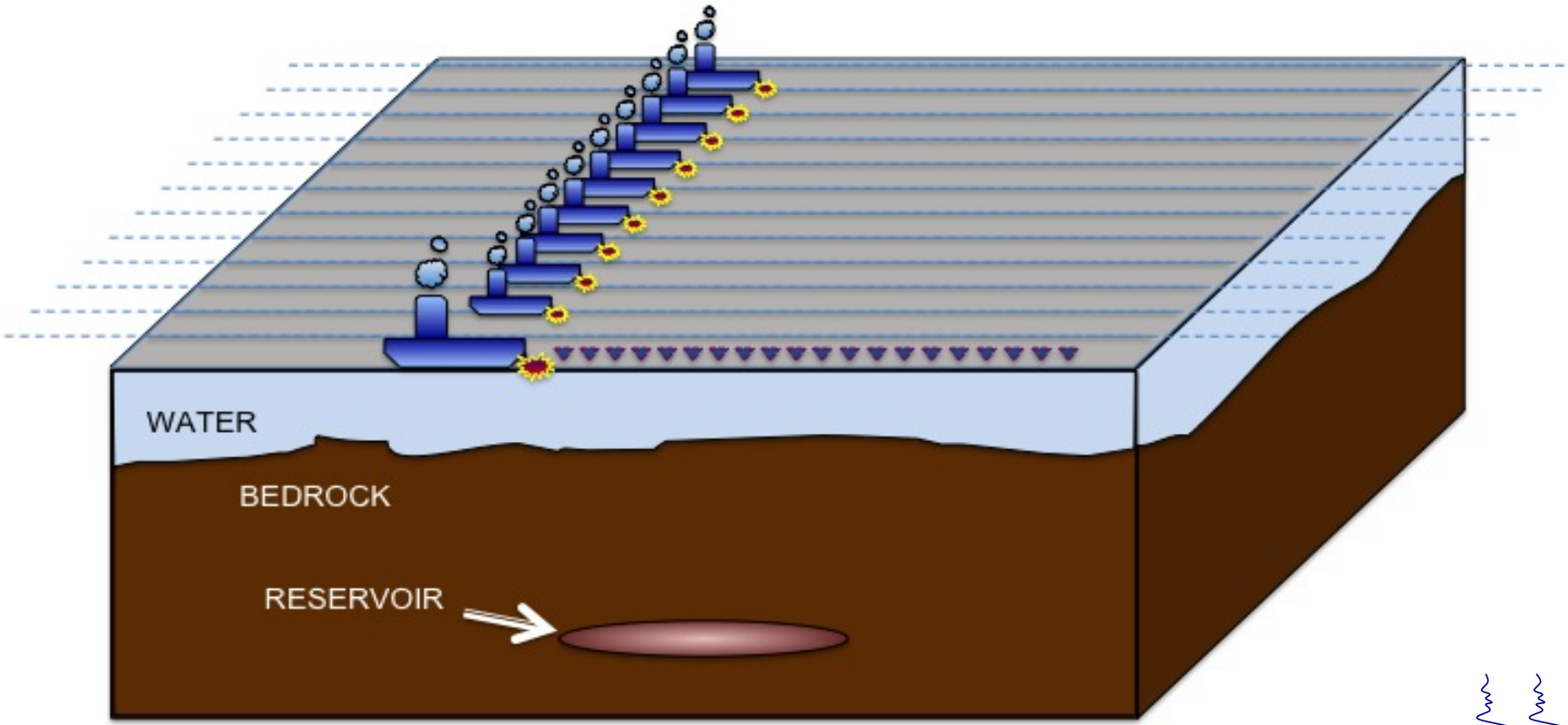


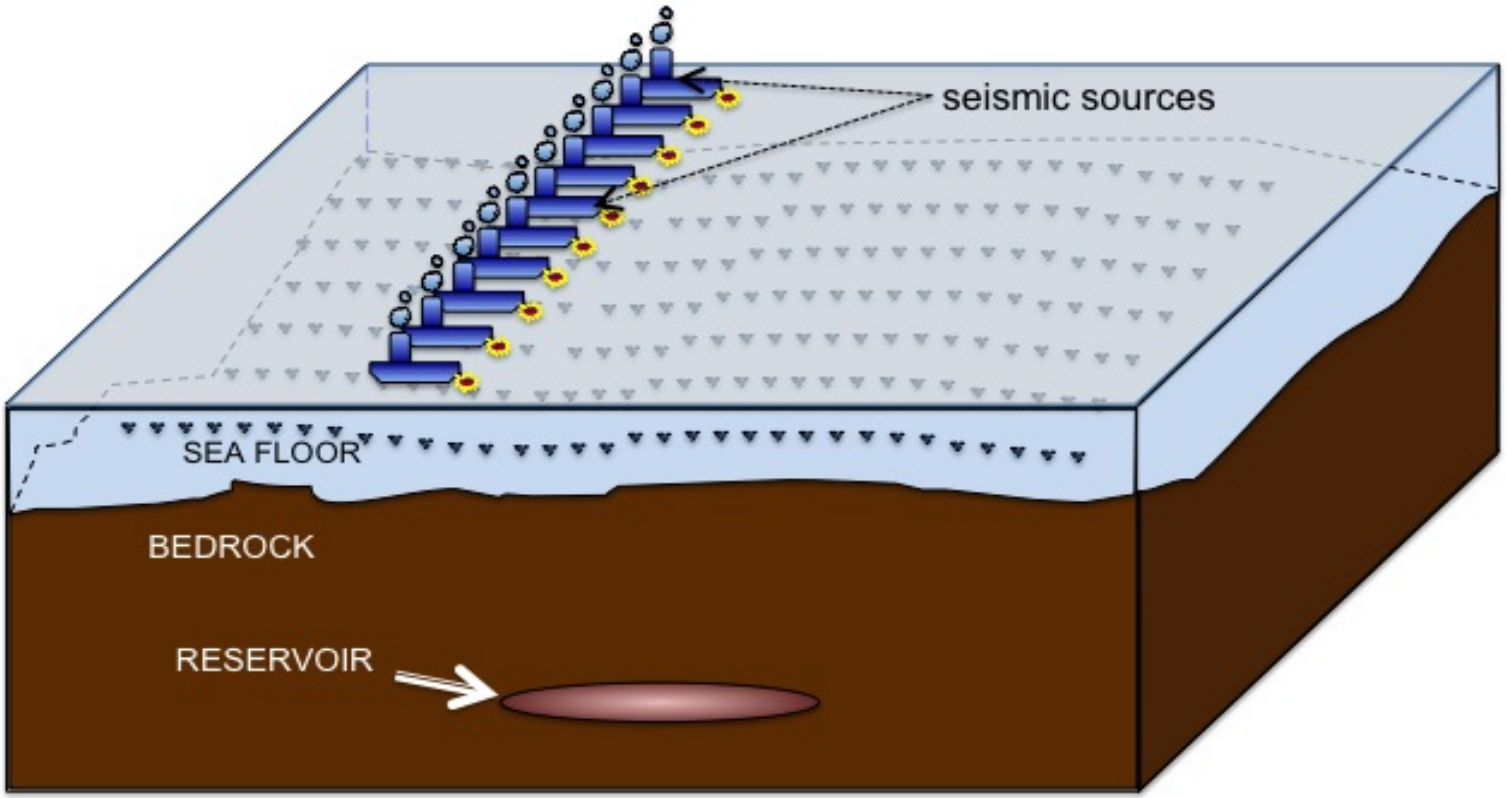
What is simultaneous shooting?

Wide-azimuth shooting (10 seismic sources)



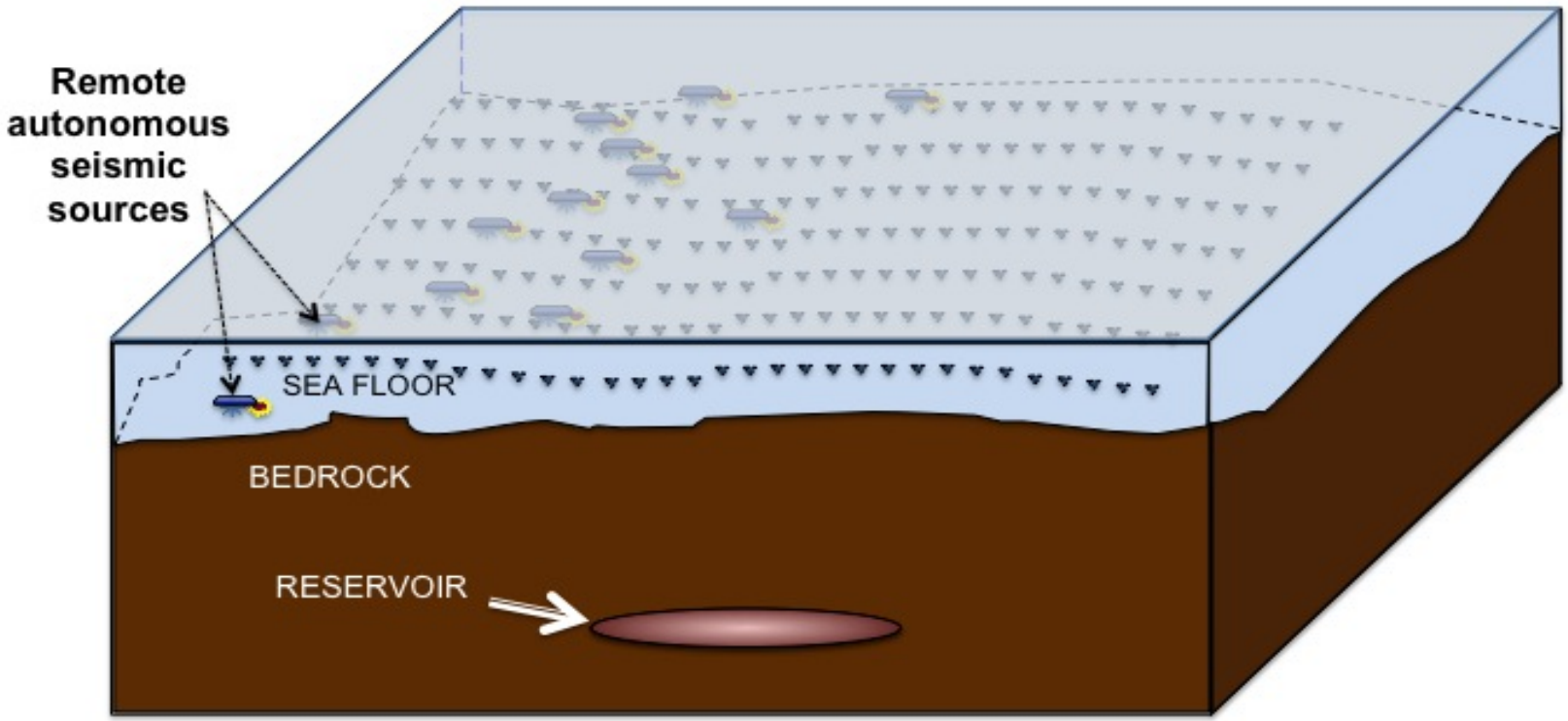
What is simultaneous shooting?

Ocean-bottom cable/seismometer acquisition



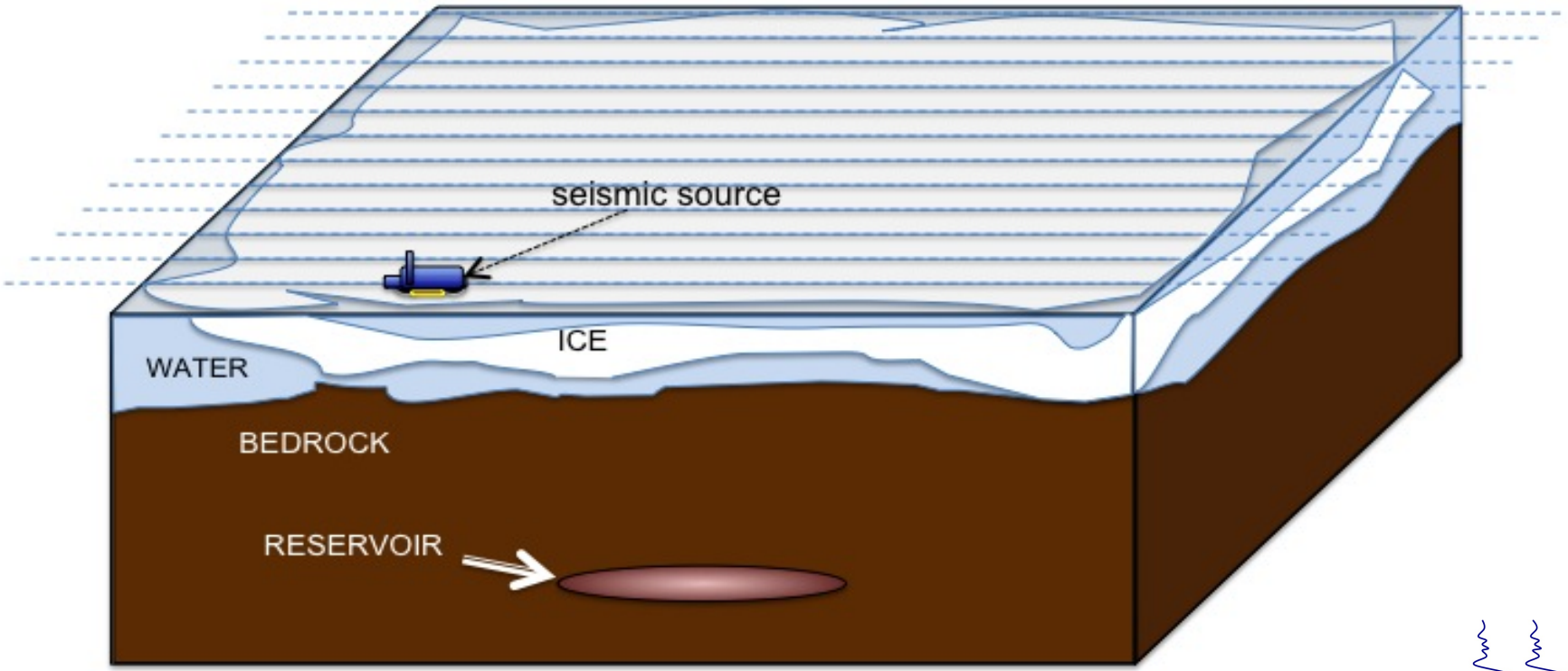
What is simultaneous shooting?

Remote autonomous source acquisition



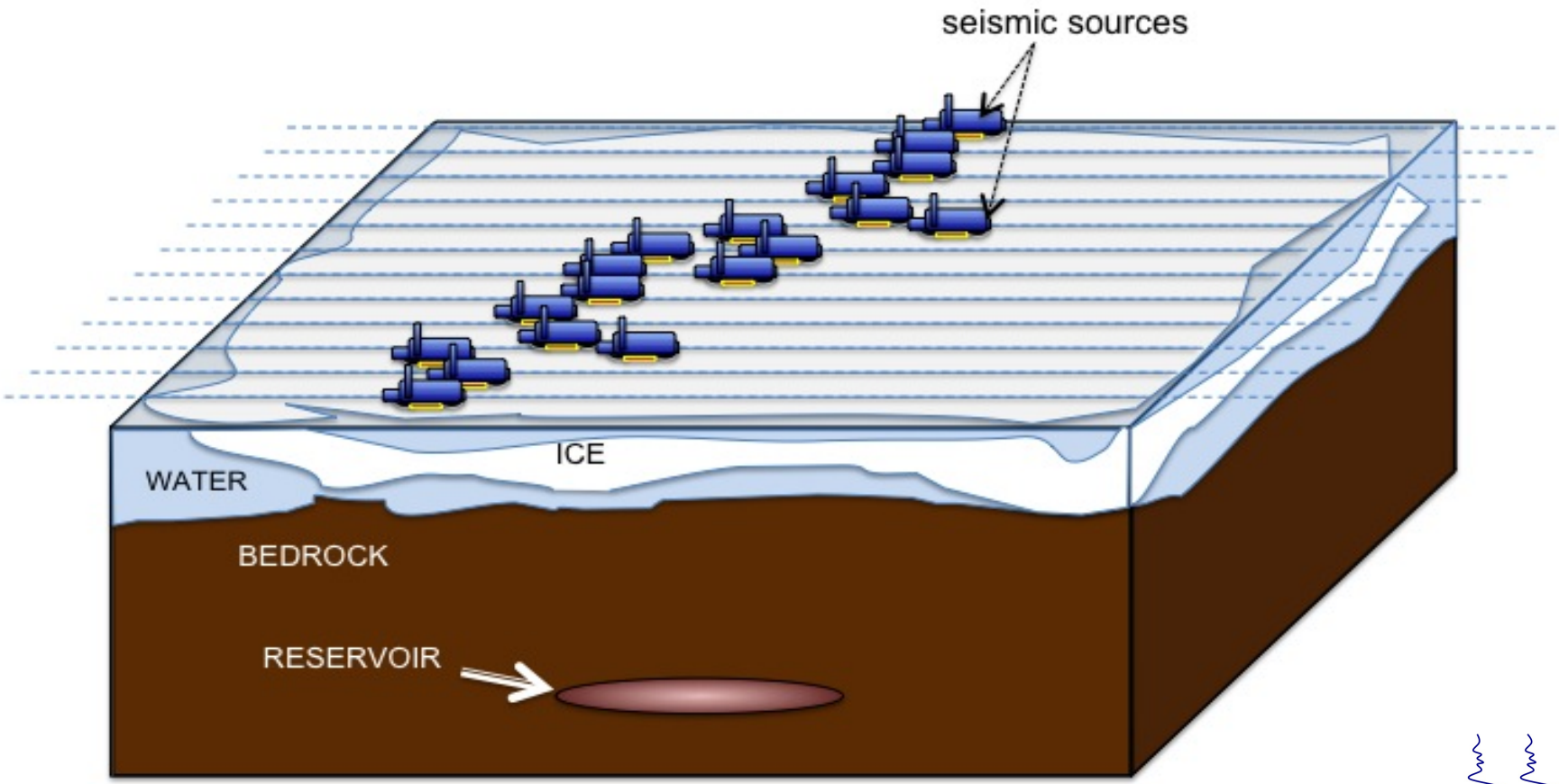
What is simultaneous shooting?

Frontier (E.g. Arctic acquisition)



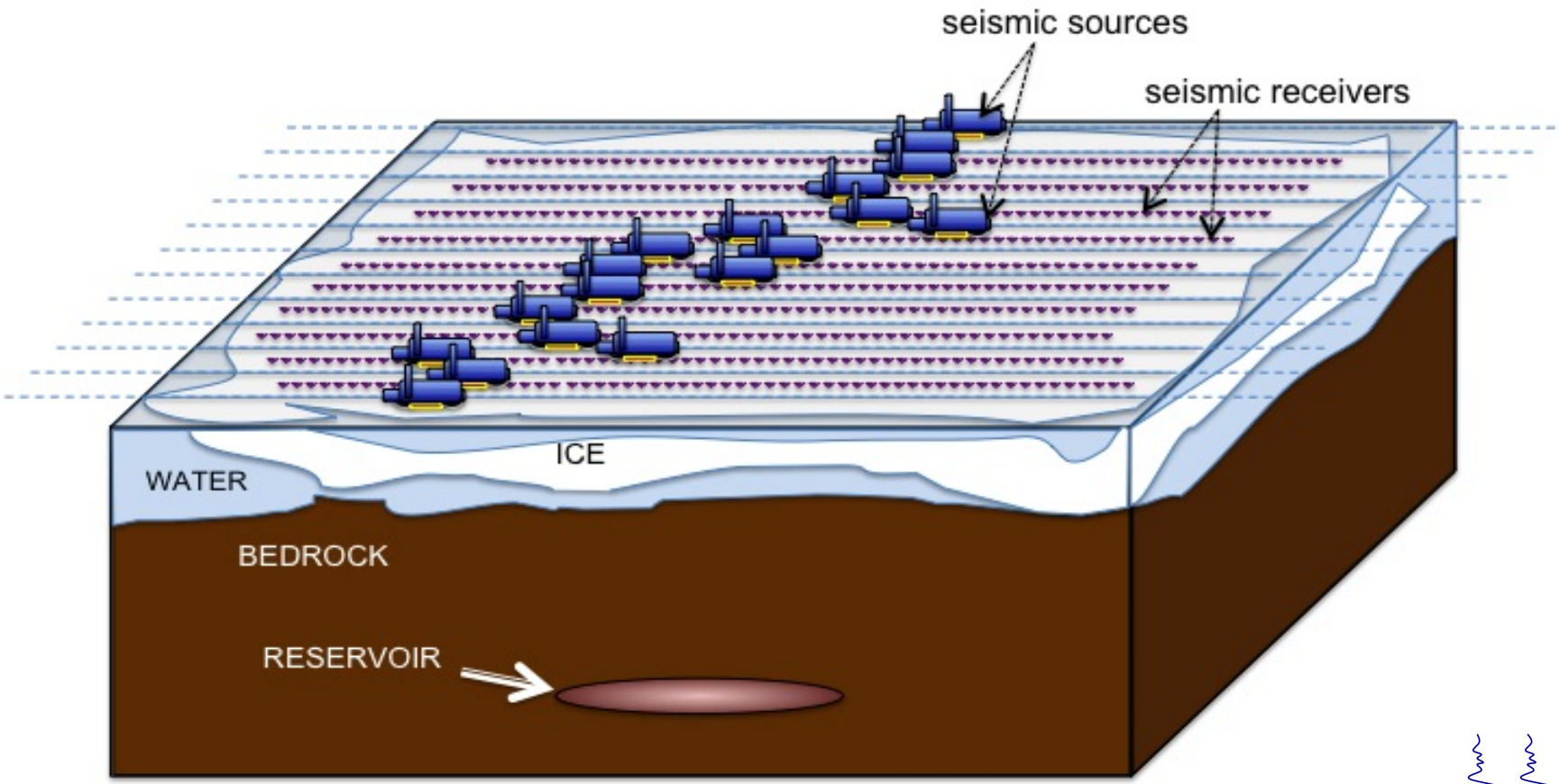
What is simultaneous shooting?

Multiple seismic sources: can reduce acquisition time



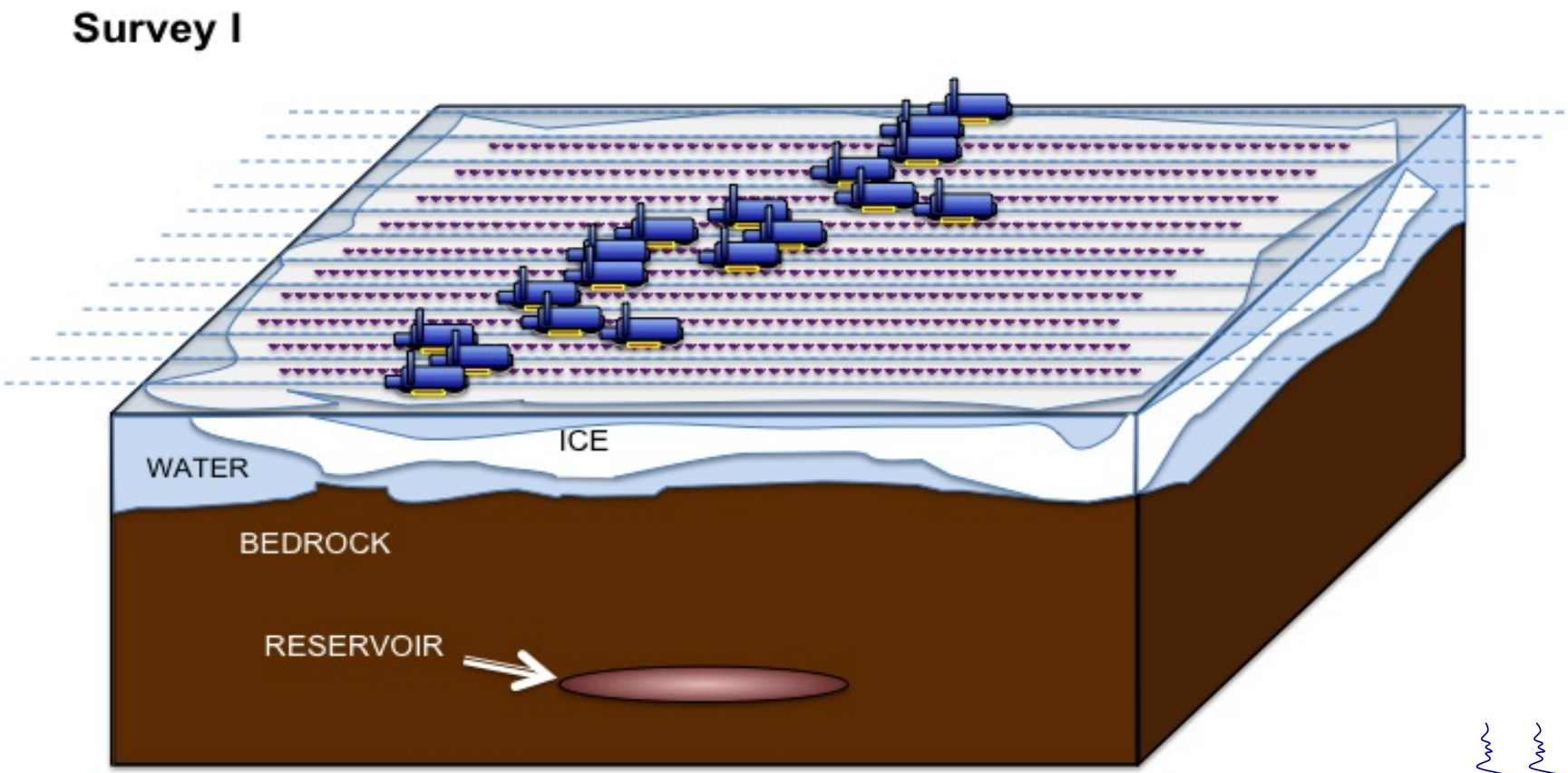
What is simultaneous shooting?

Multiple seismic sources: seasonal data acquisition



What is simultaneous shooting?

Asynchronous time-lapse data with multiple seismic sources



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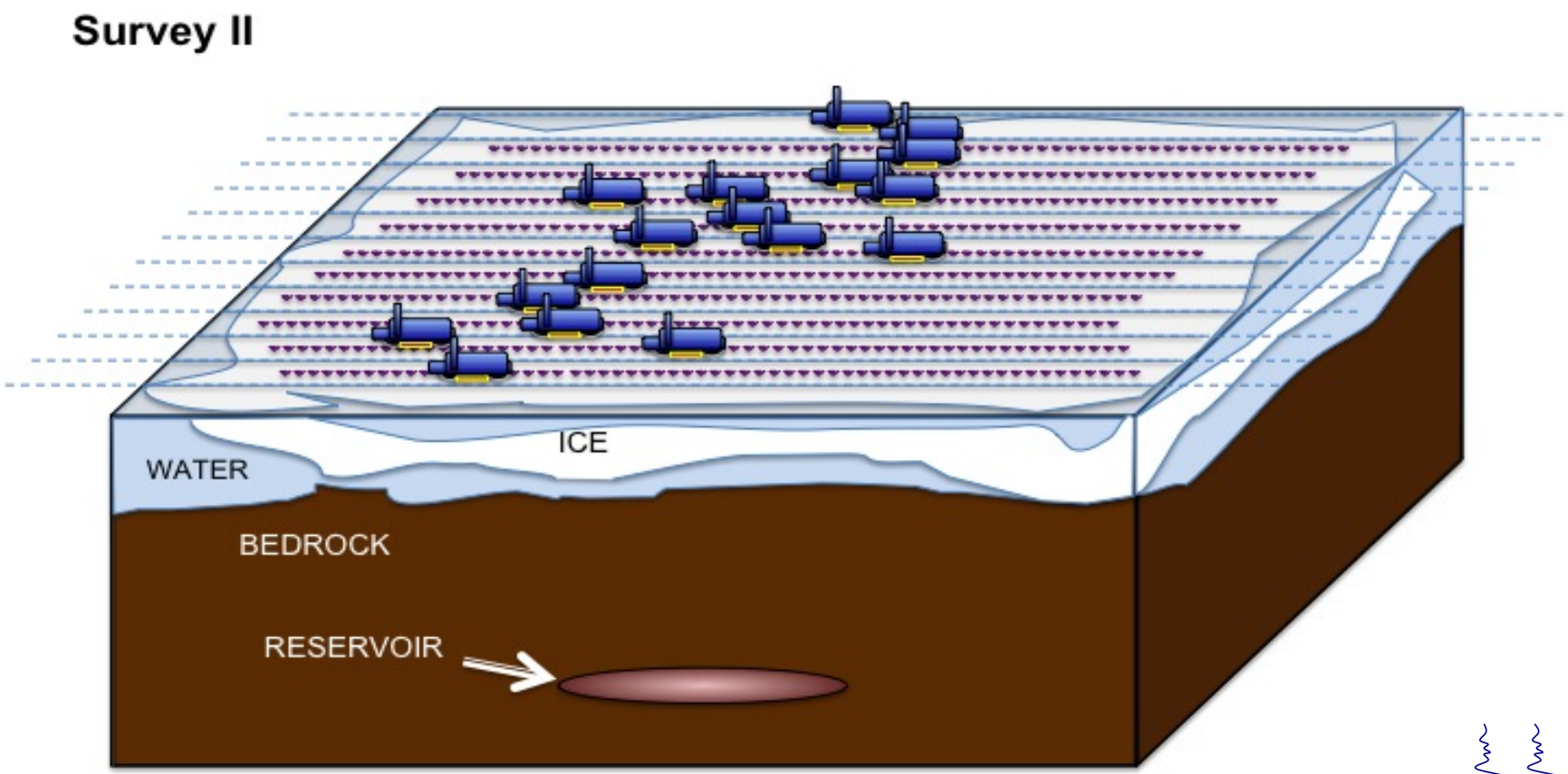

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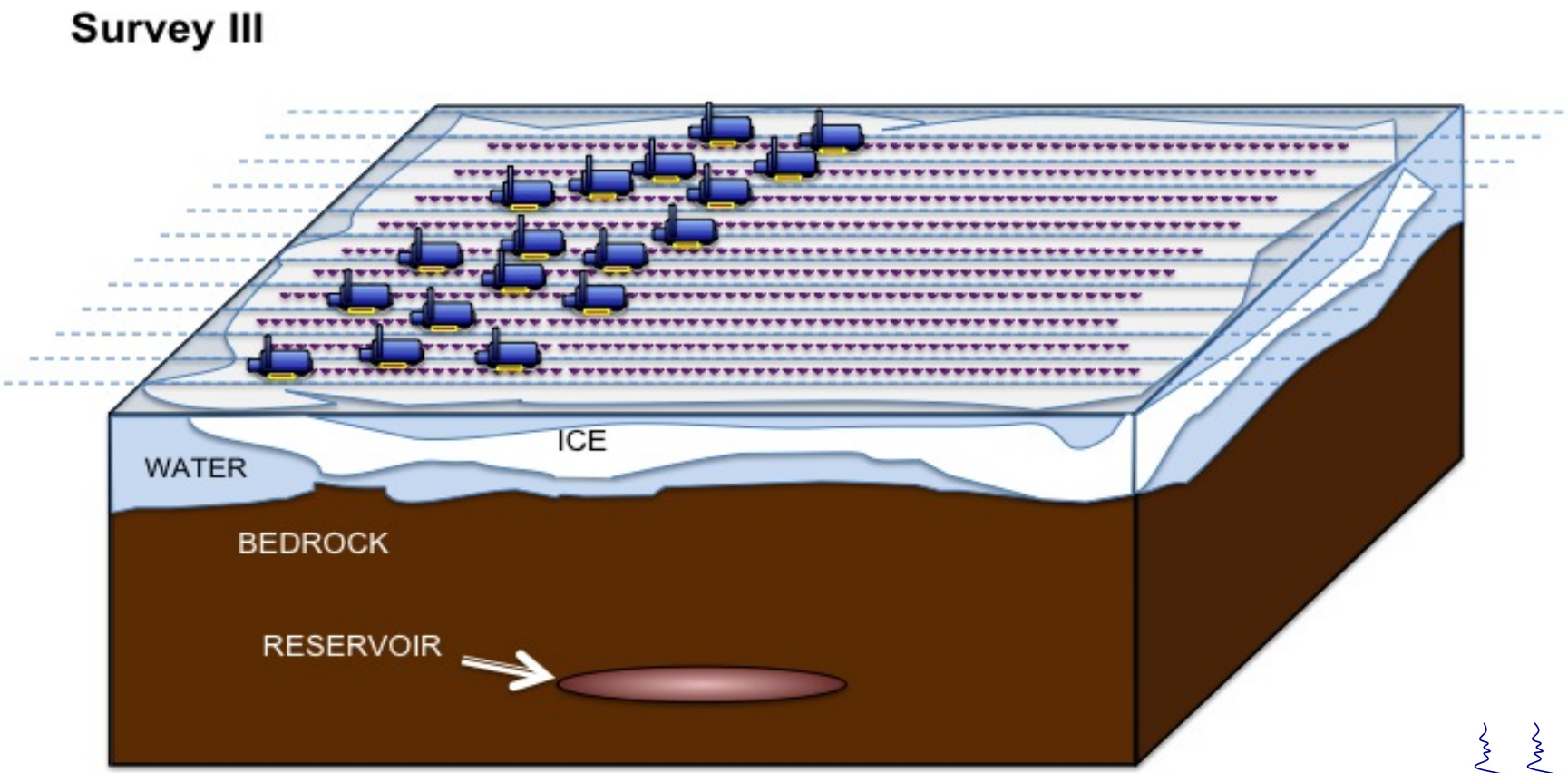
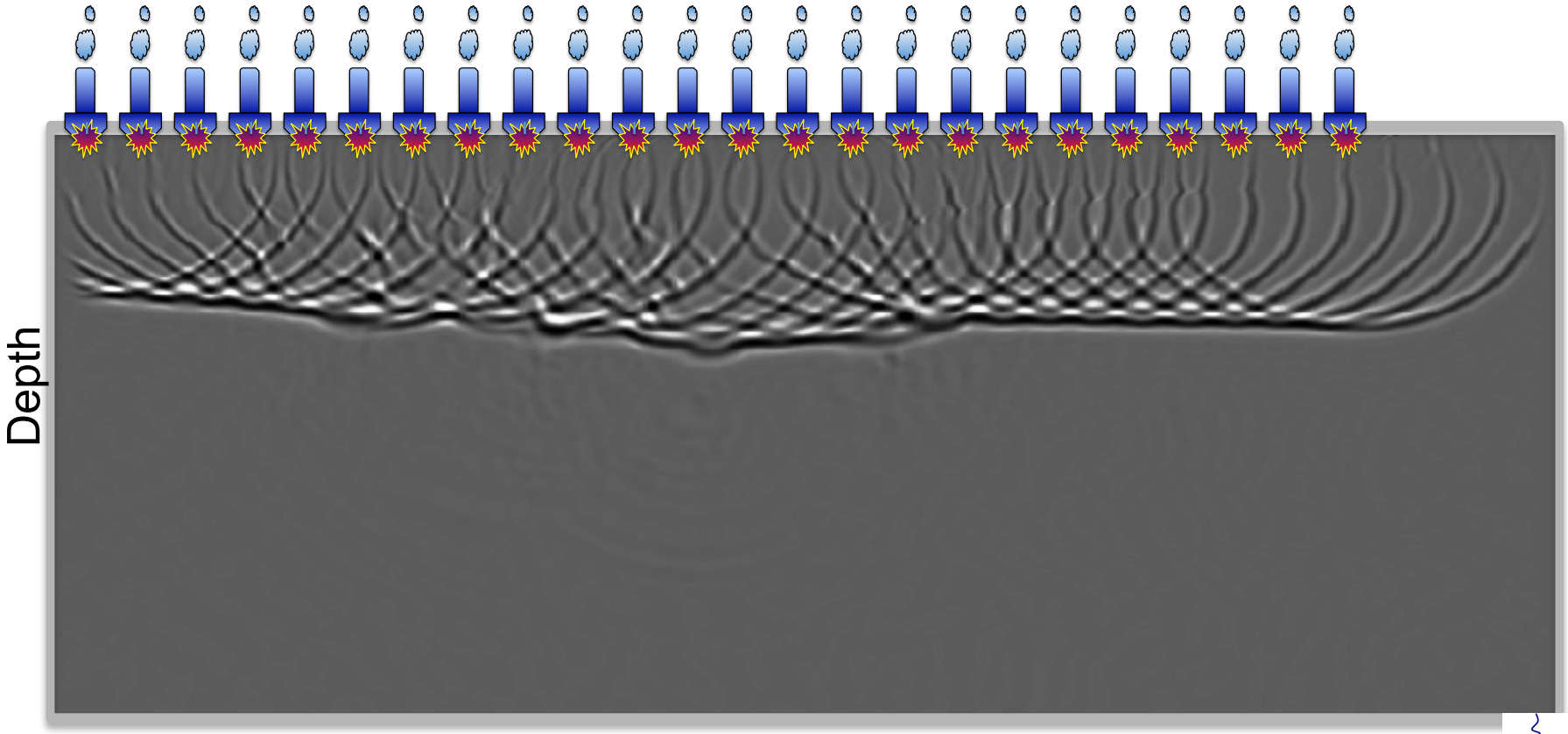


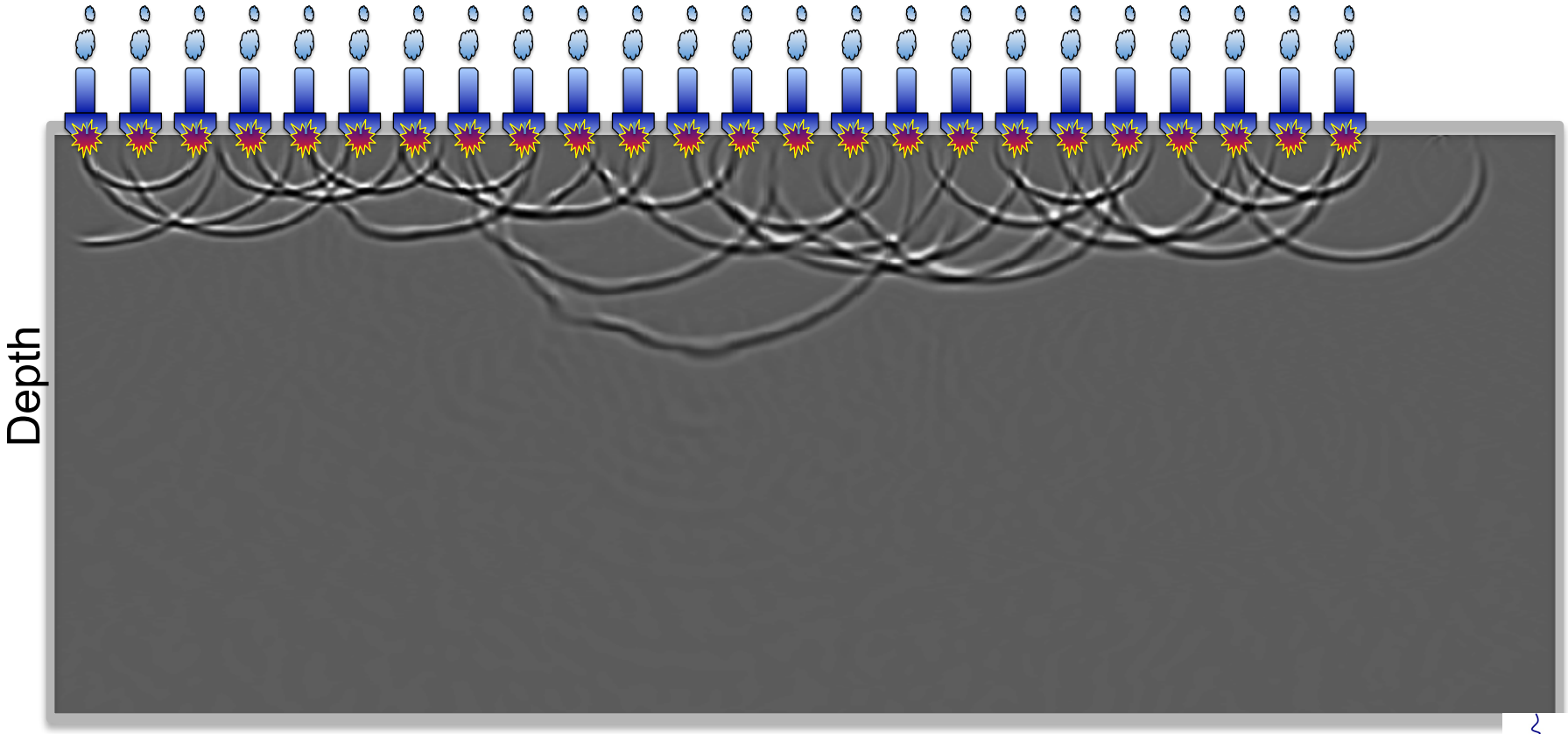
Source wavefields

Simultaneous shooting [29 sources] (synchronous)



Source wavefields

Simultaneous shooting [29 sources] (asynchronous)



Why simultaneous shooting?

- **Improved shot-sampling**: *reduces shot-interpolation requirements in 3D seismic acquisition*
- **Lower acquisition cost**: *enables simultaneous acquisition of multiple azimuths in 3D wide- or multi- azimuth data acquisition at lower cost*
- **Longer offsets**: *enables better imaging or improved AVO information*
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Pros

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  - data acquisition at short time intervals possible.
  - pseudo-continuous reservoir monitoring possible.
  - repetition of survey geometries/timing difficult but unnecessary.

Cons

- **Non-repeatability**:
  - undesirable non-repeatability/imaging artifacts present.

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Source wavefields at fixed relative time [Survey I]

Non-repeatability: Geometry

Source wavefields at fixed relative time [Survey II]

Non-repeatability: Geometry

Source wavefields at fixed relative time [Survey III]

Non-repeatability: Geometry + Shot-timing

Conventional processing of simultaneous source data

1. **Separate the data sets into independent shot records**
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Our approach

1. **Directly invert the data without separation**

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2 Methodology

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Time-lapse (4D) imaging

$$\mathbf{L}_0\mathbf{m}_0 = \mathbf{d}_0$$
$$\mathbf{L}_1\mathbf{m}_1 = \mathbf{d}_1$$

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

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

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Joint least-squares migration/inversion

$$S(\mathbf{m}_0, .., \mathbf{m}_N) = \sum_{i=0}^{N} \left|\left| \widehat{\mathbf{L}}_i \mathbf{m}_i - \widehat{\mathbf{d}}_i \right|\right|_2$$

$S(\mathbf{m}_0, .., \mathbf{m}_N)$: cost function

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$S(\mathbf{m}_0, .., \mathbf{m}_N)$: cost function
$\widehat{\mathbf{d}}_i$: Simultaneous-source (Field encoded) data
$\widehat{\mathbf{L}}_i$: Phase-encoding modeling operator

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$S(\mathbf{m}_0, .., \mathbf{m}_N)$: cost function
N: Number of surveys

Joint least-squares migration/inversion

$$S(\mathbf{m}_0,..,\mathbf{m}_N) = \sum_{i=0}^{N} \left|\left| \widehat{\mathbf{L}}_i \mathbf{m}_i - \widehat{\mathbf{d}}_i \right|\right|_2 +$$

$$\sum_{i=0}^{N} ||\epsilon_i \mathbf{R}_i \mathbf{m}_i||_2 \quad \textit{Structural constraints}$$

$S(\mathbf{m}_0,..,\mathbf{m}_N)$: cost function

R_i: structural constraints with strength (ϵ_i)

Joint least-squares migration/inversion

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$$\sum_{i=0}^{N} ||\epsilon_i \mathbf{R}_i \mathbf{m}_i||_2 \quad \textit{Non - stationary dip filters}$$

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$$\sum_{i=0}^{N} ||\epsilon_i \mathbf{R}_i \mathbf{m}_i||_2 \quad \textit{Non - stationary dip filters}$$

- **Dip estimation**: Fomel's plane-wave destruction method

$S(\mathbf{m}_0,..,\mathbf{m}_N)$: cost function
R_i: structural constraints with strength (ϵ_i)

Joint least-squares migration/inversion

$$S(\mathbf{m}_0,..,\mathbf{m}_N) = \sum_{i=0}^{N} \left|\left| \widehat{\mathbf{L}}_i \mathbf{m}_i - \widehat{\mathbf{d}}_i \right|\right|_2 +$$

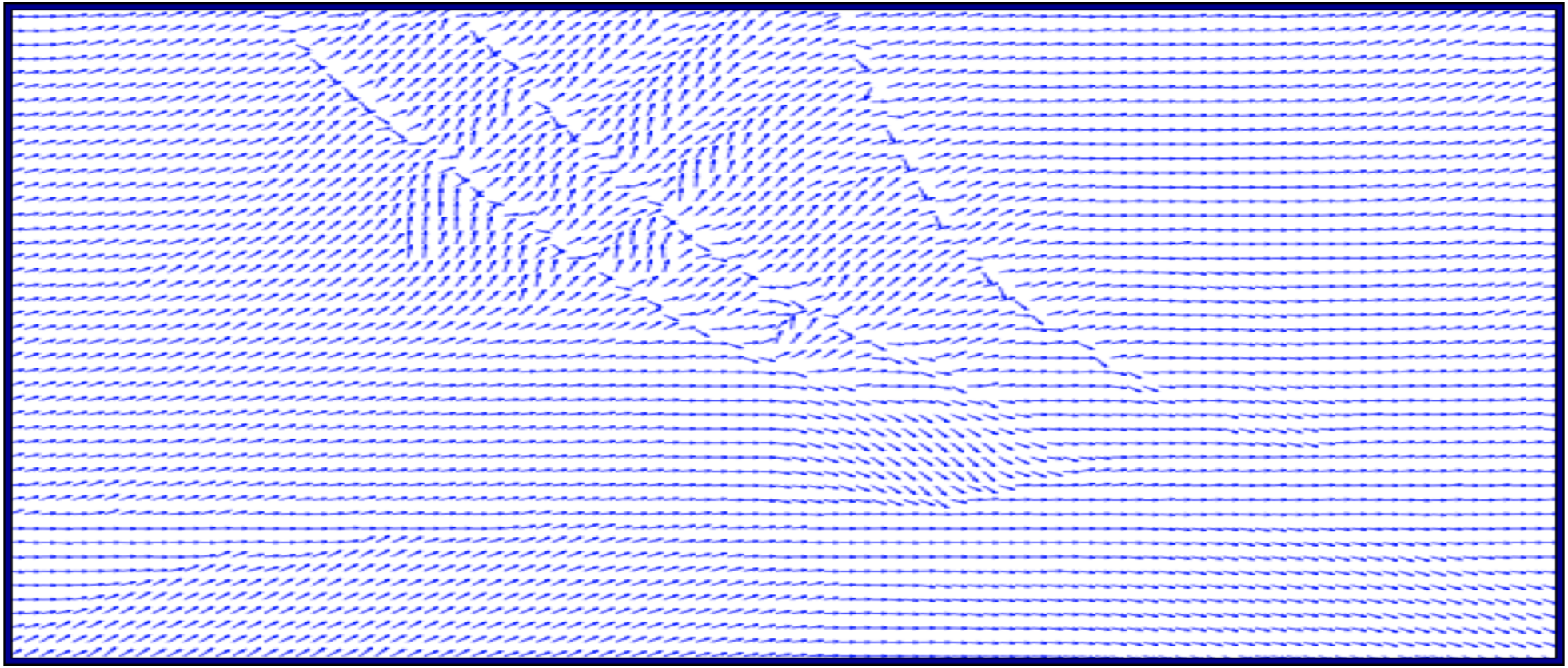
$$\sum_{i=0}^{N} ||\epsilon_i \mathbf{R}_i \mathbf{m}_i||_2 \quad \textit{Non - stationary dip filters}$$

- **Dip estimation**: Fomel's plane-wave destruction method
- **Dip filtering**: Hale's Directional Laplacian method

$S(\mathbf{m}_0,..,\mathbf{m}_N)$: cost function
R_i: structural constraints with strength (ϵ_i)

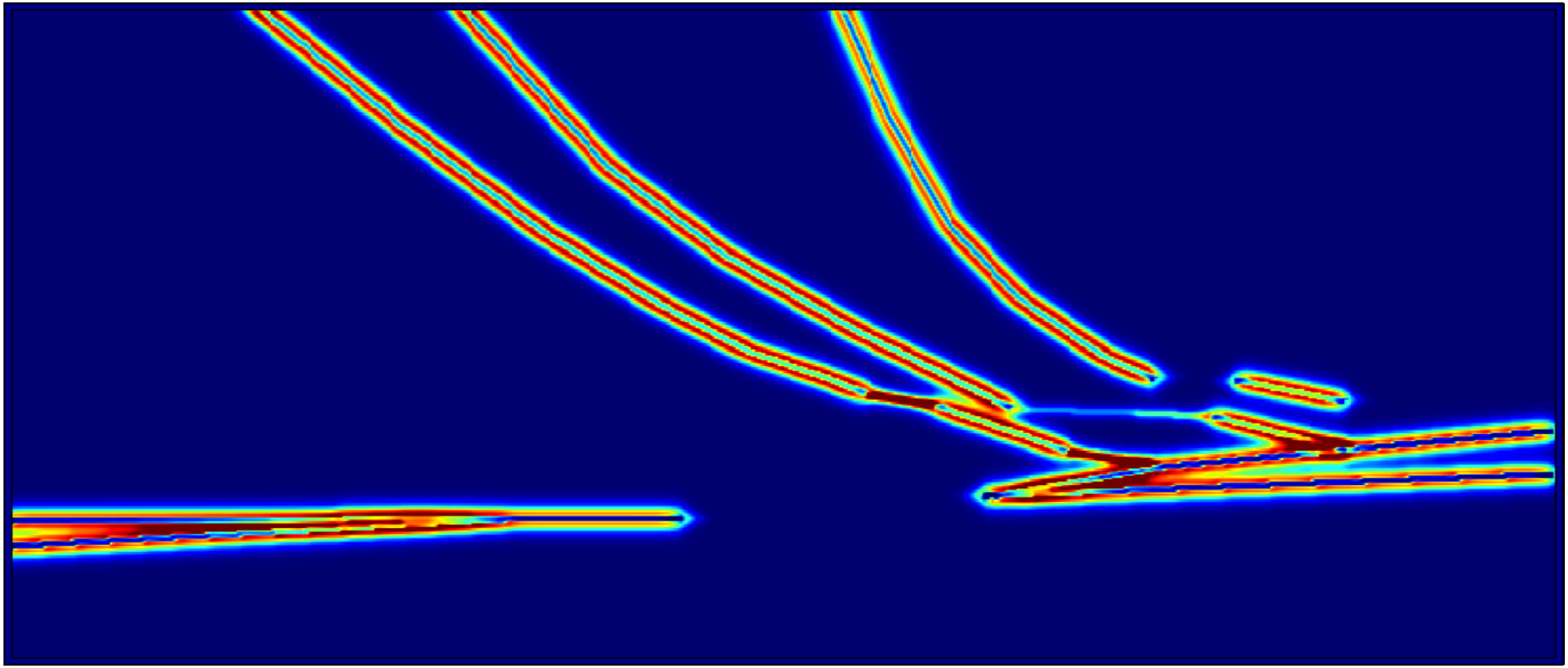
Joint least-squares migration/inversion

Dip estimates from baseline image



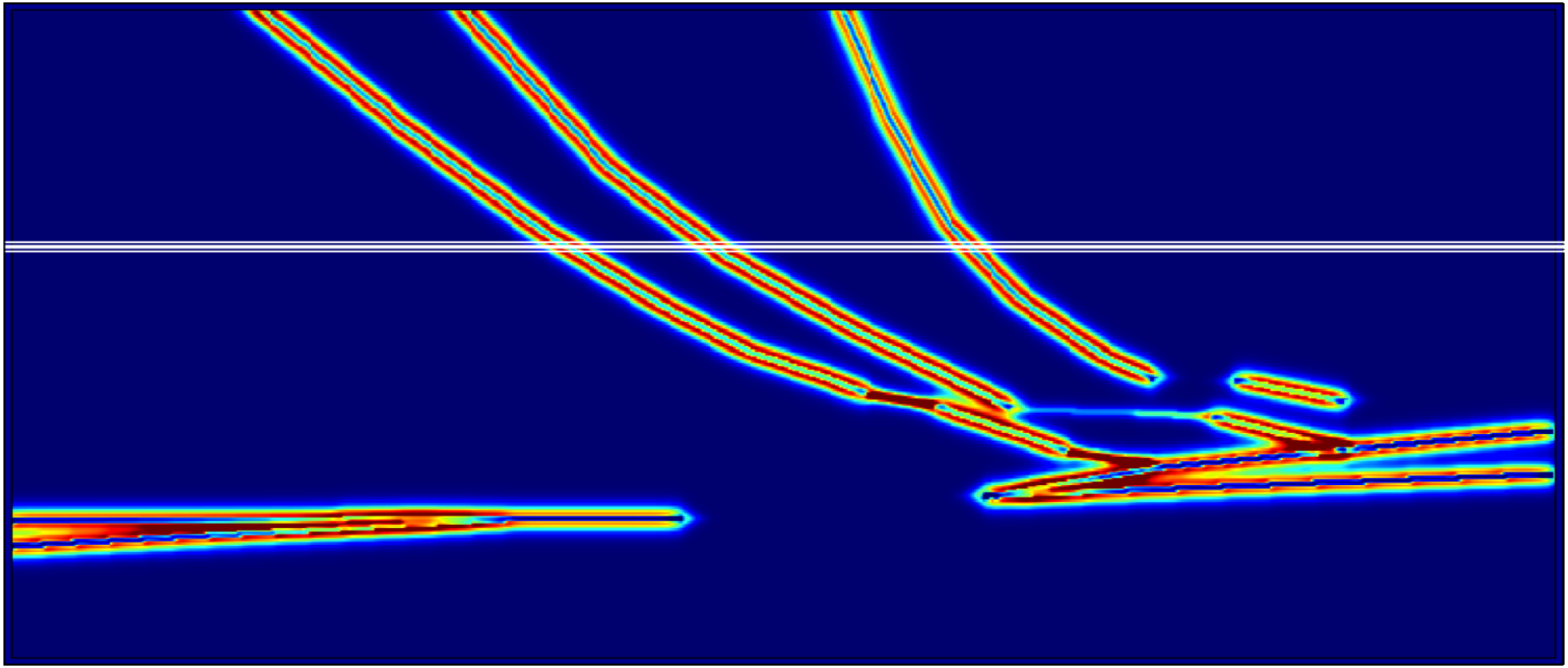
Joint least-squares migration/inversion

Dip-contrast variance



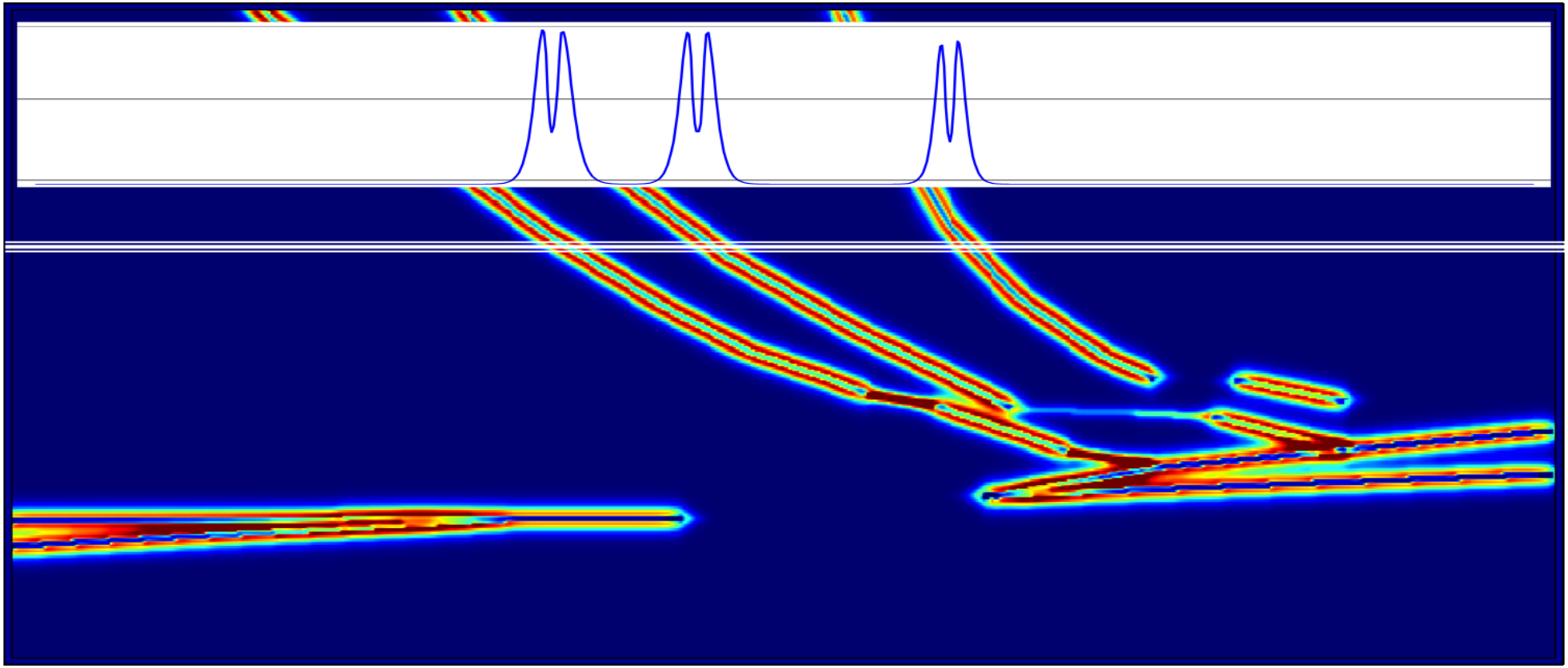
Joint least-squares migration/inversion

Dip-contrast variance



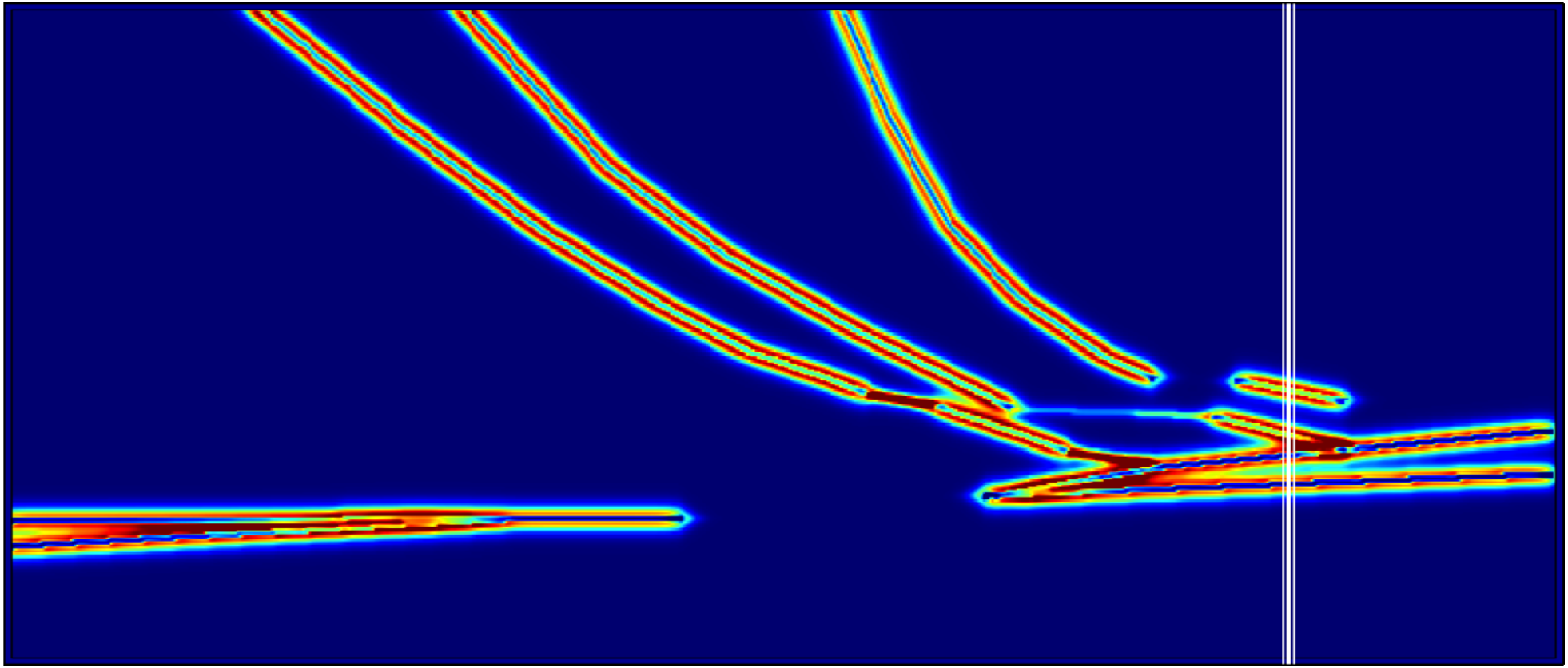
Joint least-squares migration/inversion

Dip-contrast variance



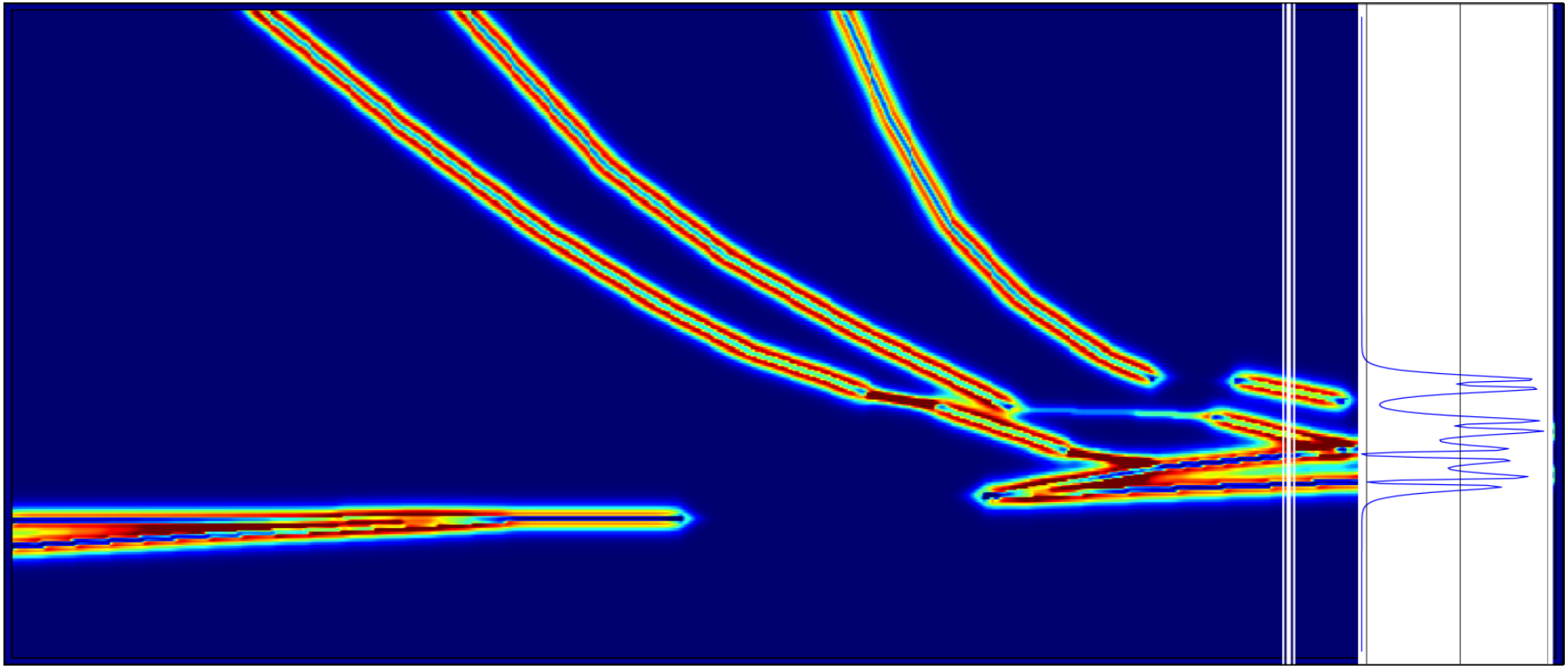
Joint least-squares migration/inversion

Dip-contrast variance



Joint least-squares migration/inversion

Dip-contrast variance



Joint least-squares migration/inversion

$$S(\mathbf{m}_0,..,\mathbf{m}_N) = \sum_{i=0}^{N} \left|\left| \widehat{\mathbf{L}}_i \mathbf{m}_i - \widehat{\mathbf{d}}_i \right|\right|_2 +$$

$$\sum_{i=0}^{N} ||\epsilon_i \mathbf{R}_i \mathbf{m}_i||_2 \quad Non-stationary\ dip\ filters$$

Hale, D., 2007: Local dip filtering with directional Laplacians: CWP Report 567, 91-102

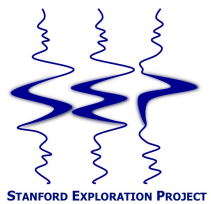
Ayeni et. al., 2009: Joint inversion of simultaneous source time-lapse seismic data sets, SEP Report 138, 155-170

$S(\mathbf{m}_0,..,\mathbf{m}_N)$: cost function
R_i: structural constraints with strength (ϵ_i)

Joint least-squares migration/inversion

$$S(\mathbf{m}_0,..,\mathbf{m}_N) = \sum_{i=0}^{N} \left|\left| \widehat{\mathbf{L}}_i \mathbf{m}_i - \widehat{\mathbf{d}}_i \right|\right|_2 +$$
$$\sum_{i=0}^{N} ||\epsilon_i \mathbf{R}_i \mathbf{m}_i||_2 +$$
$$\sum_{i=1}^{N} ||\zeta_i \mathbf{\Lambda}_i (\mathbf{m}_{i-1}, \mathbf{m}_i)||_2 \quad \textit{coupling constraints}$$

$S(\mathbf{m}_0,..,\mathbf{m}_N)$: cost function
Λ_i: temporal constraints with strength (ζi)



Joint least-squares migration/inversion

$$S(\mathbf{m}_0,..,\mathbf{m}_N) = \sum_{i=0}^{N} \left|\left| \widehat{\mathbf{L}}_i \mathbf{m}_i - \widehat{\mathbf{d}}_i \right|\right|_2 +$$
$$\sum_{i=0}^{N} ||\epsilon_i \mathbf{R}_i \mathbf{m}_i||_2 +$$
$$\sum_{i=1}^{N} ||\zeta_i \mathbf{\Lambda}_i (\mathbf{m}_{i-1}, \mathbf{m}_i)||_2 +$$
$$\sum_{i=1}^{N} ||\beta_i \mathbf{\Gamma}_i (\Delta m_i)||_{hb} \quad \textit{sparsity constraints (hybrid norm)}$$

$S(\mathbf{m}_0,..,\mathbf{m}_N)$: cost function
Γi: sparsity constraints with strength (βi)

Joint least-squares migration/inversion

$$S(\mathbf{m}_0,..,\mathbf{m}_N) = \sum_{i=0}^{N} \left|\left| \widehat{\mathbf{L}}_i \mathbf{m}_i - \widehat{\mathbf{d}}_i \right|\right|_2 +$$
$$\sum_{i=0}^{N} ||\epsilon_i \mathbf{R}_i \mathbf{m}_i||_2 +$$
$$\sum_{i=1}^{N} ||\zeta_i \mathbf{\Lambda}_i (\mathbf{m}_{i-1}, \mathbf{m}_i)||_2 +$$
$$\sum_{i=1}^{N} ||\beta_i \mathbf{\Gamma}_i (\Delta m_i)||_{hb}$$

Iteratively minimize S

Outline

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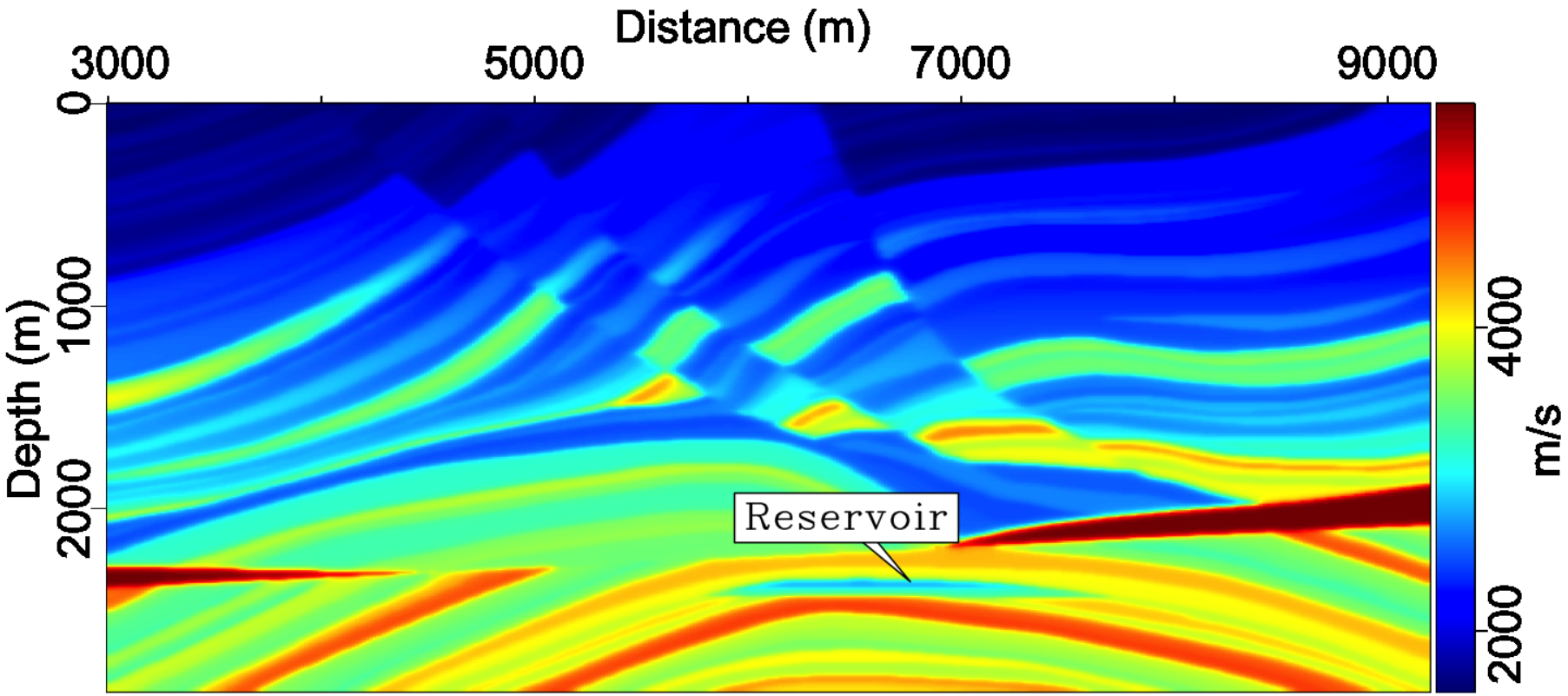
Velocity model (baseline)



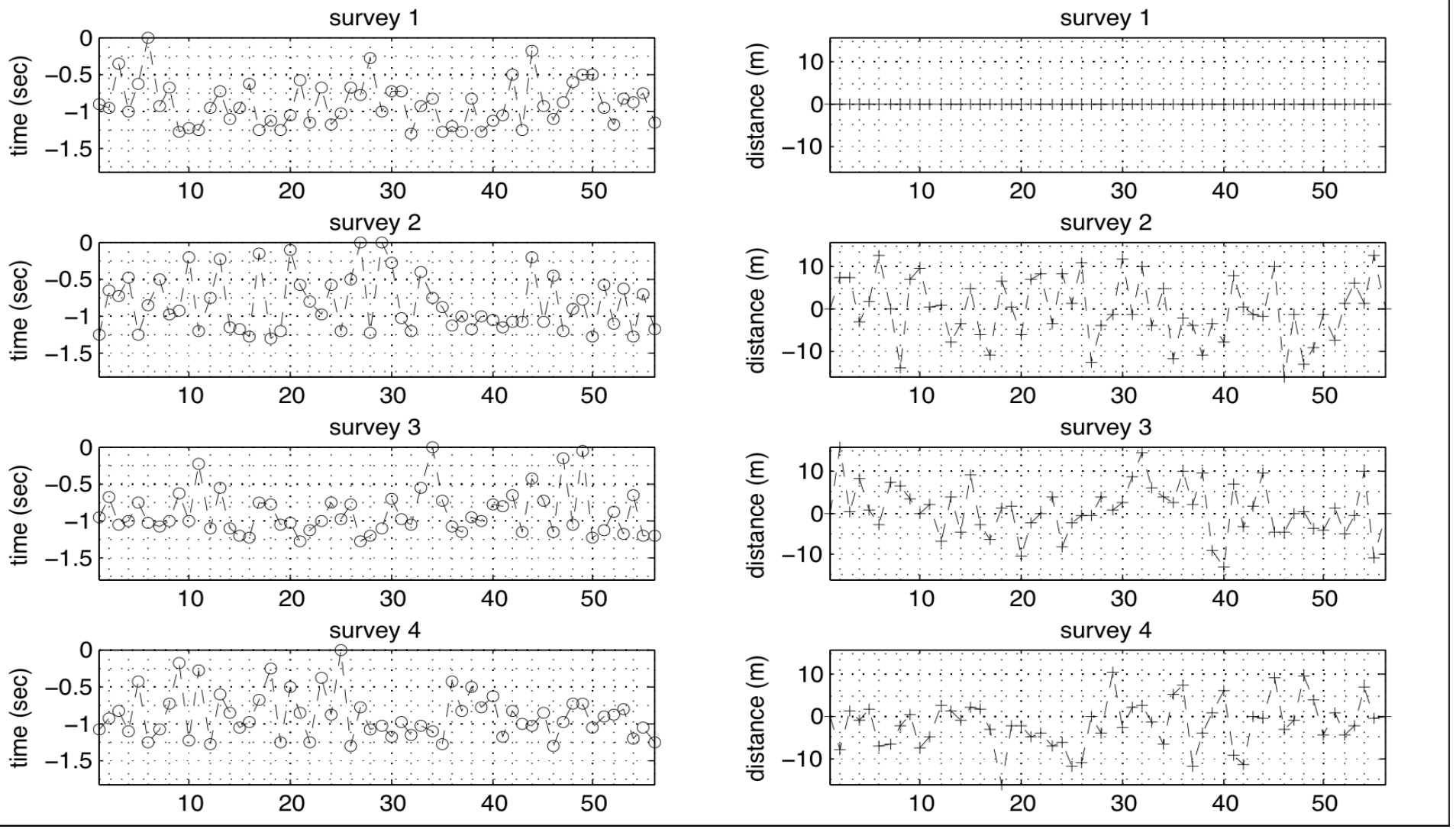
Data summary

Table I: Modeling parameters

	Shots	Receivers
Number	56	388
spacing (m)	96	16

- Non-repeated geometry [Max. shot-displacement: 32 m]
- Non-repeated shot-timing [Max. relative delay: 2.0 s]
- All shots encoded
- Born single-scatter data
- Neglect geomechanical changes

Non-repeatability: Timing (left) and Geometry (right)



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Full image volume

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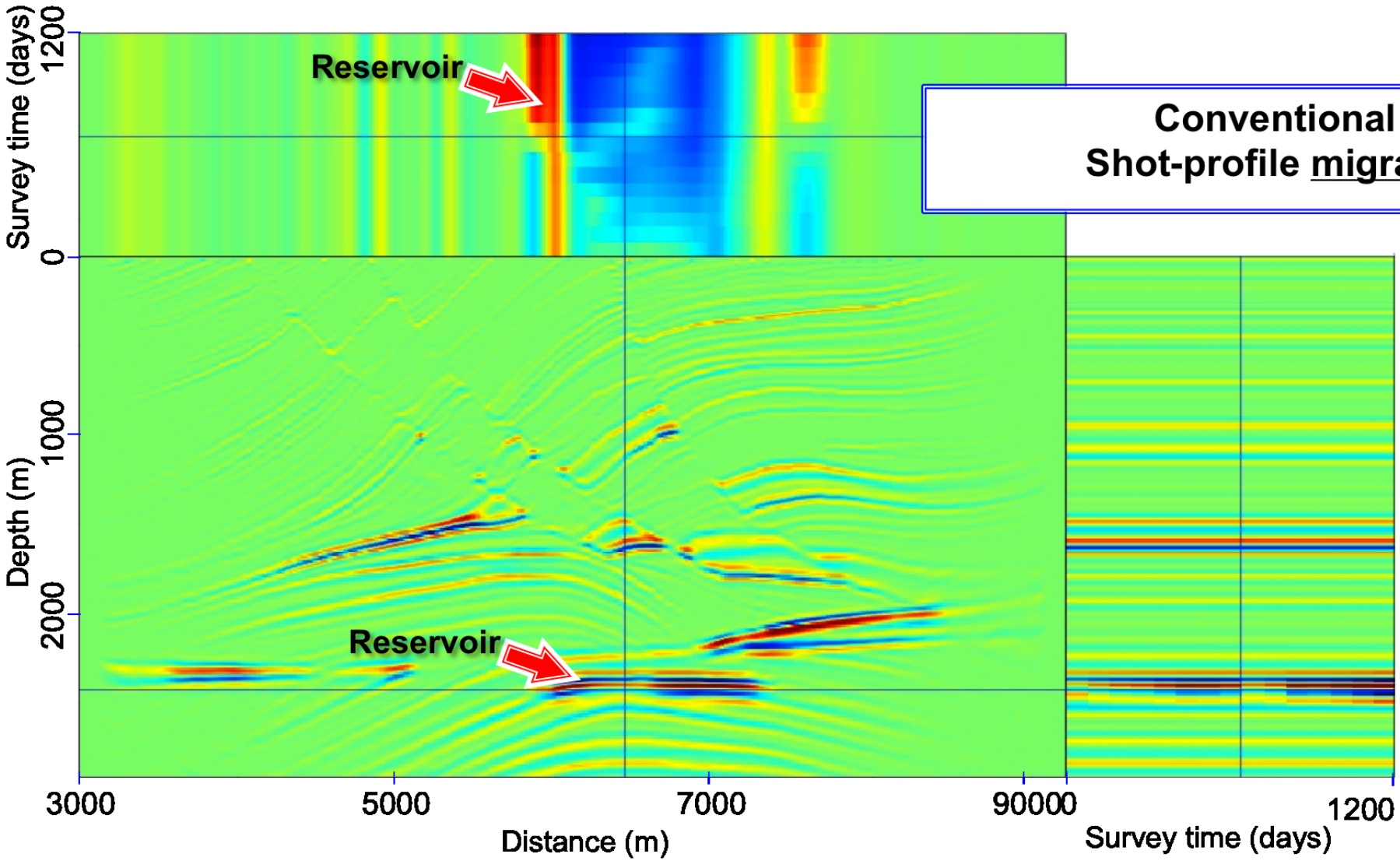
Full image volume



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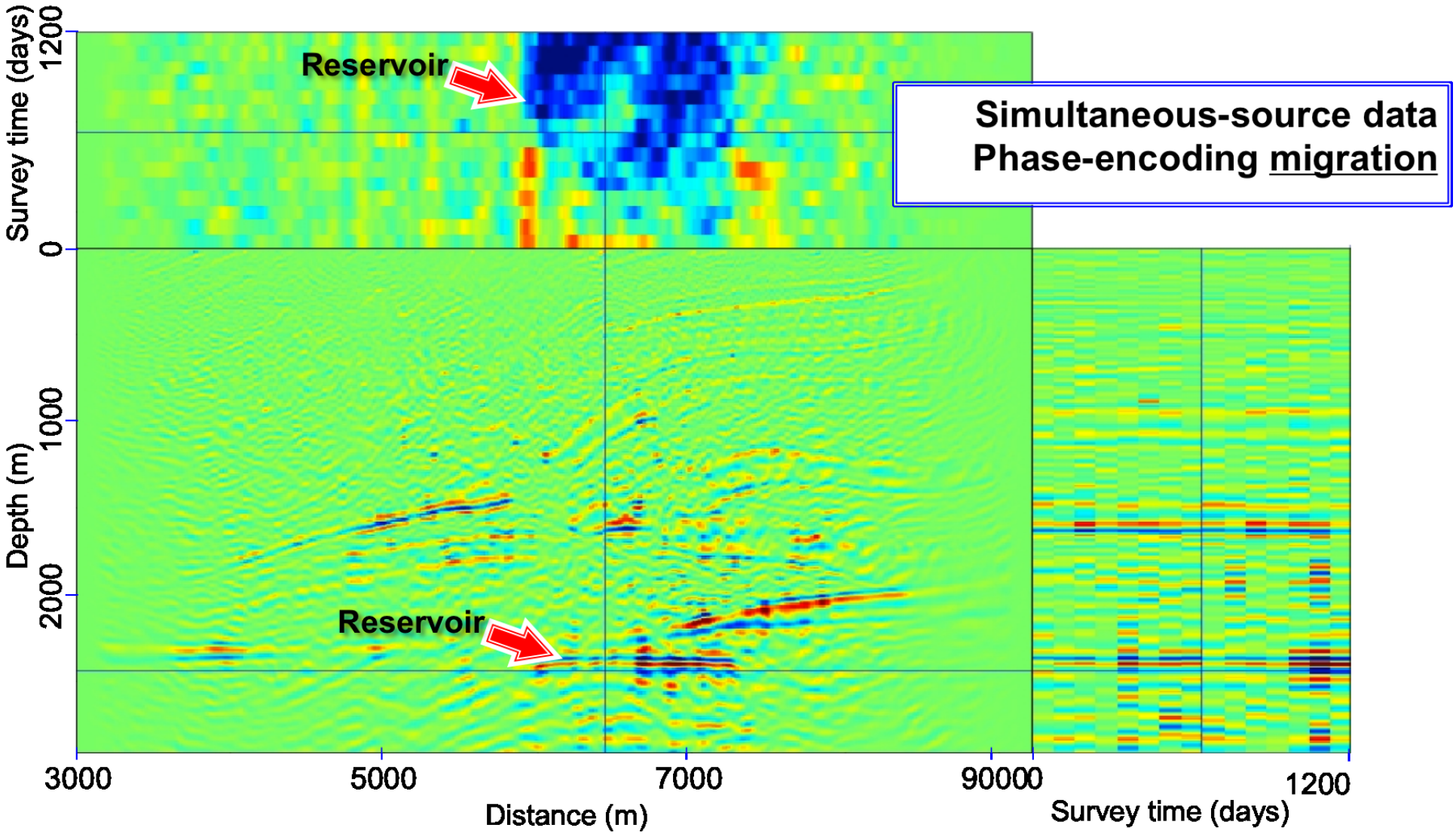

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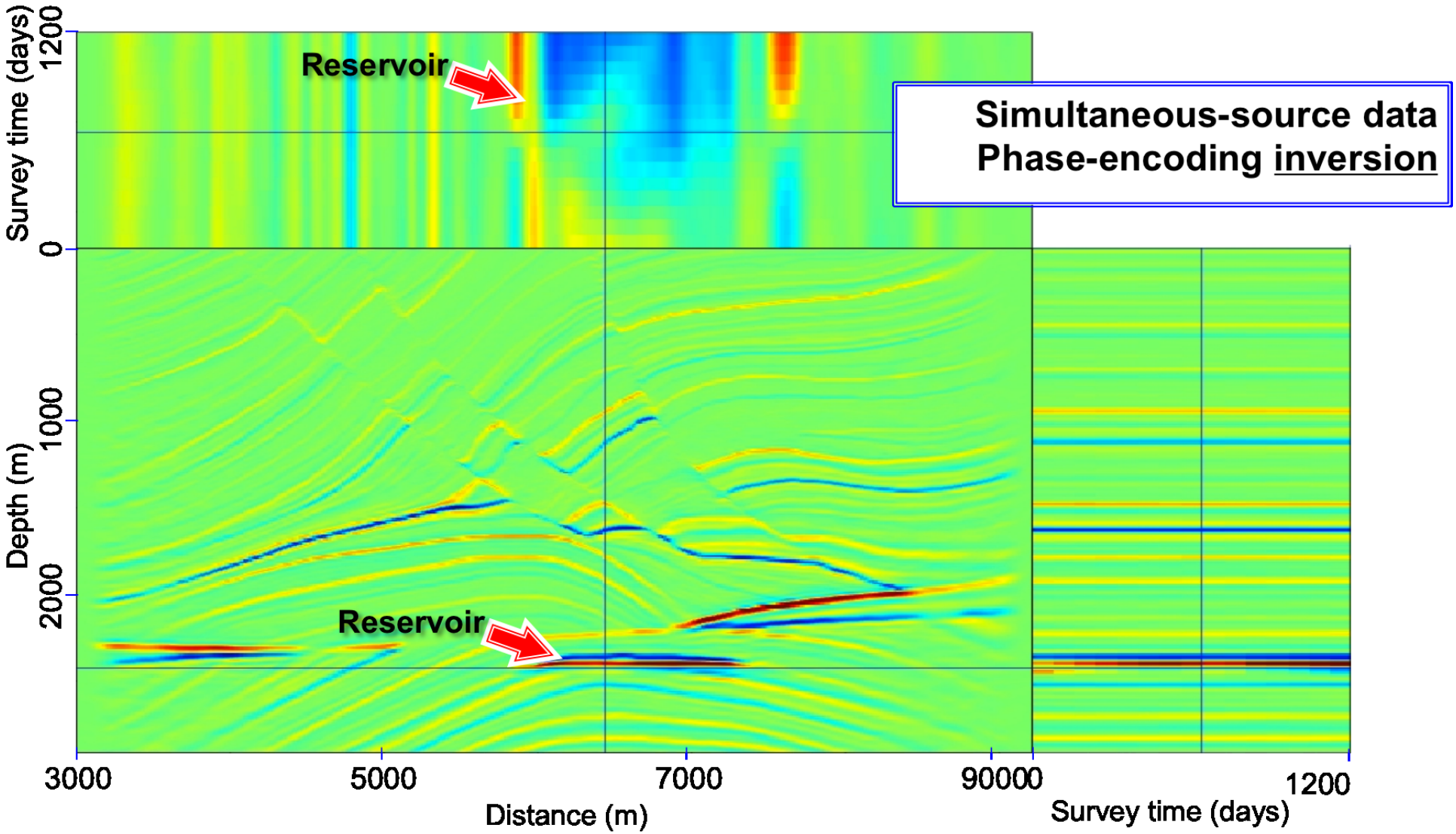

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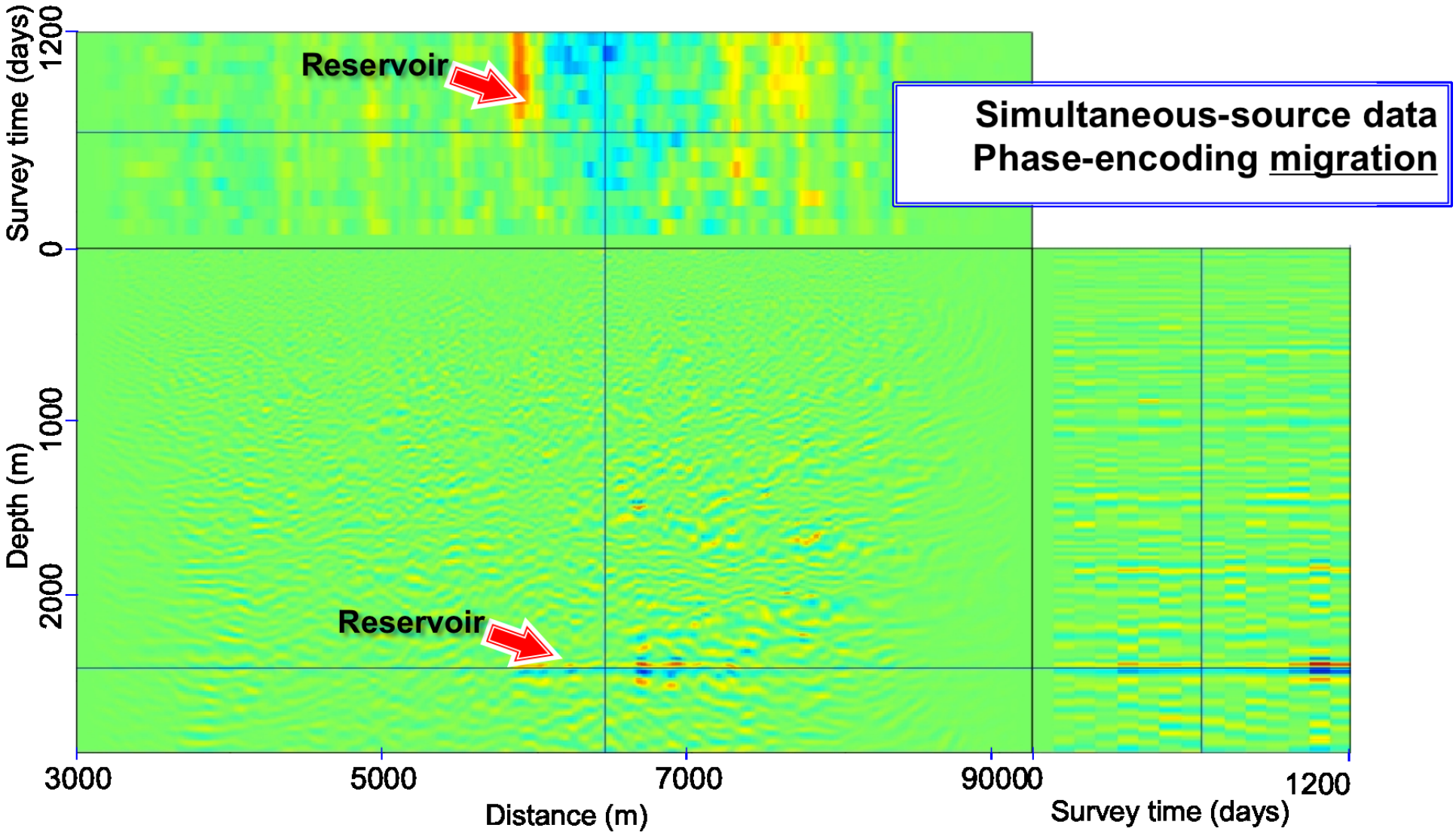
Time-lapse (4D) image volume

Time-lapse (4D) image volume



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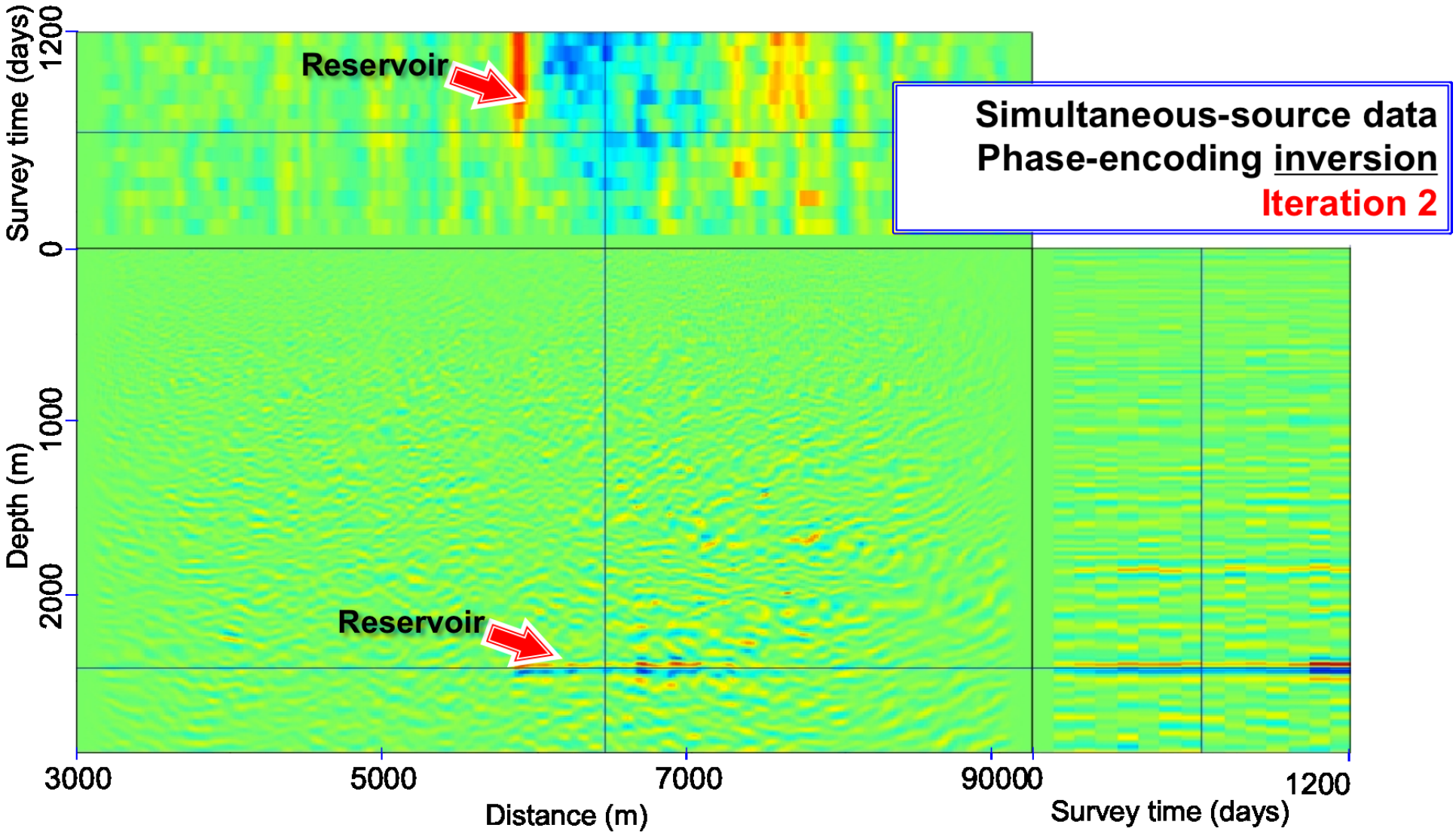
Time-lapse (4D) image volume



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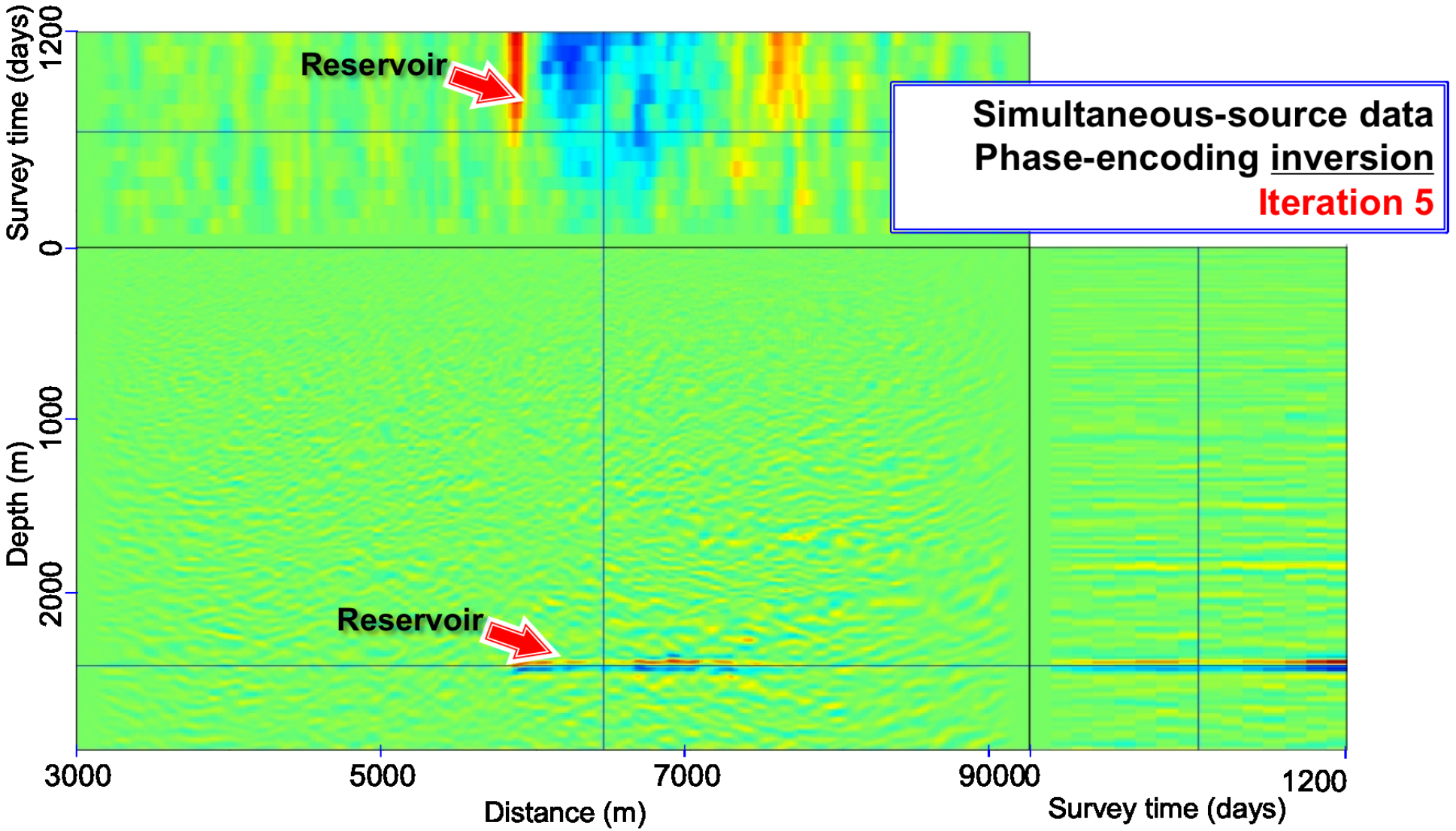
Time-lapse (4D) image volume



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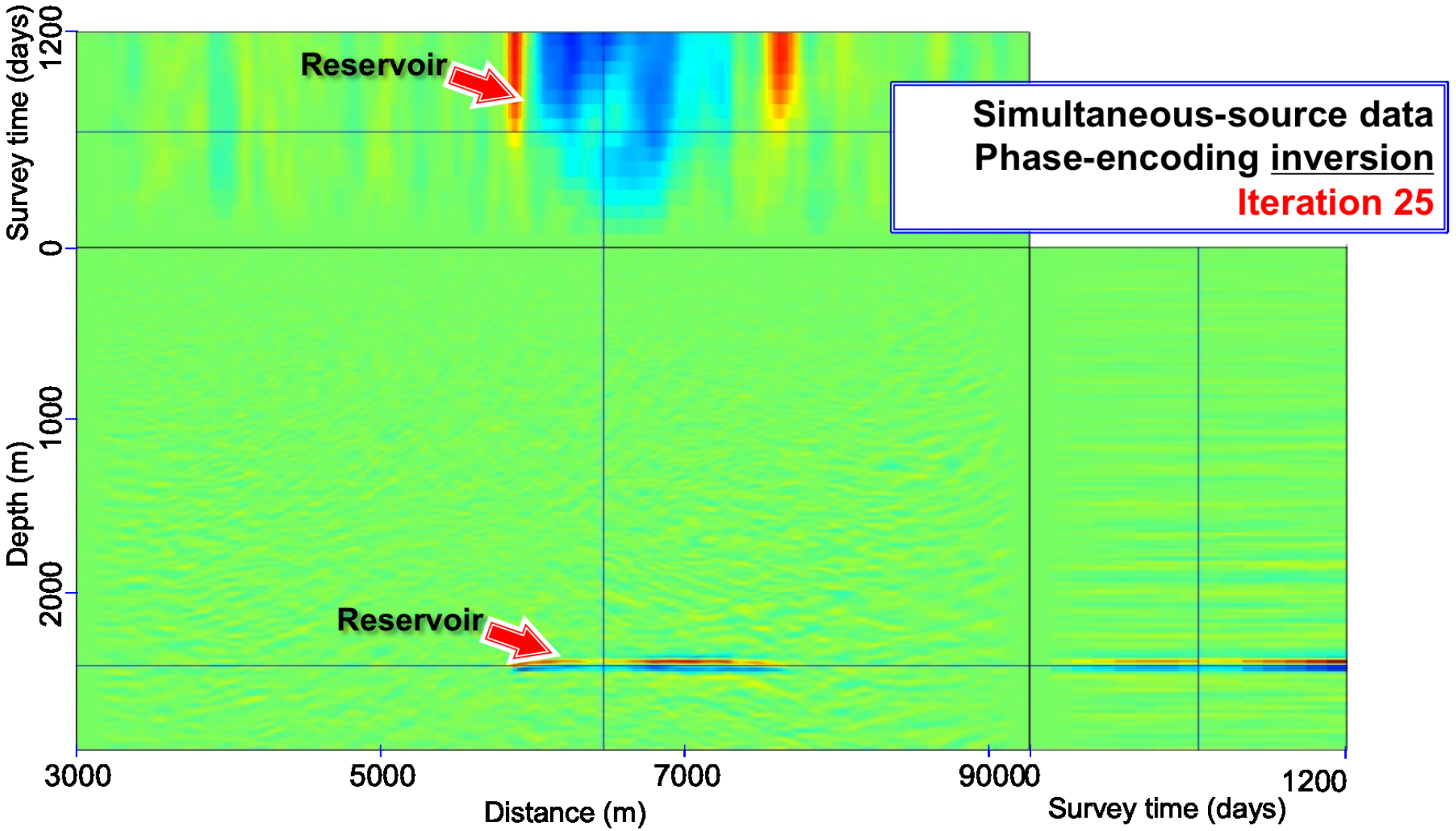
Time-lapse (4D) image volume



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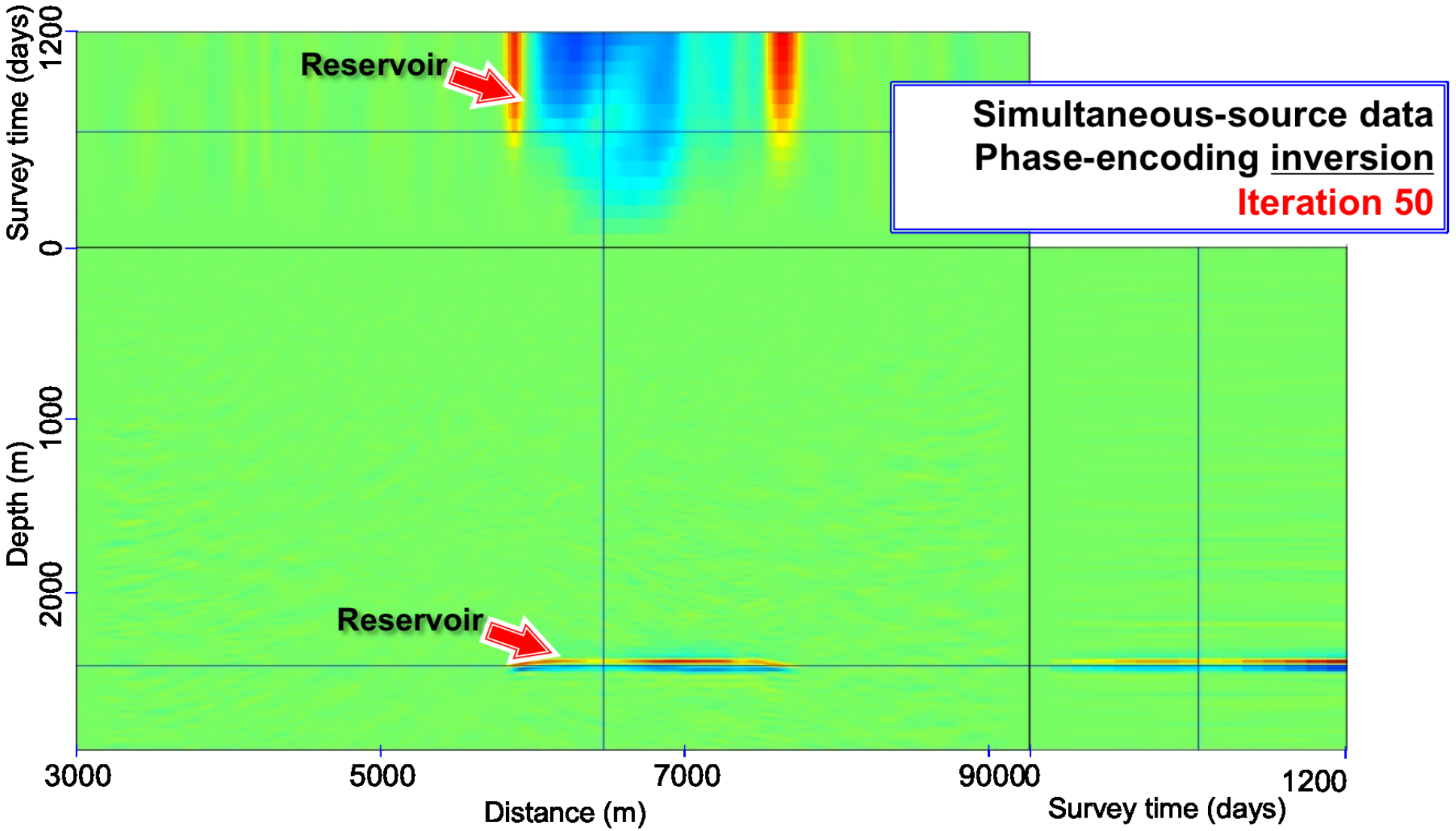
Time-lapse (4D) image volume



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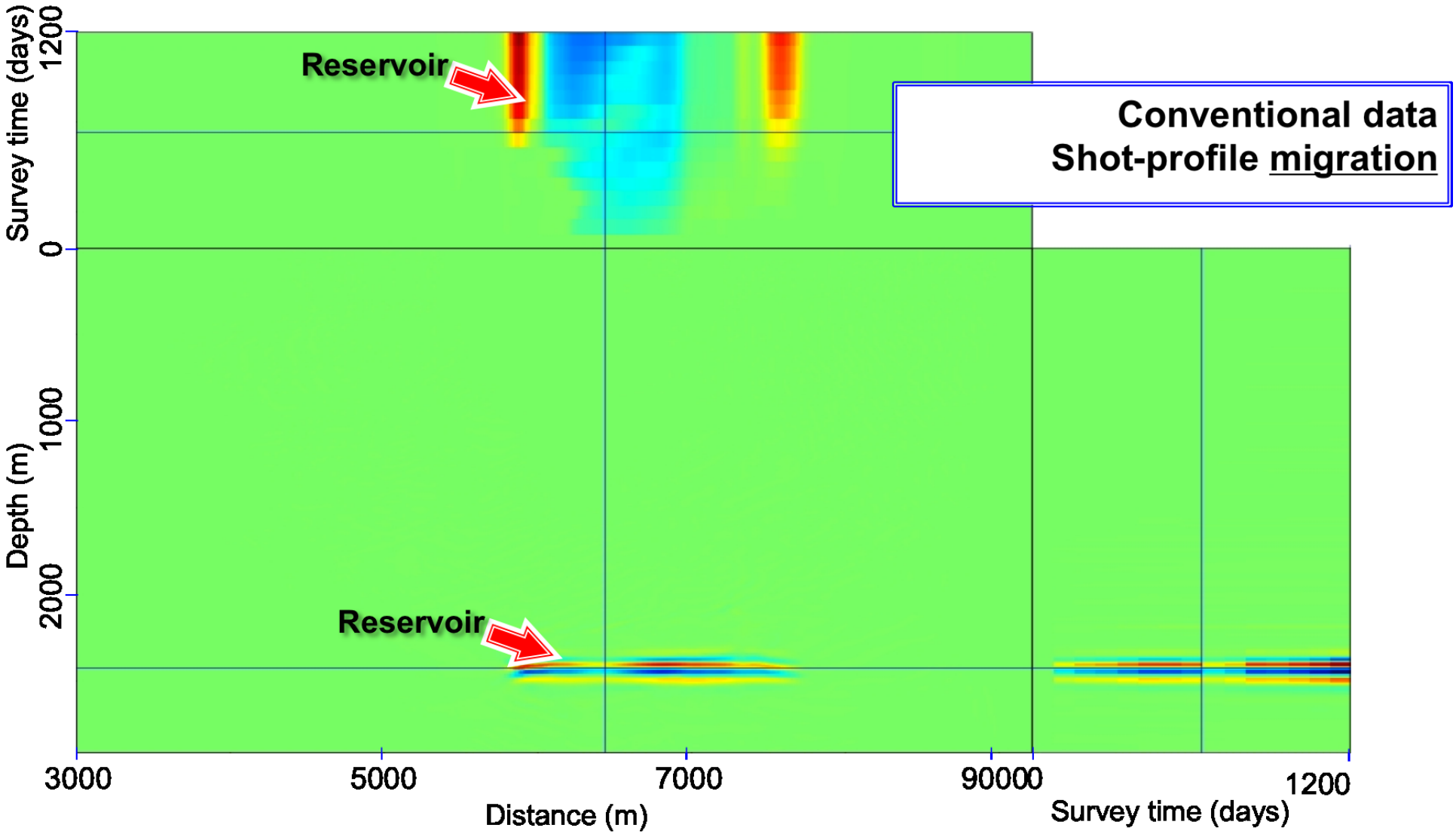
Time-lapse (4D) image volume



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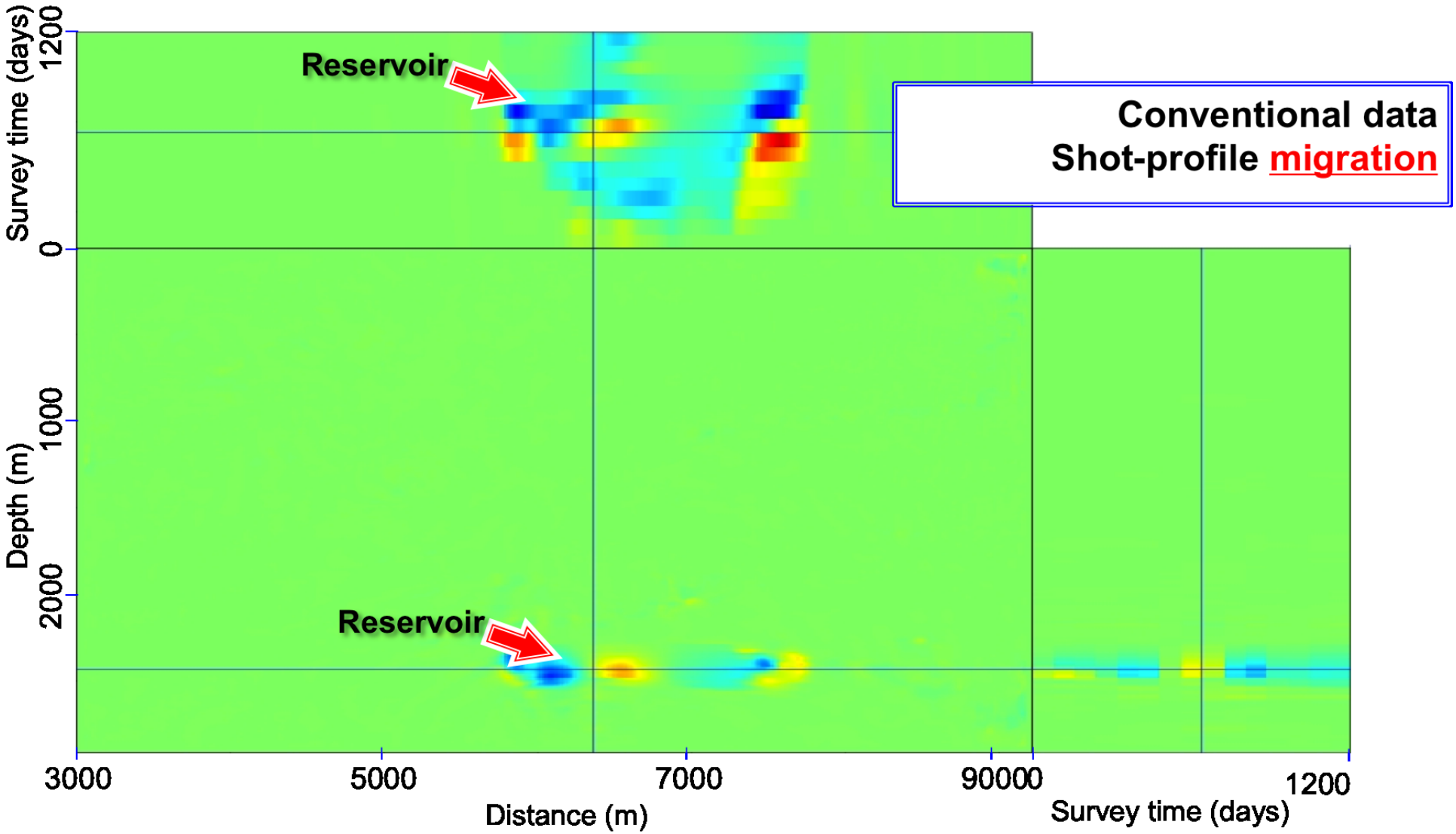
TIme-lapse seismic attributes

- Rate of reservoir change (production rate)

Weighted RMS difference



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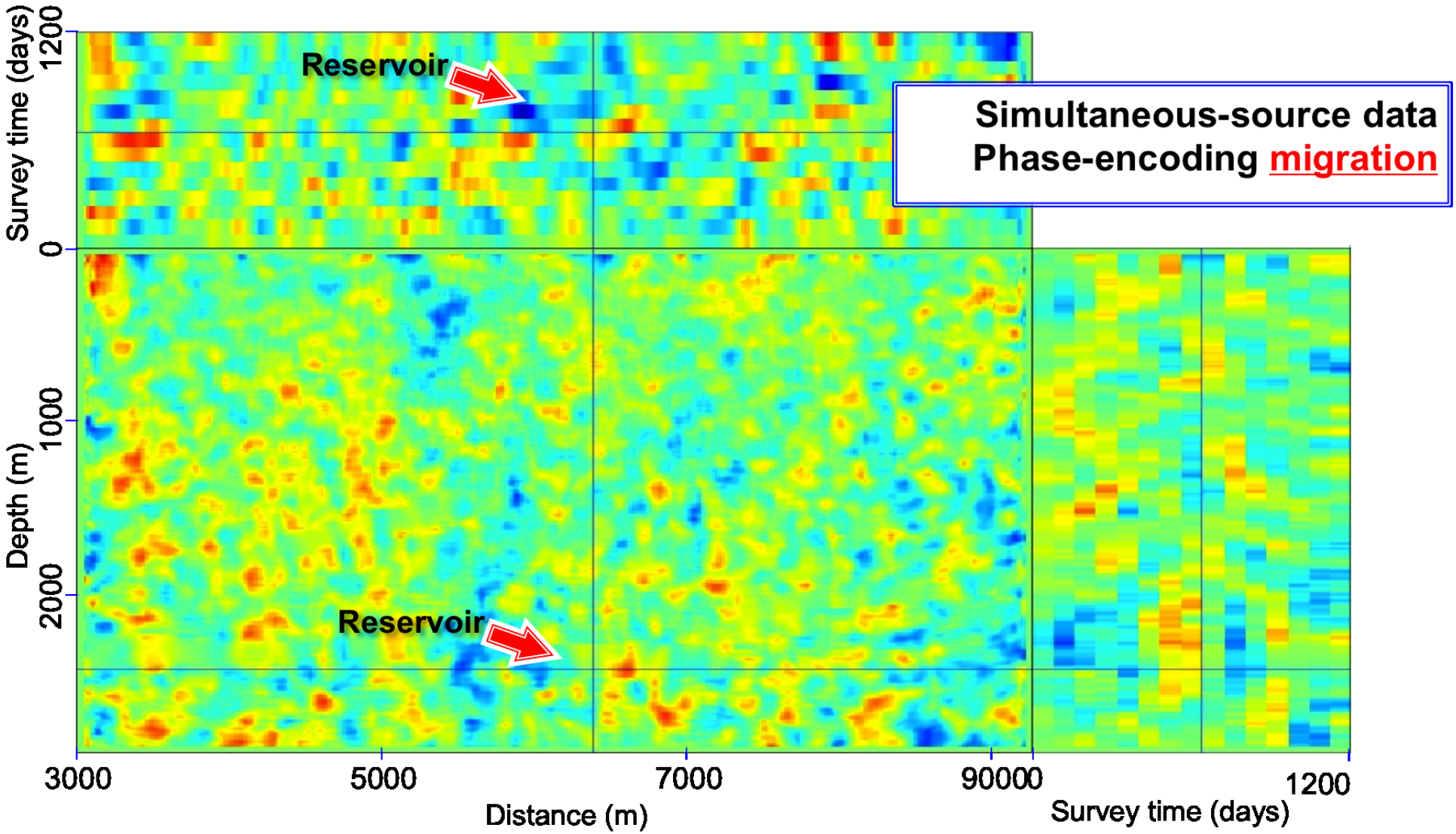
Weighted RMS difference



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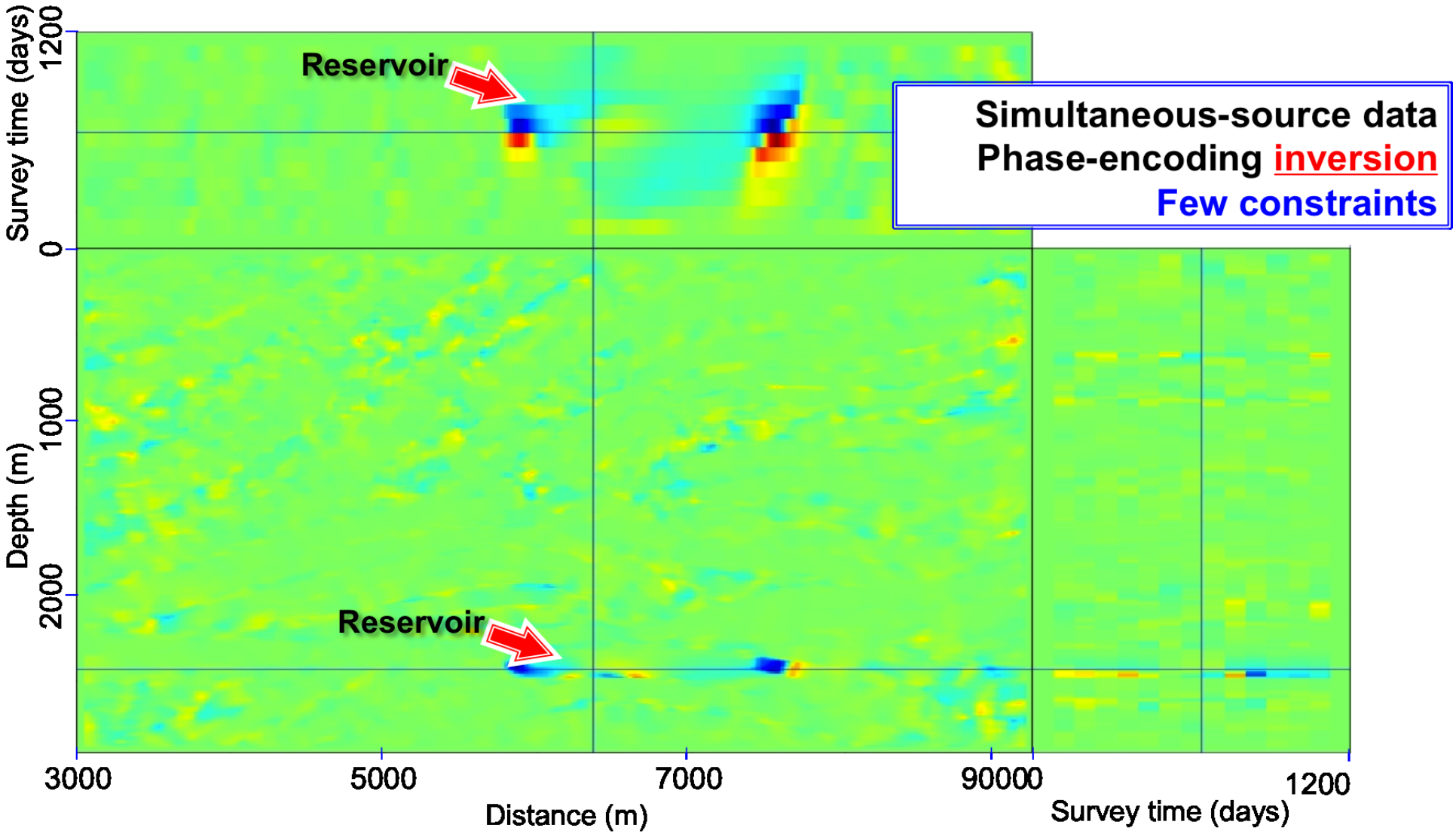
Weighted RMS difference



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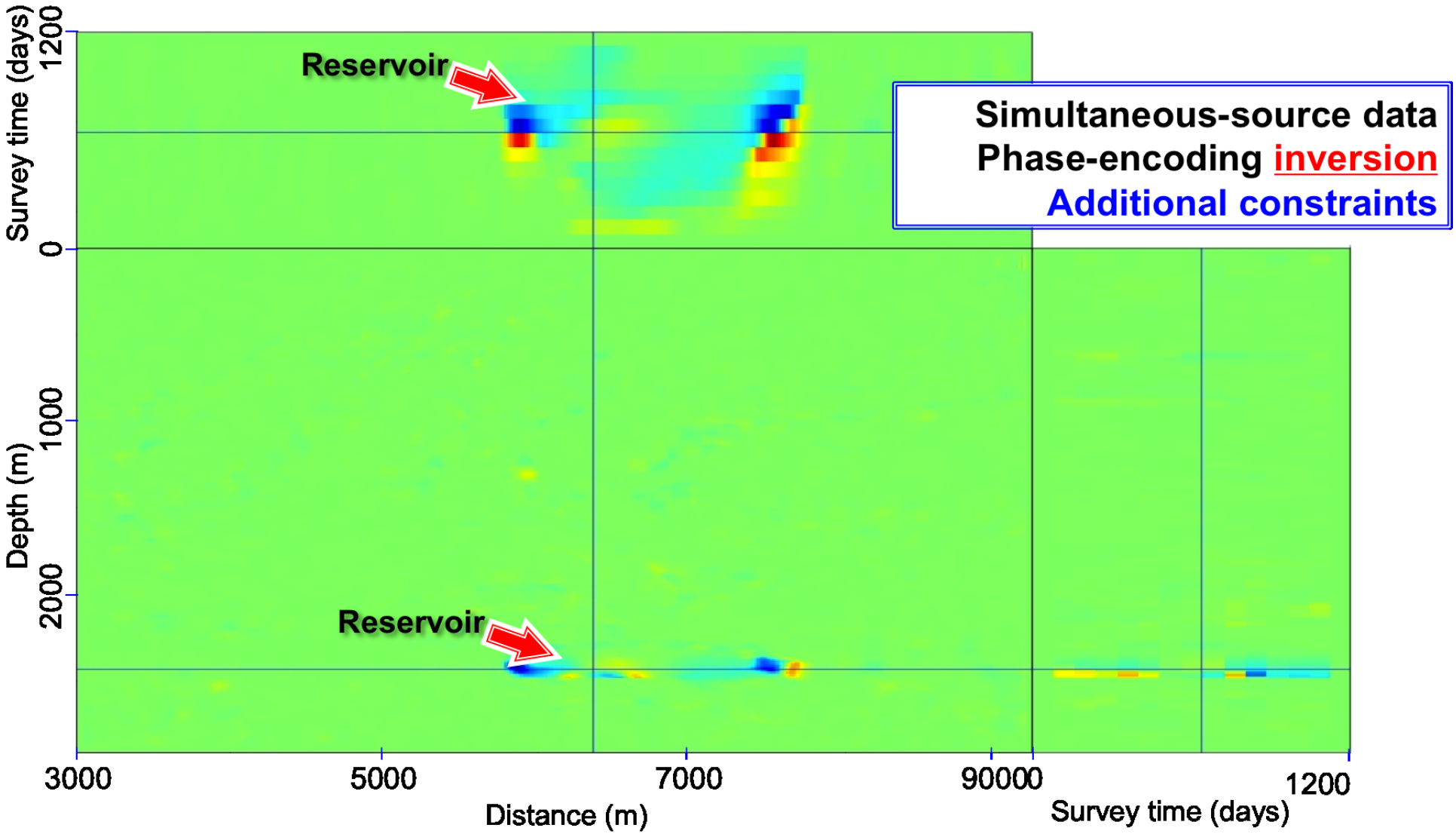
Weighted RMS difference



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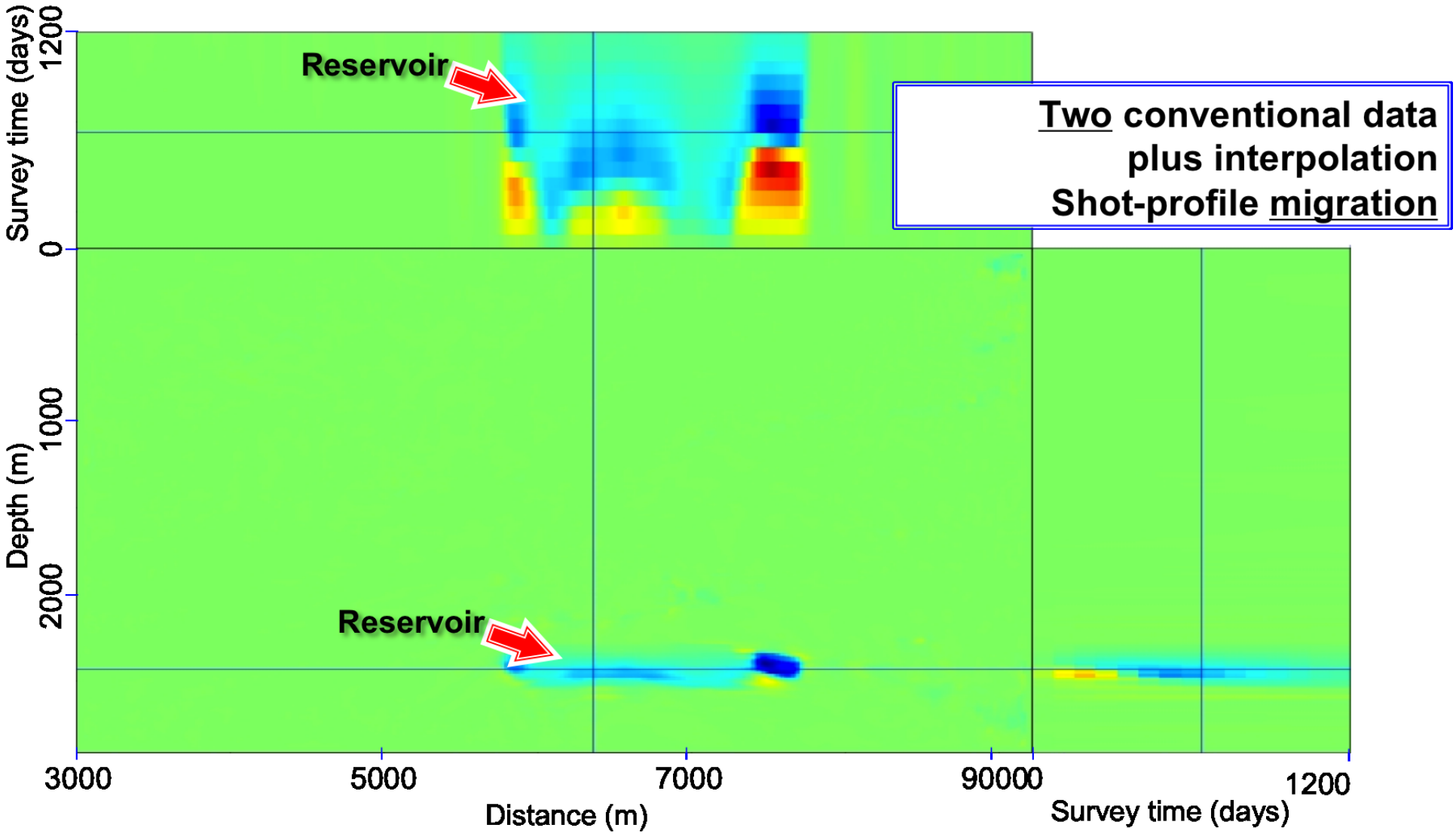
Weighted RMS difference



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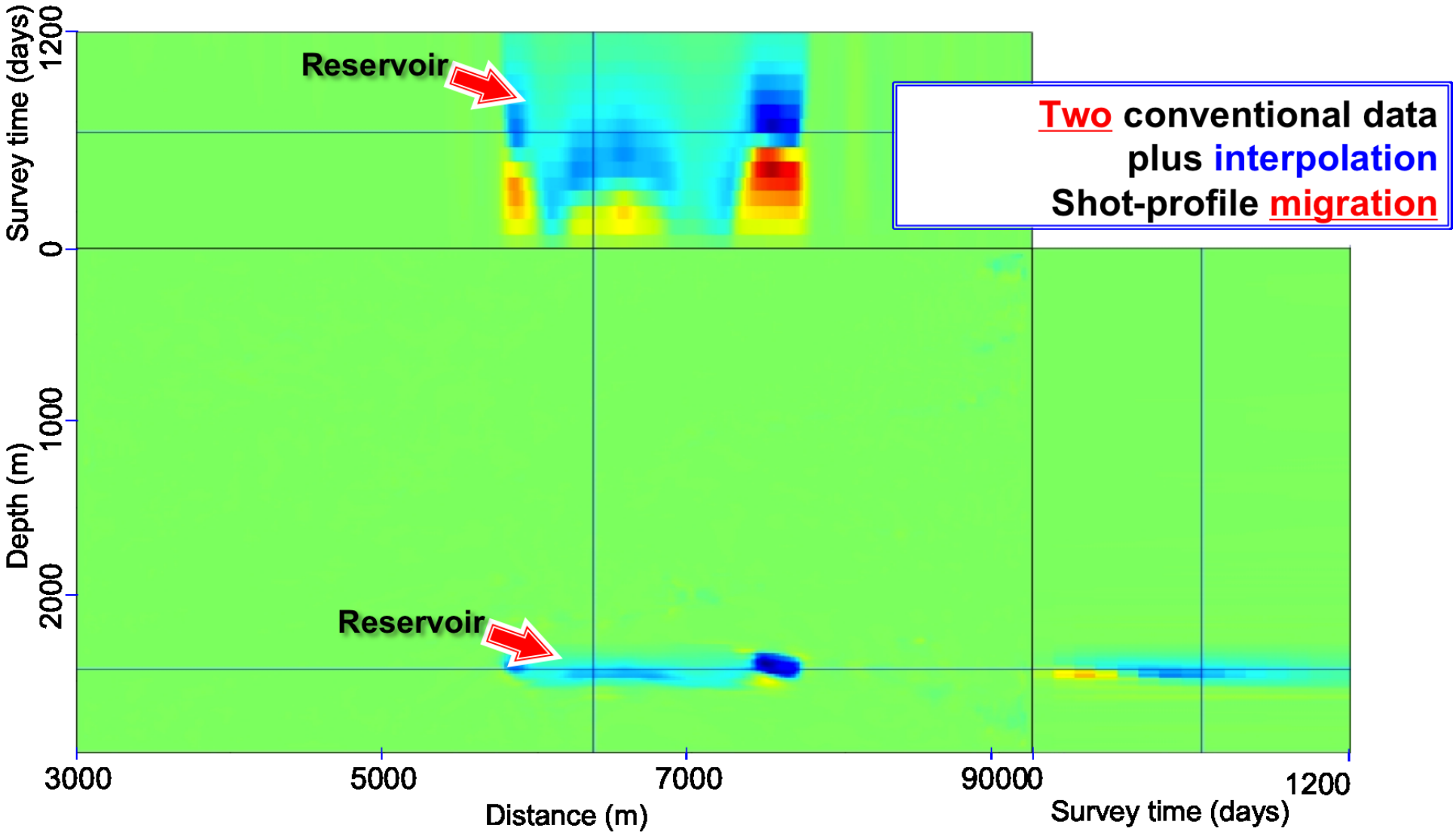
Weighted RMS difference



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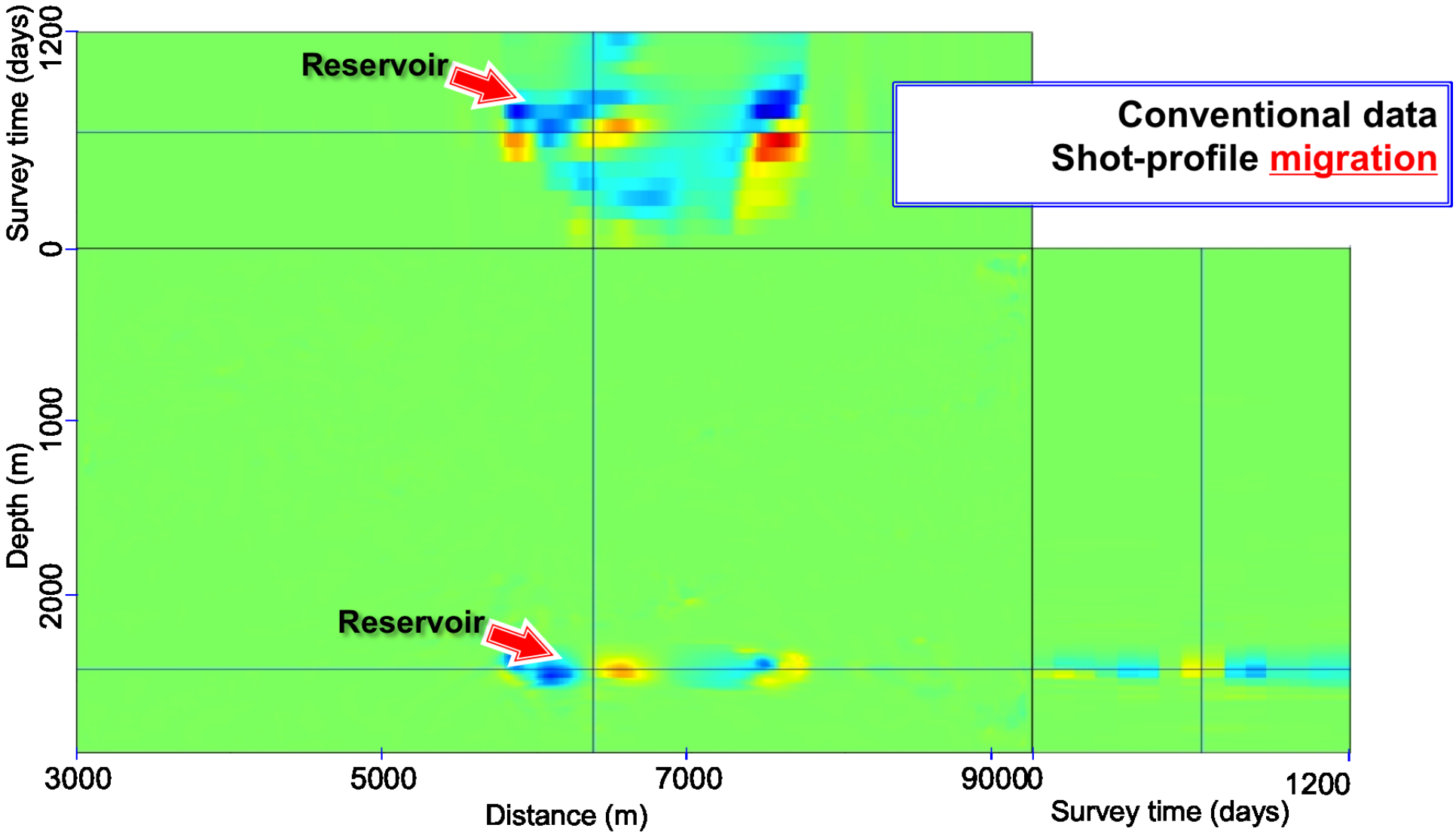
Weighted RMS difference



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Other Applications - SEP 142

1. Permanent monitoring with simultaneous-source/encoded data
2. Account for inaccurate baseline velocity

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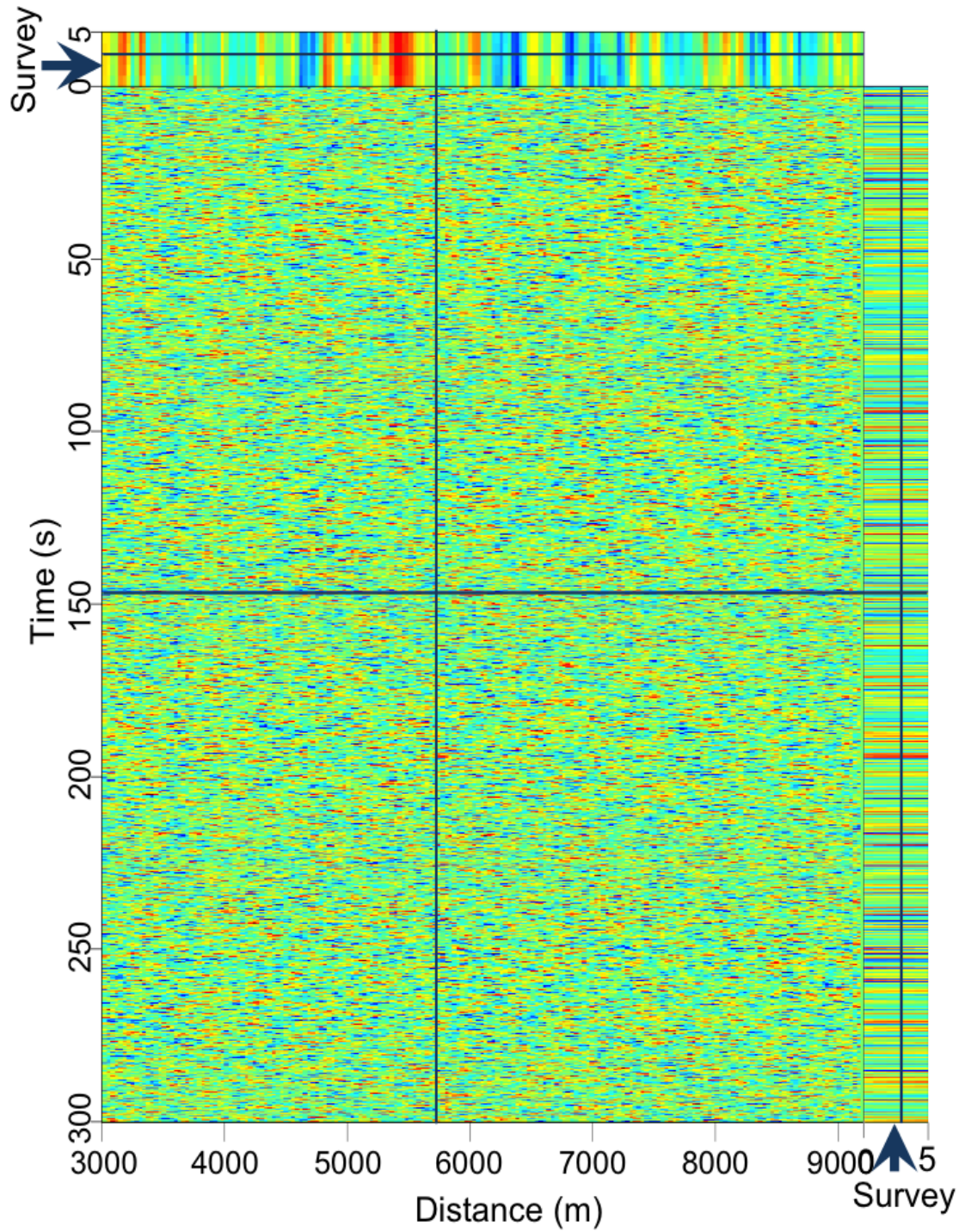
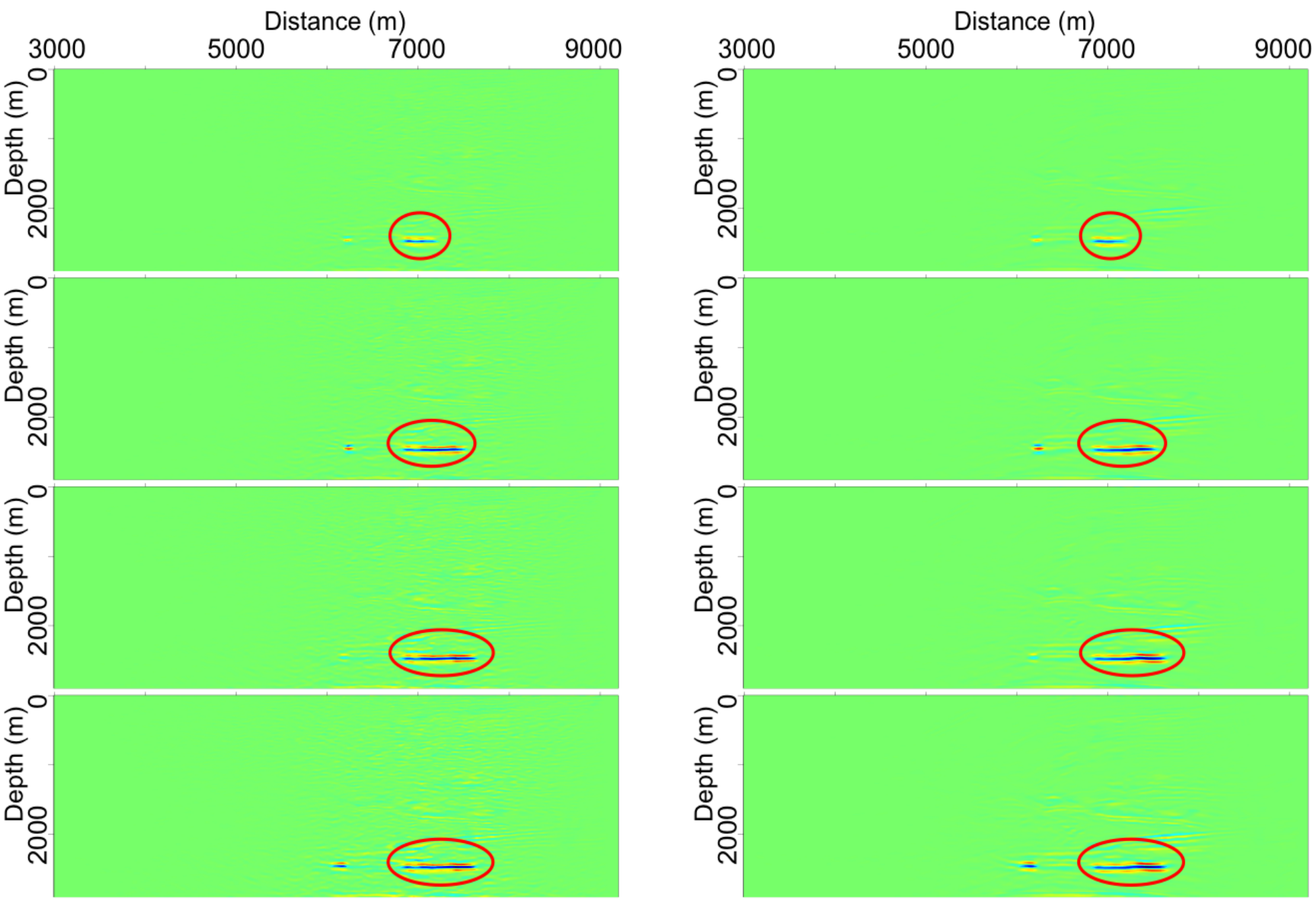
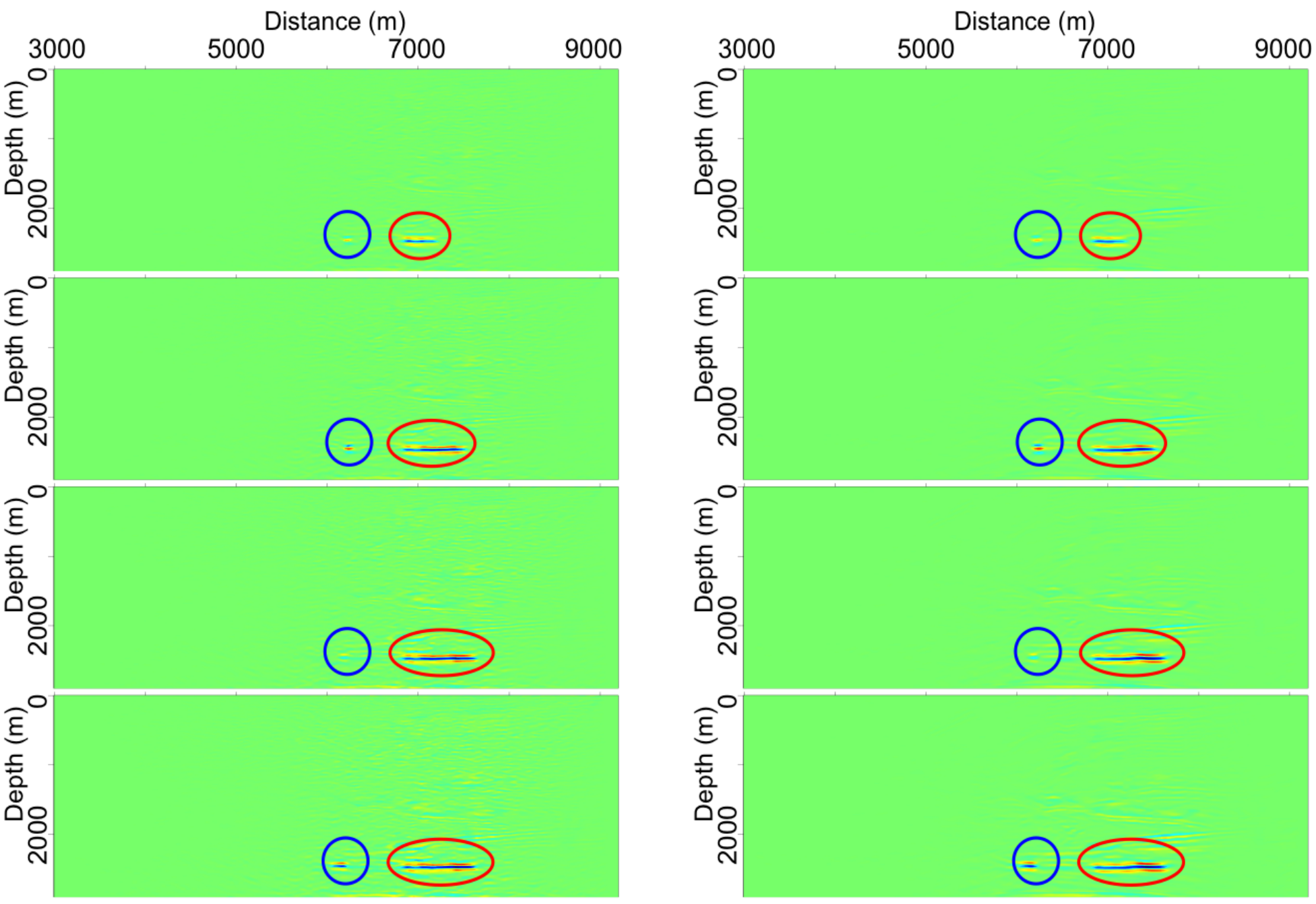
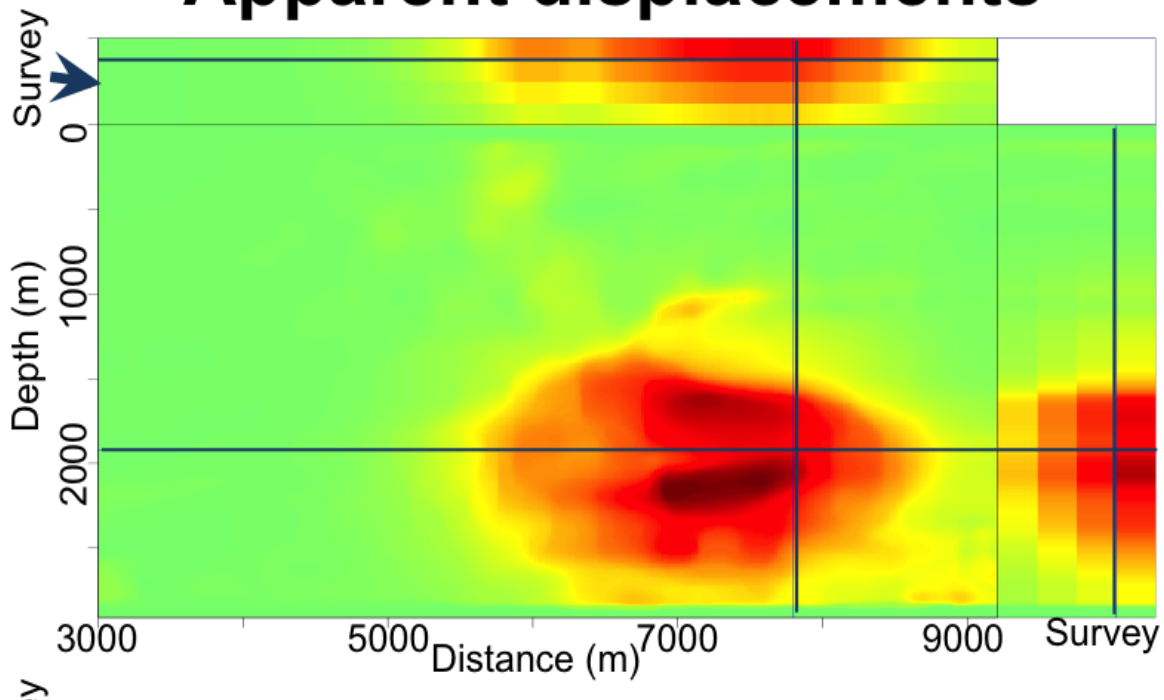

Survey
0
5
50
100
150
200
250
300
Time (s)
3000
4000
5000
6000
7000
8000
9000
Distance (m)
0
5
Survey

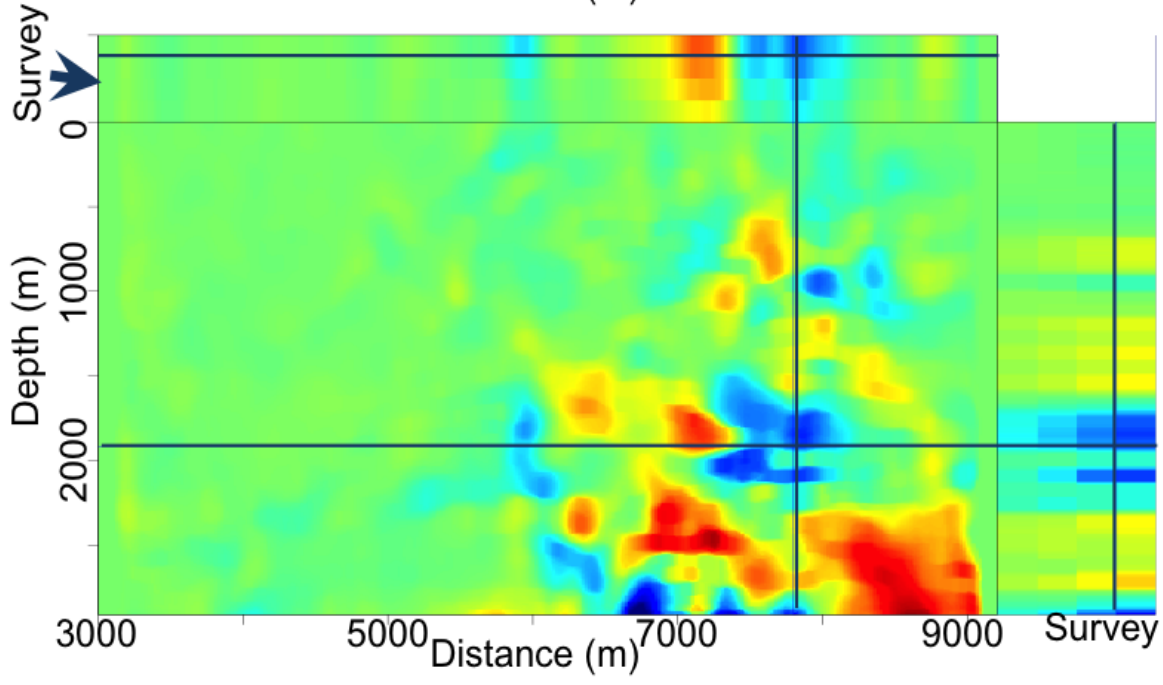

Encoded permanent-array data
Conventional recording
Distance (m)
3000
5000
7000
9000
Depth (m)
0
2000


Encoded permanent-array data
Conventional recording
Distance (m)
3000
5000
7000
9000
Depth (m)
0
2000

Apparent displacements



Vertical components



Horizontal components

Conclusions

1. Acquisition with multiple simultaneously-shooting seismic sources can reduce cost and time requirements

2. Hydrocarbon reservoirs can be monitored efficiently with simultaneous-source data

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1. Acquisition with multiple simultaneously-shooting seismic sources can reduce cost and time requirements
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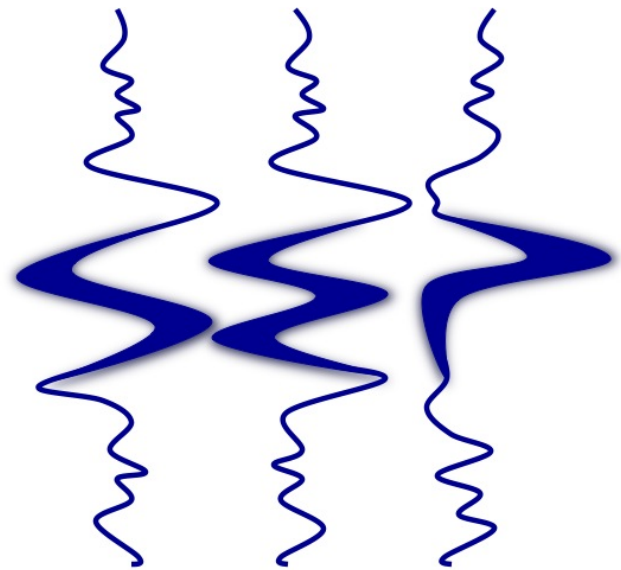
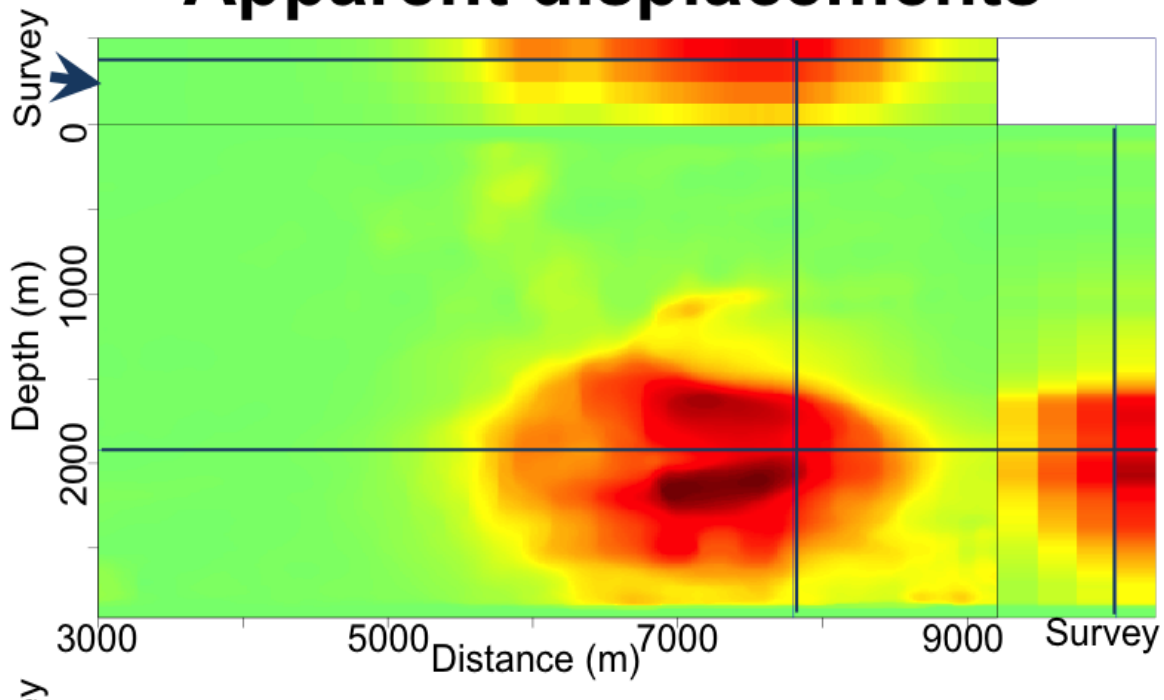
Thanks

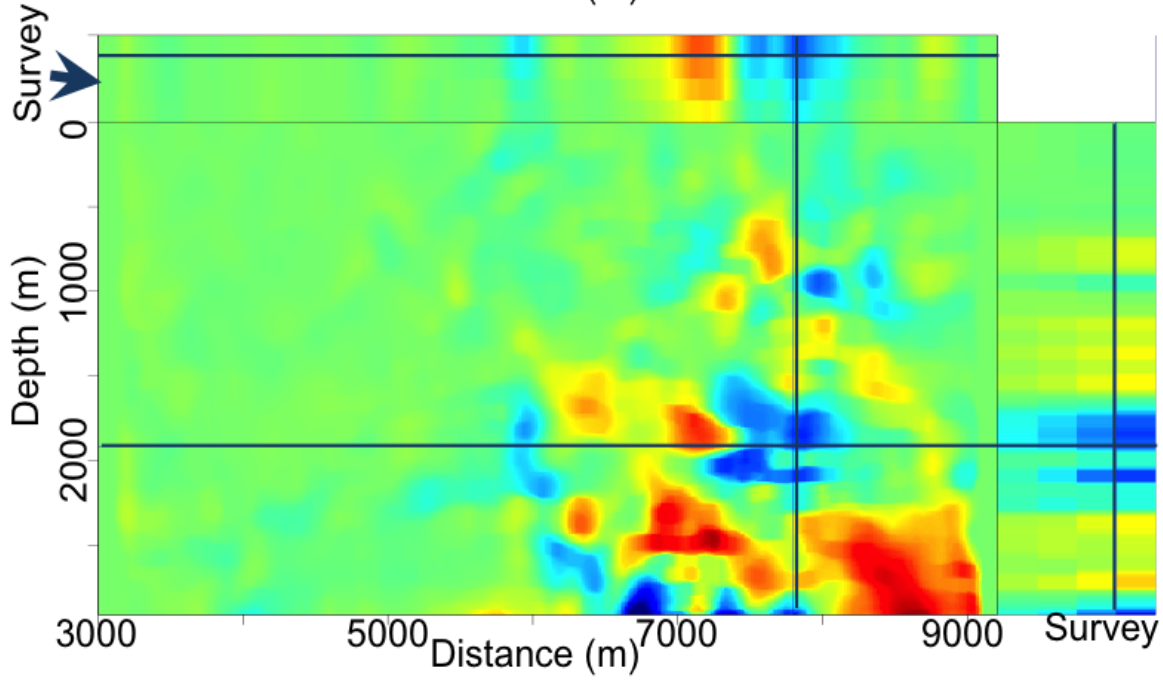


STANFORD EXPLORATION PROJECT

Apparent displacements



Vertical components



Horizontal components