Reconstruction of S-waves from low-cost randomized and simultaneous acquisition

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SLIM
University of British Columbia

Outline

- Advantages of S-waves
- Why S-wave is not commonly used in practice?
- Elastic decomposition
- Jittered subsampling
- Single component reconstruction w\
    - rank minimization
    - sparsity promotion
- Various joint reconstruction formulations w/ sparsity promotion
- Conclusions

Advantages of S-waves

- Imaging through gas chimneys

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- High resolution imaging (thin layers)

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- Elastic rock properties

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- Imaging through gas chimneys
- High resolution imaging (thin layers)
- Reservoir detection & monitoring
- Elastic rock properties
- Improve accuracy & confidence

Why S-wave is not commonly used in practice?

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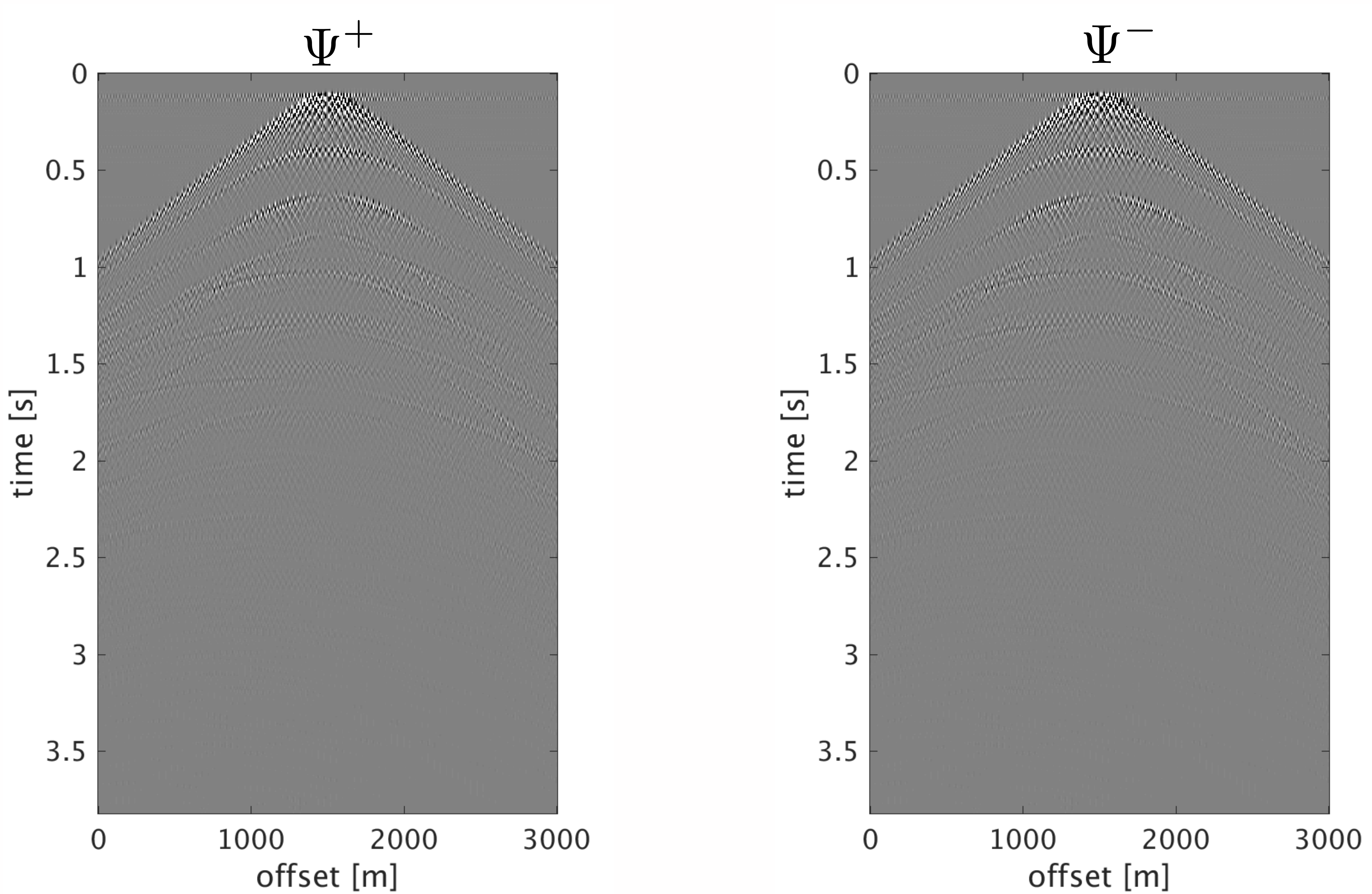

Why S-wave is not commonly used in practice?

Low S-wave velocity

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Nyquist criterion

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Denser sampling

Higher acquisition costs

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Compressive sensing

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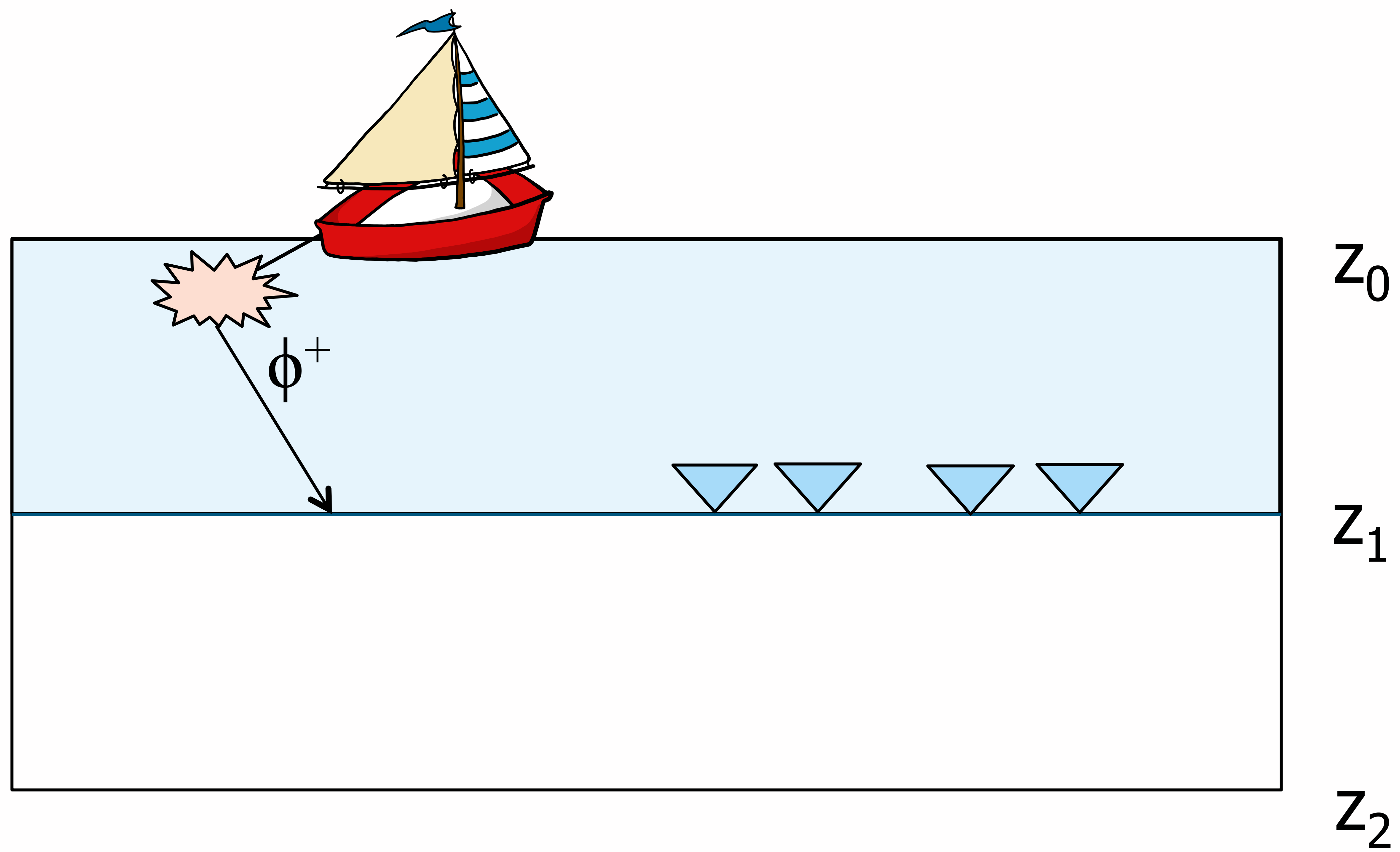
Solution

Compressive sensing

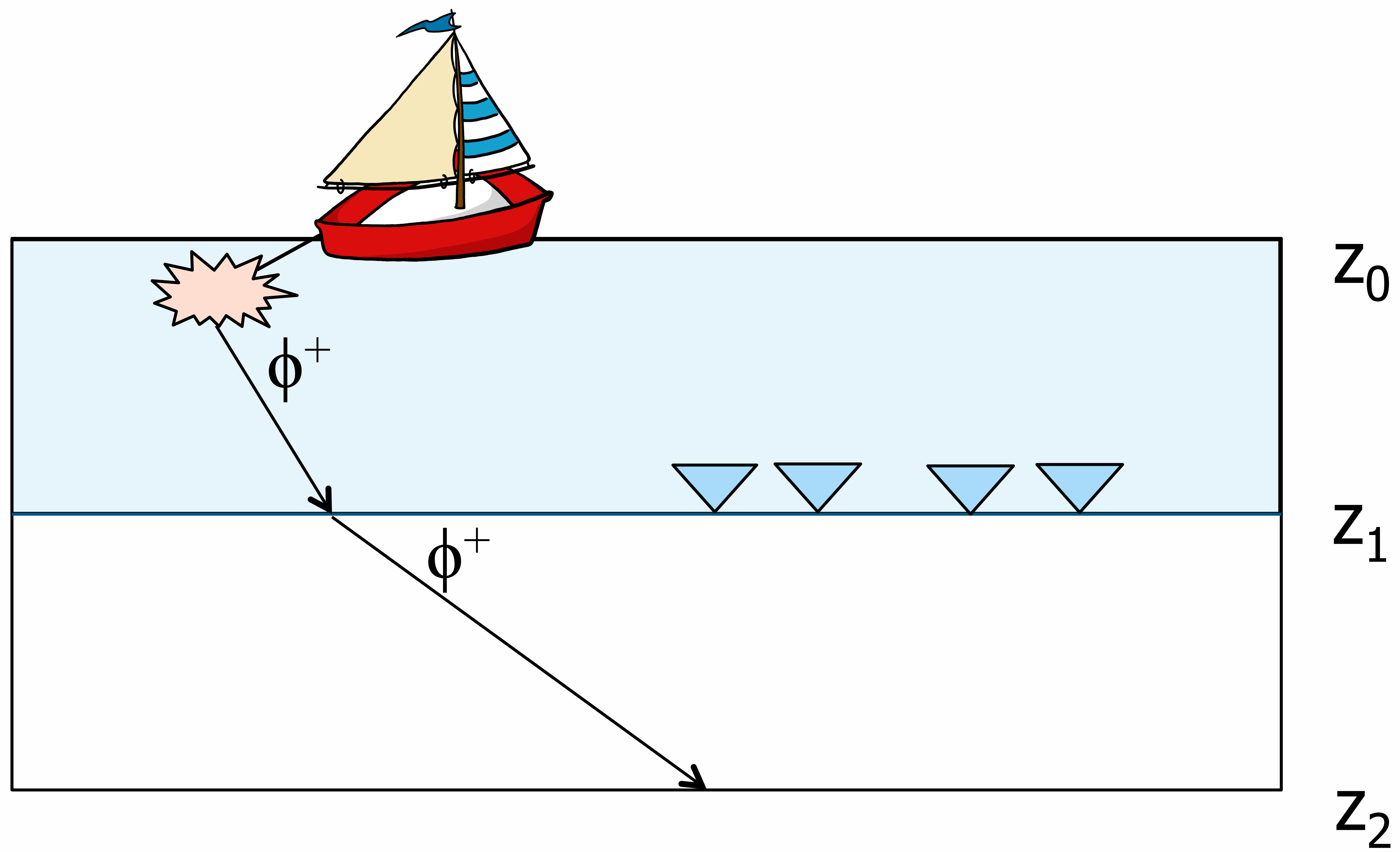
Randomized undersampling

Lower acquisition costs

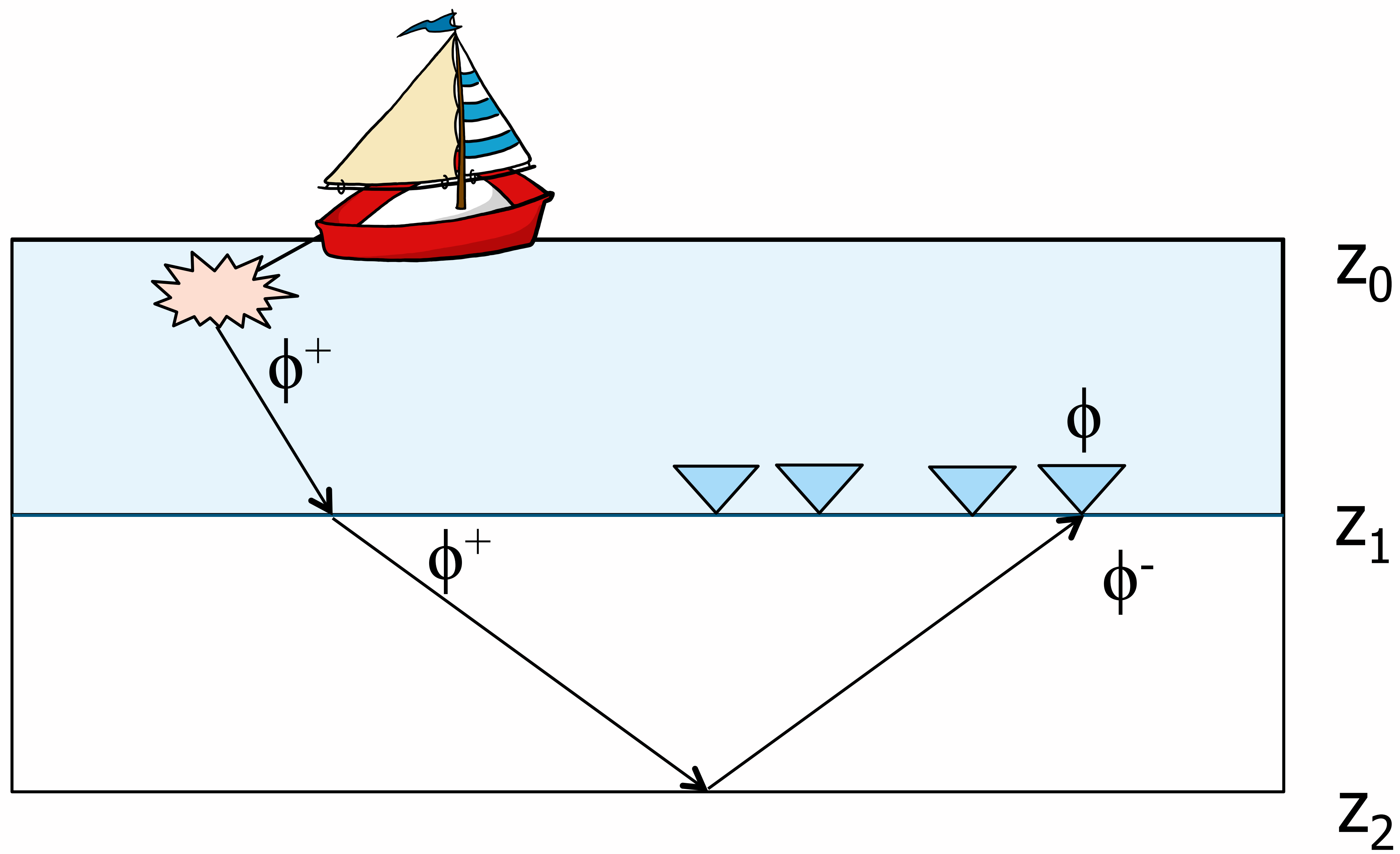
Ocean bottom acquisition



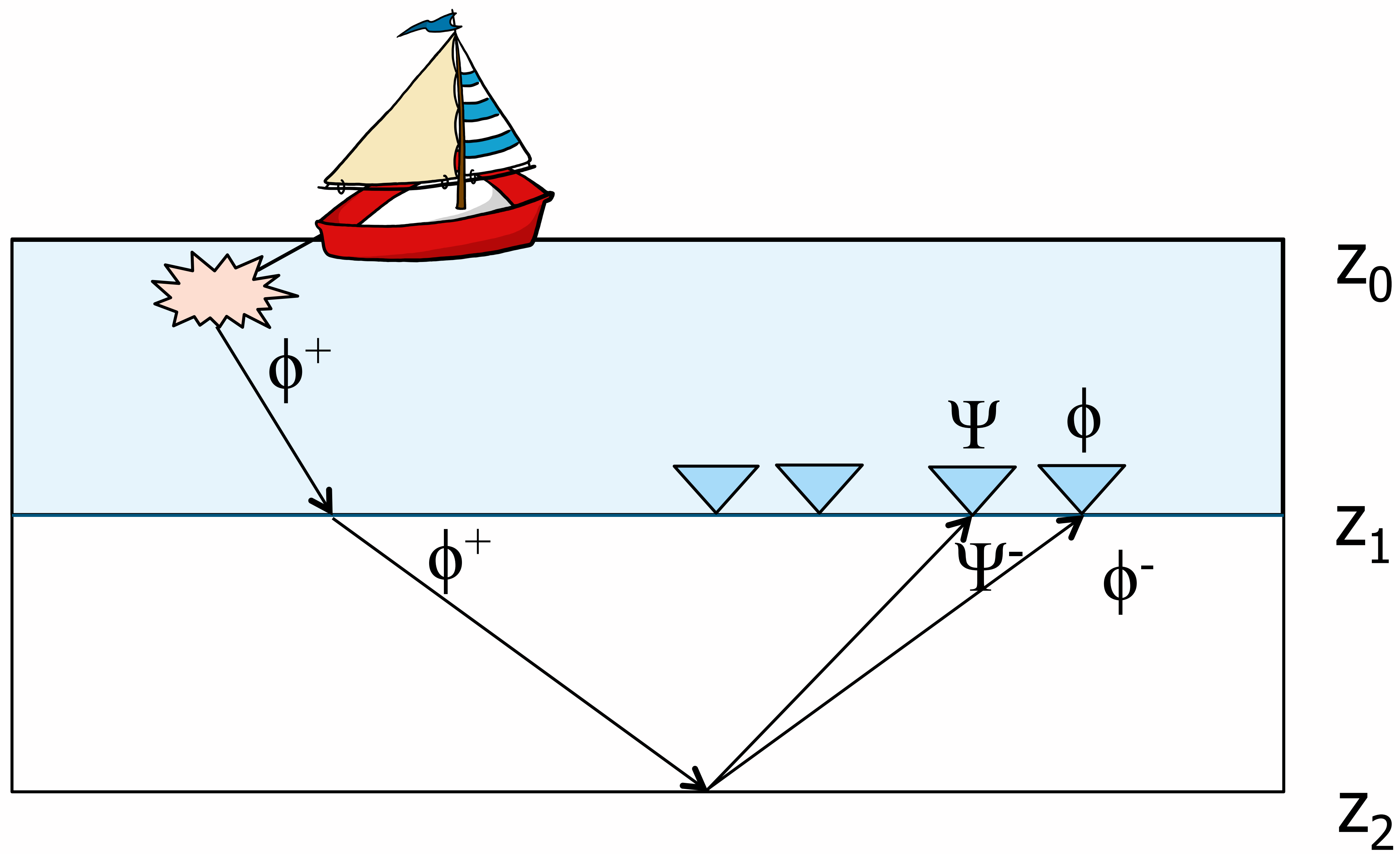
Ocean bottom acquisition



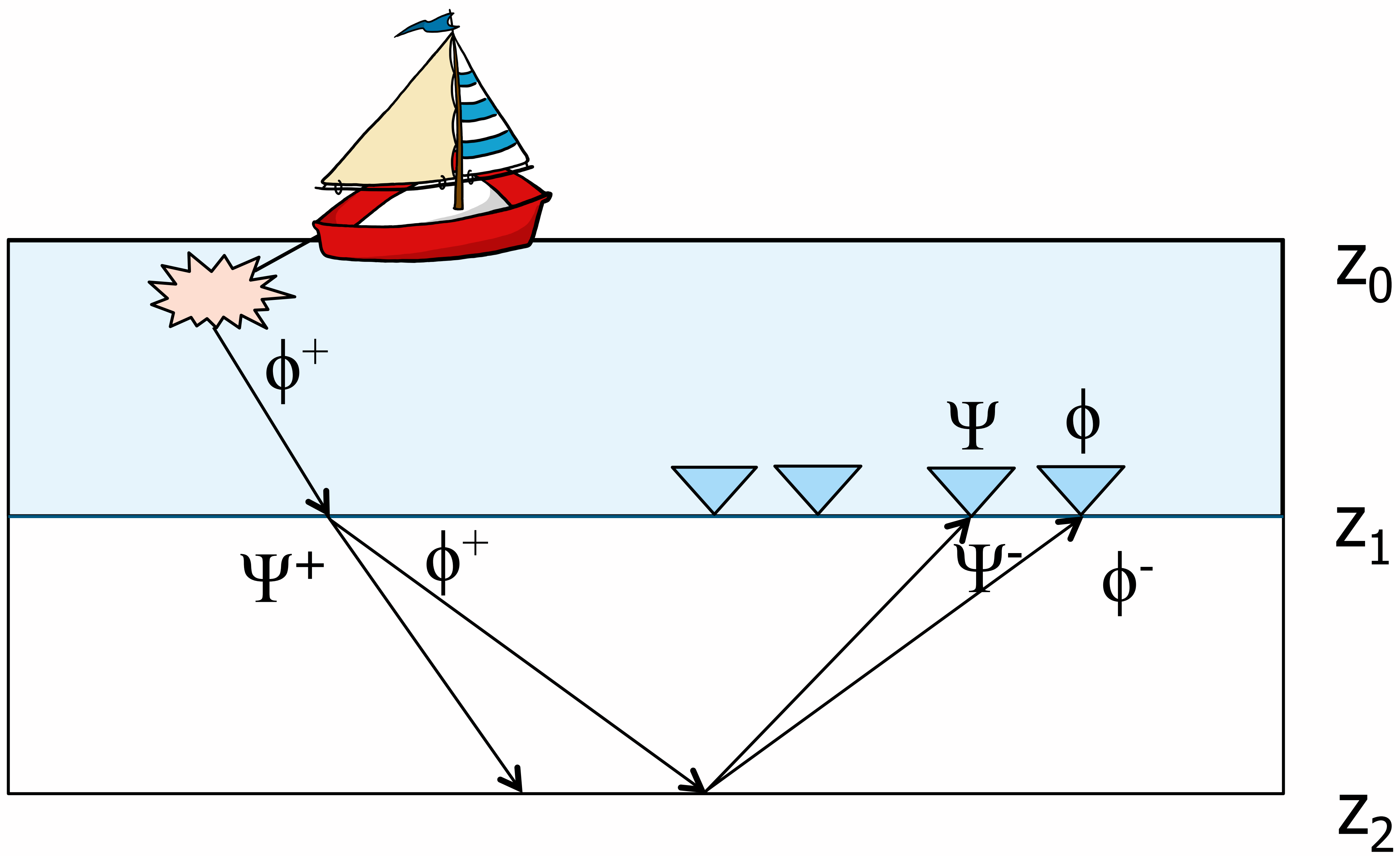
Ocean bottom acquisition



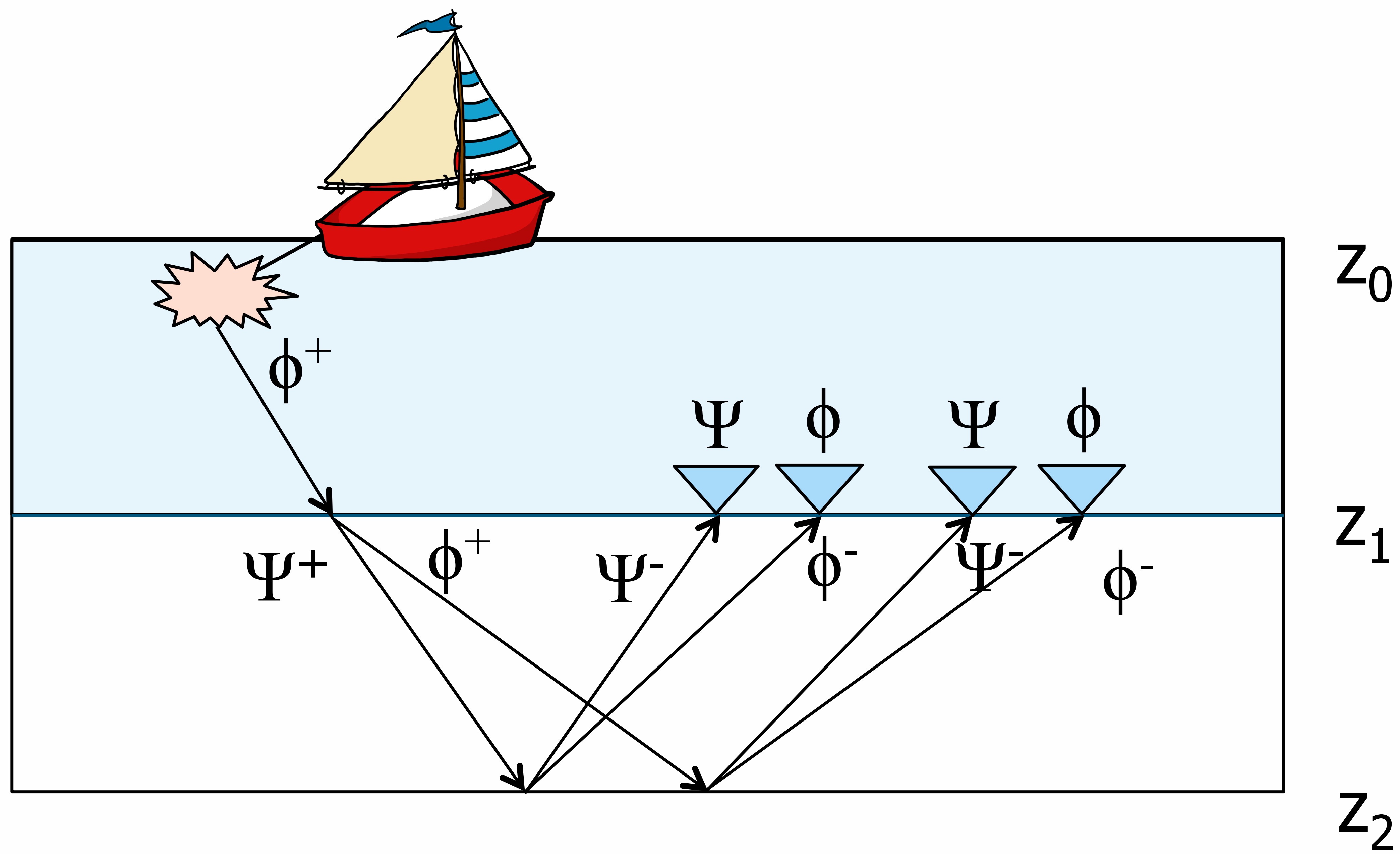
Ocean bottom acquisition



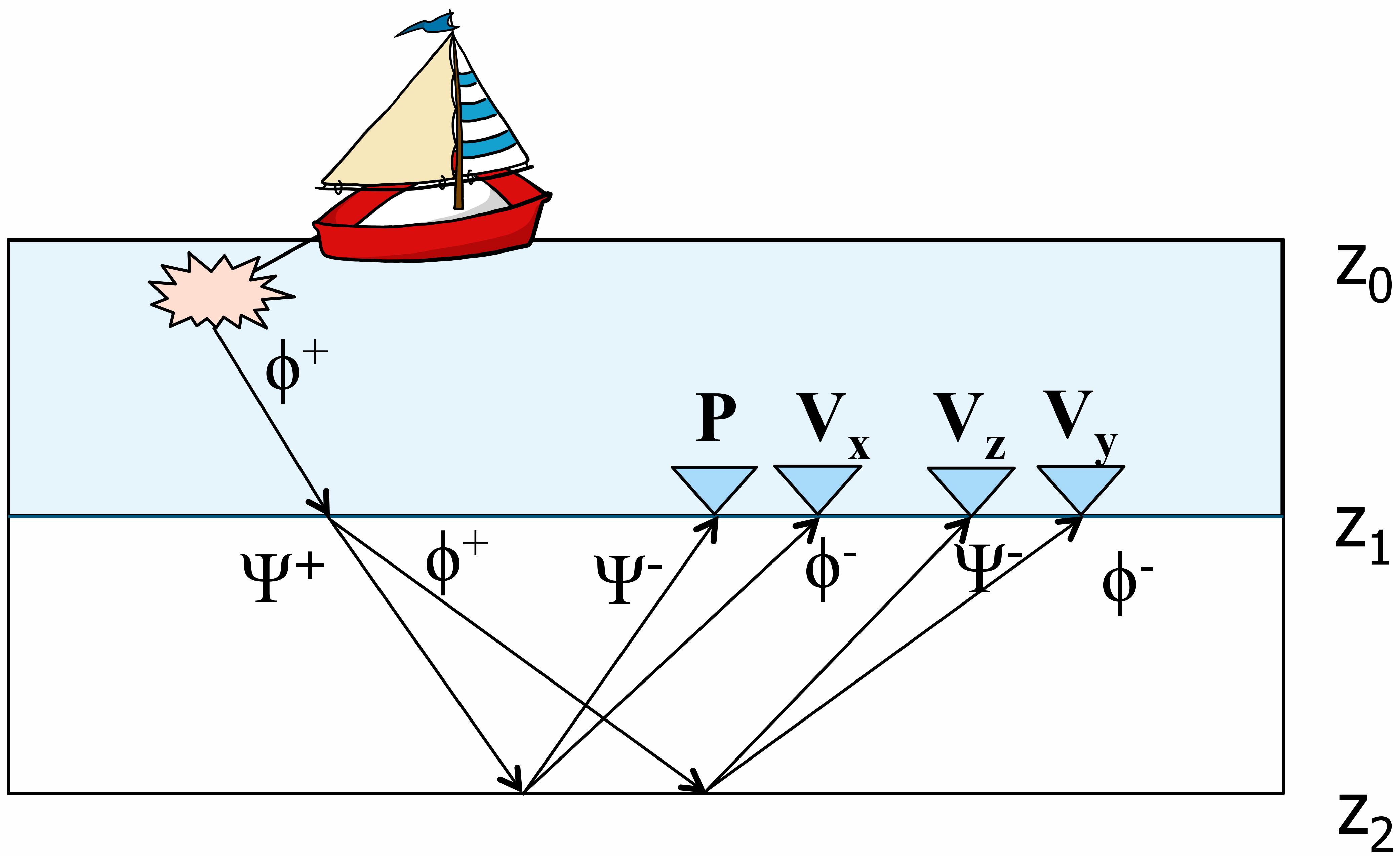
Ocean bottom acquisition



Ocean bottom acquisition



Ocean bottom acquisition



Wavefield decomposition

Wapenaar, C., and A. Berkhout, 2014, Elastic wave field extrapolation: Redatuming of single- and multi-component seismic data: Elsevier Science. Advances in Exploration Geophysics.

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Elastic wavefield decomposition

$$\mathbf{d} = \mathbf{N}\mathbf{q}$$

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Elastic wavefield decomposition

$$\mathbf{d} = \mathbf{N}\mathbf{q}$$

$$\begin{pmatrix} \phi^+ \\ \psi_y^+ \\ \phi^- \\ \psi_y^- \end{pmatrix} = \begin{pmatrix} \mathbf{N}_1^+ & \mathbf{N}_2^+ \\ \mathbf{N}_1^- & \mathbf{N}_2^- \end{pmatrix} \begin{pmatrix} -\tau_{xz} \\ -\tau_{zz} \\ v_x \\ v_z \end{pmatrix}$$

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Elastic wavefield decomposition

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At the ocean bottom:

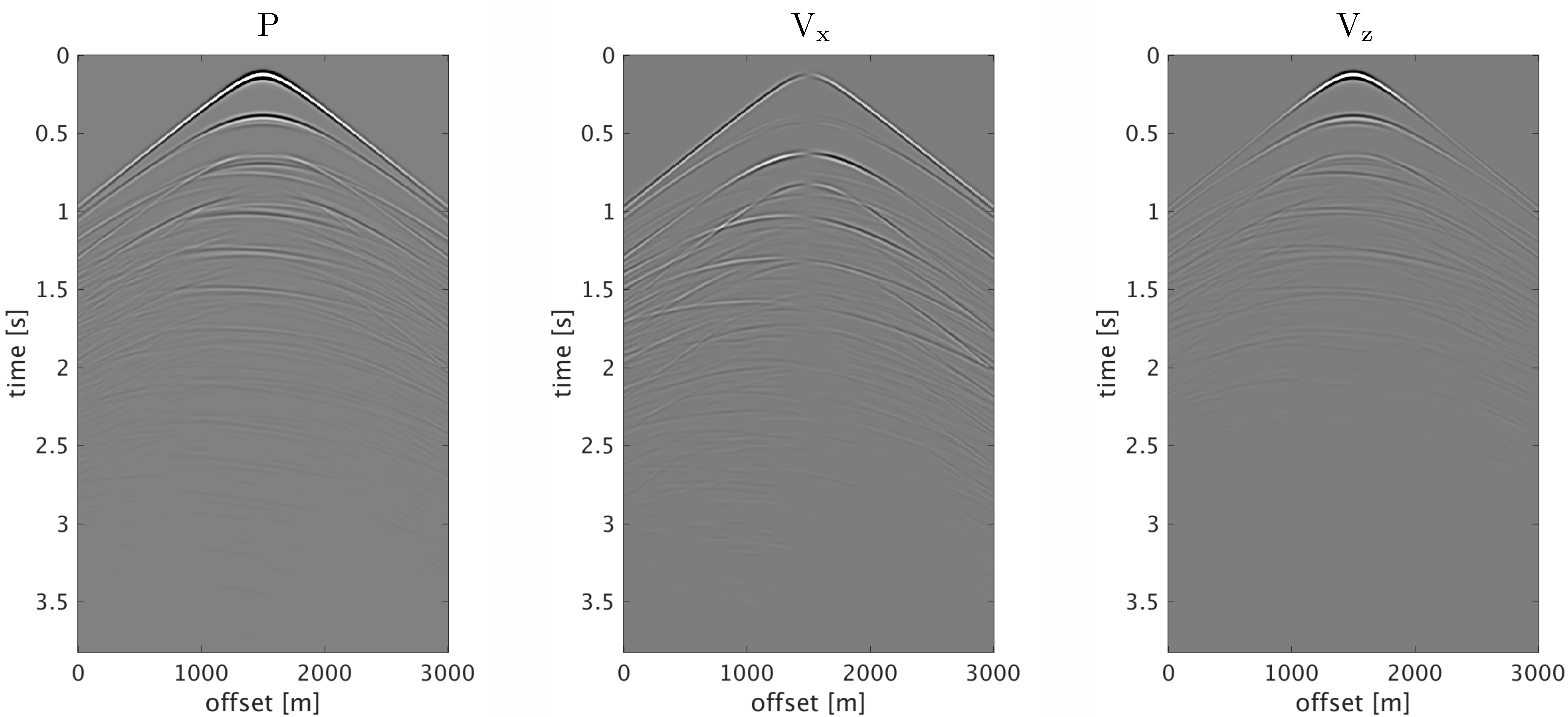
$$\tau_{xz} = 0 \qquad \tau_{zz} = -p$$

Elastic wavefield composition

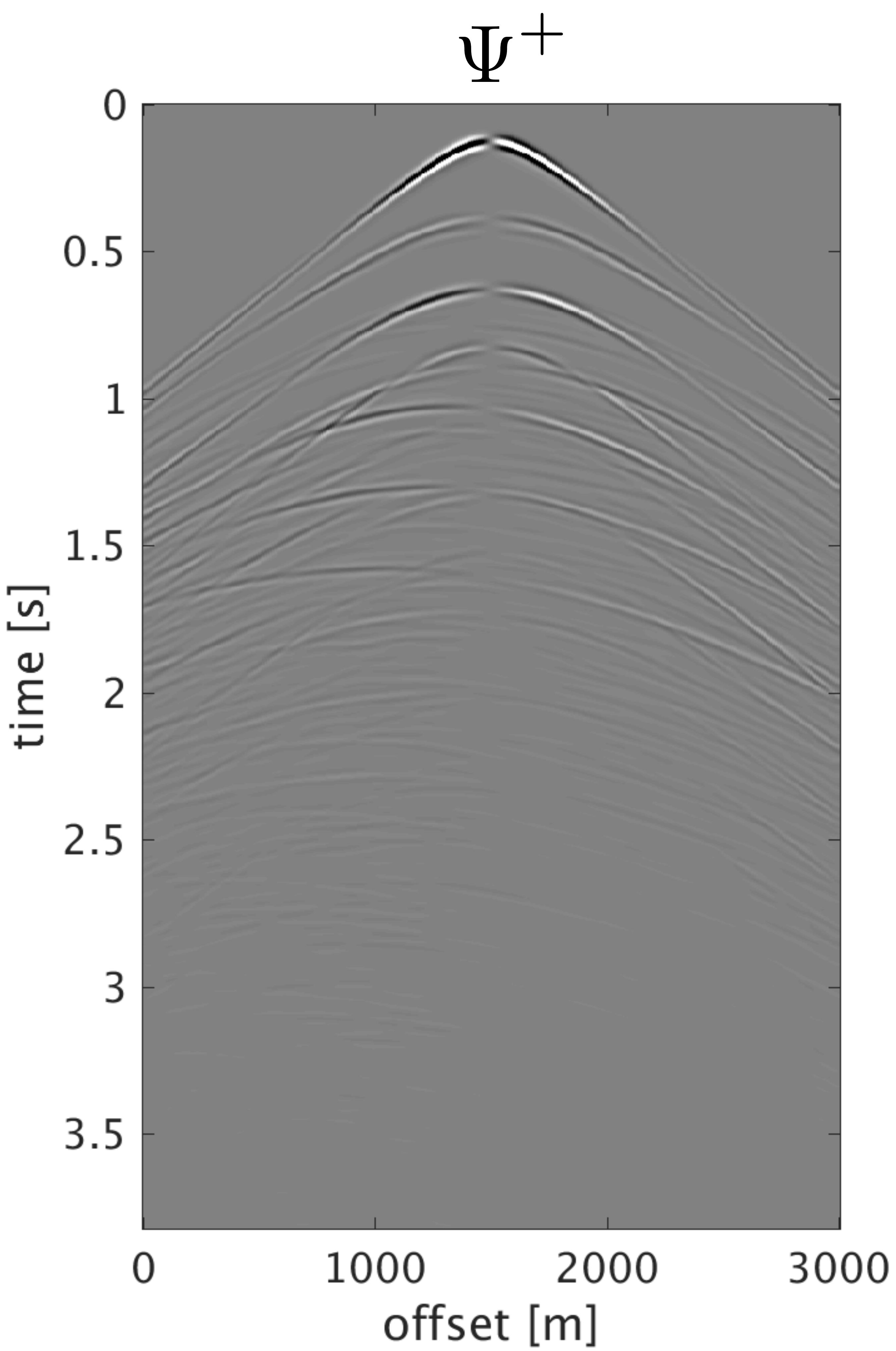
$$\mathbf{q} = \mathbf{L}\mathbf{d}$$

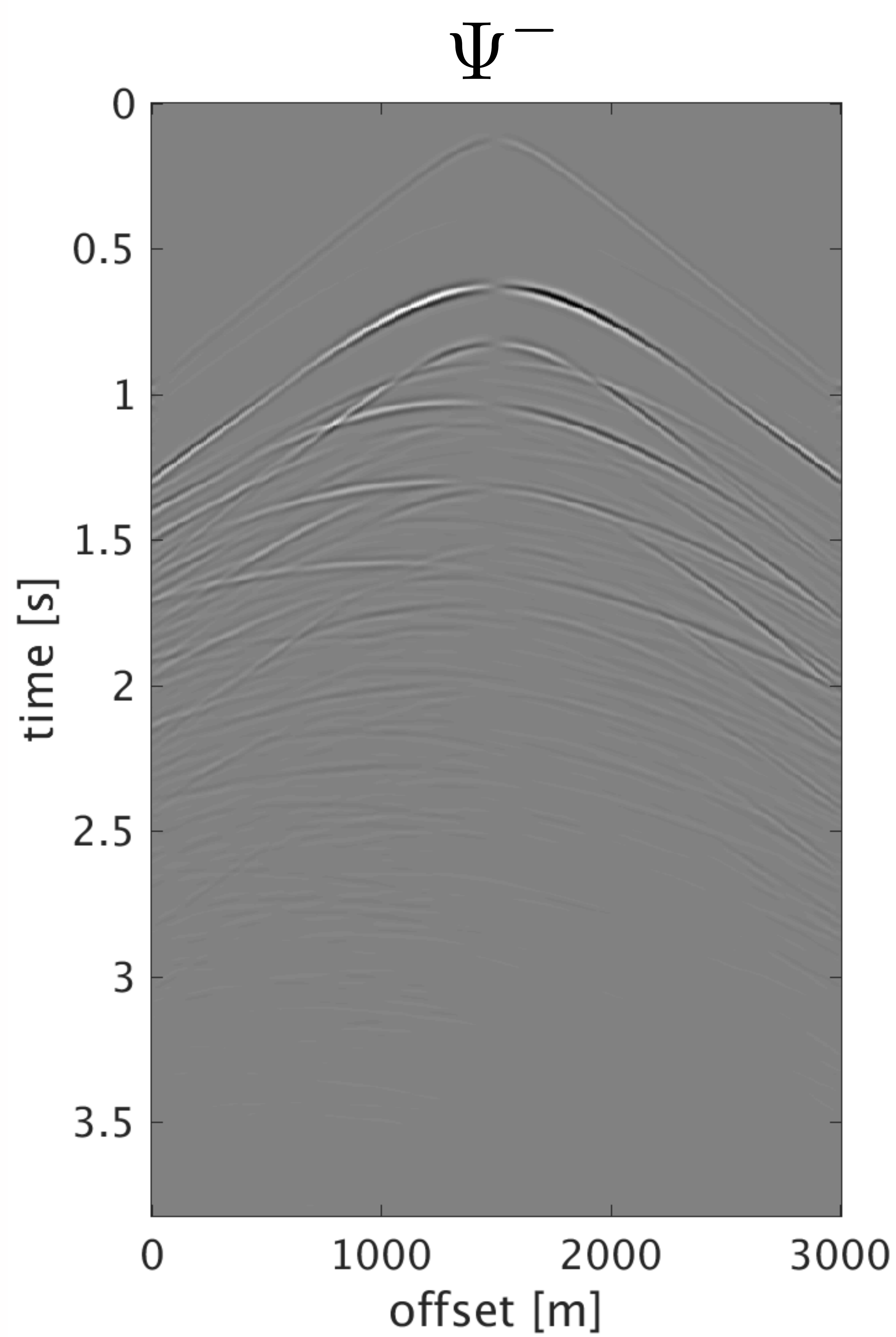
$$\begin{pmatrix} -\tau_{xz} \\ -\tau_{zz} \\ v_x \\ v_z \end{pmatrix} = \begin{pmatrix} \mathbf{L}_1^+ & \mathbf{L}_1^- \\ \mathbf{L}_2^+ & \mathbf{L}_2^- \end{pmatrix} \begin{pmatrix} \phi^+ \\ \psi_y^+ \\ \phi^- \\ \psi_y^- \end{pmatrix}$$

Multicomponent data

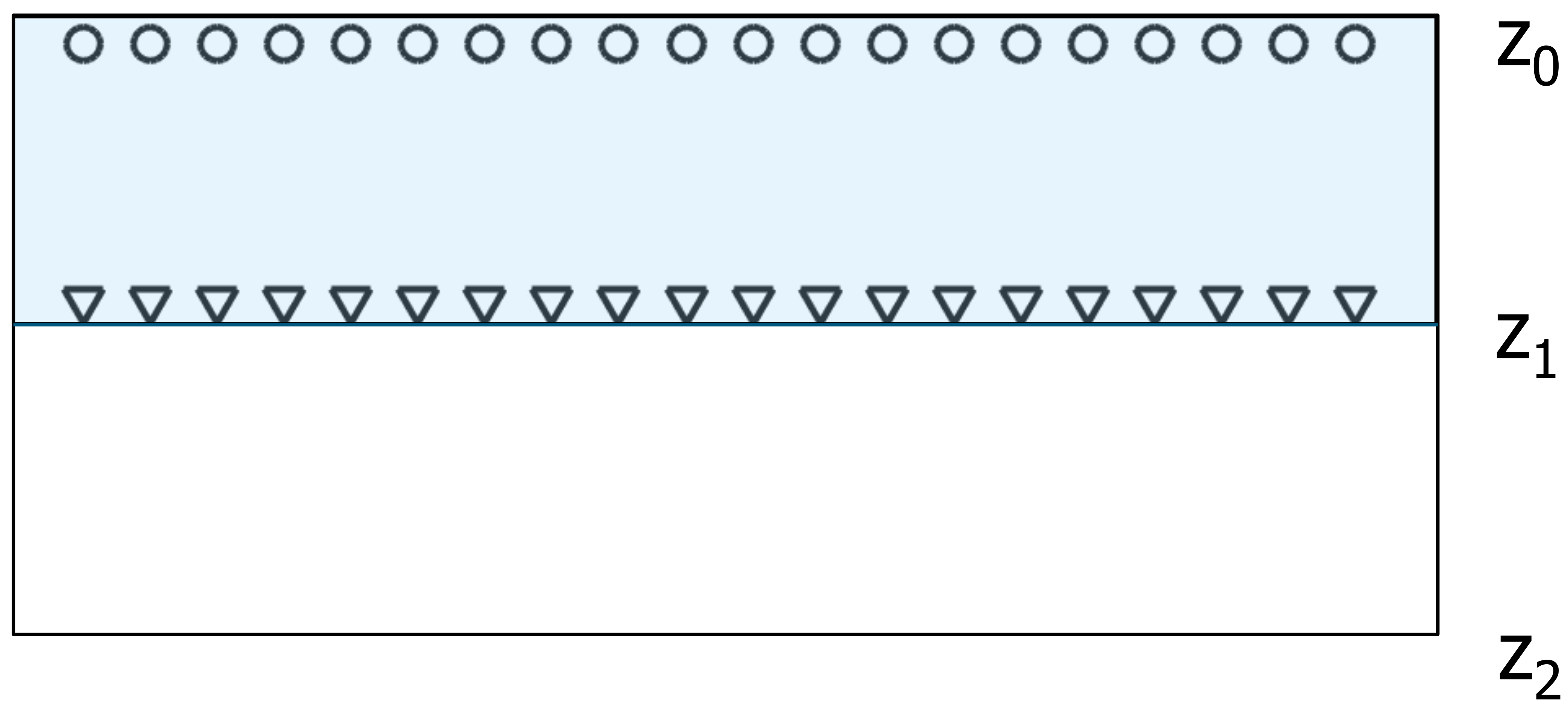


Elastic decomposition

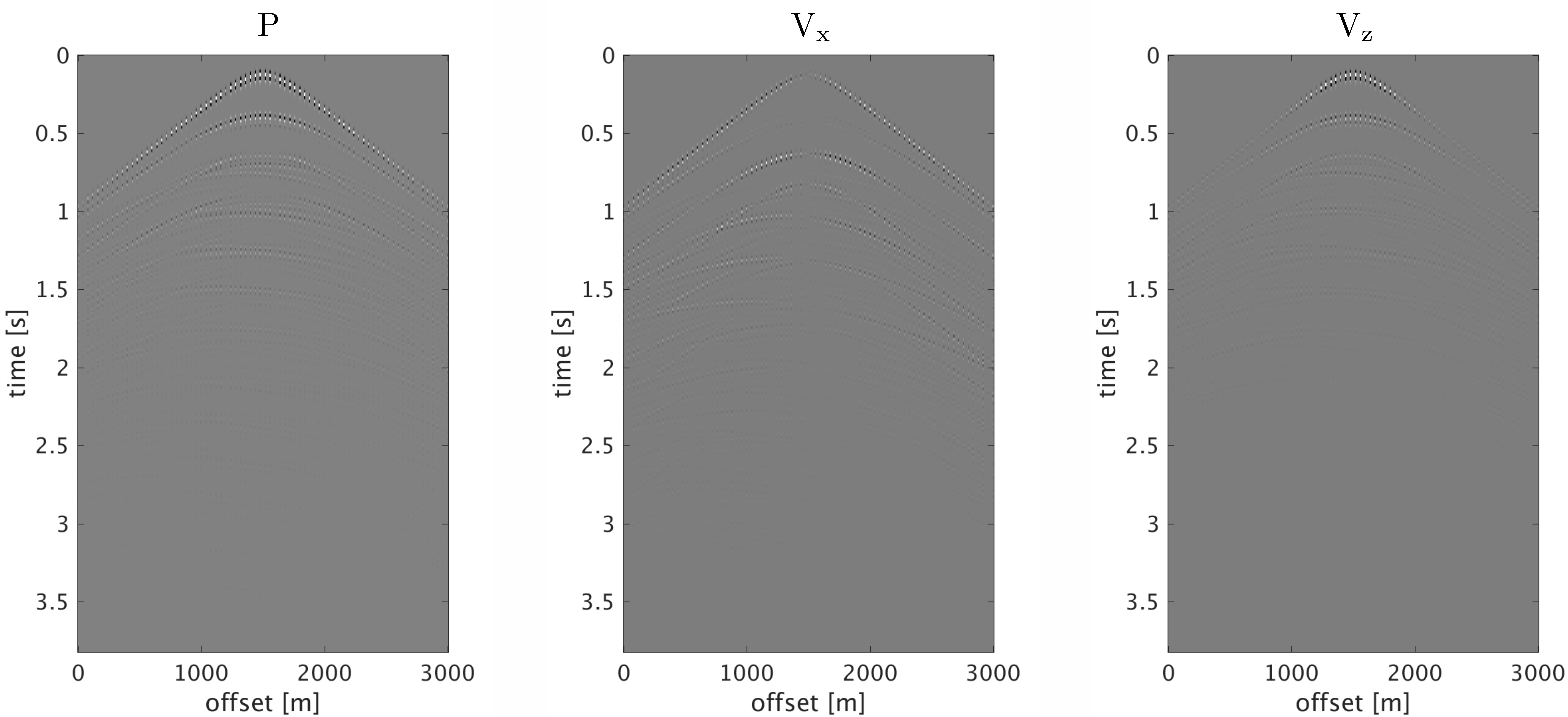




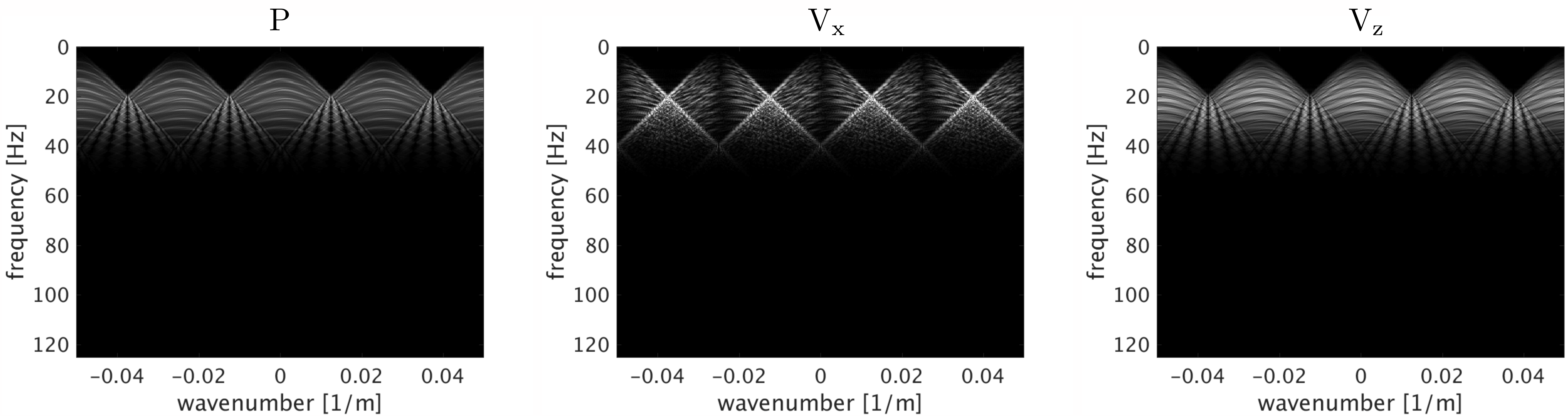
Can't afford dense acquisition



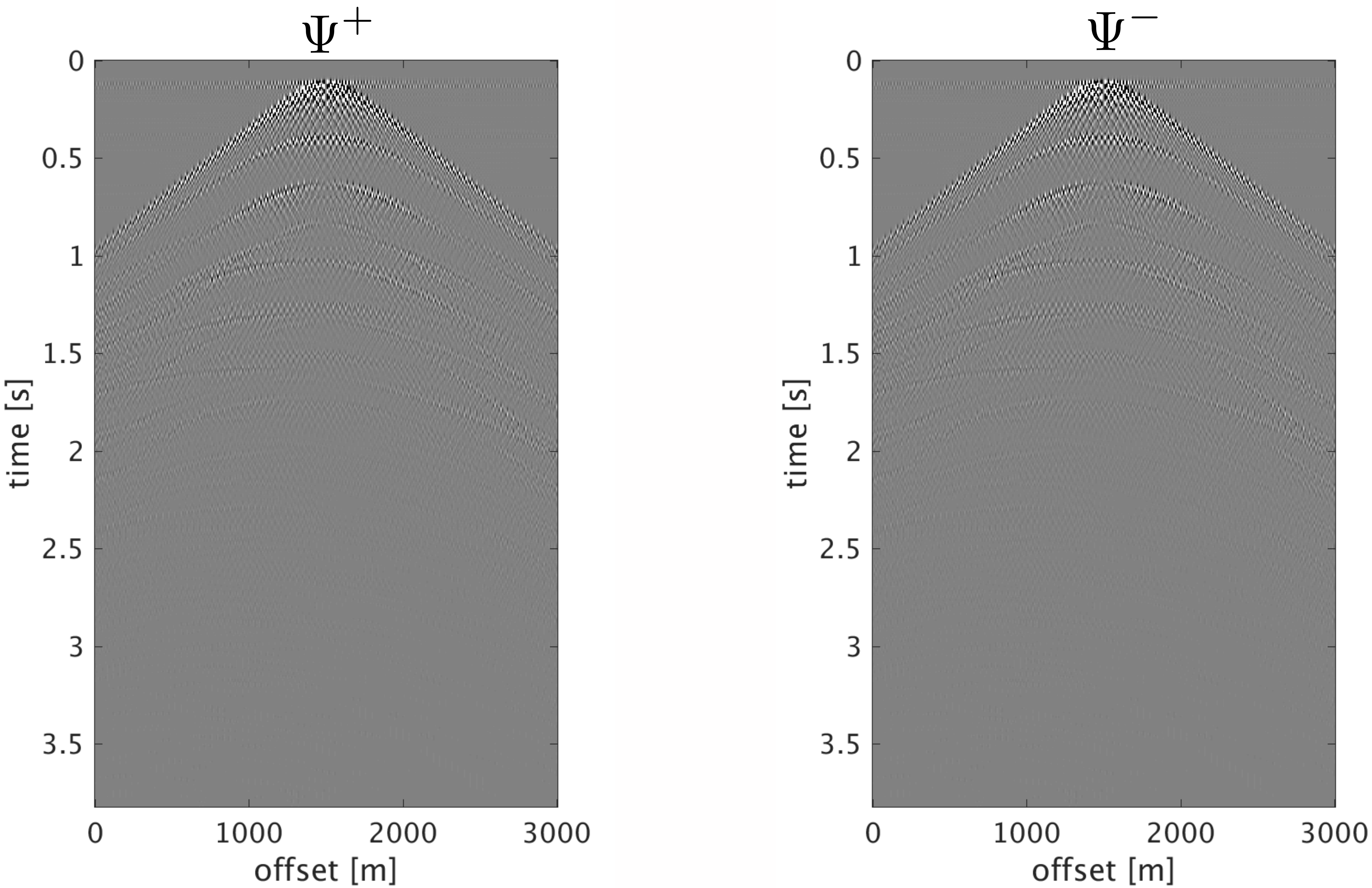
40 m source interval receiver gathers



f-k spectrum, 40 m source interval



Decomposed S-waves



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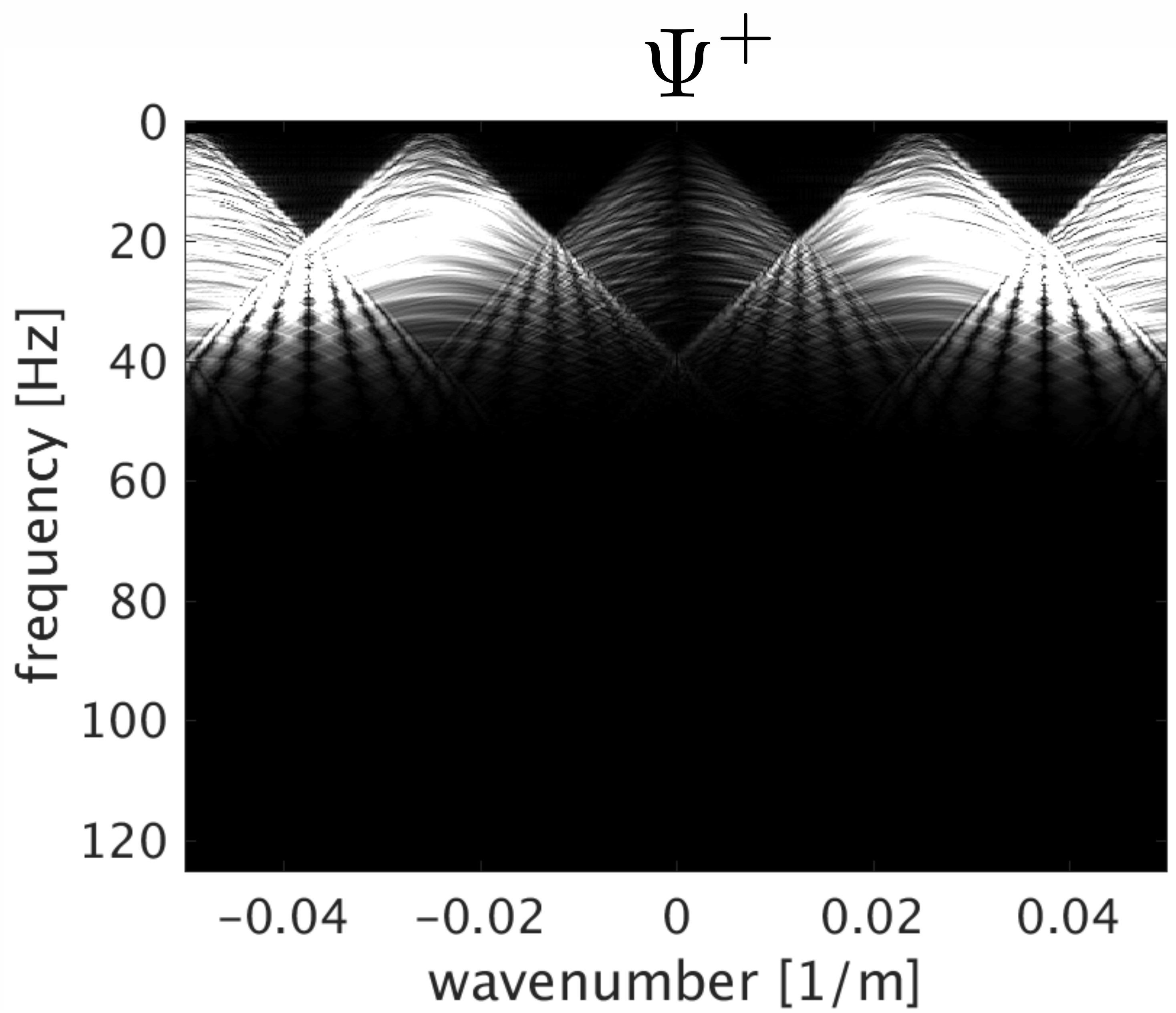

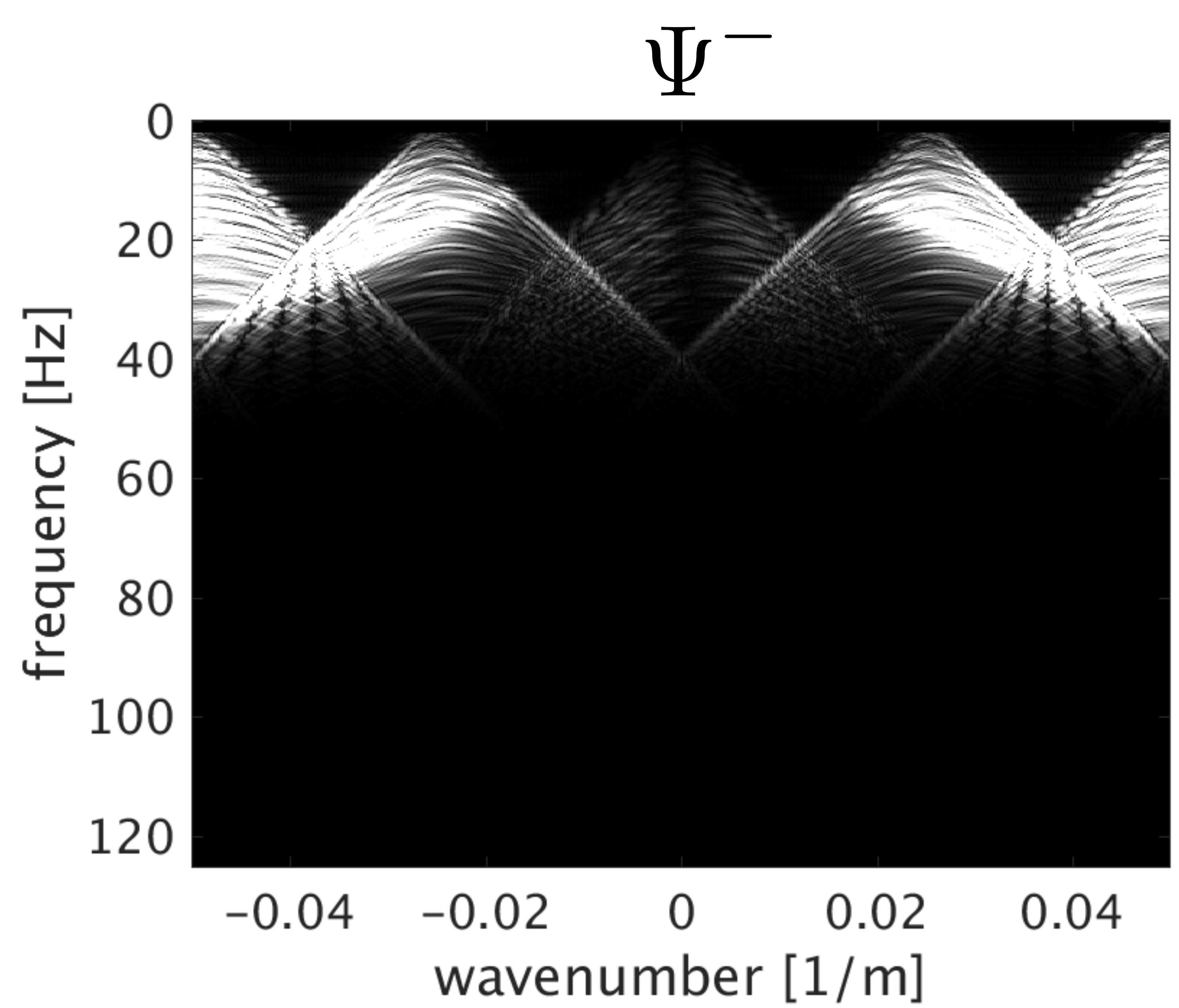

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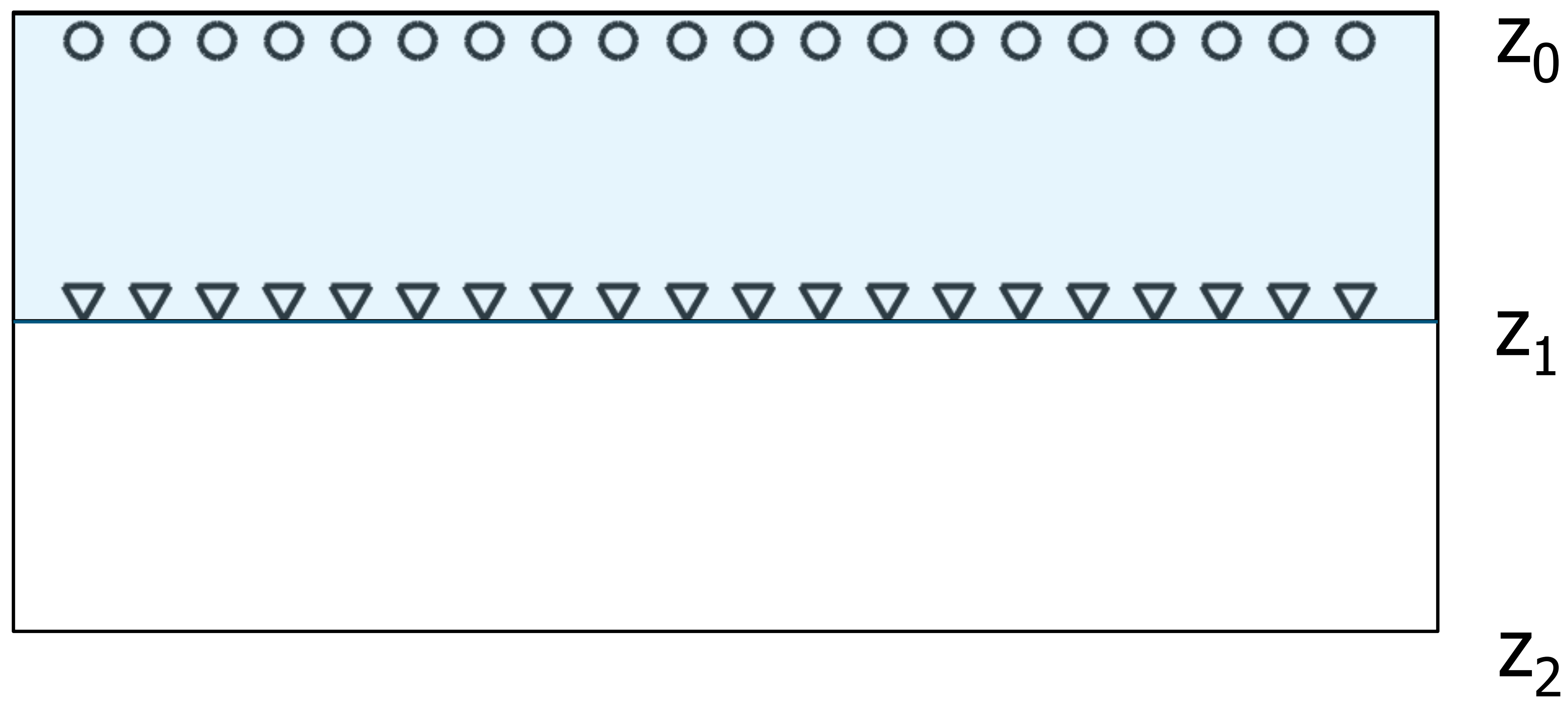

Hennenfent, G., and F. J. Herrmann, 2008, Simply denoise: Wavefield reconstruction via jittered undersampling: Geophysics, 73, V19–V28.

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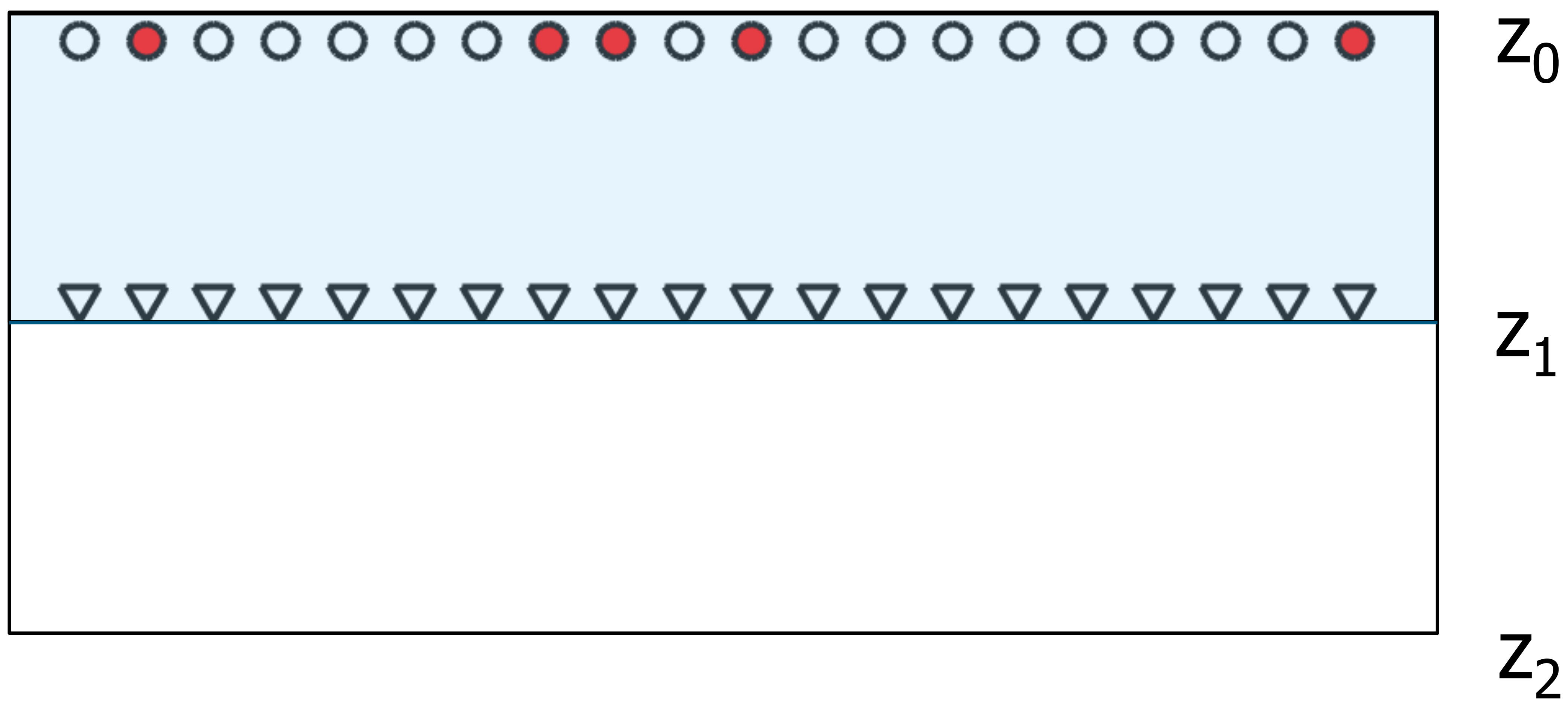
Jittered under-sampled acquisition



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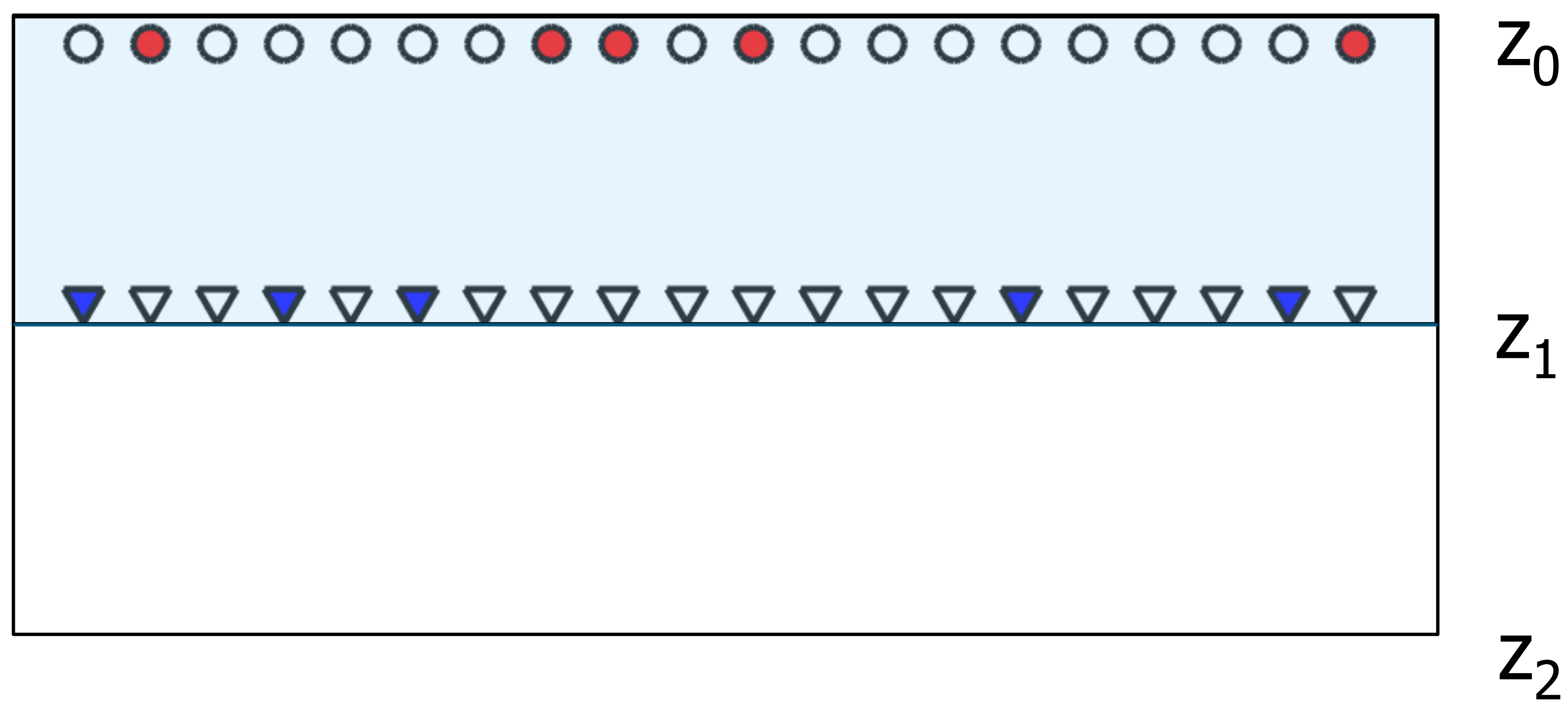
Jittered under-sampled acquisition



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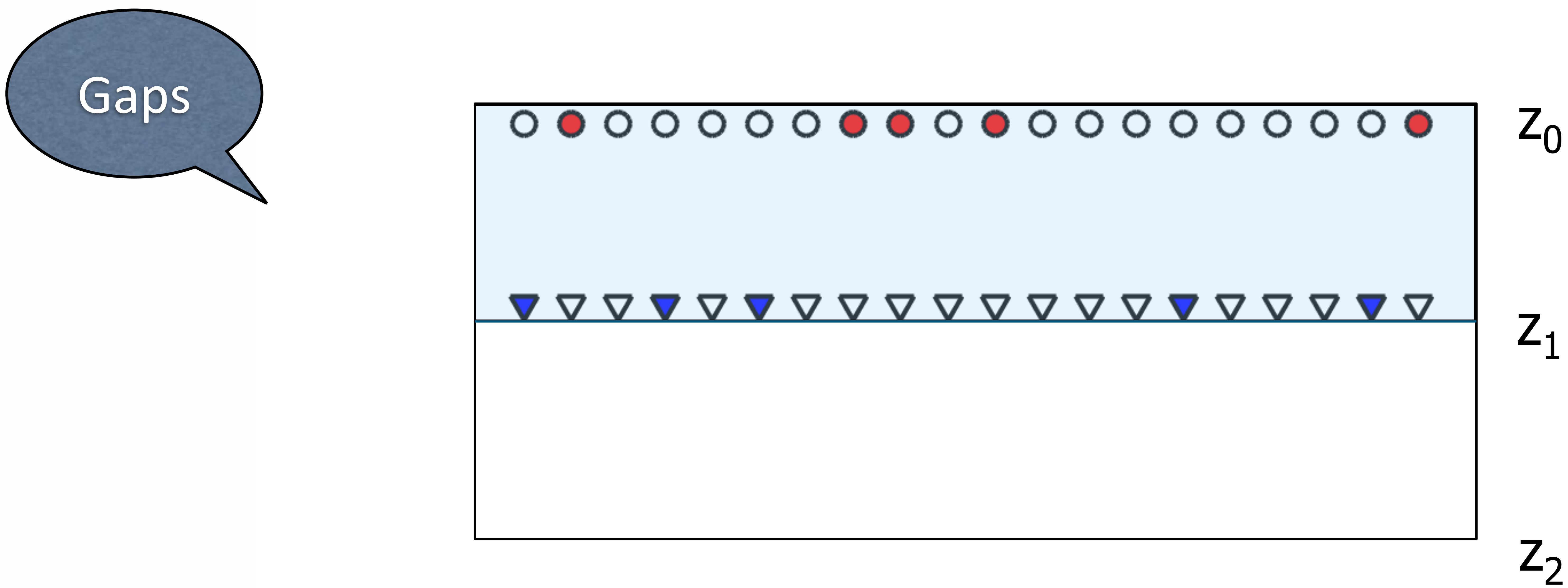
Jittered under-sampled acquisition



Single component reconstruction w\
(i) rank minimization

Kumar, R., Silva, C.D., Akalin, O., Aravkin, A.Y., Mansour, H., Recht, B. and Herrmann, F.J. [2015] Efficient matrix completion for seismic data reconstruction. Geophysics, 80(05), V97–V114. (Geophysics).

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Reconstruction w\ rank minimization

$$\min_{\mathbf{X}} \|\mathbf{X}\|_* \quad \text{subject to} \quad \|\mathbf{A}(\mathbf{X}) - \mathbf{b}\|_2 \leq \sigma \qquad (\mathrm{BPDN}_\sigma)$$

$$\mathbf{A} = \mathbf{M}\mathbf{S}^H \qquad \|\mathbf{X}\|_* = \|\lambda\|_1$$

Kumar, R., Silva, C.D., Akalin, O., Aravkin, A.Y., Mansour, H., Recht, B. and Herrmann, F.J. [2015] Efficient matrix completion for seismic data reconstruction. Geophysics, 80(05), V97–V114. (Geophysics).

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$$\mathbf{A} = \mathbf{M}\mathbf{S}^H \qquad \|\mathbf{X}\|_* = \|\lambda\|_1$$

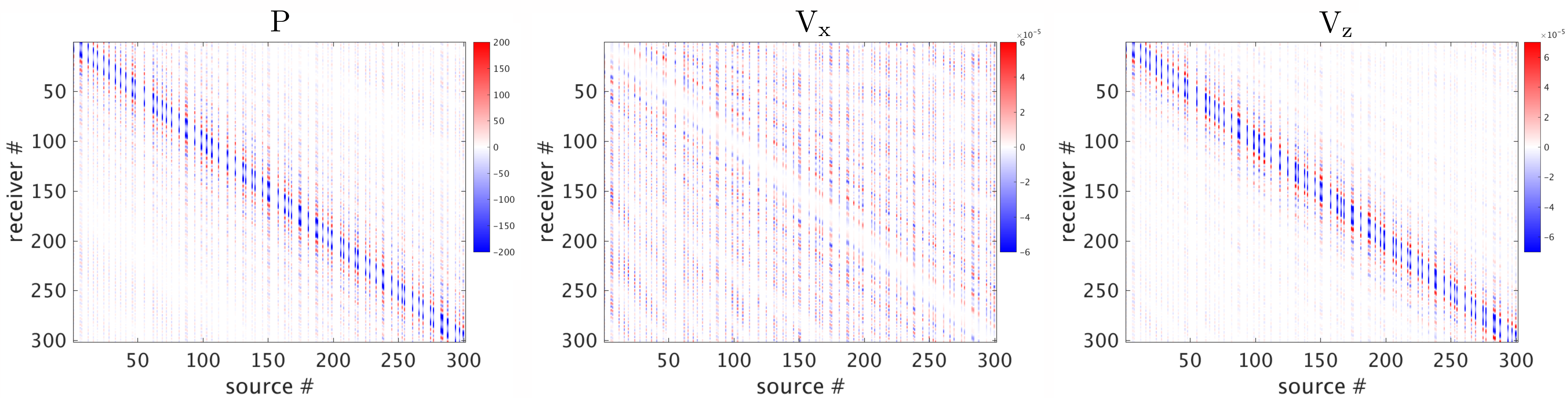
SPGℓ_1

$$\min_{\mathbf{X}} \|\mathbf{A}(\mathbf{X}) - \mathbf{b}\|_2 \quad \text{subject to } \|\mathbf{X}\|_* \leq \tau \qquad (\mathrm{LASSO}_\tau)$$

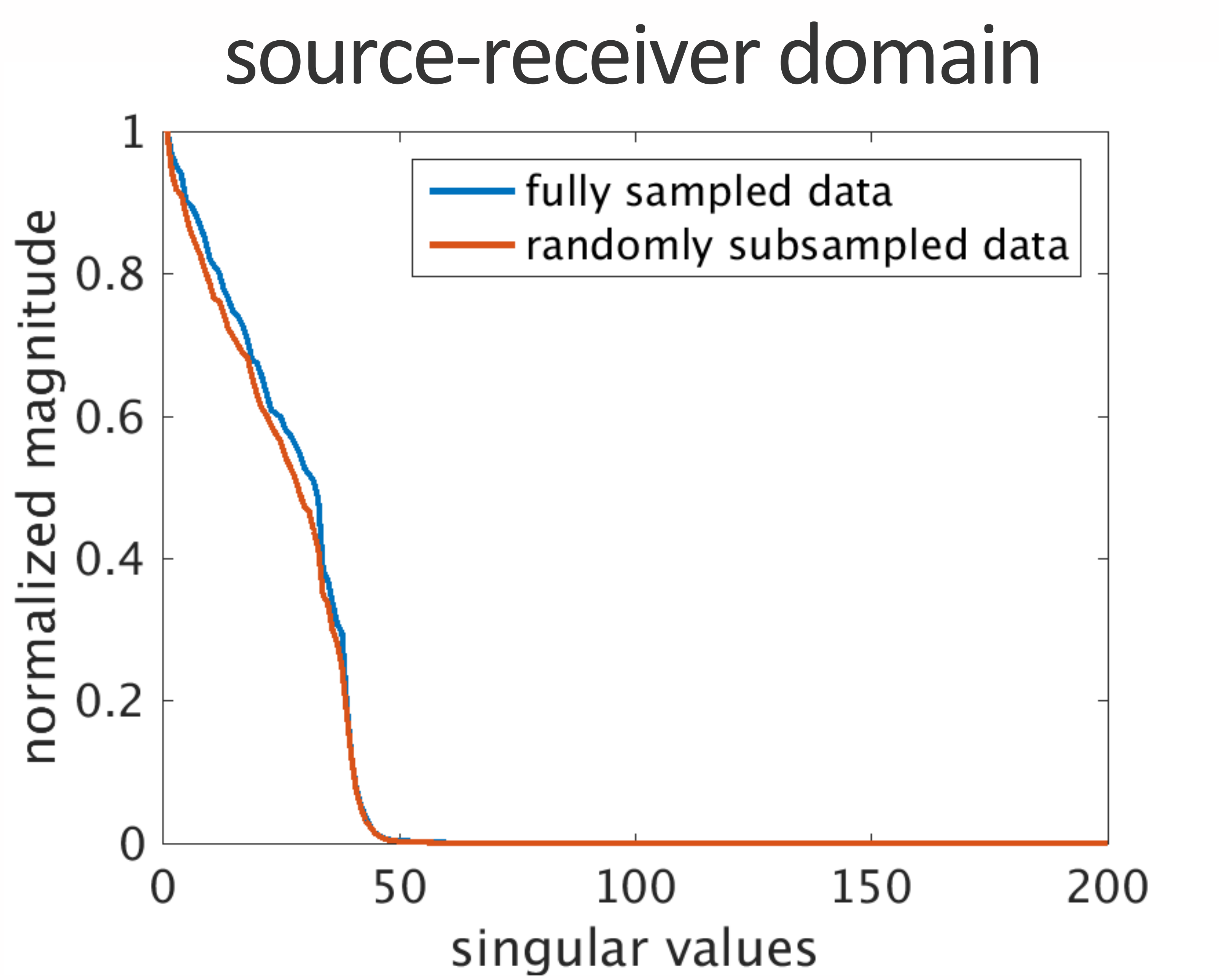
$$\mathbf{X} = \mathbf{L}\mathbf{R}^H \qquad \|\mathbf{X}\|_* \leq \frac{1}{2}(\|\mathbf{L}\|_F^2 + \|\mathbf{R}\|_F^2)$$

$$\mathbf{X} \in \mathbf{C}^{n\times m}, \quad \mathbf{L} \in \mathbf{C}^{n\times k}, \quad \mathbf{R} \in \mathbf{C}^{m\times k}, \quad k \ll m, n$$

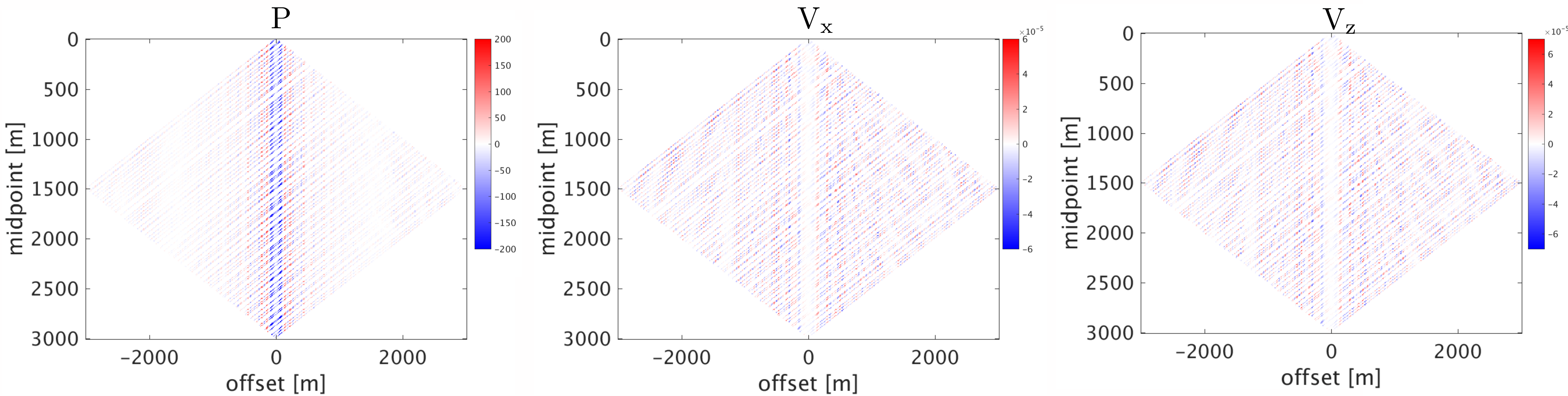
Randomly subsampled frequency slices, 25 Hz



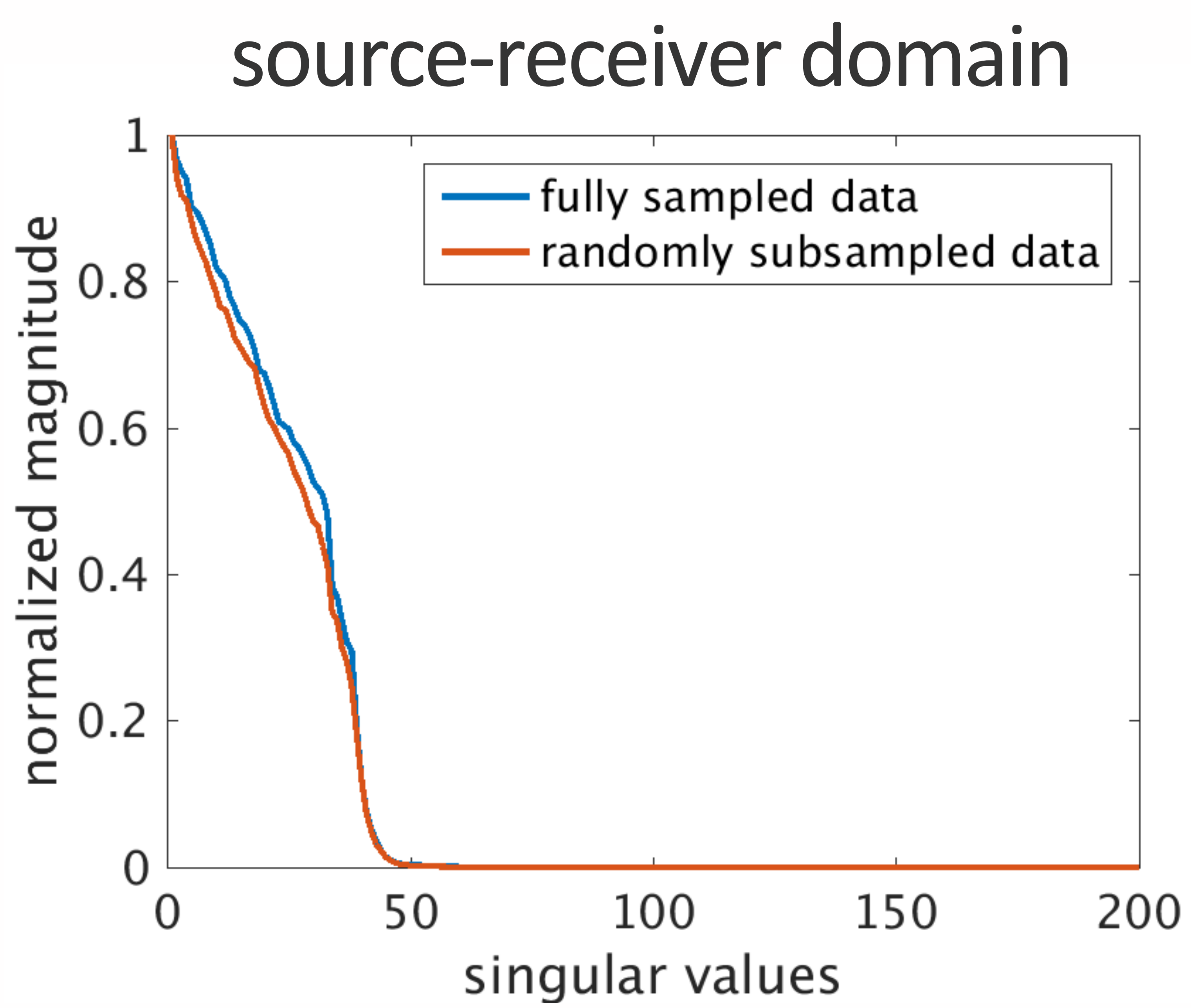
Singular values decay

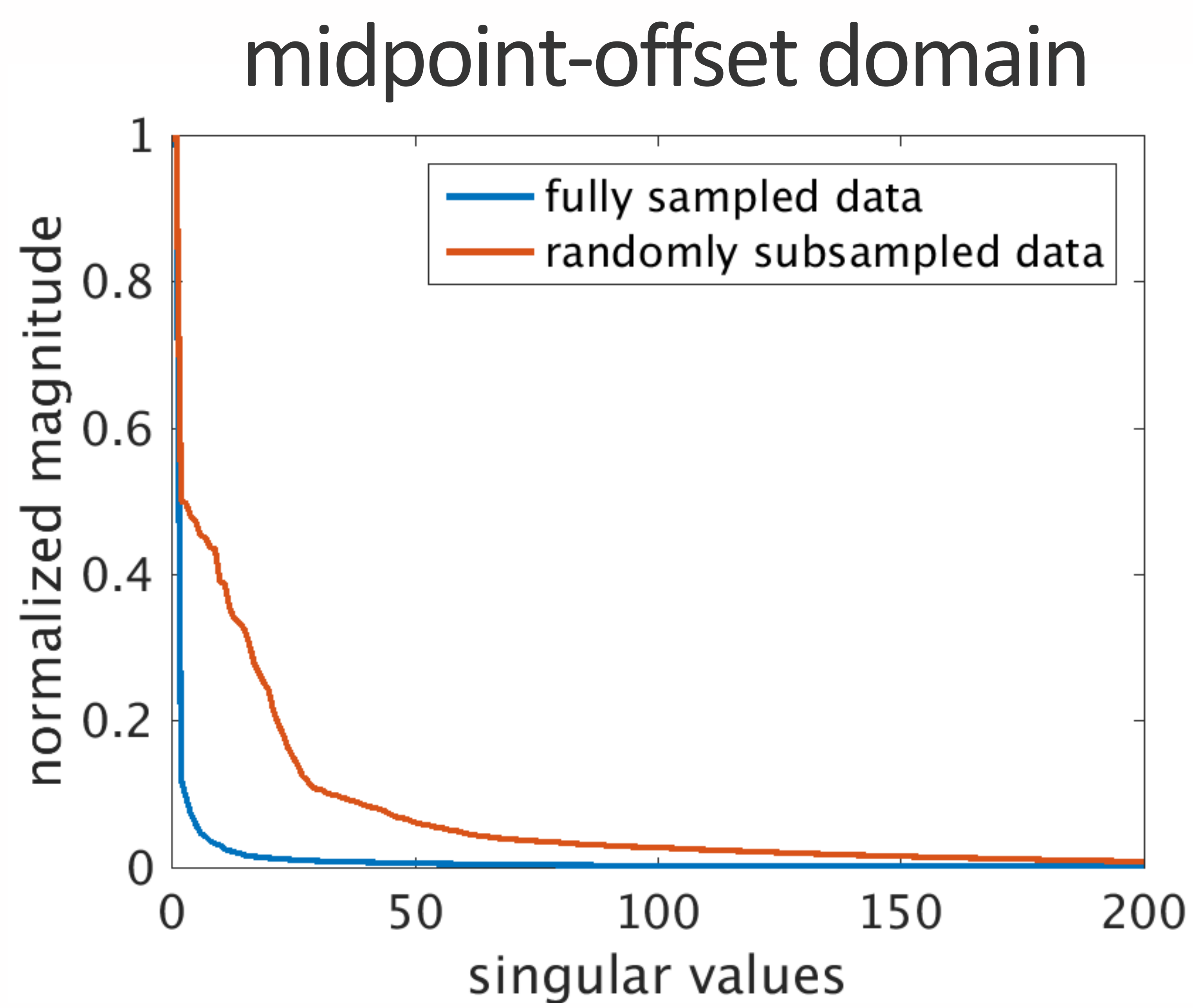


Midpoint-offset domain

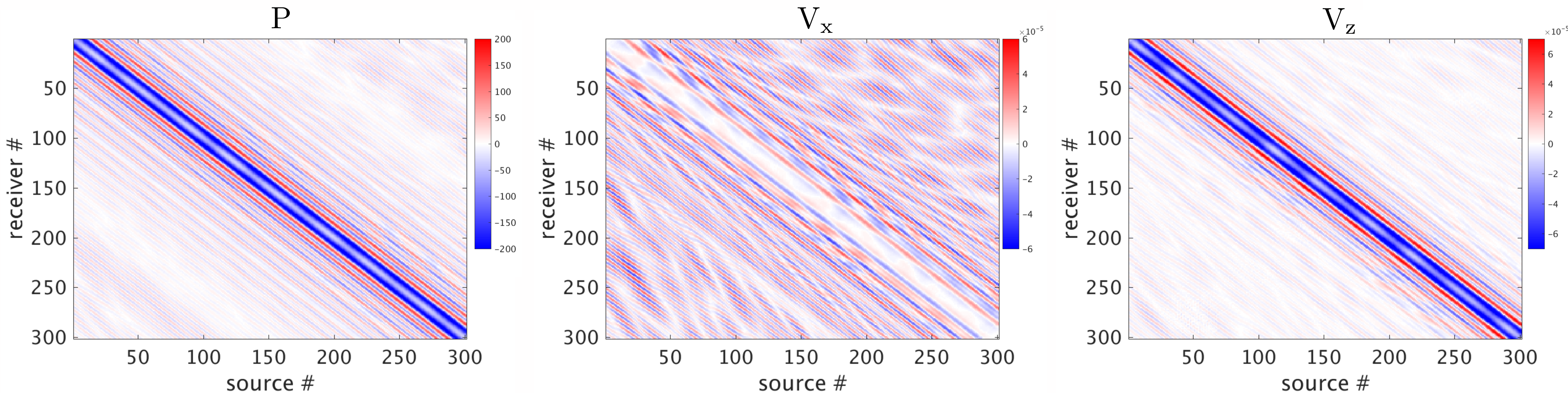


Singular values decay

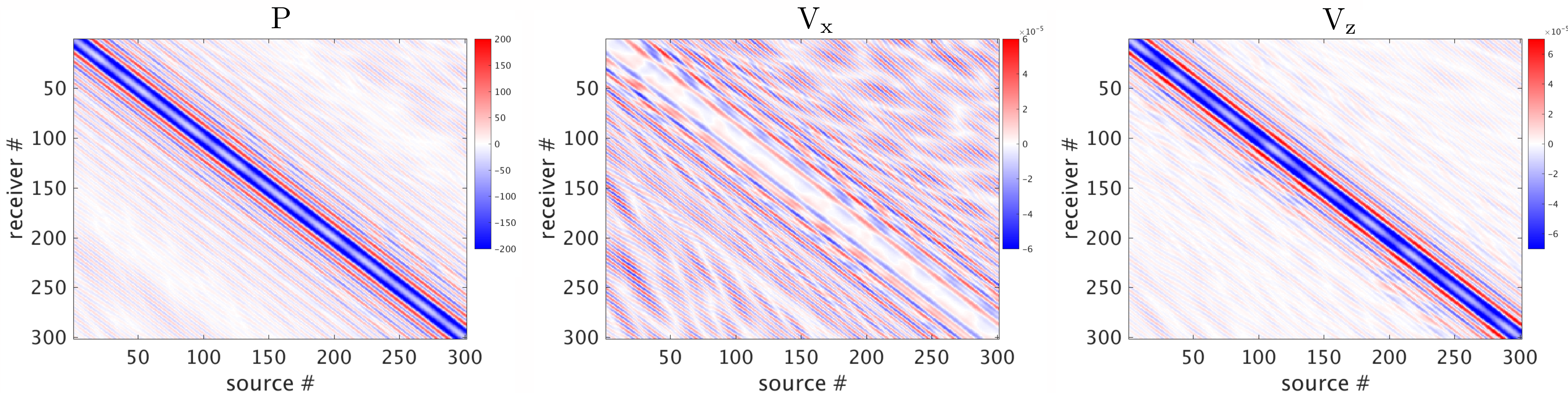




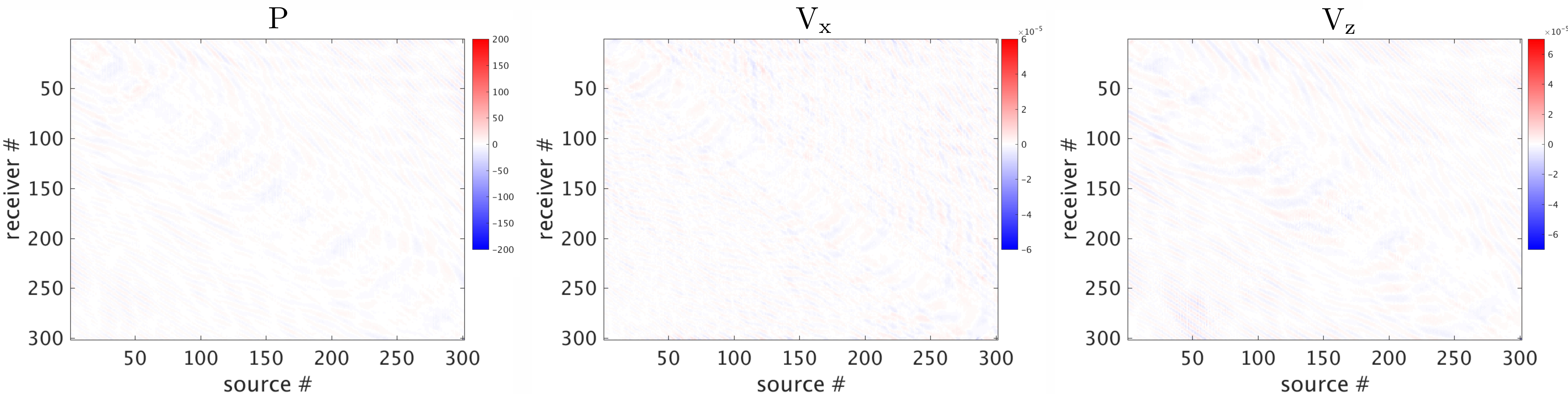
Reconstructed frequency slices, 25 Hz



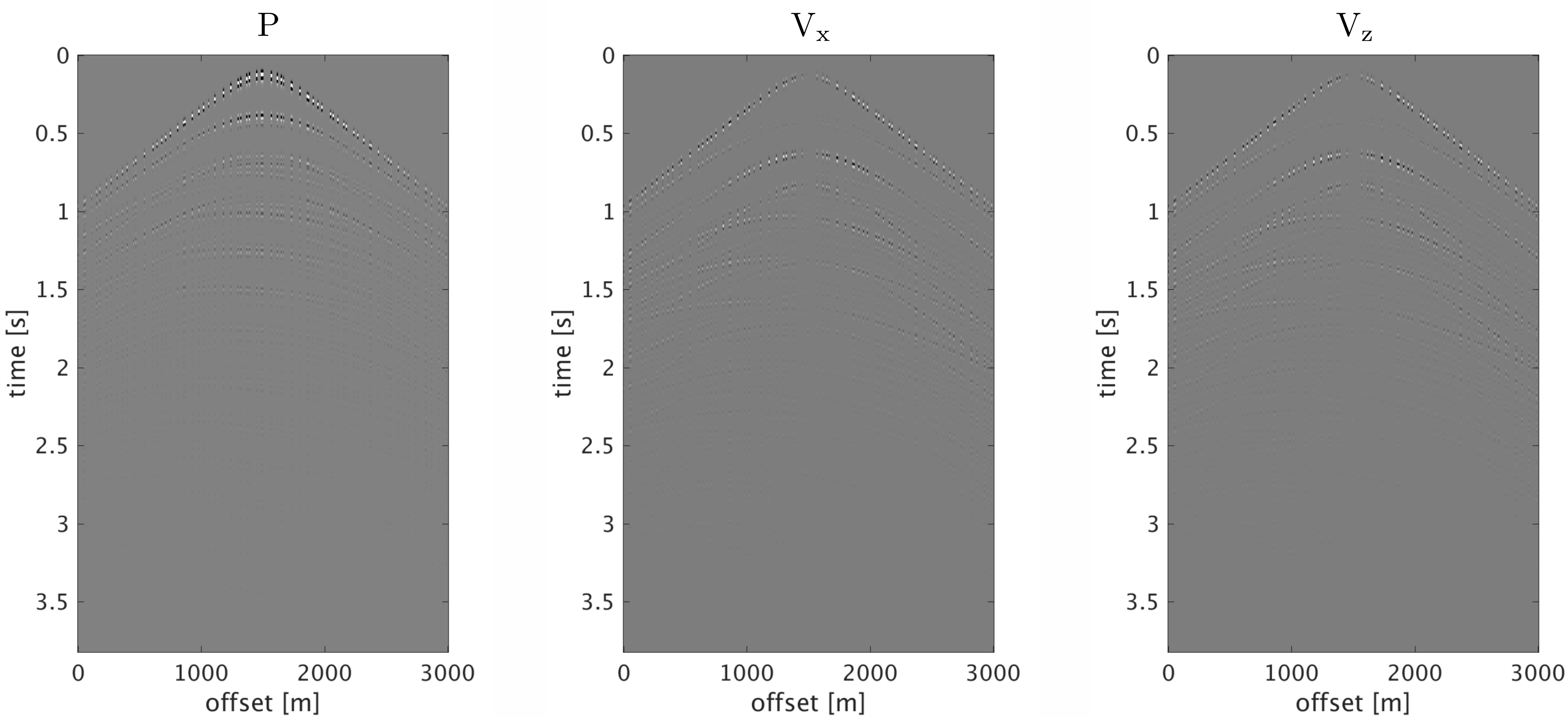
Densely sampled frequency slices, 25 Hz



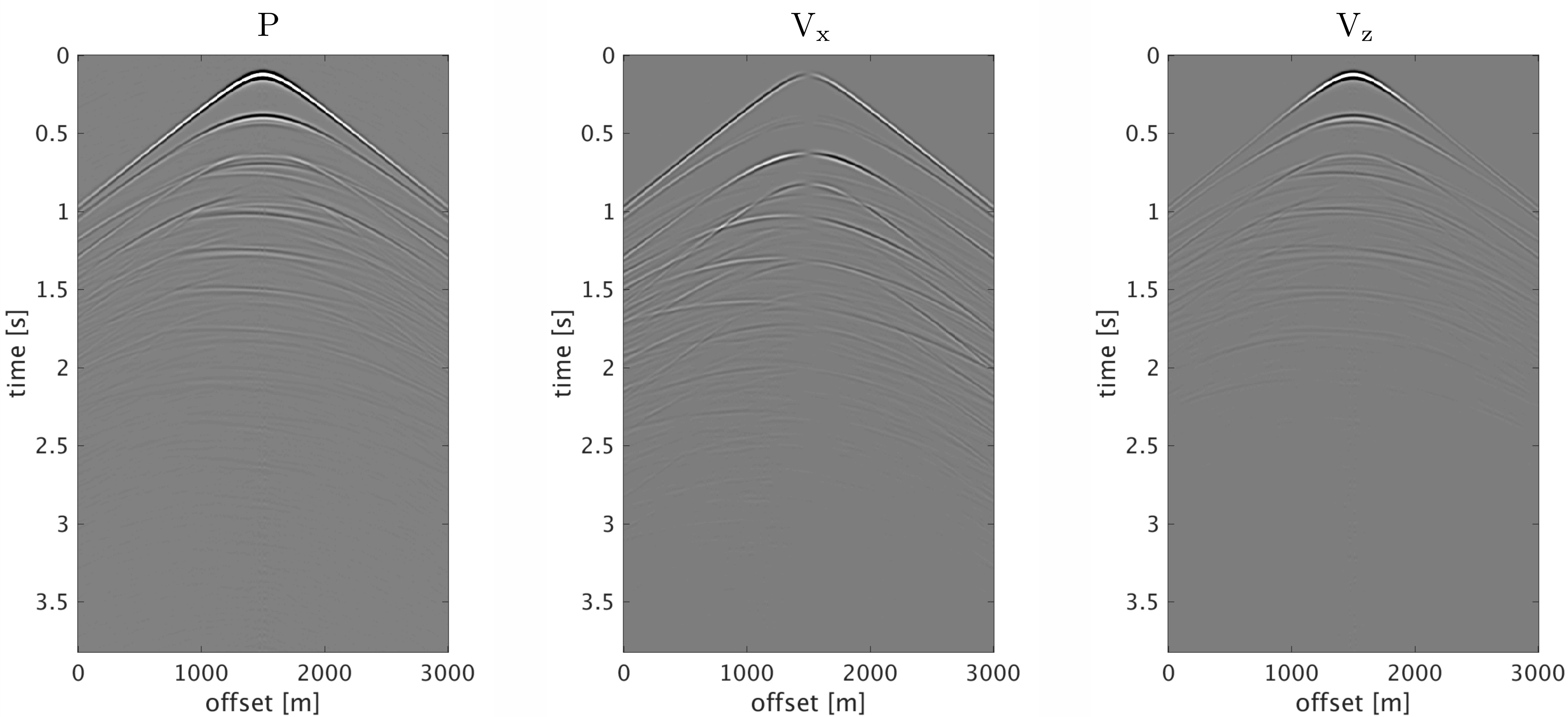
Residual



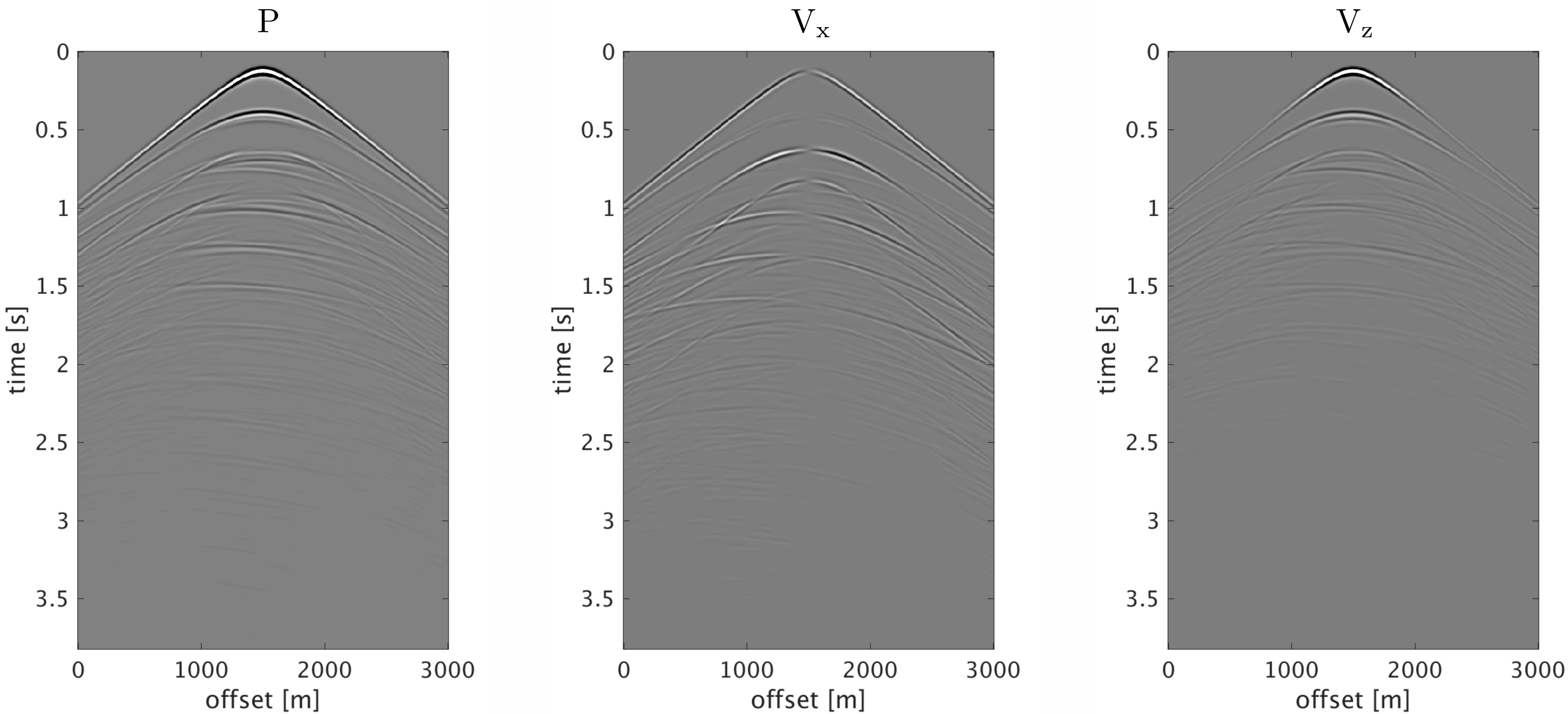
75% jittered subsampling



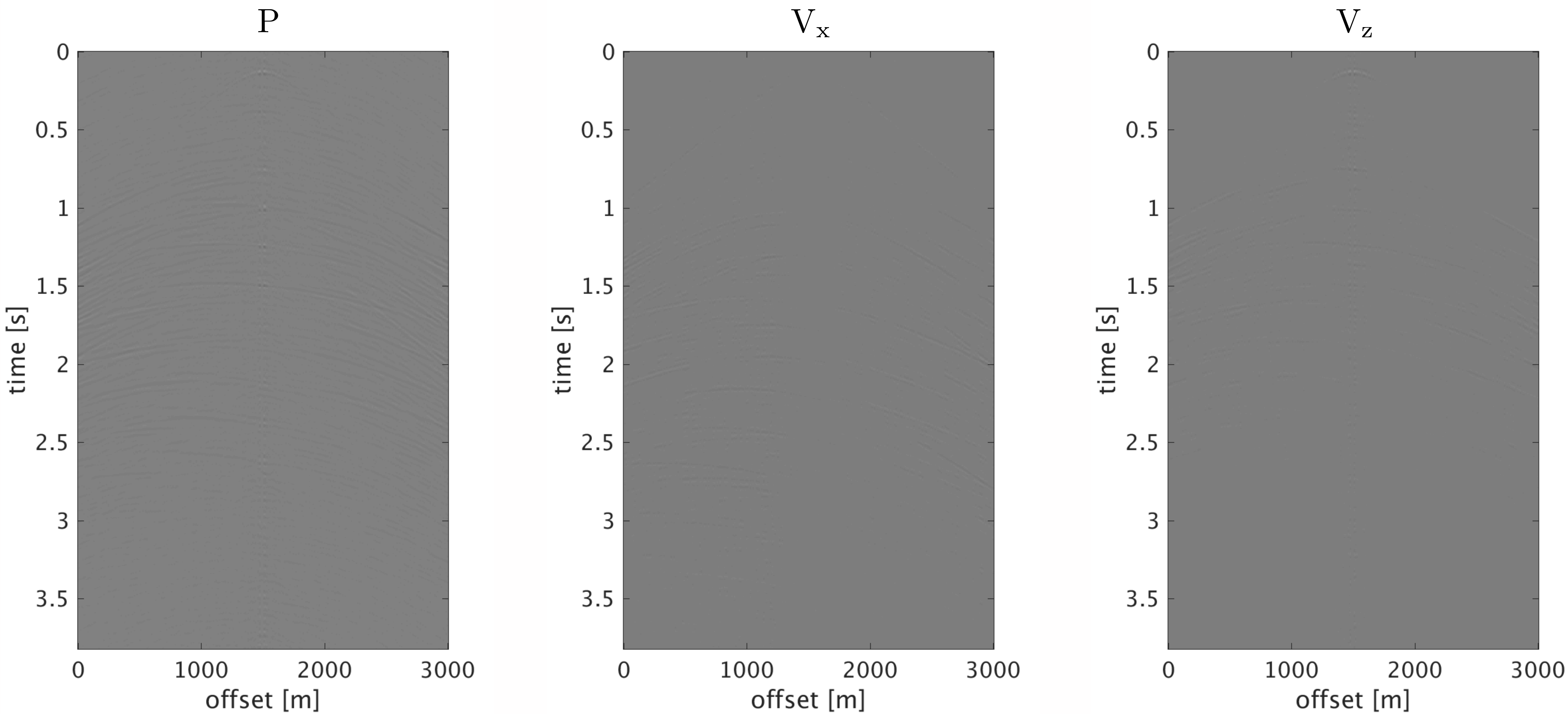
Reconstructed receiver gathers



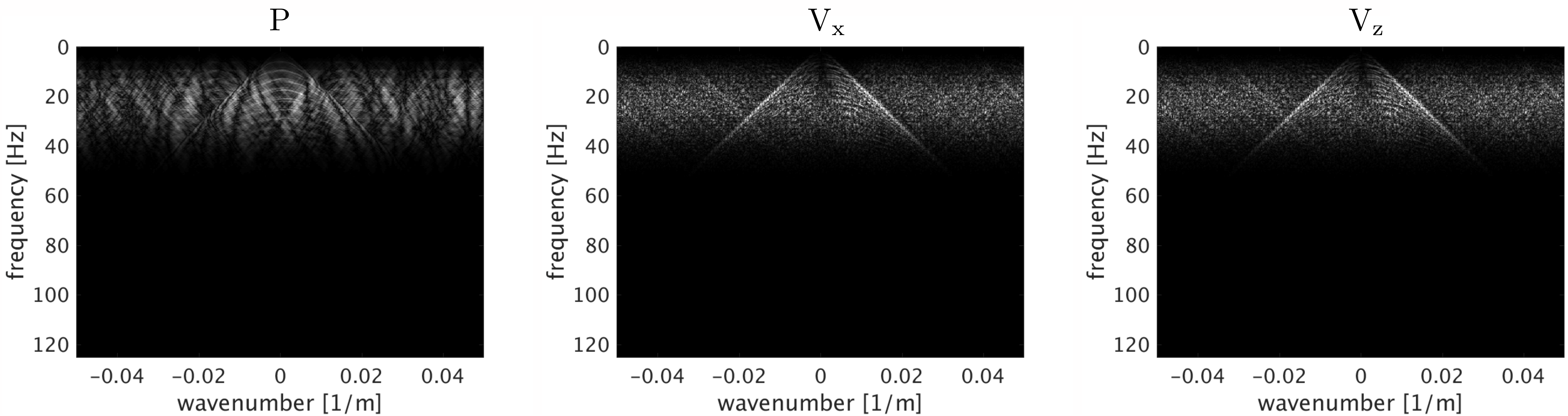
Densely sampled receiver gathers, 10 m



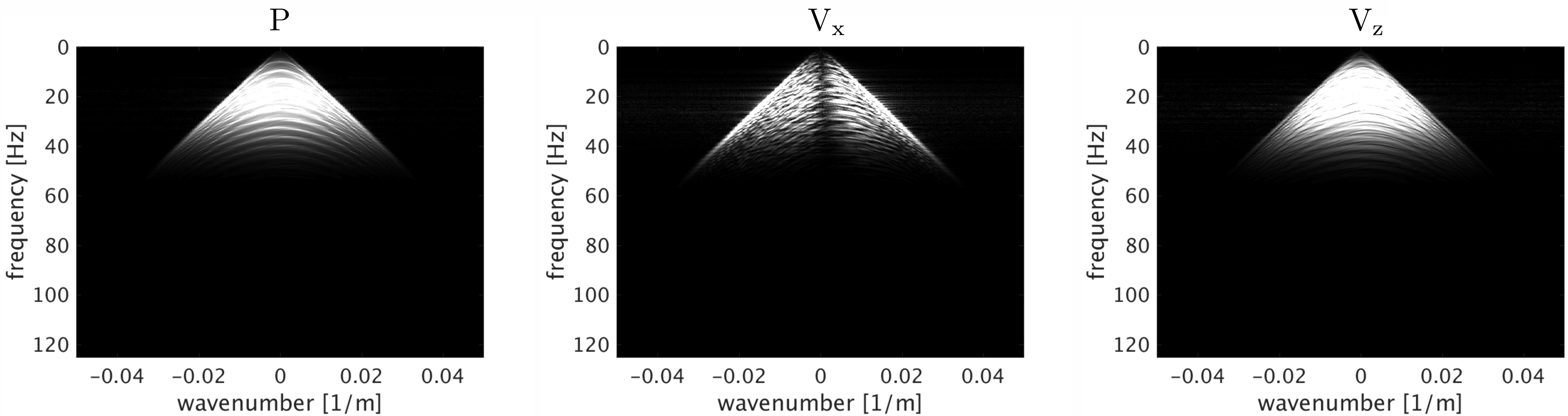
Residual



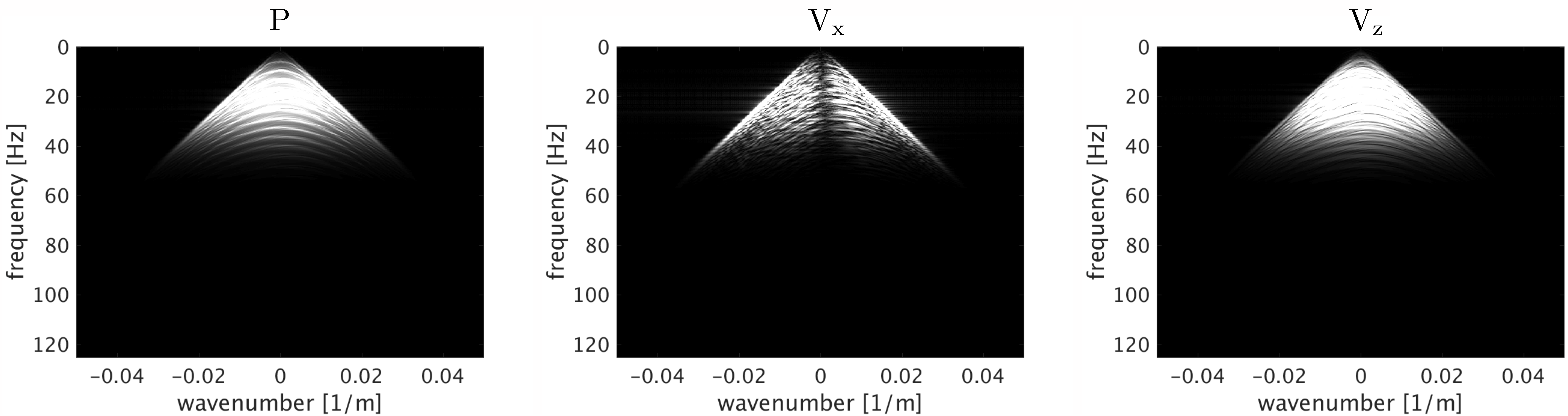
f-k spectrum, 75% jittered subsampling



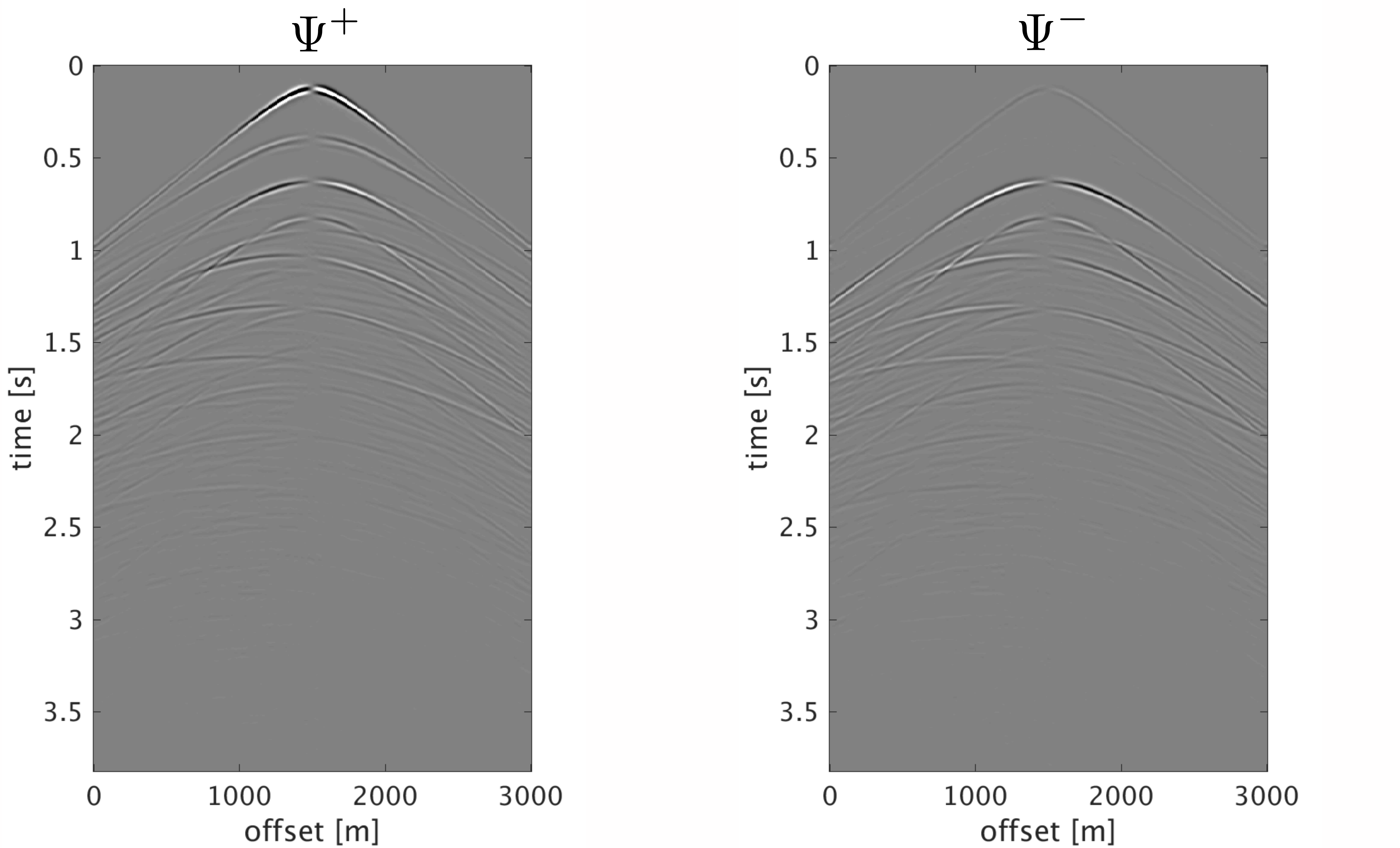
f-k spectrum, reconstruction



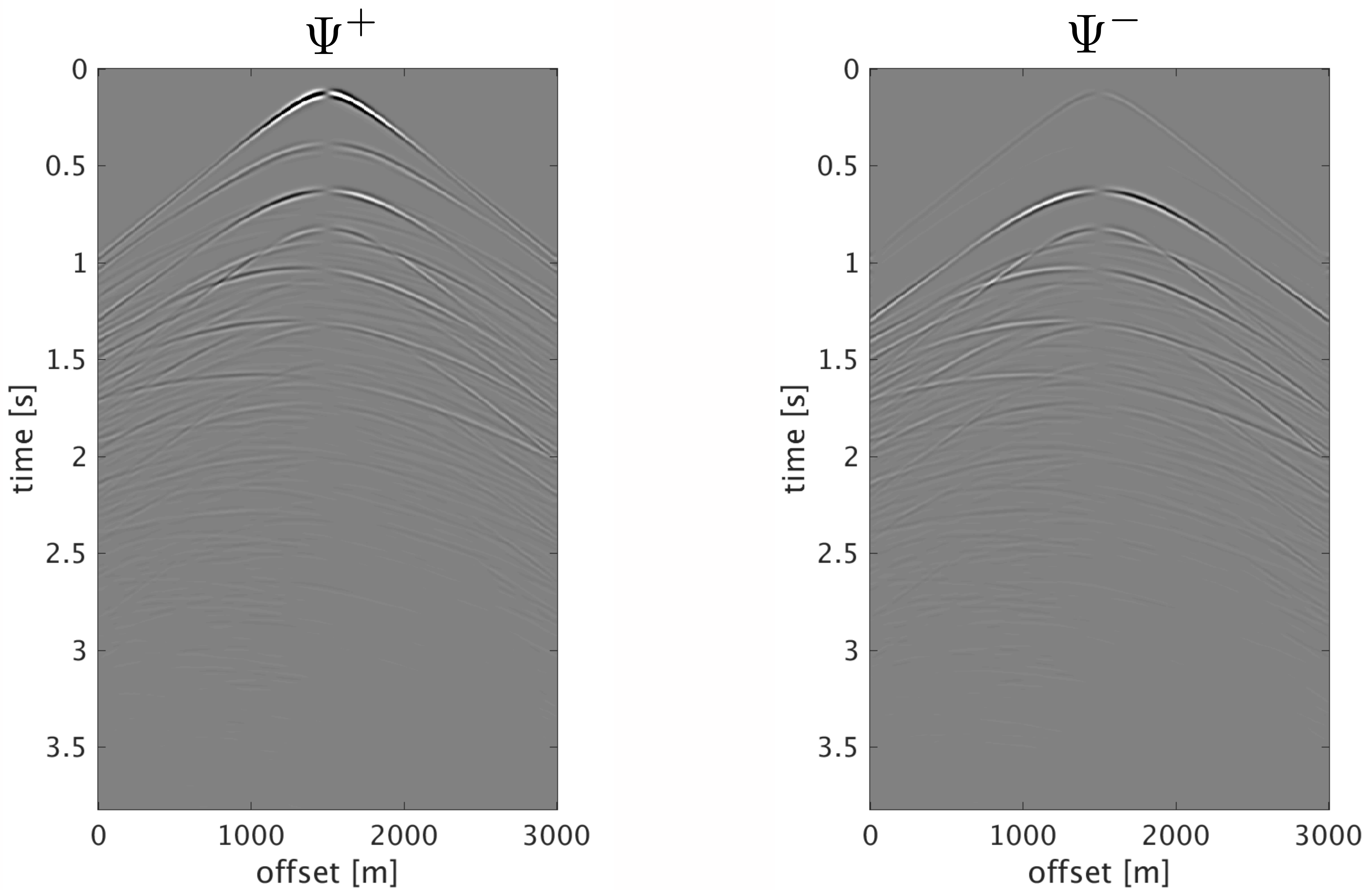
f-k spectrum, densely sampled



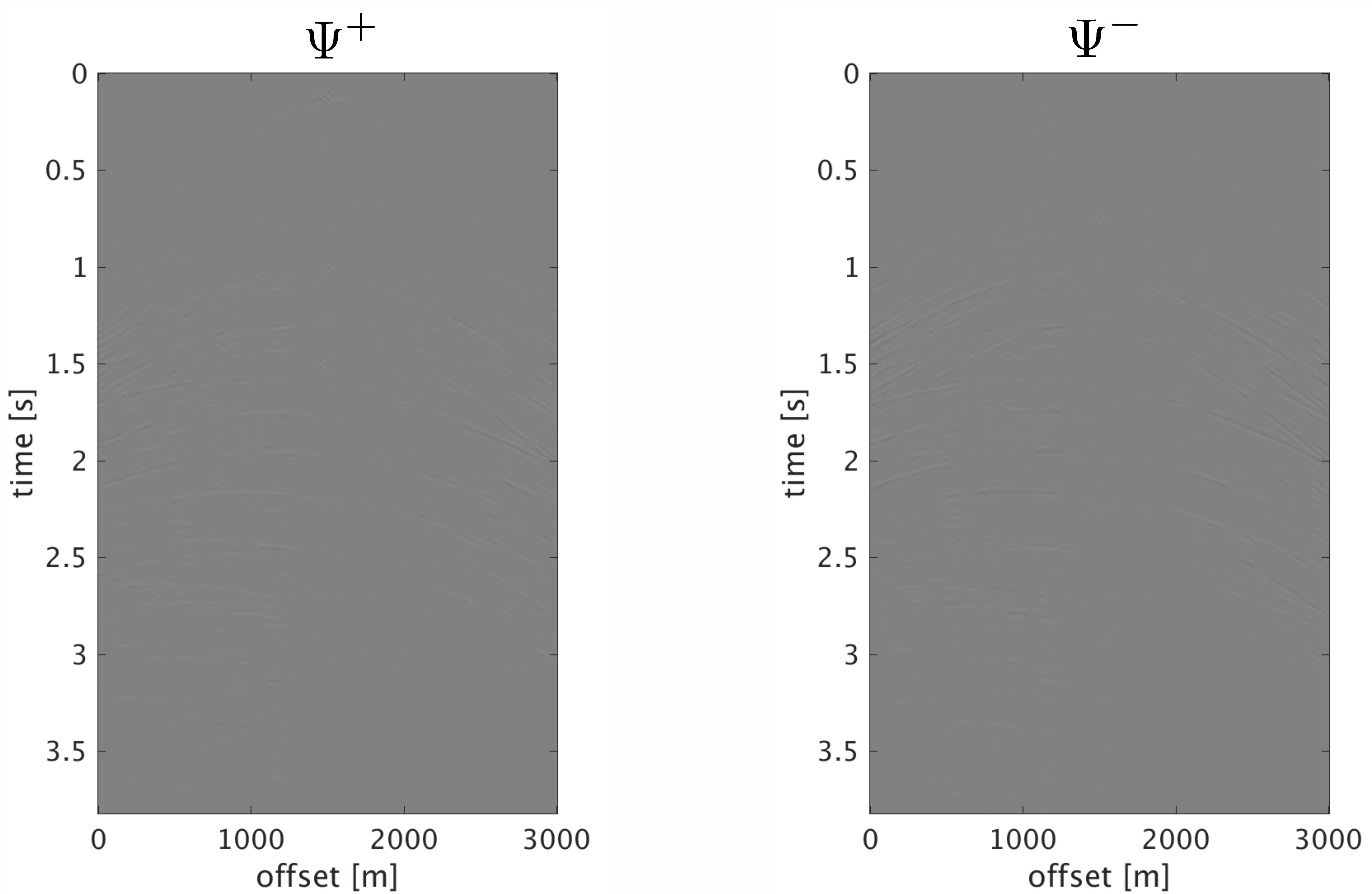
Reconstructed S-waves



True S-waves



Residual



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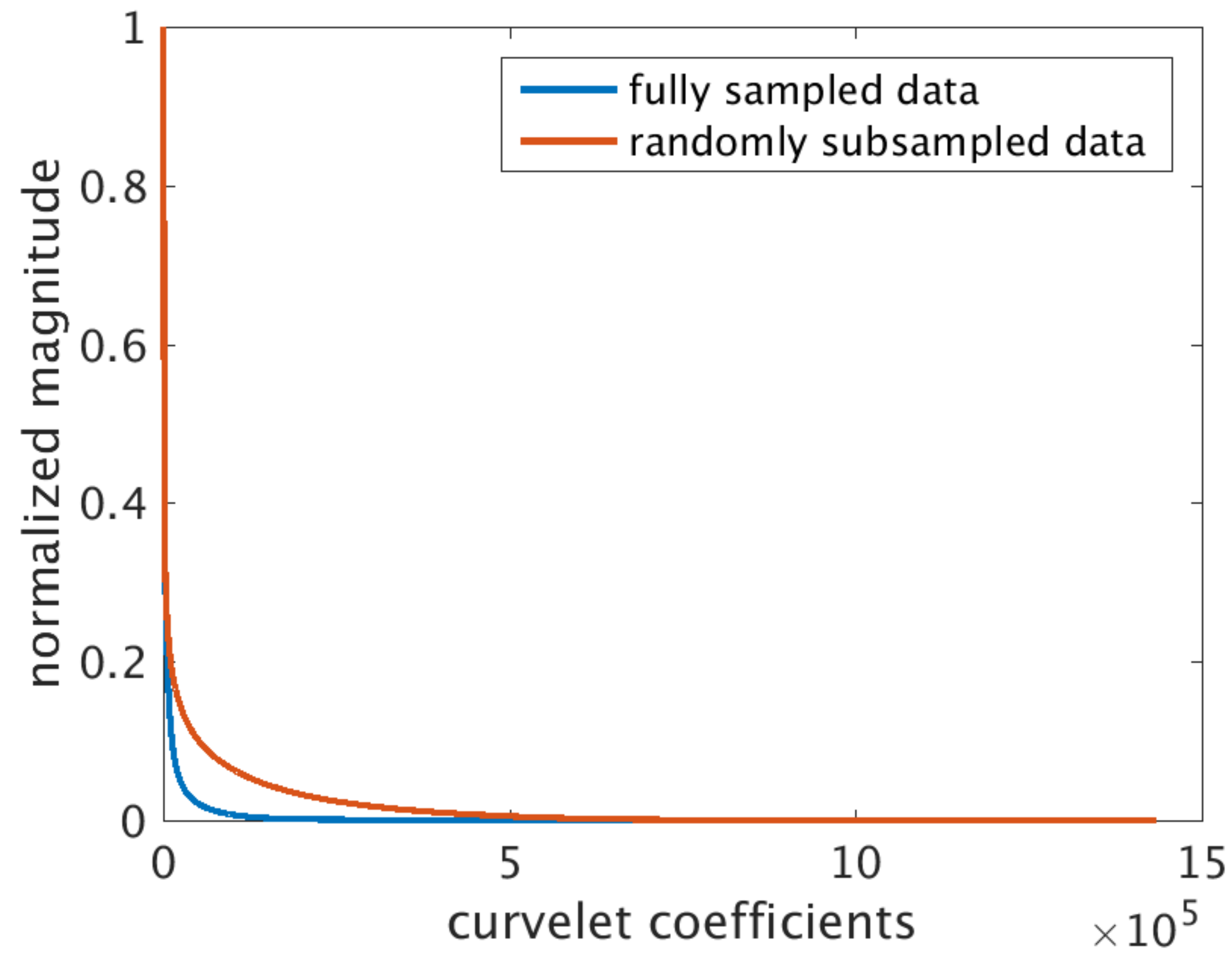
Single component reconstruction w\
(ii) sparsity promotion

Single component reconstruction w\ sparsity promotion

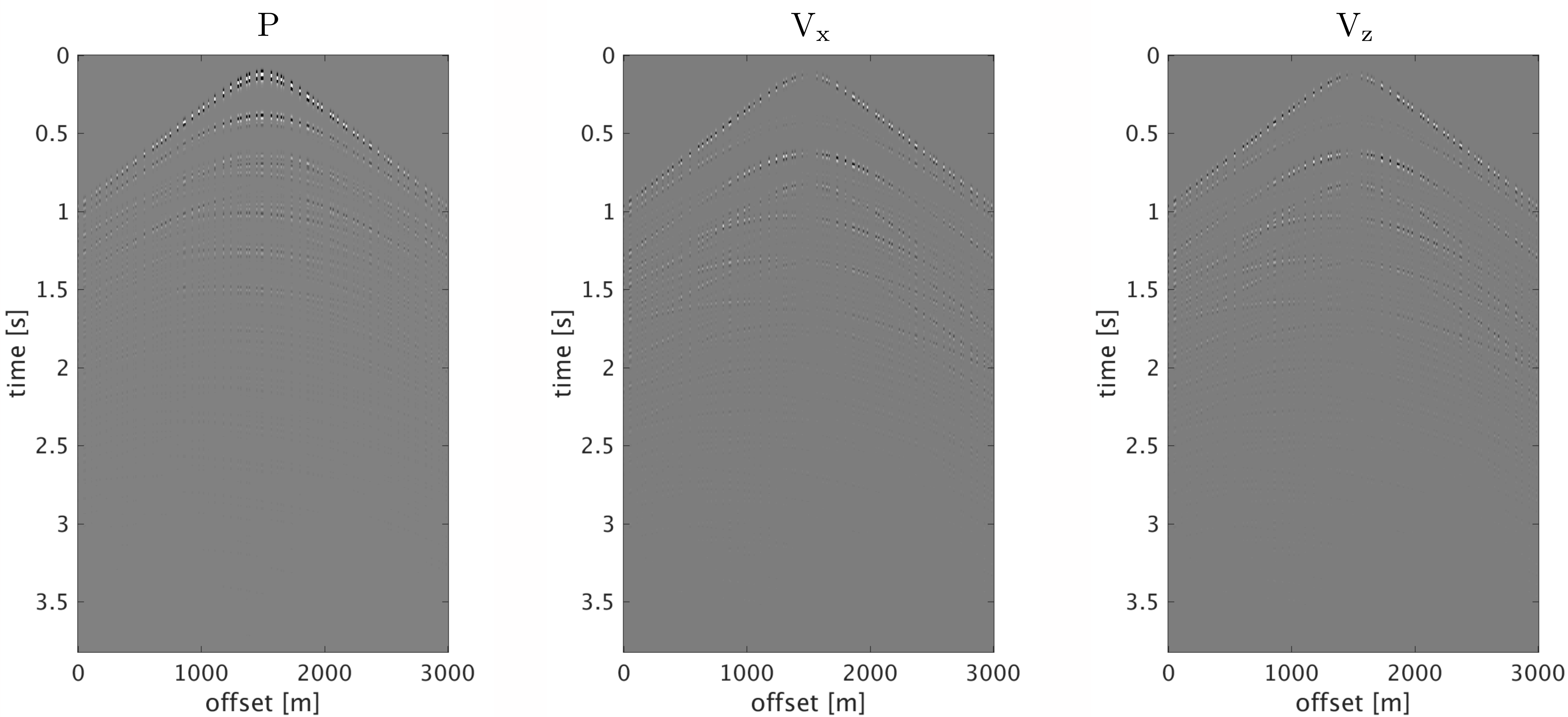
$$\min_{\mathbf{x}} \|\mathbf{x}\|_1 \quad \text{subject to} \quad \|\mathbf{A}\mathbf{x} - \mathbf{b}\|_2 \leq \sigma \qquad (\mathrm{BPDN}_\sigma)$$

$\mathbf{x}$: curvelet coefficients

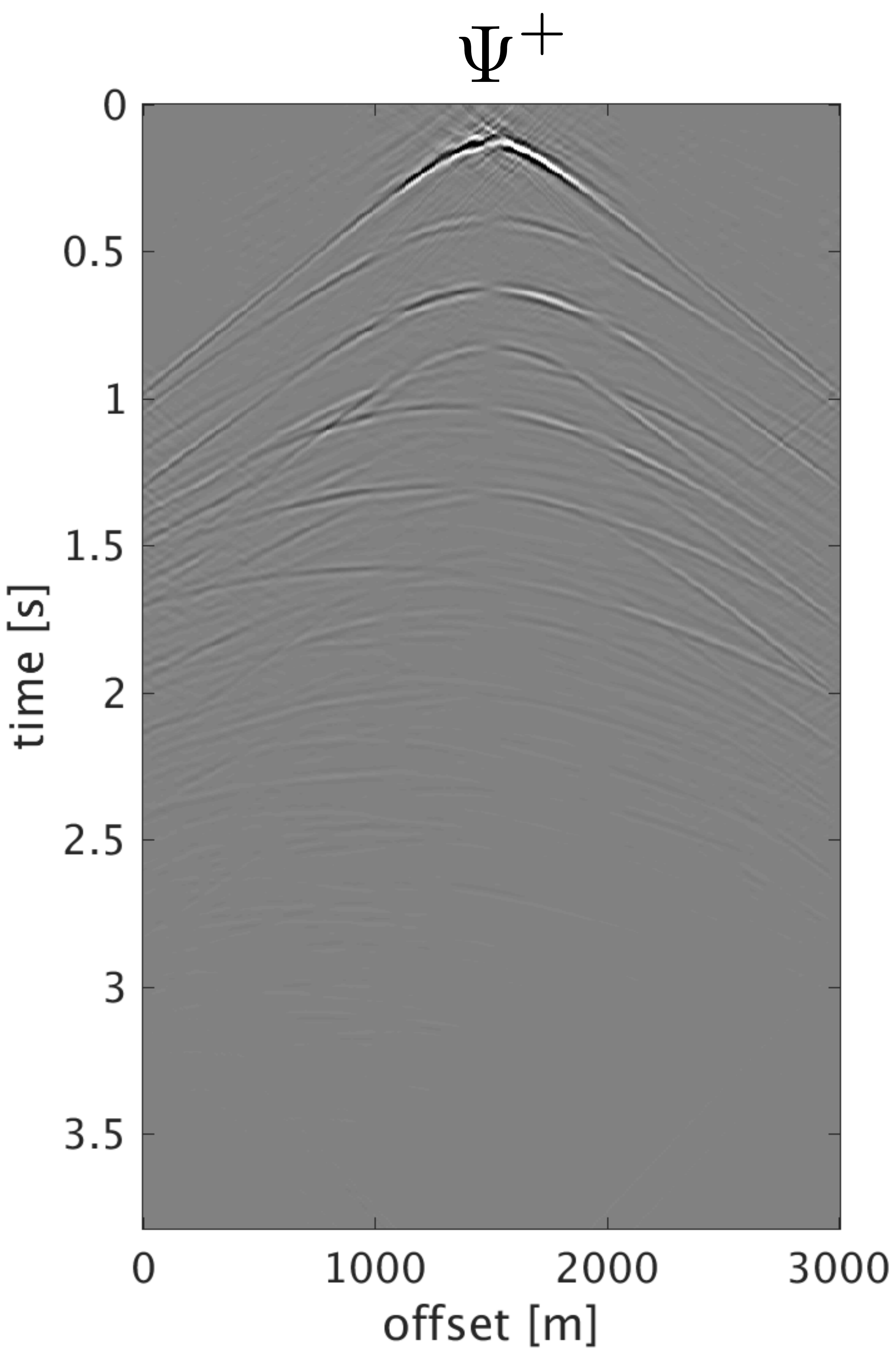
$$\mathbf{A} = \mathbf{M}\mathbf{S}^{\mathbf{H}}$$

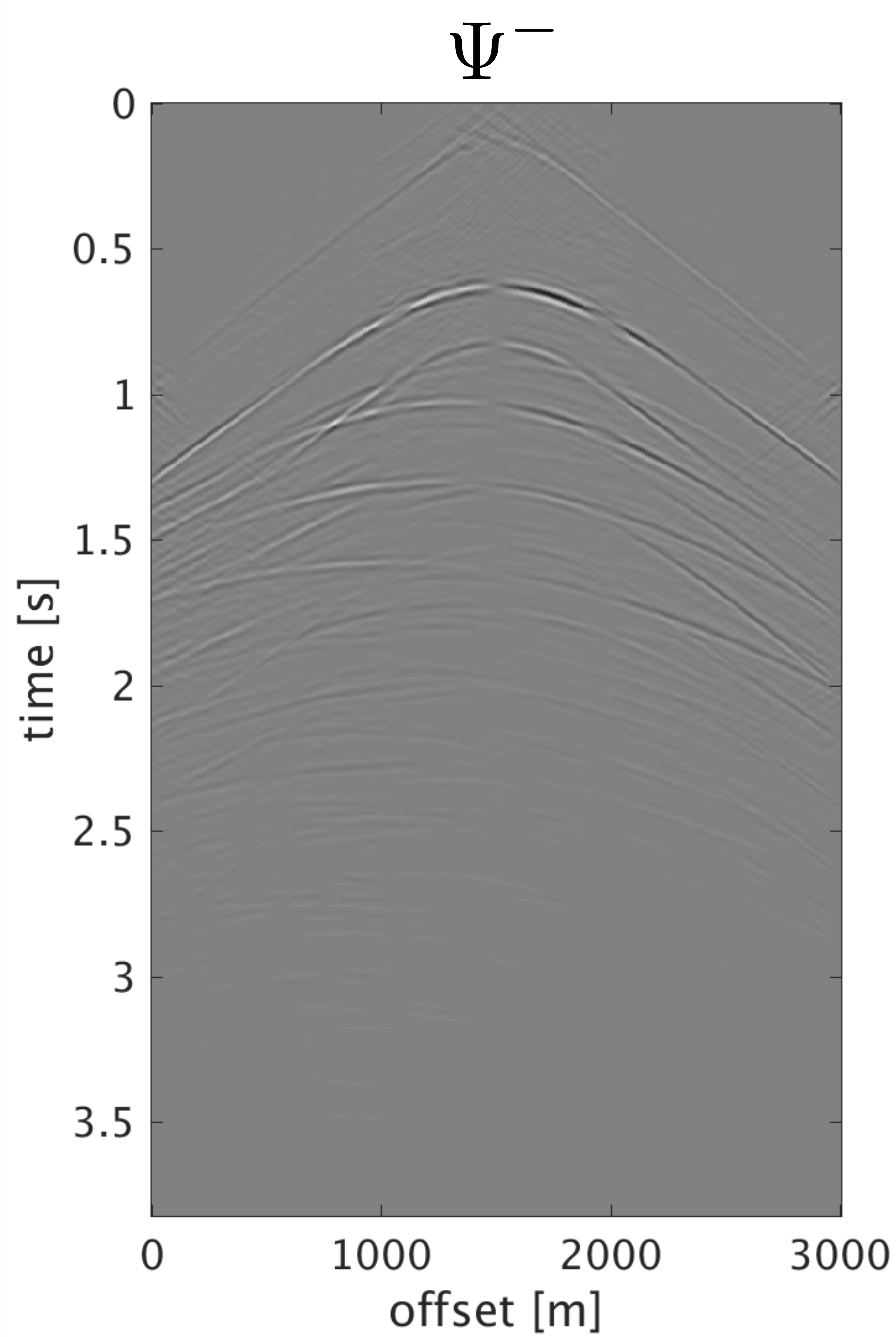


75% jittered subsampling

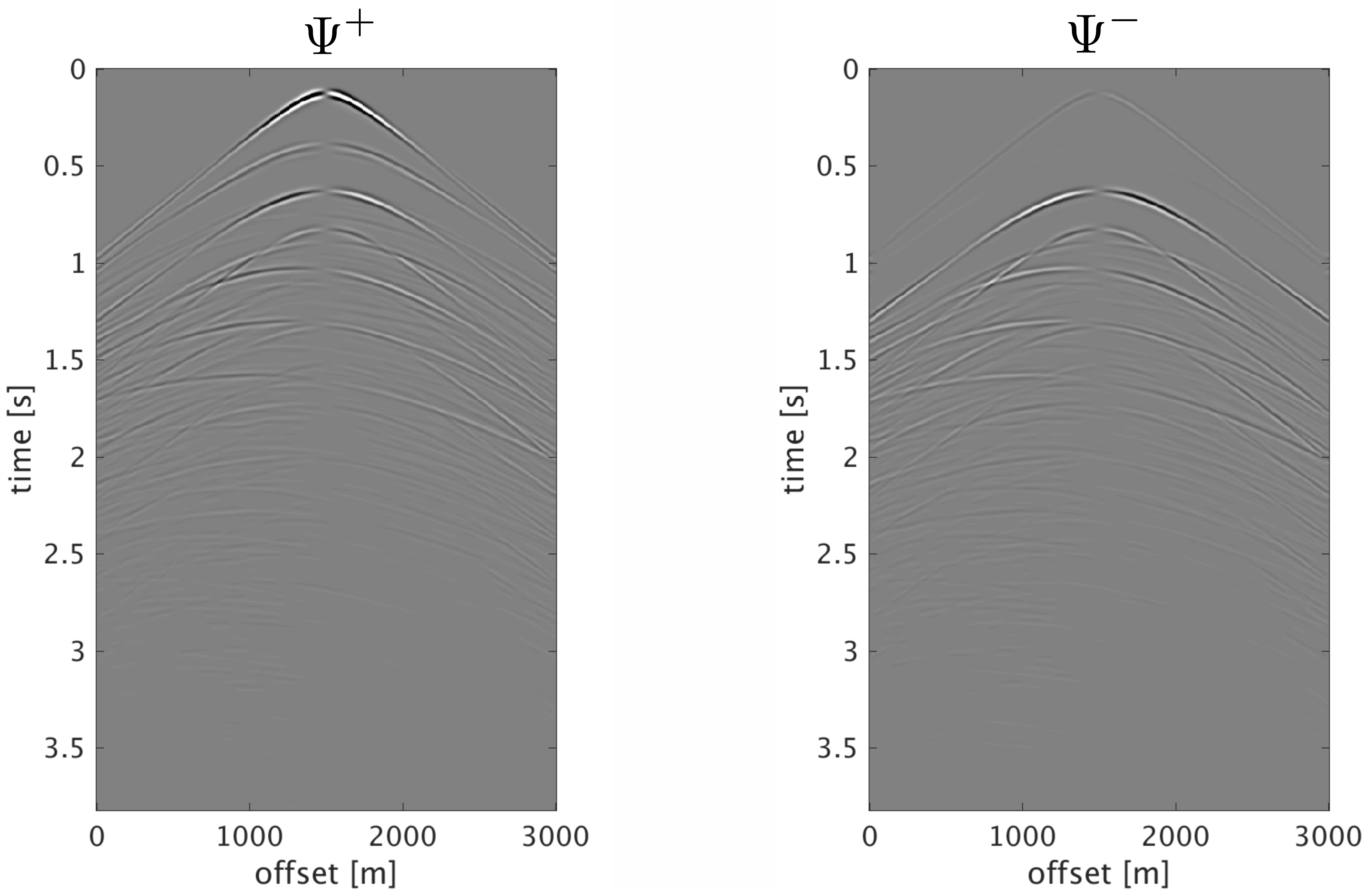


Reconstructed S-waves

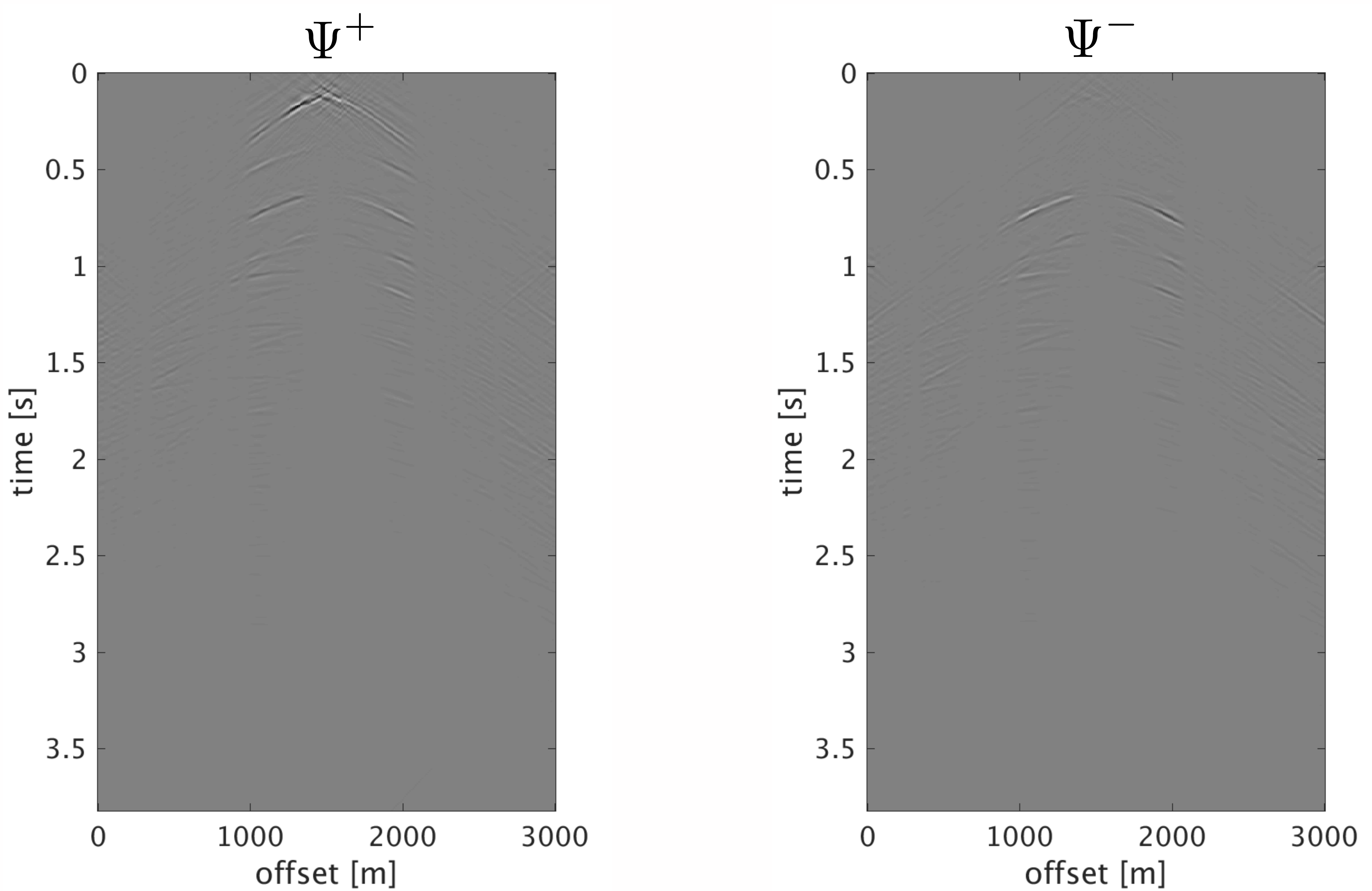




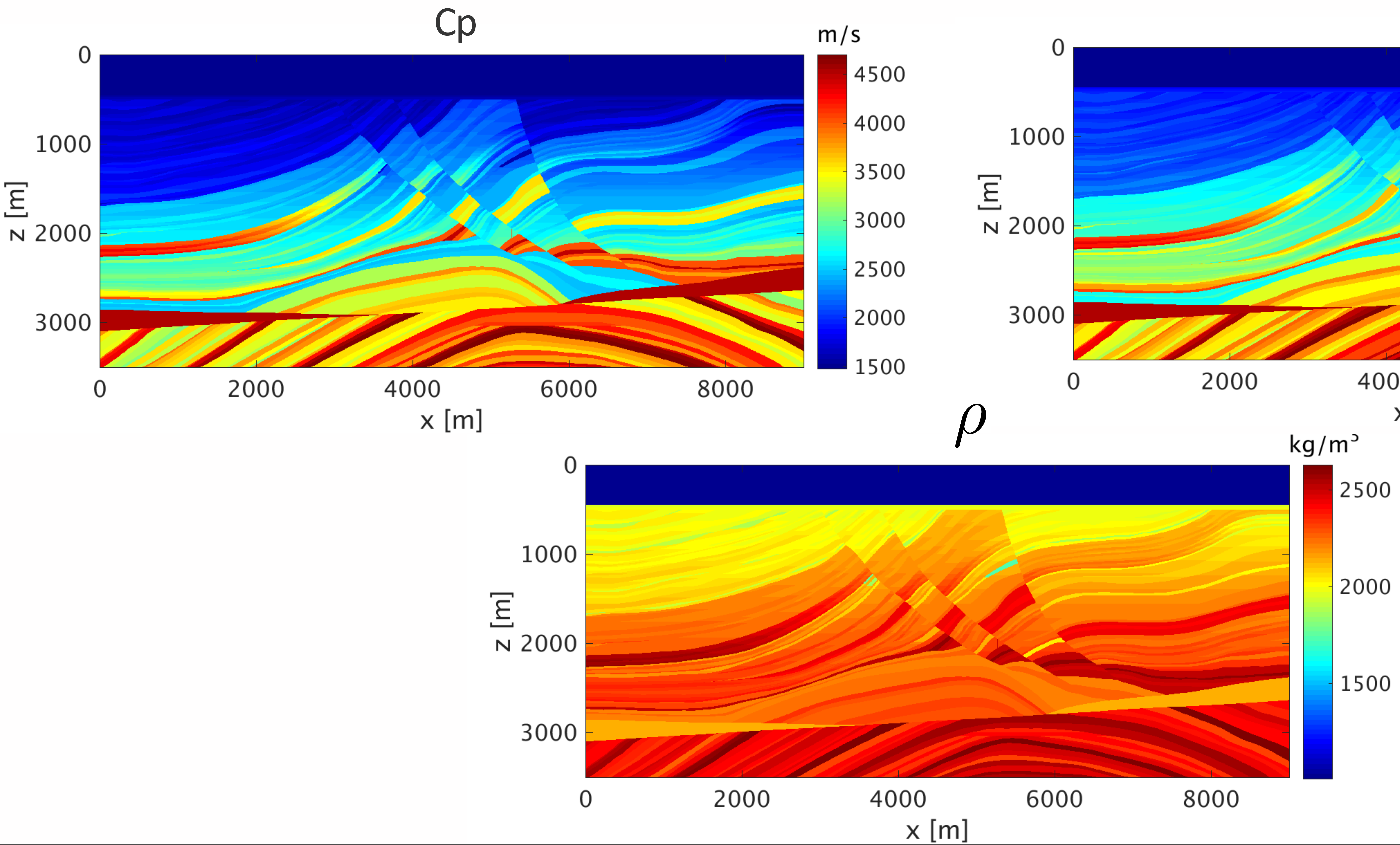
Densely sampled *S*-waves



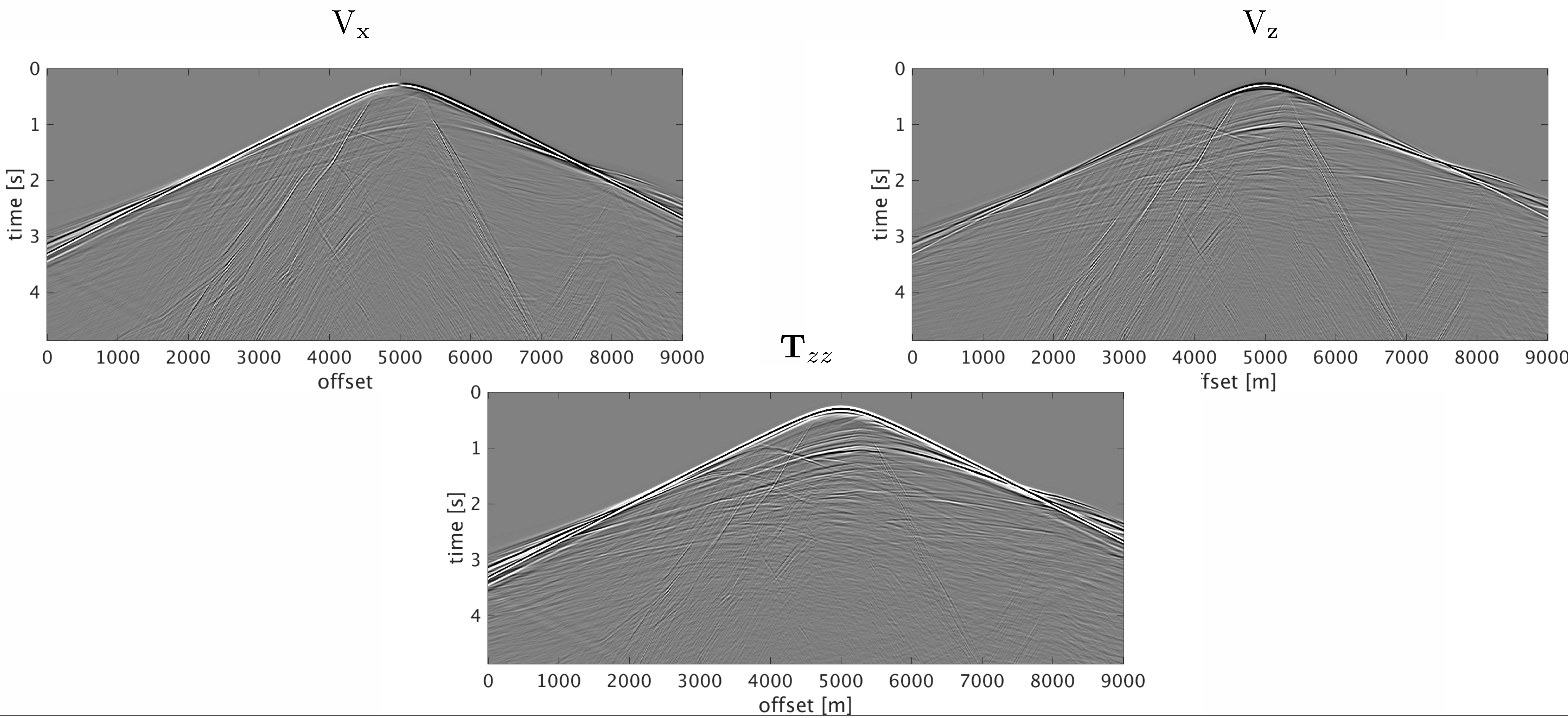
Residual



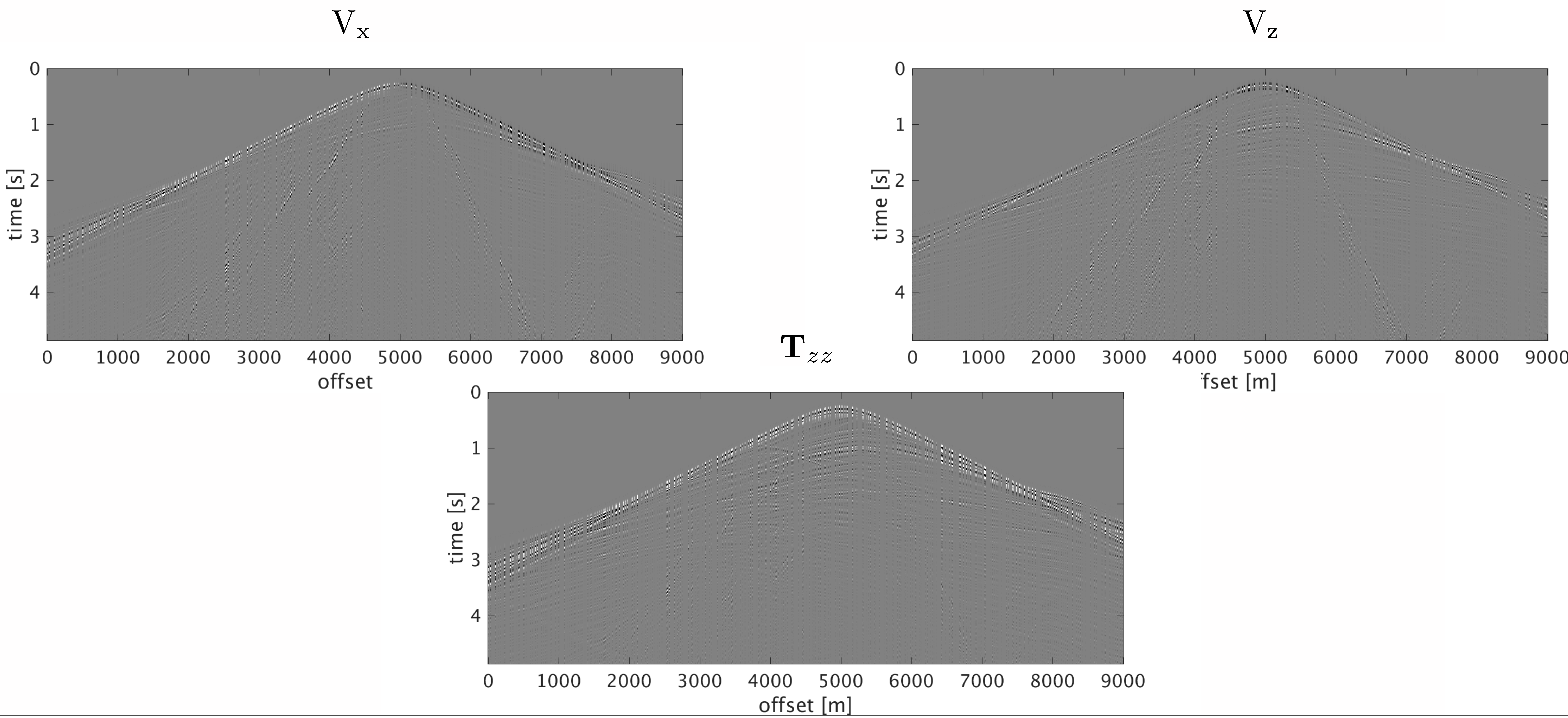
Marmousi II data



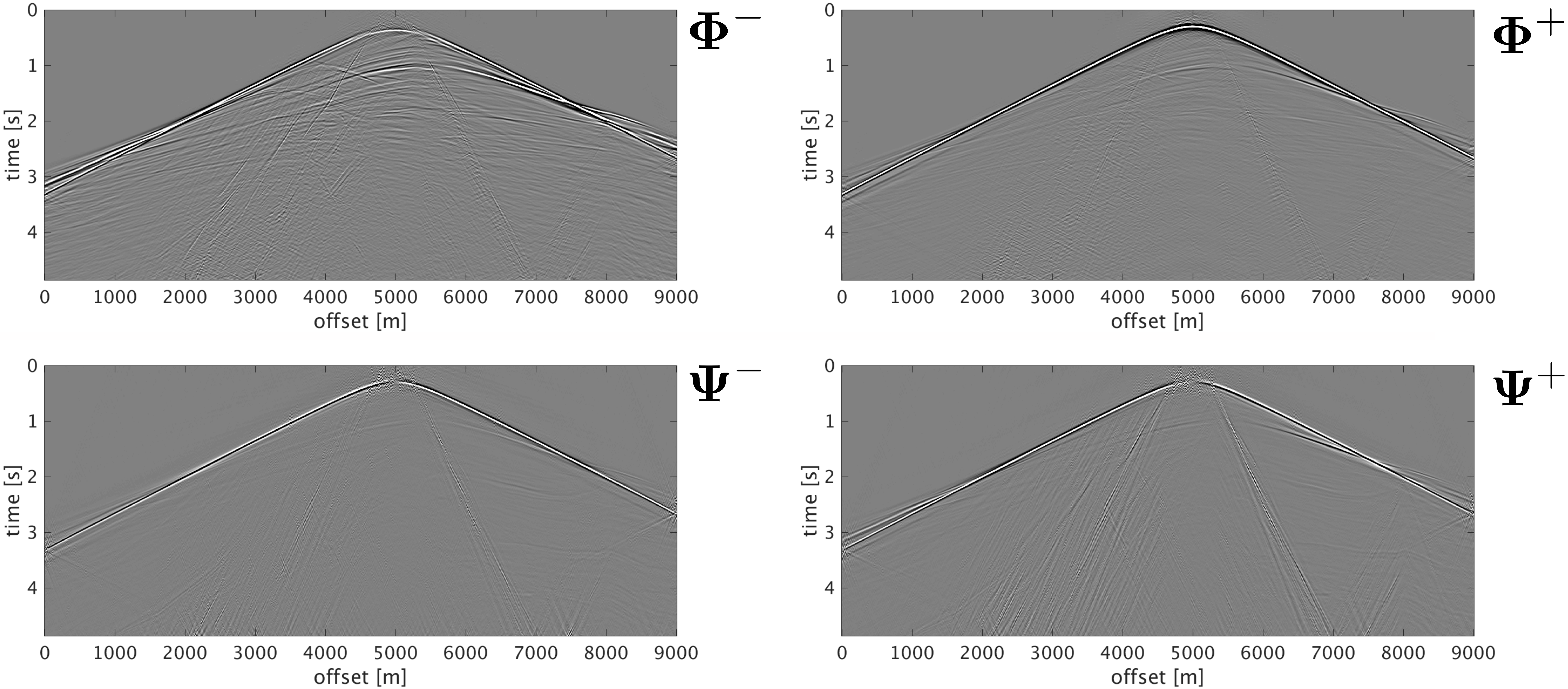
Densely sampled data



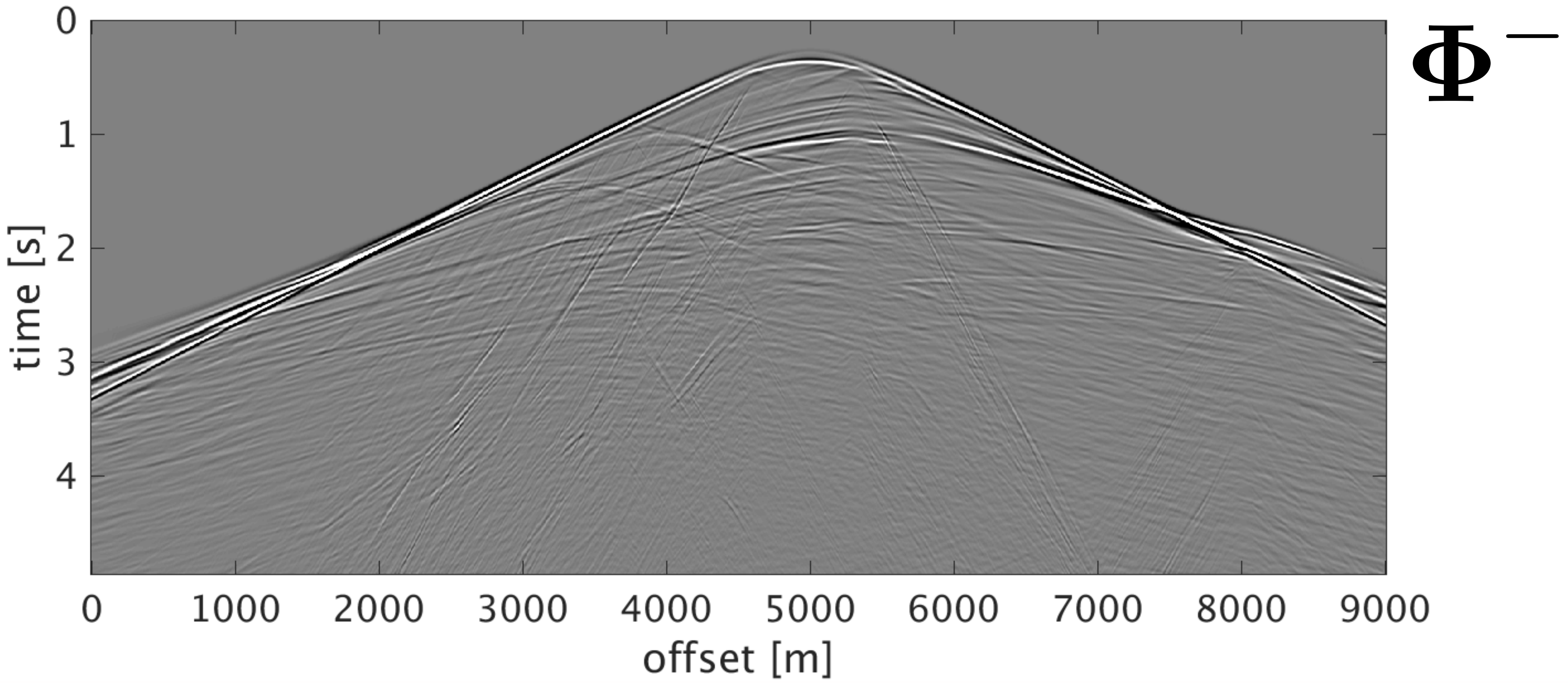
75% jittered subsampling

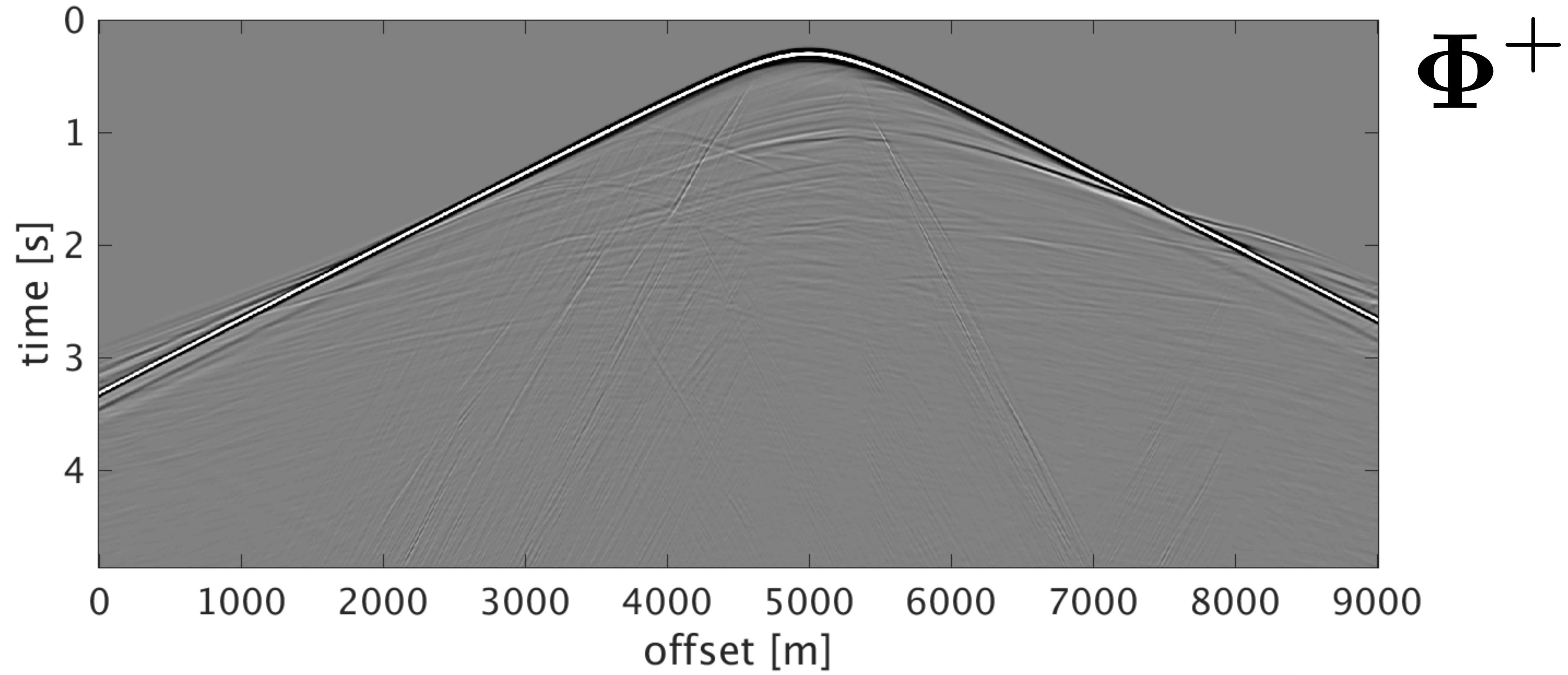


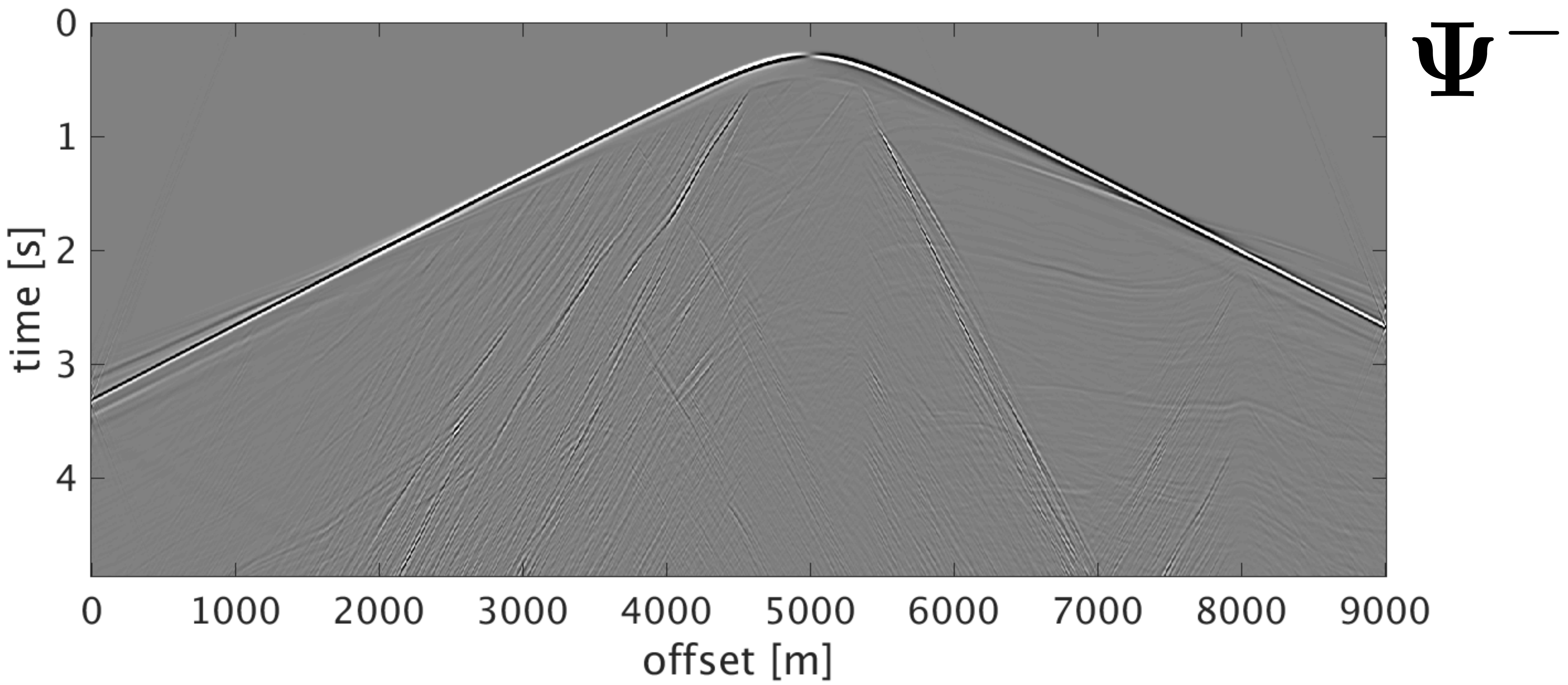
Reconstructed data

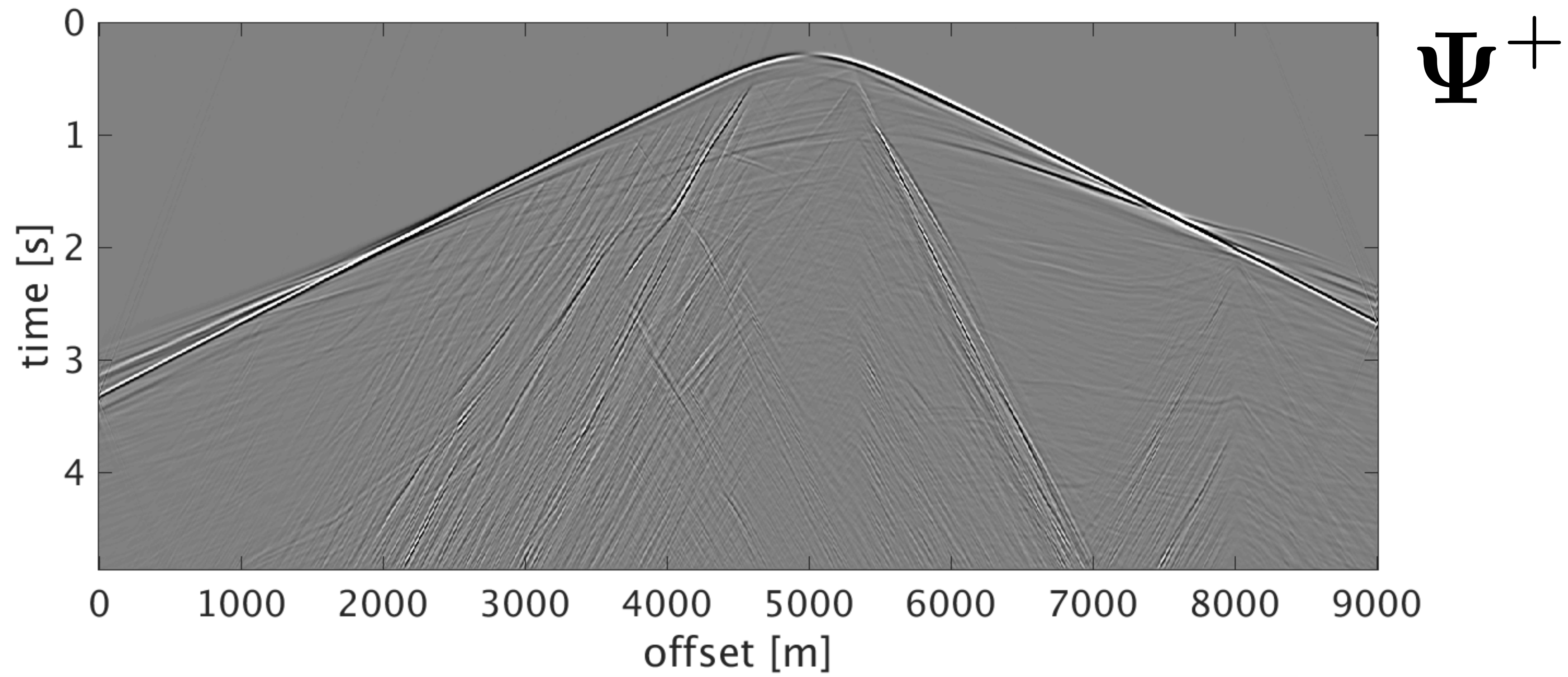


Densely sampled data

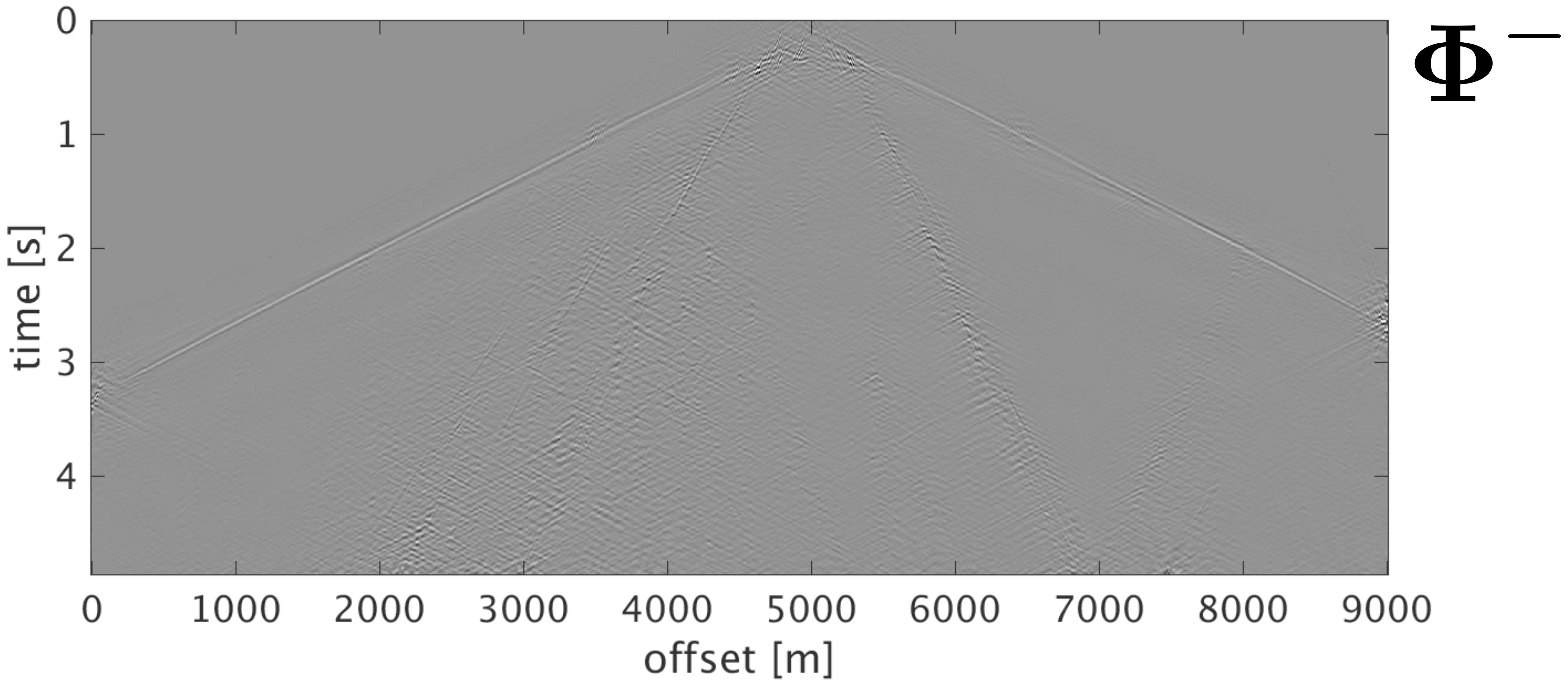




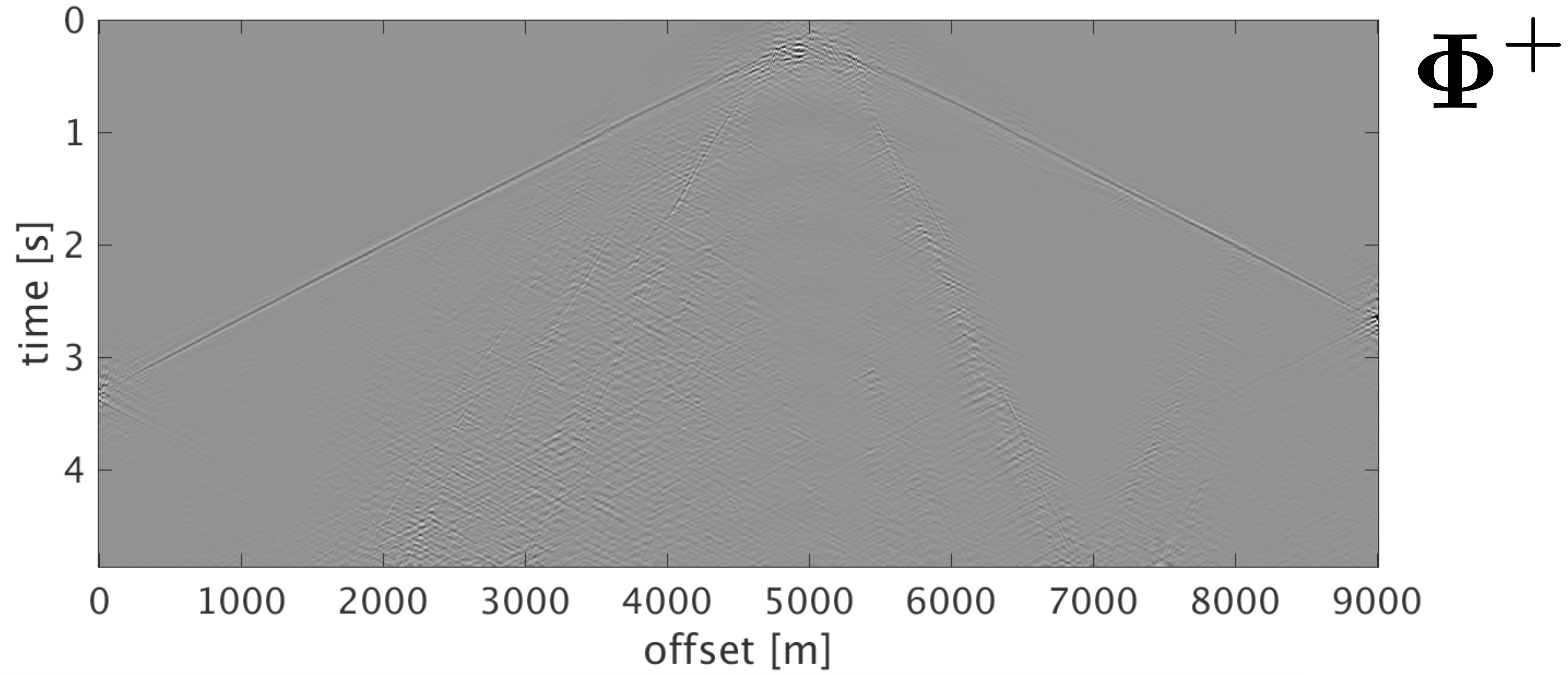




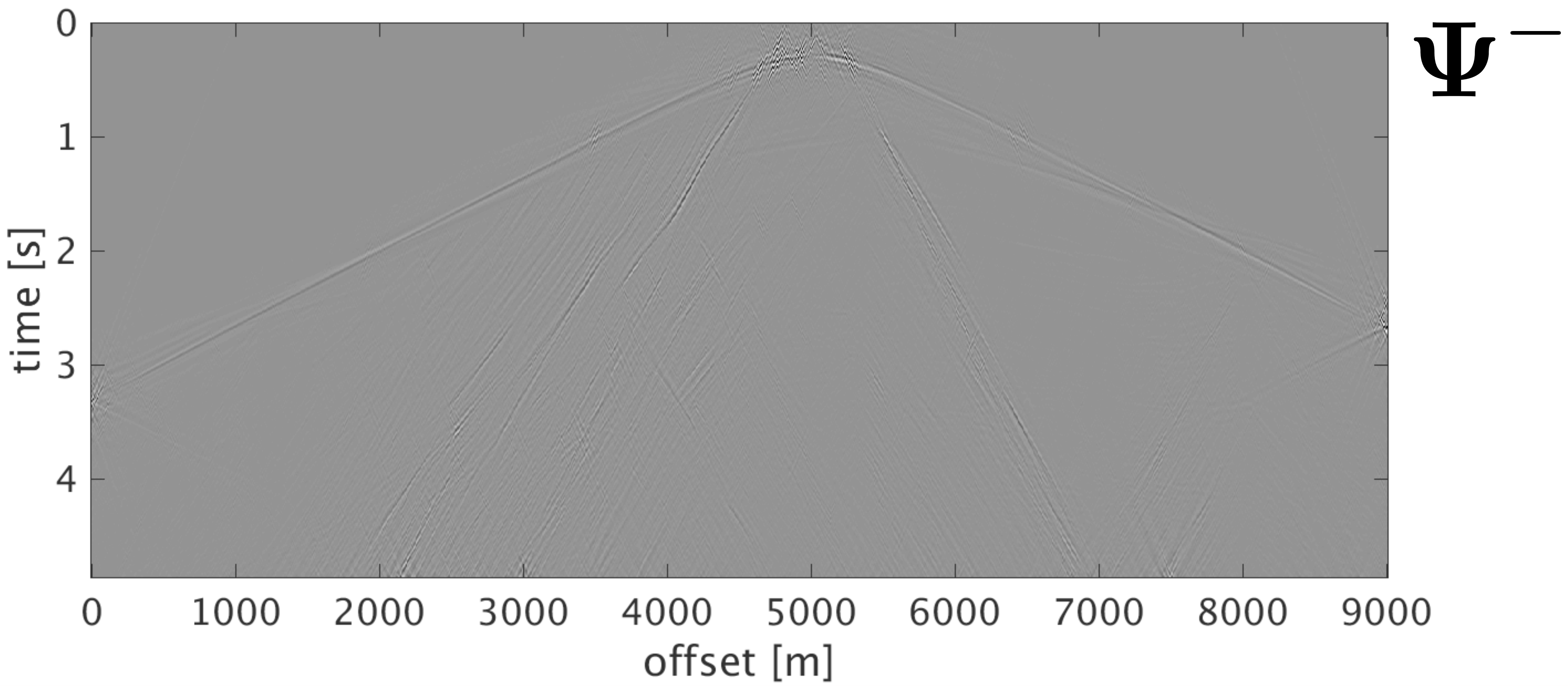
Residual



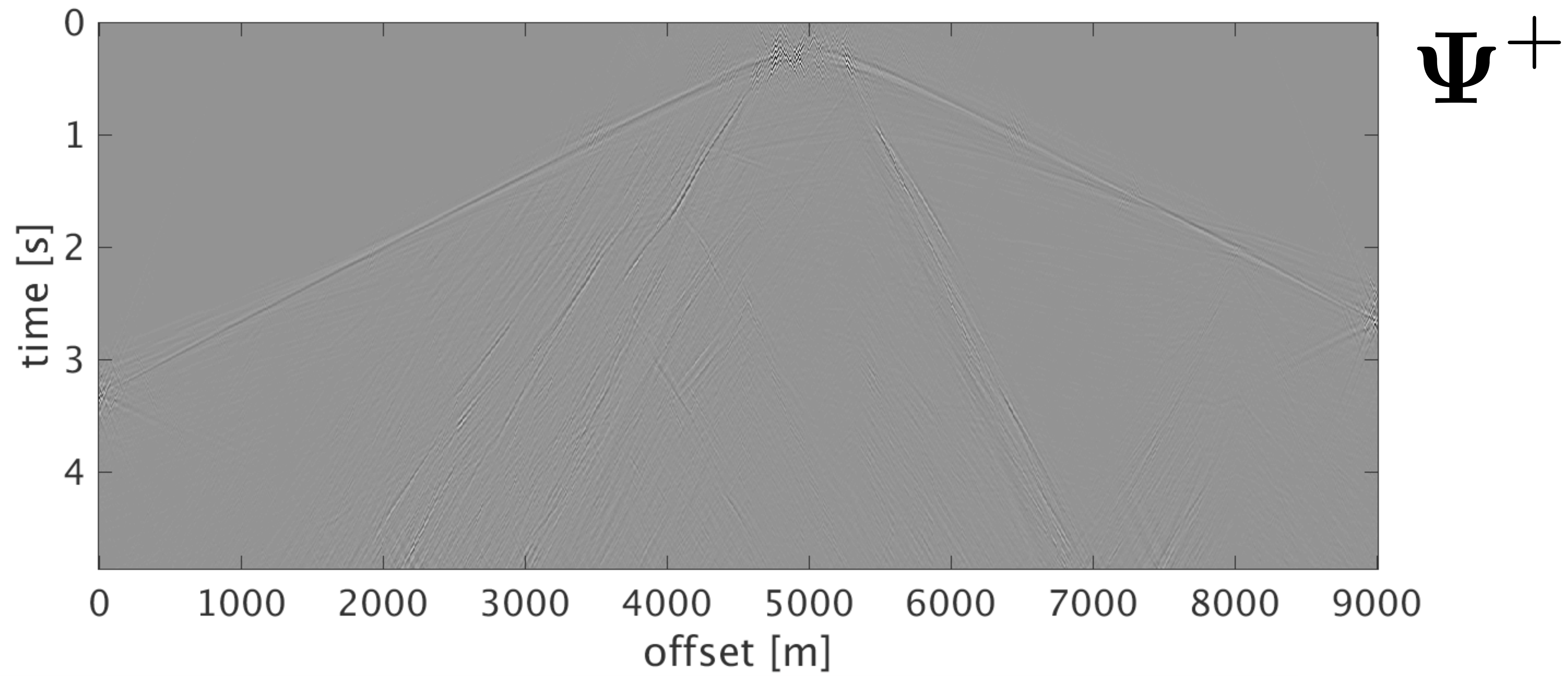
Φ^-
time [s]
0
1
2
3
4
0 1000 2000 3000 4000 5000 6000 7000 8000 9000
offset [m]



Φ^+
time [s]
0
1
2
3
4
0 1000 2000 3000 4000 5000 6000 7000 8000 9000
offset [m]



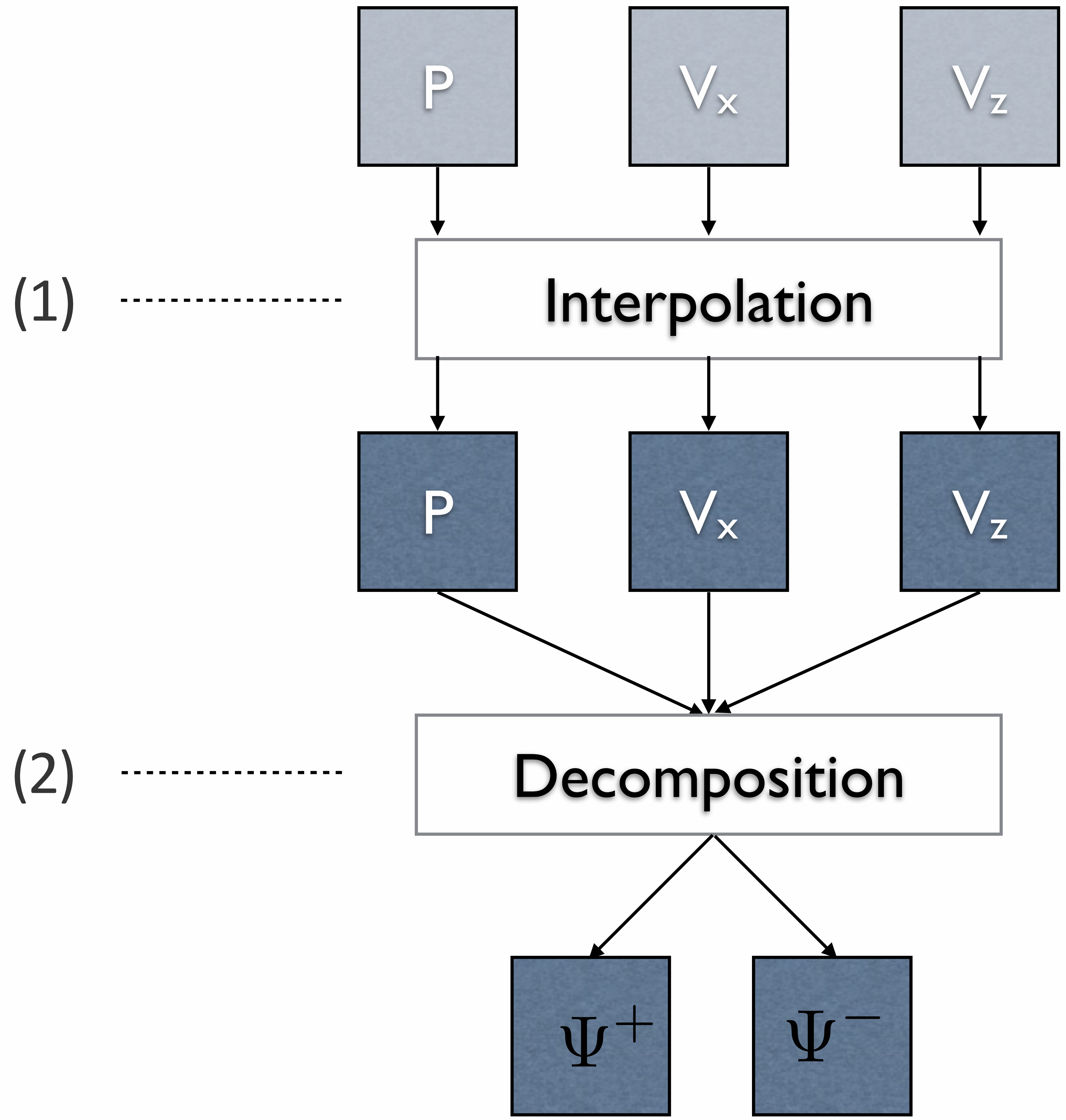
Ψ^-
time [s]
0
1
2
3
4
0 1000 2000 3000 4000 5000 6000 7000 8000 9000
offset [m]



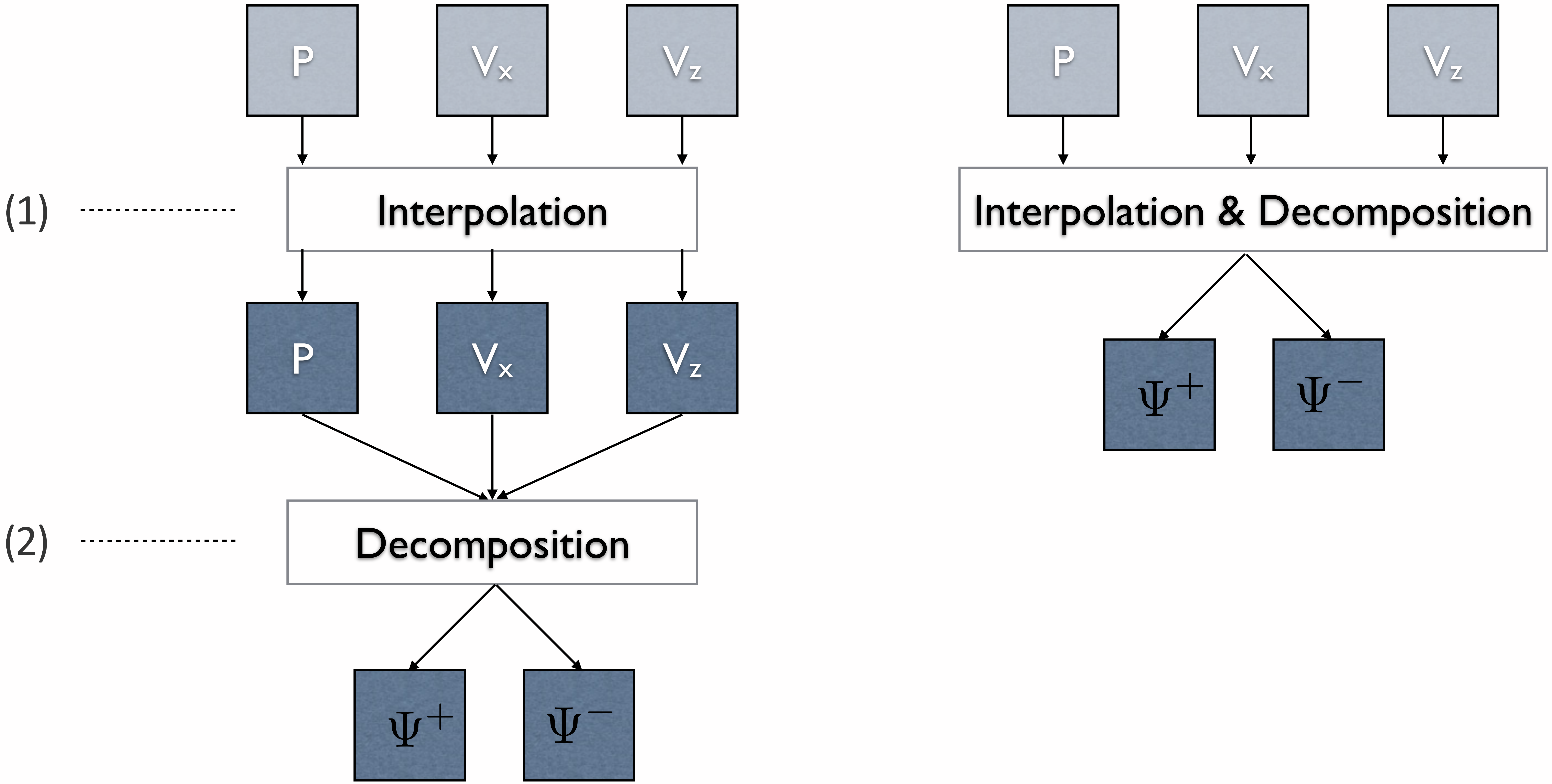
Ψ^+
time [s]
0
1
2
3
4
0 1000 2000 3000 4000 5000 6000 7000 8000 9000
offset [m]

Joint interpolation decomposition

Joint interpolation decomposition



Joint interpolation decomposition



Joint interpolation decomposition w\ curvelets

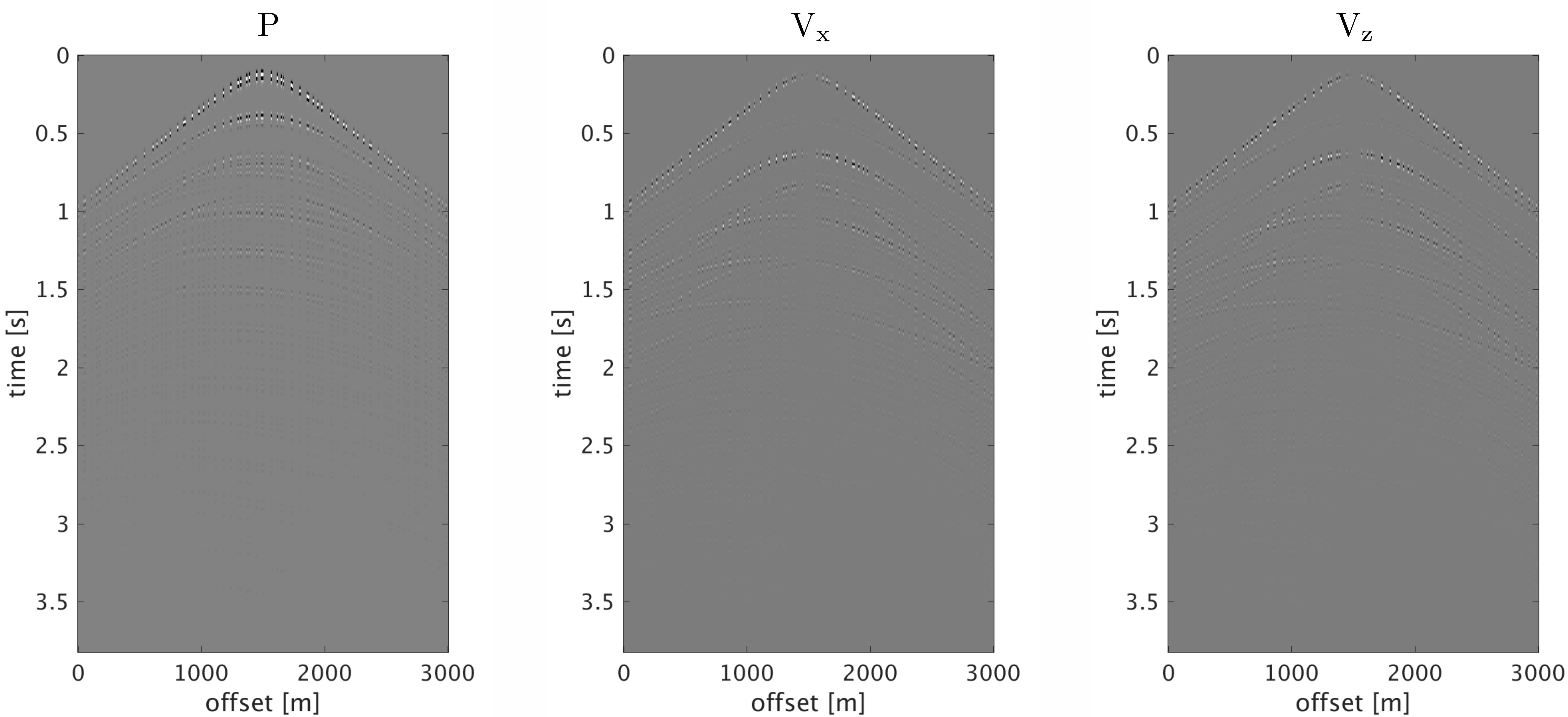
$$\min_{\mathbf{x}} \|\mathbf{x}\|_1 \quad \text{subject to} \quad \|\mathbf{A}\mathbf{x} - \mathbf{b}\|_2 \leq \sigma \qquad (\mathrm{BPDN}_\sigma)$$

$\mathbf{x}$: coefficients of the decomposed data

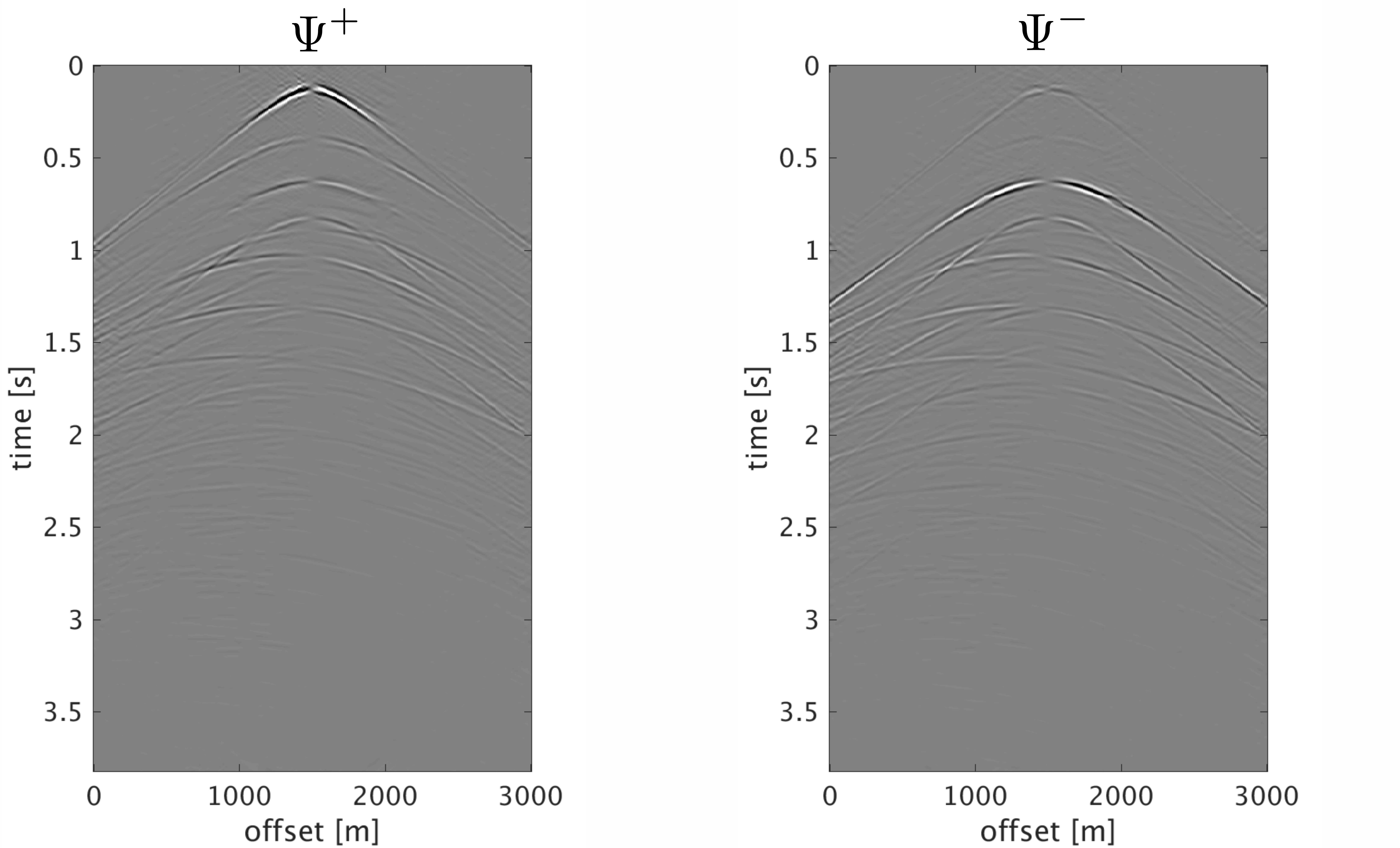
Sparsifying transform:

$$\mathbf{A}_c = \mathbf{M}\mathbf{F}^H\mathbf{L}\mathbf{F}\mathbf{S}^H$$

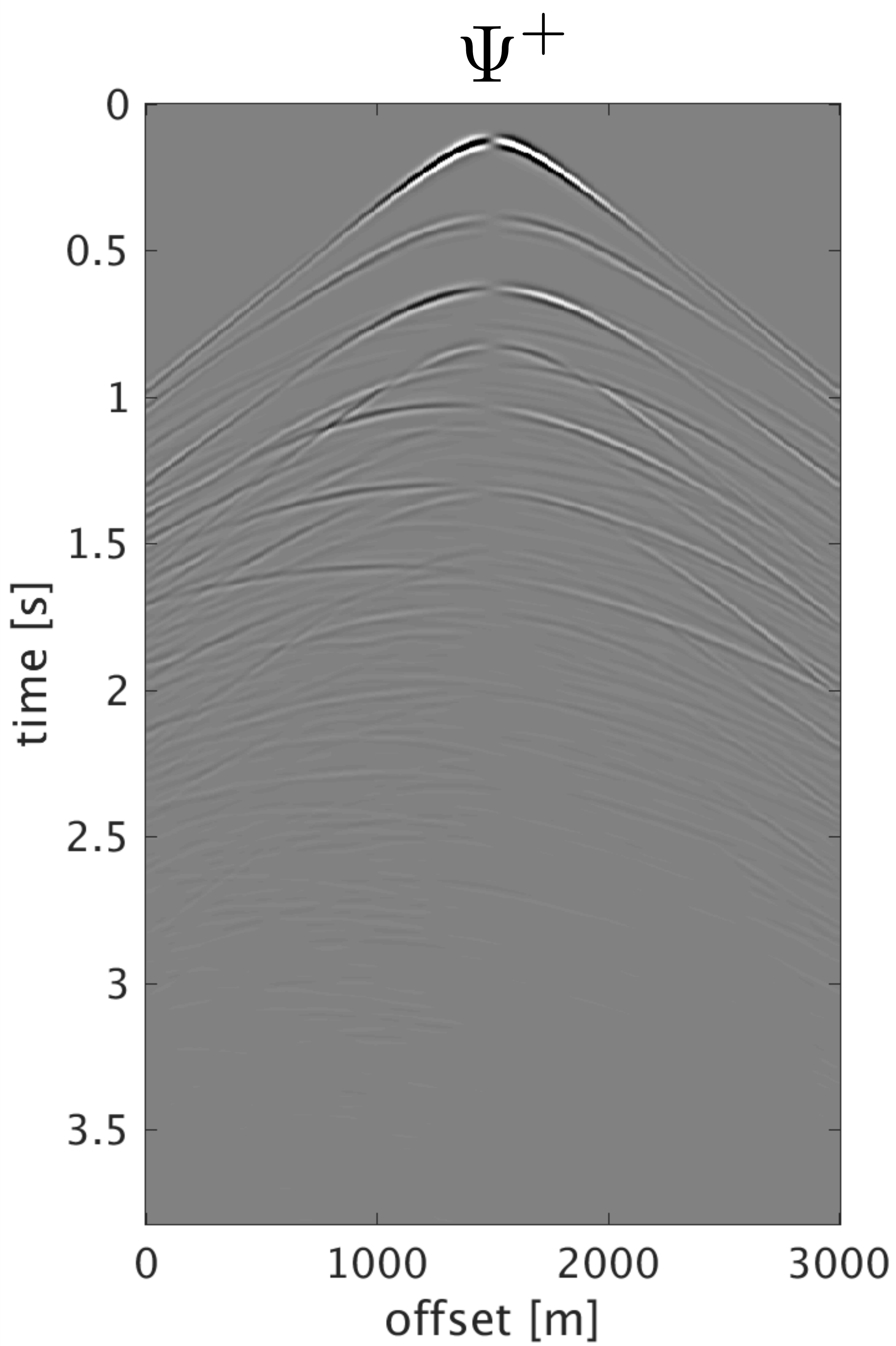
75% jittered subsampling

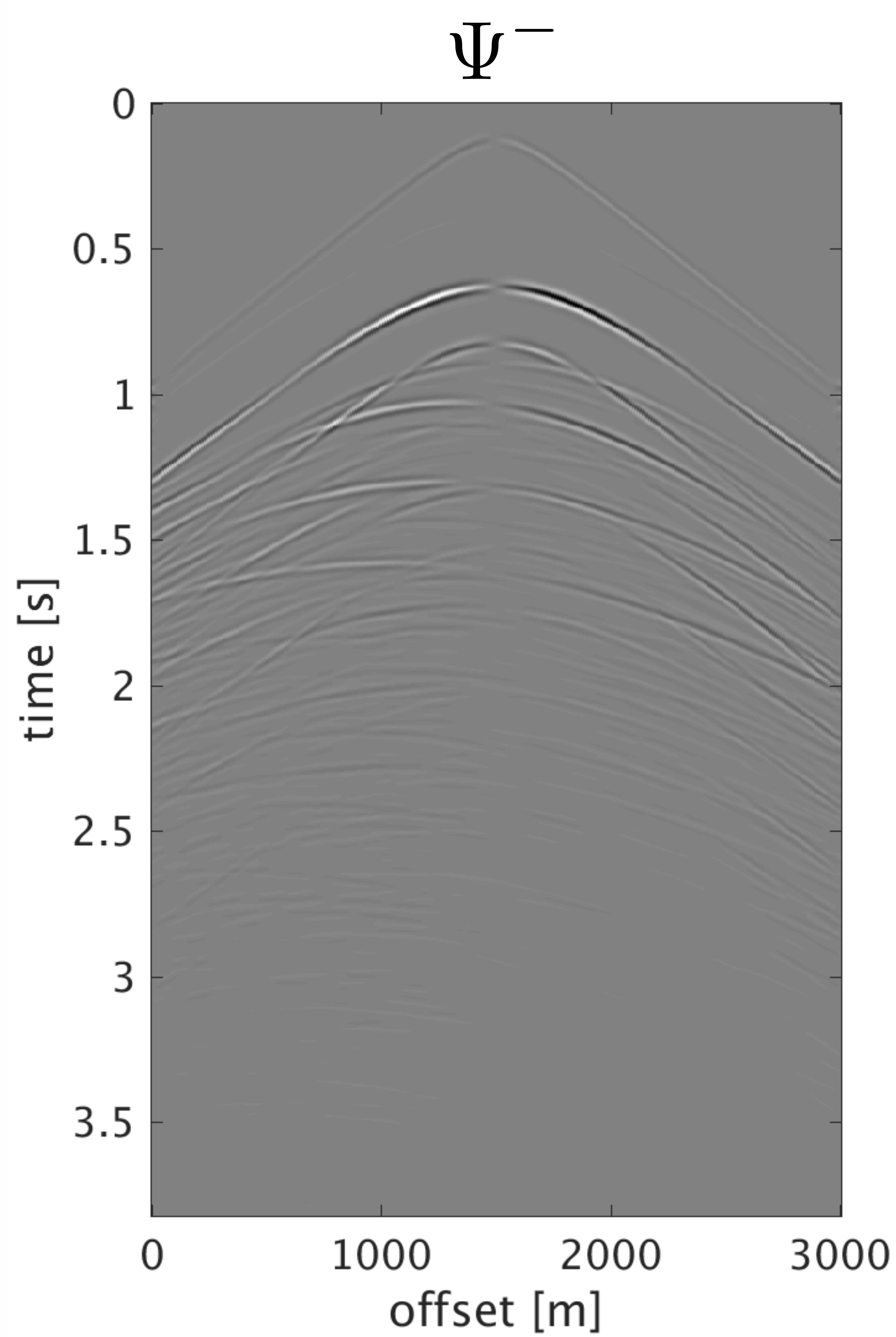


Joint interpolation decomposition in the curvelet domain

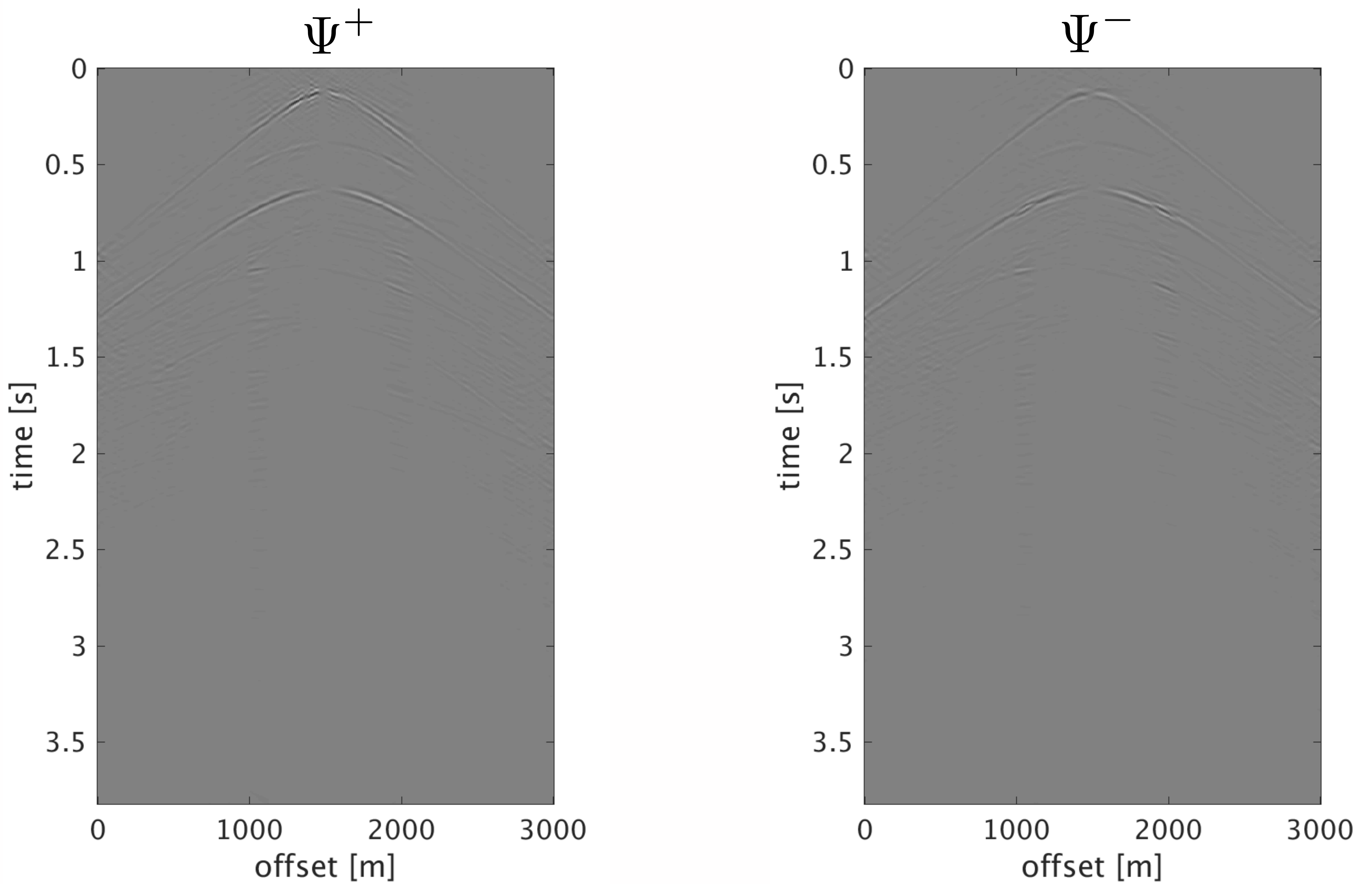


Densely sampled S-waves



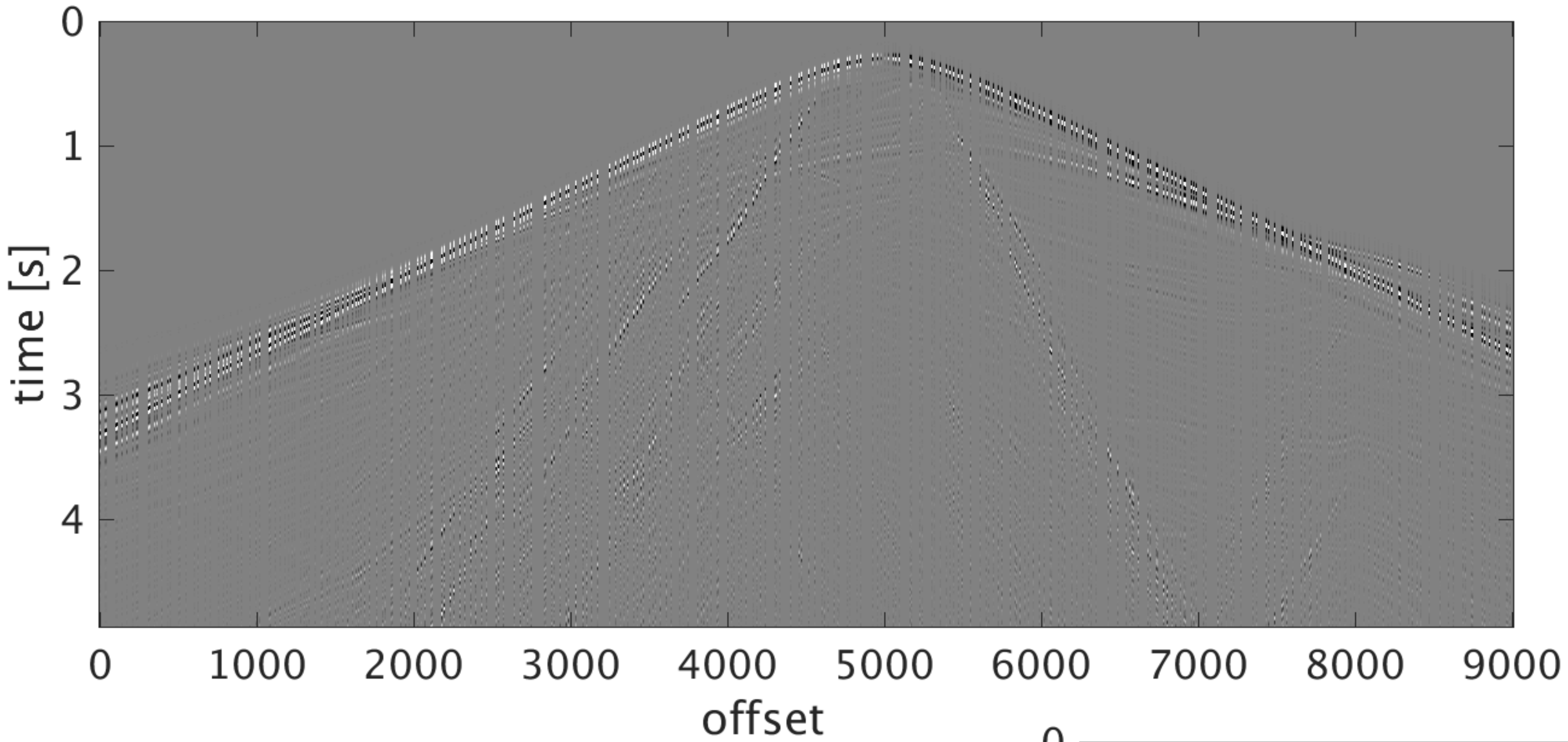


Residual

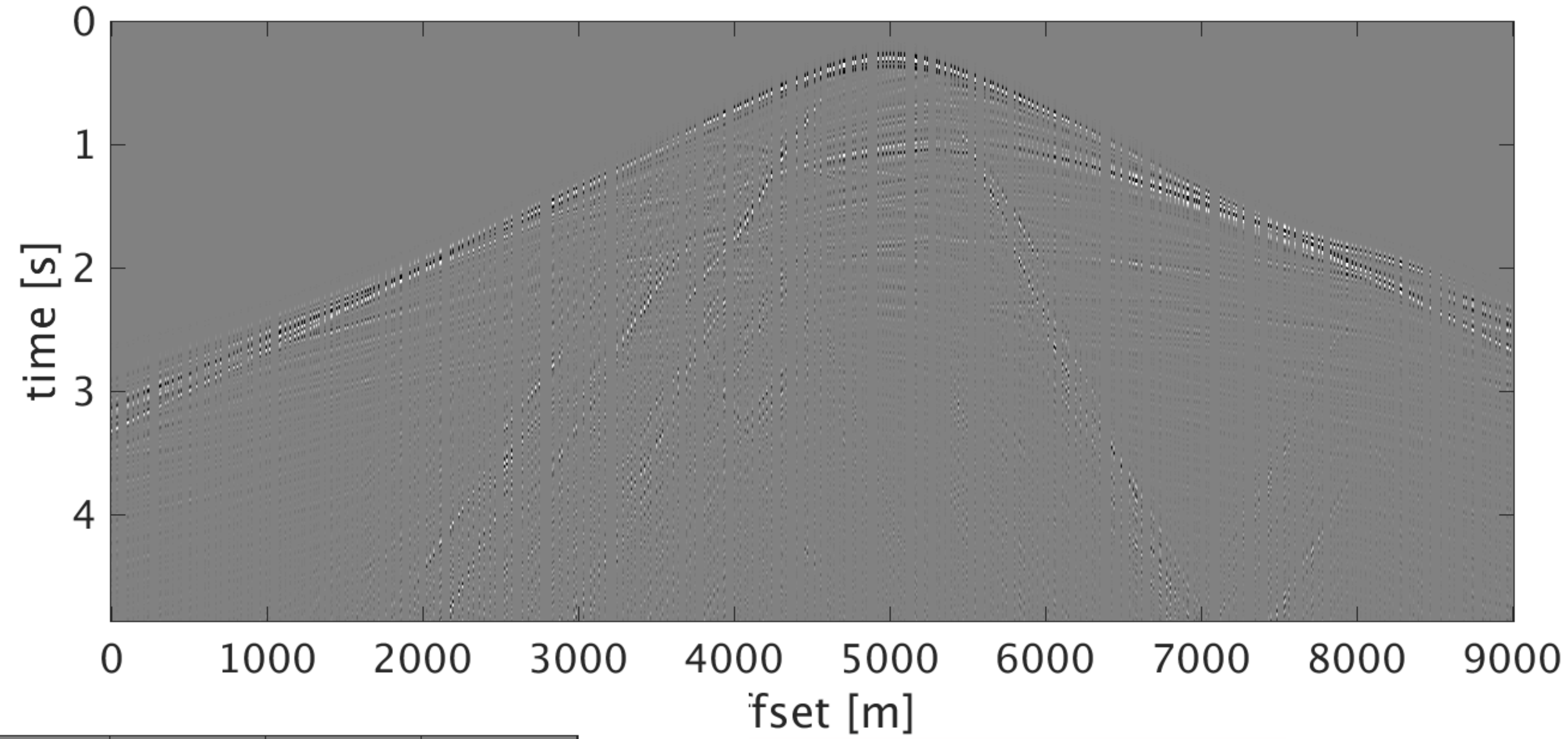


75% jittered subsampling

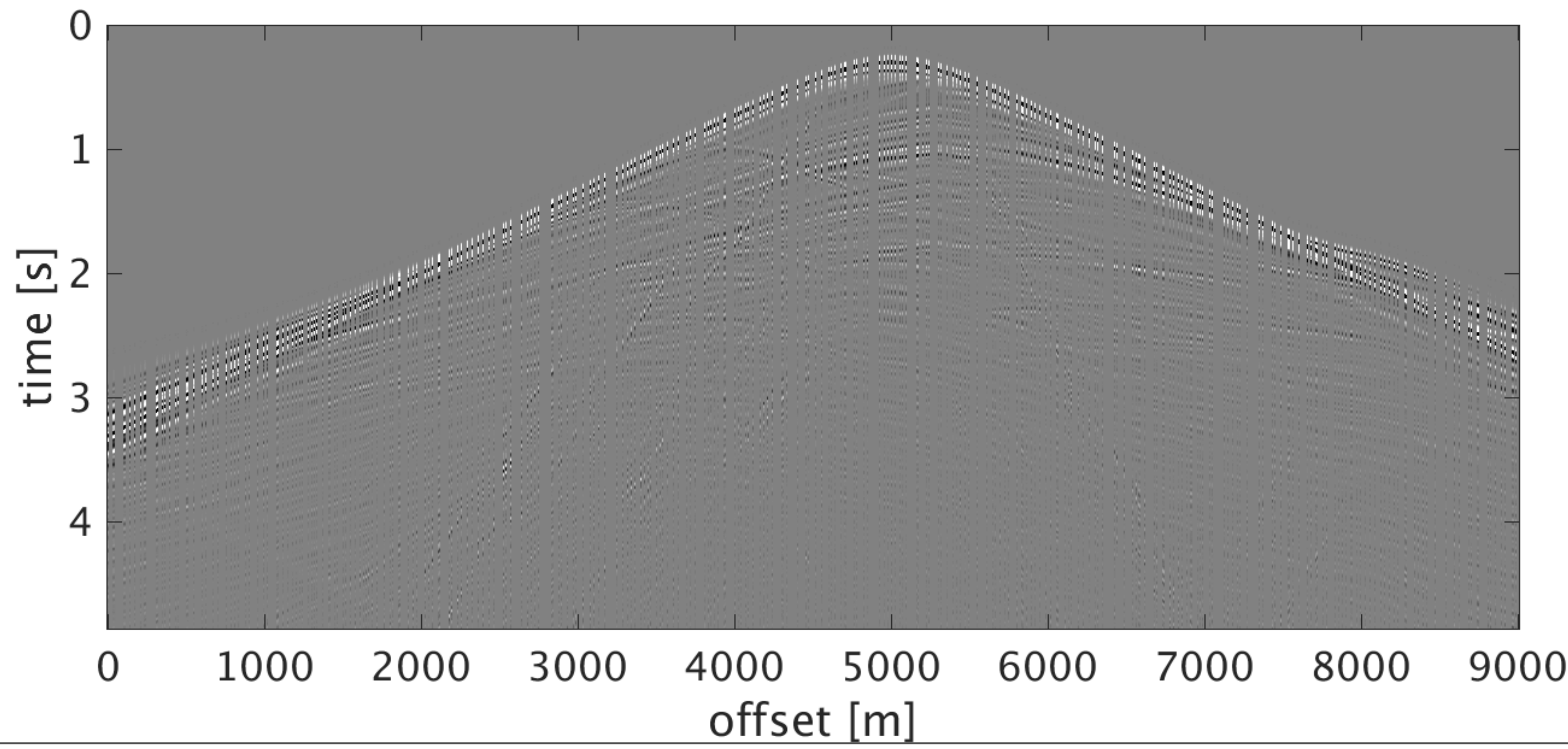
$\mathrm{V_x}$



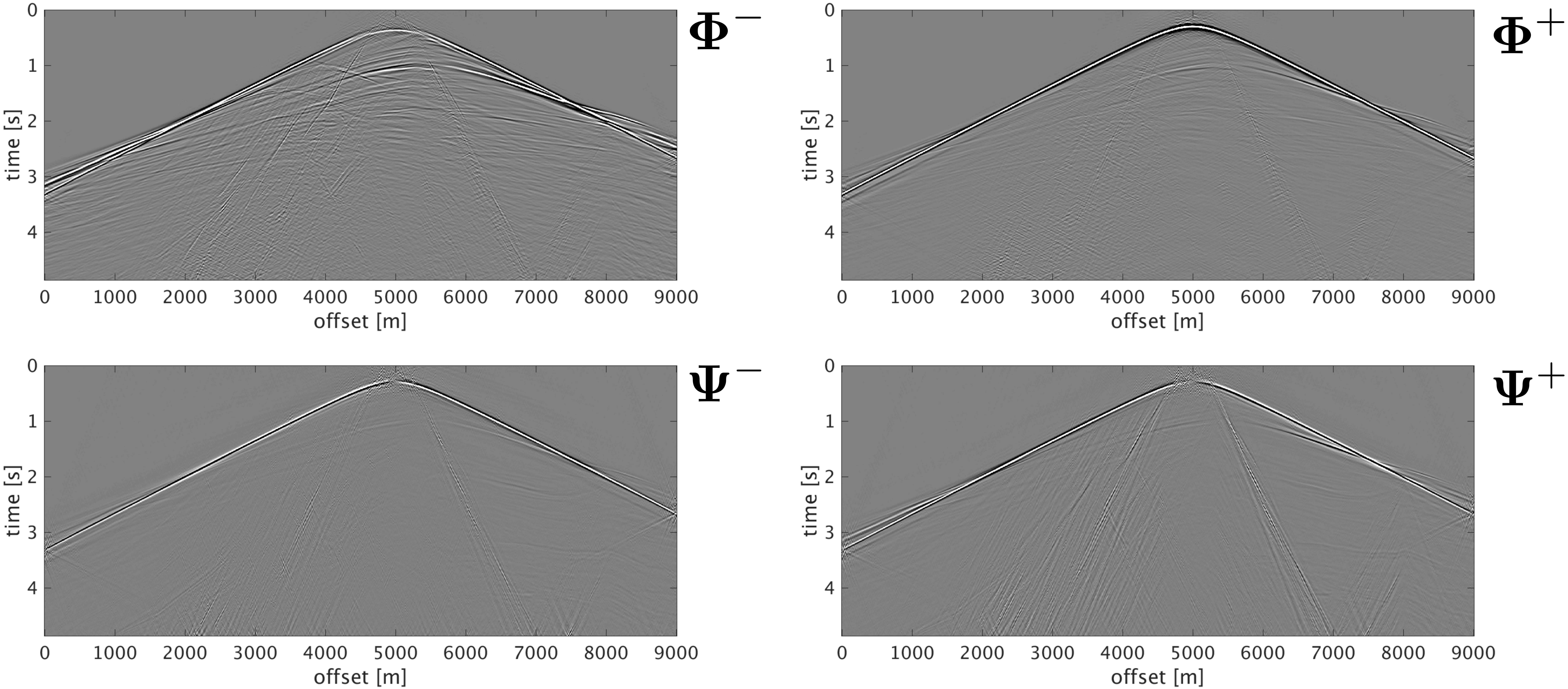
$\mathrm{V_z}$



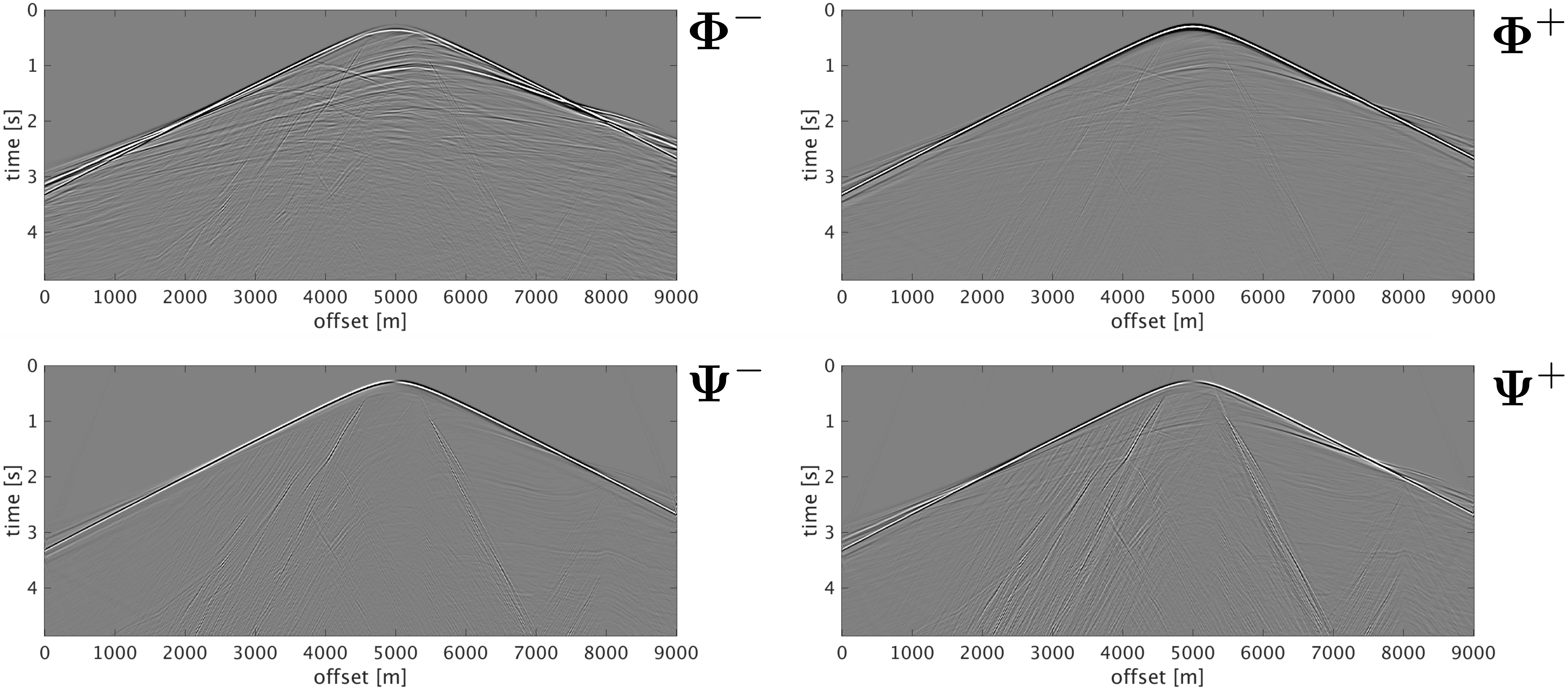
$\mathbf{T}_{zz}$



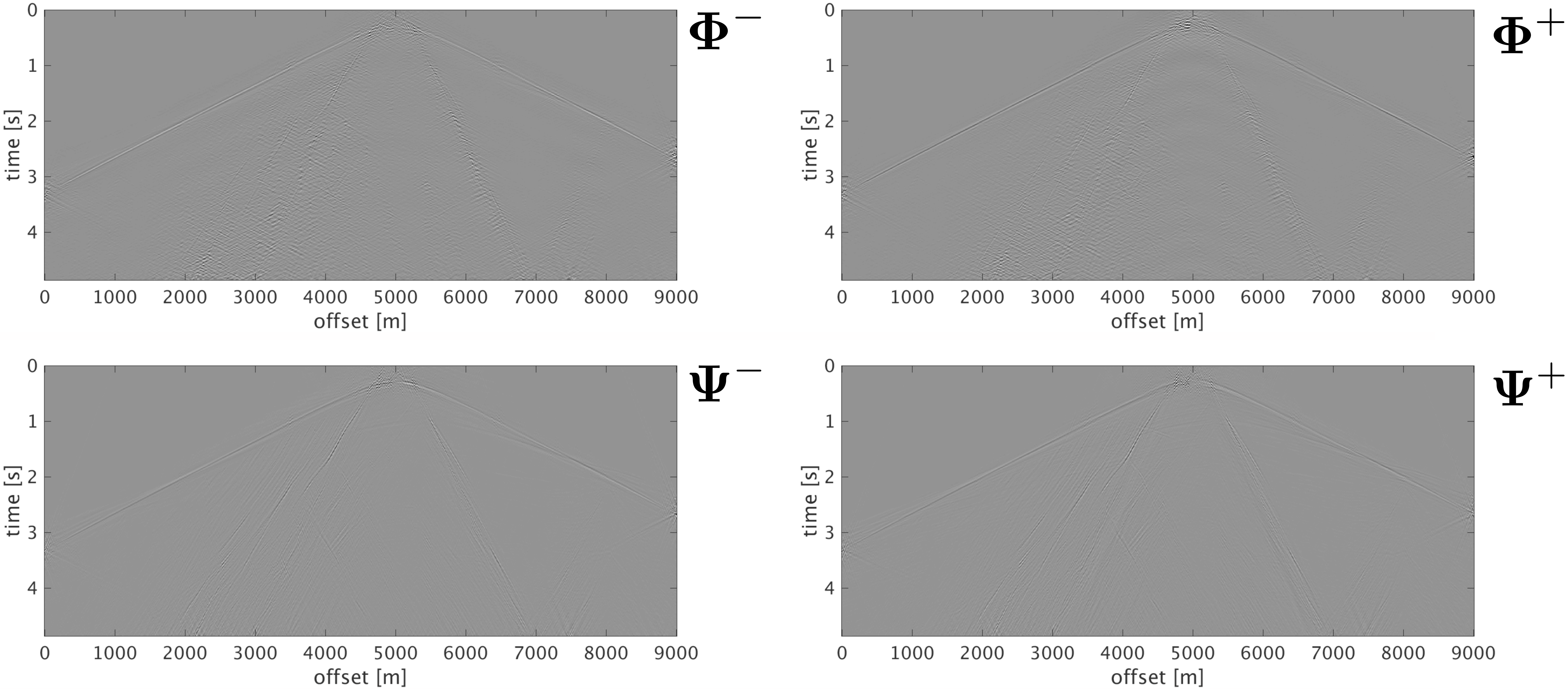
Reconstructed data



Densely data



Residual


Φ^-
Φ^+
Ψ^-
Ψ^+
time [s]
0
1
2
3
4
offset [m]
0
1000
2000
3000
4000
5000
6000
7000
8000
9000

Joint interpolation decomposition in the f-k domain

Joint interpolation decomposition, f-k

$$\min_{\mathbf{x}} \|\mathbf{x}\|_1 \quad \text{subject to} \quad \|\mathbf{A}\mathbf{x} - \mathbf{b}\|_2 \leq \sigma \qquad (\mathrm{BPDN}_\sigma)$$

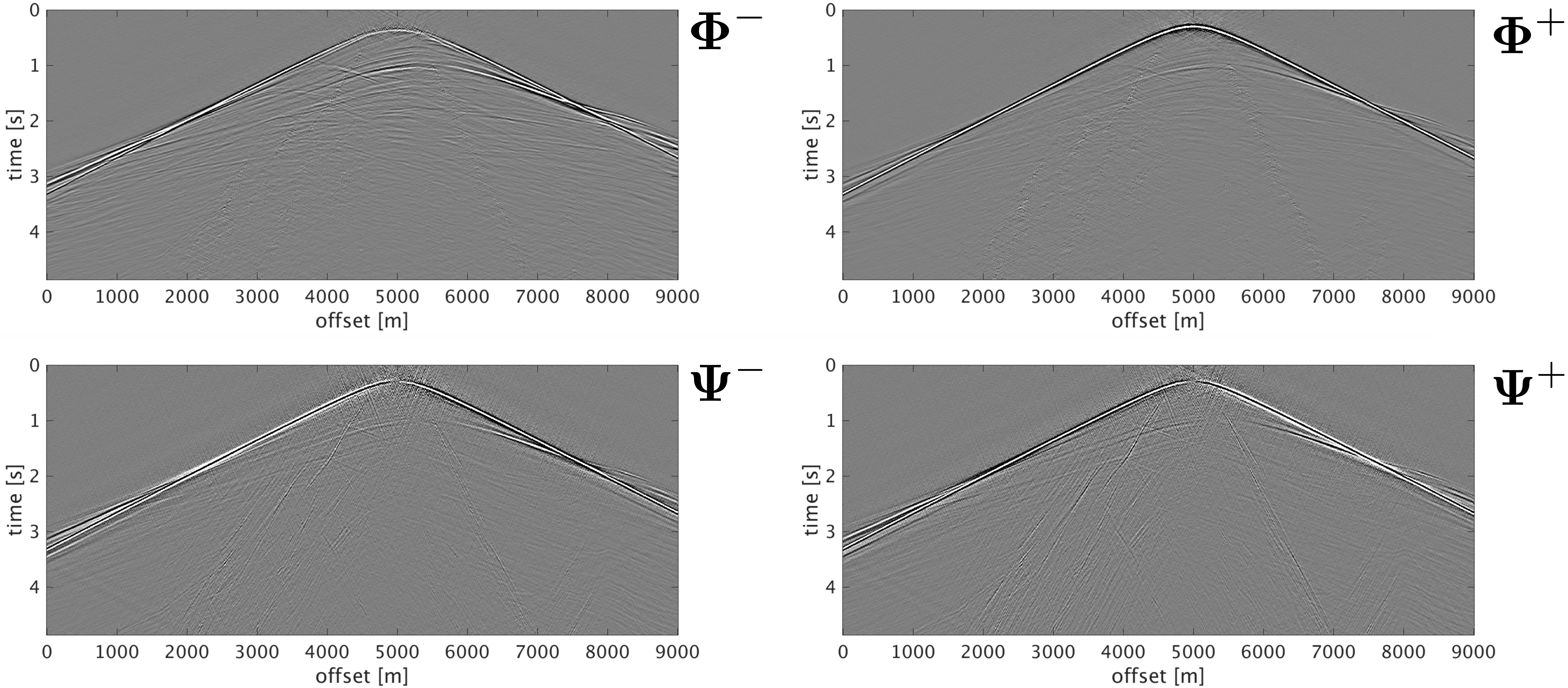
$\mathbf{x}$: coefficients of the decomposed data

Sparsifying transform:

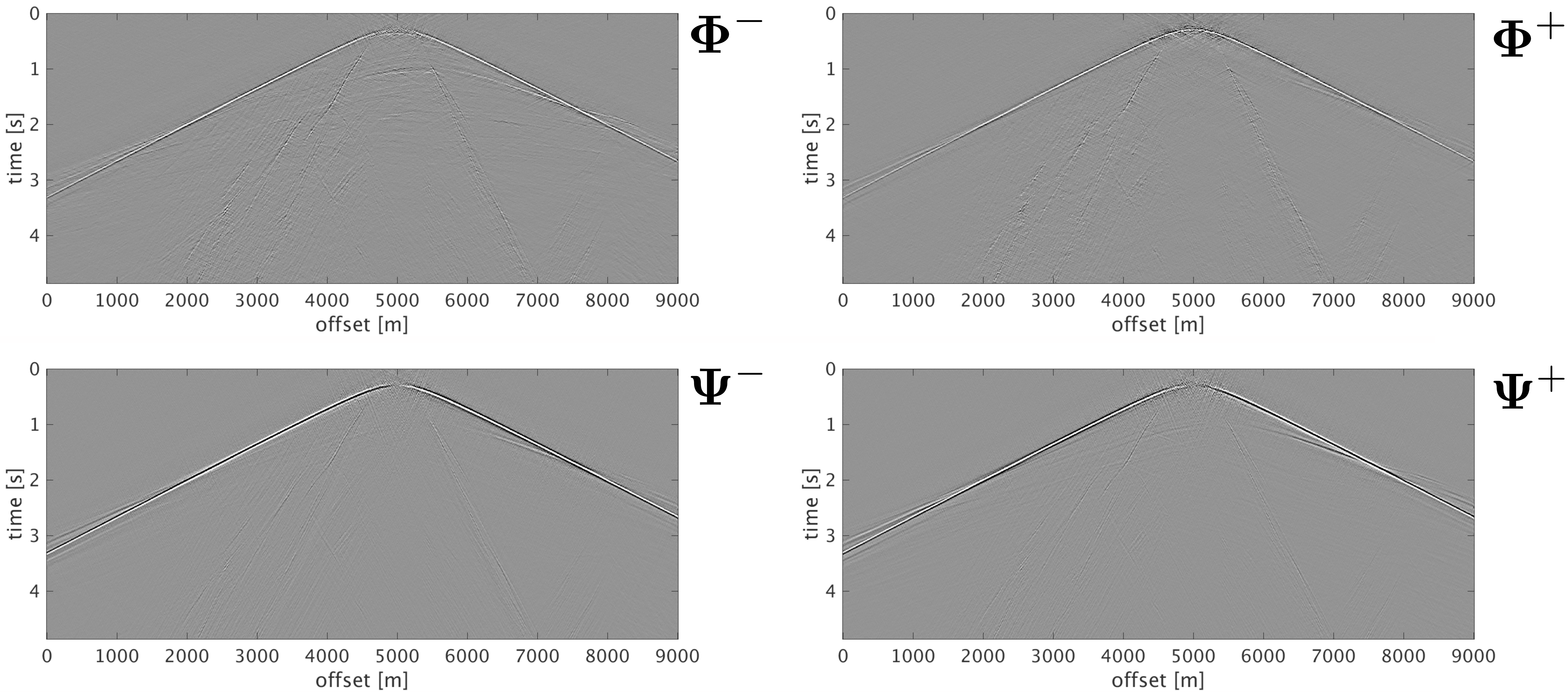
$$\mathbf{A}_c = \mathbf{M}\mathbf{F}^H\mathbf{L}\mathbf{F}\mathbf{S}^H$$

$$\mathbf{A}_{fk} = \mathbf{M}\mathbf{F}^H\mathbf{L}$$

Reconstructed data, f-k



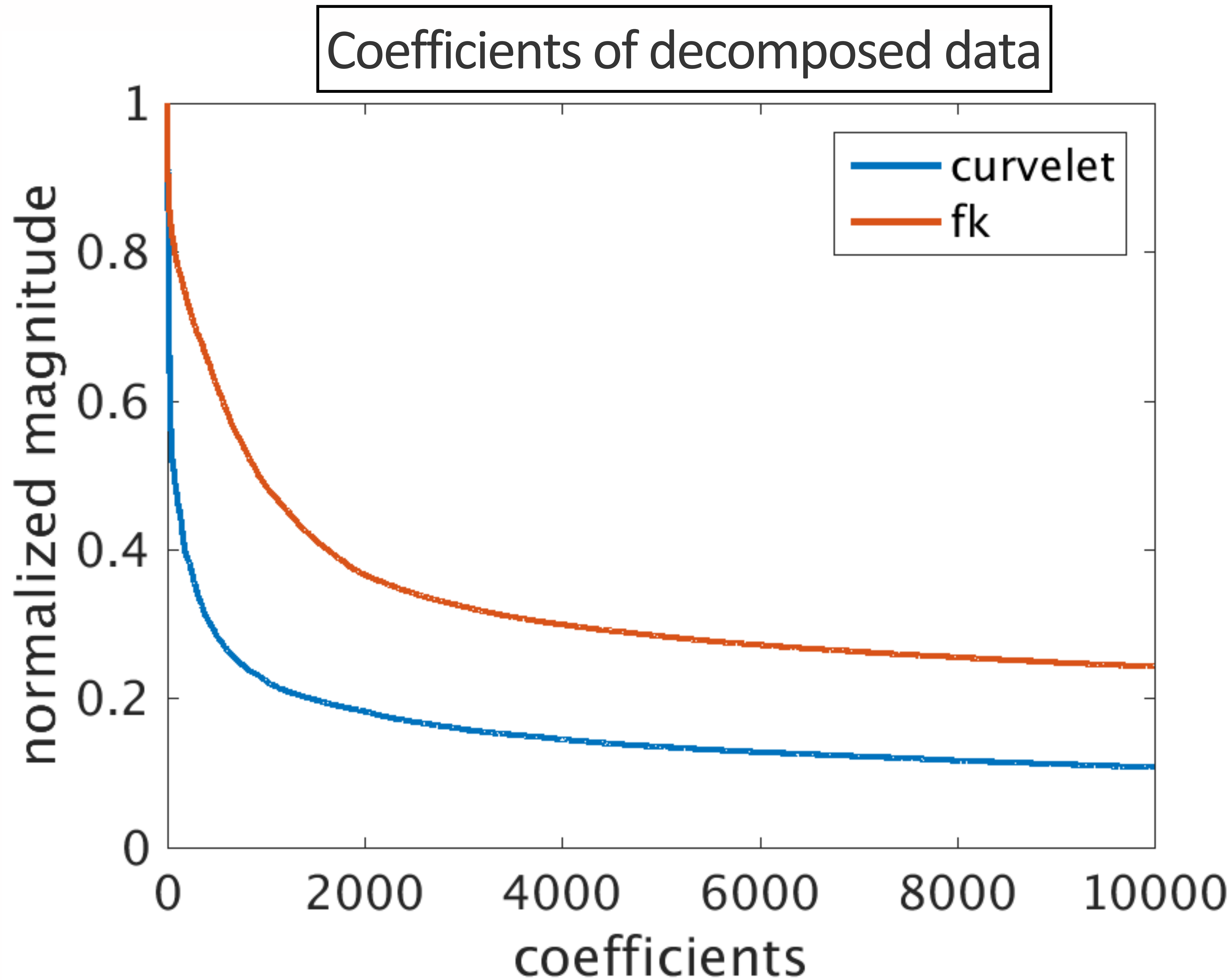
Residual



Φ^-
Φ^+
Ψ^-
Ψ^+
time [s]
offset [m]
0
1
2
3
4
0
1000
2000
3000
4000
5000
6000
7000
8000
9000

Why curvelets are better?

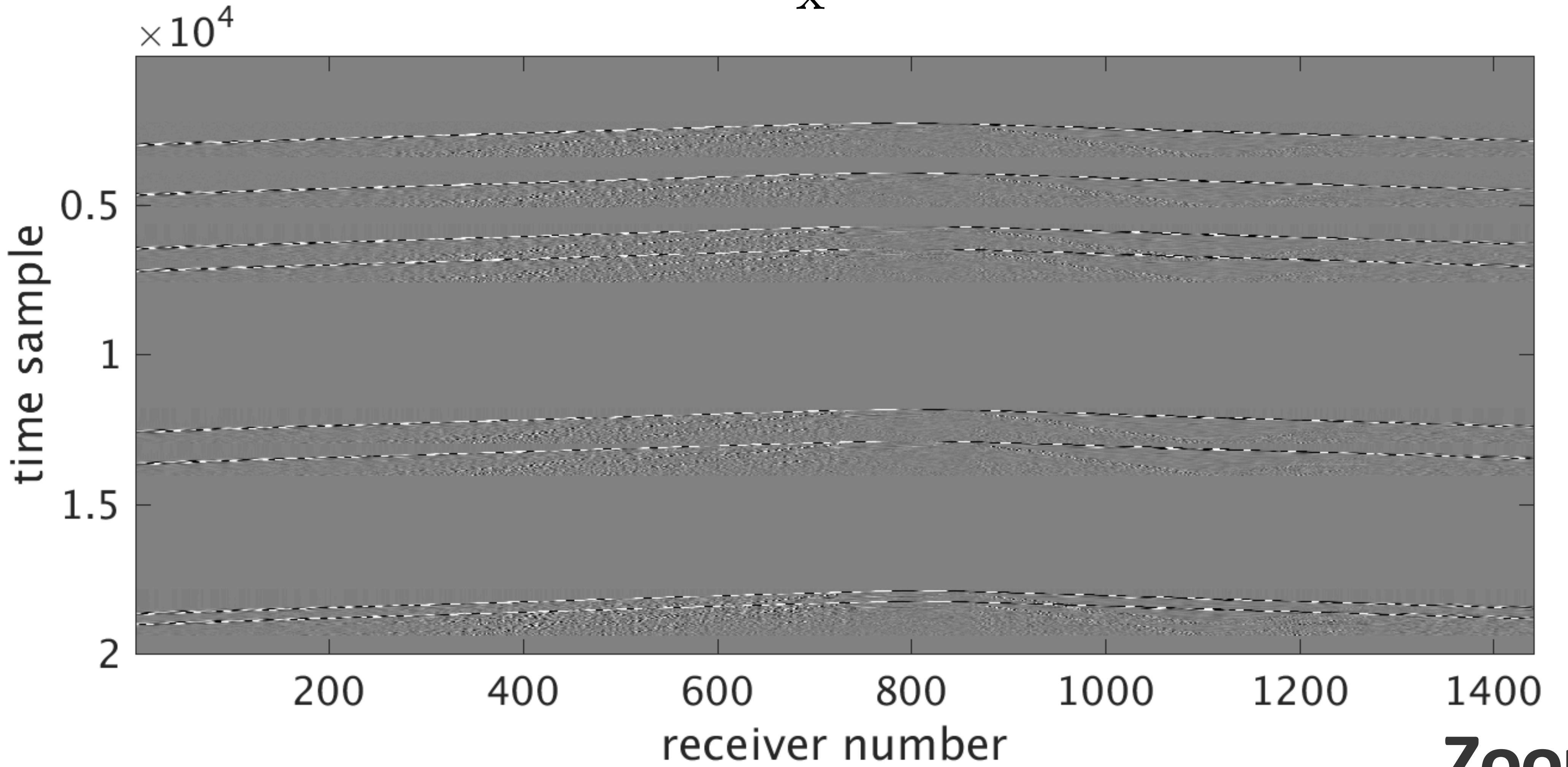
- Better at capturing curve-like events.
- Sparser representation.



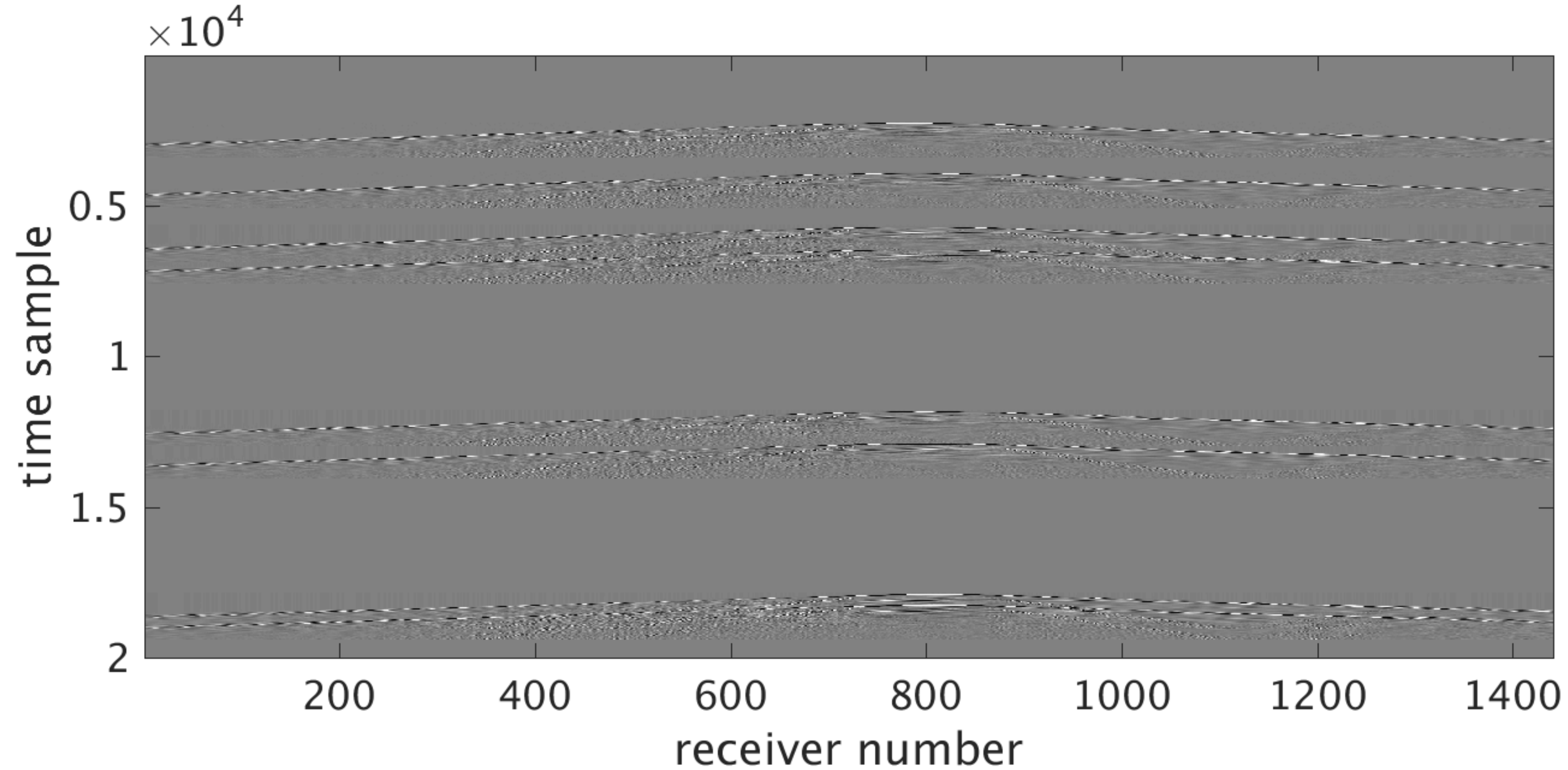
Joint source separation decomposition

Jittered continuous recording, 1 boat, 2 air guns

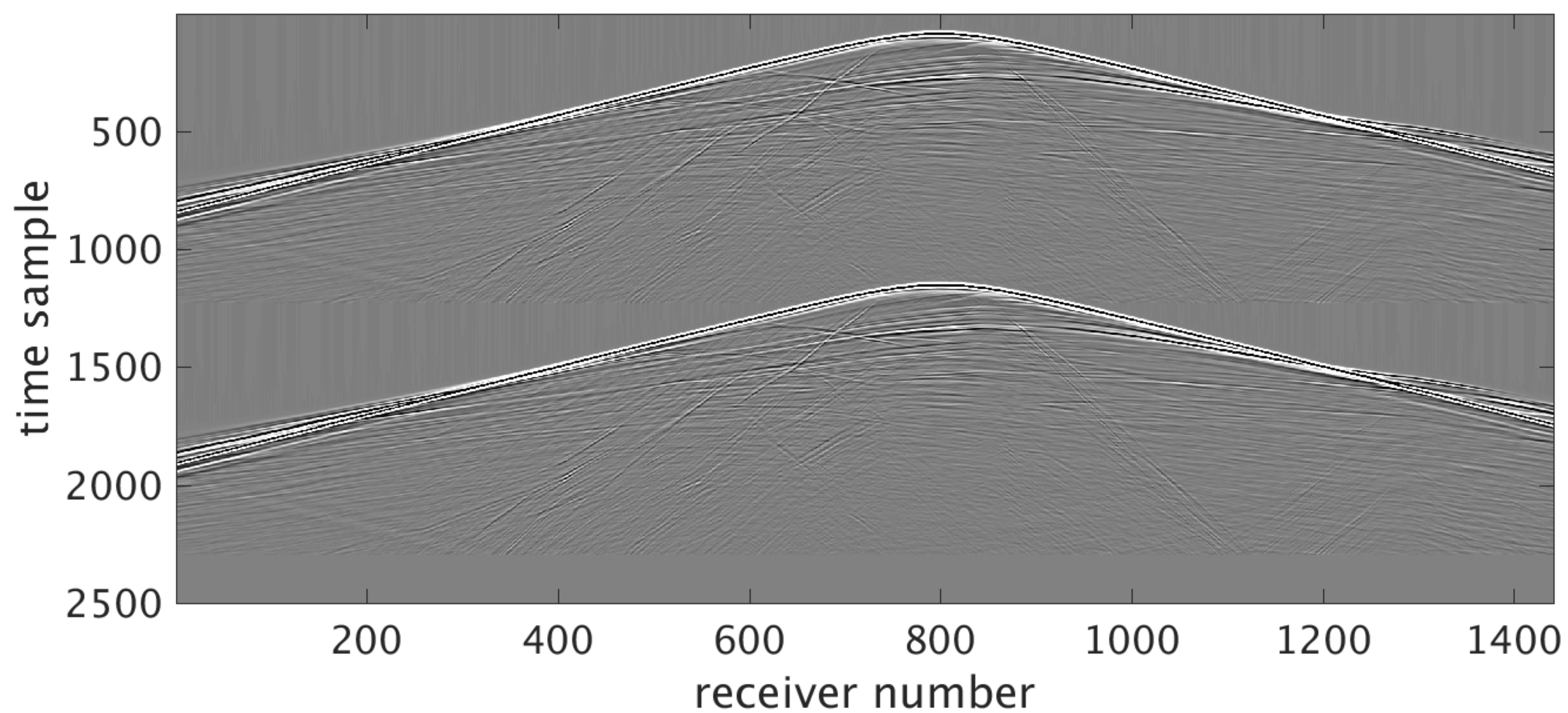
V_x



V_z



Zoomed T_{zz}



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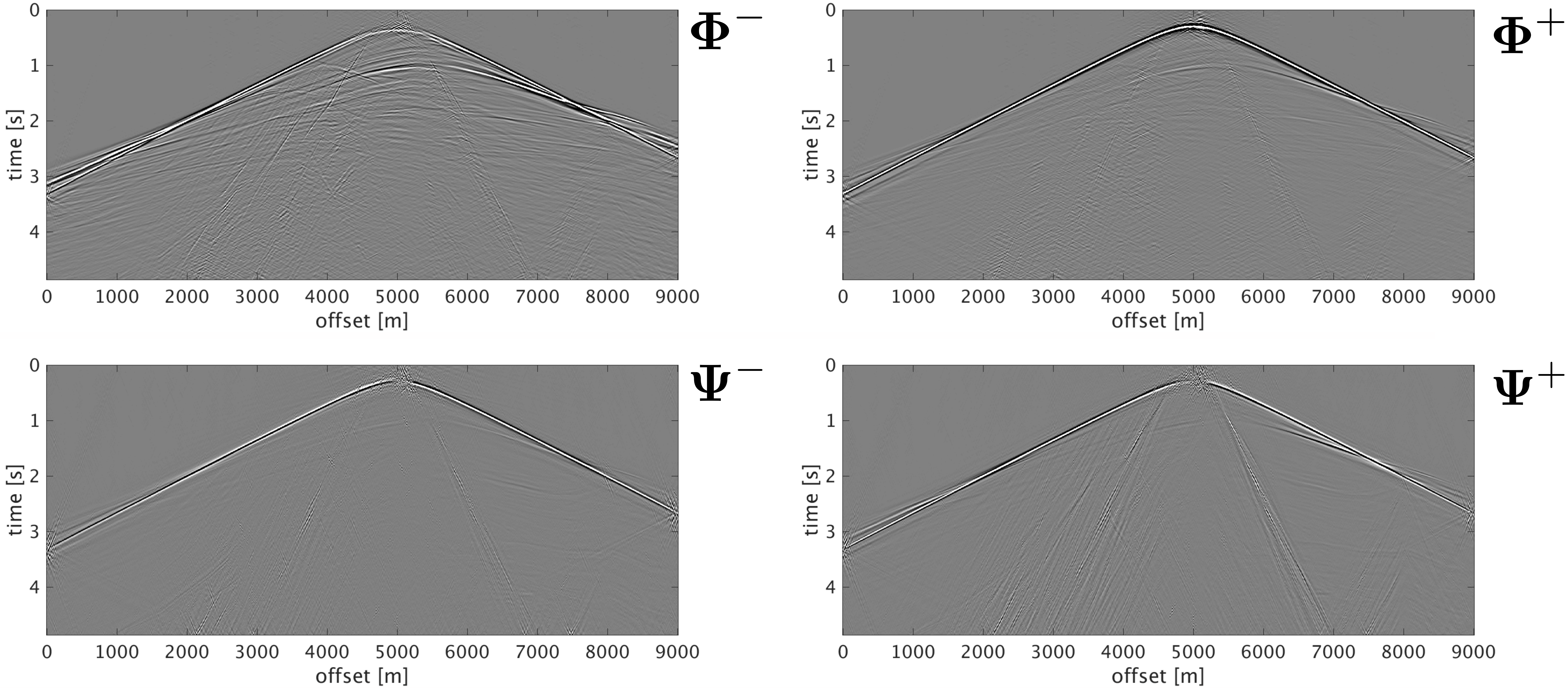
$\mathbf{x}$: curvelet coefficients of the decomposed data

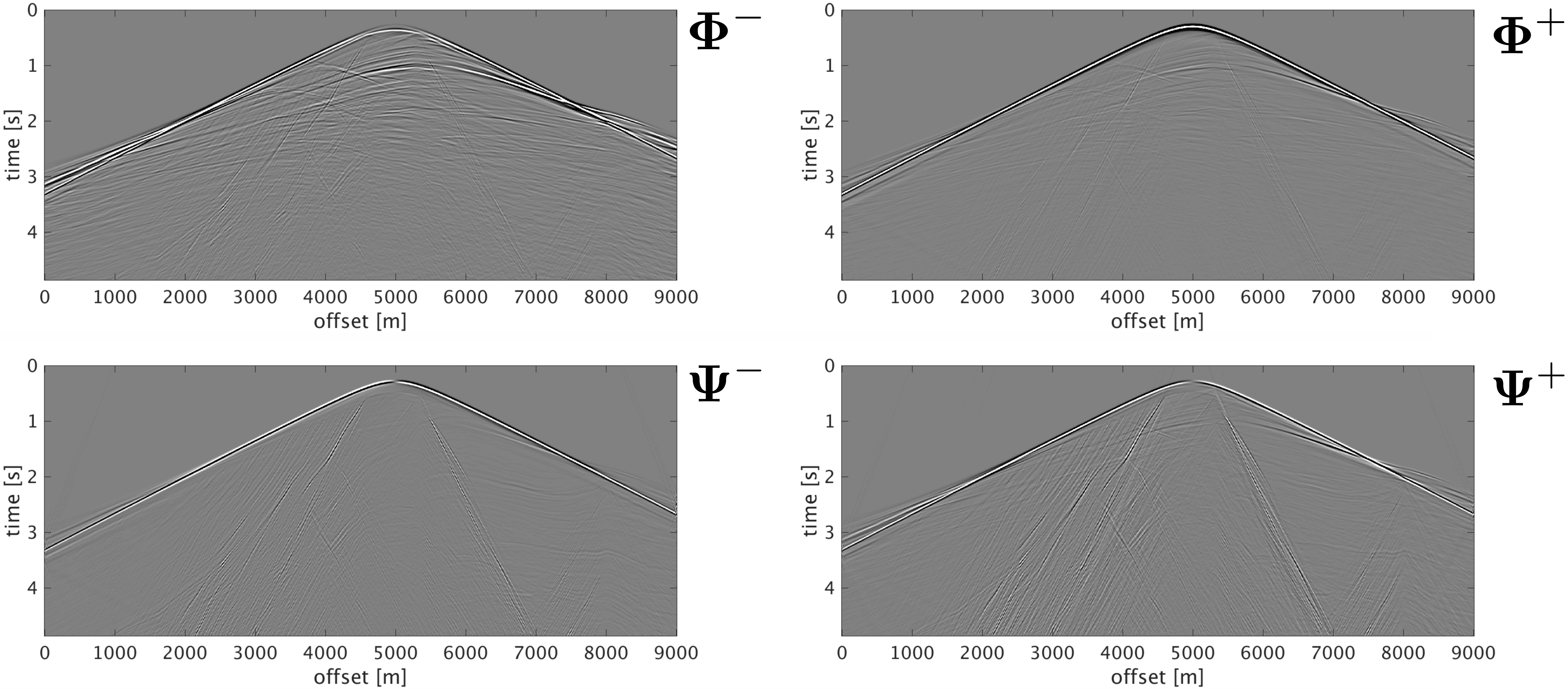
$$\mathbf{A}_c = \mathbf{M}\mathbf{F}^H\mathbf{L}\mathbf{F}\mathbf{S}^H$$

$\mathbf{M}$: blending matrix

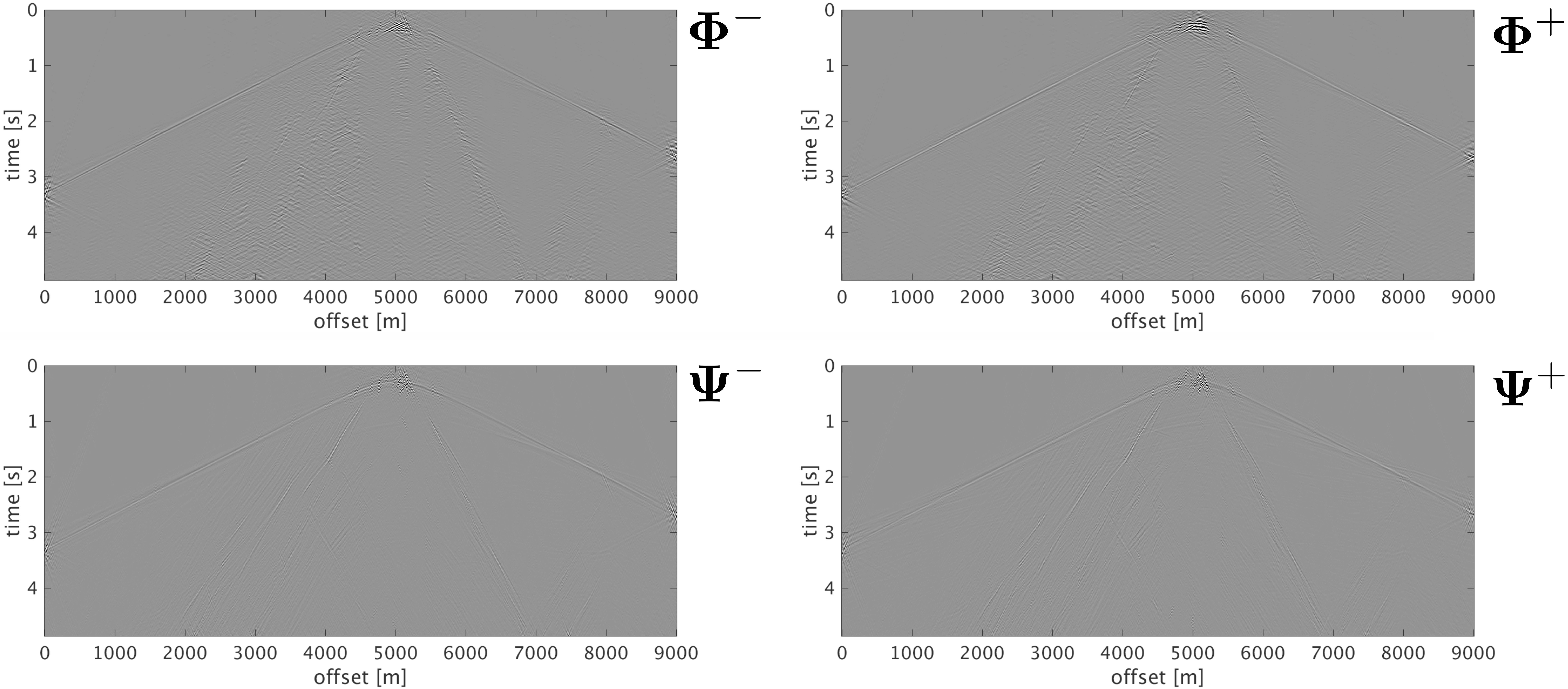
Reconstructed data



Densely data



Residual



Φ^-
Φ^+
Ψ^-
Ψ^+
time [s]
0
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Advantages of the joint formulations

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- Minimize parameters selection.
- Ensure preservation of amplitude ratios.

Conclusions

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- Utilize the multicomponent data to its available **full extent** at a lower cost compared w\ conventional acquisition.

Future work

- Examining the noise effect → another reason why S-waves are not used, yet another motivation for joint formulations.
- Joint formulations w\ rank minimization.
- P-S imaging

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أرامكو السعودية
saudi aramco

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Thank you for your attention!