Subsalt velocity analysis by target-oriented wavefield tomography

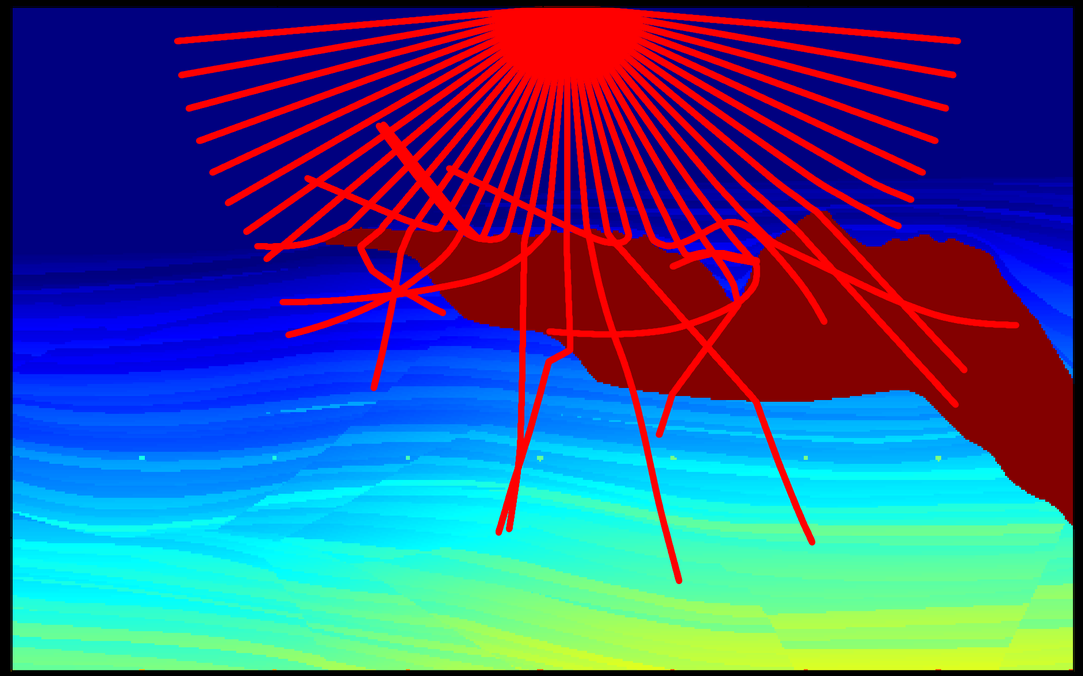
Yaxun Tang and Biondo Biondi

SEP-143, pp. 1

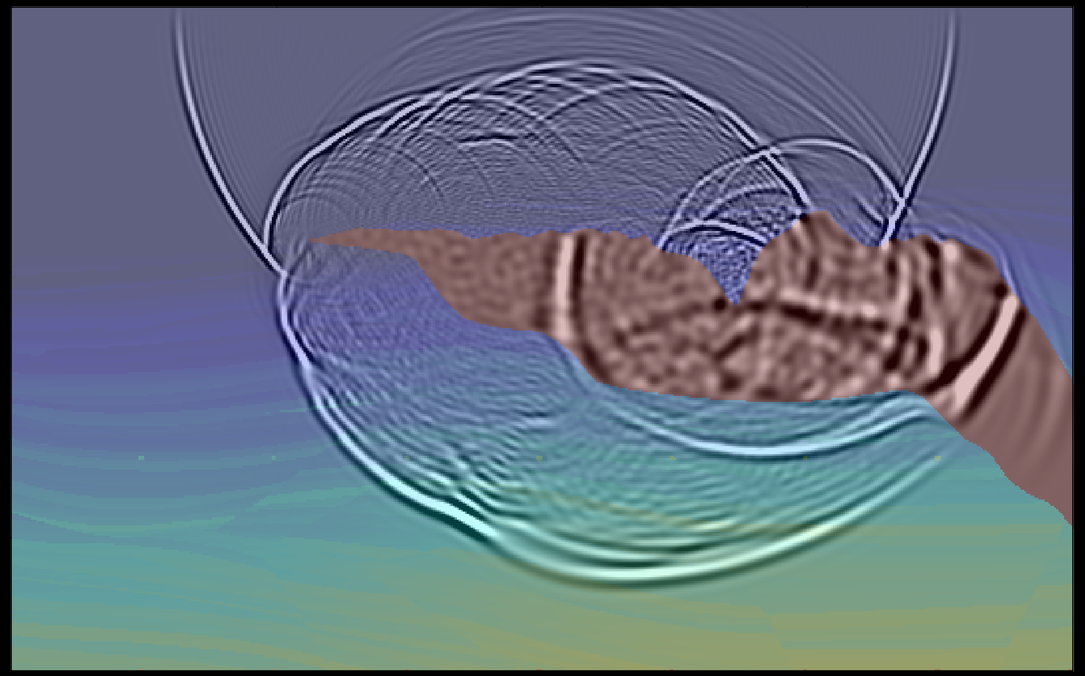
Rays vs. waves

Distance

Depth

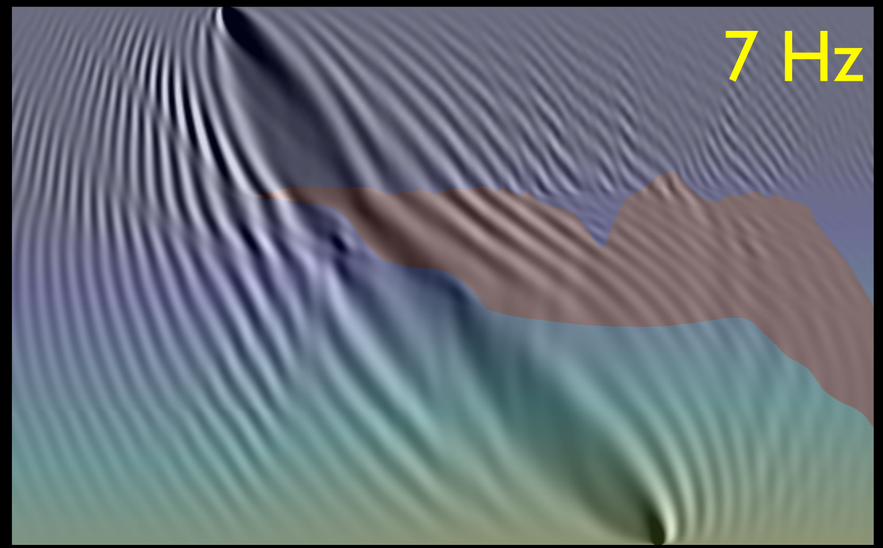


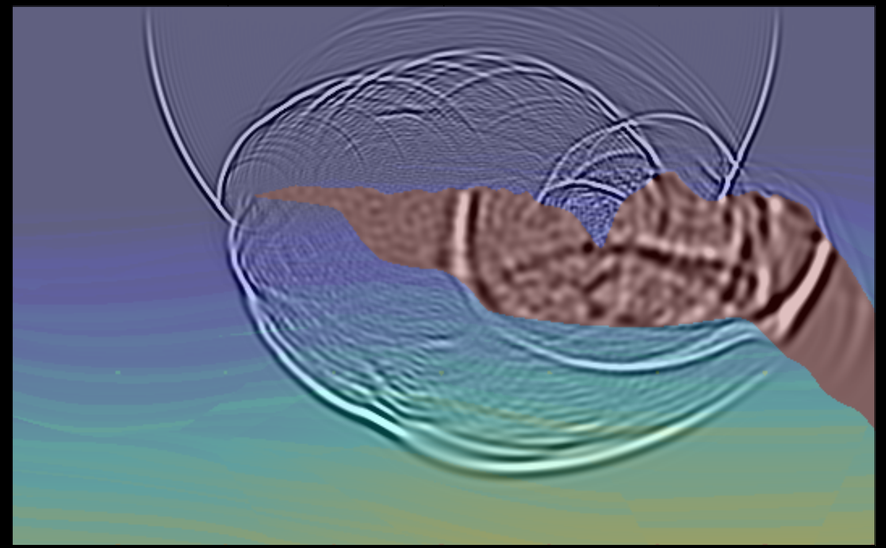
Distance

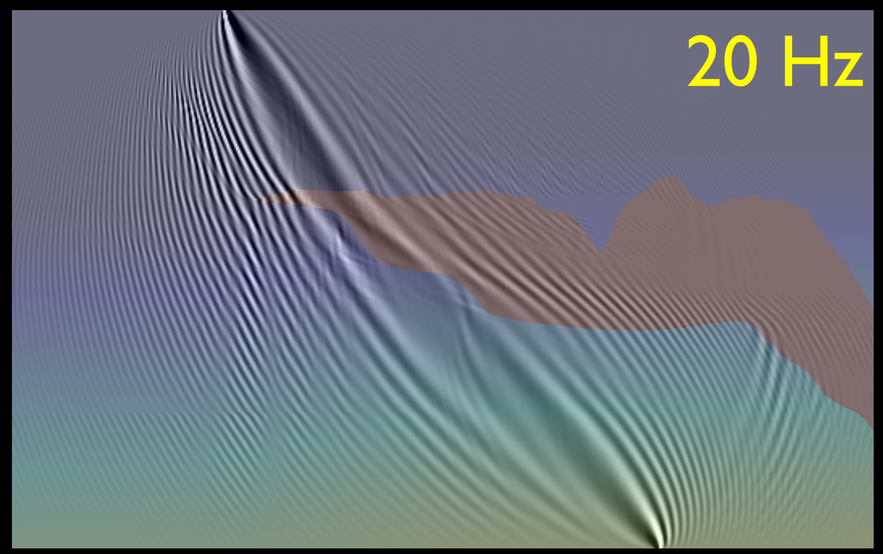


Wavefield-based methods become
necessary for complex geology

Frequency-dependent velocity sensitivity





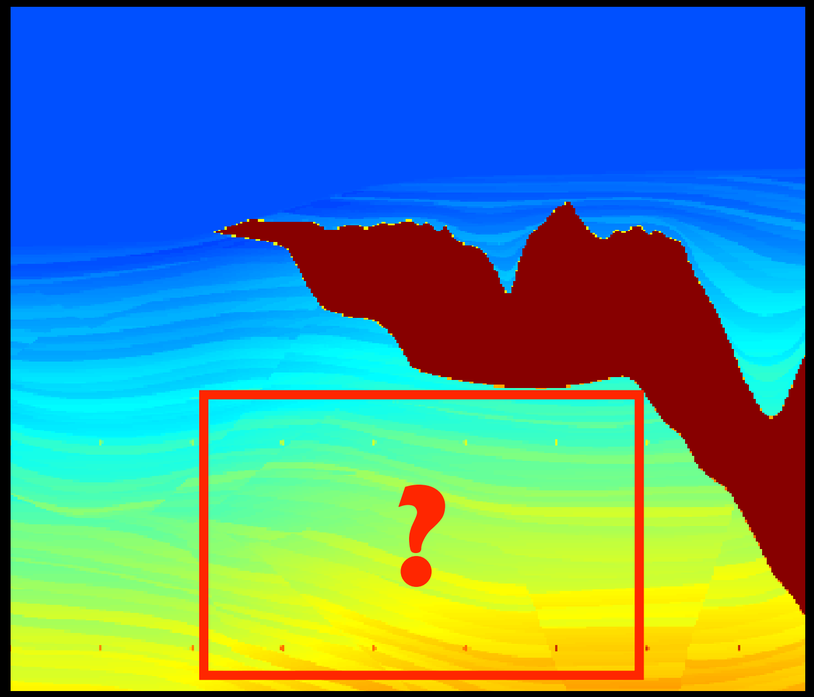


Wavefield-based methods become necessary for complex geology

But expensive!

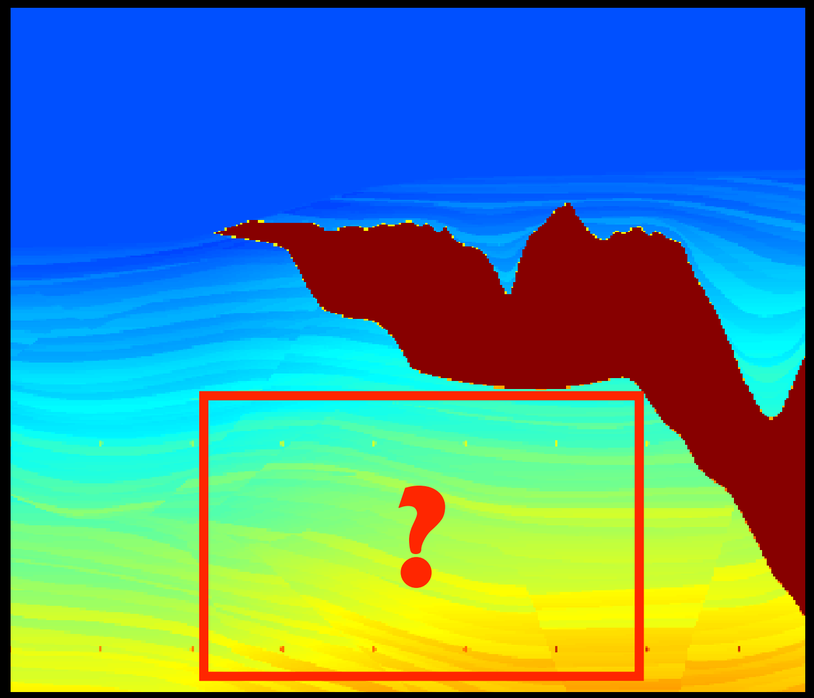
Research goal

- ✓ Develop cost-effective, target-oriented and automatic wavefield tomography
- ✓ Use wavefield-based methods for the most challenging areas (subsalt regions)
- ✓ Interpretation-driven interactive wavefield-based velocity analysis



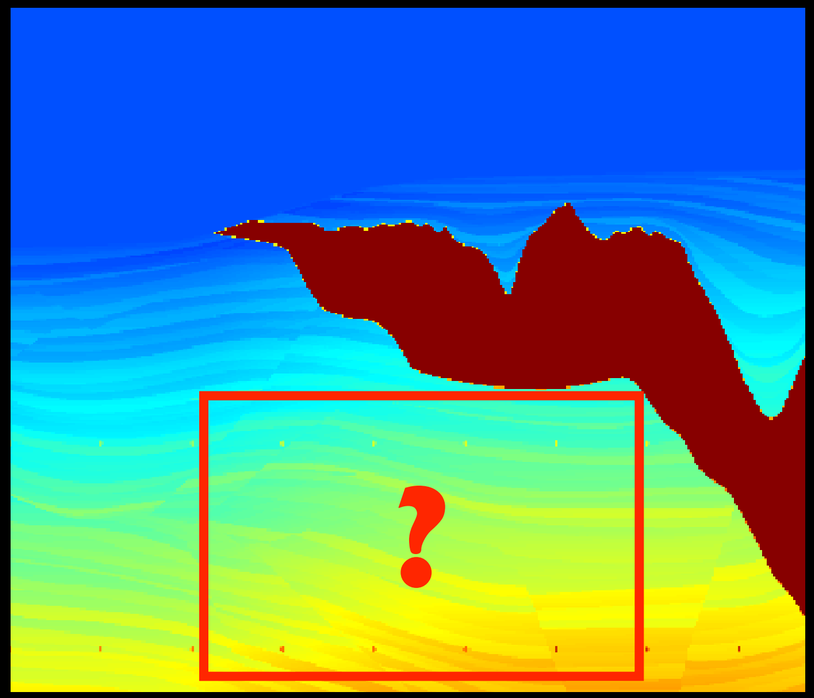
Research goal

- ✓ Develop cost-effective, target-oriented and automatic wavefield tomography
- ✓ Use wavefield-based methods for the most challenging areas (subsalt regions)
- ✓ Interpretation-driven interactive wavefield-based velocity analysis



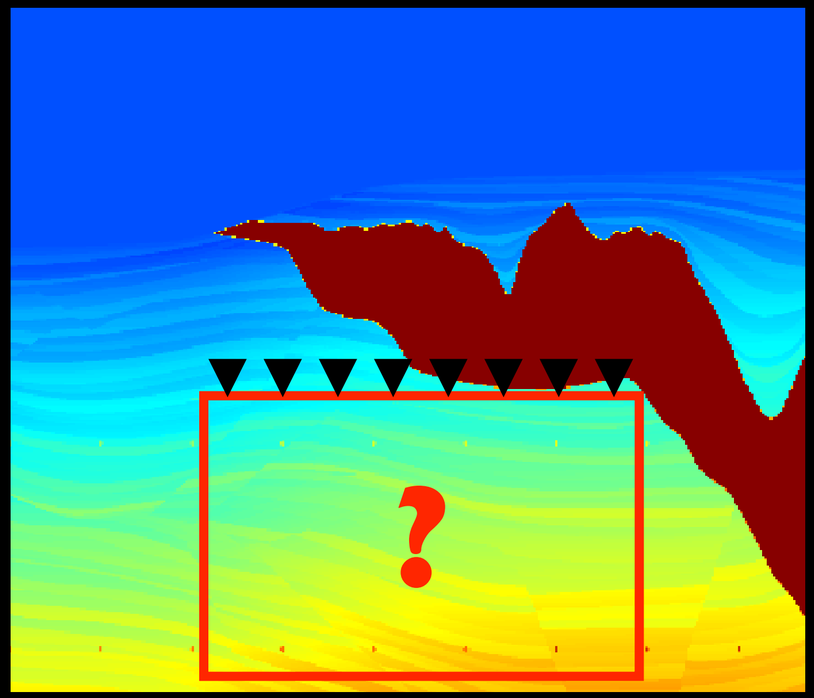
Research goal

- ✓ Develop cost-effective, target-oriented and automatic wavefield tomography
- ✓ Use wavefield-based methods for the most challenging areas (subsalt regions)
- ✓ Interpretation-driven interactive wavefield-based velocity analysis



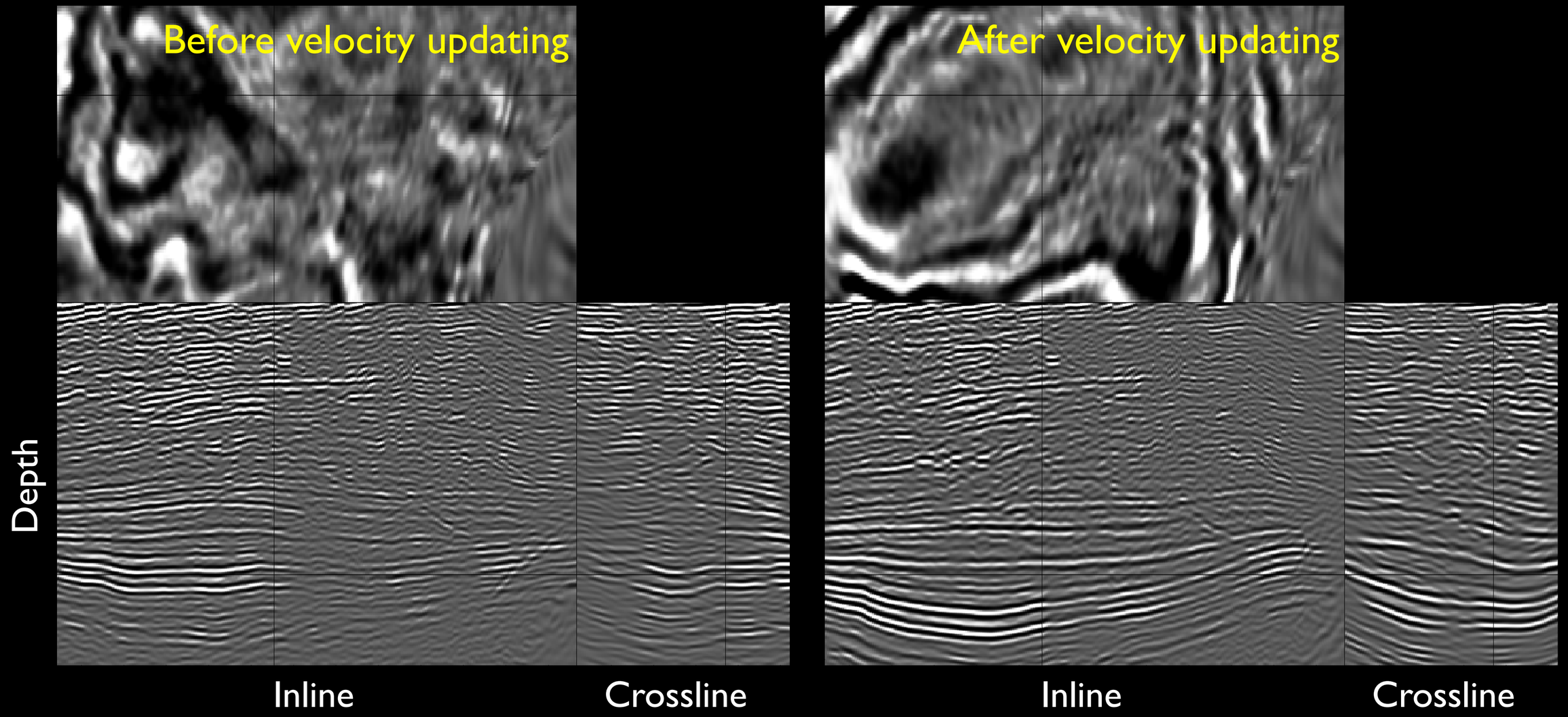
Research goal

- ✓ Develop cost-effective, target-oriented and automatic wavefield tomography
- ✓ Use wavefield-based methods for the most challenging areas (subsalt regions)
- ✓ Interpretation-driven interactive wavefield-based velocity analysis



Design a new data set specifically for velocity analysis

3-D wavefield tomography using synthesized data

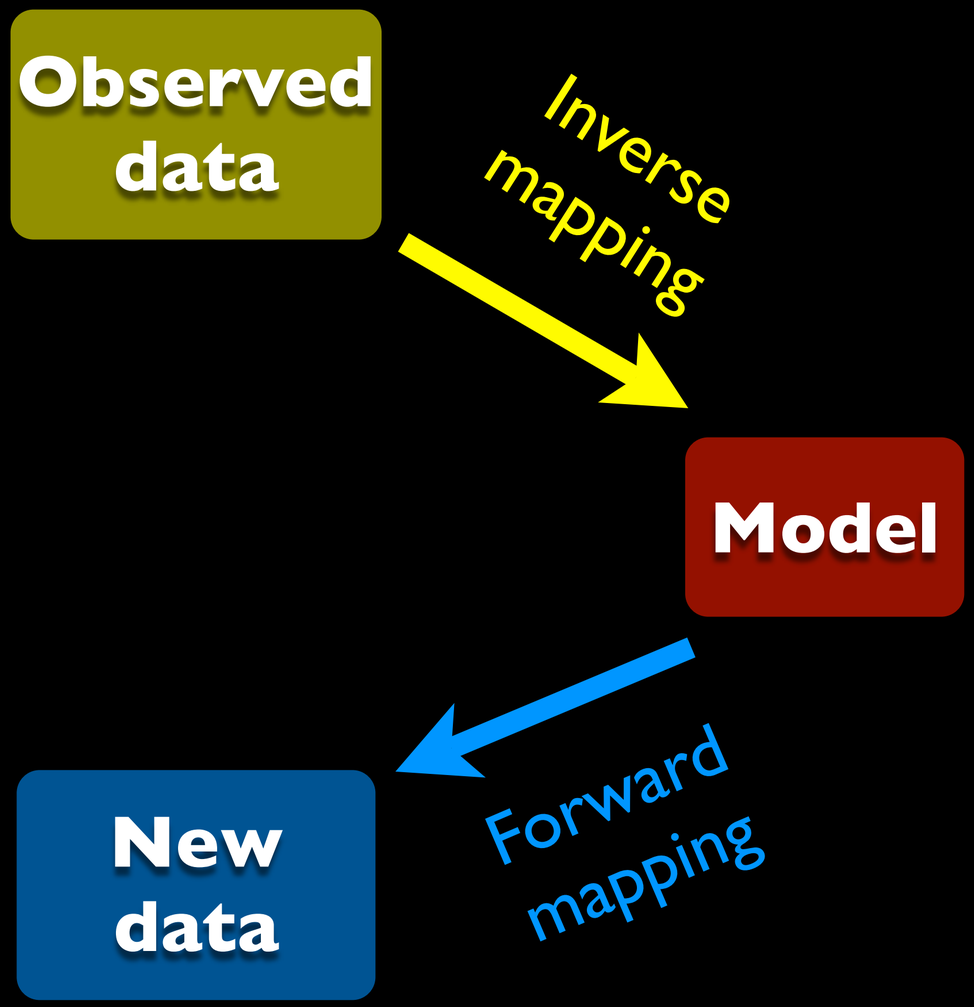


~190X faster than using original surface data

Agenda

- Target-oriented Born wavefield modeling
- Velocity analysis using synthesized Born data
- 2-D synthetic-data example
- 3-D field-data example

Seismic data mapping



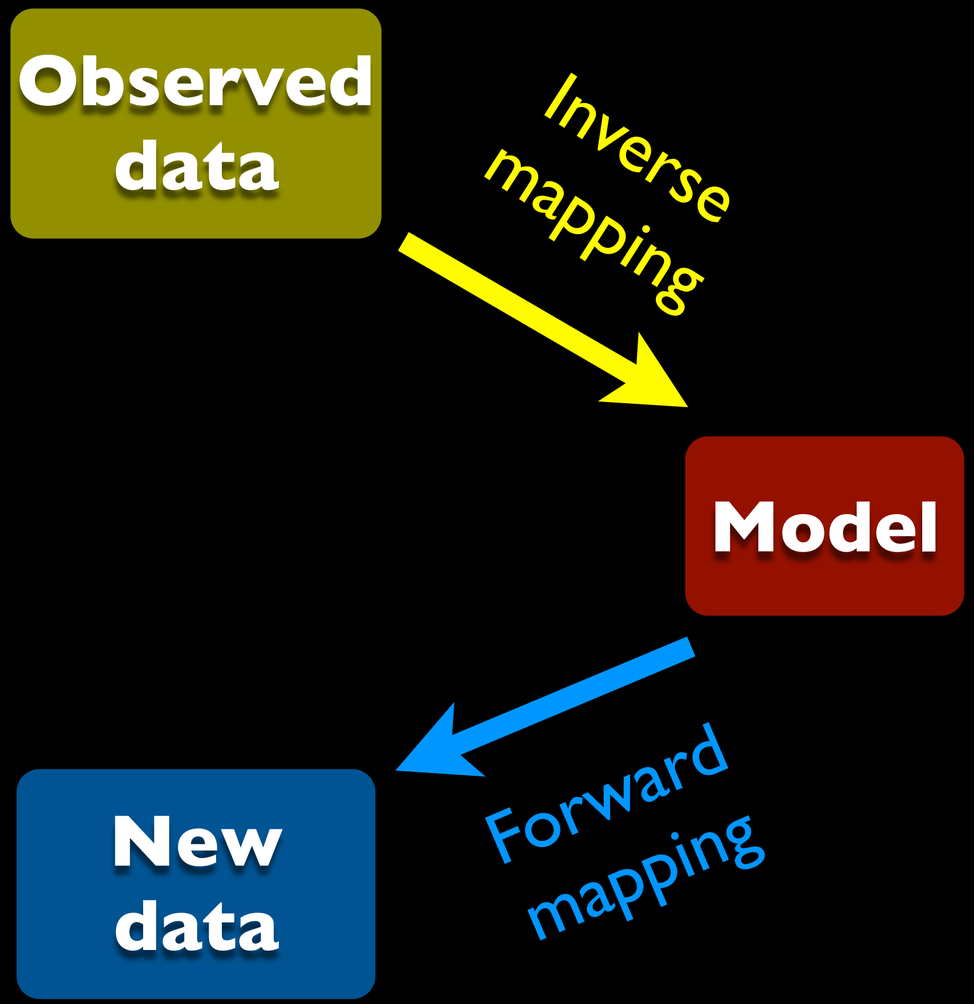
Extensively used in data regularization
e.g., AMO (Biondi et al., 1998)

Mapping operator = Inverse DMO

(Ronen, 1985)

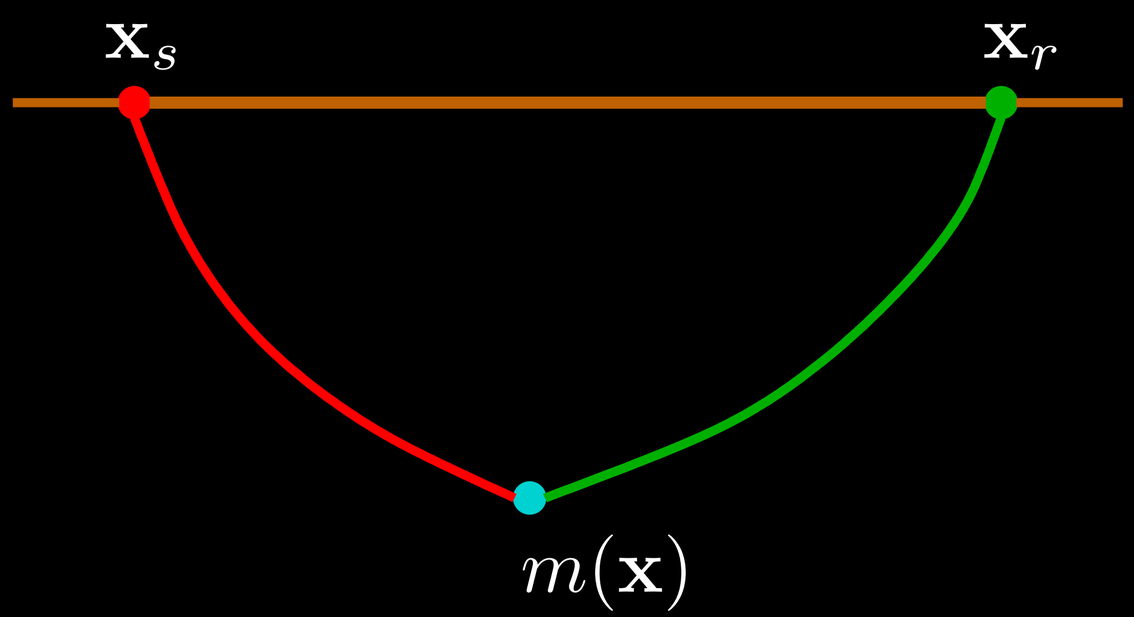
Hubral et al., 1996

Born wavefield modeling



- We use generalized Born modeling for the data mapping
- Collect the new data set at the top of the target area; computation can be localized both vertically and laterally
- New data set is much smaller than original data set but contains all the necessary information for tomography

Convential Born wavefield modeling



Born forward:

$$\mathbf{d} = \mathbf{L}\mathbf{m}$$ "Demigration"

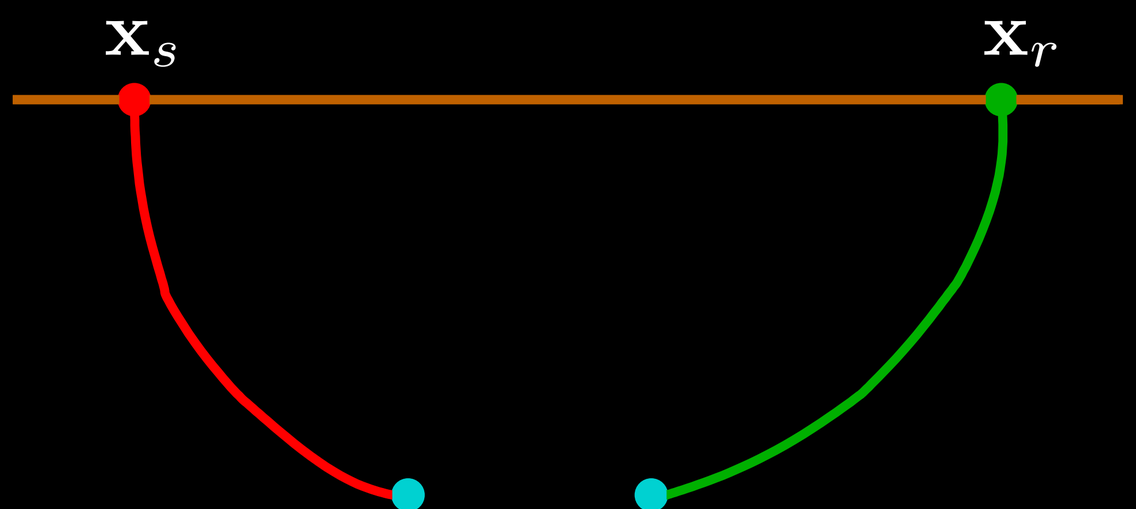
Born adjoint:

$$\hat{\mathbf{m}} = \mathbf{L}^*\mathbf{d}$$ "Migration"

$\mathbf{L}$: Born modeling operator $\mathbf{d}$: Born modeled data

$\mathbf{m}$: Stacked reflectivity (zero-subsurface offset)

Generalized Born wavefield modeling



Born forward:

$$\mathbf{d} = \mathbf{L}\mathbf{m} \quad \text{“Demigration”}$$

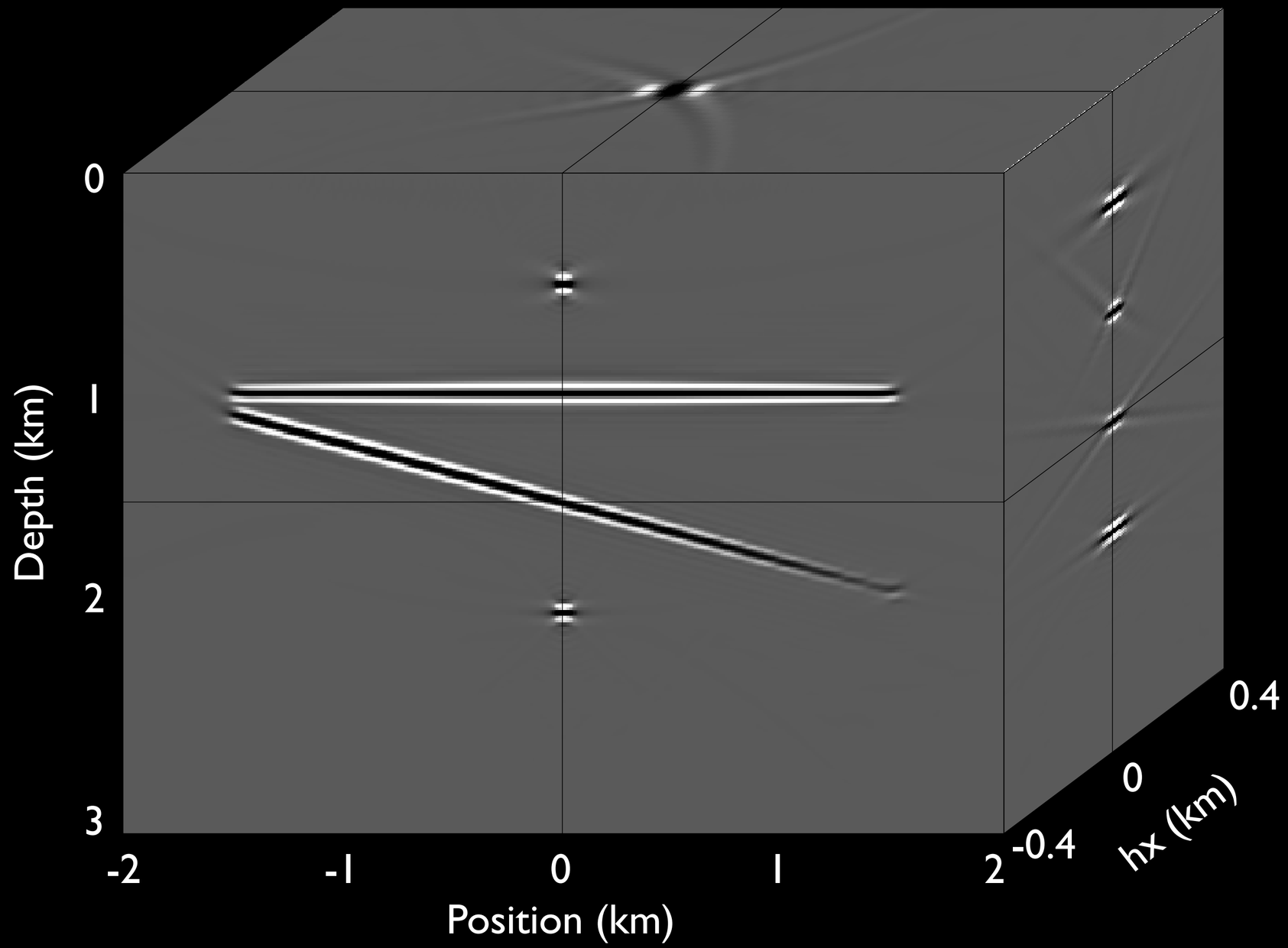
Born adjoint:

$$\hat{\mathbf{m}} = \mathbf{L}^*\mathbf{d} \quad \text{“Migration”}$$

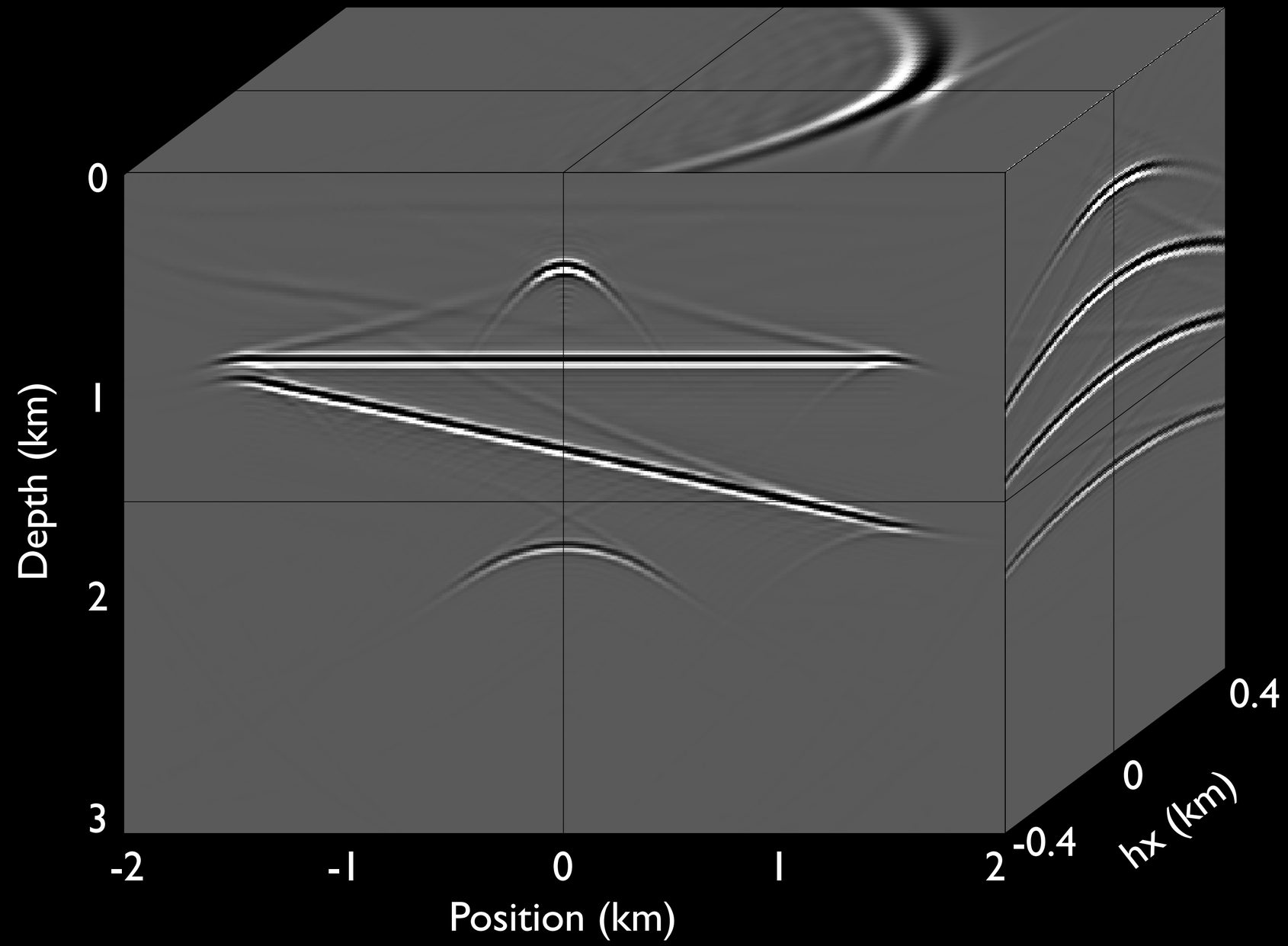
$\mathbf{L}$: Born modeling operator $\mathbf{d}$: Born modeled data

$\mathbf{m}$: Reflectivity as a function of prestack parameters, e.g., subsurface offset, reflection angle, etc.

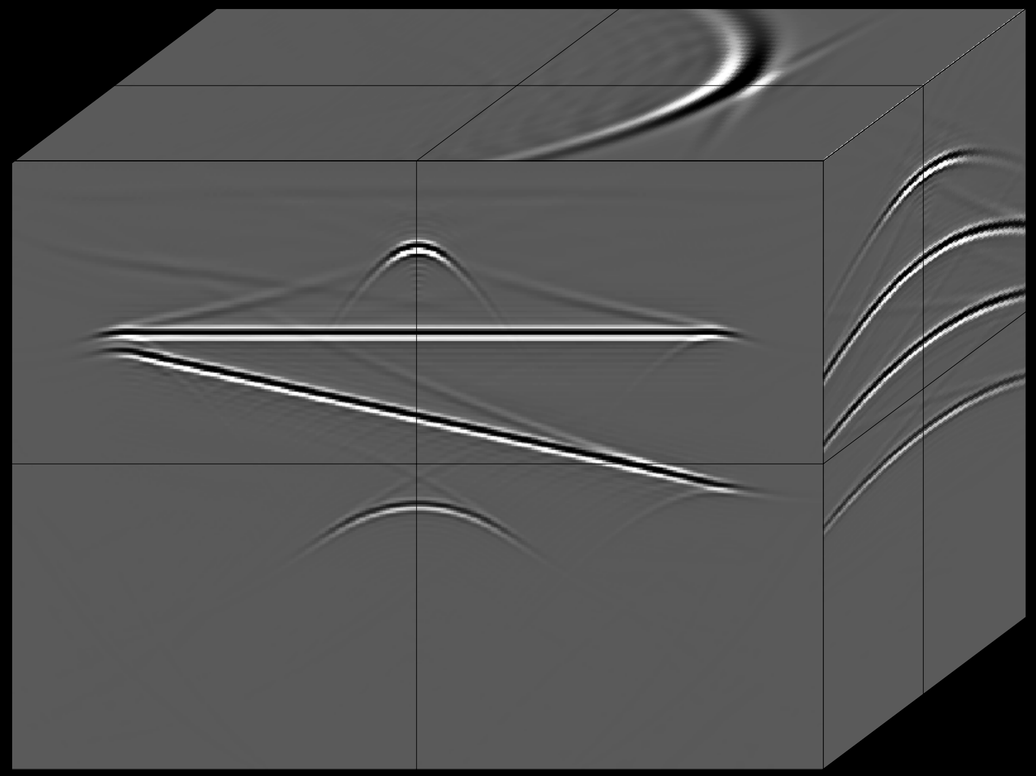
Image cube with correct velocity



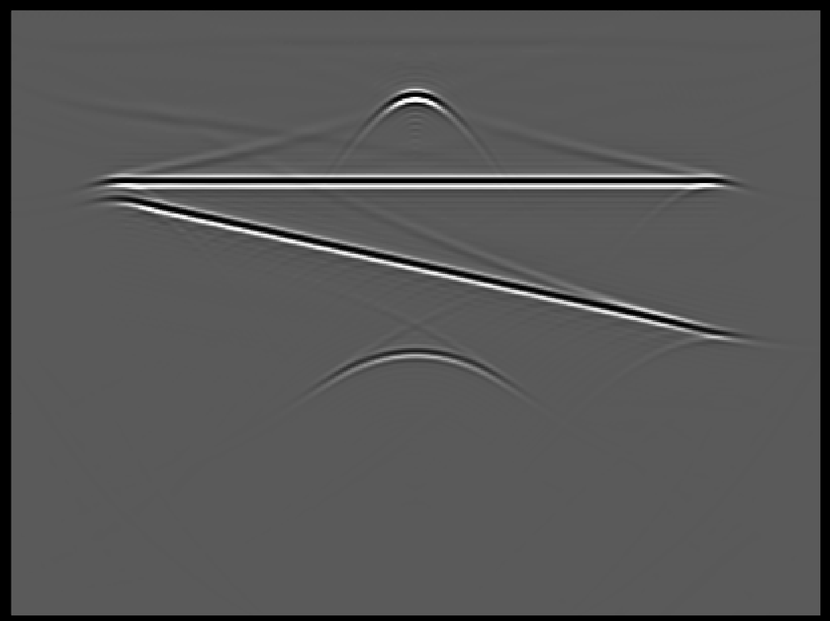
Initial image (15% slower velocity)



Which initial image for modeling?

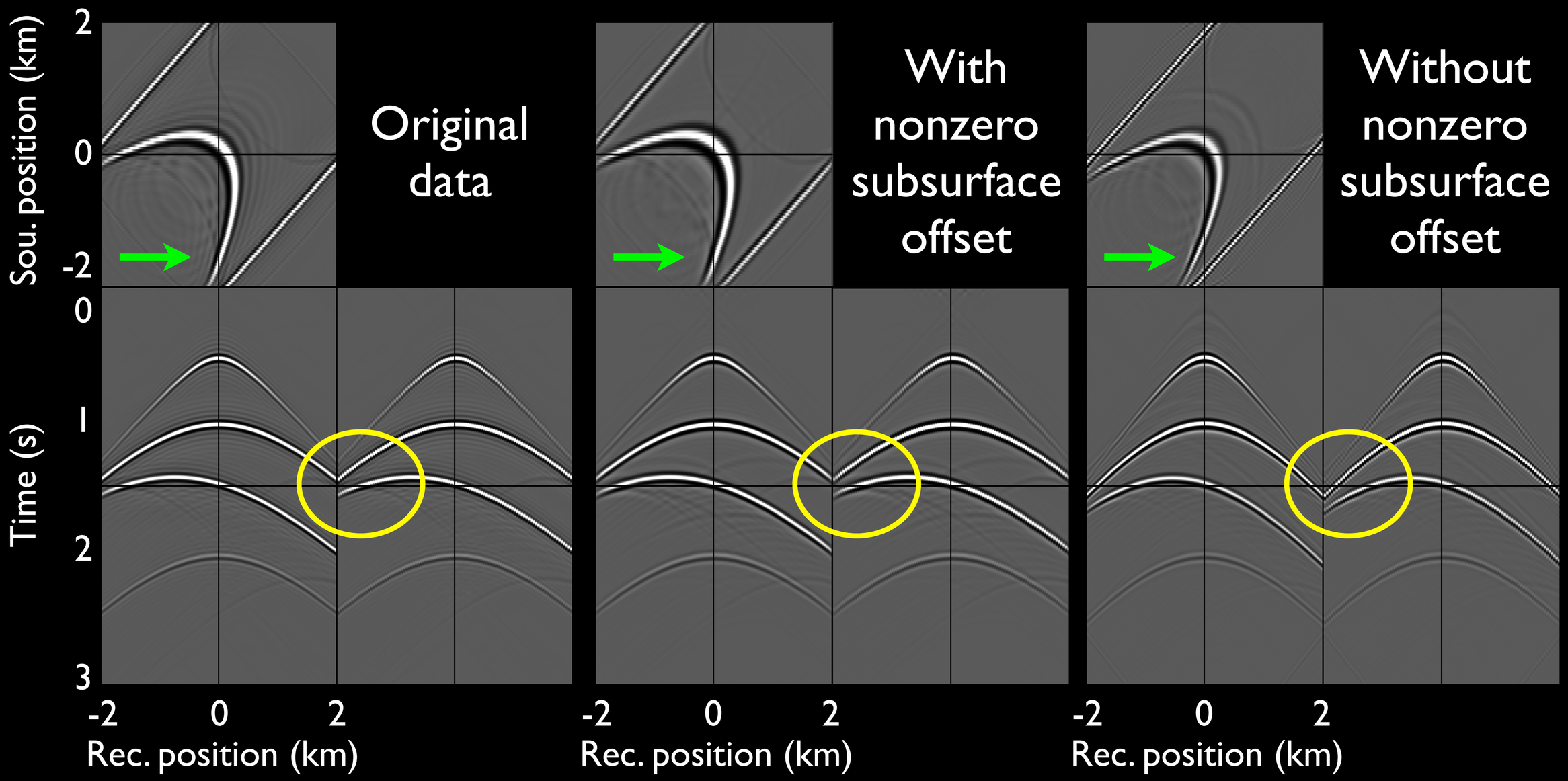


With nonzero subsurface offset

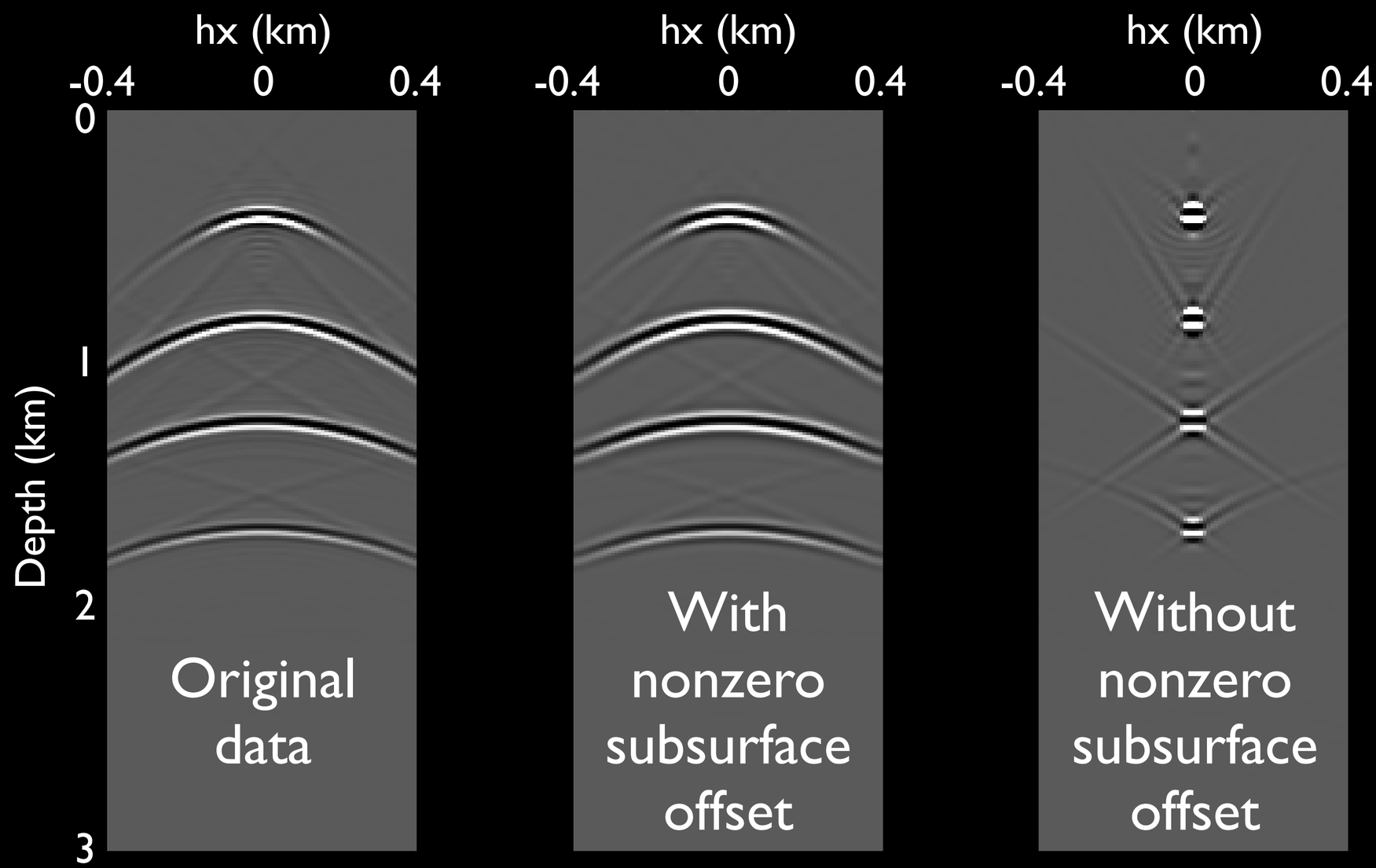


Without nonzero subsurface offset

Original data vs. modeled data



Subsurface-offset gathers obtained using 15% slower velocity



Data mapping via Born modeling operator

$\mathbf{d}_{\text{obs}}$

Observed data

Inverse mapping

Model

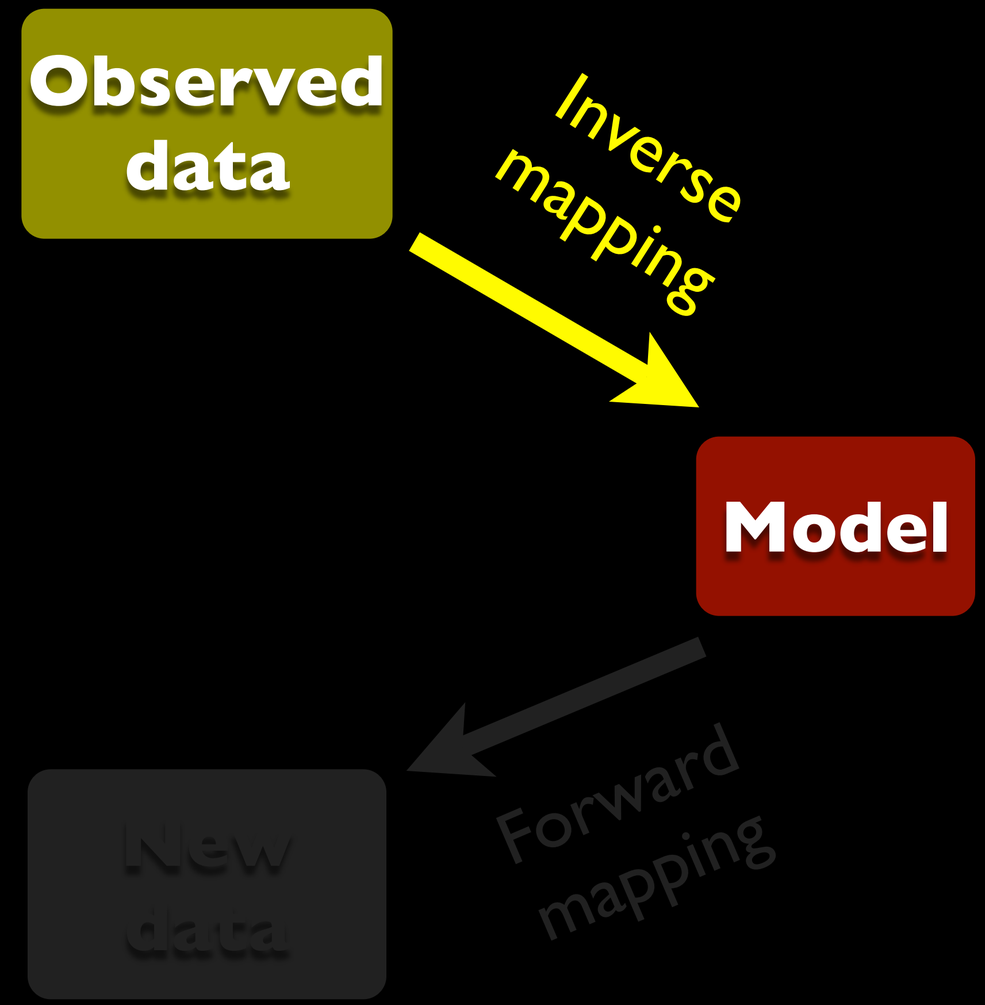
Forward mapping

New data

Data mapping via Born modeling operator

$\mathbf{L}_0$ uses an initial velocity $\mathbf{v}_0$

$$\mathbf{m} = \mathbf{L}_0^{-1}\mathbf{d}_{\text{obs}}$$



Data mapping via Born modeling operator

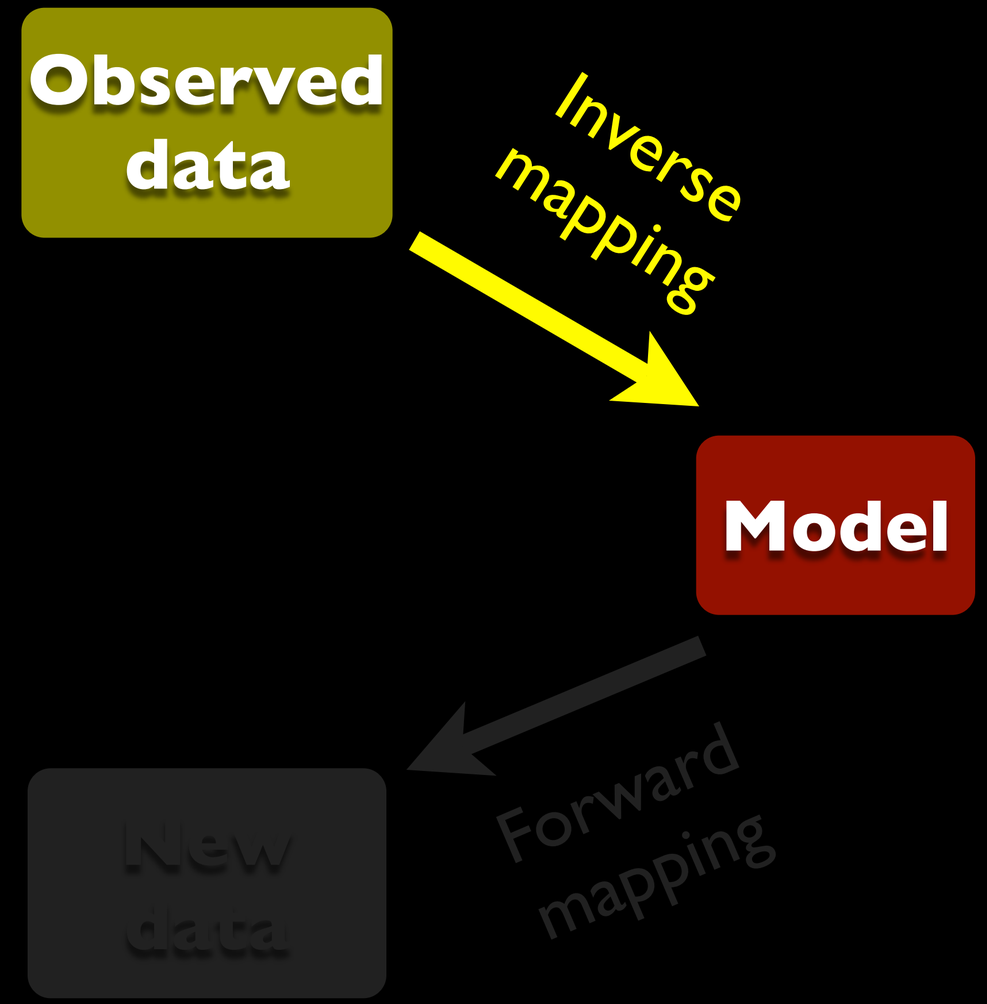
$\mathbf{L}_0$ uses an initial velocity $\mathbf{v}_0$

$$\mathbf{m} \approx \frac{1}{\text{diag}\{\mathbf{H}_0\}} \mathbf{L}_0^* \mathbf{d}_{\text{obs}}$$

$$\mathbf{H}_0 = \mathbf{L}_0^* \mathbf{L}_0$$

- Diagonal approximation
- Phase-encoding (Tang, 2008, 2009)

"True amplitude migration"



Data mapping via Born modeling operator

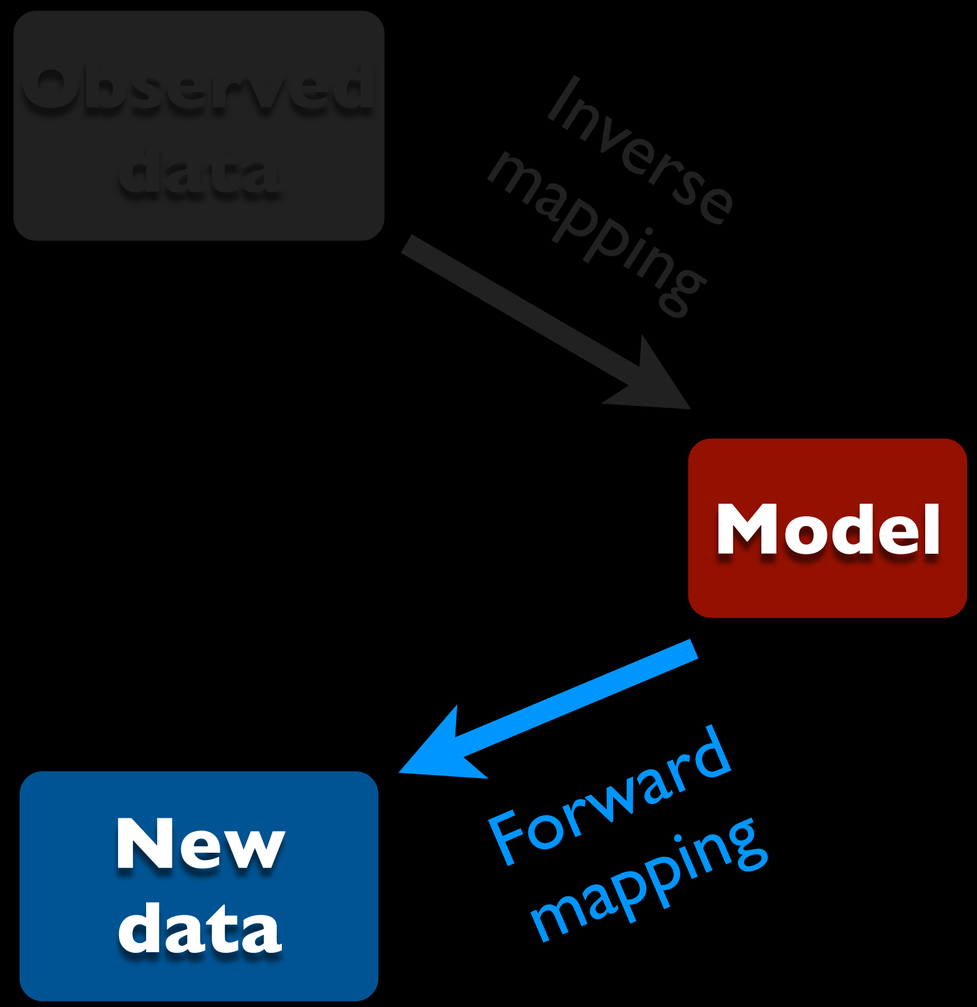
$\mathbf{L}_0$ uses an initial velocity $\mathbf{v}_0$

$$\mathbf{m} \approx \frac{1}{\text{diag}\{\mathbf{H}_0\}} \mathbf{L}_0^* \mathbf{d}_{\text{obs}}$$

$$\mathbf{H}_0 = \mathbf{L}_0^* \mathbf{L}_0$$

$$\tilde{\mathbf{d}}_{\text{obs}} = \tilde{\mathbf{L}}_0 \mathbf{m}$$

"Demigration"

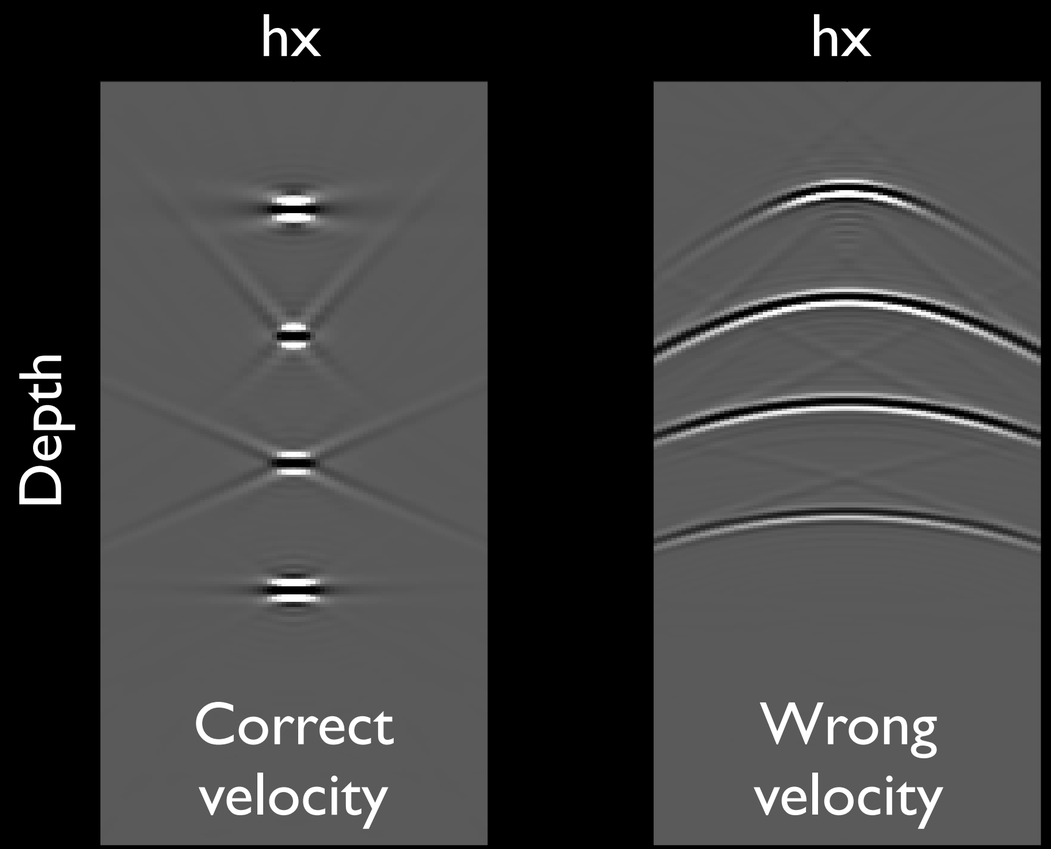


Automatic image-domain wavefield tomography

Differential semblance optimization (DSO):

$$J_{\mathrm{DSO}}(\mathbf{v}) = \frac{1}{2}\sum_{\mathbf{x},\mathbf{h}} |\mathbf{h}|^2 \widehat{m}^2_{\mathrm{target}}(\mathbf{x},\mathbf{h})$$

Shen and Symes (2008)



Focusing of subsurface offset gather can be a measure of velocity accuracies

Normalized differential semblance

Normalize DSO by image RMS amplitudes:

$$J(\mathbf{v}) = \frac{1}{2} \sum_{x,y} \frac{\sum_{z,\mathbf{h}} |\mathbf{h}|^2 \widehat{m}^2_{\text{target}}(x,y,z,\mathbf{h})}{\sum_{z,\mathbf{h}} \widehat{m}^2_{\text{target}}(x,y,z,\mathbf{h})}$$

$\widehat{m}_{\text{target}}$: Image cube in the target region obtained using the new data set

$\mathbf{h}$: Subsurface offset

Gradient-based nonlinear optimization

For the kth iteration:

Compute the image residual $\Delta\widehat{\mathbf{m}}^k_{\text{target}}$

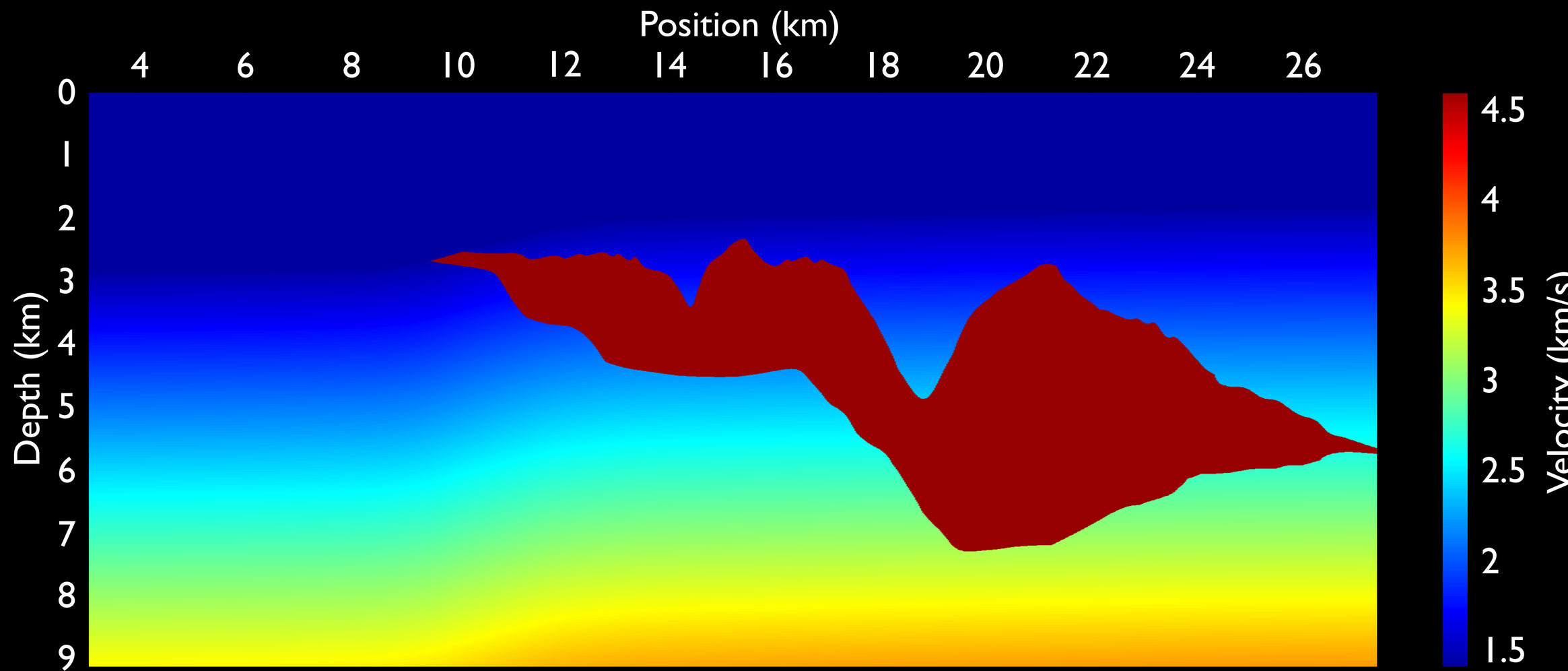
Compute the gradient $\mathbf{g}_k$

Find the search direction $\mathbf{p}_k$

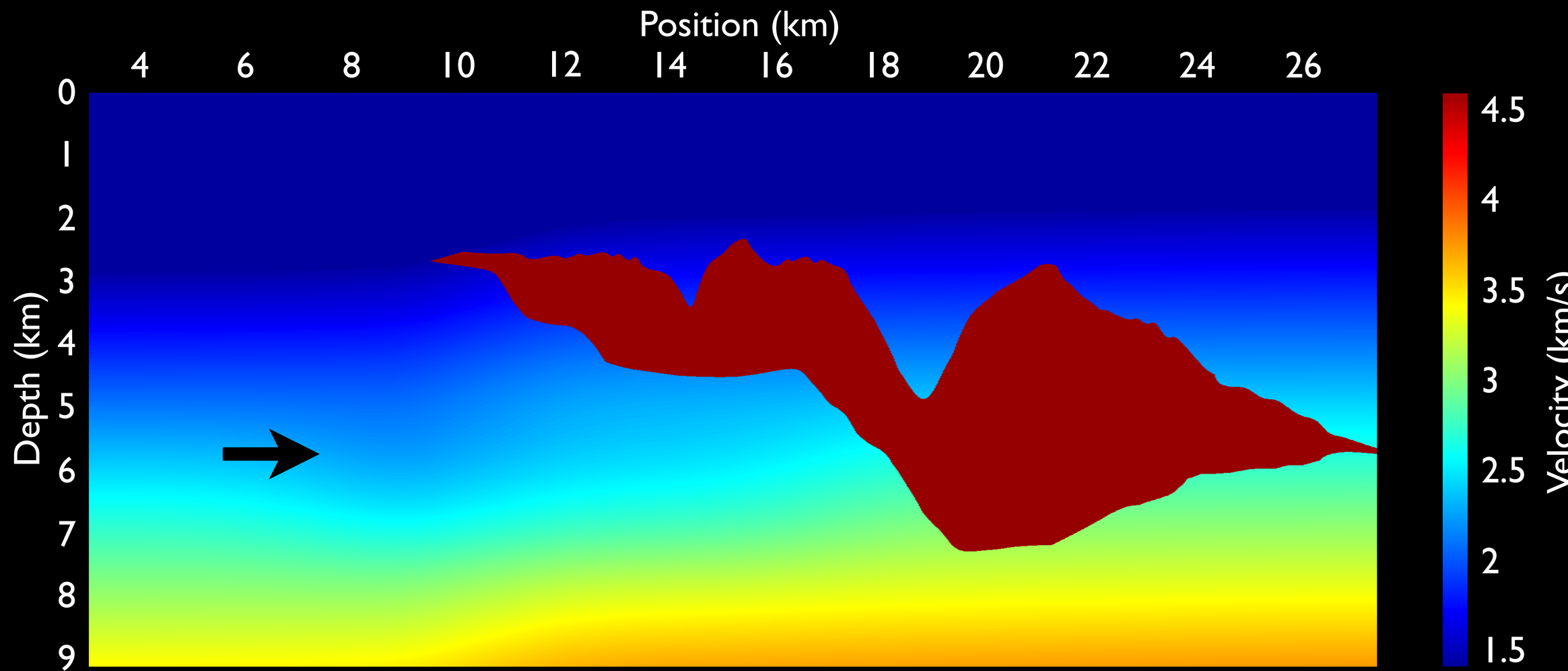
Perform line search $J(\mathbf{v}_k + \alpha\mathbf{p}_k) < J(\mathbf{v}_k)$

Update the model $\mathbf{v}_k = \mathbf{v}_k + \alpha\mathbf{p}_k$

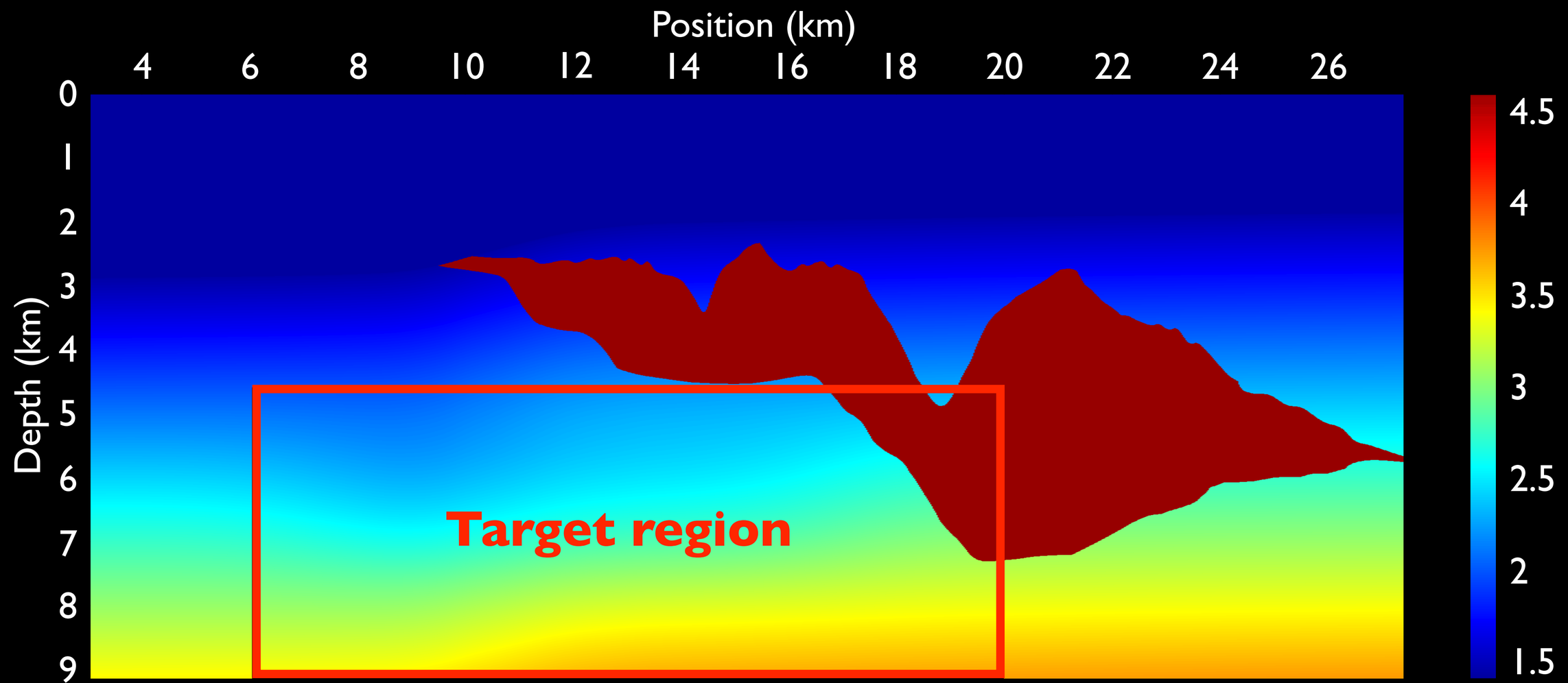
The true velocity



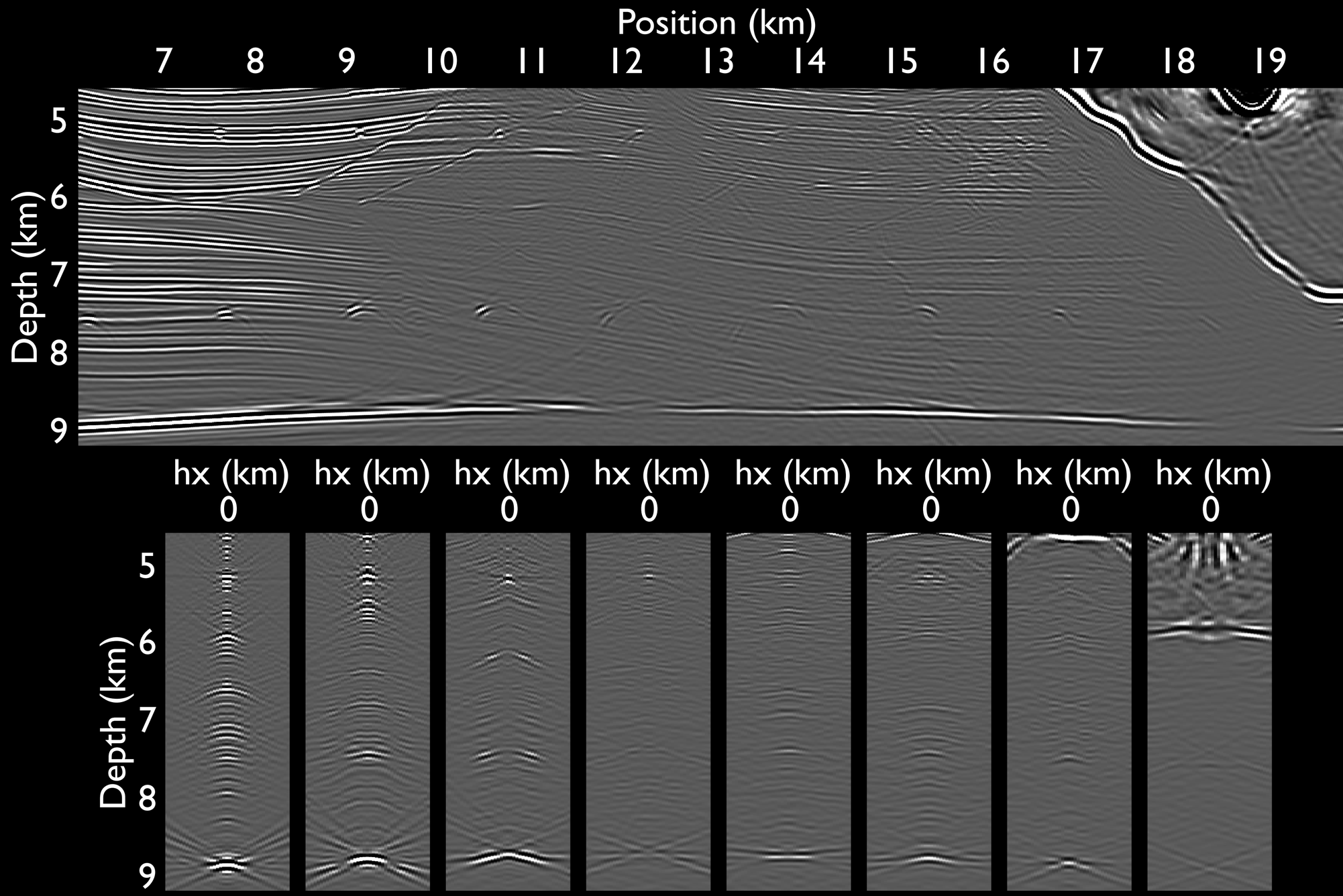
The initial velocity



The initial velocity



Migration of the original data (initial velocity)



Born plane-wave modeling

Position

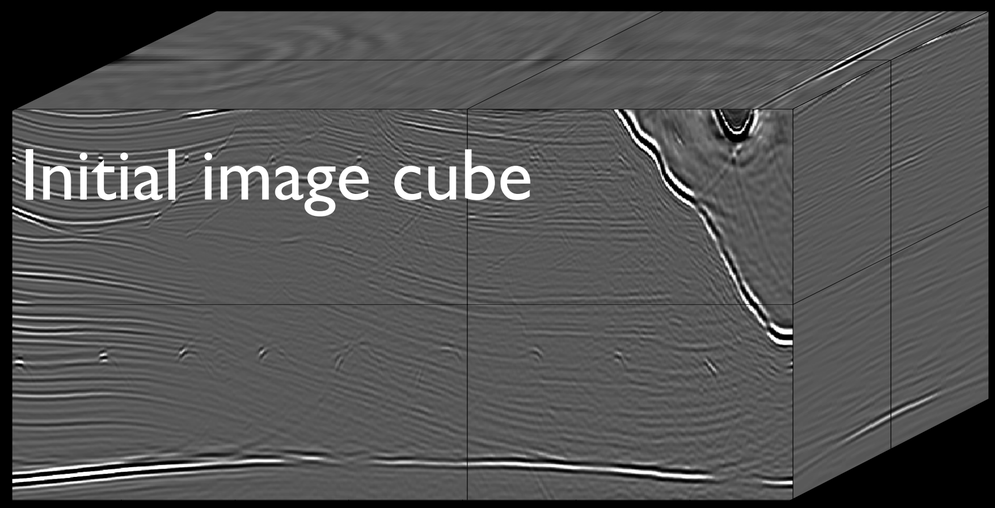
Position

Depth

Source wavefield

Receiver wavefield

t = 0.5 s

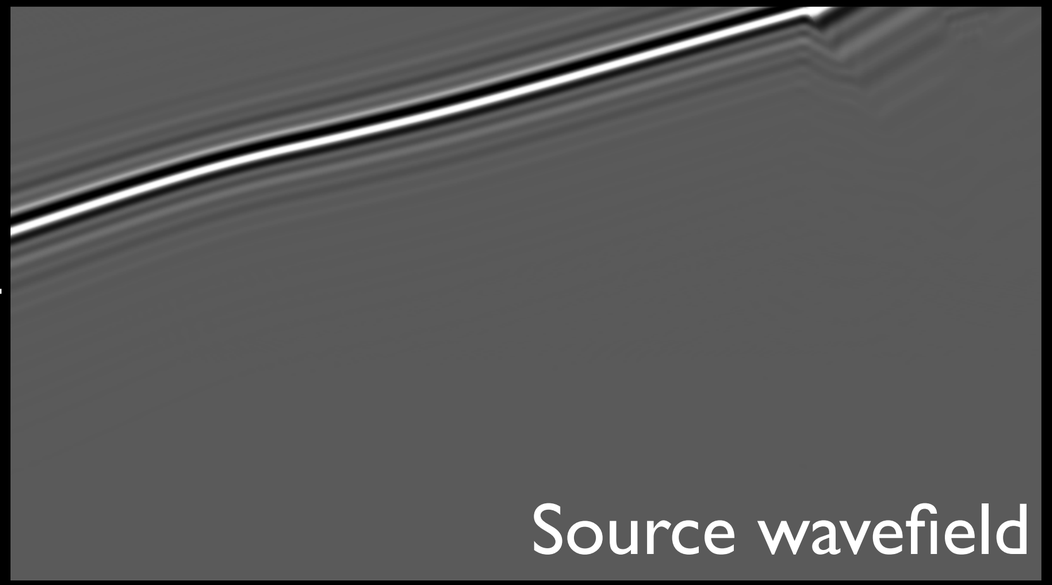


Born plane-wave modeling

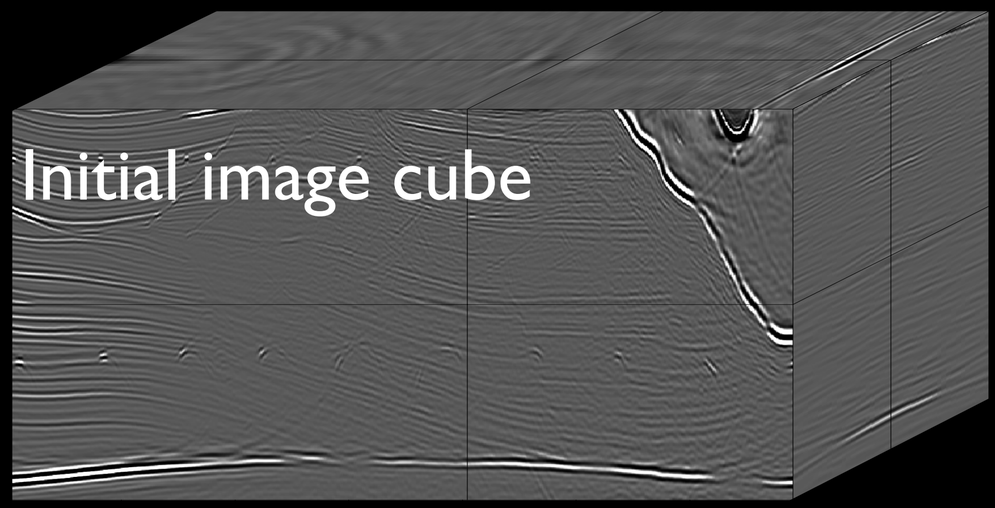
Position

Position

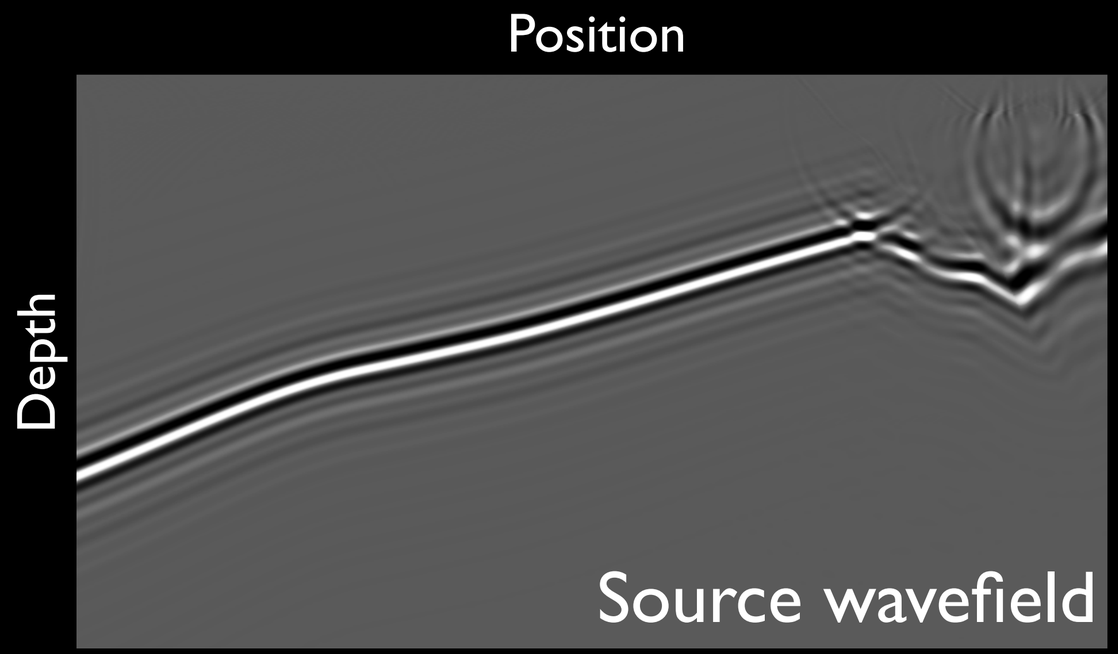
Depth

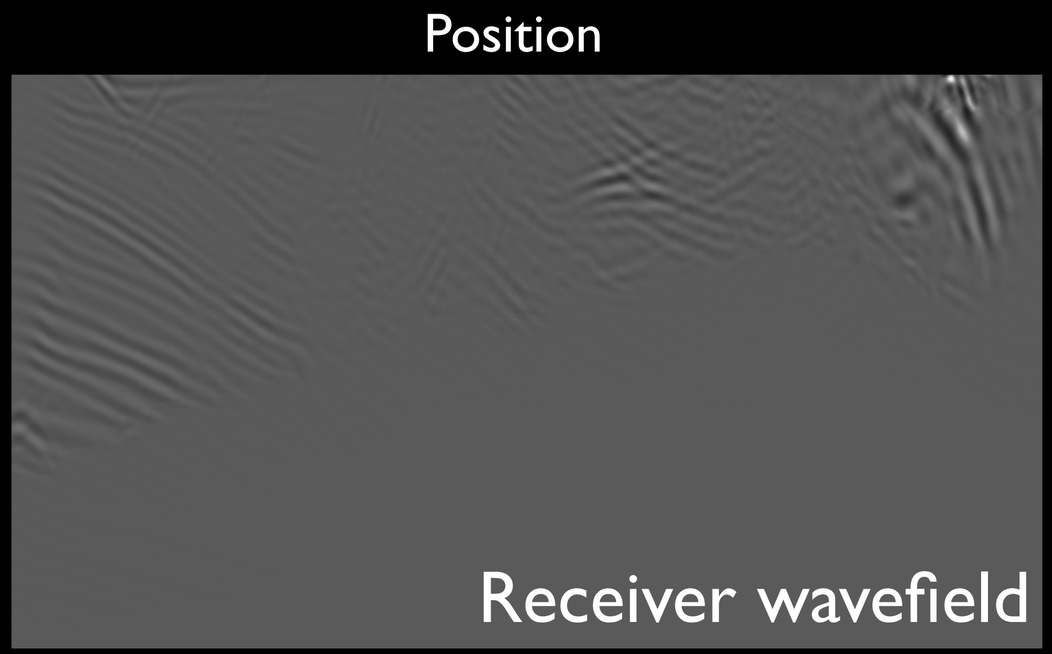


t = 1.0 s

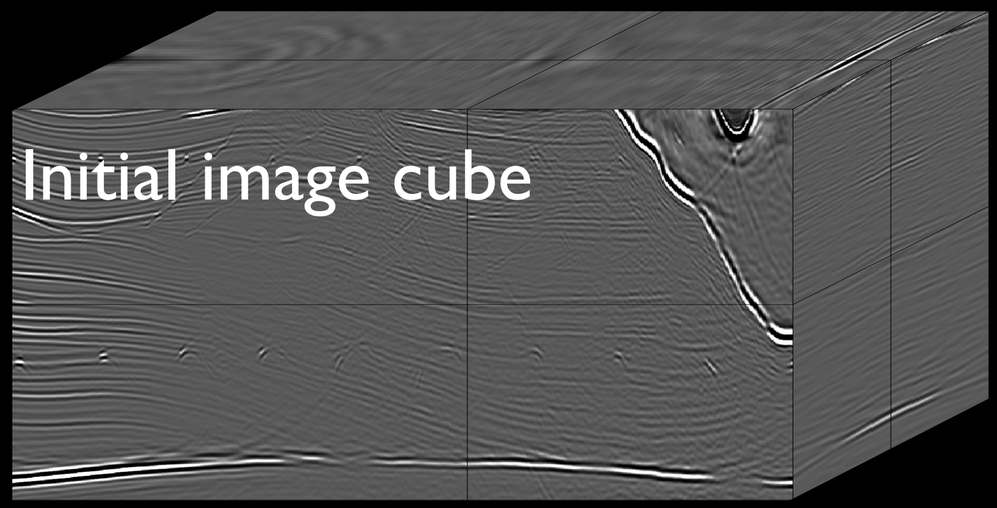


Born plane-wave modeling

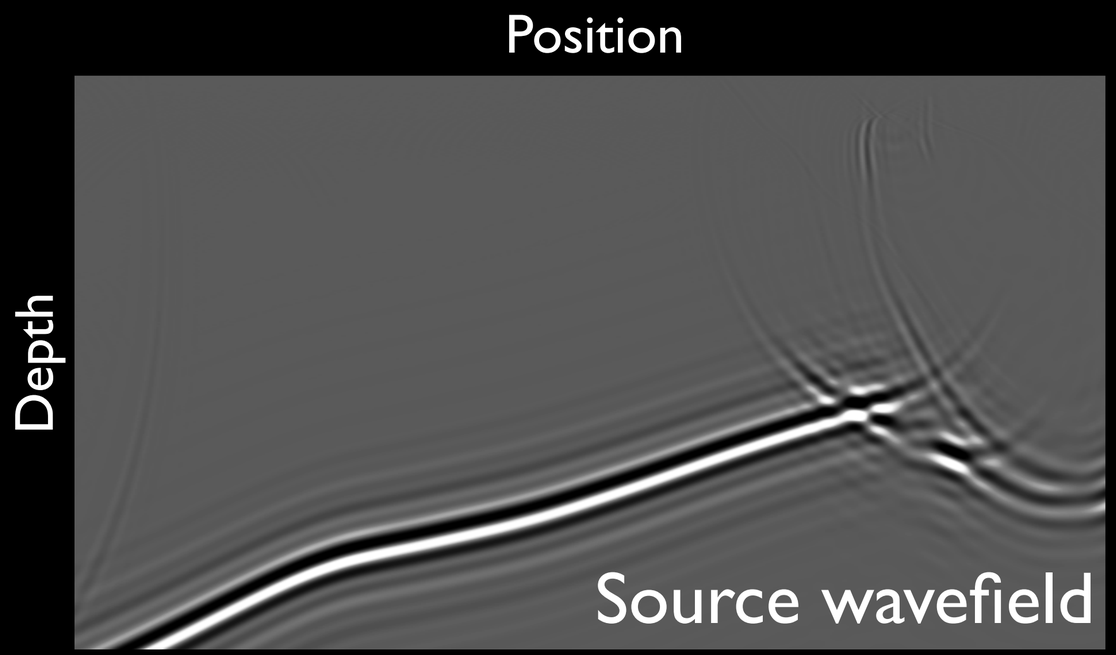


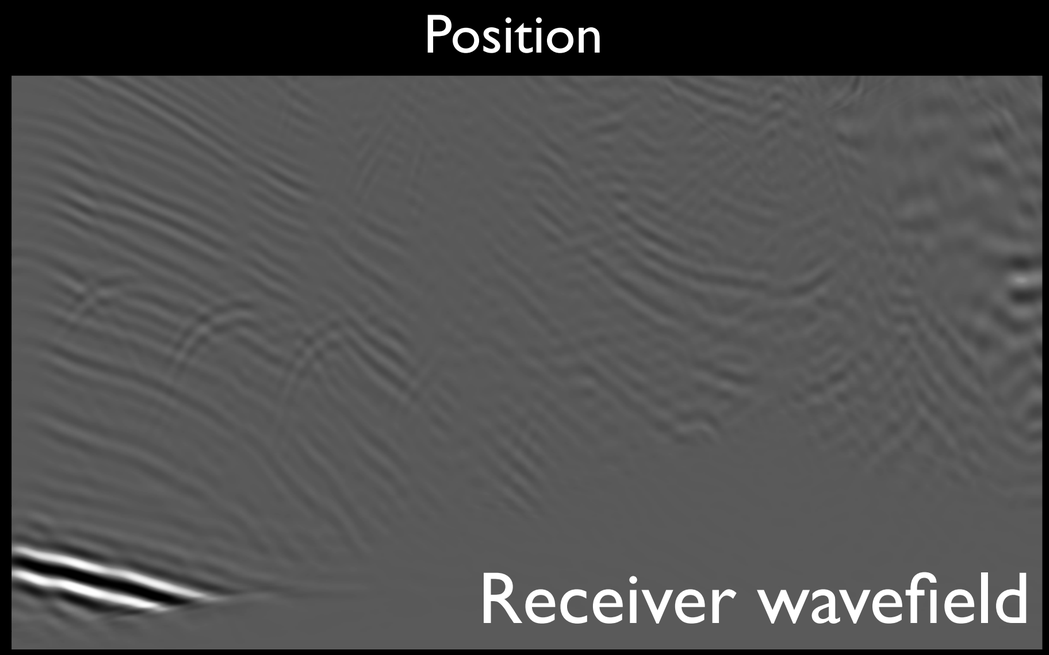


t = 1.5 s

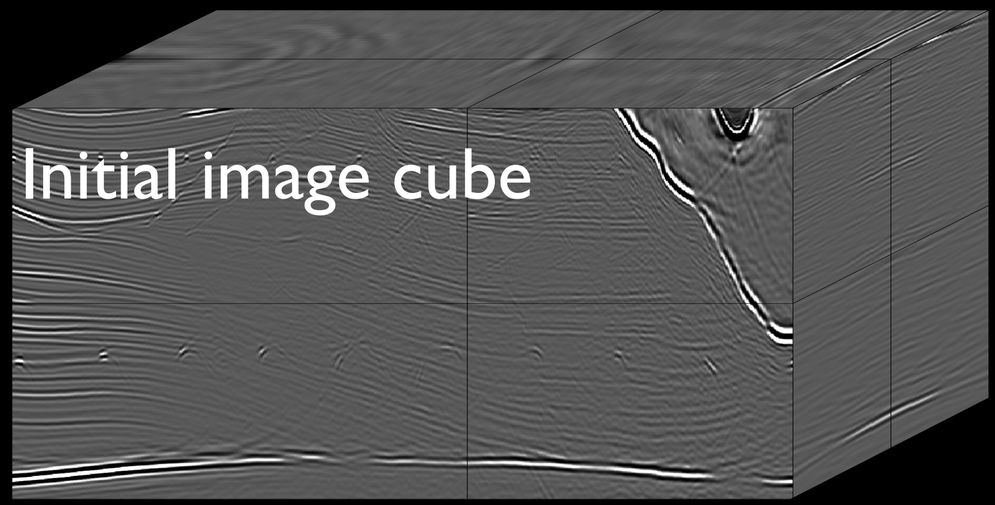


Born plane-wave modeling

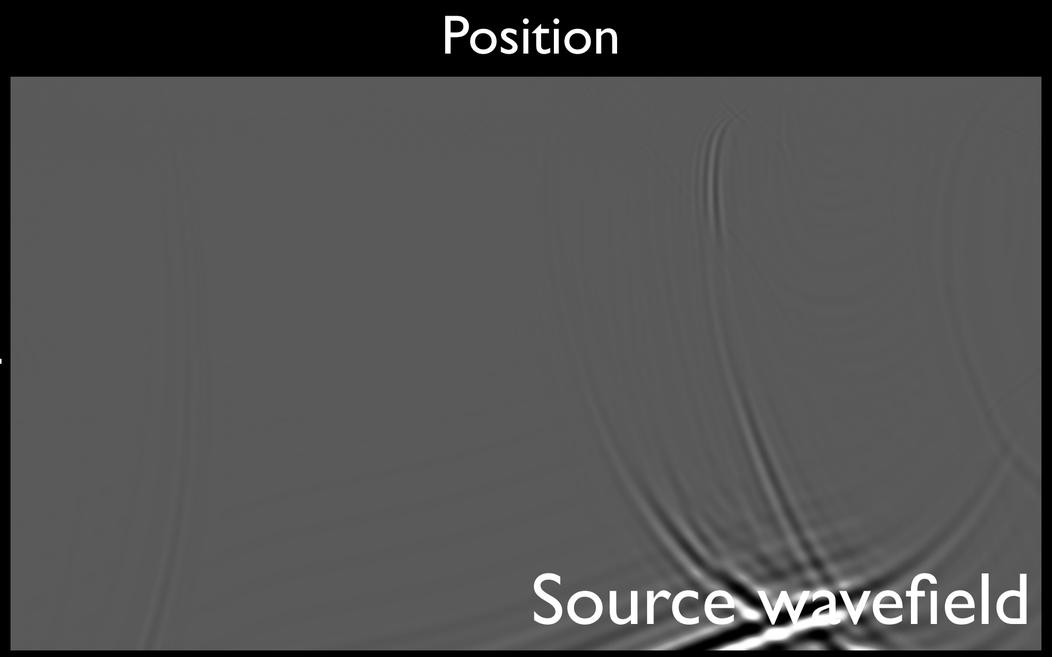


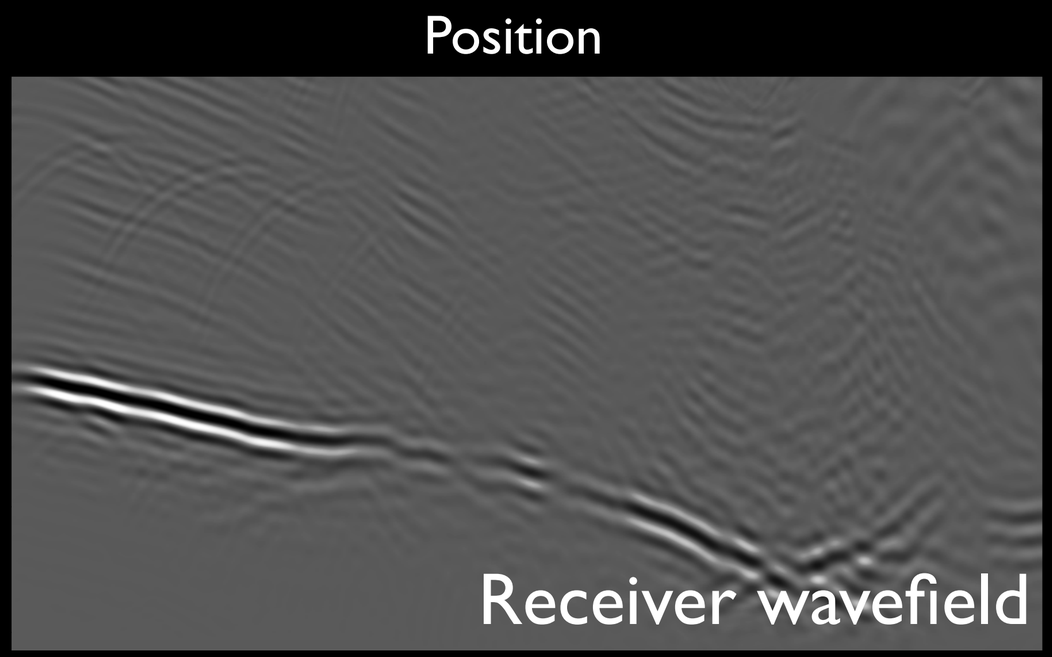


t = 2.0 s

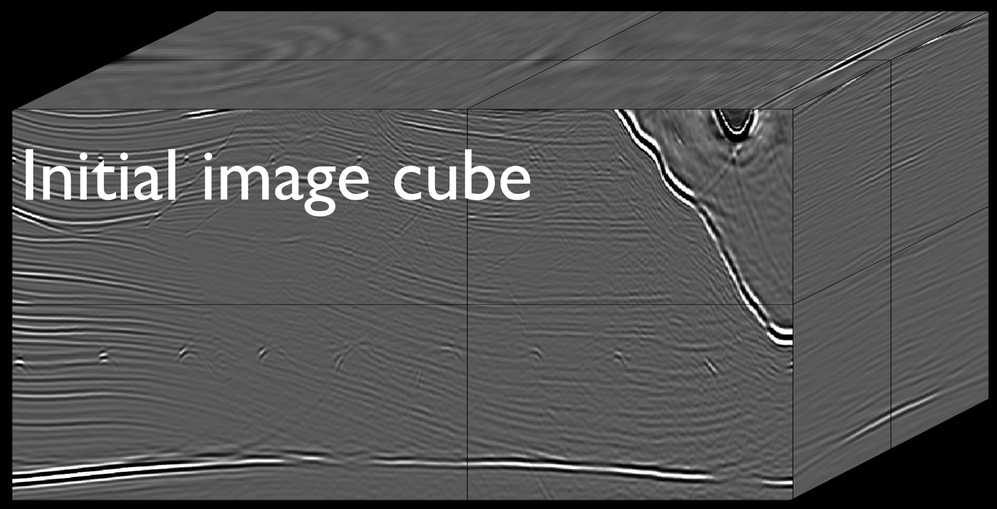


Born plane-wave modeling

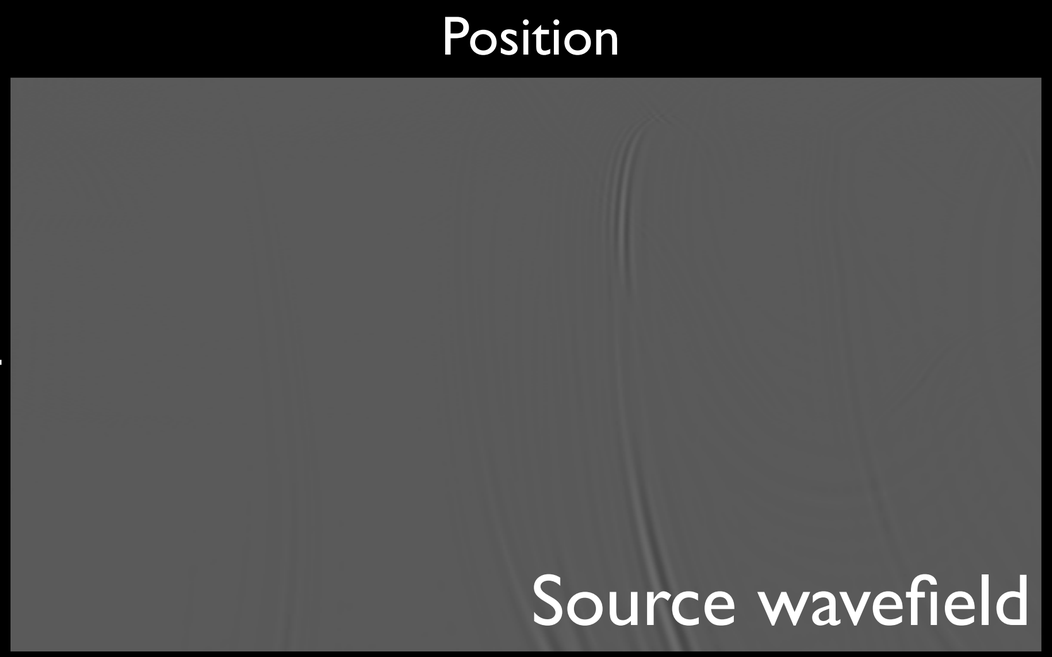


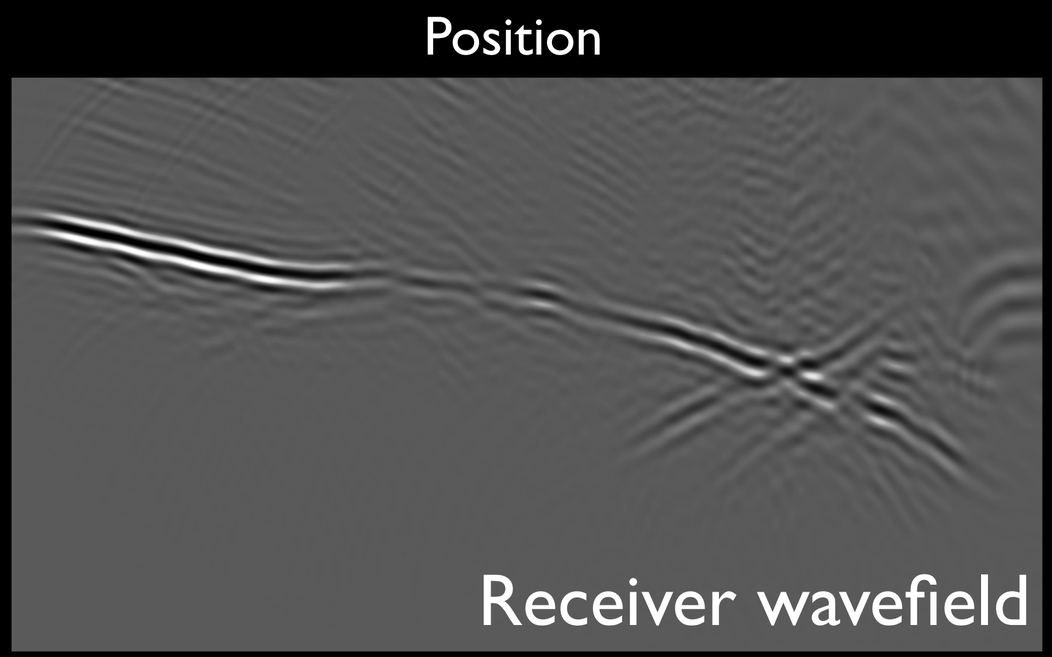


t = 2.5 s

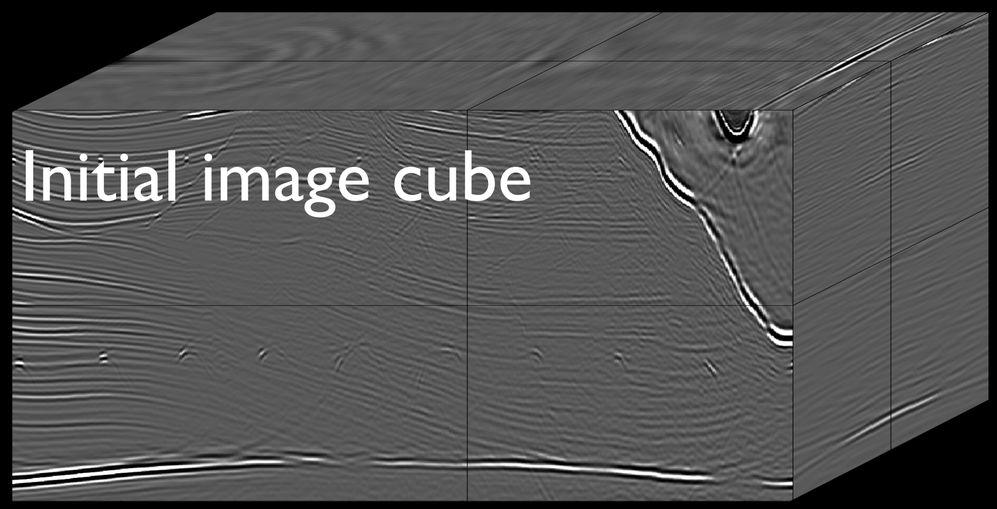


Born plane-wave modeling





t = 3.0 s



Born plane-wave modeling

Position

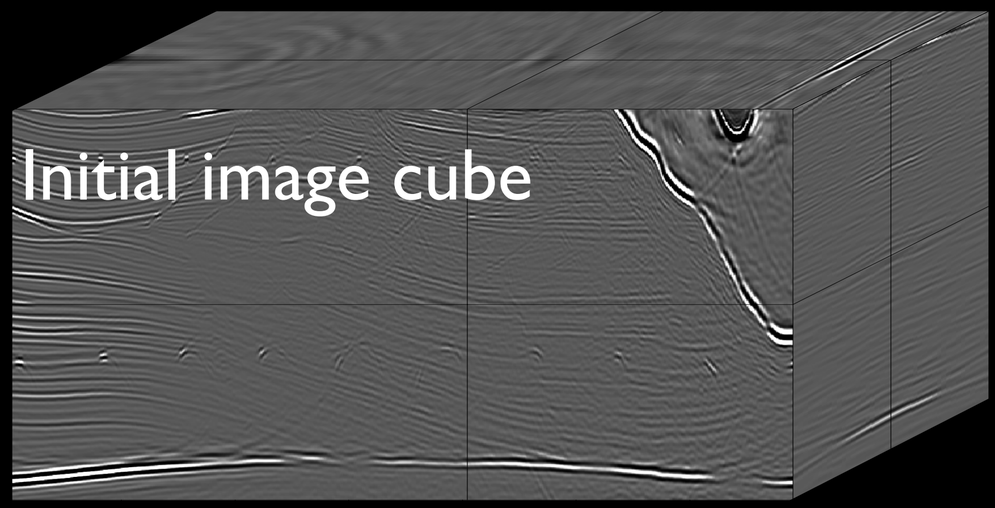
Position

Depth

Source wavefield

Receiver wavefield

t = 3.5 s



Born plane-wave modeling

Position

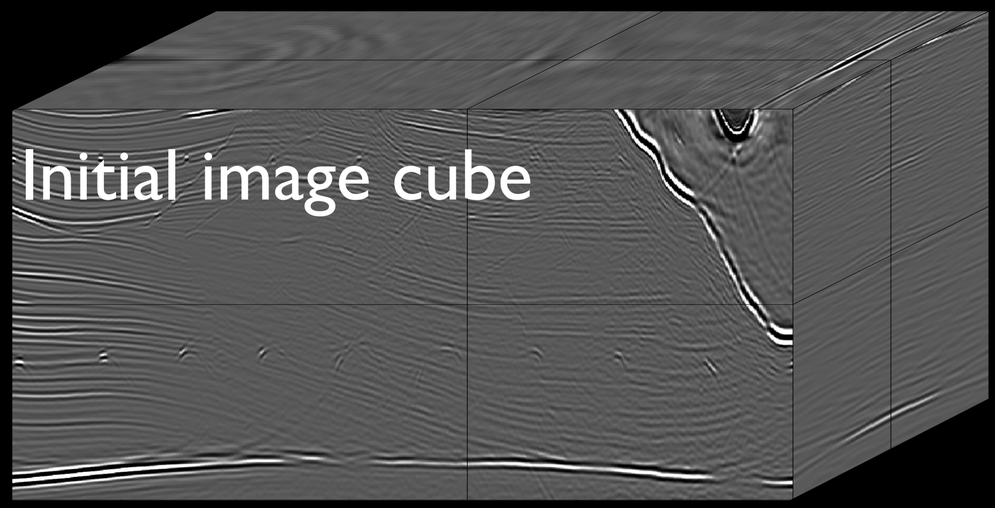
Position

Depth

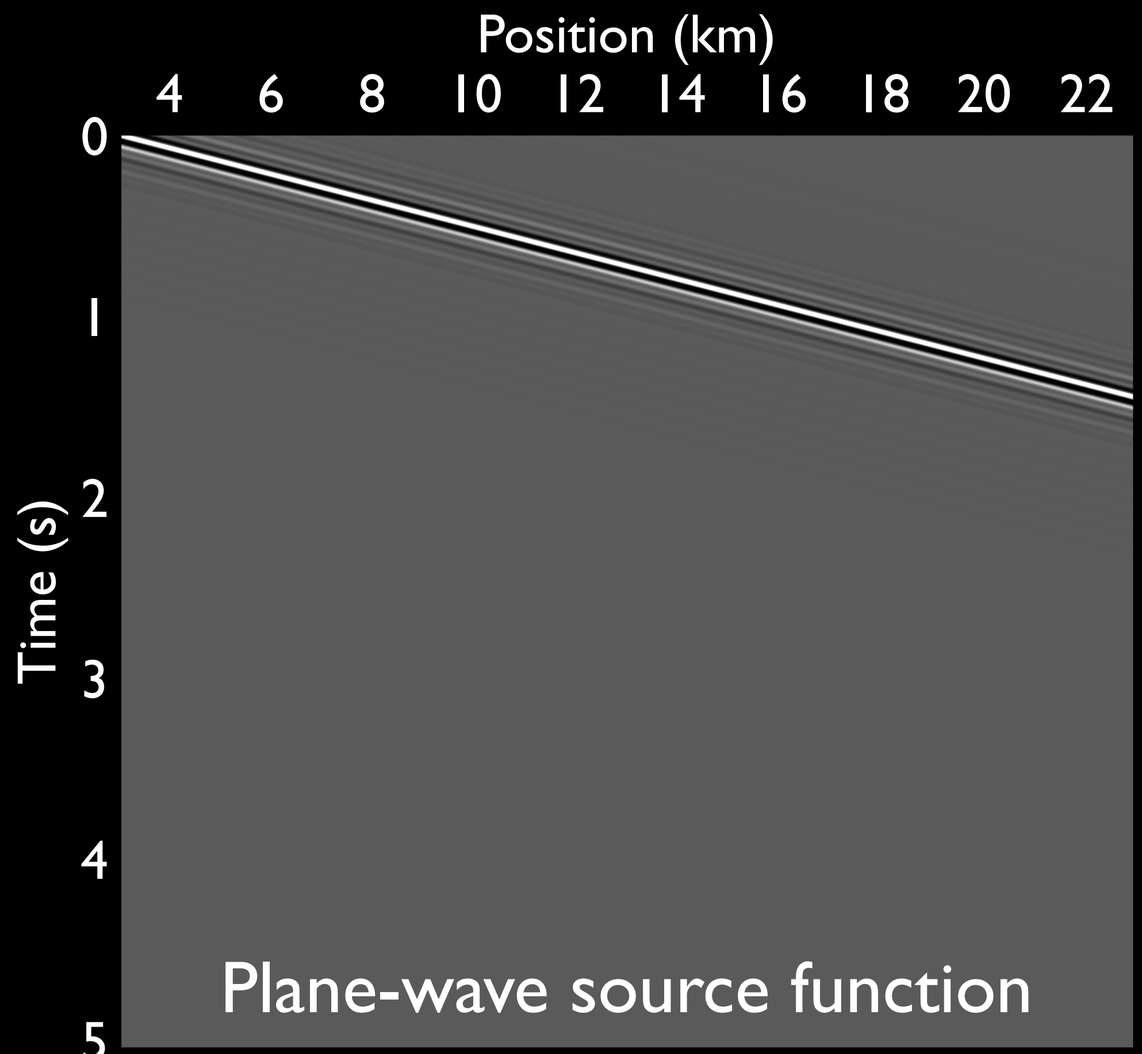
Source wavefield

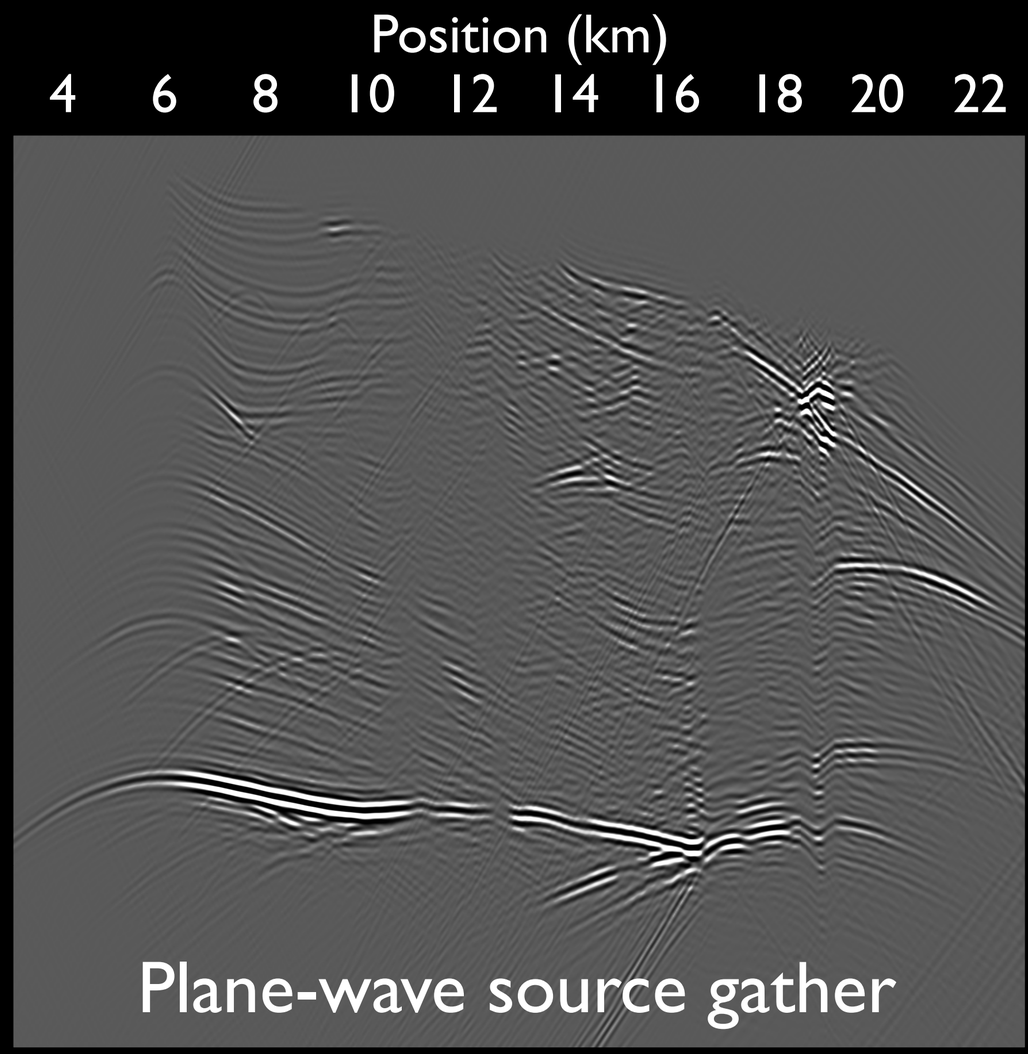
Receiver wavefield

t = 4.0 s



Synthesized data



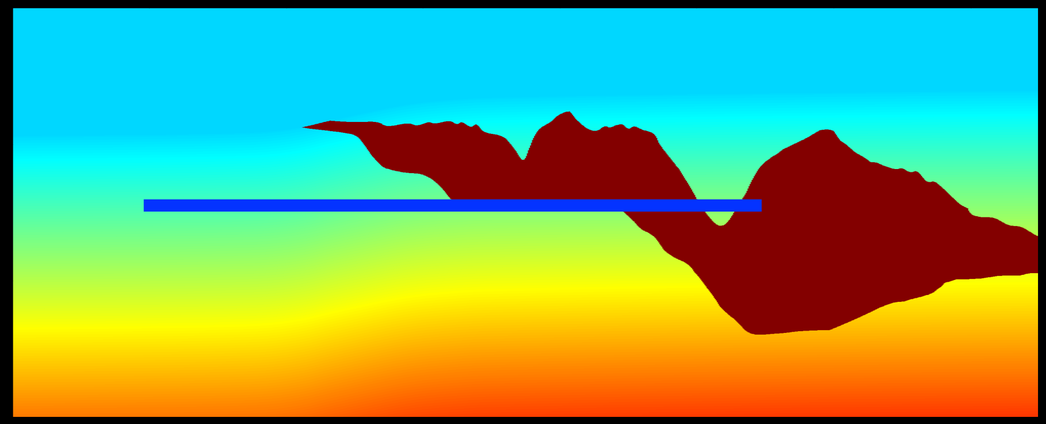


New data vs. original data

New acquisition geometry:

41 plane-wave source gathers
at depth level 4.6 km

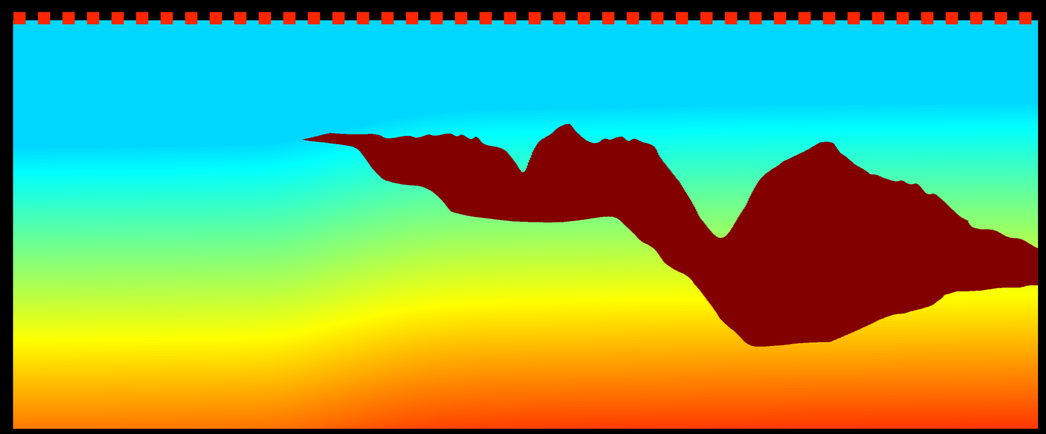
From -45° to 45°



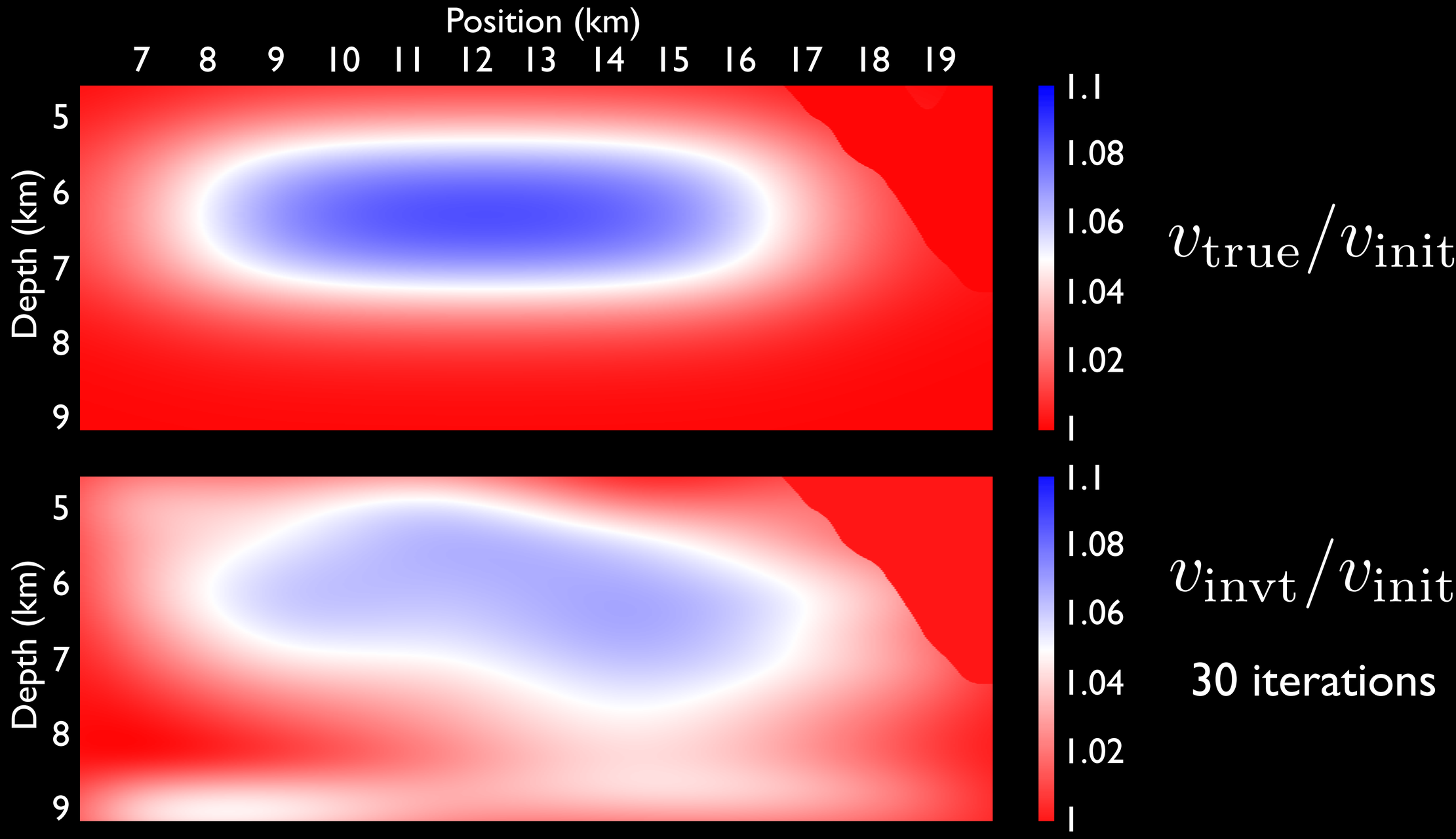
~48X faster!

Original acquisition geometry:

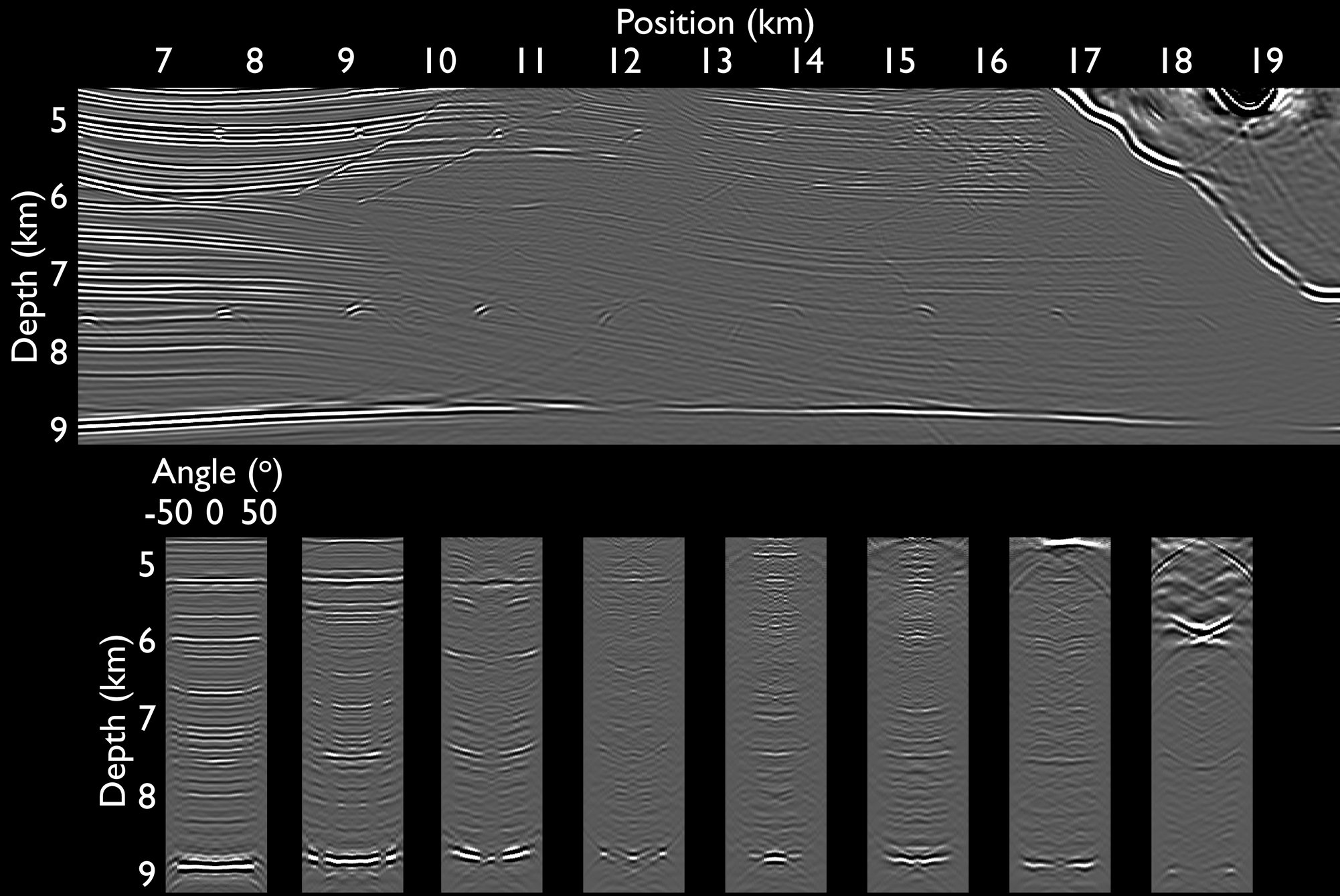
500 point-source gathers
recorded at the surface



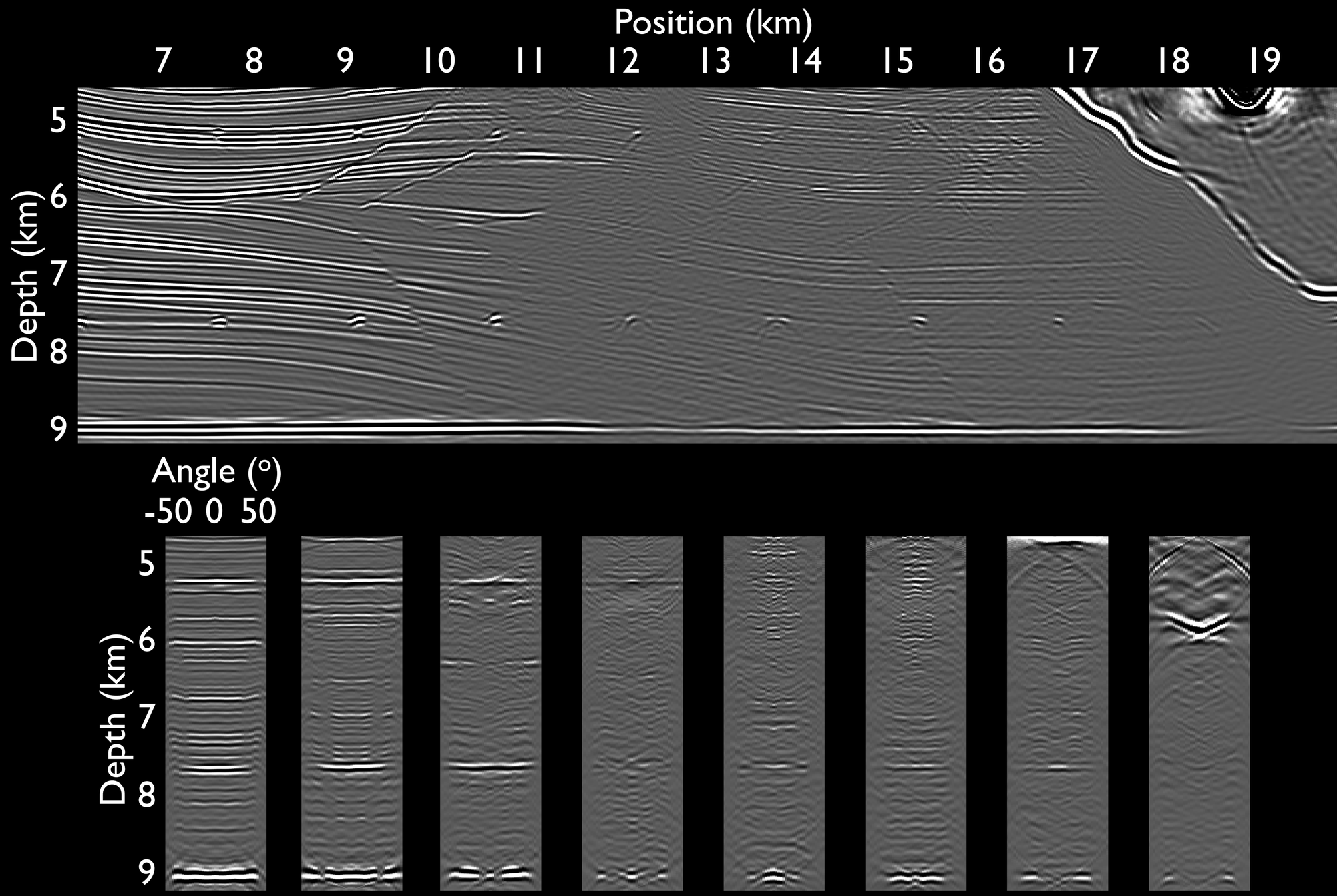
Velocity ratios



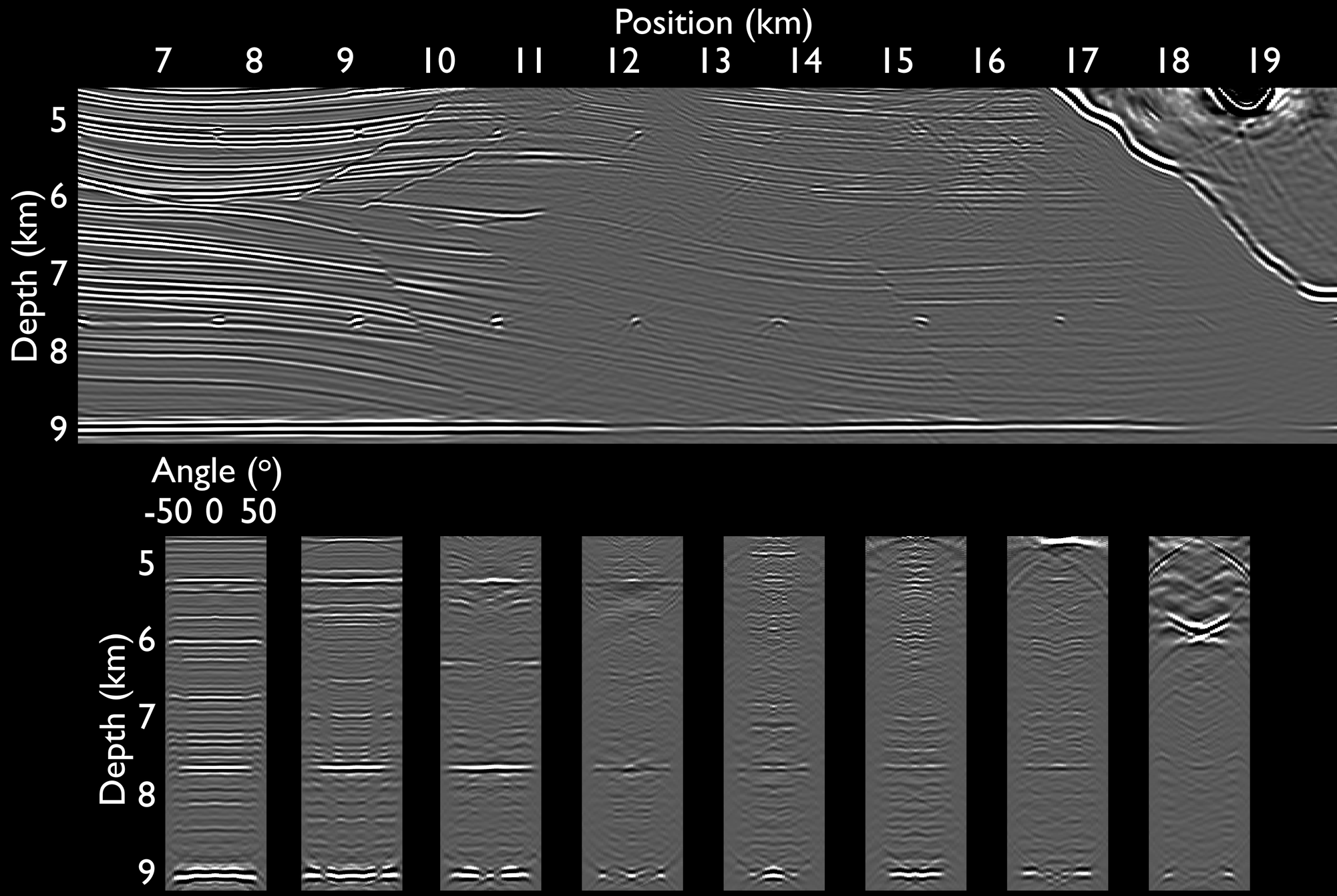
Migration of the original data (initial velocity)



Migration of the original data (updated velocity)



Migration of the original data (true velocity)

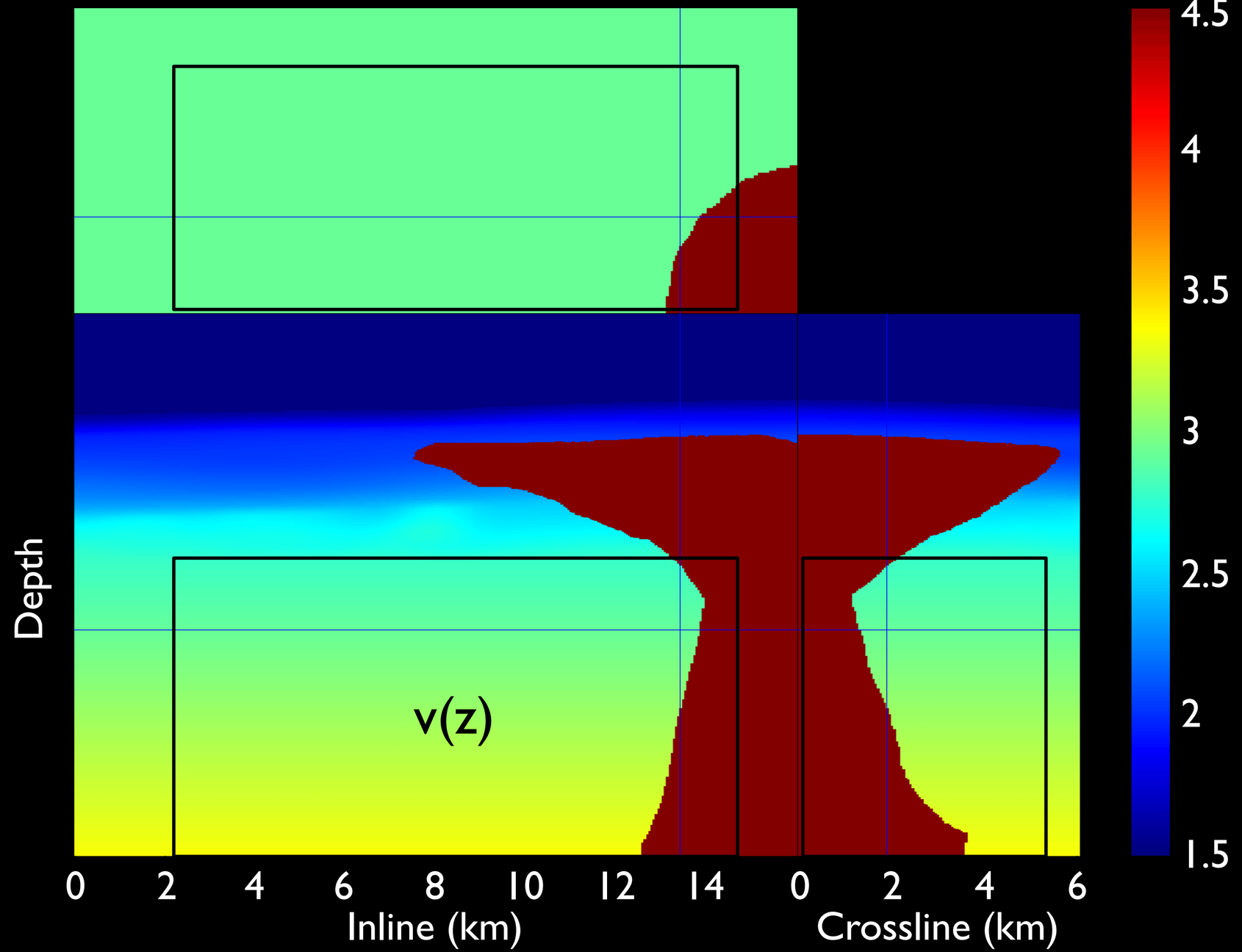


3-D Gulf of Mexico field-data example

- **Narrow azimuth acquisition**
- **Dimensions: 20 km X 6 km**
- **Maximum offset: 8.2 km**
- **Number of shots: 100125**
- **Maximum frequency used for imaging: 20 Hz**
- **280 CPUs from CEES**

  CEES: Stanford Center for Earth & Environmental Science

Initial velocity model



Subsalt velocity analysis

- **Step 1: Generate initial image cubes**
  - Conical wave migration (~2 weeks)
  - Conical-wave-domain Hessian (~1 week)
  - Both inline & crossline subsurface offsets

- **Step 2: 3-D Born wavefield modeling**
  - 315 plane-wave source gathers (21 inline & 15 crossline)
  - Maximum frequency for modeling is 18 Hz

- **Step 3: DSO velocity analysis**
  - Only inline subsurface offsets are used
  - Approximately 2 hours per iteration (40 iterations)

Subsalt velocity analysis

- **Step 1: Generate initial image cubes**
  - Conical wave migration (~2 weeks)
  - Conical-wave-domain Hessian (~1 week)
  - Both inline & crossline subsurface offsets

- **Step 2: 3-D Born wavefield modeling**
  - 315 plane-wave source gathers (21 inline & 15 crossline)
  - Maximum frequency for modeling is 18 Hz

- **Step 3: DSO velocity analysis**
  - Only inline subsurface offsets are used
  - Approximately 2 hours per iteration (40 iterations)

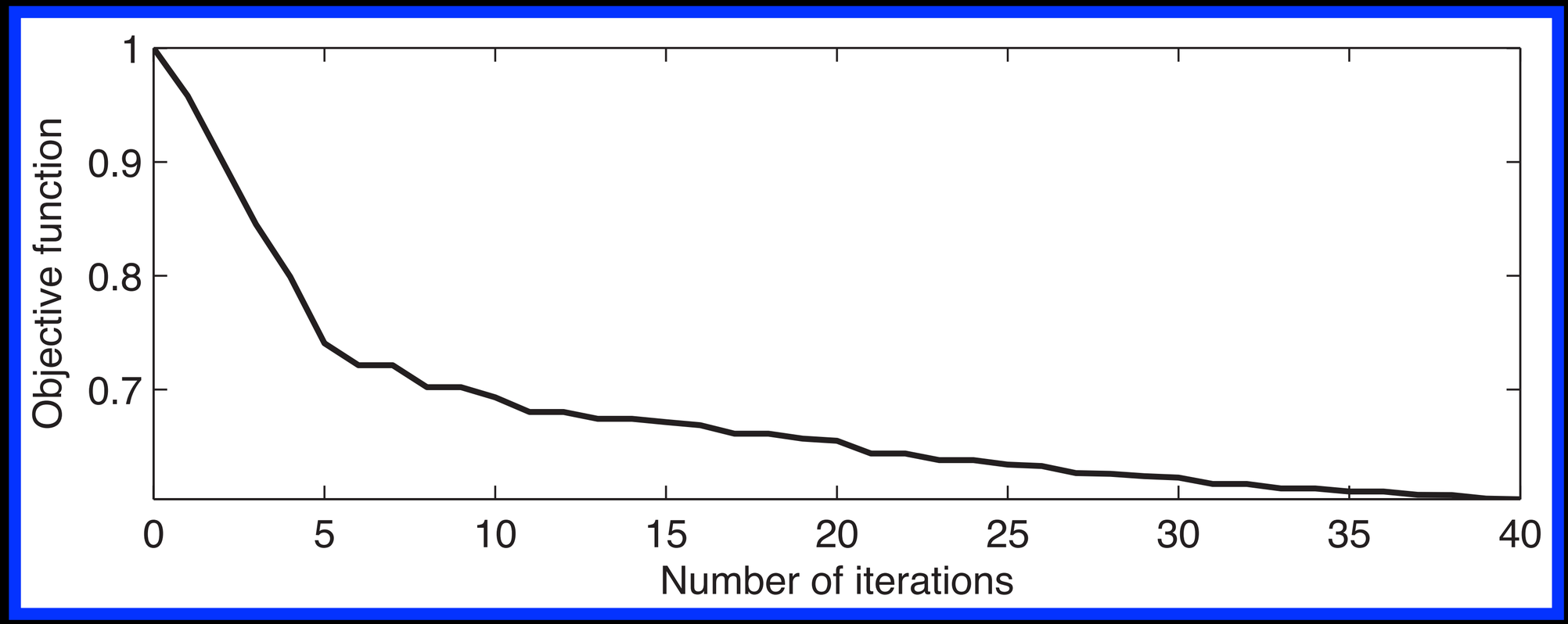
Subsalt velocity analysis

- **Step 1: Generate initial image cubes**
  - Conical wave migration (~2 weeks)
  - Conical-wave-domain Hessian (~1 week)
  - Both inline & crossline subsurface offsets

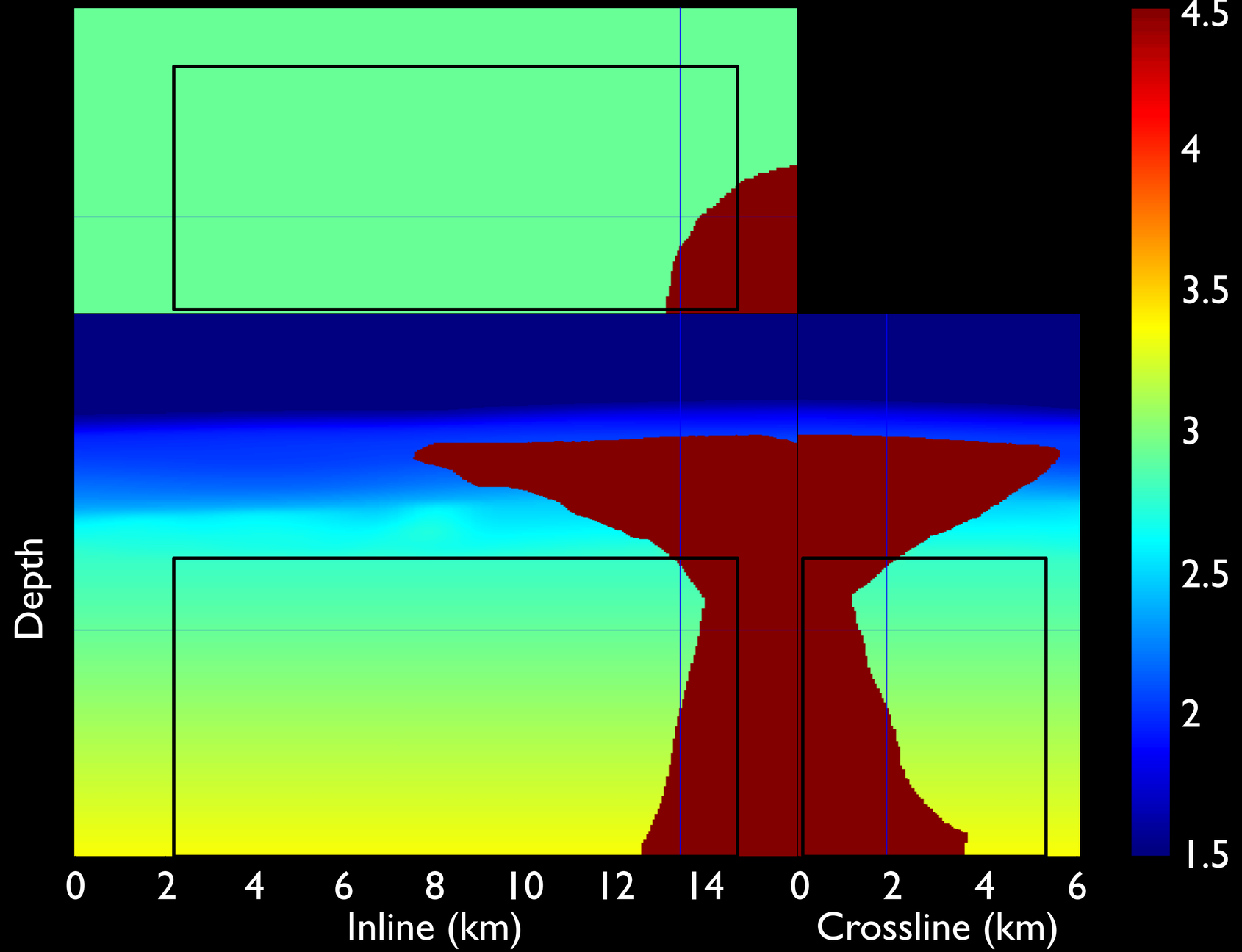
- **Step 2: 3-D Born wavefield modeling**
  - 315 plane-wave source gathers (21 inline & 15 crossline)
  - Maximum frequency for modeling is 18 Hz

- **Step 3: DSO velocity analysis**
  - Only inline subsurface offsets are used
  - Approximately 2 hours per iteration (40 iterations)

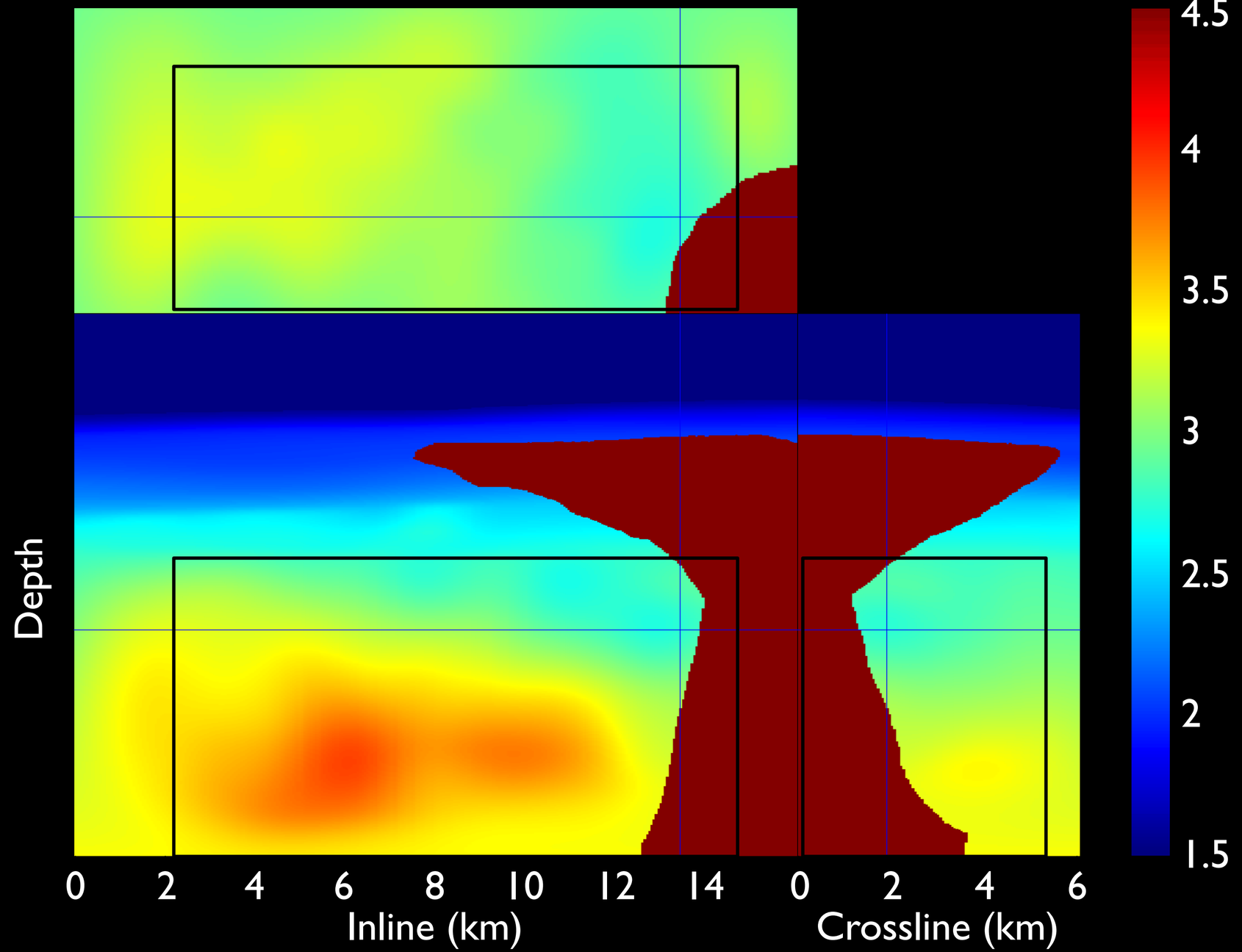
Evolution of the objective function



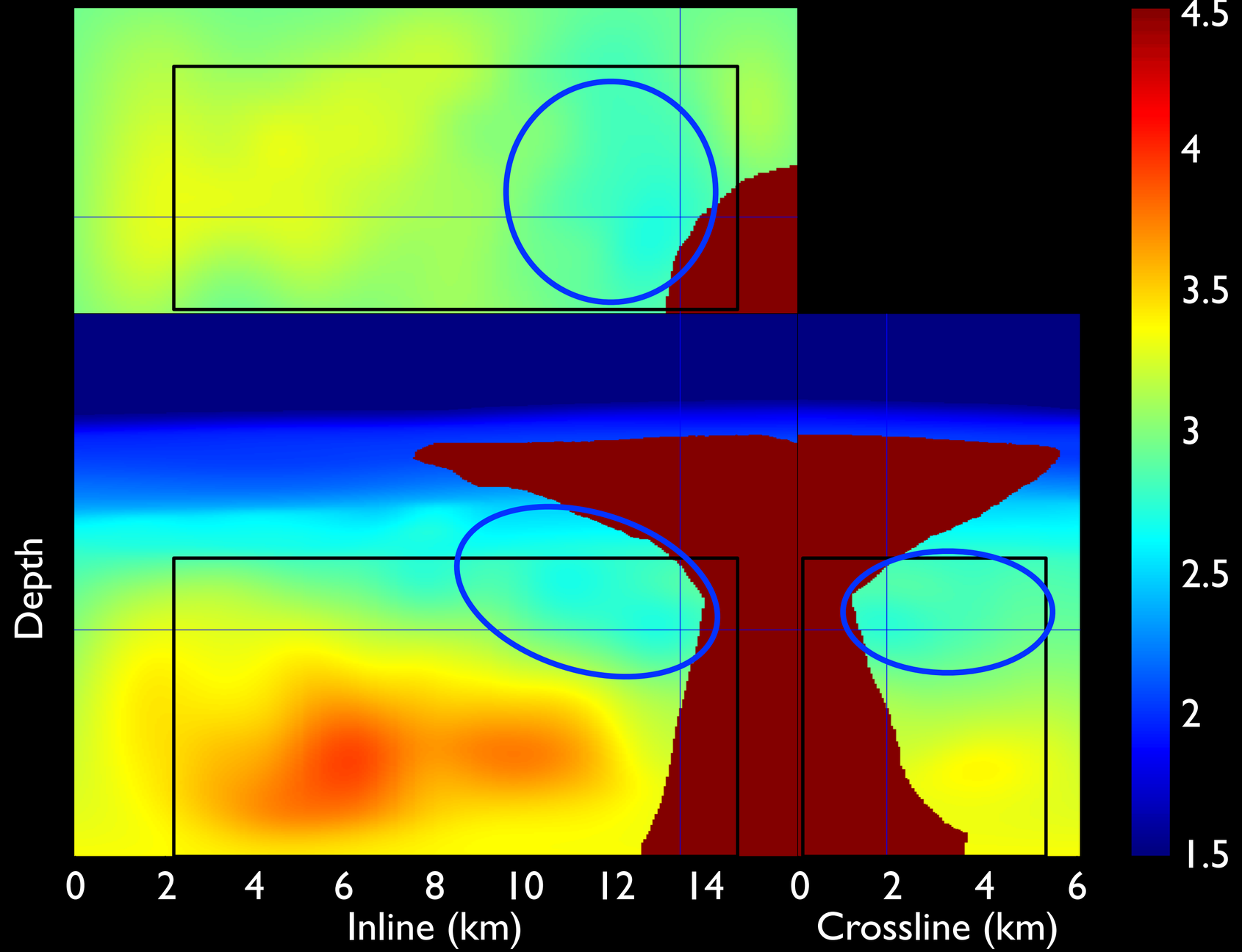
Initial velocity model



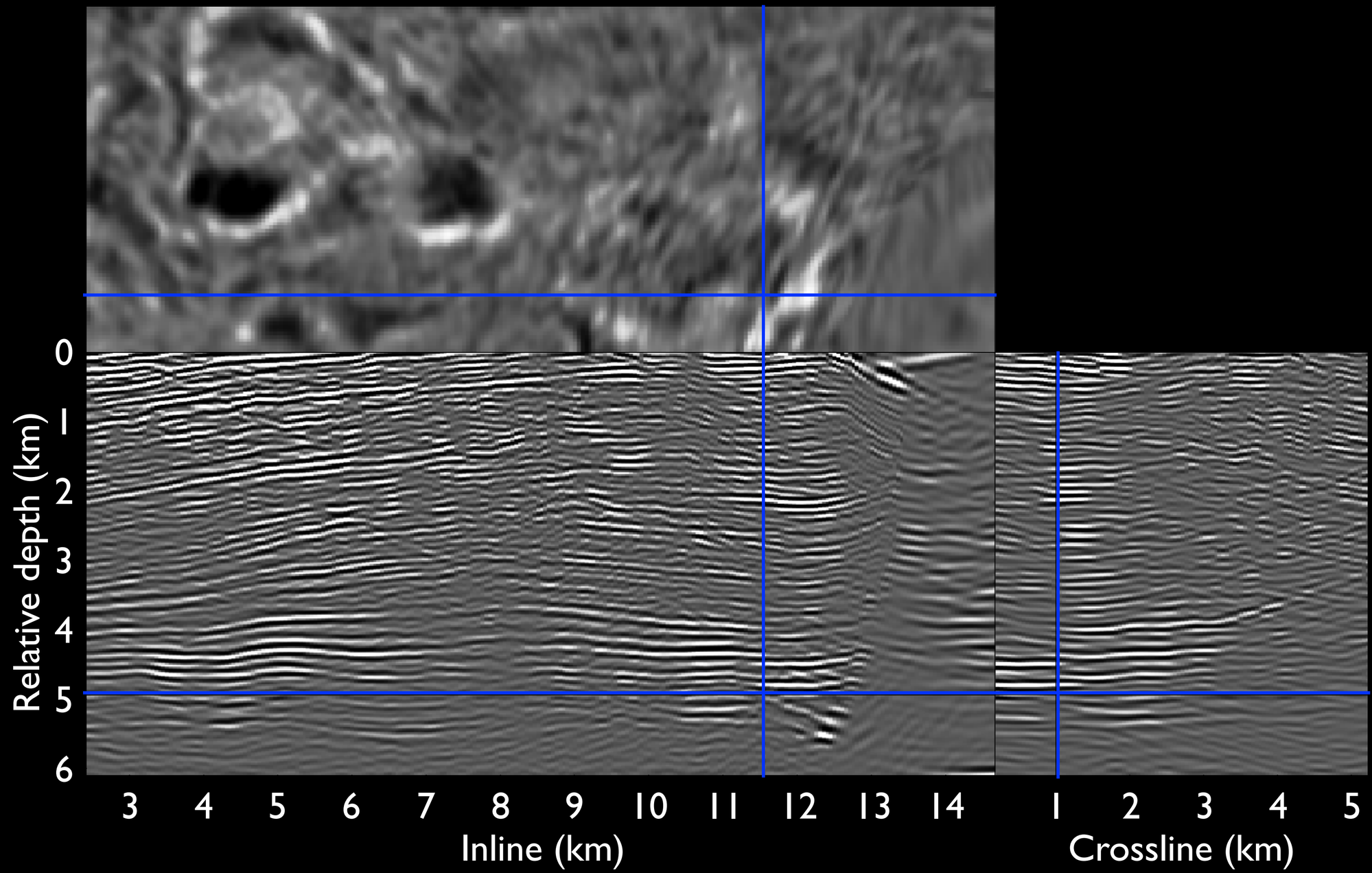
Updated velocity model



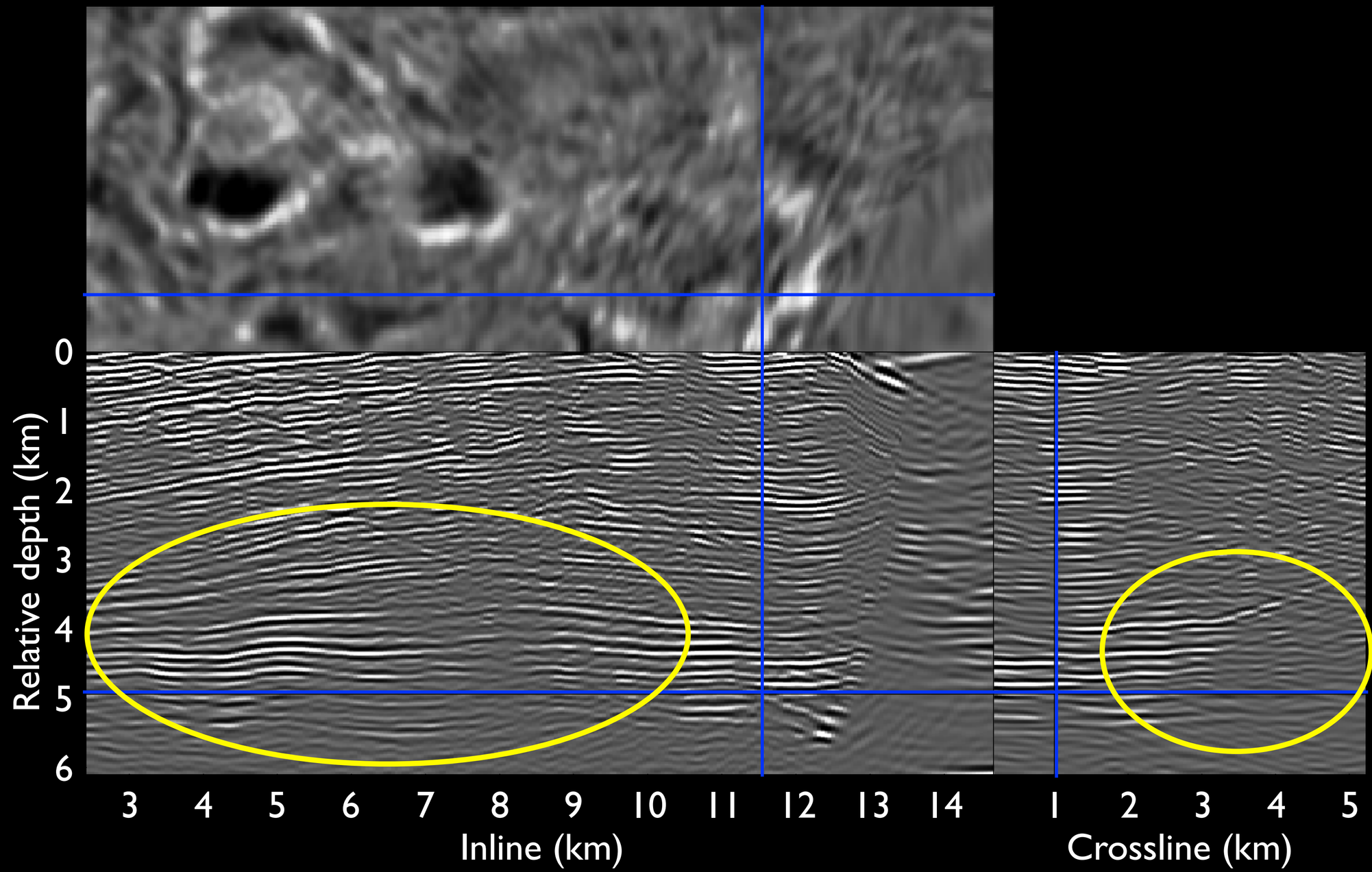
Updated velocity model



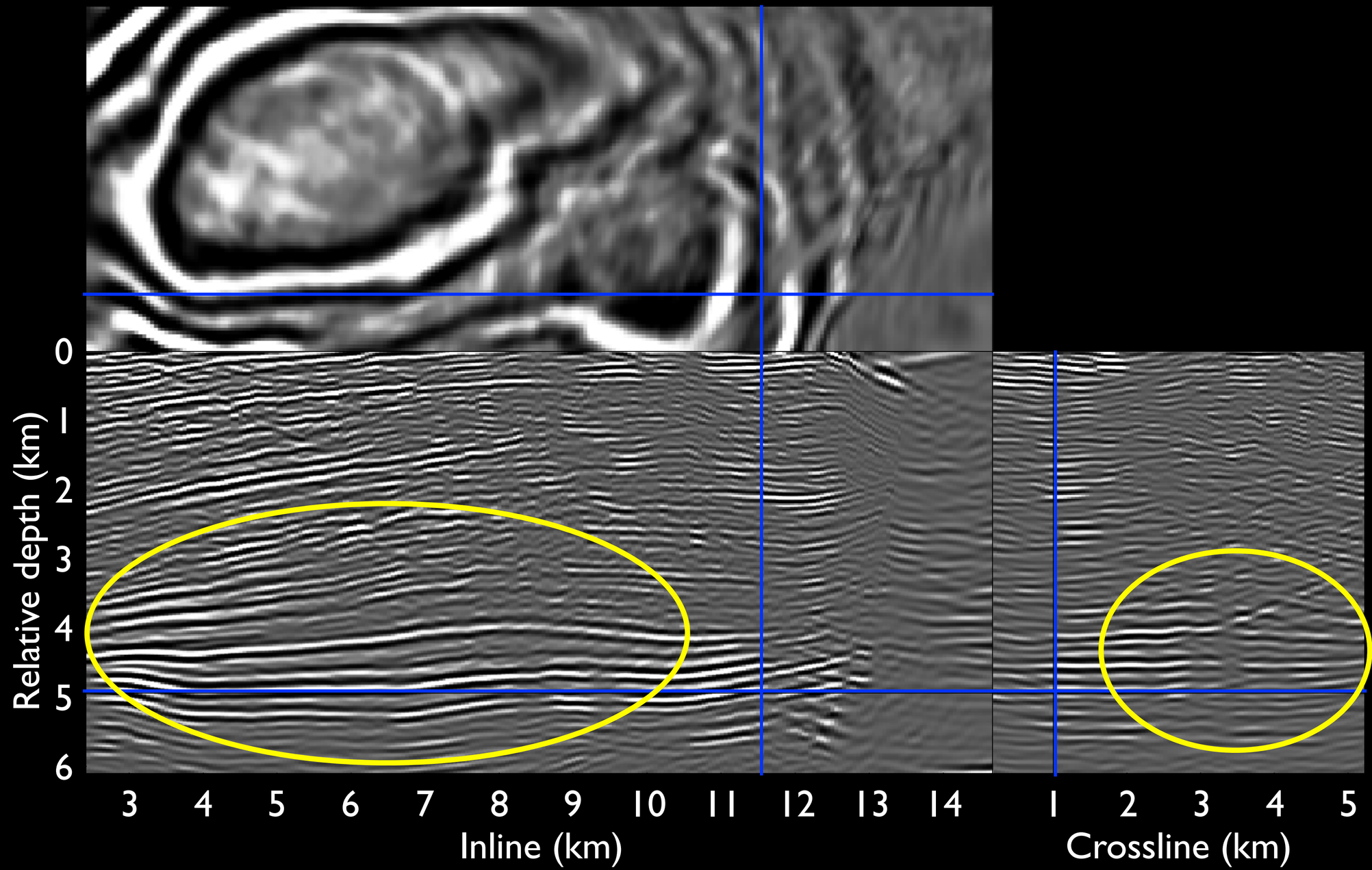
Migration of original data (initial velocity)



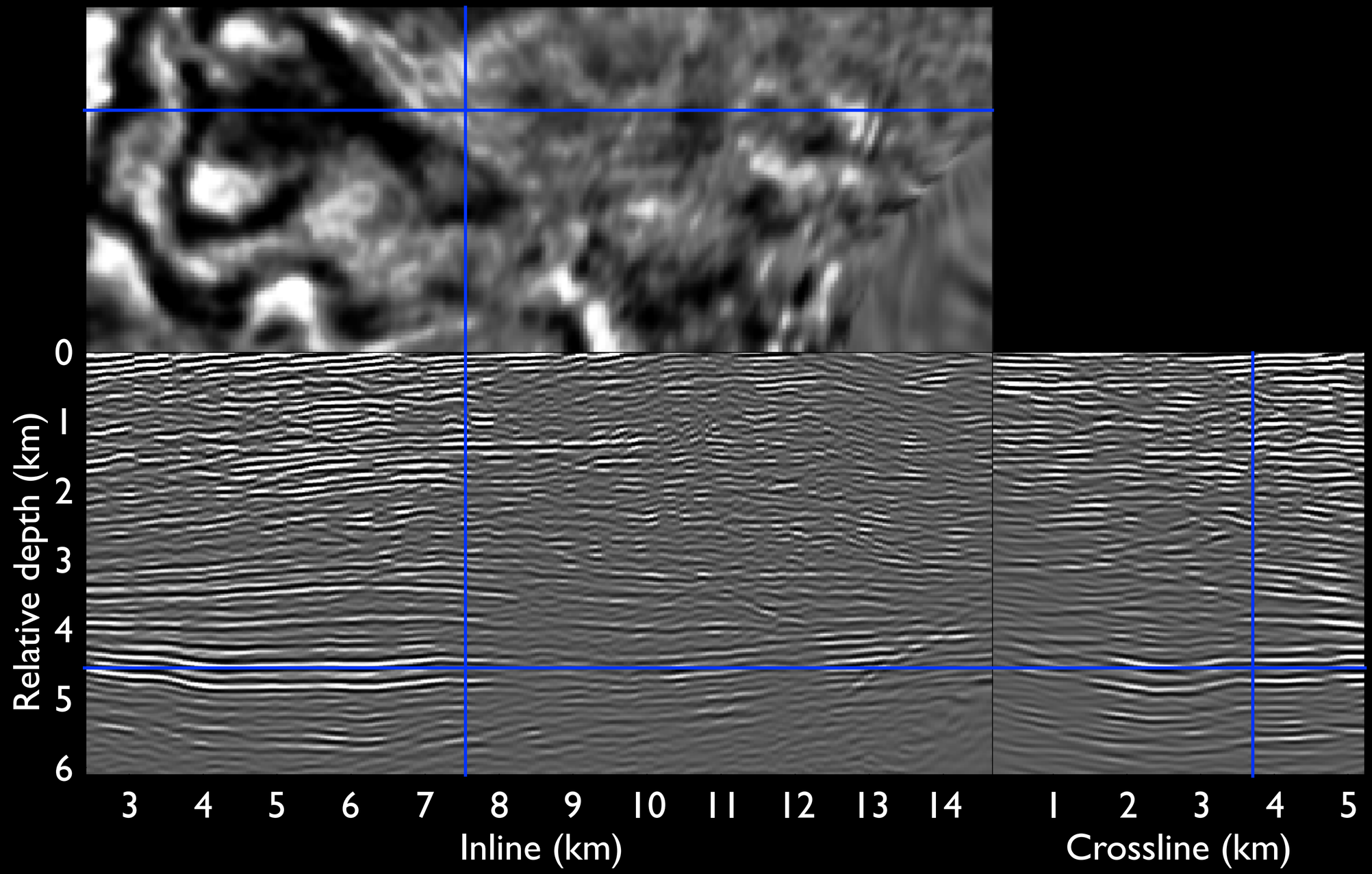
Migration of original data (initial velocity)



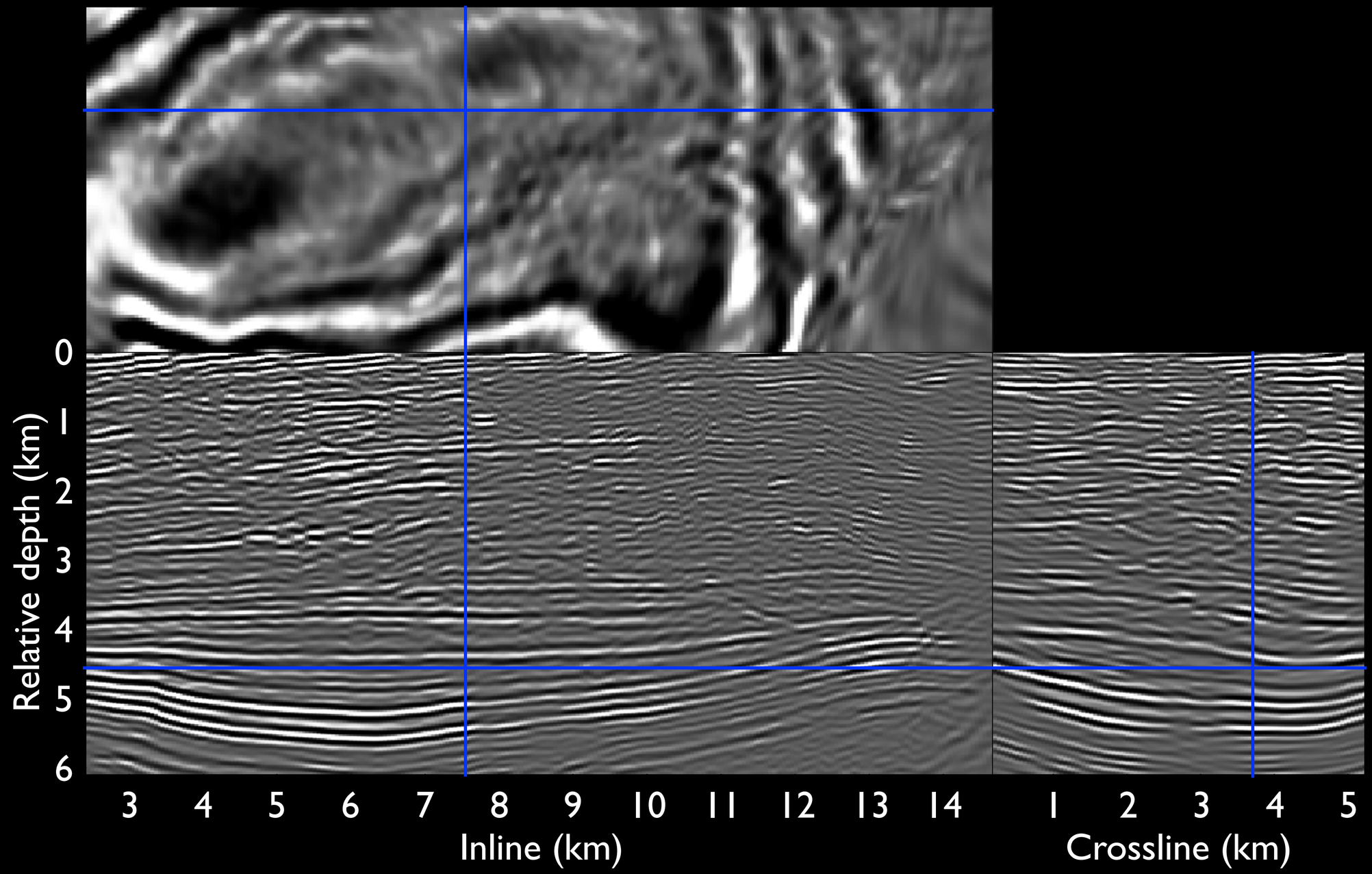
Migration of original data (updated velocity)



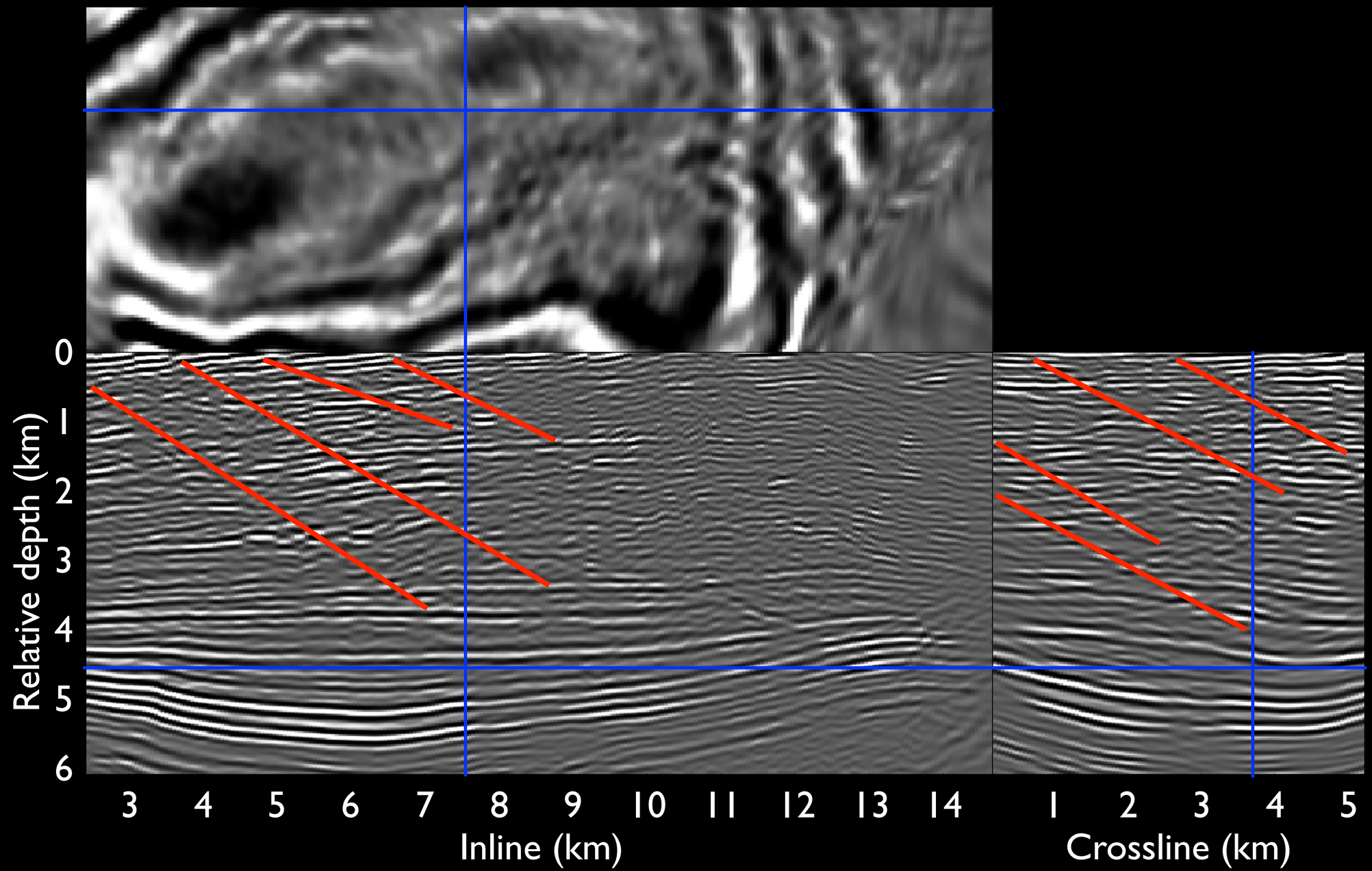
Migration of original data (initial velocity)



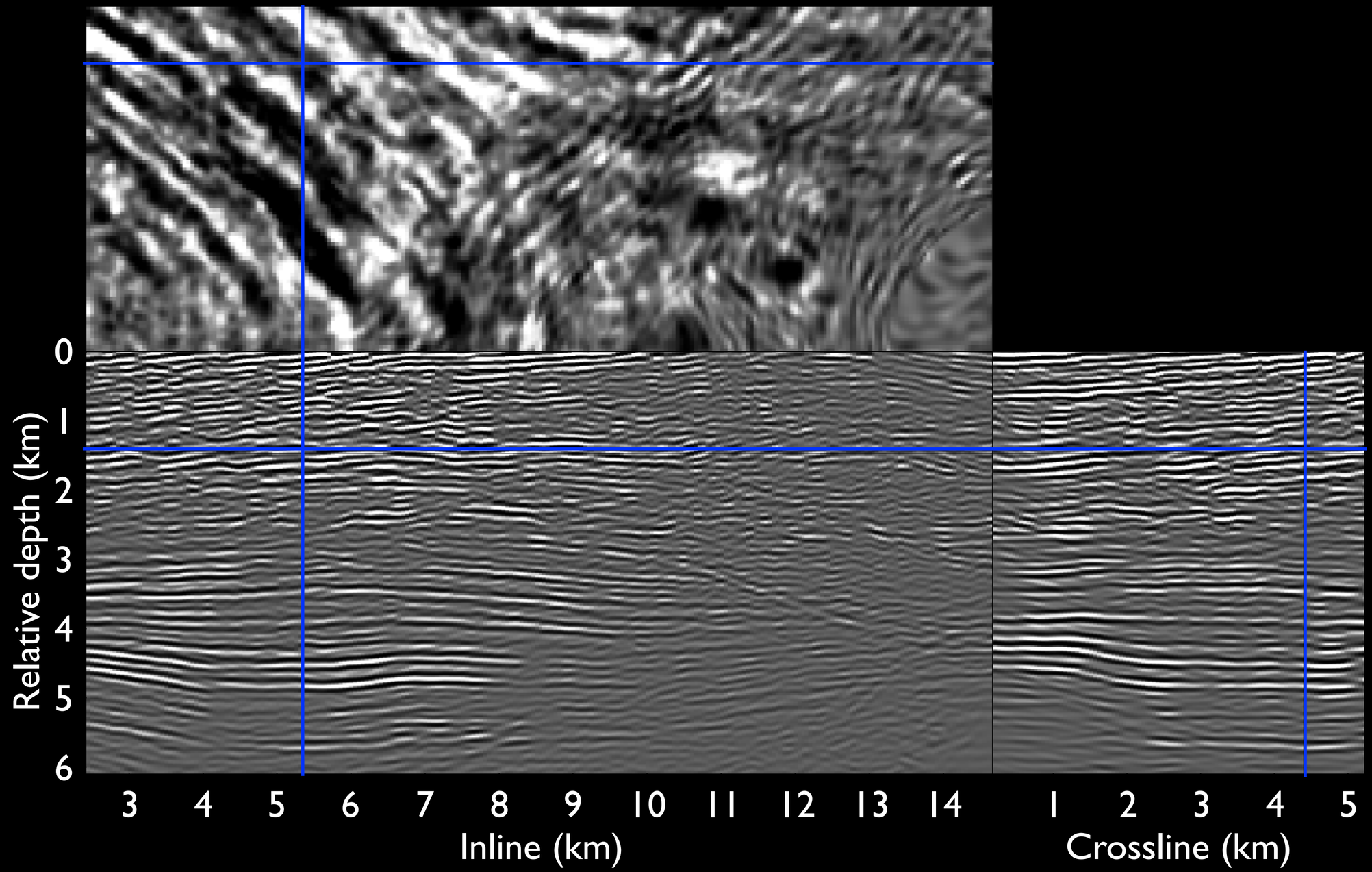
Migration of original data (updated velocity)



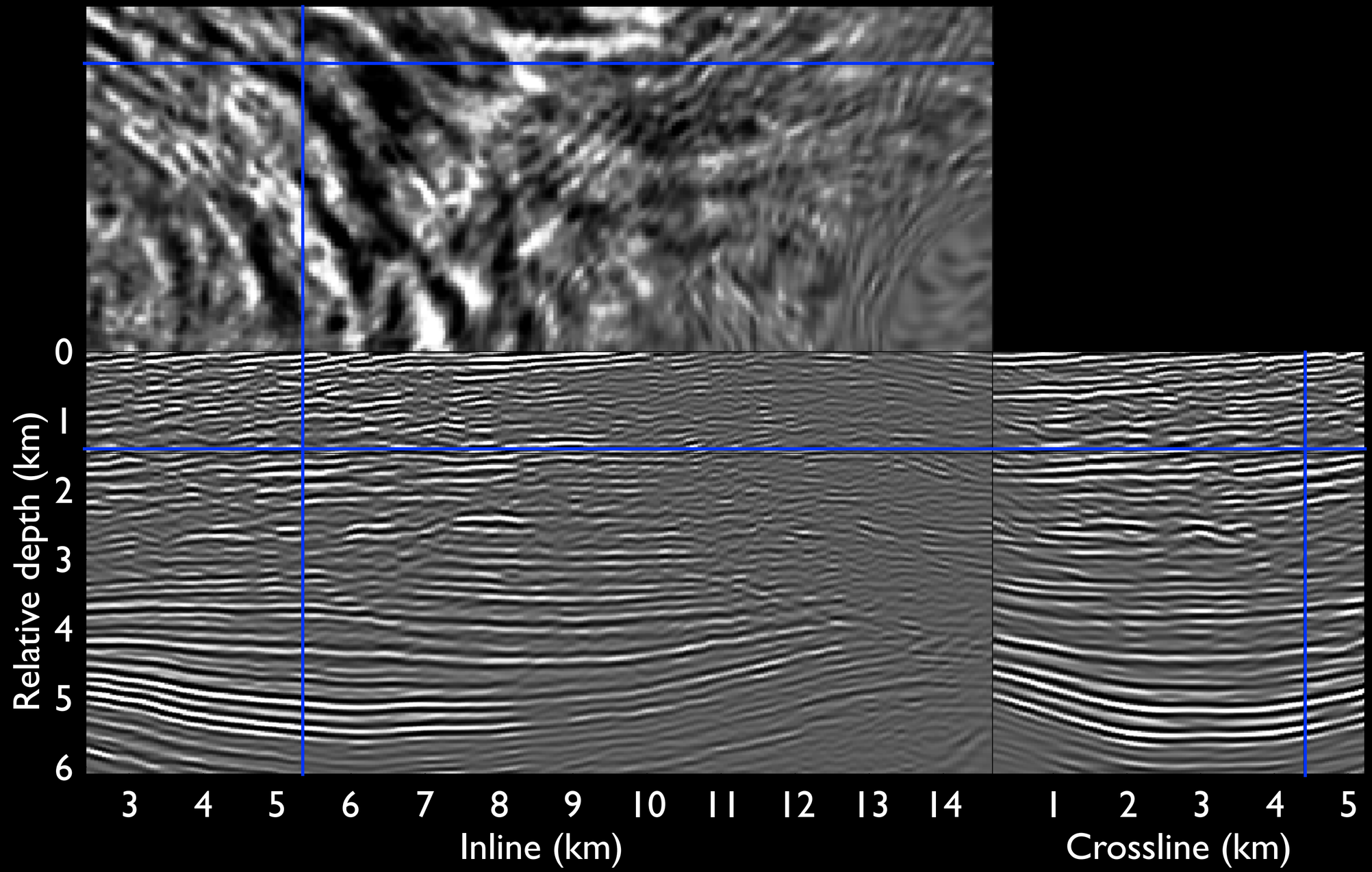
Migration of original data (updated velocity)



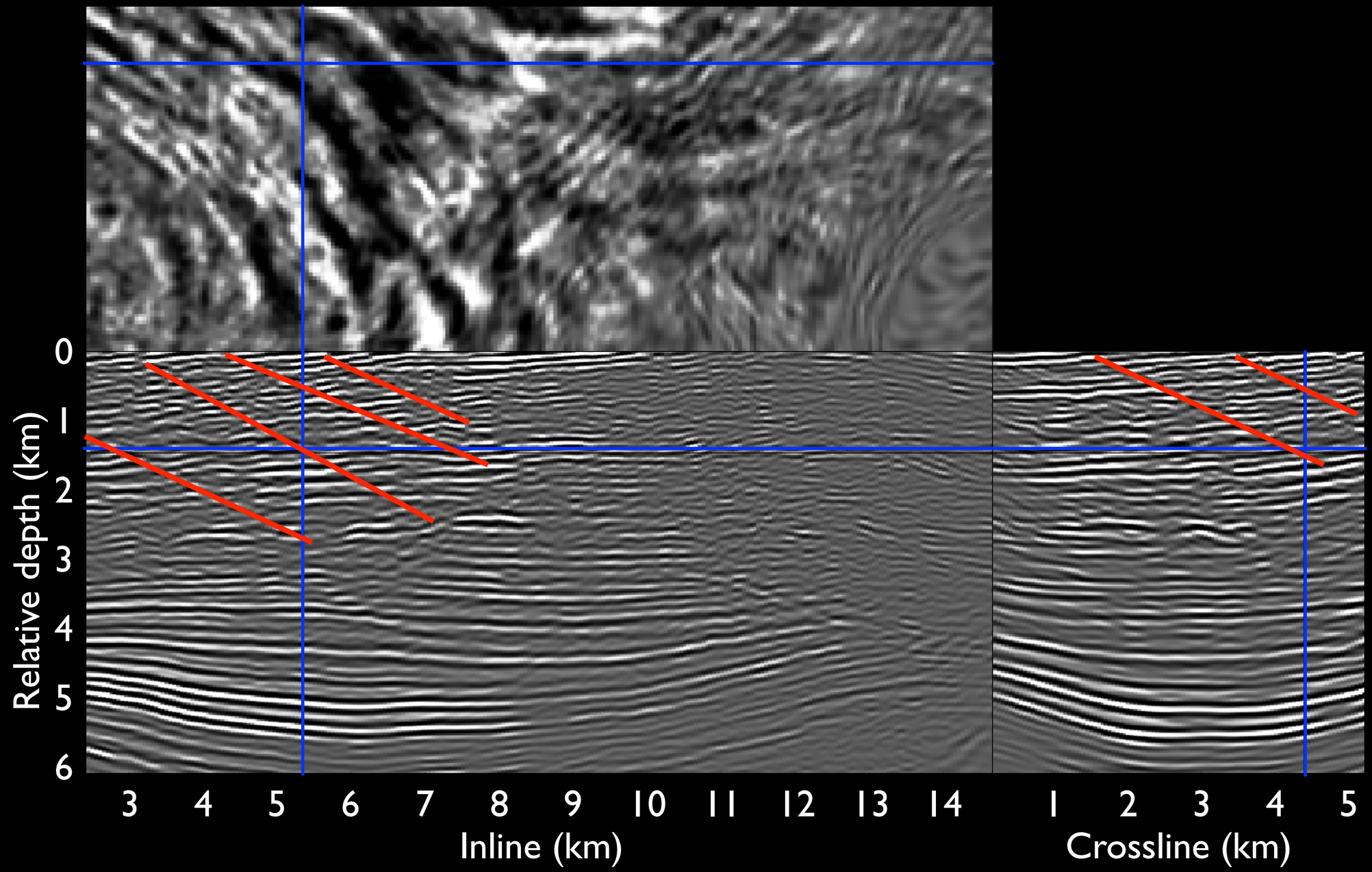
Migration of original data (initial velocity)



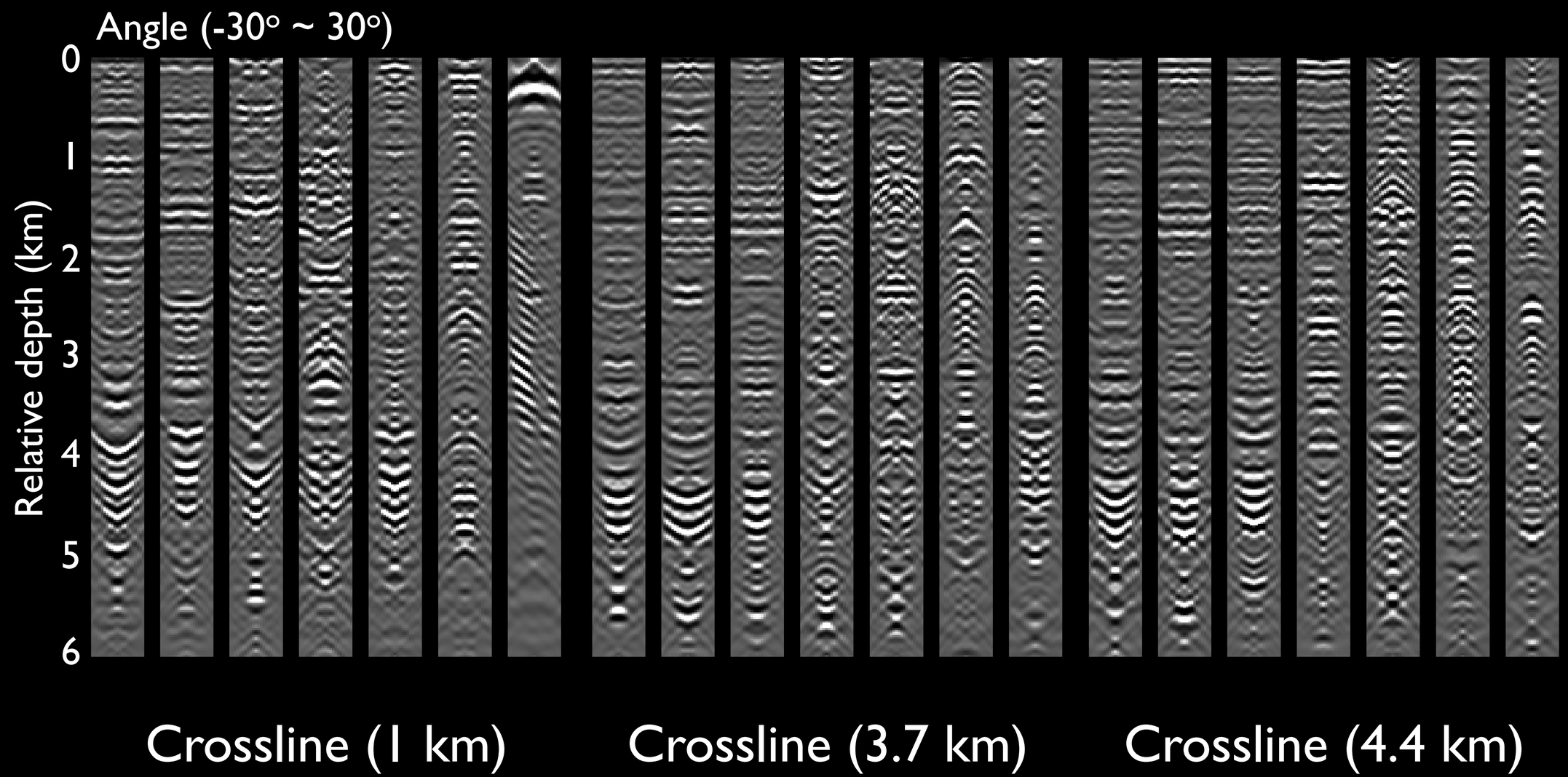
Migration of original data (updated velocity)



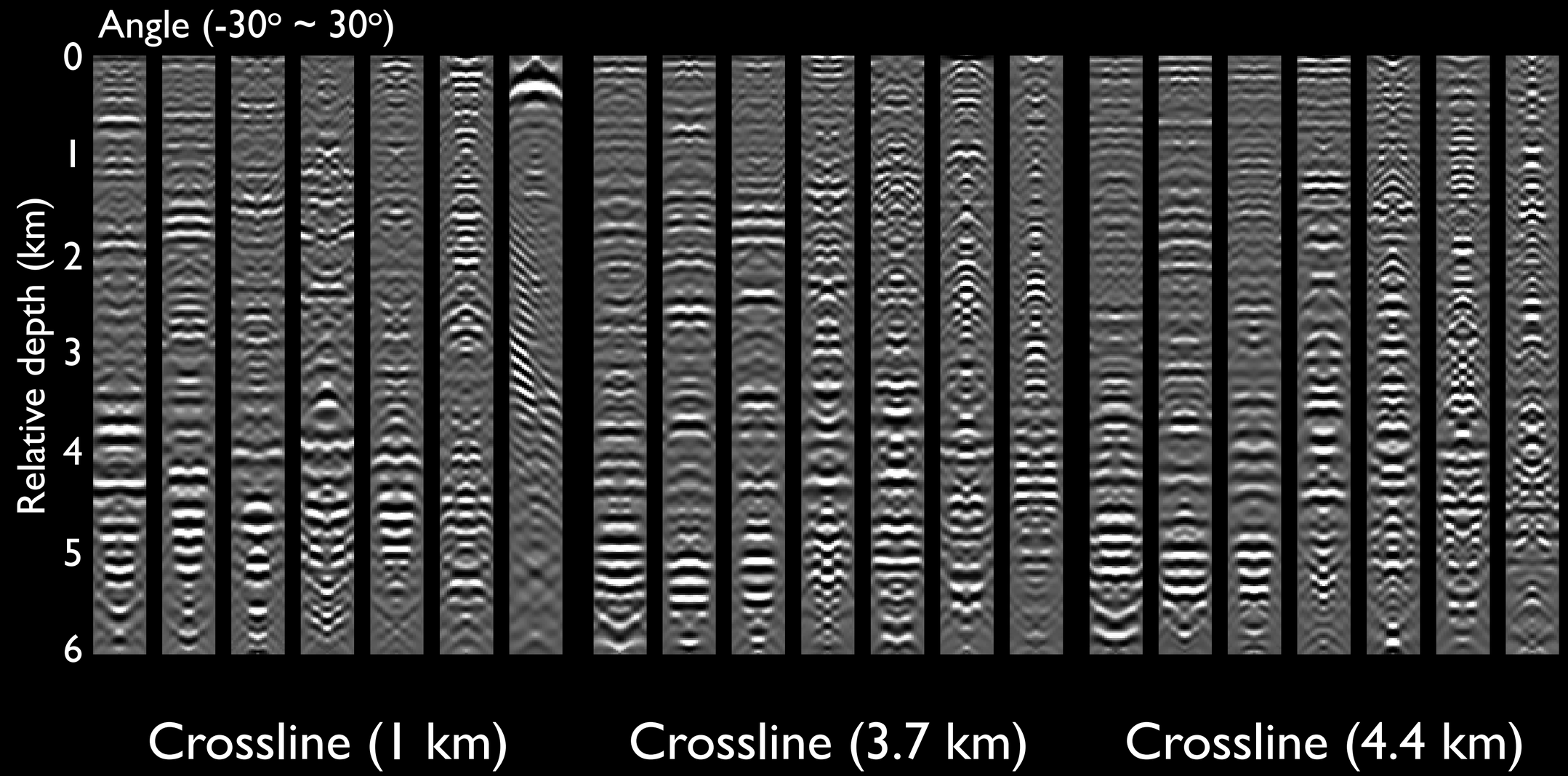
Migration of original data (updated velocity)



Angle gathers (initial velocity)



Angle gathers (updated velocity)



Conclusions

- **Target-oriented tomography can be achieved via Born wavefield modeling**
- **Born modeling is flexible and no picking is required**
- **The new data set correctly preserves velocity information useful for velocity analysis**
- **Computational cost is significantly reduced thanks to the smaller data size and the target-oriented inversion strategy**

Conclusions

- **Target-oriented tomography can be achieved via Born wavefield modeling**
- **Born modeling is flexible and no picking is required**
- **The new data set correctly preserves velocity information useful for velocity analysis**
- **Computational cost is significantly reduced thanks to the smaller data size and the target-oriented inversion strategy**

Conclusions

- **Target-oriented tomography can be achieved via Born wavefield modeling**
- **Born modeling is flexible and no picking is required**
- **The new data set correctly preserves velocity information useful for velocity analysis**
- **Computational cost is significantly reduced thanks to the smaller data size and the target-oriented inversion strategy**

Conclusions

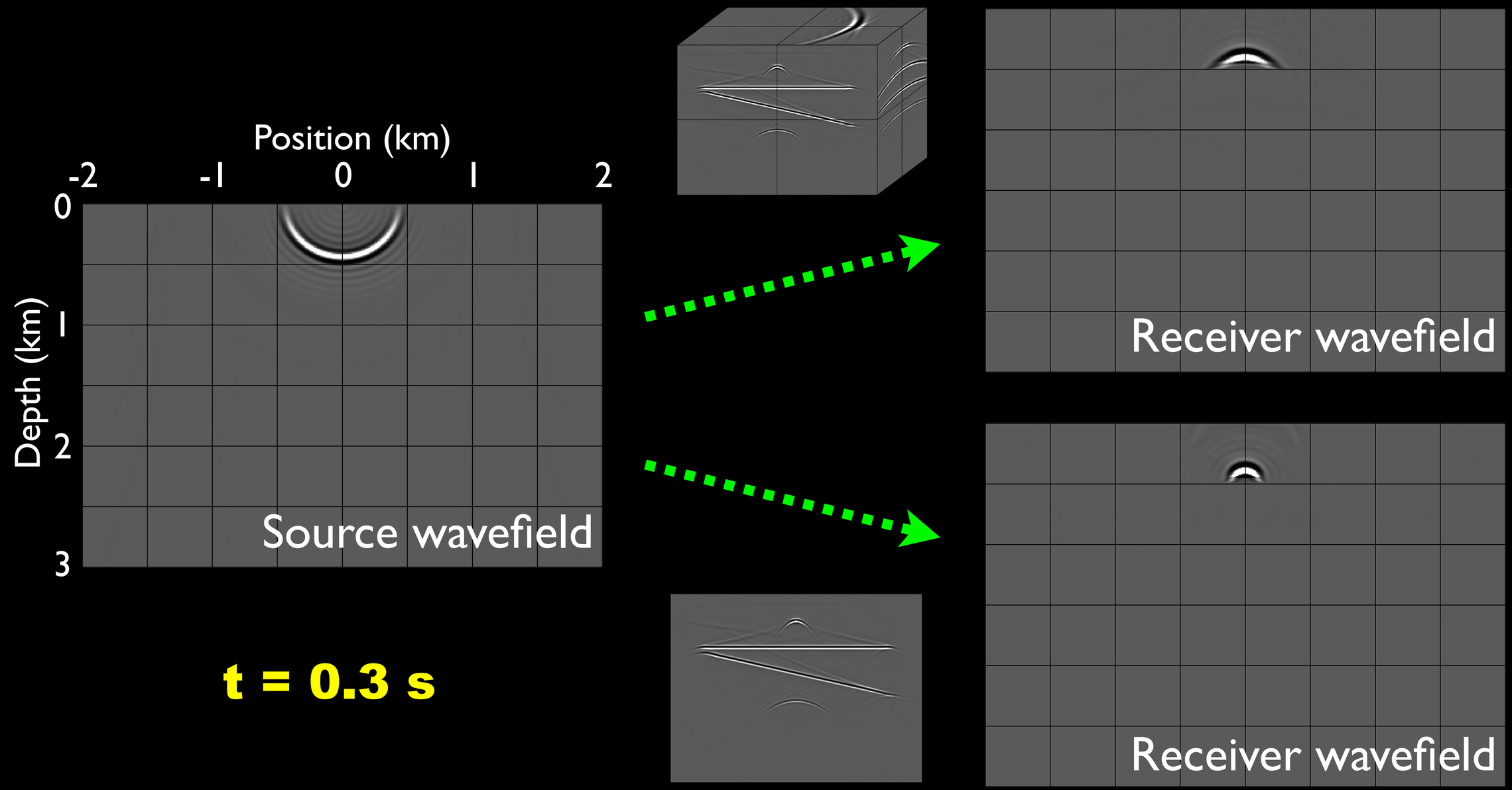
- Target-oriented tomography can be achieved via Born wavefield modeling
- Born modeling is flexible and no picking is required
- The new data set correctly preserves velocity information useful for velocity analysis
- Computational cost is significantly reduced thanks to the smaller data size and the target-oriented inversion strategy

Acknowledgements

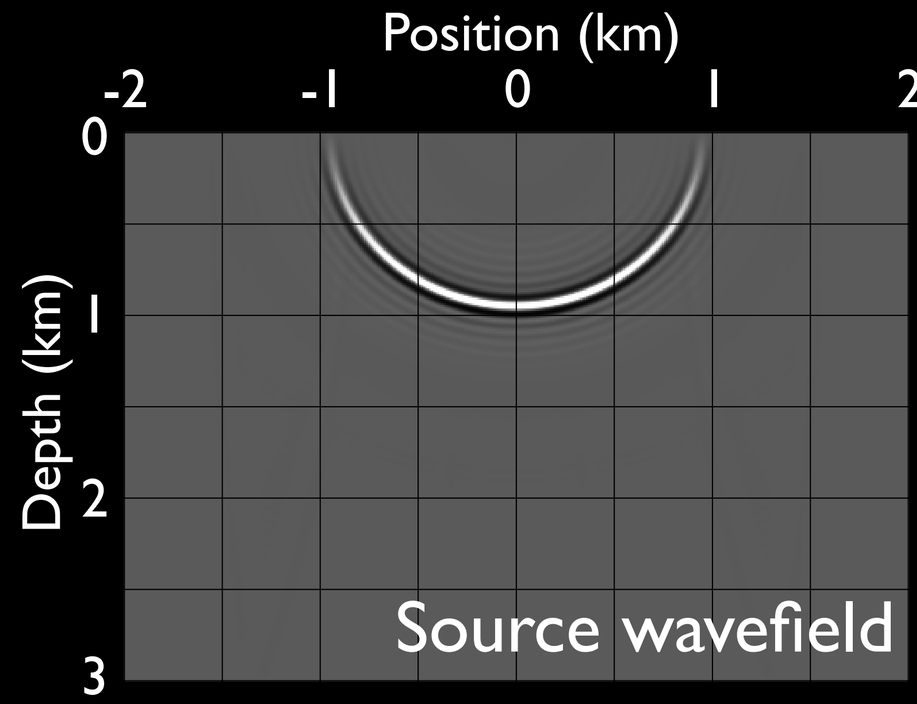
- SMAART JV for the Sigsbee2A synthetic data set
- BP and ExxonMobil for the GOM field data set
- Stanford Center for Computational Earth and Environmental Science (CEES) for providing computing resources

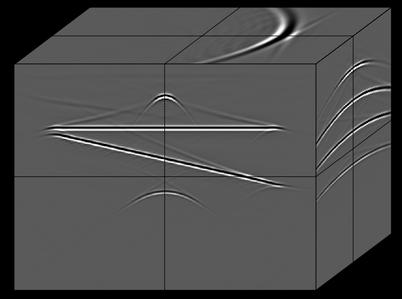
Thanks for your attention

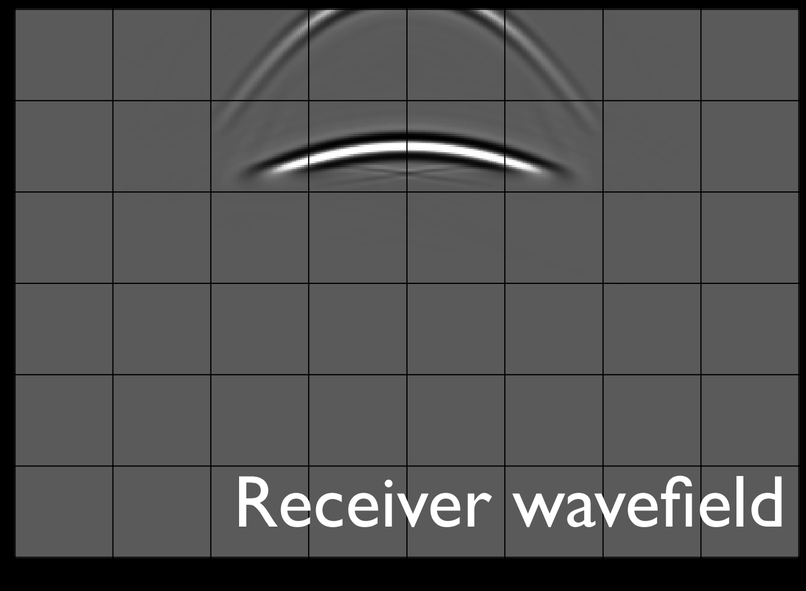
Born wavefield modeling



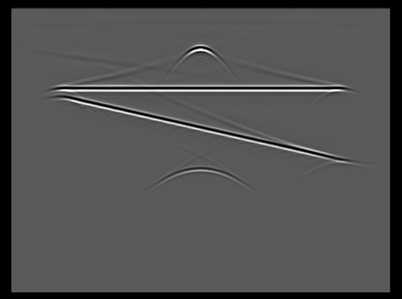
Born wavefield modeling

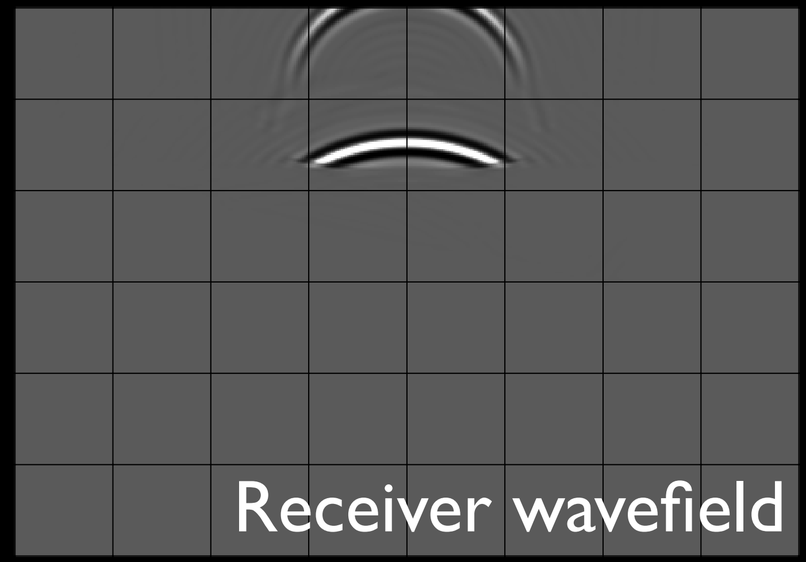




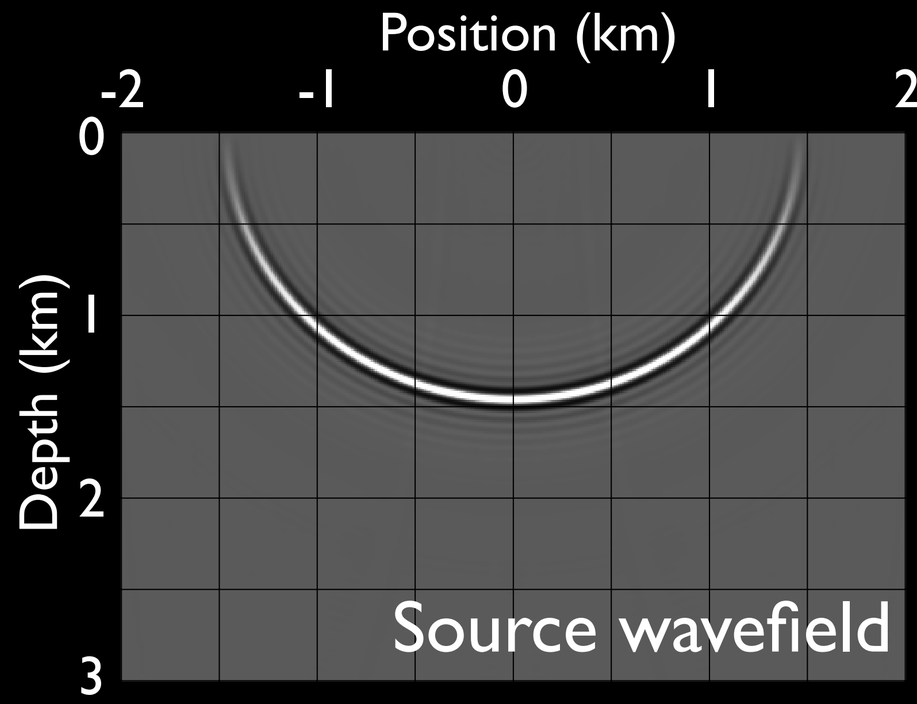


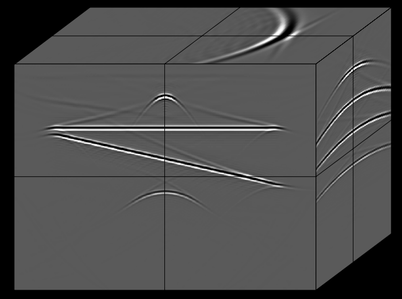
t = 0.6 s

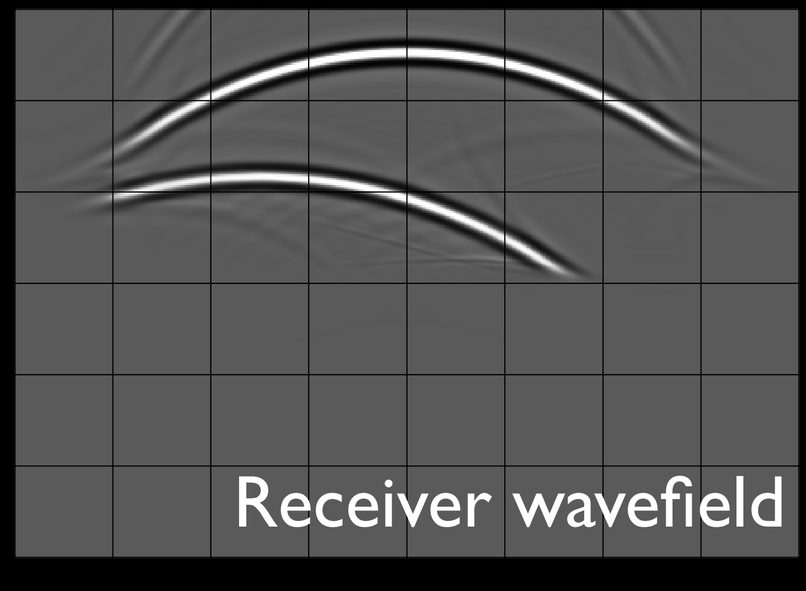




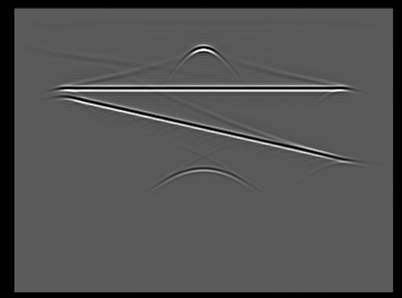
Born wavefield modeling

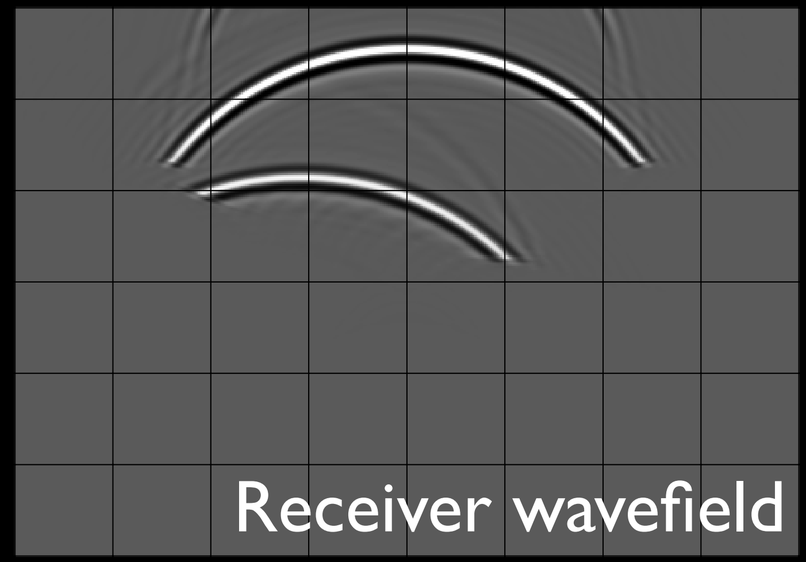




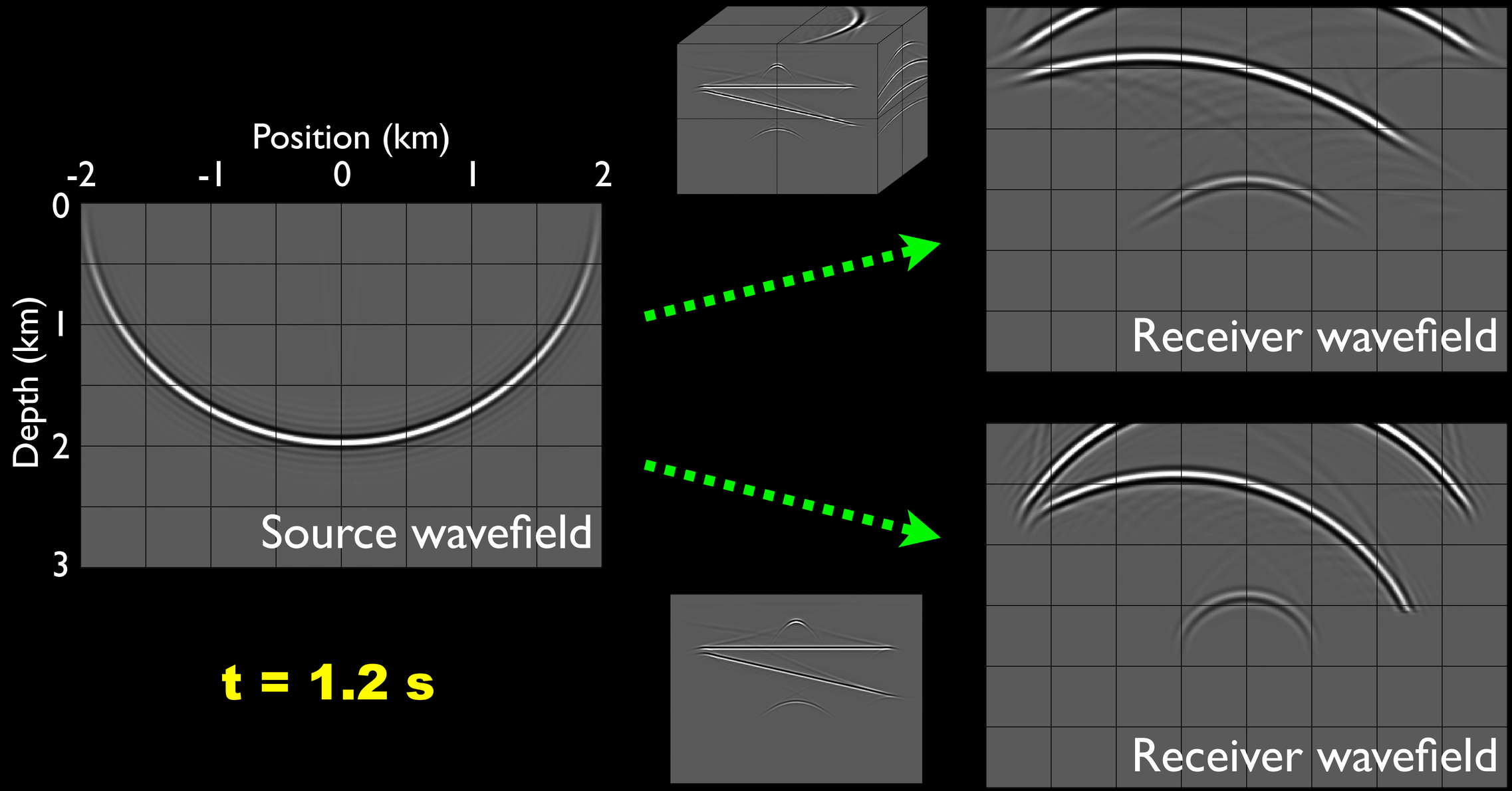


t = 0.9 s

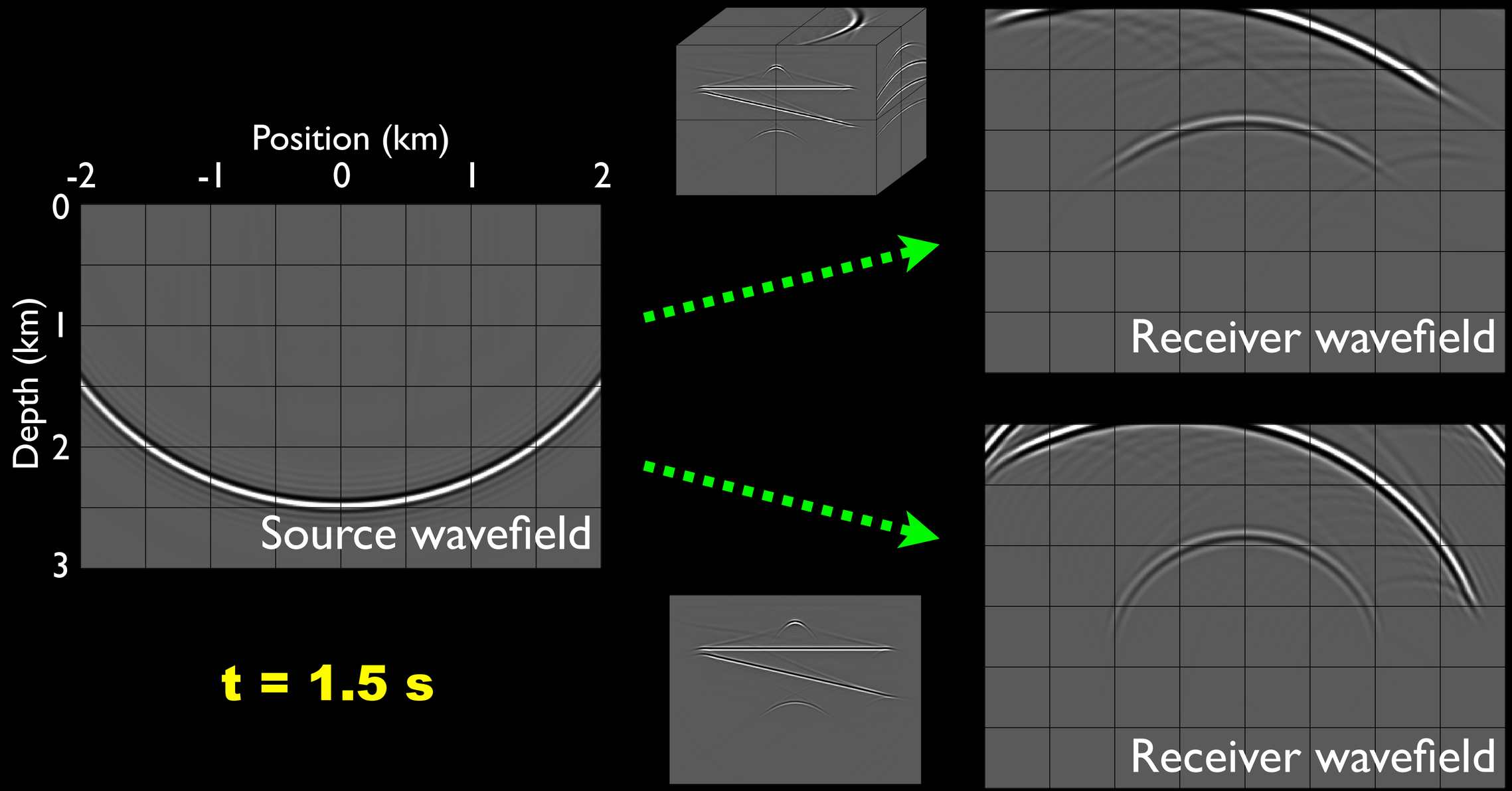




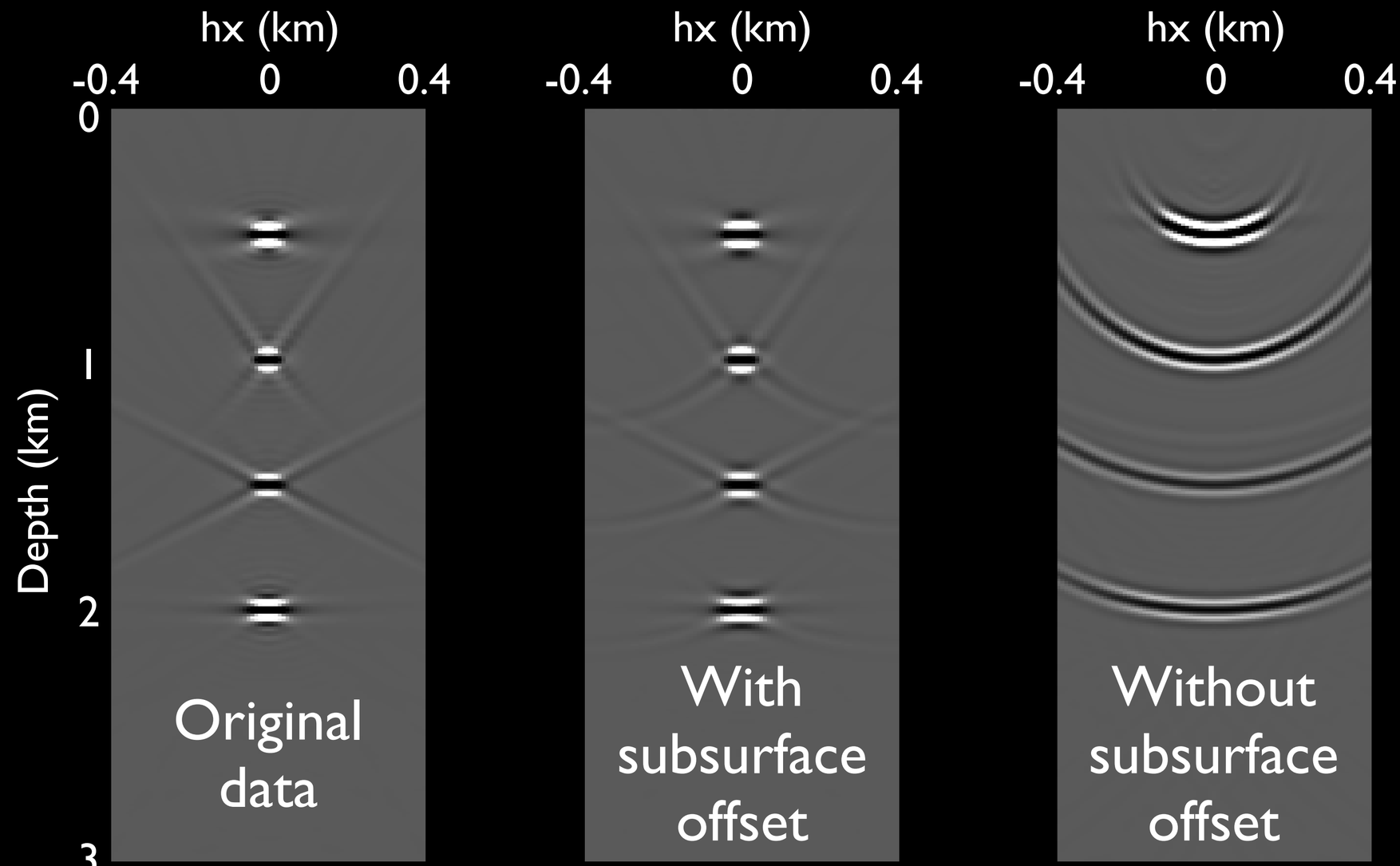
Born wavefield modeling



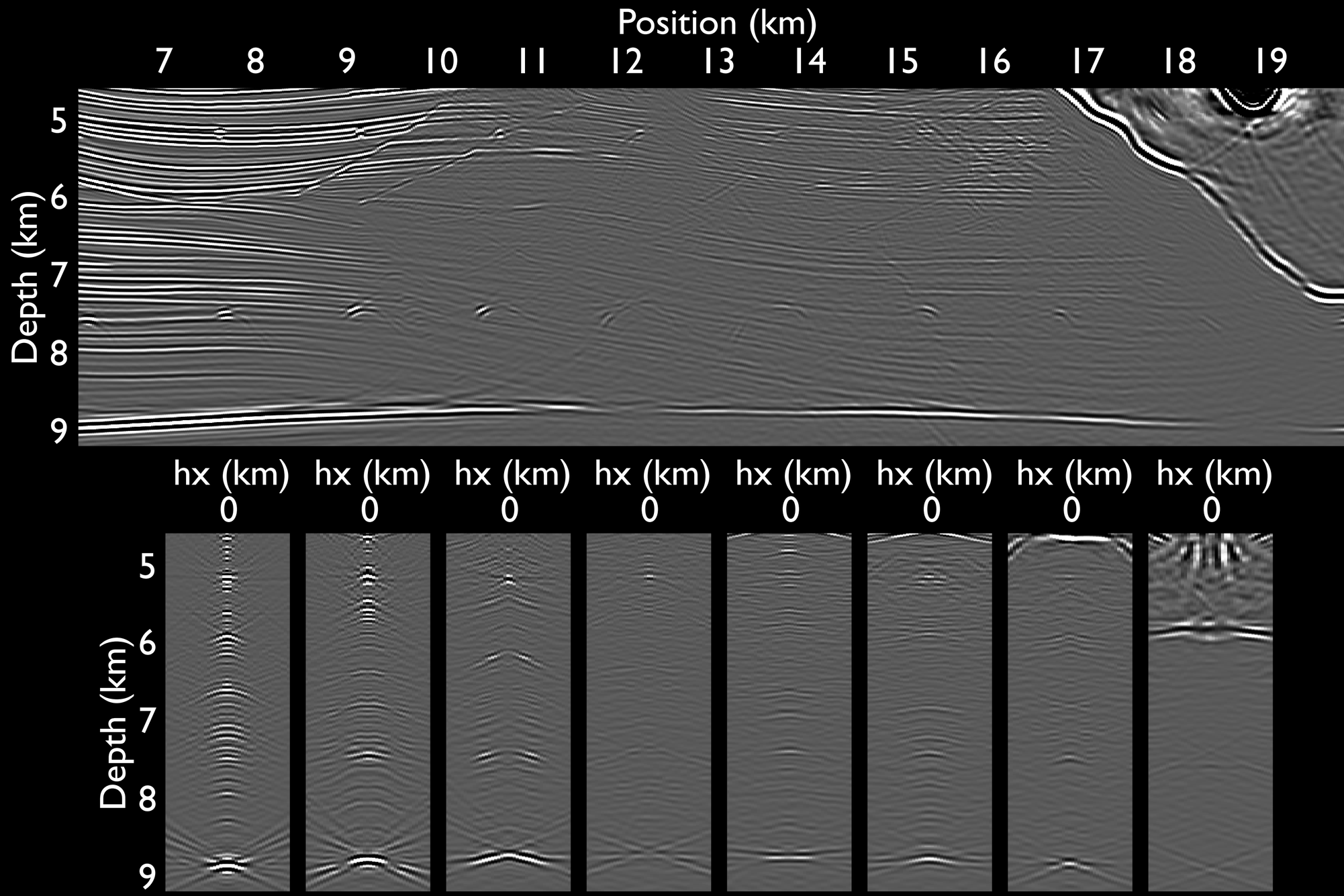
Born wavefield modeling



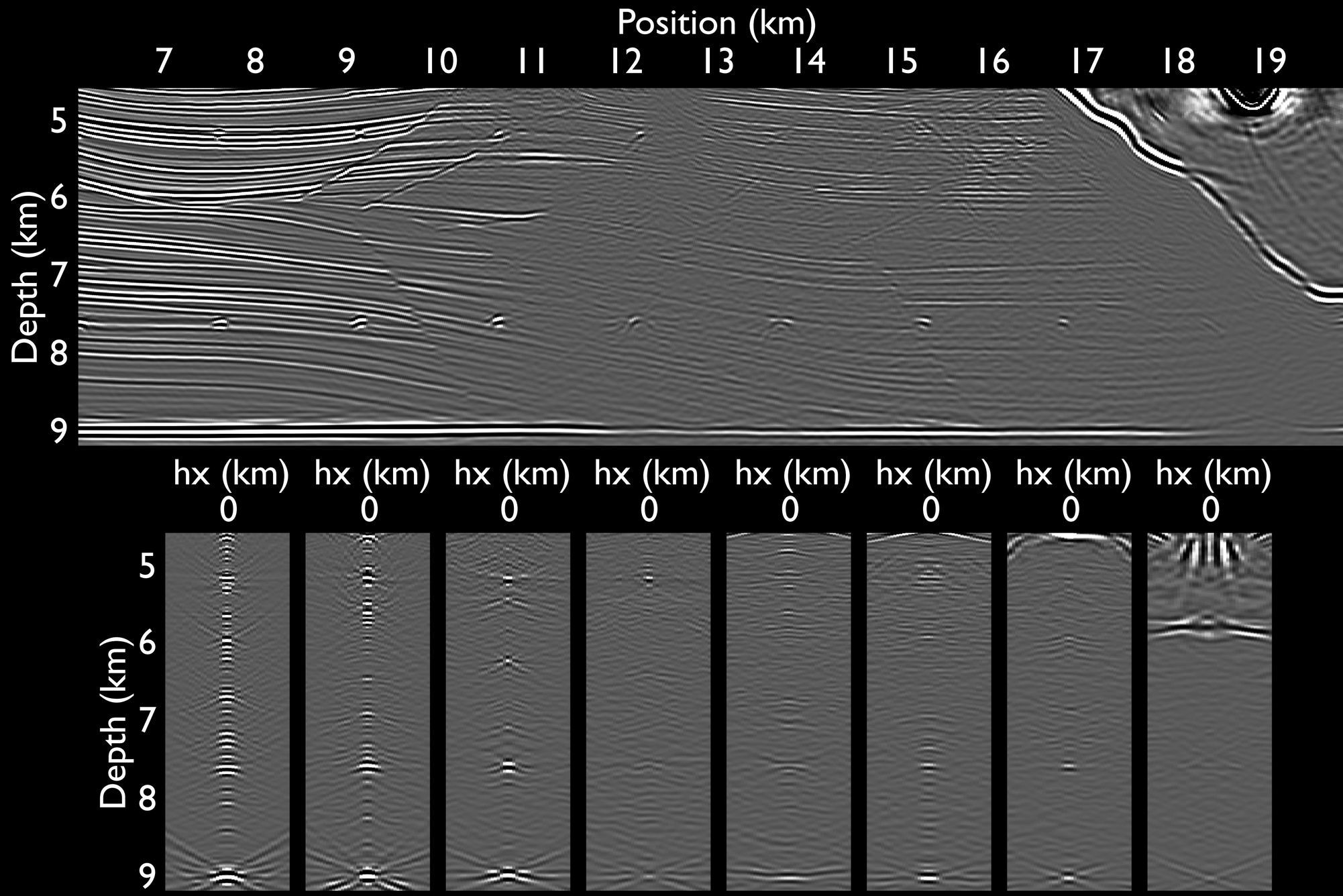
Migration using true velocity



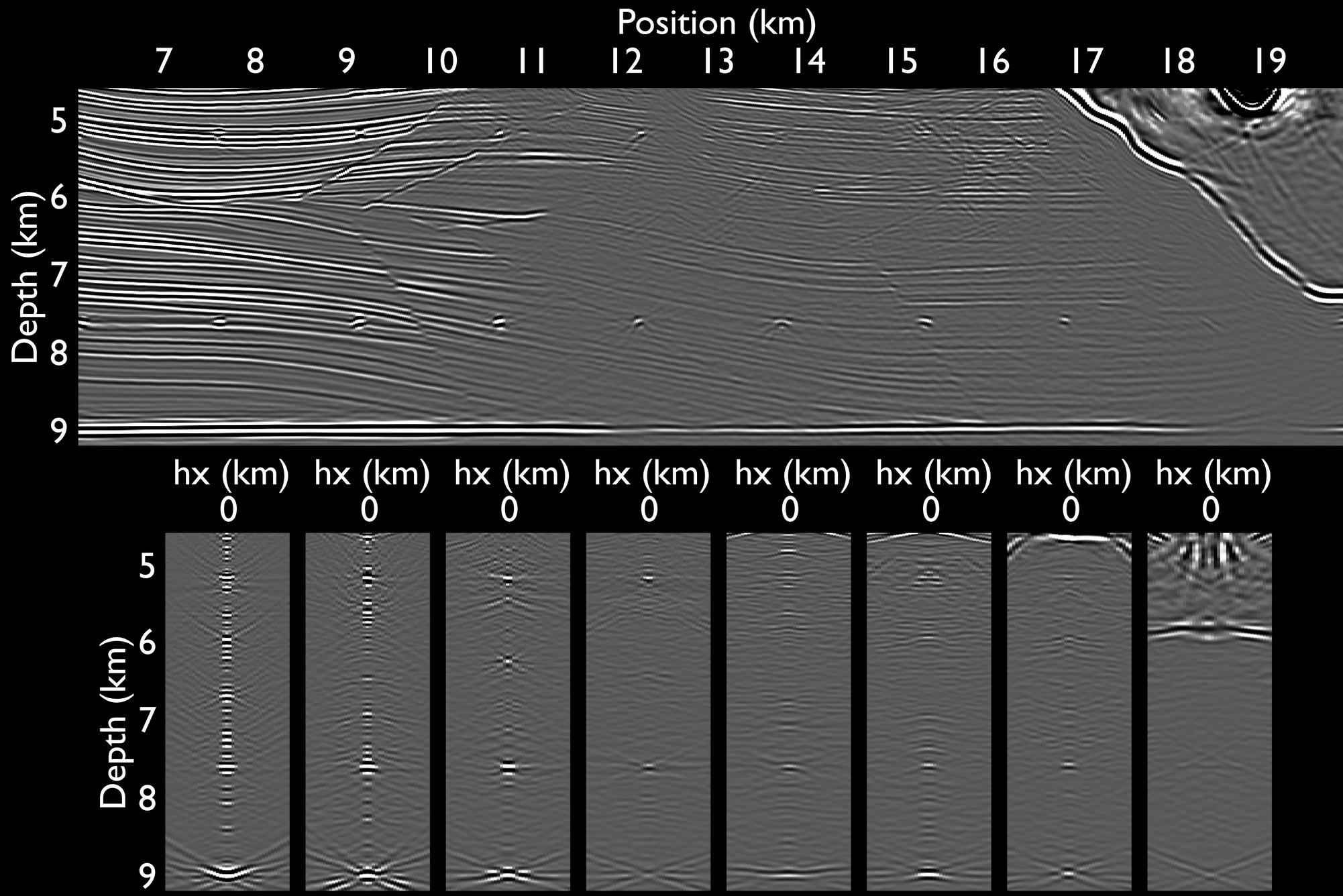
Migration of the original data (initial velocity)



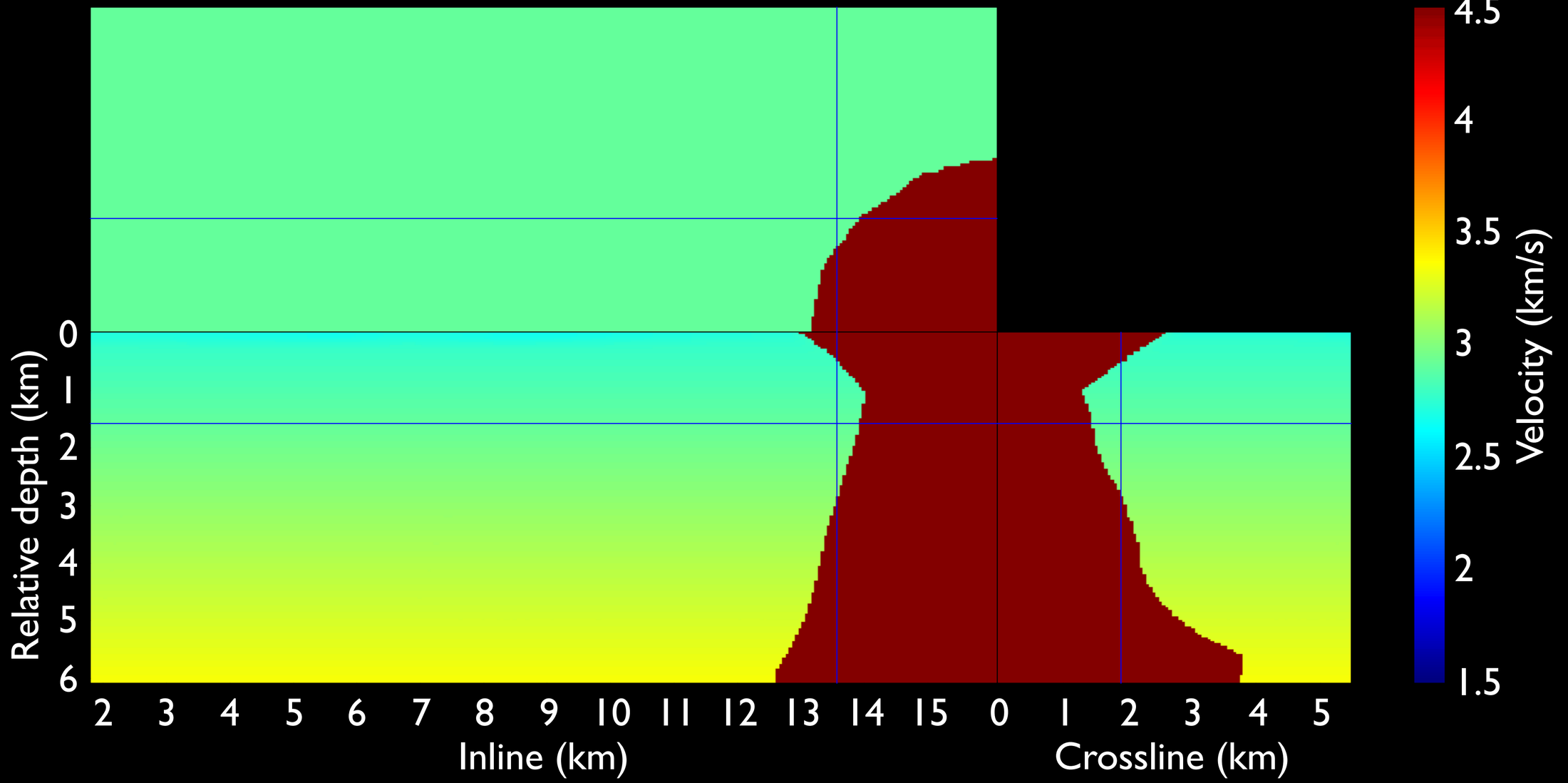
Migration of the original data (updated velocity)



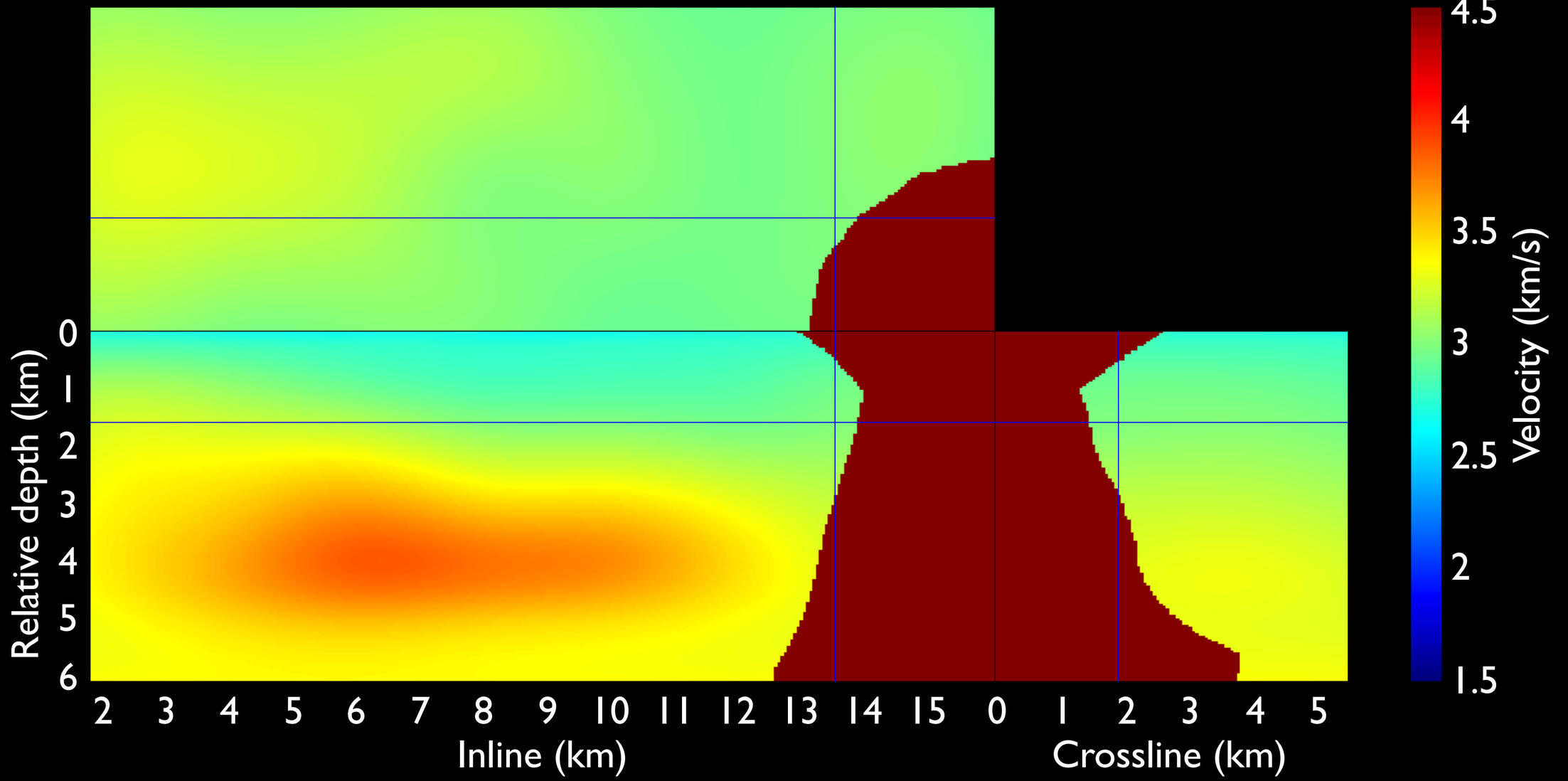
Migration of the original data (true velocity)



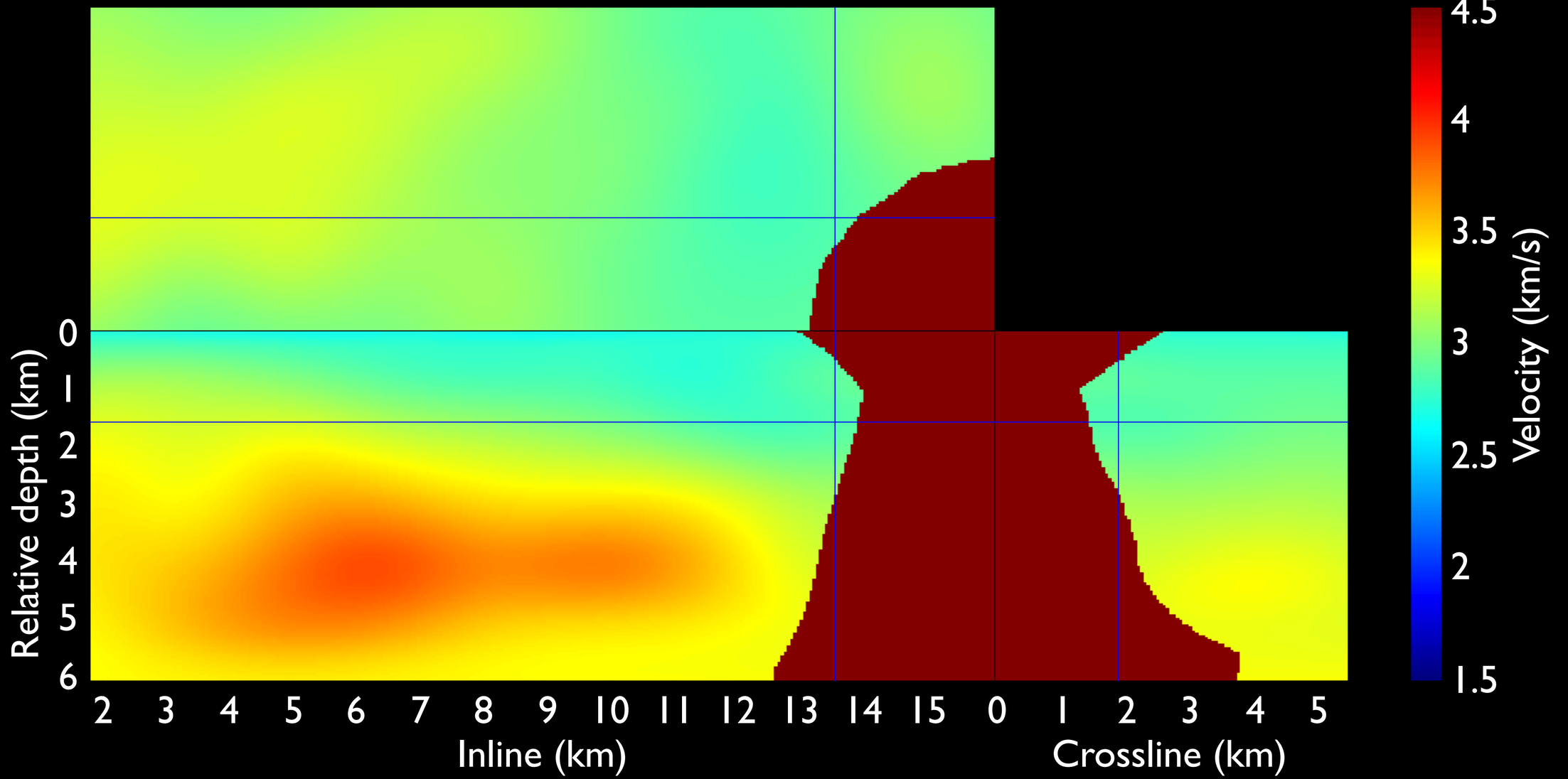
Initial velocity



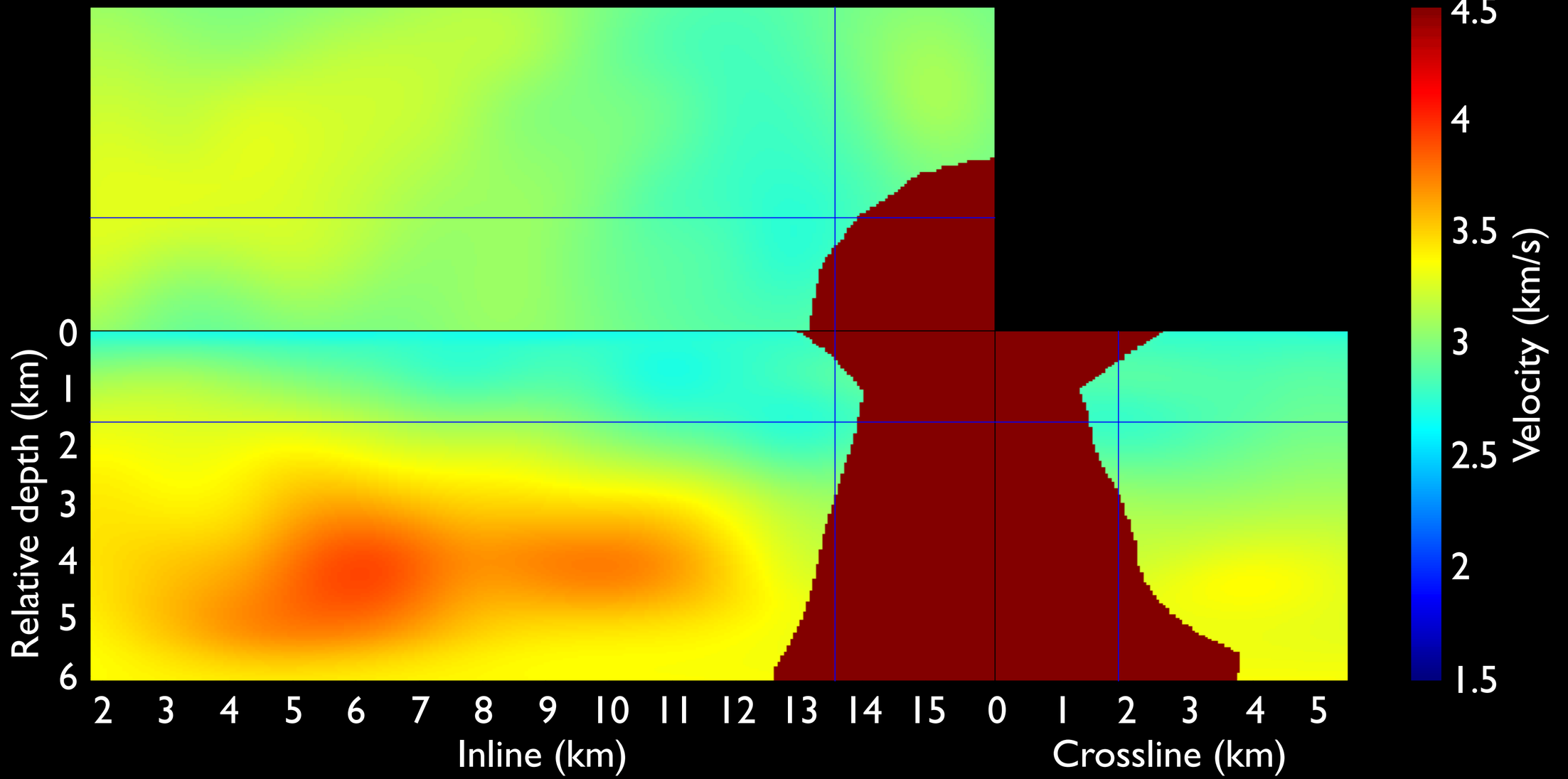
Inverted velocity at iteration 10



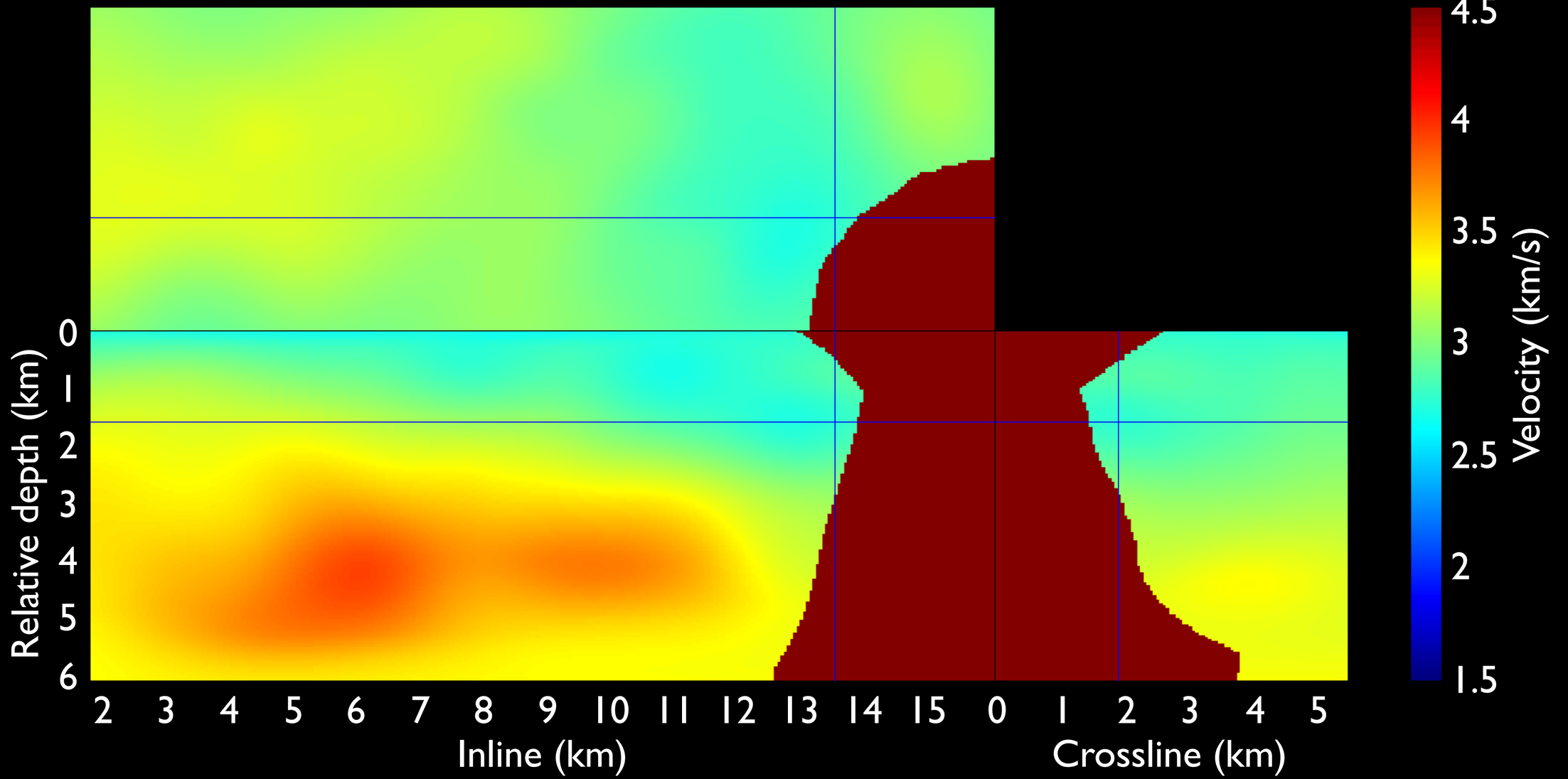
Inverted velocity at iteration 20



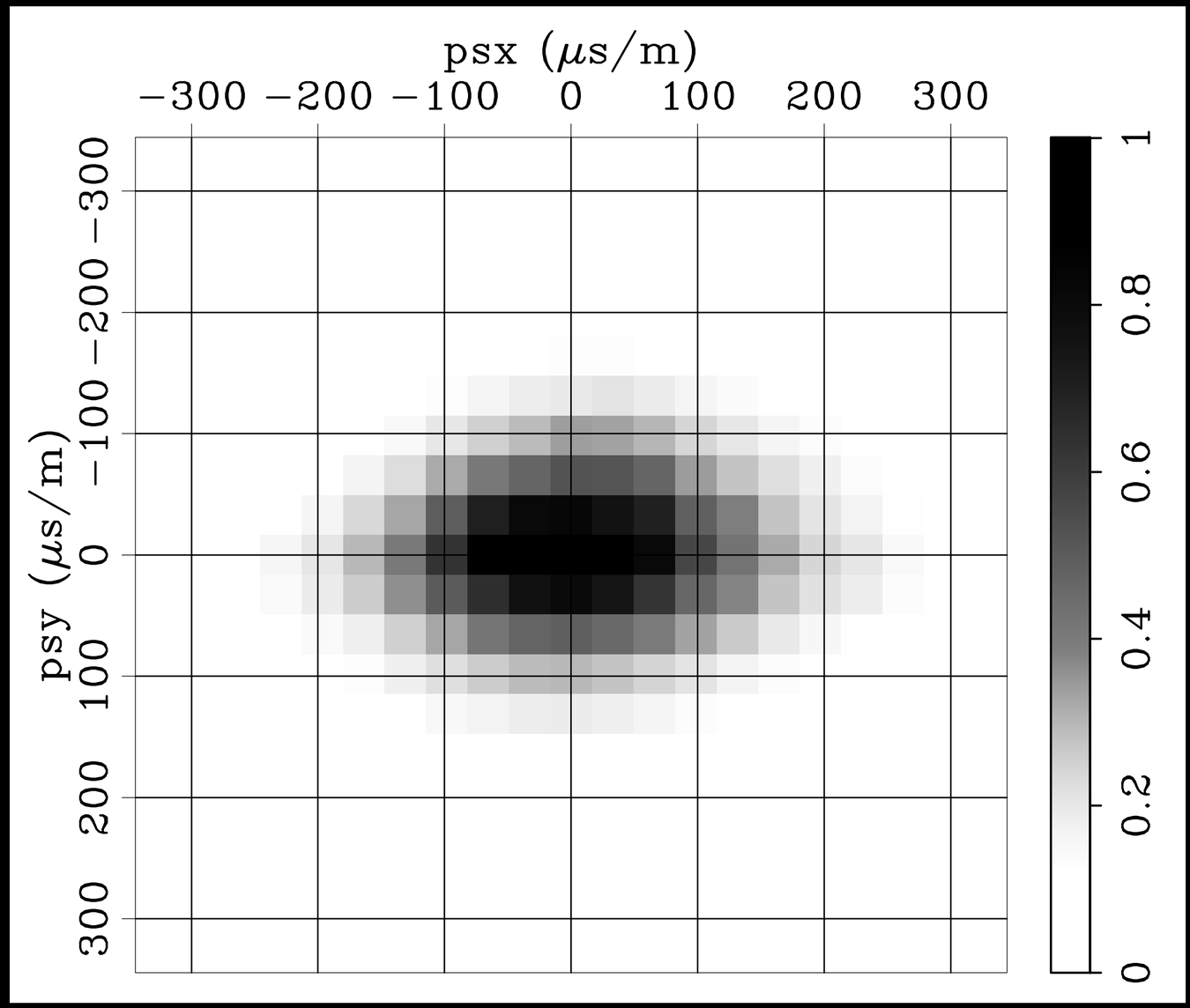
Inverted velocity at iteration 30



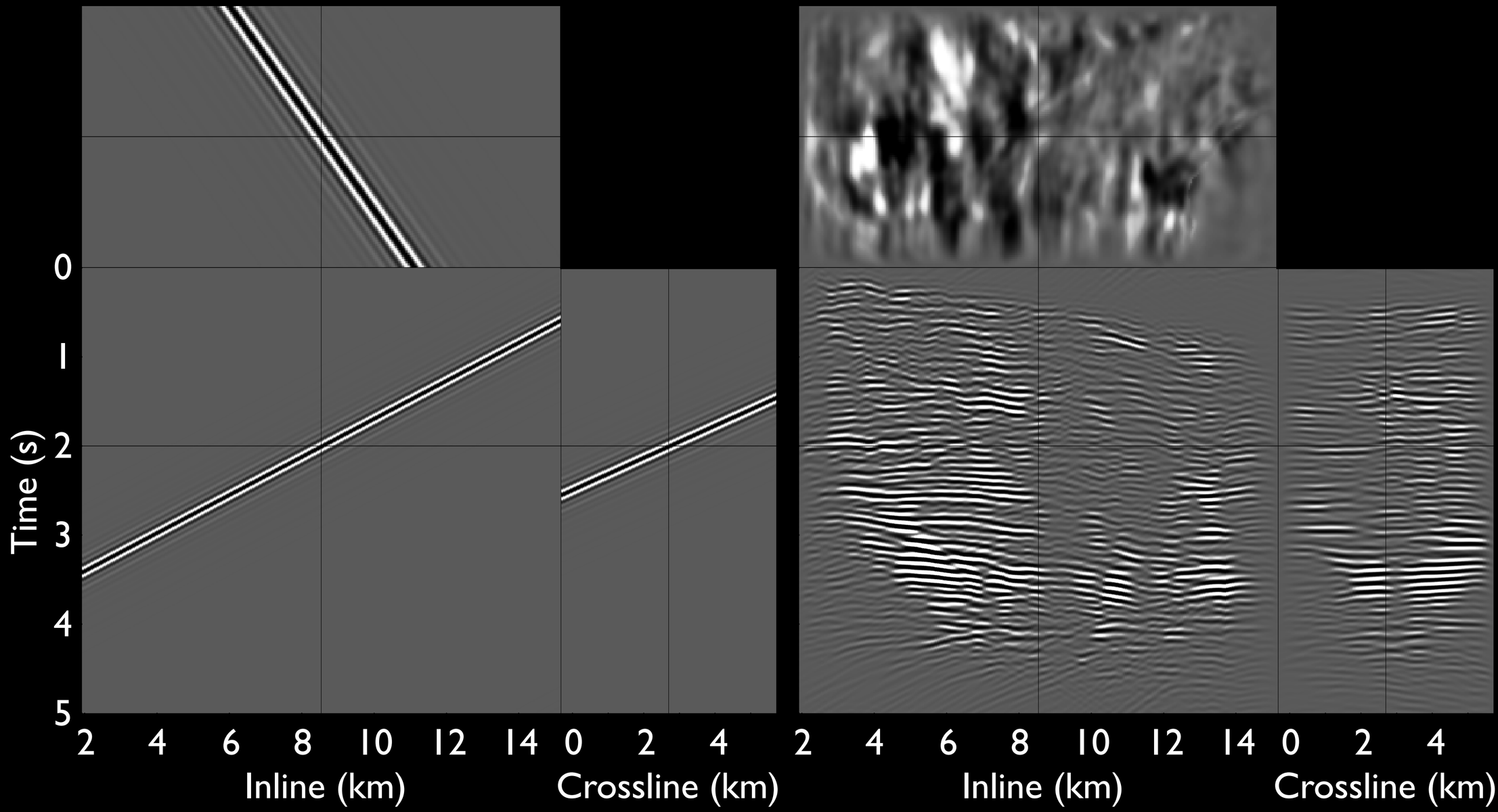
Inverted velocity at iteration 40



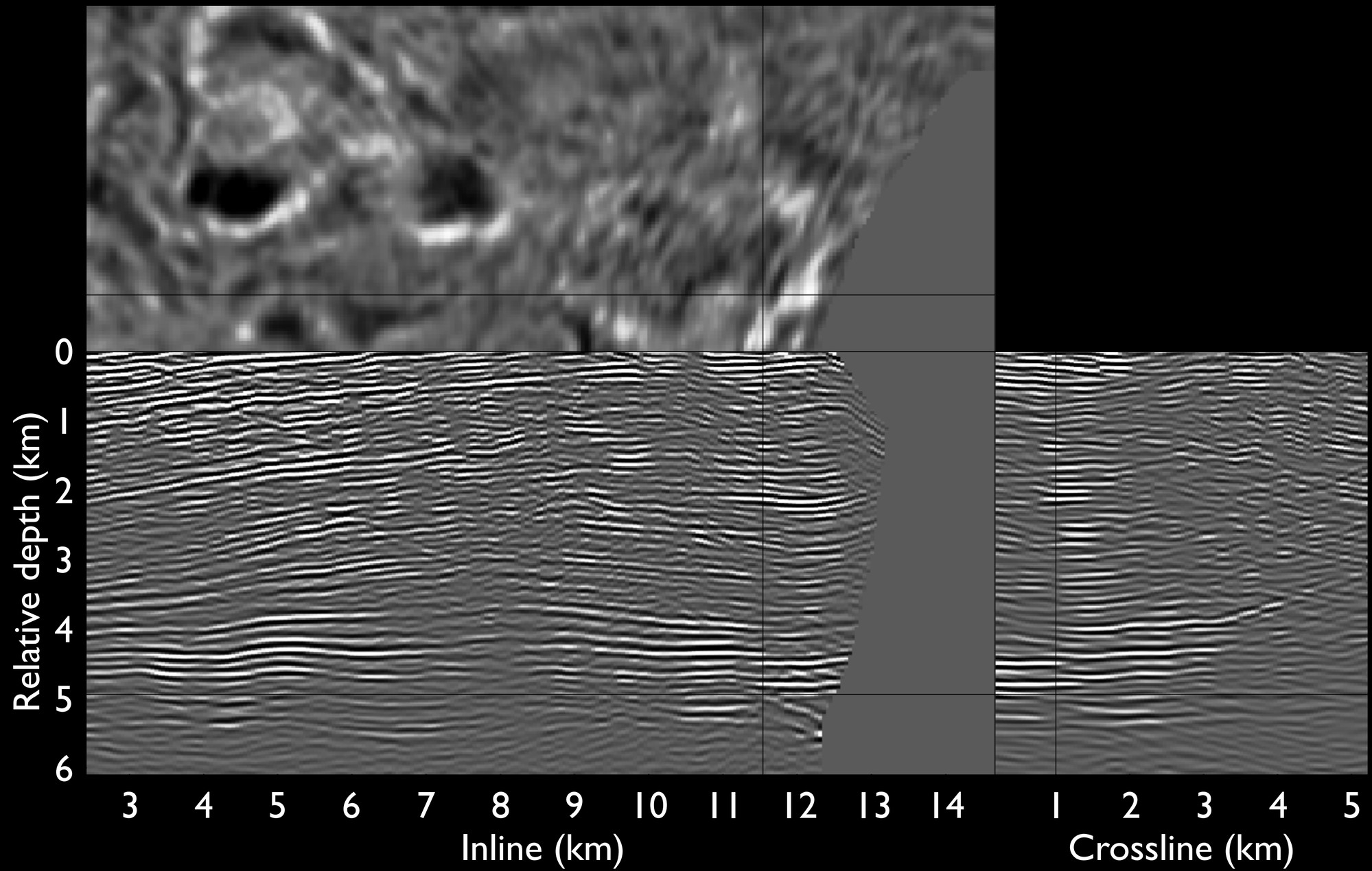
Average source visibility



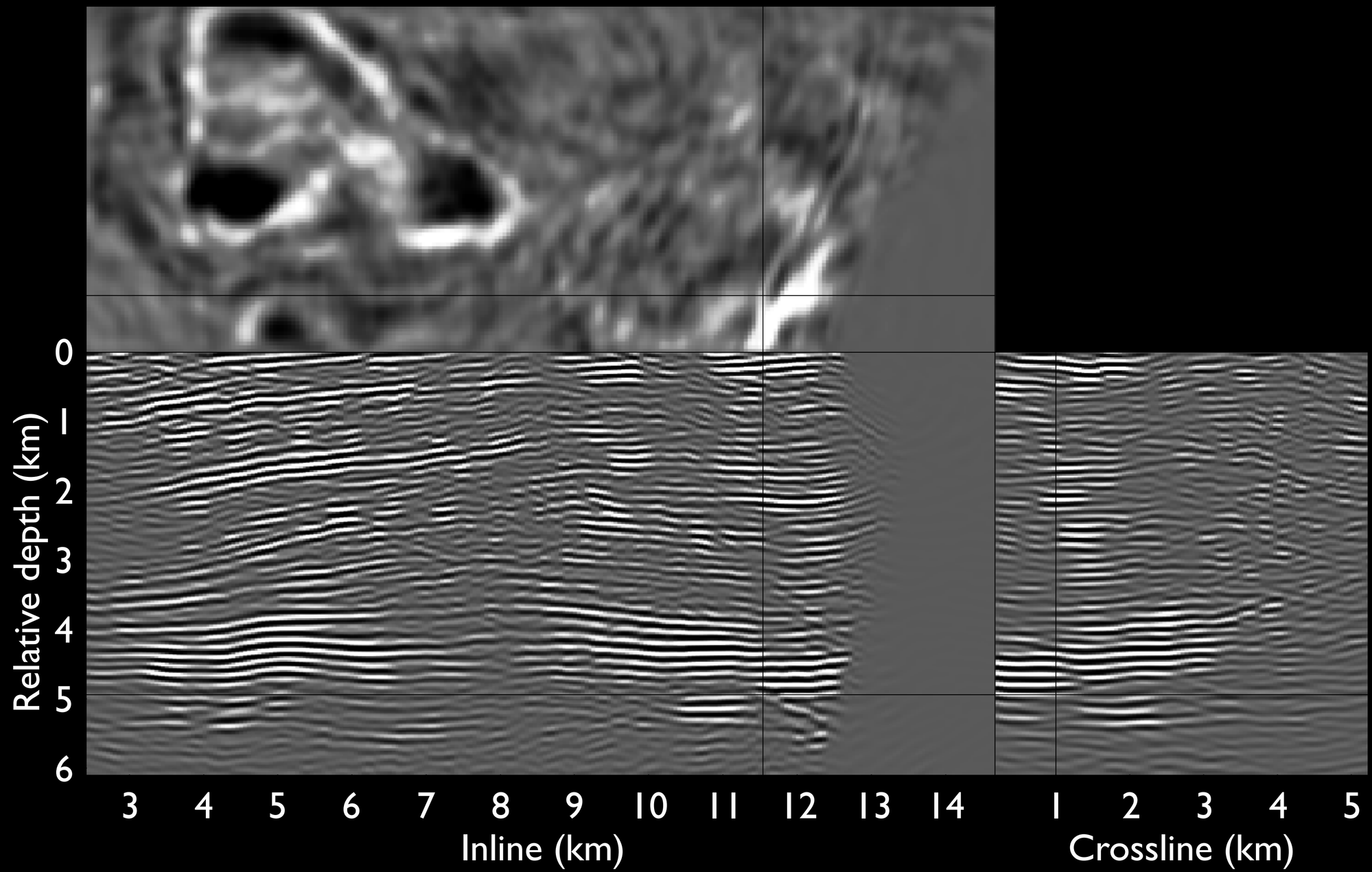
3-D Born plane-wave data



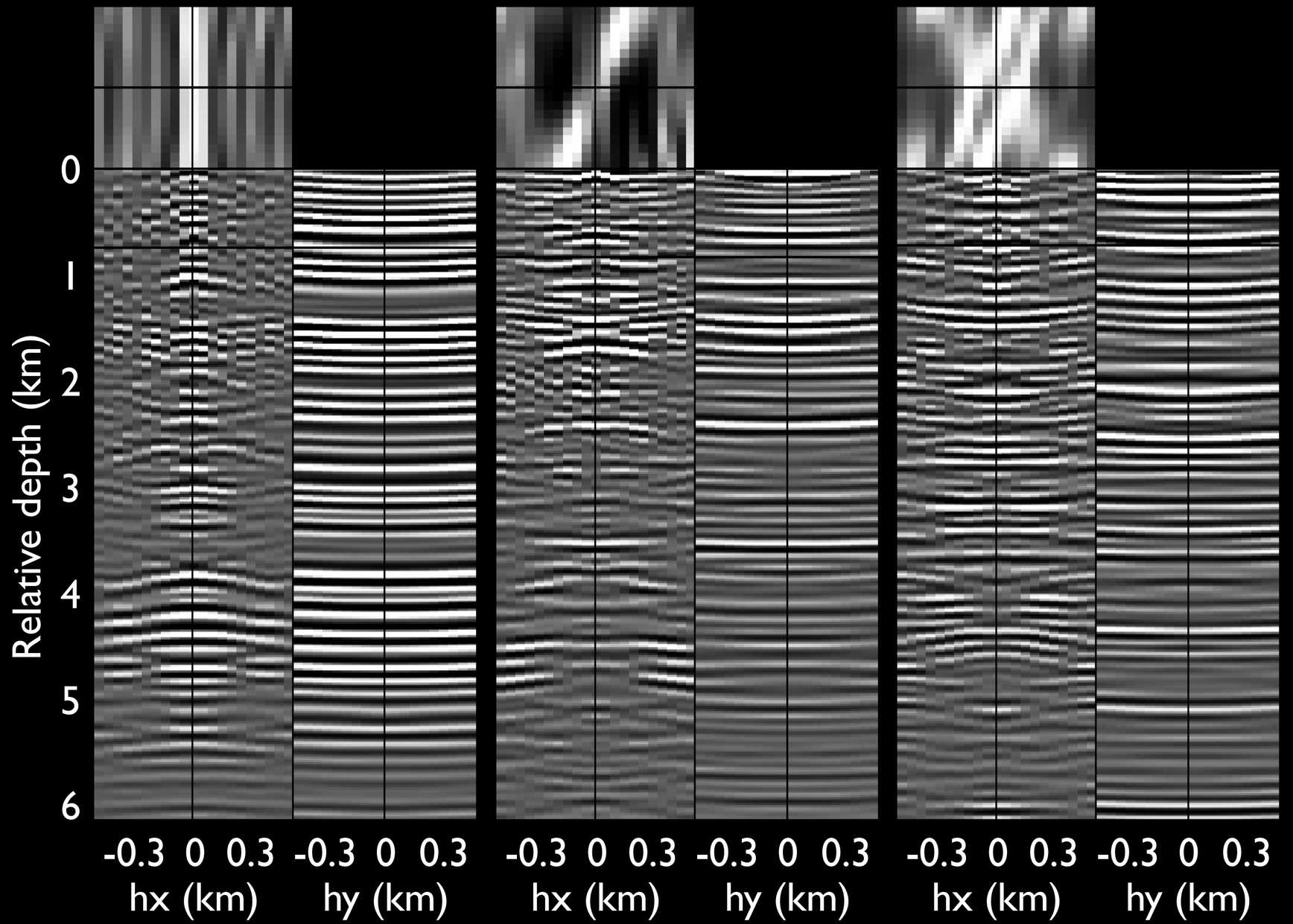
Initial image cube for modeling



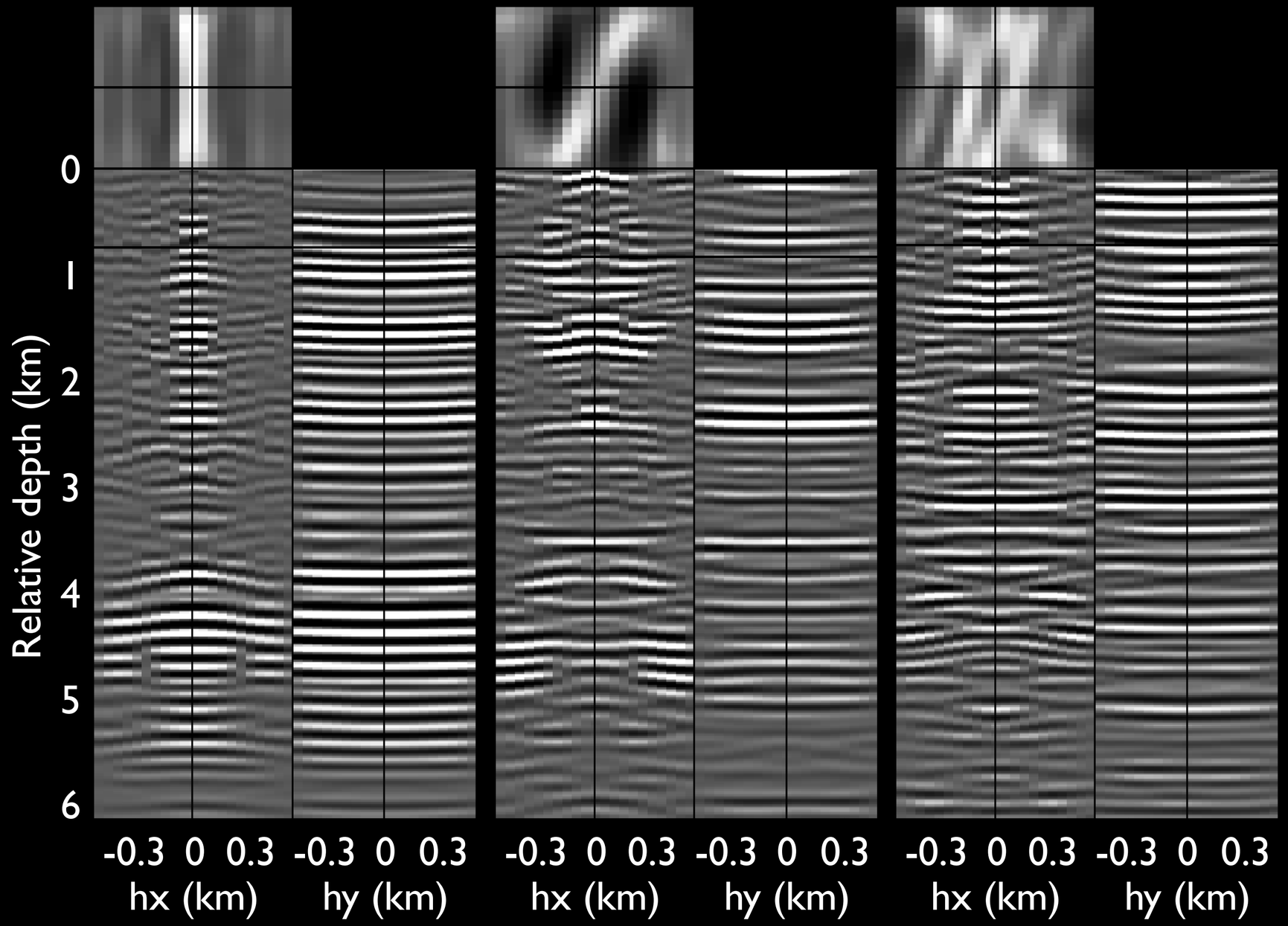
Initial image cube for modeling



3-D subsurface-offset gathers using original data

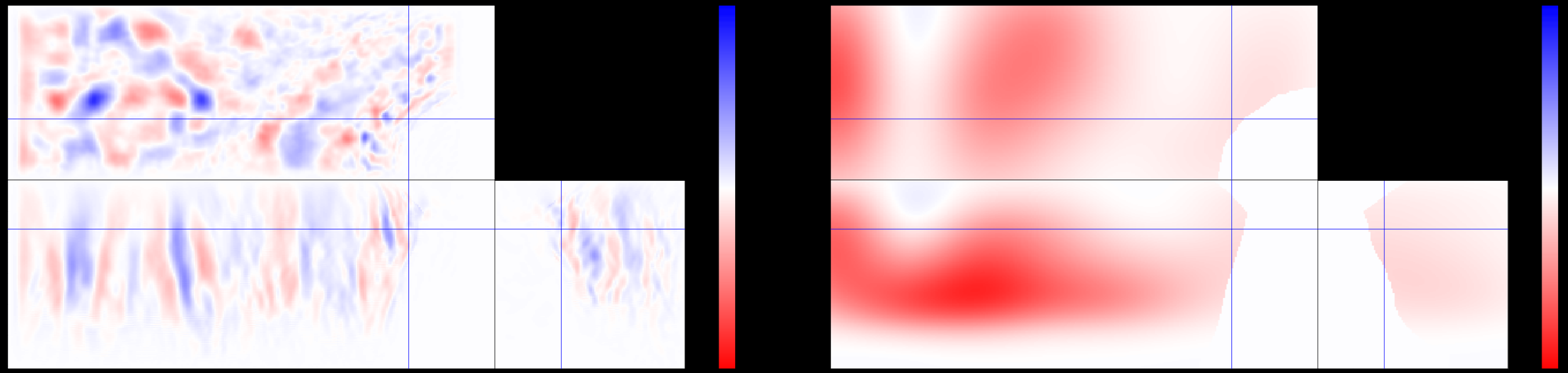


3-D subsurface-offset gathers using Born data



Raw and preconditioned gradients

Iteration 1



Iteration 31