Fast 3D velocity updates using image-space generalized sources

Claudio Guerra and Biondo Biondi

SEP 140, pp 1-10
May 2010

For complex geology ...

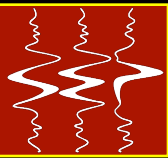
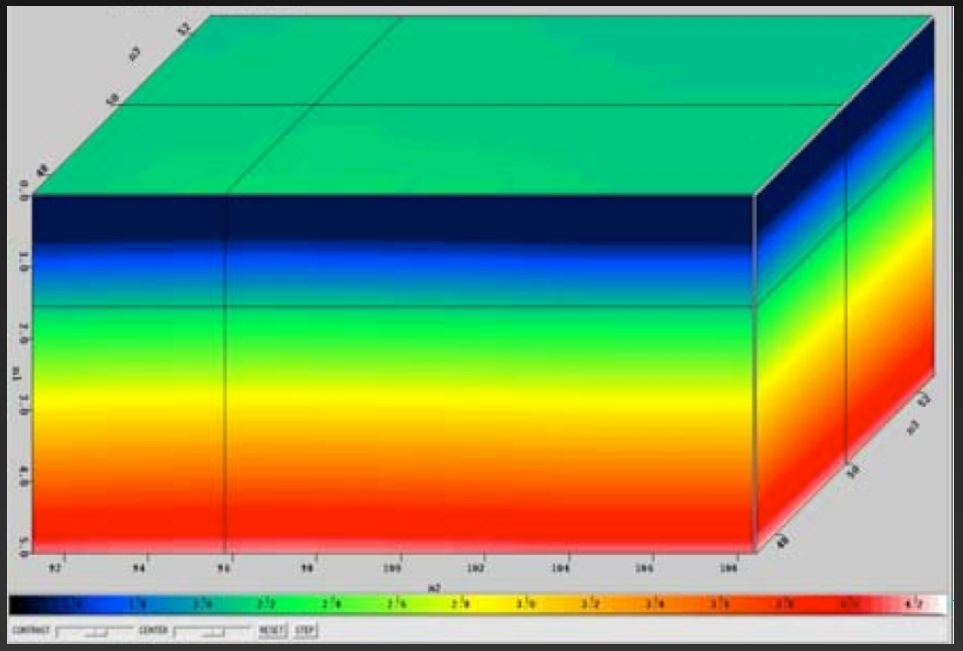


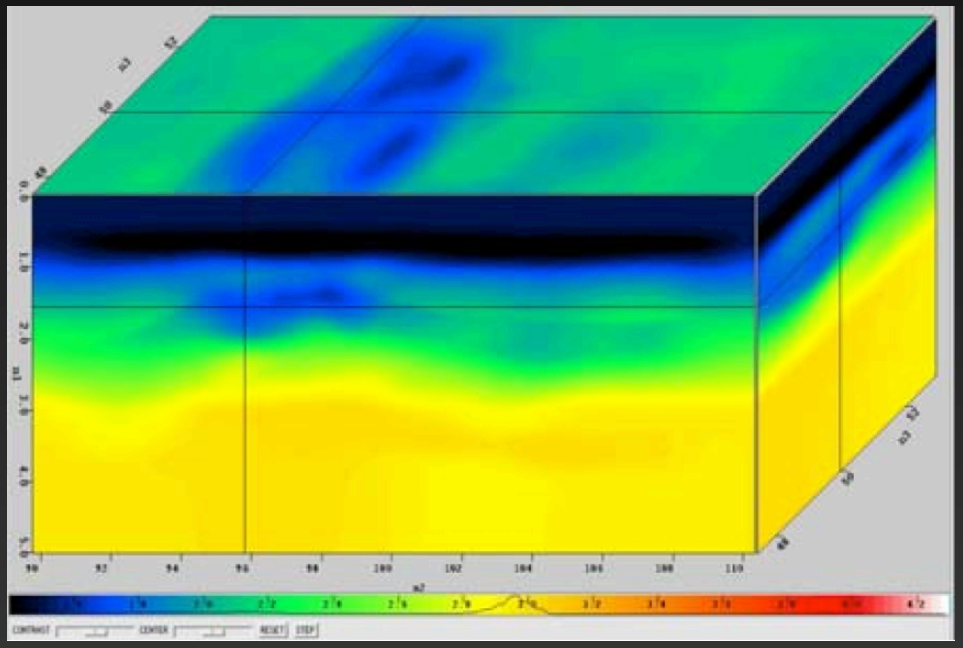
Image-space wave-equation tomography (ISWET) is theoretically more robust than ray-based methods

However ...

- **ISWET has rarely been applied in 3D**
  - **High cost and lower flexibility than ray-based methods**



Initial velocity

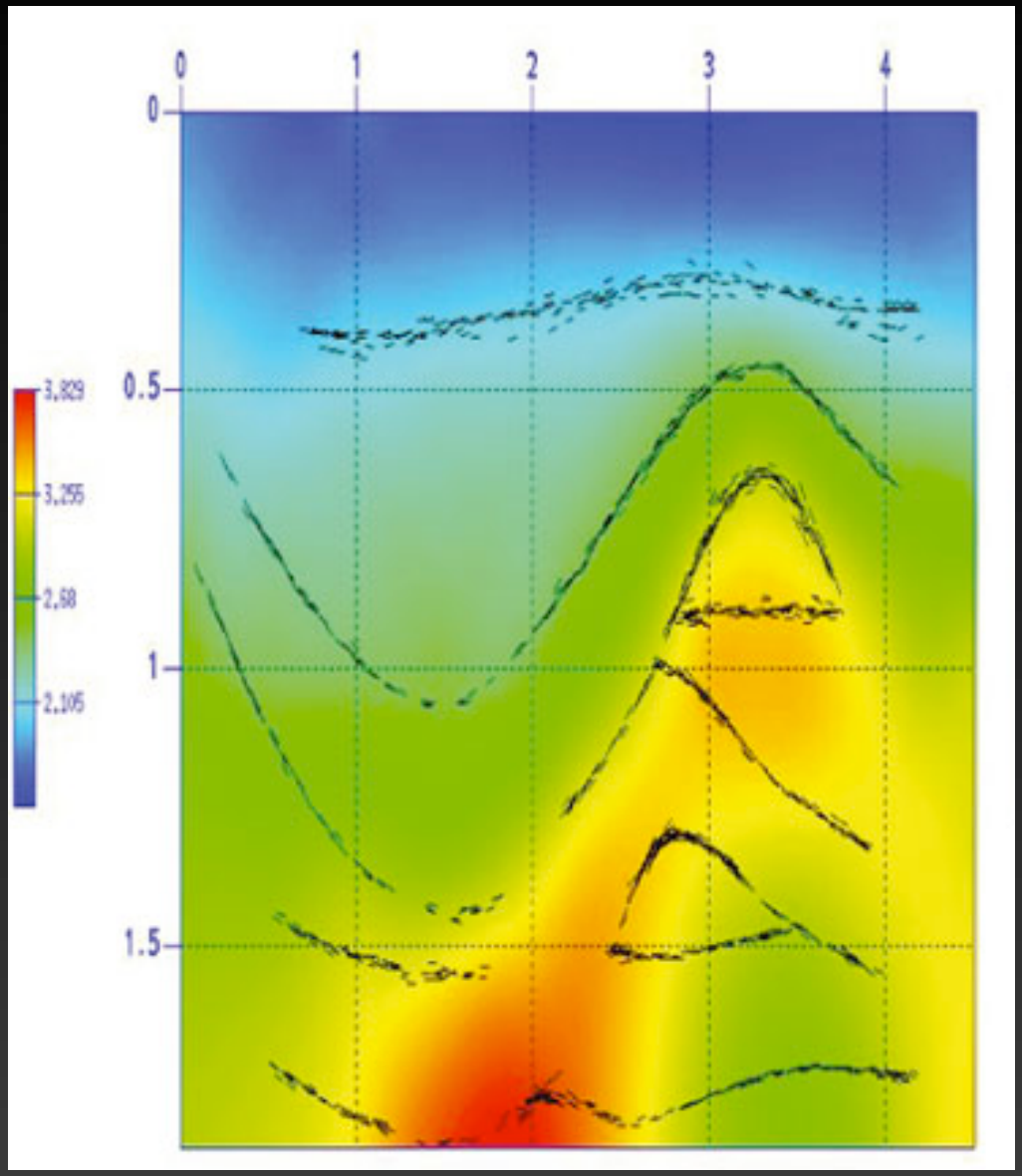


Final velocity

Fei et al., 2009

Ray-based strategies

Grid-based

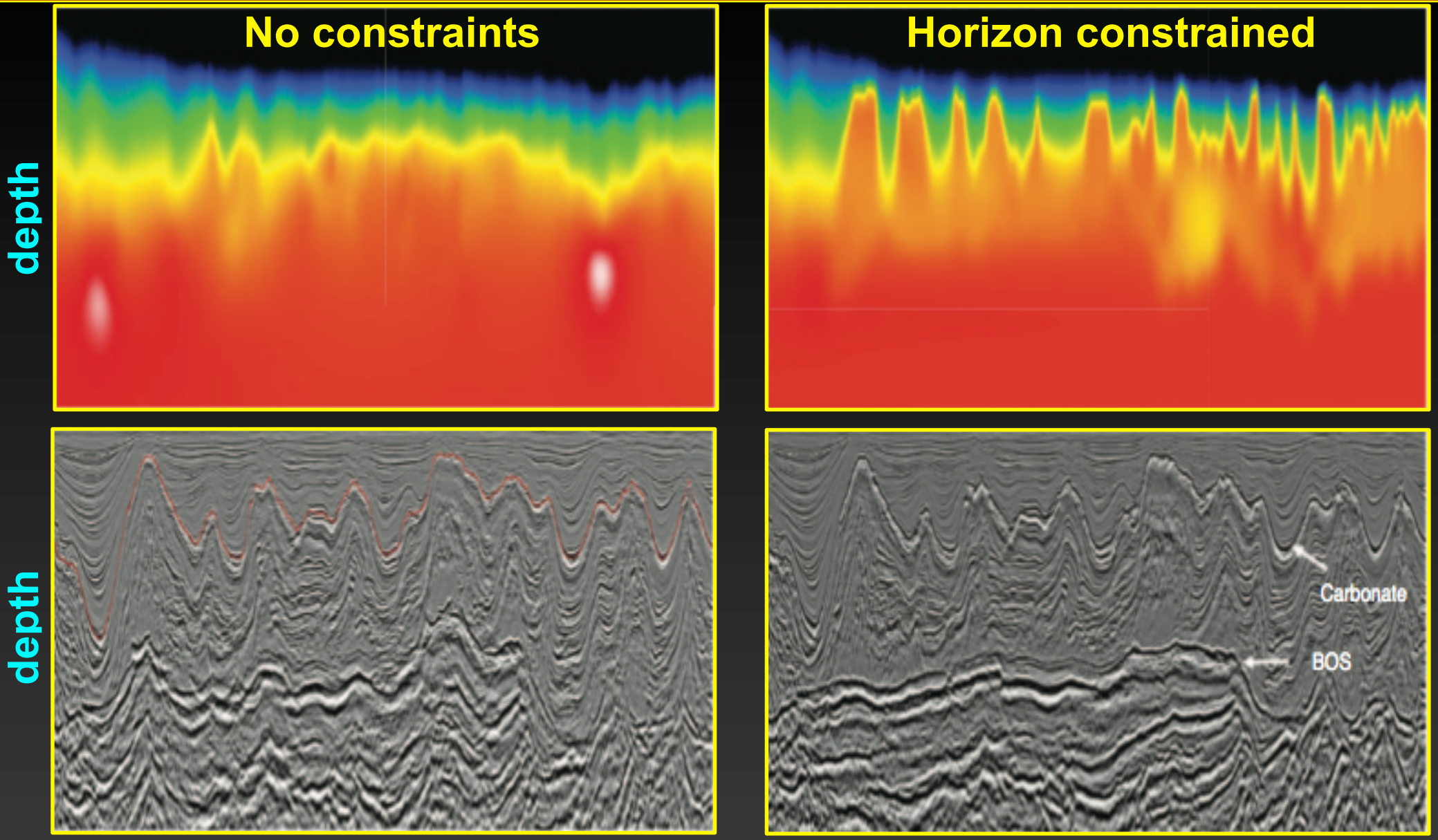


www.sintef.no

Horizon-based

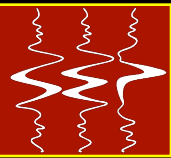
Jones et al., 1998

Hybrid tomography



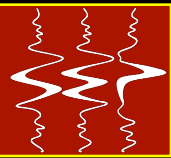
Wang et al., 2008

3D-ISWET as routine processing



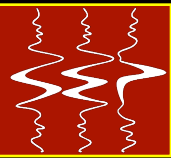
- **Reduce cost**

3D-ISWET as routine processing



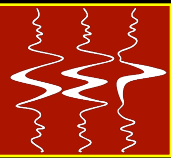
- **Reduce cost**
- **Improve flexibility**

3D-ISWET as routine processing



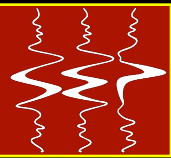
- **Reduce cost**
- **Improve flexibility**
- **Keep robustness**

Reducing 3D-ISWET cost



- **Decrease data size**

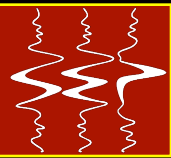
Reducing 3D-ISWET cost



- **Decrease data size**

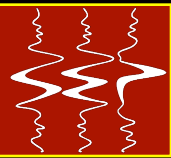
- **Solve in a target-oriented manner**
  - **Wavefield propagation restricted to the inaccurate velocity region**

Improving 3D-ISWET flexibility



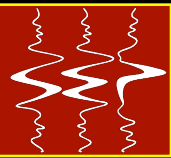
- **Incorporate strategies from ray-based methods into ISWET**

Improving 3D-ISWET flexibility



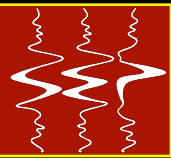
- **Incorporate strategies from ray-based methods into ISWET**
  - **Use image-space generalized wavefields**

Keeping 3D-ISWET robustness



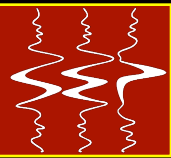
- **Guarantee correct kinematics and reasonable amplitudes**

Outline



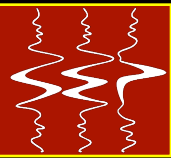
- **Generalized-source domain**
- **Pre-stack exploding-reflector model**
- **Image-space phase-encoded wavefields**
- **3D-field data ISWET example**
- **Conclusions**

Generalized-source domain



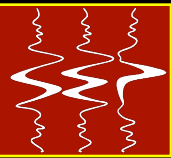
- **Wavefields combined using linearity of wave propagation**

Generalized-source domain



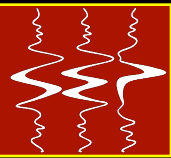
- **Wavefields combined using linearity of wave propagation**
  - **Smaller number of seismic experiments**

Generalized-source domain



- **Wavefields combined using linearity of wave propagation**
  - **Smaller number of seismic experiments**
  - **Keeping intact kinematic information**

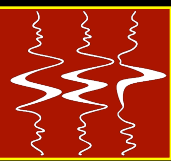
Generalized-source domain



- **Wavefields combined using linearity of wave propagation**
  - **Smaller number of seismic experiments**
  - **Keeping intact kinematic information**

- **Seismic acquisition**
  - **Simultaneous-sources**

Generalized-source domain

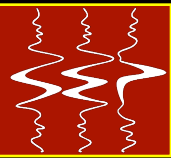


- **Wavefields combined using linearity of wave propagation**
  - **Smaller number of seismic experiments**
  - **Keeping intact kinematic information**

- **Seismic acquisition**
  - **Simultaneous-sources**

- **Seismic processing**
  - **plane-wave encoding (Whitmore, 1995)**
  - **random-phase encoding (Romero et al., 2000)**
  - **controlled illumination (Rietveld et al., 1992)**

Generalized-source domain



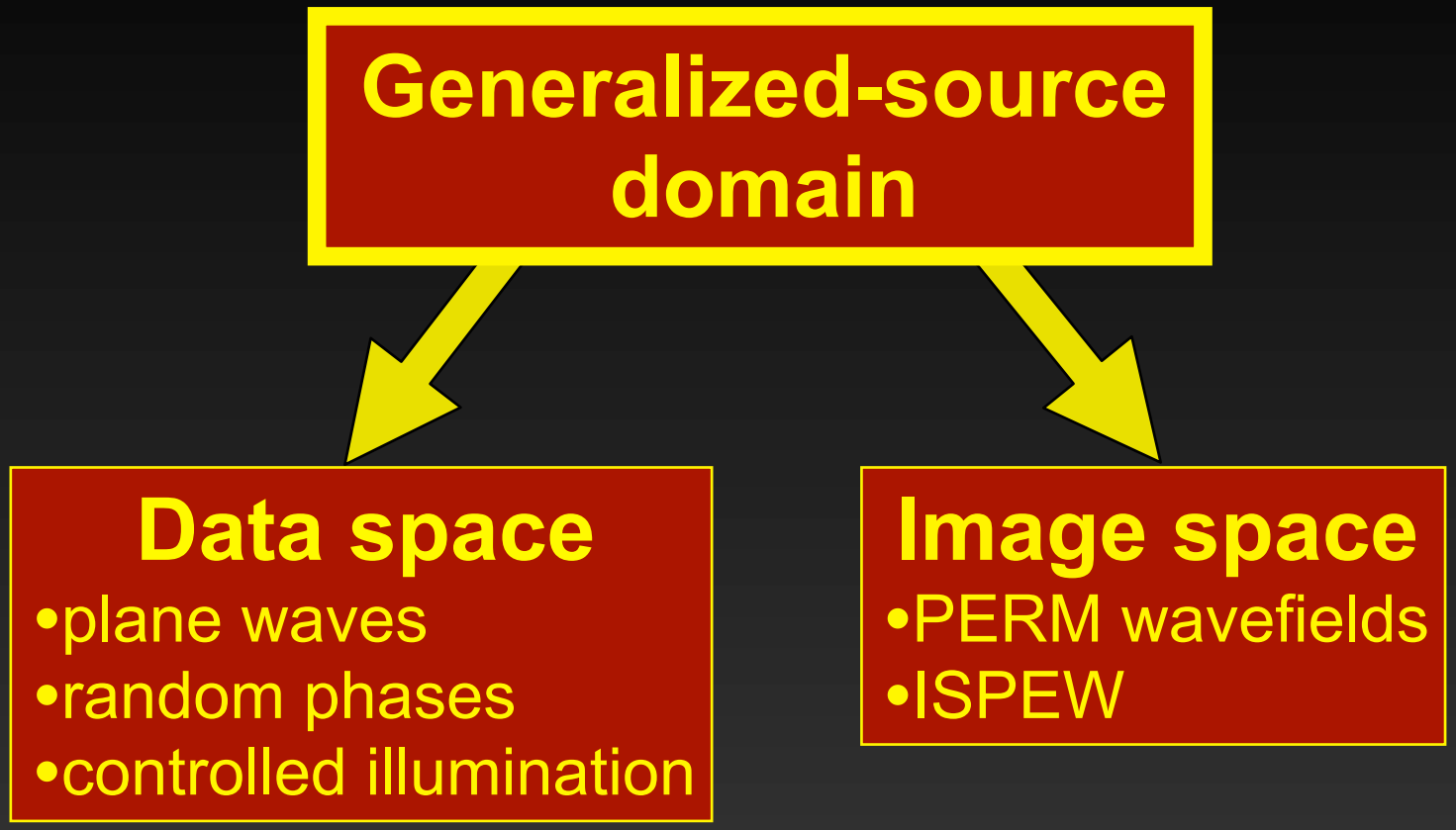
- **Data-space generalized sources**
  - **plane-wave encoding**
  - **random-phase encoding**
  - **controlled illumination**

Generalized-source domain

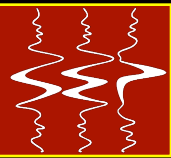
- **Data-space generalized sources**
  - **plane-wave encoding**
  - **random-phase encoding**
  - **controlled illumination**

- **Image-space generalized sources**
  - **Pre-stack exploding-reflector modeling - PERM (Biondi, 2006)**
  - **Image-space phase-encoded wavefields - ISPEW (Guerra and Biondi, 2008)**

Generalized-source domain

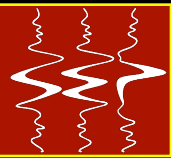


Outline



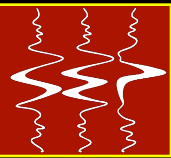
- ✓ Generalized-source domain
- **Pre-stack exploding reflector model**
- Image-space phase-encoded wavefields
- 3D-field data ISWET example
- Conclusions

Exploding reflectors



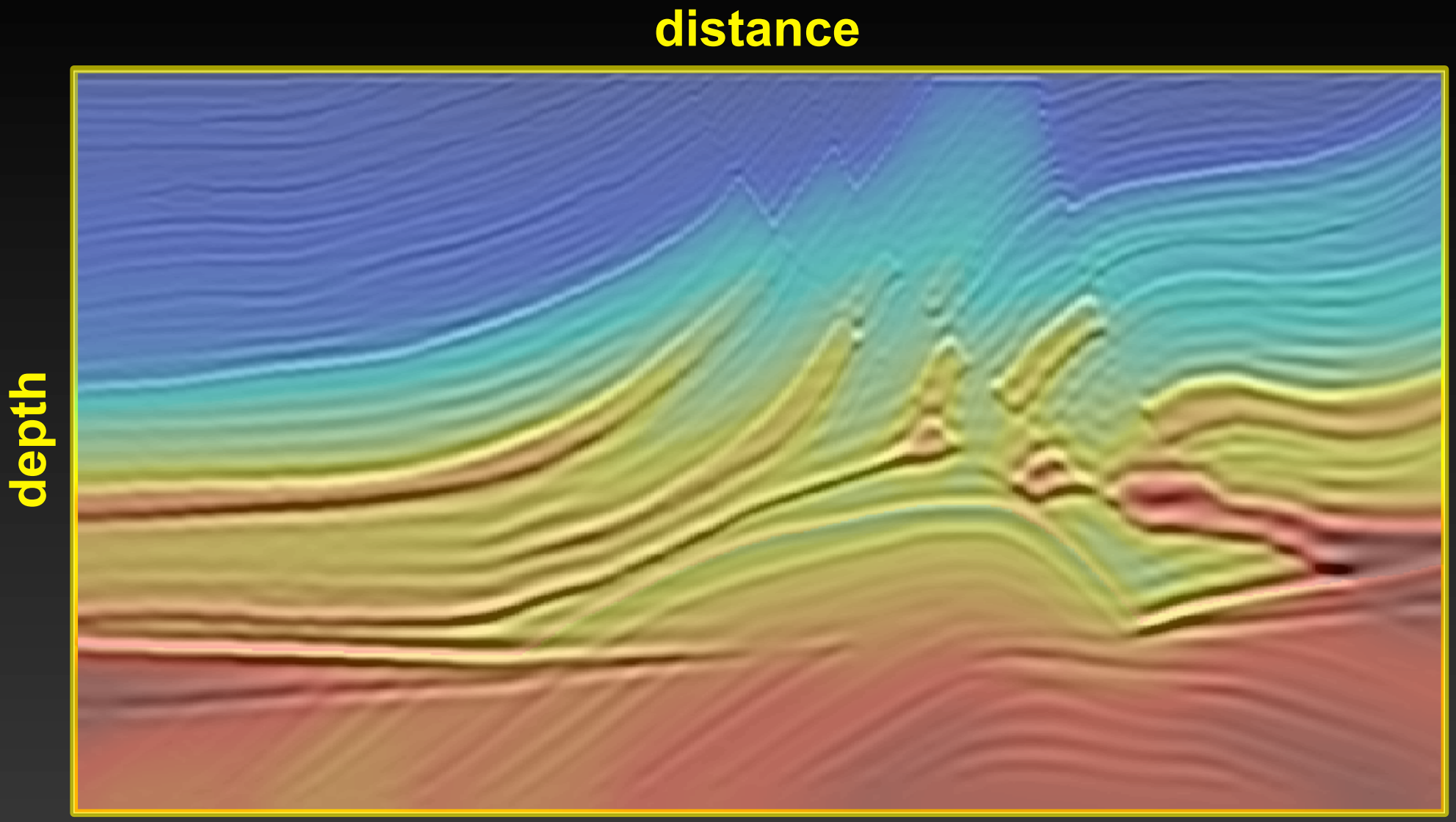
- **The exploding-reflector model synthesizes zero-offset data, assuming focused reflectors at zero-subsurface-offset**

Exploding reflectors

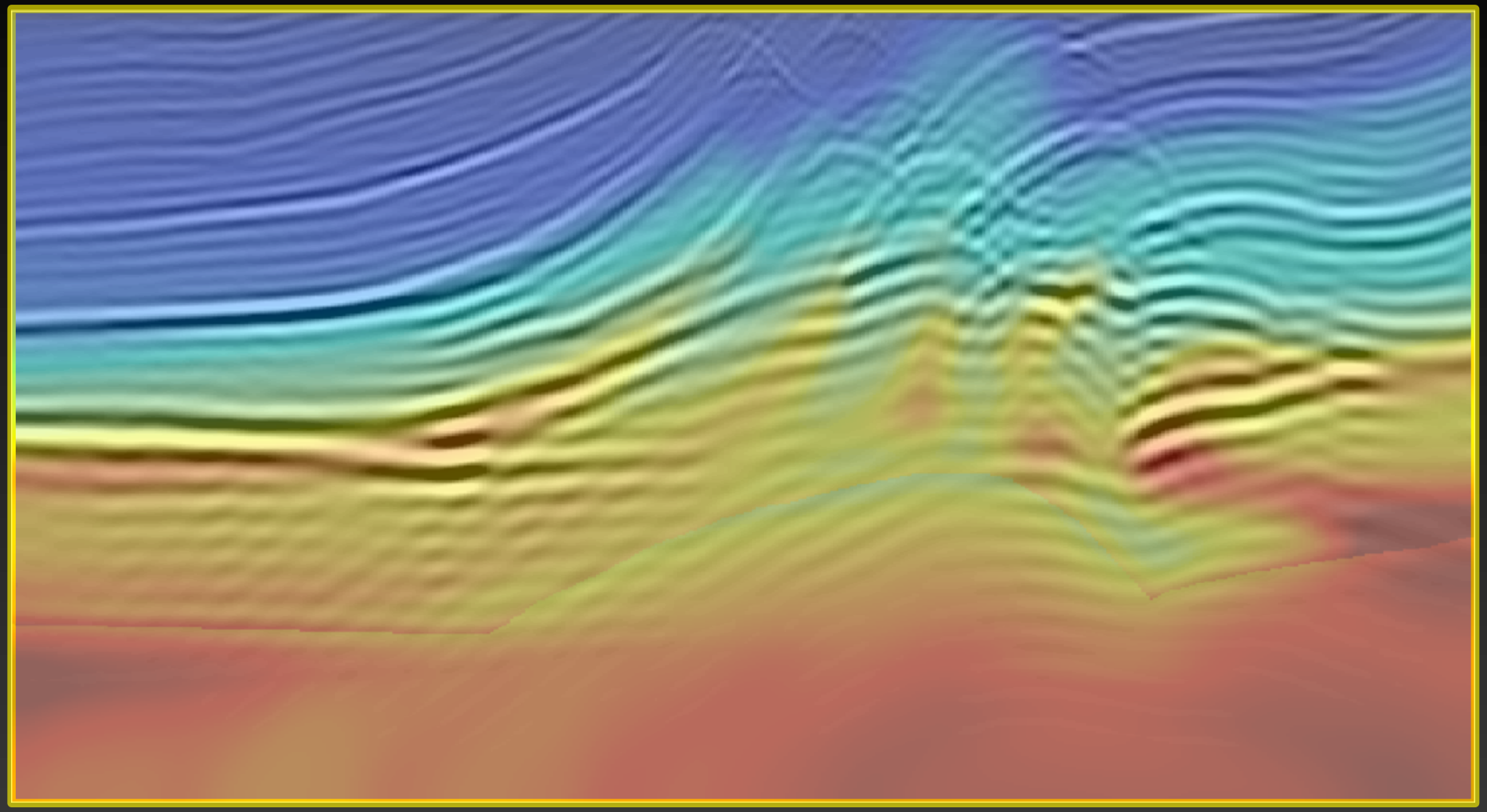


- **The exploding-reflector model synthesizes zero-offset data, assuming focused reflectors at zero-subsurface-offset**
  - **Accurate velocity**
  - **Complete illumination**

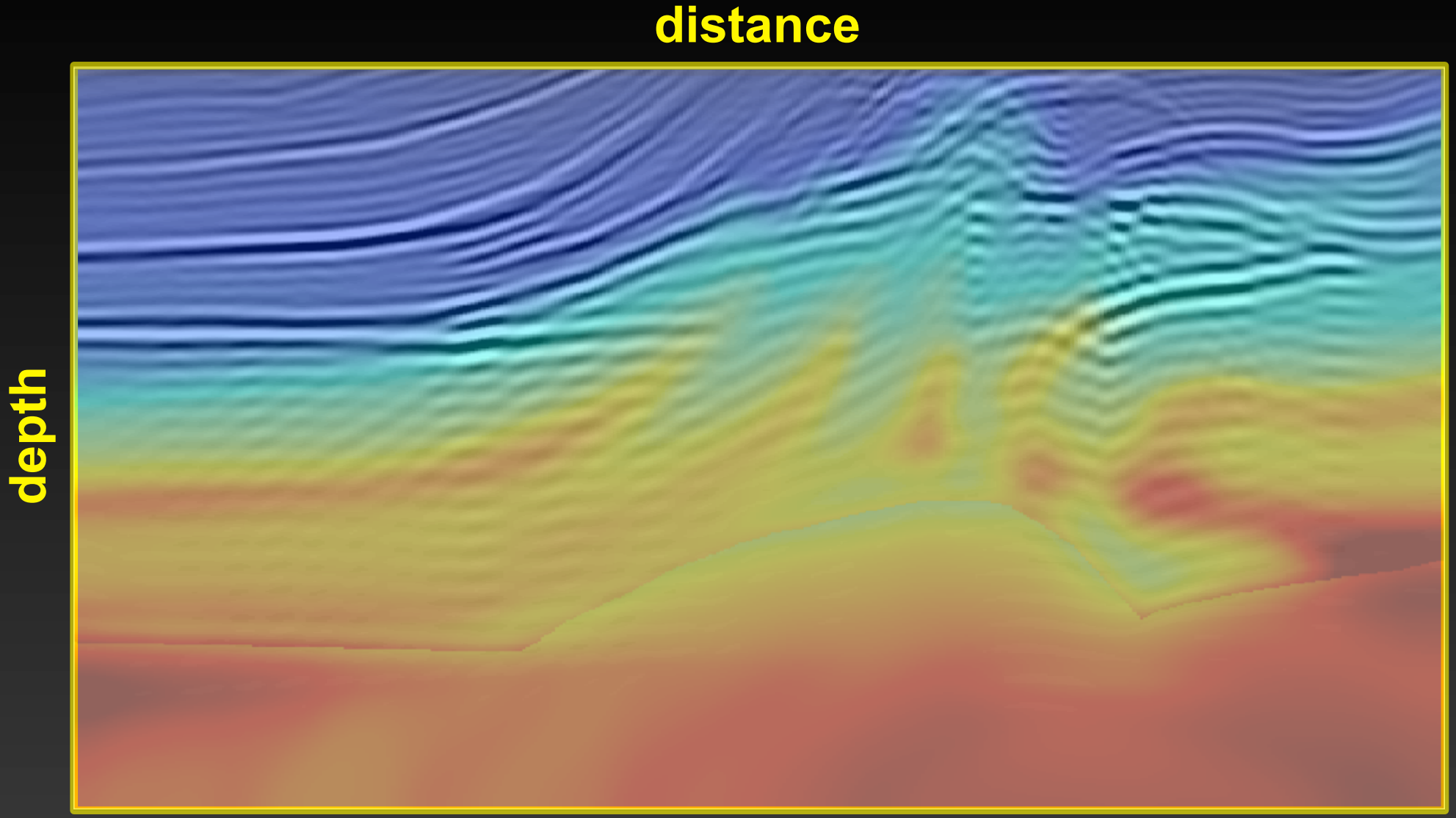
Exploding reflectors



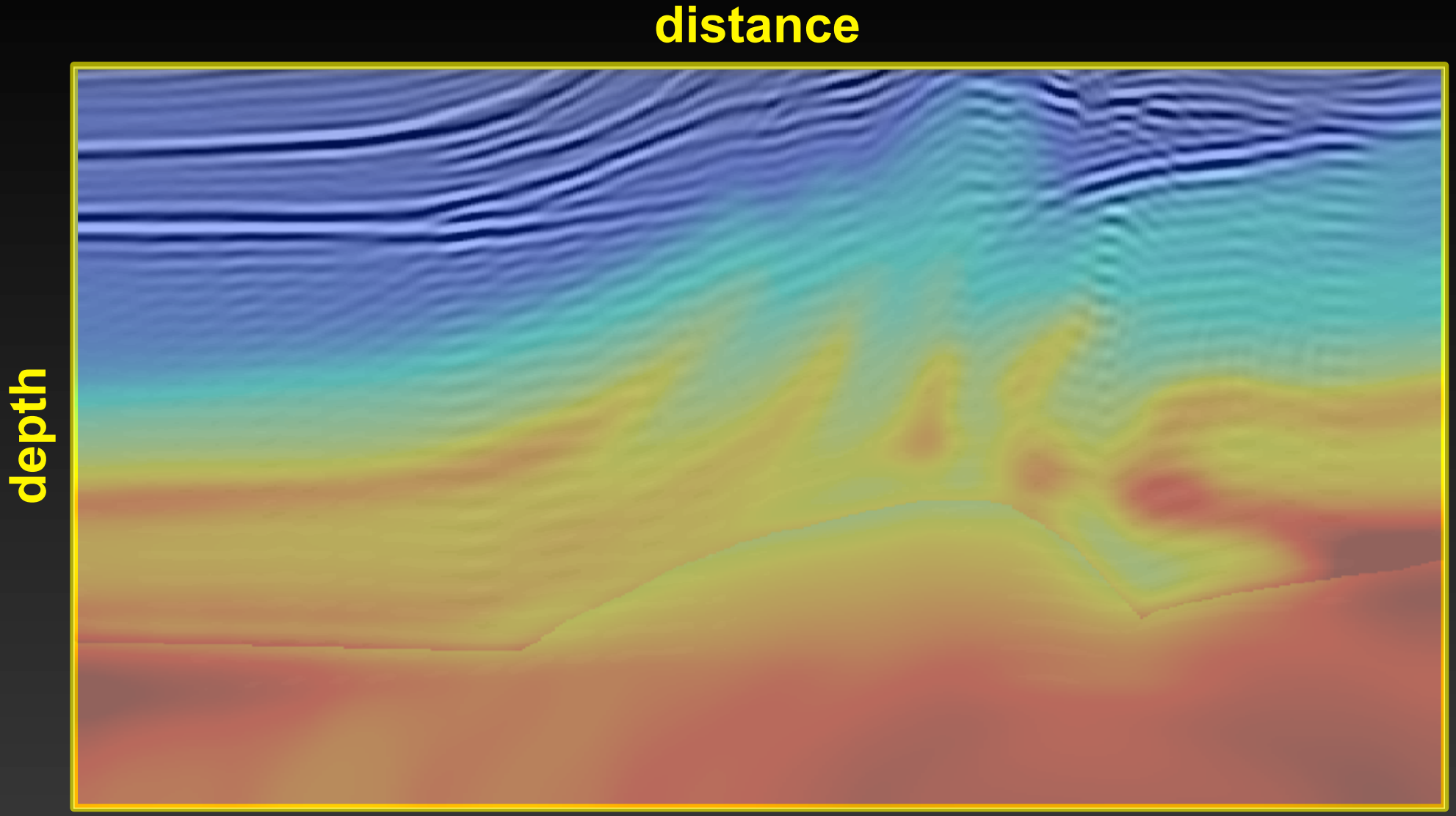
Exploding reflectors



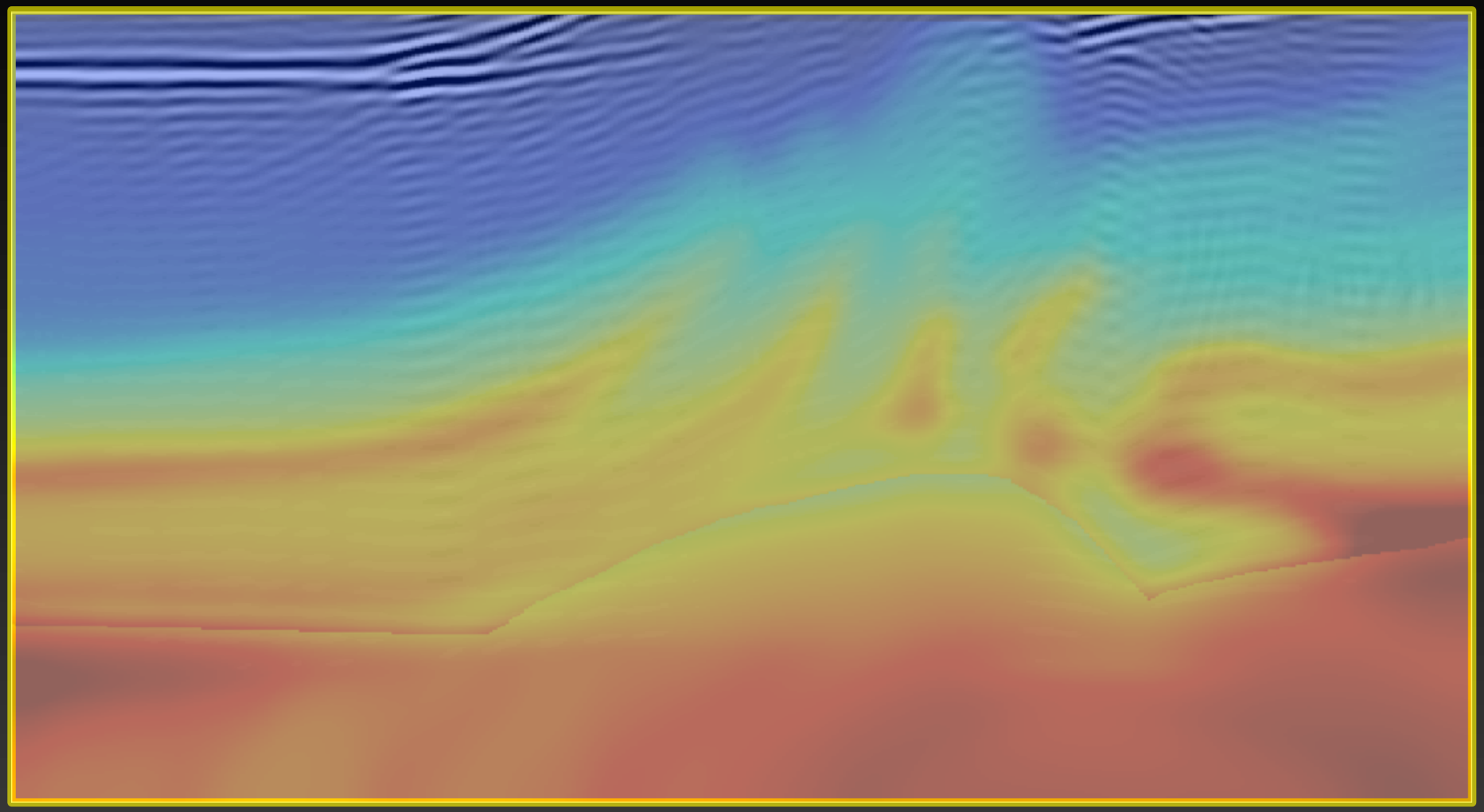
Exploding reflectors



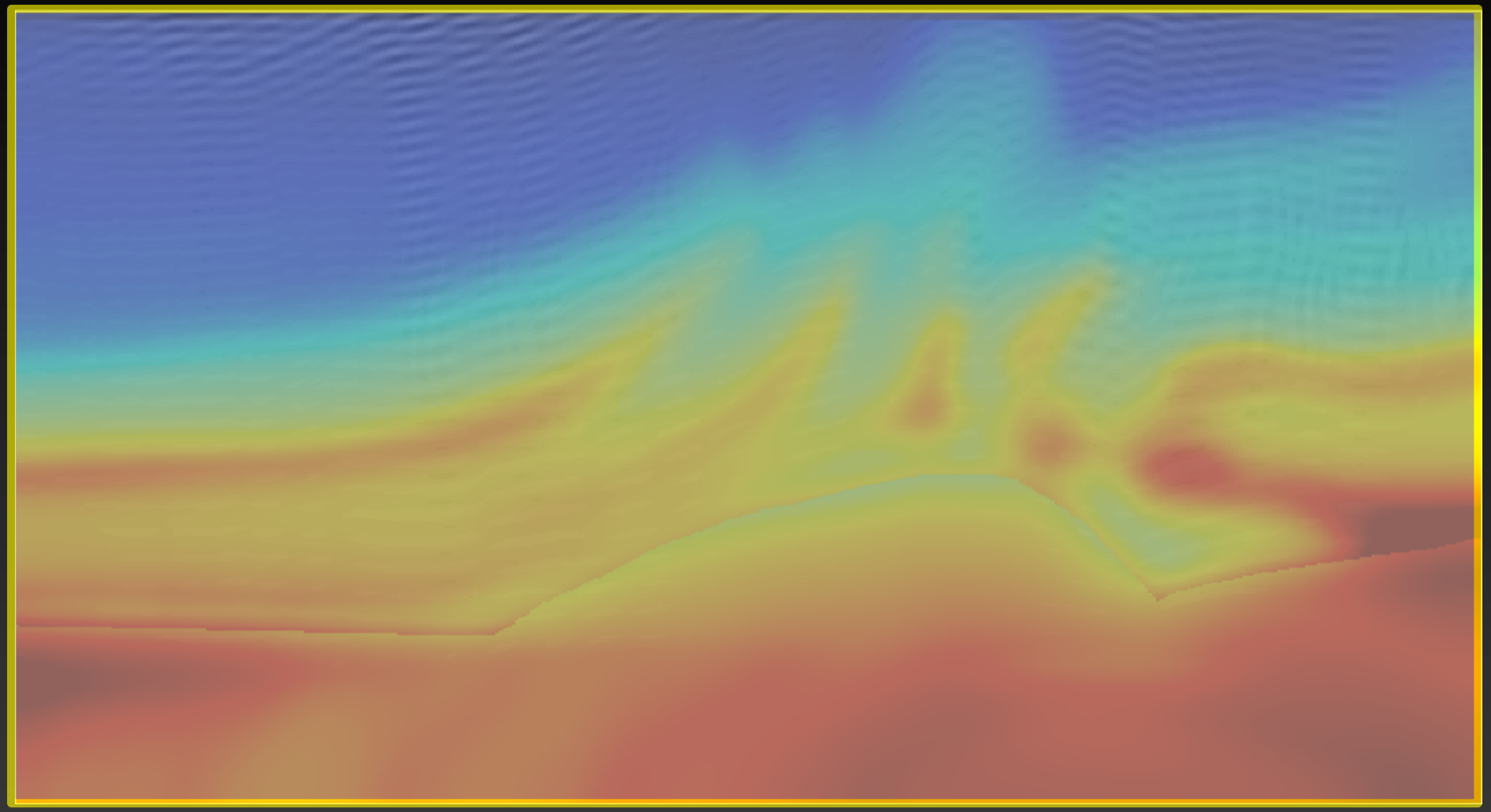
Exploding reflectors



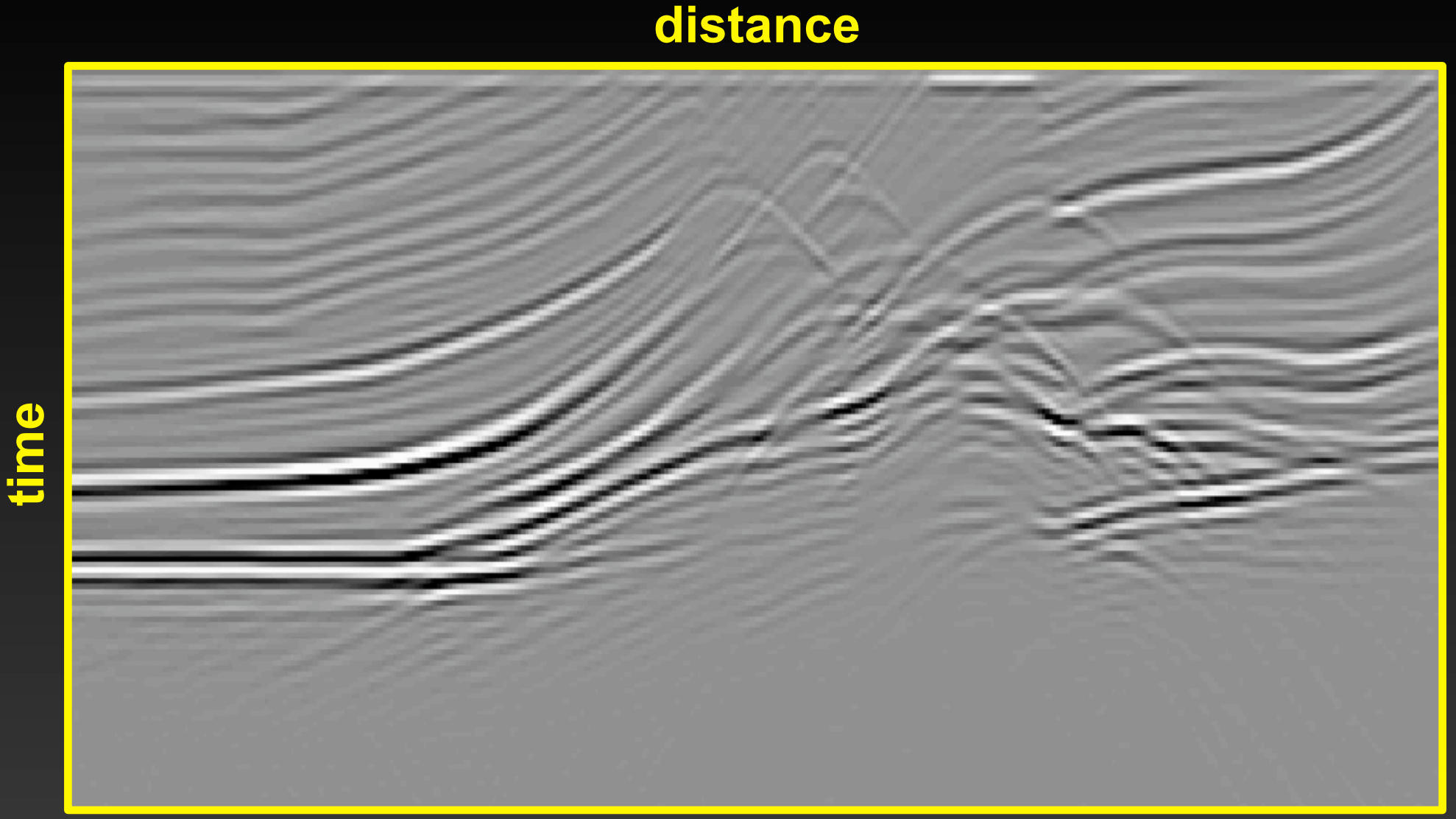
Exploding reflectors



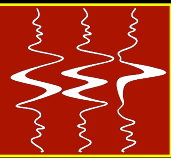
Exploding reflectors



Zero-offset section

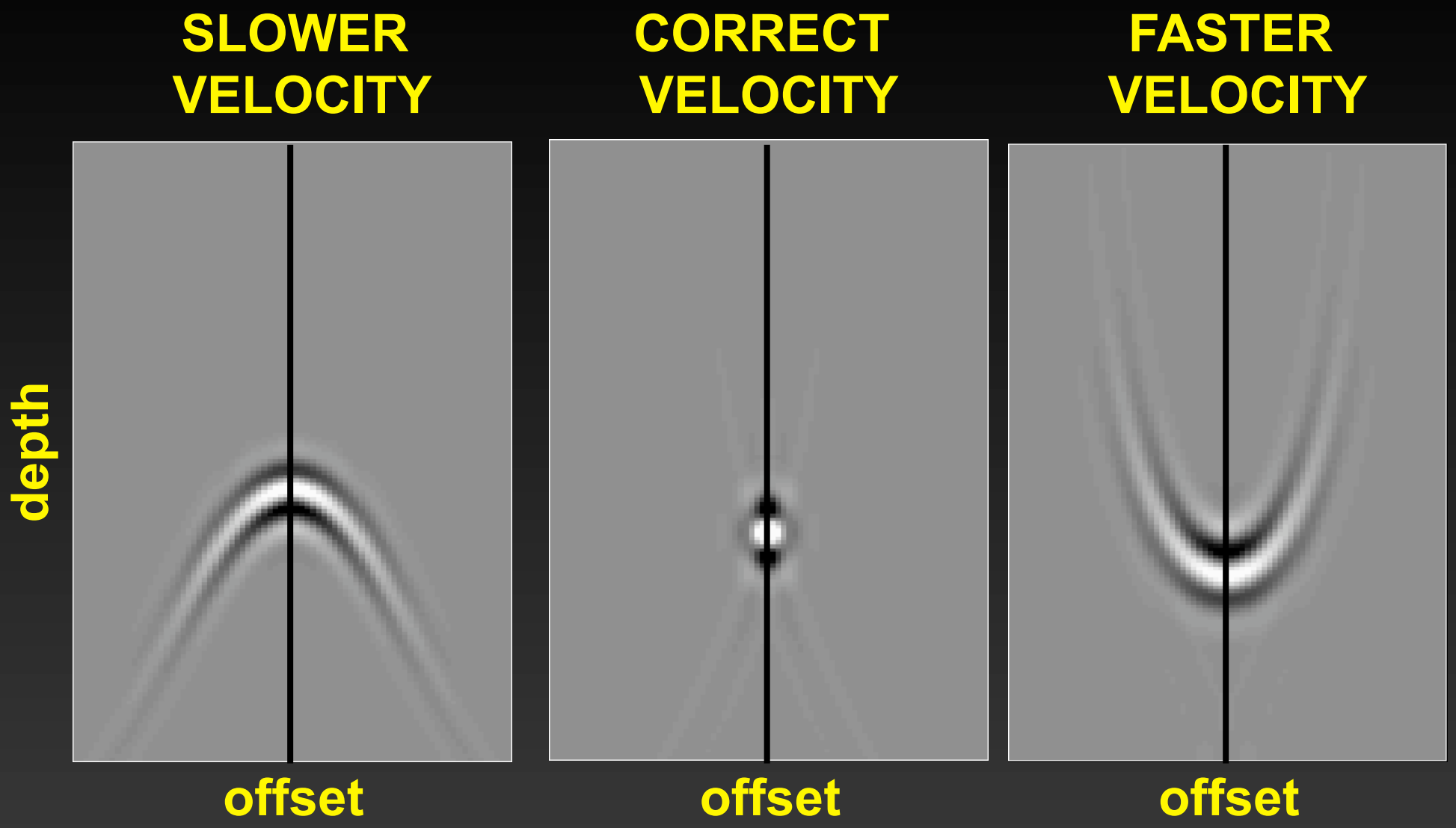


PERM

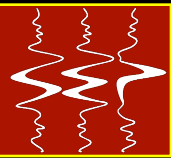


- **Generalizes the exploding-reflector model**
  - **Subsurface-offset gathers are used to model source and receiver wavefields**

Subsurface-offset gathers

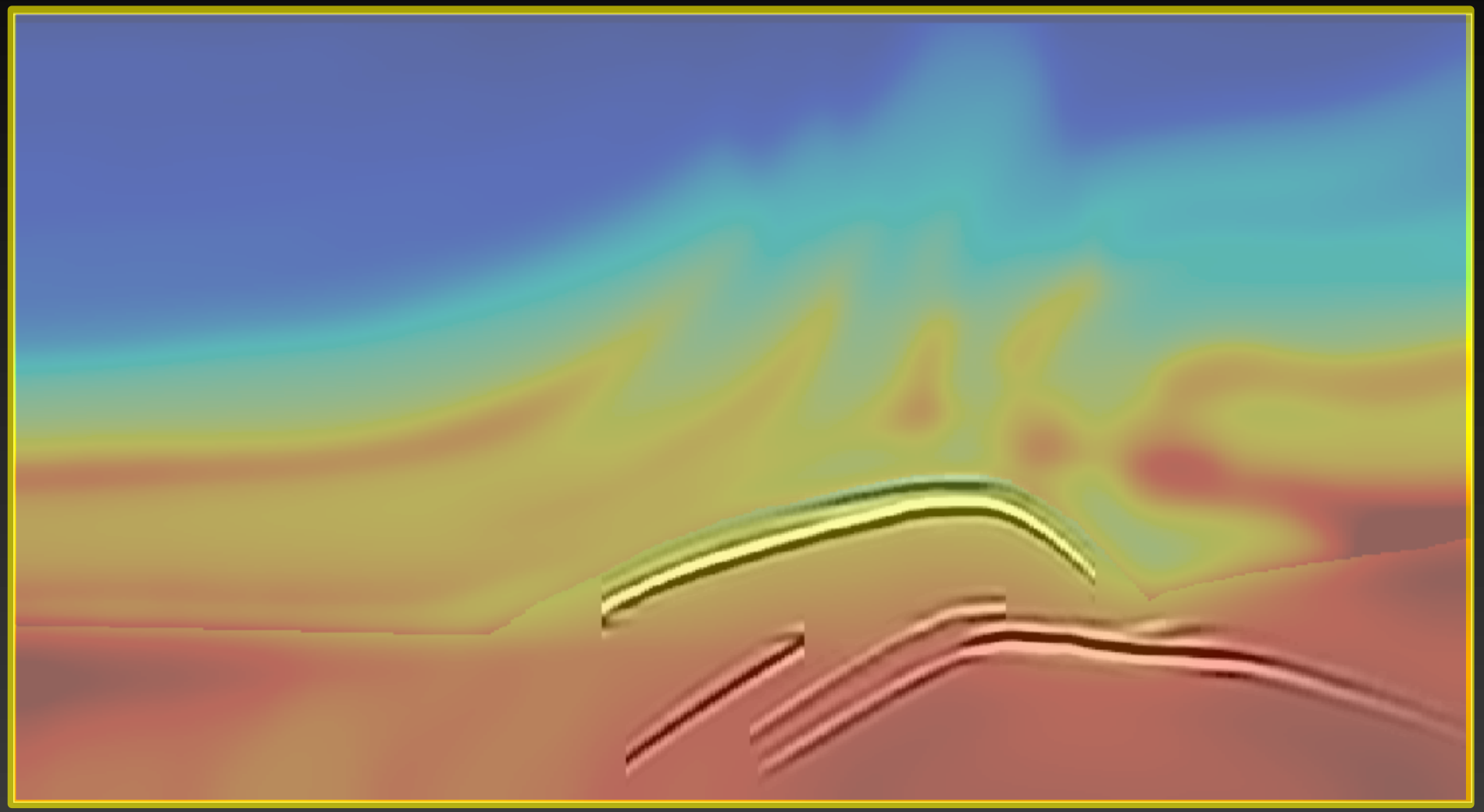


PERM

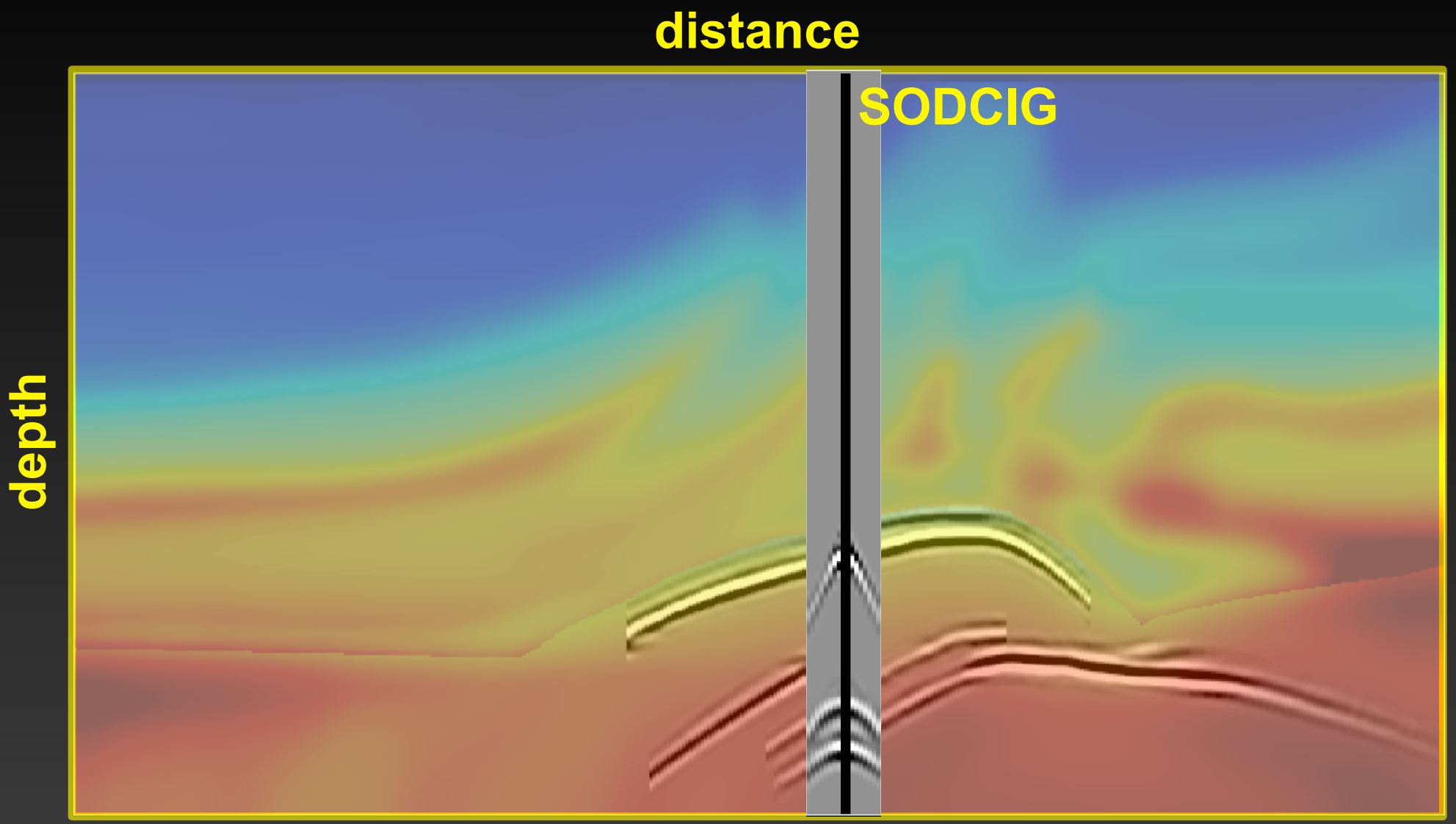


- **Generalizes the exploding-reflector model**
  - **Subsurface-offset gathers are used to model source and receiver wavefields**
- **Uses selected reflectors as the initial conditions**
  - **Naturally incorporates a horizon-based tomography strategy into wave-extrapolation methods**

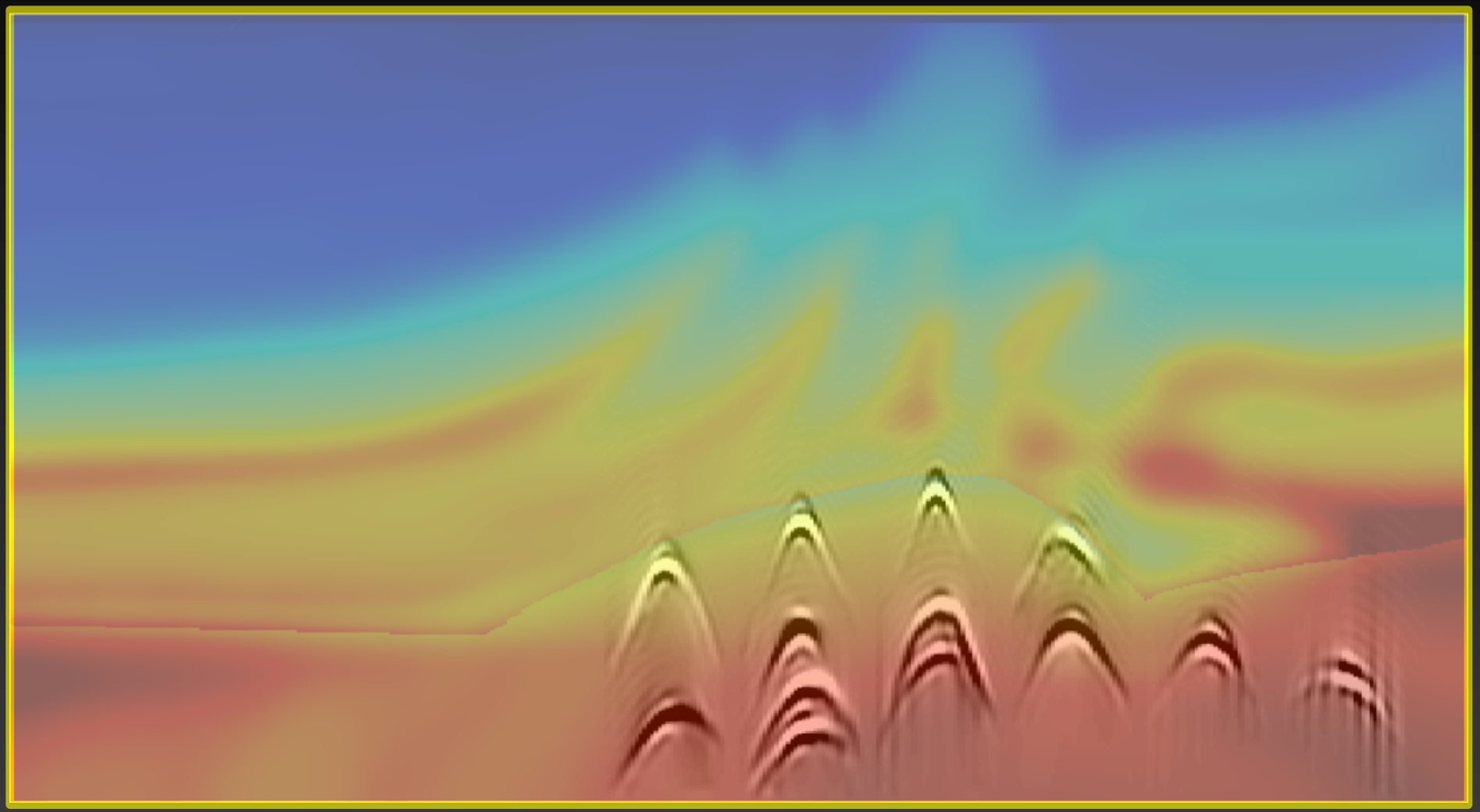
Modeling receiver wavefield



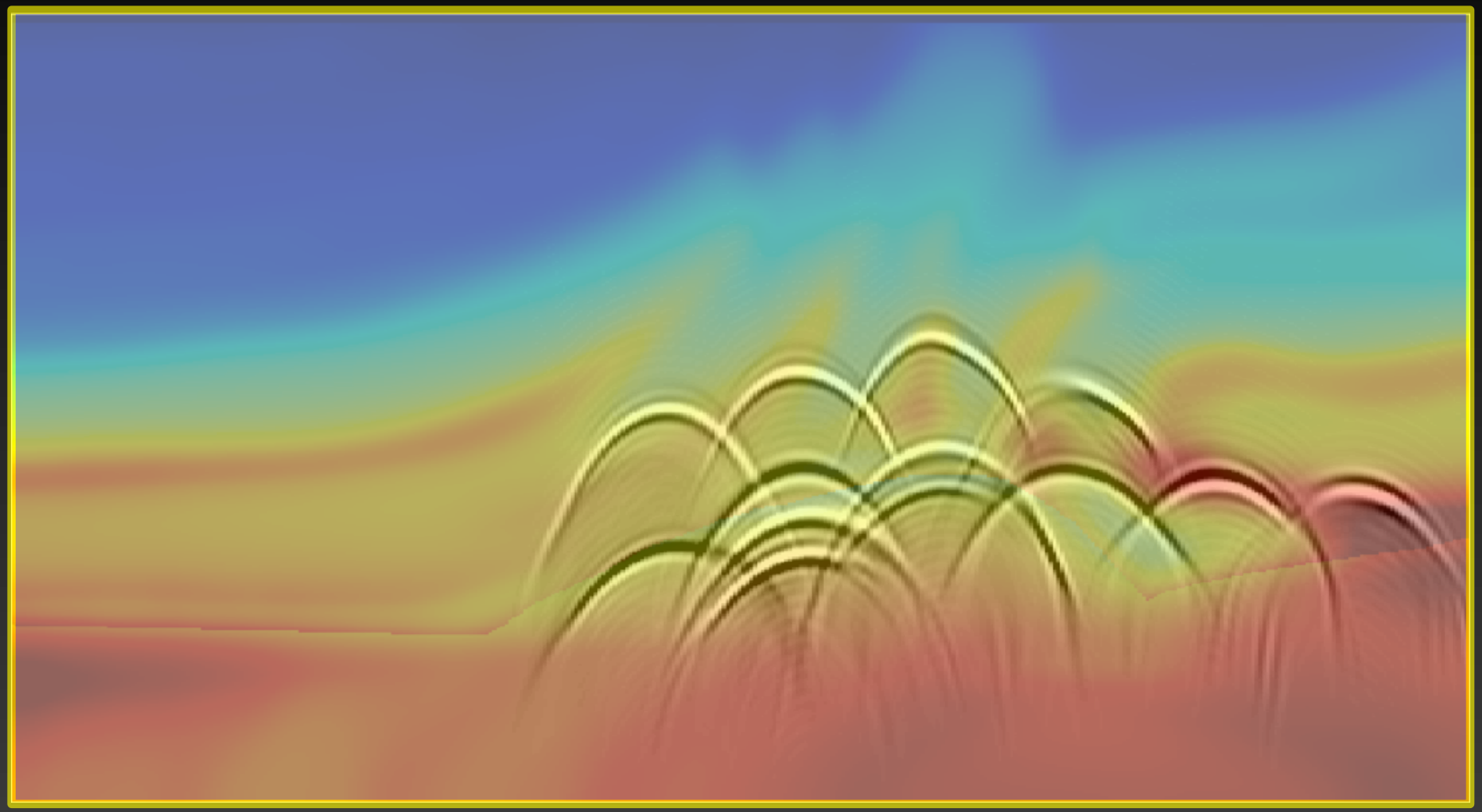
Modeling receiver wavefield



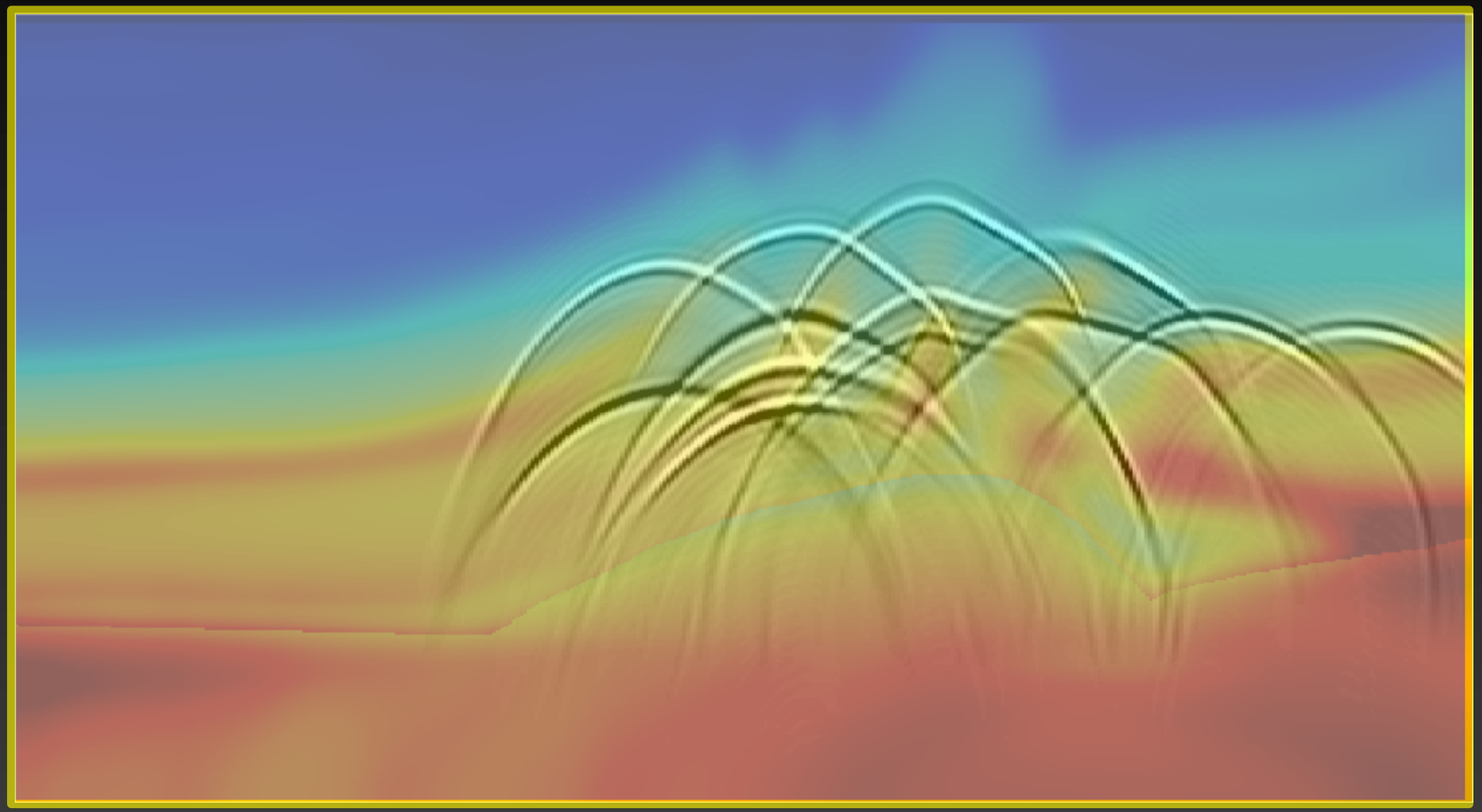
Modeling receiver wavefield



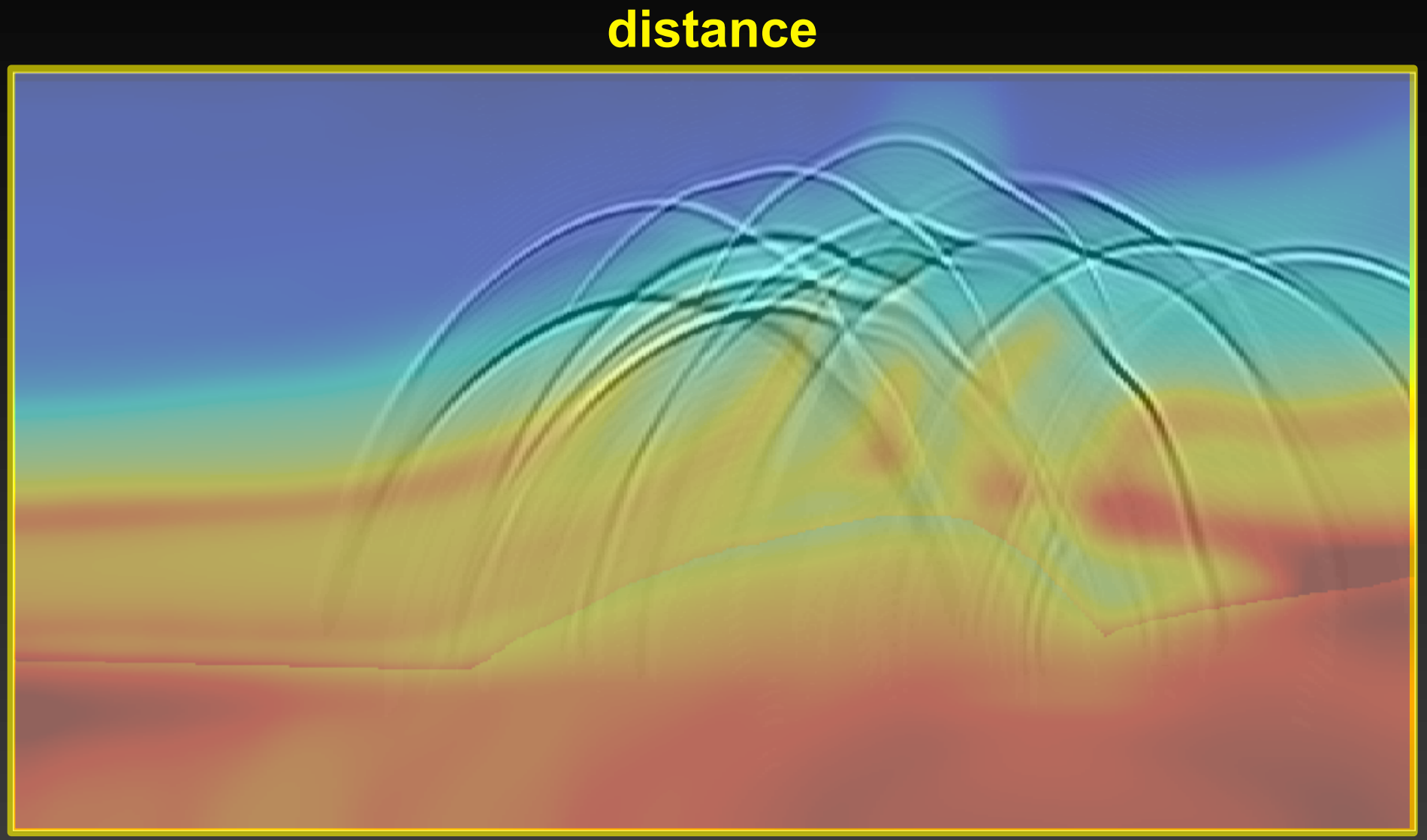
Modeling receiver wavefield



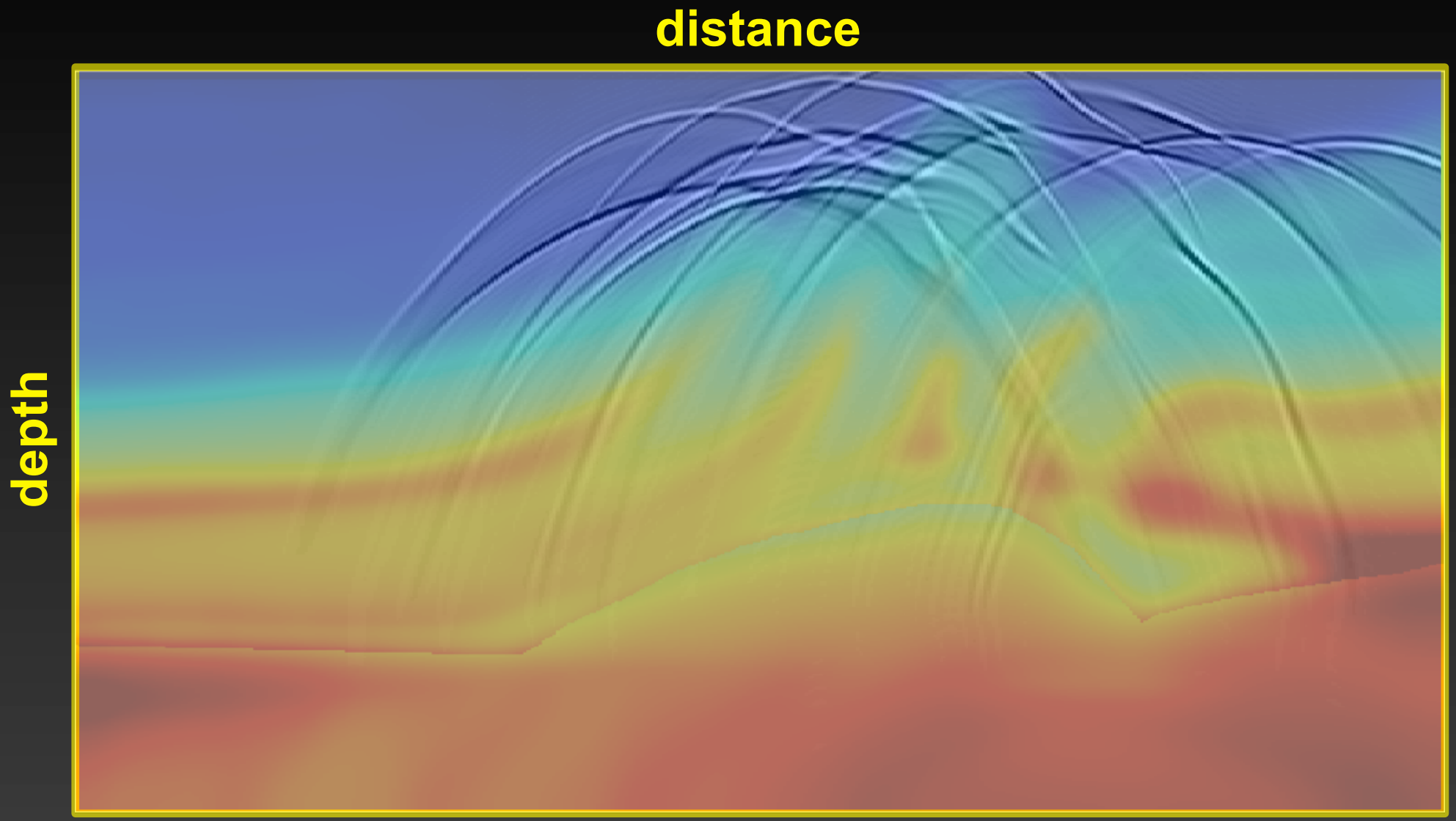
Modeling receiver wavefield



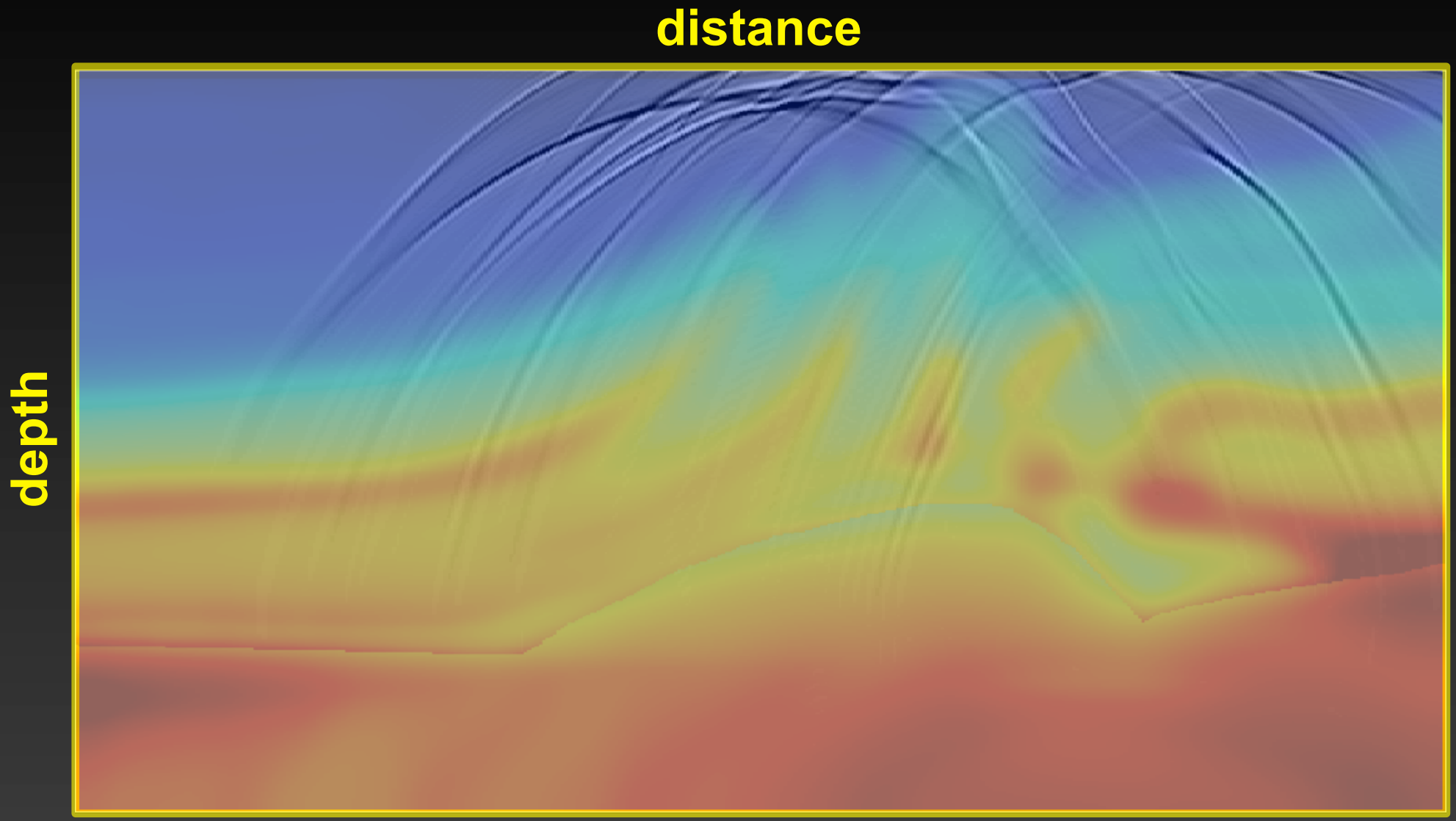
Modeling receiver wavefield



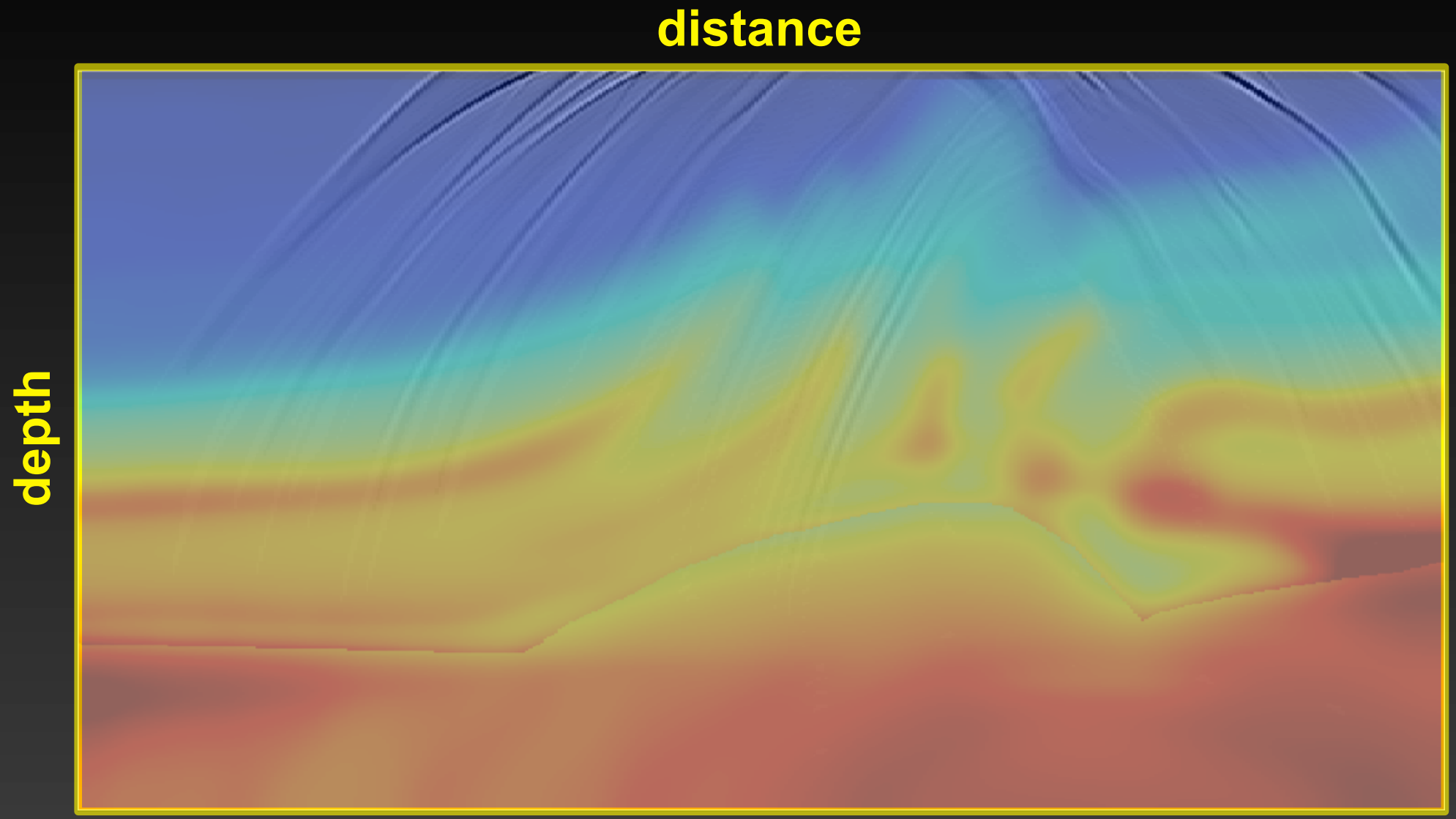
Modeling receiver wavefield



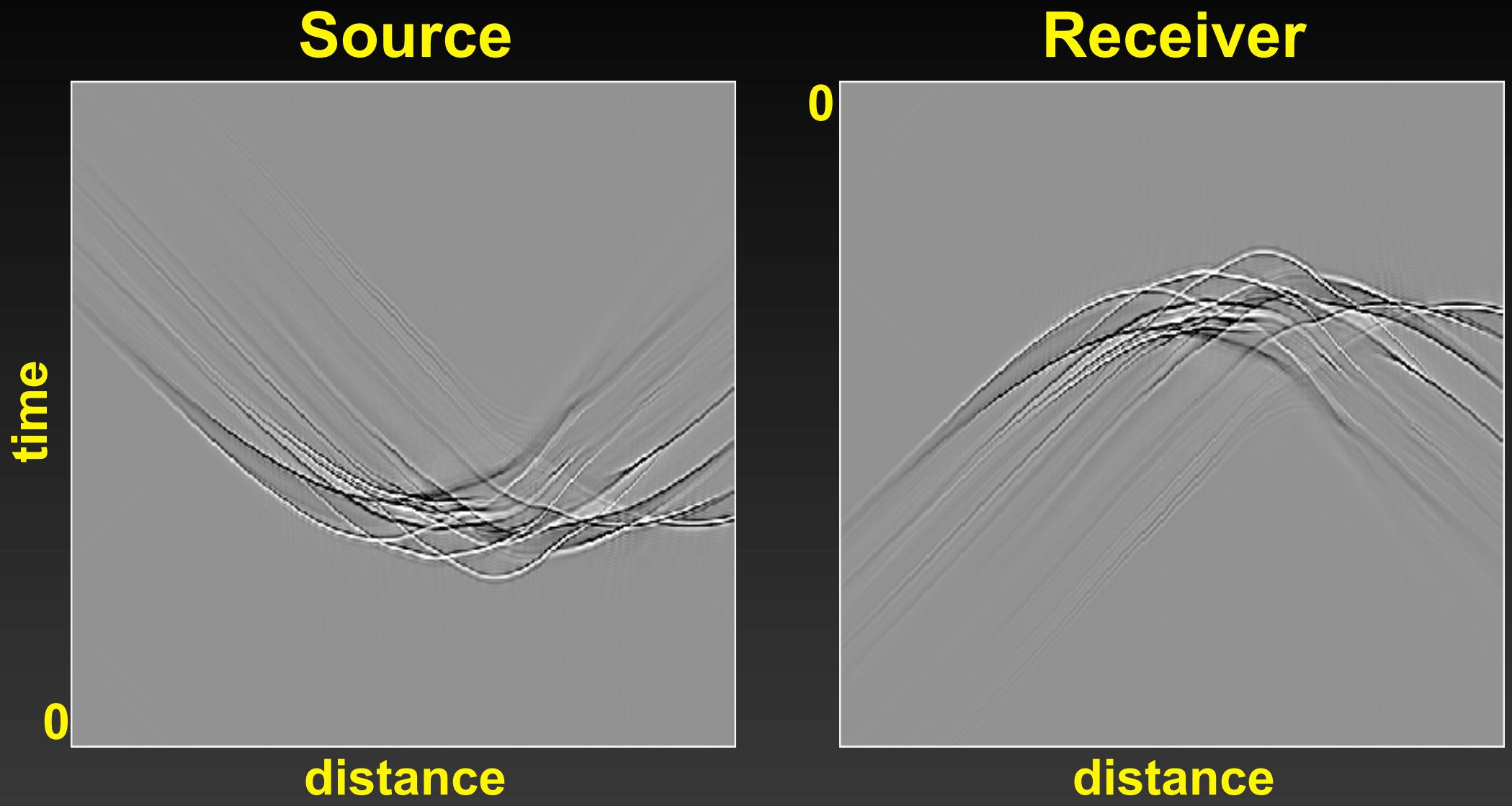
Modeling receiver wavefield



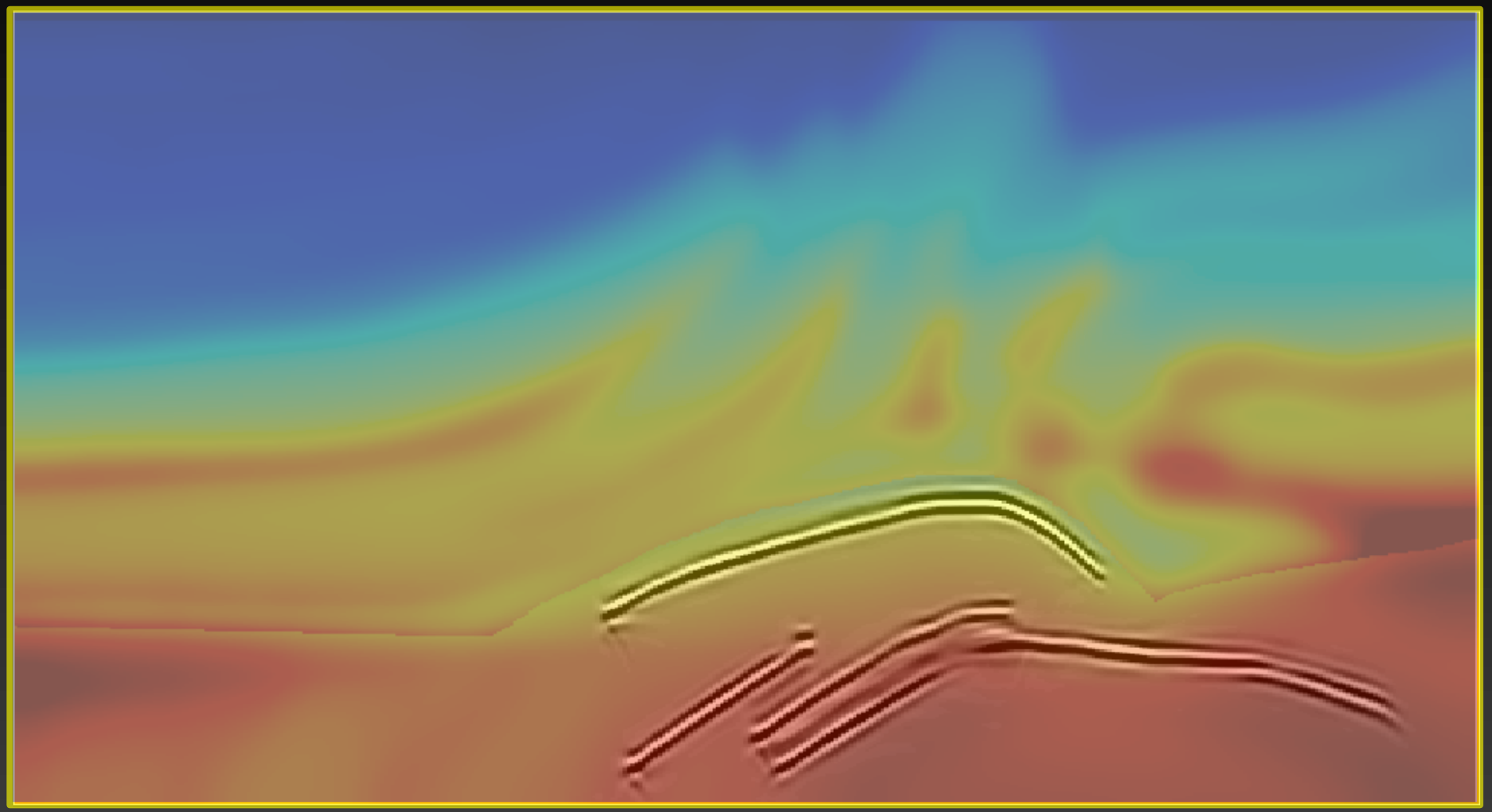
Modeling receiver wavefield



PERM data



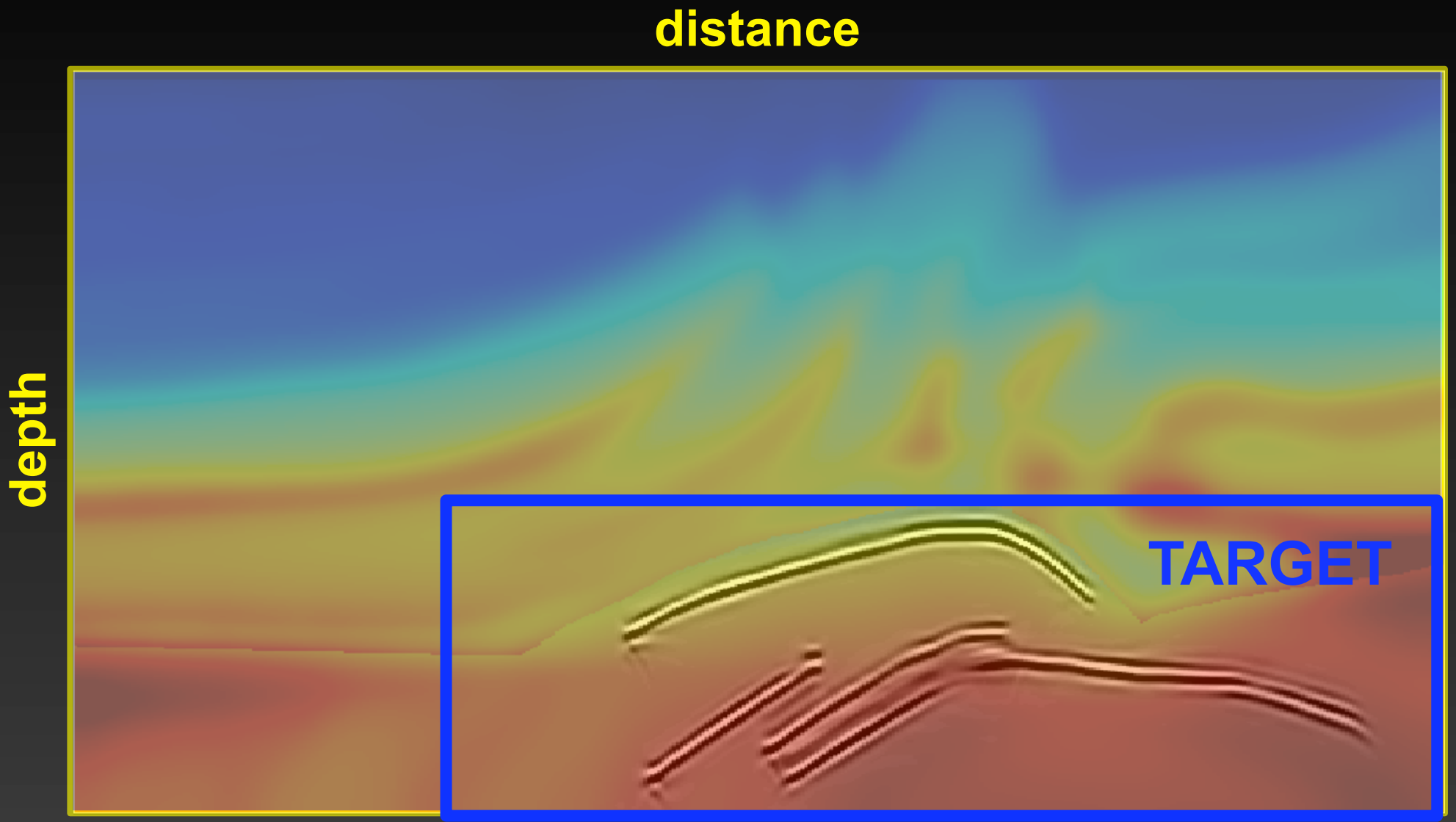
Migration of PERM data



PERM

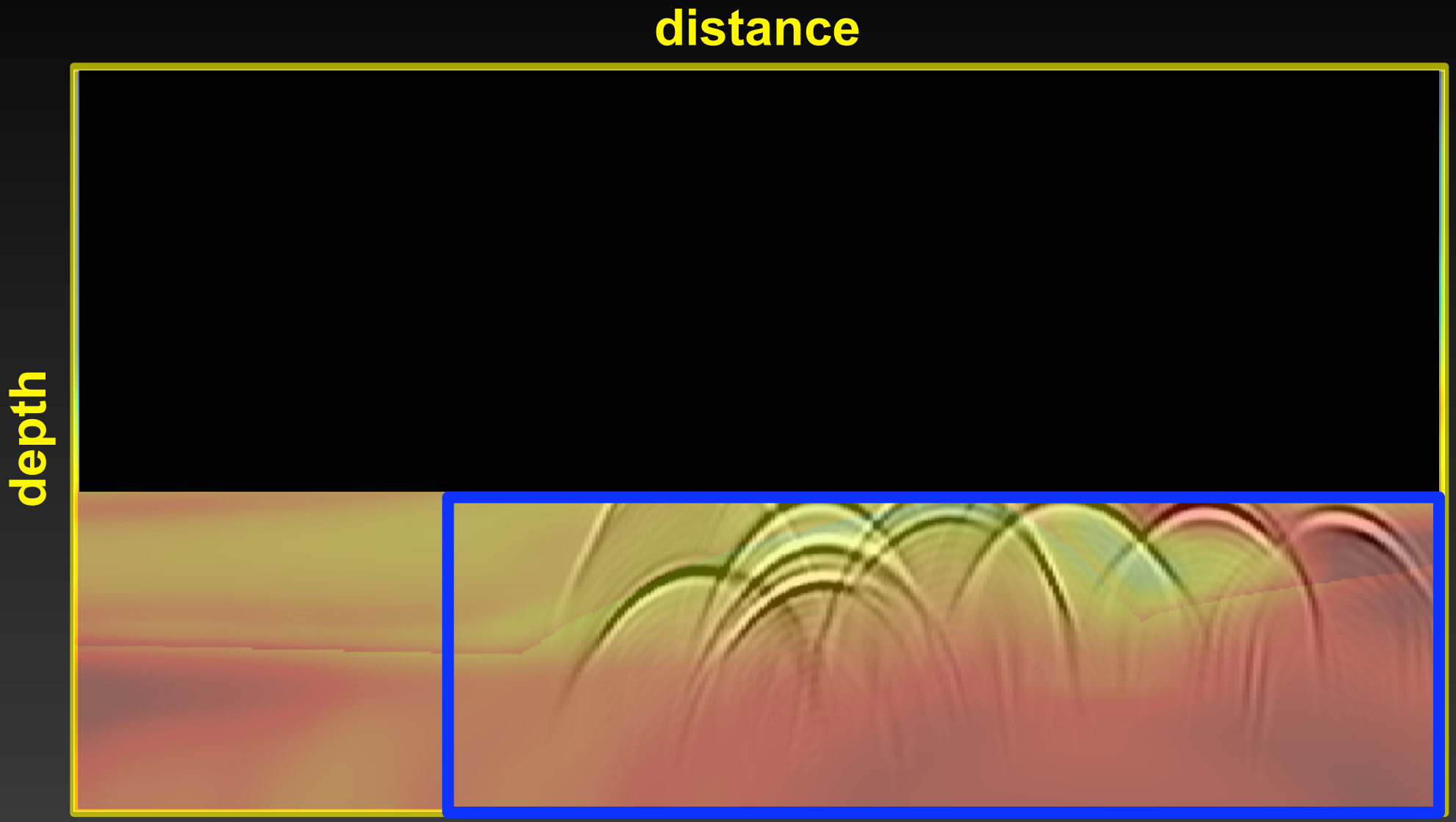
- **Generalizes the exploding-reflector model**
- **Uses selected reflectors as the initial conditions**
- **Number of wavefields depends on the separation of SODCIGs injected into the modeling**

Target-oriented strategy



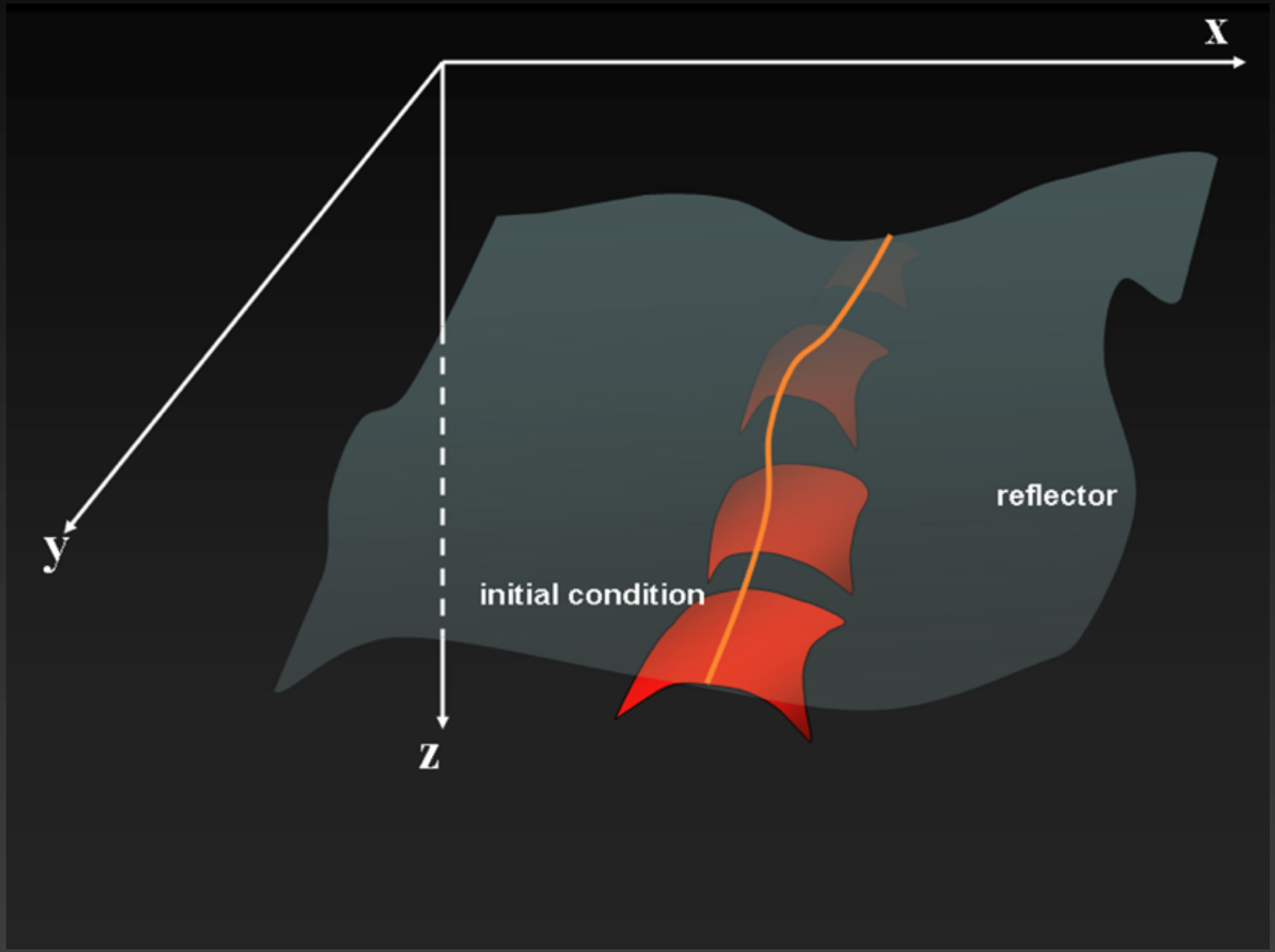
Target-oriented strategy

Wavefields collected at the top of the target



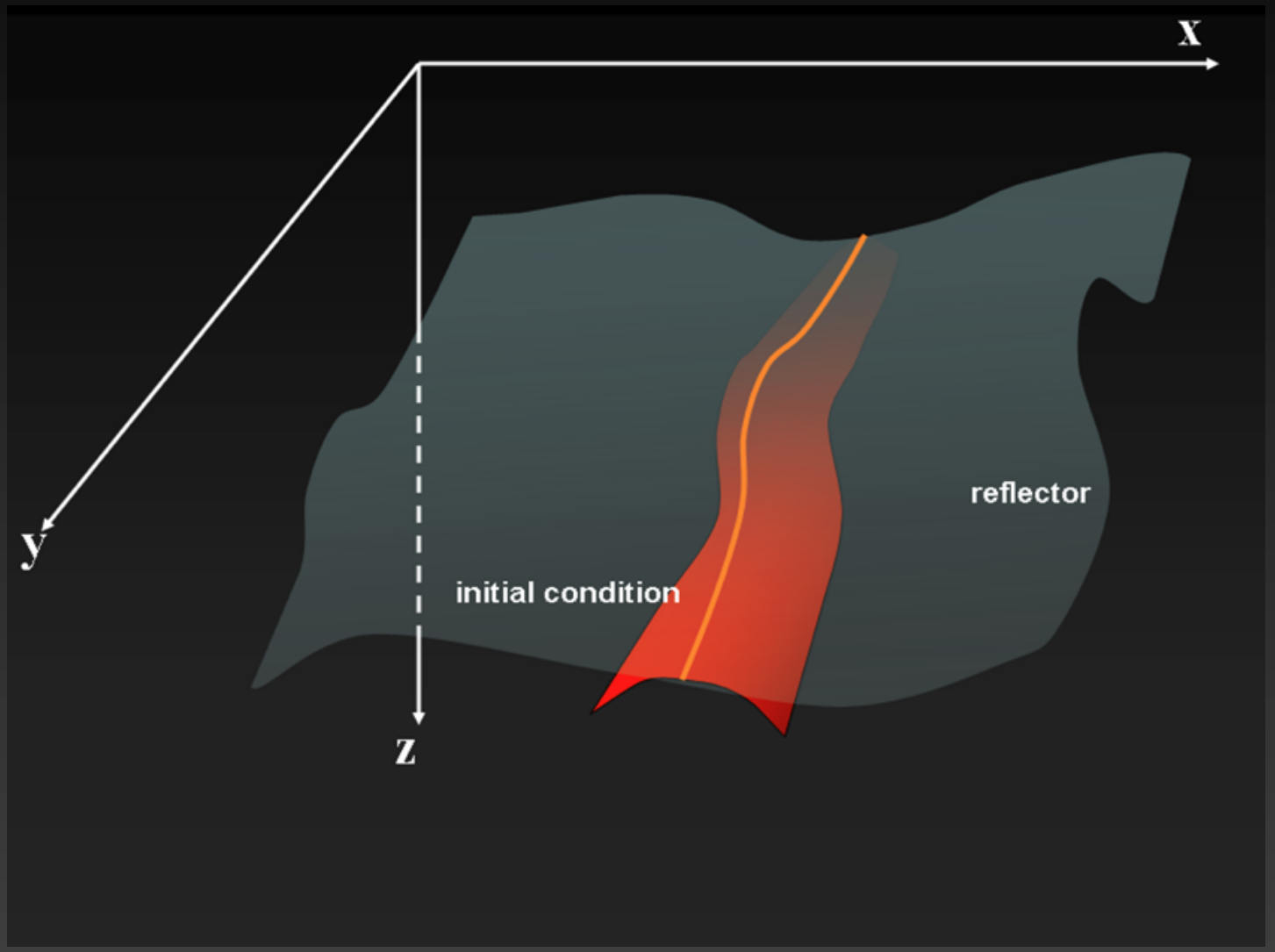
In 3D

- **About 1,000 PERM wavefields**
  - **Using crossline offsets**

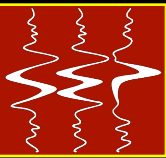


Using Common-azimuth migrated images

- **Less than 100 PERM wavefields**
  - **Only inline subsurface-offsets are computed**

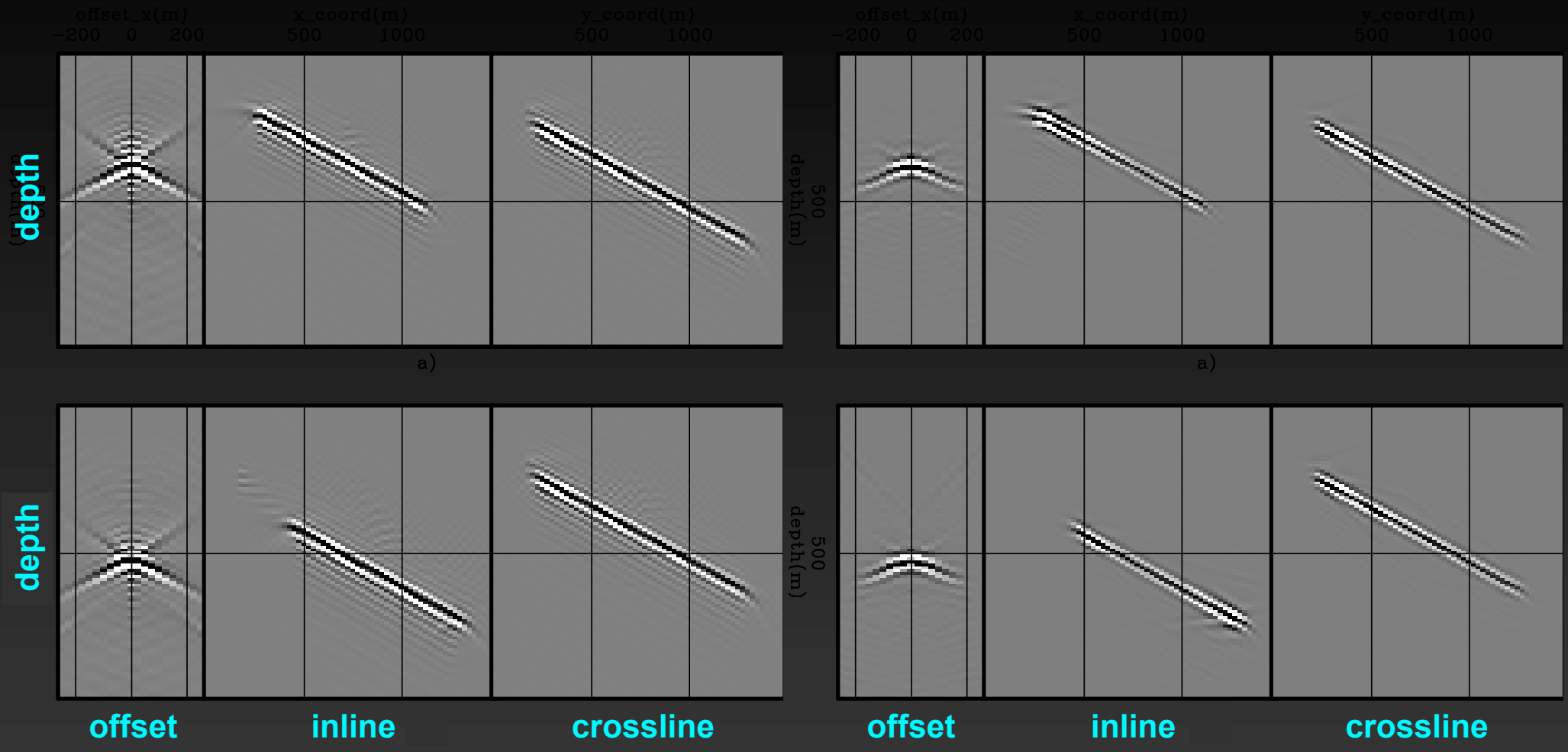


Using CAM images as the initial conditions

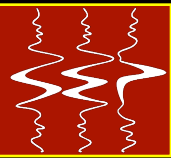


CAM

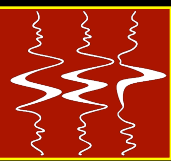
PERM



Outline

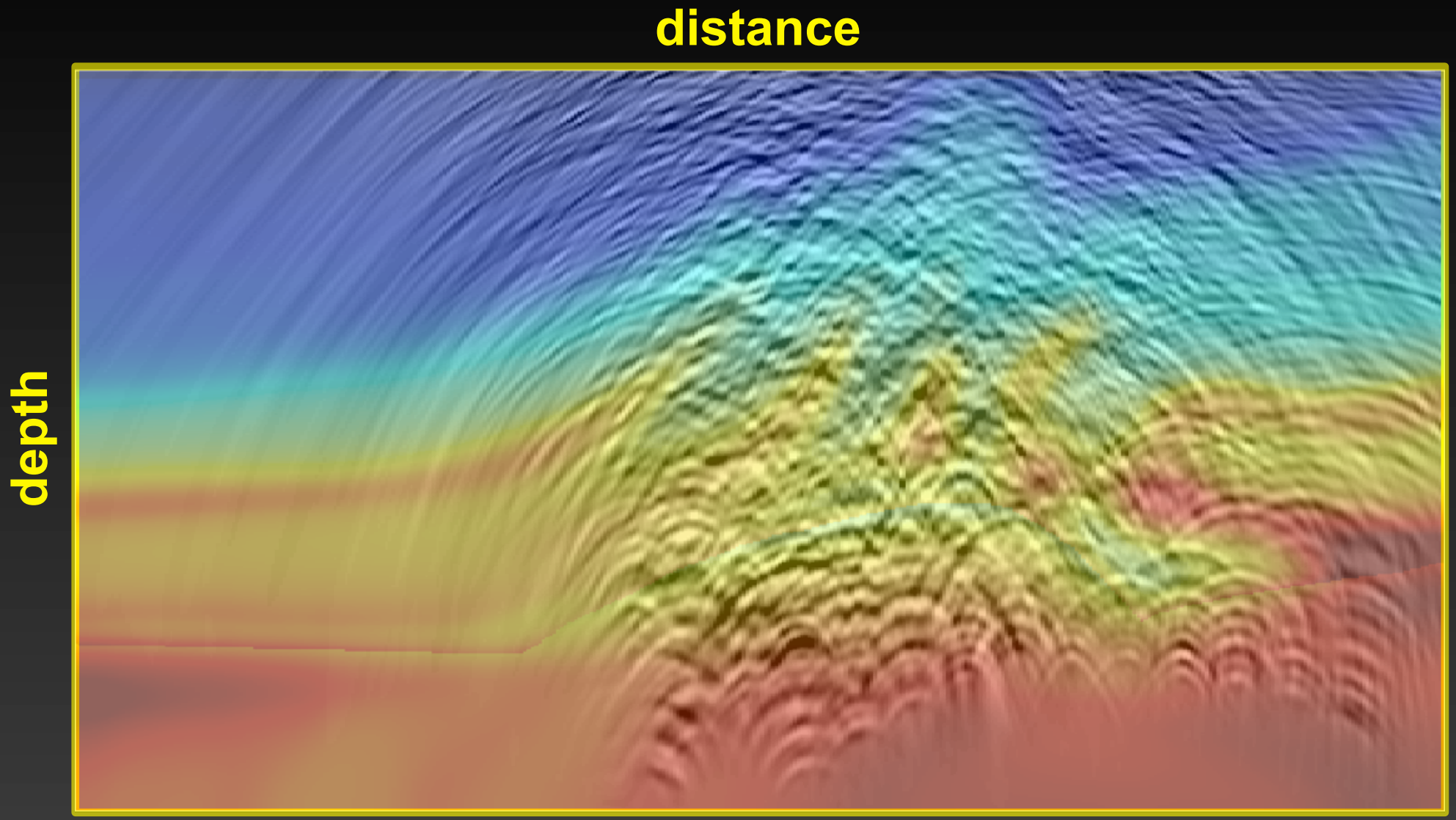


- ✓ Generalized-source domain
- ✓ Pre-stack exploding reflector model
- • Image-space phase-encoded wavefields
- • 3D-field data ISWET example
- • Conclusions

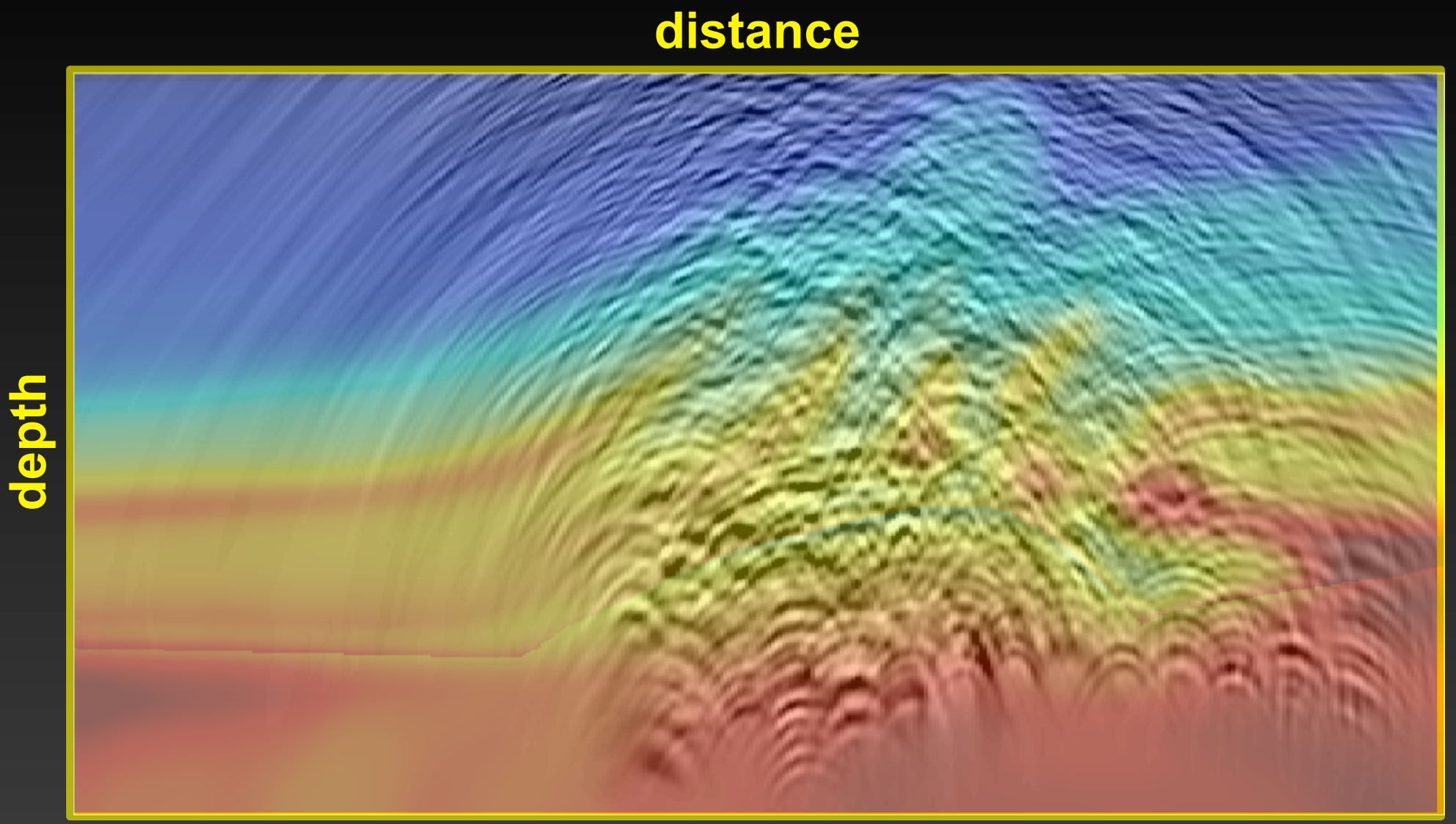


Further data reduction by phase-encoding the modeling experiments

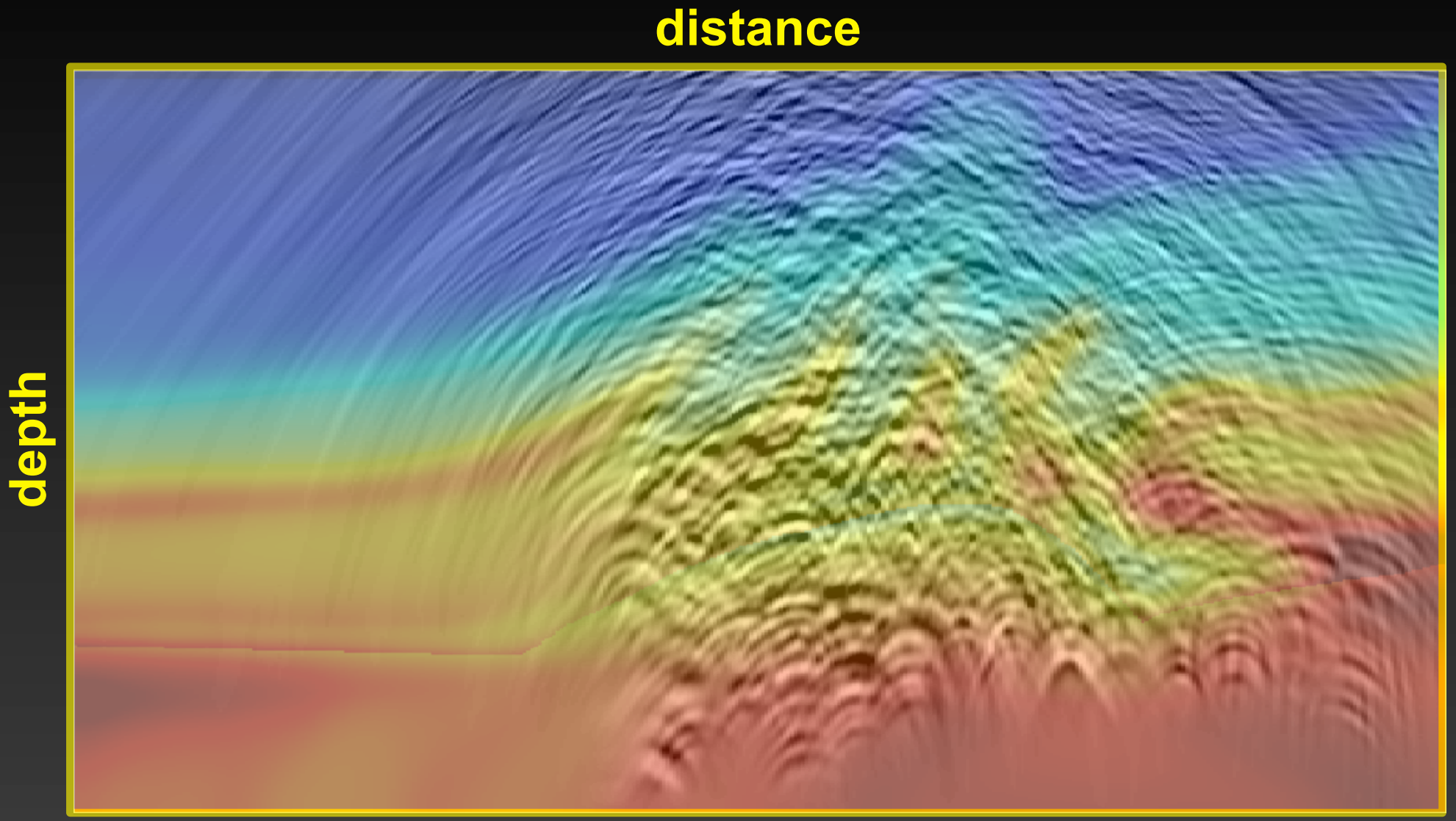
Phase-encoded receiver wavefield



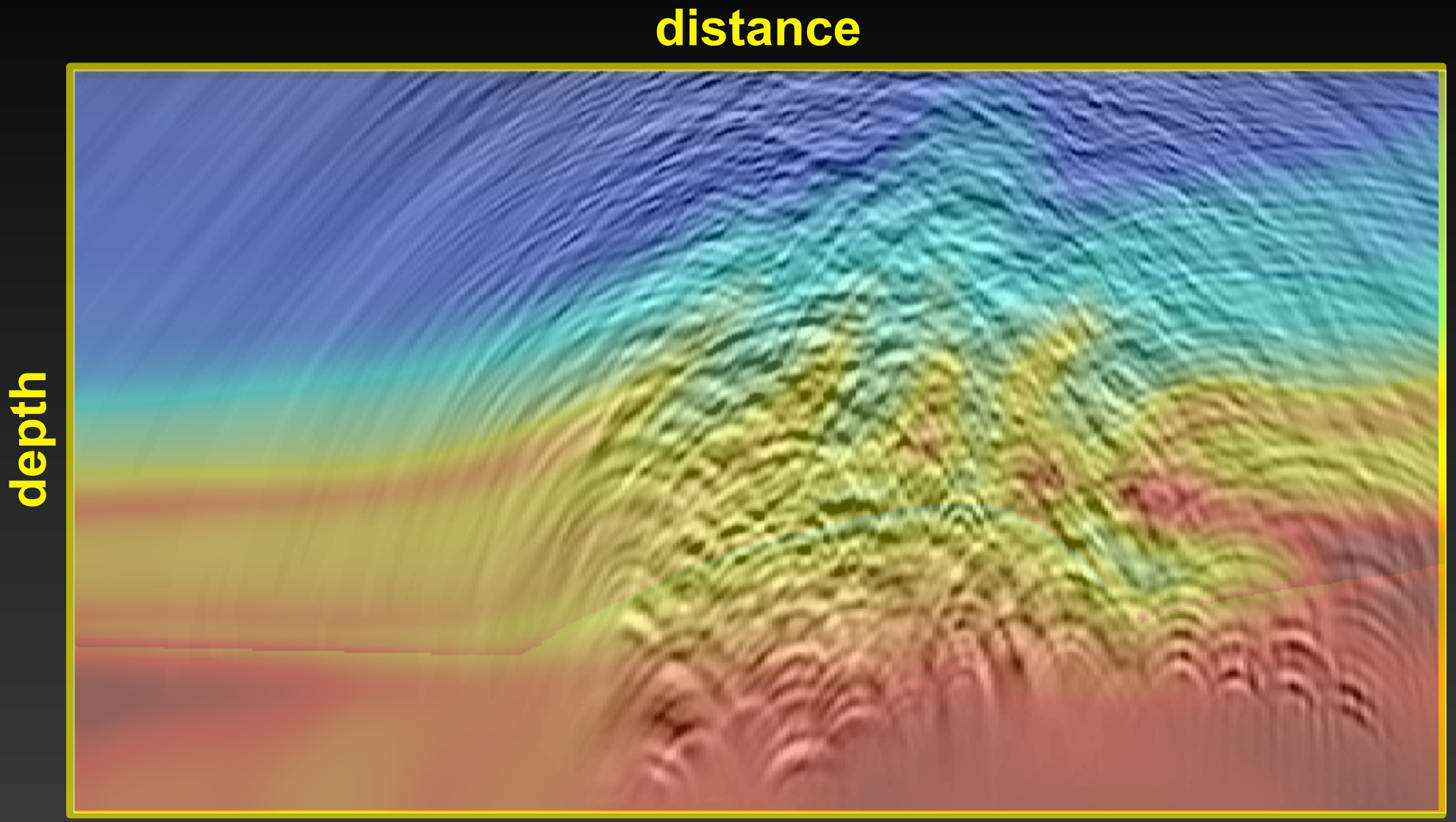
Phase-encoded receiver wavefield



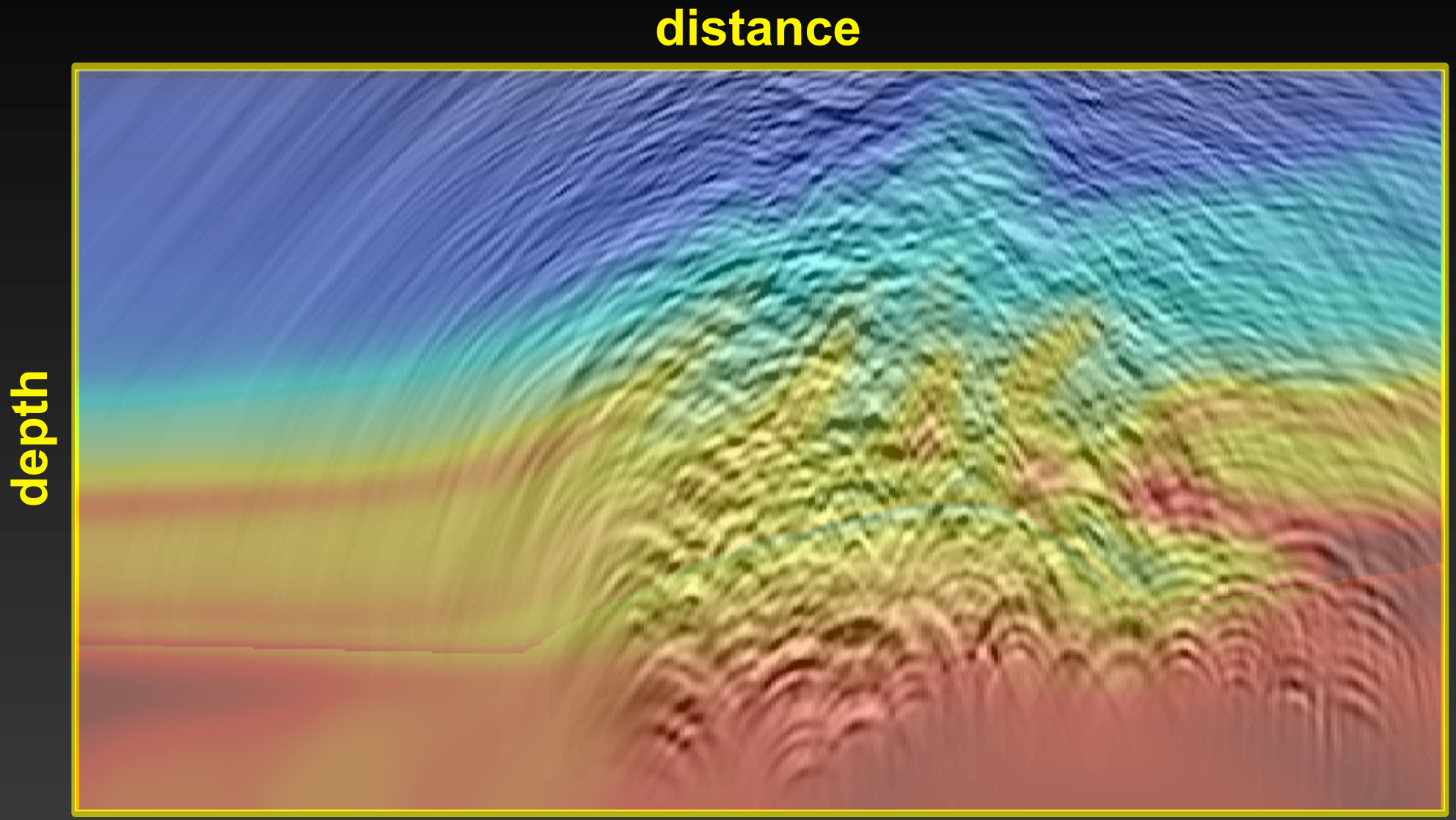
Phase-encoded receiver wavefield



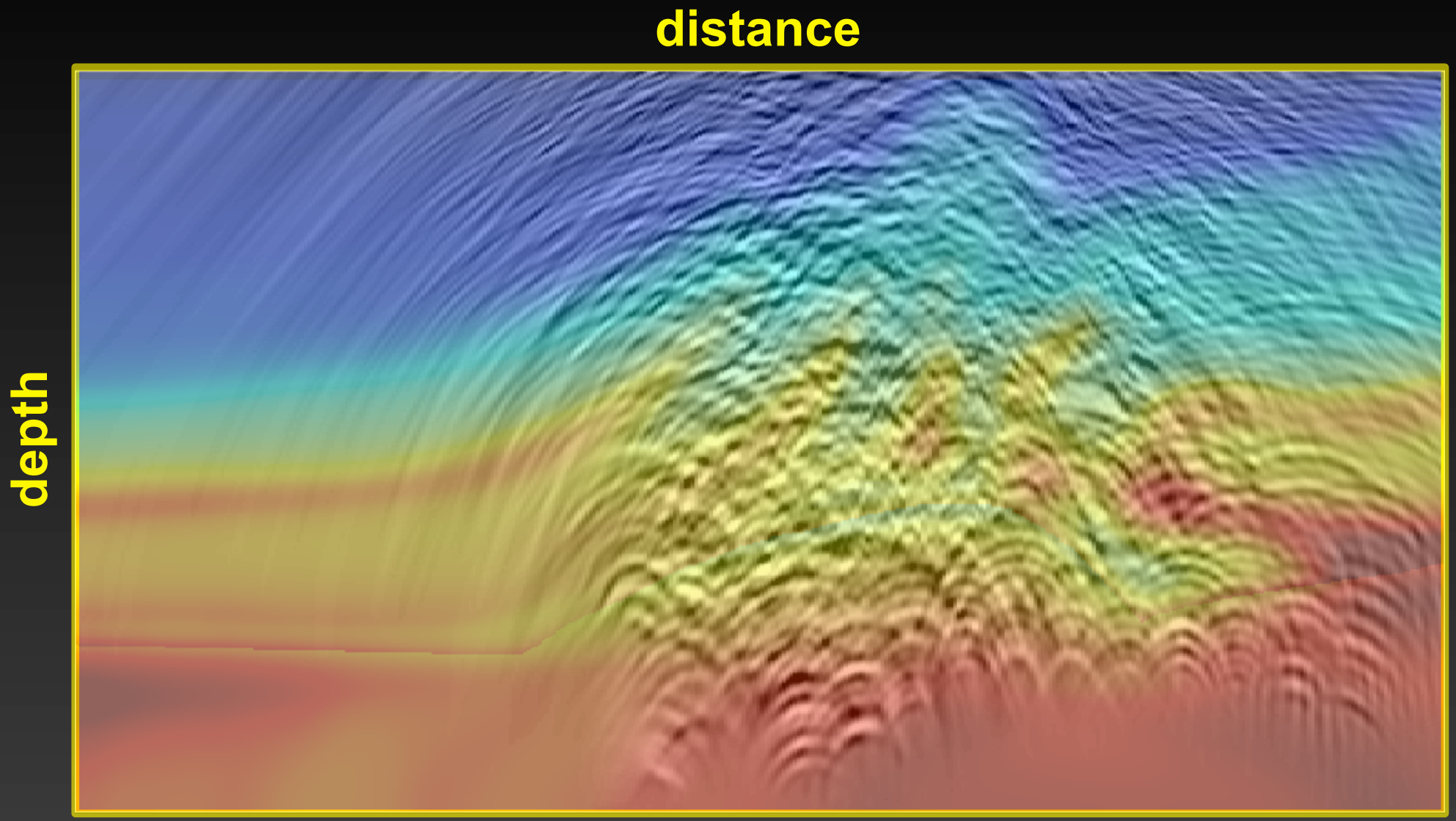
Phase-encoded receiver wavefield



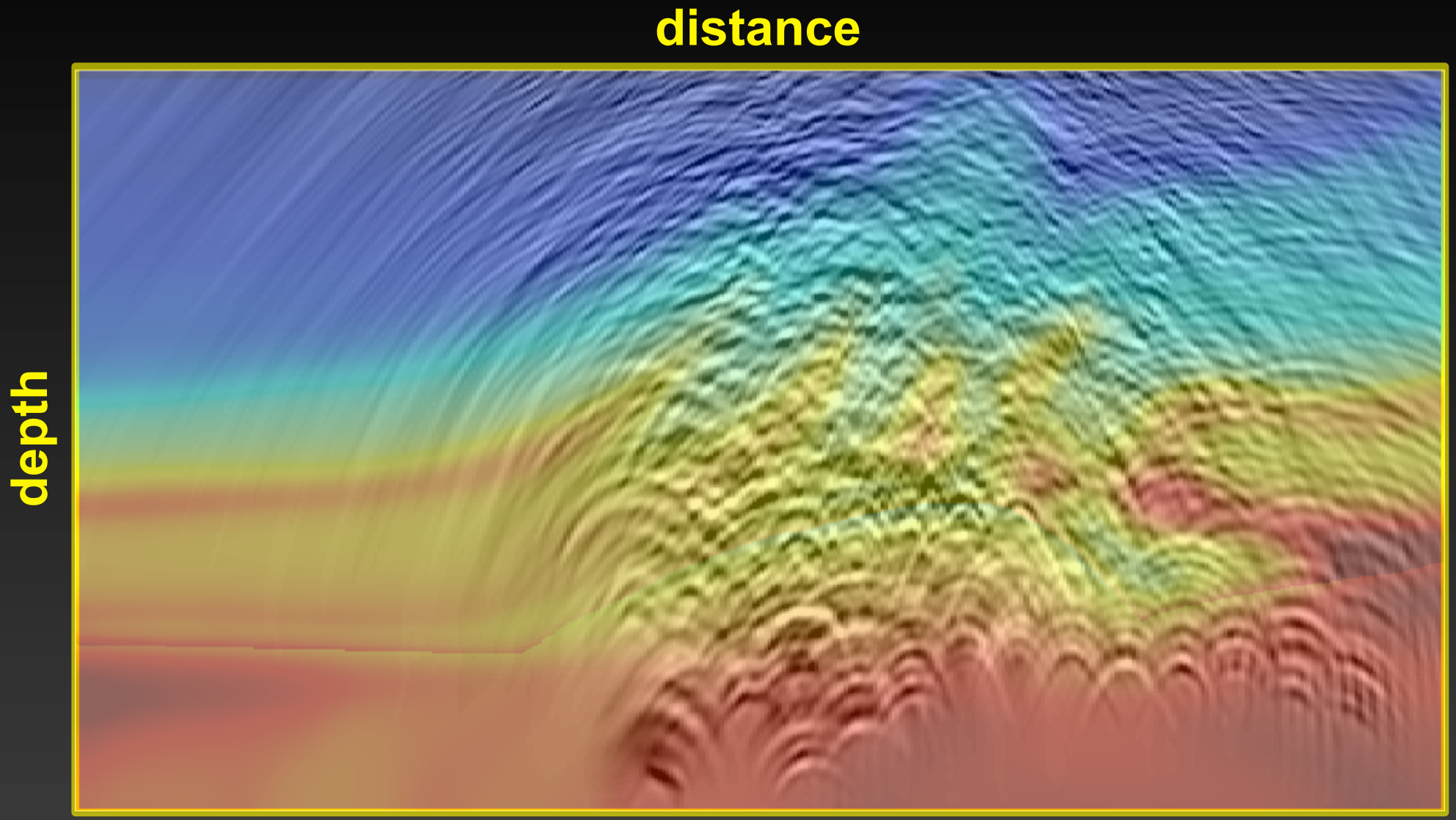
Phase-encoded receiver wavefield



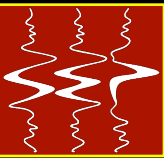
Phase-encoded receiver wavefield

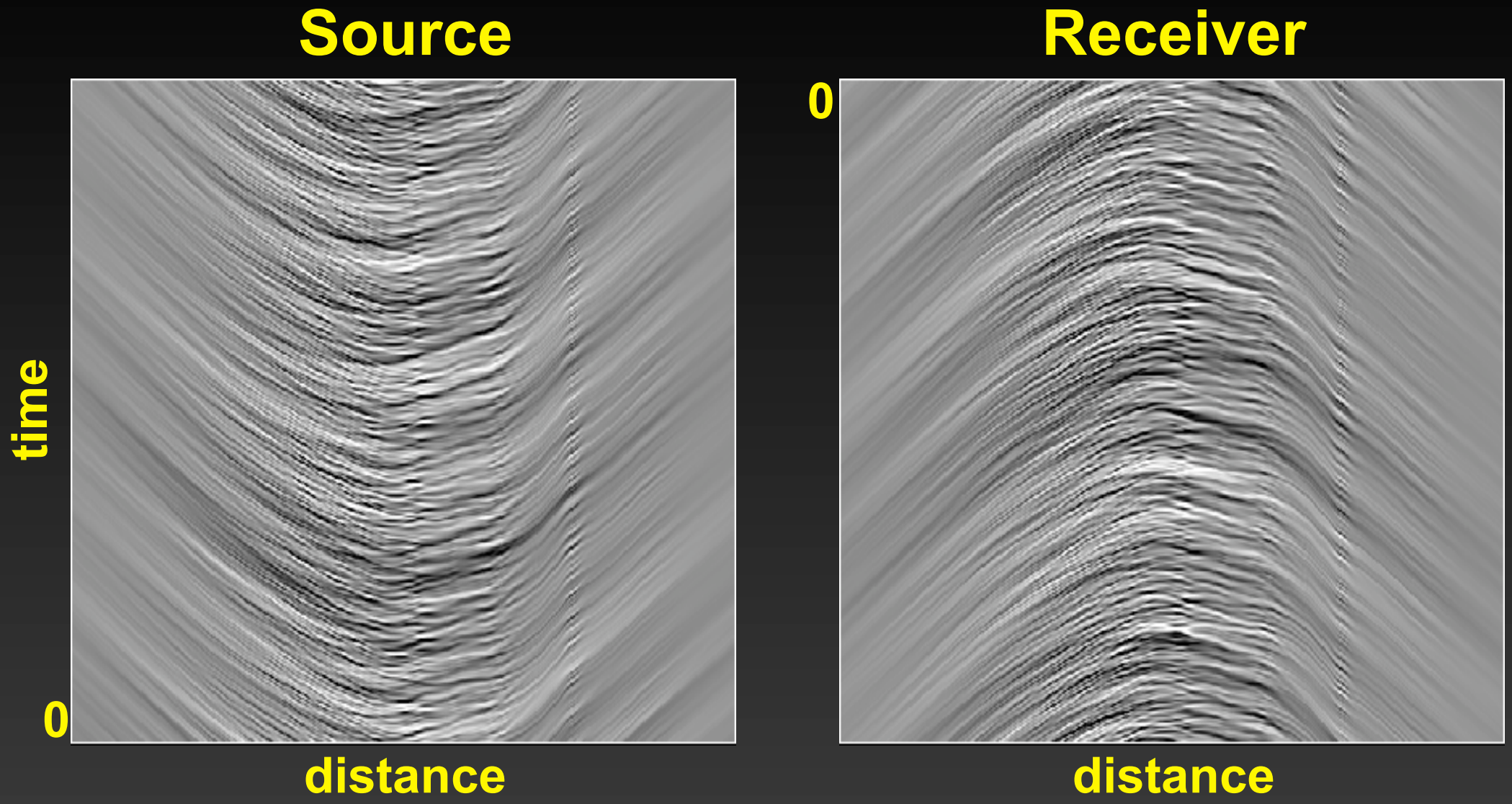


Phase-encoded receiver wavefield

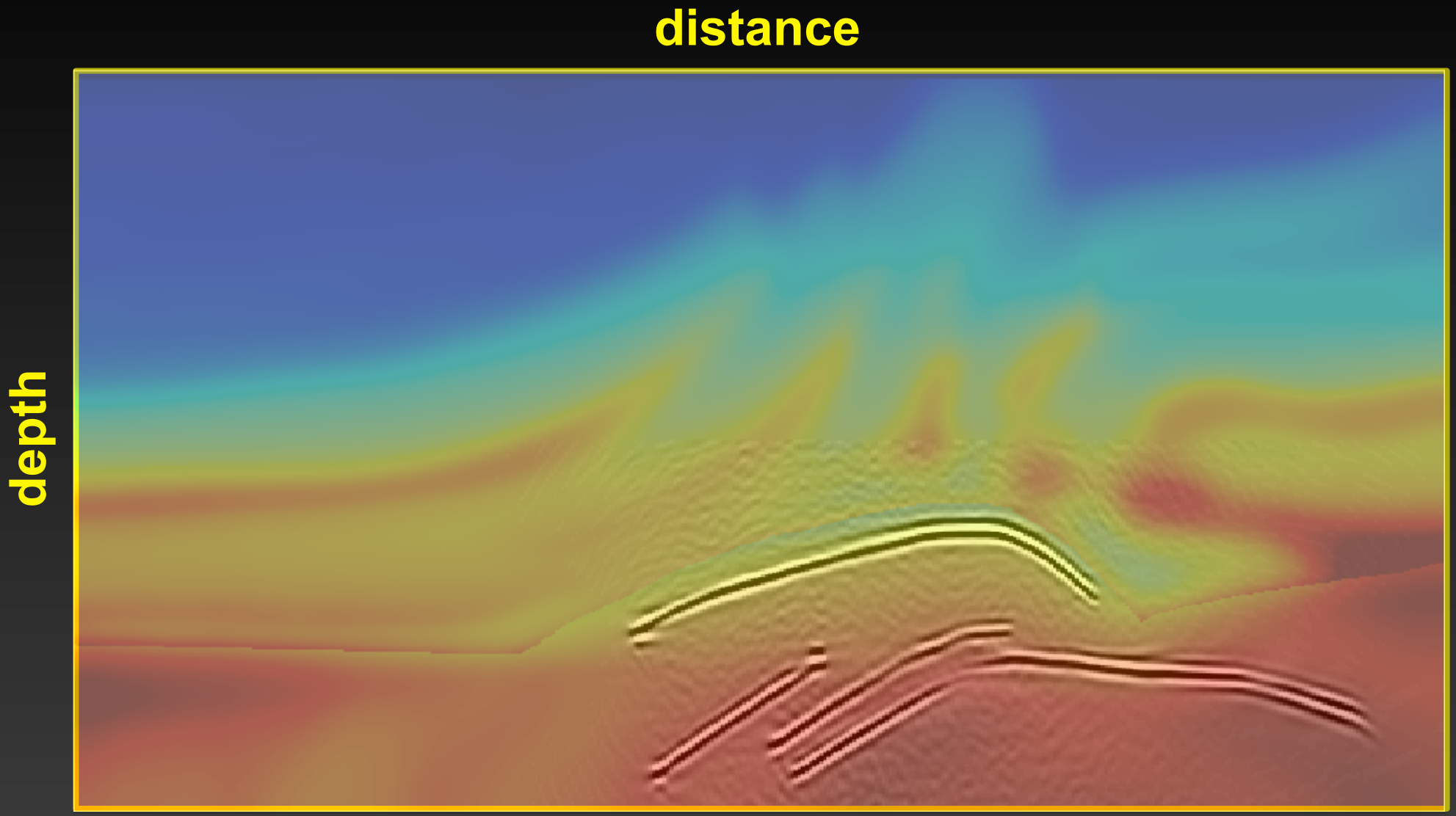


ISPEW data

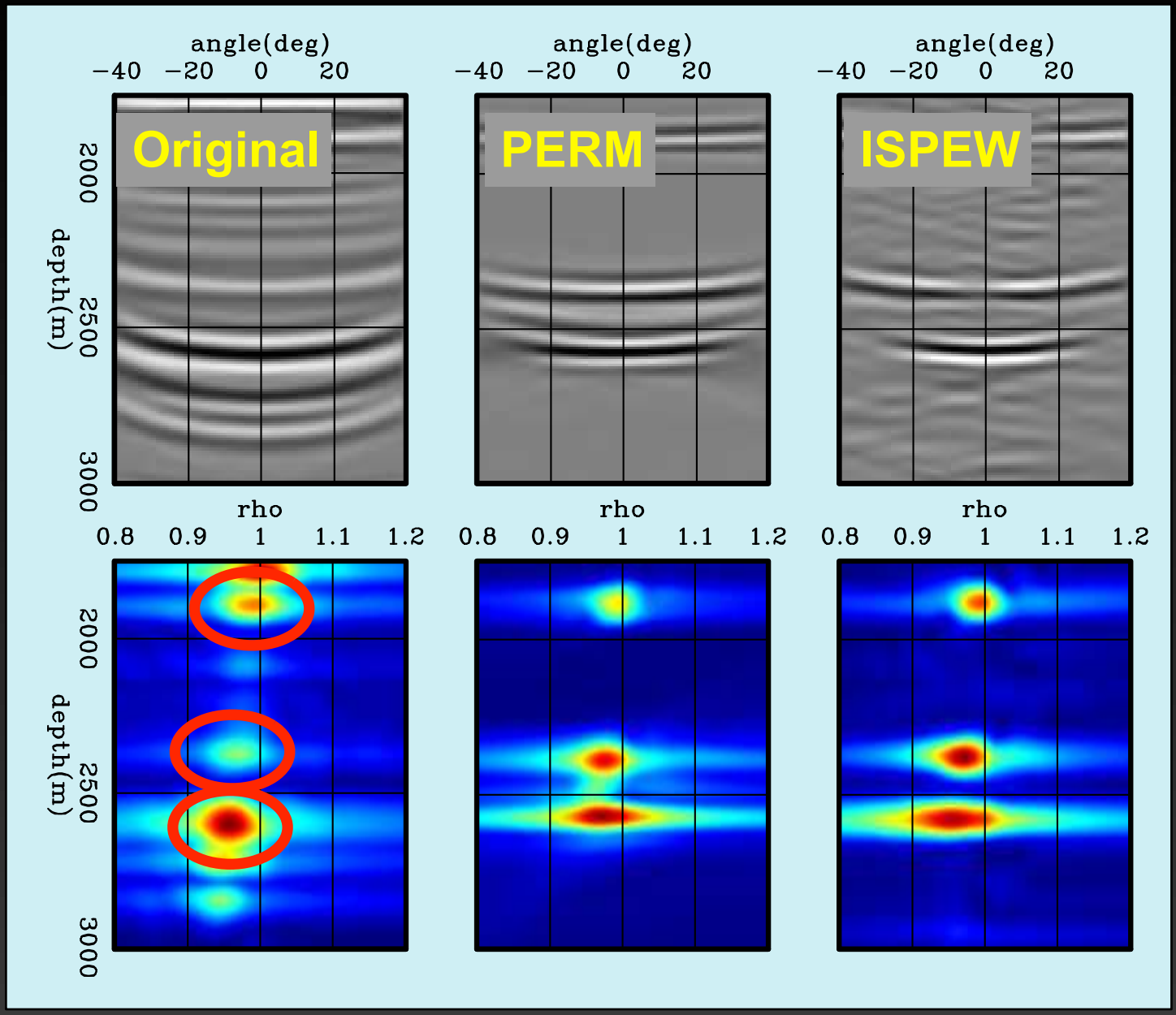




Migration of ISPEW

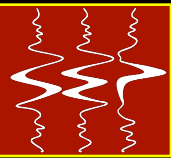


Moveout information



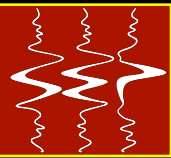
rho - curvature parameter

Outline



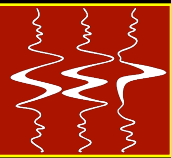
- ✓ Generalized-source domain
- ✓ Pre-stack exploding reflector model
- ✓ Image-space phase-encoded wavefields
- • 3D-field data ISWET example
- • Conclusions

Generalized-source domain ISWET



- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**

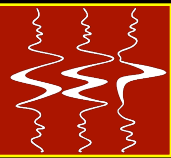
Generalized-source domain ISWET



- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**

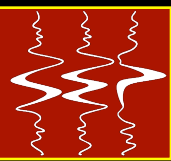
- **Small number of wavefields**

Generalized-source domain ISWET



- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**
- **Small number of wavefields**
- **Wavefields initiated at selected reflectors**

Generalized-source domain ISWET

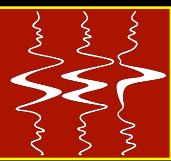


- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**
- **Small number of wavefields**
- **Wavefields initiated at selected reflectors**
  - **Horizon-based ISWET**

Generalized-source domain ISWET

- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**
- **Small number of wavefields**
- **Wavefields initiated at selected reflectors**
  - **Horizon-based ISWET**
- **Easily solved in a target-oriented way**

GS-ISWET Objective function



$$J(s) = \frac{1}{2} \left\| \Delta \widetilde{I}(s) \right\|_2$$

$J(s) =$ objective function $\quad \Delta \widetilde{I}(s) =$ perturbed image

GS-ISWET Objective function

$$J(s) = \frac{1}{2} \left\| \Delta \widetilde{I}(s) \right\|_2$$

Residual pre-stack depth migration (Sava, 2004)

Differential semblance optimization (DSO) operator (Symes and Carazzone, 1991)

$J(s) = \text{objective function} \quad \Delta \widetilde{I}(s) = \text{perturbed image}$

Differential-semblance objective function

$$J(s) = \frac{1}{2} \left\| \mathbf{h} \widetilde{I}(s) \right\|_2$$

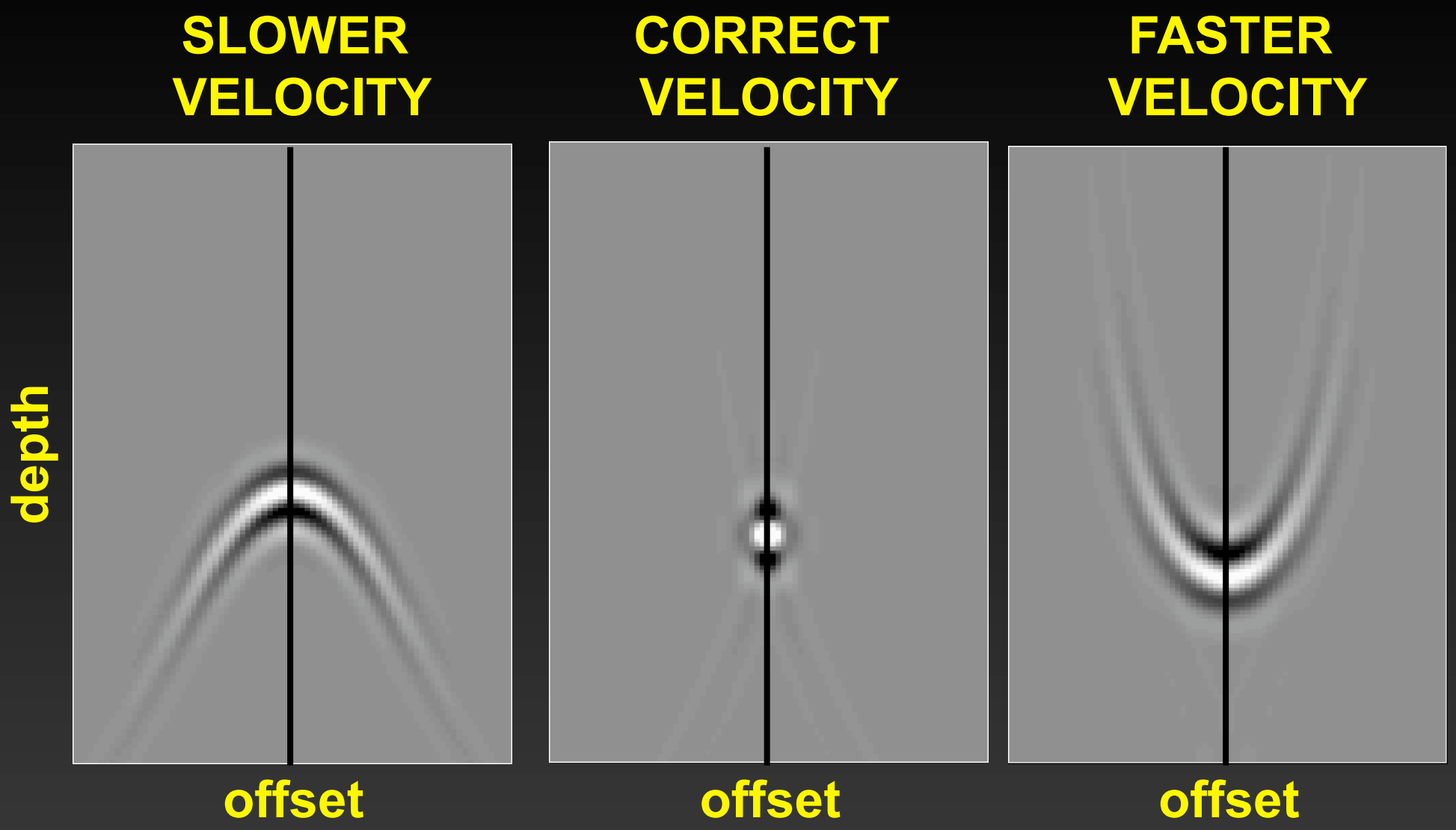
$J(s)$ = objective function

$\mathbf{h}$ = DSO operator

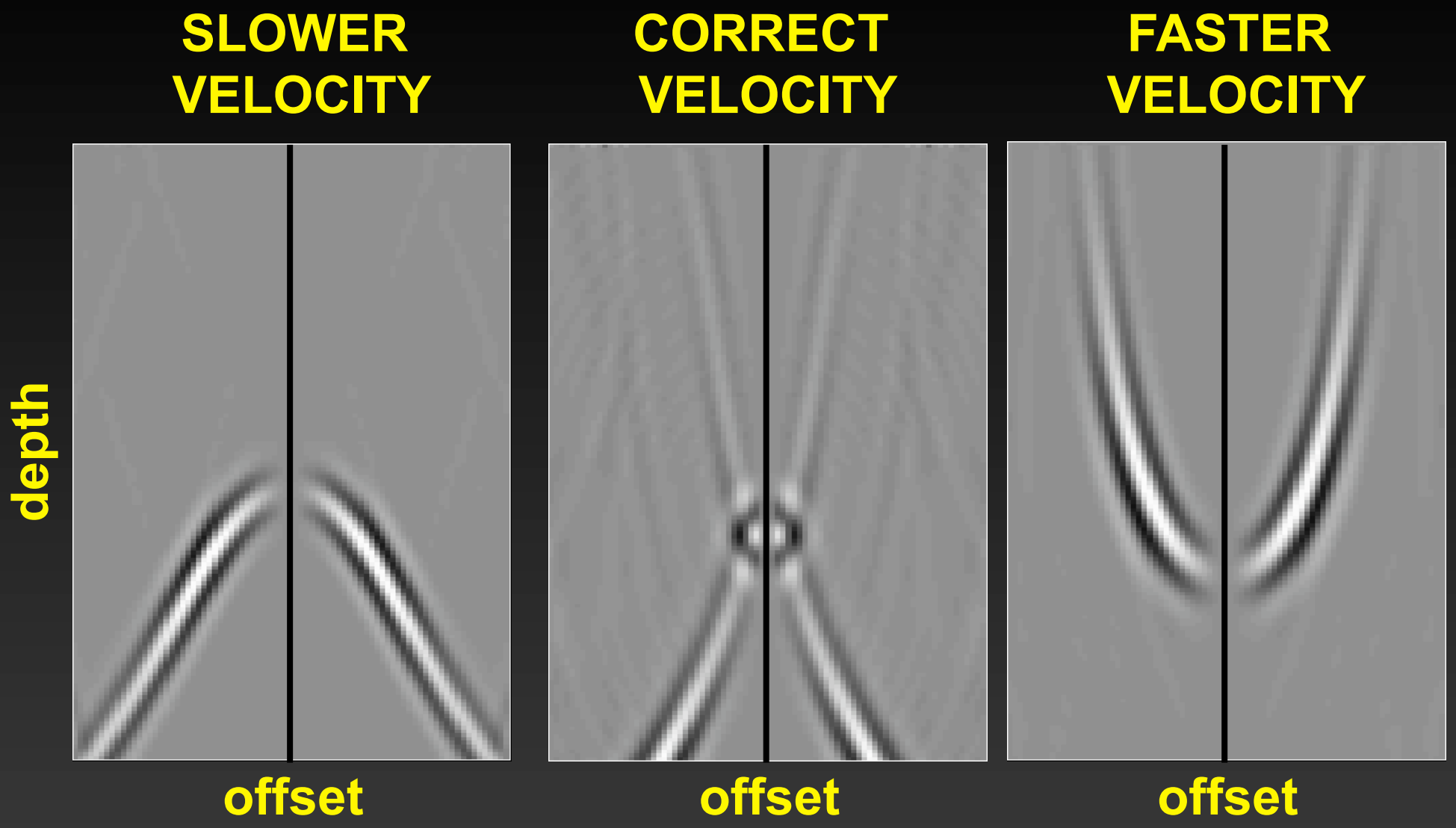
$\Delta \widetilde{I}(s)$ = perturbed image

$\widetilde{I}(s)$ = current image

DSO operator



DSO operator



DSO gradient

$$J(s) = \frac{1}{2}\left\|\mathbf{h}\widetilde{I}(s)\right\|_2$$

$$\nabla J(s) = \left(\frac{\partial \widetilde{I}}{\partial s}\right)' \mathbf{h}^2 \widetilde{I}\Big|_{s=s_o}$$

$J(s)$ = objective function

$\mathbf{h}$ = DSO operator

s_o = current velocity

$\Delta\widetilde{I}(s)$ = perturbed image

$\widetilde{I}(s)$ = current image

3D-North Sea data example

- **Dimensions: 12 x 4 km**

3D-North Sea data example

- **Dimensions: 12 x 4 km**

- **AMO data with 3600 m maximum offset**
  - **CAM images as the initial conditions**
  - **20 ISPEW**
  - **Target region: 600-3200 m depth range**
  - **Solving for the chalk layer velocity**

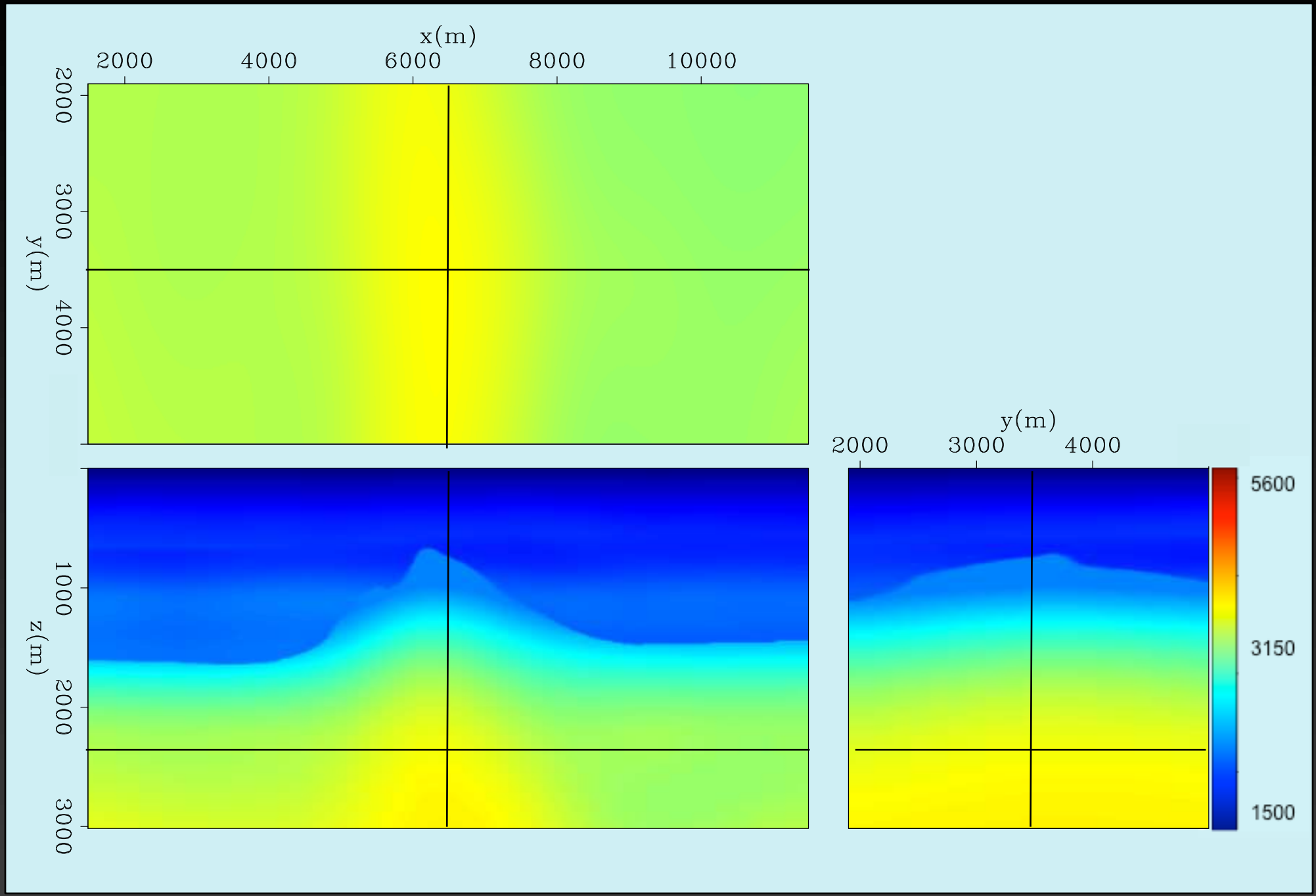
3D-North Sea data example

- **Dimensions: 12 x 4 km**

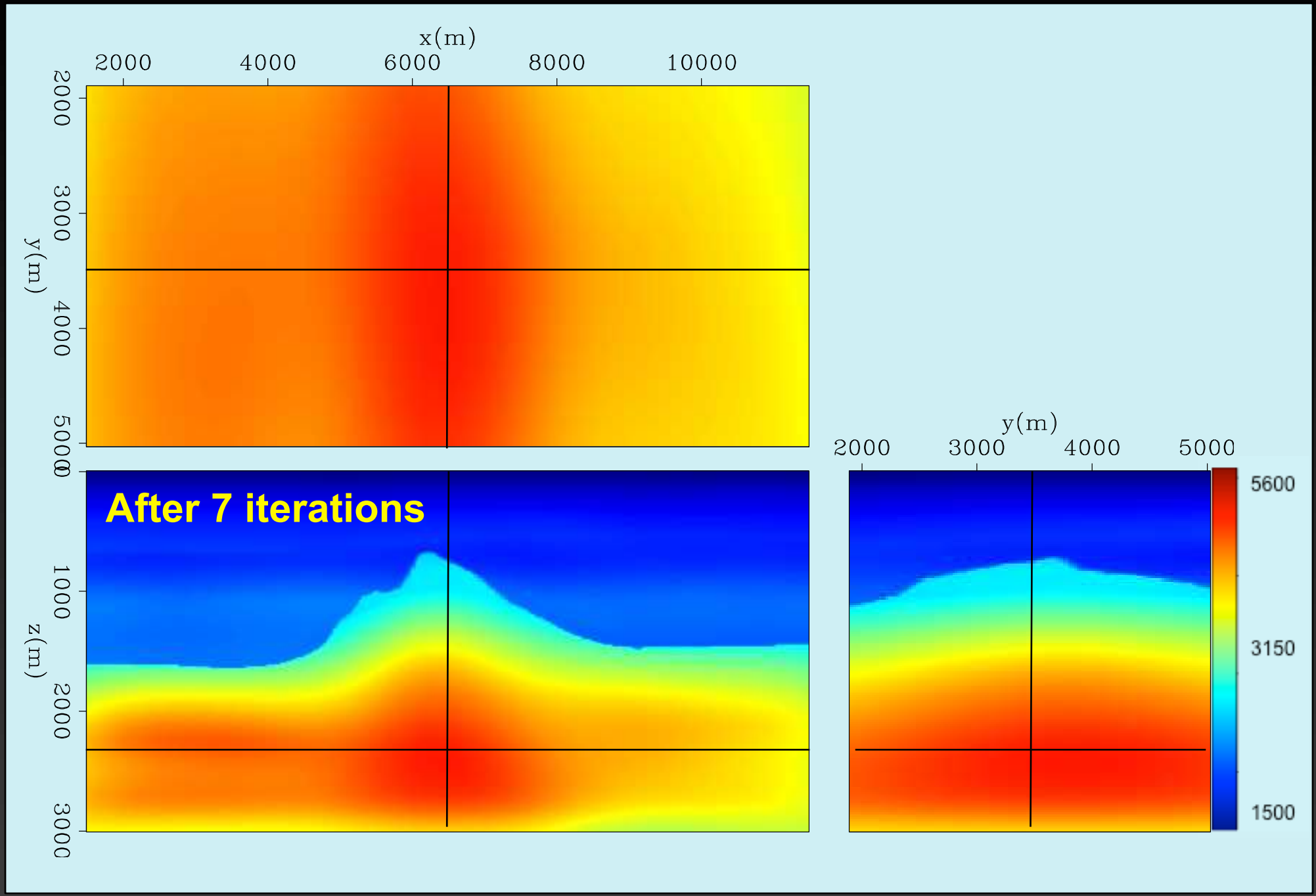
- **AMO data with 3600 m maximum offset**
  - **CAM images as the initial conditions**
  - **20 ISPEW**
  - **Target region: 600-3200 m depth range**
  - **Solving for the chalk layer velocity**

- **CEES: 20 Dual Nehalem 5520, 24Gb RAM**
  - **Perturbed image: 20 min**
  - **Gradient: 40 min**

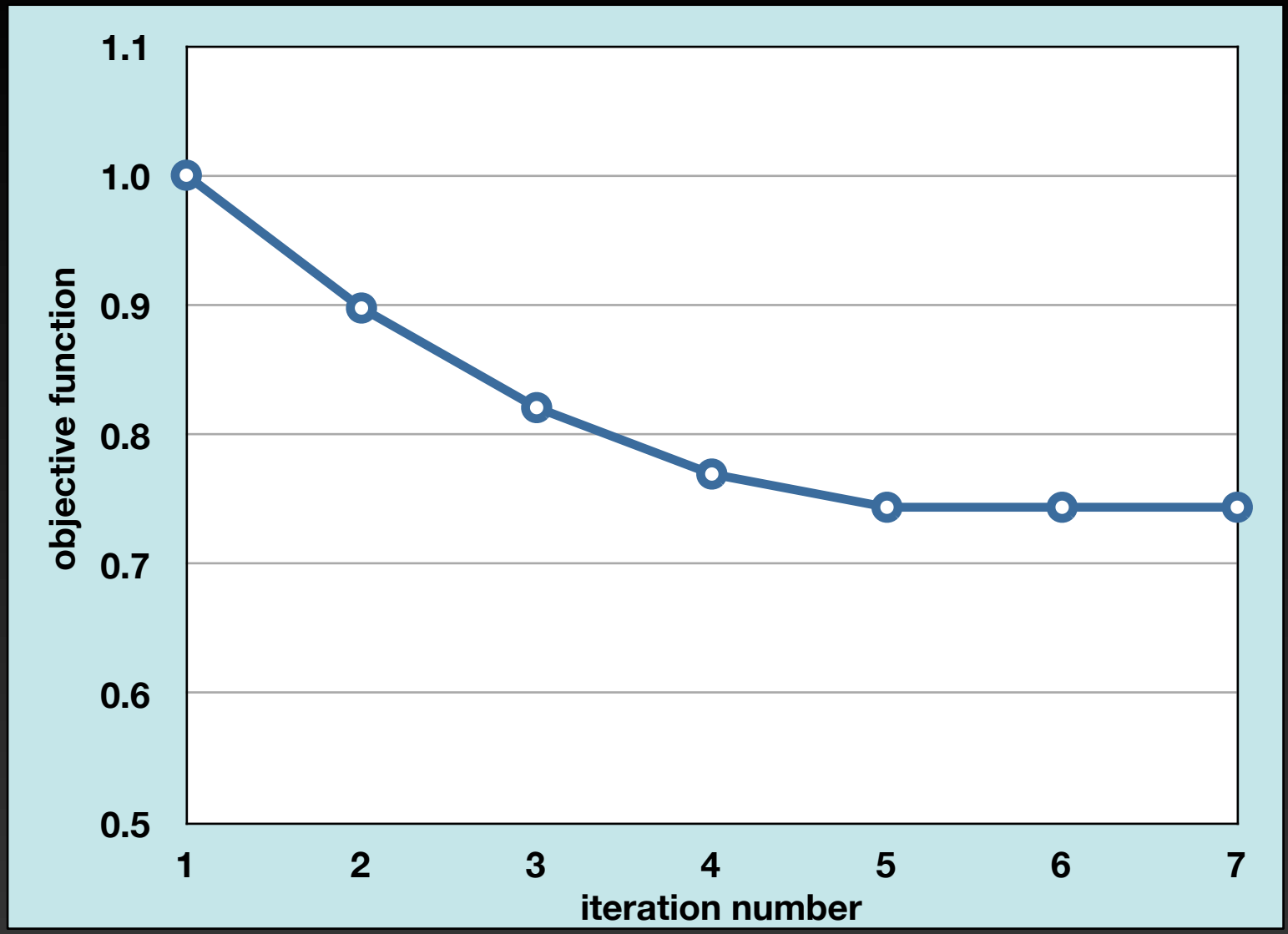
Initial velocity model



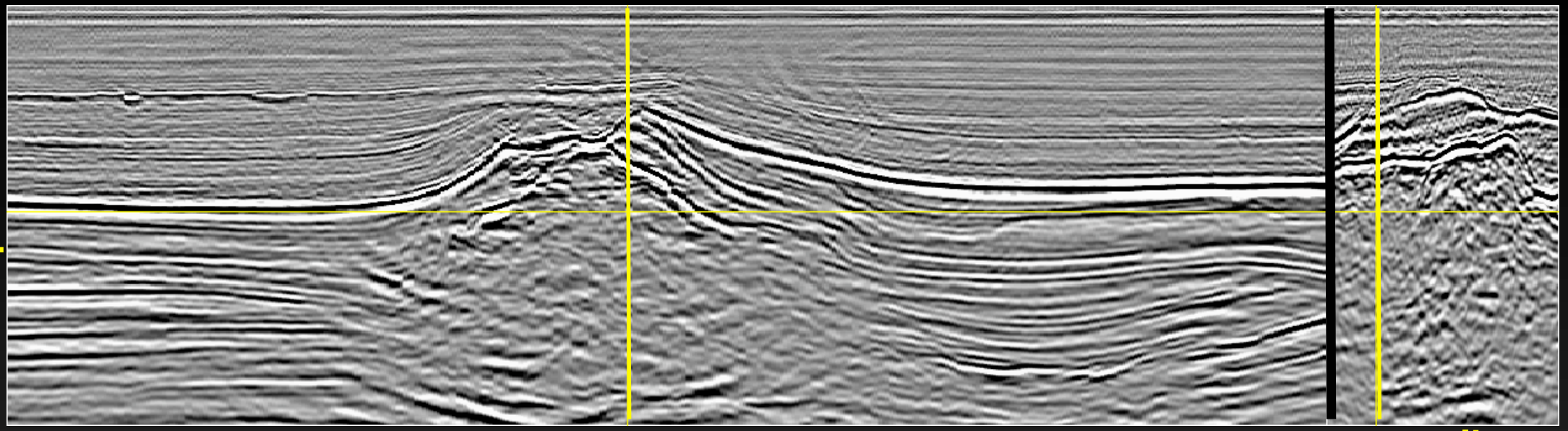
Optimized after 7 iterations



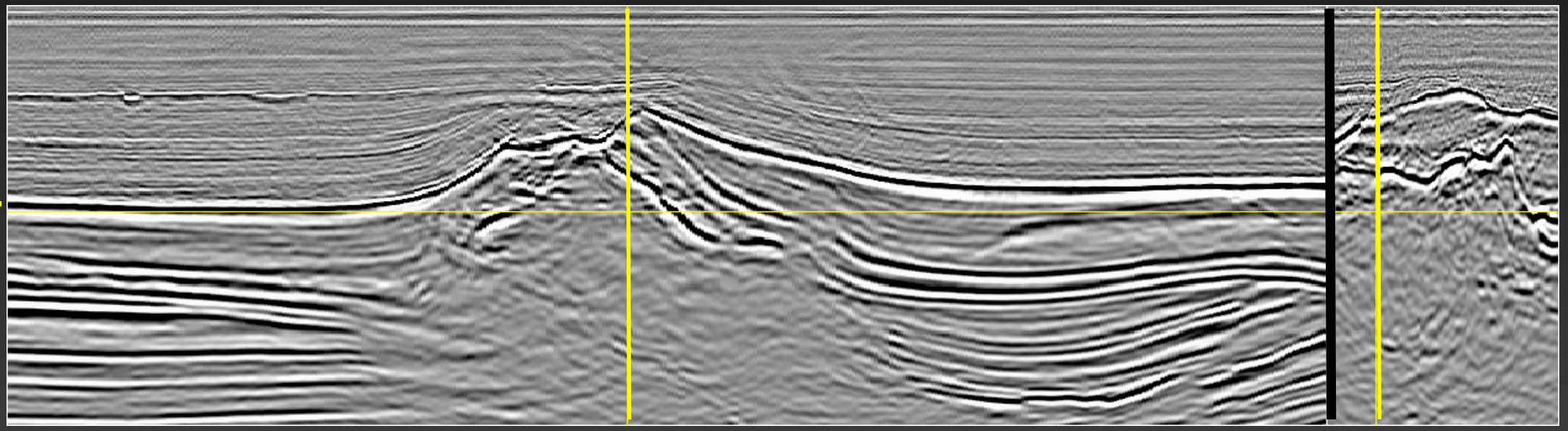
Objective function



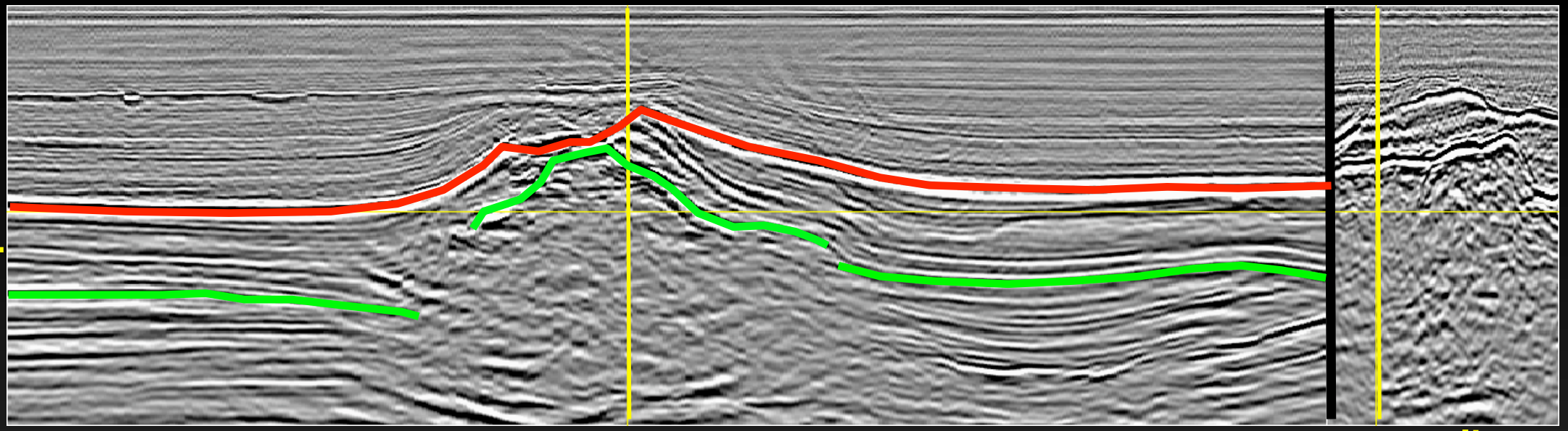
Initial



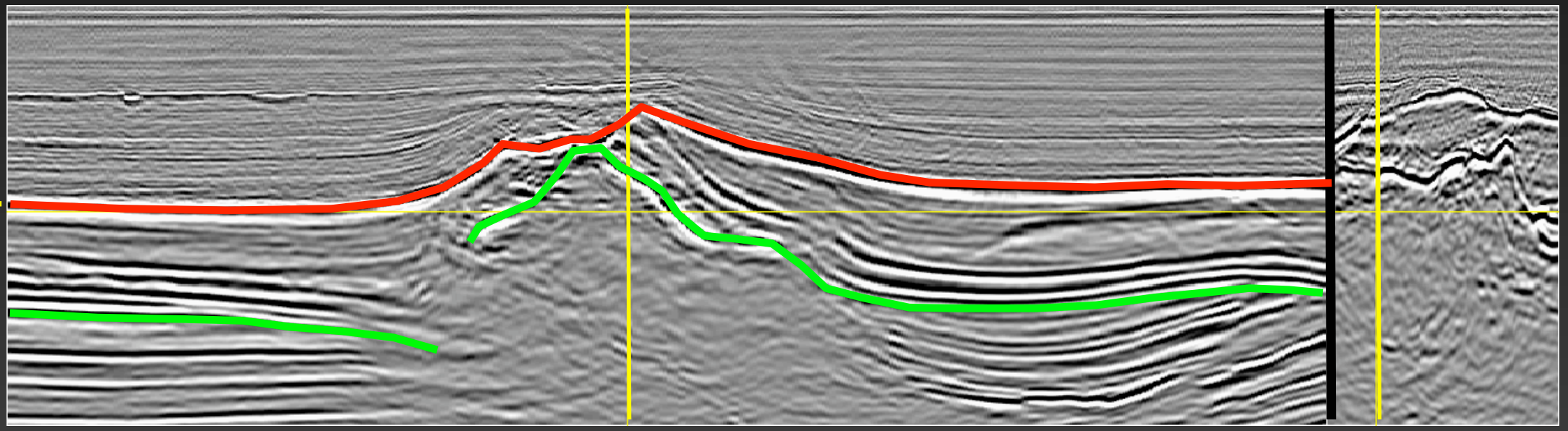
Optimized



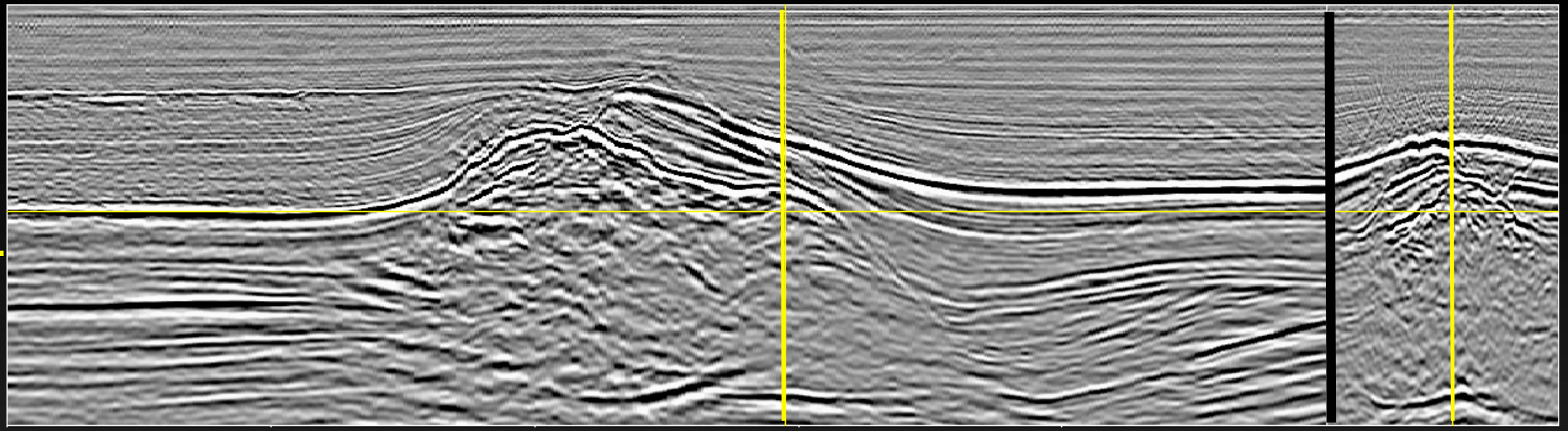
Initial



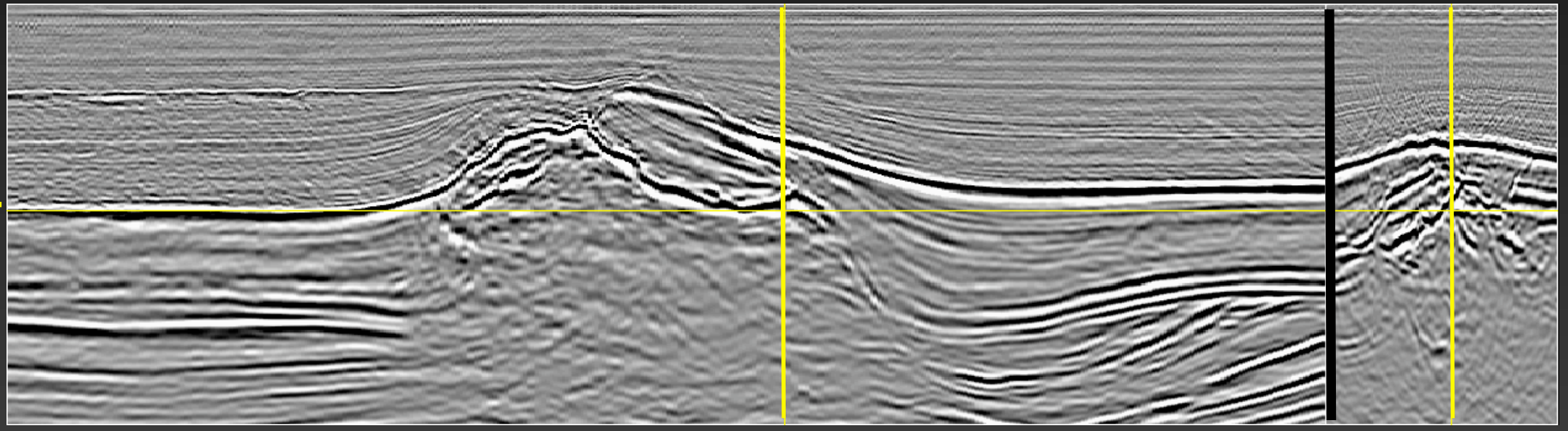
Optimized



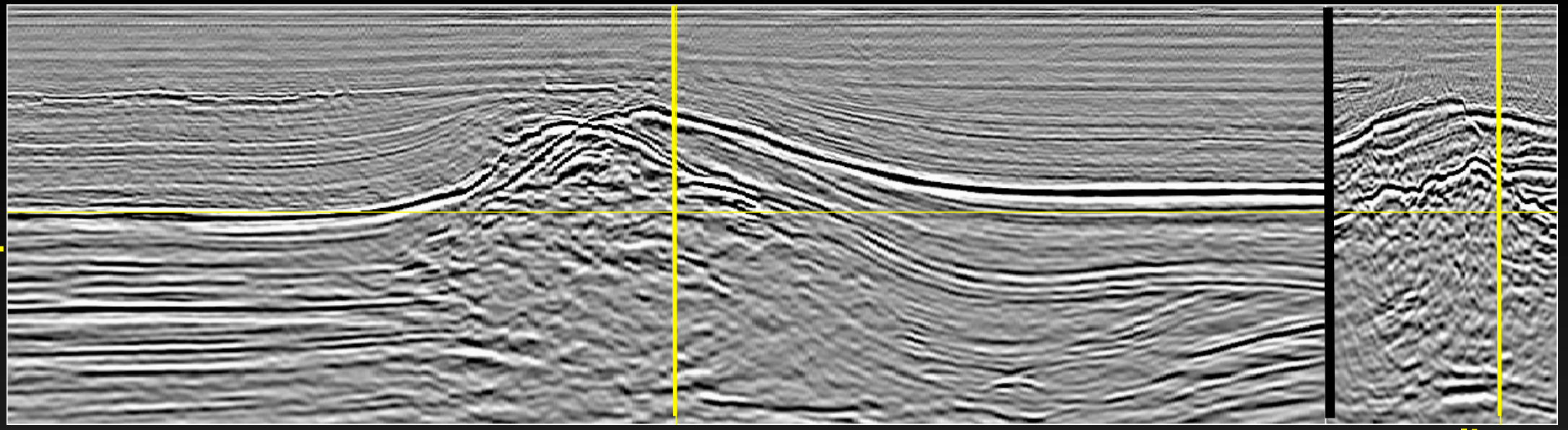
Initial



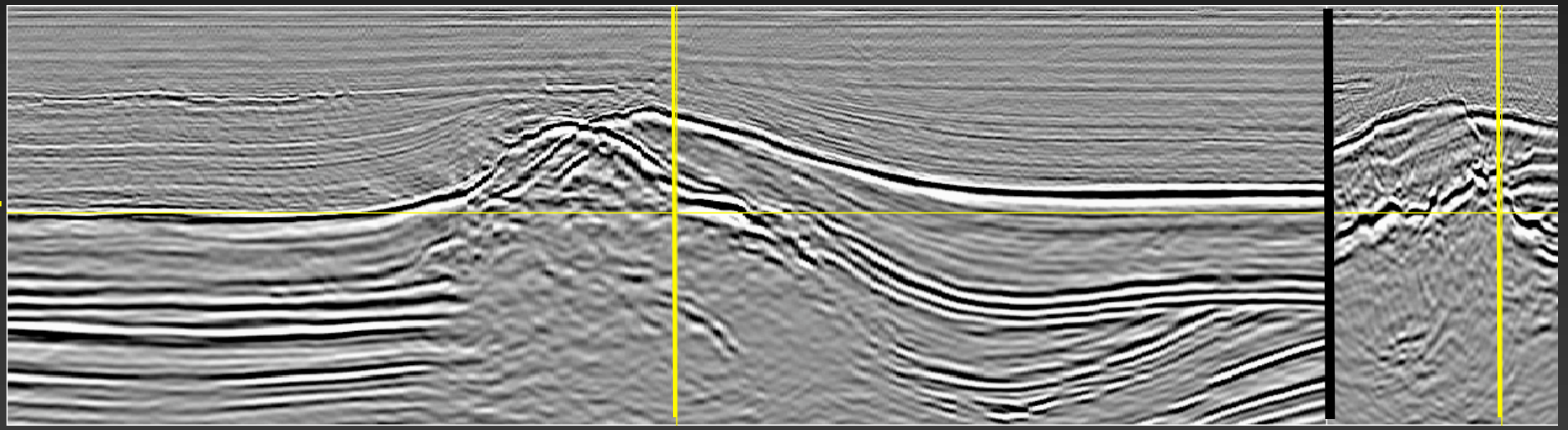
Optimized



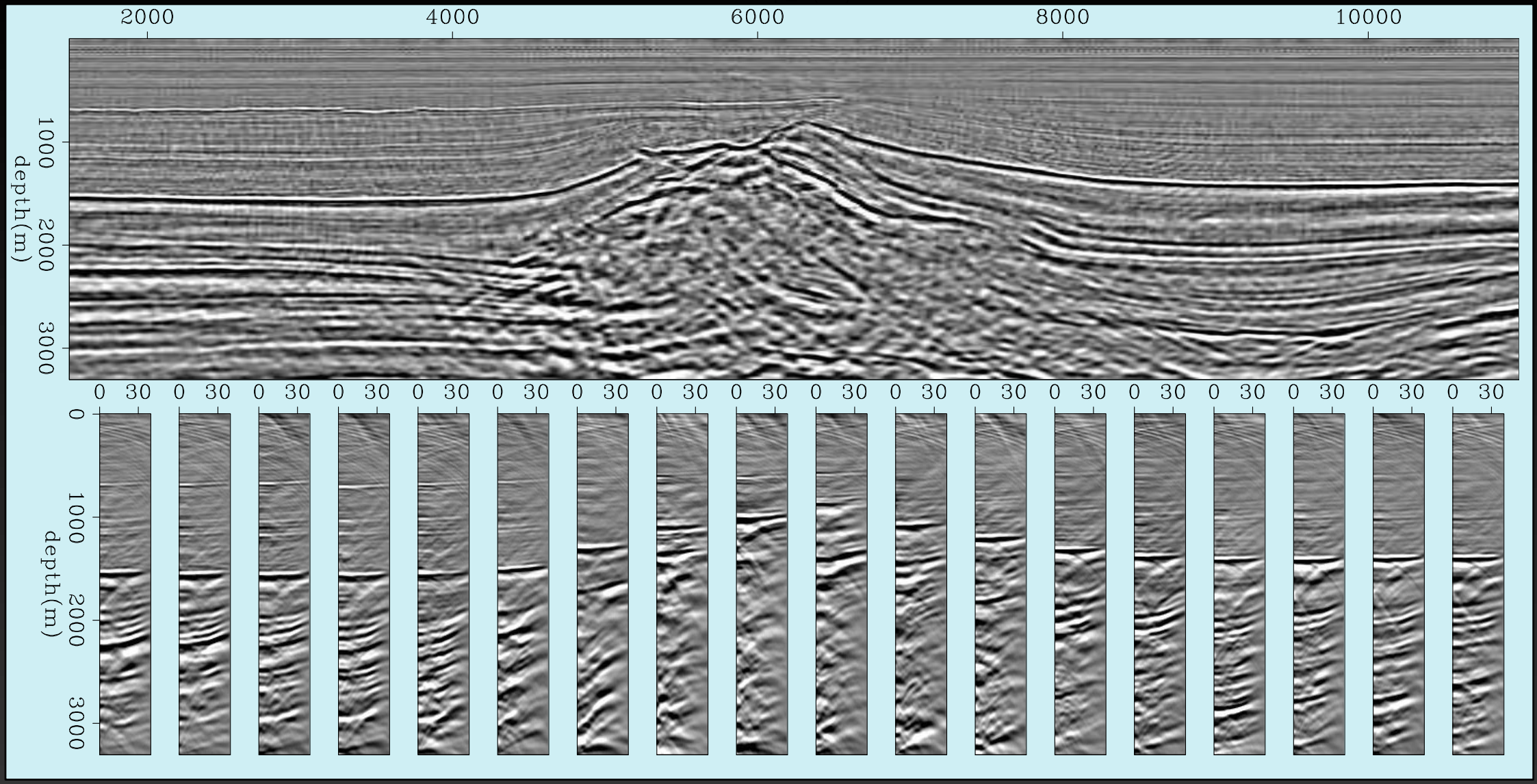
Initial



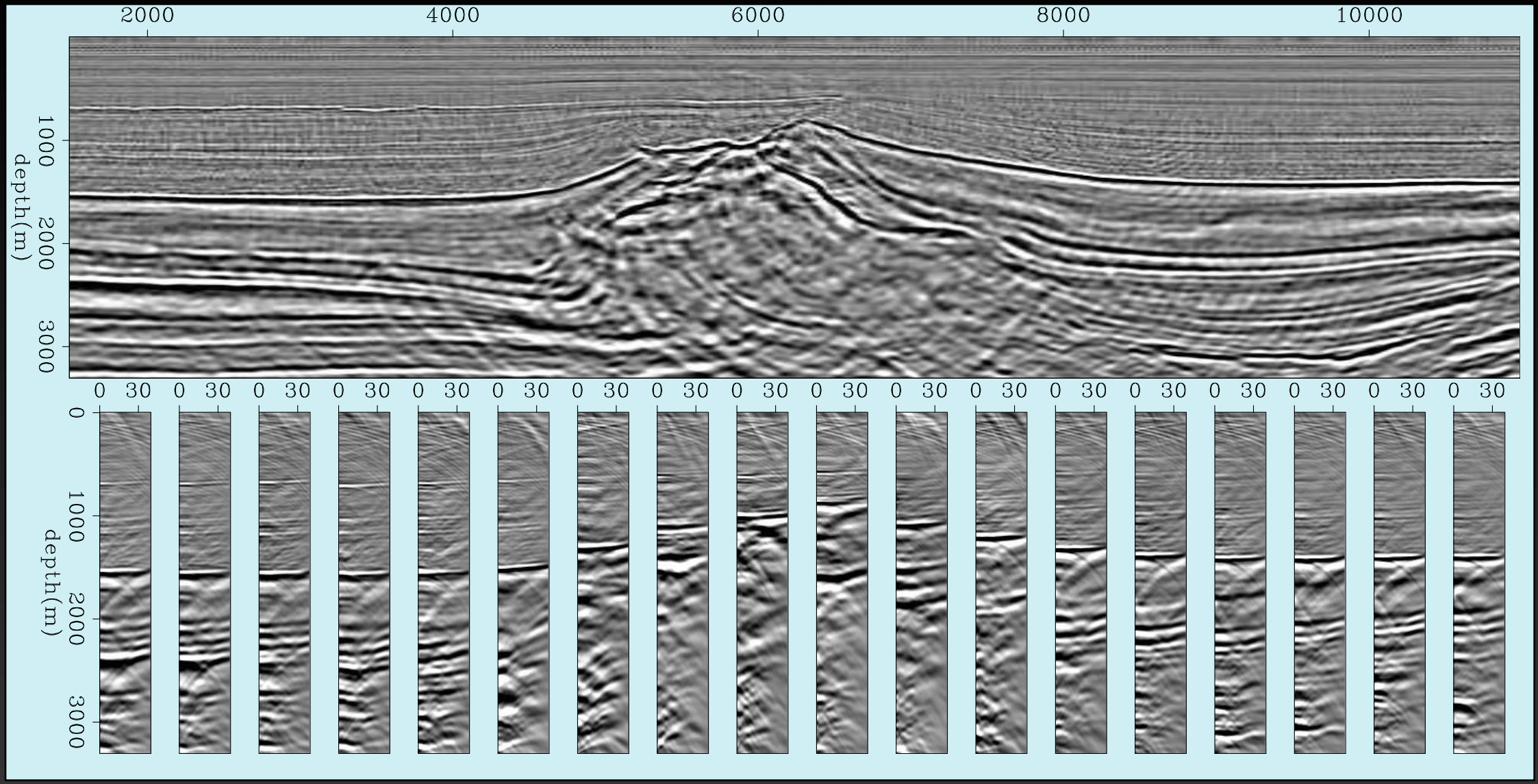
Optimized



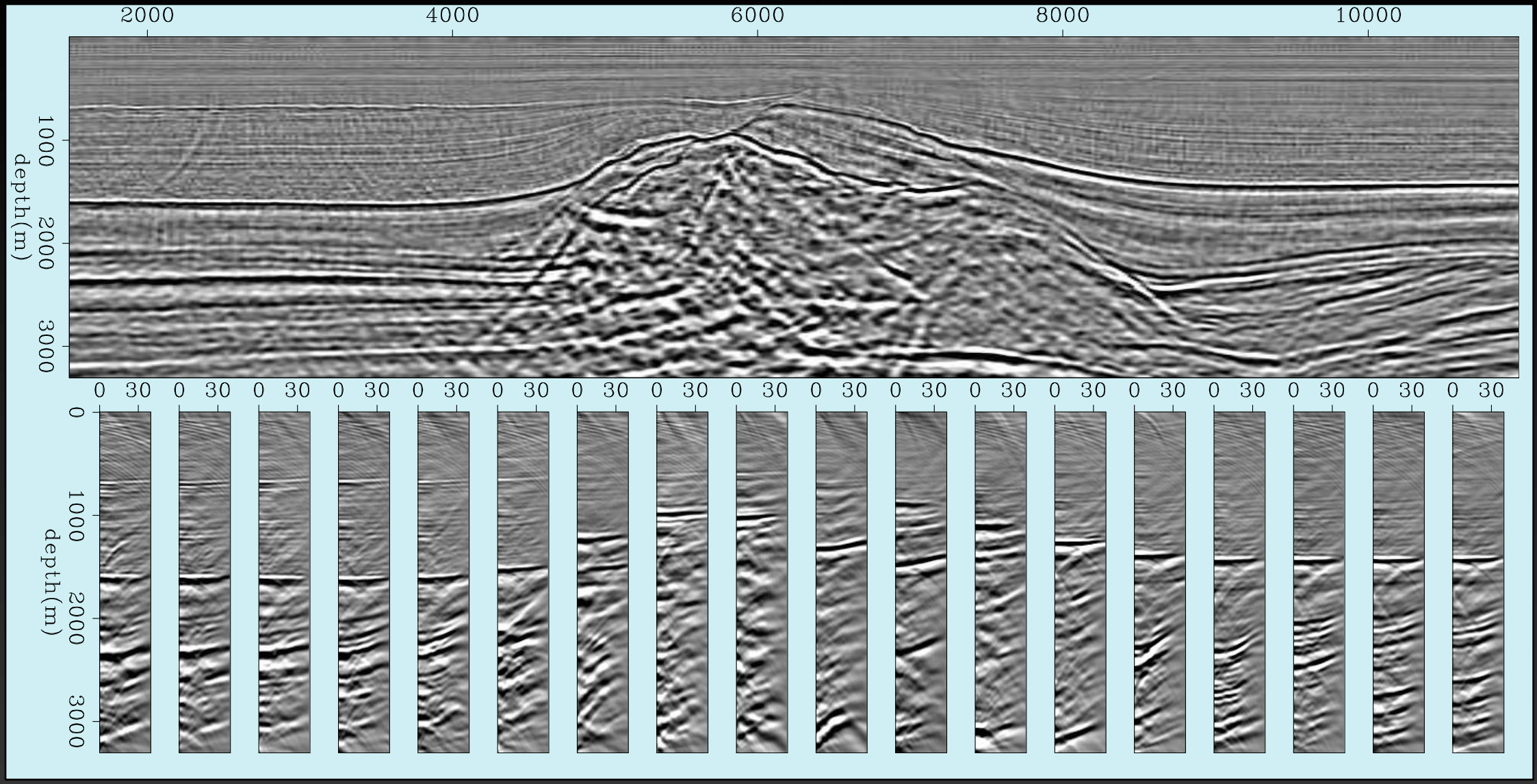
Initial


2000
4000
6000
8000
10000
1000
2000
3000
depth(m)
0 30
0
1000
2000
3000
depth(m)

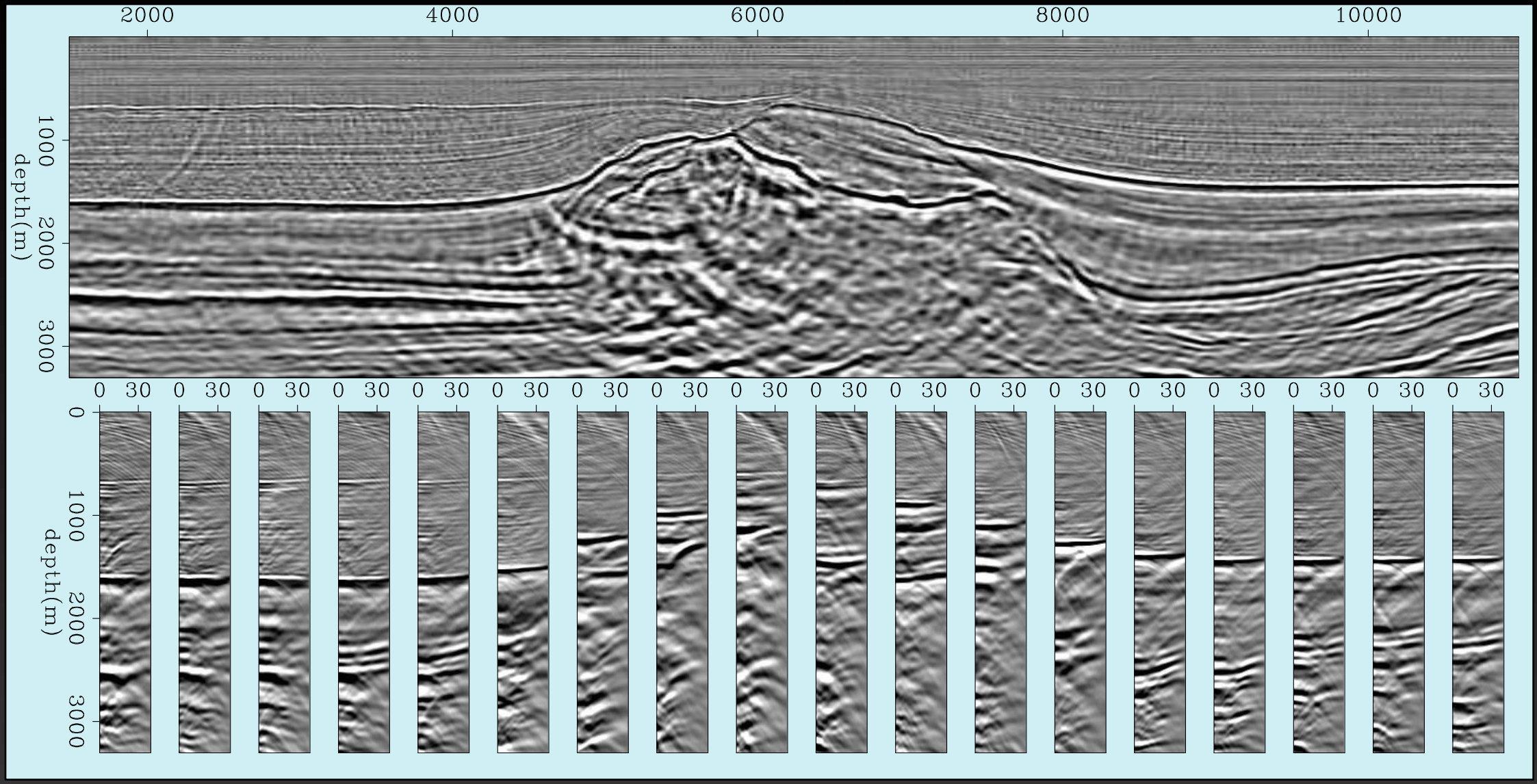
Optimized


2000
4000
6000
8000
10000
1000
2000
3000
depth(m)
0 30
0
1000
2000
3000
depth(m)

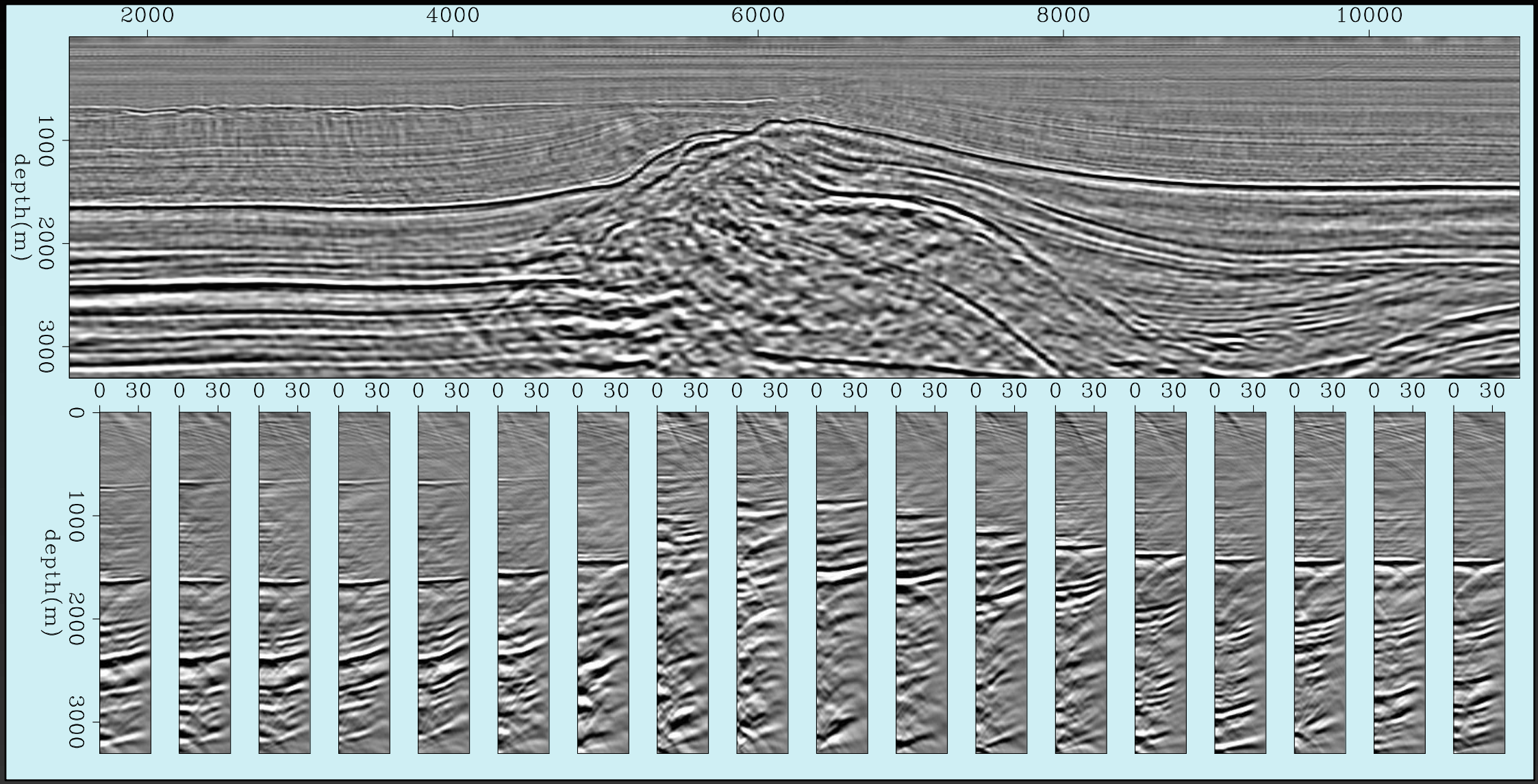
Initial


2000
4000
6000
8000
10000
1000
2000
3000
depth(m)
0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30
0
1000
2000
3000
depth(m)

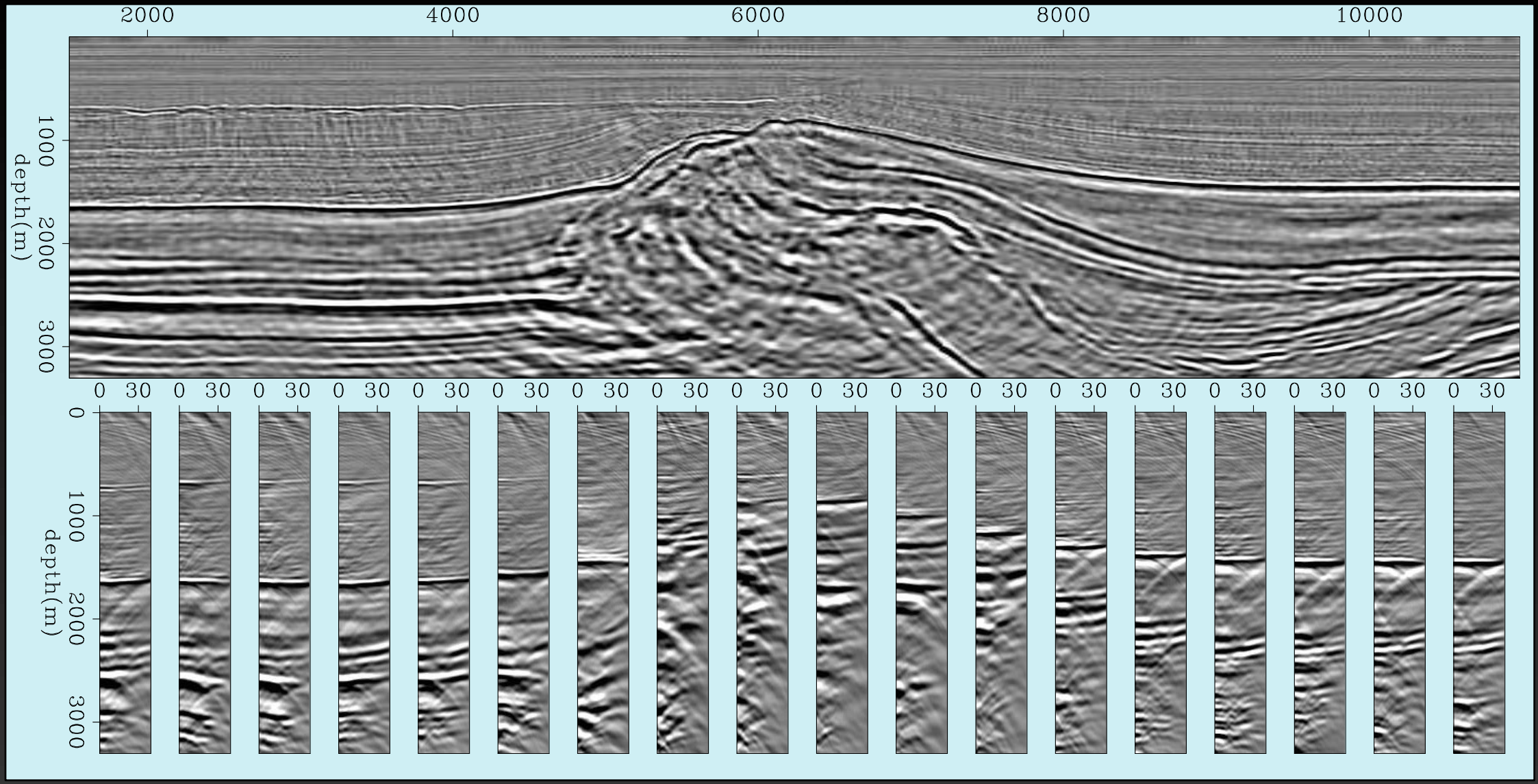
Optimized


2000
4000
6000
8000
10000
depth(m)
1000
2000
3000
0 30
0
1000
2000
3000
depth(m)

Initial


2000
4000
6000
8000
10000
1000
2000
3000
depth(m)
0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30 0 30
0
1000
2000
3000
depth(m)

Optimized

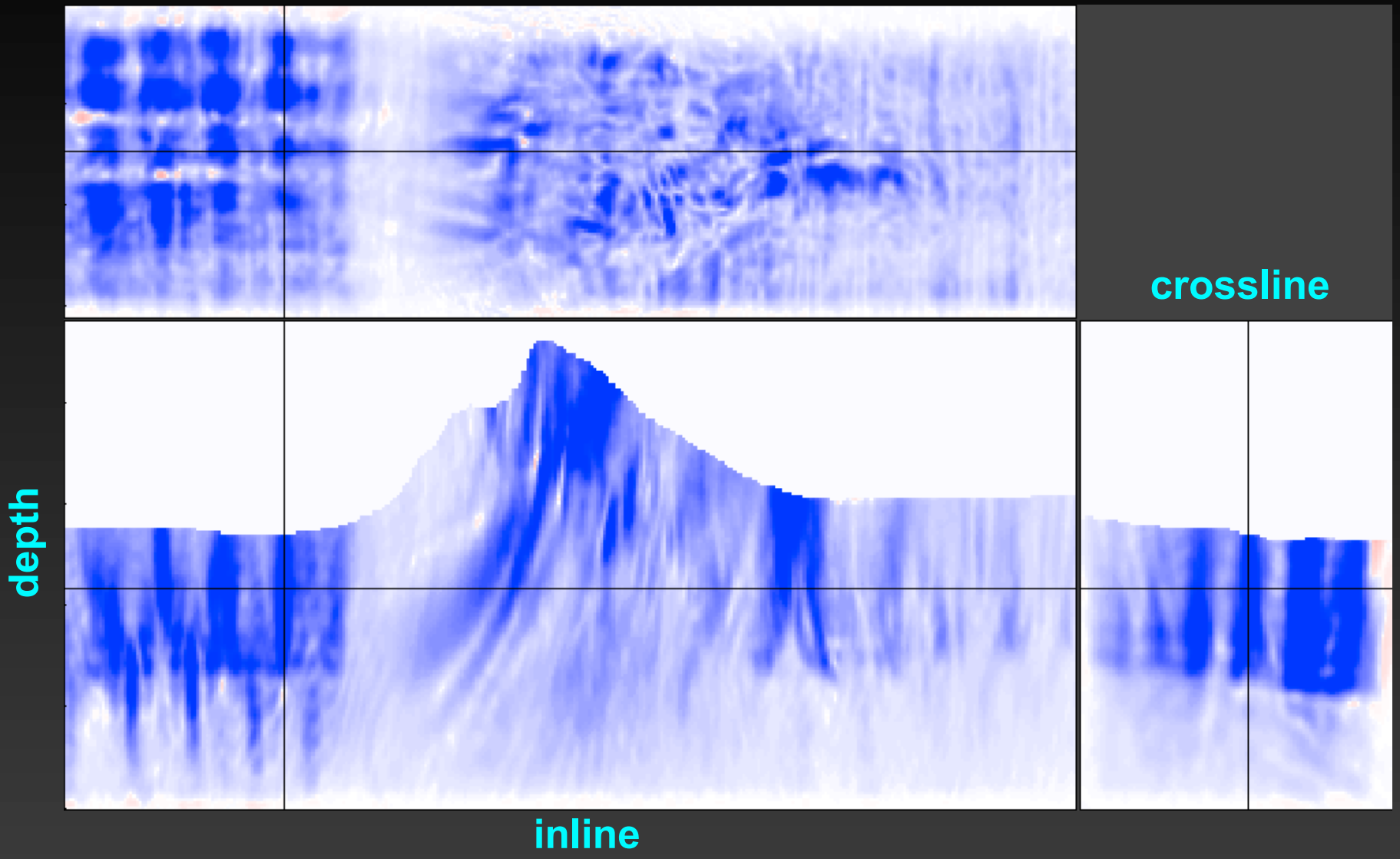

2000
4000
6000
8000
10000
1000
2000
3000
depth(m)
0 30
0
1000
2000
3000
depth(m)

3D-North Sea: Next steps

- **New round of modeling/MVA**
- **Top of salt interpretation**
- **Salt flooding**
- **Base of salt interpretation**
- **Sub-salt velocity definition**

Potential for grid-tomography

Gradient with 1 pair of ISPEW



Conclusions

- **Image-space generalized wavefields accelerate ISWET**
  - **reduced data size**
  - **target-oriented strategy**
  - **2 h per iteration**

Conclusions

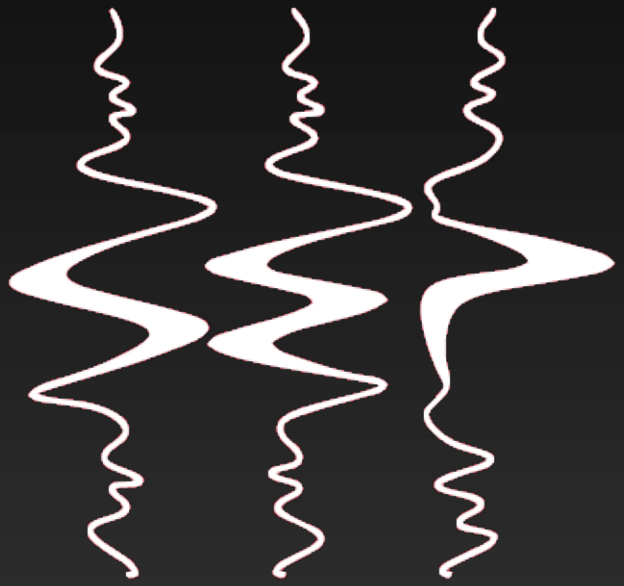
- **Image-space generalized wavefields accelerate ISWET**
  - **reduced data size**
  - **target-oriented strategy**
  - **2 h per iteration**

- **Image-space generalized wavefields naturally incorporate a horizon-based strategy**
  - **Potential for grid-based strategy**

Acknowledgements

- Pierre Jousselin, from Total, for discussing about velocity model building in the North Sea
- Bob Clapp for continuously improving SEP's visualization/interpretation capability
- Dennis Michael, from CEES, for his continuous support
- TotalFinaElf for providing the North Sea dataset

Thanks



STANFORD

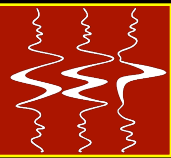
EXPLORATION PROJECT

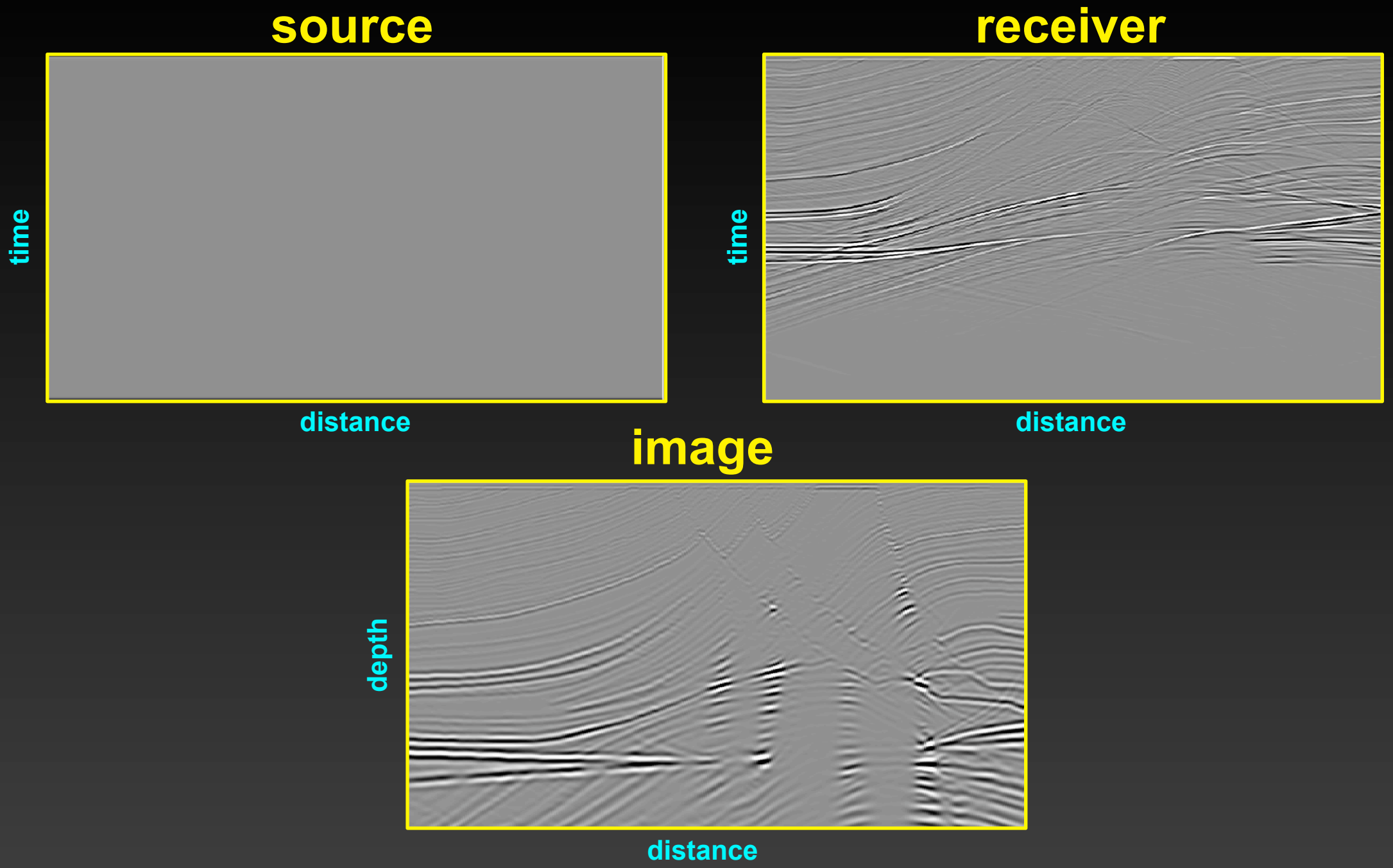
Fast 3D velocity updates using the pre-stack exploding-reflector model

Claudio Guerra and Biondo Biondi

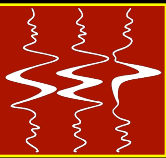
SEP 140, pp 1-10
May 2010

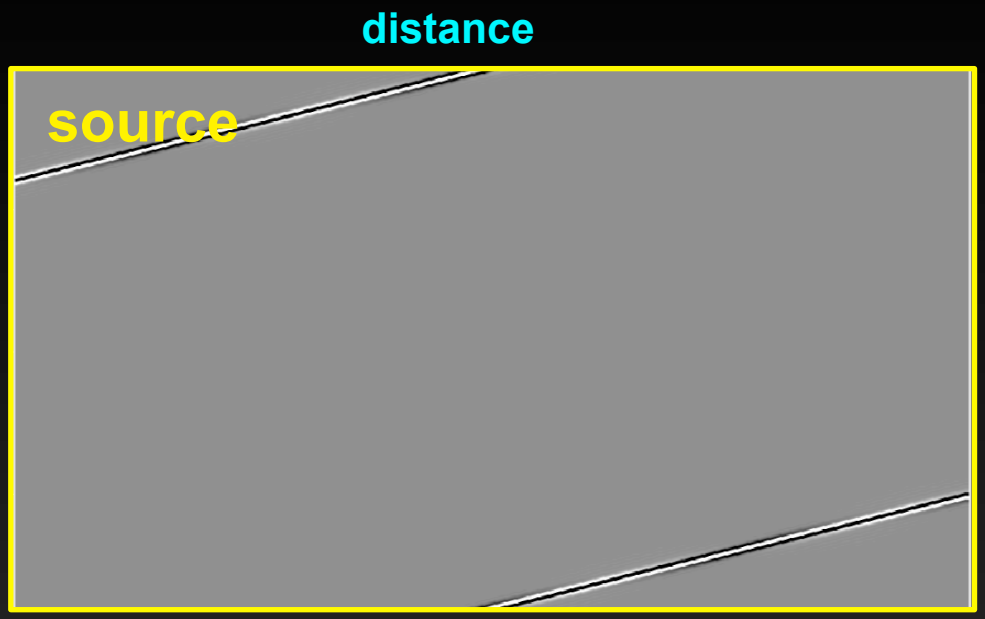
Data-space: 0° plane wave

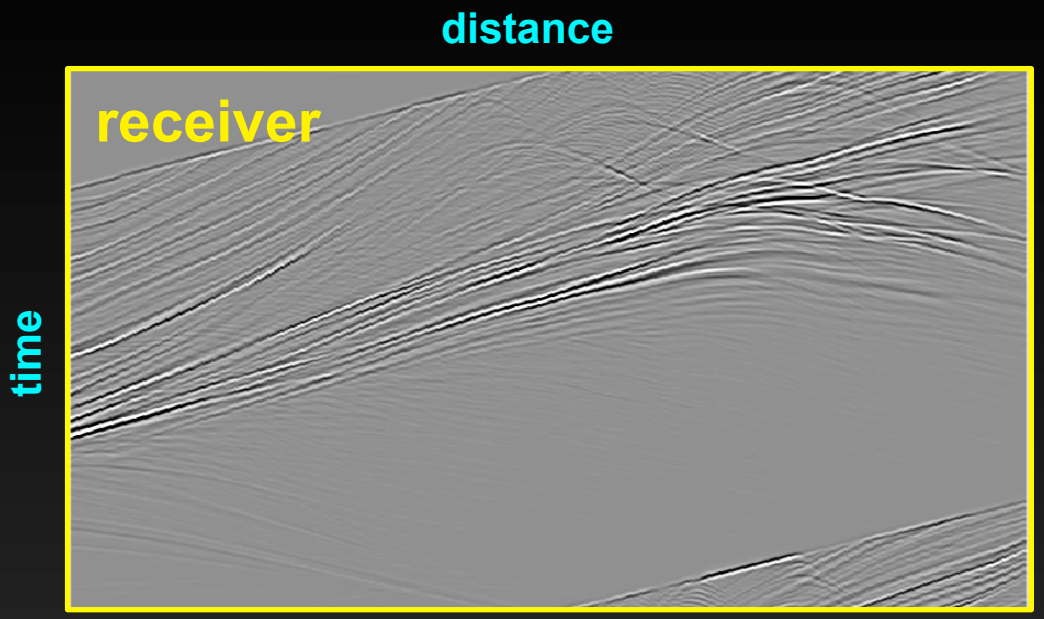


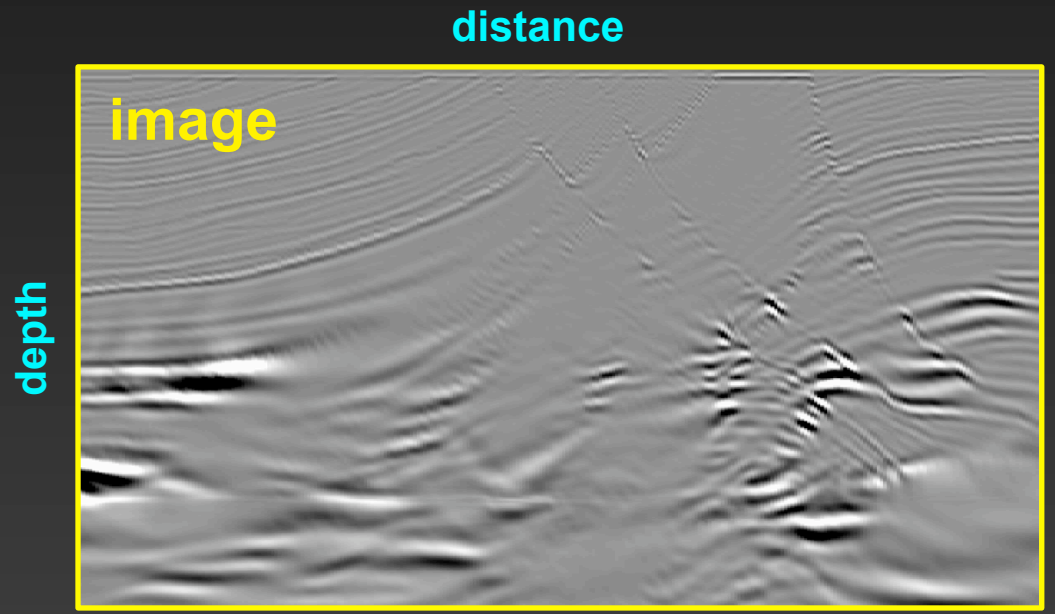


Data-space: plane waves

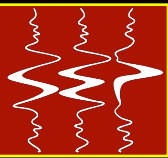


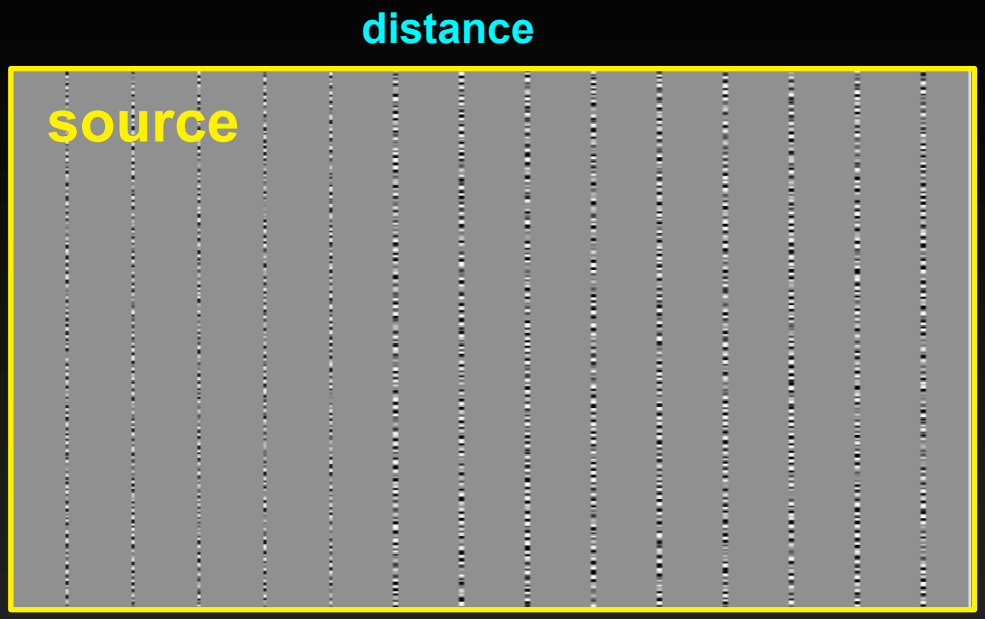


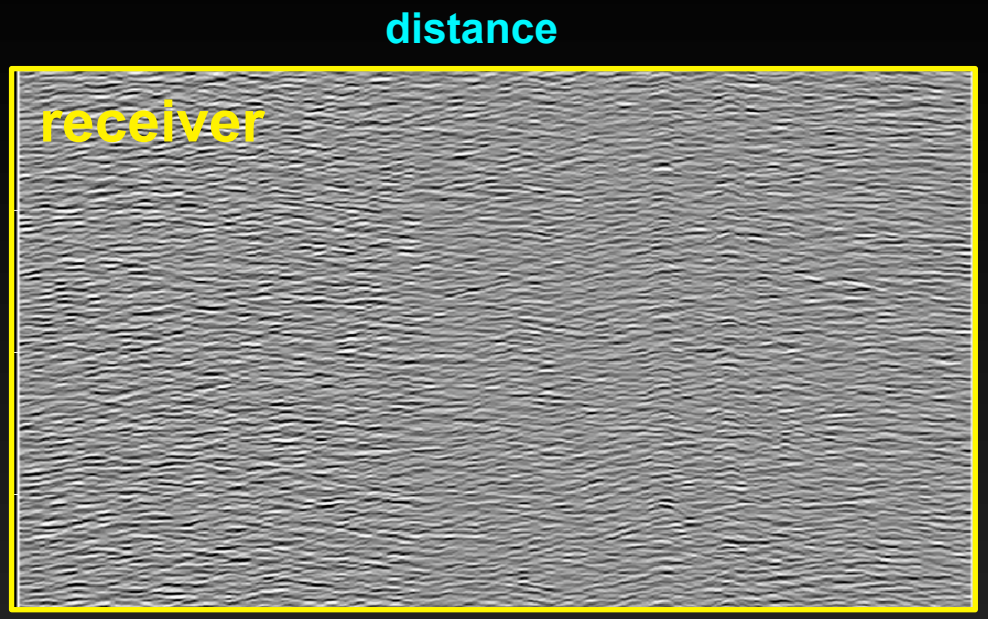


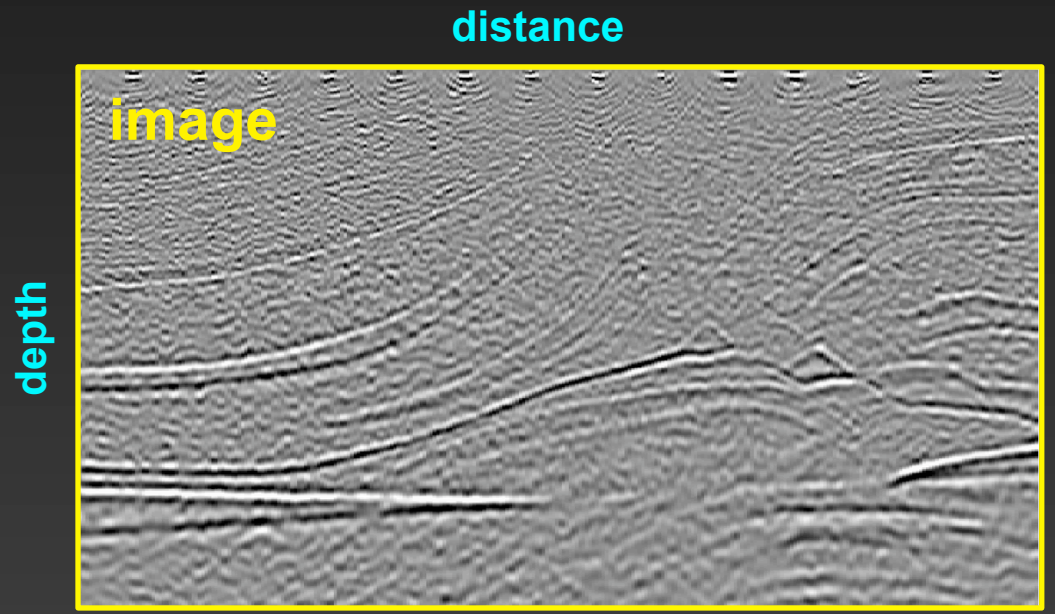


Data-space: random phases

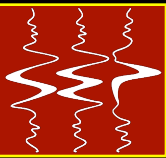


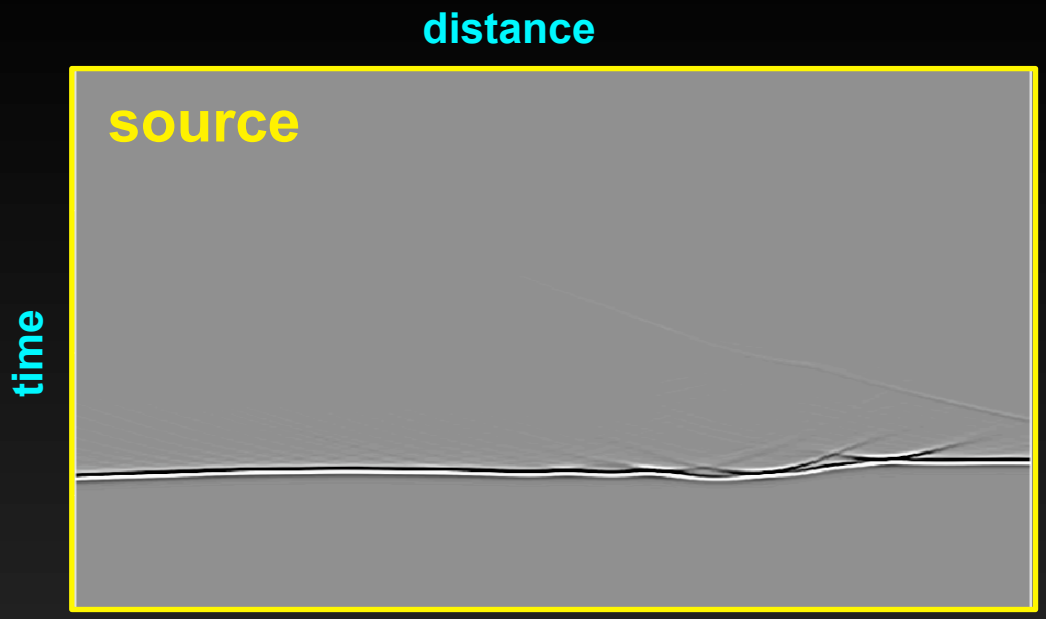


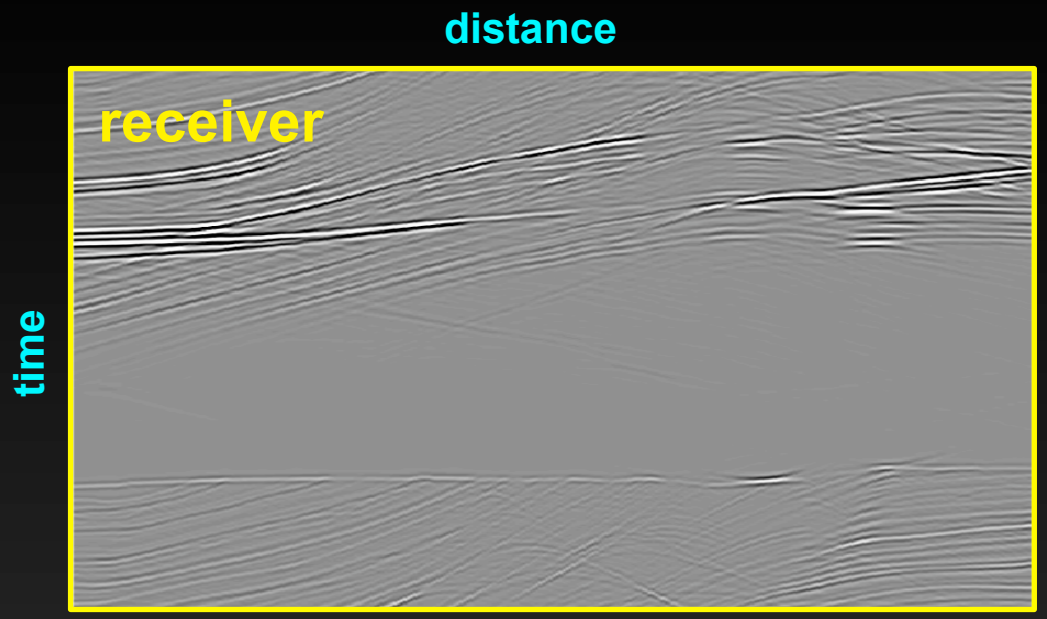




Data-space: controlled illumination







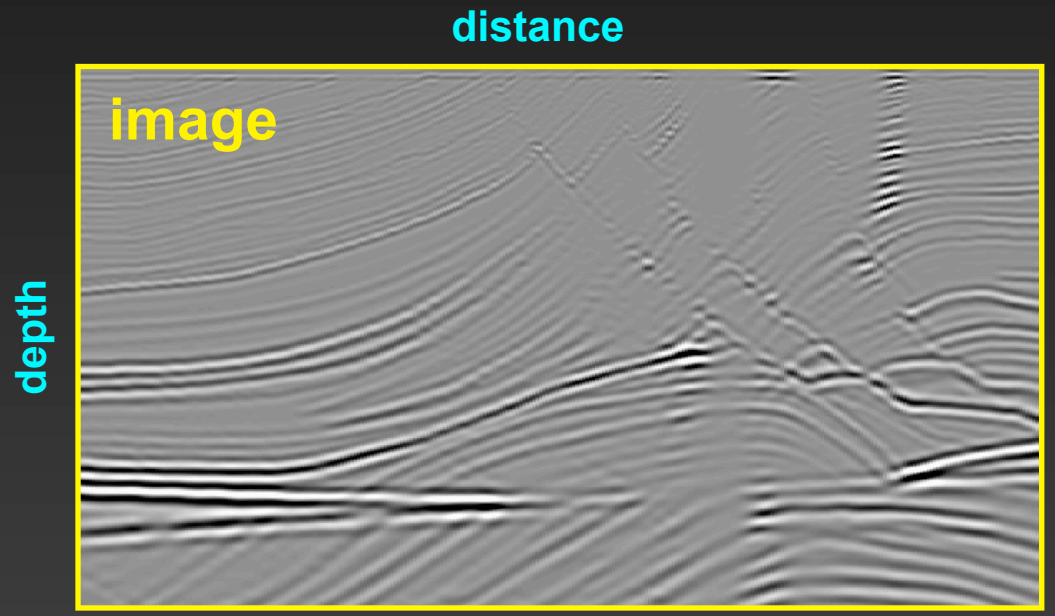
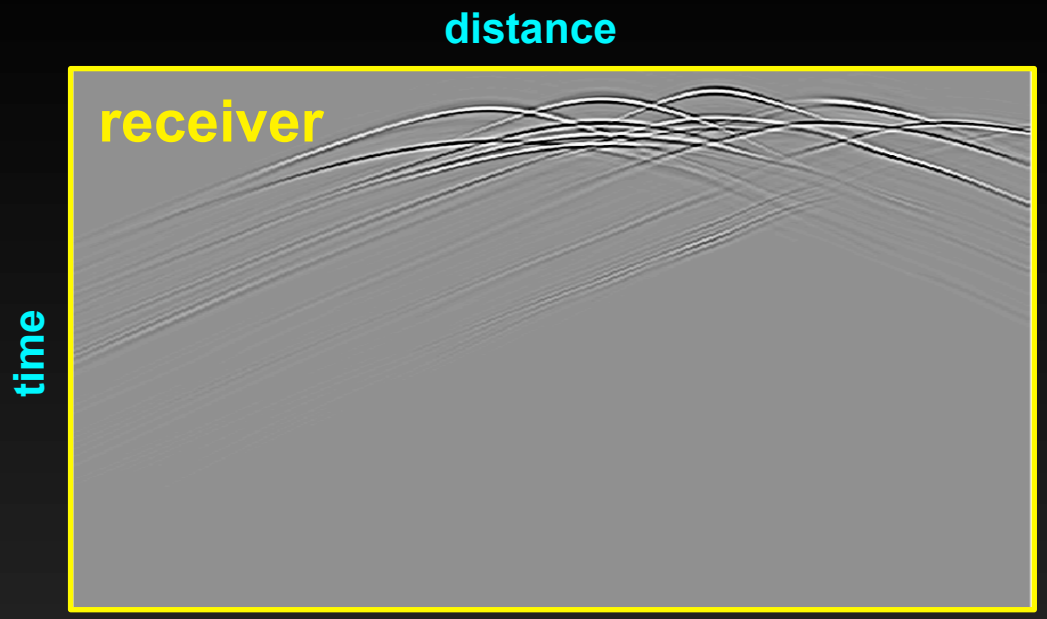


Image-space: prestack-exploding reflector



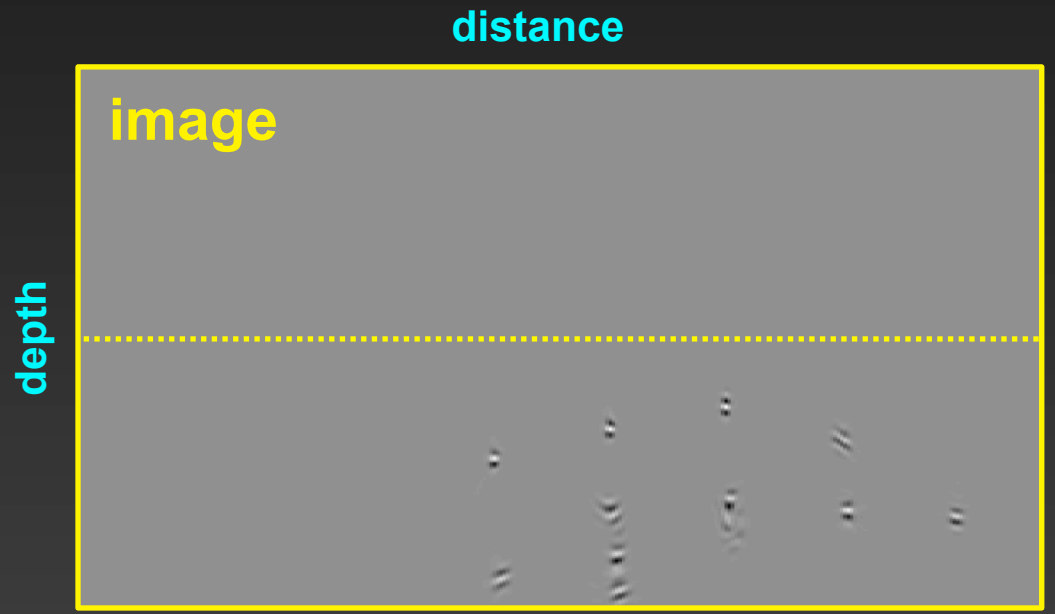
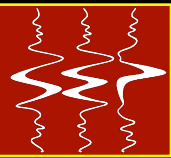
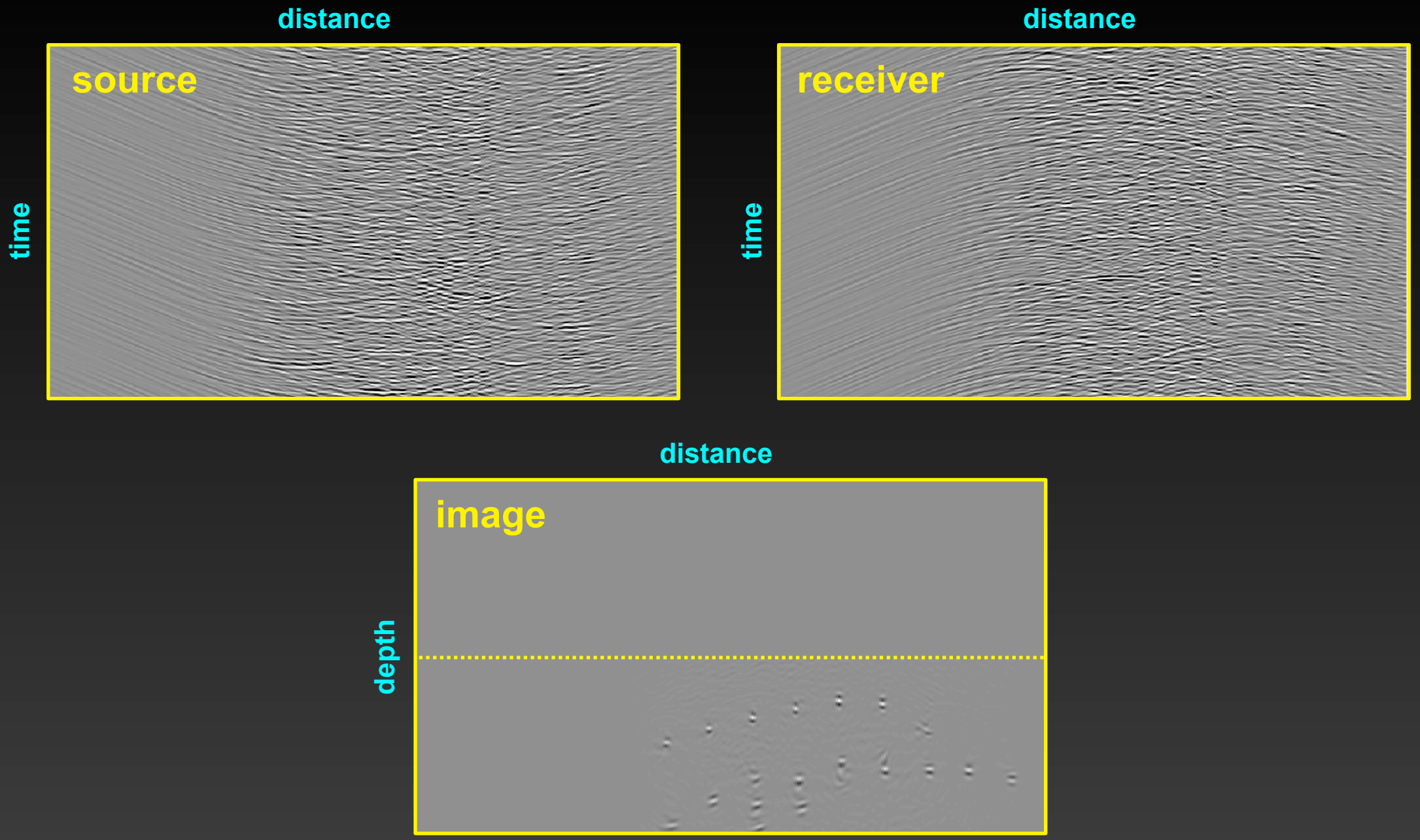
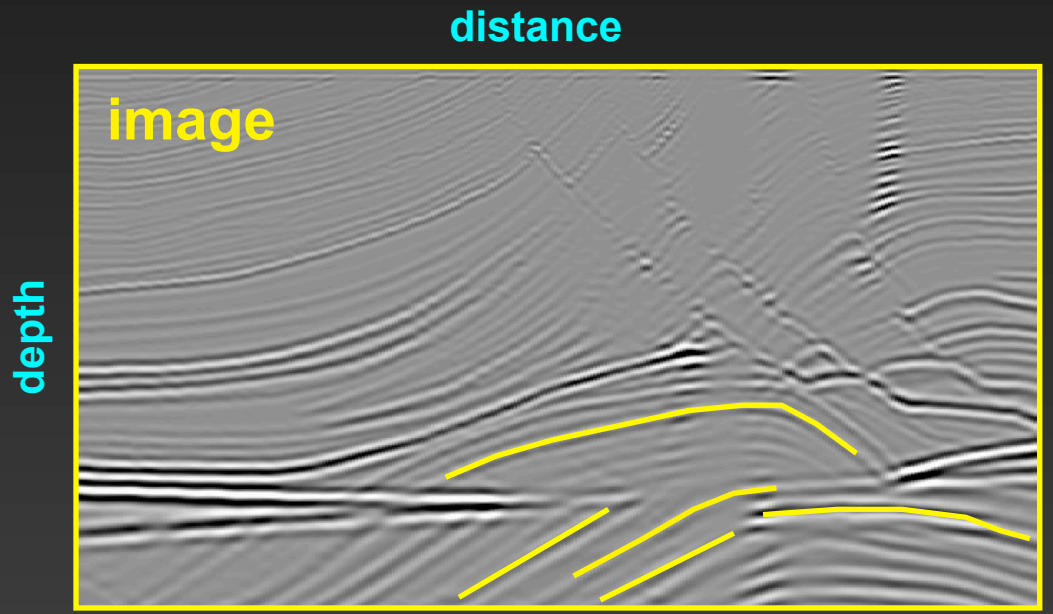


Image-space: random phases (ISPEW)

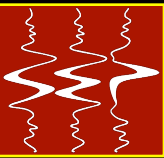




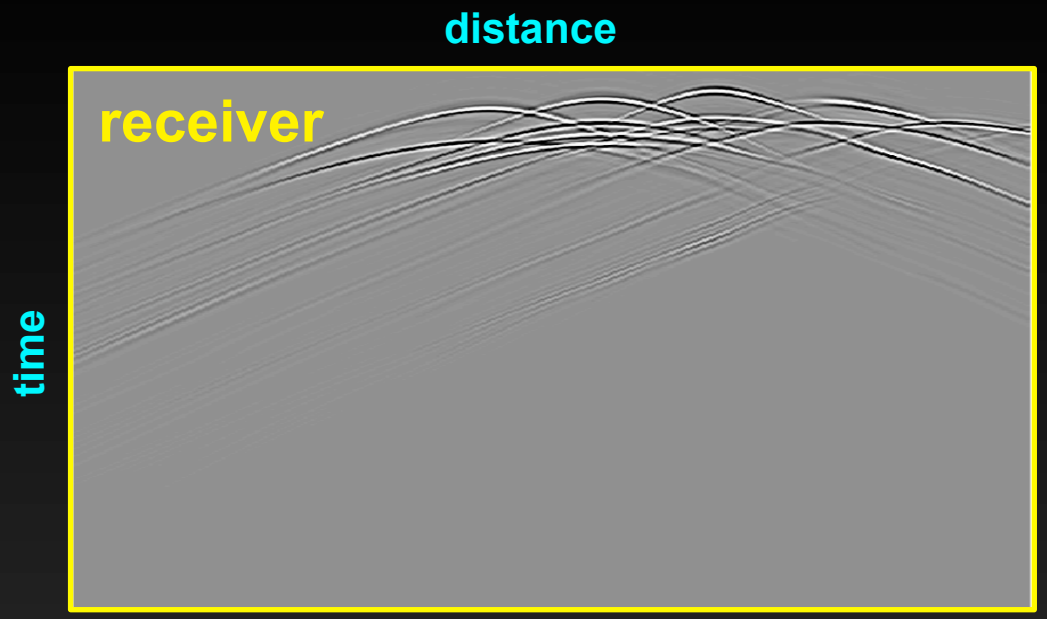
- **Models wavefields from selected reflectors**



PERM

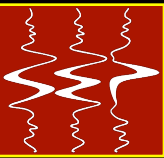


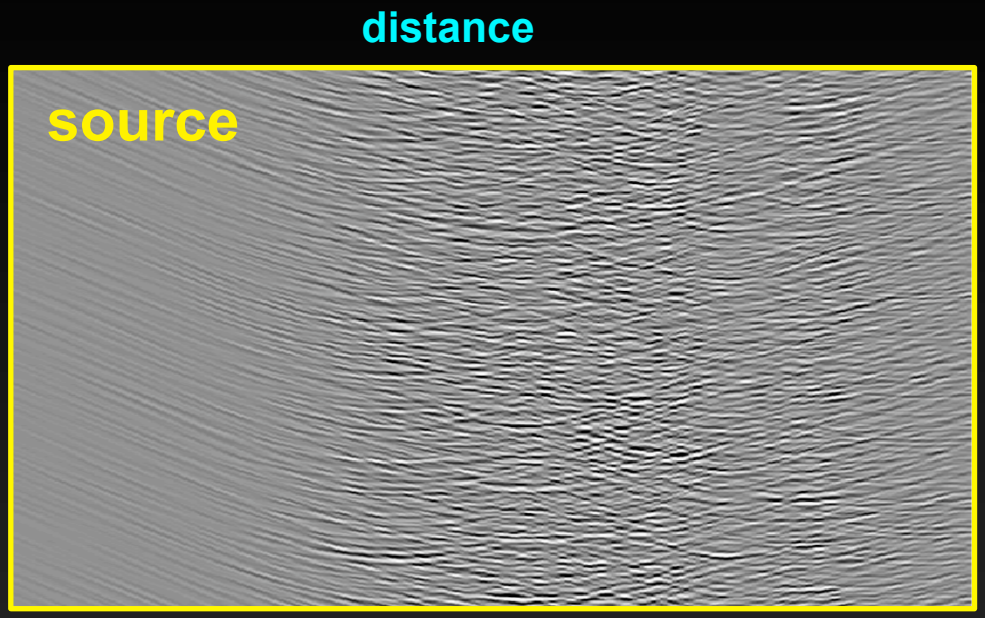

distance
source
time

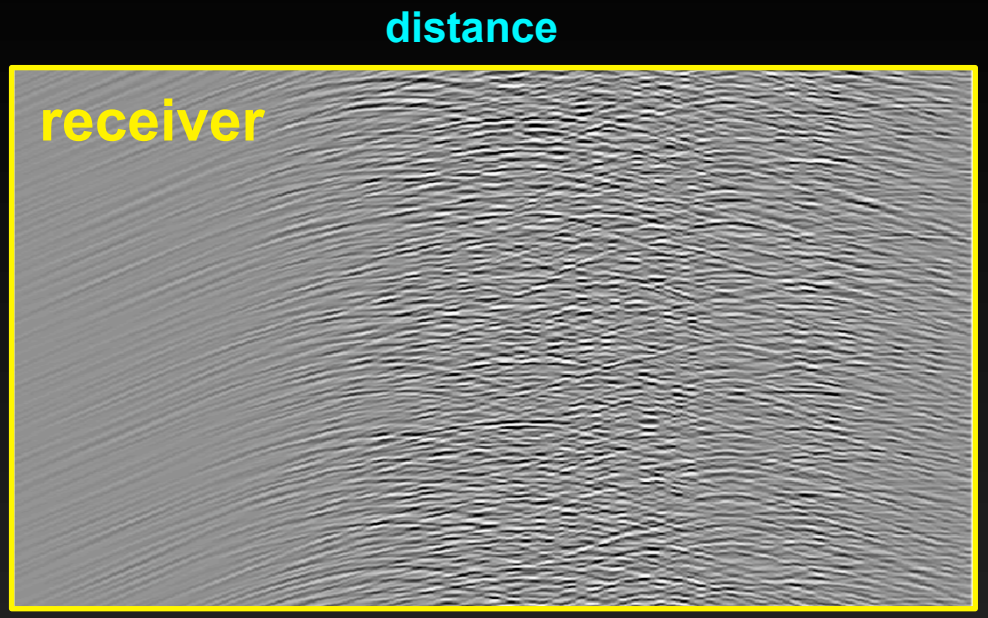

distance
receiver
time


distance
image
depth

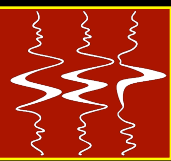
ISPEW




distance
source
time


distance
receiver
time


distance
image
depth



Source wavefield

$$\begin{cases} \left(\frac{\partial}{\partial z} - i\Lambda\right) \widetilde{P}_d(\mathbf{x}, \mathbf{r}_m, \omega) &= \widetilde{I}_d(\mathbf{x}, \mathbf{h}, \mathbf{r}_m, \omega) \\ \widetilde{P}_d(x, y, z = z_{\max}, \mathbf{r}_m, \omega) &= 0 \end{cases}$$

Receiver wavefield

$$\begin{cases} \left(\frac{\partial}{\partial z} + i\Lambda\right) \widetilde{P}_u(\mathbf{x}, \mathbf{r}_m, \omega) &= \widetilde{I}_u(\mathbf{x}, \mathbf{h}, \mathbf{r}_m, \omega) \\ \widetilde{P}_u(x, y, z = z_{\max}, \mathbf{r}_m, \omega) &= 0 \end{cases}$$

Λ = SSR operator

$\widetilde{P}_d$ = phase encoded source wavefield

$\widetilde{I}_d$ = source wavefield initial condition

$\mathbf{r}_m$ = index of random realizations

$\widetilde{P}_u$ = phase encoded receiver wavefield

$\widetilde{I}_u$ = receiver wavefield initial condition

Image-space phase-encoded wavefields

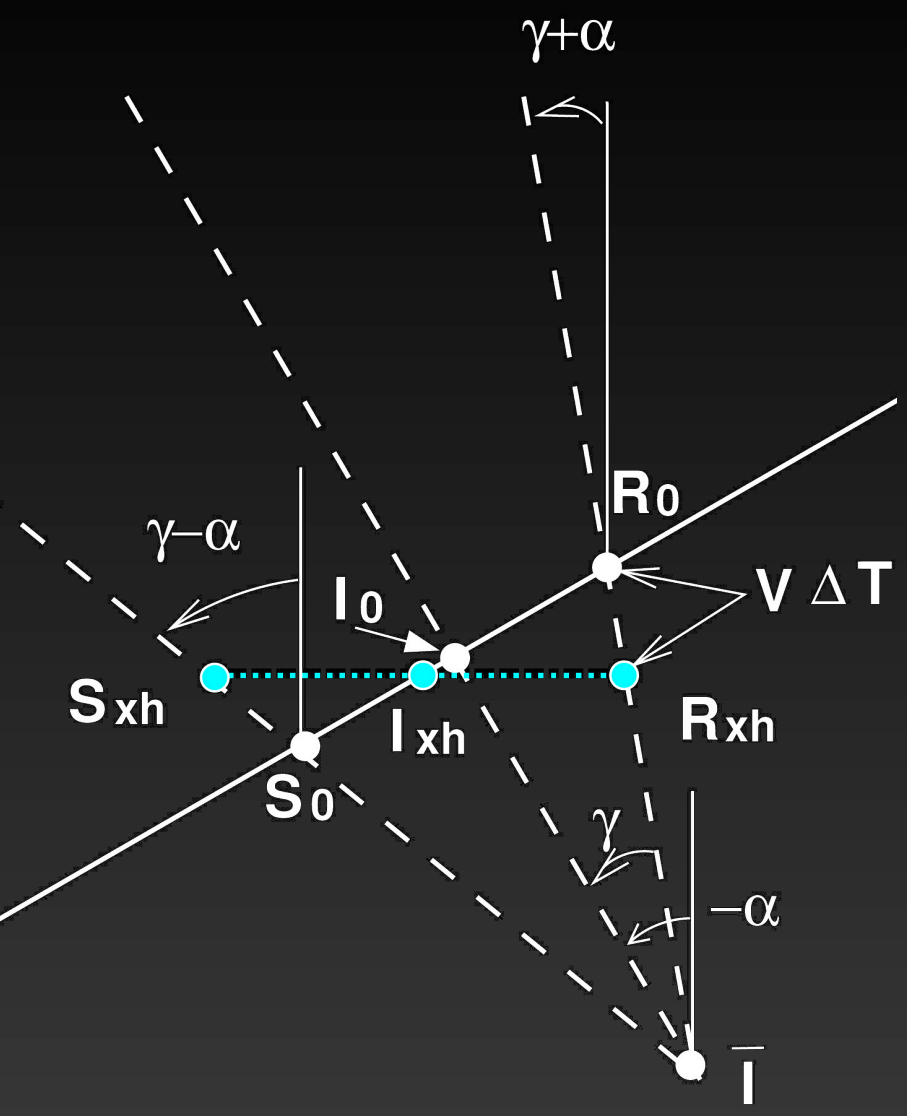
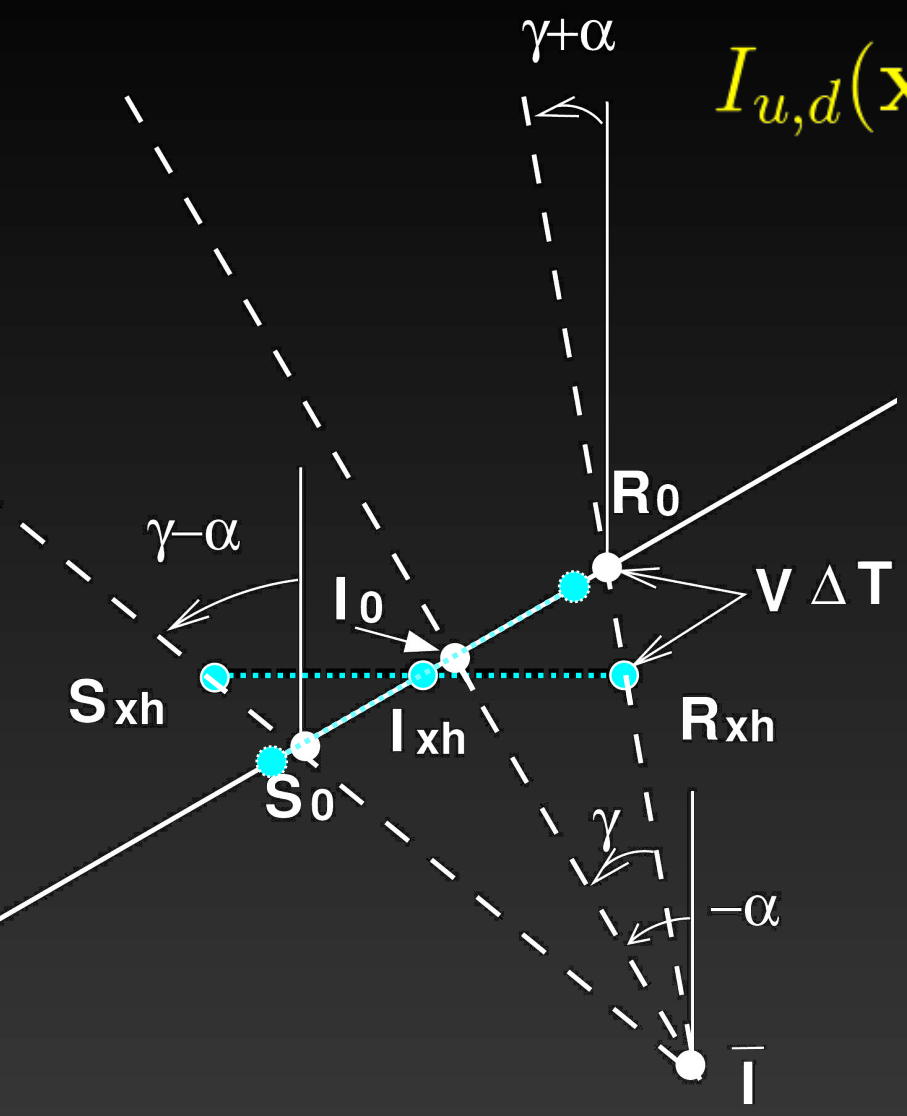


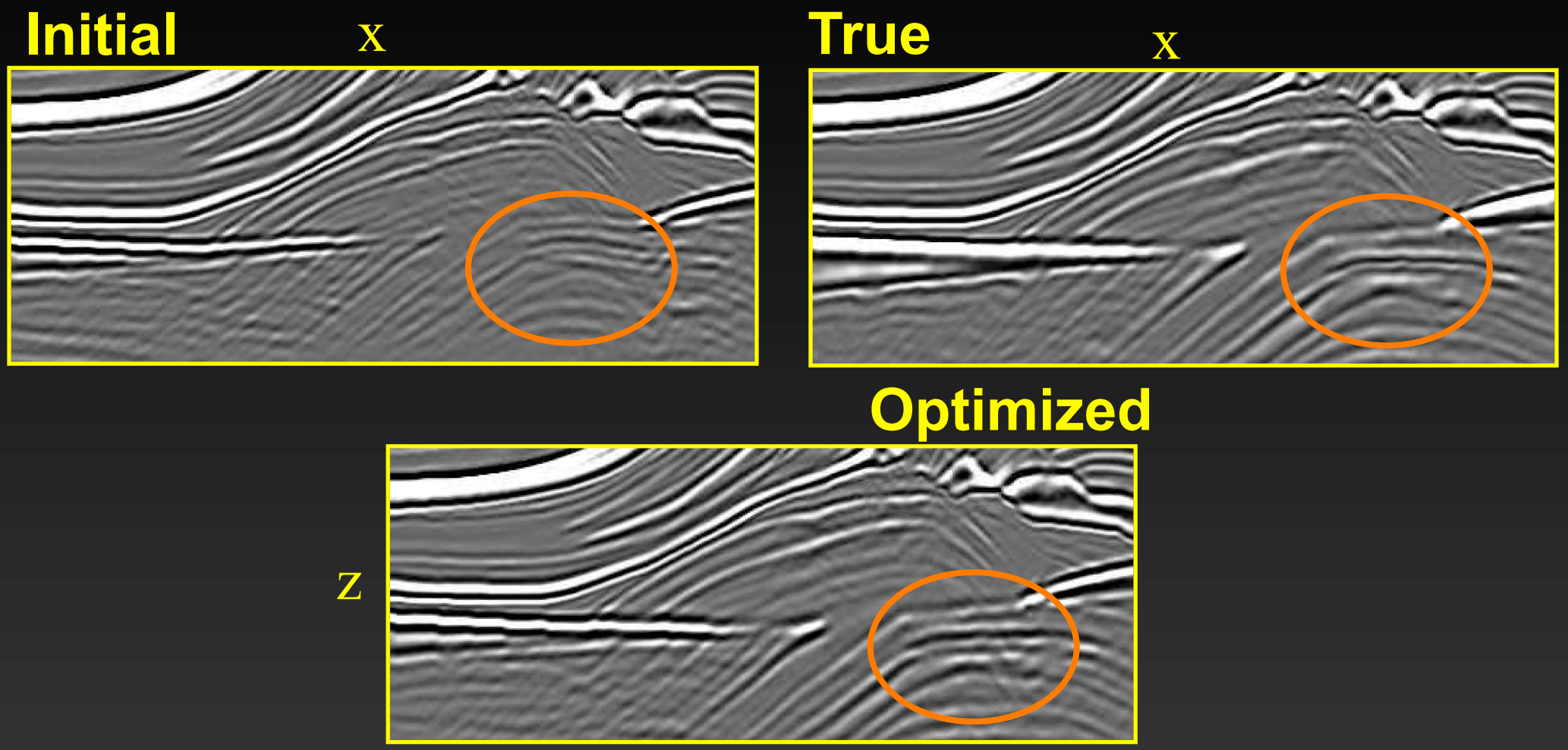
Image-space phase-encoded wavefields



$$I_{u,d}(\mathbf{x},\mathbf{h}) = \iiint\limits_{\alpha\gamma x'} \varrho I(\mathbf{x},\mathbf{h};x')dx'd\gamma d\alpha \Big|_{\zeta}$$

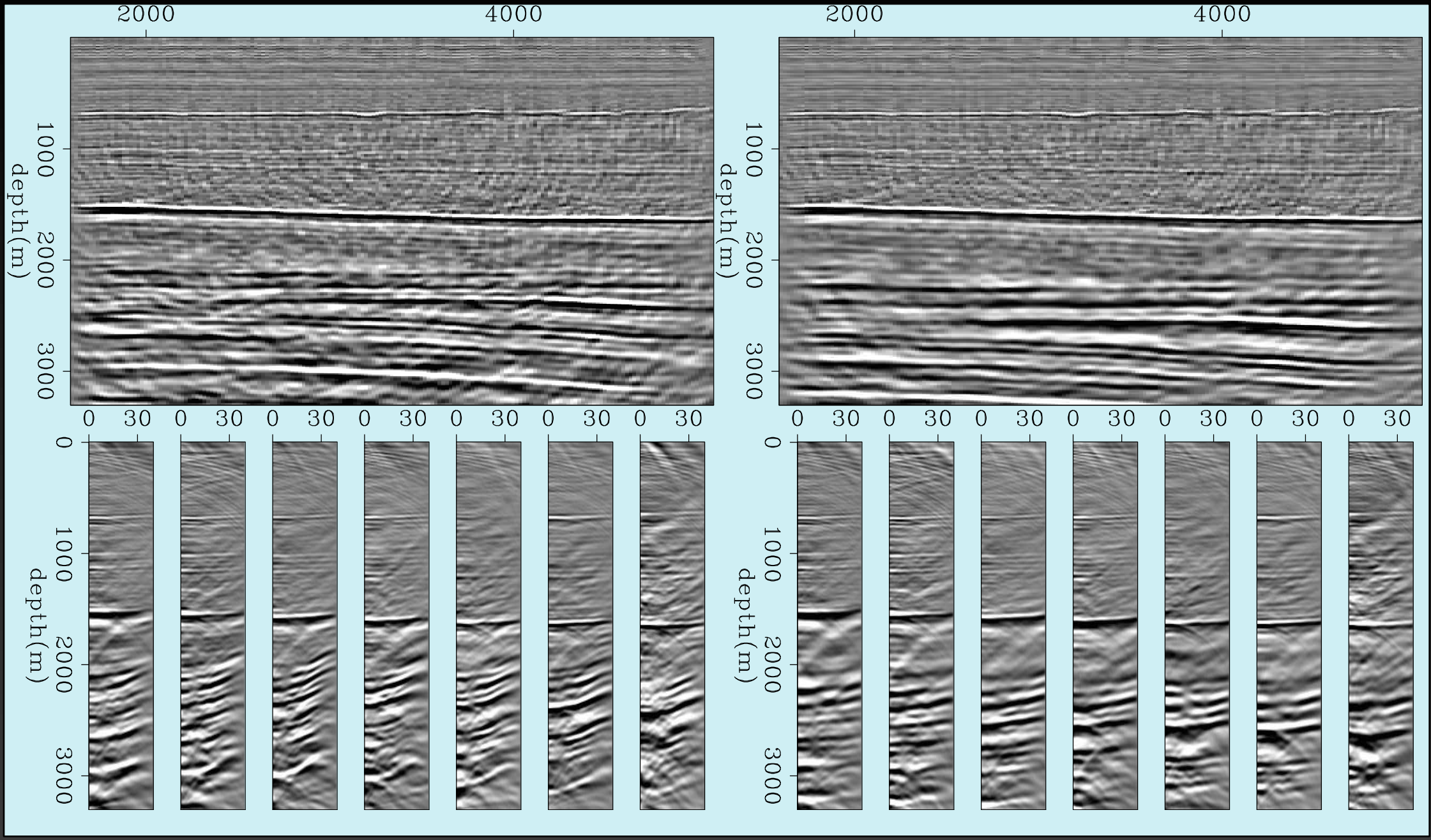
$$\zeta(\alpha,\gamma,\mathrm{h},x') = z - \mathrm{h}tg(\gamma) - x'tg(\alpha) \pm \mathrm{h}tg(\gamma \pm \alpha)$$

Motivation



Initial

Optimized



Initial

Optimized