



Fast 3D velocity updates using image-space generalized sources

Claudio Guerra and Biondo Biondi

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For complex geology ...

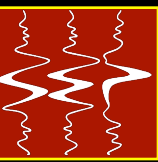
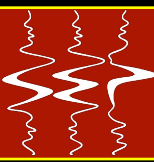
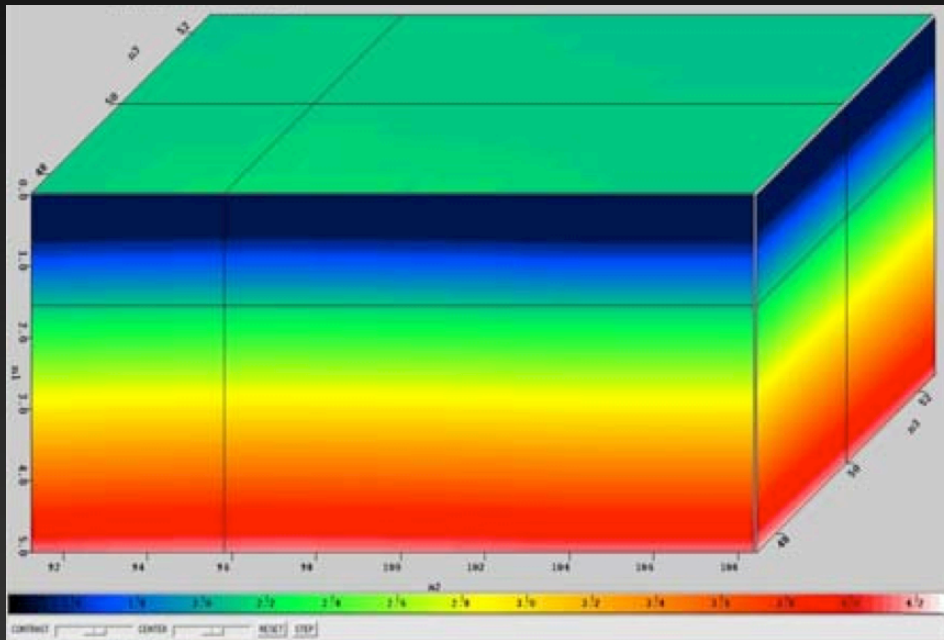


Image-space wave-equation tomography (ISWET) is theoretically more robust than ray-based methods

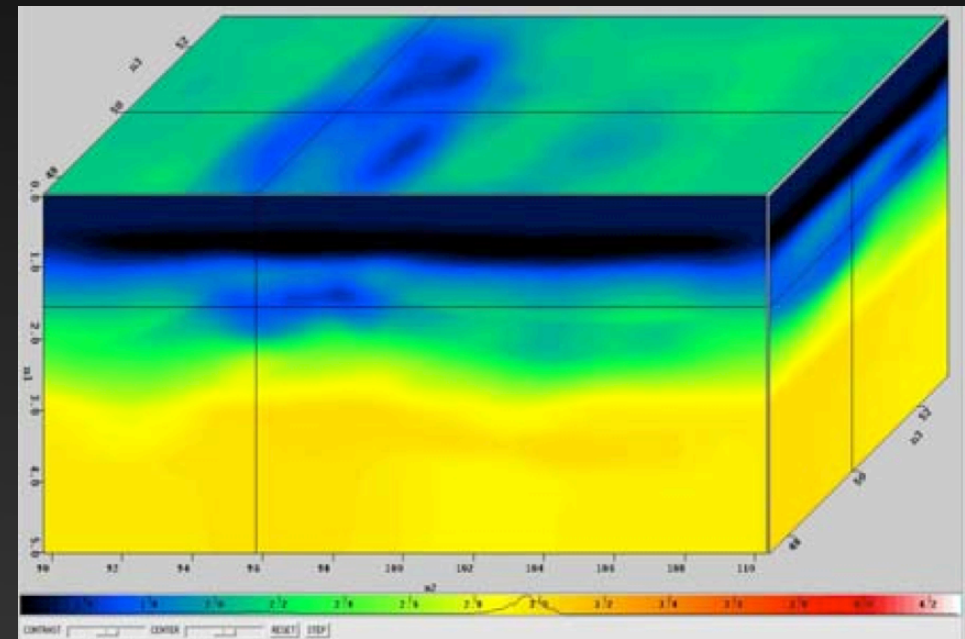
However ...



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

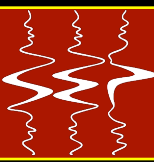


Initial velocity

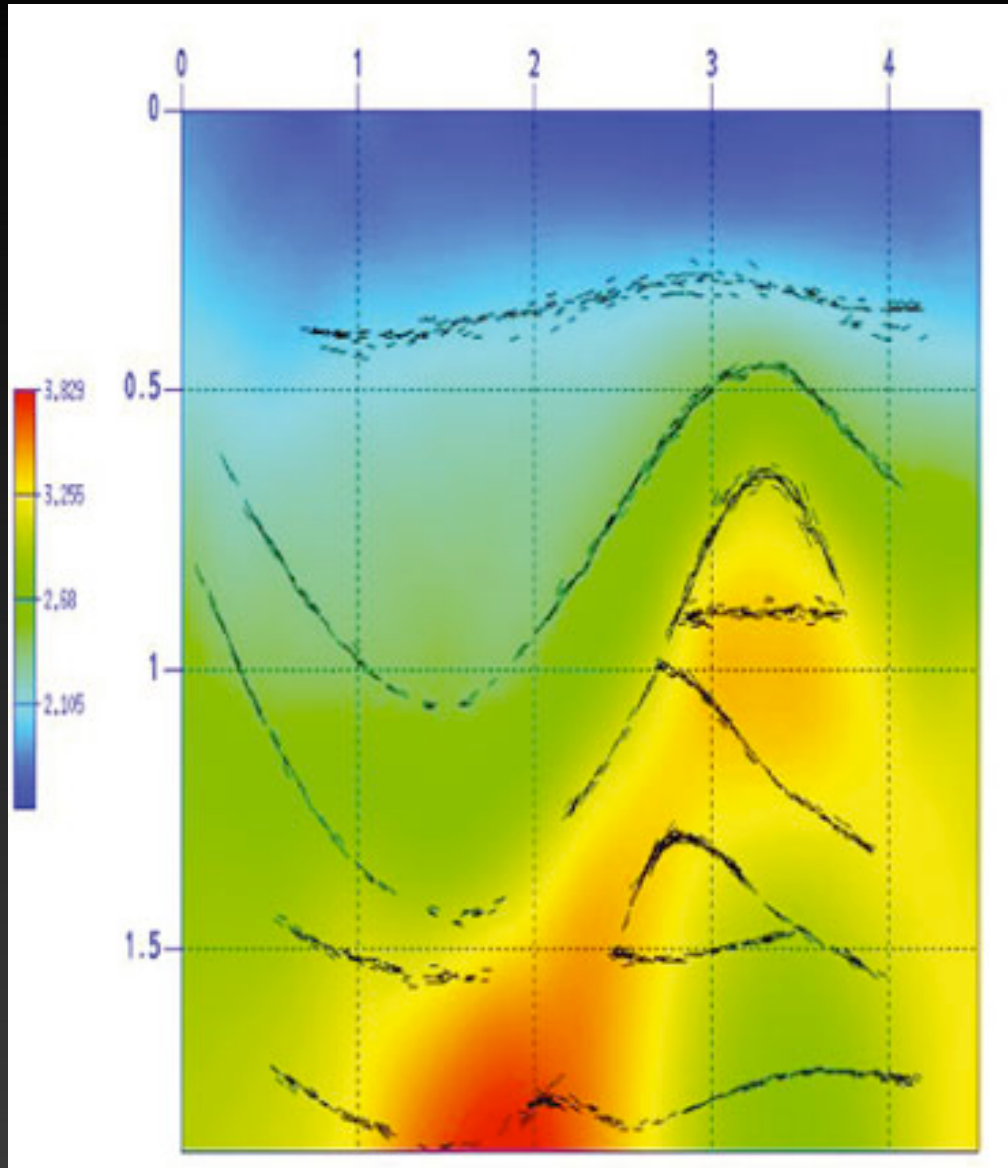


Final velocity

Fei et al., 2009



Grid-based



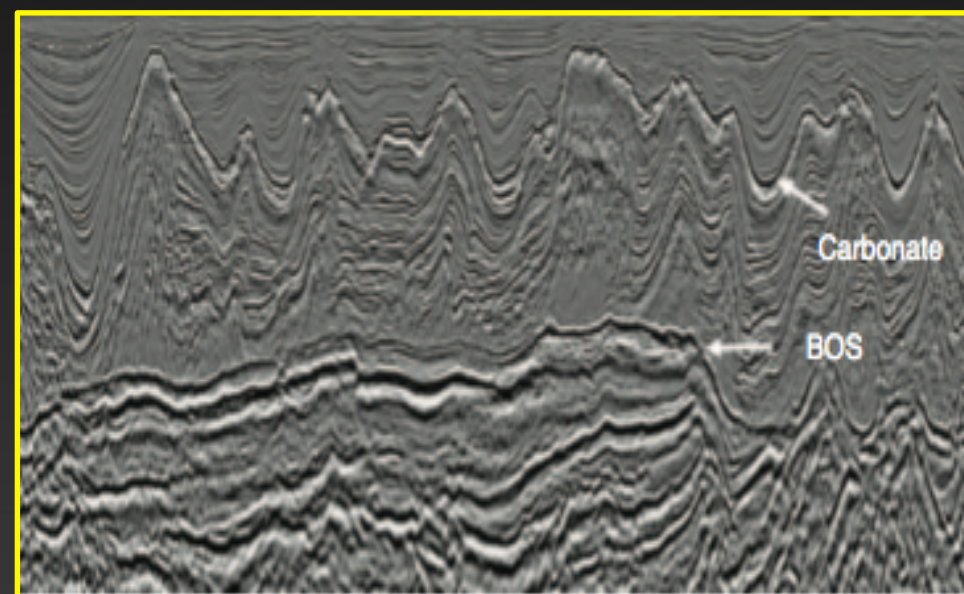
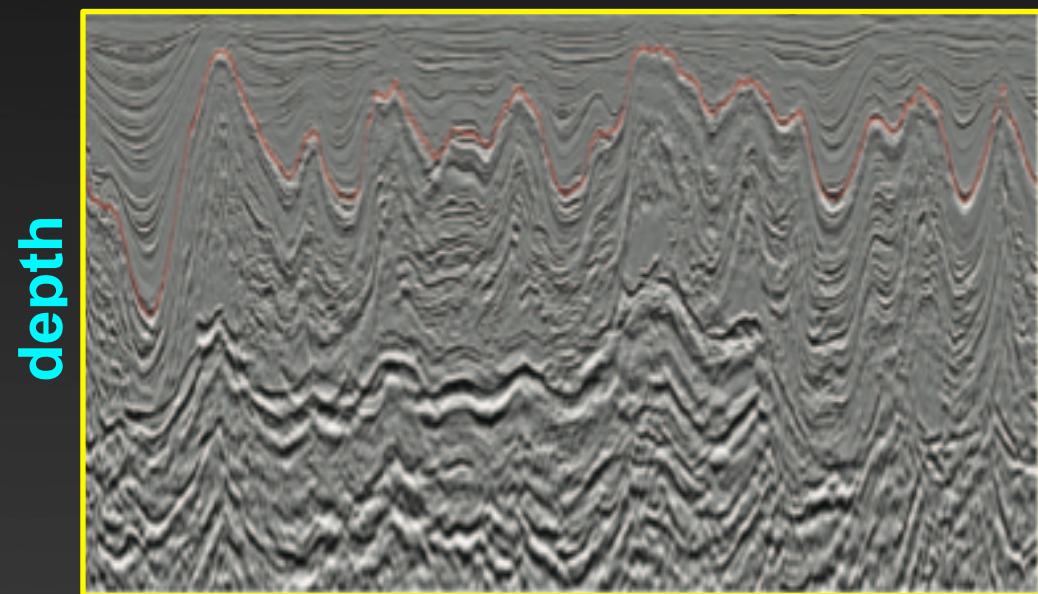
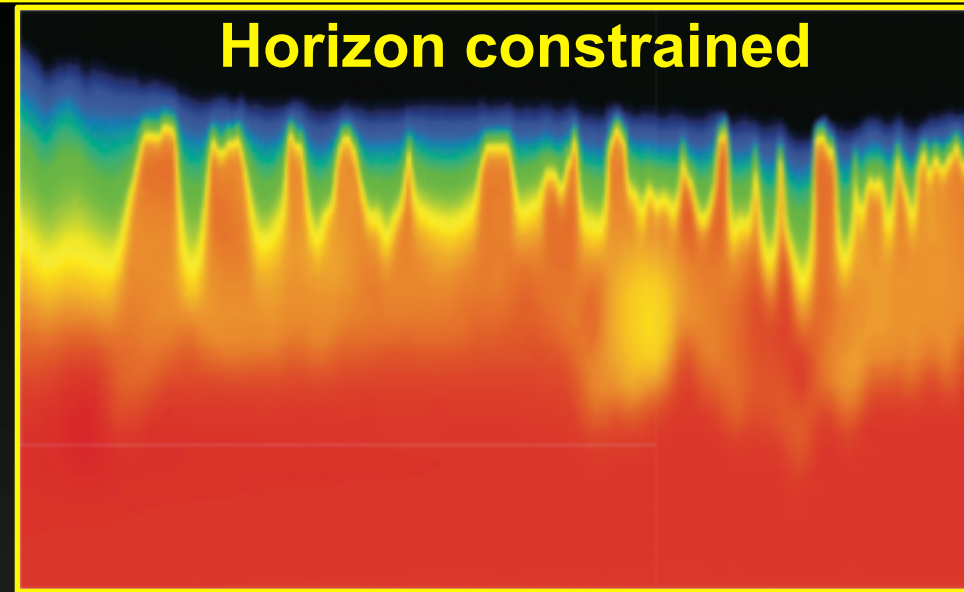
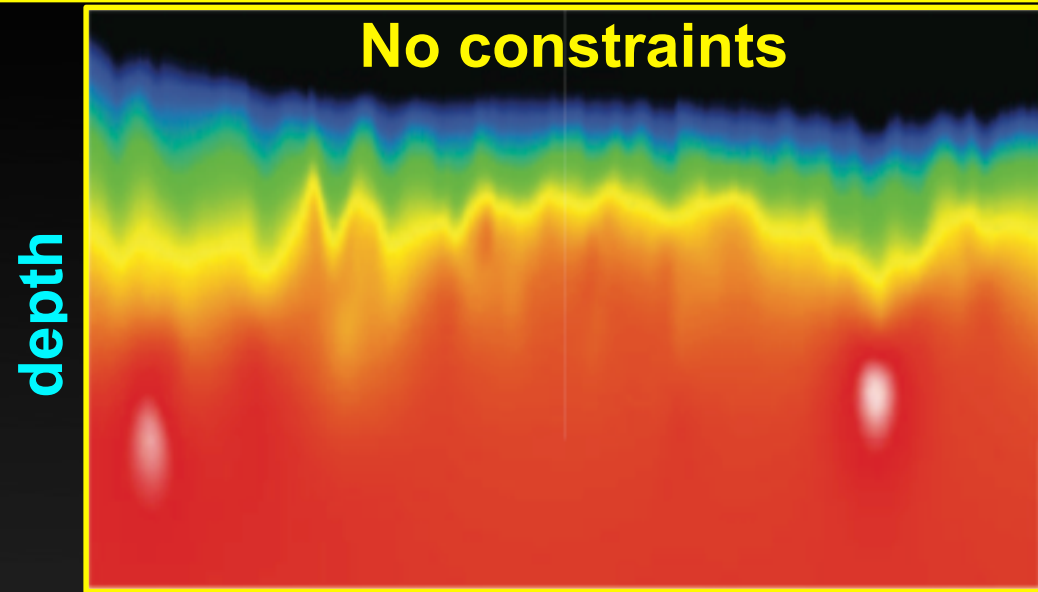
www.sintef.no

Horizon-based



Jones et al., 1998

Hybrid tomography

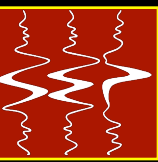


distance

Wang et al., 2008

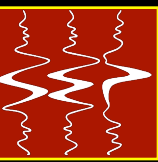
distance

3D-ISWET as routine processing



- **Reduce cost**

3D-ISWET as routine processing



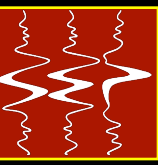
- **Reduce cost**
- **Improve flexibility**

3D-ISWET as routine processing

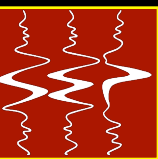


- **Reduce cost**
- **Improve flexibility**
- **Keep robustness**

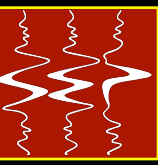
Reducing 3D-ISWET cost



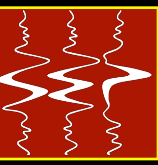
- **Decrease data size**



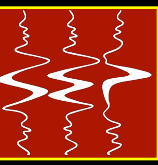
- **Decrease data size**
- **Solve in a target-oriented manner**
 - **Wavefield propagation restricted to the inaccurate velocity region**



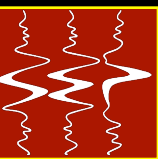
- **Incorporate strategies from ray-based methods into ISWET**



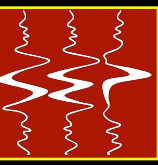
- **Incorporate strategies from ray-based methods into ISWET**
 - **Use image-space generalized wavefields**



- **Guarantee correct kinematics and reasonable amplitudes**



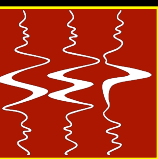
- **Generalized-source domain**
- **Pre-stack exploding-reflector model**
- **Image-space phase-encoded wavefields**
- **3D-field data ISWET example**
- **Conclusions**



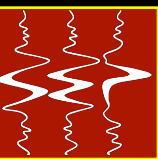
- **Wavefields combined using linearity of wavefield propagation**



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 - **Smaller number of seismic experiments**



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 - **Smaller number of seismic experiments**
 - **Keeping intact kinematic information**

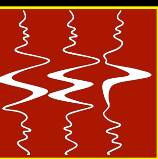


- **Wavefields combined using linearity of wavefield propagation**
 - **Smaller number of seismic experiments**
 - **Keeping intact kinematic information**

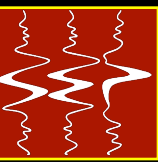
- **Seismic acquisition**
 - **Simultaneous-sources**



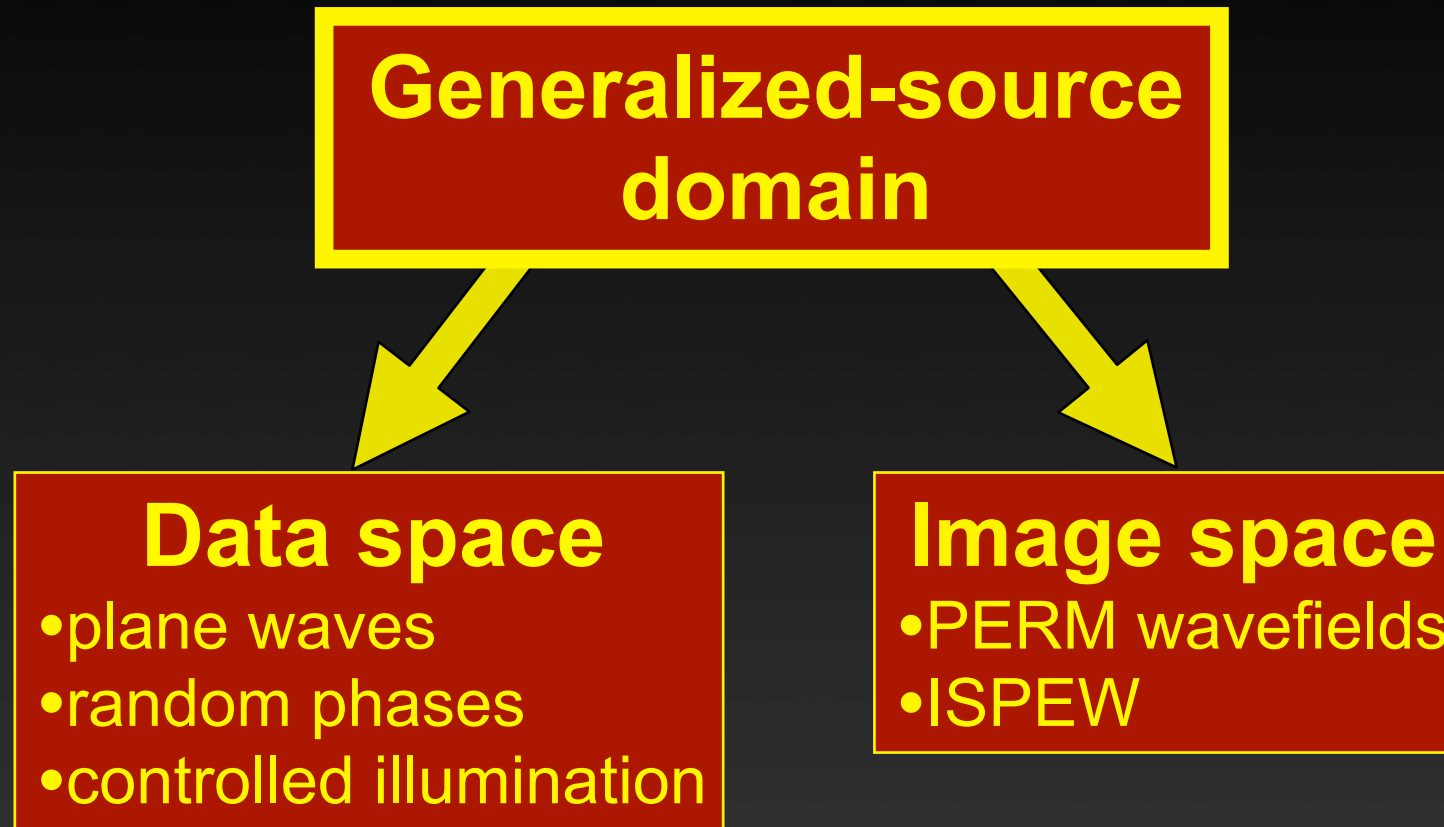
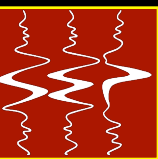
- **Wavefields combined using linearity of wavefield propagation**
 - Smaller number of seismic experiments
 - Keeping intact kinematic information
- **Seismic acquisition**
 - Simultaneous-sources
- **Seismic processing**
 - plane-wave encoding (Whitmore, 1995)
 - random-phase encoding (Romero et al., 2000)
 - controlled illumination (Rietveld et al., 1992)

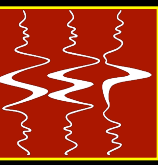


- **Data-space generalized sources**
 - plane-wave encoding
 - random-phase encoding
 - controlled illumination

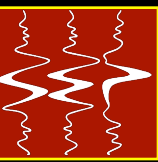


- **Data-space generalized sources**
 - plane-wave encoding
 - random-phase encoding
 - controlled illumination
- **Image-space generalized sources**
 - Pre-stack exploding-reflector modeling - PERM (Biondi, 2006)
 - Image-space phase-encoded wavefields - ISPEW (Guerra and Biondi, 2008)





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

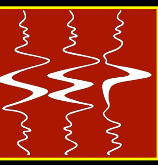


- **The exploding-reflector model synthesizes zero-offset data, assuming focused reflectors at zero-subsurface-offset**



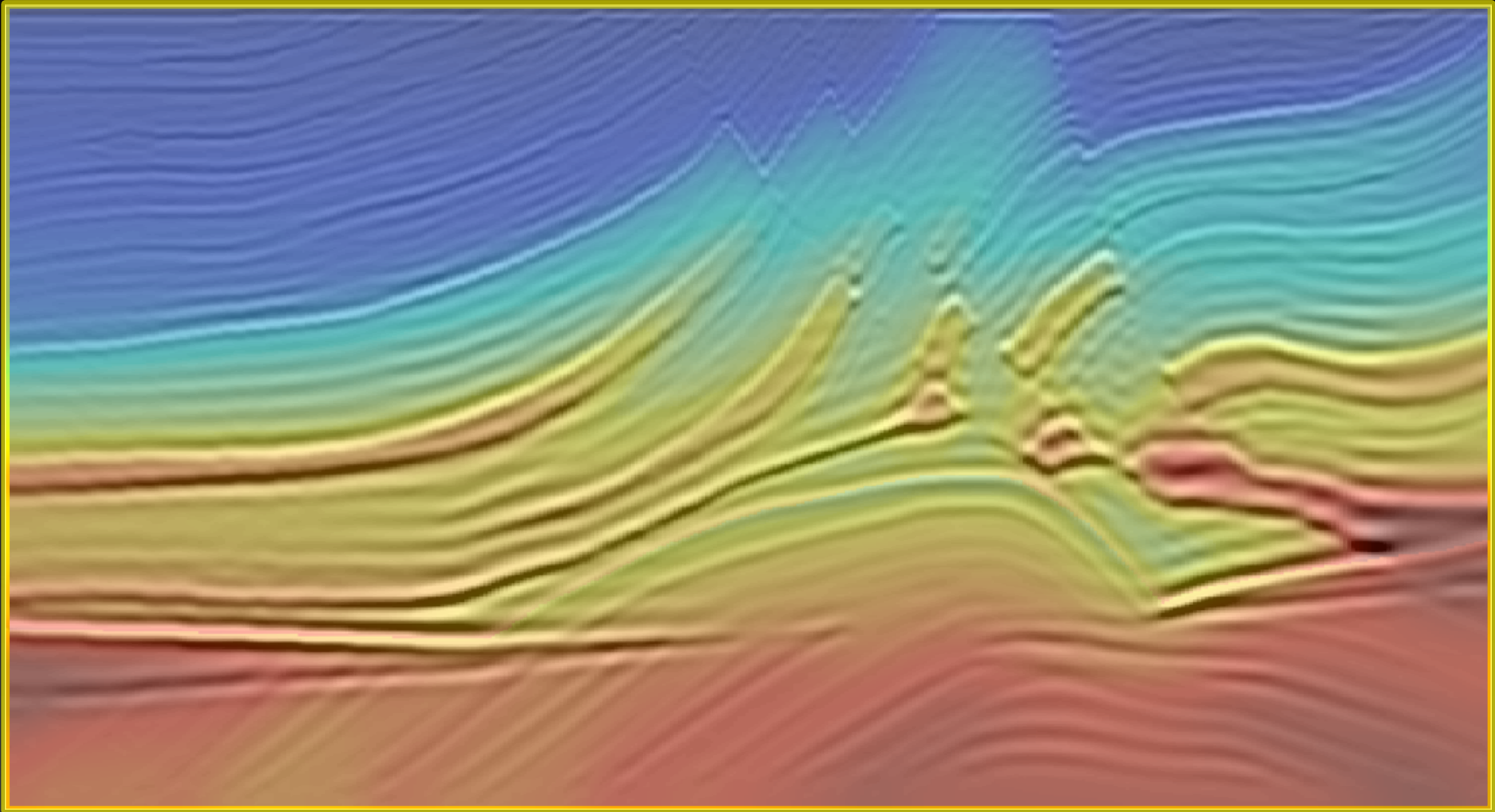
- **The exploding-reflector model synthesizes zero-offset data, assuming focused reflectors at zero-subsurface-offset**
 - **Accurate velocity**
 - **Complete illumination**

Exploding reflectors

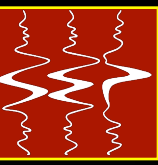


distance

depth

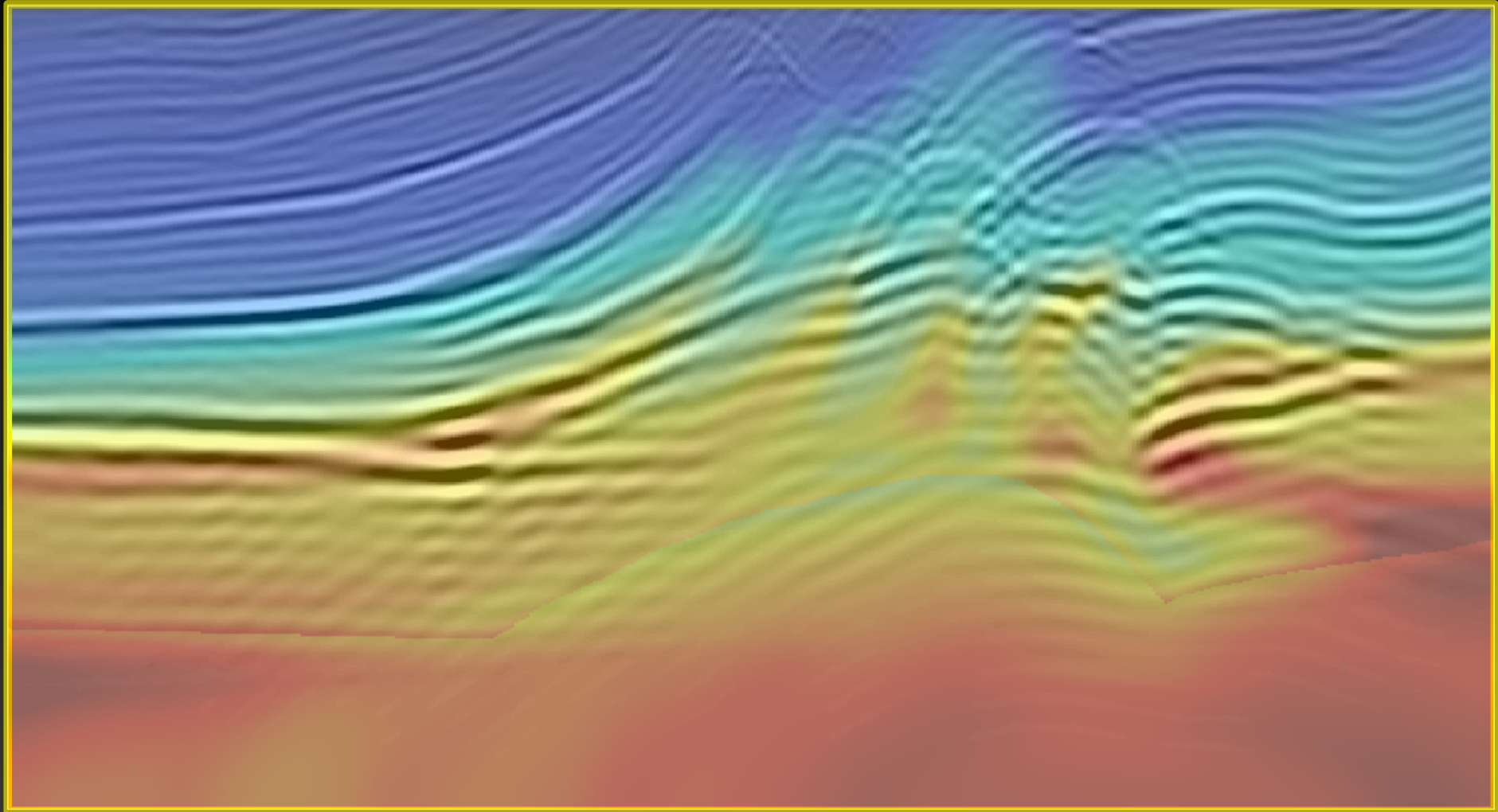


Exploding reflectors

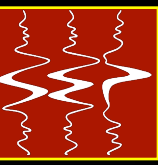


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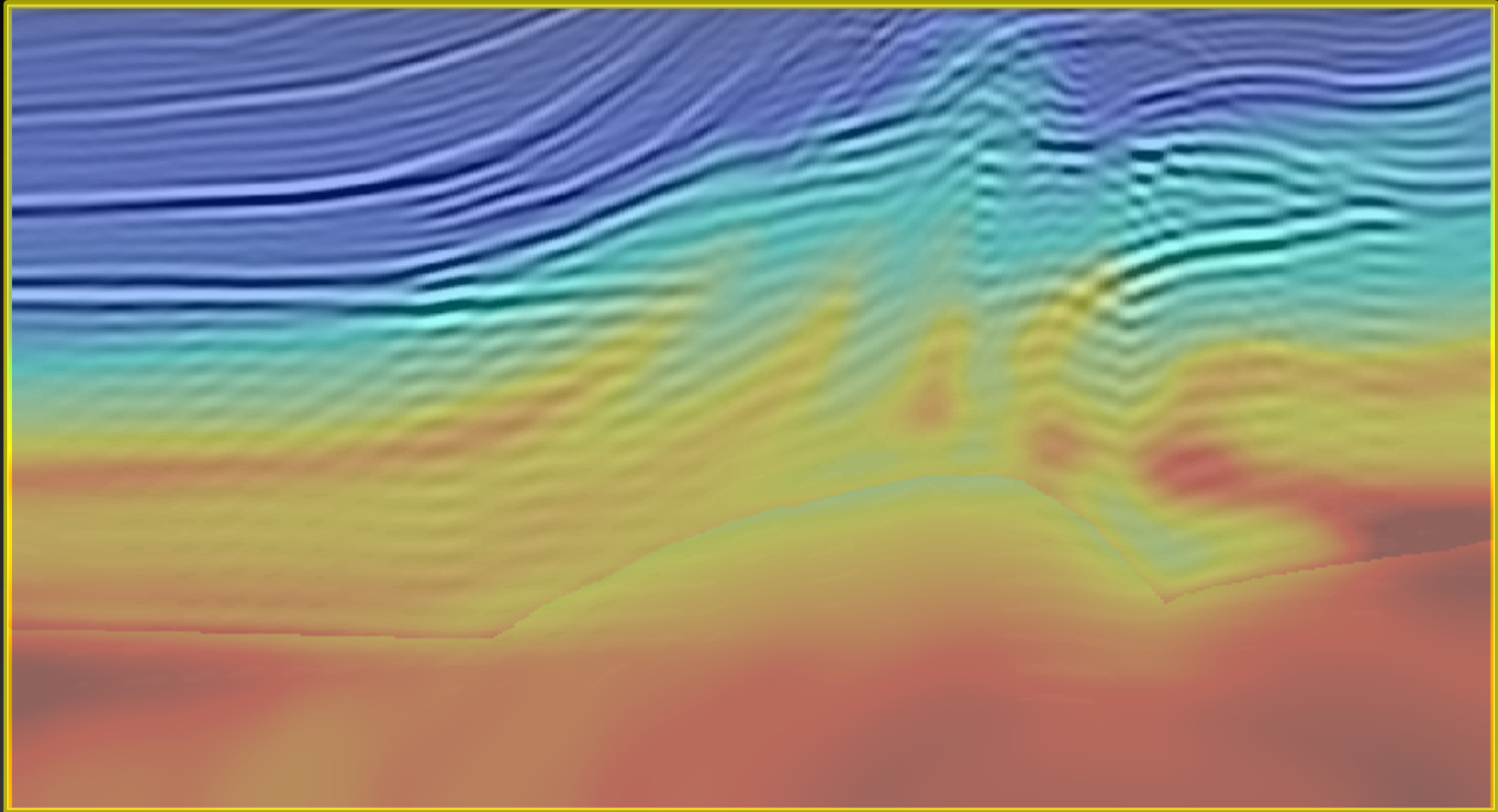


Exploding reflectors

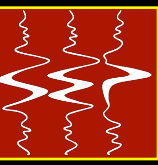


distance

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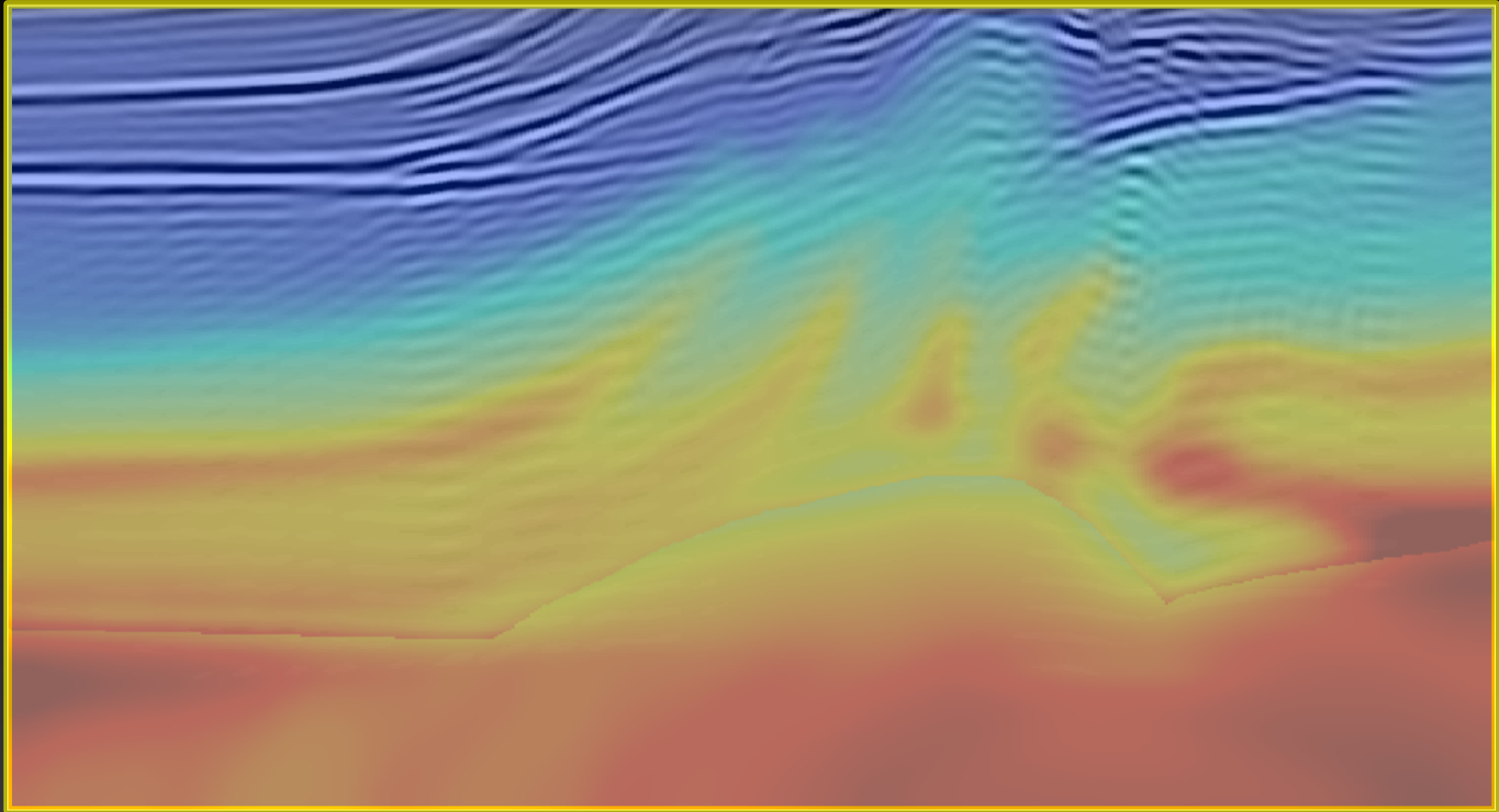


Exploding reflectors

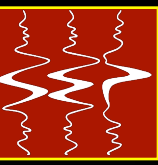


distance

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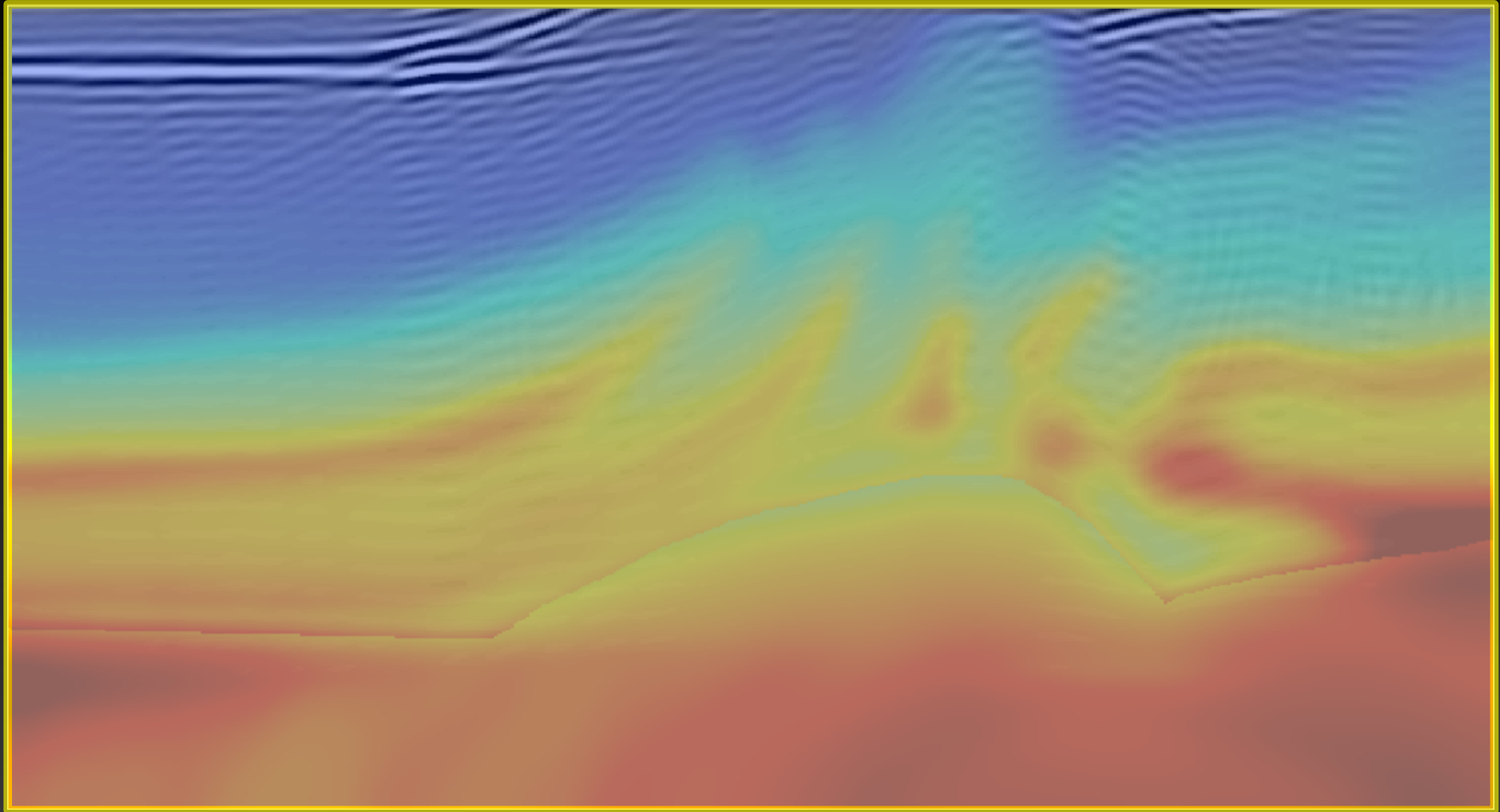


Exploding reflectors

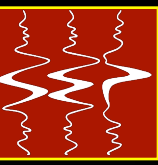


distance

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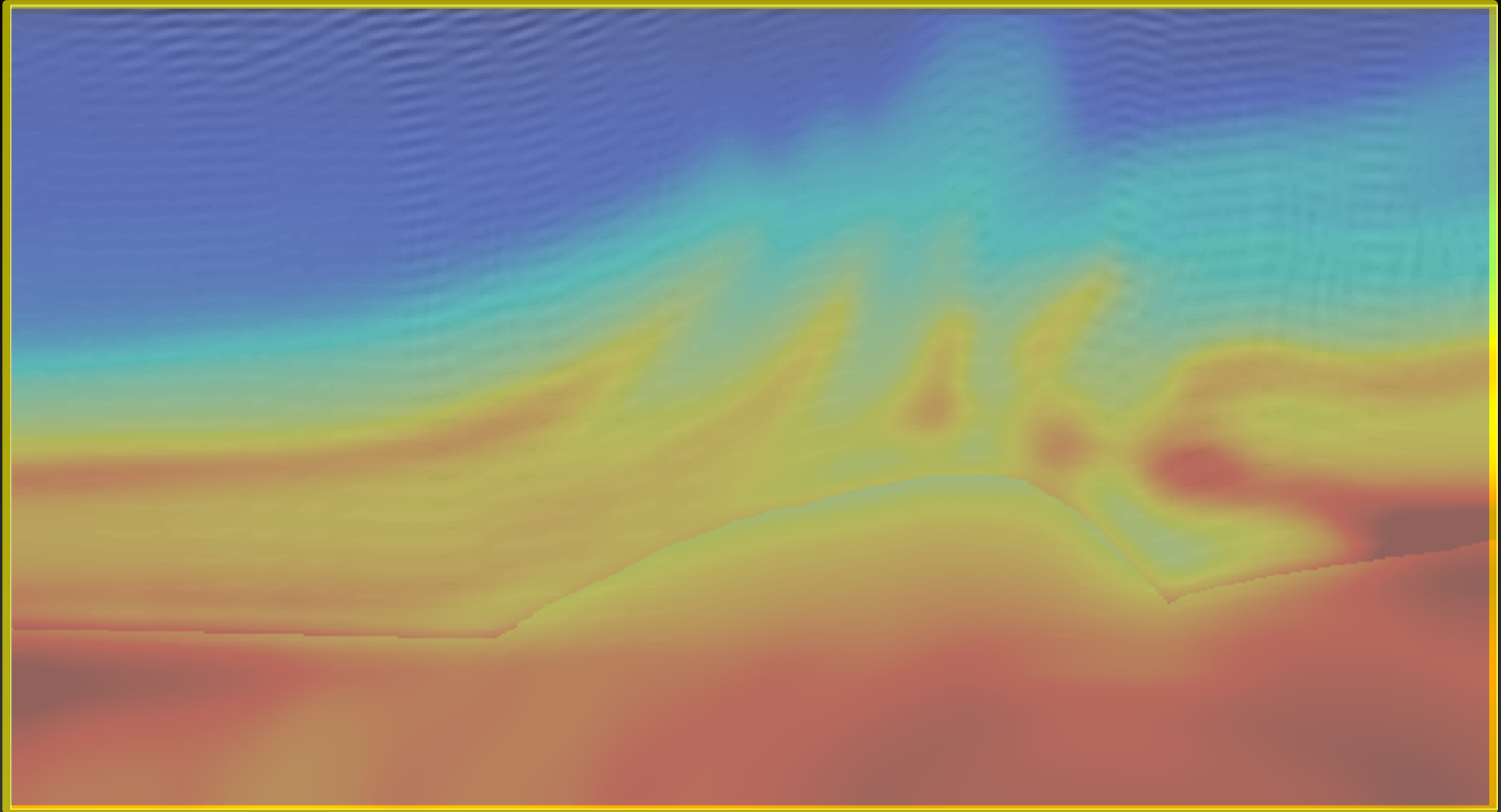


Exploding reflectors

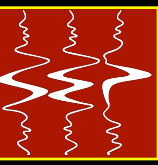


distance

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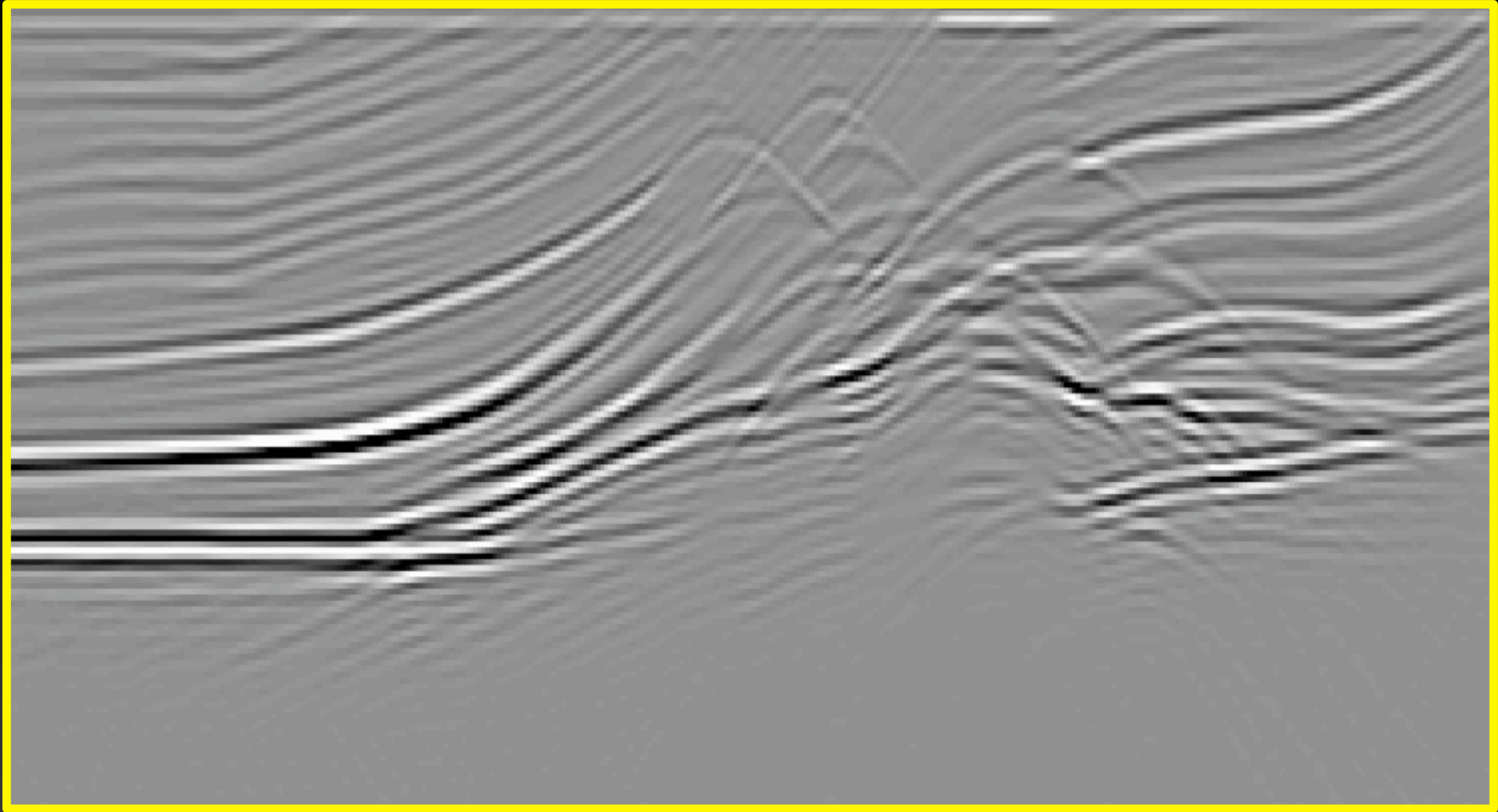


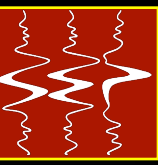
Zero-offset section



distance

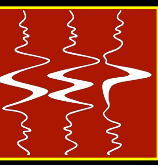
time





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

Subsurface-offset gathers

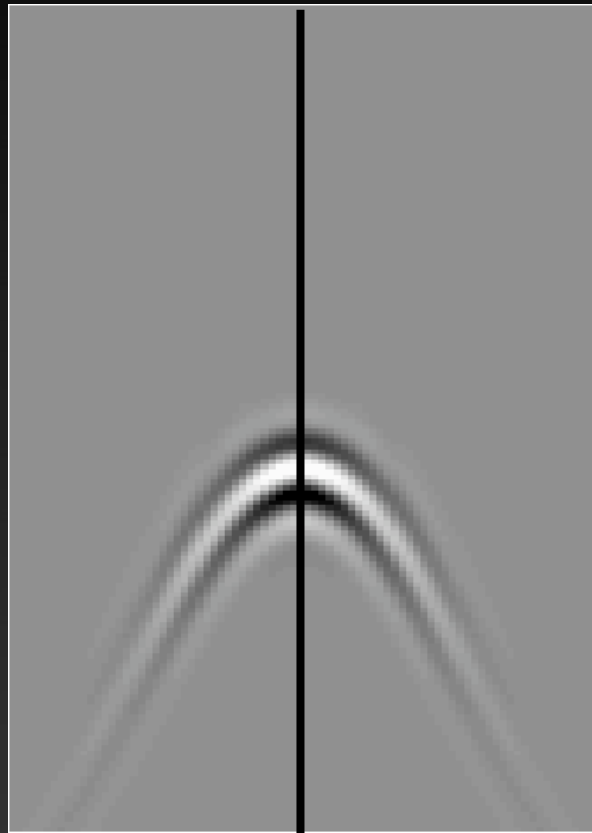


**SLOWER
VELOCITY**

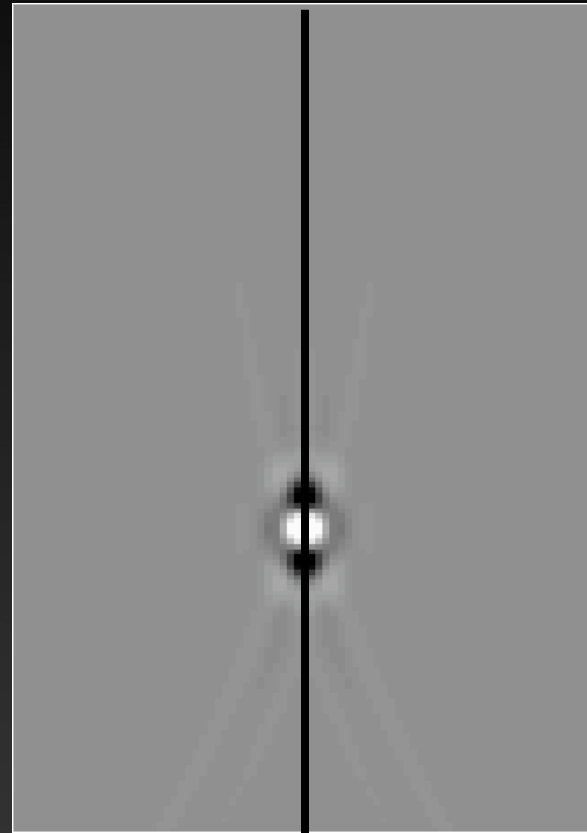
**CORRECT
VELOCITY**

**FASTER
VELOCITY**

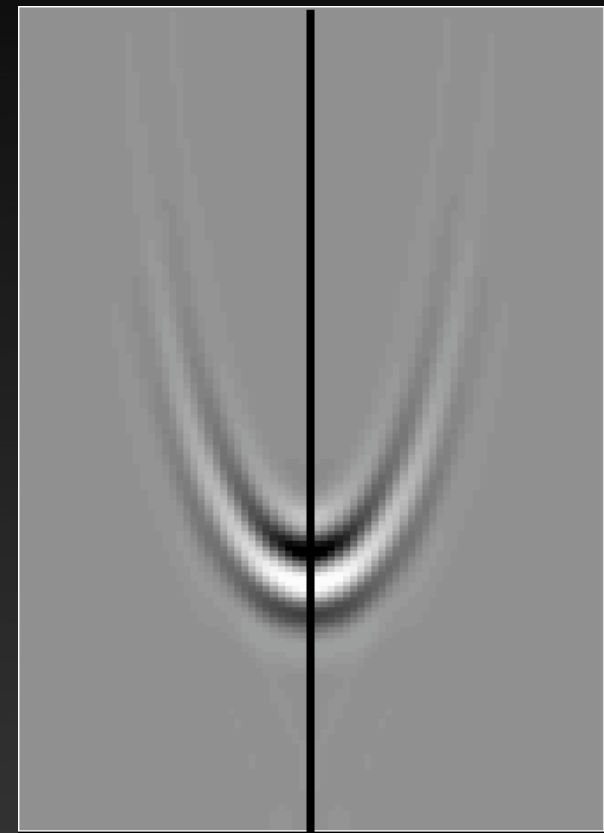
depth



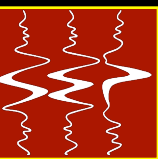
offset



offset



offset



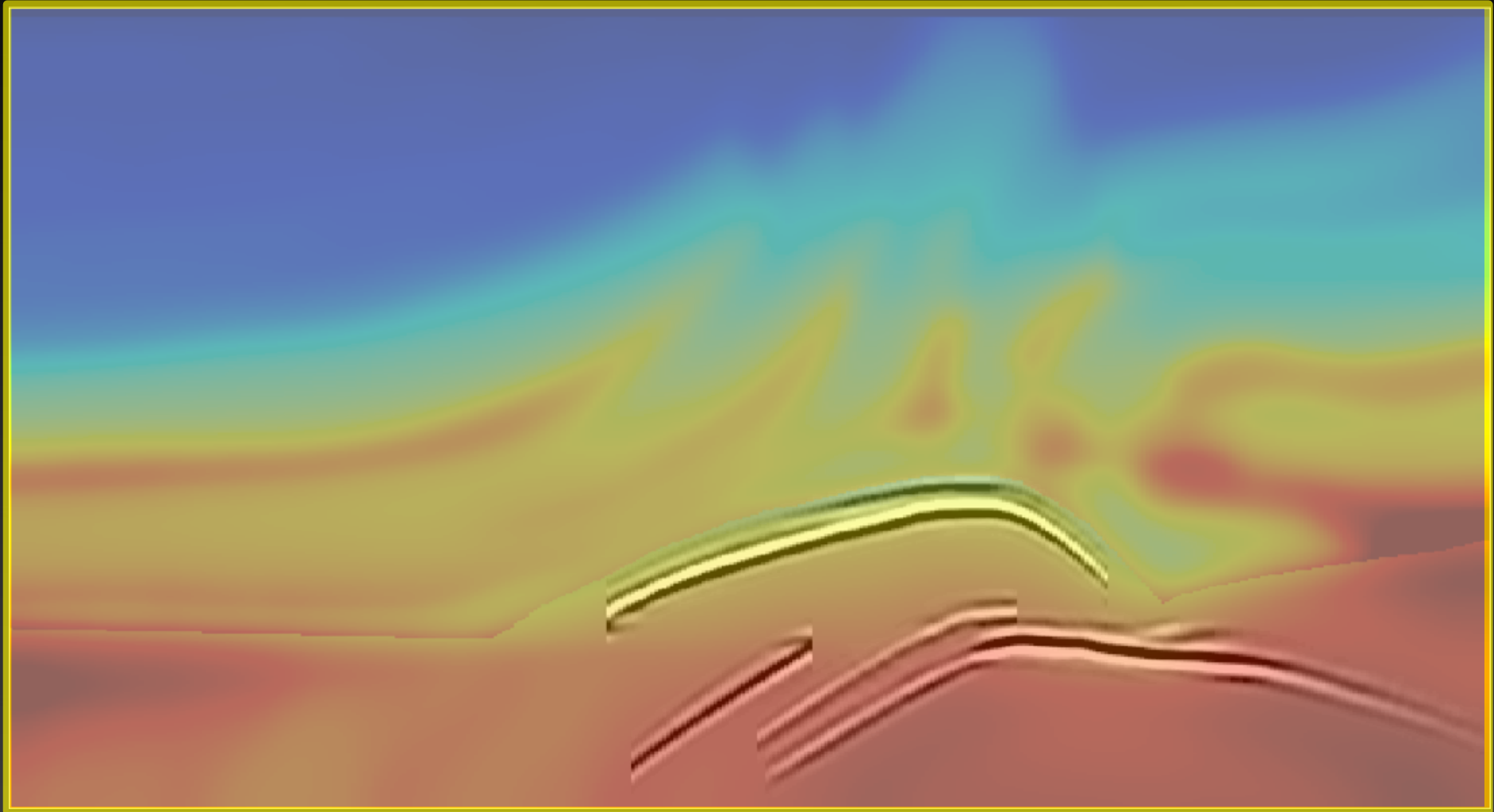
- **Generalizes the exploding-reflector model**
 - Subsurface-offset gathers are used to model source and receiver wavefields
- **Uses selected reflectors as the initial conditions**
 - Naturally incorporates a horizon-based tomography strategy into wave-extrapolation methods

Modeling receiver wavefield

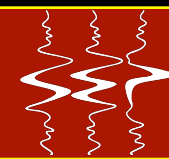


distance

depth

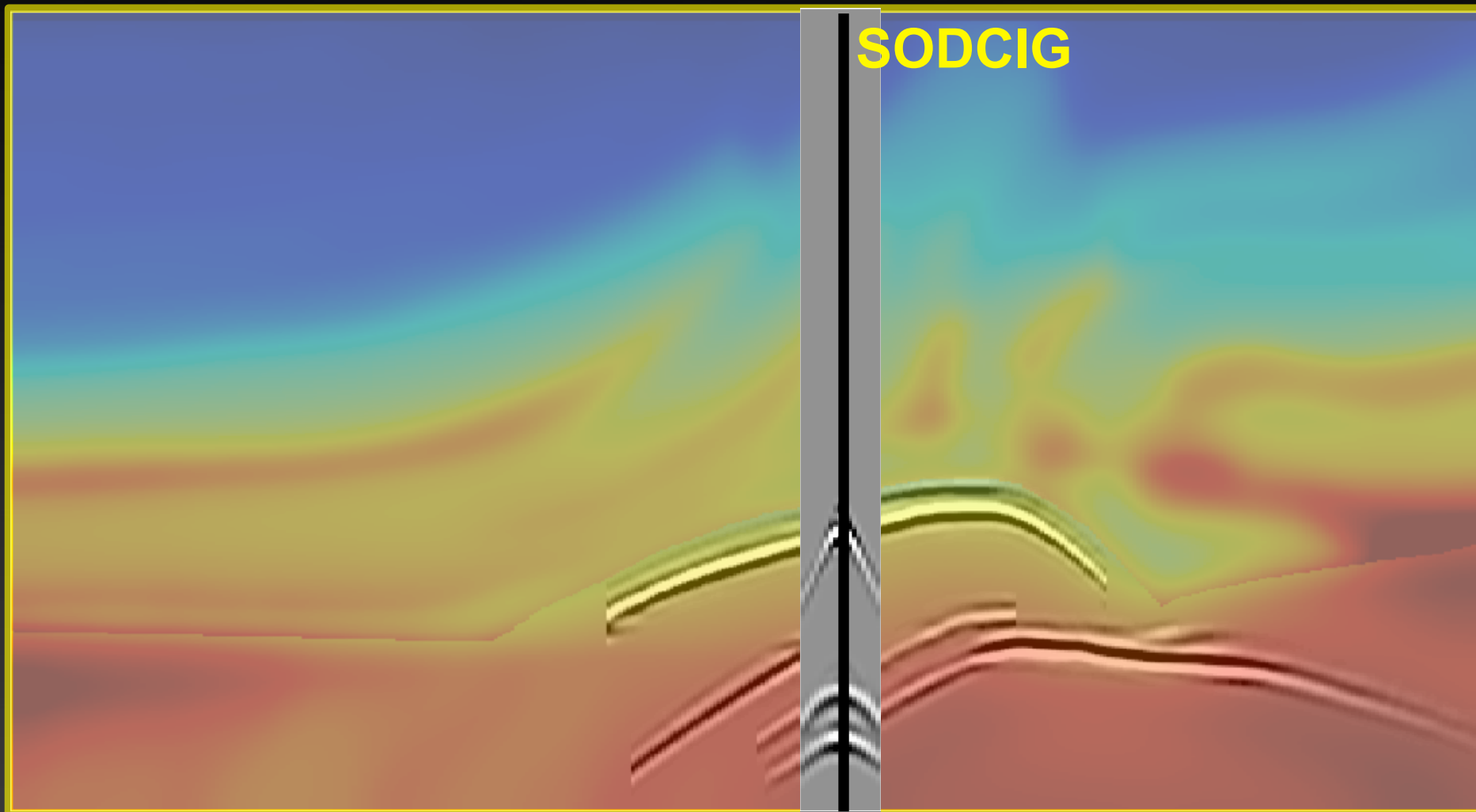


Modeling receiver wavefield

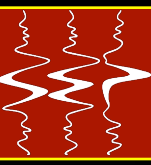


distance

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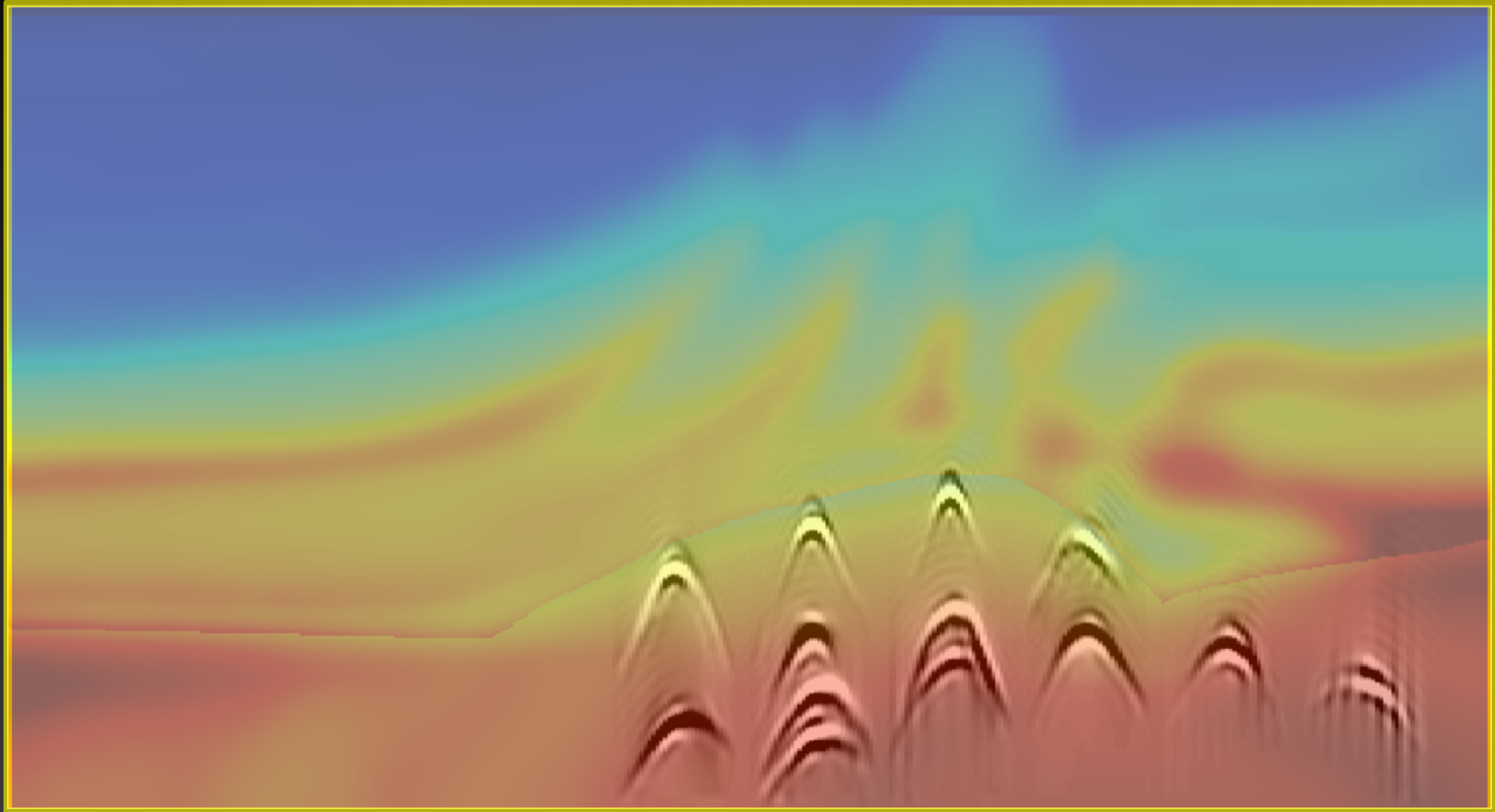


Modeling receiver wavefield

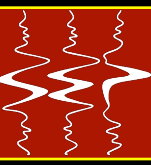


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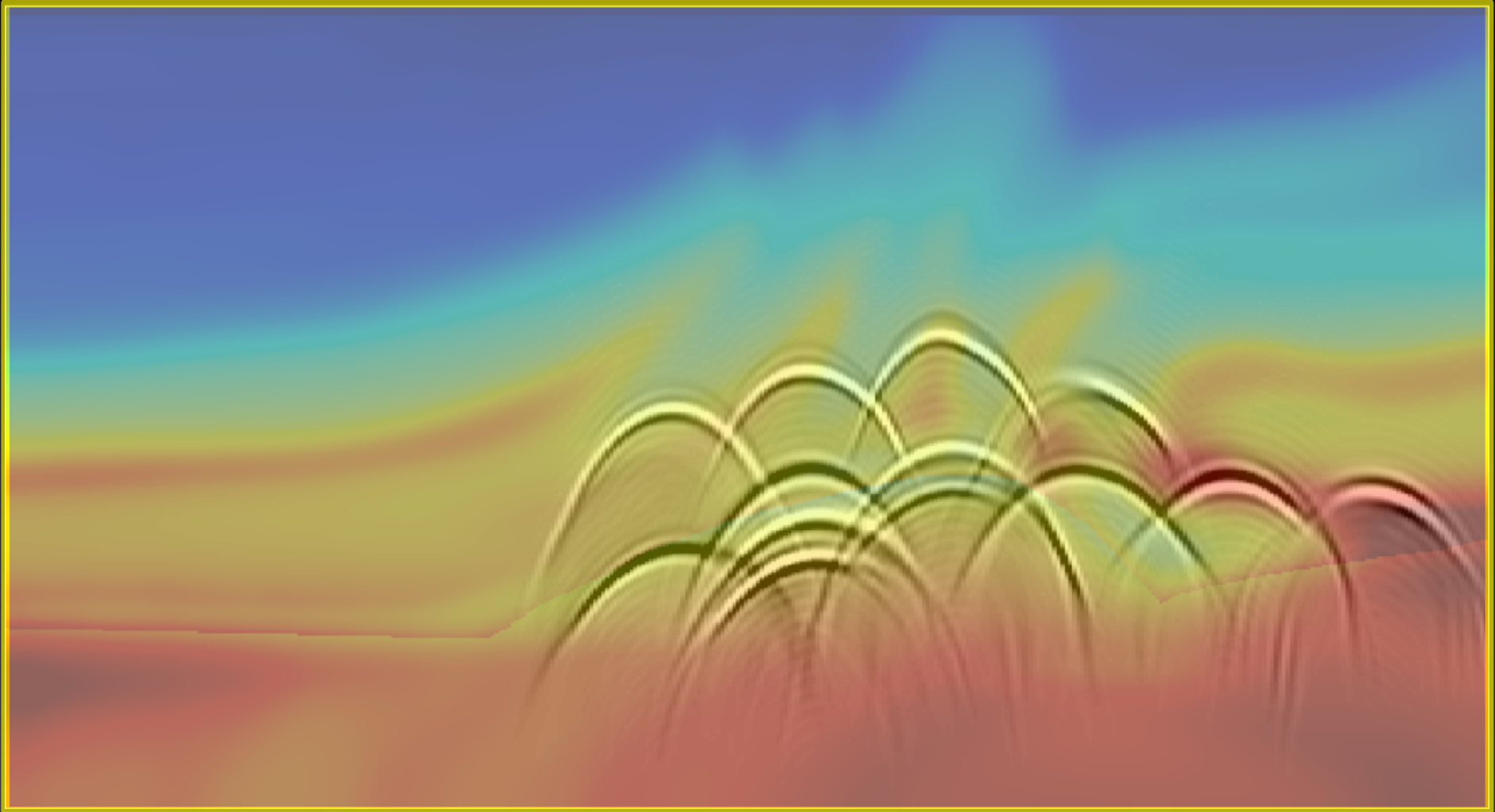


Modeling receiver wavefield

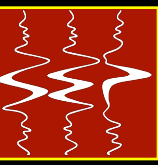


distance

depth

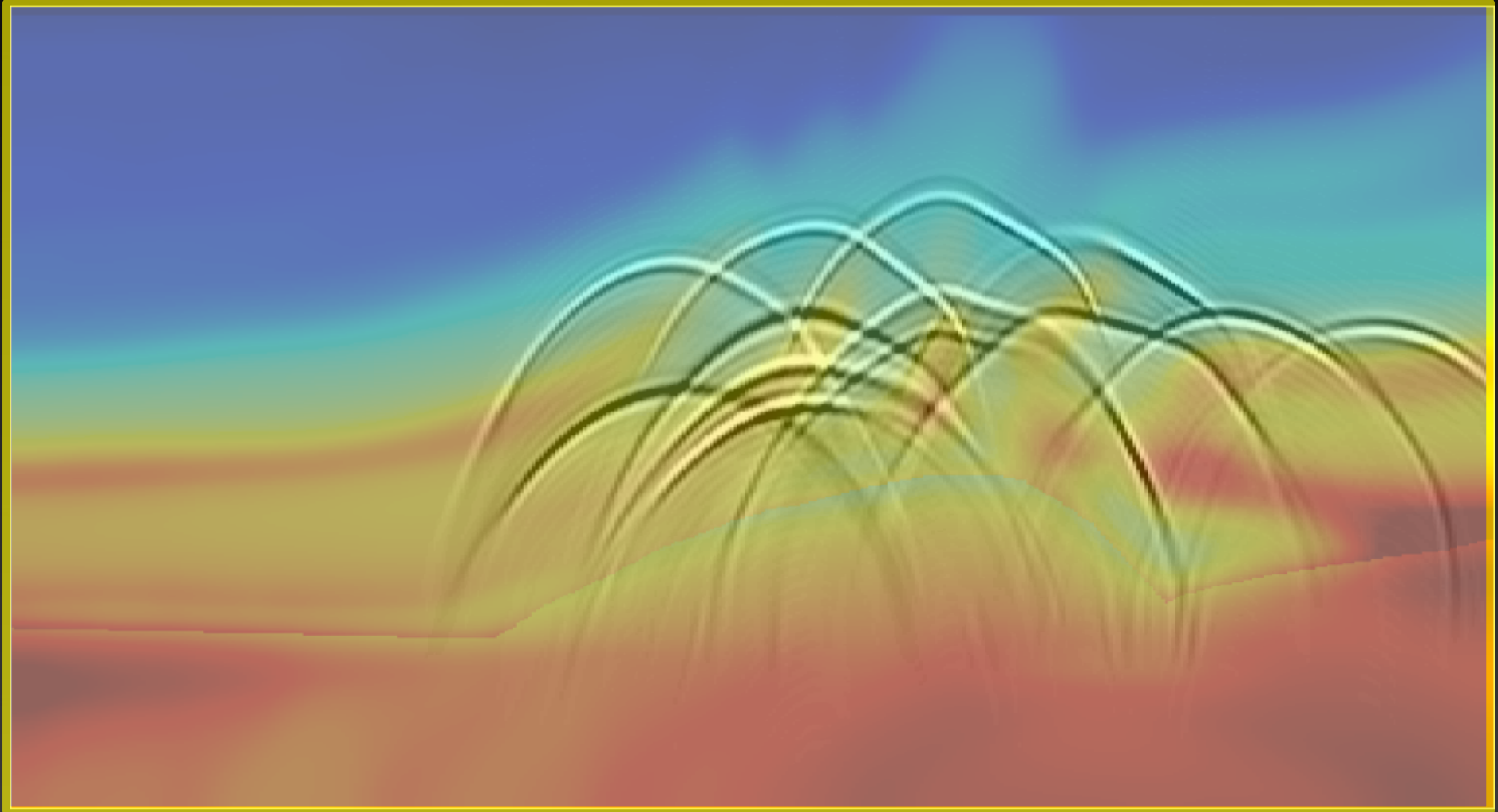


Modeling receiver wavefield

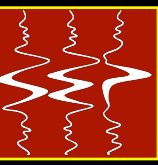


distance

depth

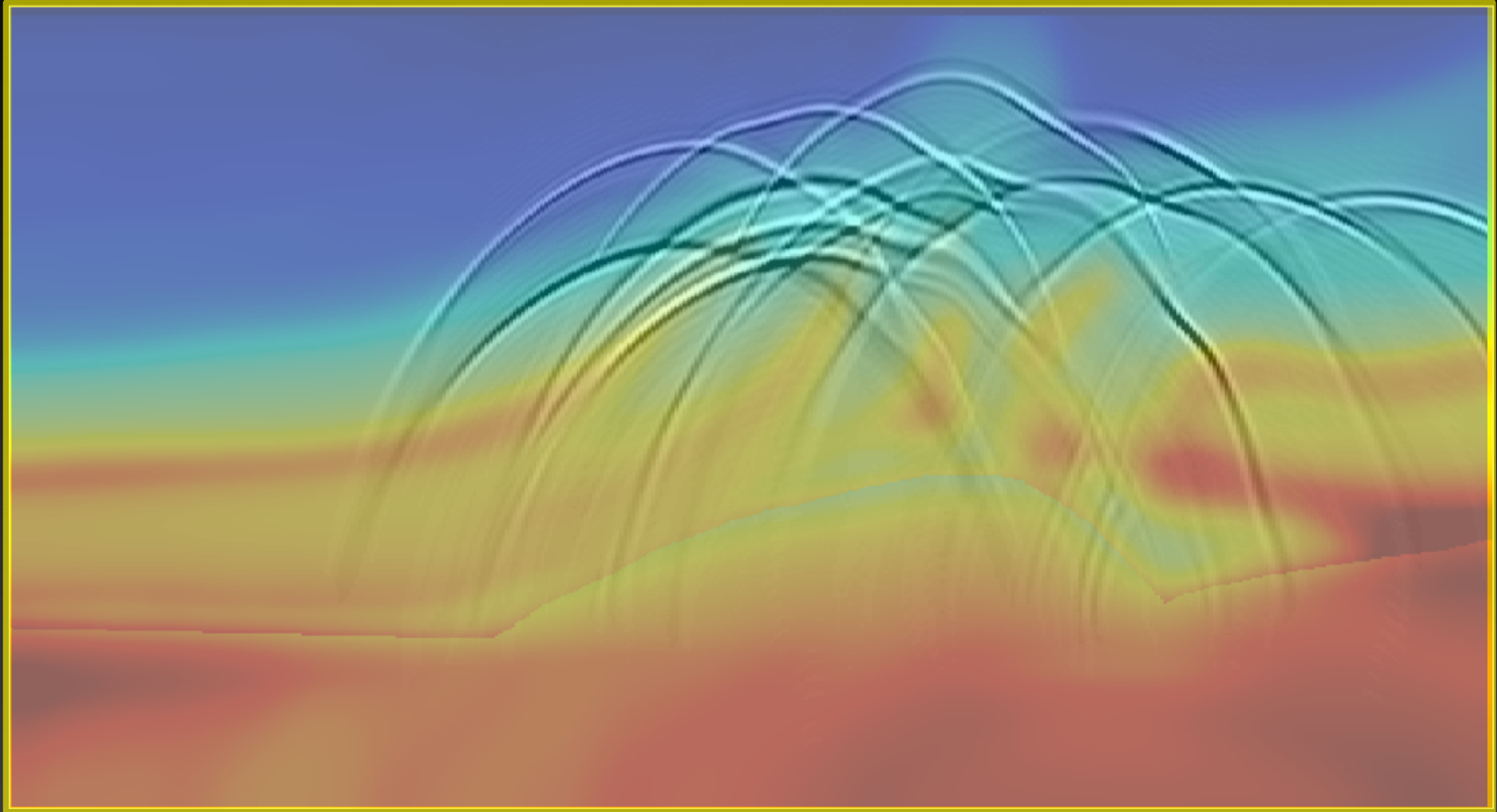


Modeling receiver wavefield

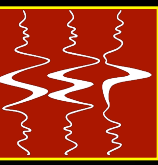


distance

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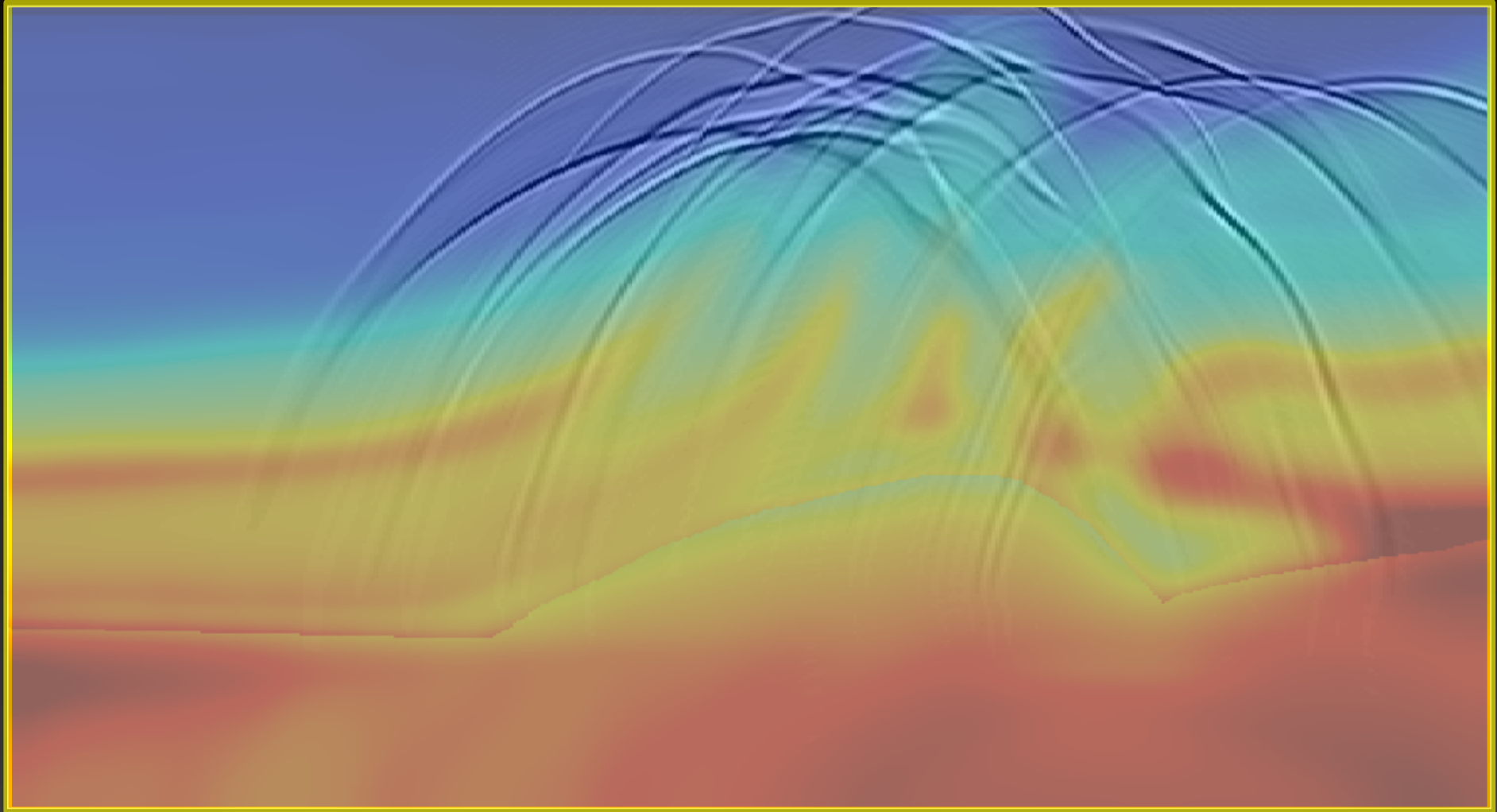


Modeling receiver wavefield

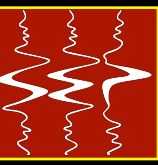


distance

depth

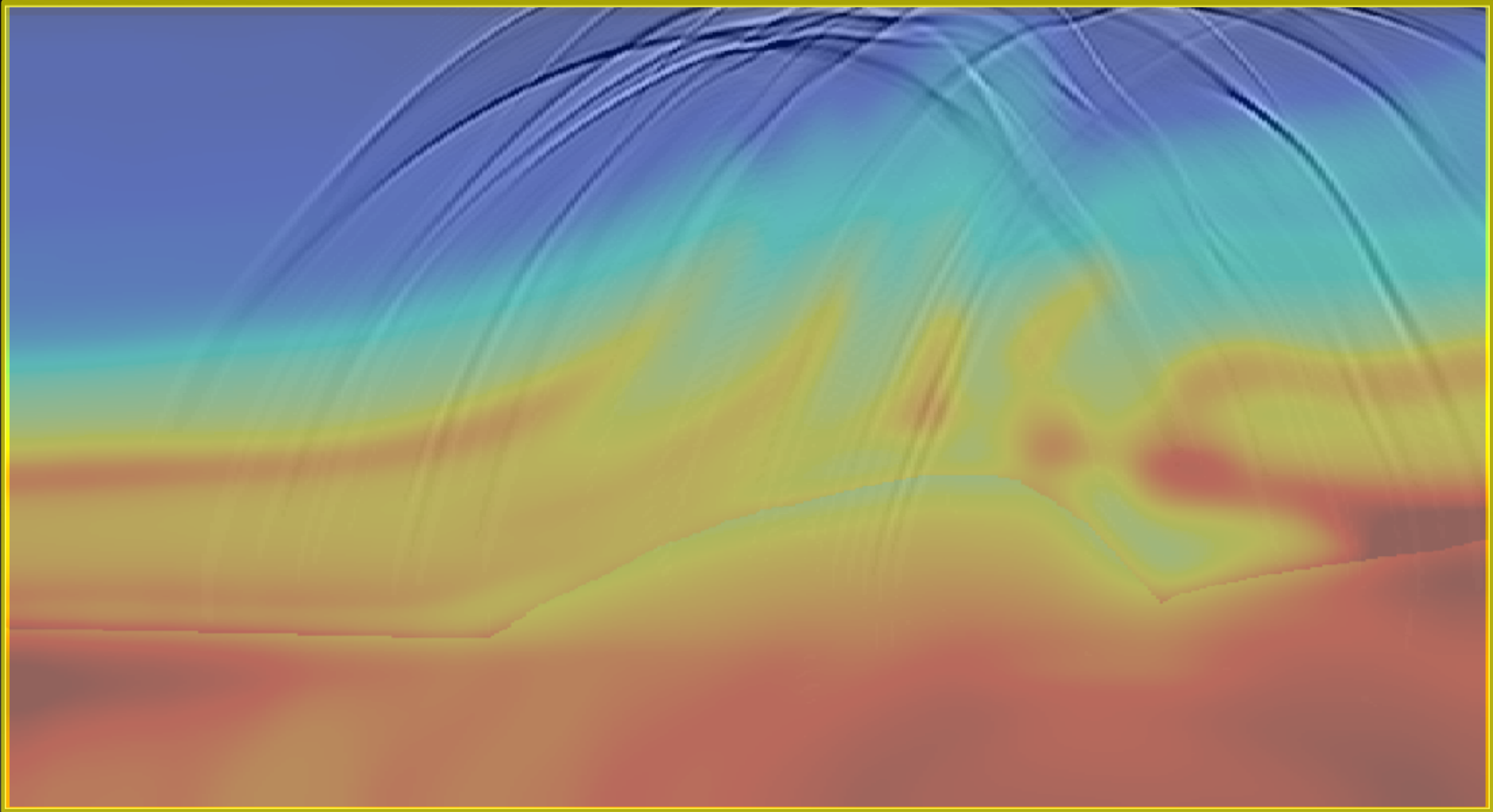


Modeling receiver wavefield

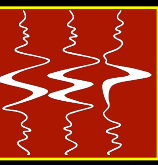


distance

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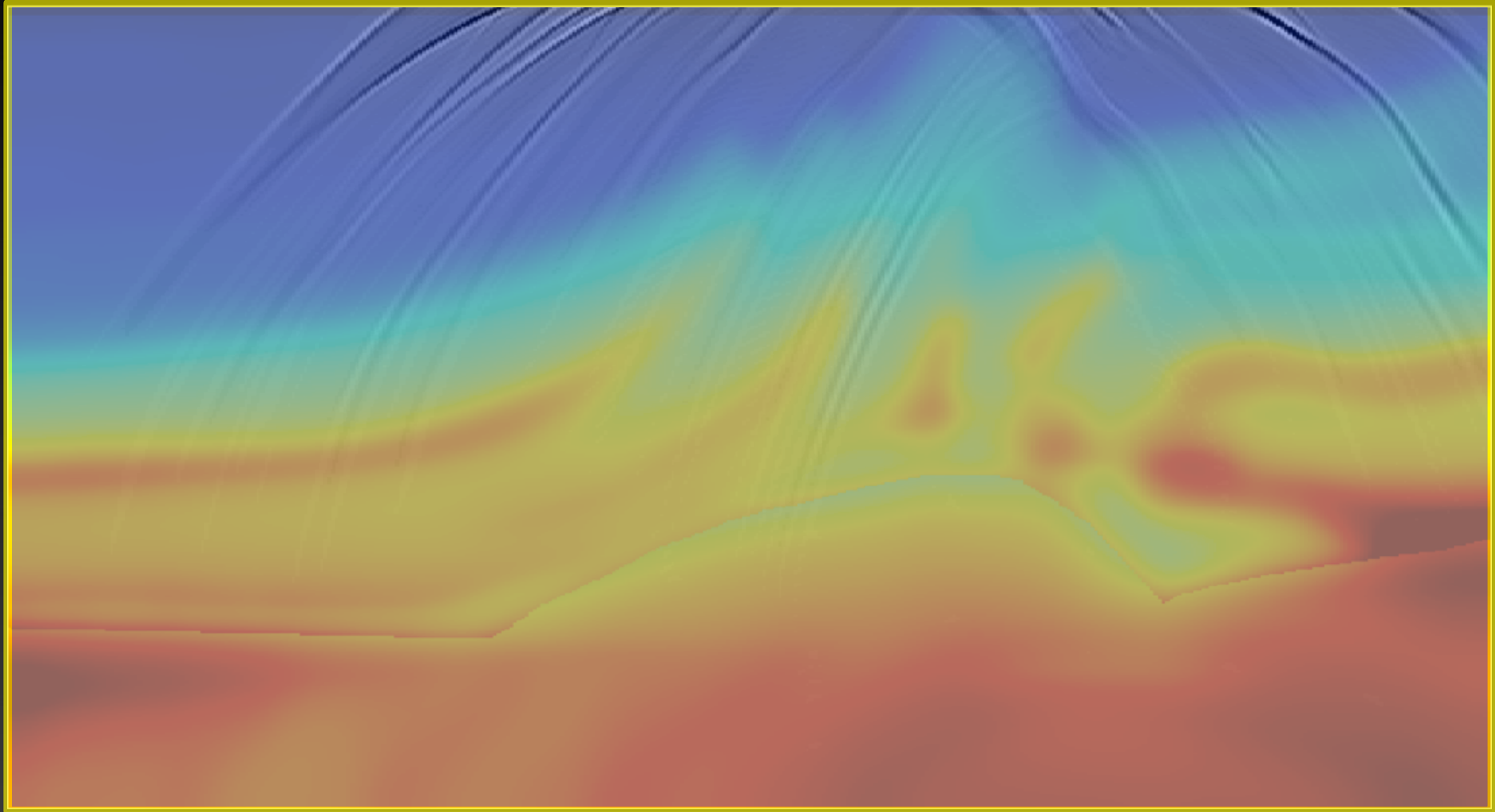


Modeling receiver wavefield



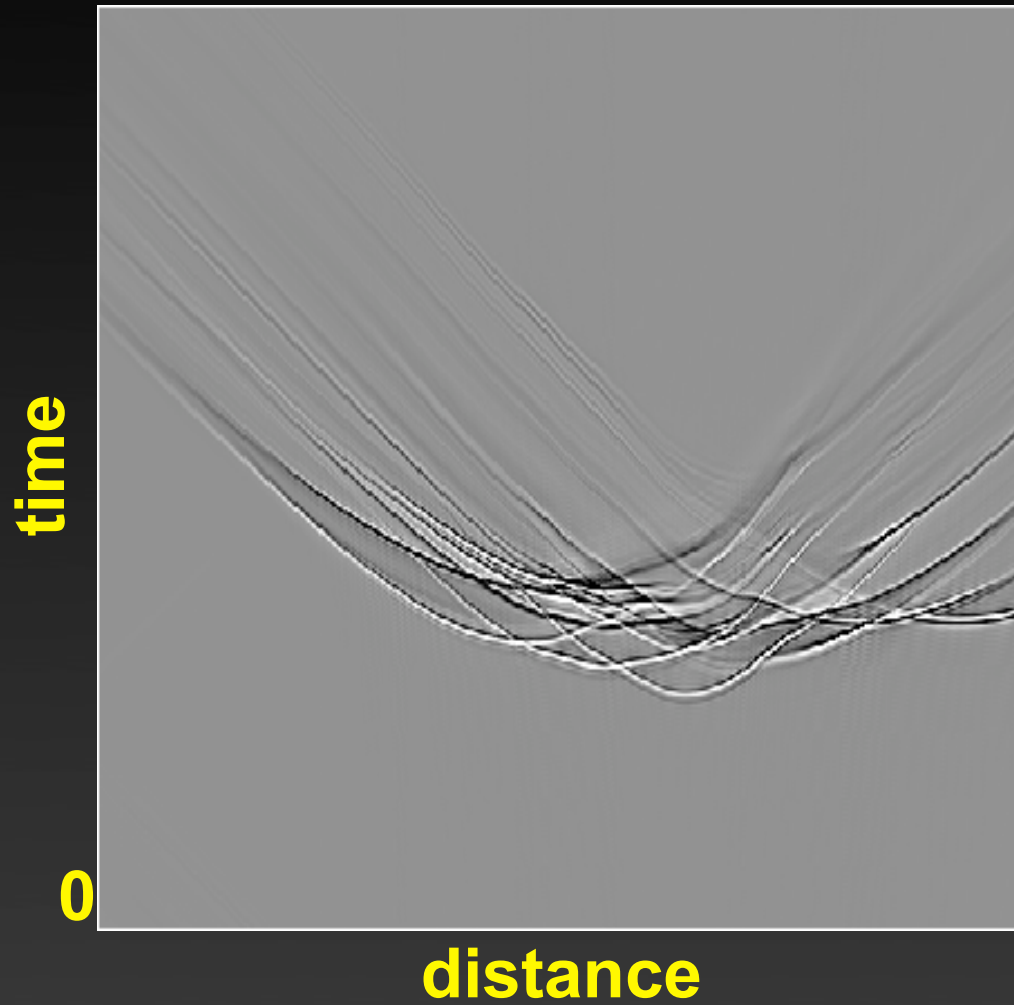
distance

depth



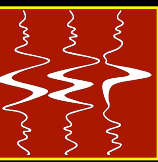


Source



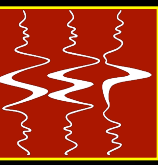
Receiver





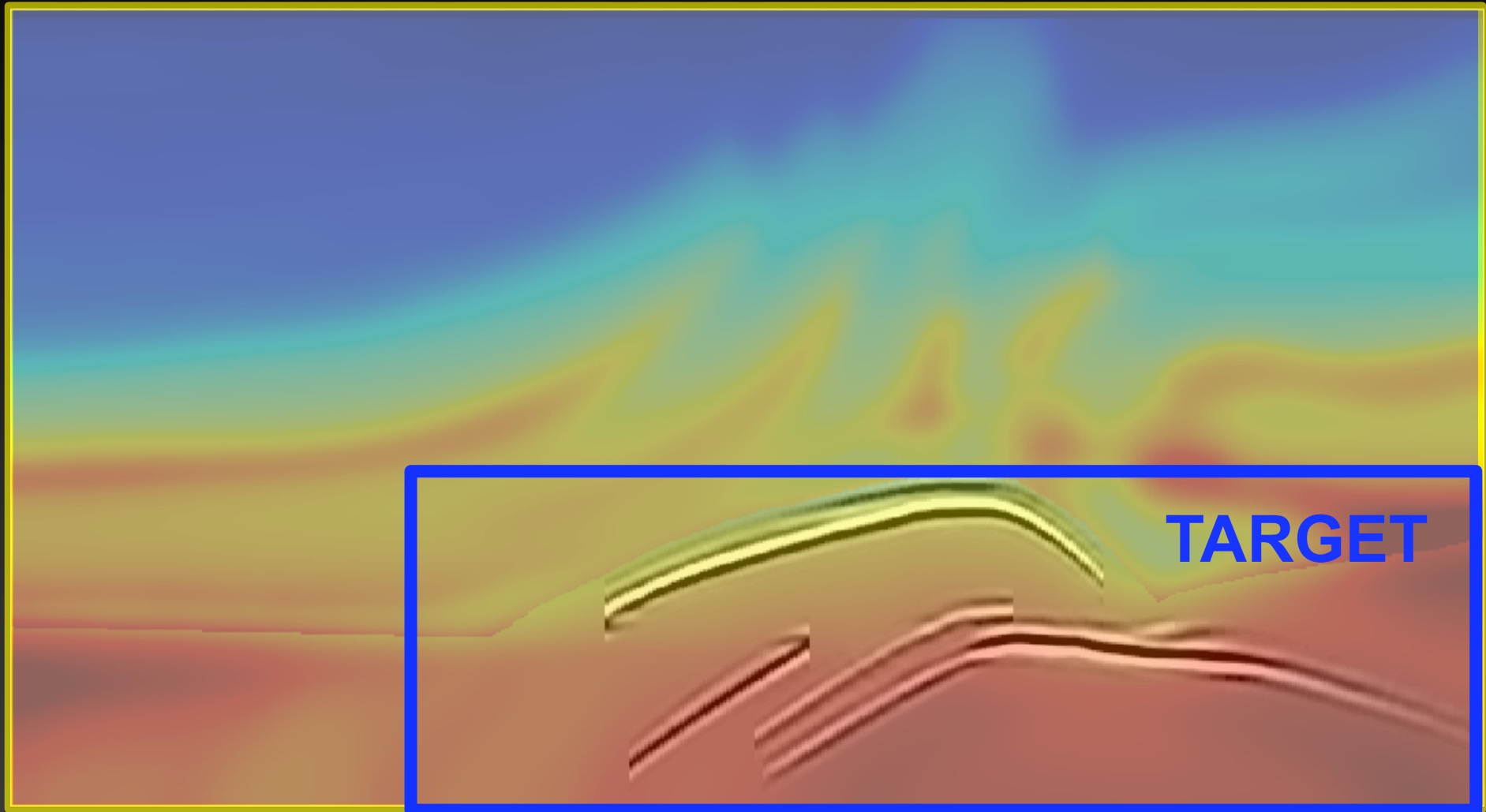
- **Generalizes the exploding-reflector model**
- **Uses selected reflectors as the initial conditions**
- **Number of wavefields depends on the separation of SODCIGs**

Target-oriented strategy



distance

depth

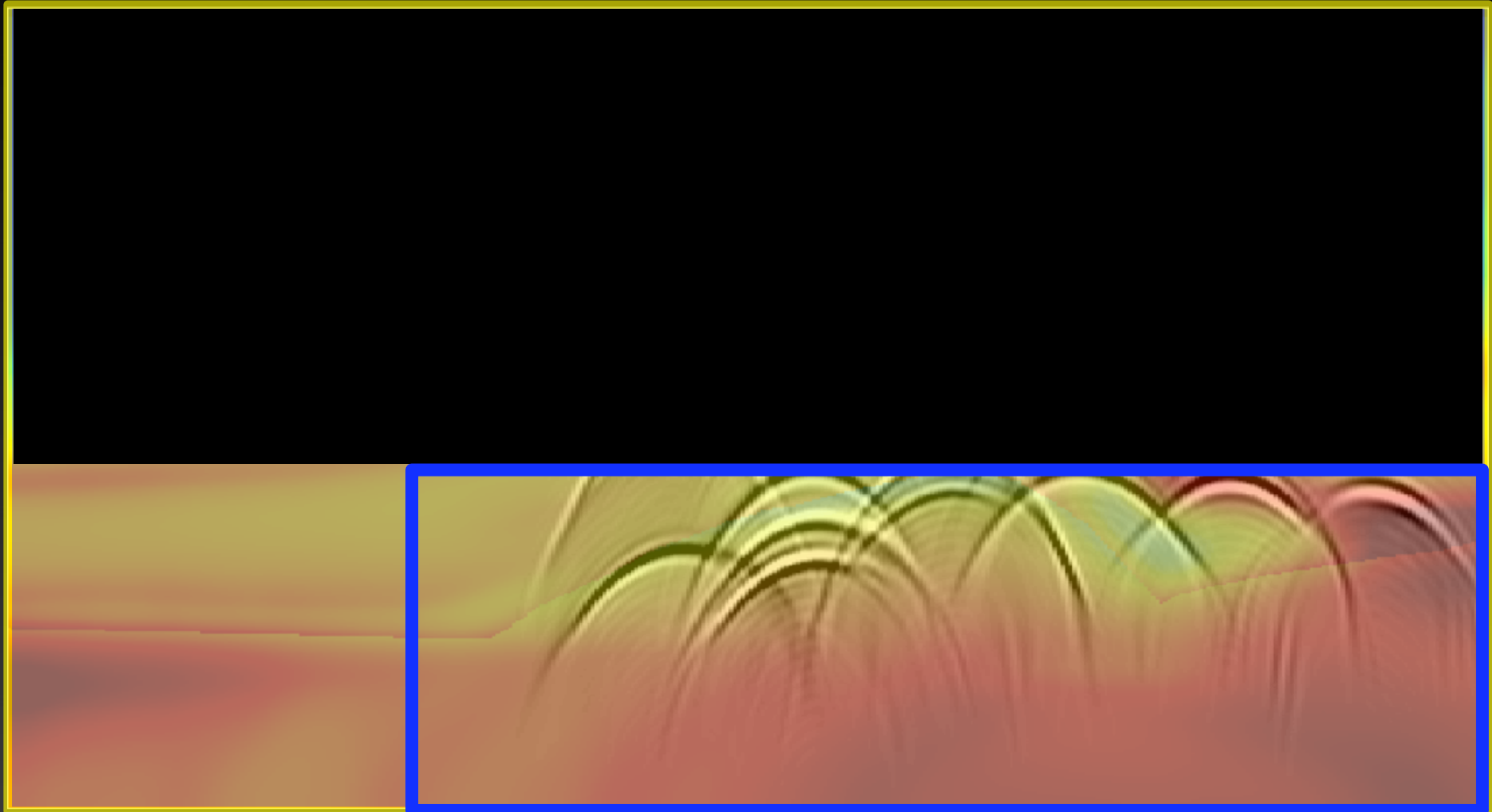


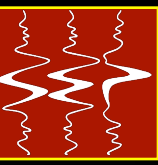


Wavefields collected at the top of the target

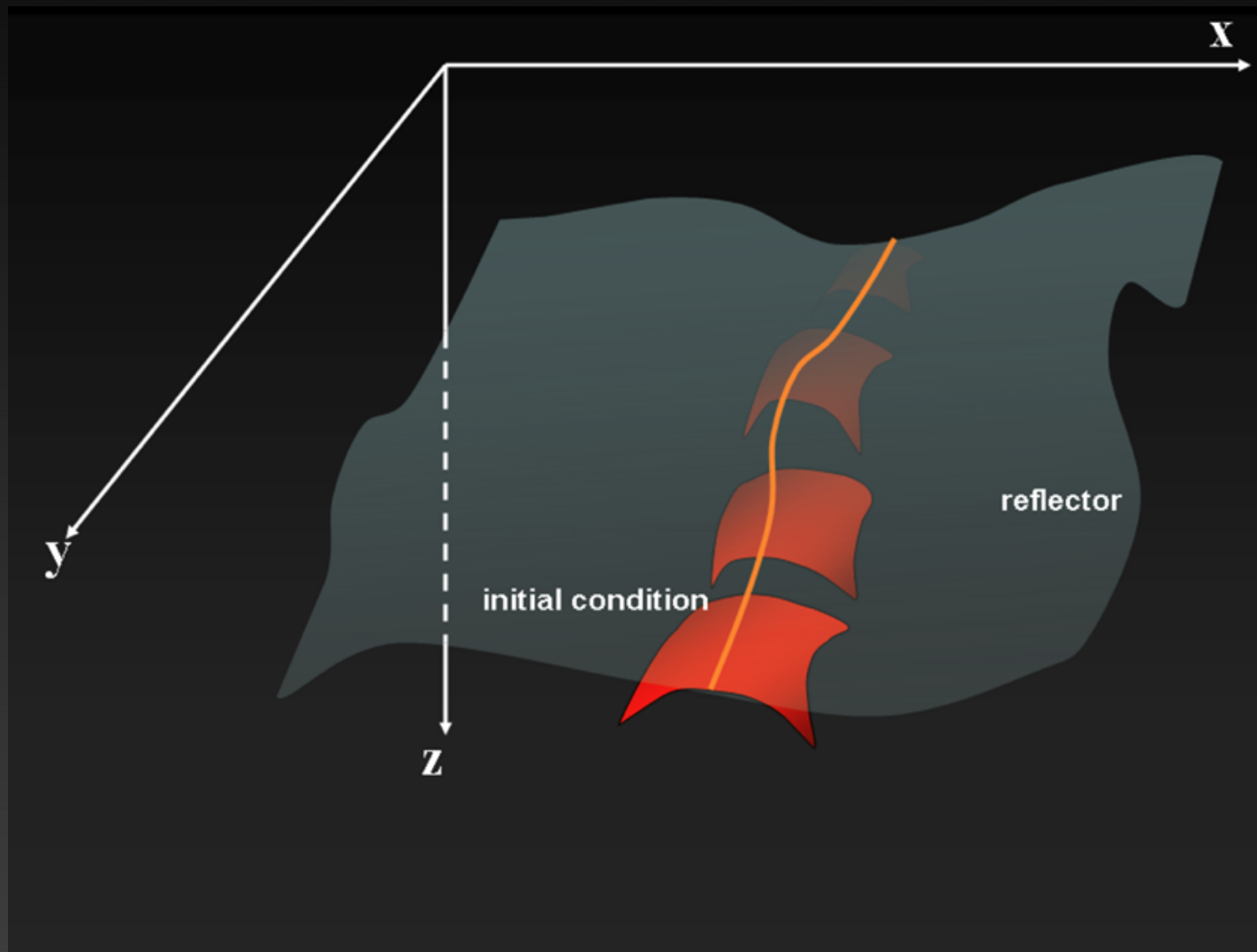
distance

depth

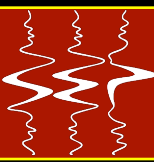




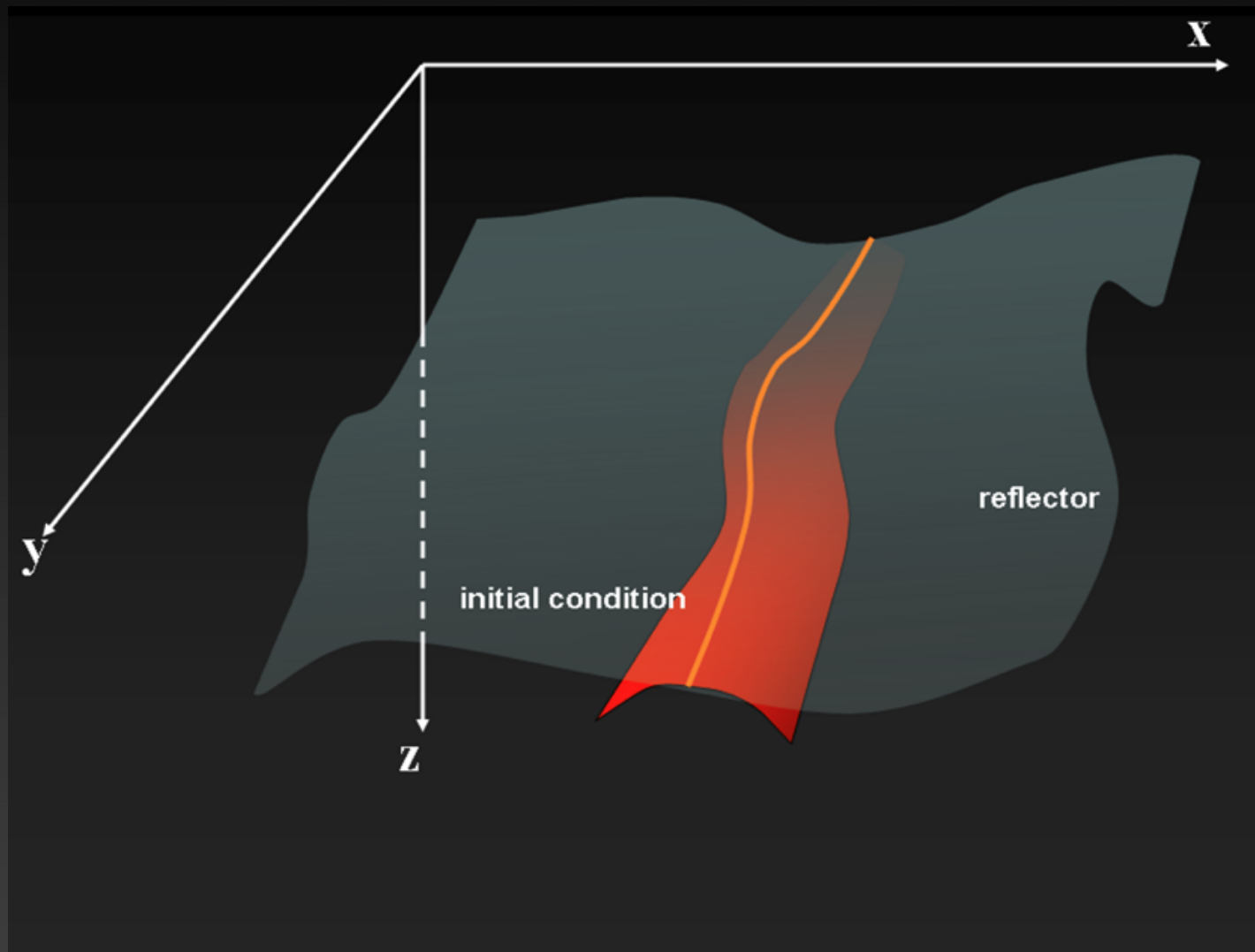
- **About 1,000 PERM wavefields**
 - Using crossline offsets



Using Common-azimuth migrated images



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

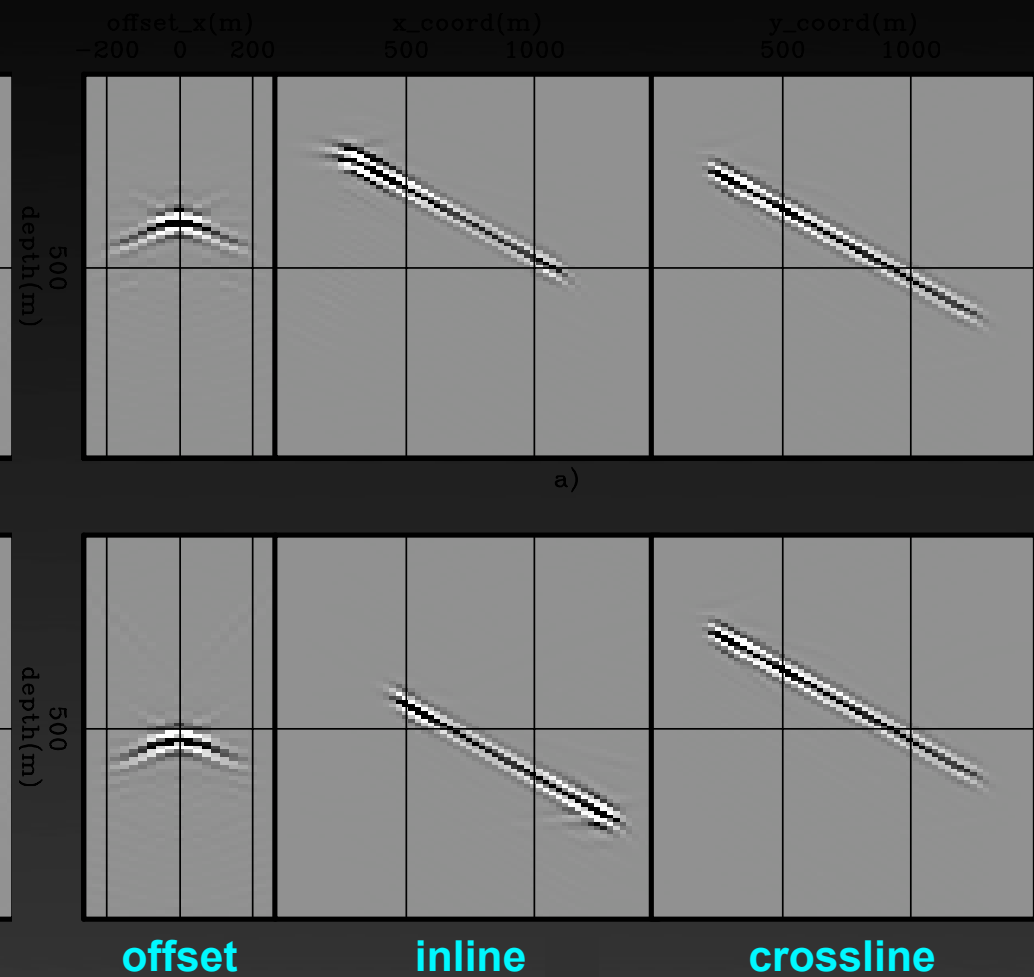
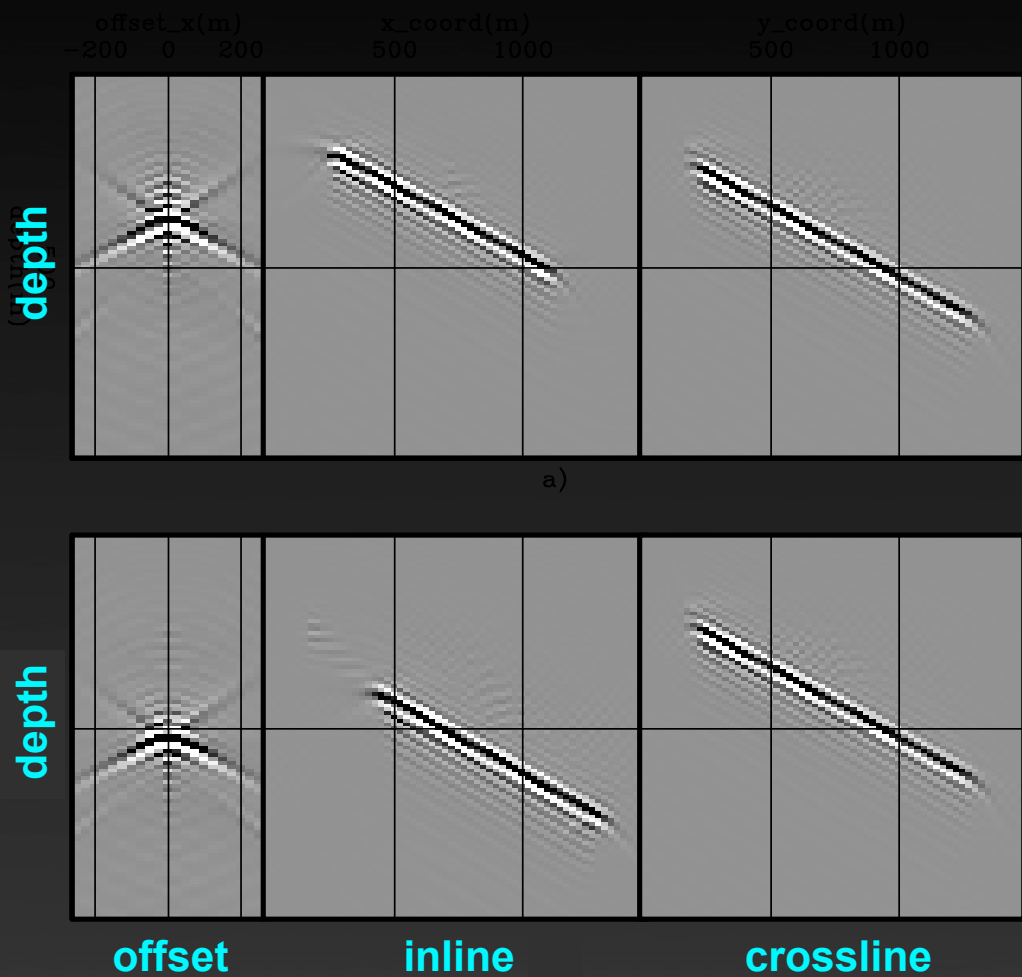


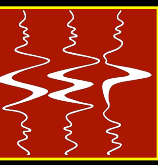
Using CAM images as the initial conditions



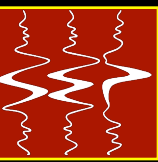
CAM

PERM



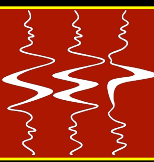


- ✓ **Generalized-source domain**
- ✓ **Pre-stack exploding reflector model**
- **Image-space phase-encoded wavefields**
- **3D-field data ISWET example**
- **Conclusions**



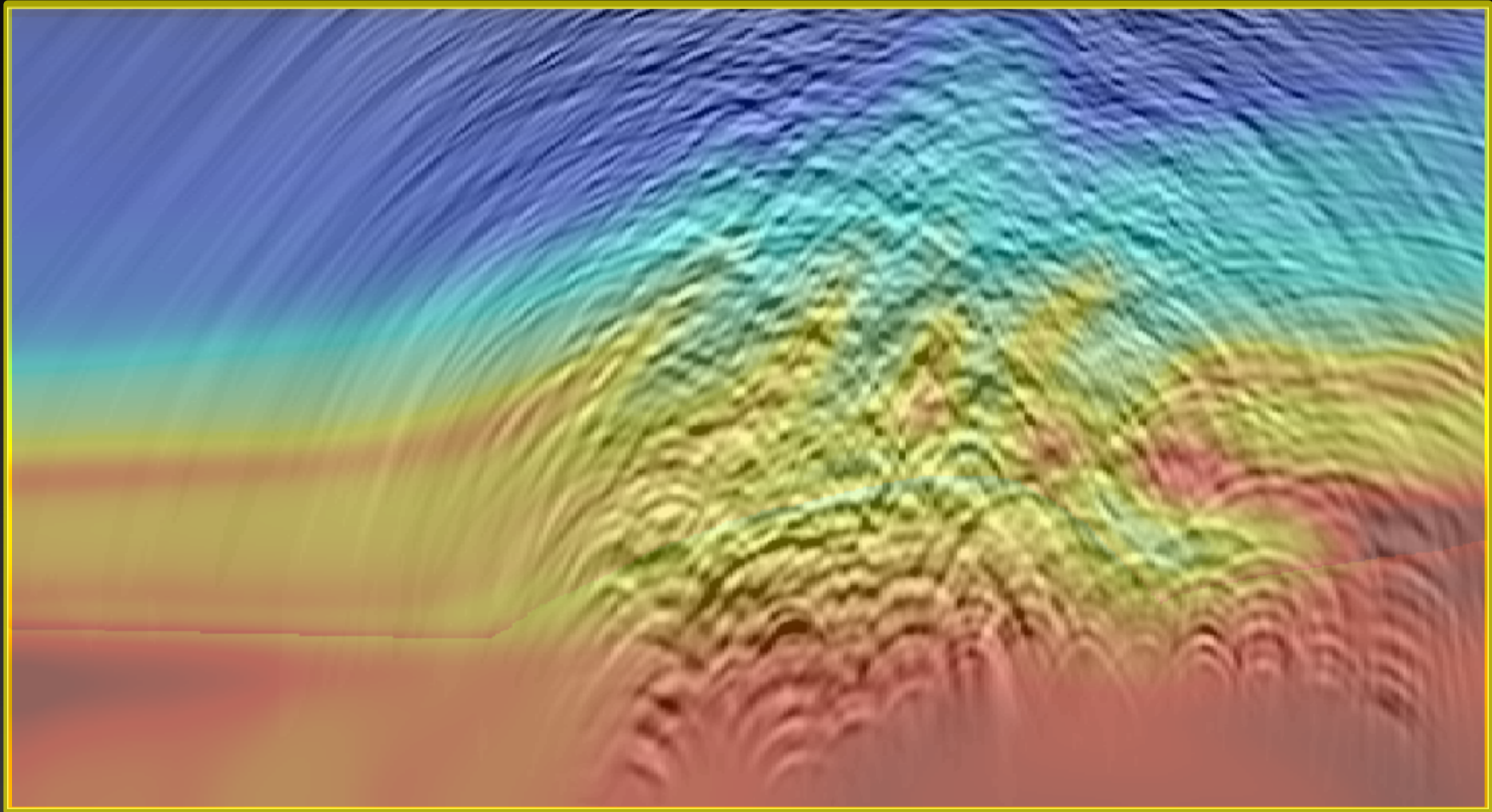
**Further data reduction
by phase-encoding the modeling
experiments**

Phase-encoded receiver wavefield

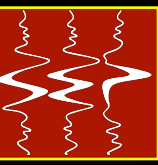


distance

depth

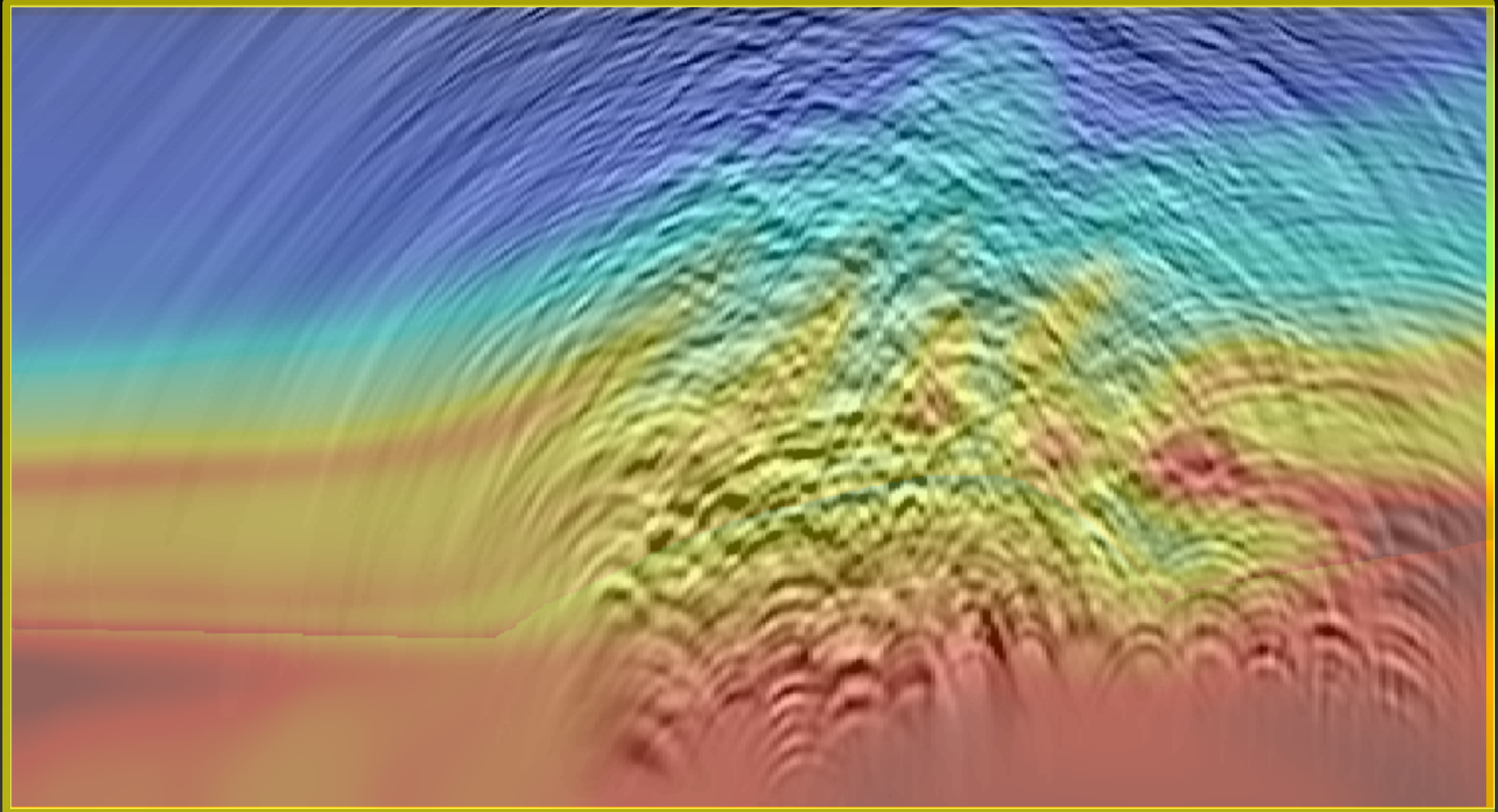


Phase-encoded receiver wavefield

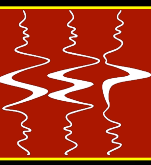


distance

depth

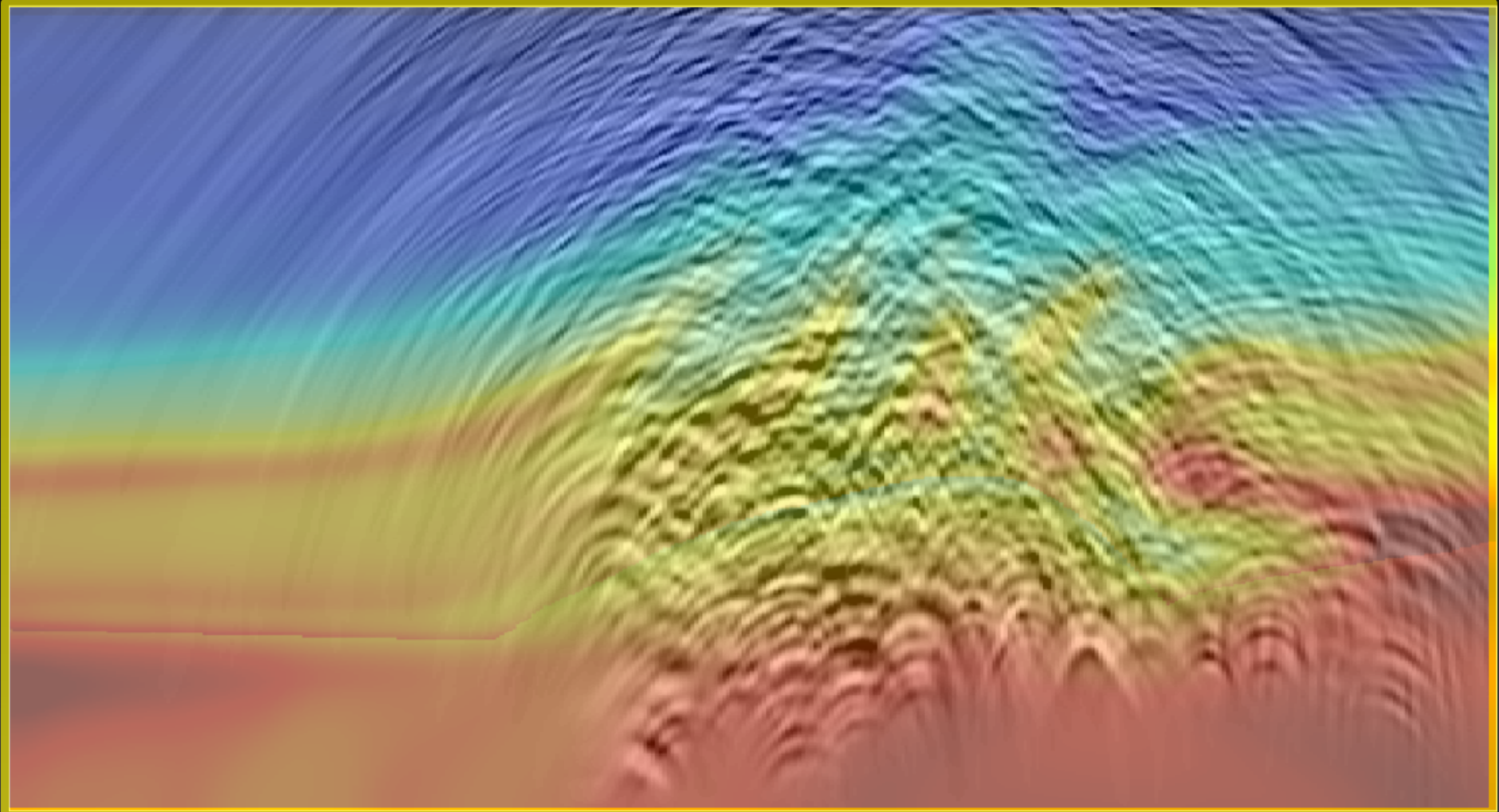


Phase-encoded receiver wavefield

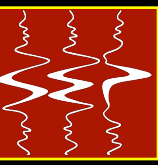


distance

depth

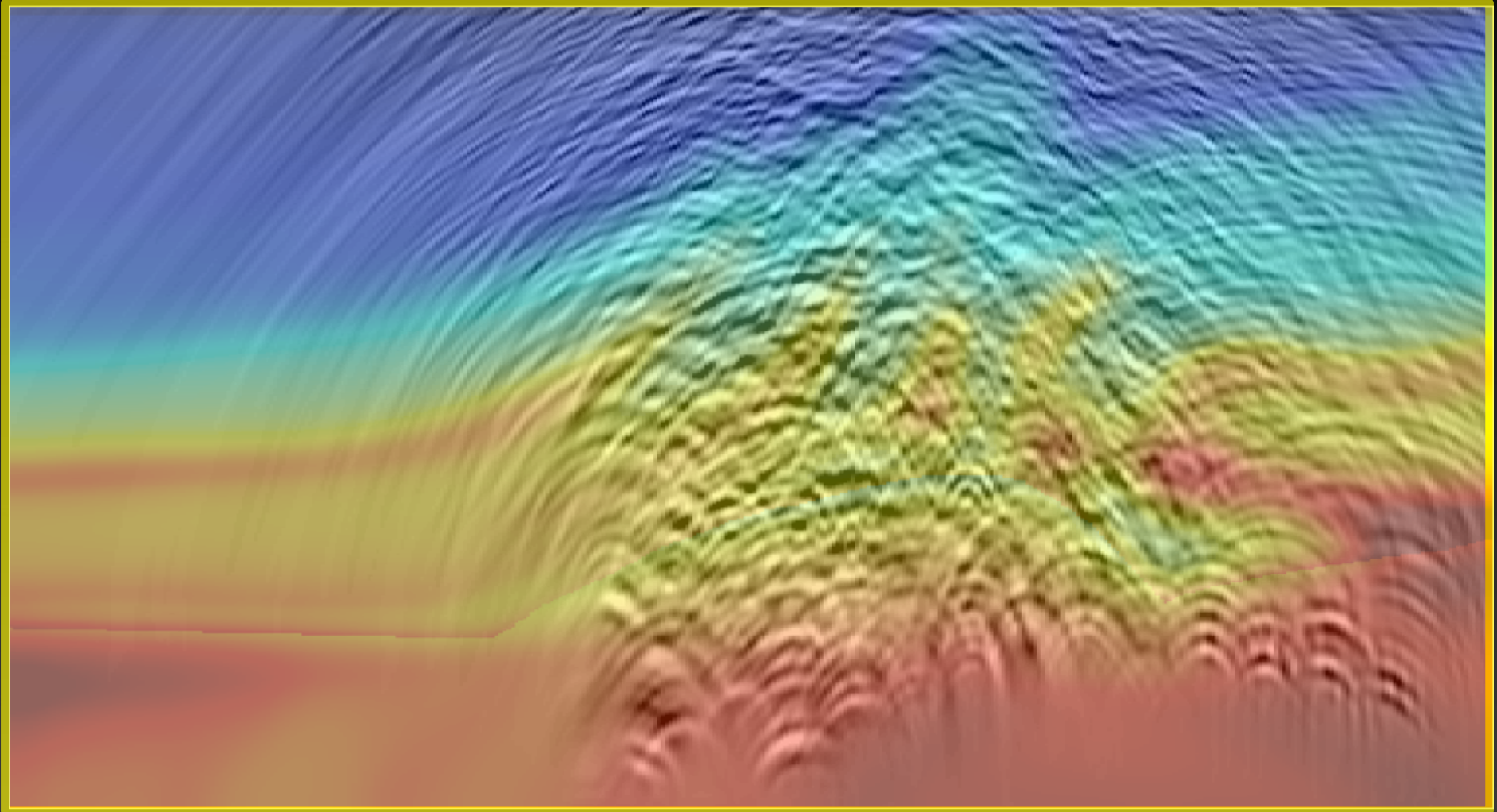


Phase-encoded receiver wavefield

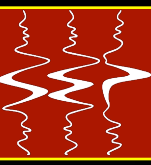


distance

depth

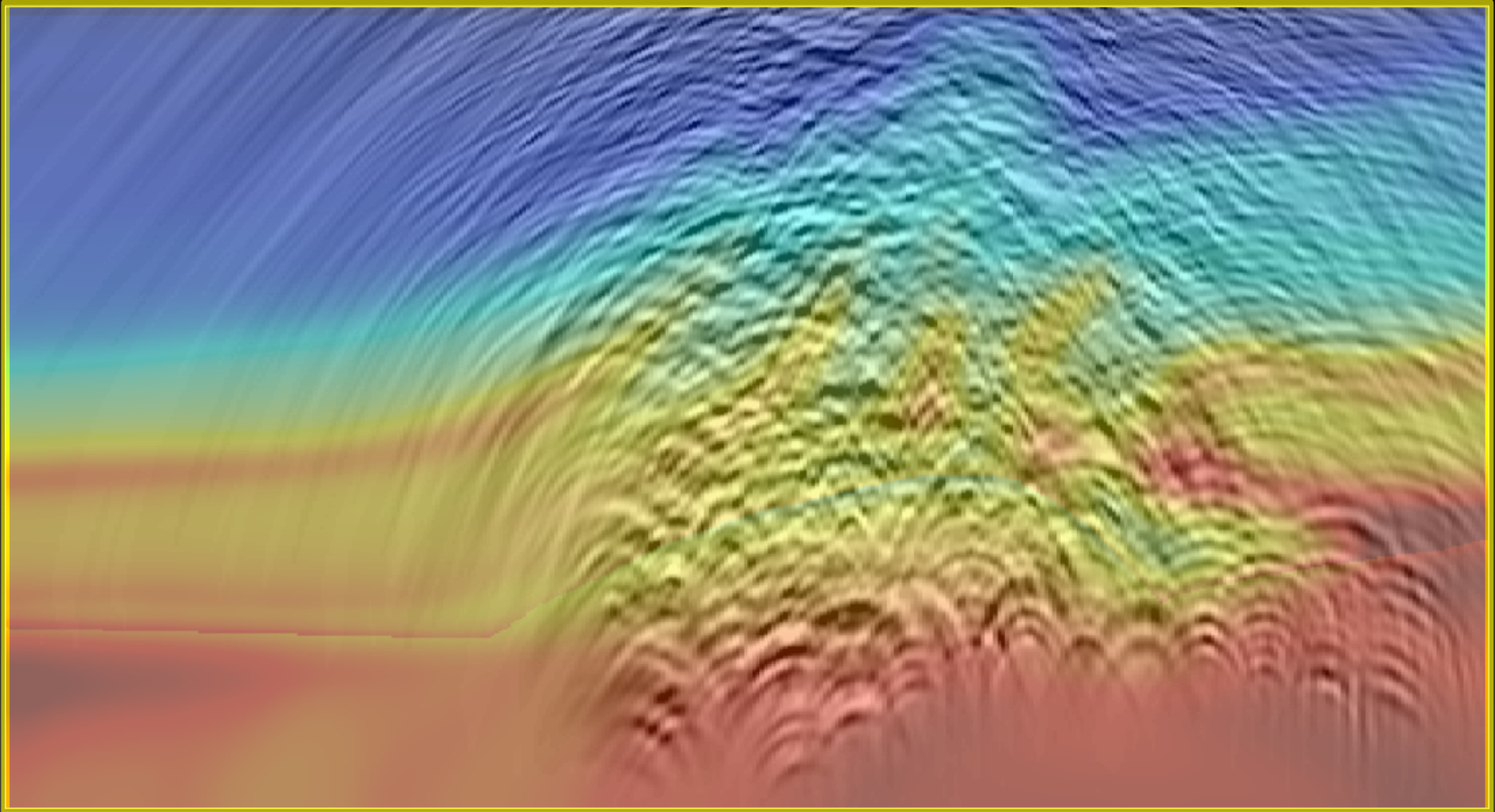


Phase-encoded receiver wavefield

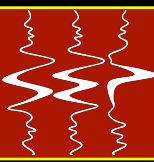


distance

depth

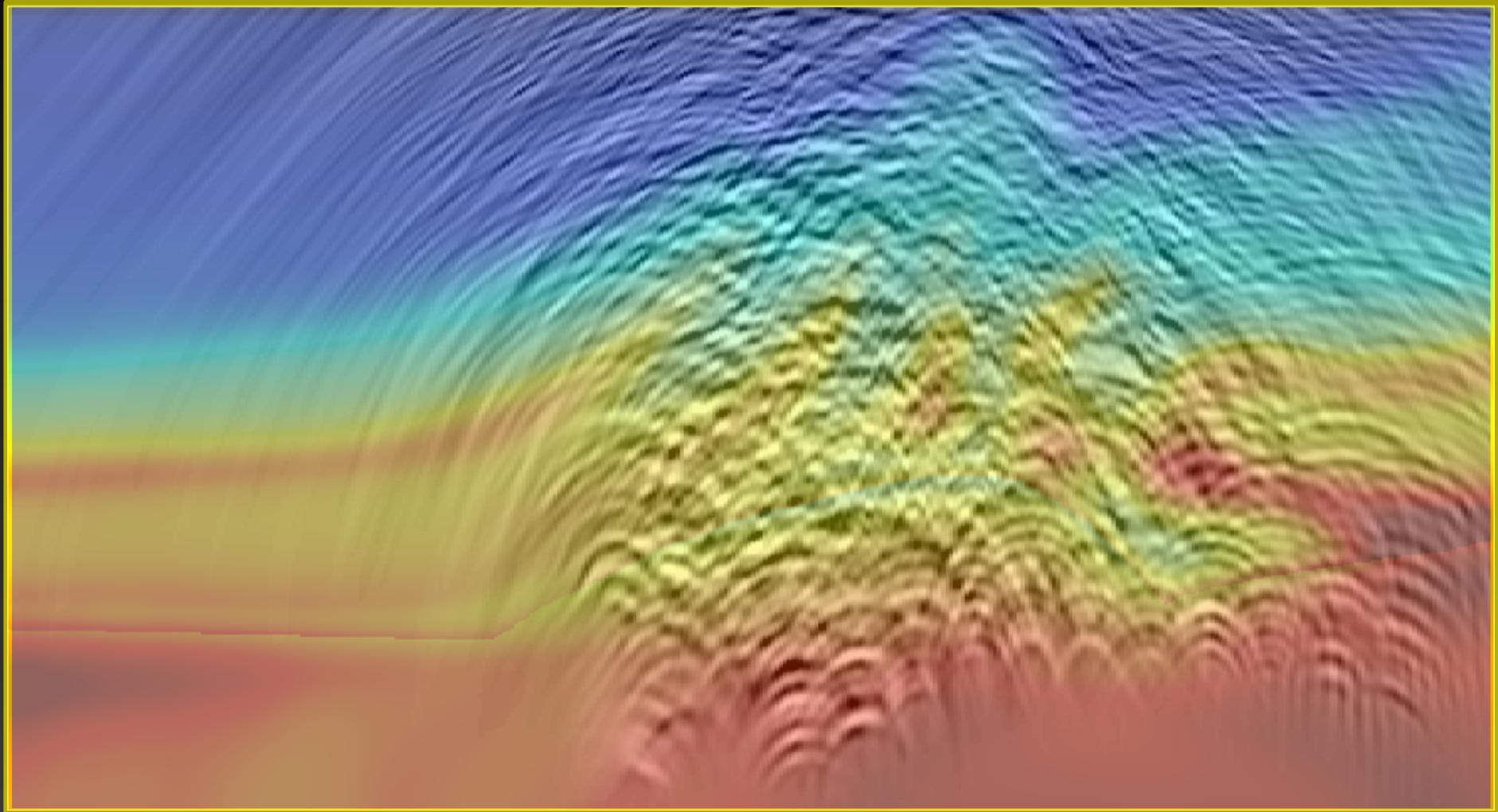


Phase-encoded receiver wavefield

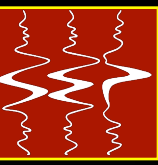


distance

depth

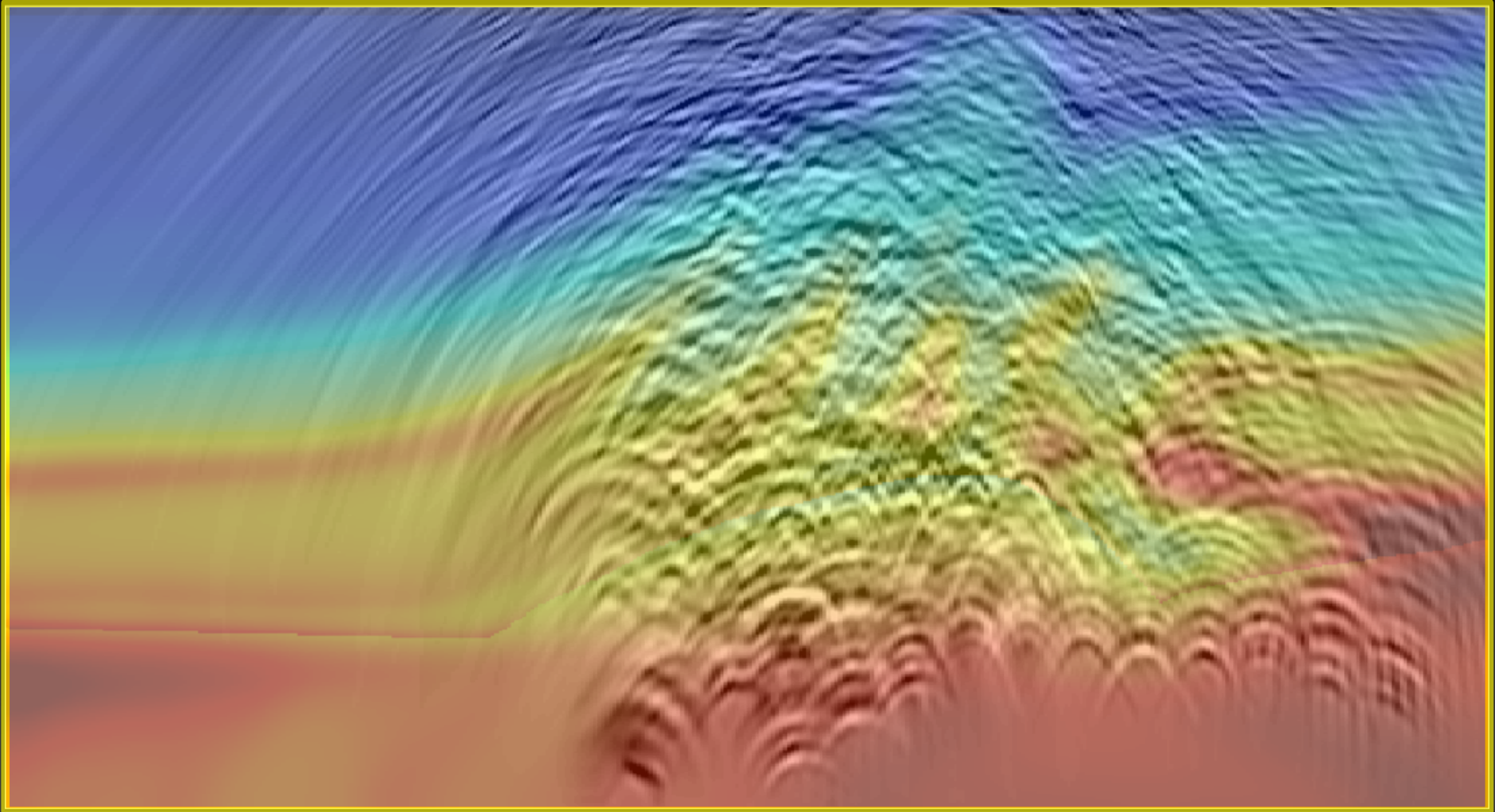


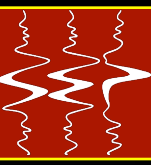
Phase-encoded receiver wavefield



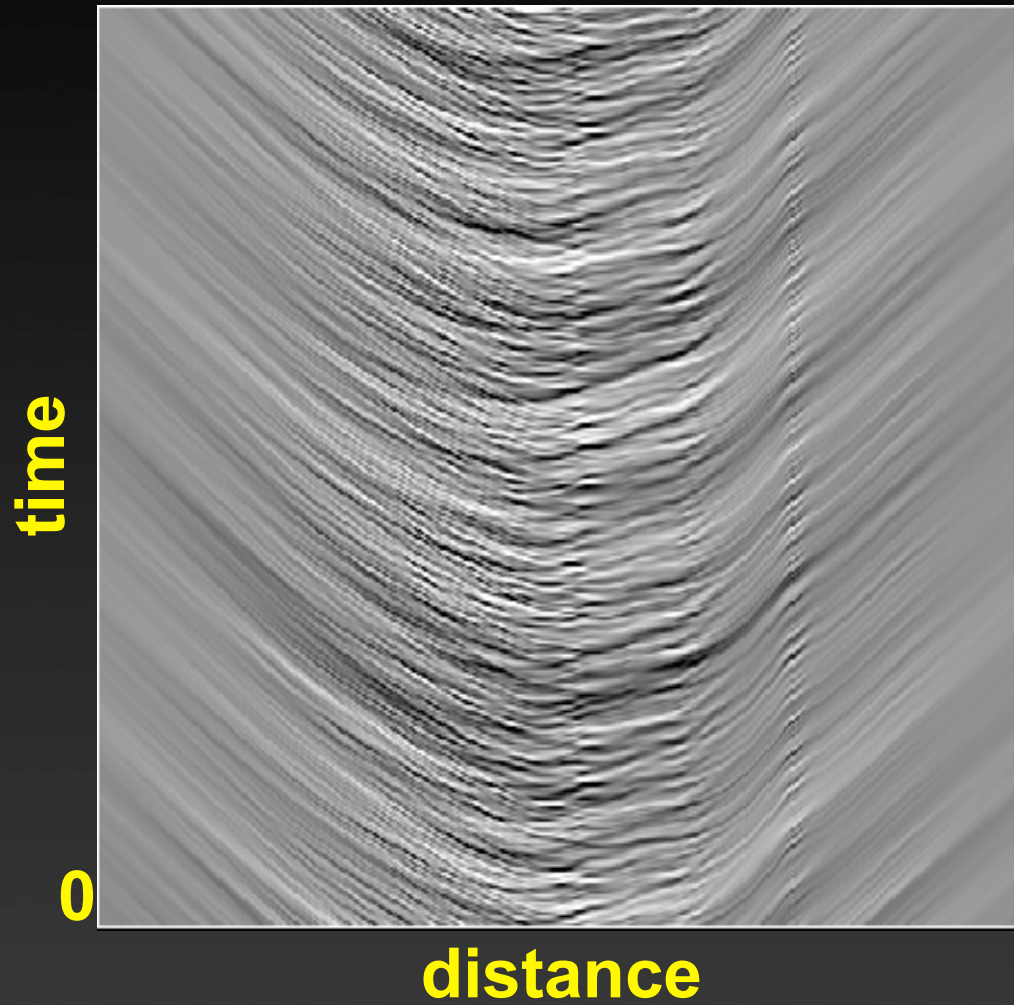
distance

depth

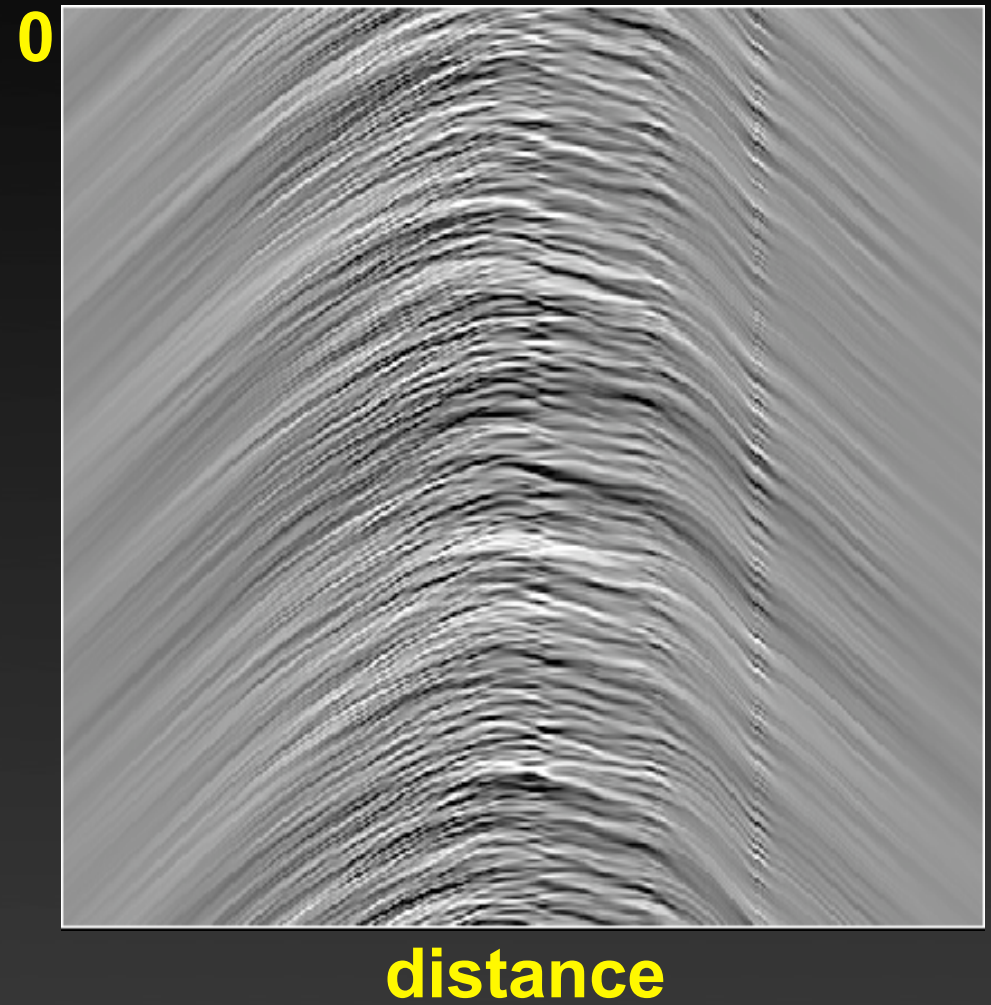




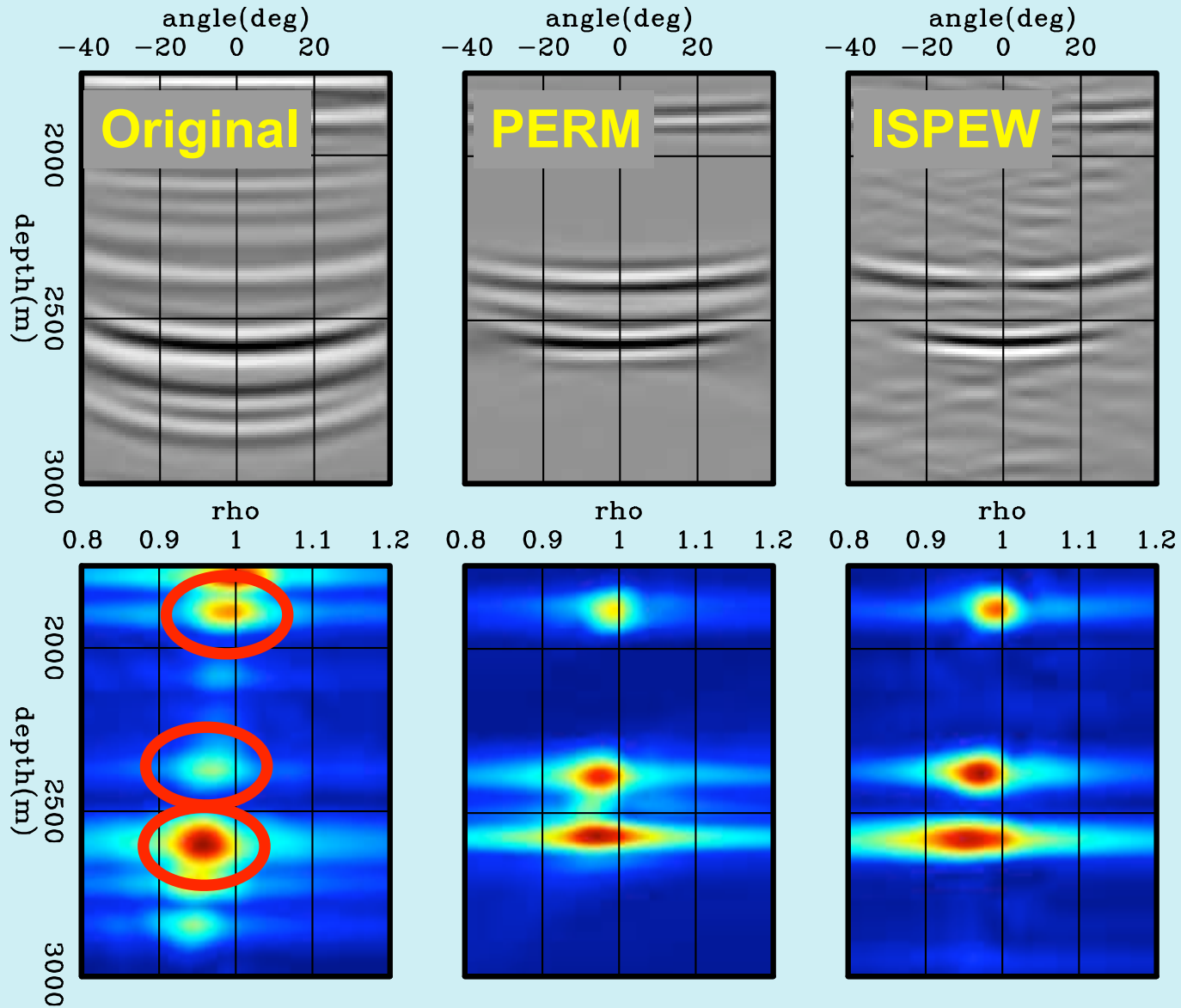
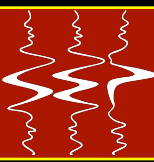
Source



Receiver



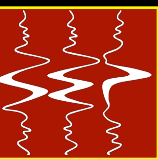
Moveout information



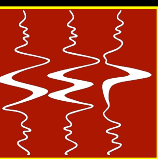
**rho - curvature
parameter**



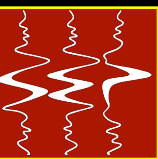
- ✓ **Generalized-source domain**
- ✓ **Pre-stack exploding reflector model**
- ✓ **Image-space phase-encoded wavefields**
- **3D-field data ISWET example**
- **Conclusions**



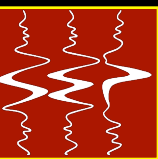
- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**



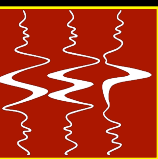
- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**
- **Small number of wavefields**



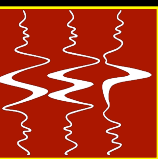
- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**
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- **Wavefields initiated at selected reflectors**



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

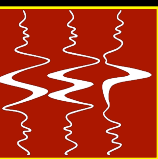


- **ISWET extended from shot-profile to the generalized source domain (Tang et al., 2009 - SEP136)**
- **Small number of wavefields**
- **Wavefields initiated at selected reflectors**
 - **Horizon-based ISWET**
- **Easily solved in a target-oriented way**



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

$J(\mathbf{s})$ = objective function $\Delta \tilde{I}(\mathbf{s})$ = perturbed image



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

Residual pre-stack depth migration (Sava, 2004)

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

$J(\mathbf{s}) =$ objective function $\Delta \tilde{I}(\mathbf{s}) =$ perturbed image



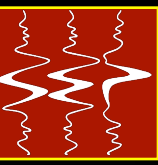
$$J(\mathbf{s}) = \frac{1}{2} \left\| \mathbf{h} \tilde{I}(\mathbf{s}) \right\|_2$$

$J(\mathbf{s})$ = objective function

\mathbf{h} = DSO operator

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

$\tilde{I}(\mathbf{s})$ = current image

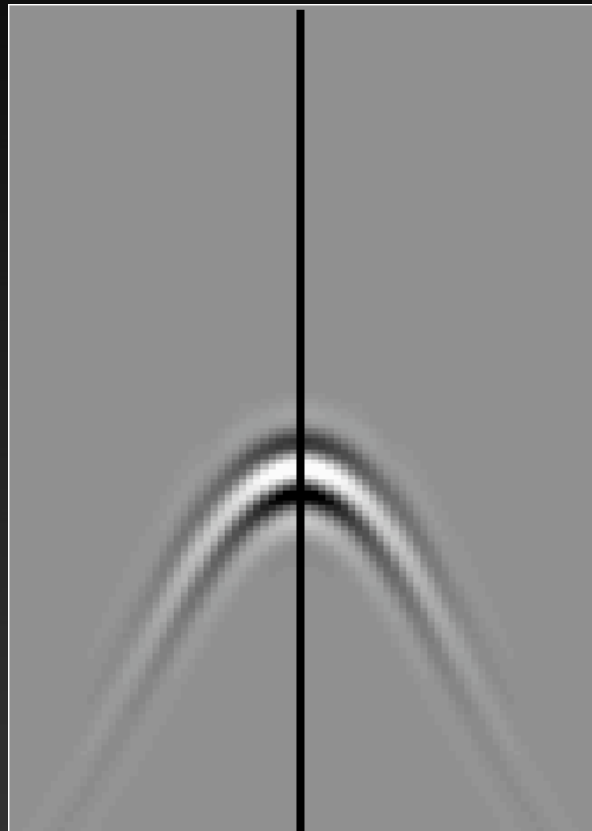


**SLOWER
VELOCITY**

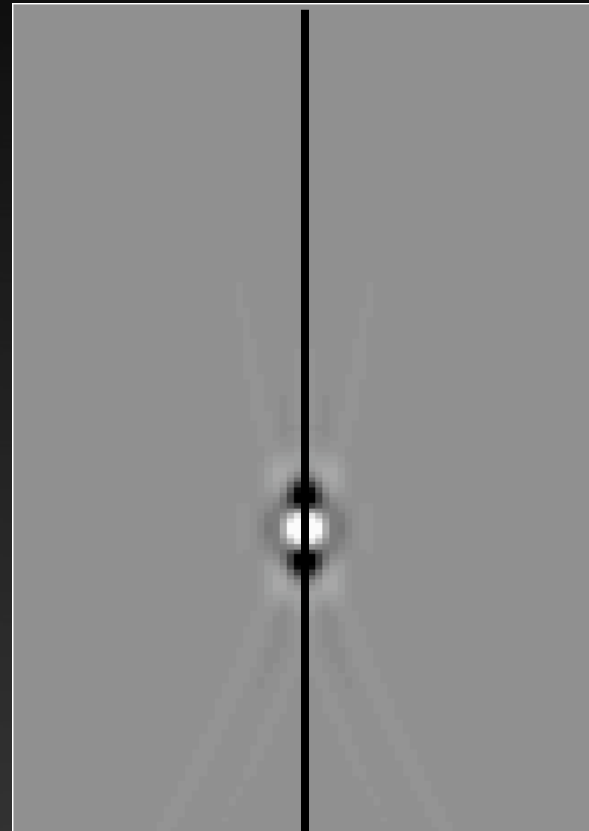
**CORRECT
VELOCITY**

**FASTER
VELOCITY**

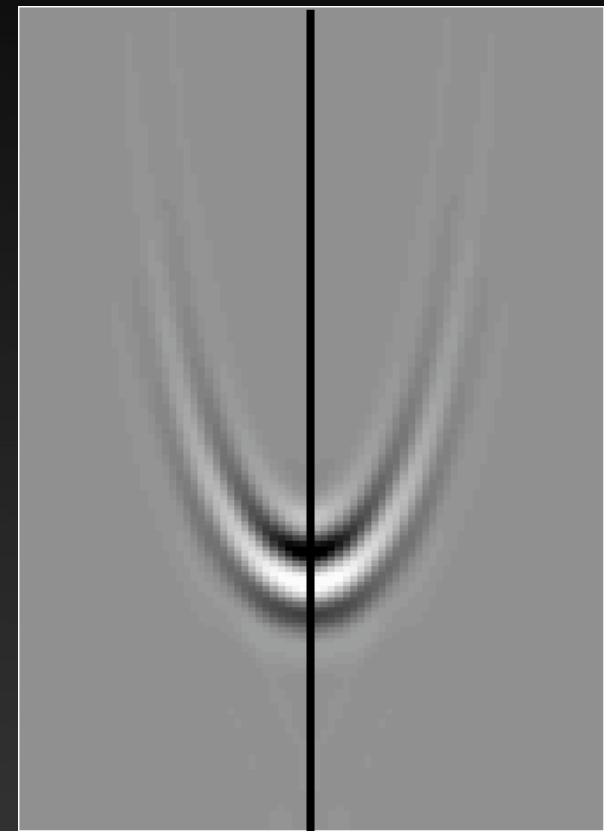
depth



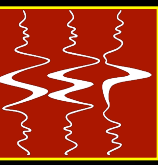
offset



offset



offset

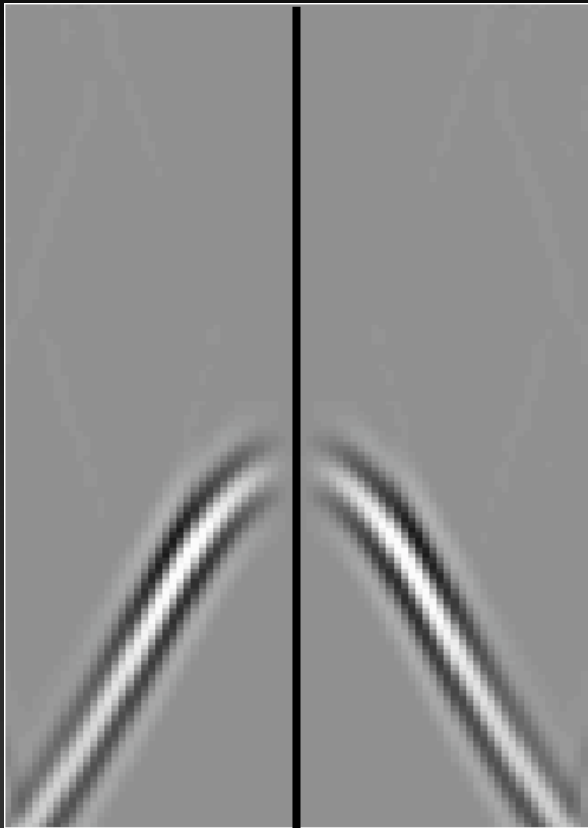


**SLOWER
VELOCITY**

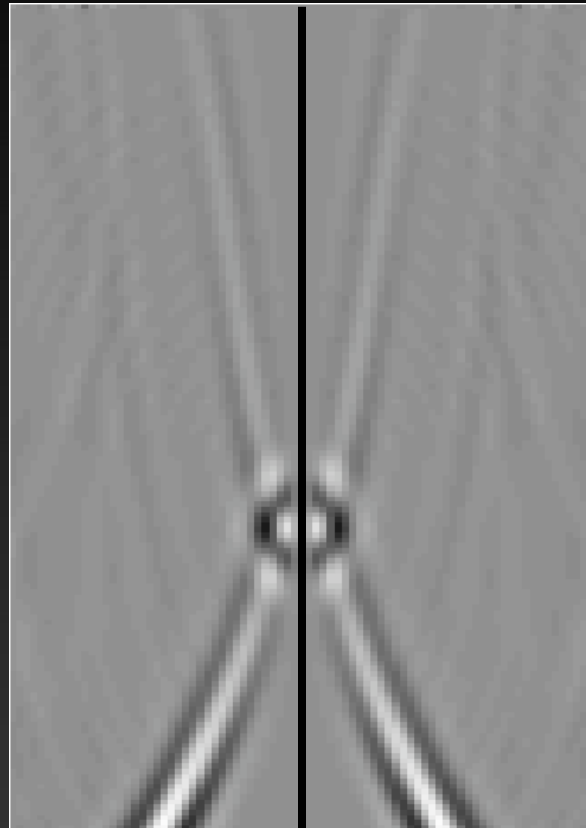
**CORRECT
VELOCITY**

**FASTER
VELOCITY**

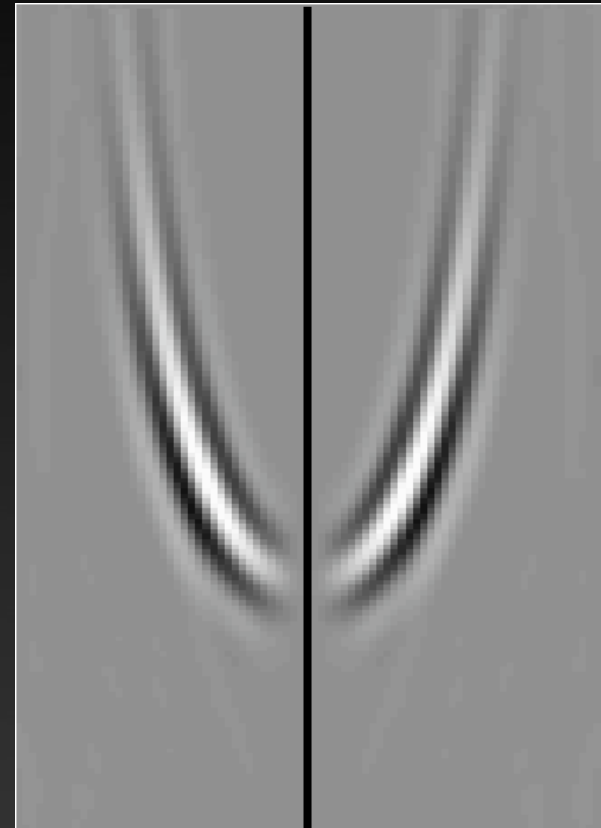
depth



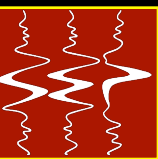
offset



offset



offset



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

$$\nabla J(s) = \left(\frac{\partial \tilde{I}}{\partial s} \right)' \mathbf{h}^2 \tilde{I} \Big|_{s=s_0}$$

$J(s)$ = objective function

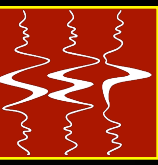
$\Delta \tilde{I}(s)$ = perturbed image

\mathbf{h} = DSO operator

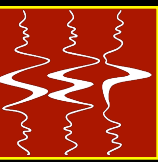
$\tilde{I}(s)$ = current image

s_0 = current velocity

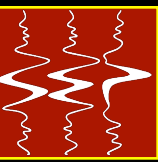
3D-North Sea data example



- **Dimensions: 12 x 4 km**

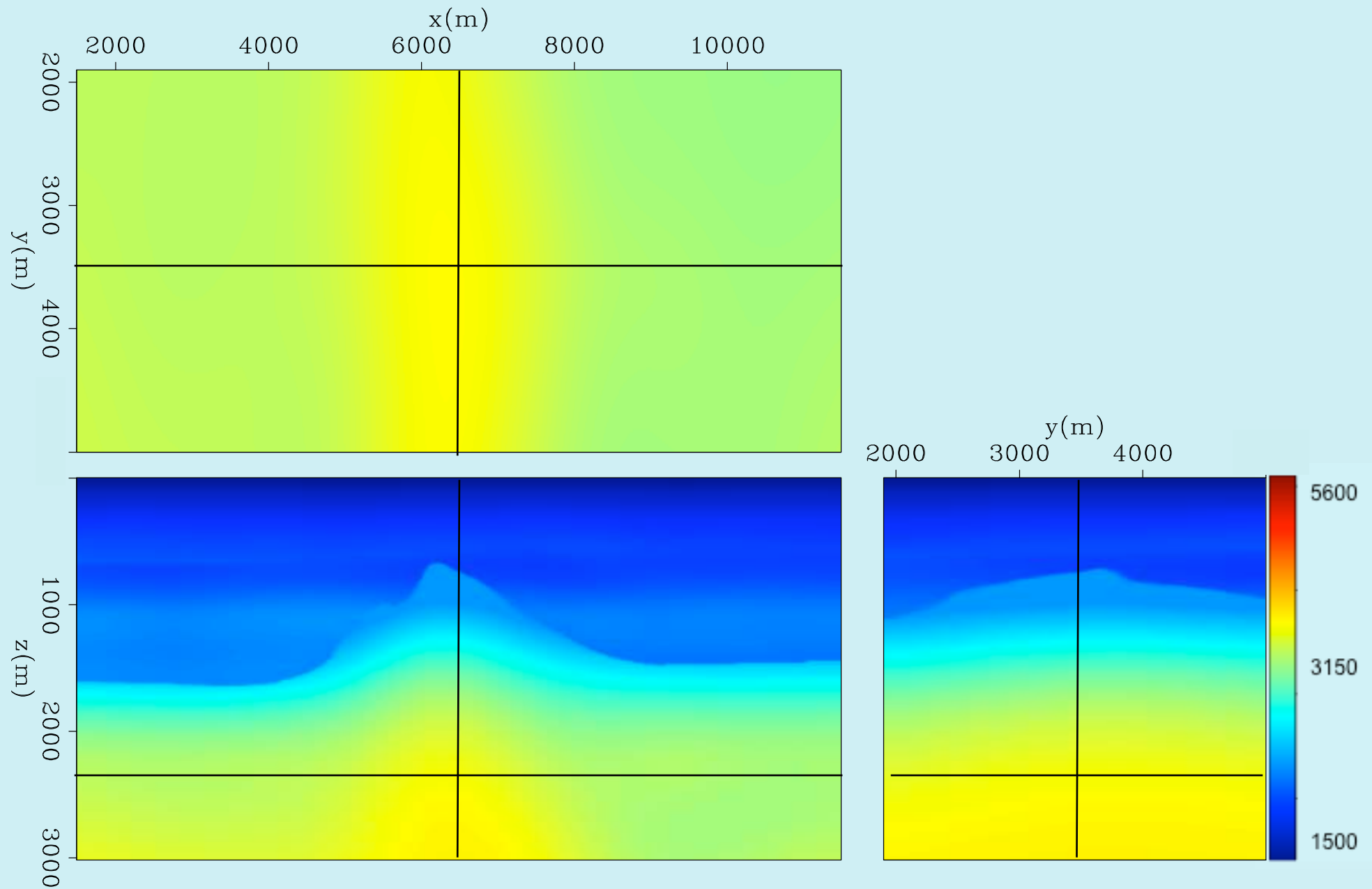
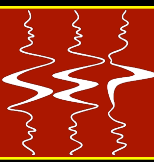


- **Dimensions: 12 x 4 km**
- **AMO data with 3600 m maximum offset**
 - **CAM images as the initial conditions**
 - **20 ISPEW**
 - **Target region: 600-3200 m depth range**

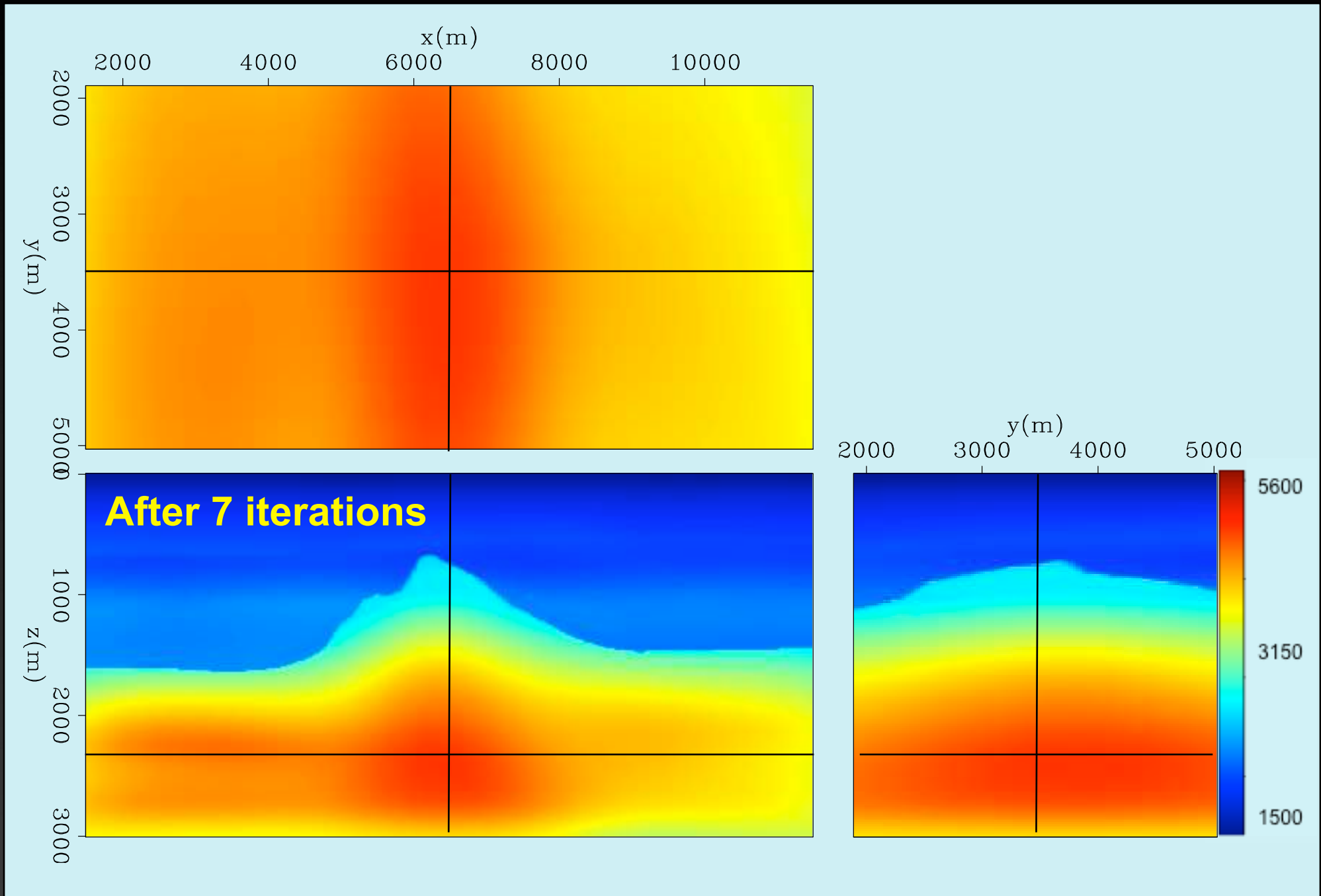


- **Dimensions: 12 x 4 km**
- **AMO data with 3600 m maximum offset**
 - **CAM images as the initial conditions**
 - **20 ISPEW**
 - **Target region: 600-3200 m depth range**
- **CEES: 20 Dual Nehalem 5520, 24Gb RAM**
 - **Perturbed image: 20 min**
 - **Gradient: 40 min**

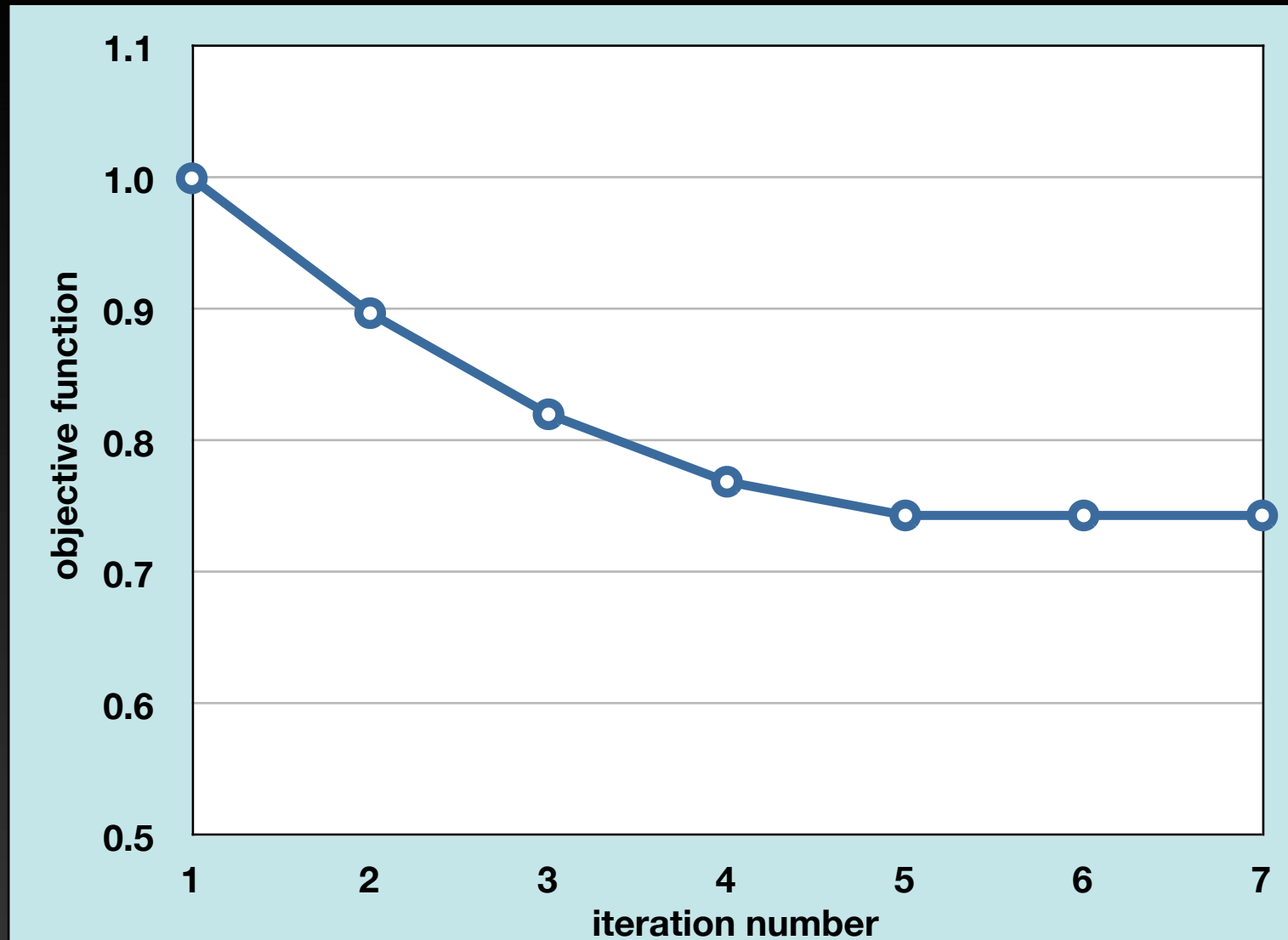
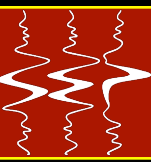
Initial velocity model



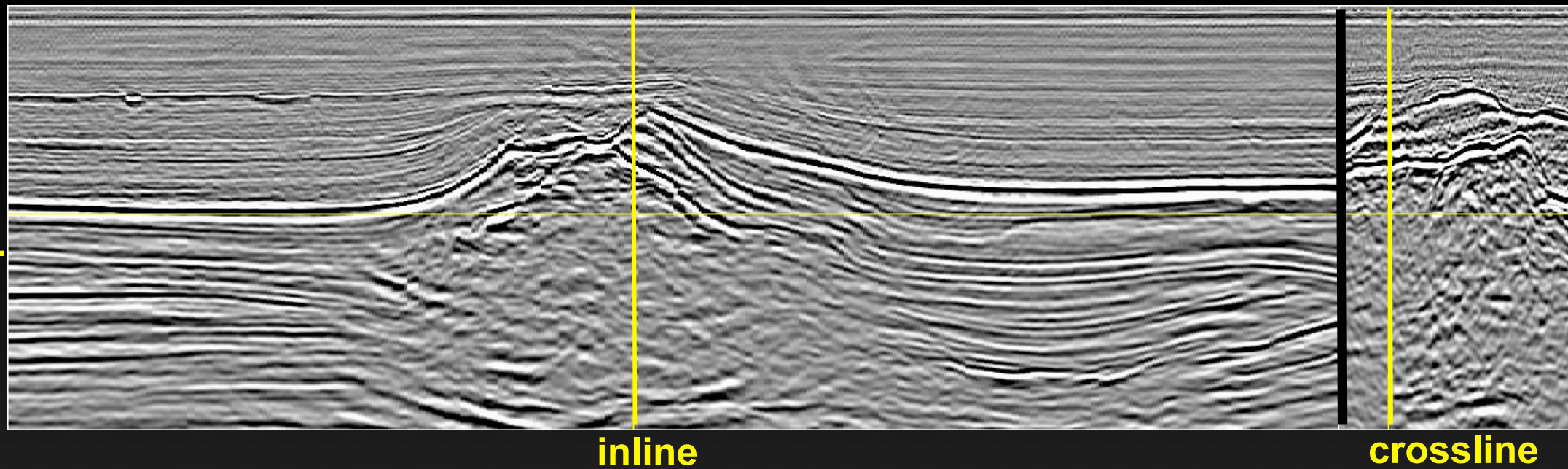
Optimized after 7 iterations



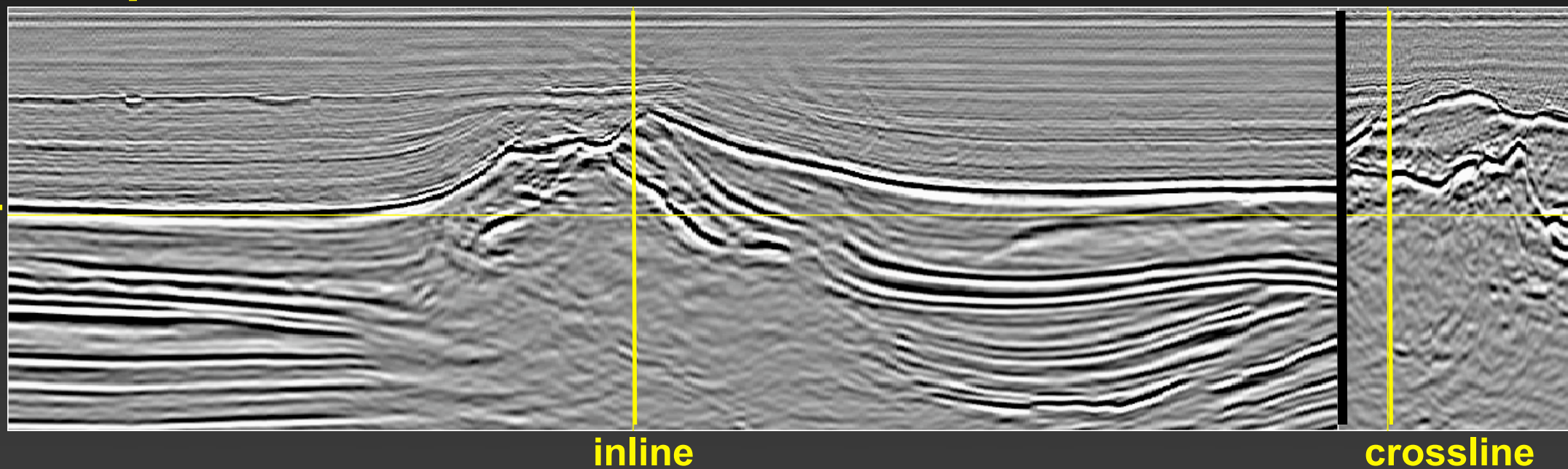
Objective function



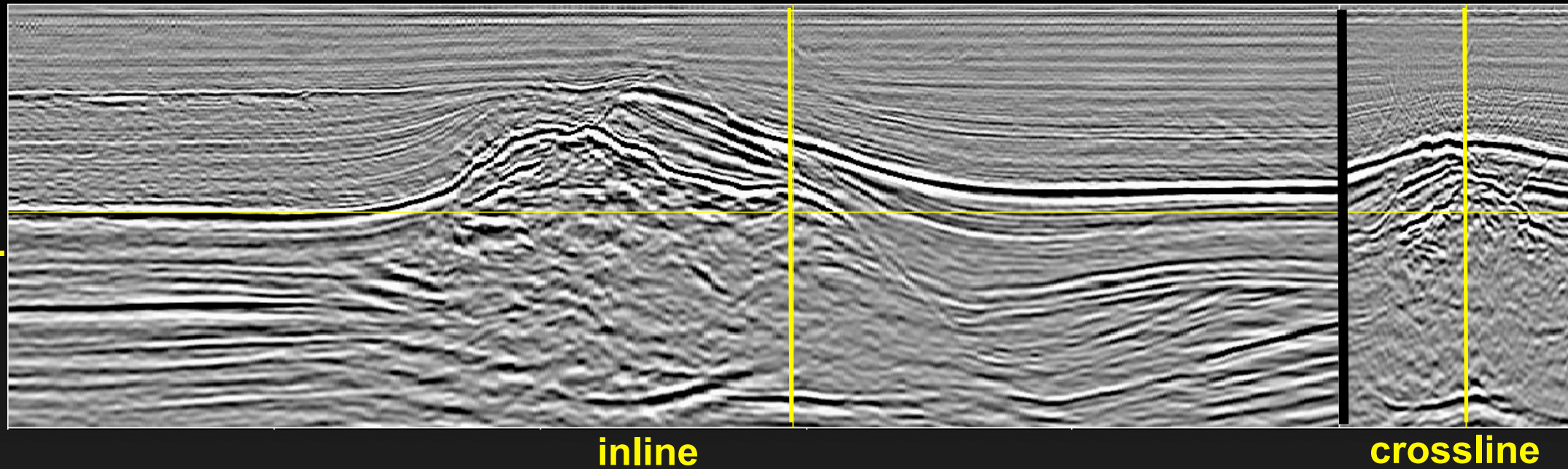
Initial



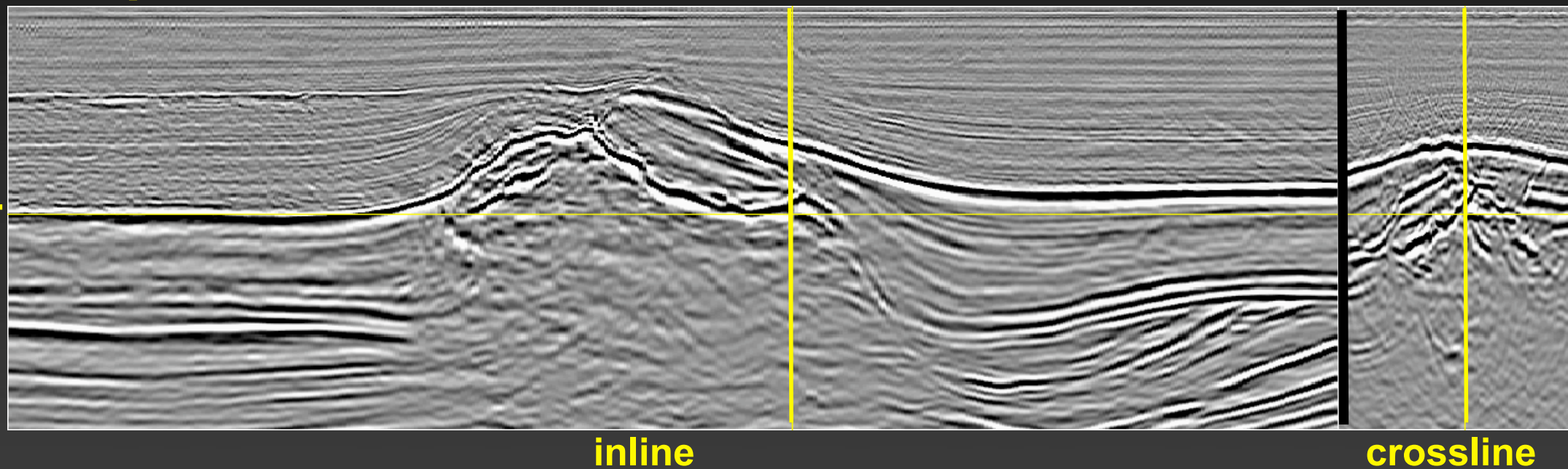
Optimized



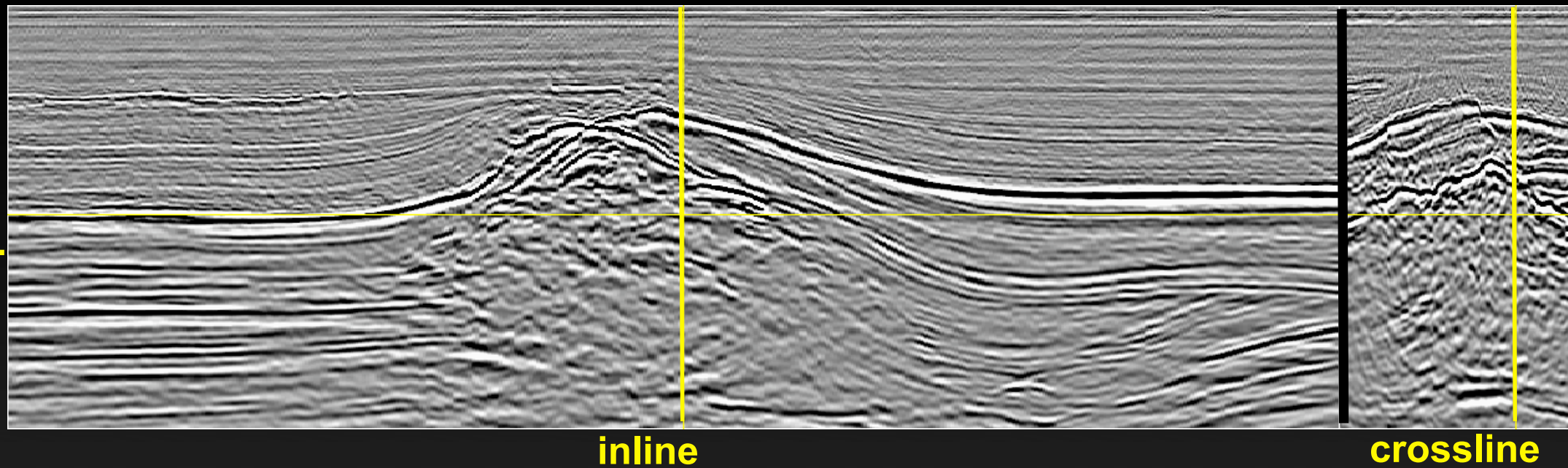
Initial



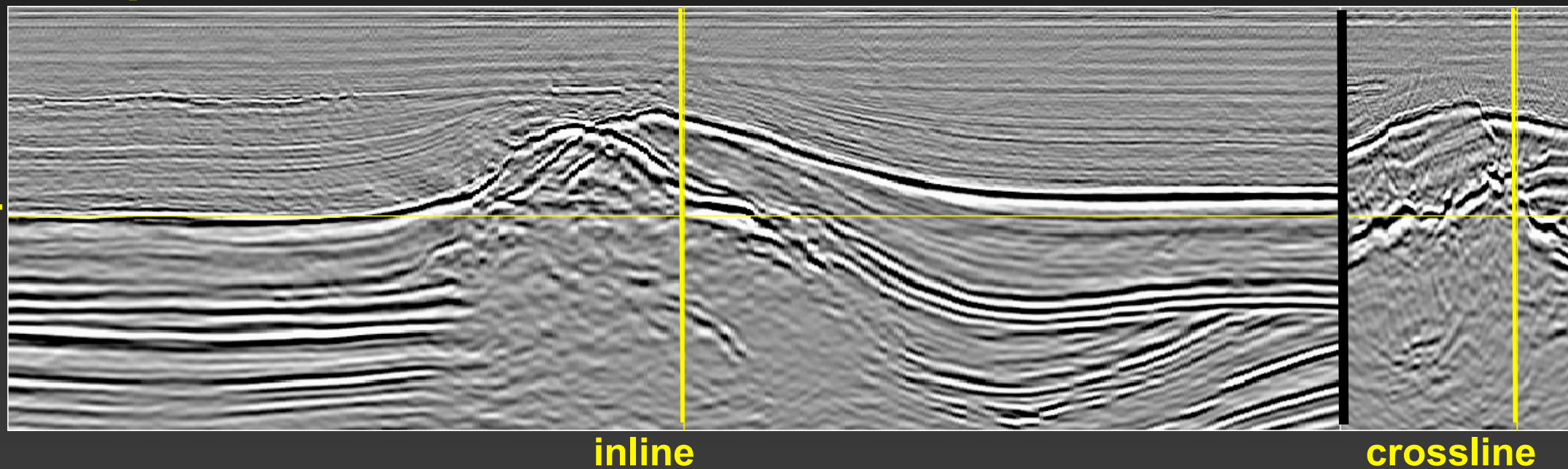
Optimized



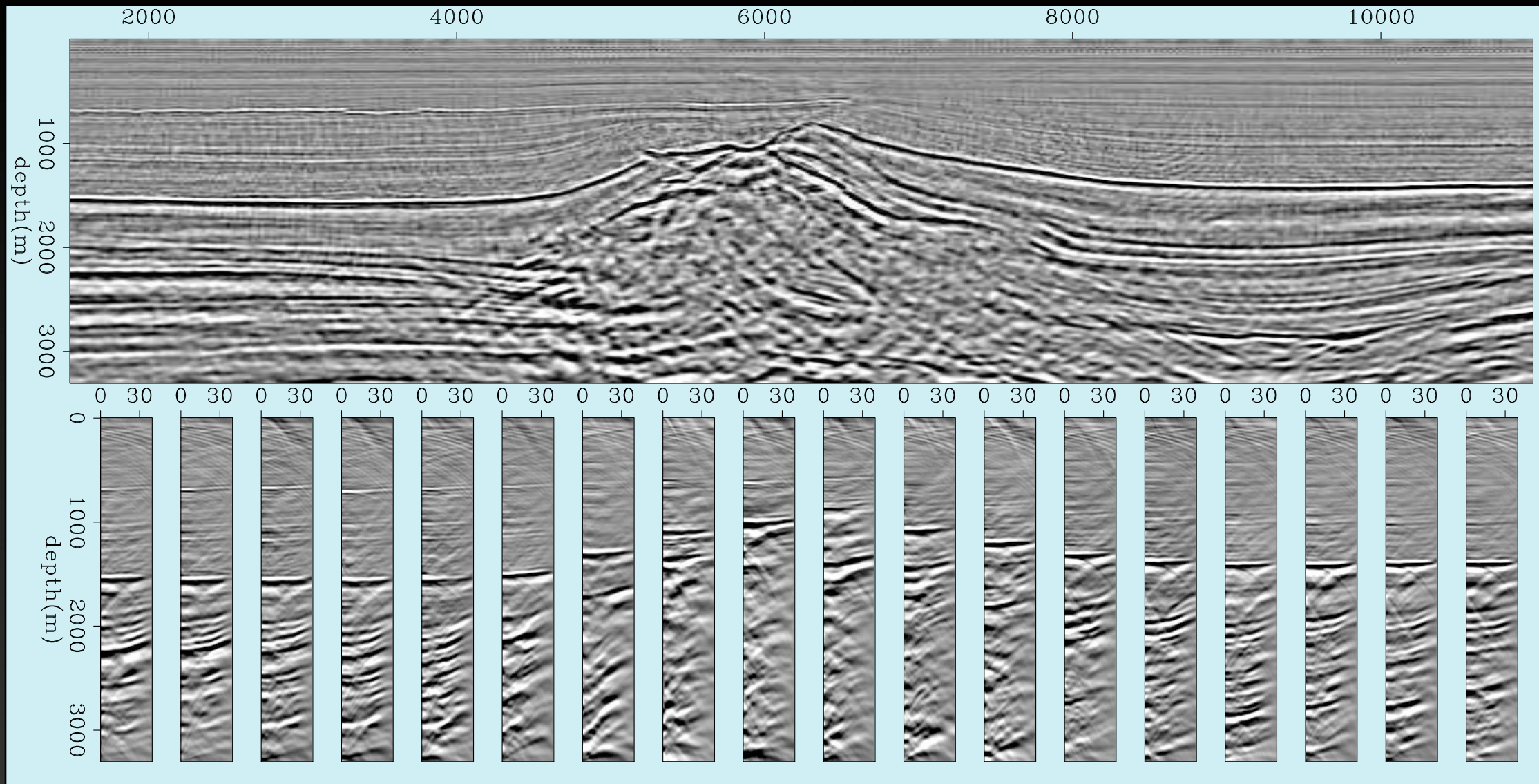
Initial



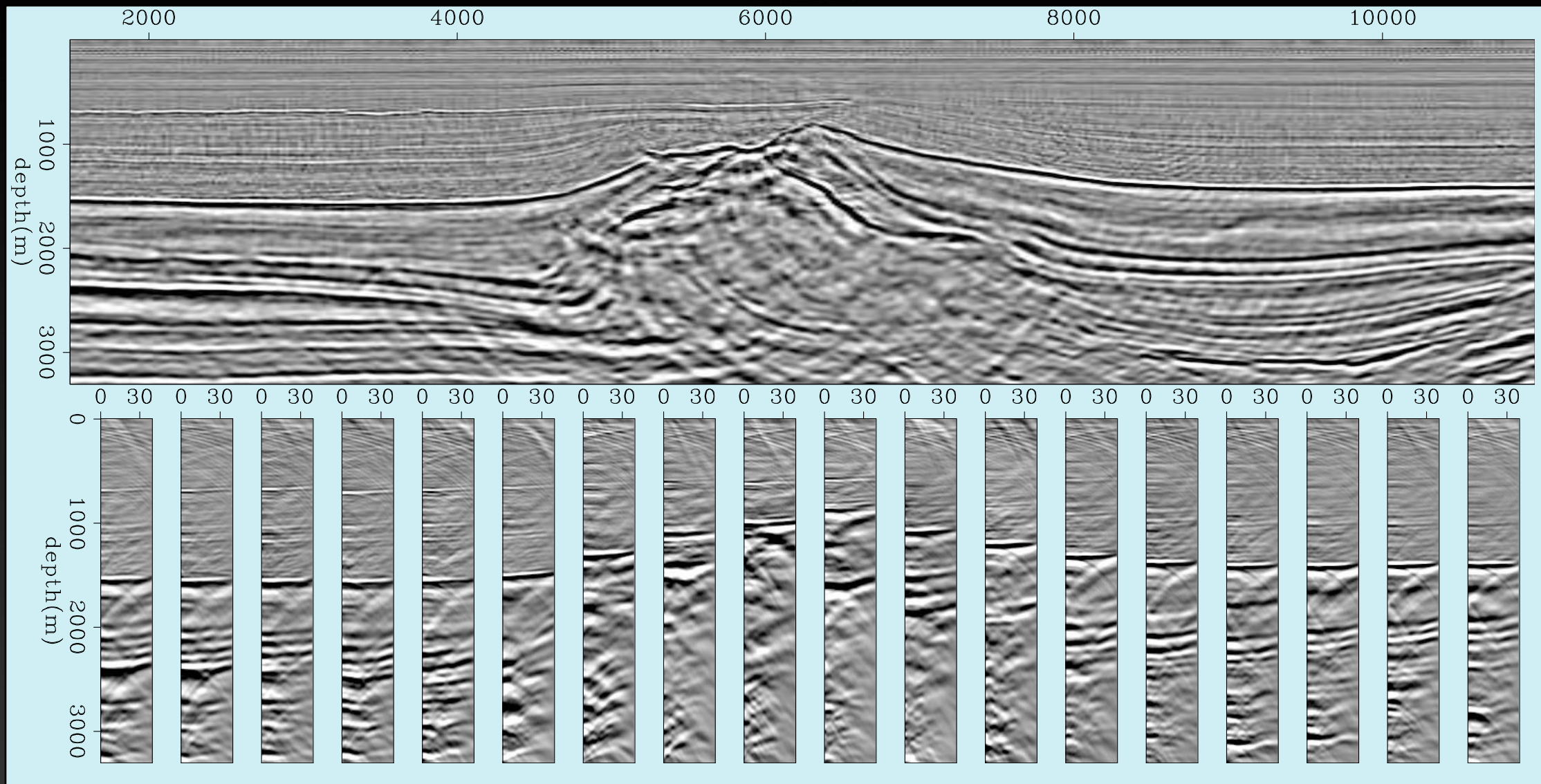
Optimized



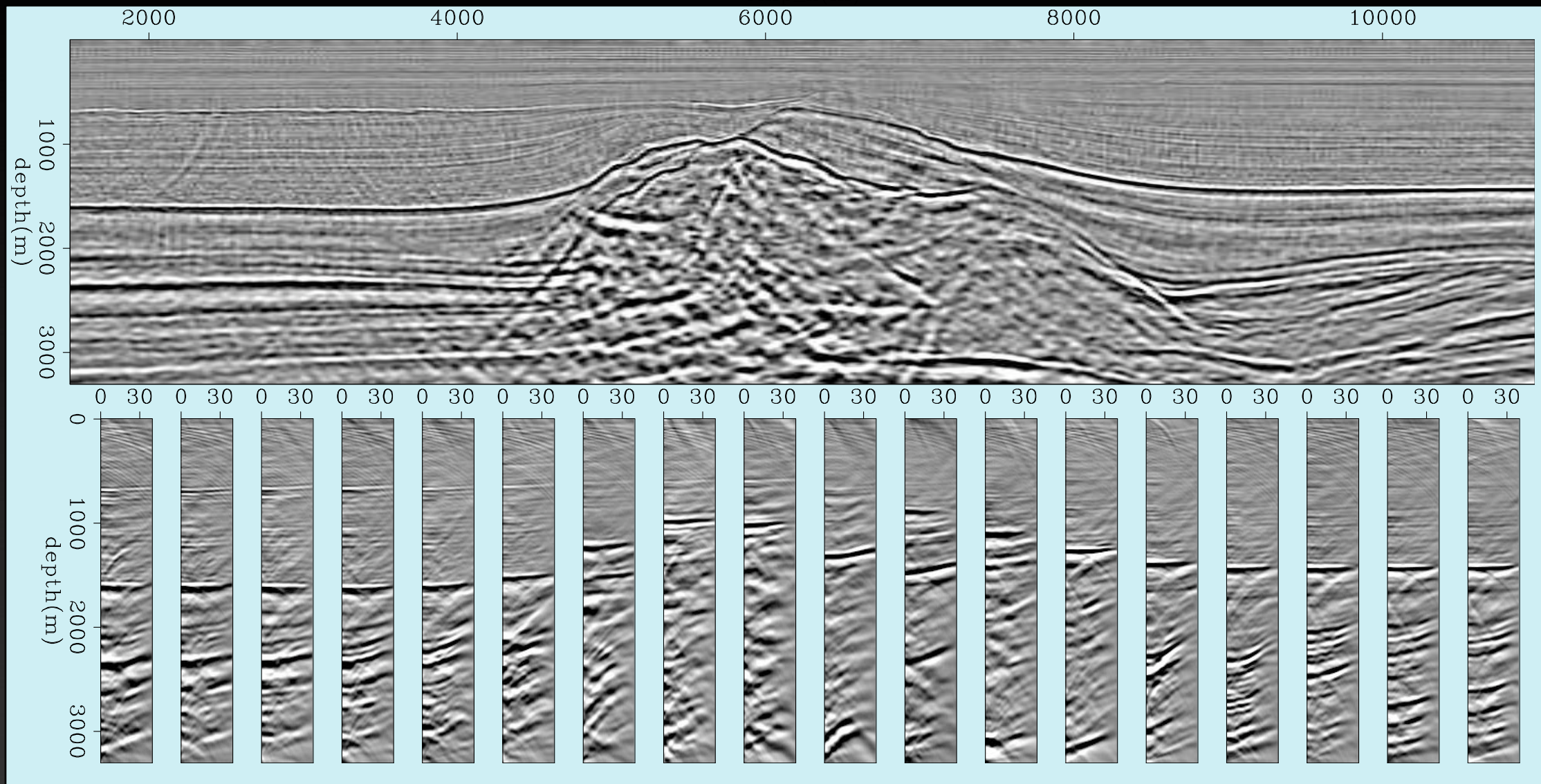
Initial



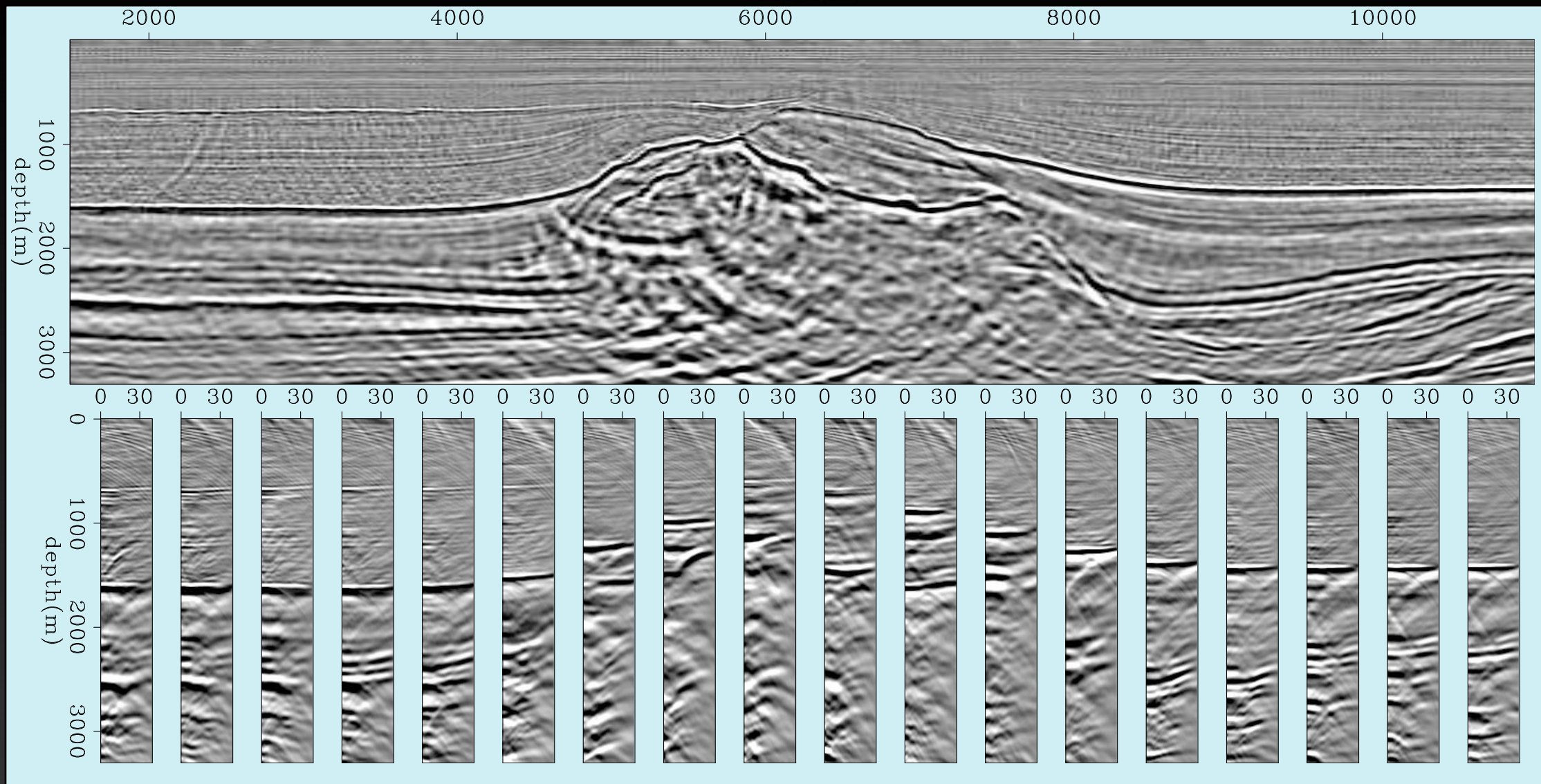
Optimized



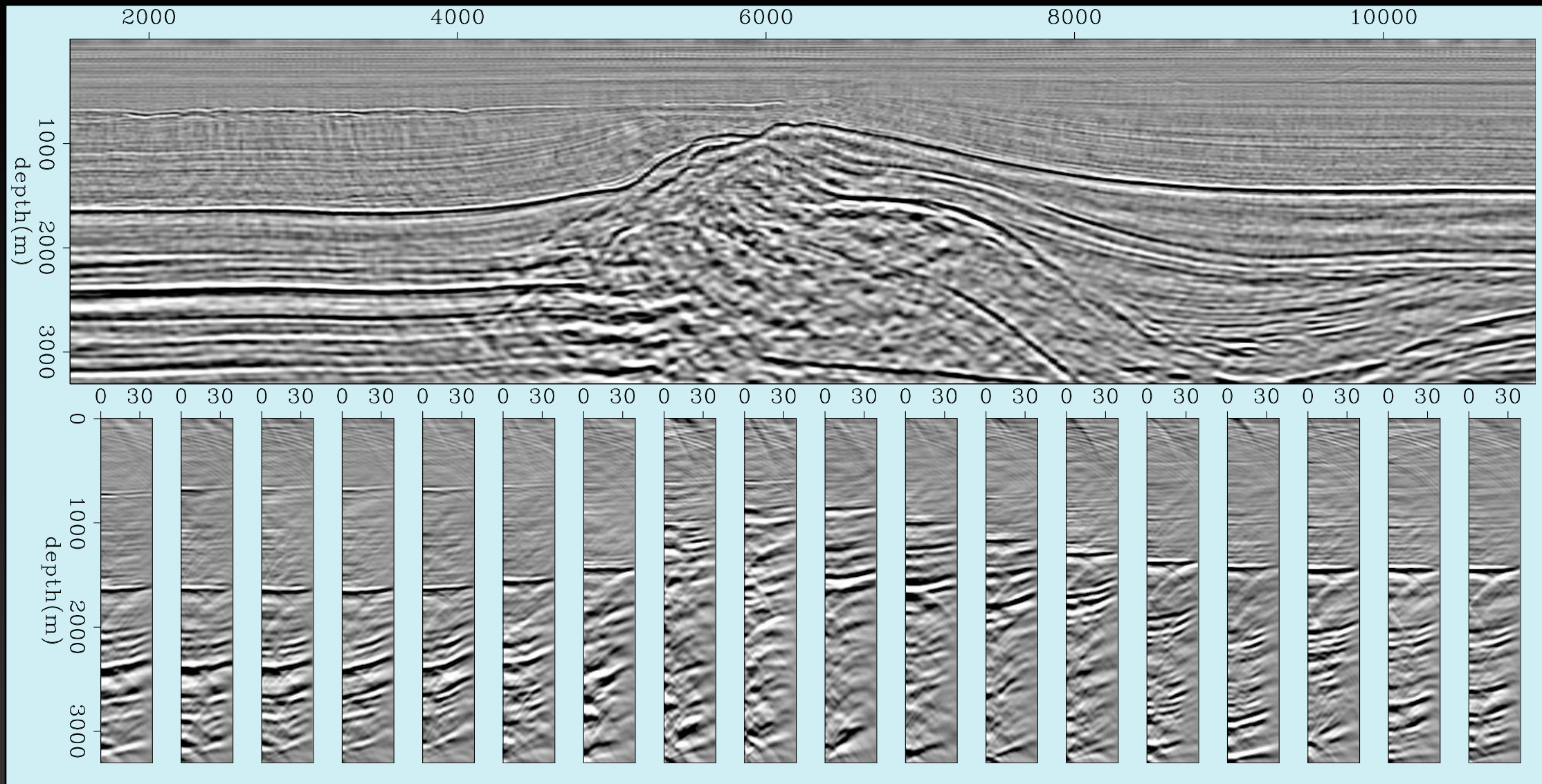
Initial



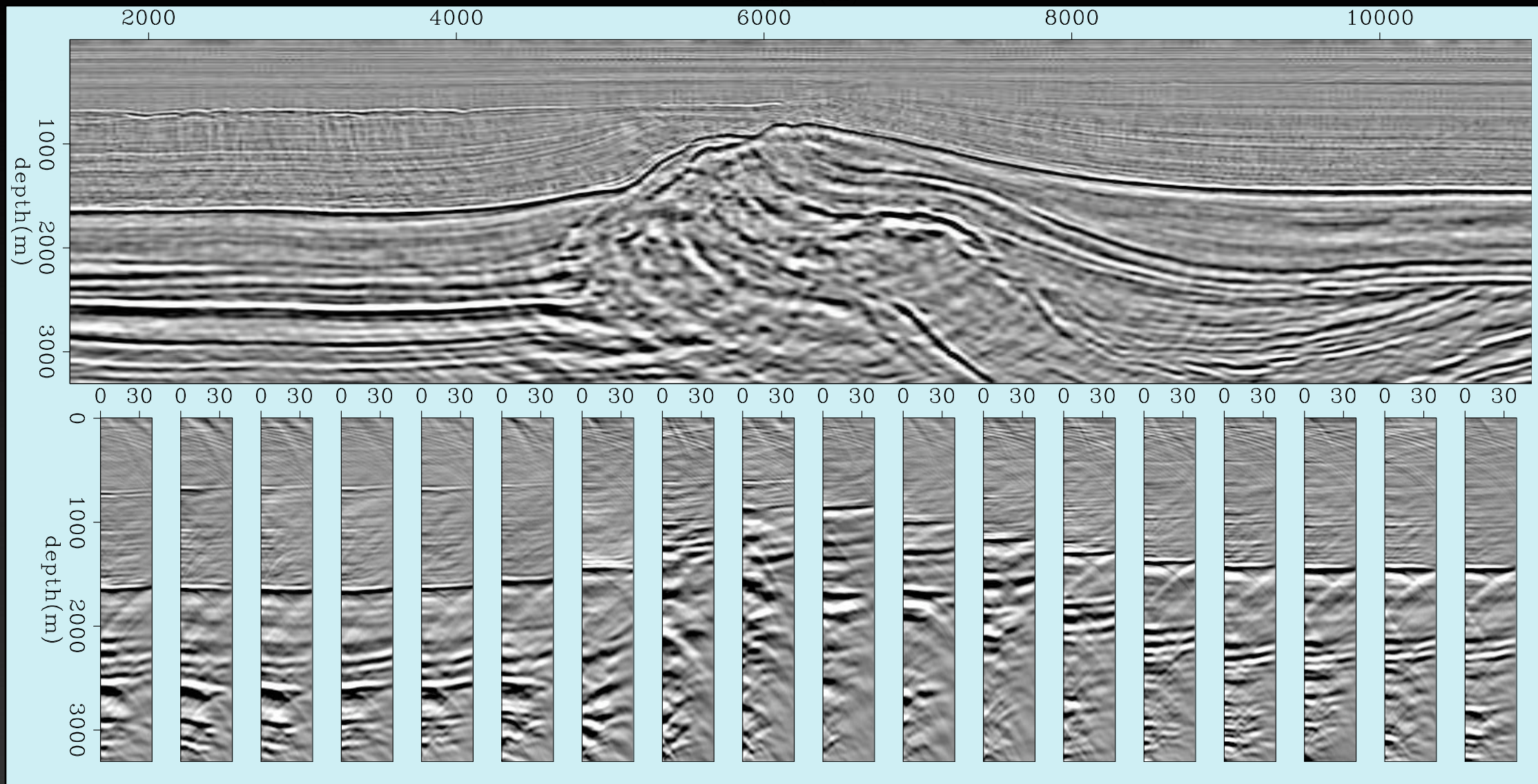
Optimized

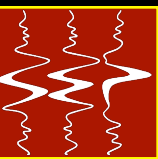


Initial



Optimized



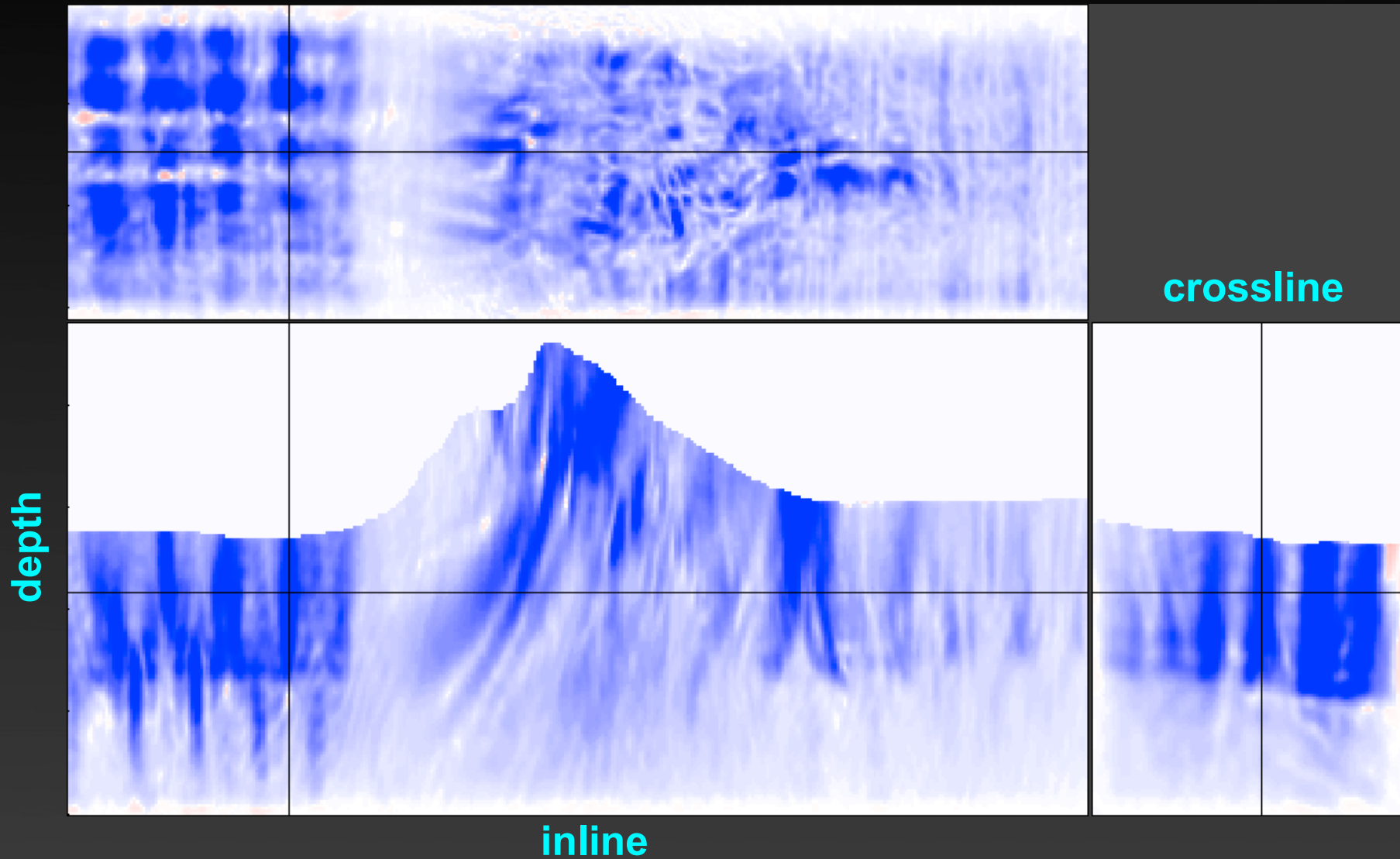


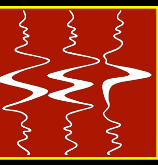
- **New round of modeling/MVA**
- **Top of salt interpretation**
- **Salt flooding**
- **Base of salt interpretation**
- **Sub-salt velocity definition**

Potential for grid-tomography



Gradient with 1 pair of ISPEW



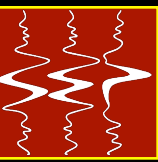


- **Image-space generalized wavefields accelerate ISWET**
 - **reduced data size**
 - **target-oriented strategy**
 - **2 h per iteration**



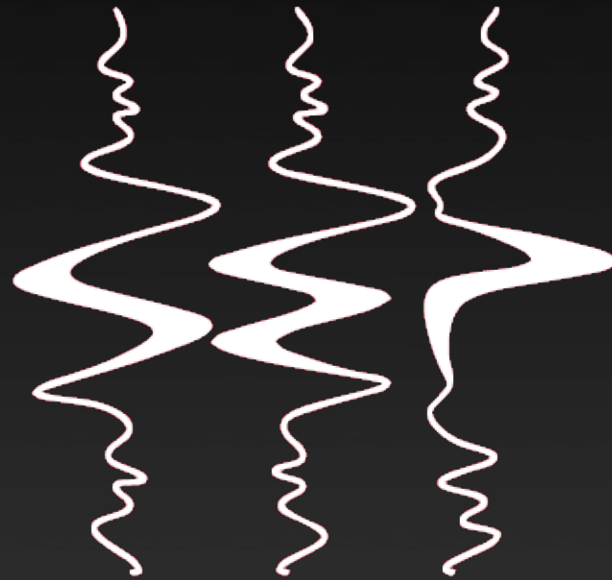
- **Image-space generalized wavefields accelerate ISWET**
 - reduced data size
 - target-oriented strategy
 - 2 h per iteration
- **Image-space generalized wavefields naturally incorporate a horizon-based strategy**
 - Potential for grid-based strategy

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

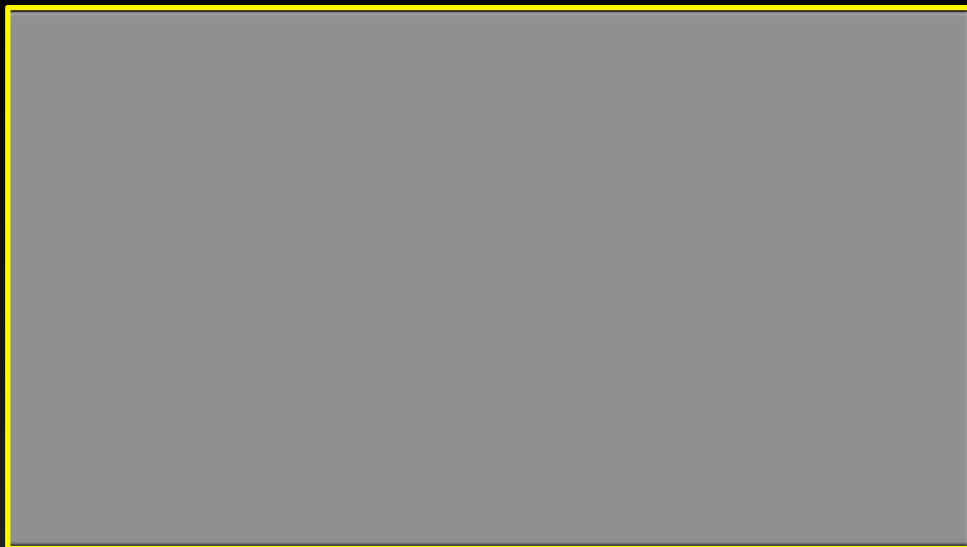
**SEP 140, pp 1-10
May 2010**

Data-space: 0° plane wave



source

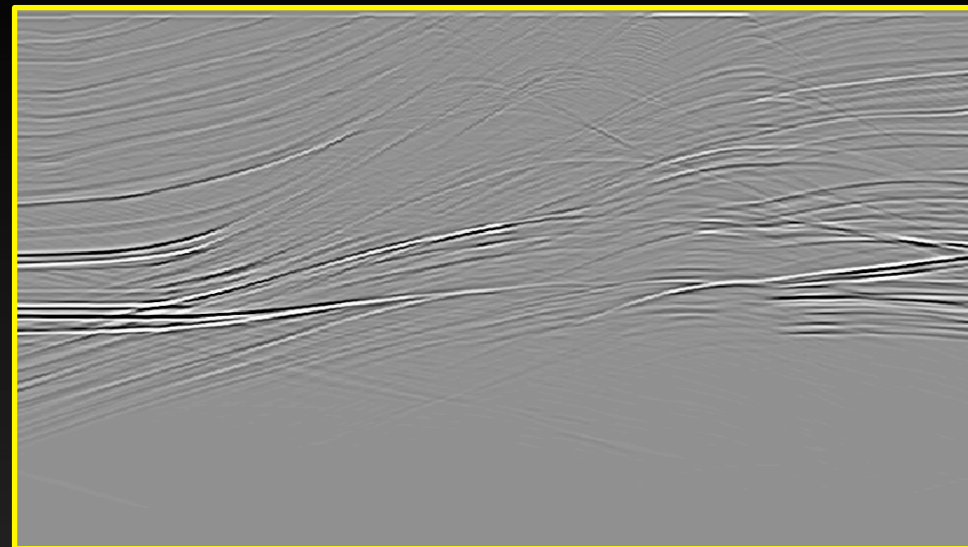
time



distance

receiver

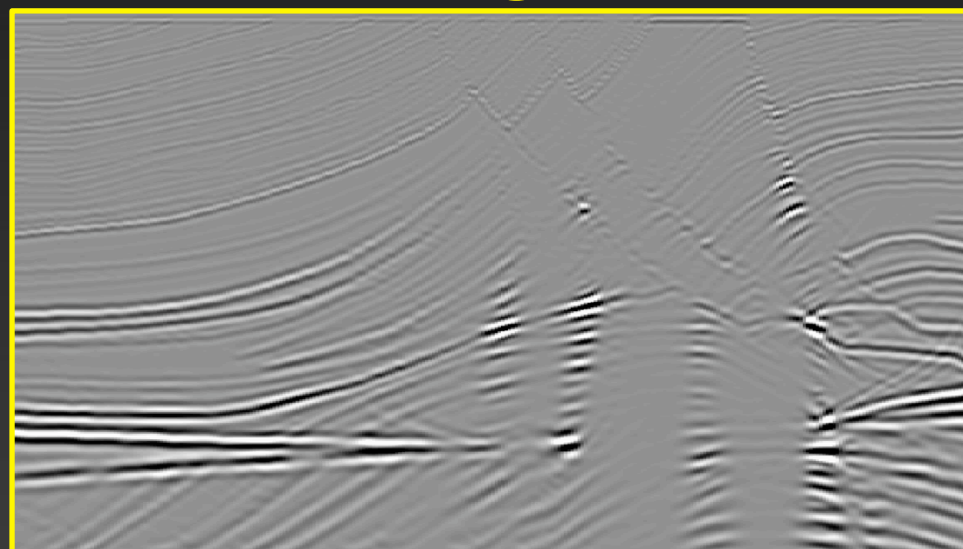
time



distance

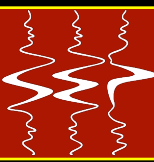
image

depth



distance

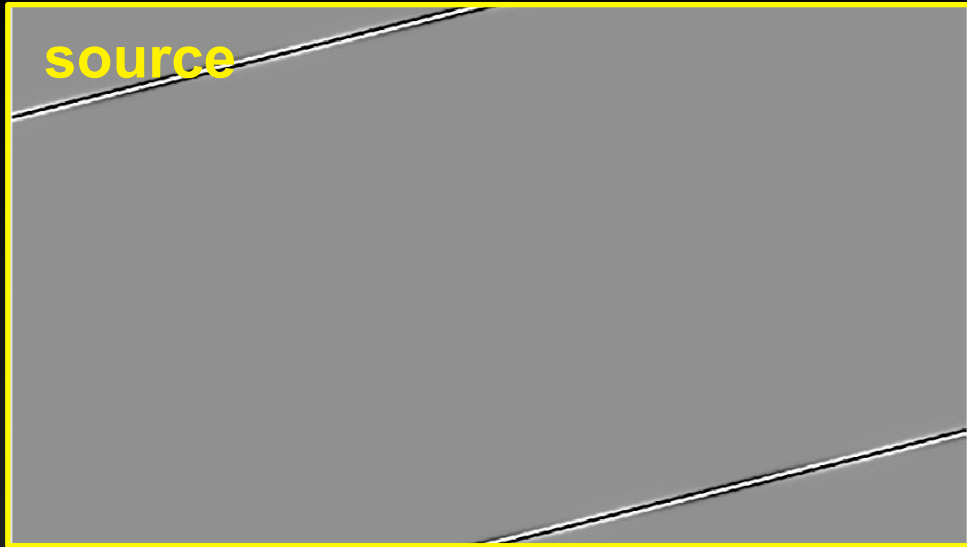
Data-space: plane waves



distance

source

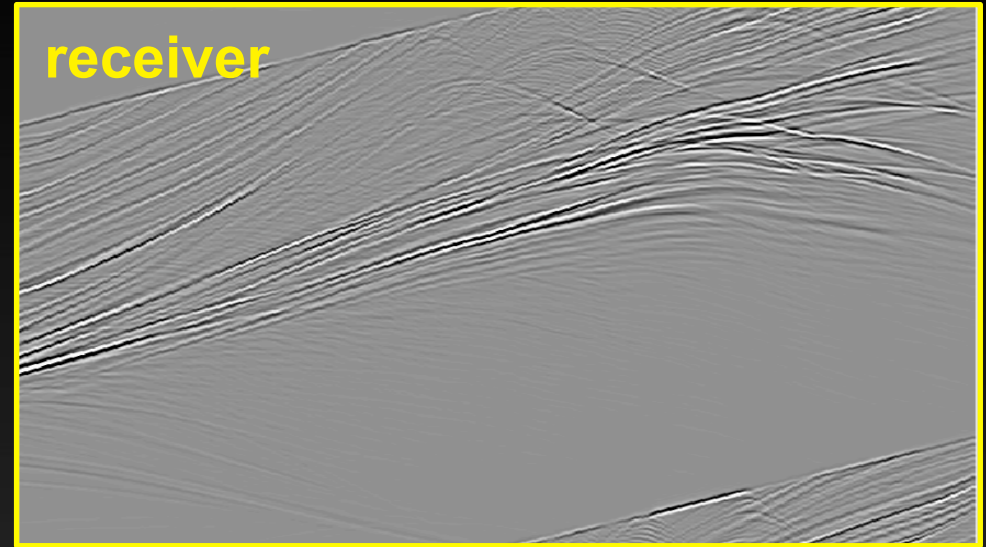
time



distance

receiver

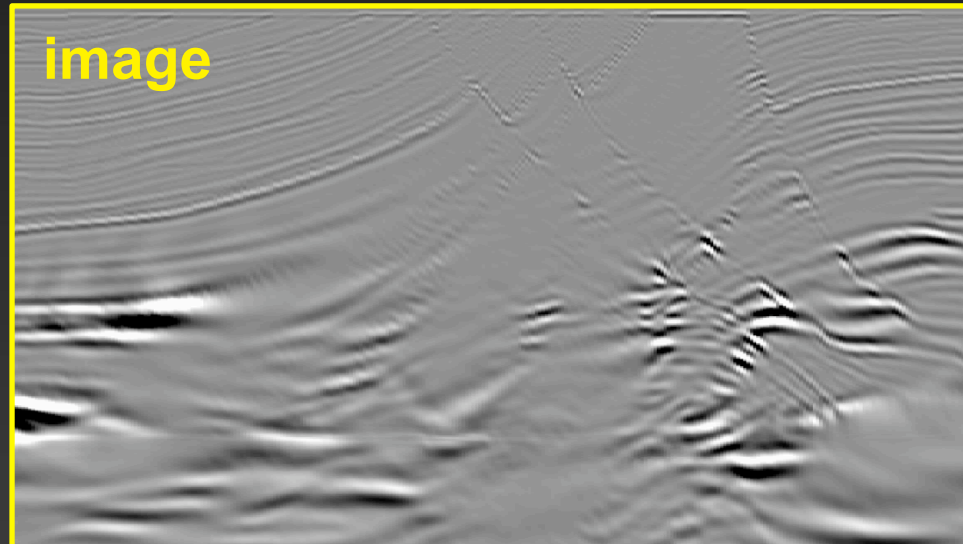
time



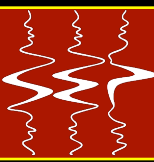
distance

image

depth



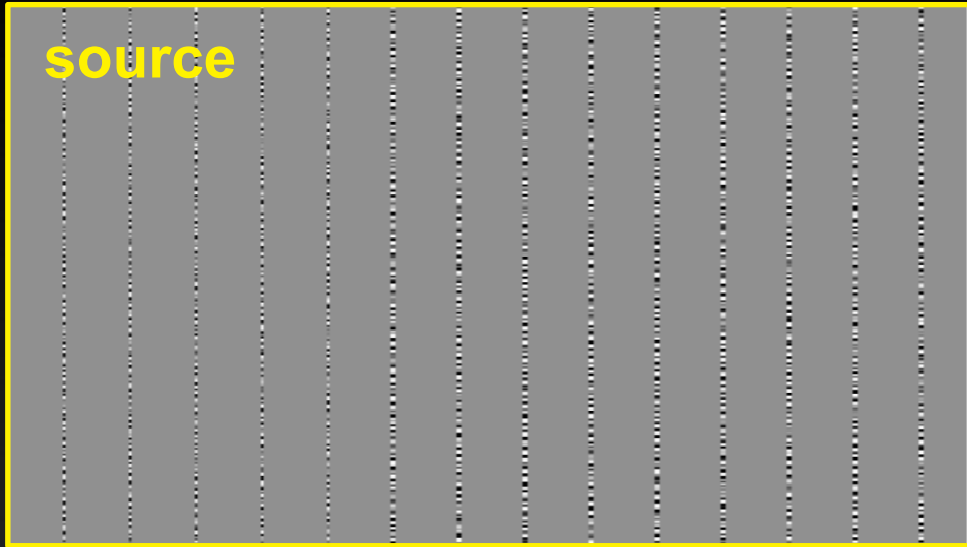
Data-space: random phases



distance

source

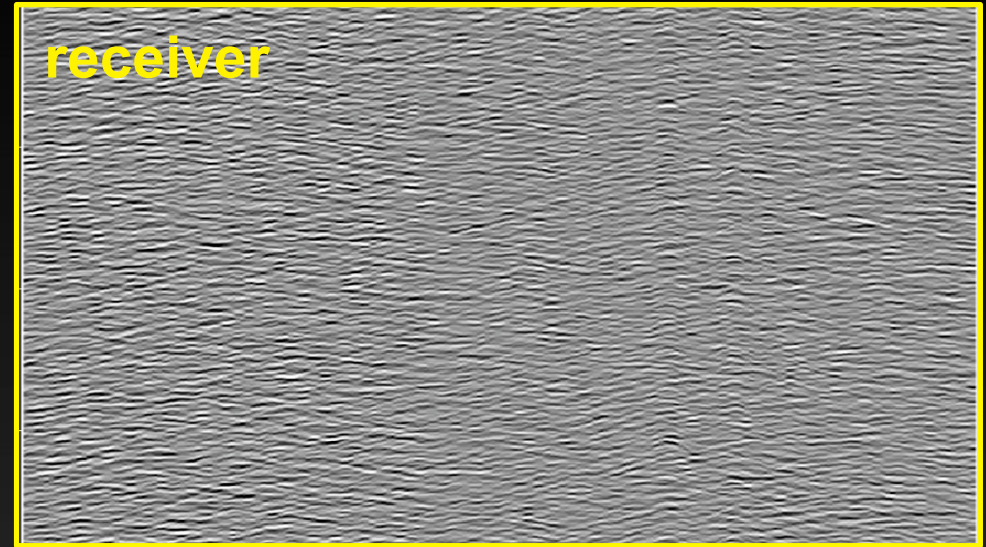
time



distance

receiver

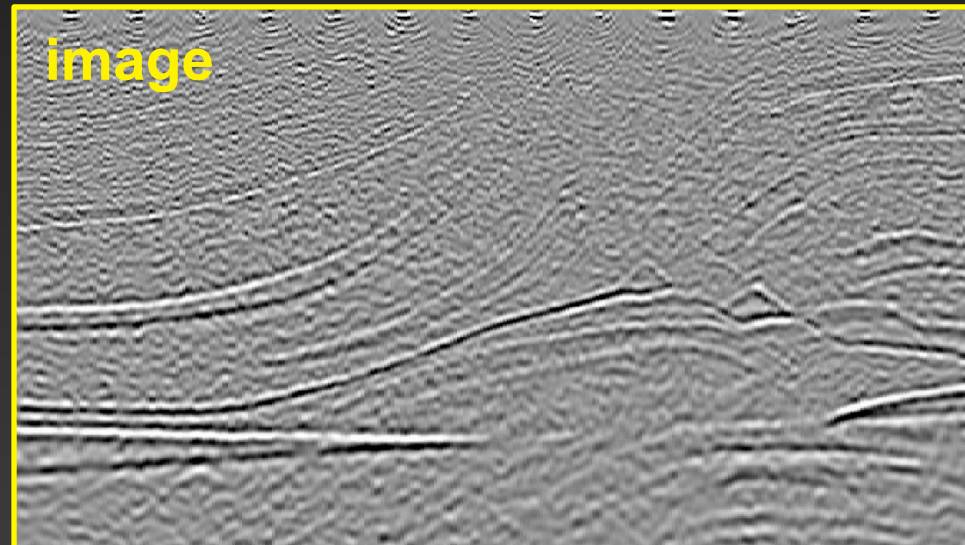
time



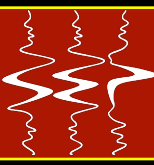
distance

image

depth



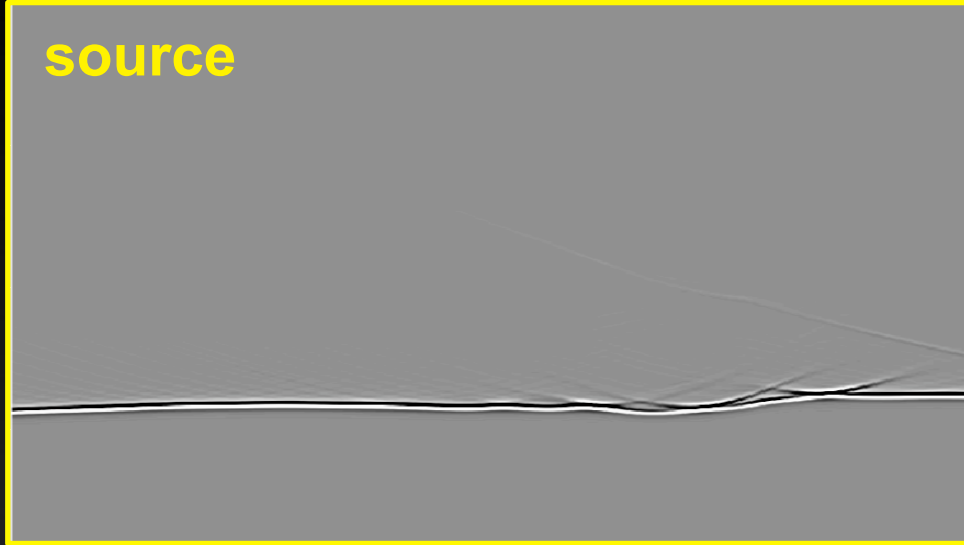
Data-space: controlled illumination



distance

source

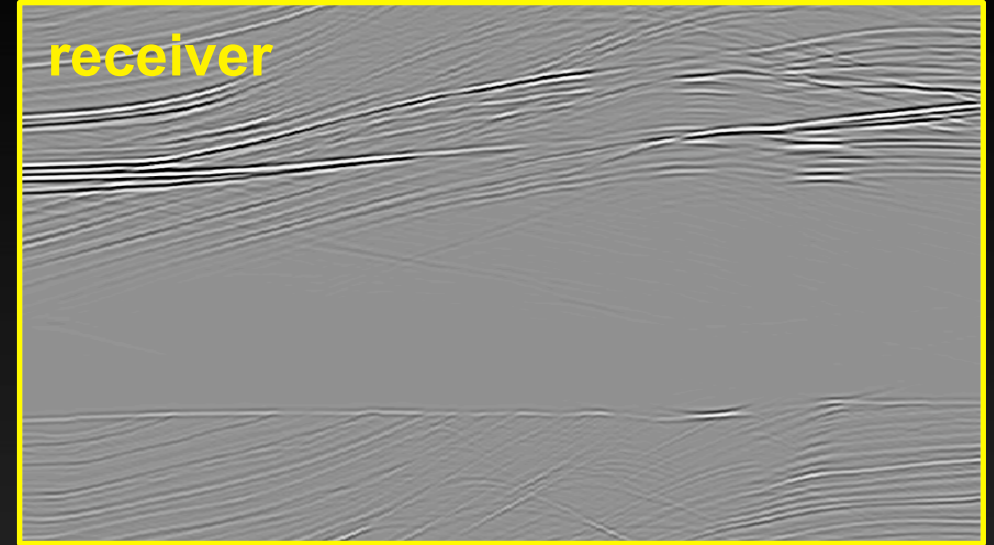
time



distance

receiver

time



distance

image

depth

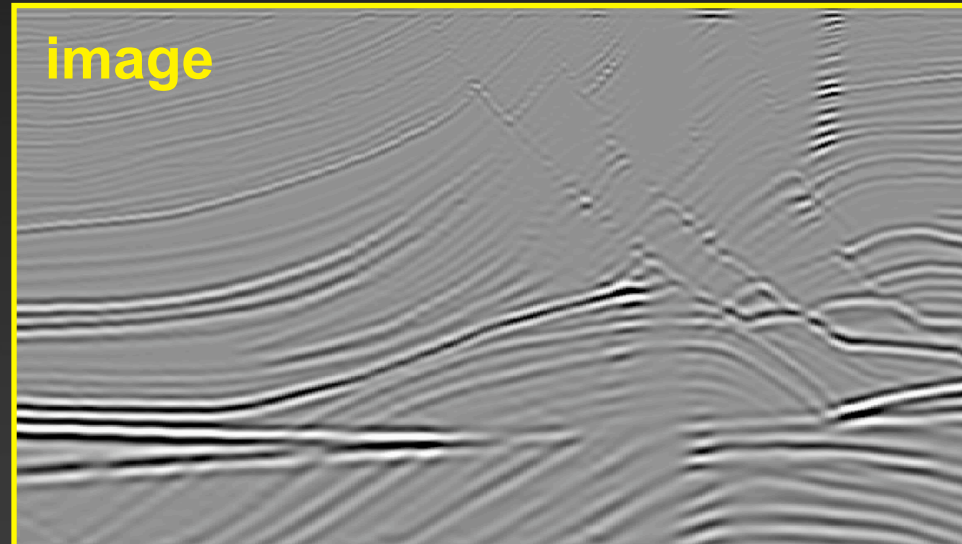


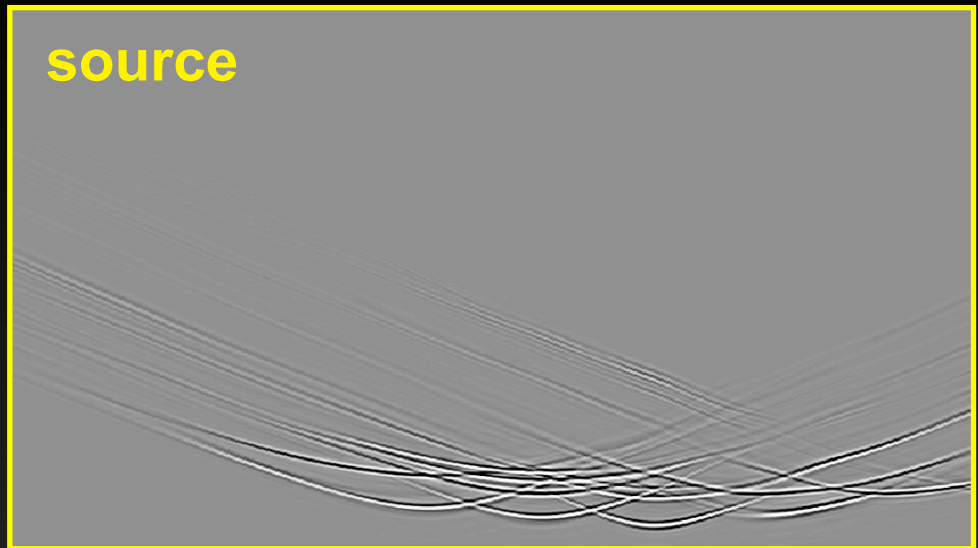
Image-space: prestack-exploding reflector



distance

source

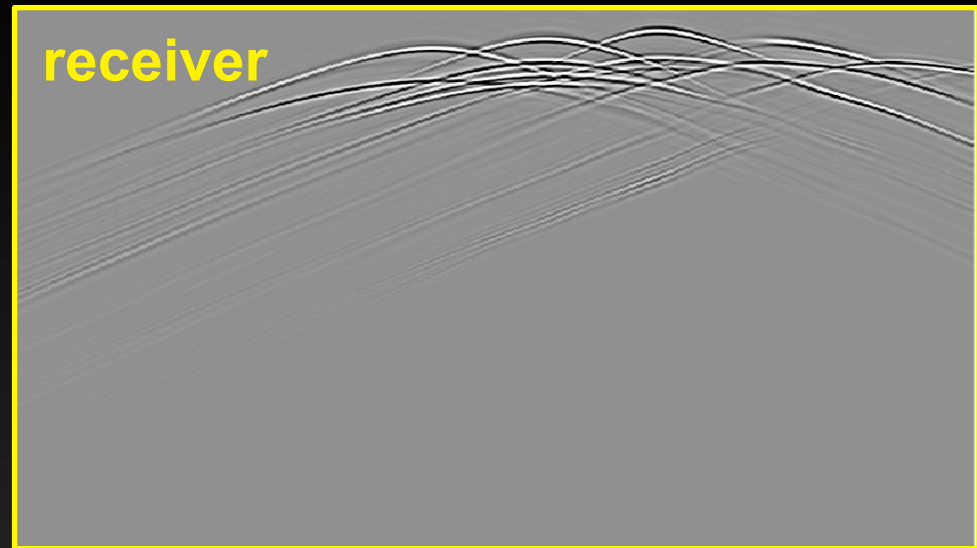
time



distance

receiver

time



distance

image

depth

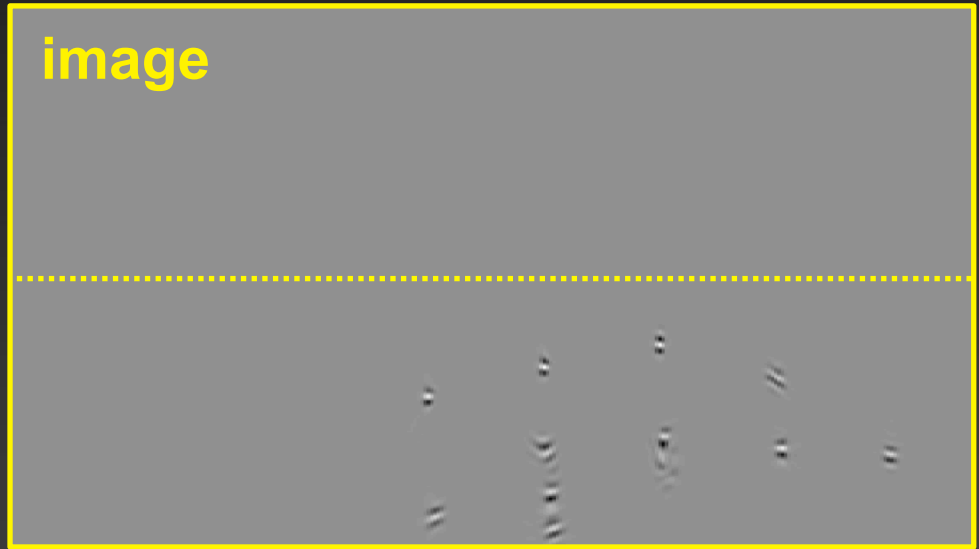
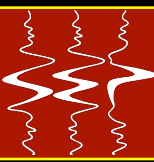


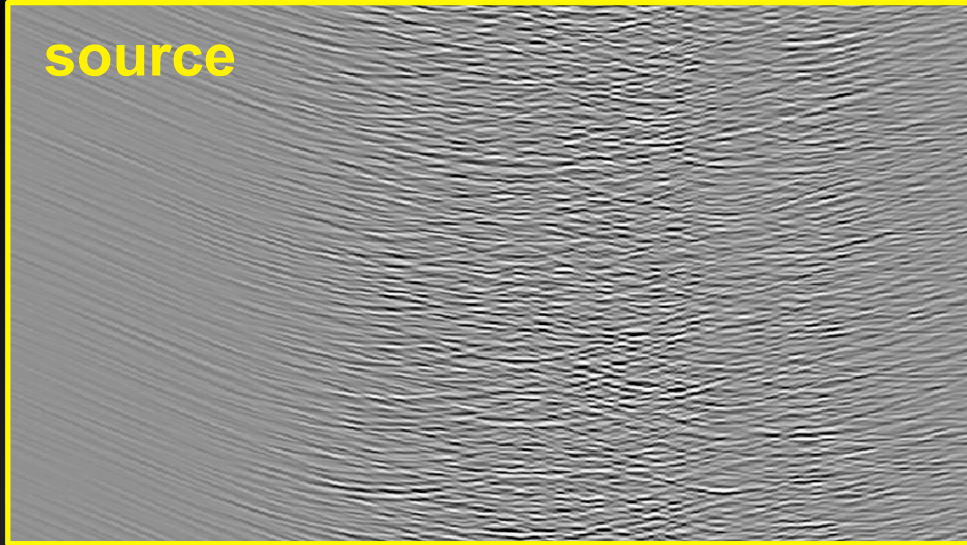
Image-space: random phases (ISPEW)



distance

source

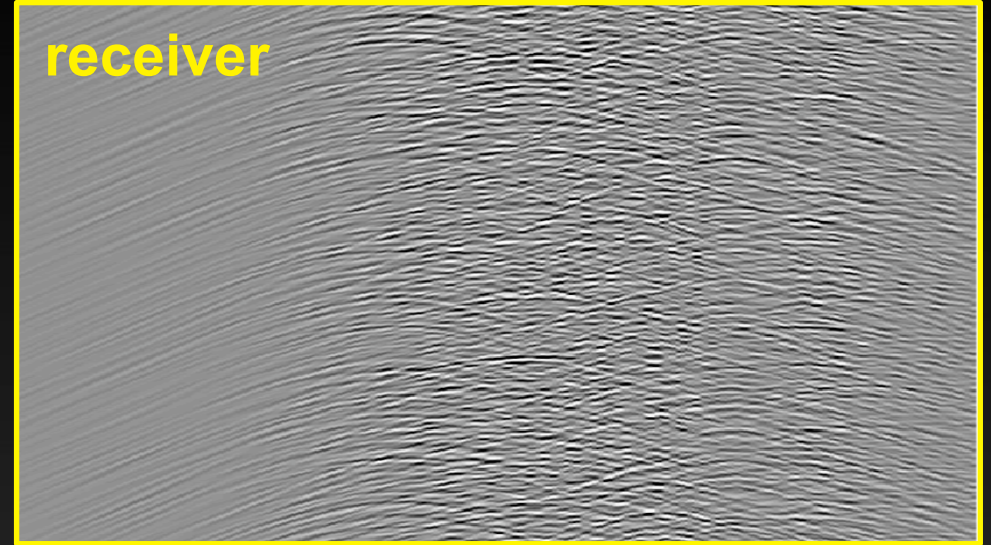
time



distance

receiver

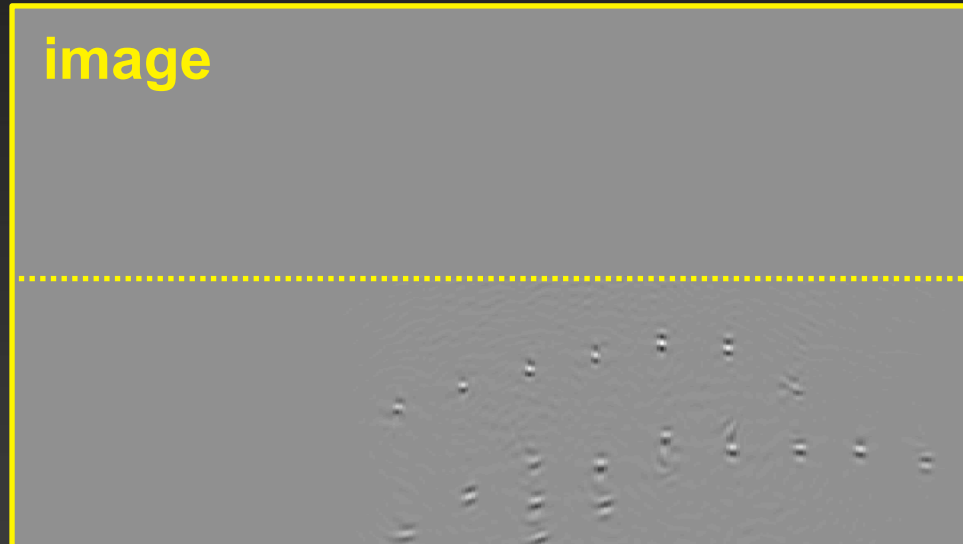
time

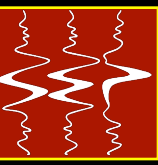


distance

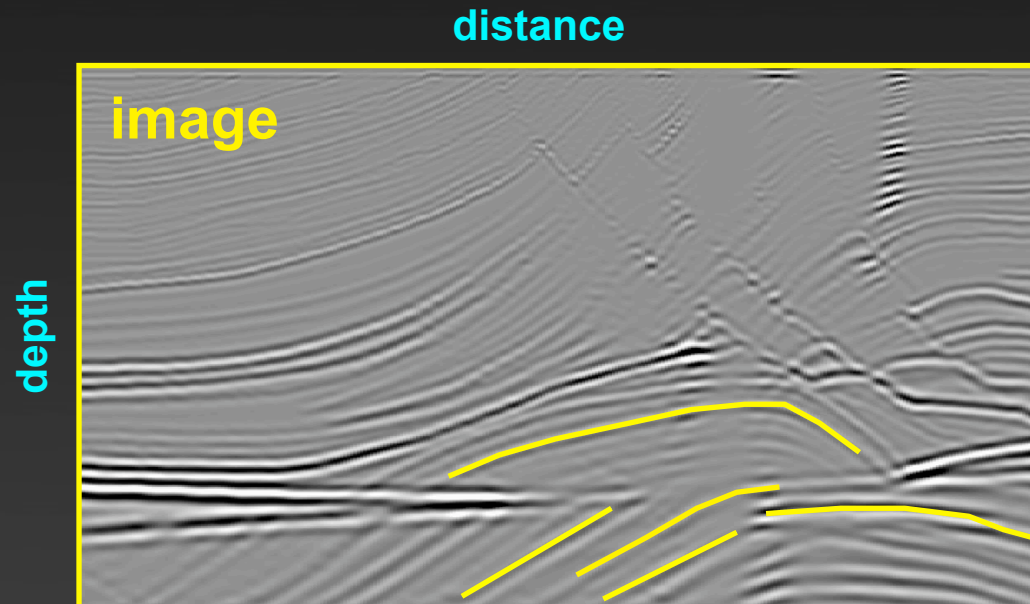
image

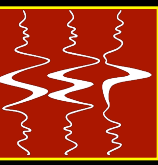
depth





- Models wavefields from selected reflectors

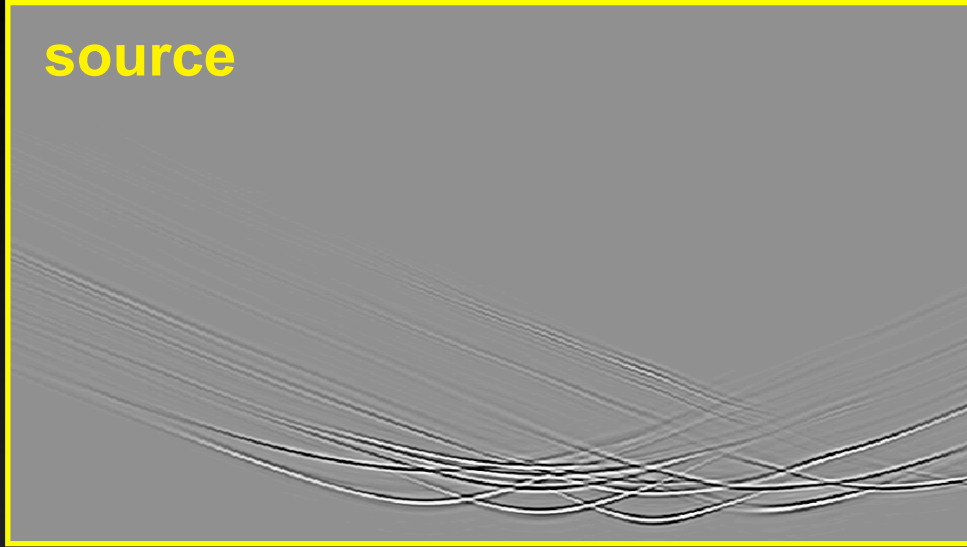




distance

source

time



distance

receiver

time



distance

image

depth

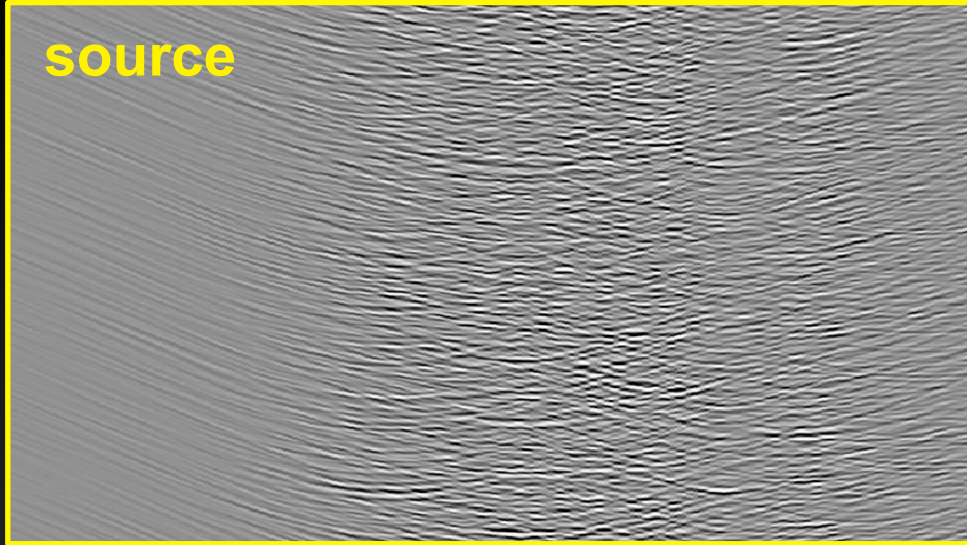




distance

source

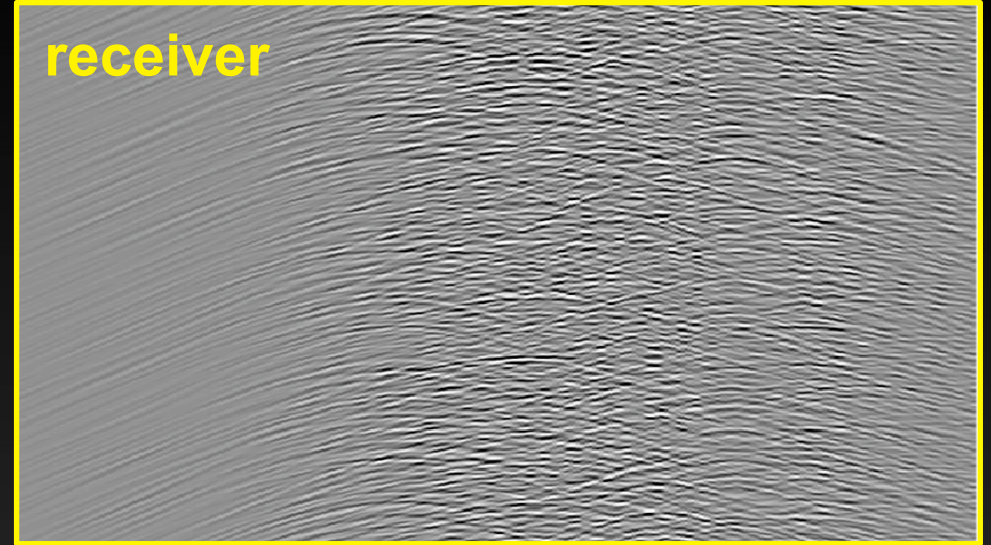
time



distance

receiver

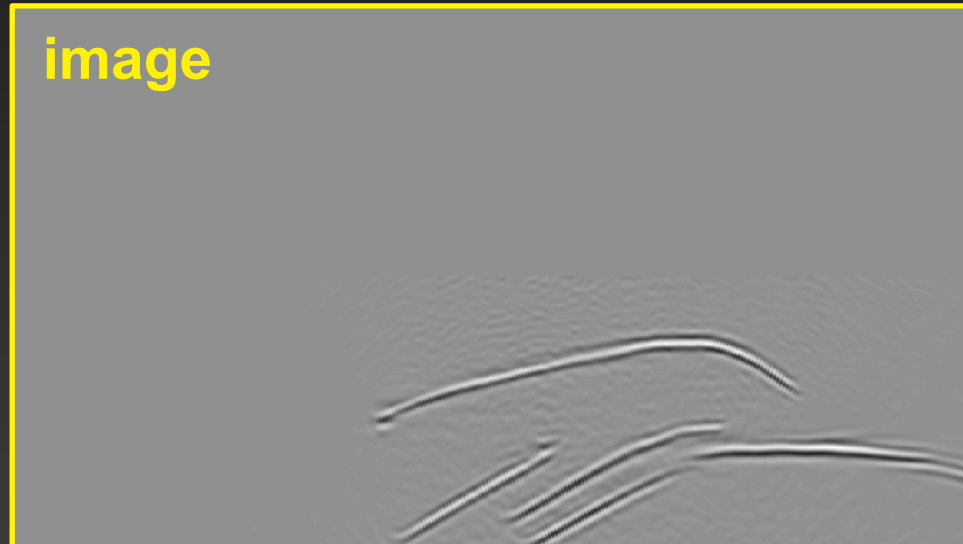
time

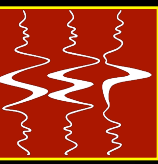


distance

image

depth





Source wavefield

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

Receiver wavefield

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

Λ = SSR operator

\tilde{P}_d = phase encoded source wavefield

\tilde{I}_d = source wavefield initial condition

\mathbf{r}_m = index of random realizations

\tilde{P}_u = phase encoded receiver wavefield

\tilde{I}_u = receiver wavefield initial condition

Image-space phase-encoded wavefields

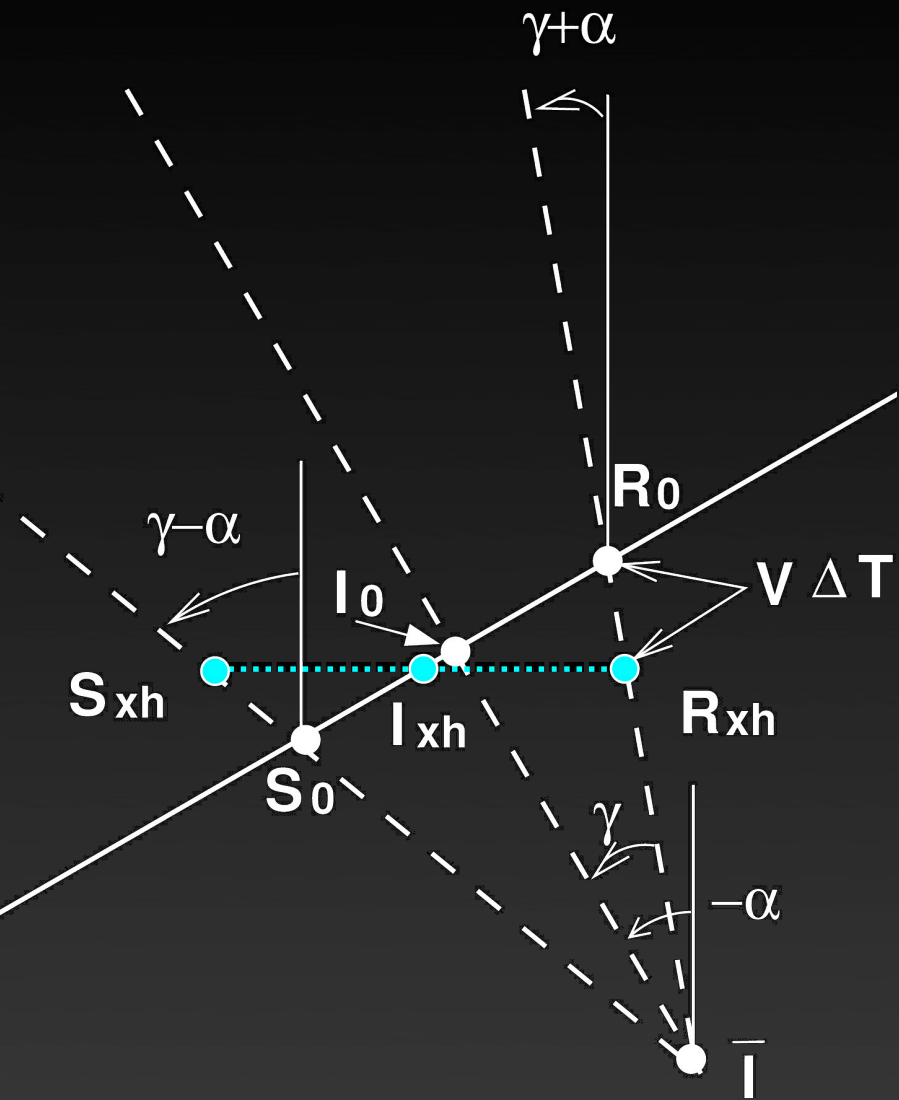
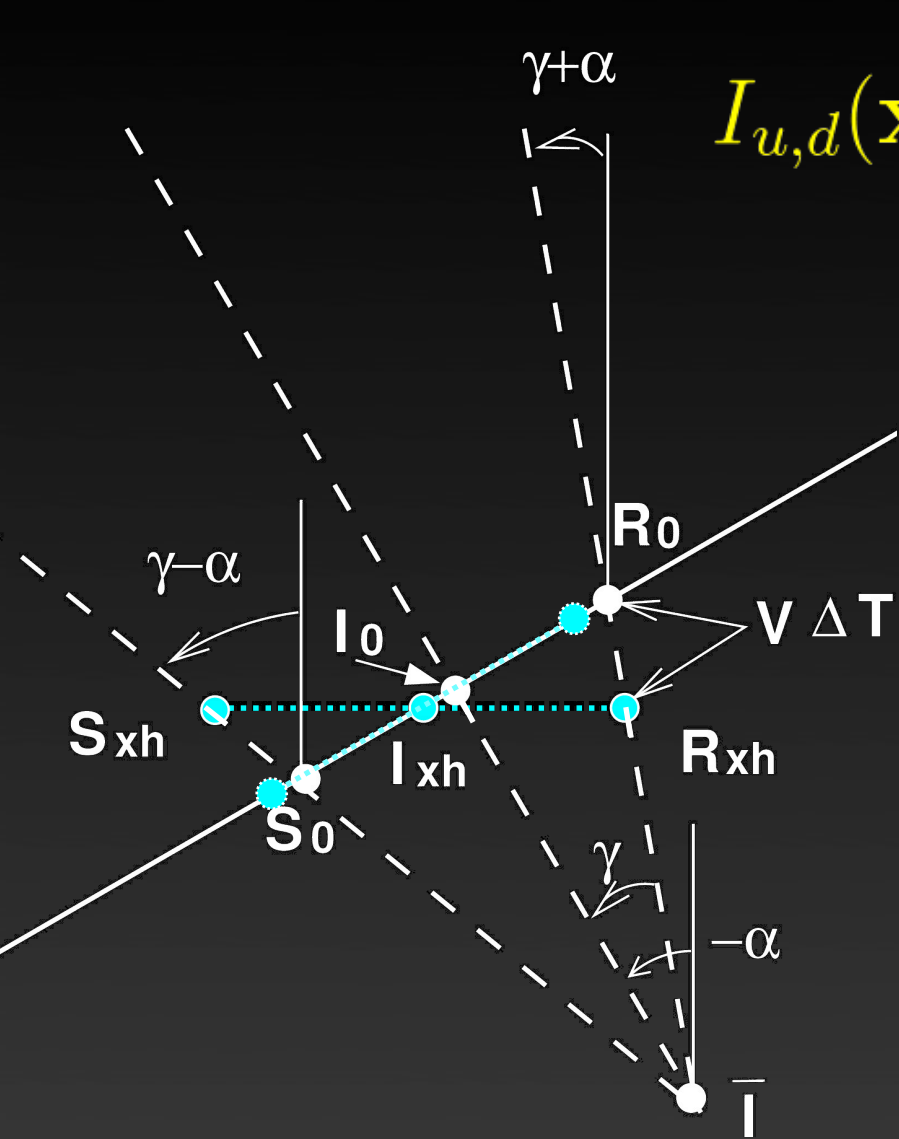
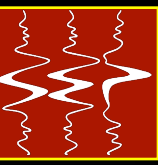


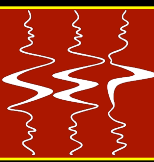
Image-space phase-encoded wavefields



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

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

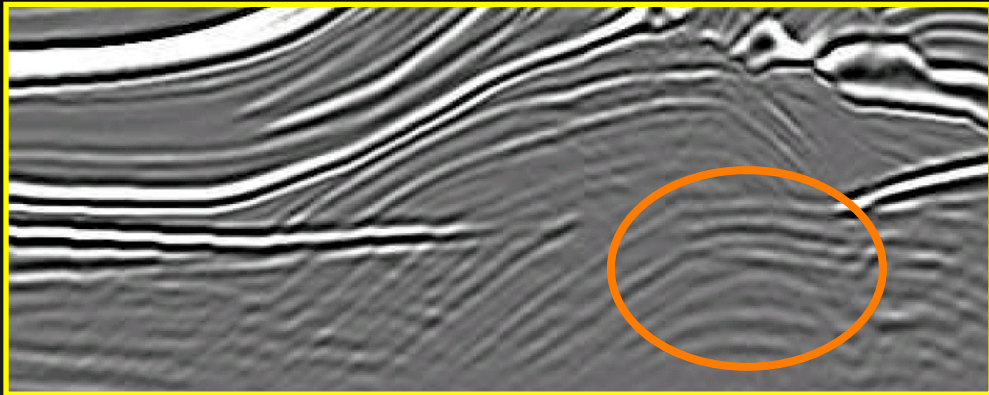
Motivation



Initial

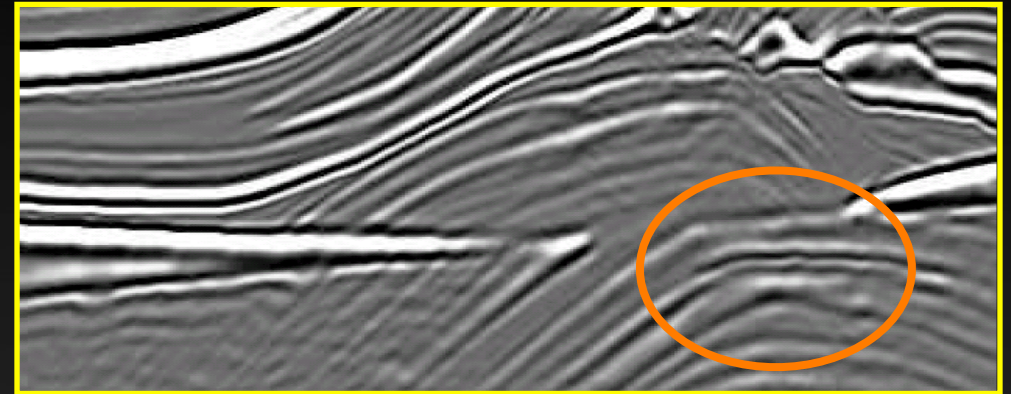
x

z



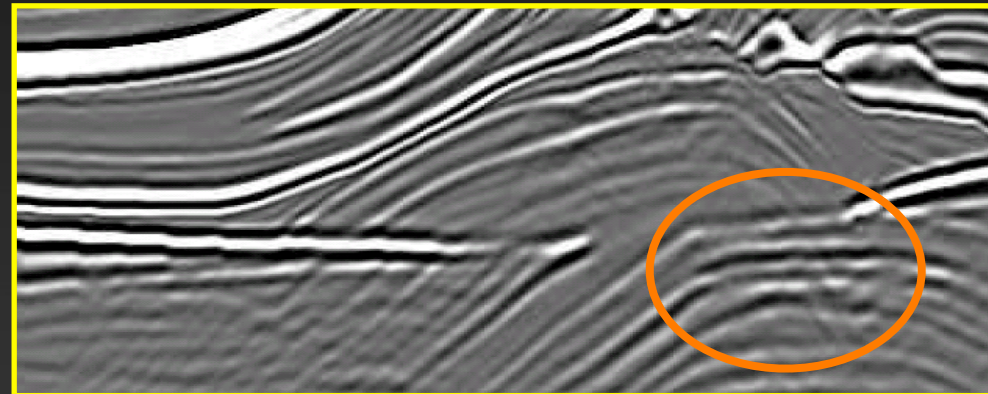
True

x



Optimized

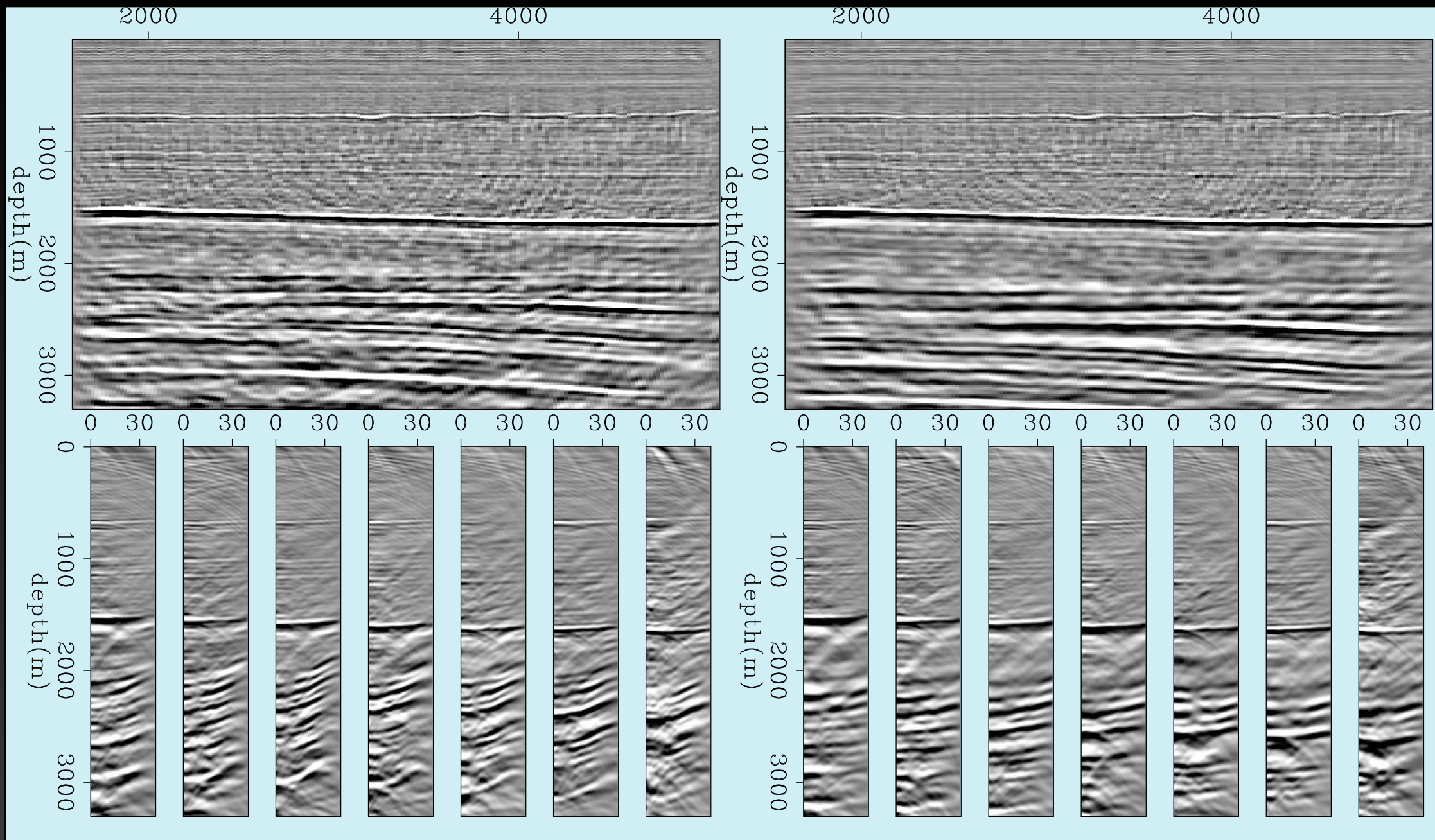
z



20x faster

Initial

Optimized



Initial

Optimized

