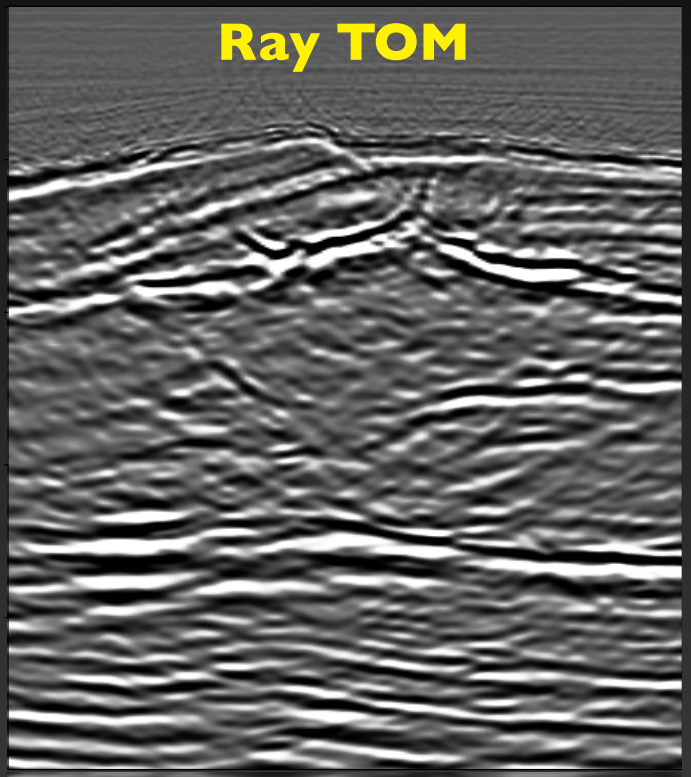
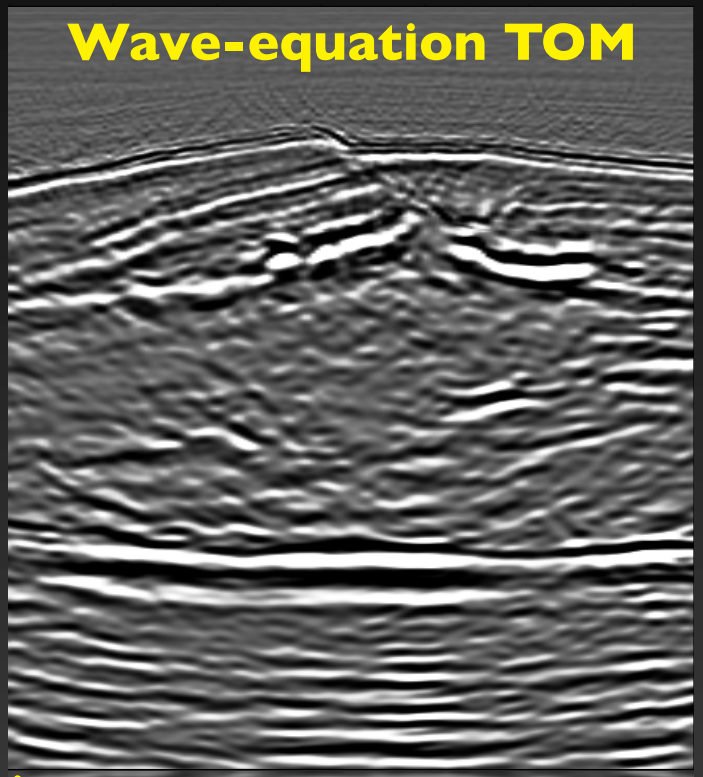
Migration-velocity analysis using image-space generalized wavefields

Claudio Guerra* and Biondo Biondi†





*Petrobras

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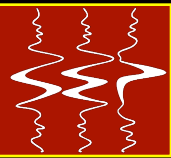
Wave-equation tomography



- **Image space (ISWET)**

$$J(s) = \|\Delta I(s)\|_n$$

$$\Delta I(s) = \mathbf{T}\Delta s$$

s = slowness $\quad$ Δs = slowness perturbation

ΔI = image perturbation $\quad$ $\mathbf{T}$ = tomographic operator

Wave-equation tomography

- **Image space (ISWET)**
  - wave-equation migration-velocity analysis (WEMVA) (Sava and Biondi, 2004)
  - differential-semblance velocity analysis (DSVA) (Shen and Symes, 2008)

For complex geology ...

- **ISWET is more appropriate than ray-based methods**

For complex geology ...

- **ISWET is more appropriate than ray-based methods**

- **Rarely been applied in 3D**
  - **Higher cost and lower flexibility compared to ray-based methods**

3D-ISWET as routine processing

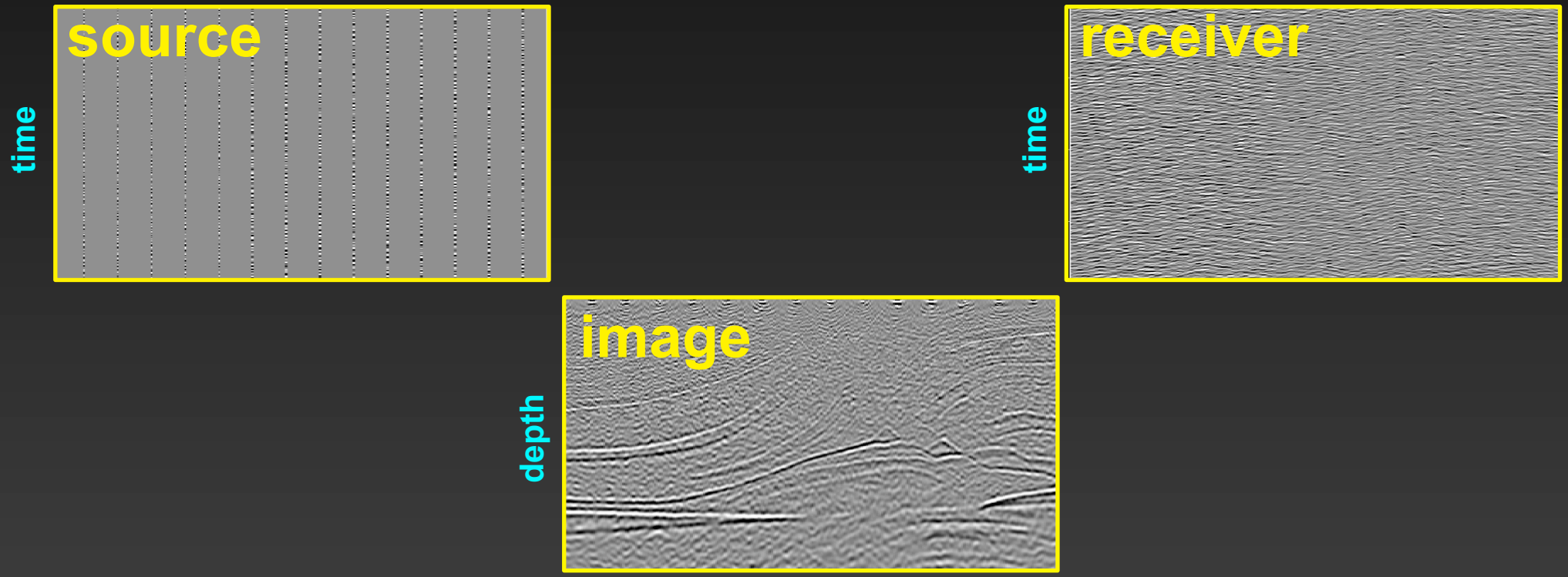
- **Improve flexibility in parameterizing the velocity model**

3D-ISWET as routine processing

- **Improve flexibility in parameterizing the velocity model**
- **Reduce cost**
  - **decrease data size (generalized sources)**

Generalized-source domain

- **Seismic acquisition**
  - Simultaneous sources
- **Seismic processing**
  - plane-wave encoding (Whitmore, 1995)
  - random-phase encoding (Romero et al., 2000)



Generalized-source domain

- **Data-space**
  - plane-wave encoding
  - random-phase encoding

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

Image-space GS domain

- **Decreased data size**
- **Flexible model parametrization**
- **Target-oriented solution**

Agenda

- The prestack exploding-reflector model
- Image-space phase-encoded wavefields
- MVA using image-space generalized sources
- 3D-field data example

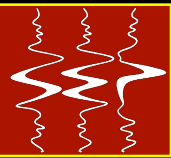
Exploding reflectors

- **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 and complete illumination**

Prestack-exploding reflector



- **Generalizes the exploding-reflector model**
  - **A prestack image computed with wavefield-extrapolation methods is used, allowing propagation of unfocused energy**

Prestack-exploding reflector

- **Generalizes the exploding-reflector model**
  - **A prestack image computed with wavefield-extrapolation methods is used, allowing propagation of unfocused energy**

- **Uses selected reflectors as the initial conditions**
  - **Naturally incorporates a horizon-based tomography strategy into wave-extrapolation methods for velocity update**

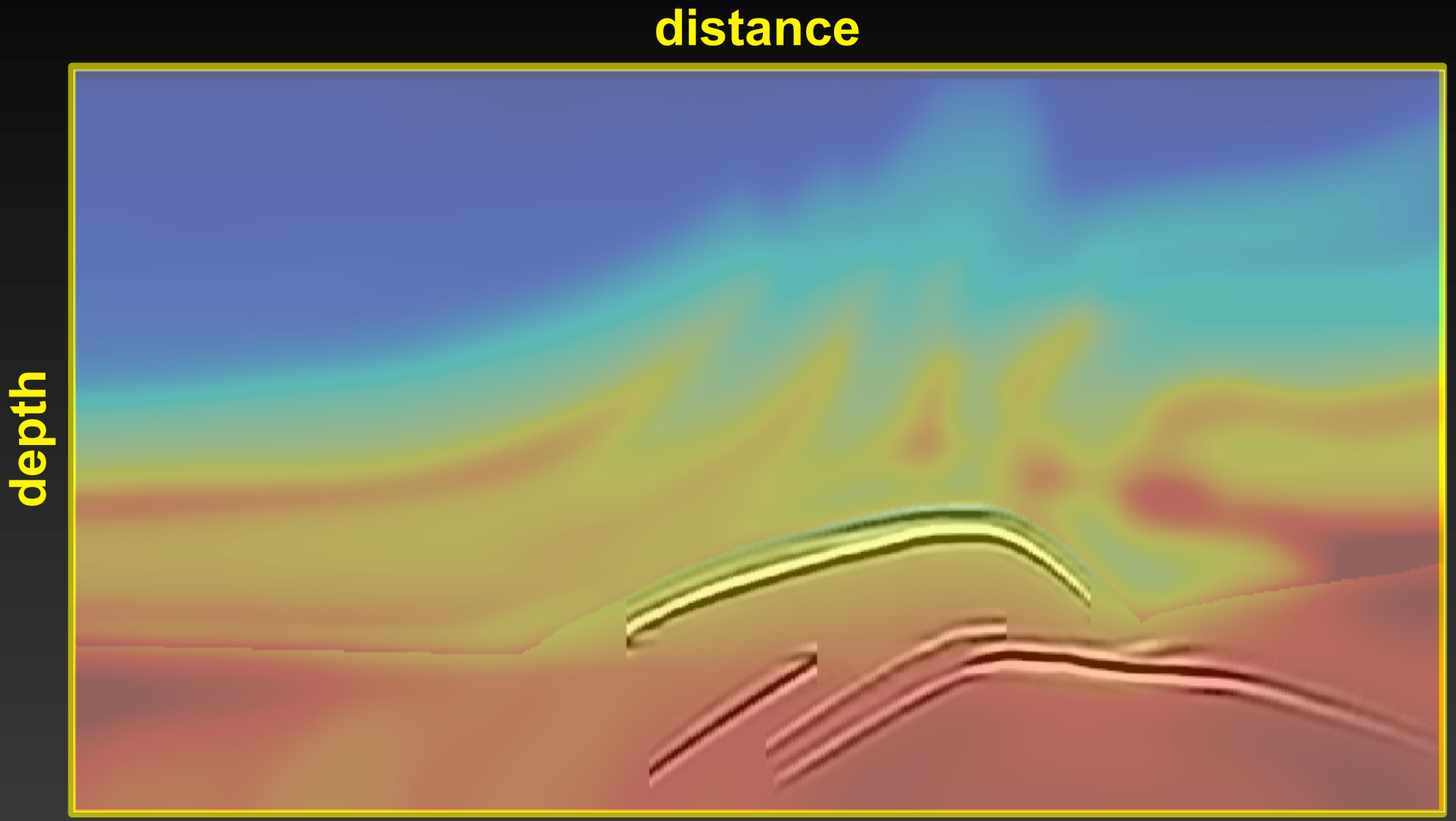
Prestack-exploding reflector

- **One-way wave equation**

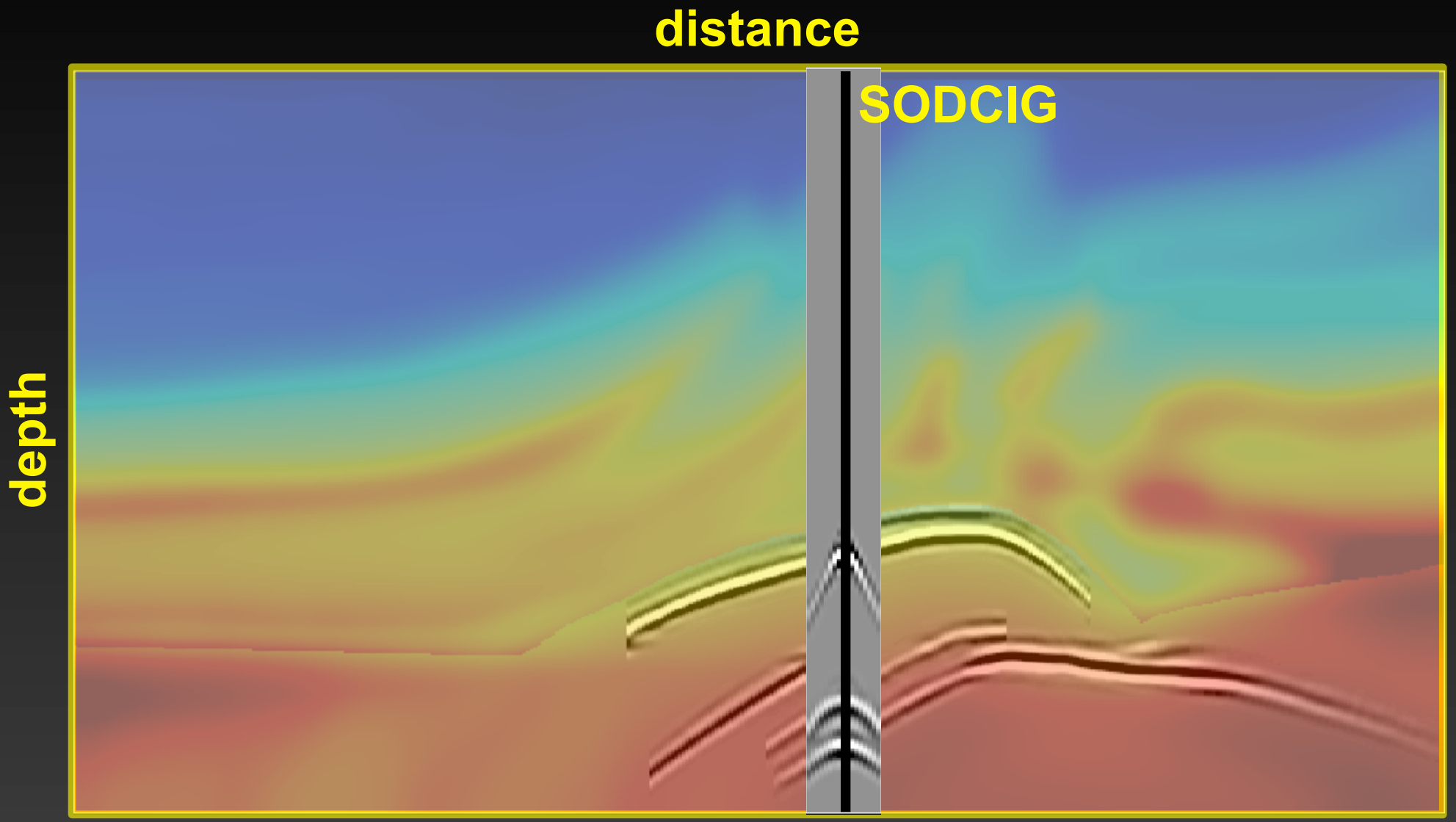
$$\begin{cases} (\frac{\partial}{\partial z} \pm i\Gamma) P^{\mp}(\mathbf{x}, \omega; \mathbf{x_m}) = I^{\mp}(\mathbf{x_m}, \mathbf{h}) \\ P^{\mp}(x, y, z = z_{max}, \omega; \mathbf{x_m}) = 0 \end{cases}$$

$$\Gamma = \sqrt{(\omega s_o)^2 - |\mathbf{k}|^2}$$

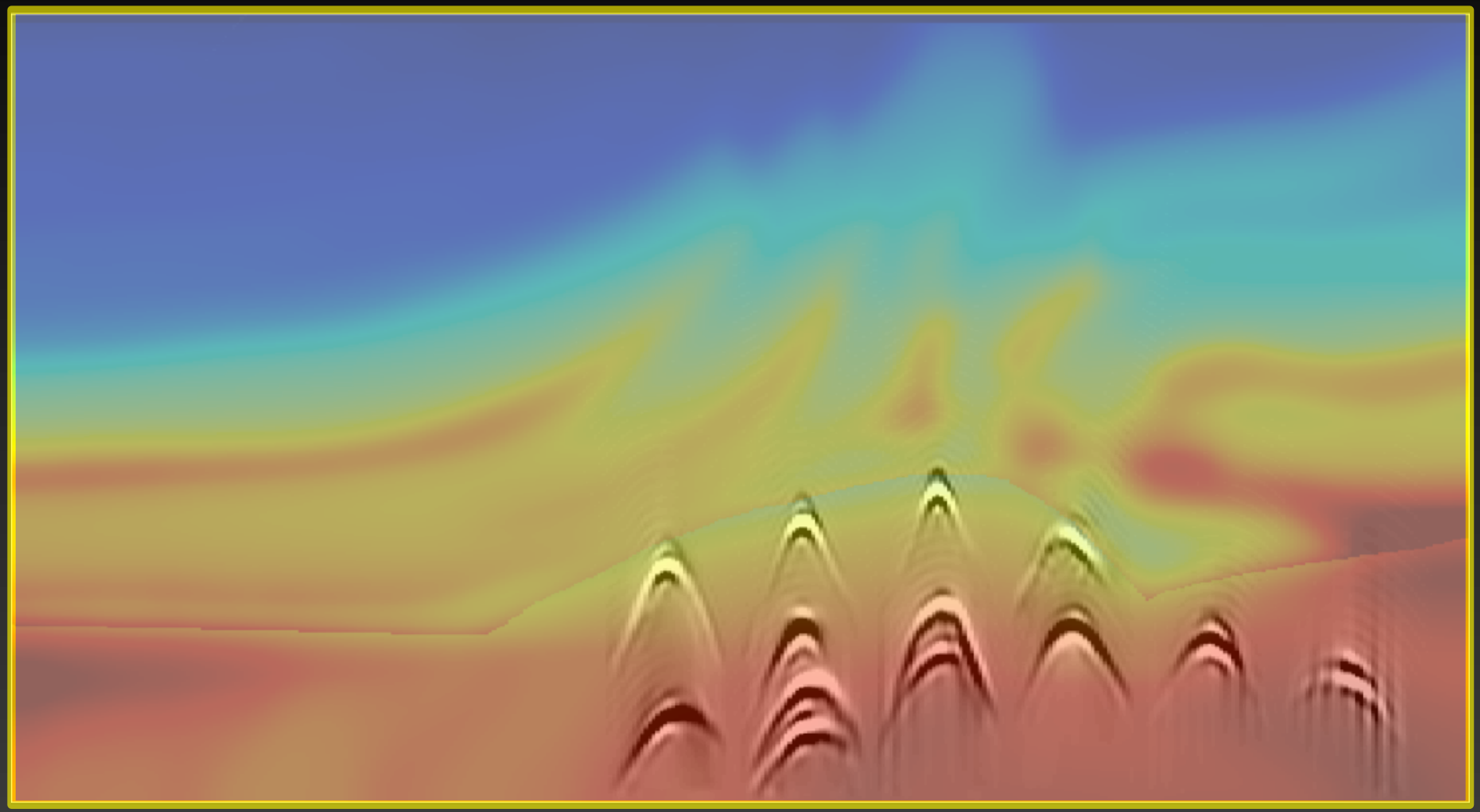
Select key reflectors



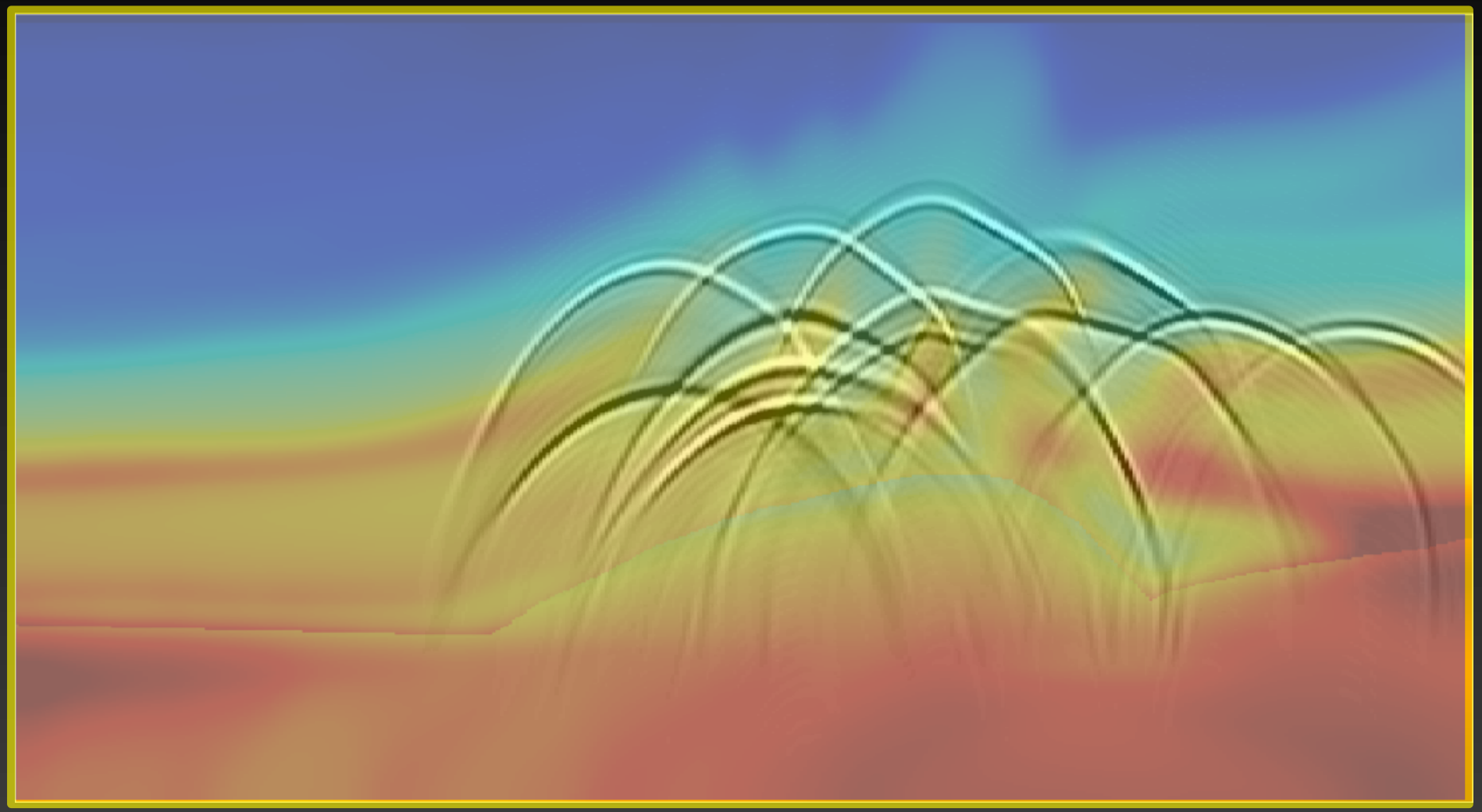
Project the offset axis



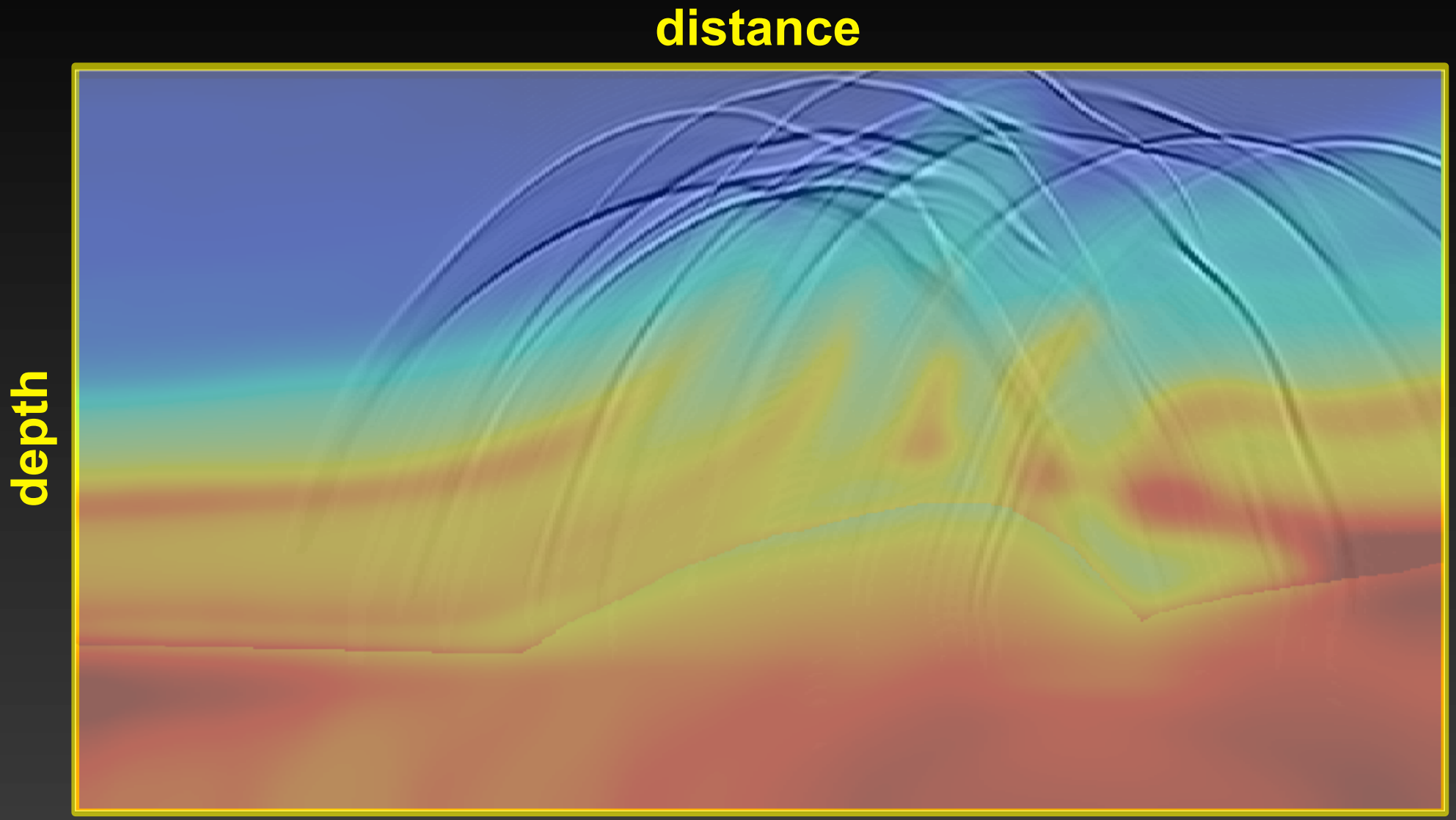
Combine CIGs



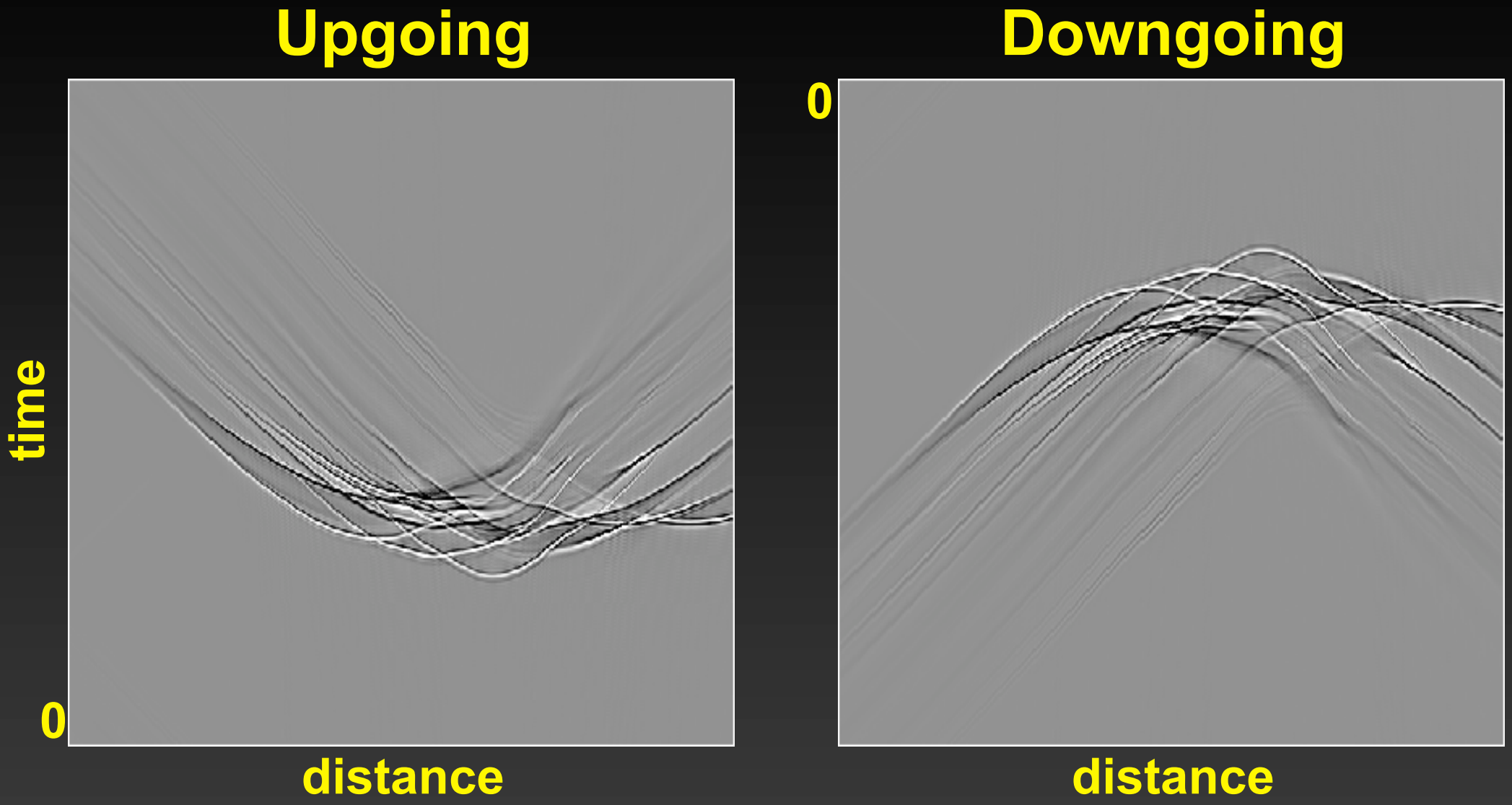
Extrapolate wavefields



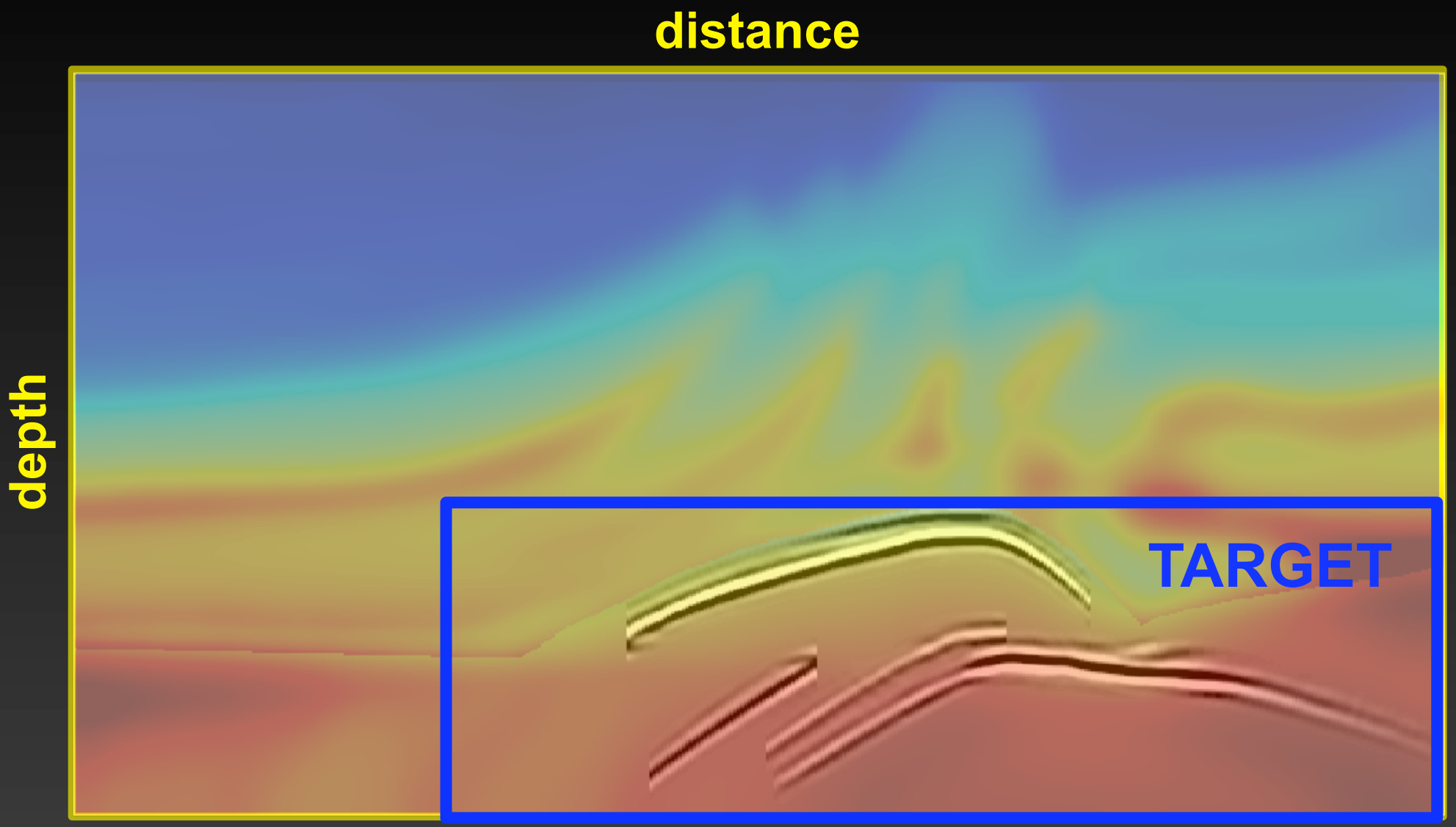
Extrapolate wavefields



Collect wavefields

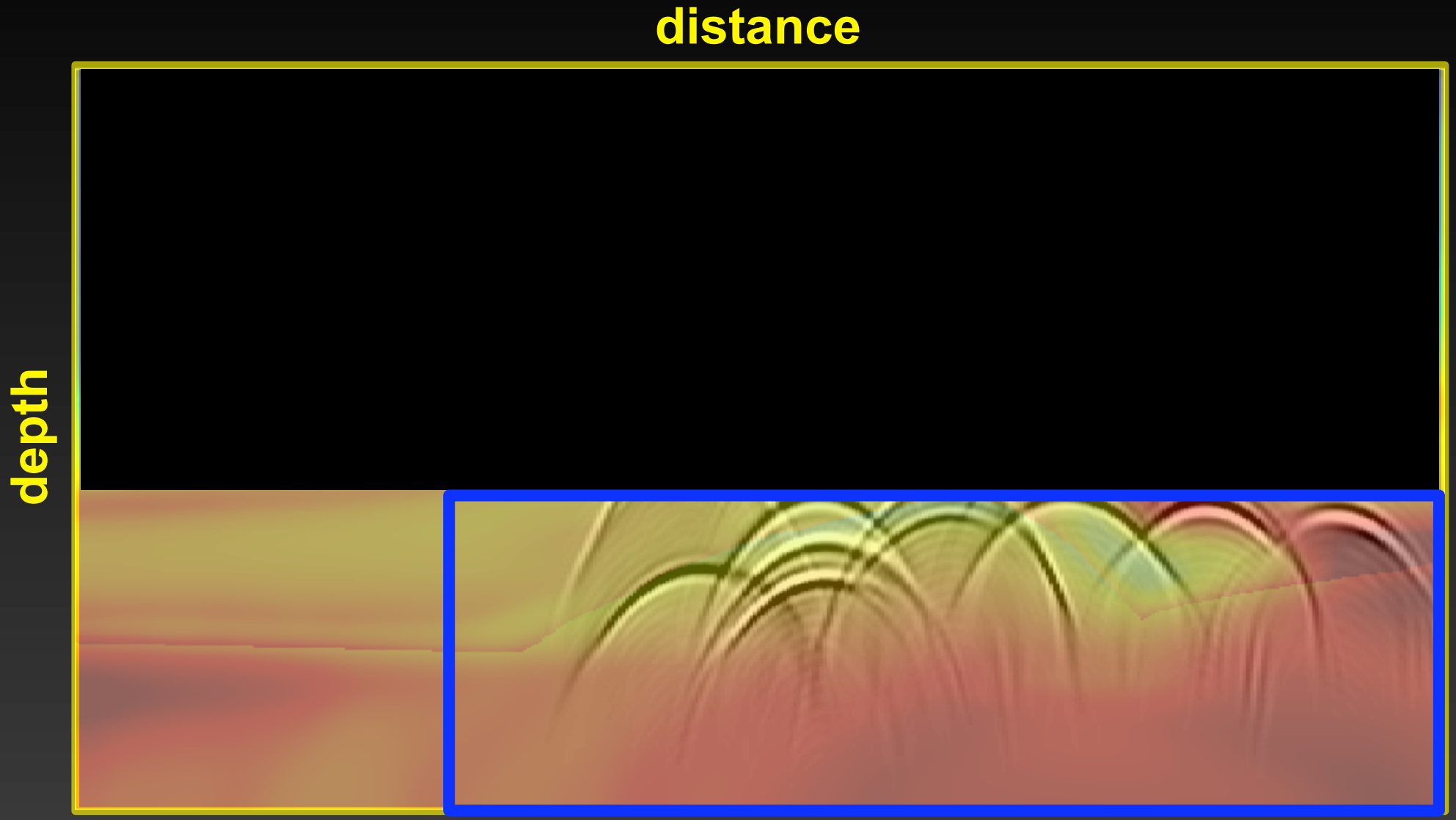


Target-oriented strategy



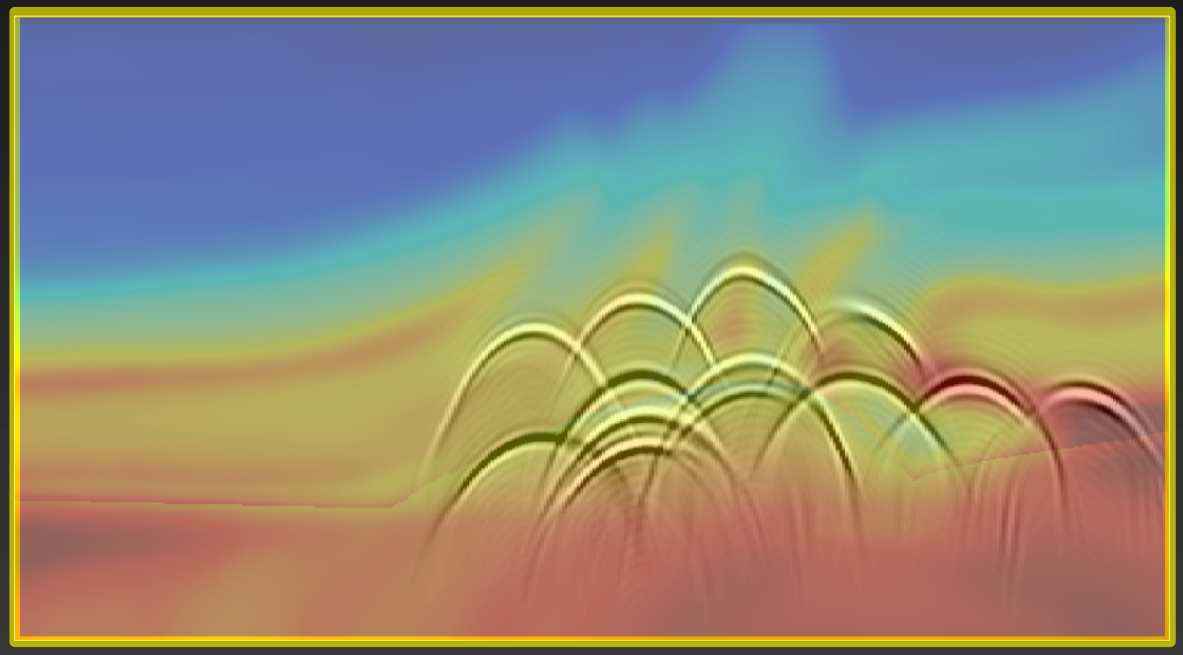
Target-oriented strategy

Wavefields are collected at the top of the target

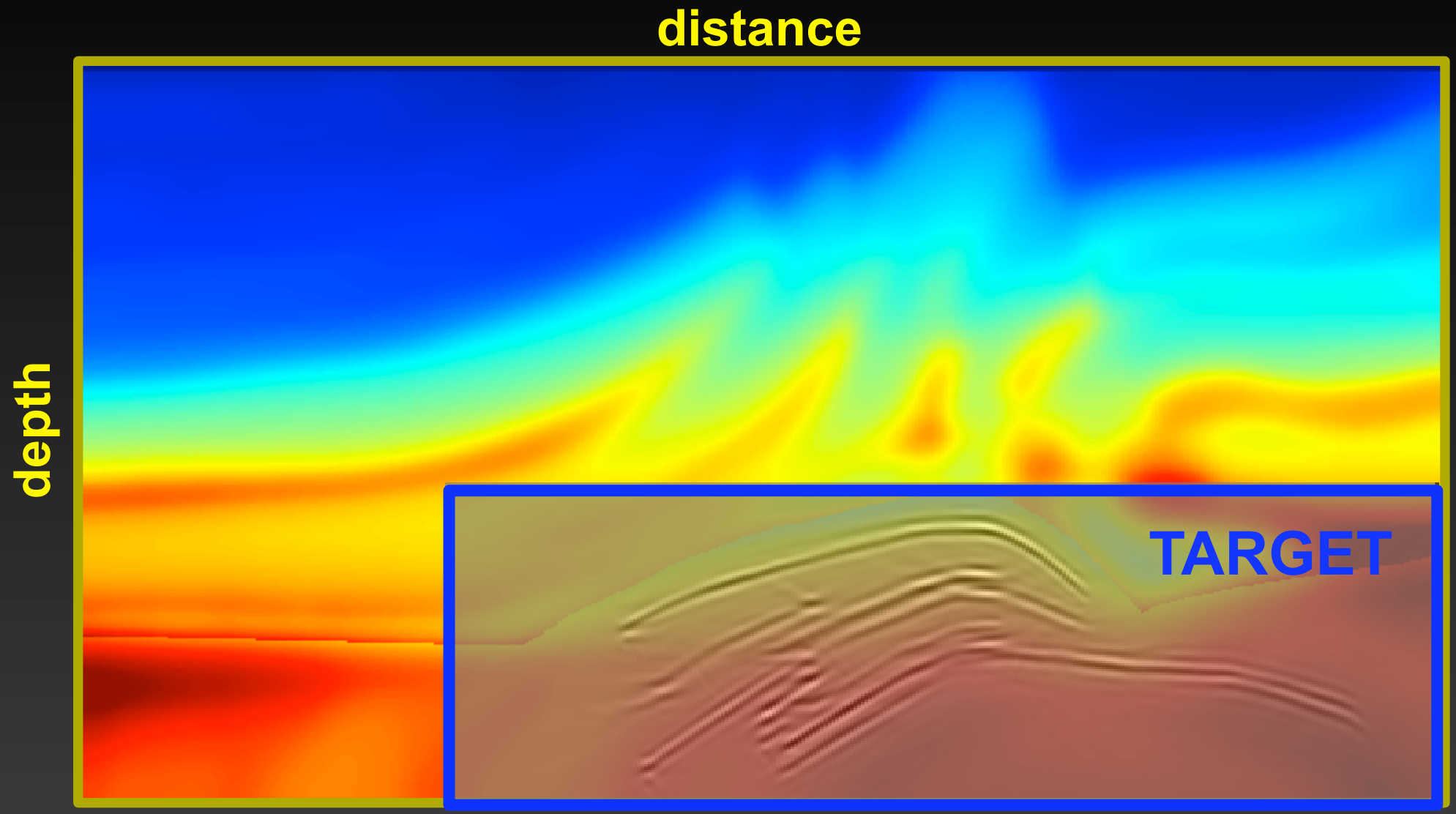


To avoid crosstalk during migration

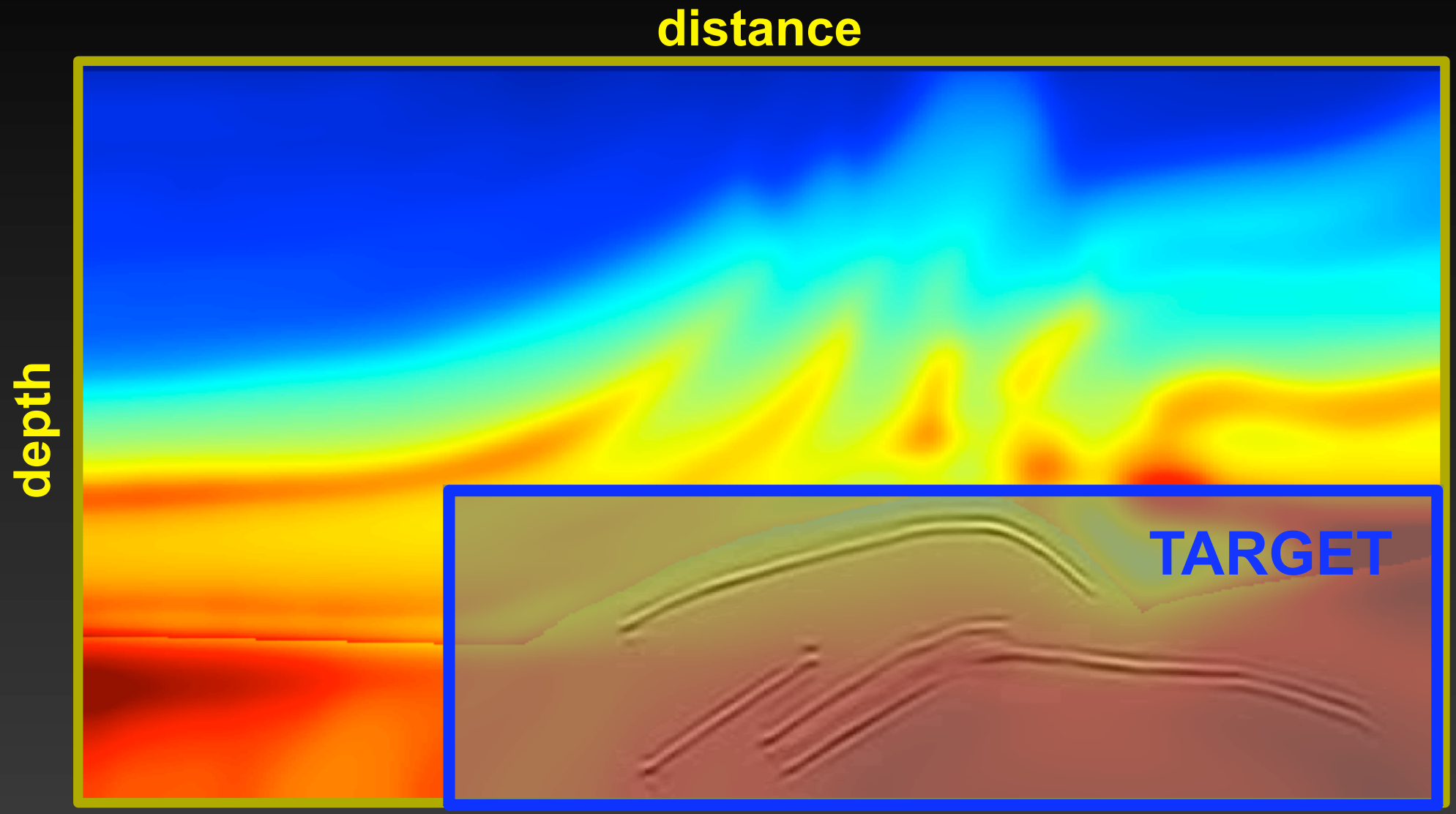
- **Decorrelation distance between SODCIGs**
- **Time-windowed imaging condition**



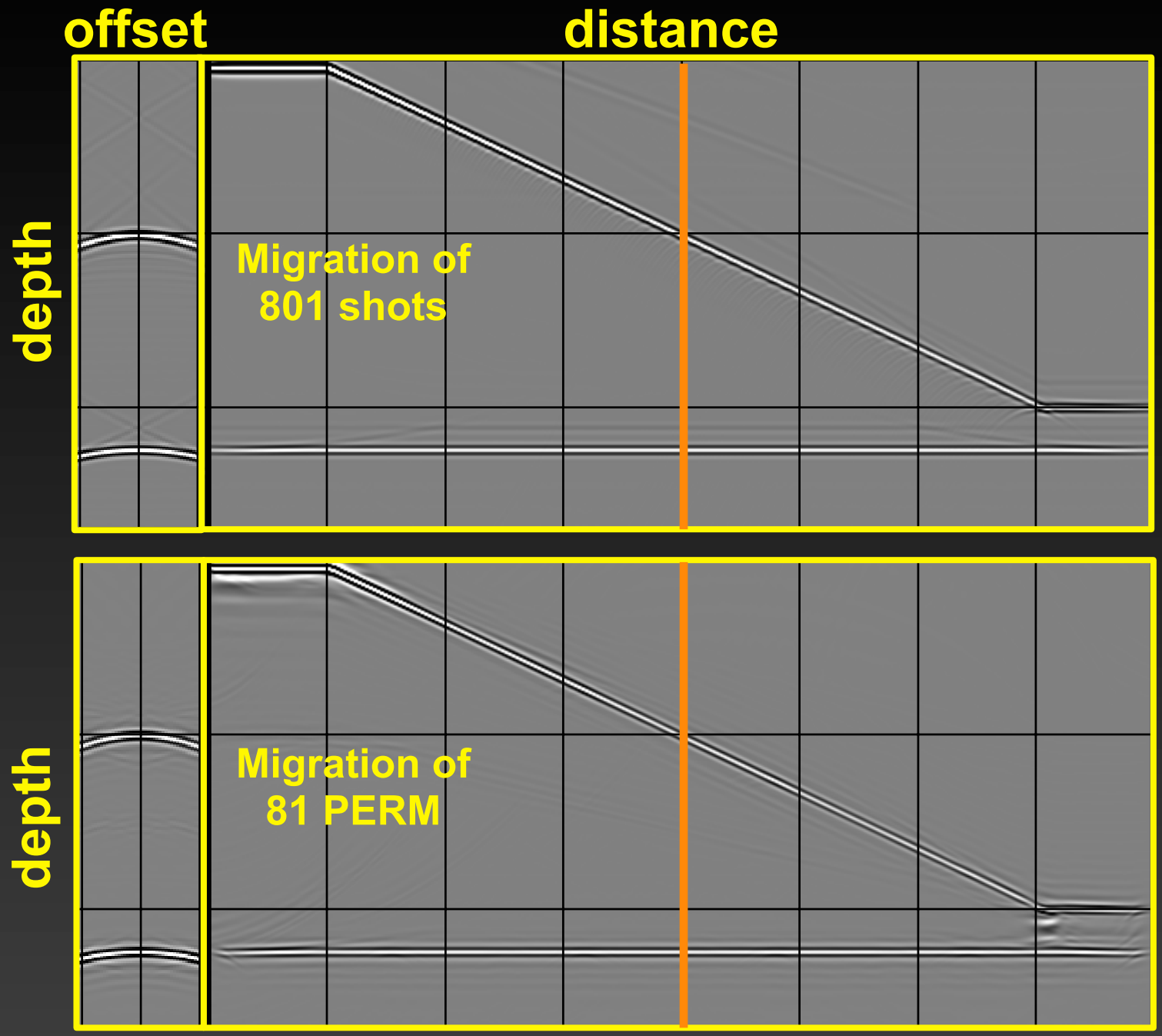
Crosstalk between reflectors



Using time-windowed IC



Correct kinematics



Agenda

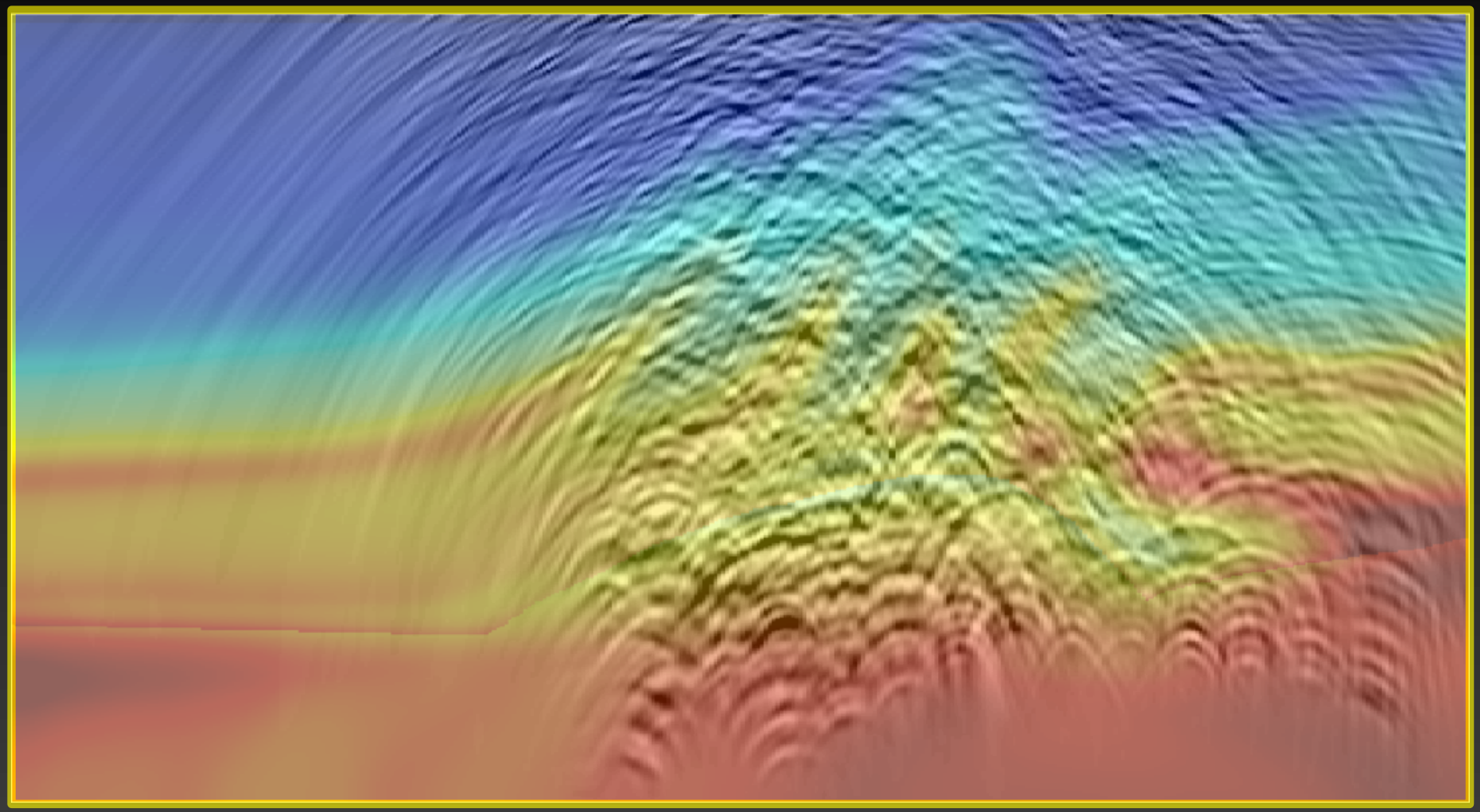
- ✓ The prestack exploding-reflector model
- **Image-space phase-encoded wavefields**
- MVA using image-space generalized sources
- 3D-field data example

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

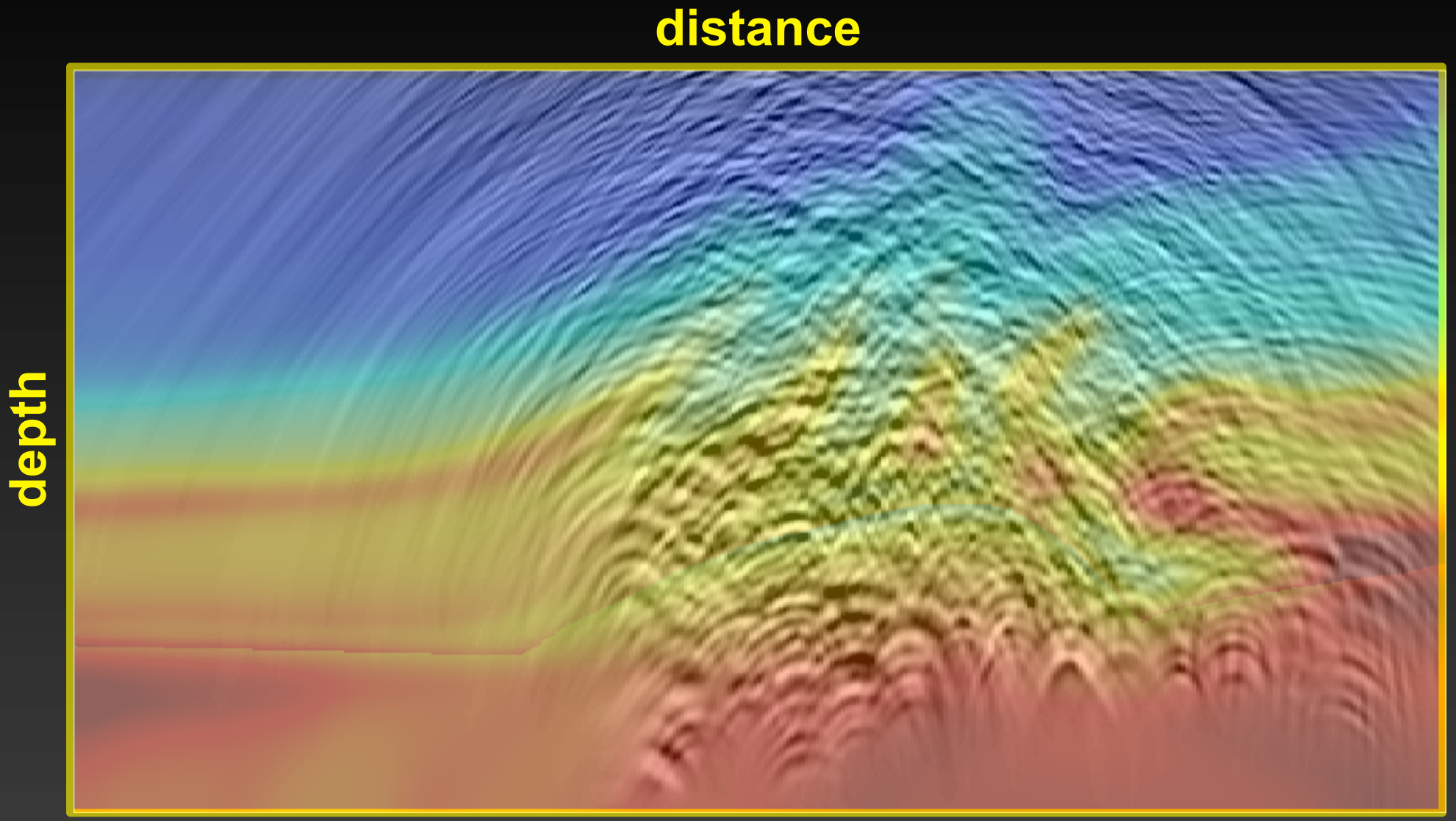
$$\begin{cases} (\frac{\partial}{\partial z} \pm i\Gamma)\widetilde{P}^{\mp}(\mathbf{x}, \mathbf{q}, \omega; \mathbf{x_m}) = \widetilde{I}^{\mp}(\mathbf{x_m}, \mathbf{h}, \mathbf{q}, \omega) \\ \widetilde{P}^{\mp}(x, y, z = z_{max}, \mathbf{q}, \omega; \mathbf{x_m}) = 0 \end{cases}$$

$$\widetilde{I}^{\mp}(\mathbf{x_m}, \mathbf{h}, \mathbf{q}, \omega) = e^{i\epsilon(\mathbf{x_m}, \mathbf{q}, \omega)} I^{\mp}(\mathbf{x_m}, \mathbf{h})$$

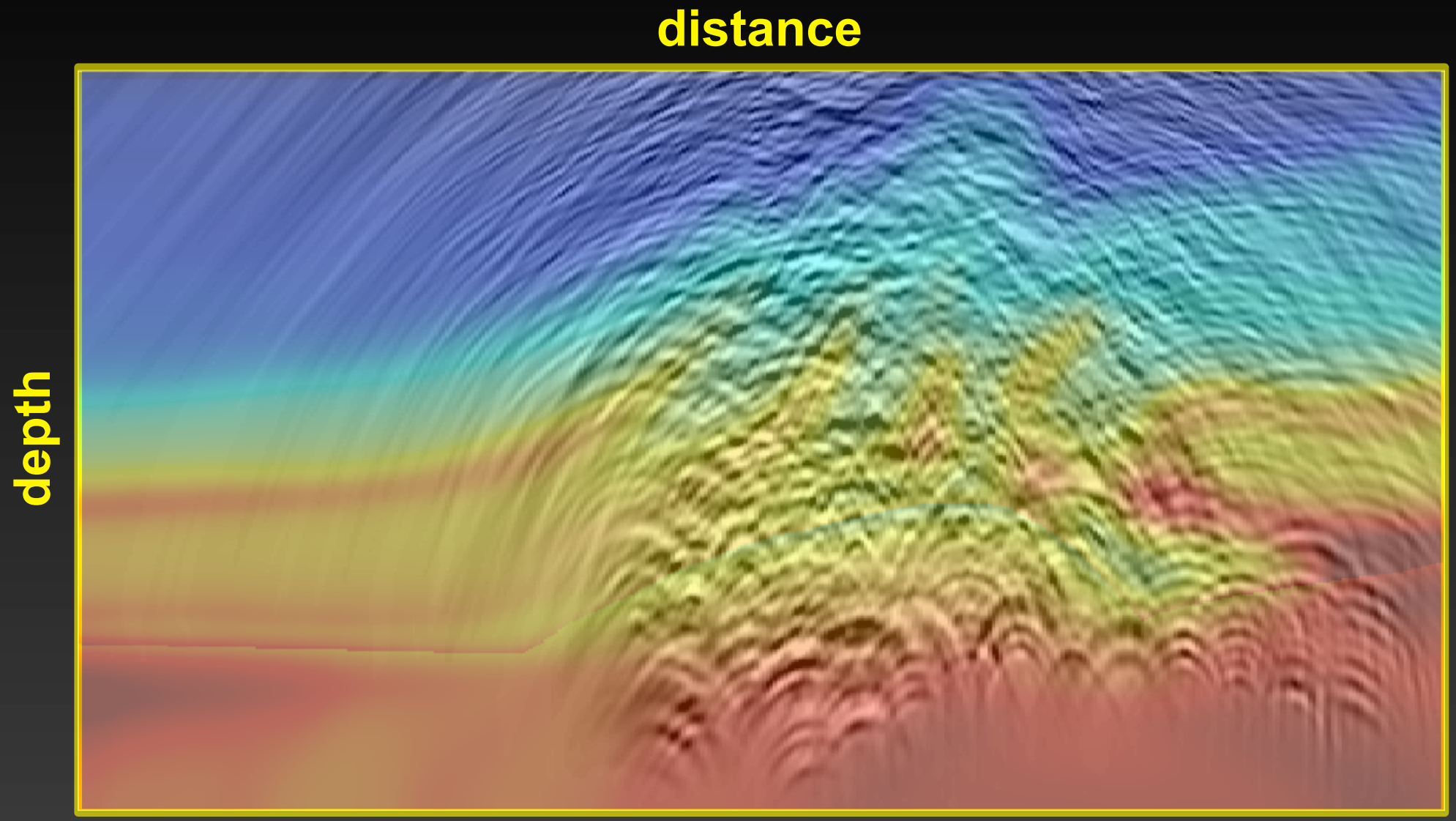
Combine phase-encoded CIGs



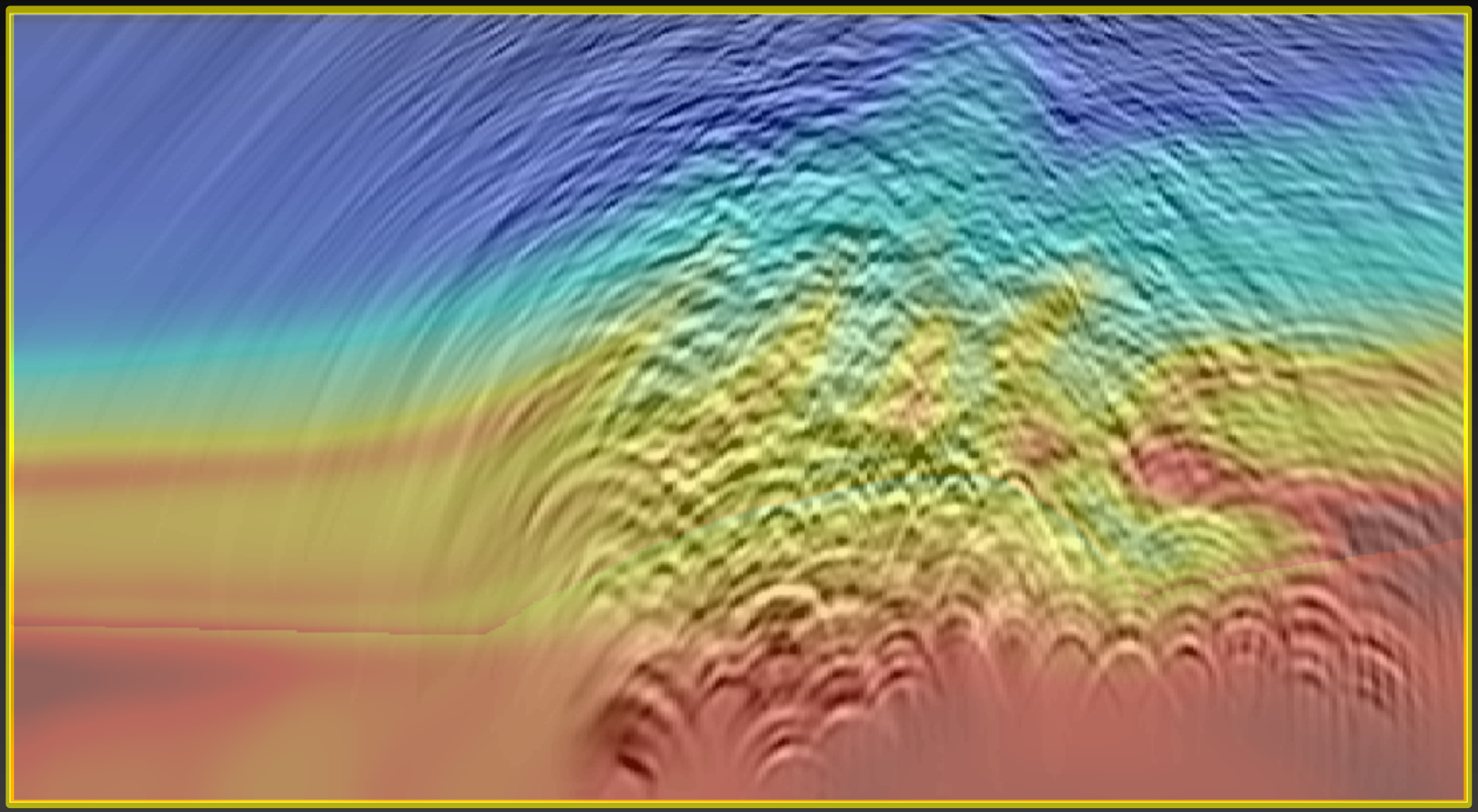
Extrapolate wavefields



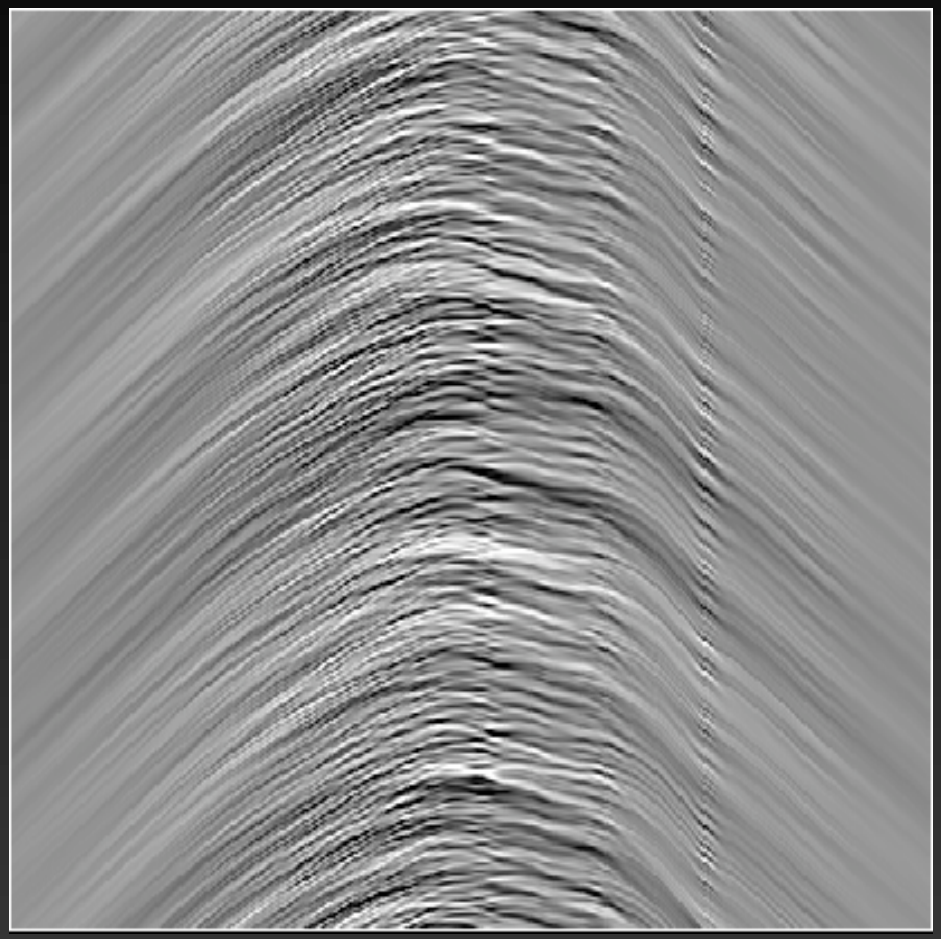
Extrapolate wavefields



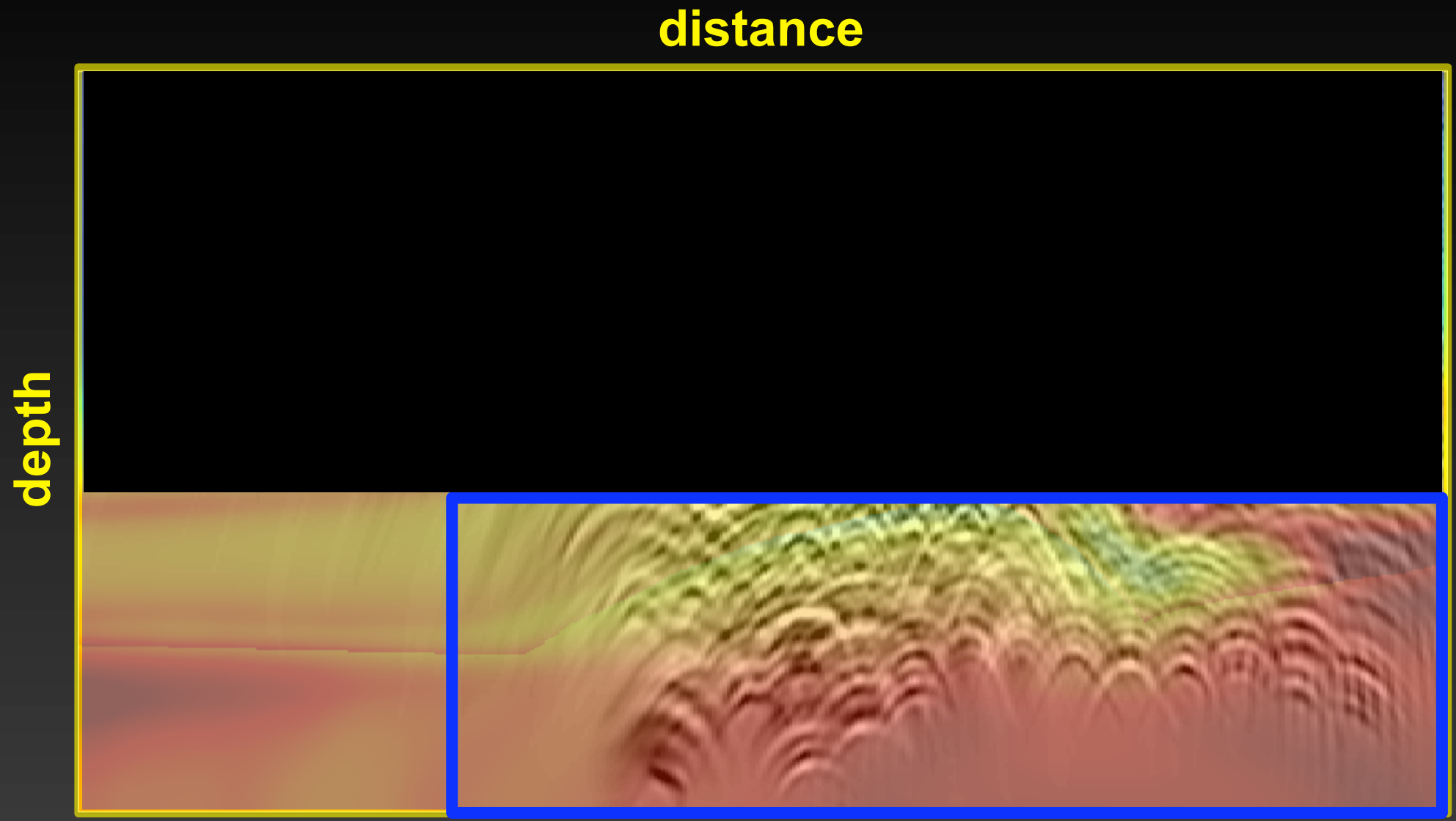
Extrapolate wavefields



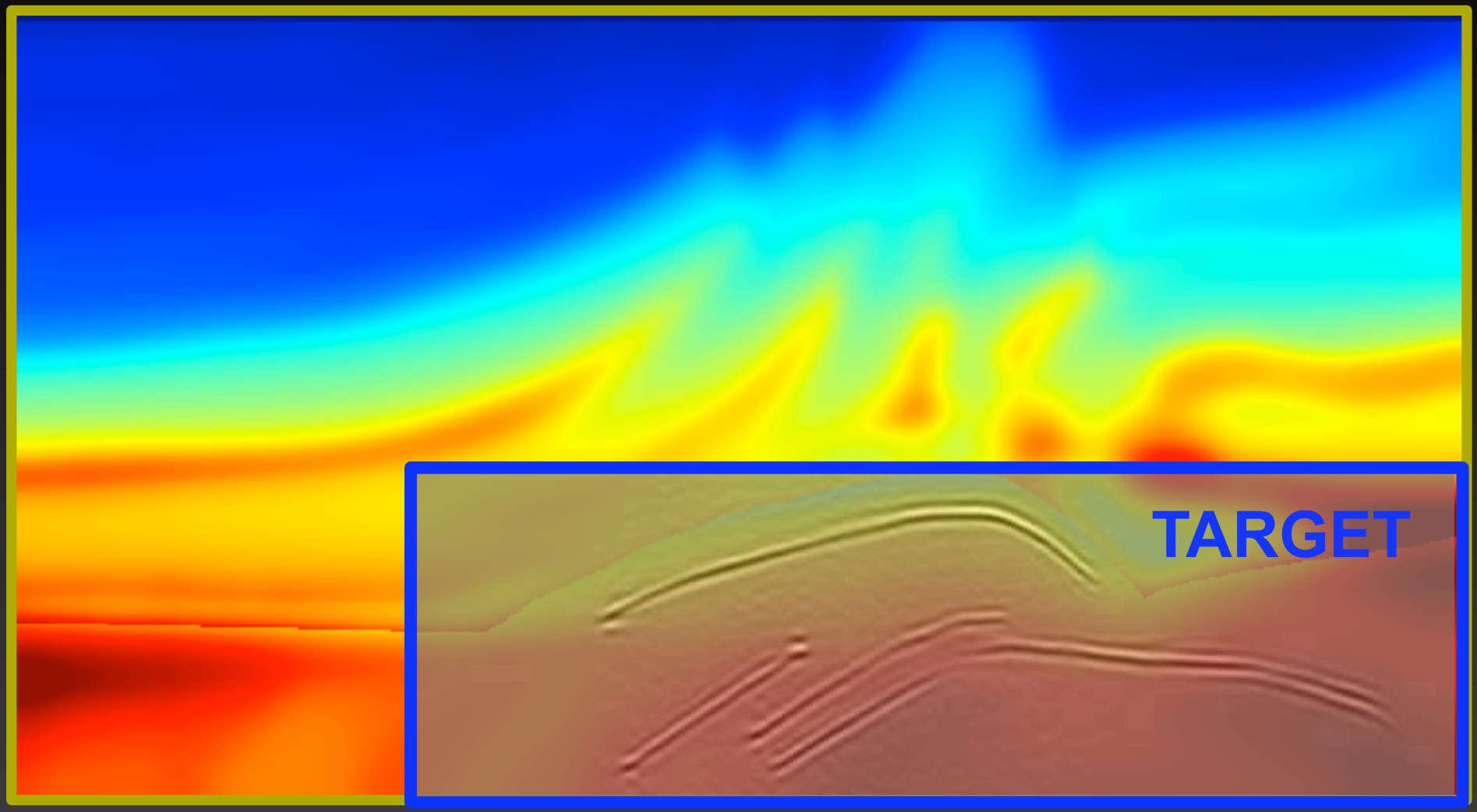
Collect wavefields



Target-oriented strategy



11 ISPEW migrated image



Agenda

- ✓ The prestack exploding-reflector model
- ✓ Image-space phase-encoded wavefields
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- • 3D-field data example

ISWET with image-space GS

- **Wavefields initiated at selected reflectors**

ISWET with image-space GS

- **Wavefields initiated at selected reflectors**
  - **Horizon-based ISWET**

ISWET with image-space GS

- **Wavefields initiated at selected reflectors**
  - **Horizon-based ISWET**
- **Easily solved in a target-oriented way**

Differential-semblance

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

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

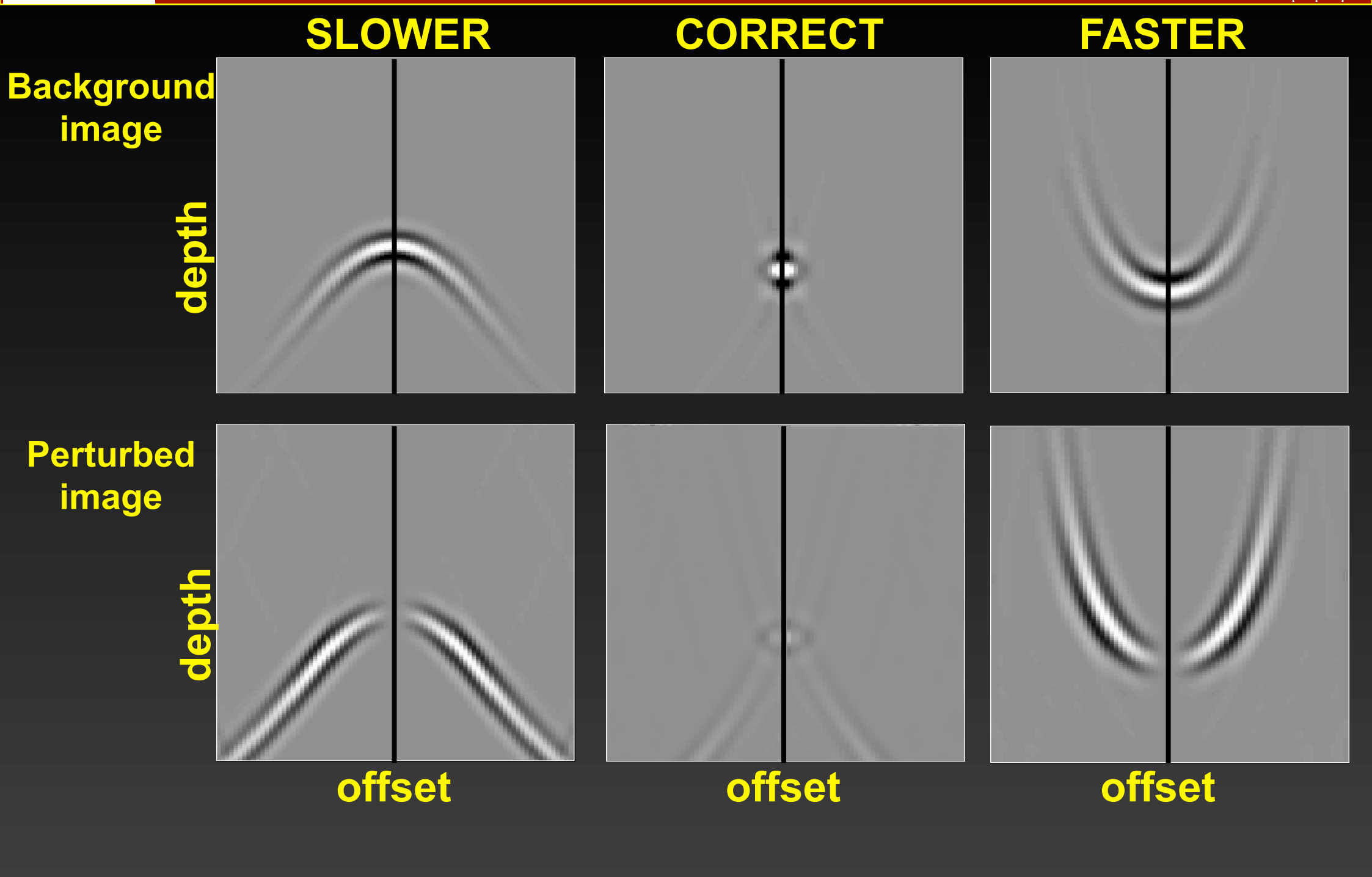
$J(s) =$ objective function

$\mathbf{h} =$ DSO operator

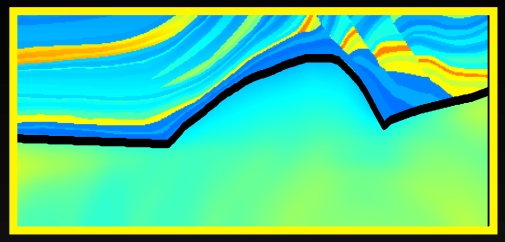
$s_o =$ current velocity

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

DSO operator = $|h|$

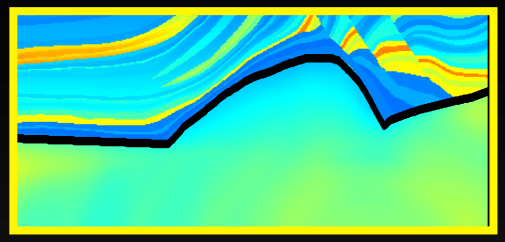


The slowness perturbation

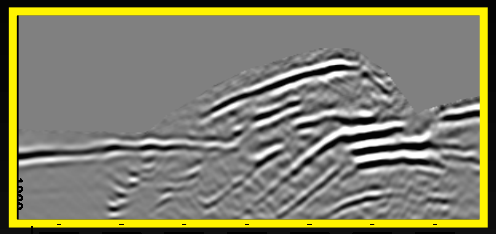


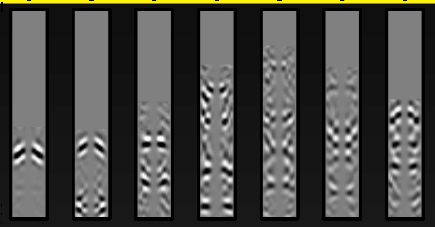
s_o

The slowness perturbation



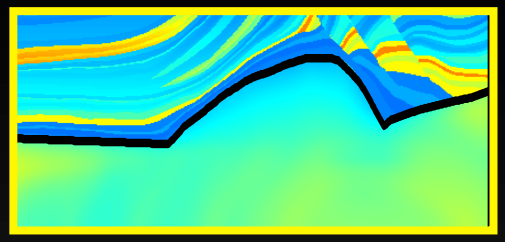
s_o



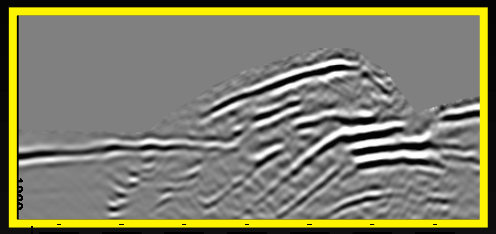


$\Delta I = |h| I_o$

The slowness perturbation



s_o



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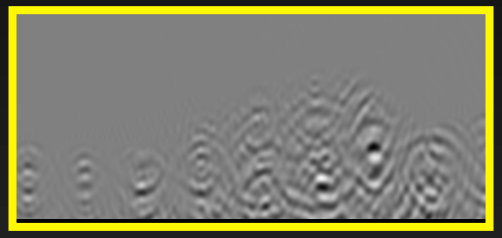
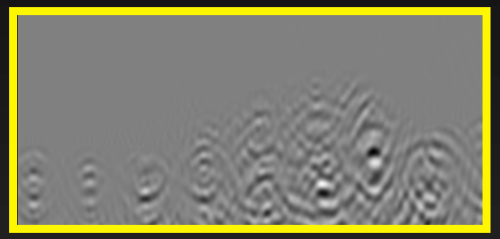
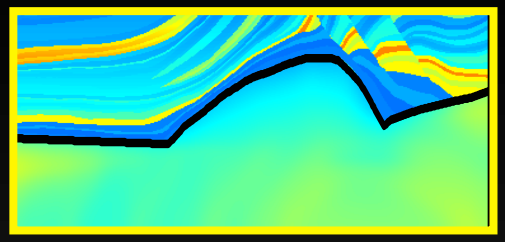


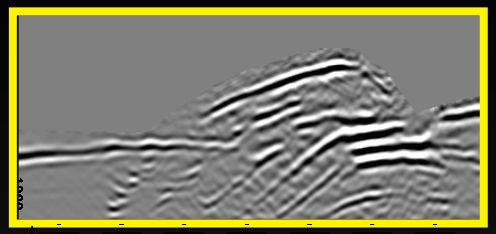
$\Delta P^{\pm} = \mathbf{T}^{\mp}\mathbf{P_o}^{\pm}\Delta I$



The slowness perturbation



s_O



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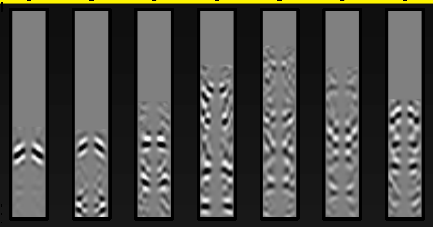
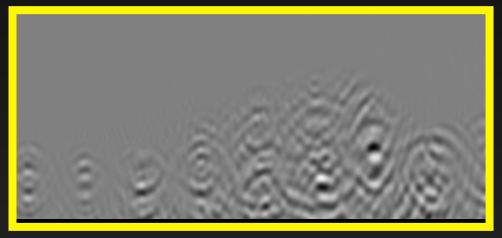
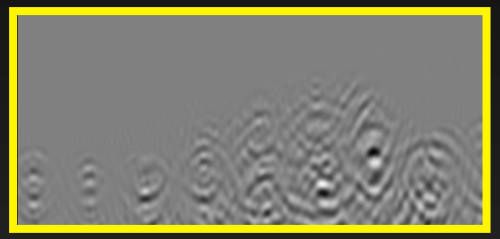
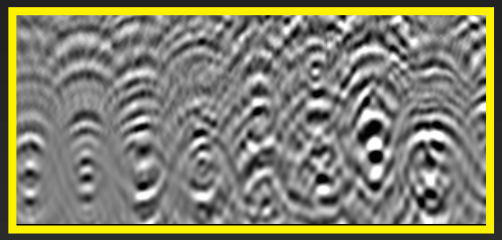


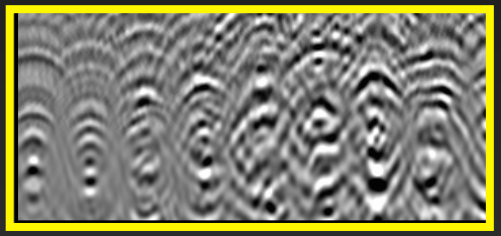


$\Delta P^{\pm} = \mathbf{T}^{\mp} \mathbf{P_o}^{\pm} \Delta I$

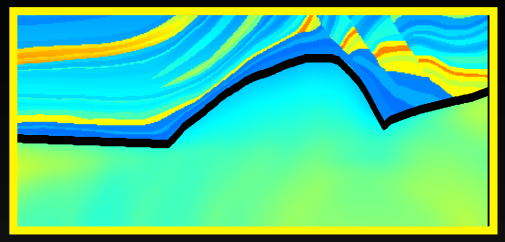




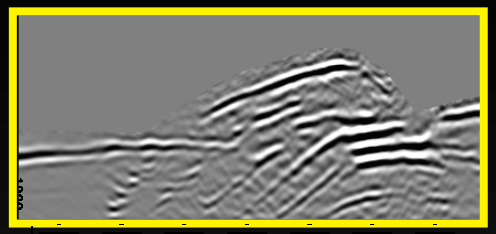
$P_{sc}^{\pm} = \mathbf{B}^{\pm} P_o^{\pm}$



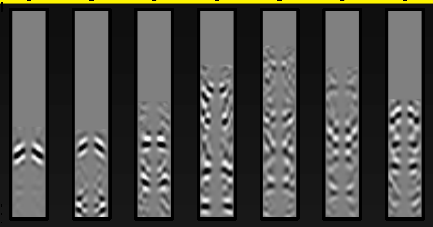
The slowness perturbation



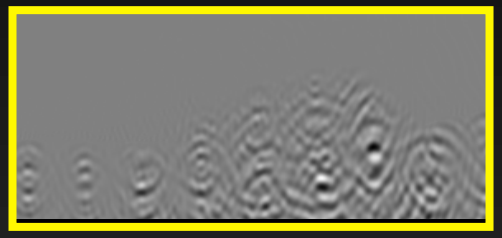
s_o

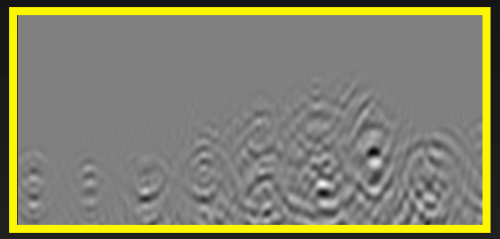


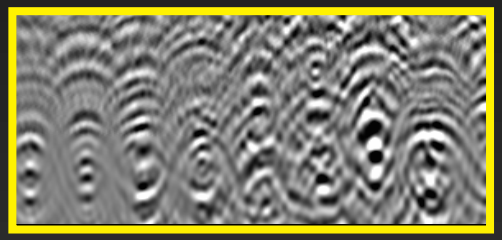
$\Delta I = |h| I_o$



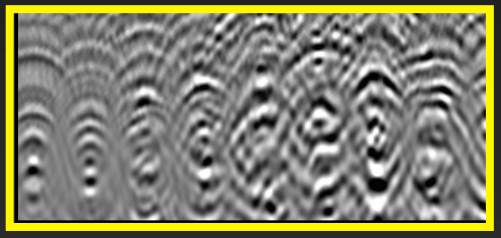
$\Delta P^{\pm} = \mathbf{T}^{\mp} \mathbf{P_o}^{\pm} \Delta I$

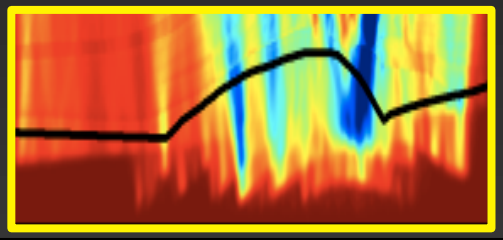






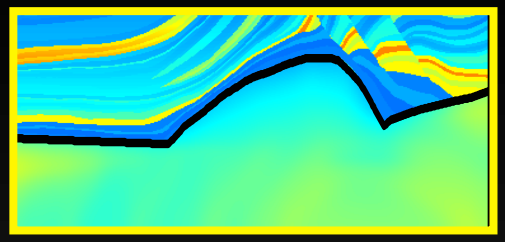
$P_{sc}^{\pm} = \mathbf{B}^{\pm} P_o{}^{\pm}$



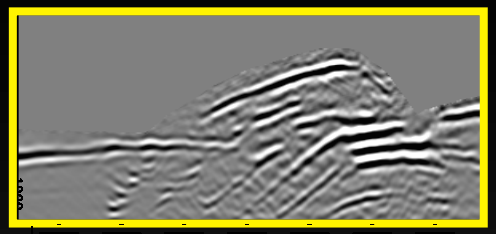


$\Delta s = P_{sc}^{+*} \Delta P^{+} + P_{sc}^{-*} \Delta P^{-}$

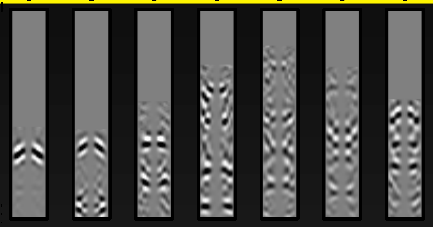
The slowness perturbation



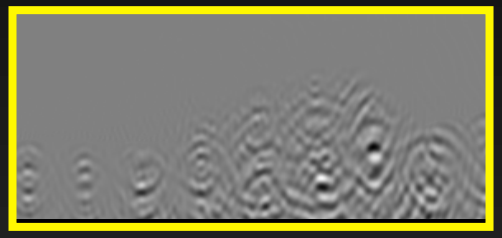
s_o

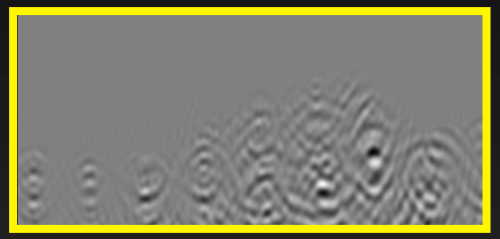


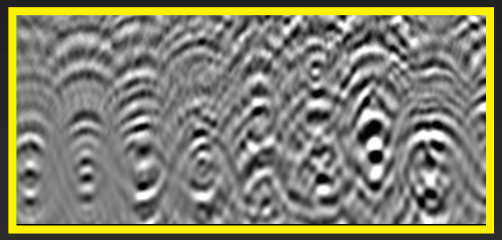
$\Delta I = |h| I_o$



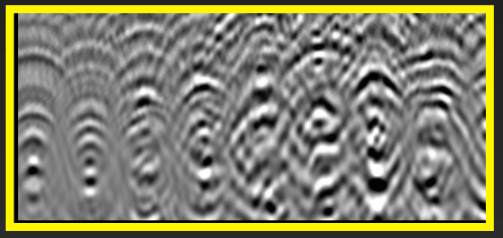
$\Delta P^{\pm} = \mathbf{T}^{\mp} \mathbf{P_o}^{\pm} \Delta I$

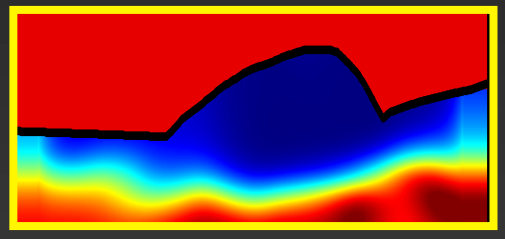




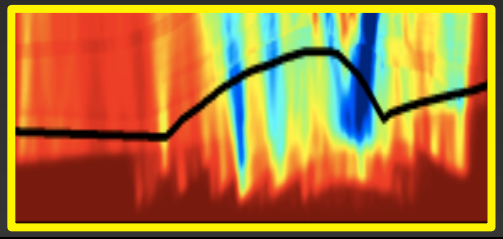


$P_{sc}^{\pm} = \mathbf{B}^{\pm} P_o{}^{\pm}$



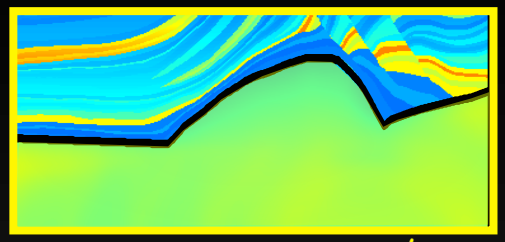


$\langle \Delta s \rangle = \mathbf{S} \Delta s$

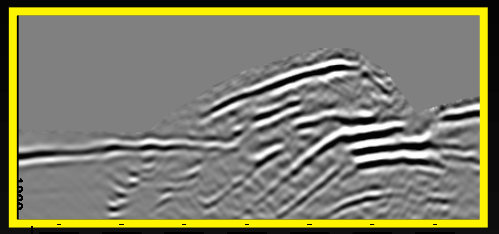


$\Delta s = P_{sc}^{+*} \Delta P^{+} + P_{sc}^{-*} \Delta P^{-}$

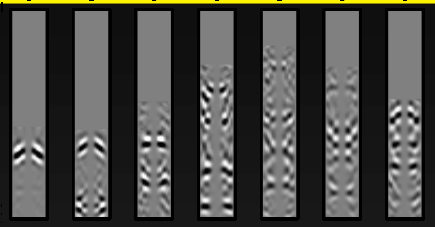
The slowness perturbation



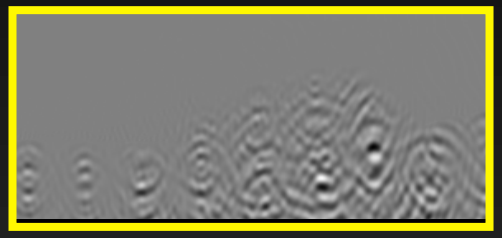
$$s_o = s_o - \lambda \langle \Delta s \rangle$$

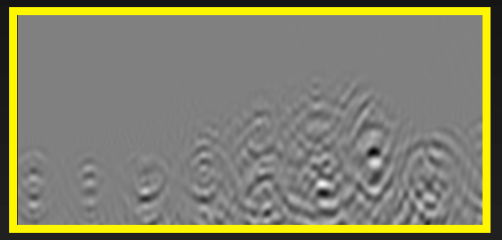


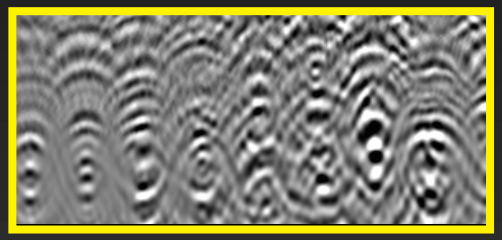
$$\Delta I = |h| I_o$$



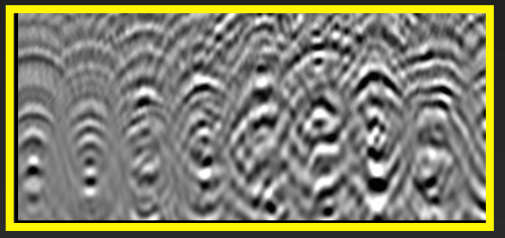
$$\Delta P^{\pm} = \mathbf{T}^{\mp} \mathbf{P_o}^{\pm} \Delta I$$

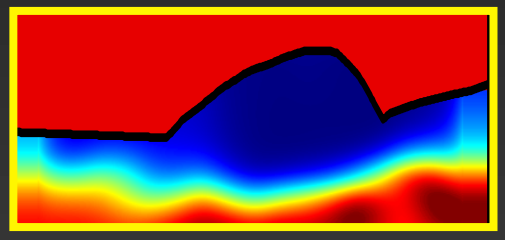




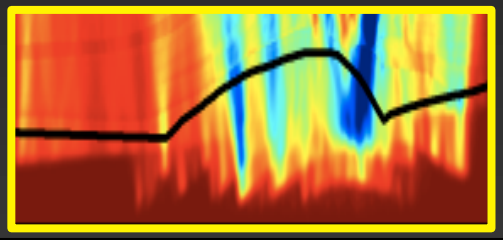


$$P_{sc}^{\pm} = \mathbf{B}^{\pm} P_o{}^{\pm}$$



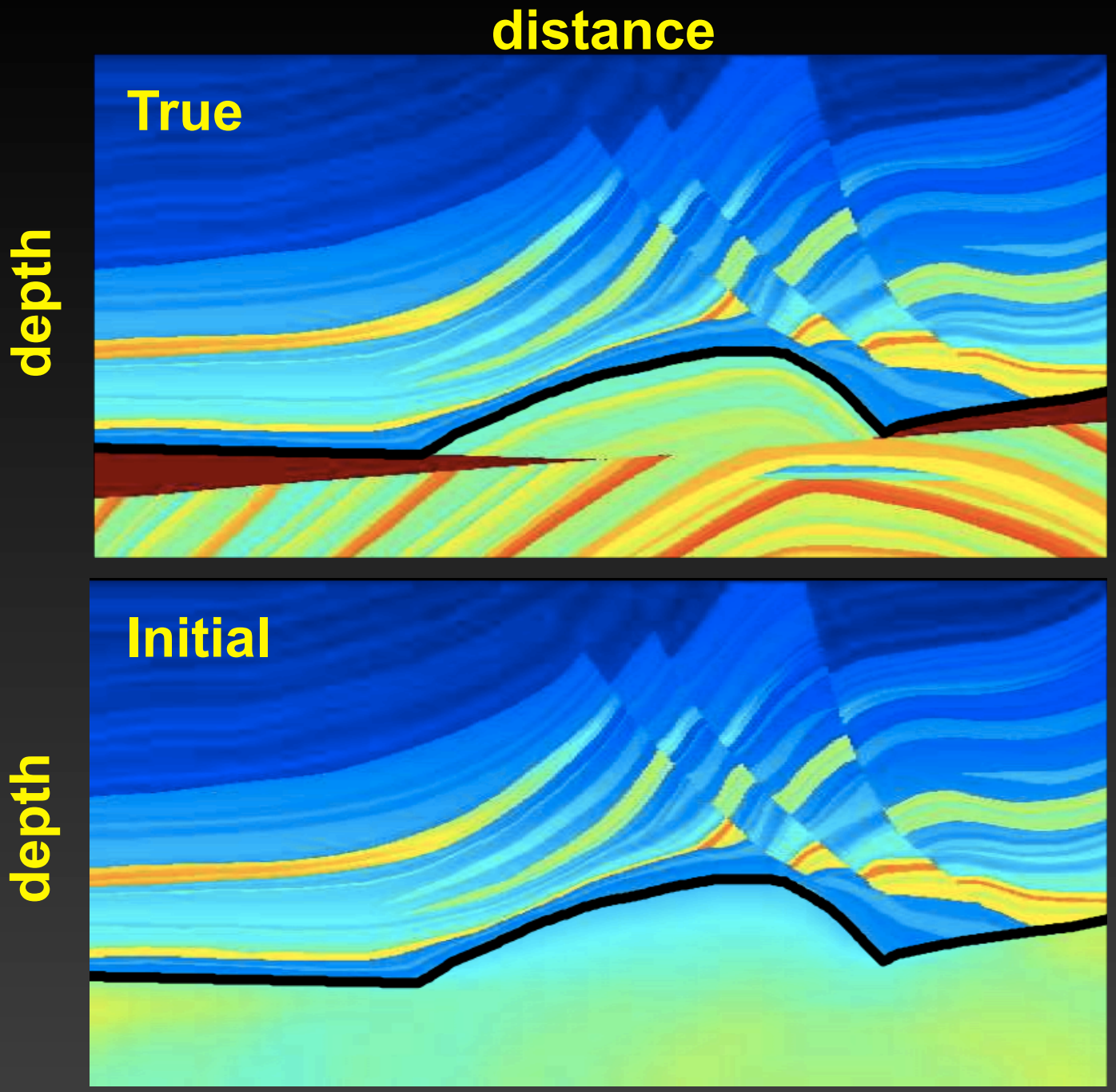


$$\langle \Delta s \rangle = \mathbf{S} \Delta s$$

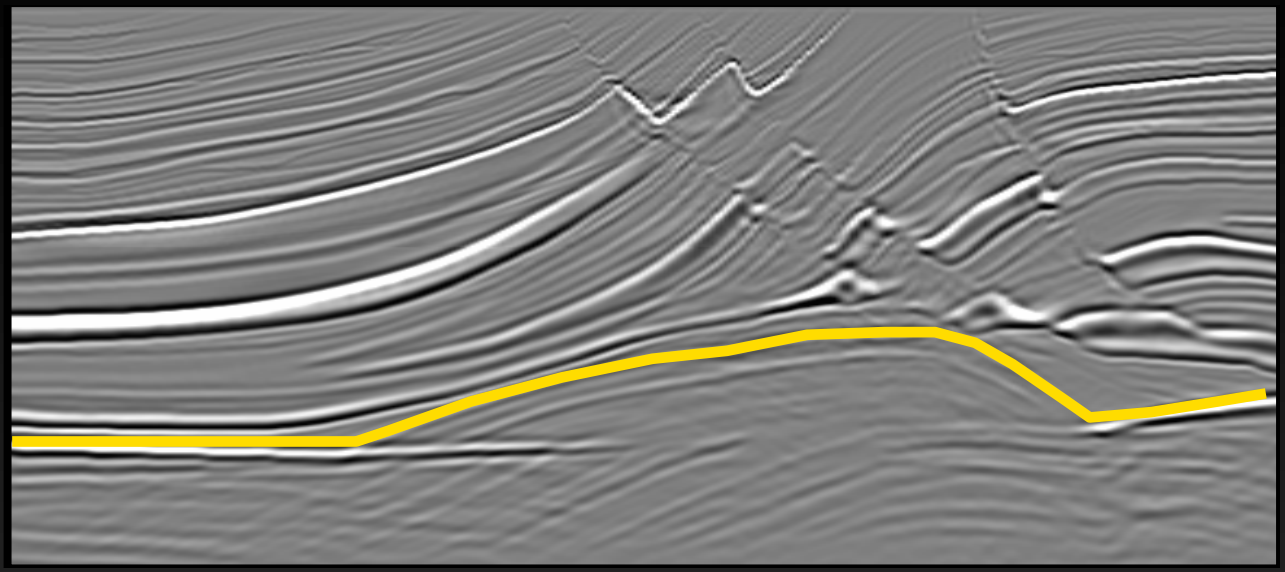


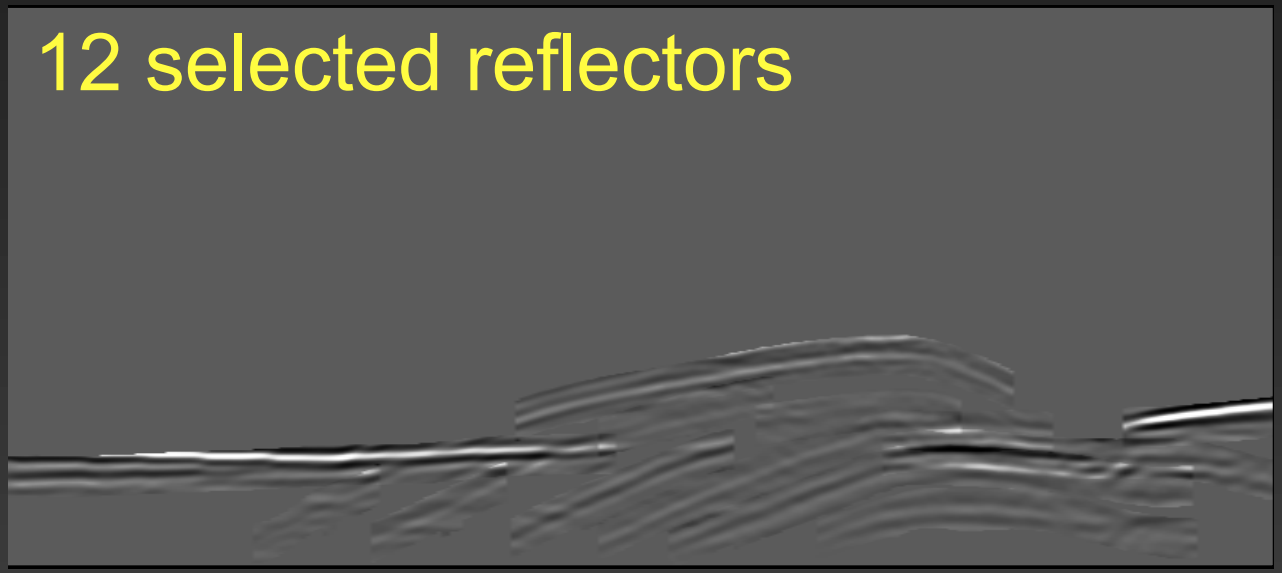
$$\Delta s = P_{sc}^{+*} \Delta P^{+} + P_{sc}^{-*} \Delta P^{-}$$

2D synthetic example

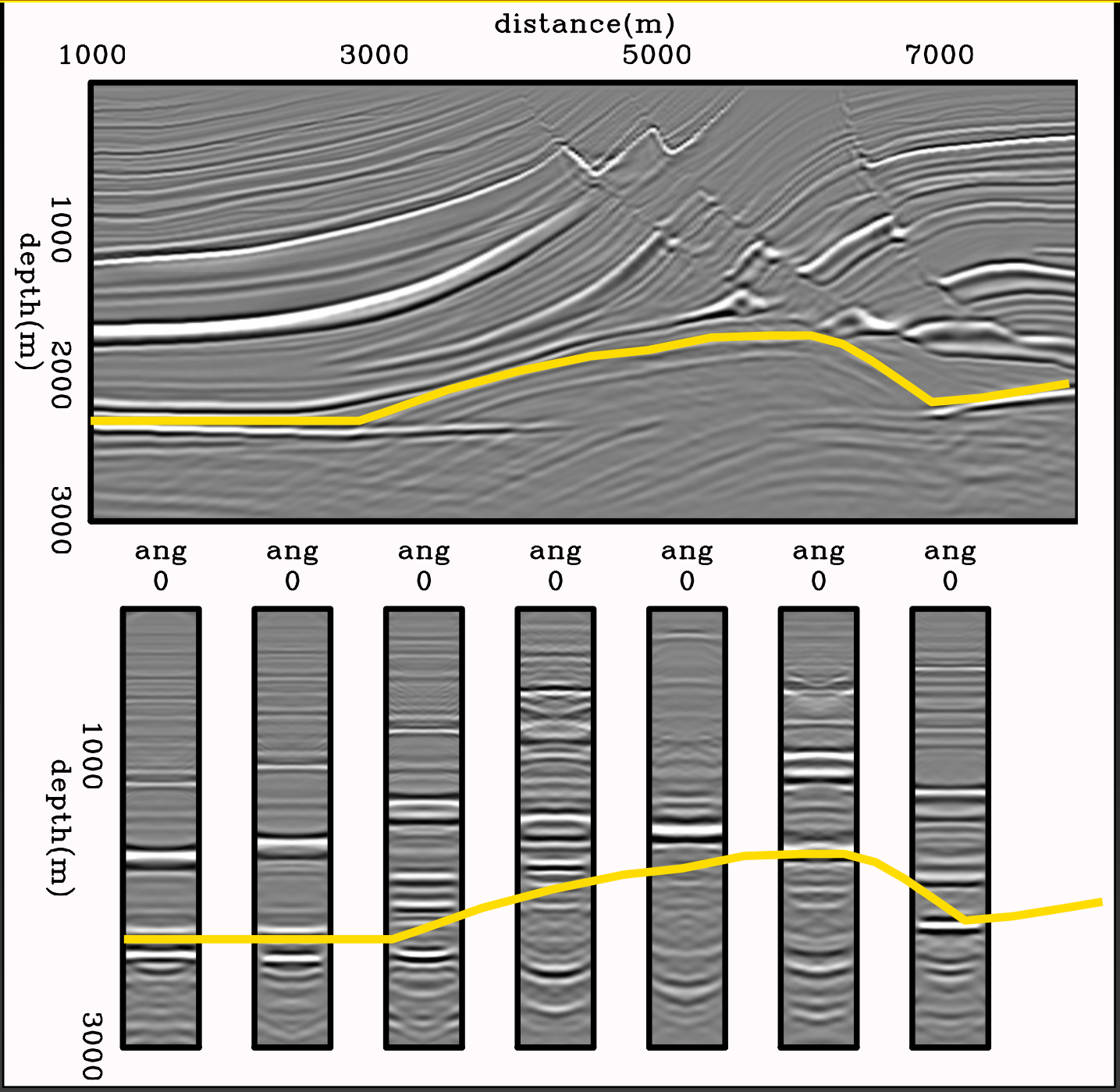


Initial image

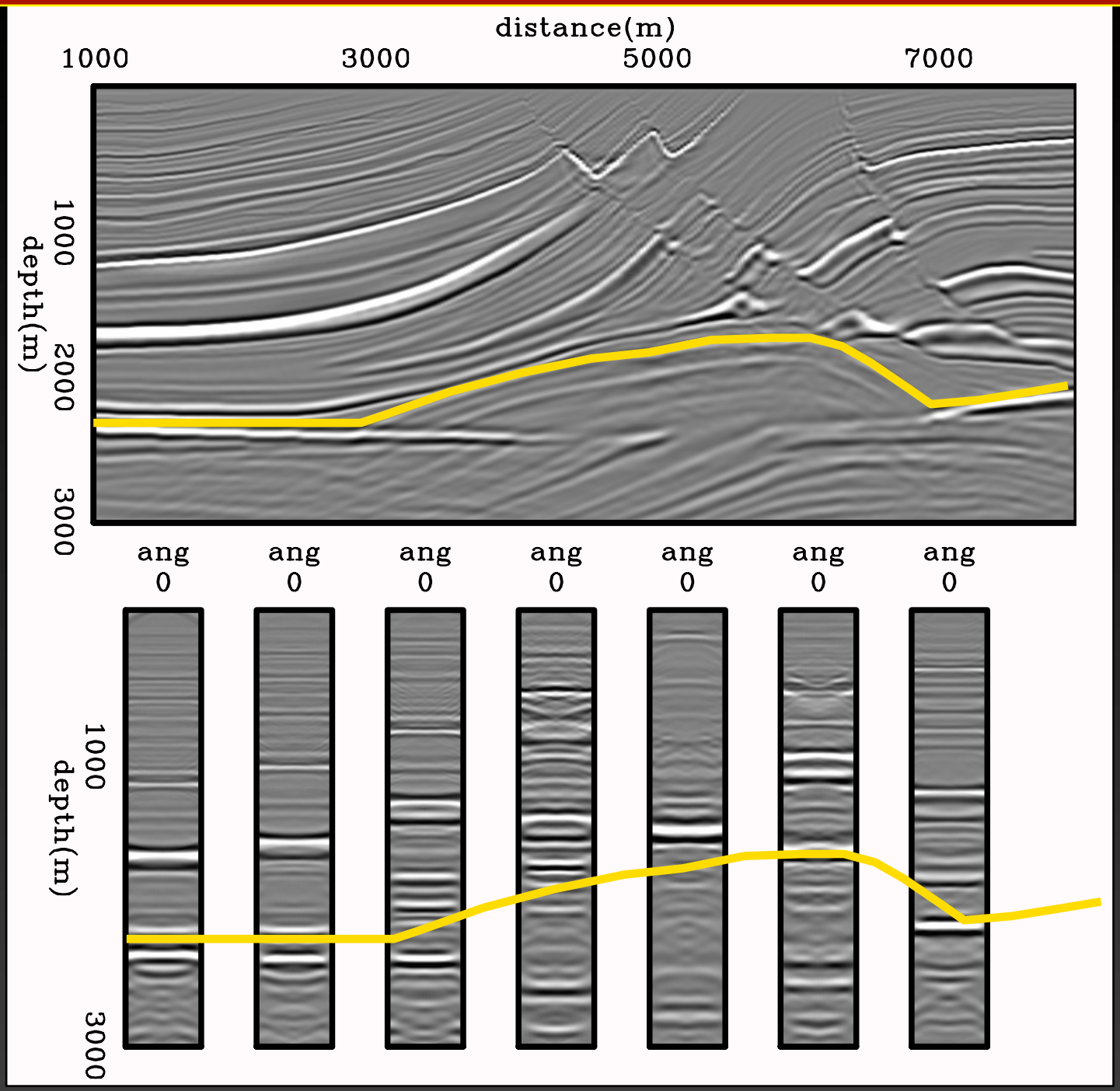




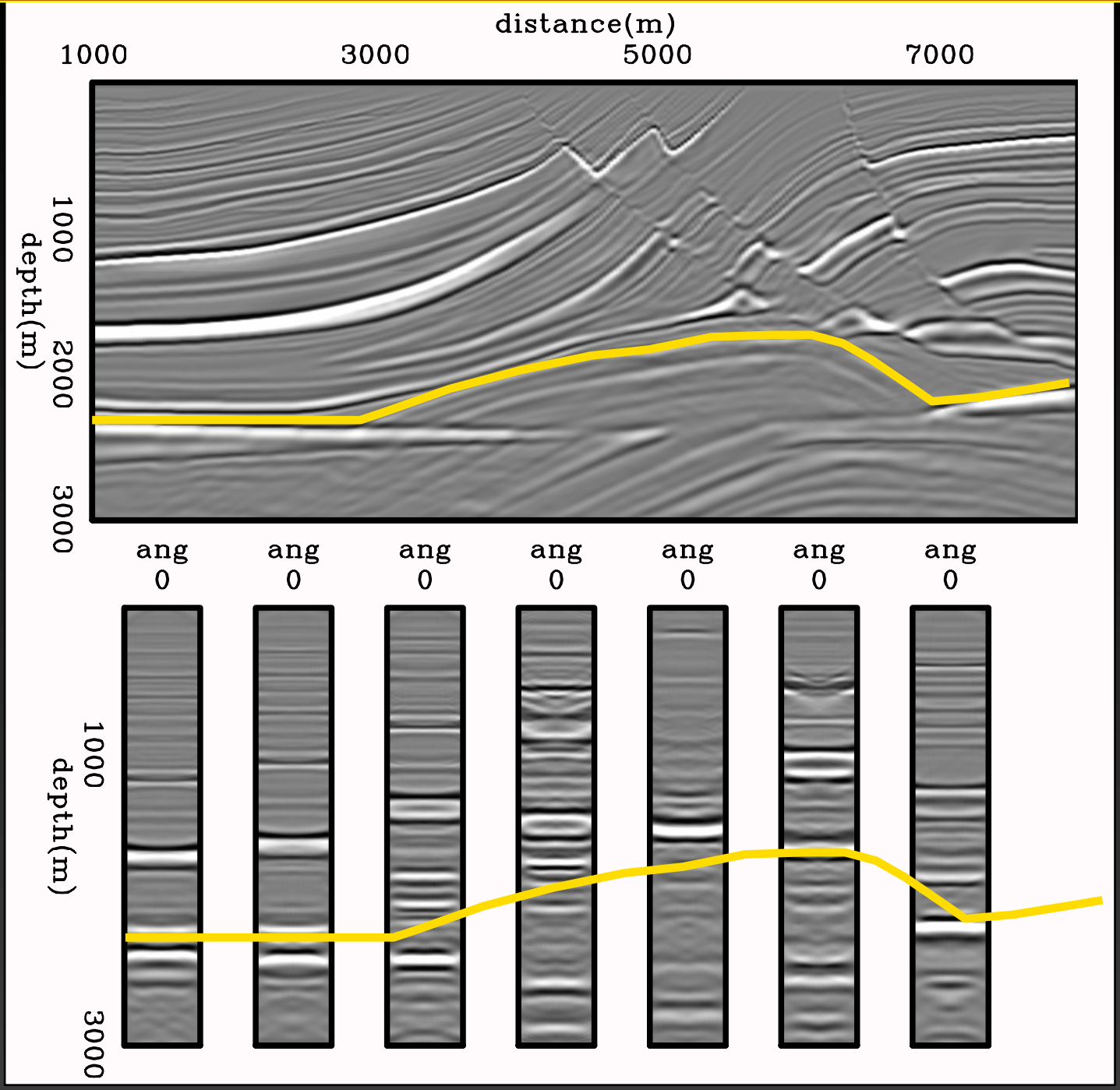
Initial image



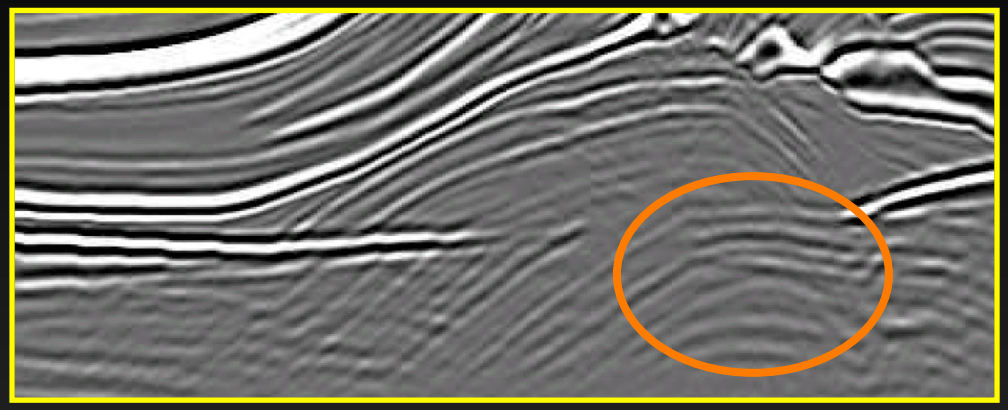
Migration with optimized velocity

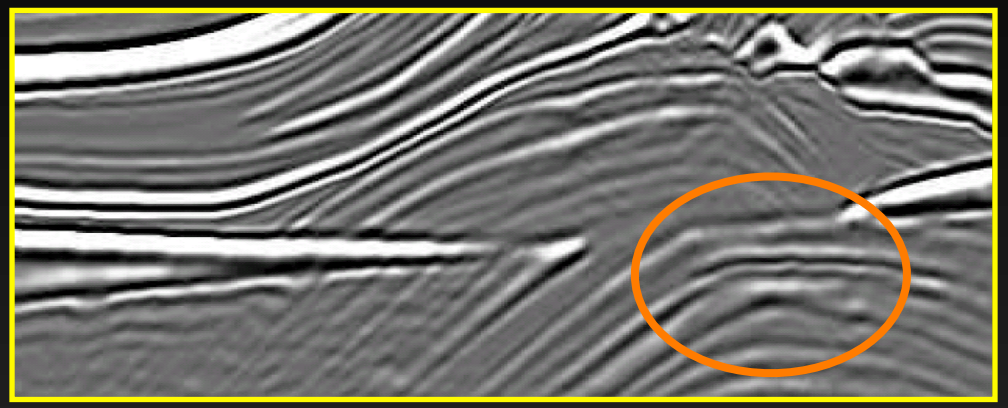


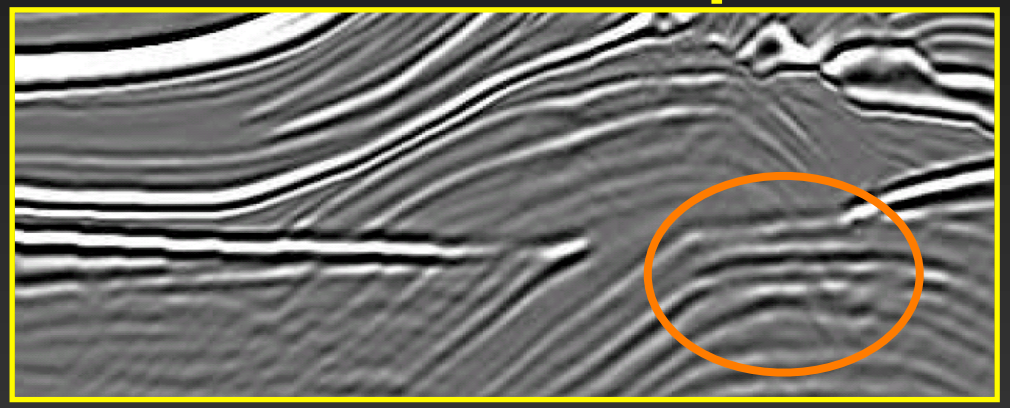
Migration with true velocity



Computational gain







30x faster

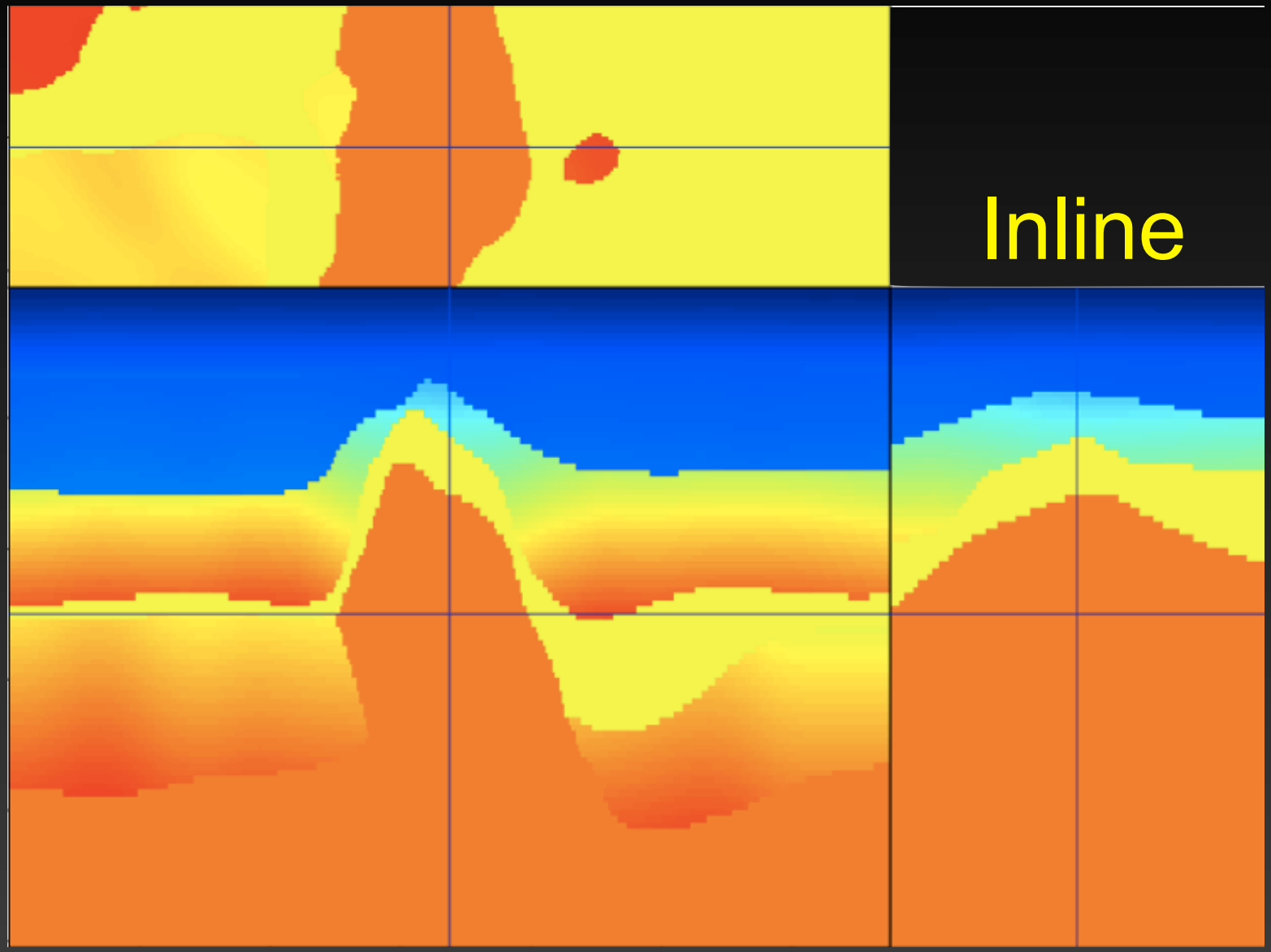
Agenda

- ✓ The prestack exploding-reflector model
- ✓ Image-space phase-encoded wavefields
- ✓ MVA using image-space generalized sources
- • 3D-field data example

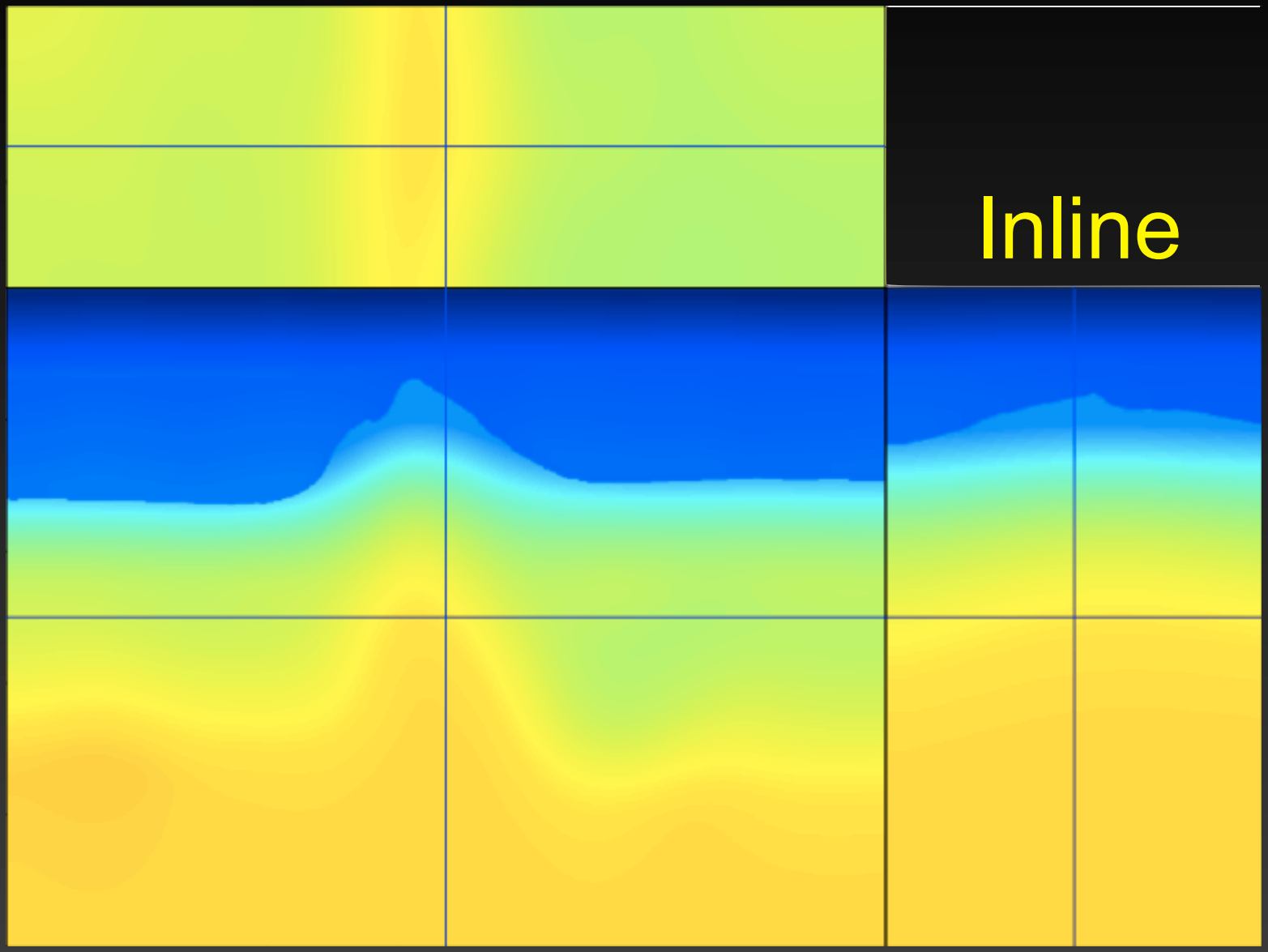
3D-North Sea data example

- **Intense faulting, irregular salt body**
- **30 ISPEW**

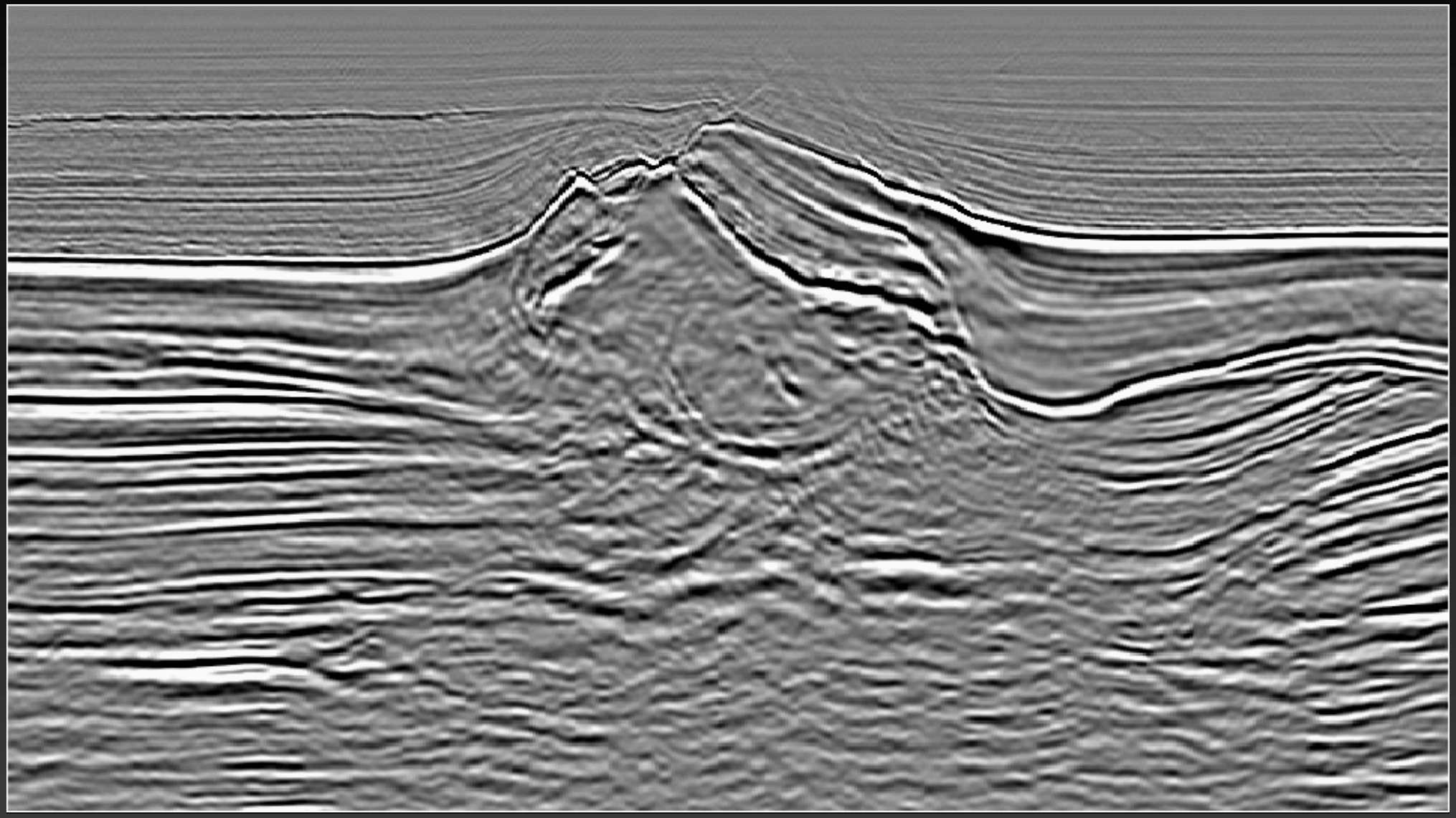
Original velocity model



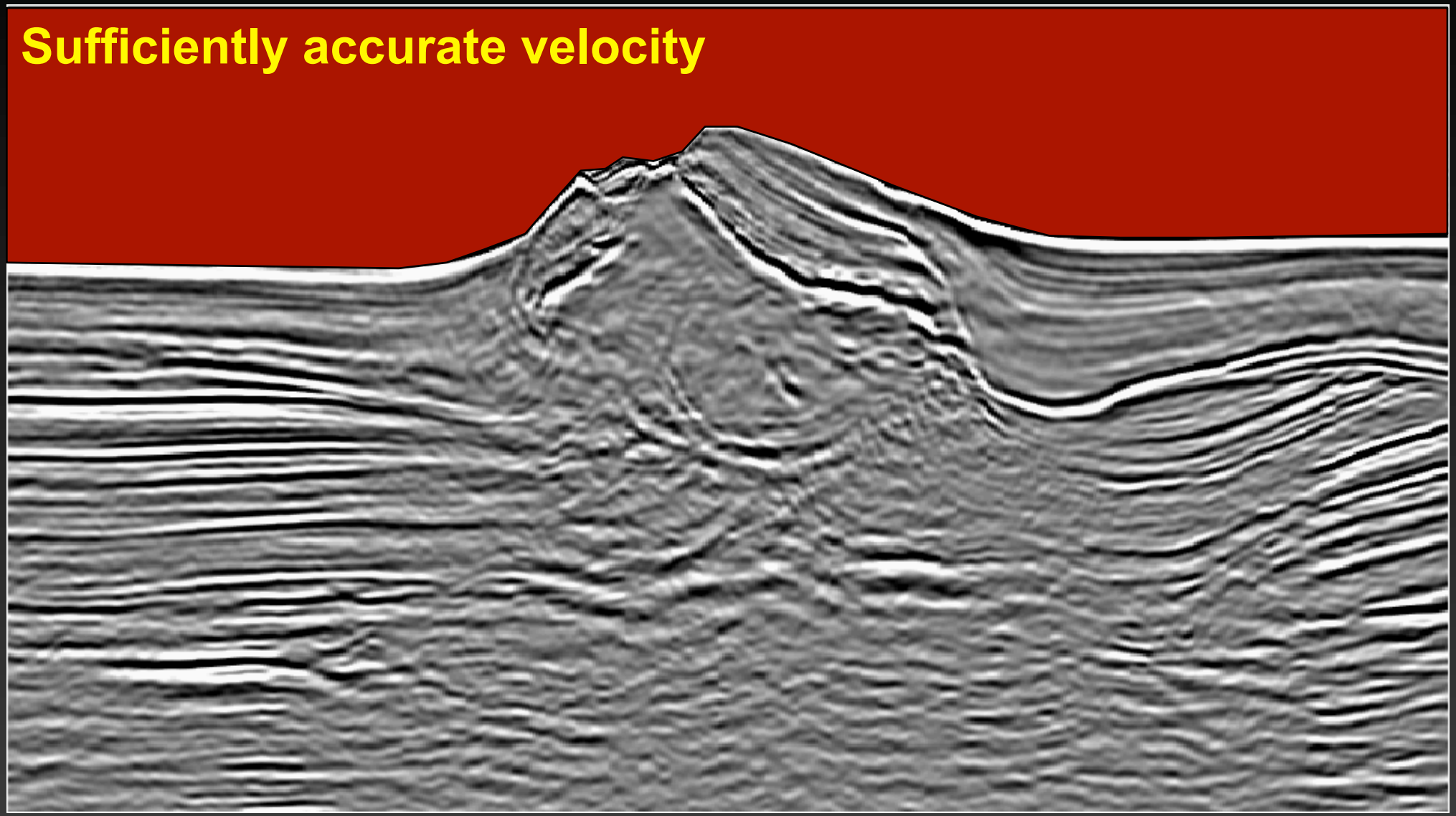
Initial velocity model



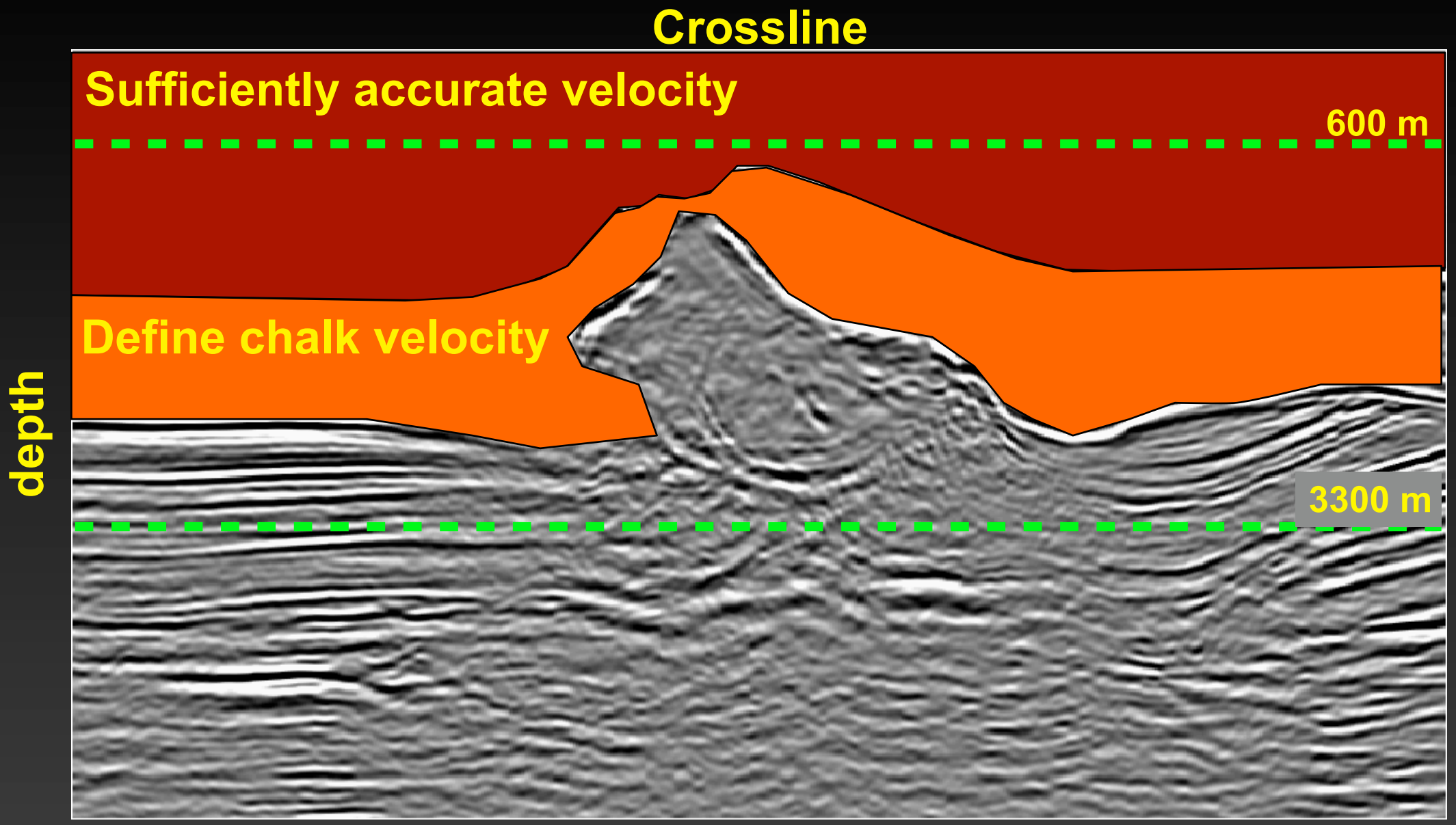
MVA strategy



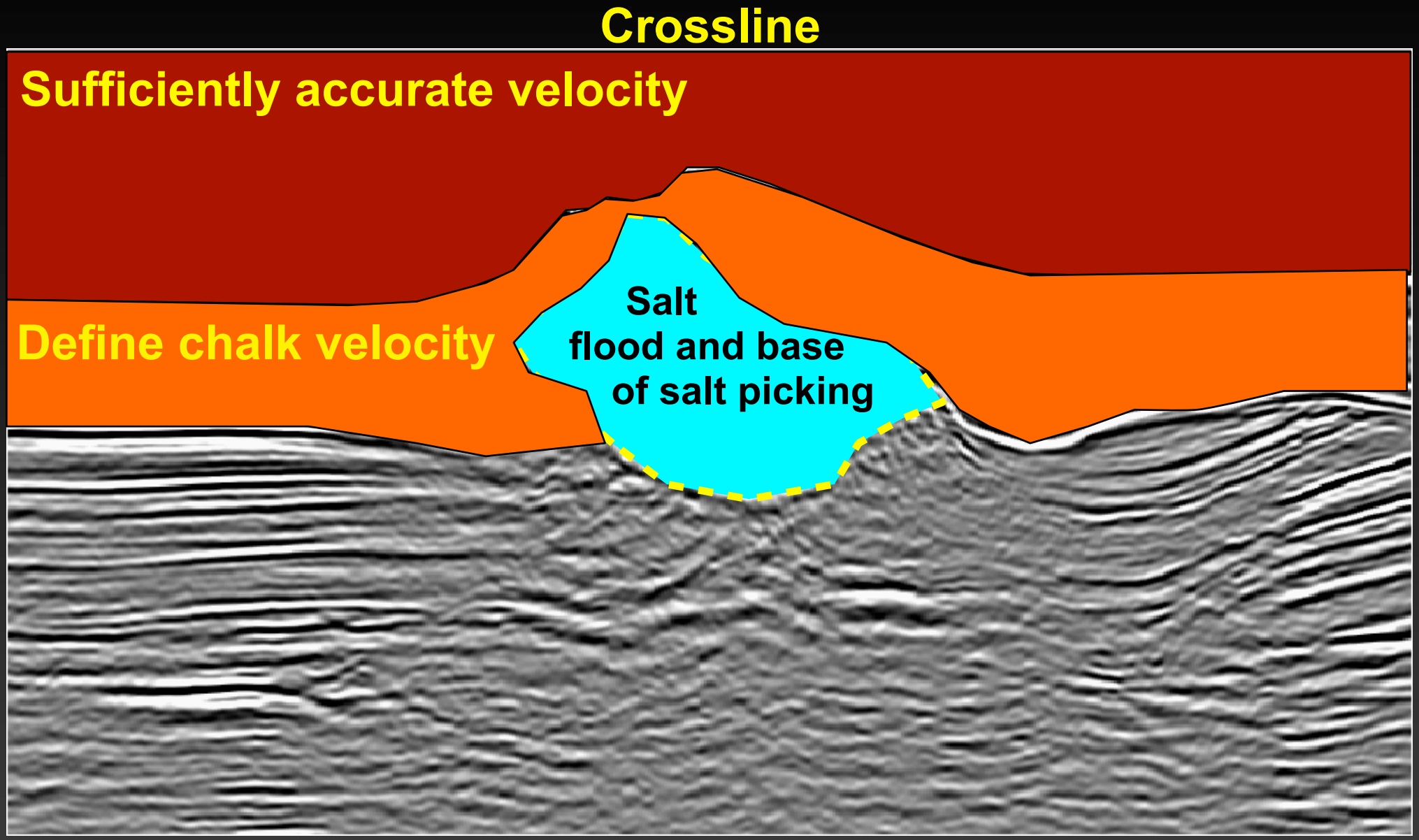
MVA strategy



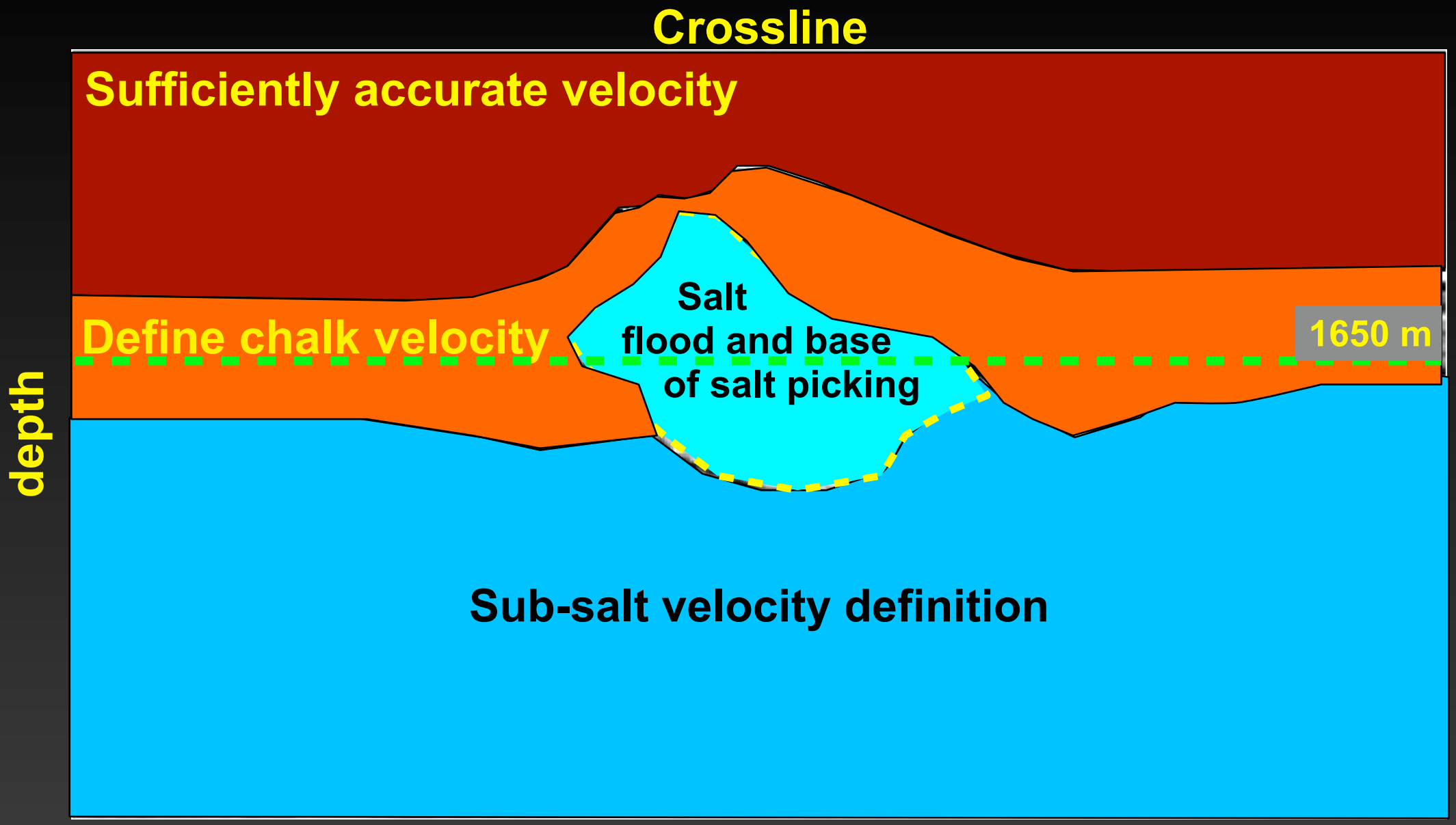
MVA strategy



MVA strategy



MVA strategy

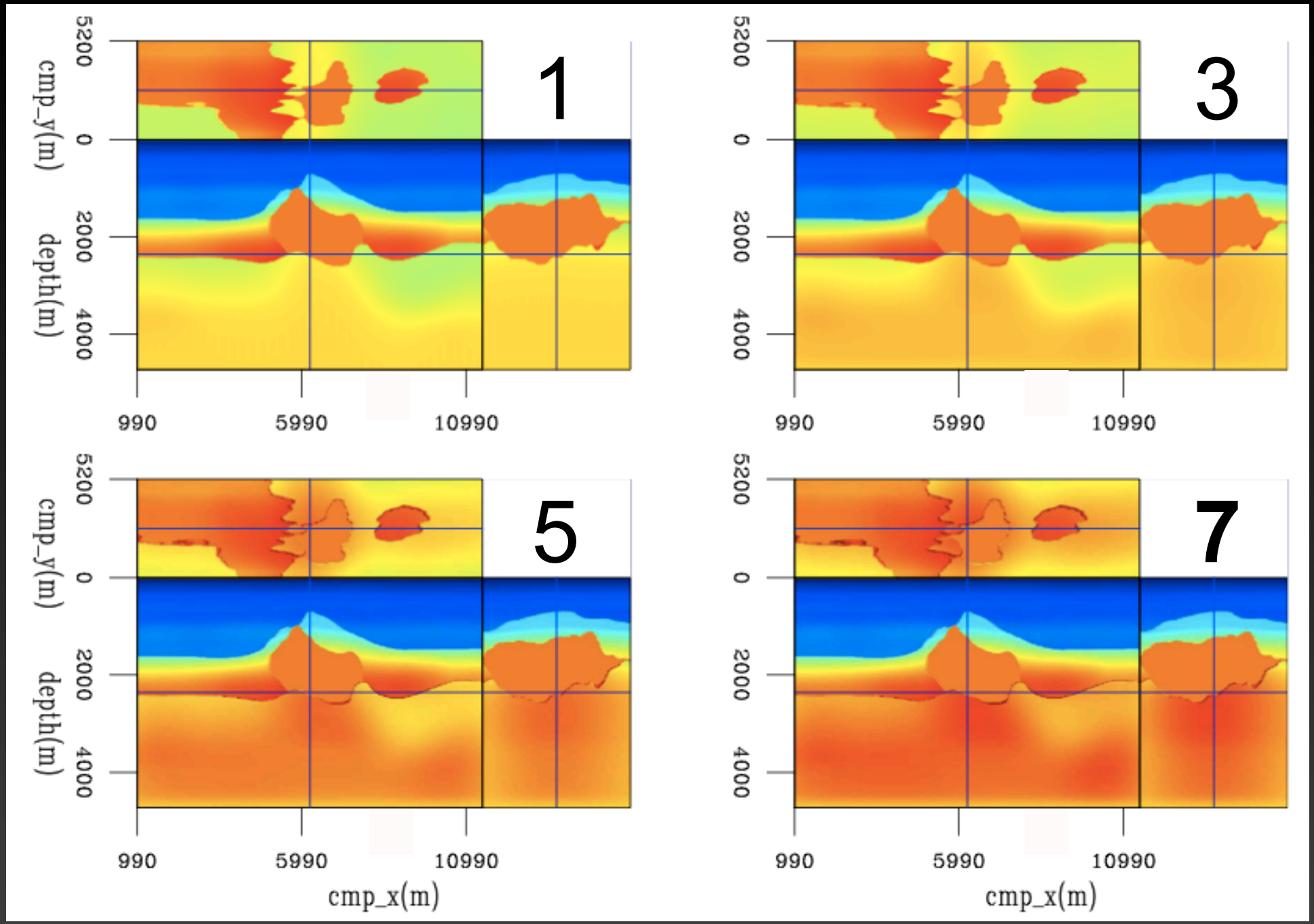


Velocity optimization

- **Non-linear conjugate gradient**
  - Maximum of 10% velocity variation between iterations
  - Two function evaluations per iteration

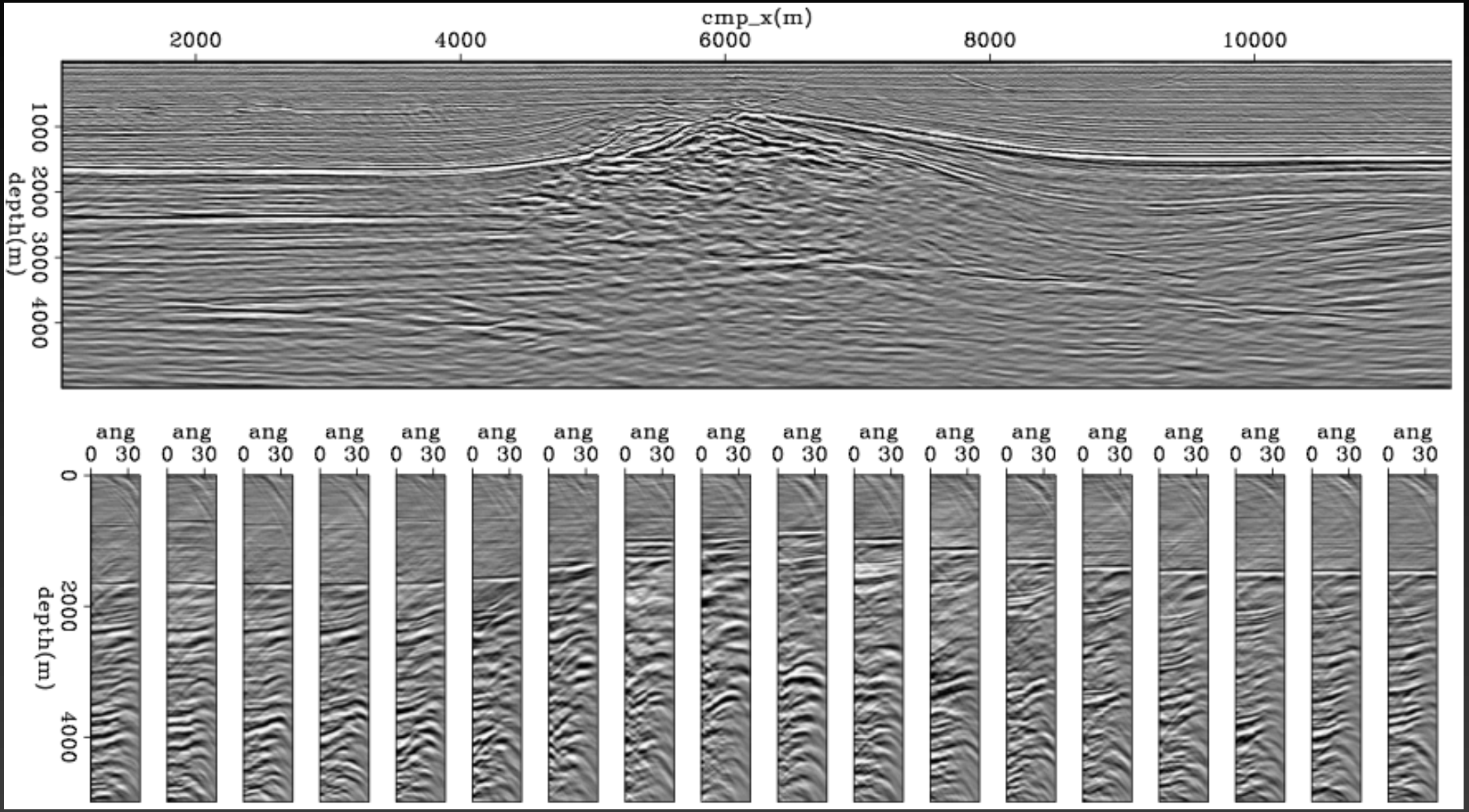
- **CEES: 30 Dual Nehalem 5520, 24Gb RAM**
  - Objective function: 30 min
  - Gradient: 60 min

Sub-salt velocity evolution



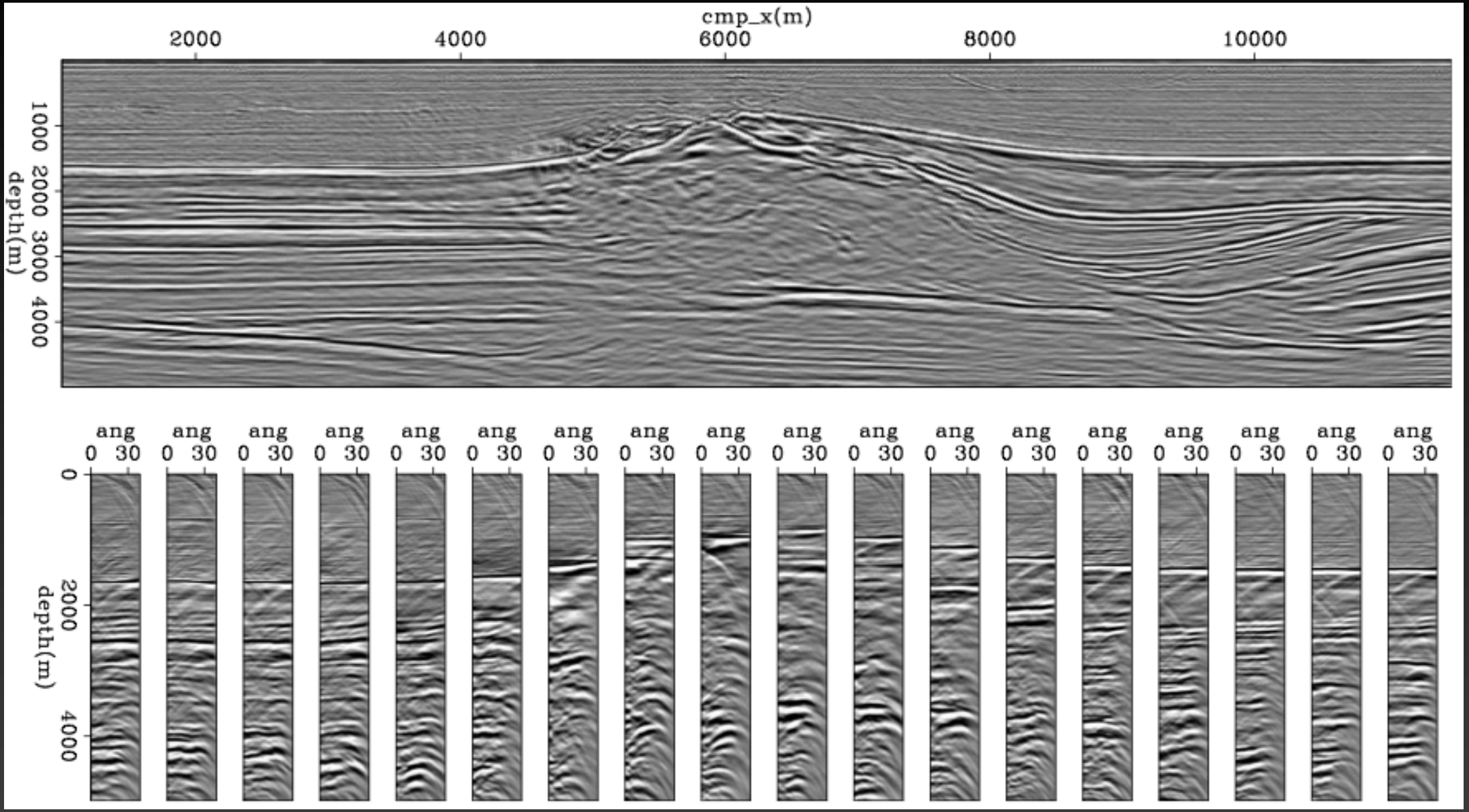
Comparison

Initial



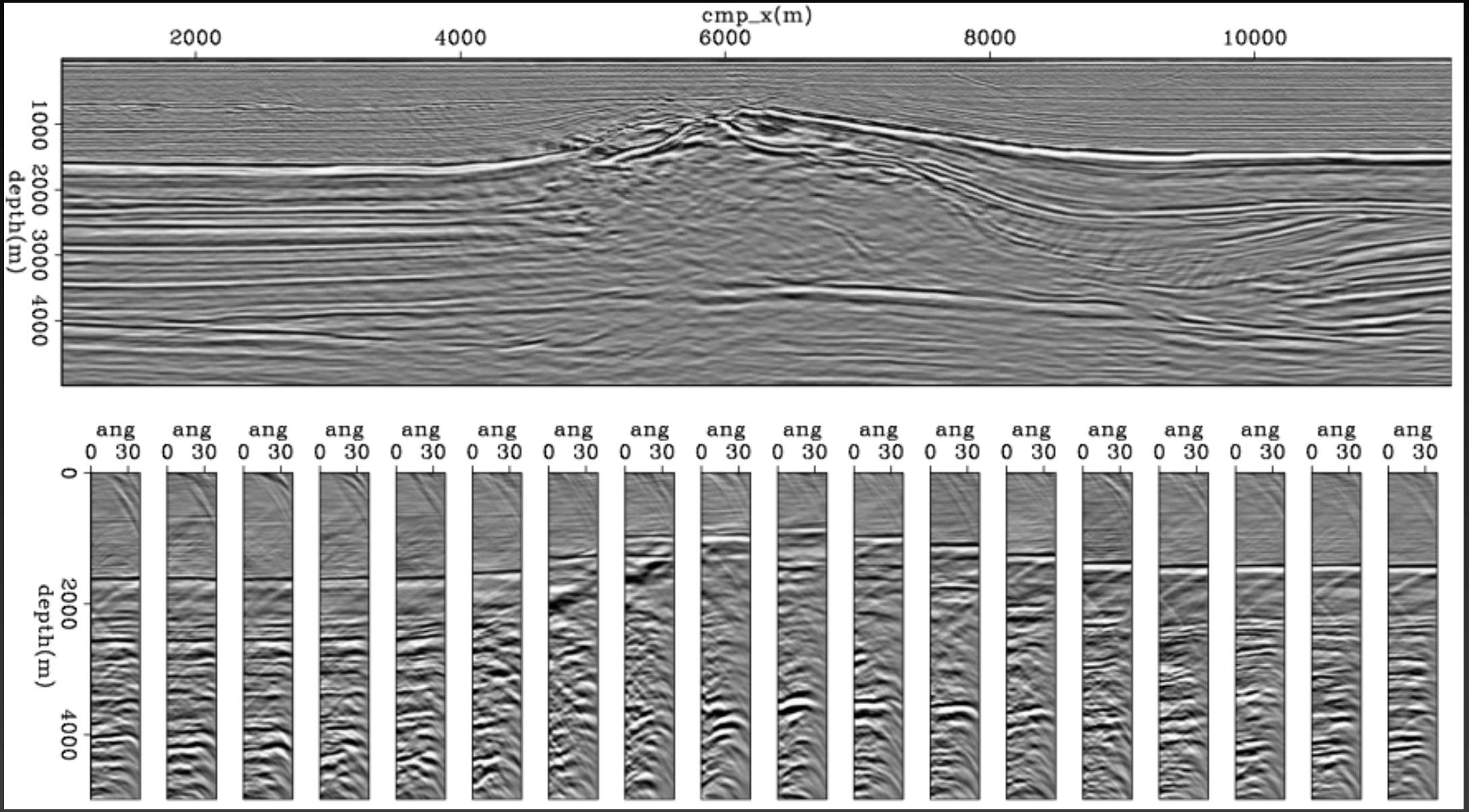
Flattened angle gathers

Final



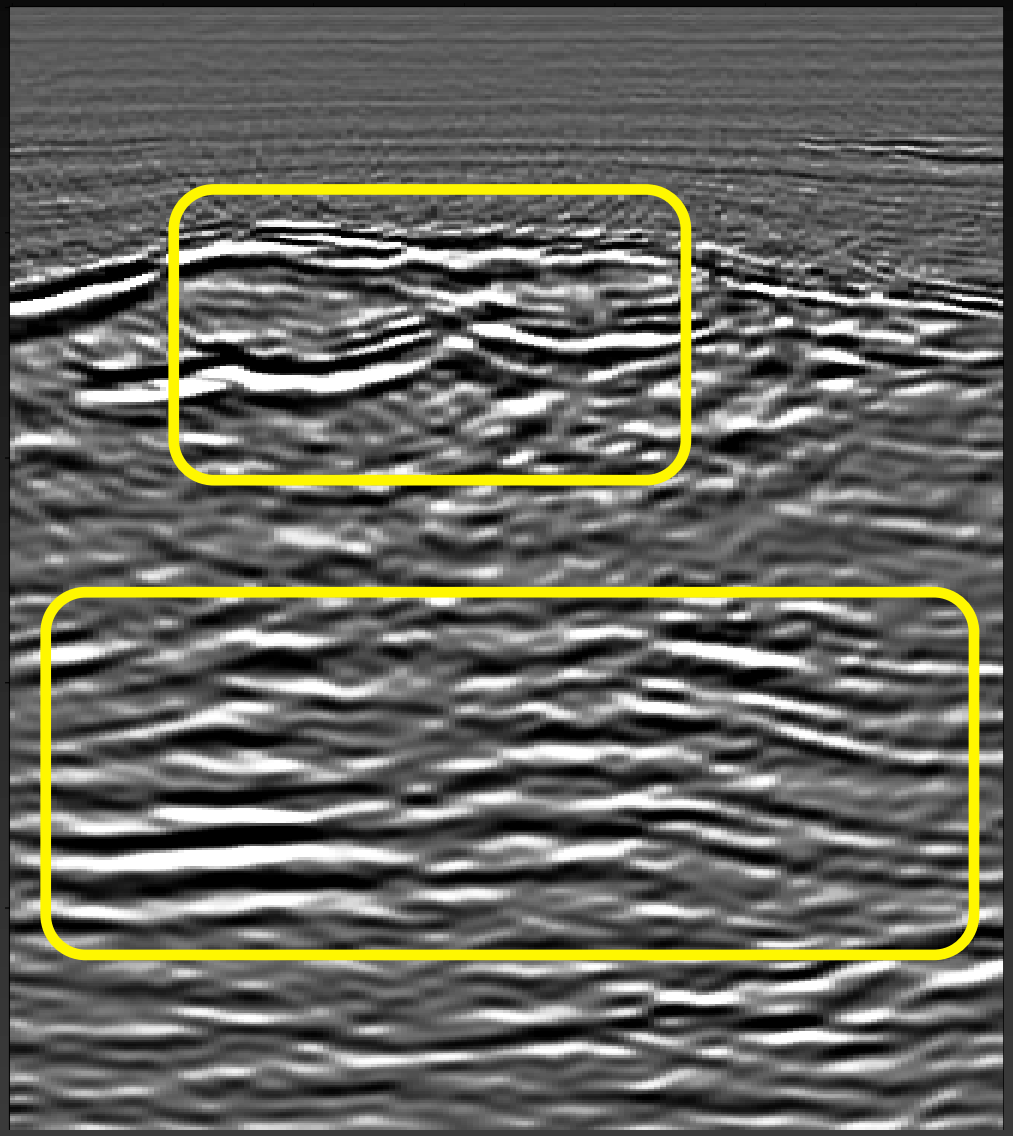
Residual moveout below the salt

Original

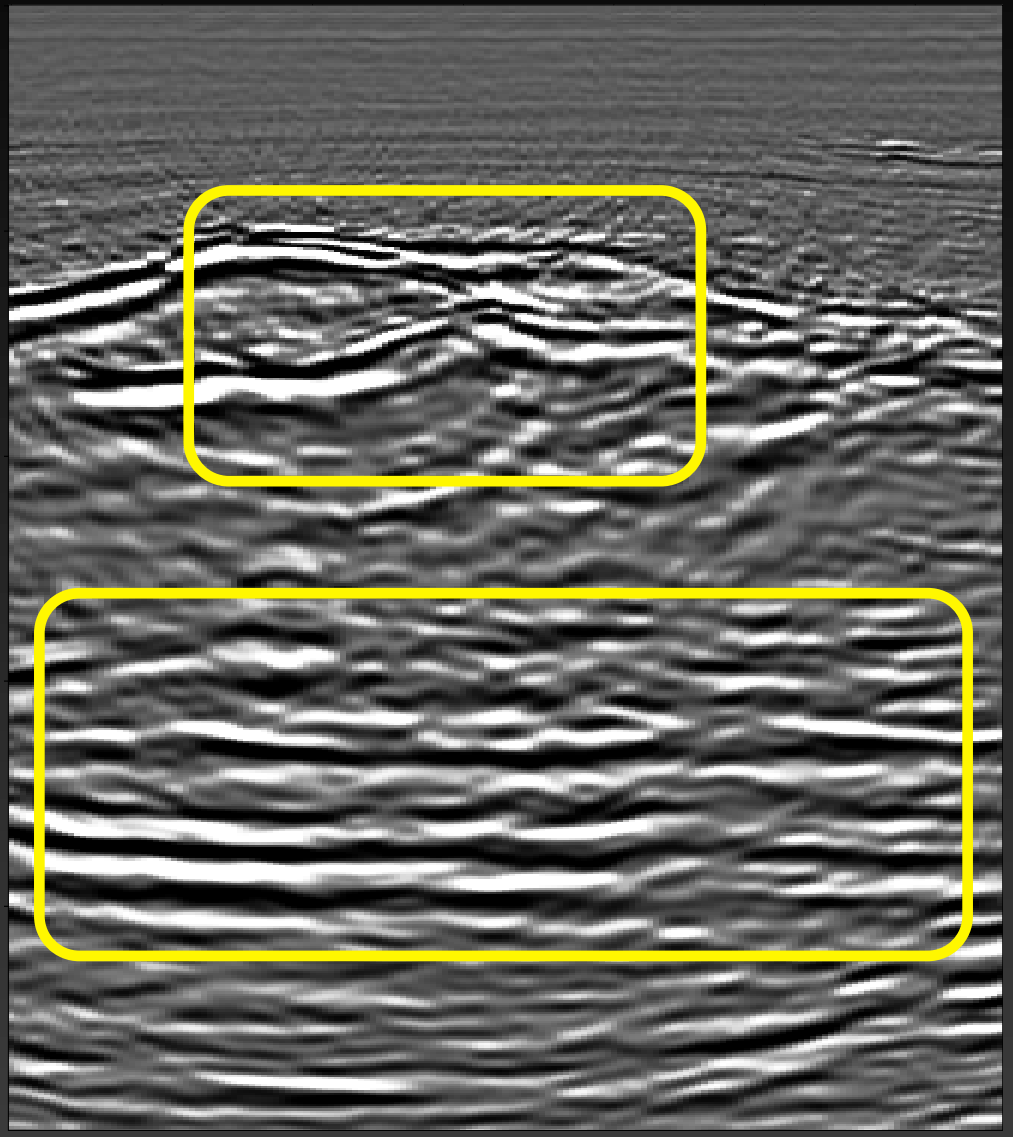


Comparison - crossline

Original

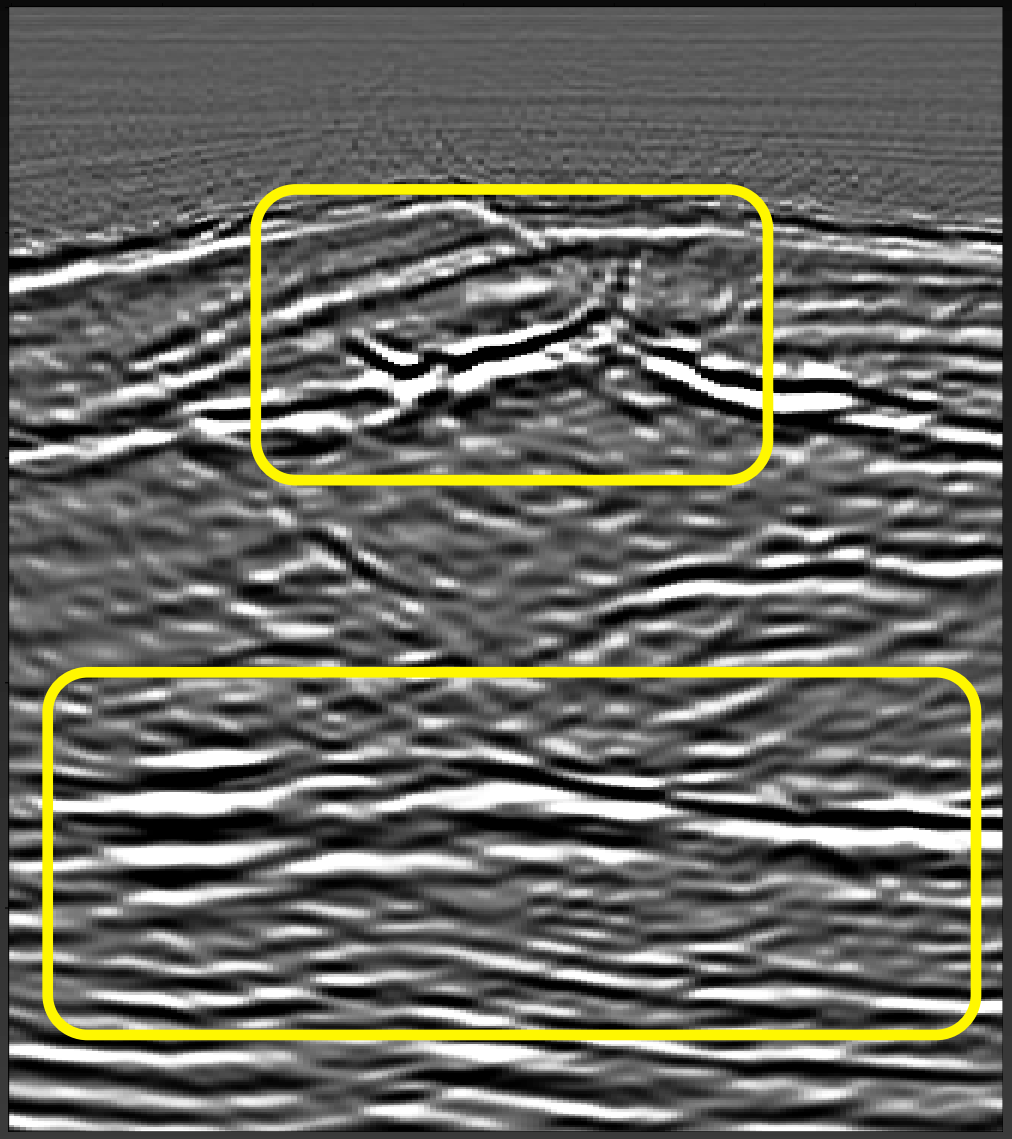


Final

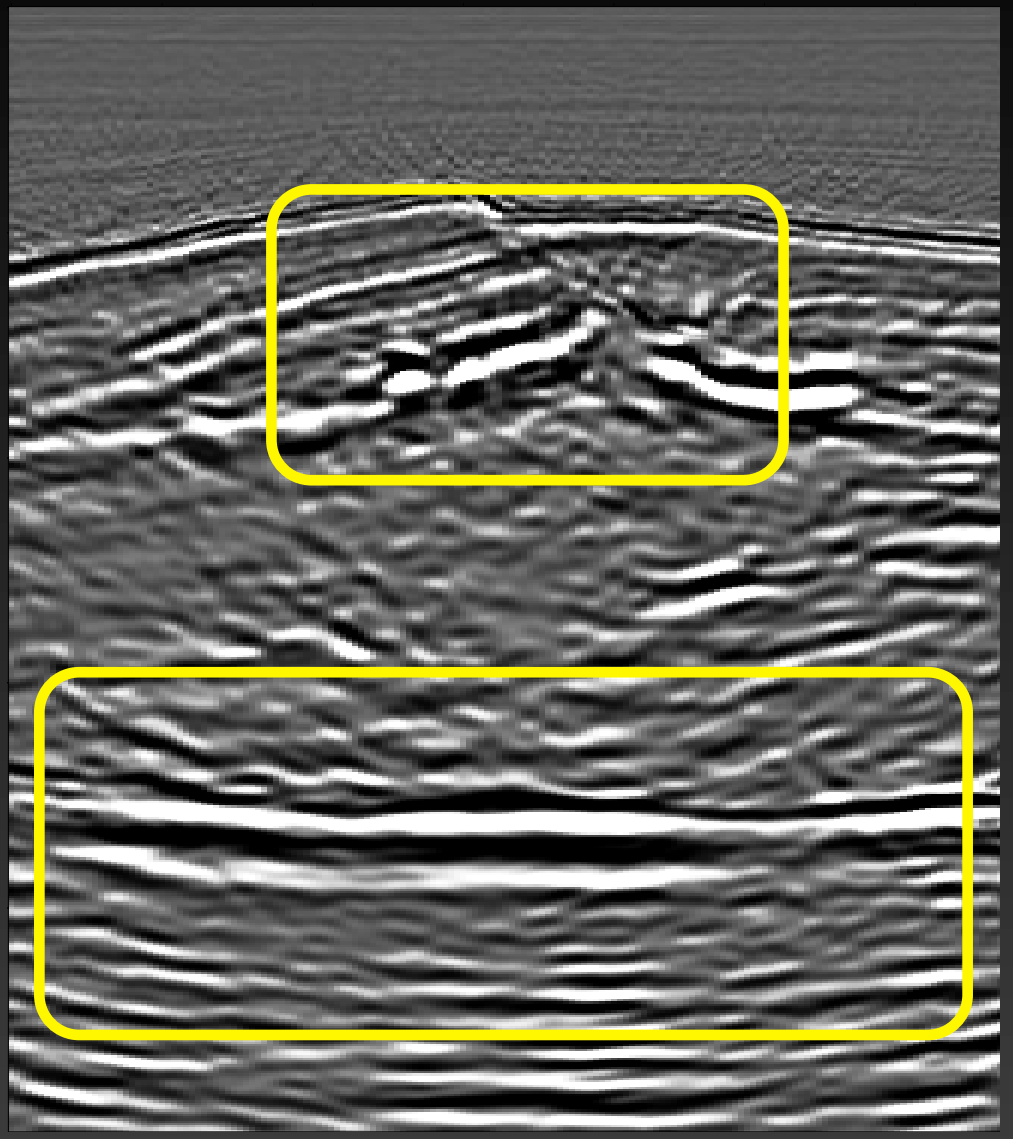


Comparison - crossline

Original

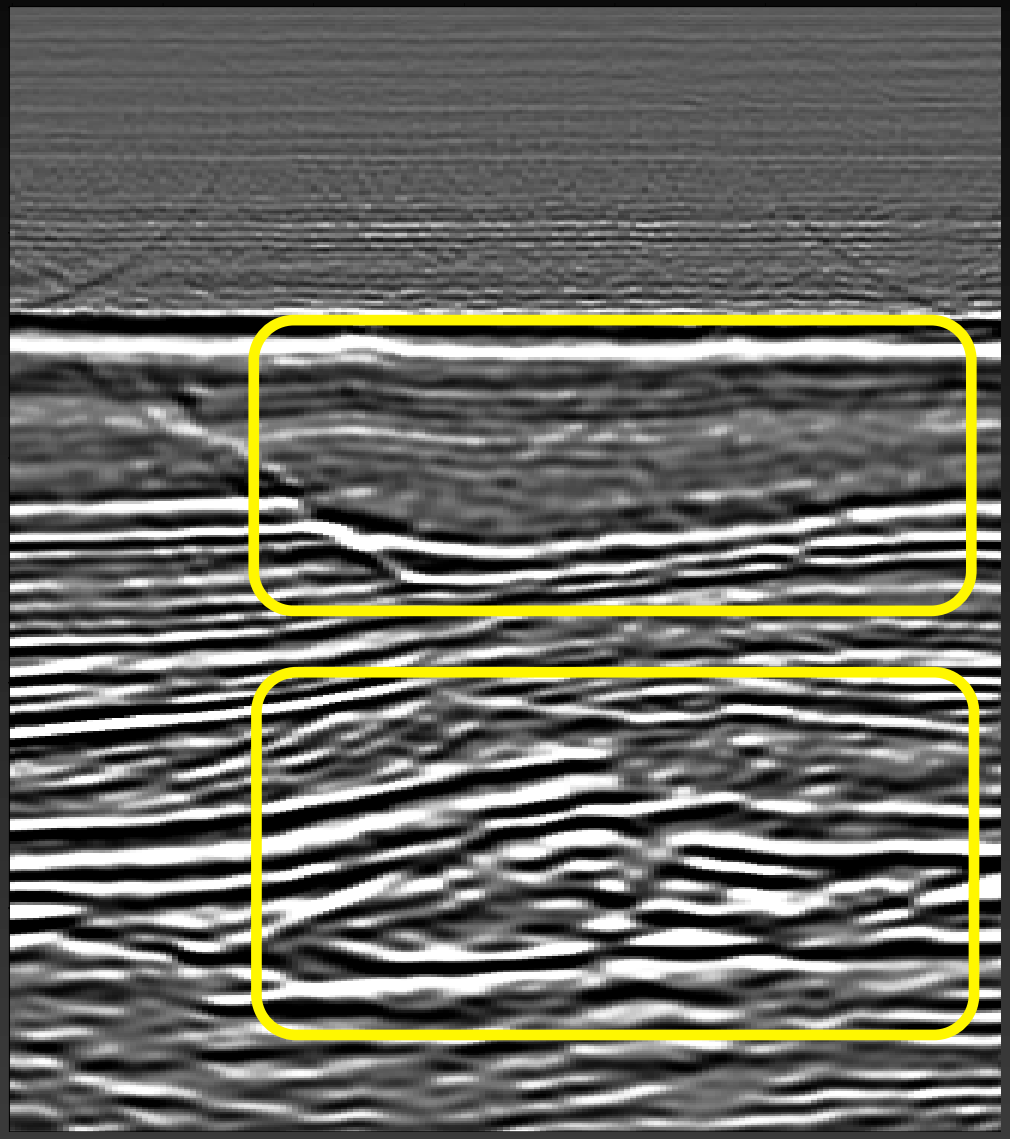


Final

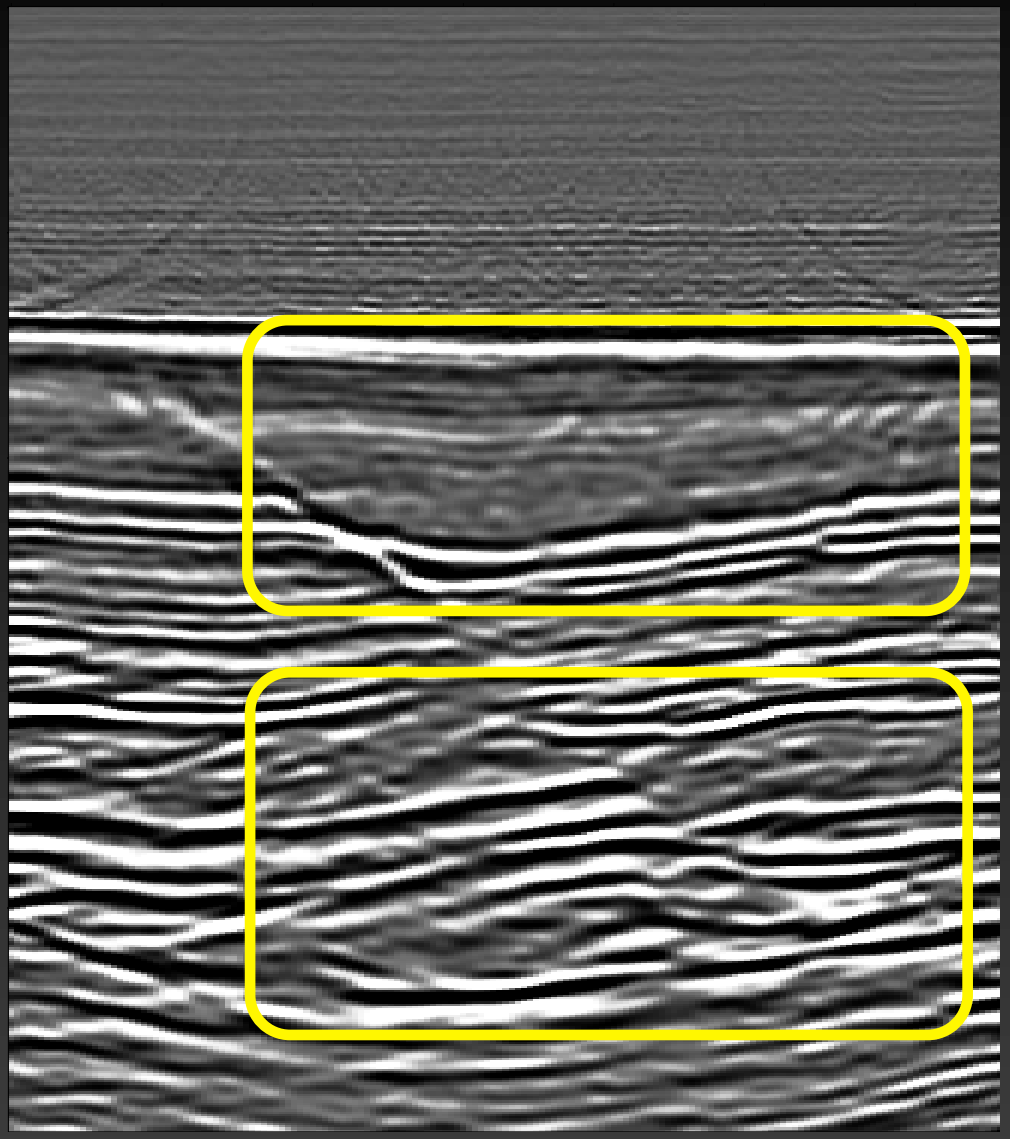


Comparison - crossline

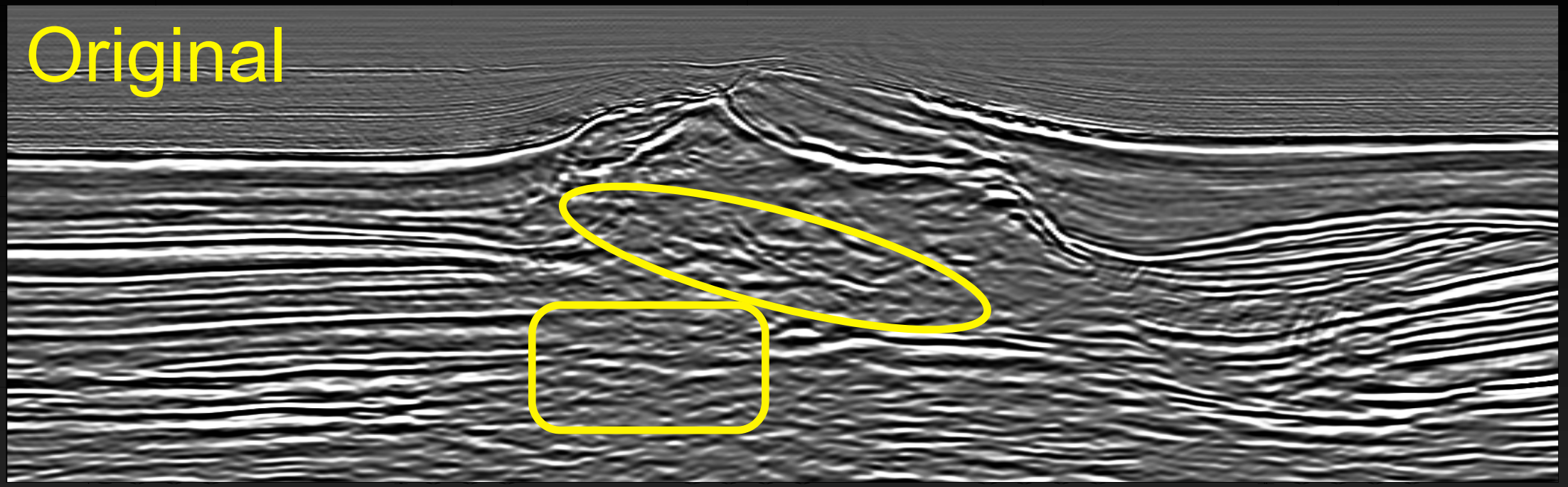
Original

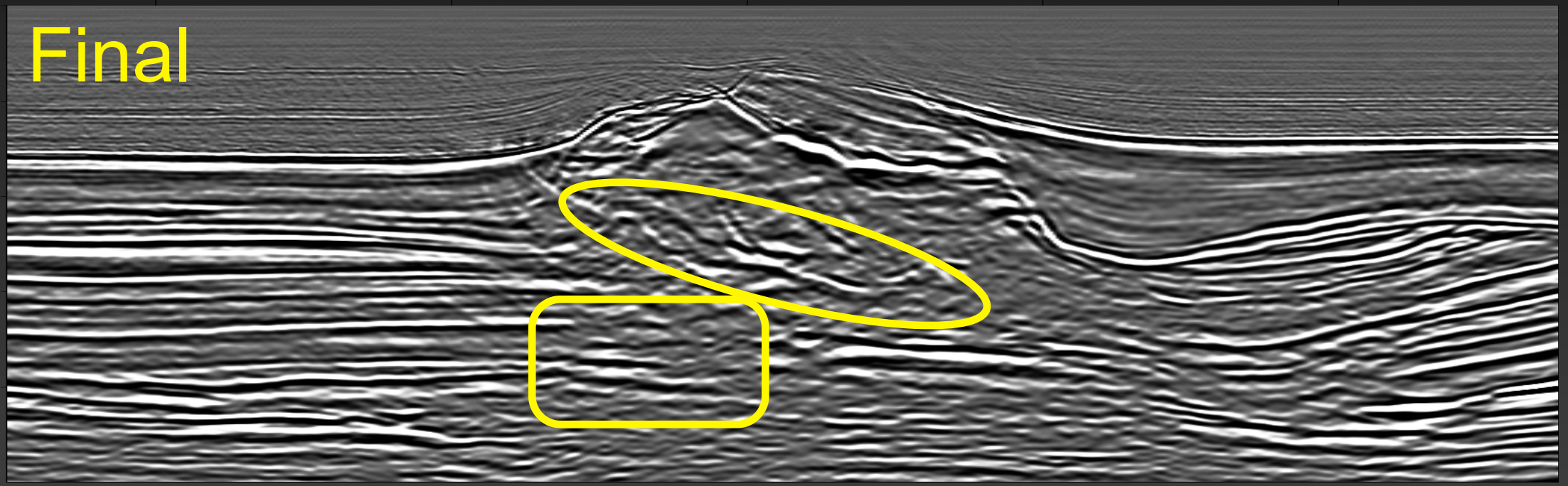


Final

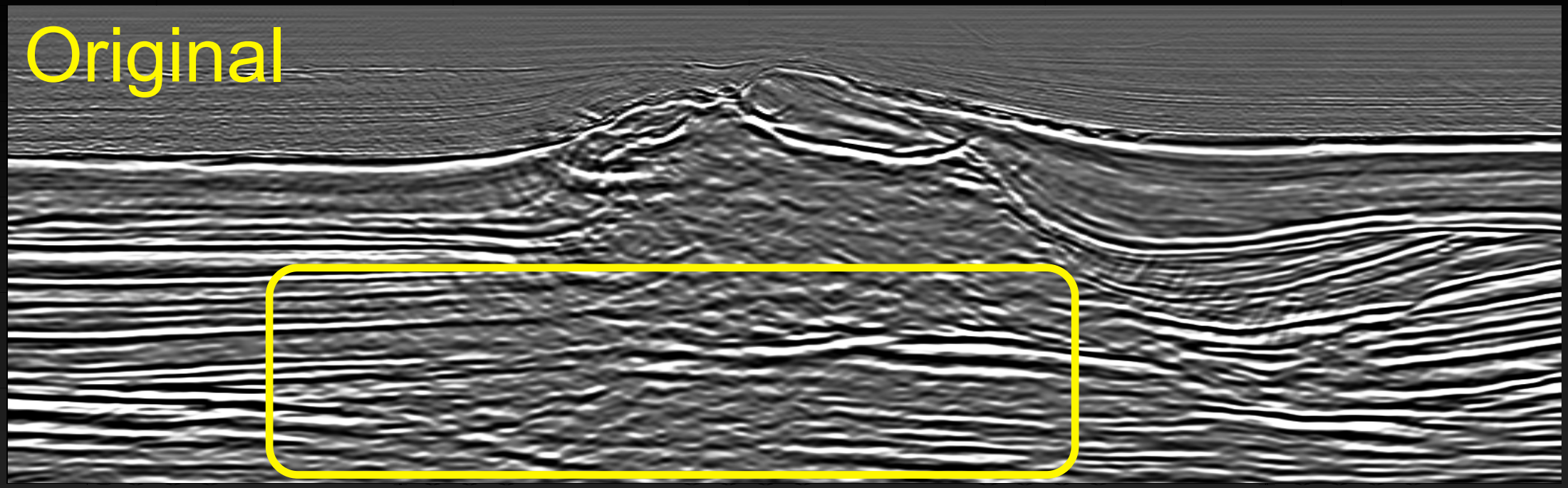


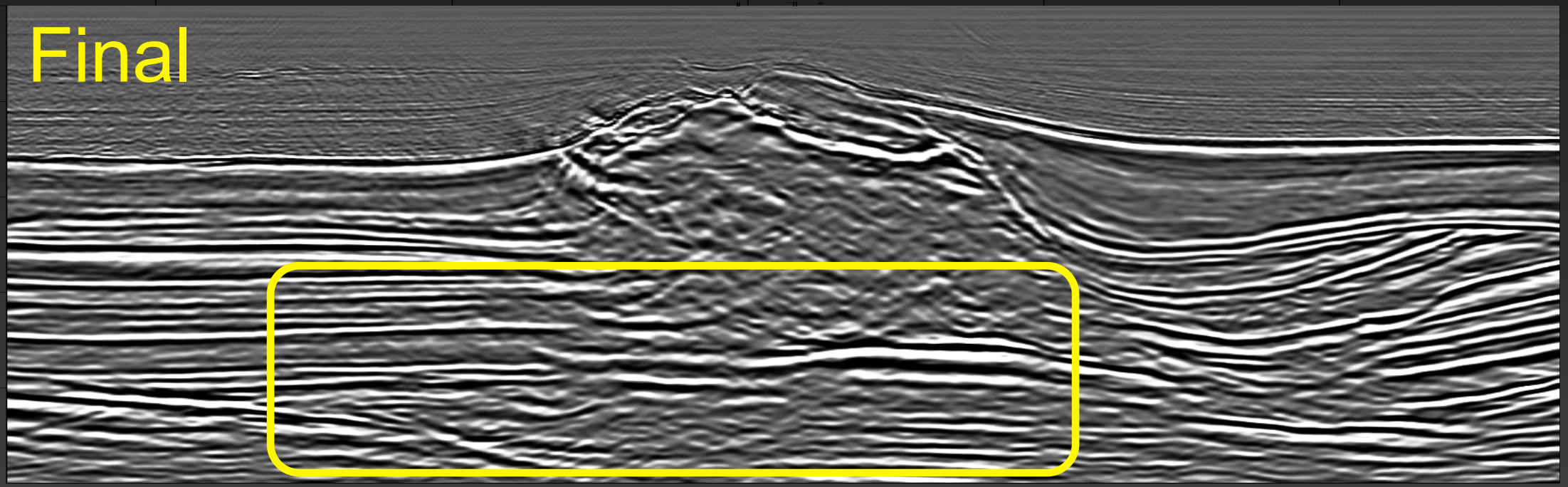
Comparison - inline





Comparison - inline





Comparison - inline

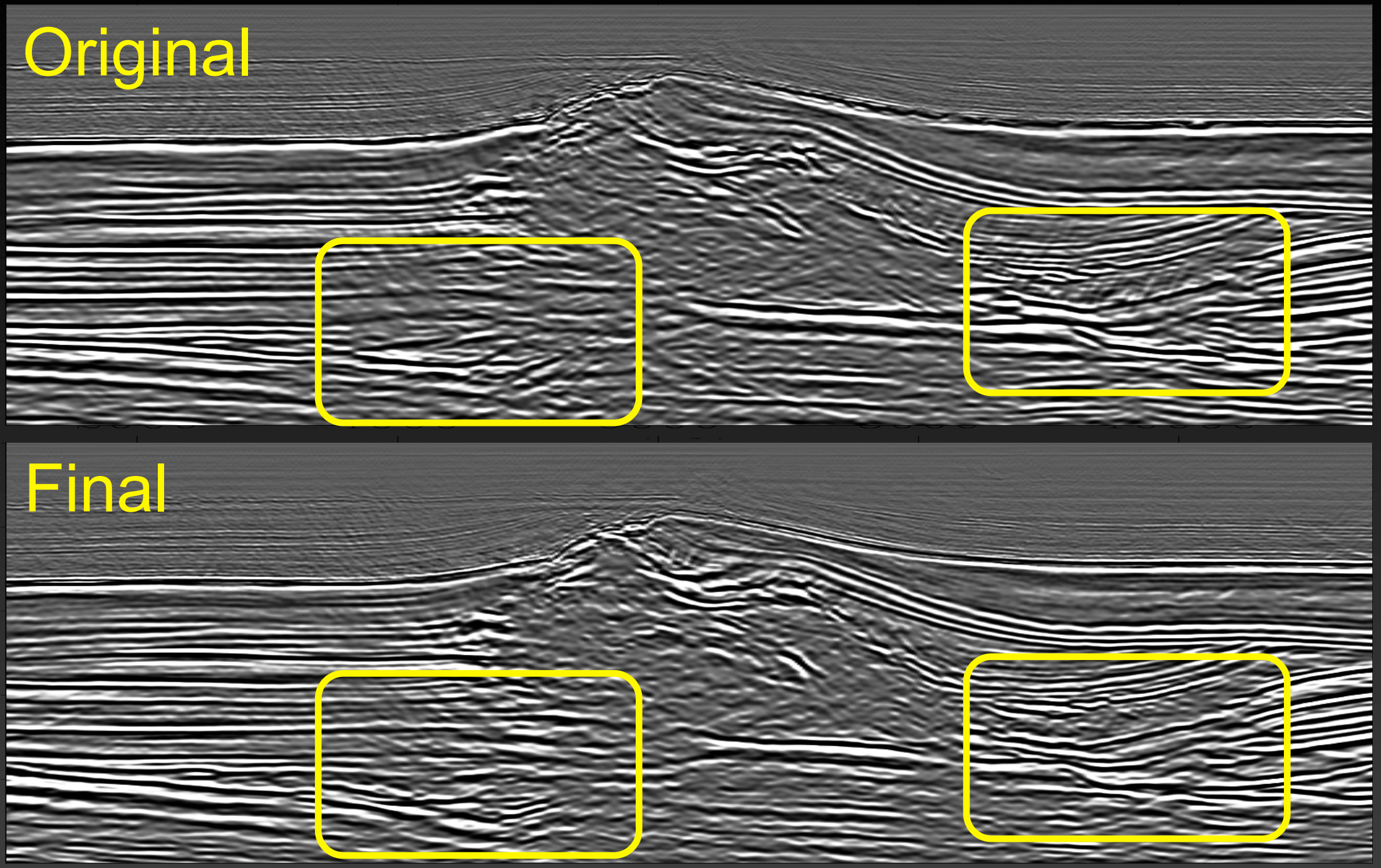


Image-space generalized wavefields

- **Accelerate ISWET**
  - **reduced data size**
  - **target-oriented strategy**

Image-space generalized wavefields

- **Accelerate ISWET**
  - **reduced data size**
  - **target-oriented strategy**

- **Naturally incorporate a horizon-based strategy**

Image-space generalized wavefields

- **Accelerate ISWET**
  - **reduced data size**
  - **target-oriented strategy**
- **Naturally incorporate a horizon-based strategy**
- **Yield accurate velocity updates**

Image-space generalized wavefields

- **Accelerate ISWET**
  - **reduced data size**
  - **target-oriented strategy**
- **Naturally incorporate a horizon-based strategy**
- **Yield accurate velocity updates**
- **Enable the routine use of ISWET**

Thanks to

- Sponsors of the **Stanford Exploration Project** for the financial support

- **TotalFinaElf** for providing the North Sea dataset

- **Petrobras** for providing all the necessary support

Thanks

Data-space: 0° plane wave

source

time

distance

downgo

time

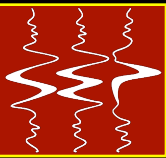
distance

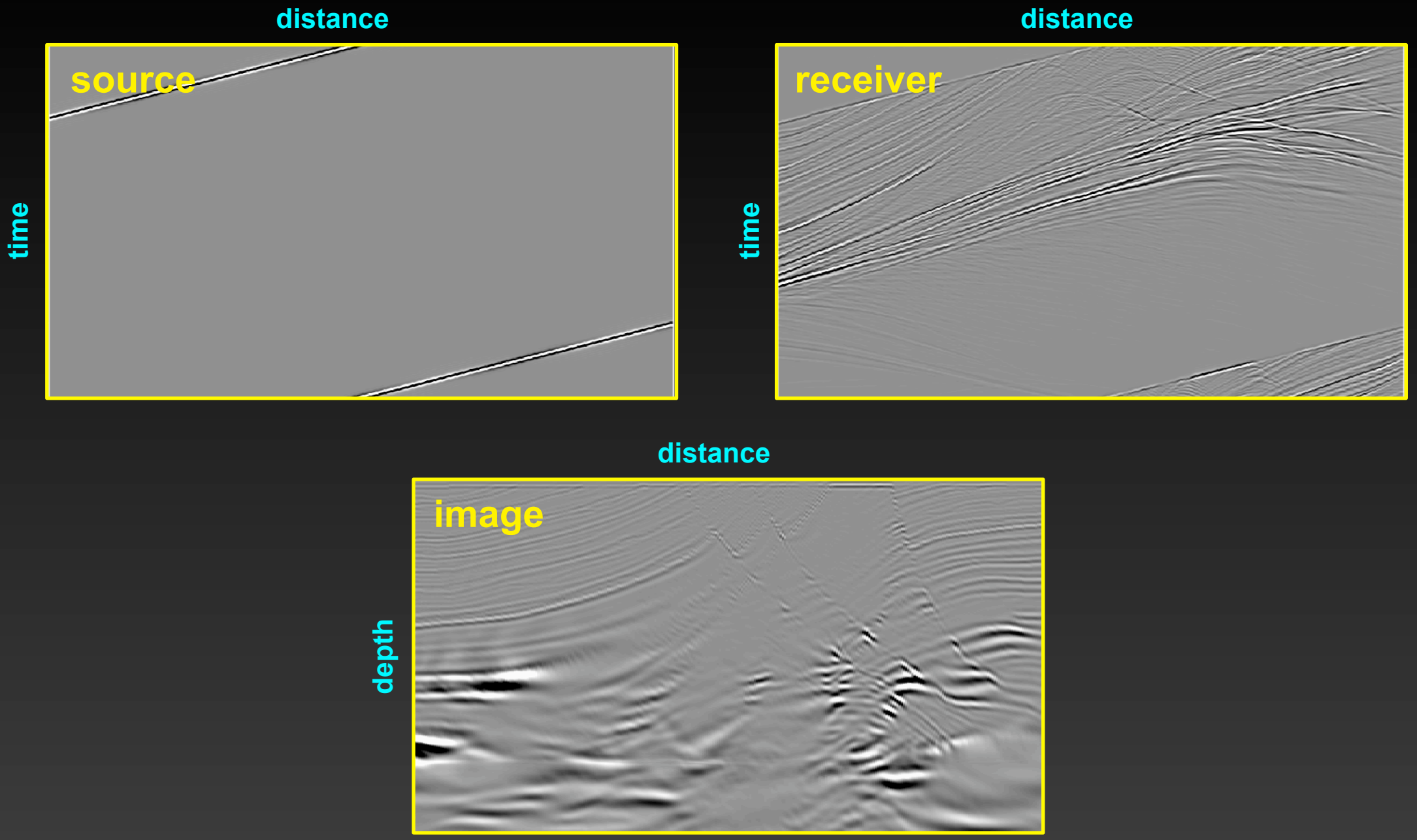
image

depth

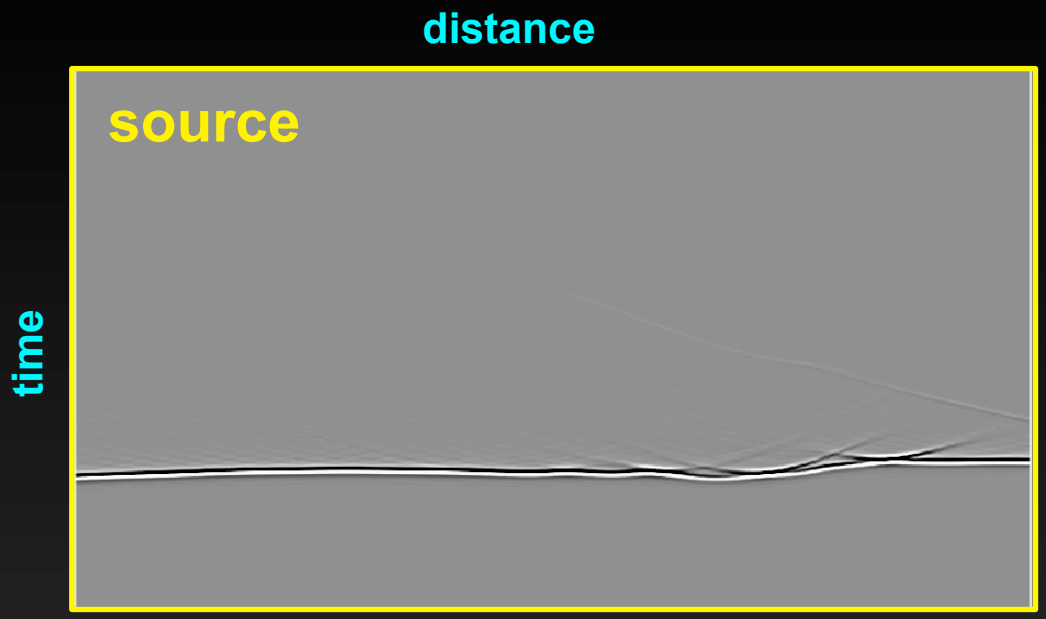
distance

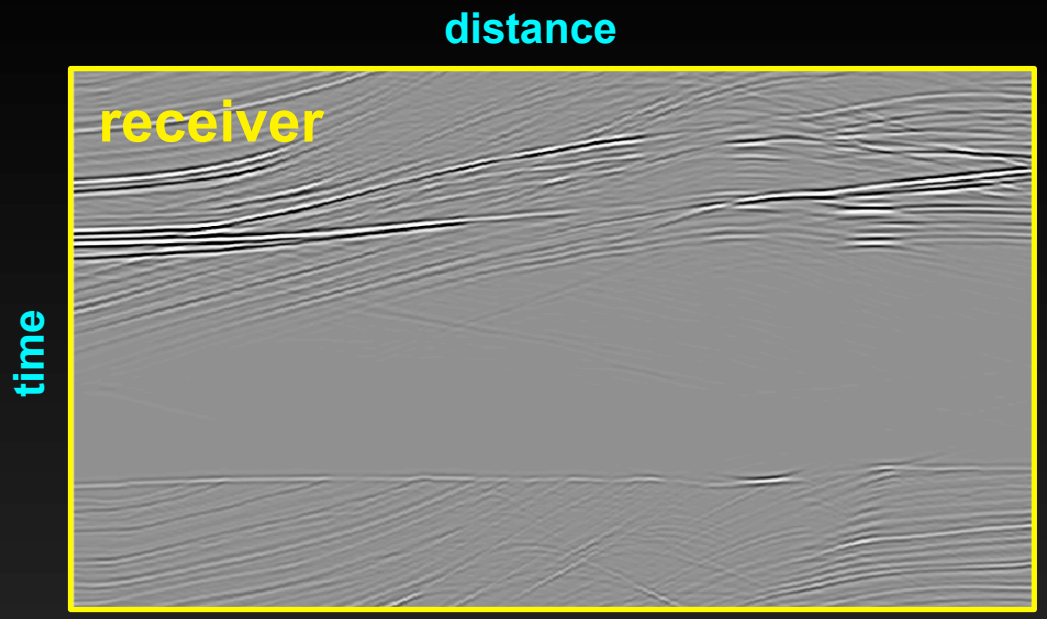
Data-space: plane waves





Data-space: controlled illumination





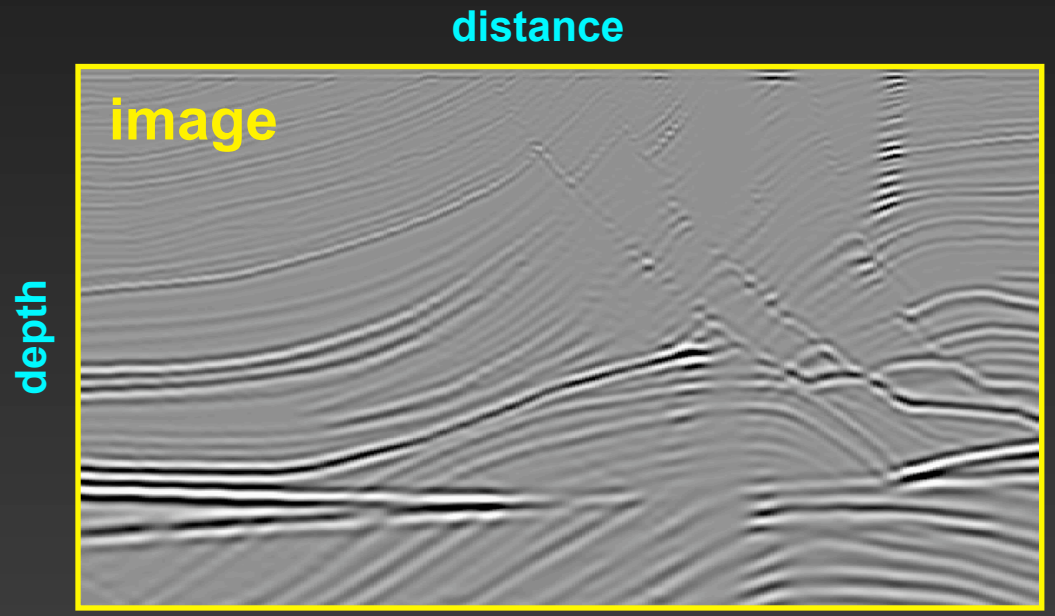
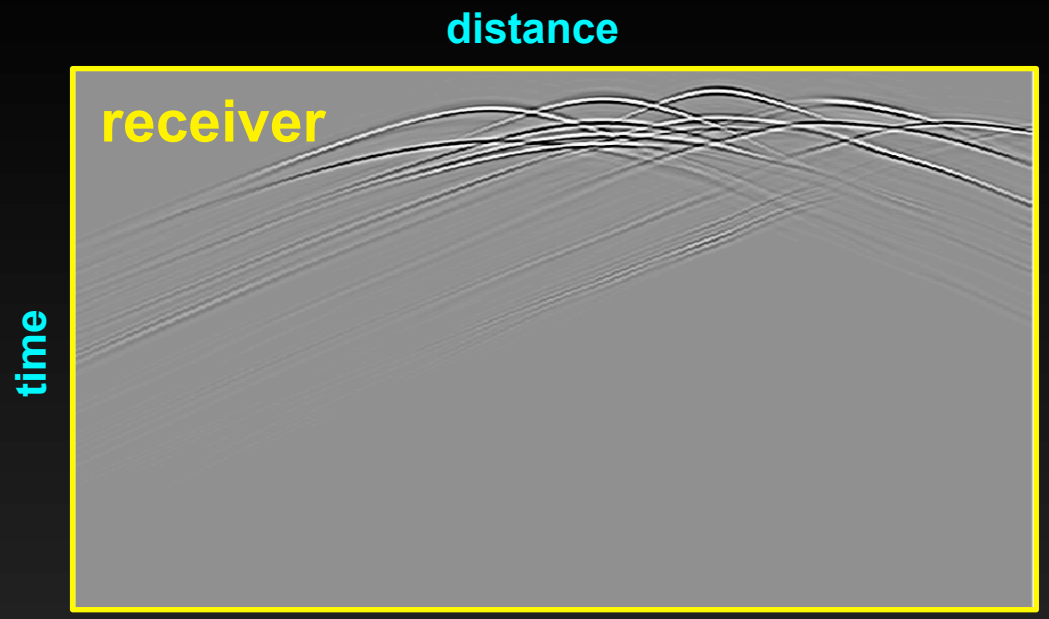


Image-space: prestack-exploding reflector



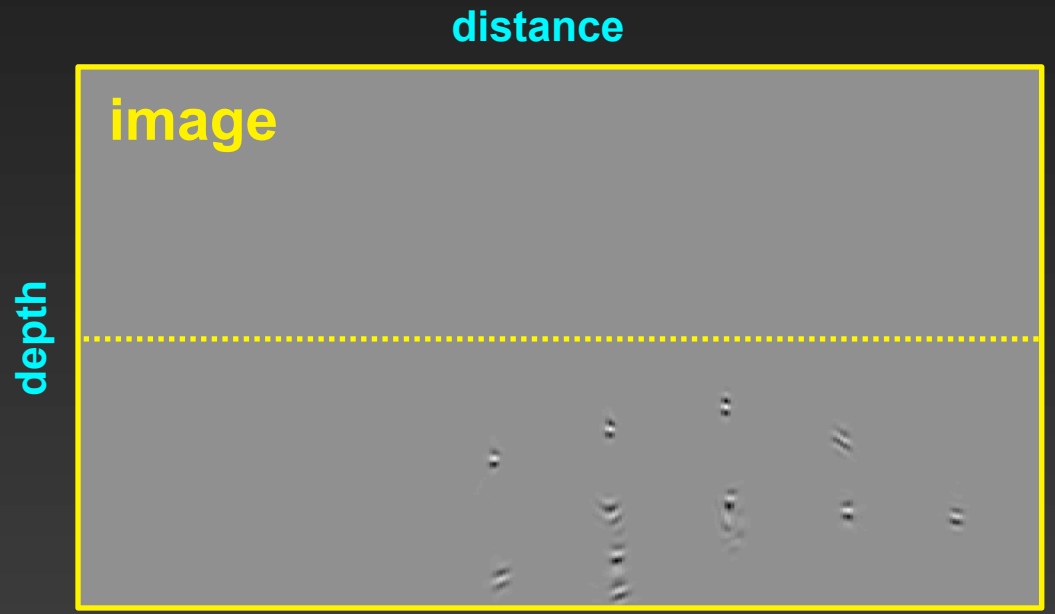
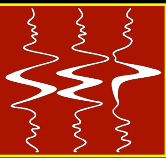
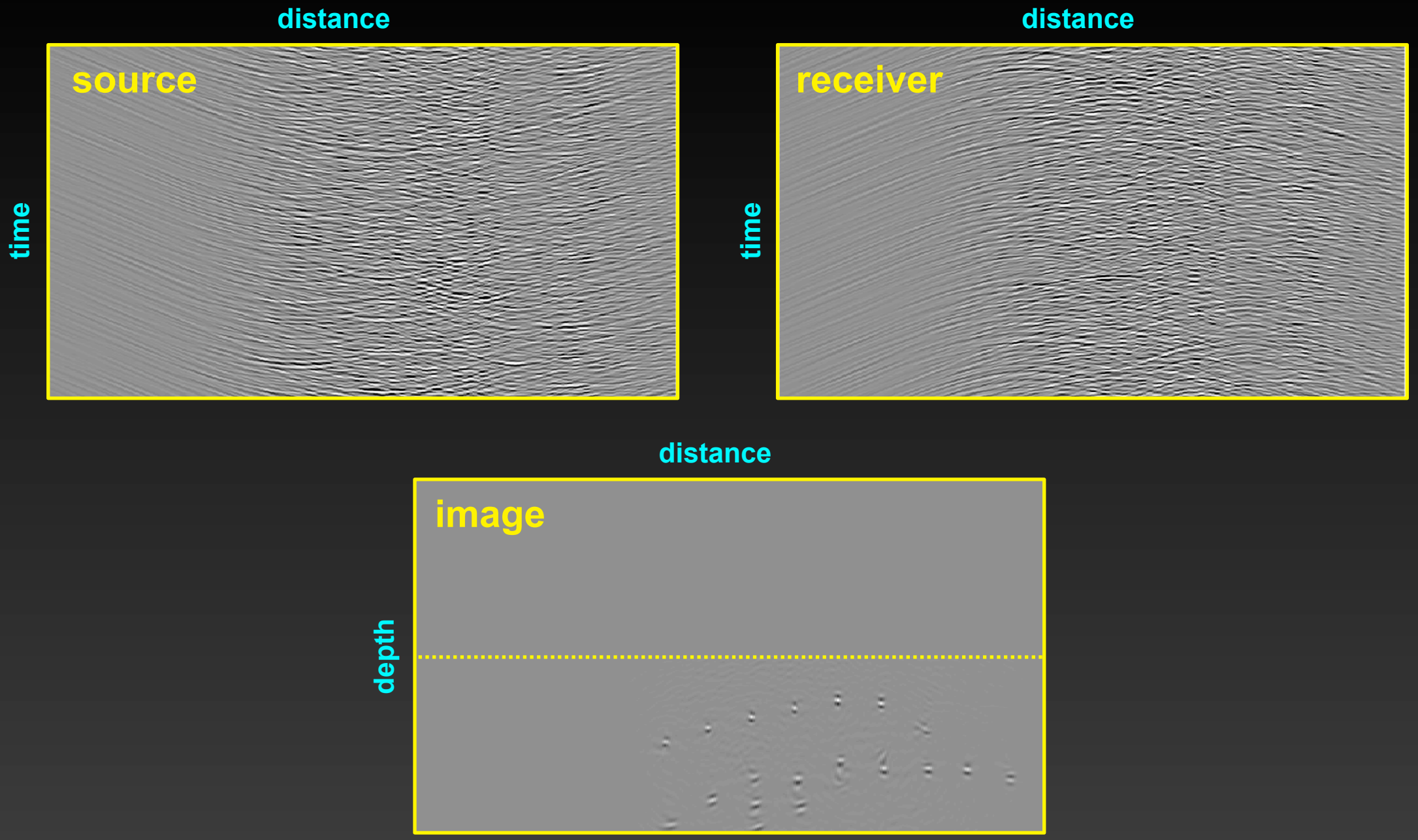
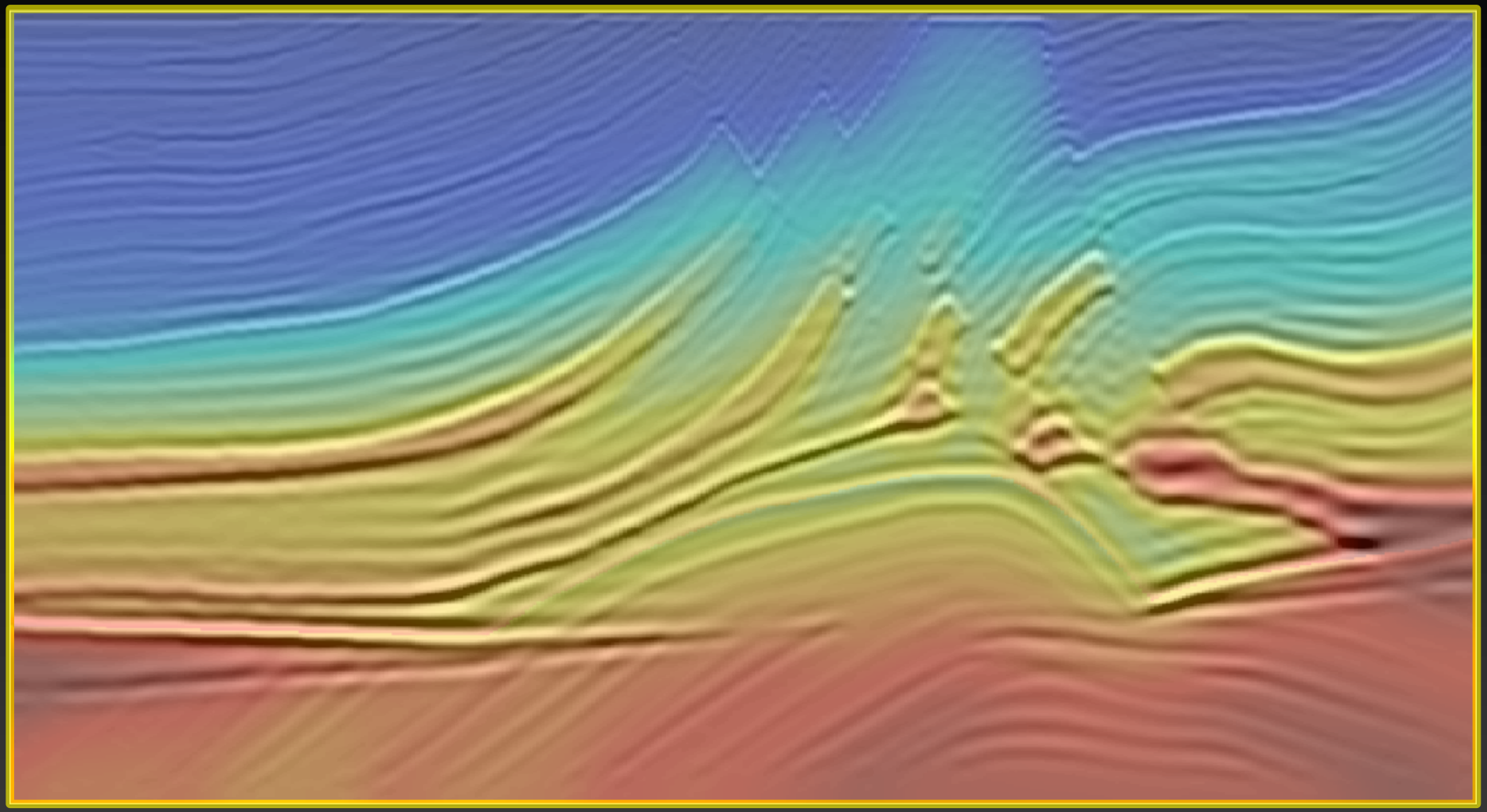


Image-space: random phases (ISPEW)

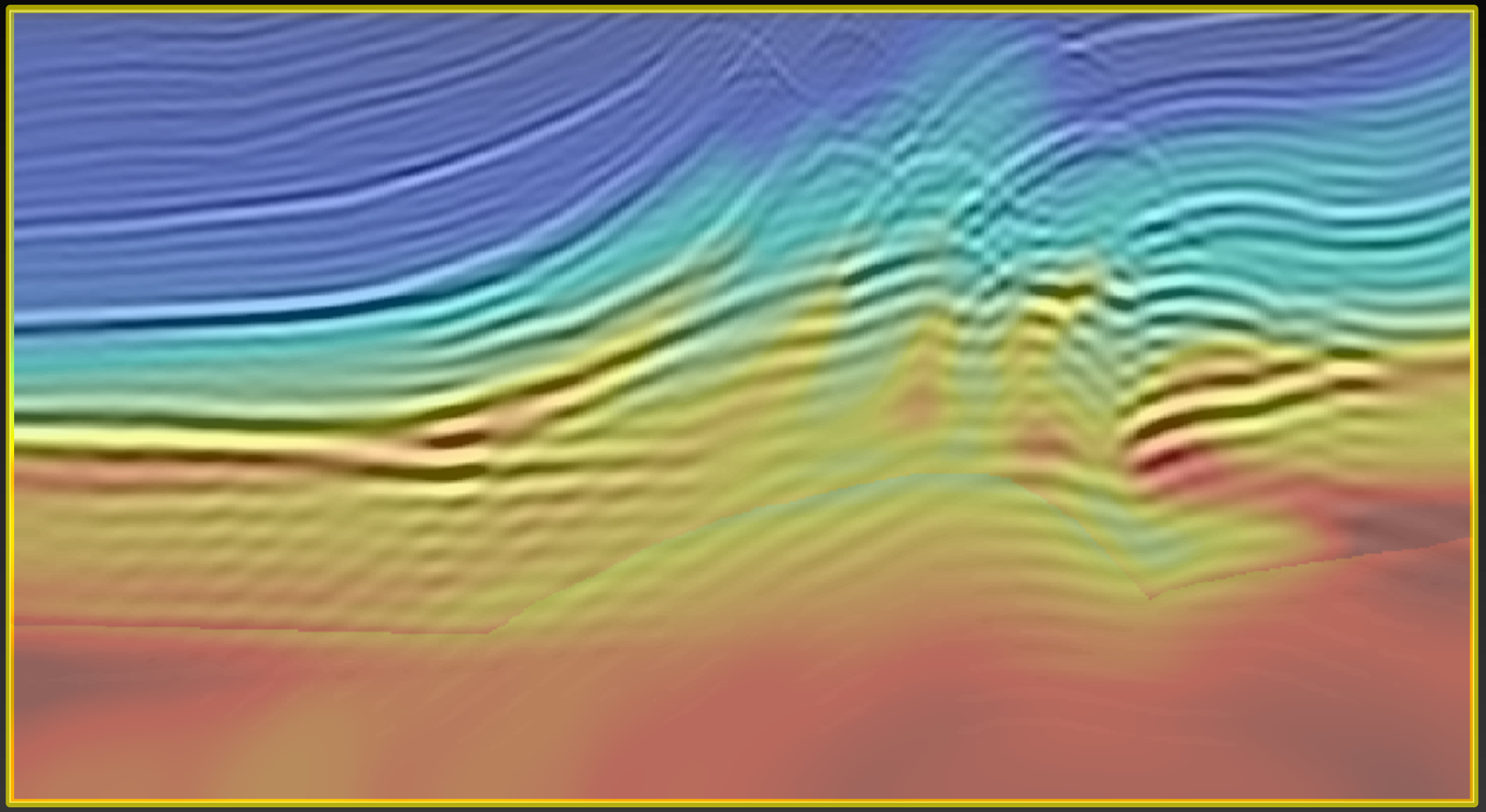




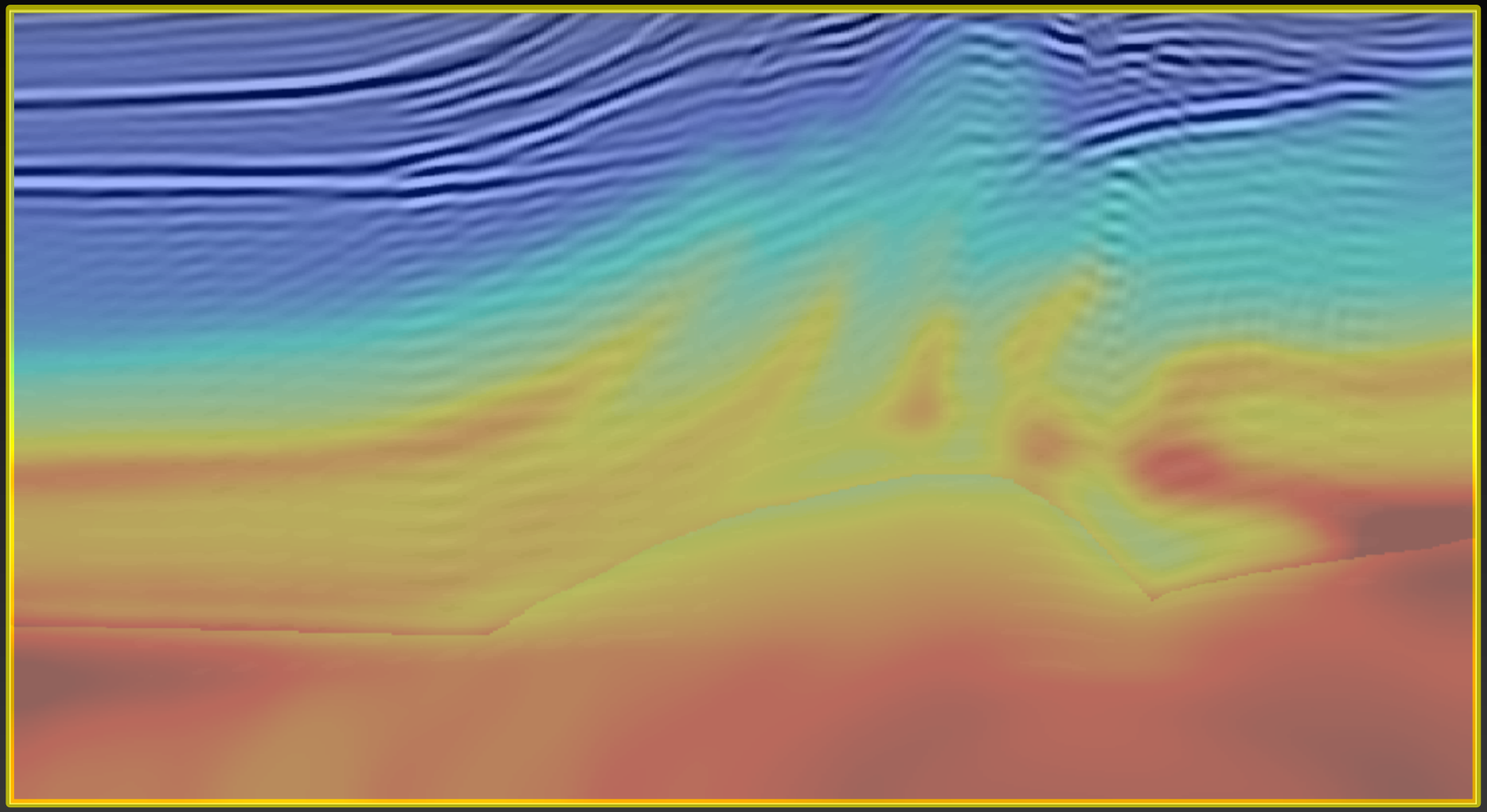
Exploding reflectors



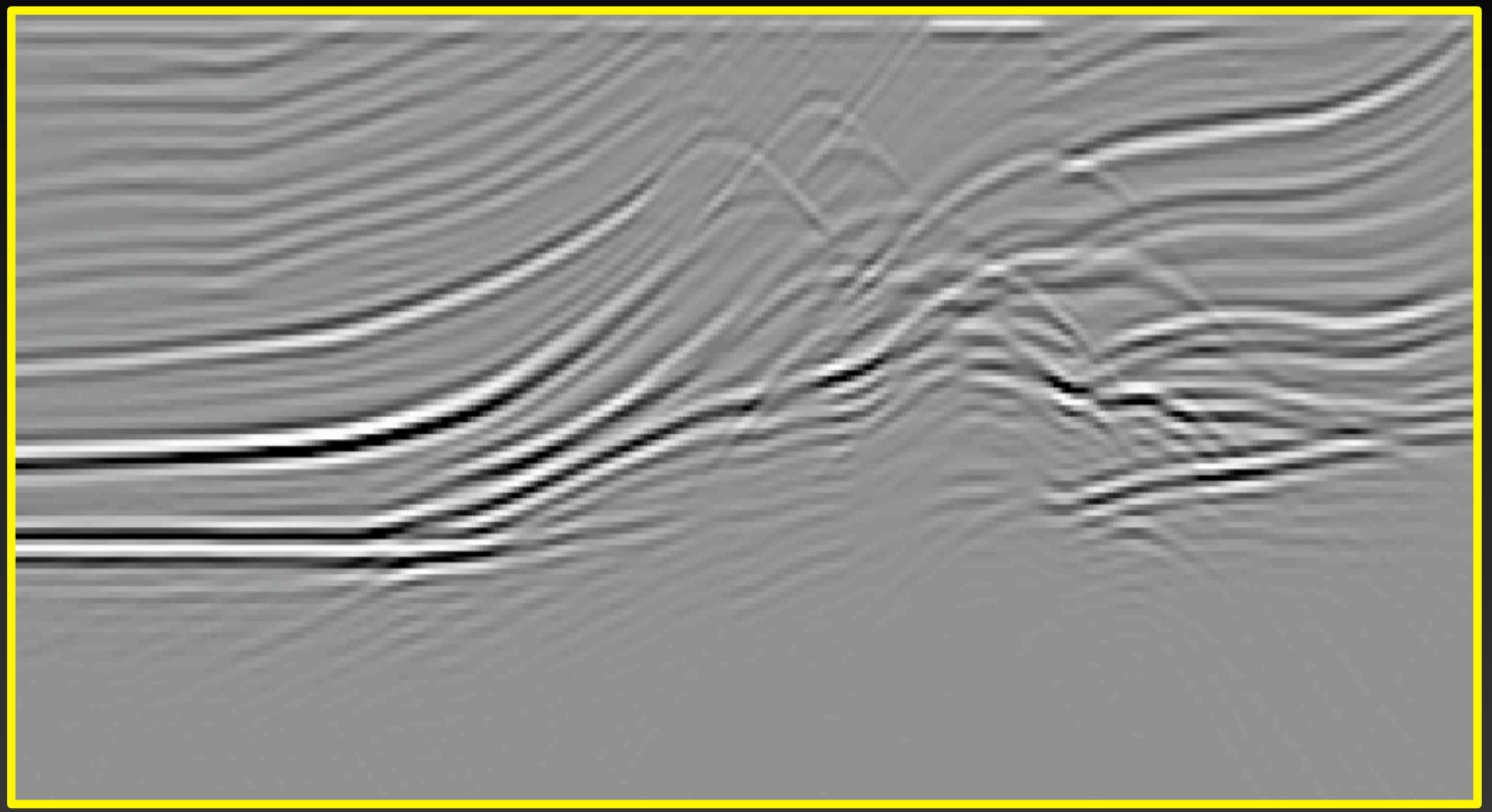
Exploding reflectors



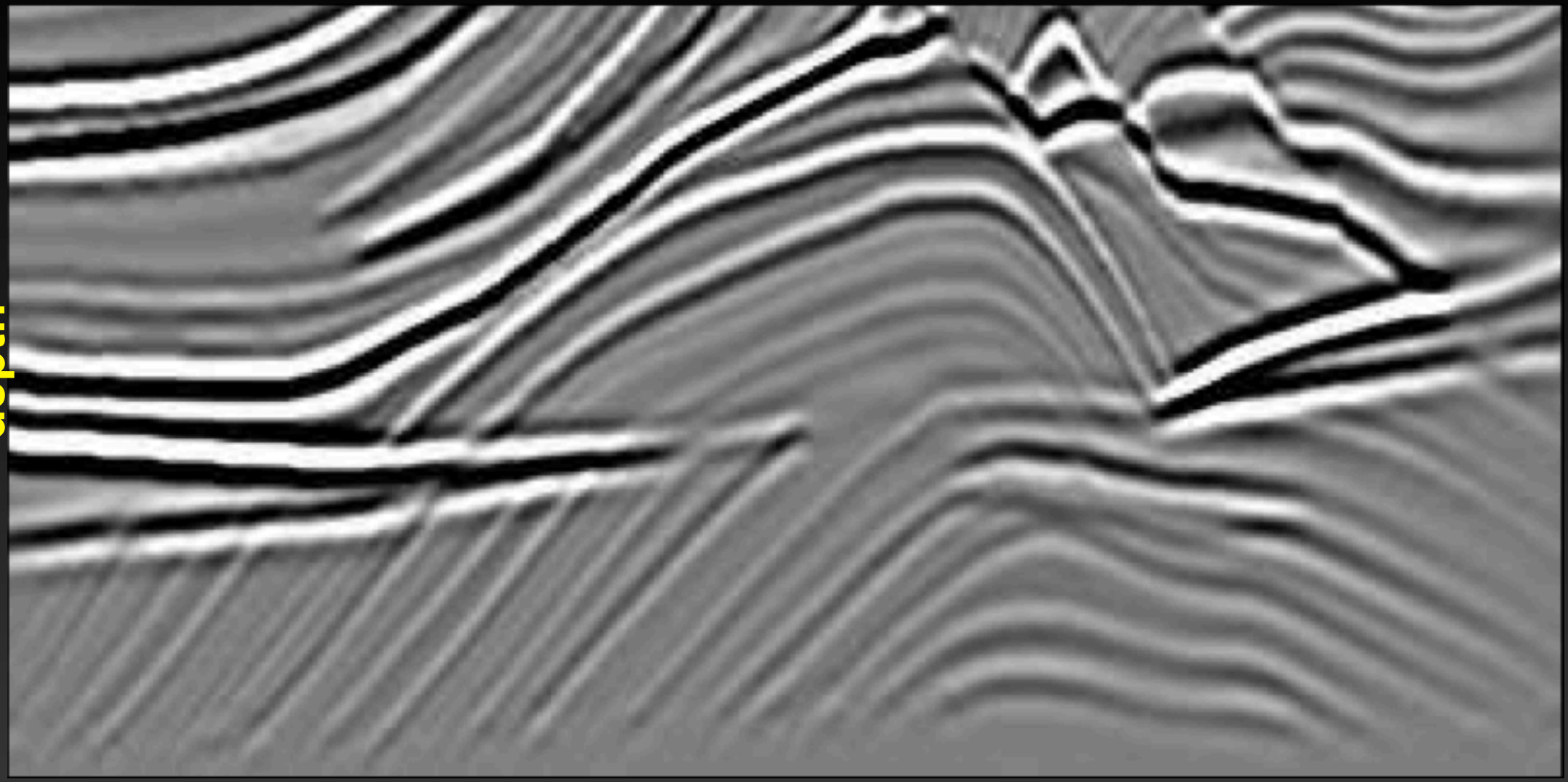
Exploding reflectors



Zero-offset section

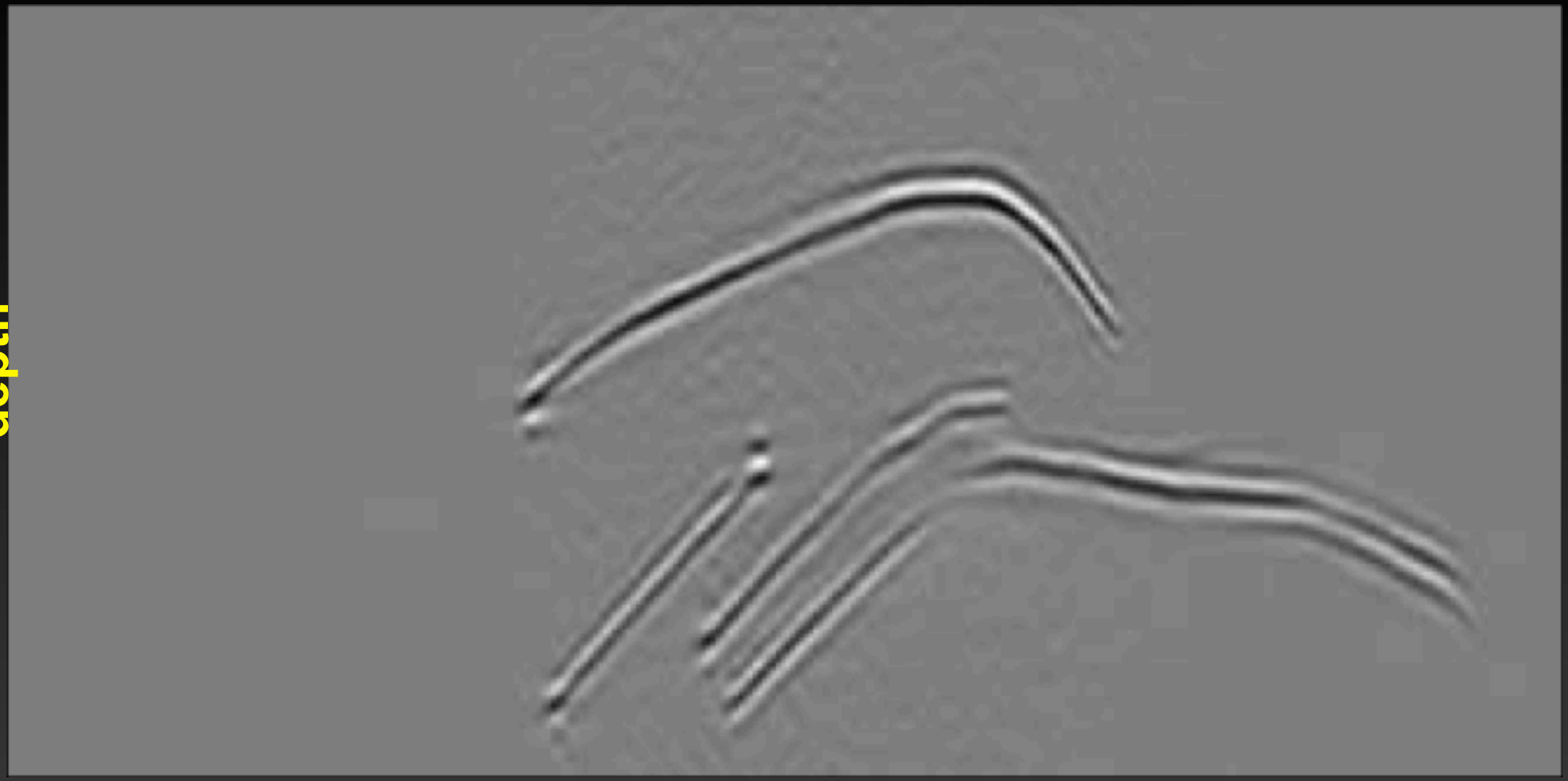


Migration of 375 shot profiles



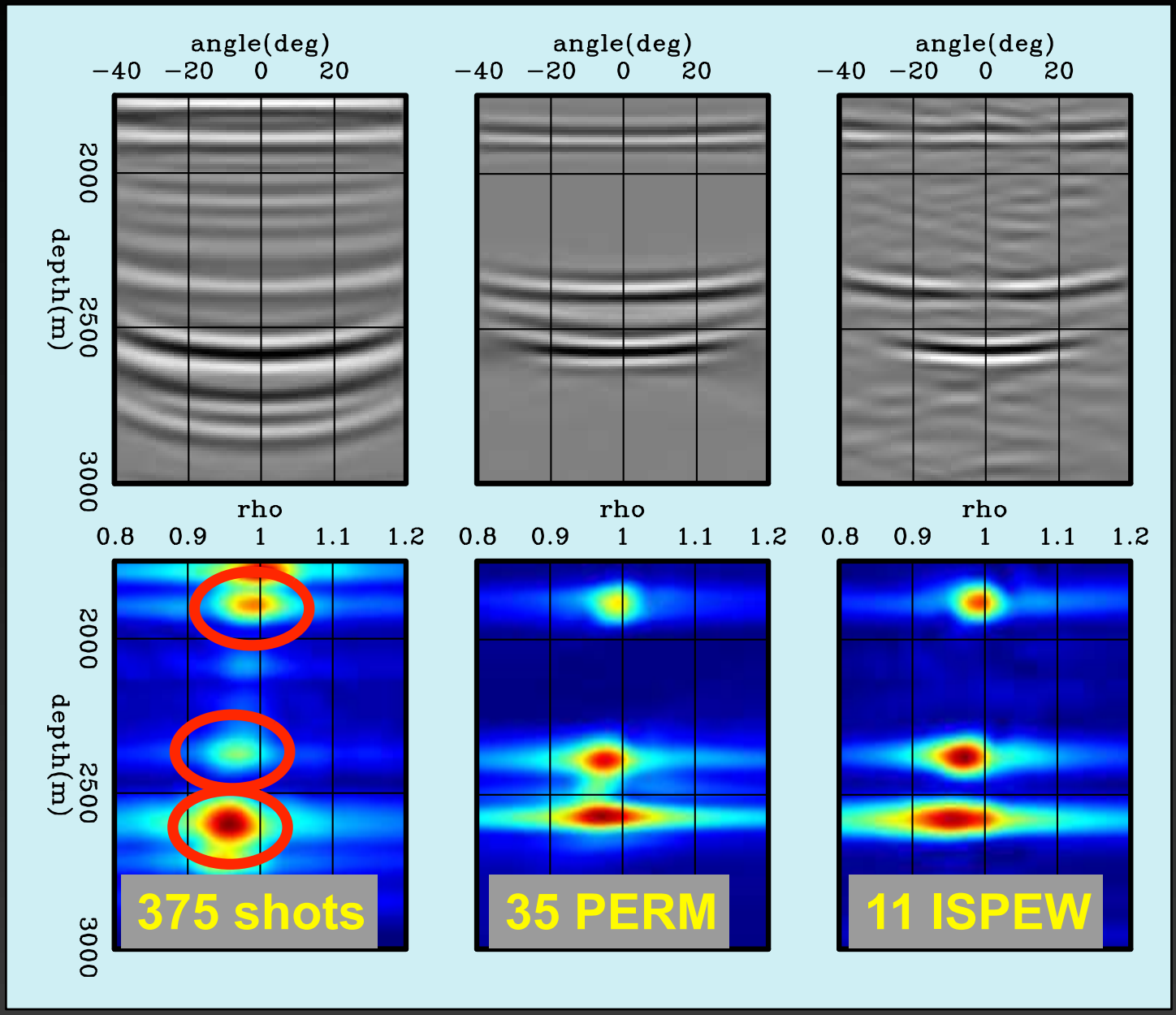
Selected reflectors

11 ISPEW migrated image



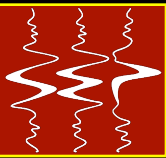
Selected reflectors

Velocity information



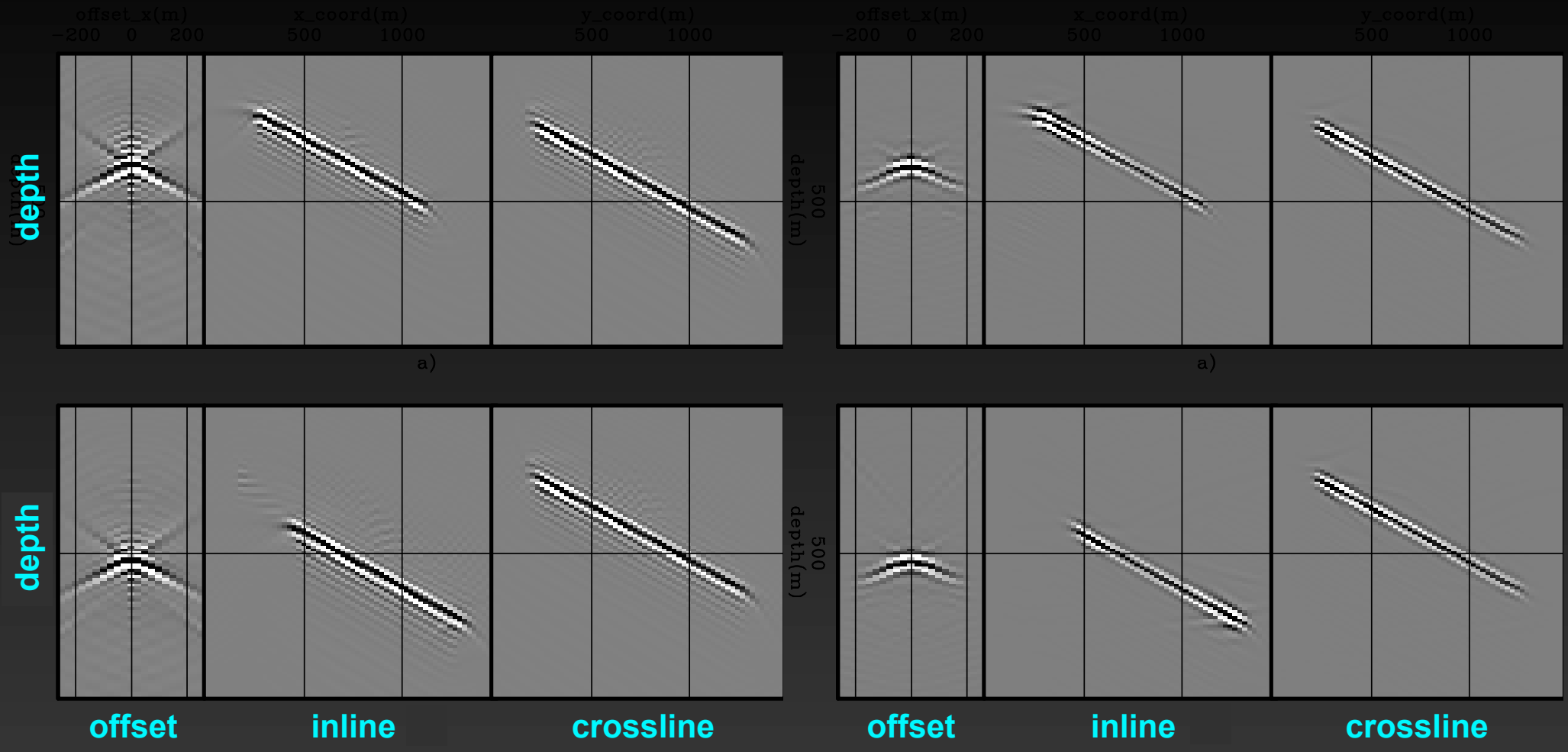
rho - curvature parameter

Using CAM images as the initial conditions

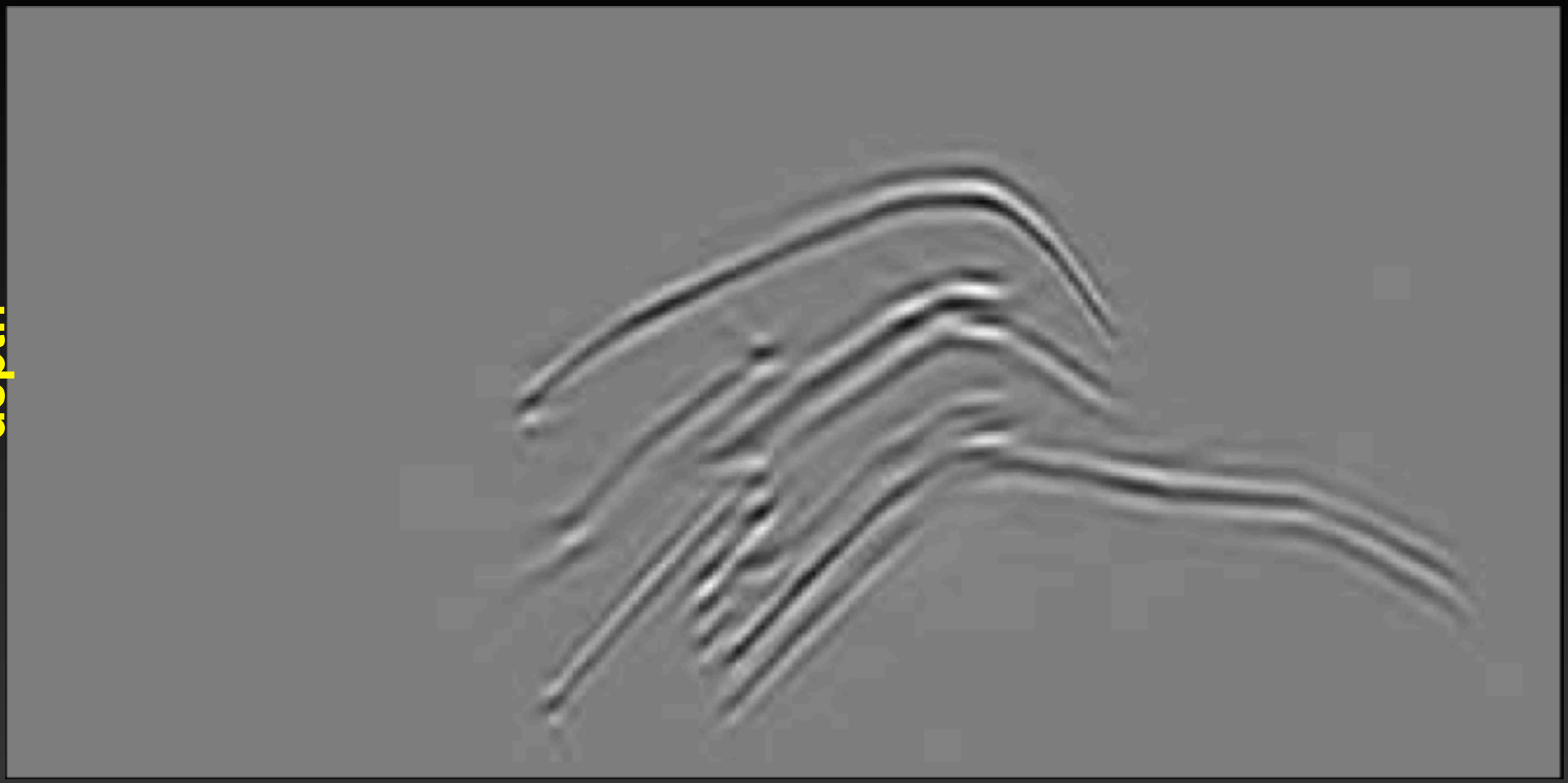


CAM

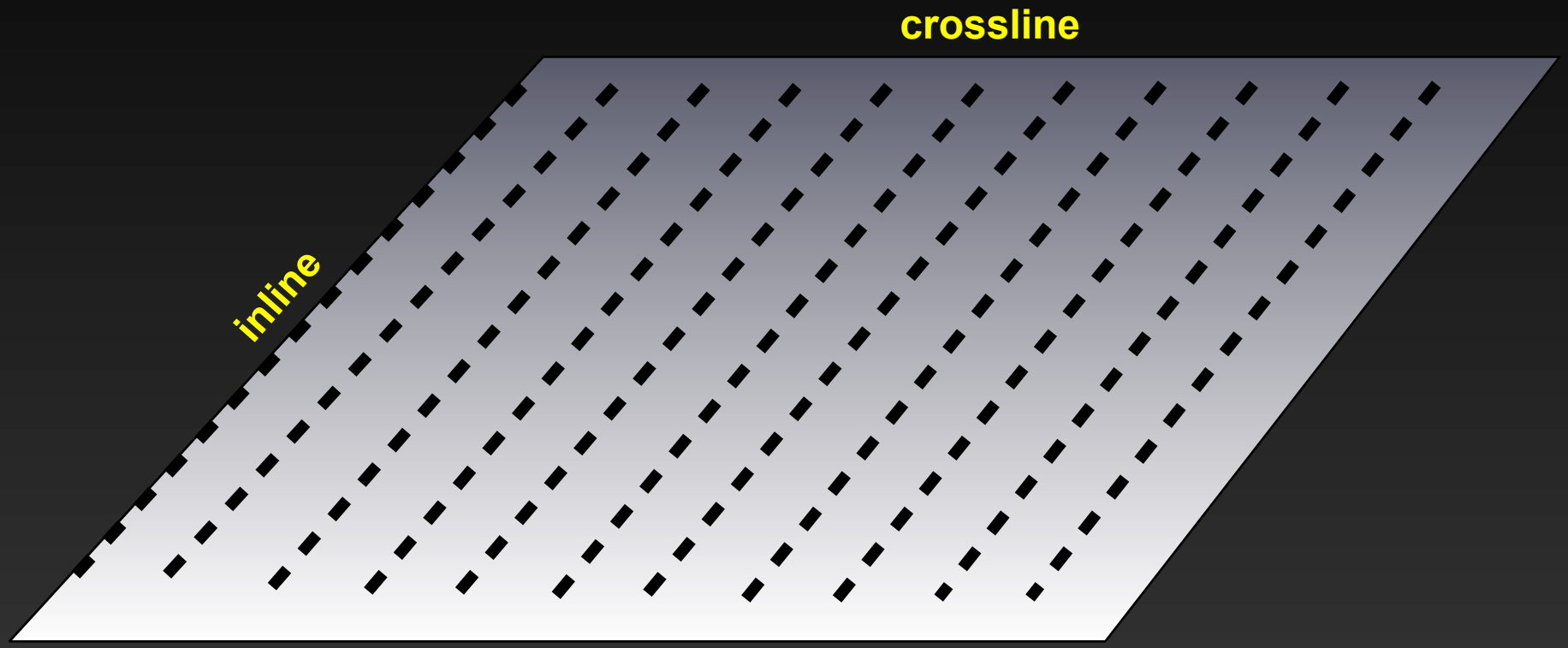
PERM



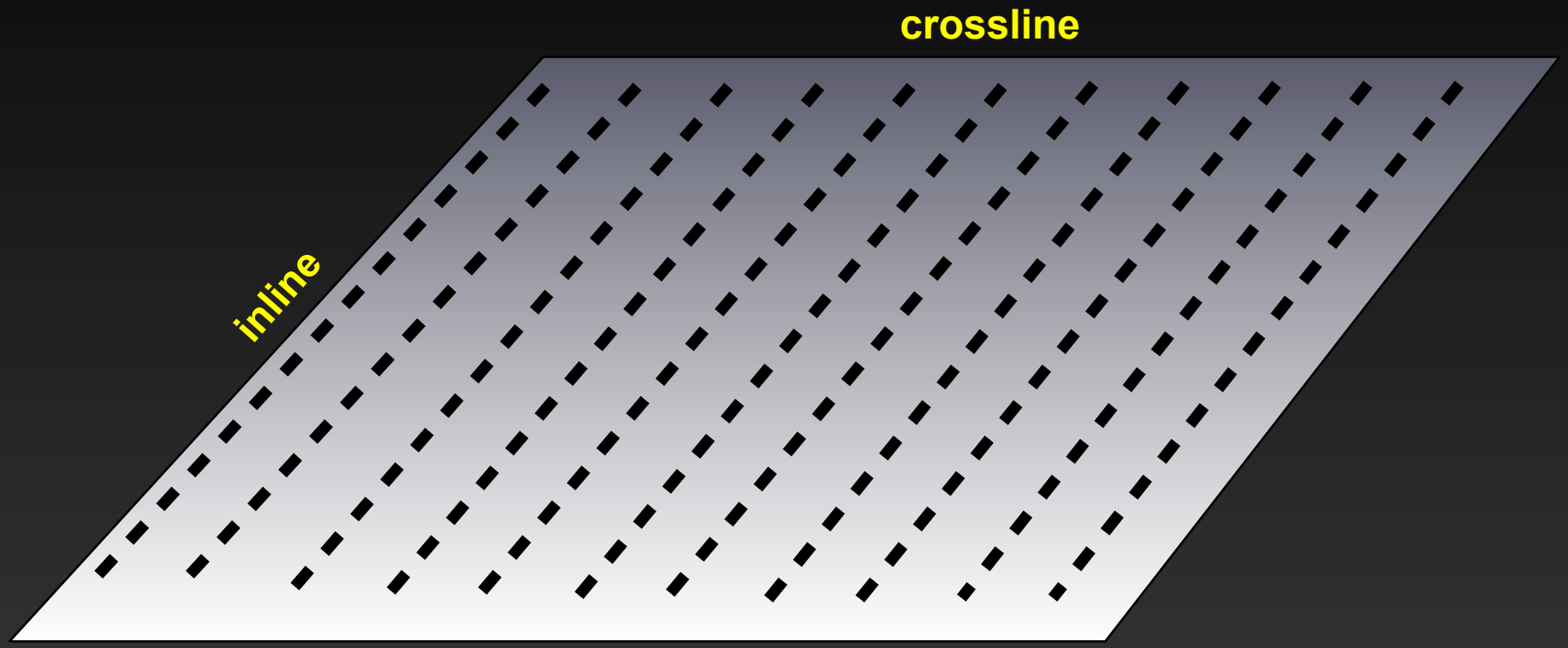
35 PERM migrated image



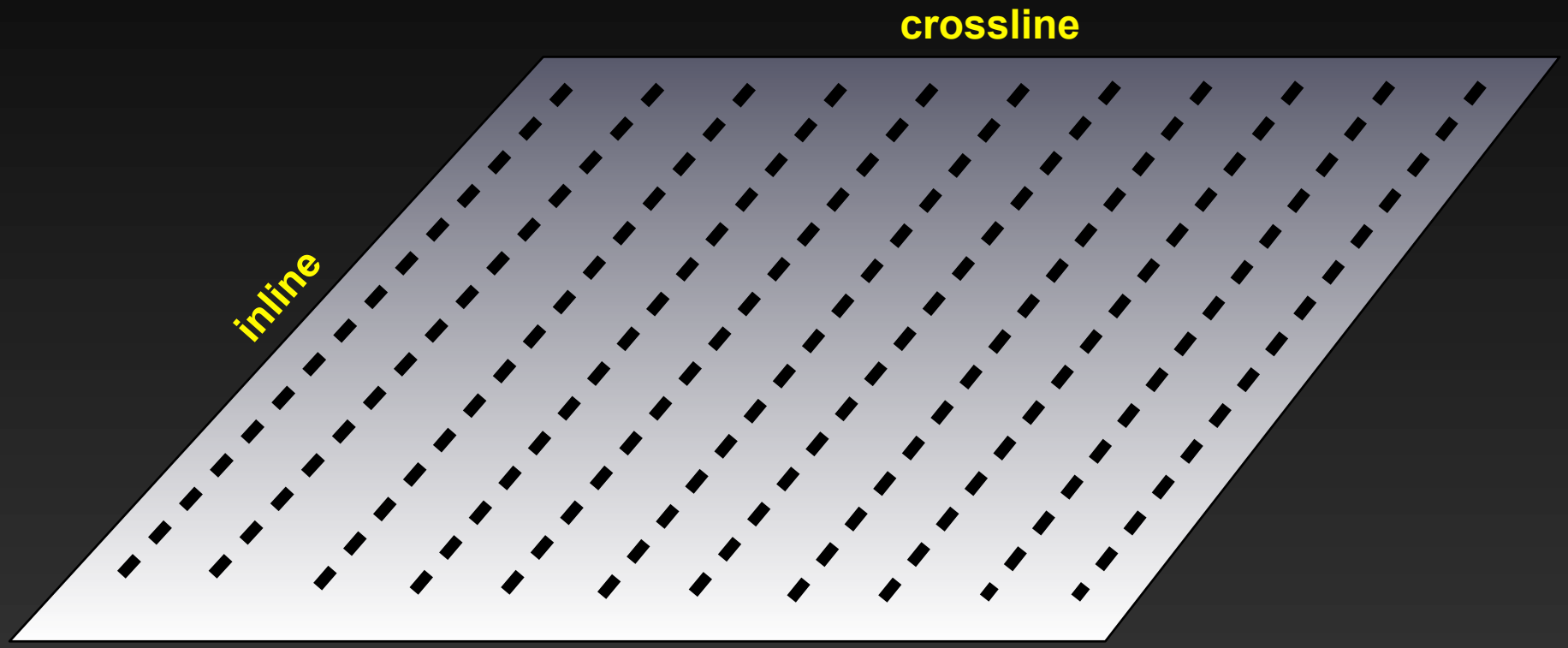
3D PERM initial conditions



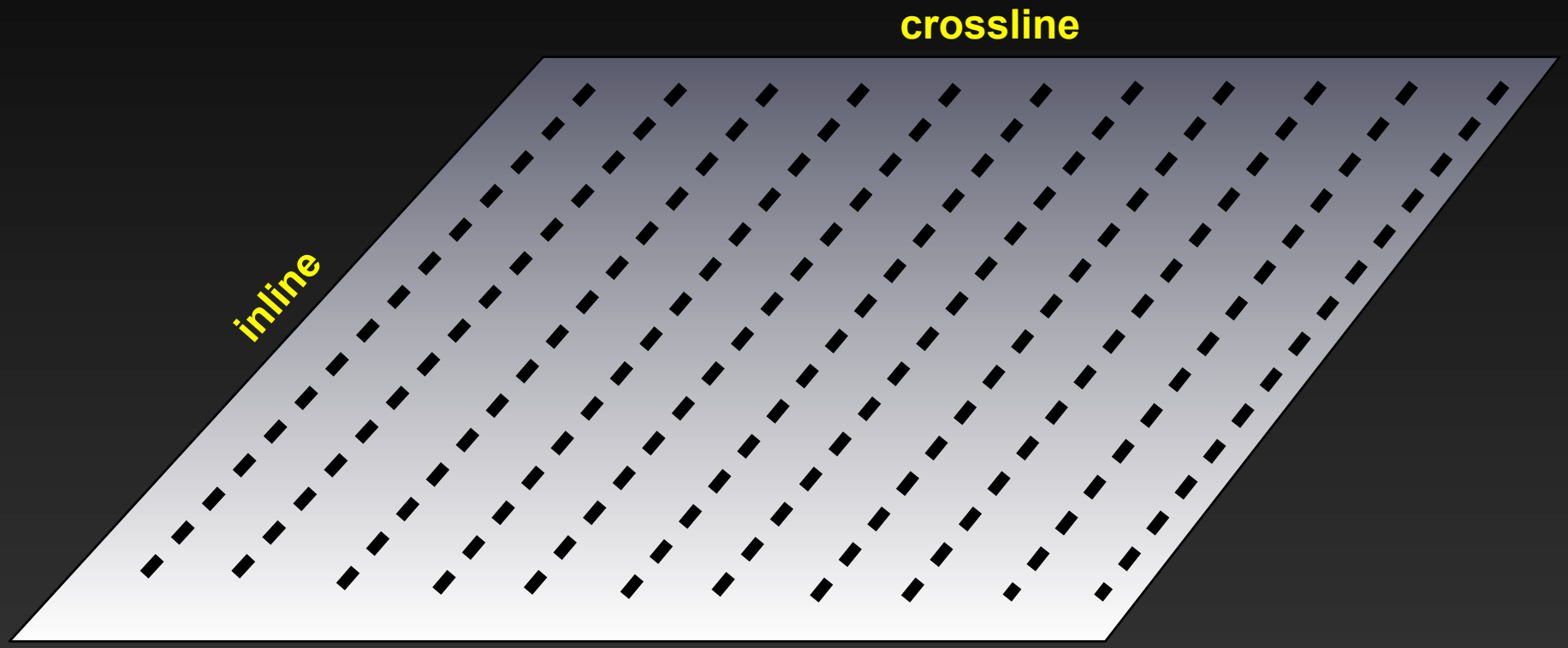
3D PERM initial conditions



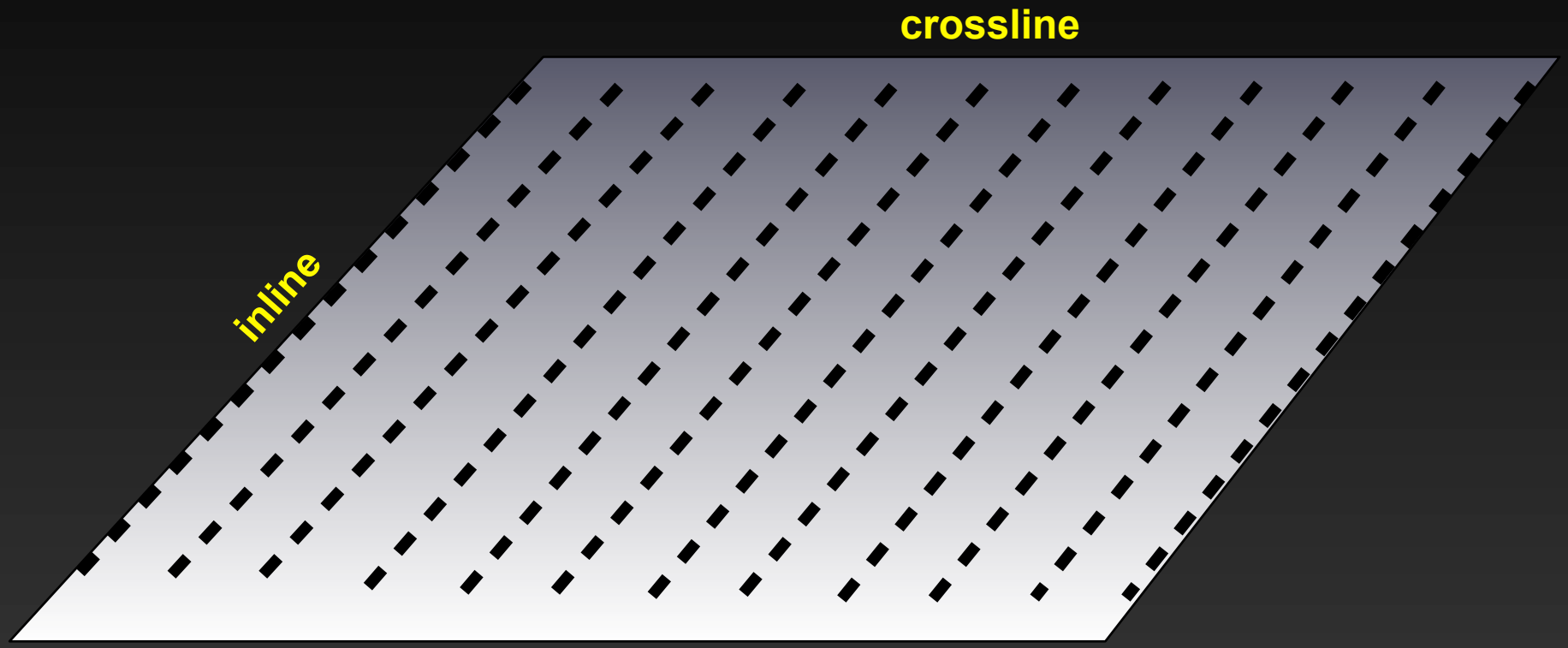
3D PERM initial conditions



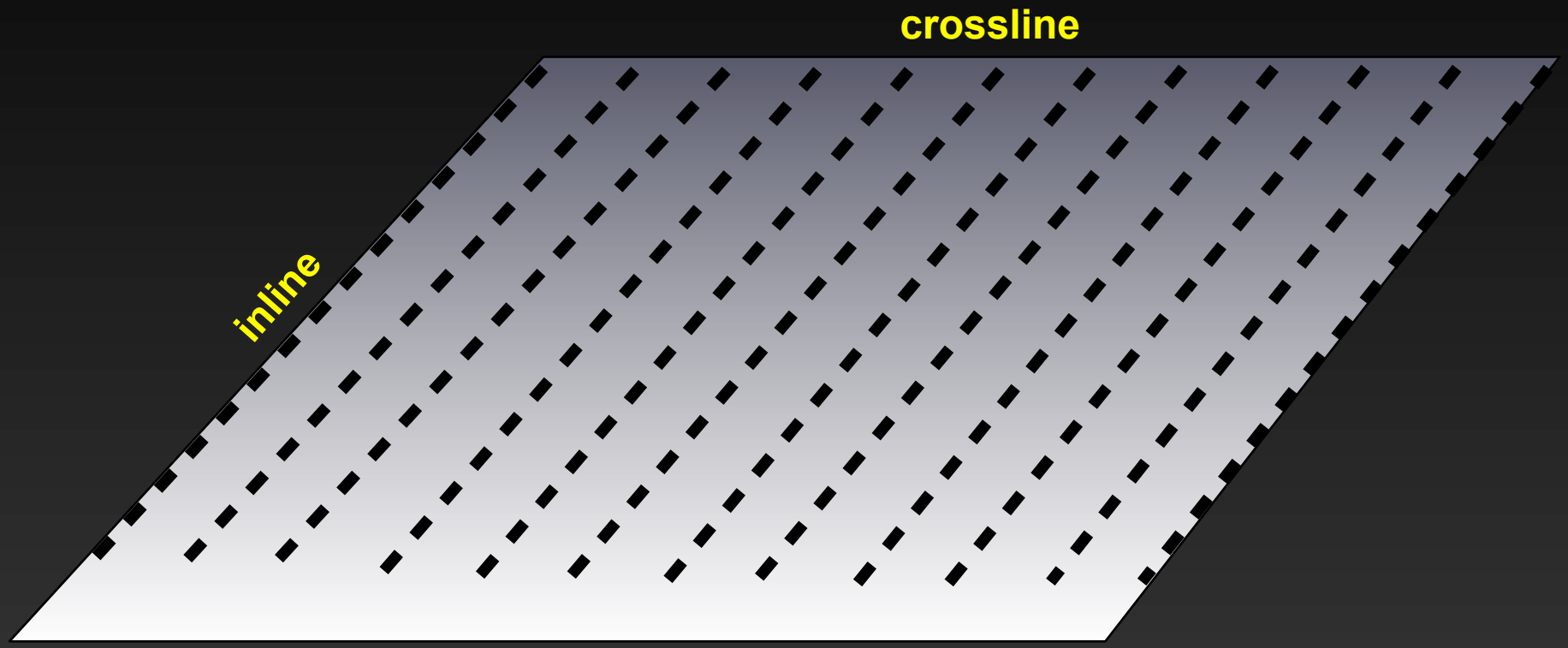
3D PERM initial conditions



3D PERM initial conditions



3D PERM initial conditions



CAM initial conditions

- **Data reduction can be of some orders of magnitude**

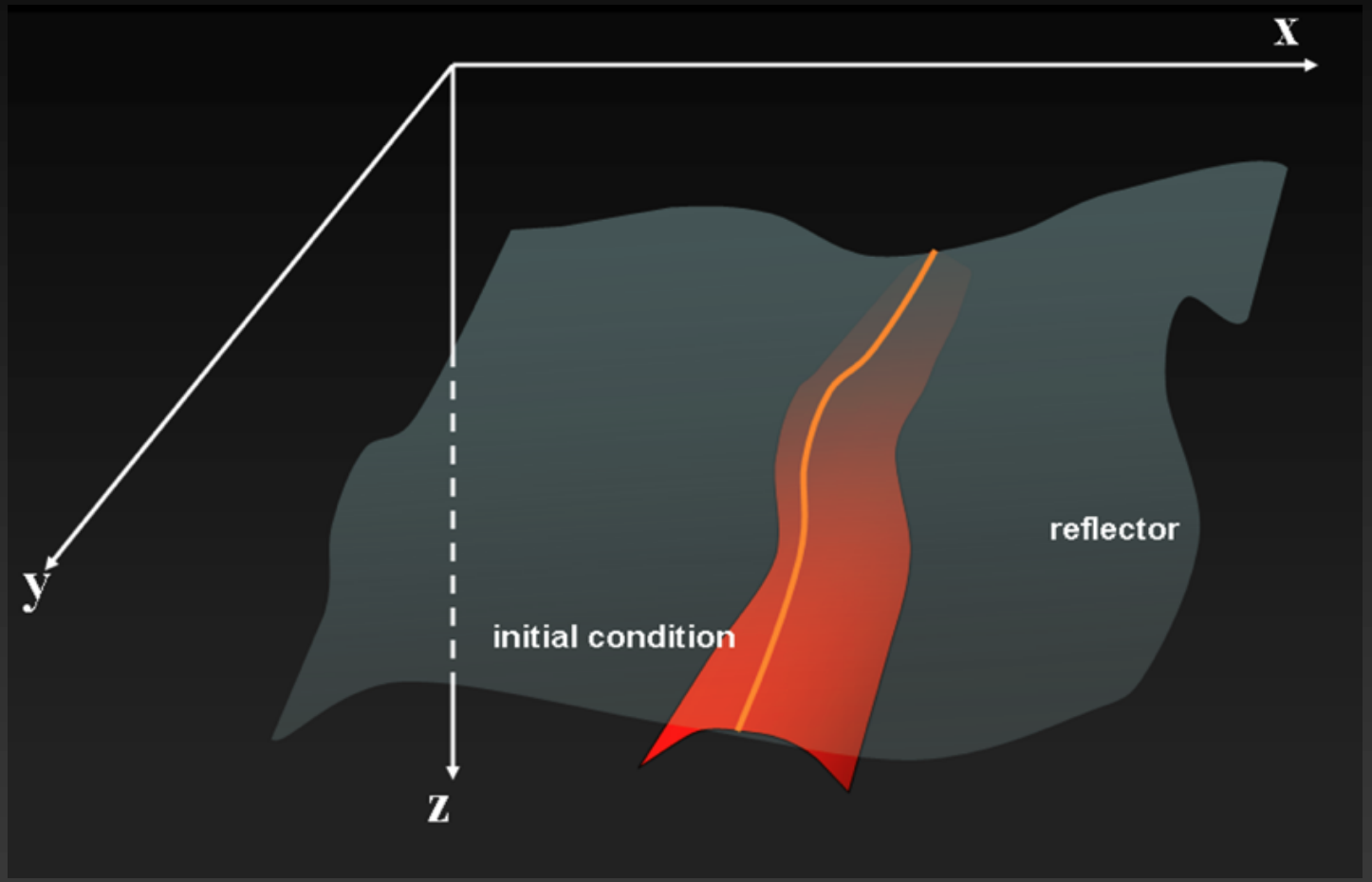


Image-space phase-encoded wavefields

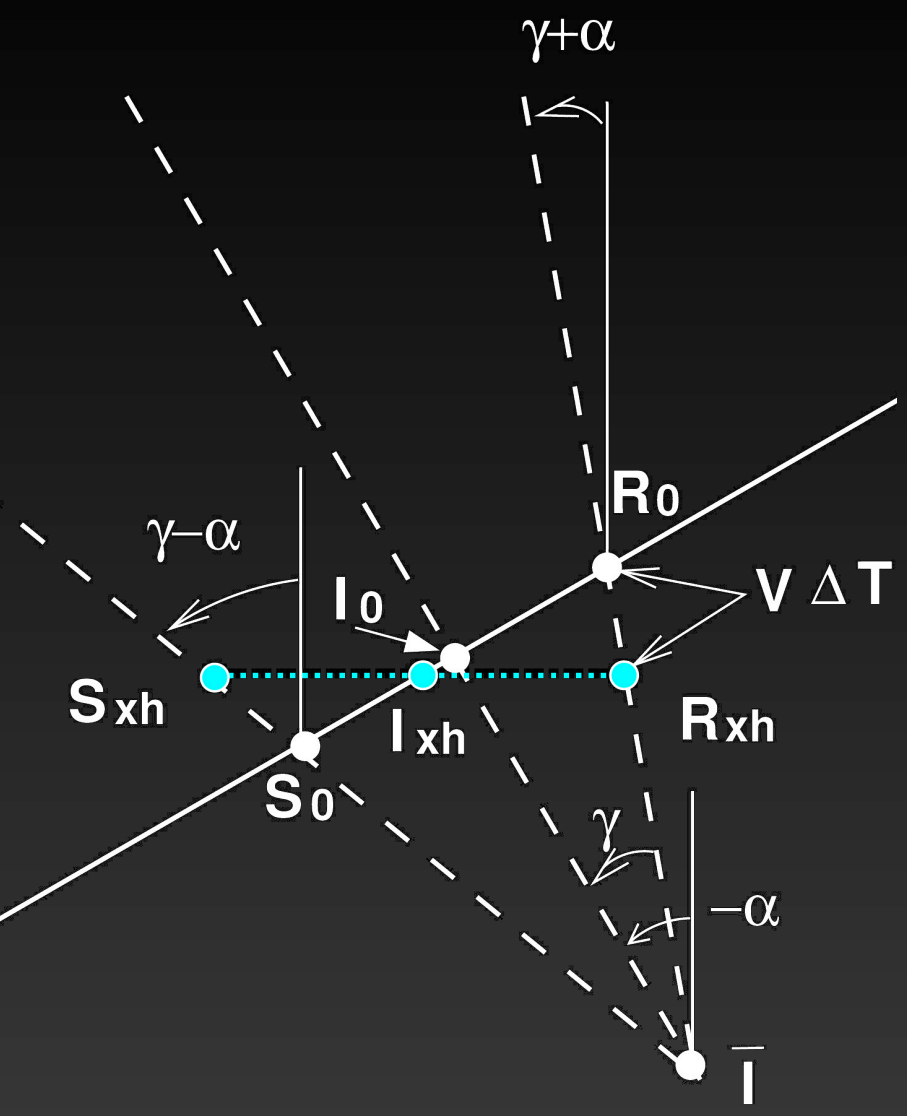
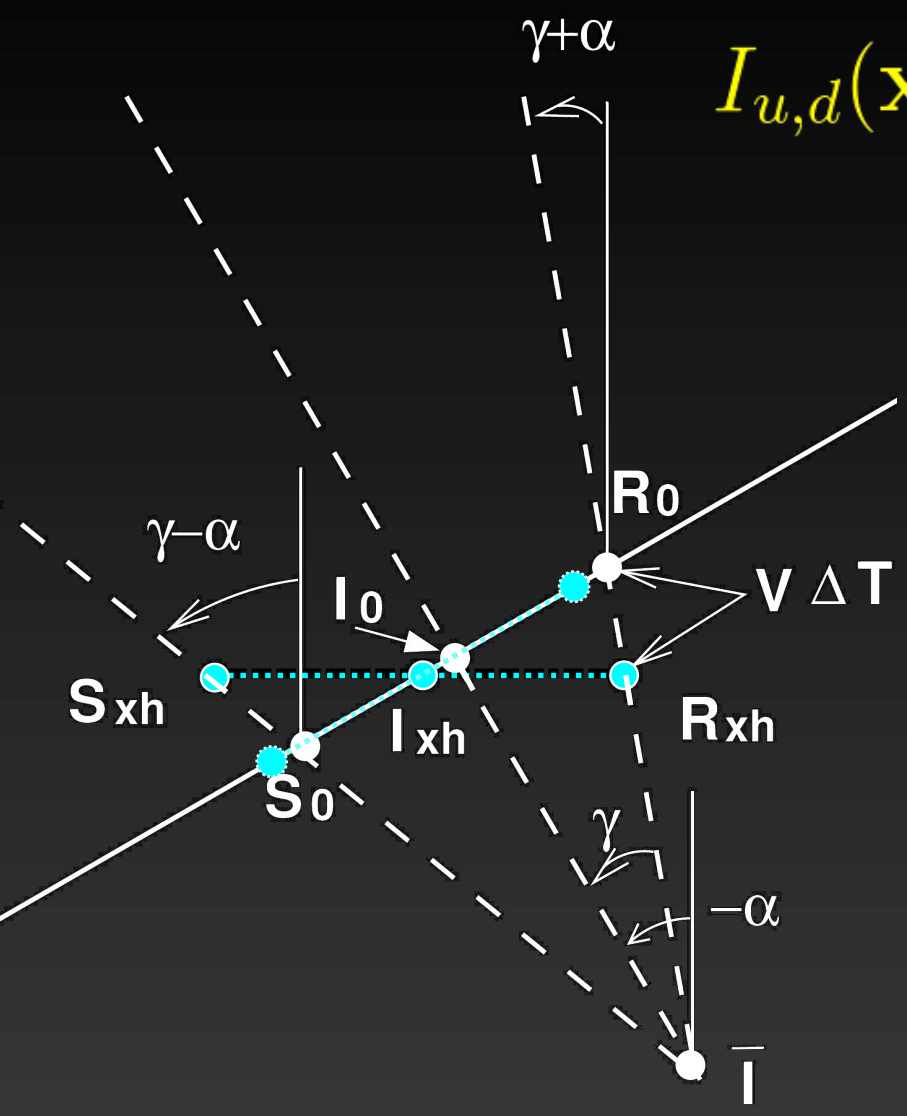


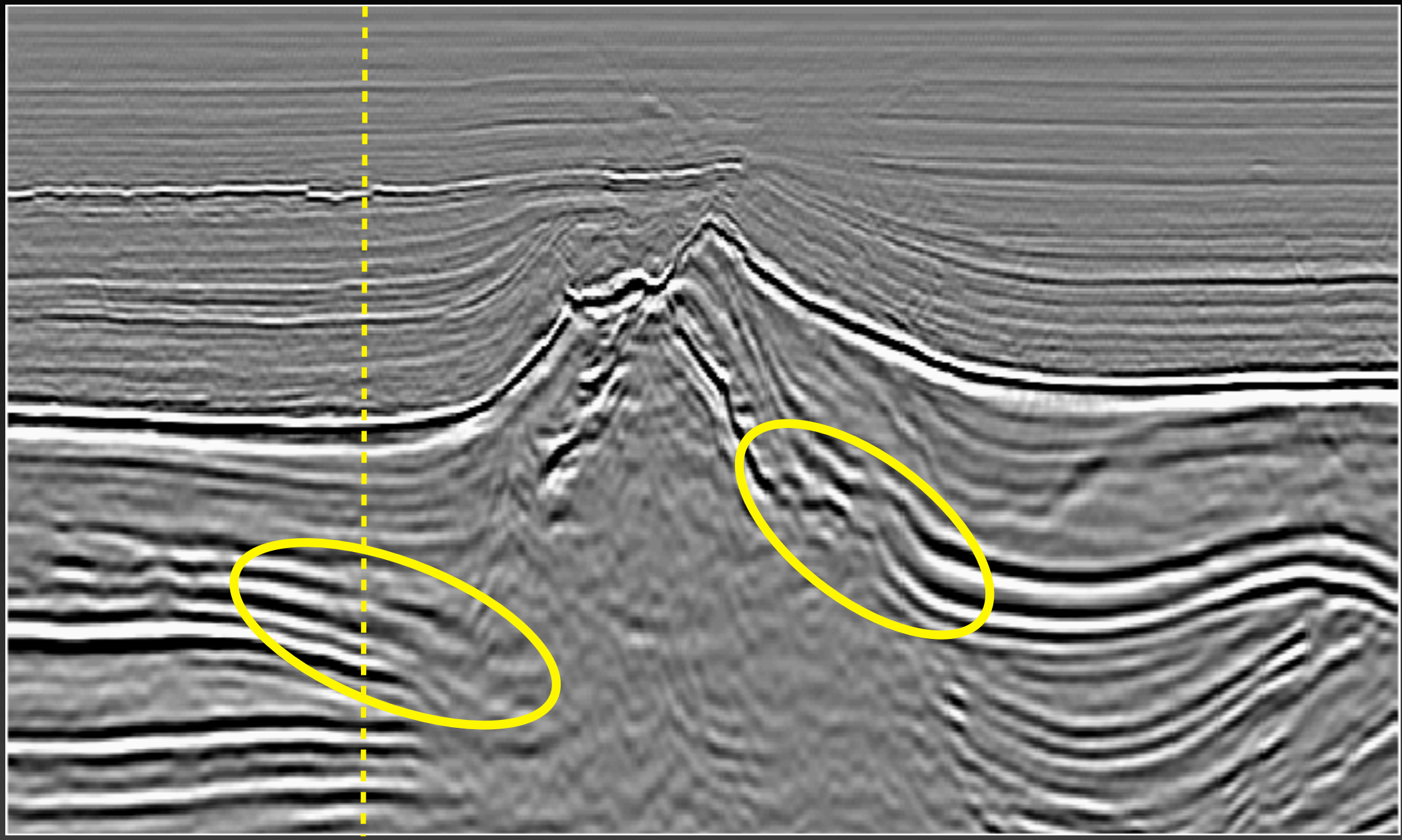
Image-space phase-encoded wavefields



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

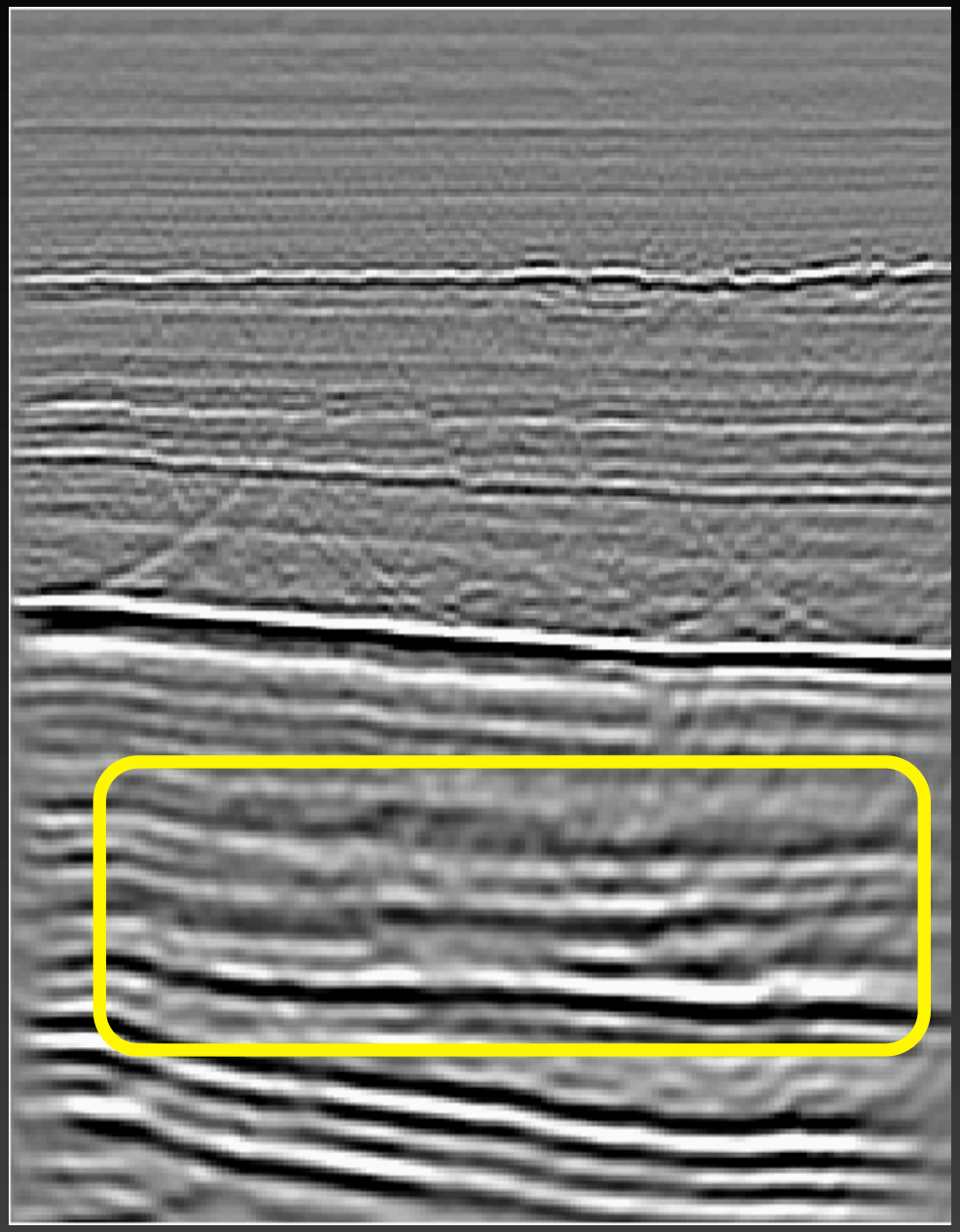
$$\zeta(\alpha,\gamma,\mathrm{h},x') = z - \mathrm{h}tg(\gamma) - x'tg(\alpha) \pm \mathrm{h}tg(\gamma \pm \alpha)$$

Target-oriented ISWET

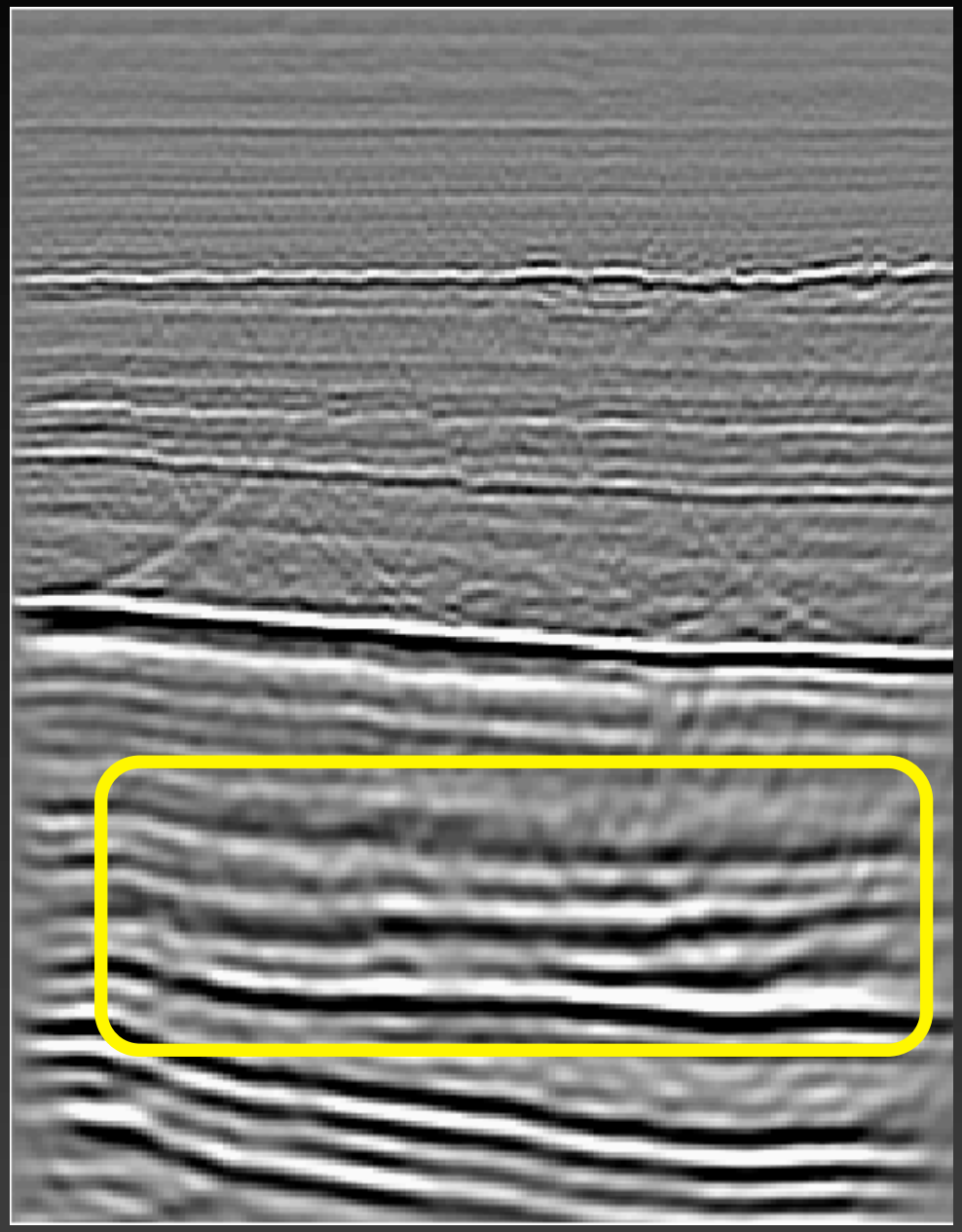


Better focusing

Before



After

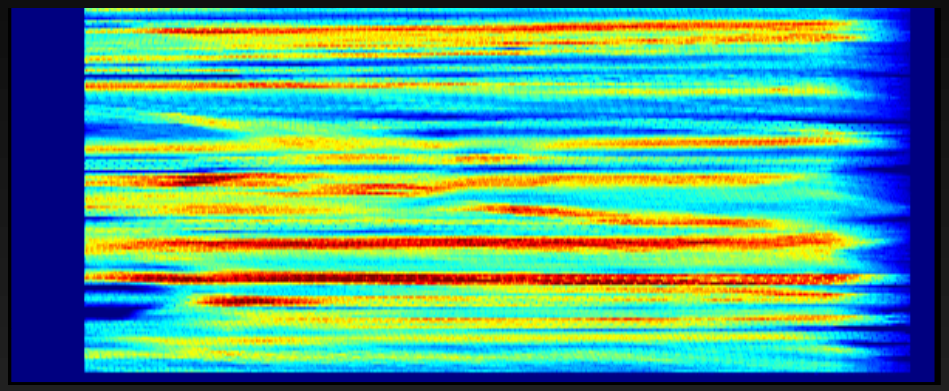


Acquisition footprint

CMP fold

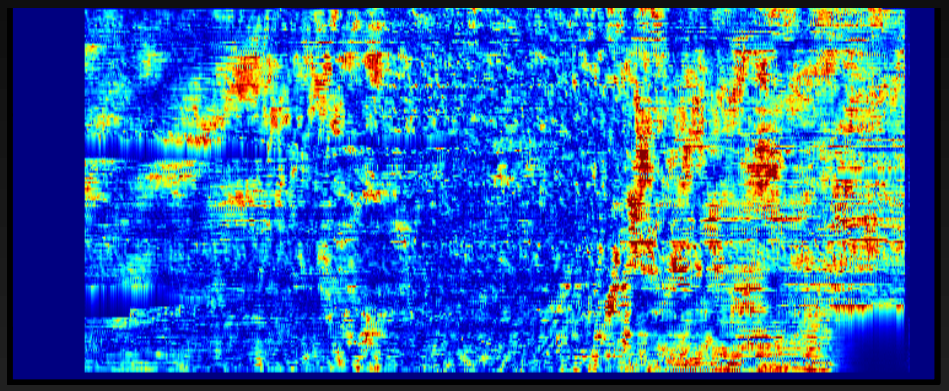
crossline

inline



RMS amplitude map

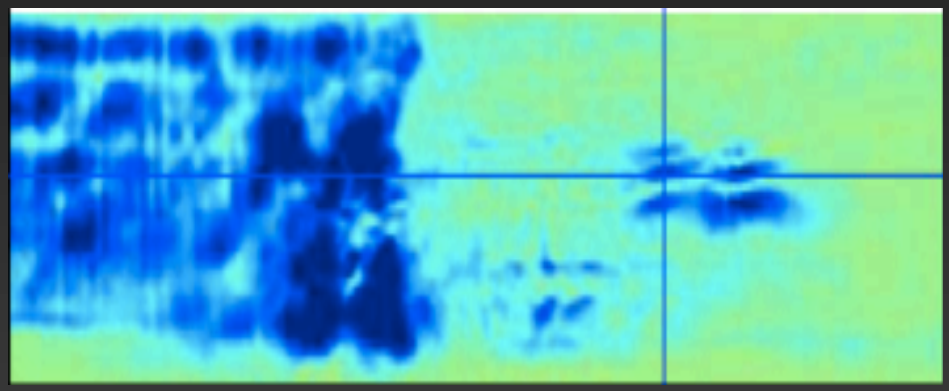
crossline



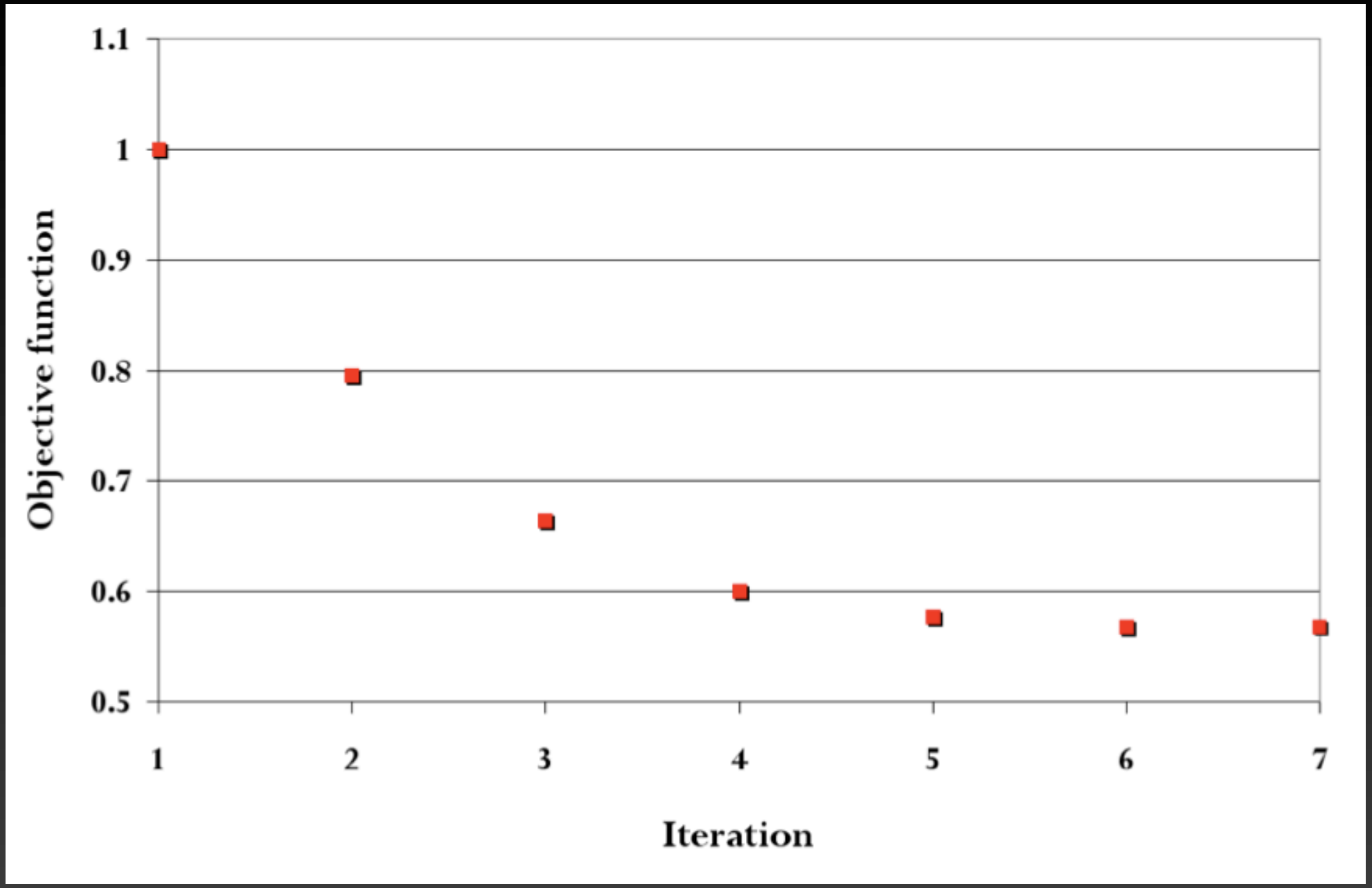
Gradient

crossline

inline

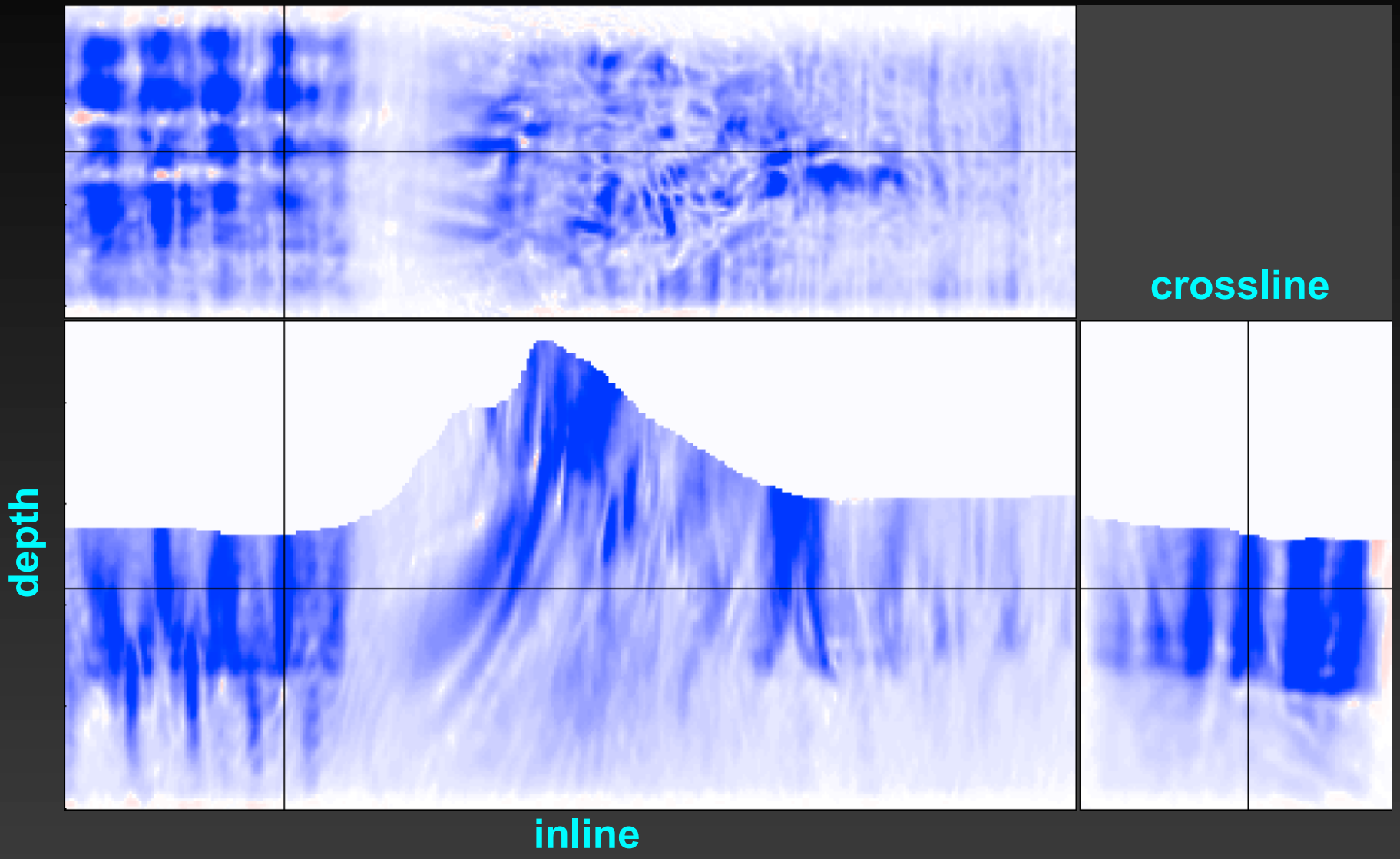


Objective function

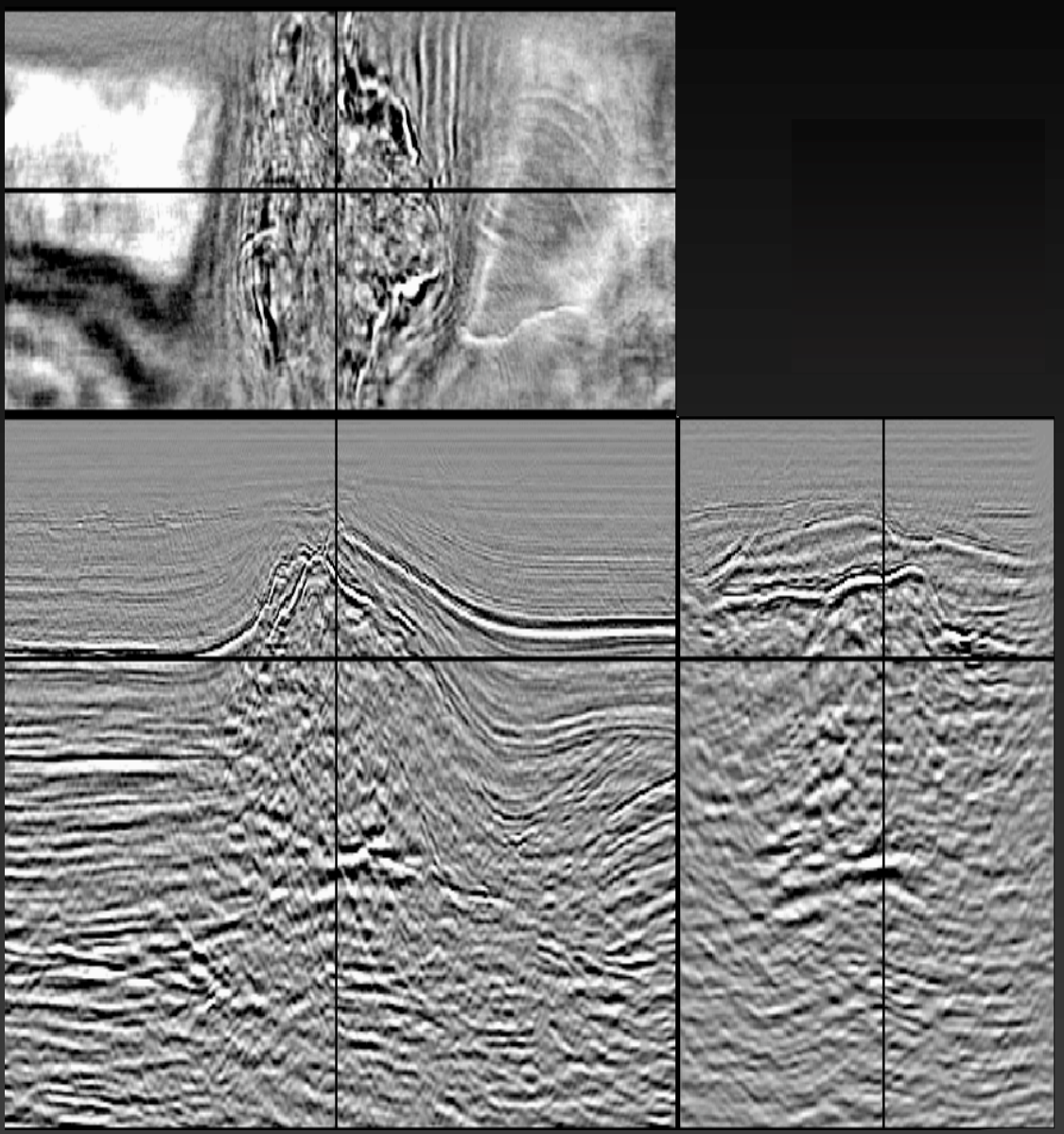


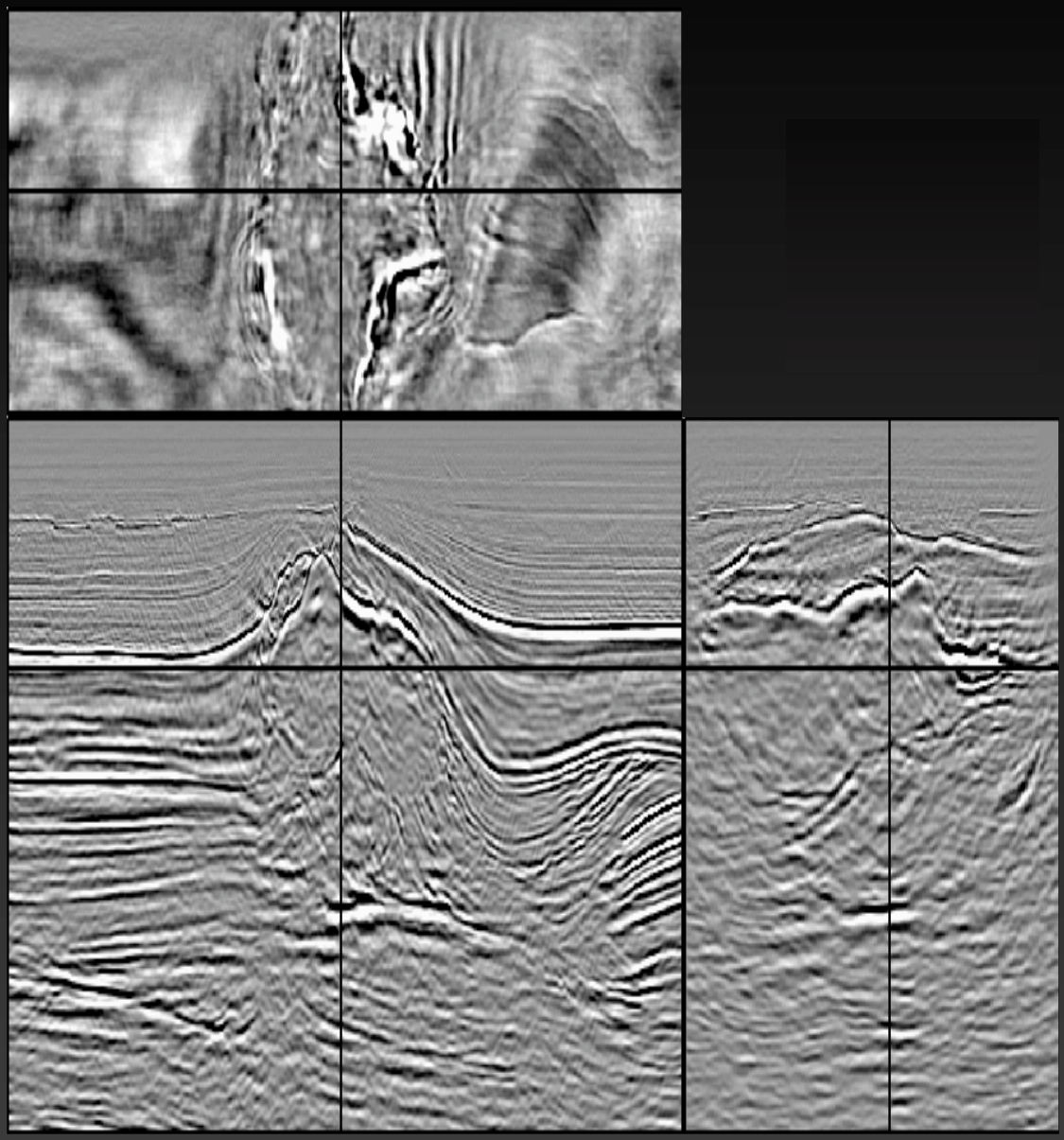
Potential for grid-tomography

Gradient with 1 pair of ISPEW

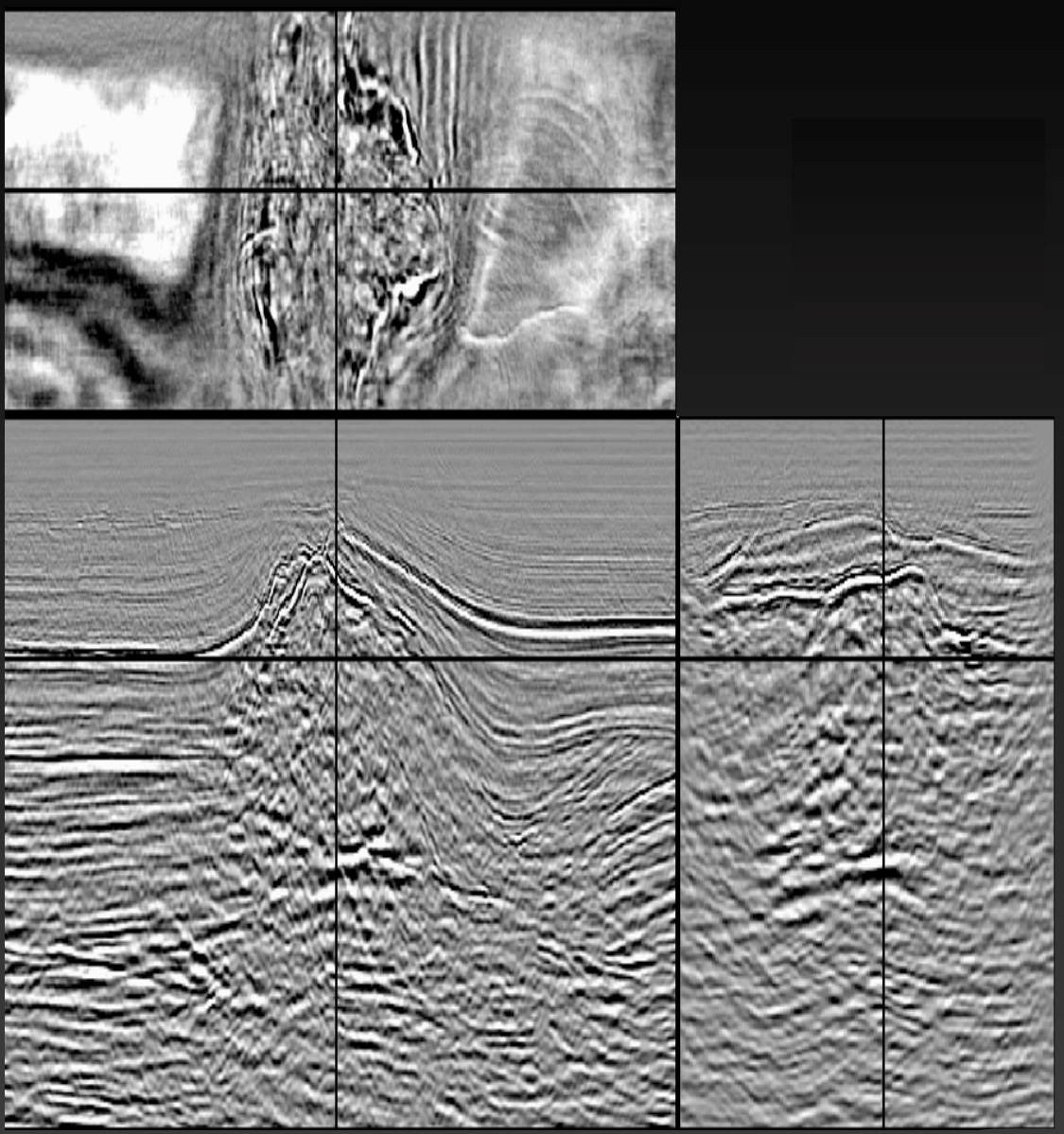


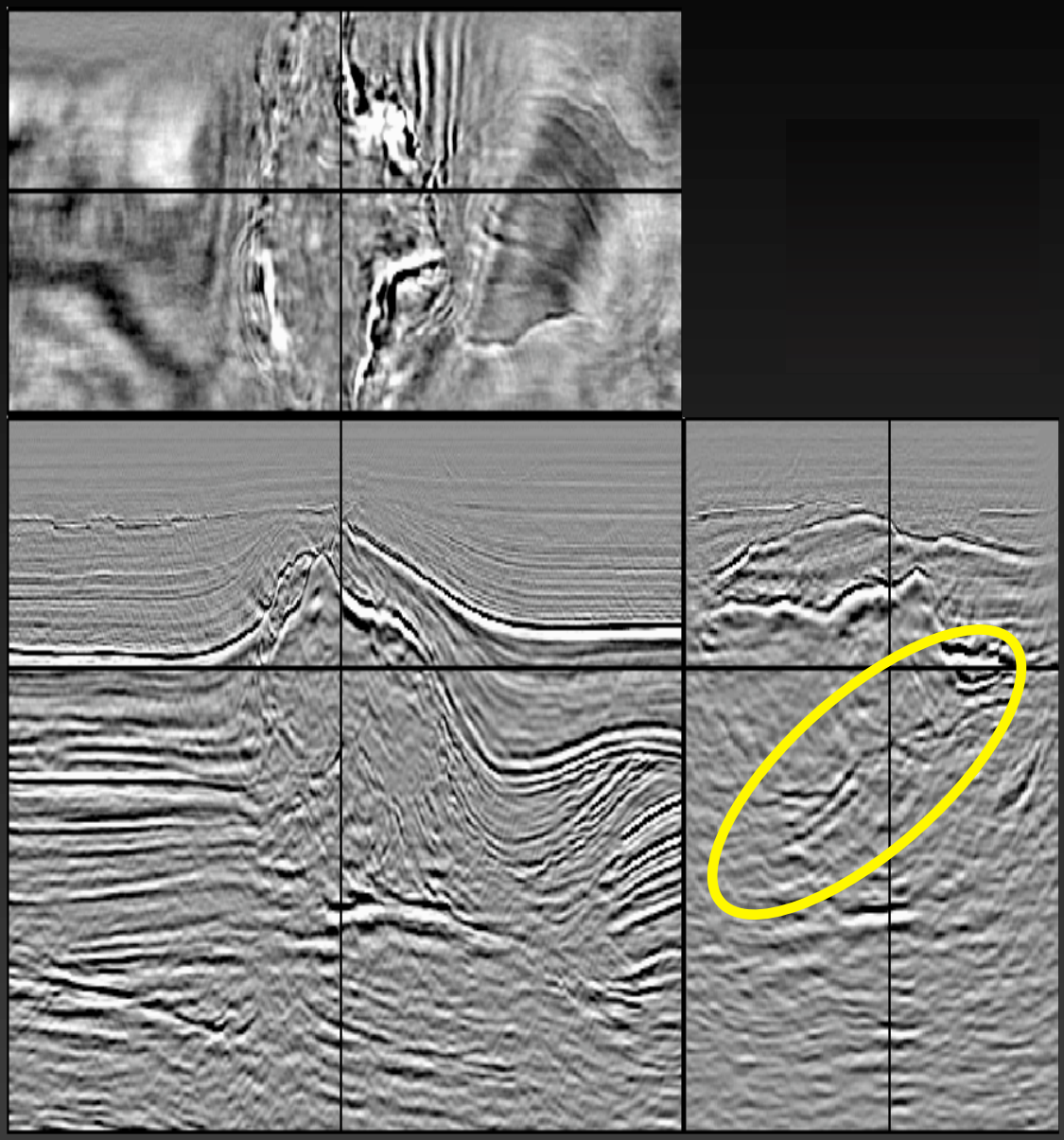
Better base of salt & focusing



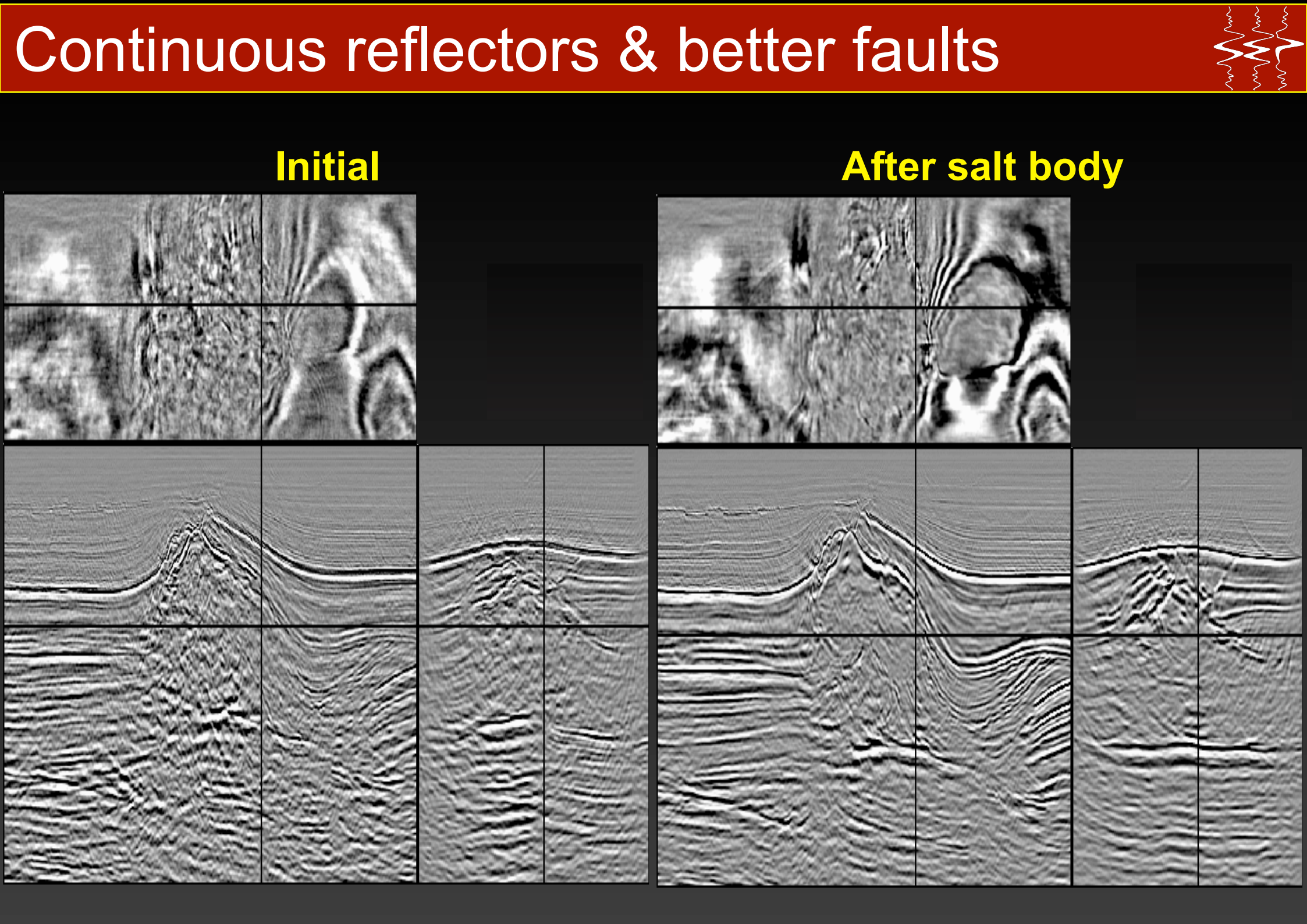


Better base of salt & focusing

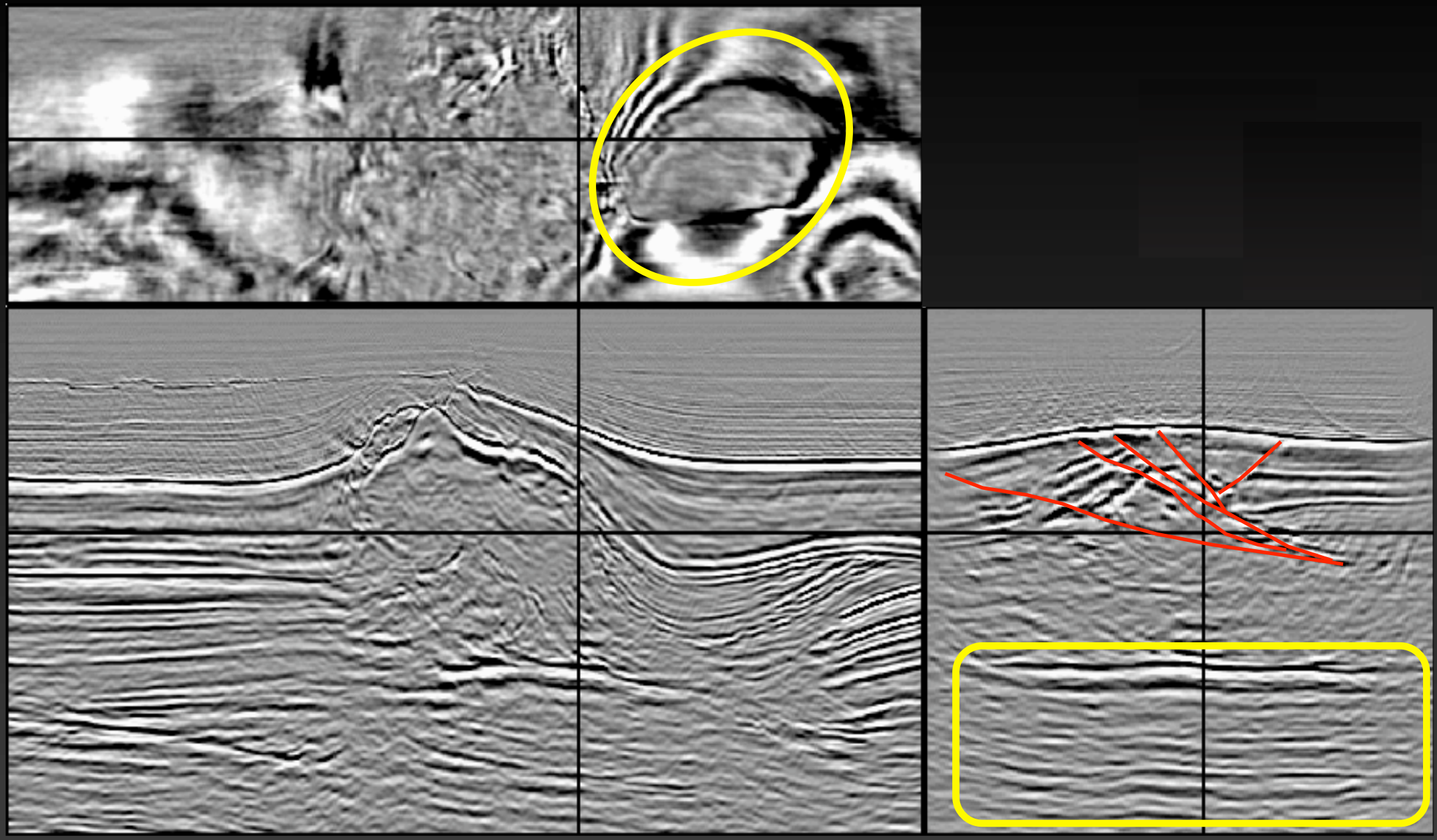




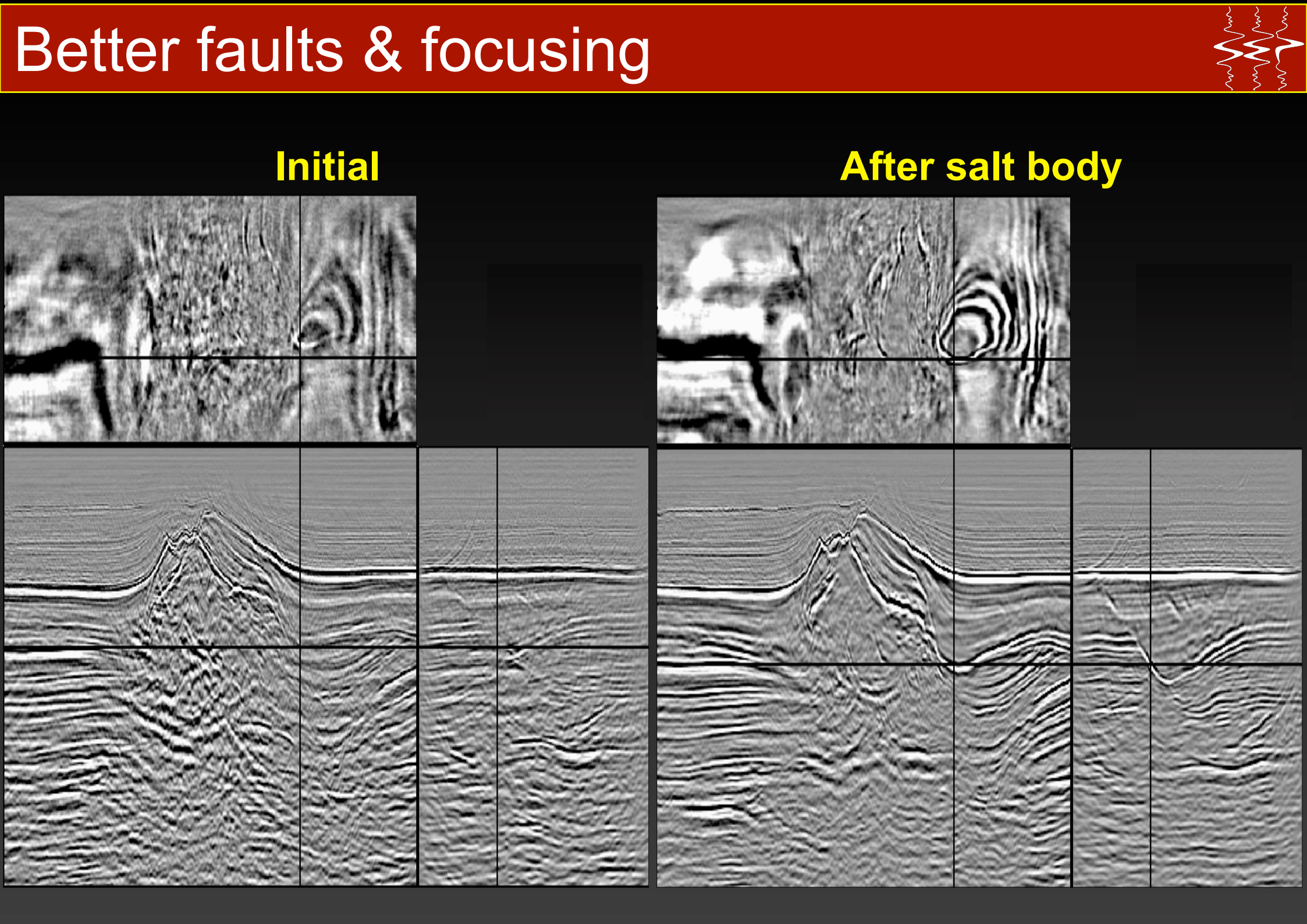
Continuous reflectors & better faults



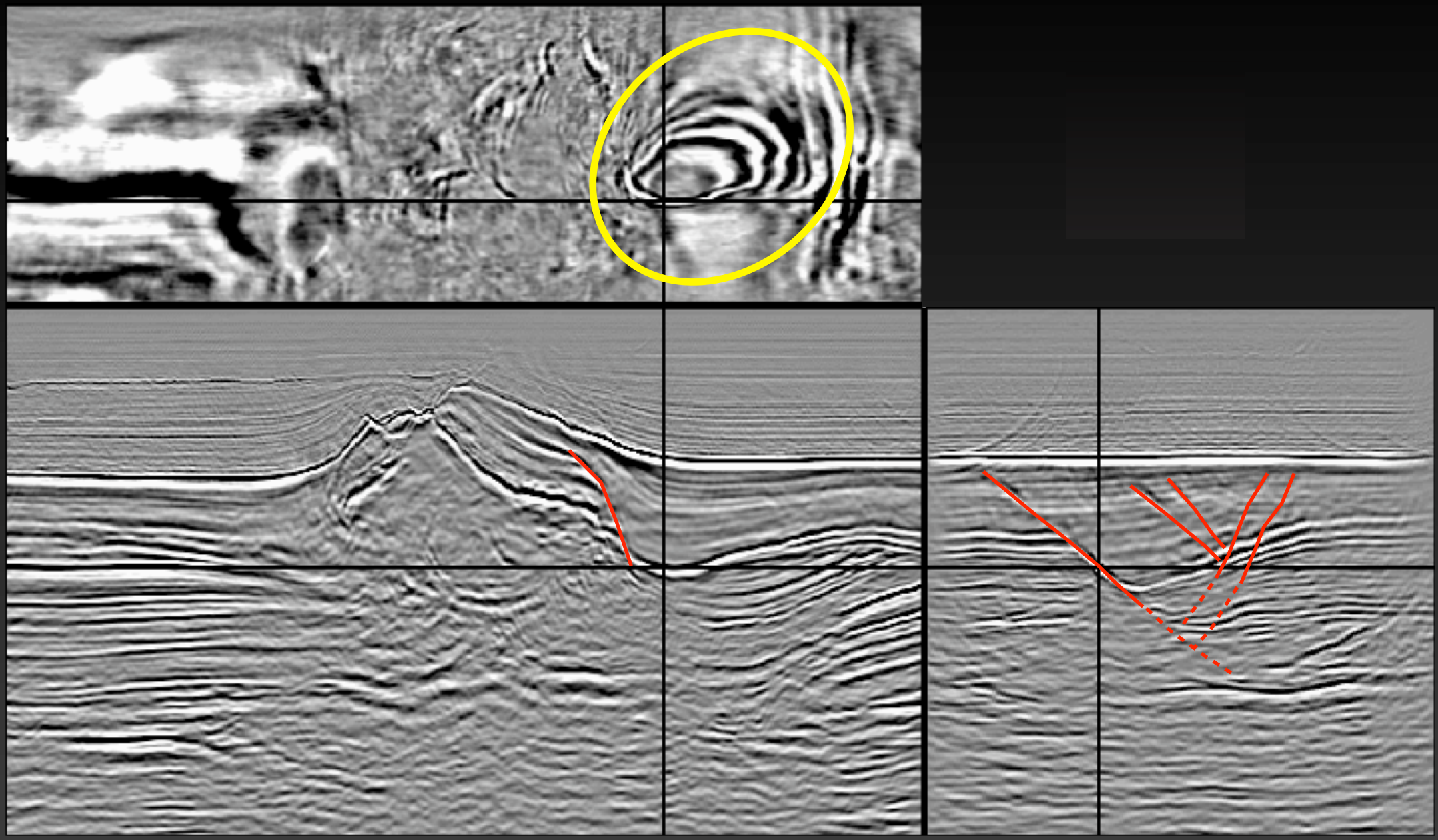
Continuous reflectors & better faults



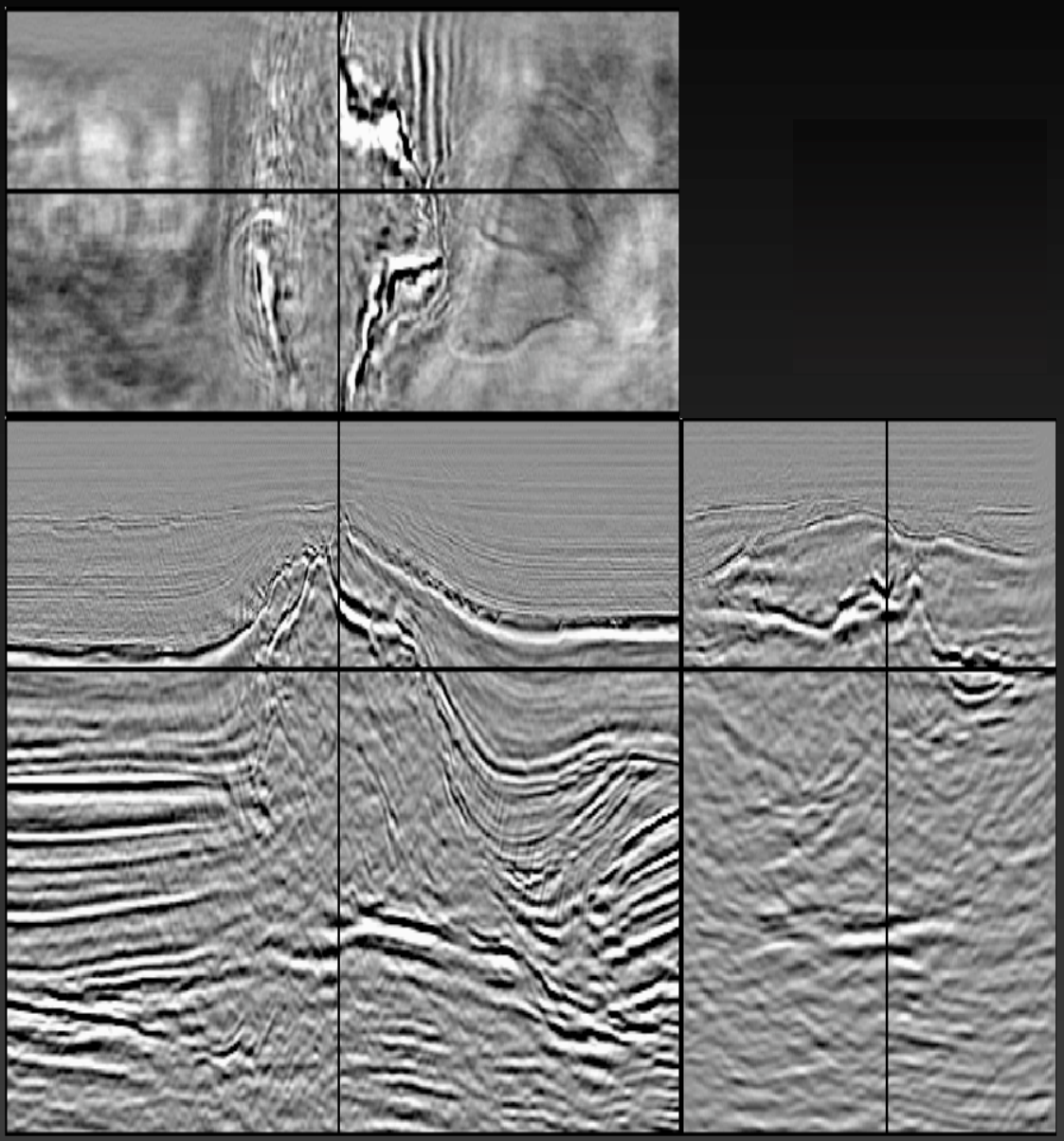
Better faults & focusing

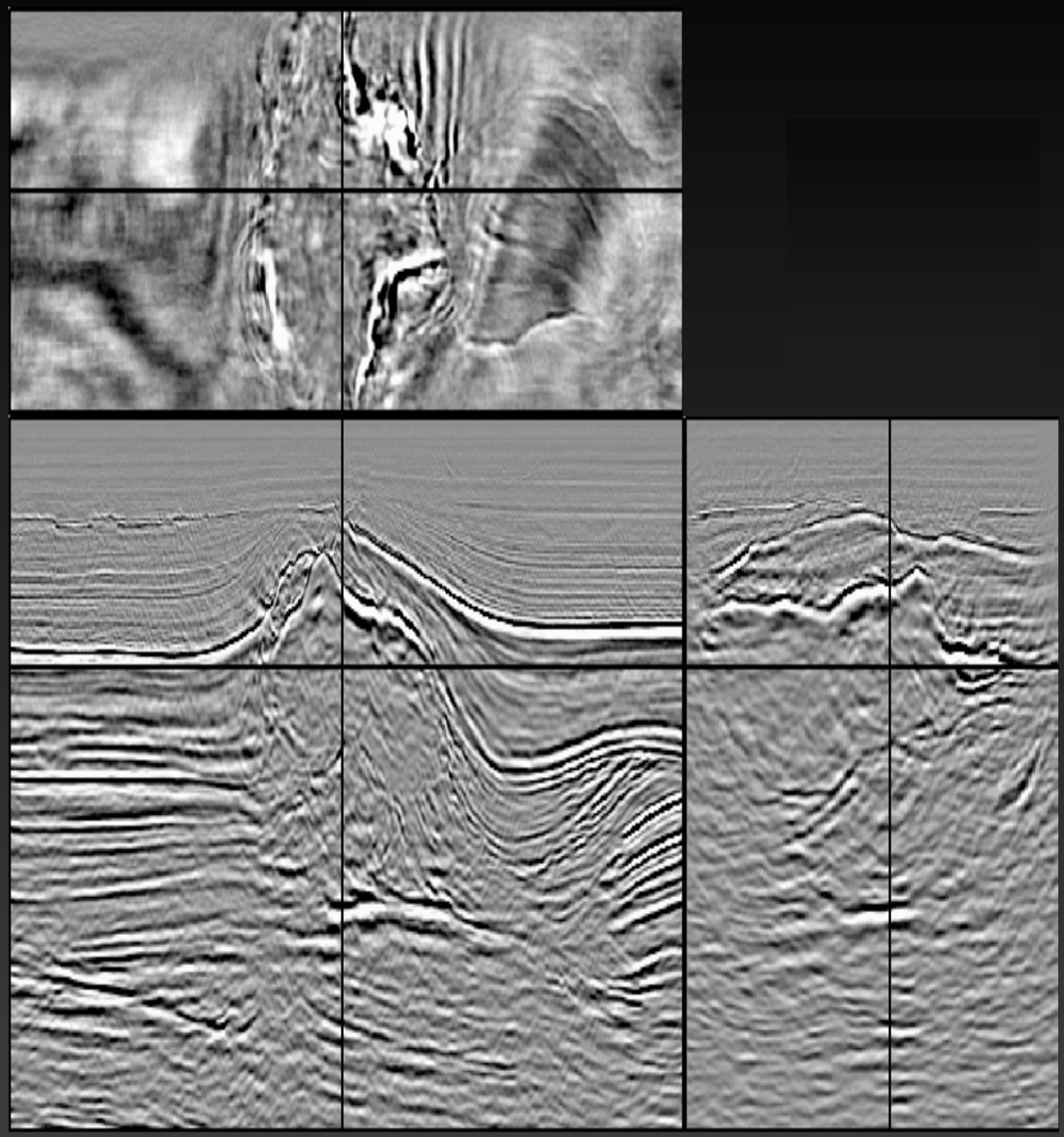


Better faults & focusing

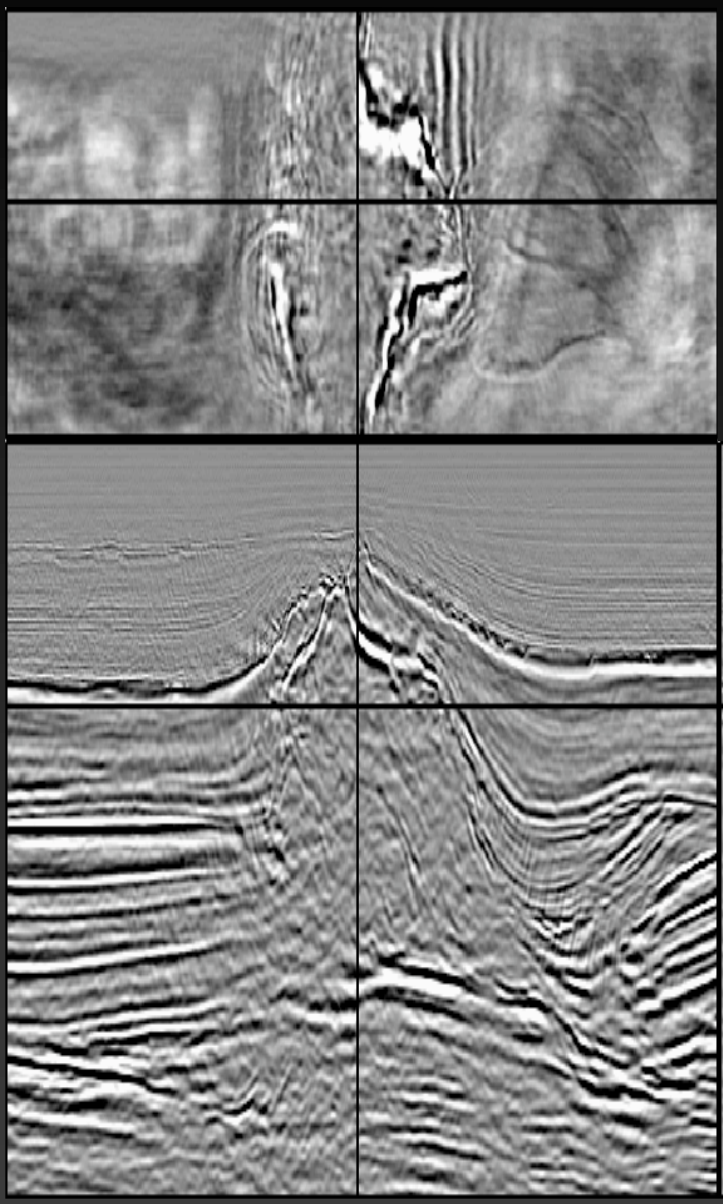


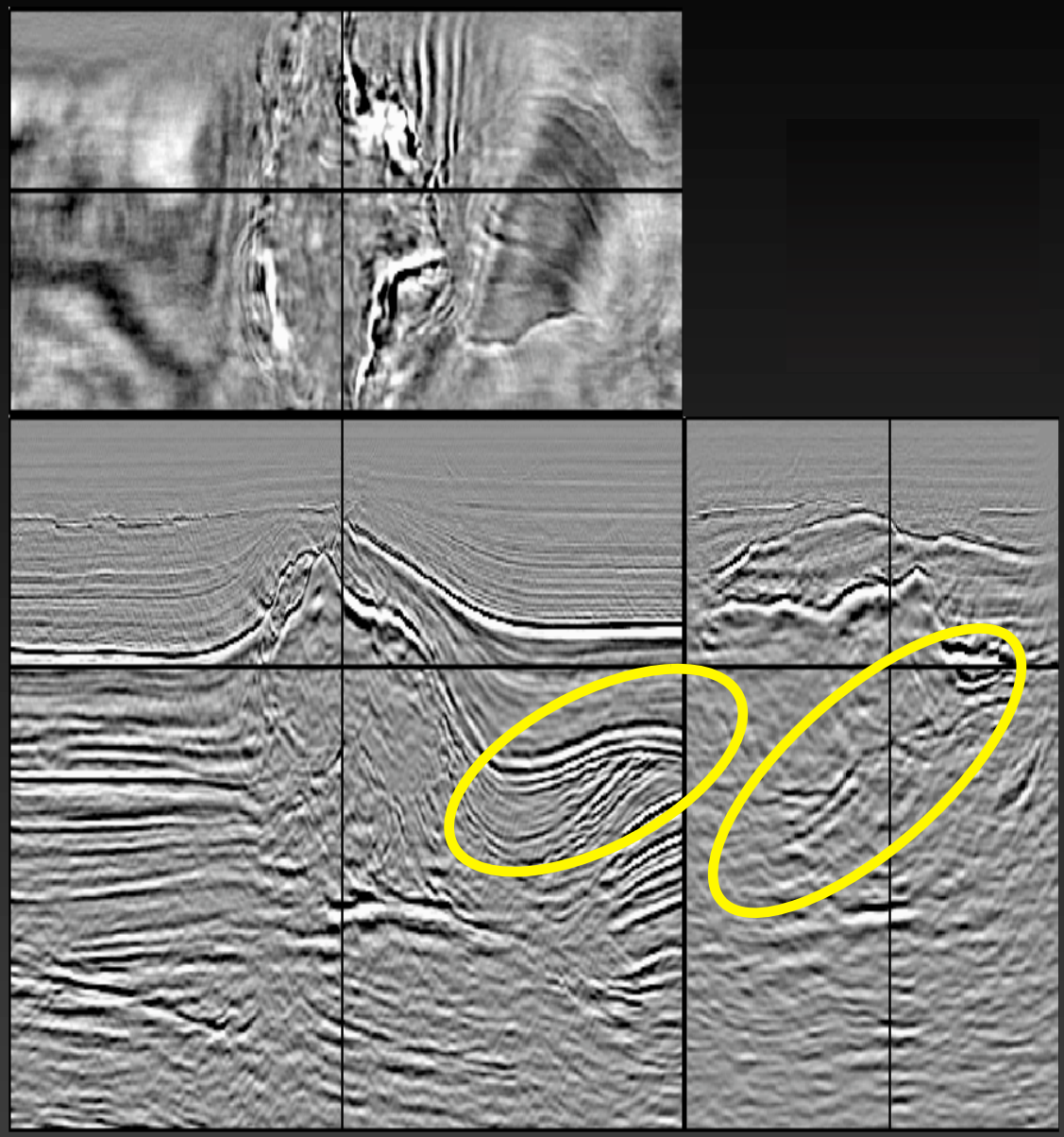
Better base of salt & focusing



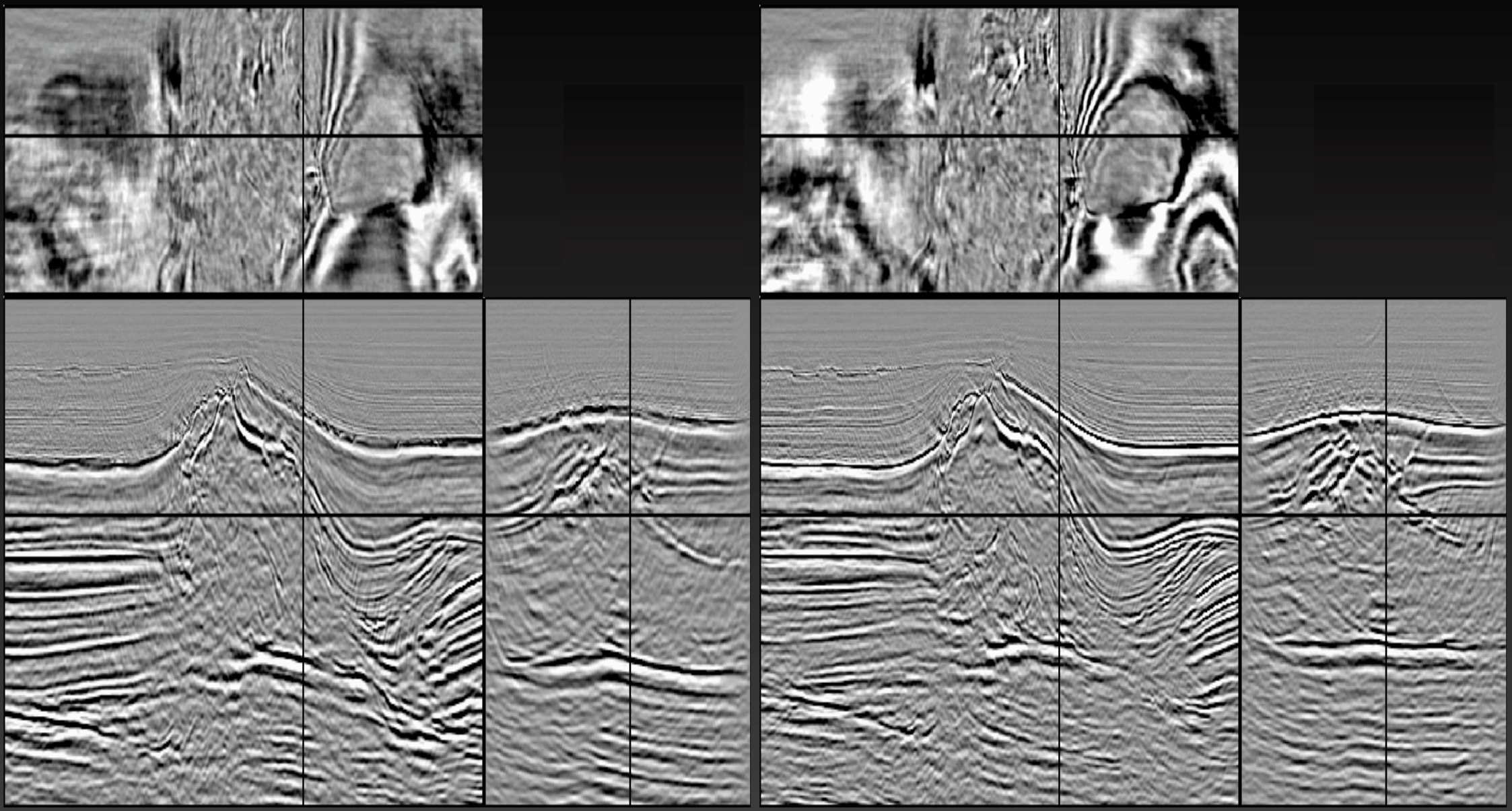


Better base of salt & focusing





Better sub-salt reflectors & faults



Better sub-salt reflectors & faults