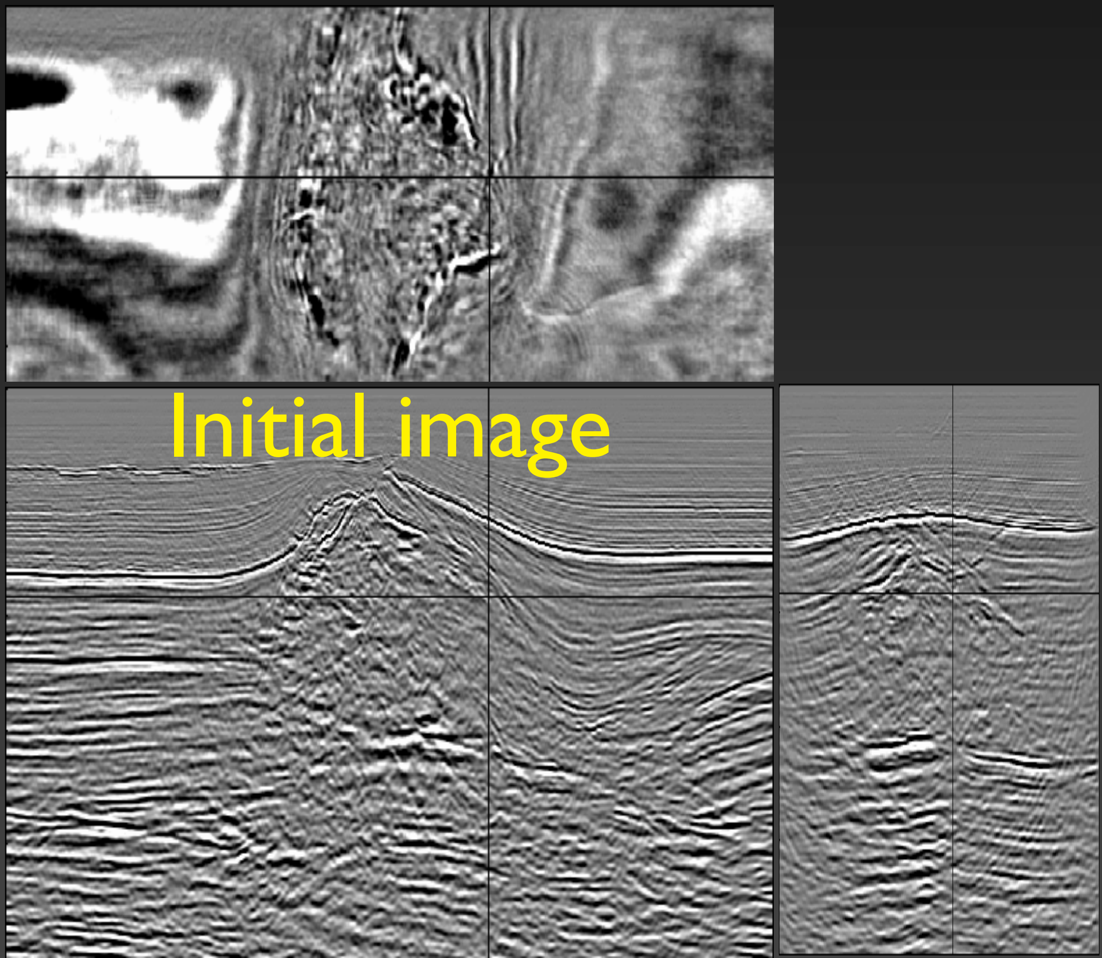
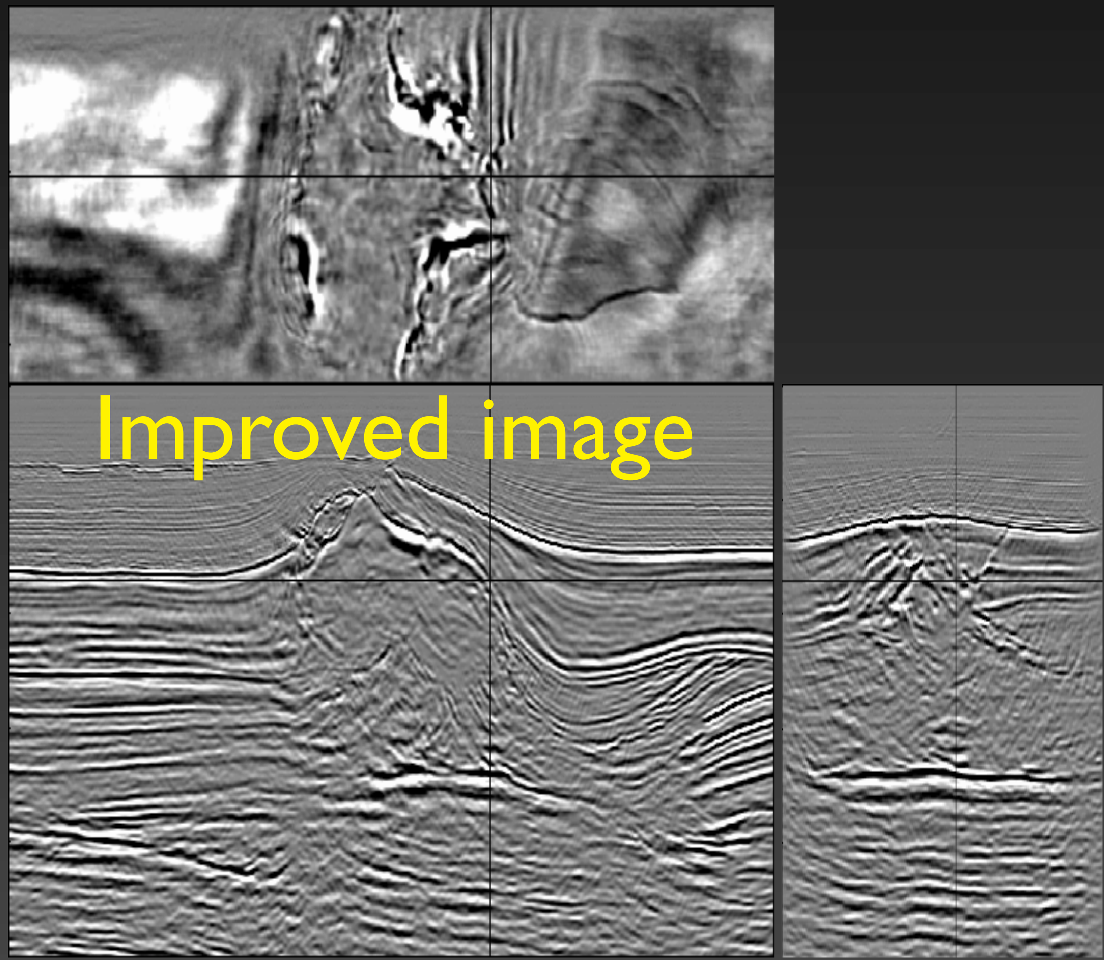
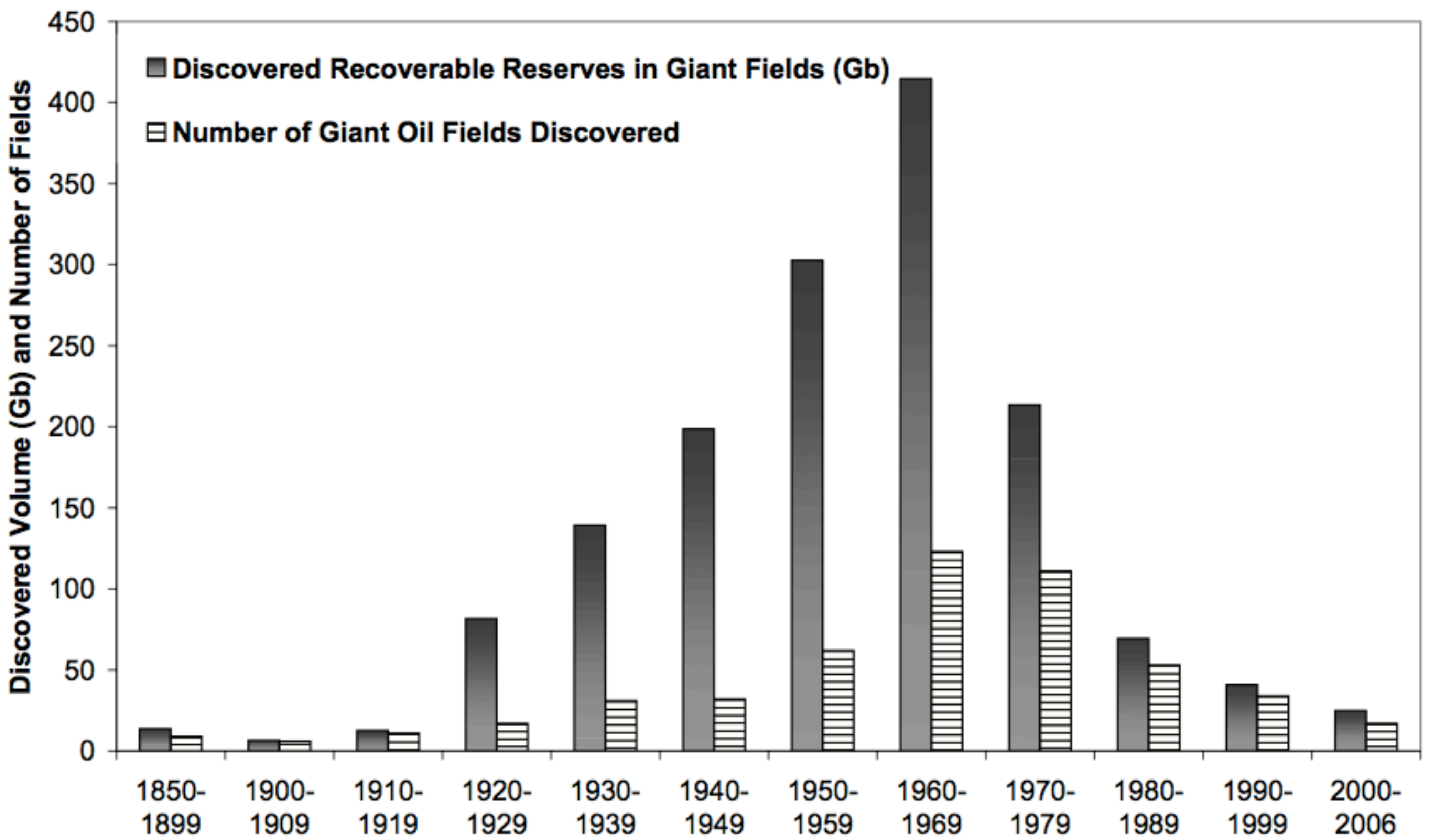
Migration-velocity analysis using image-space generalized wavefields

Claudio Guerra





End of ‘easy’ oil



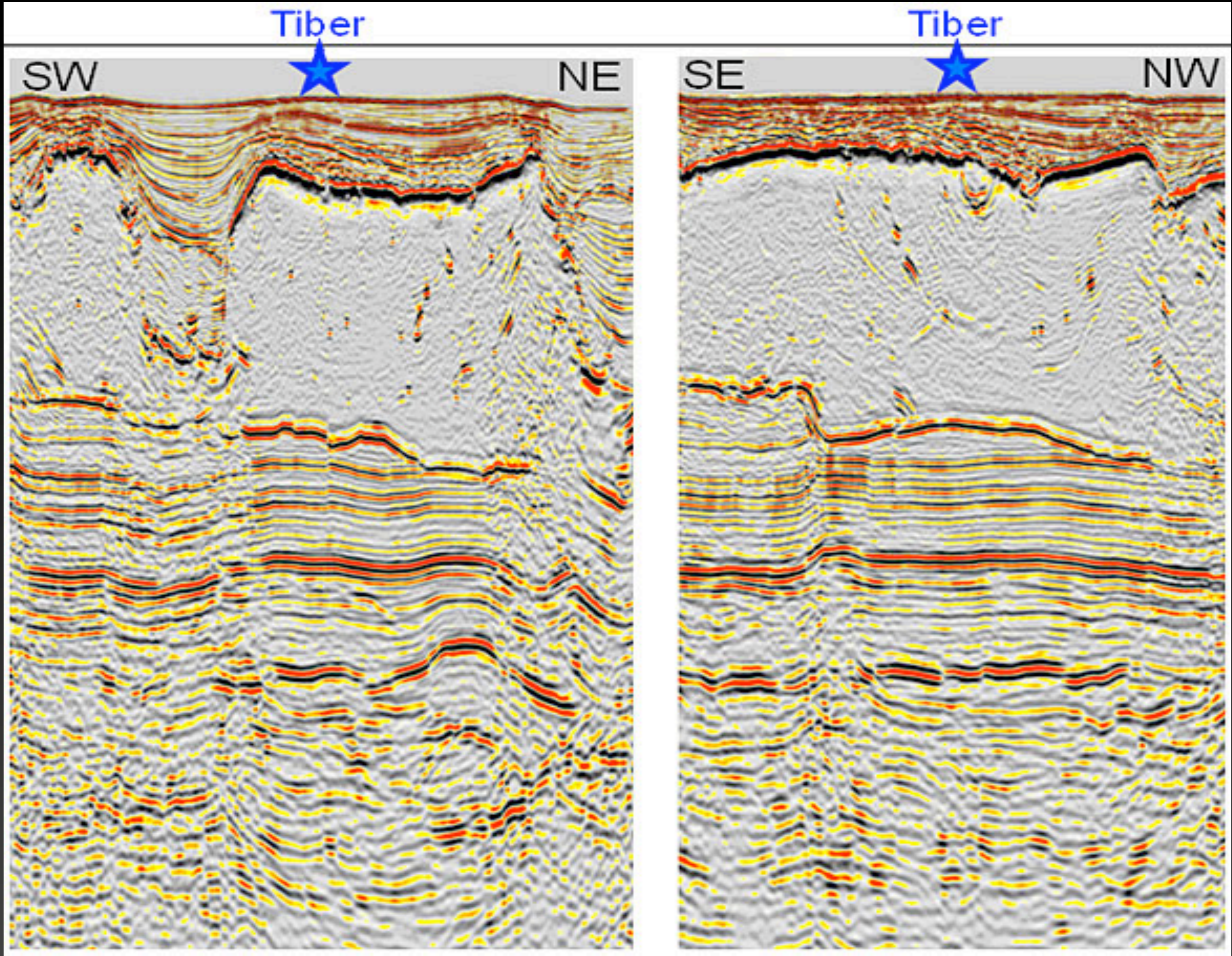
Robelius, Fredrik: Giant Oil Fields - The Highway to Oil: Giant Oil Fields and their Importance for Future Oil Production

Offshore oil production & prospectivity ...

Modified from http://pubs.usgs.gov/fs/fs-062-03/FS-062-03.pdf

and location of salt provinces

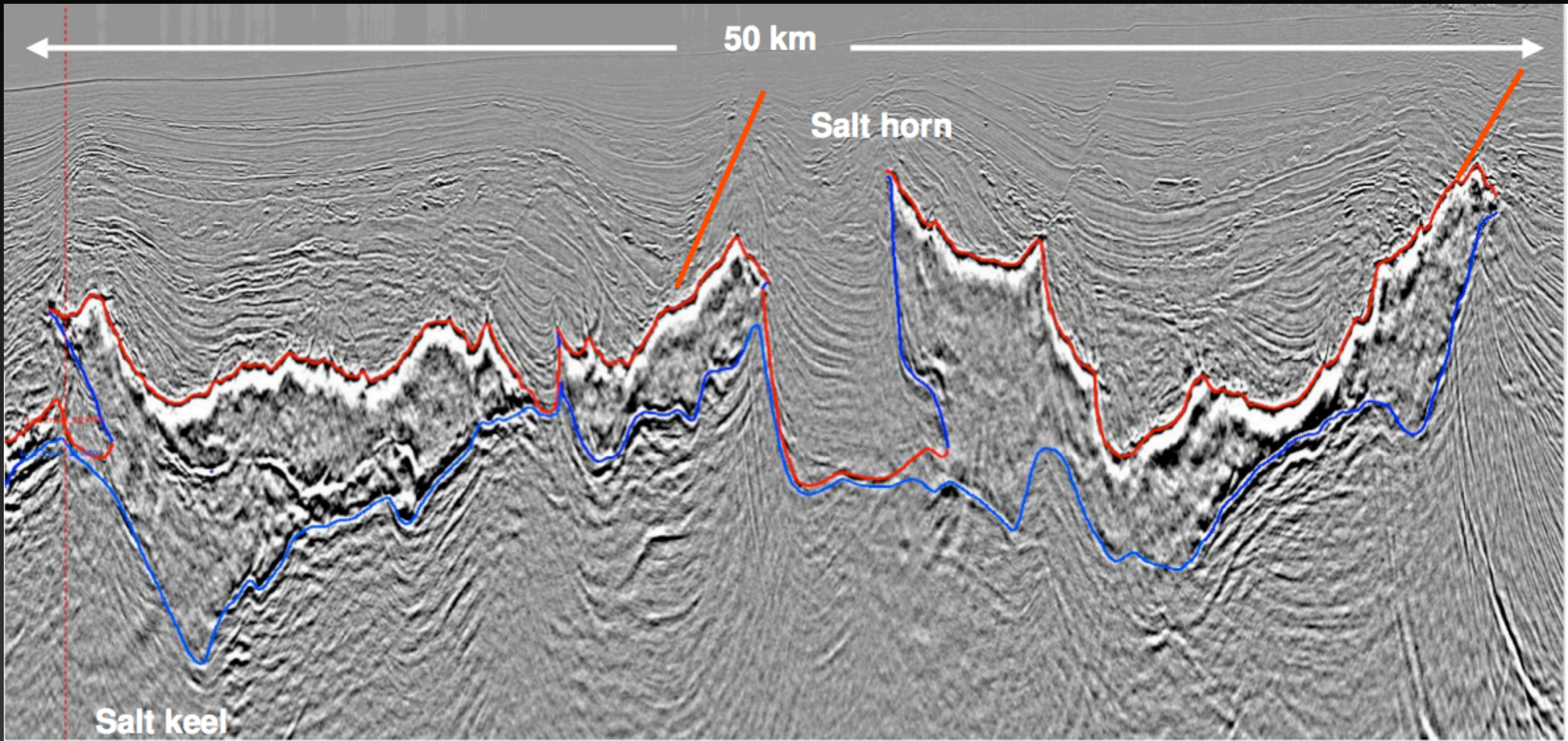
Modified from http://pubs.usgs.gov/fs/fs-062-03/FS-062-03.pdf and http://truman.seg.org/TLEreview/November/Sayers.pdf distance



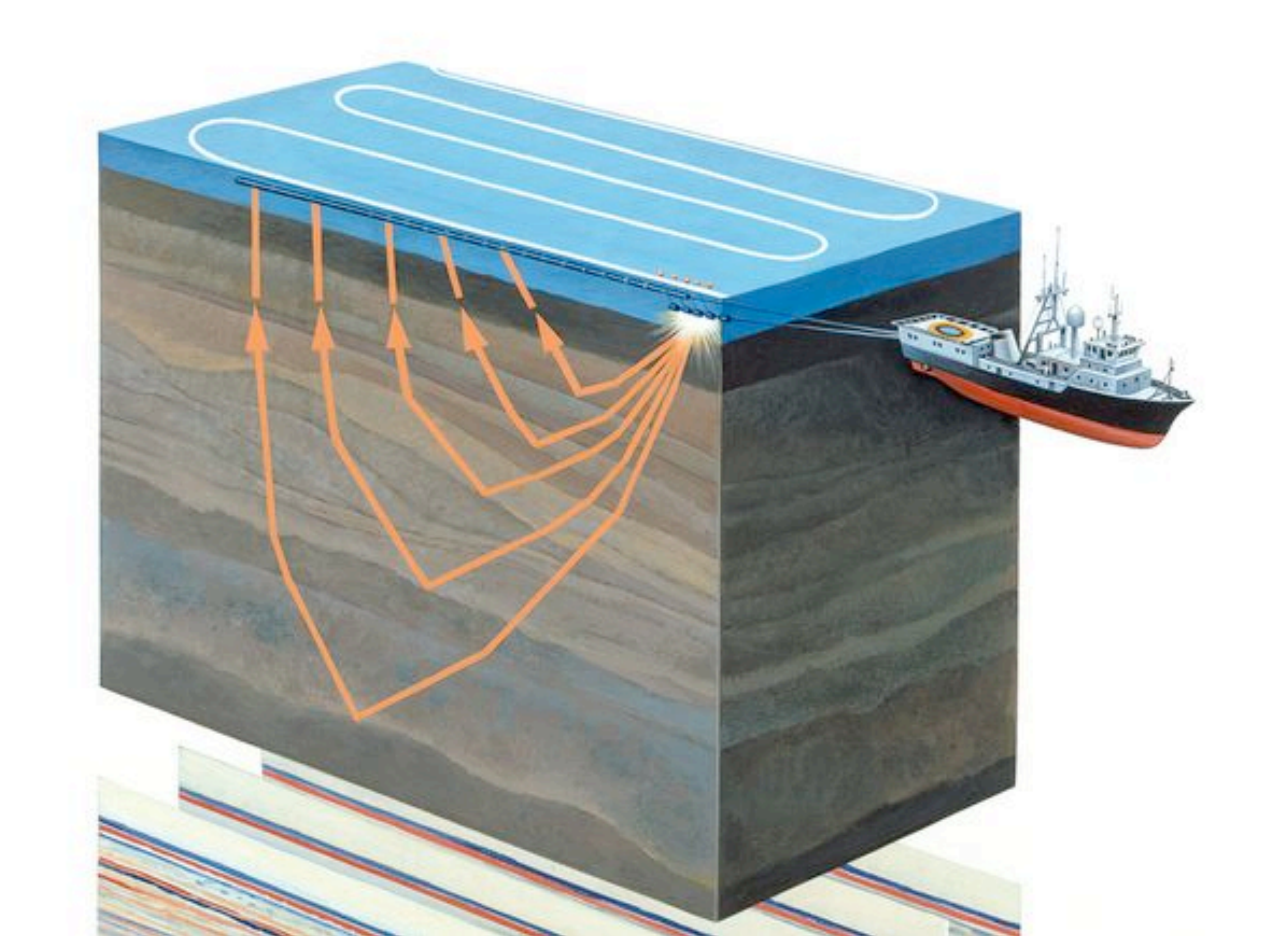
depth

http://www.cggveritas.com/data//1/rec_imgs/5547_tiber.jpg distance

depth



Li et al., 2009



http://images.nationalgeographic.com/wpf/media-live/photos/000/180/cache/energy-seismic-exploration-offshore-drilling_18083_600x450.jpg

Data space

$$d = d(\mathbf{s}, \mathbf{r}, t)$$

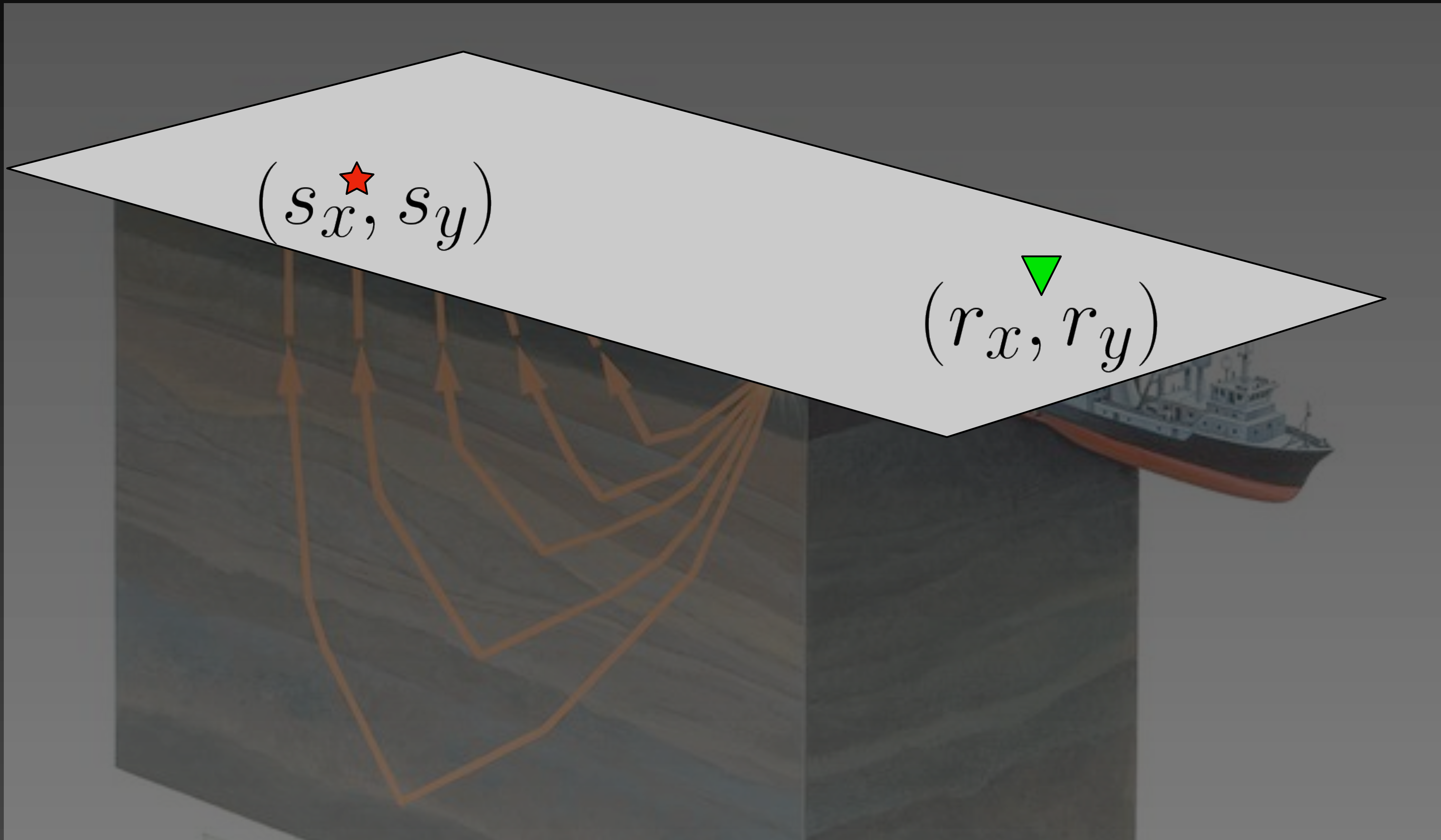


Image space

$$I = I(\mathbf{x}, \mathbf{h})$$

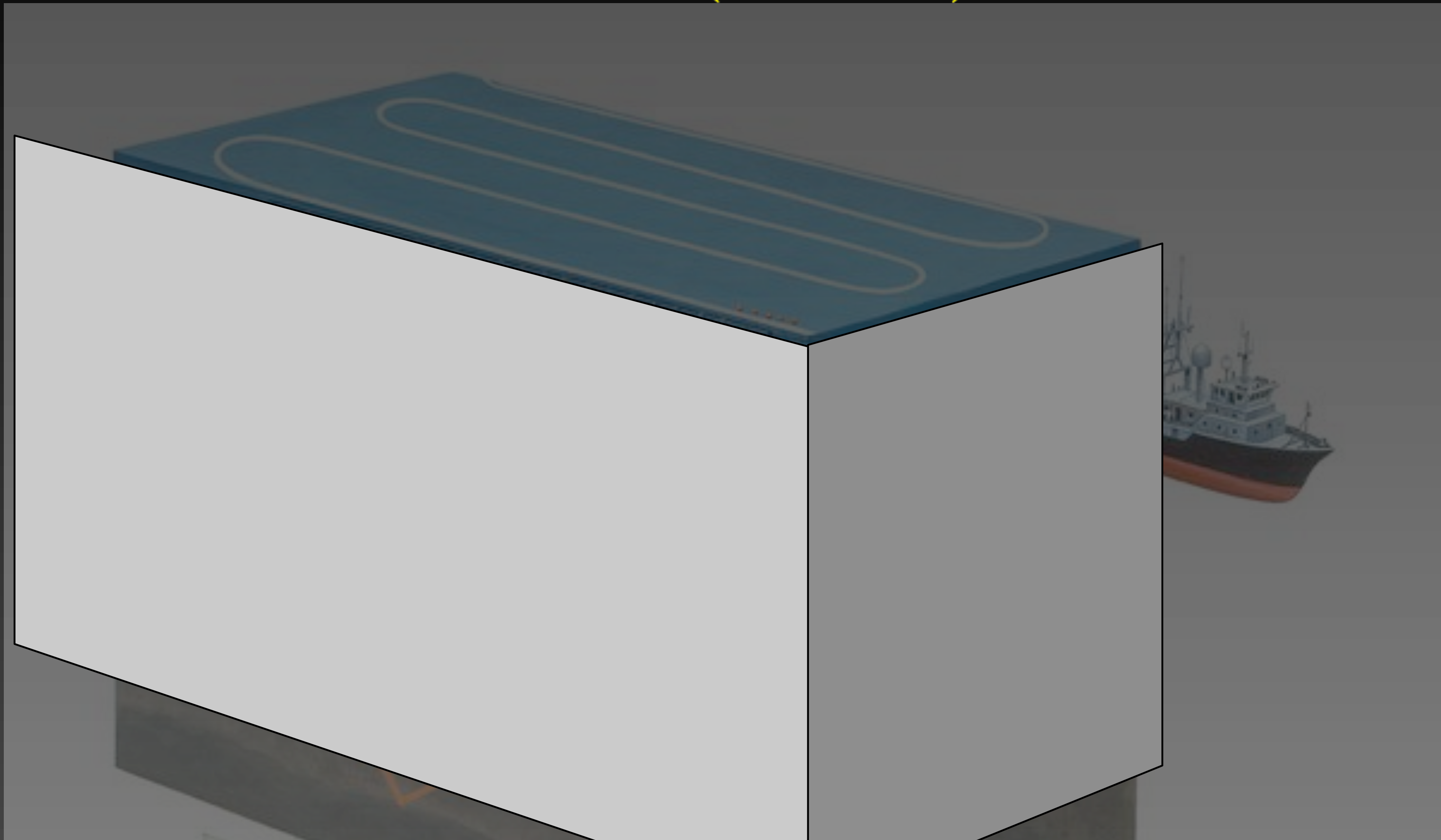
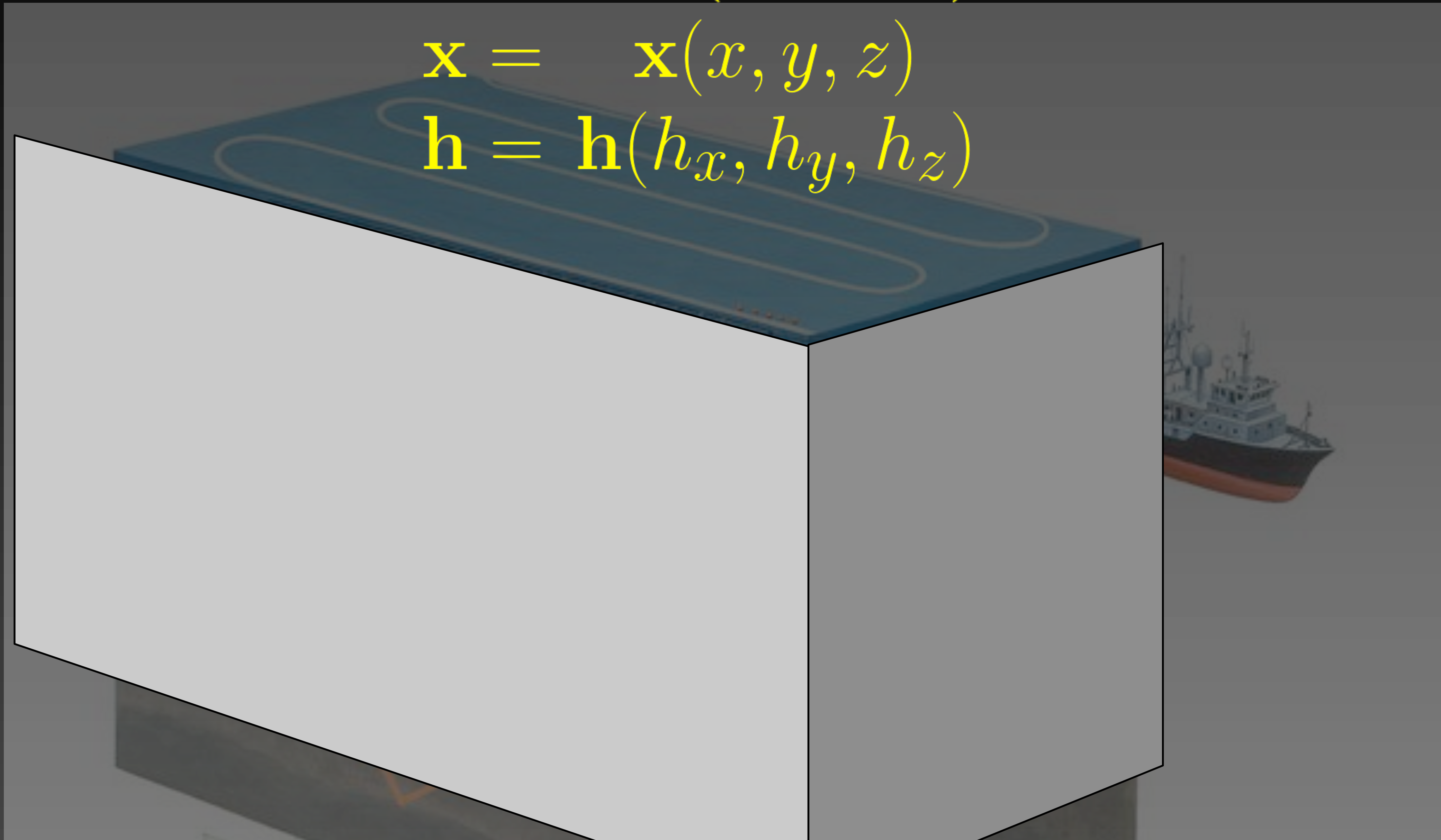


Image space

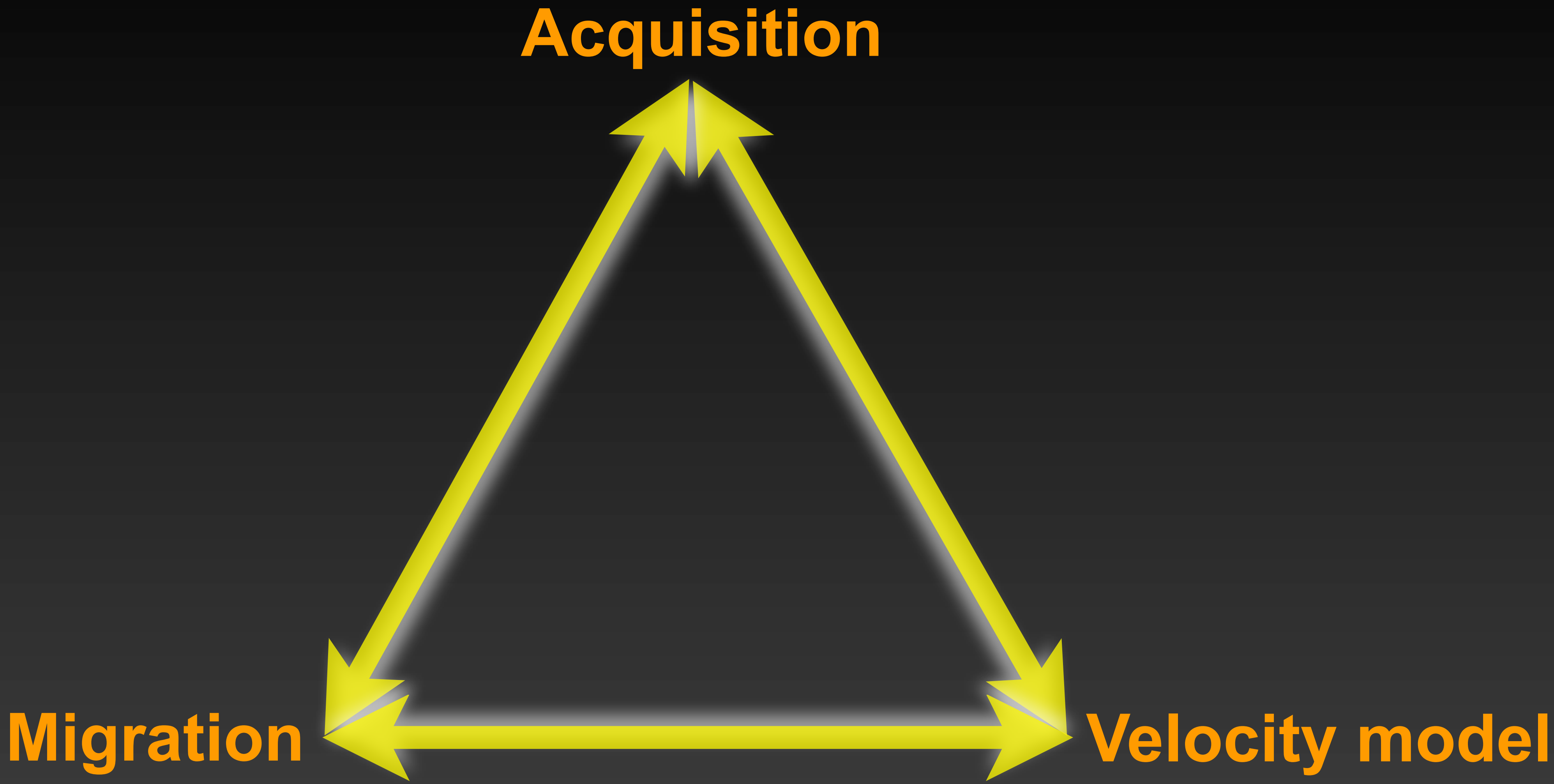
$$I = I(\mathbf{x}, \mathbf{h})$$

$$\mathbf{x} = \mathbf{x}(x, y, z)$$

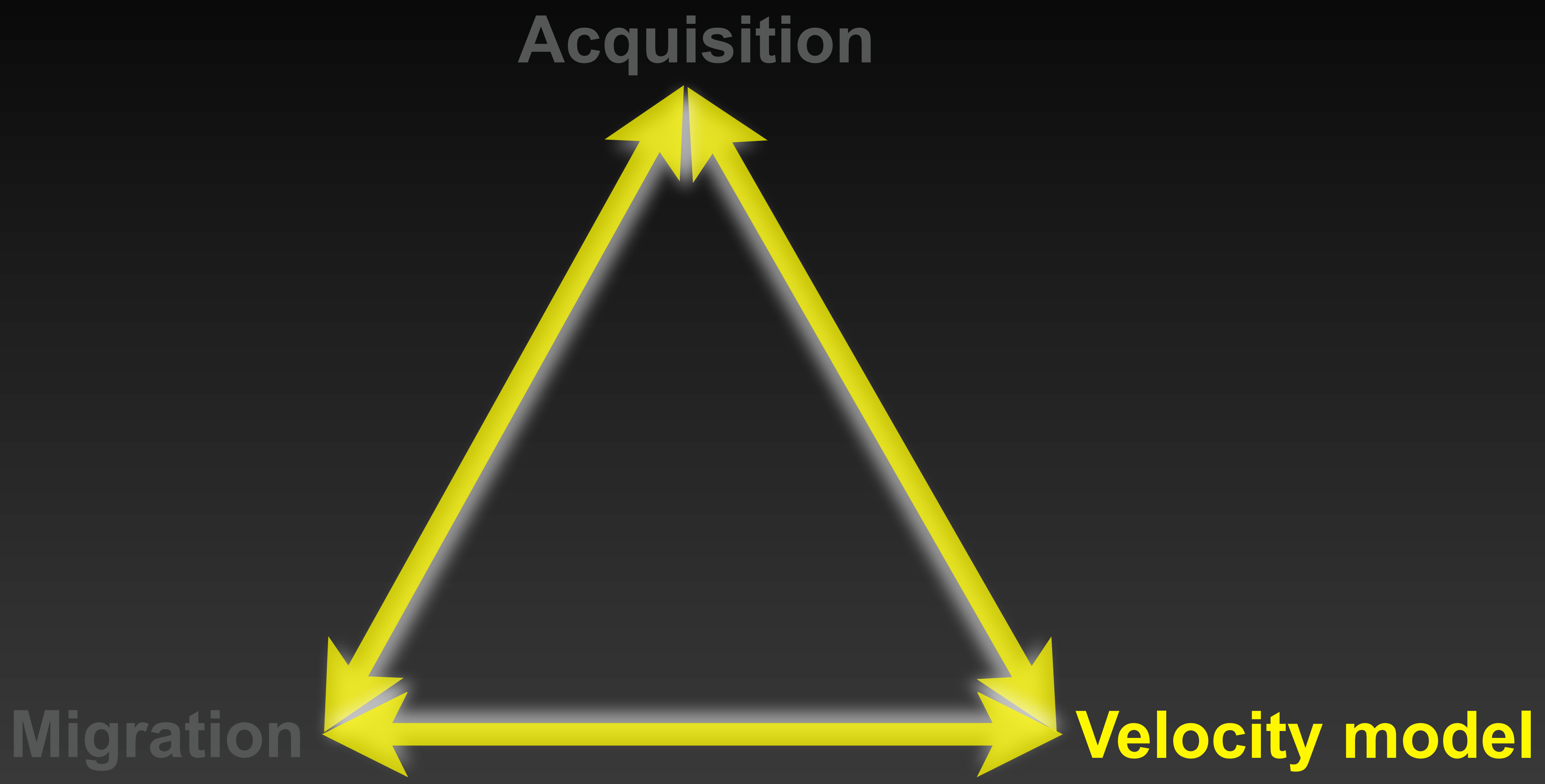
$$\mathbf{h} = \mathbf{h}(h_x, h_y, h_z)$$



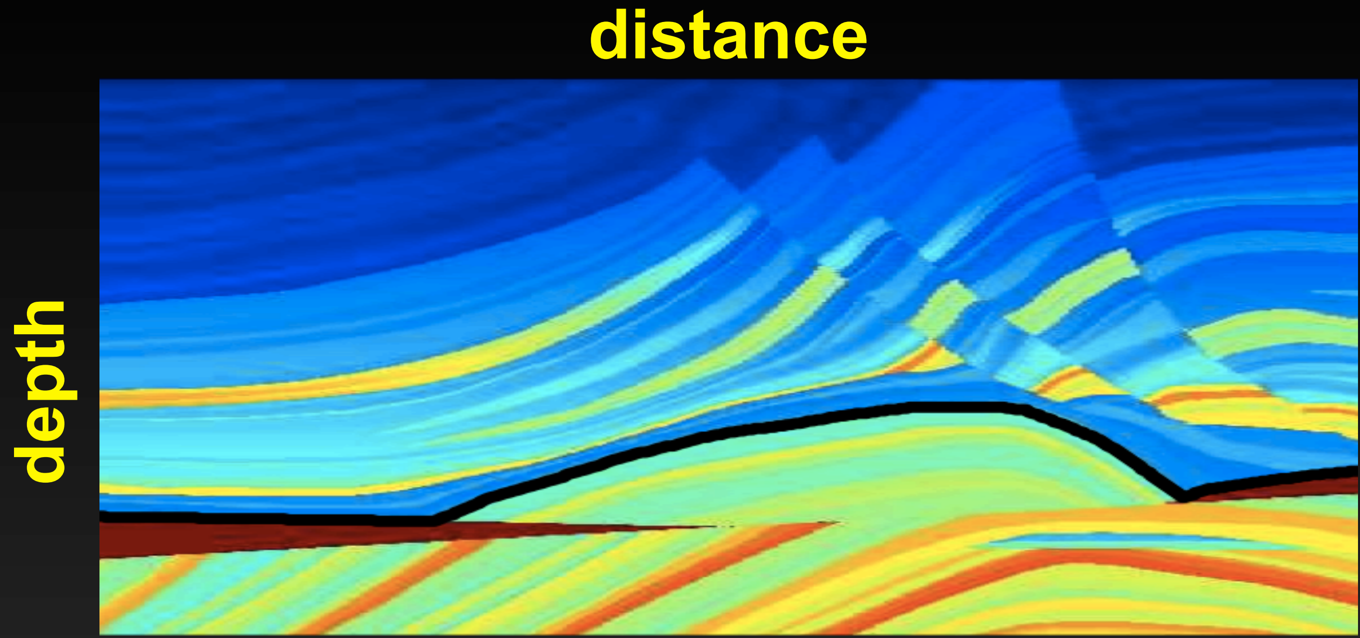
Seismic exploration technology



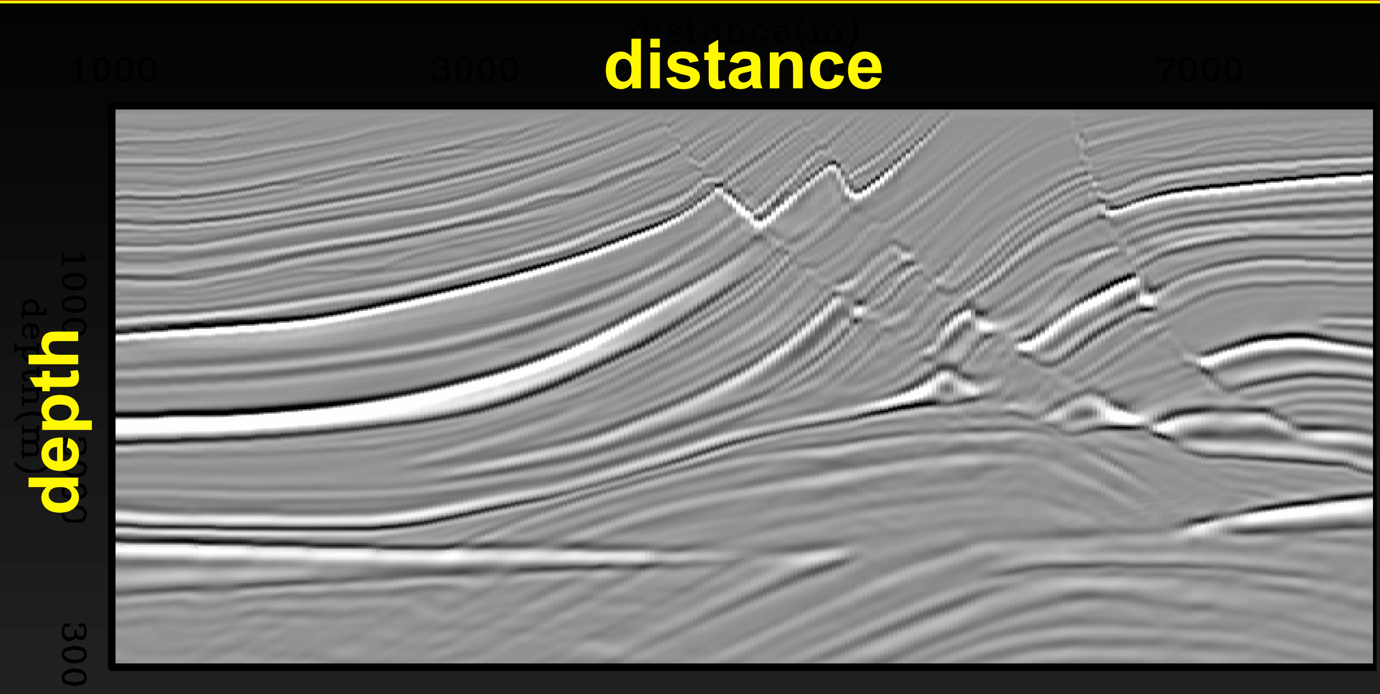
Seismic exploration technology



Importance of migration velocity

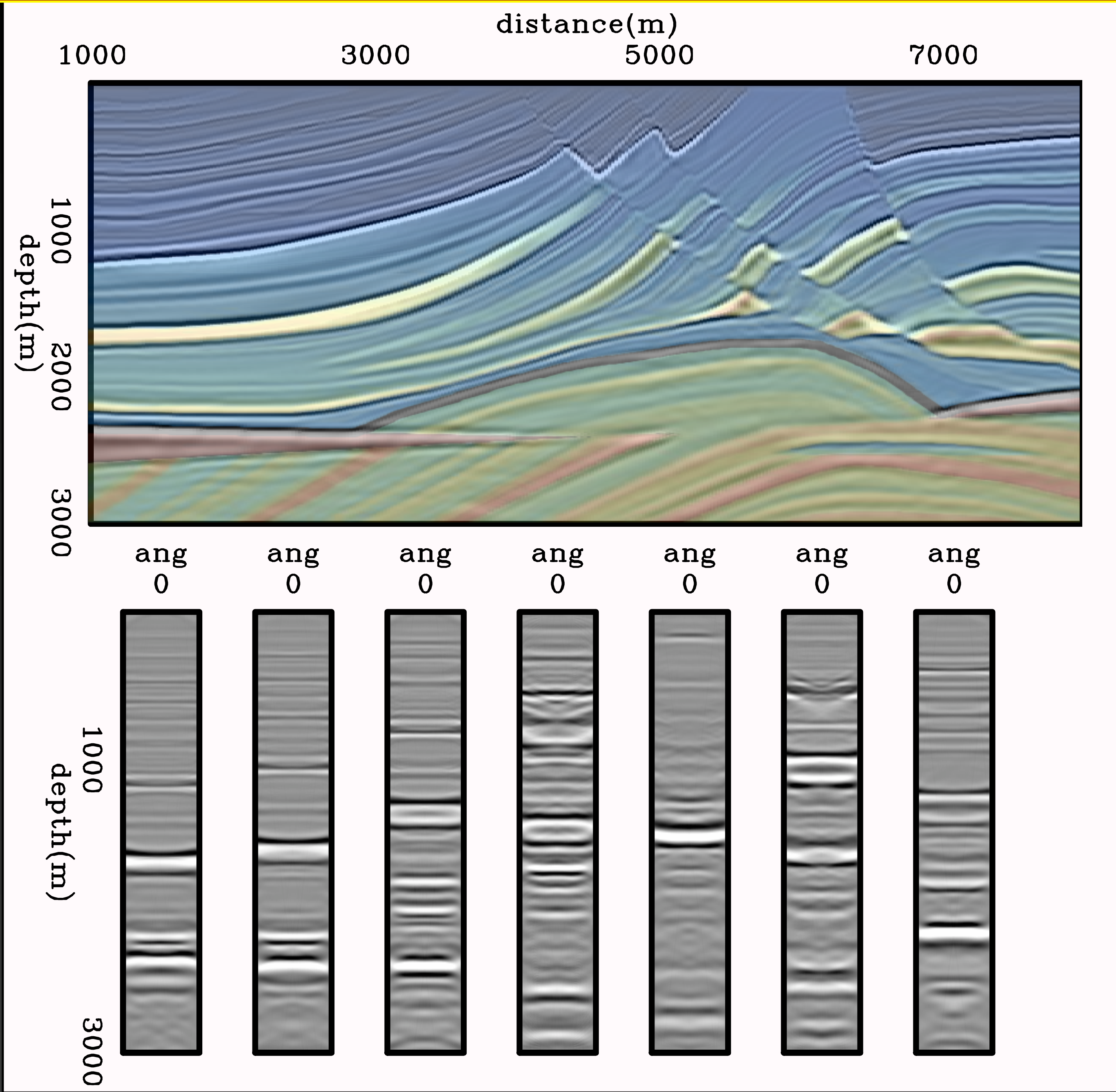


Migration with true velocity

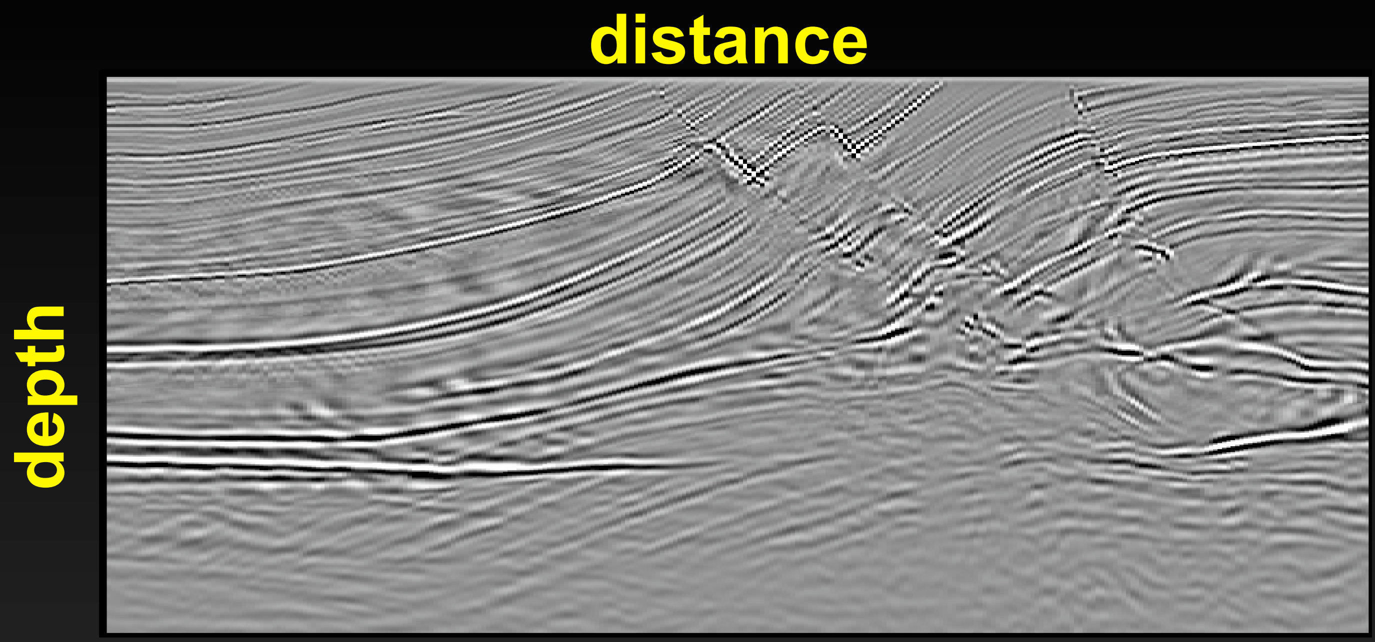


Reasonable reconstruction of the subsurface

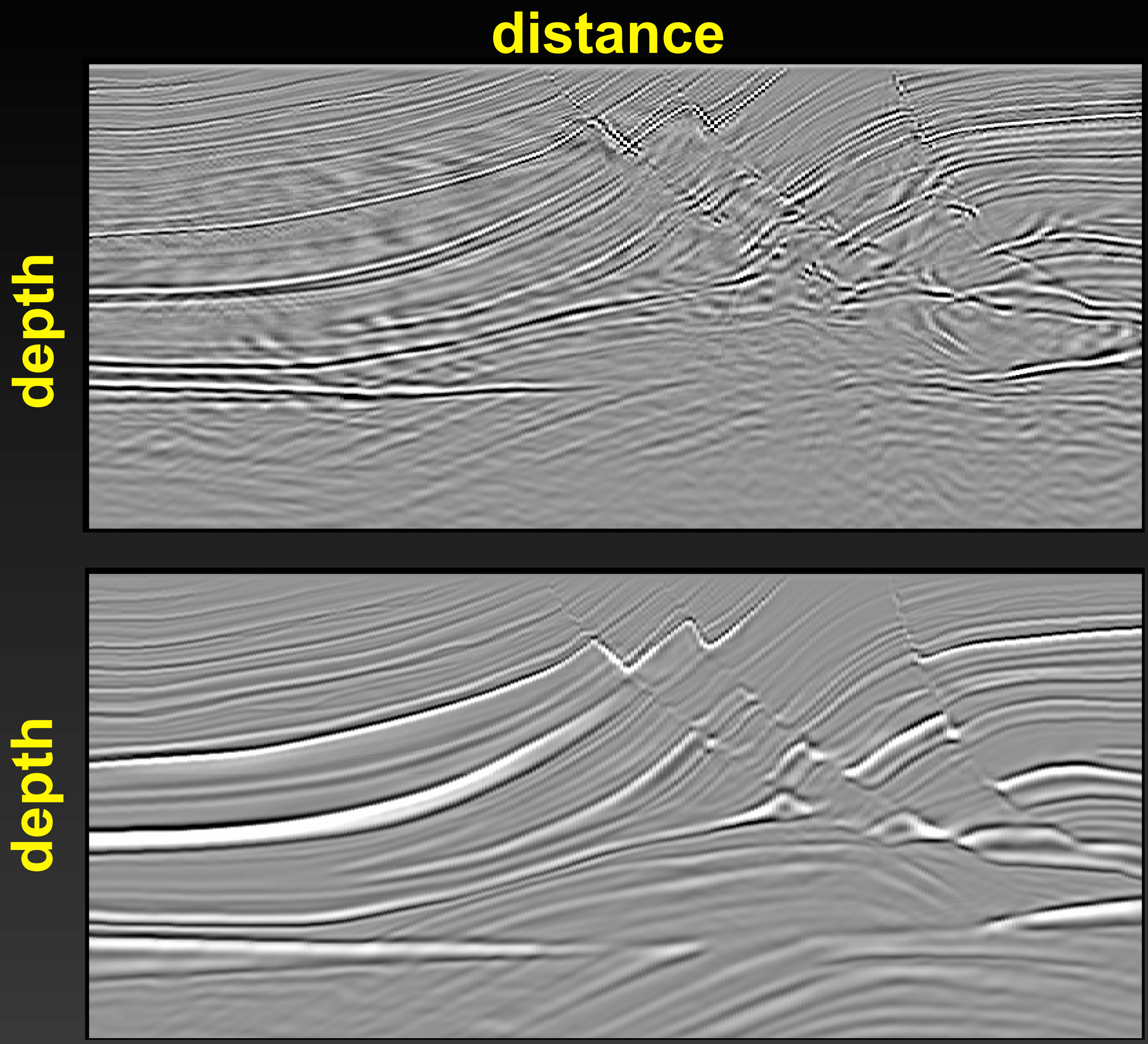
Flat reflectors in the angle gathers



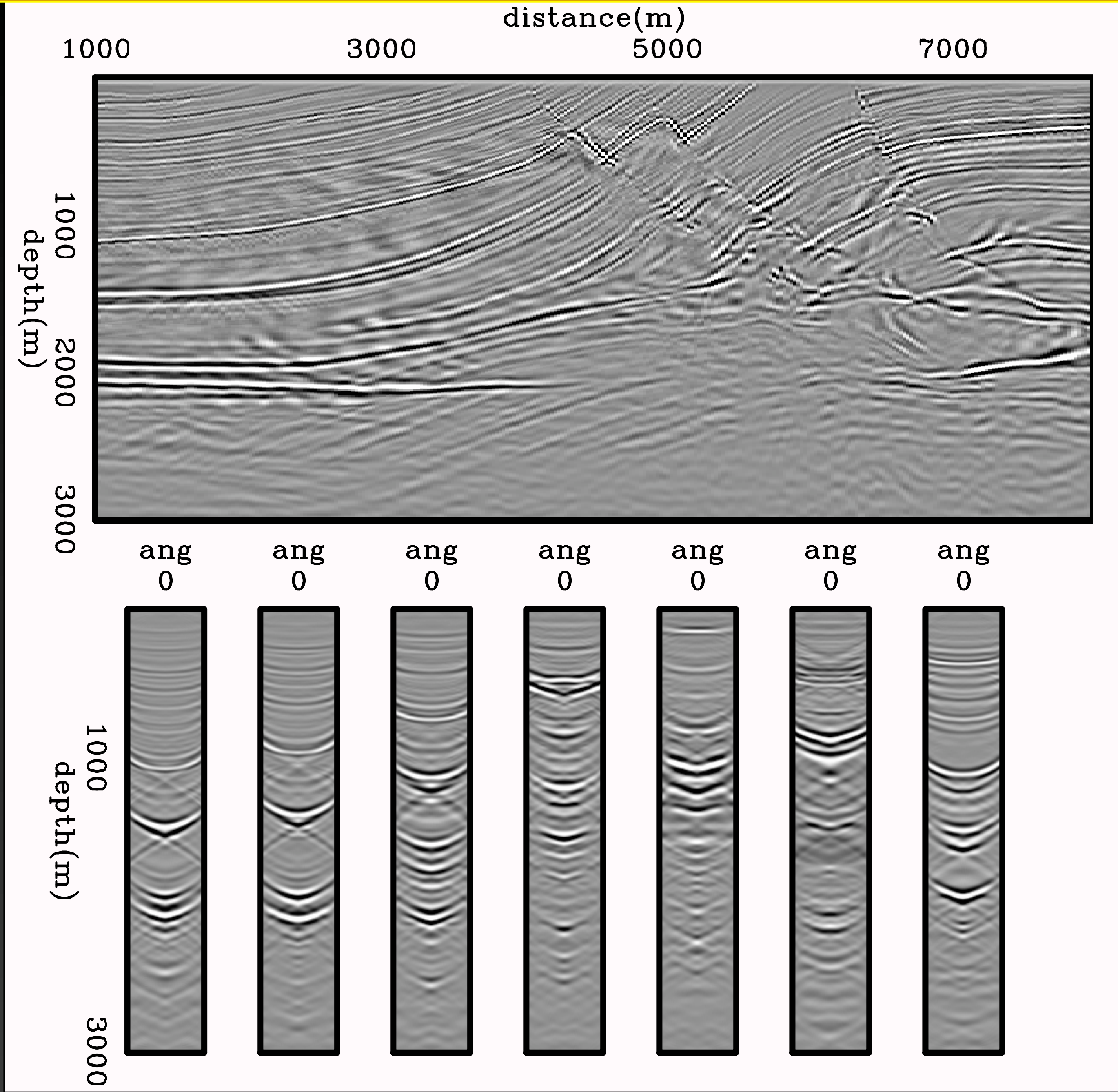
Migration with wrong velocity



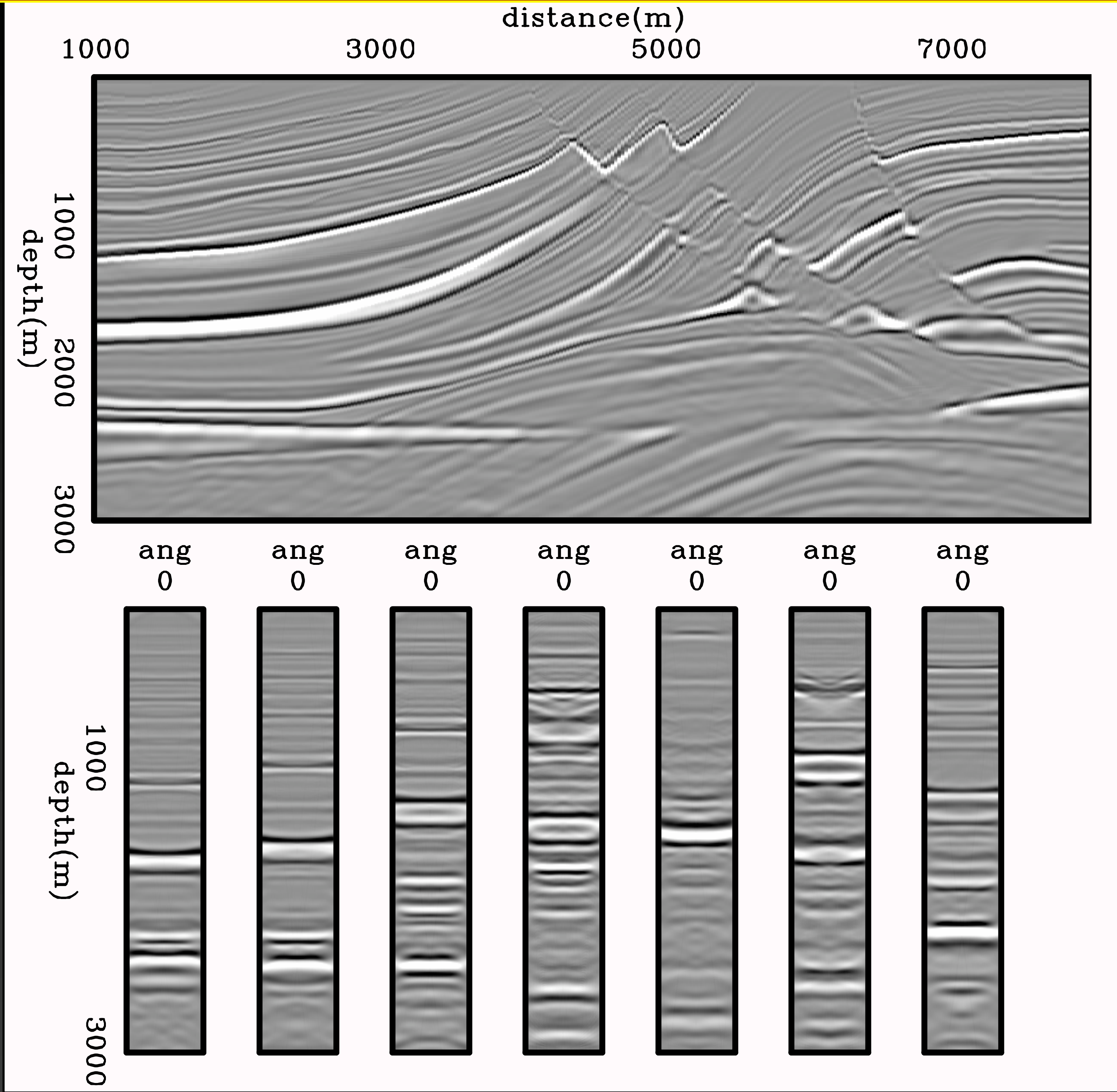
Unfocused image, wrong positioning

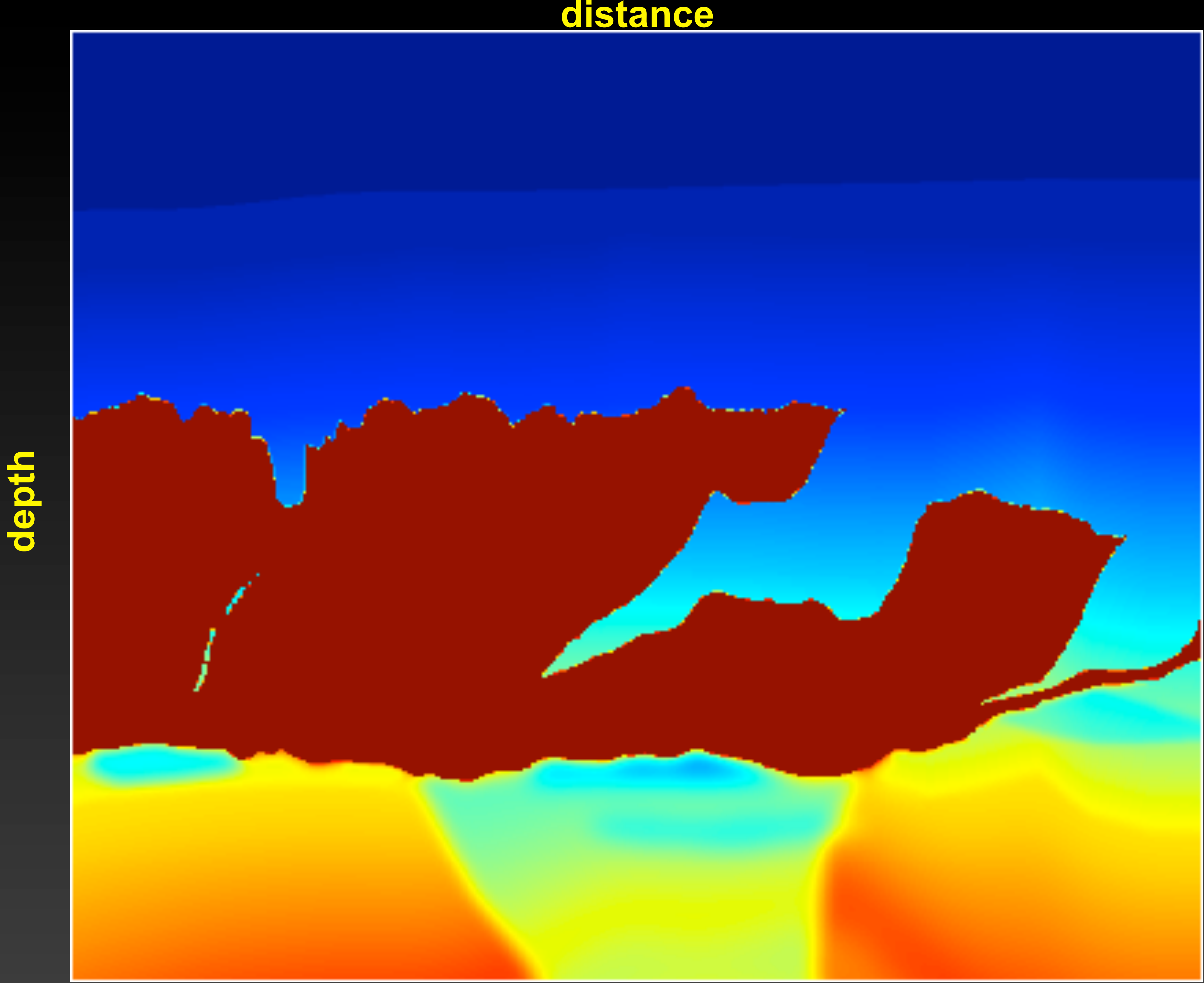


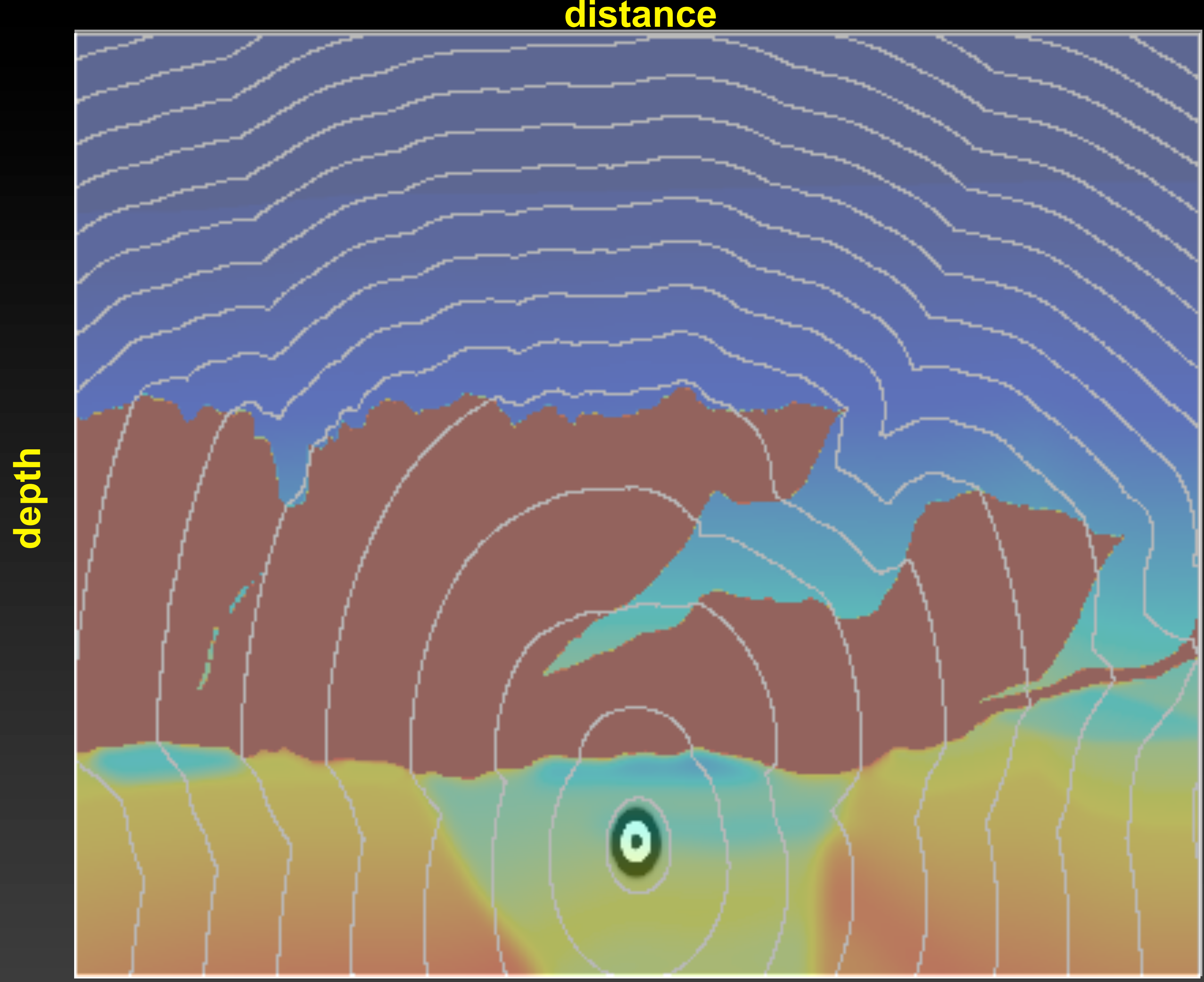
Curved reflectors in the angle gathers



Flat reflectors in the angle gathers




distance
depth


distance
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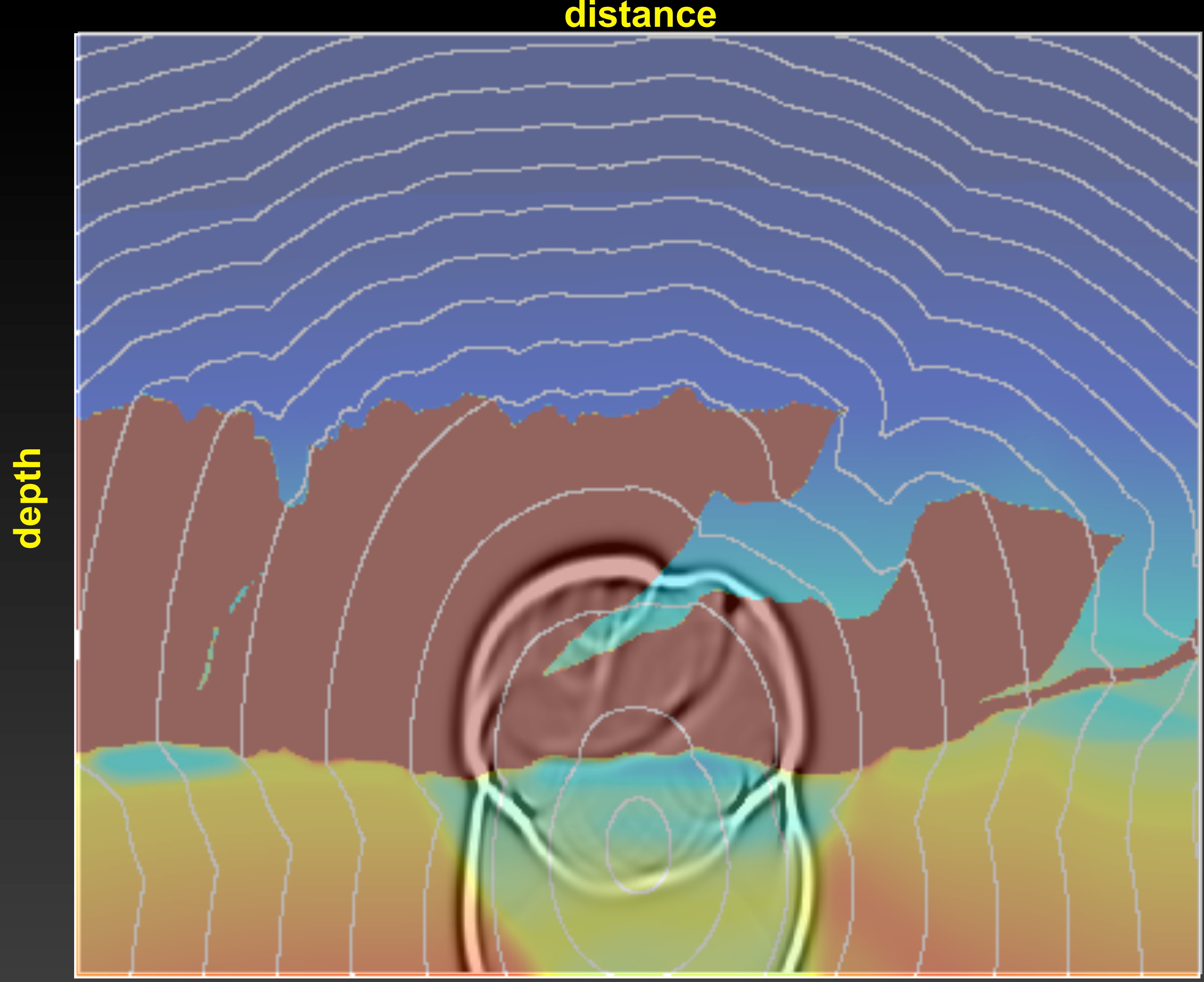
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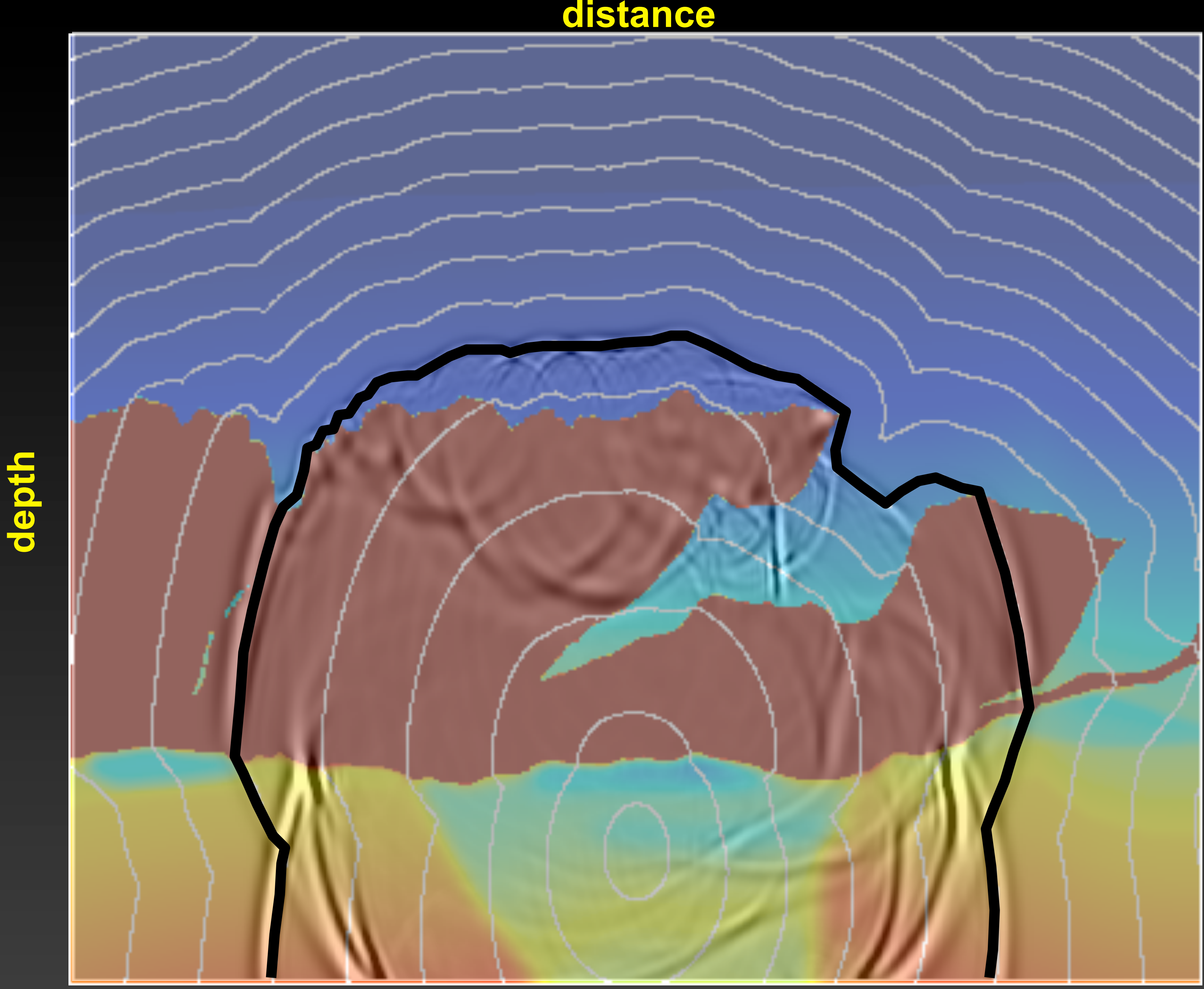
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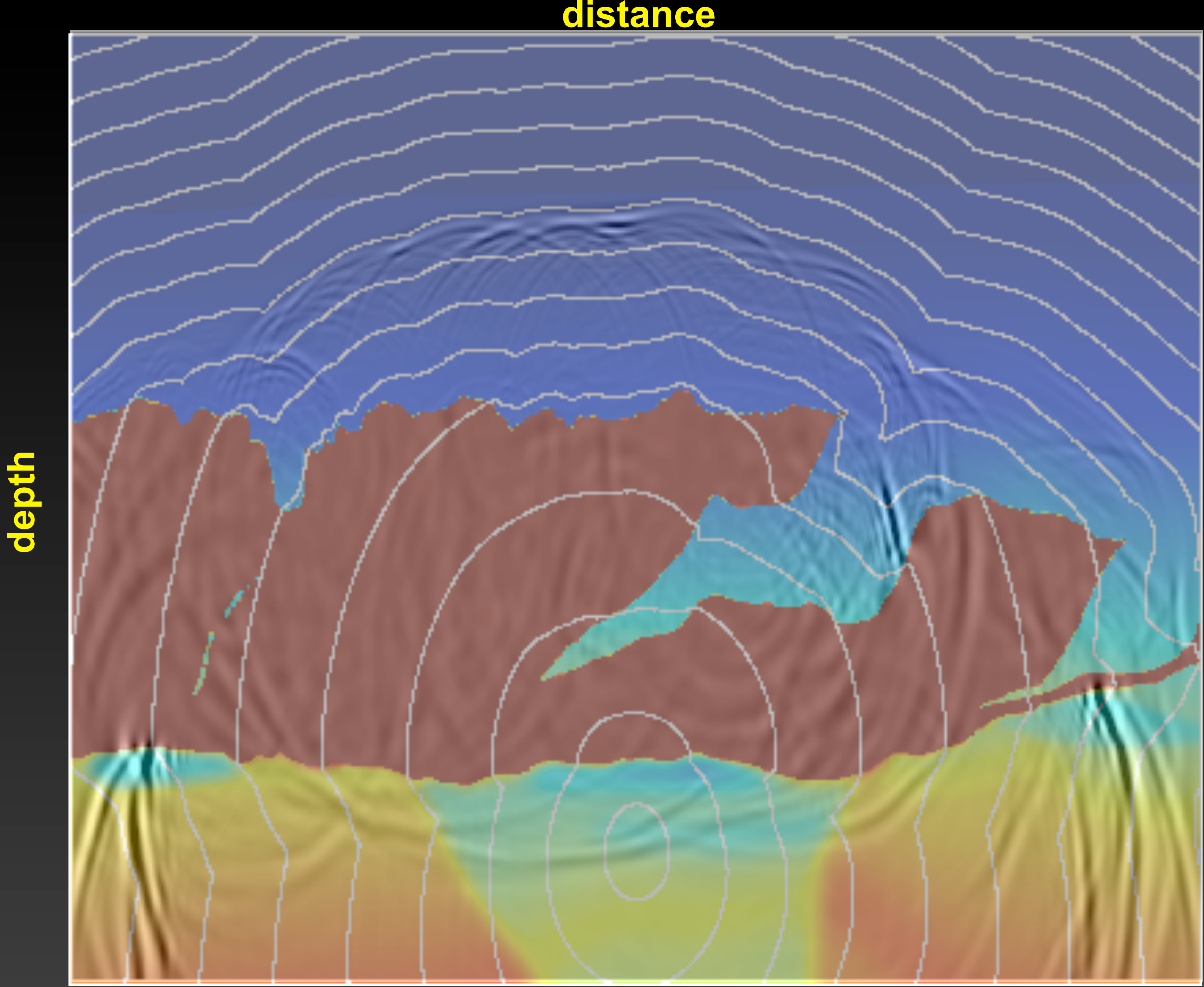

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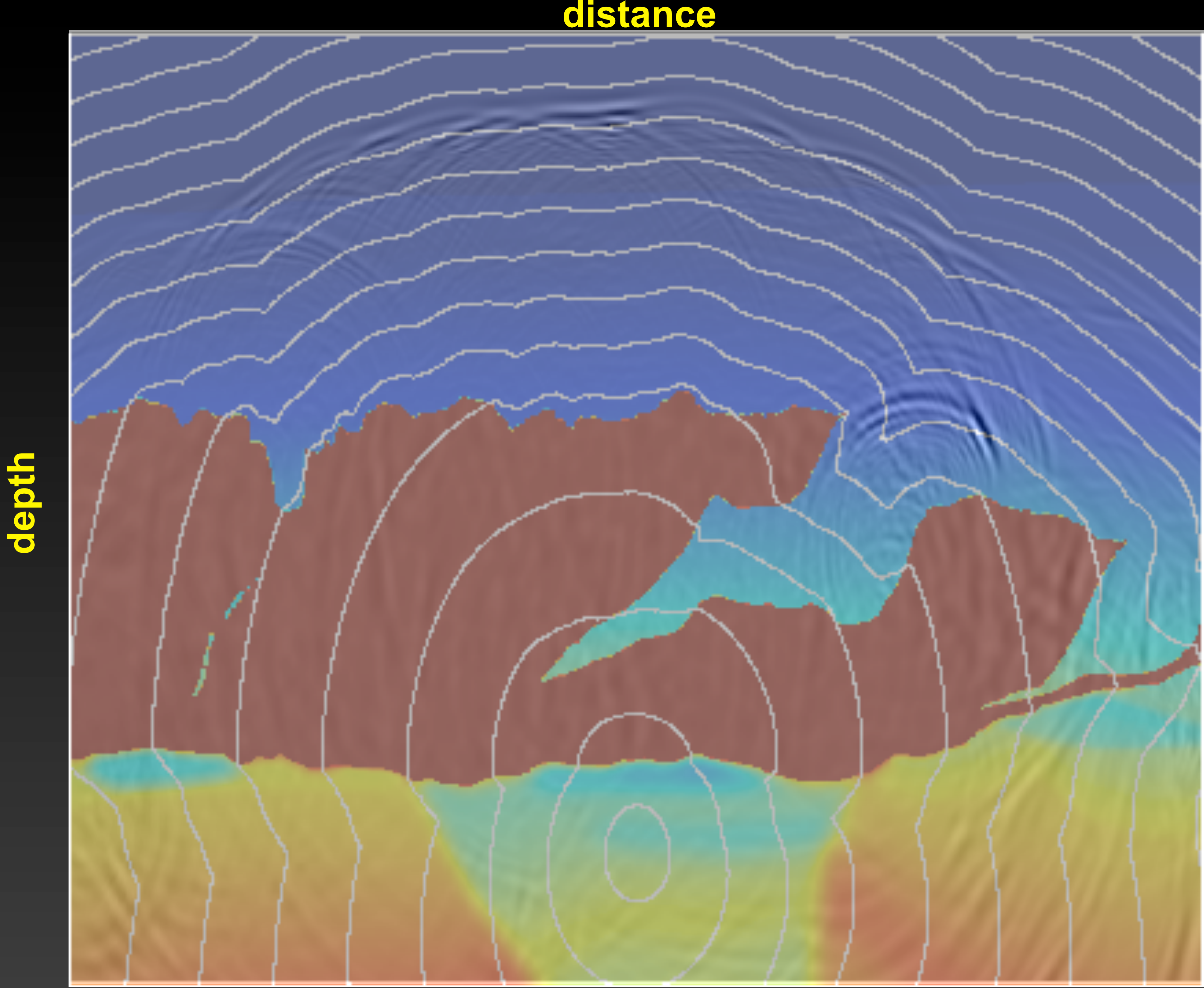

distance
depth

Wave-equation tomography

- **Data space**
  - waveform inversion

$$J(s) = \|\mathbf{F}[s] - d_{obs}\|_n$$

J = objective function

$\mathbf{F}$ = nonlinear operator

n = norm

s = slowness

d_{obs} = observed data

Wave-equation tomography

- **Image space (ISWET)**

$$I(s) \approx I_o + \left.\frac{\partial I}{\partial s}\right|_{s=s_o} \Delta s$$

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

s = slowness

s_o = background slowness

Δs = slowness perturbation

$\mathbf{T}$ = IS – tomographic operator

I = image

I_o = background image

ΔI = image perturbation

Wave-equation tomography

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

Wave-equation tomography

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

For complex geology ...

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

For complex geology ...

- ISWET is more robust than ray-based methods
- Rarely been applied in 3D
  – High cost and lower flexibility than ray-based methods

3D-ISWET as routine processing

- **Reduce cost**

3D-ISWET as routine processing

- **Reduce cost**

- **Improve flexibility**

3D-ISWET as routine processing

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

Reducing 3D-ISWET cost

- **Decrease data size**

Reducing 3D-ISWET cost

- Decrease data size

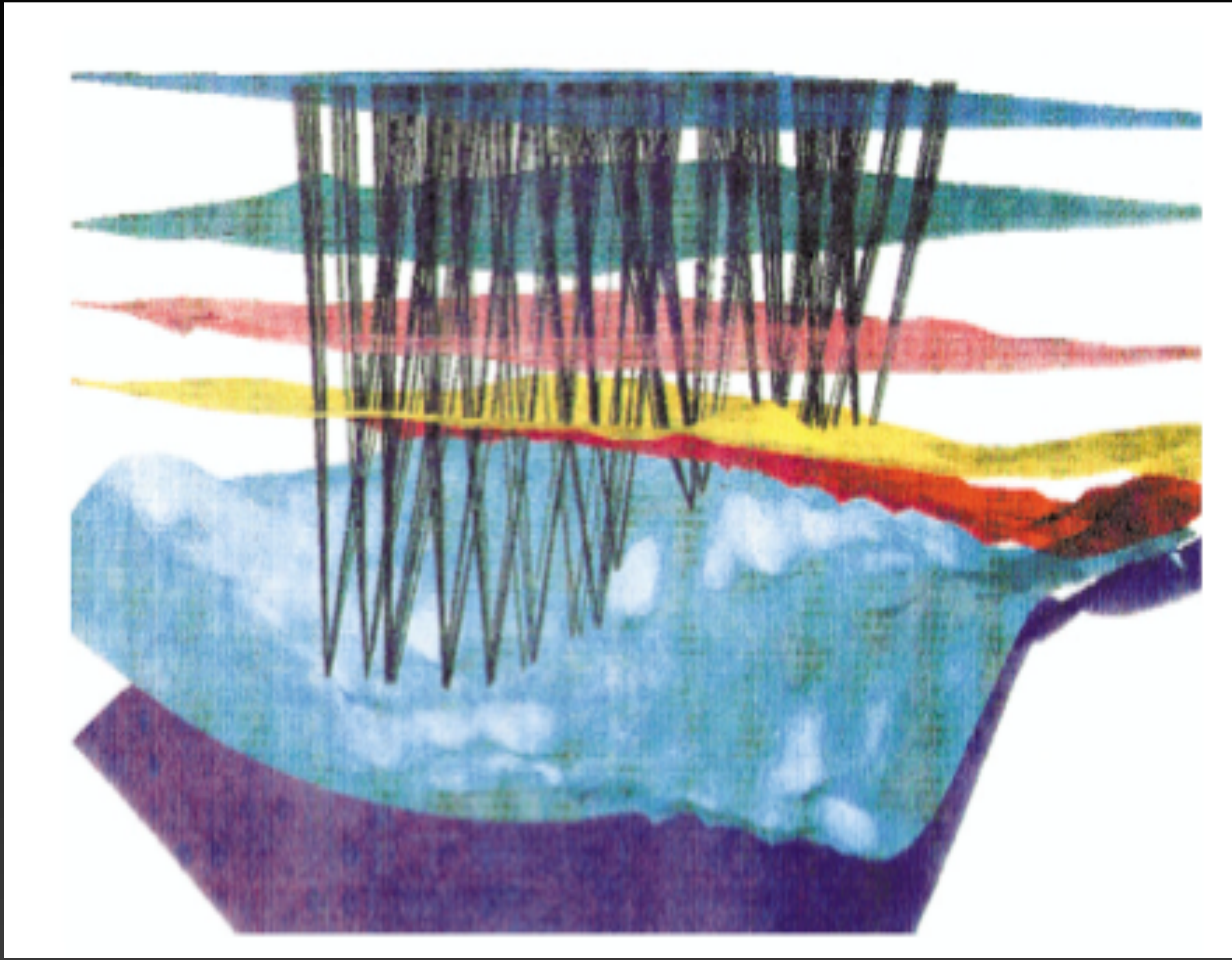
- Solve in a target-oriented manner
  - Wavefield propagation restricted to the inaccurate velocity region

Improving 3D-ISWET flexibility

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

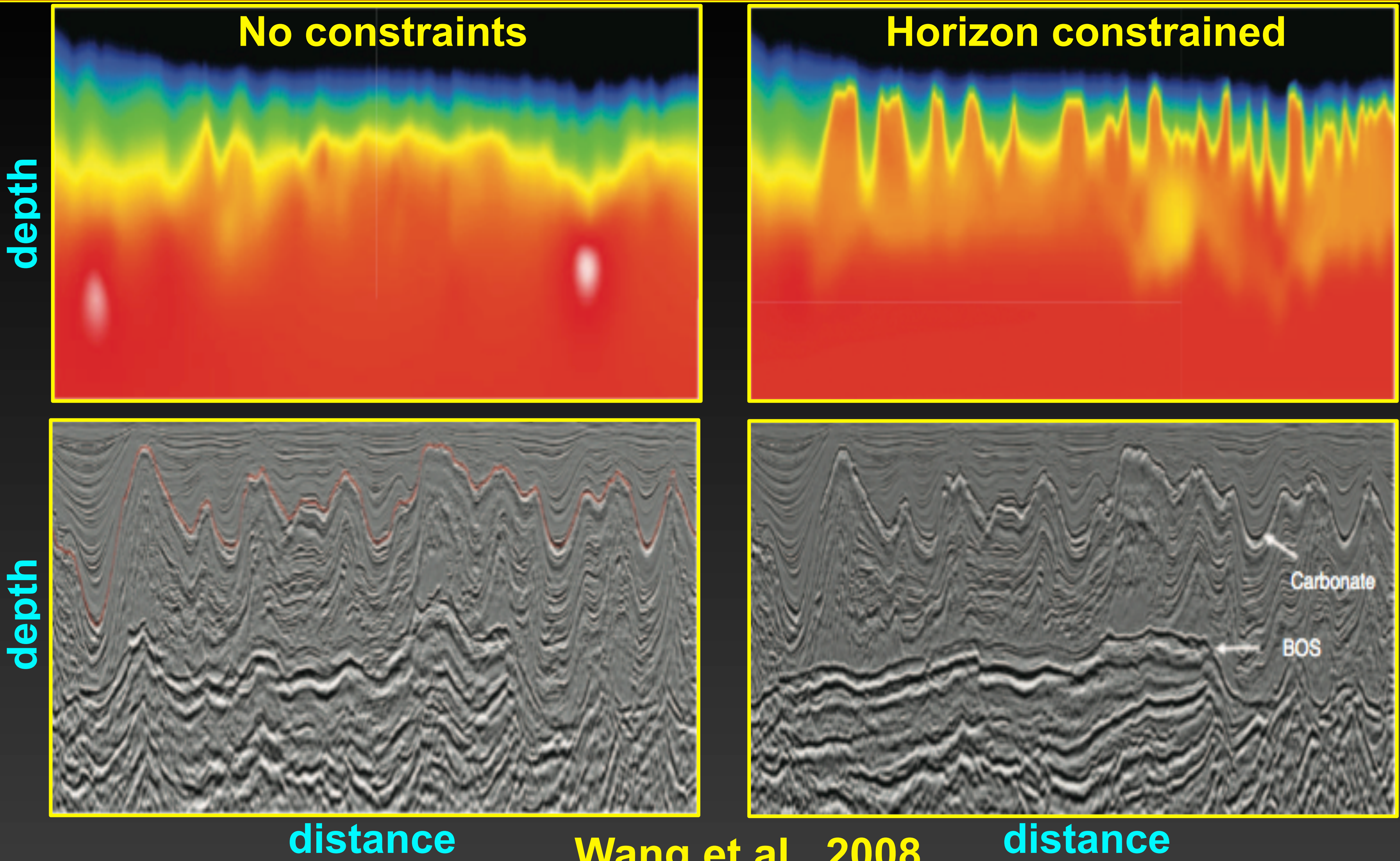
Ray-based strategies

Horizon-based



Jones et al., 1998

Ray-based strategies



Wang et al., 2008

Improving 3D-ISWET flexibility

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

Keeping 3D-ISWET robustness

- **Guarantee correct kinematics and reasonable amplitudes**

Generalized-source domain

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

Generalized-source domain

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

Generalized-source domain

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

Generalized-source domain

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

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

Generalized-source domain

- 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)

Generalized-source domain

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

Generalized-source domain

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

Generalized-source domain

Data space

- plane waves
- random phases

Image space

- PERM wavefields
- ISPEW

Generalized-source domain

Generalized-source domain

Data space
- plane waves
- random phases

Image space
- PERM wavefields
- ISPEW

Thesis content

- **Chapter 2: Pre-stack exploding-reflector model**
- **Chapter 3: Image-space phase-encoded wavefields**
- **Chapter 4: MVA using image-space generalized sources**
- **Chapter 5: 3D-field data example**

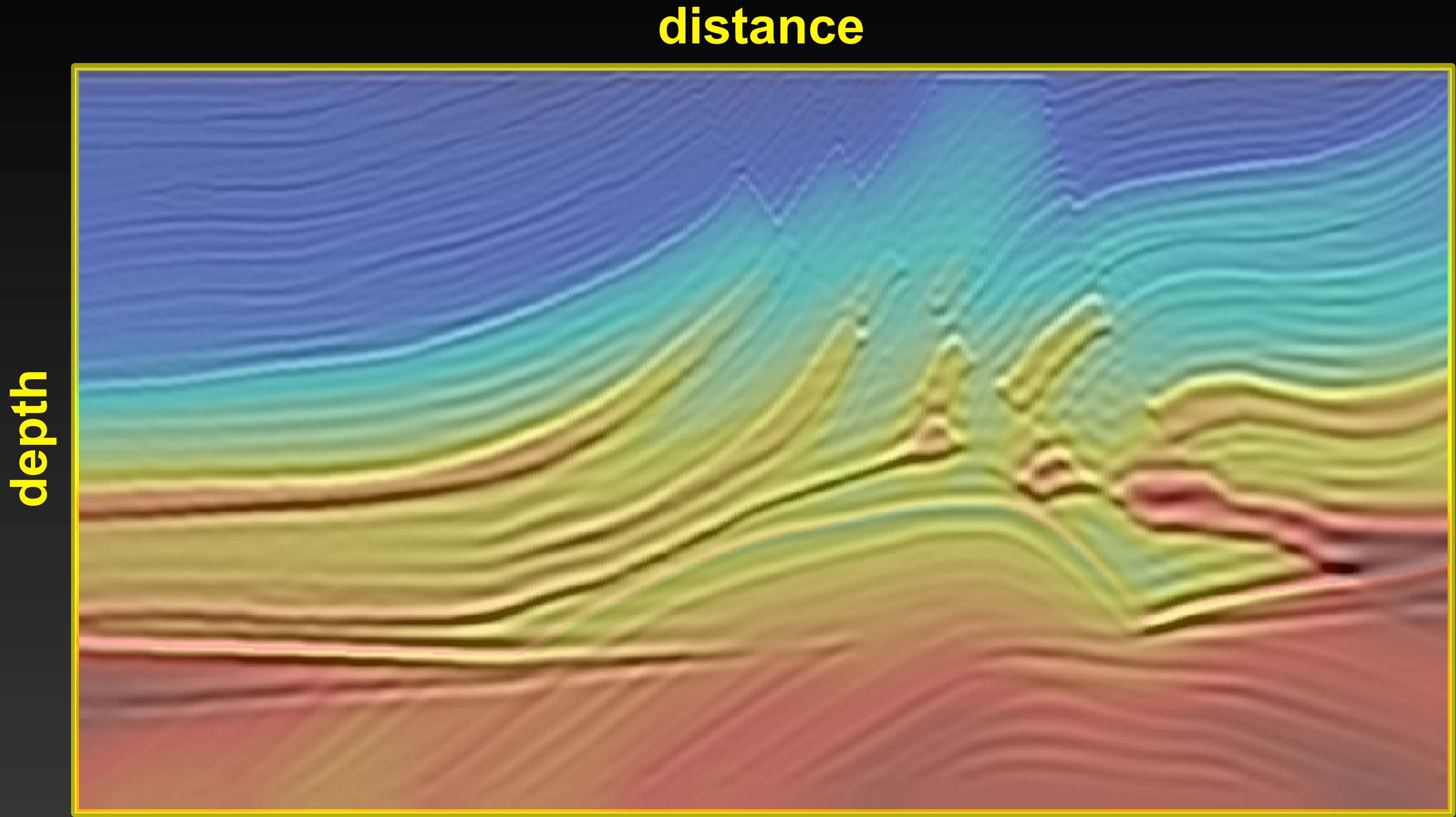
Exploding reflectors

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

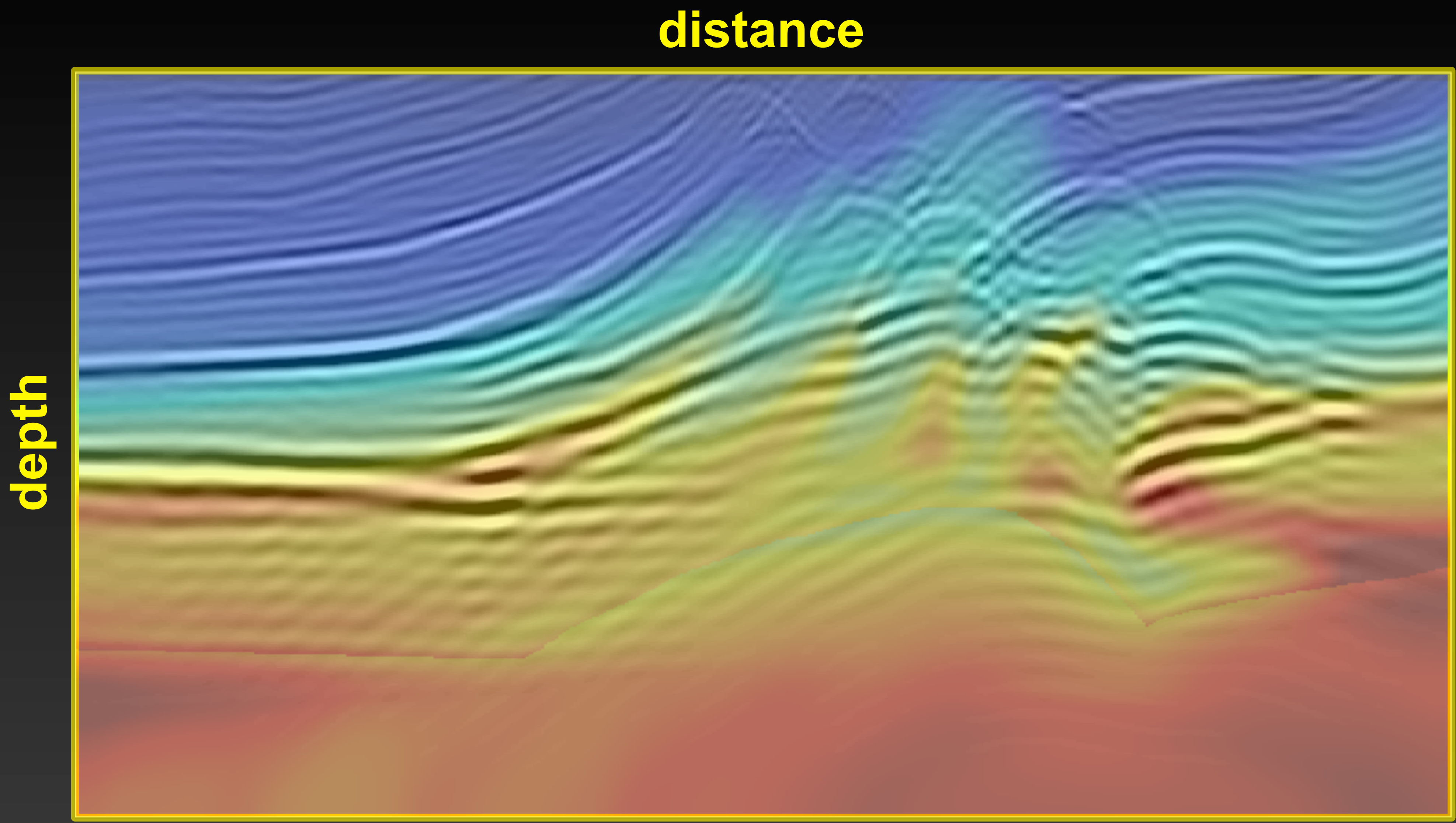
Exploding reflectors

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

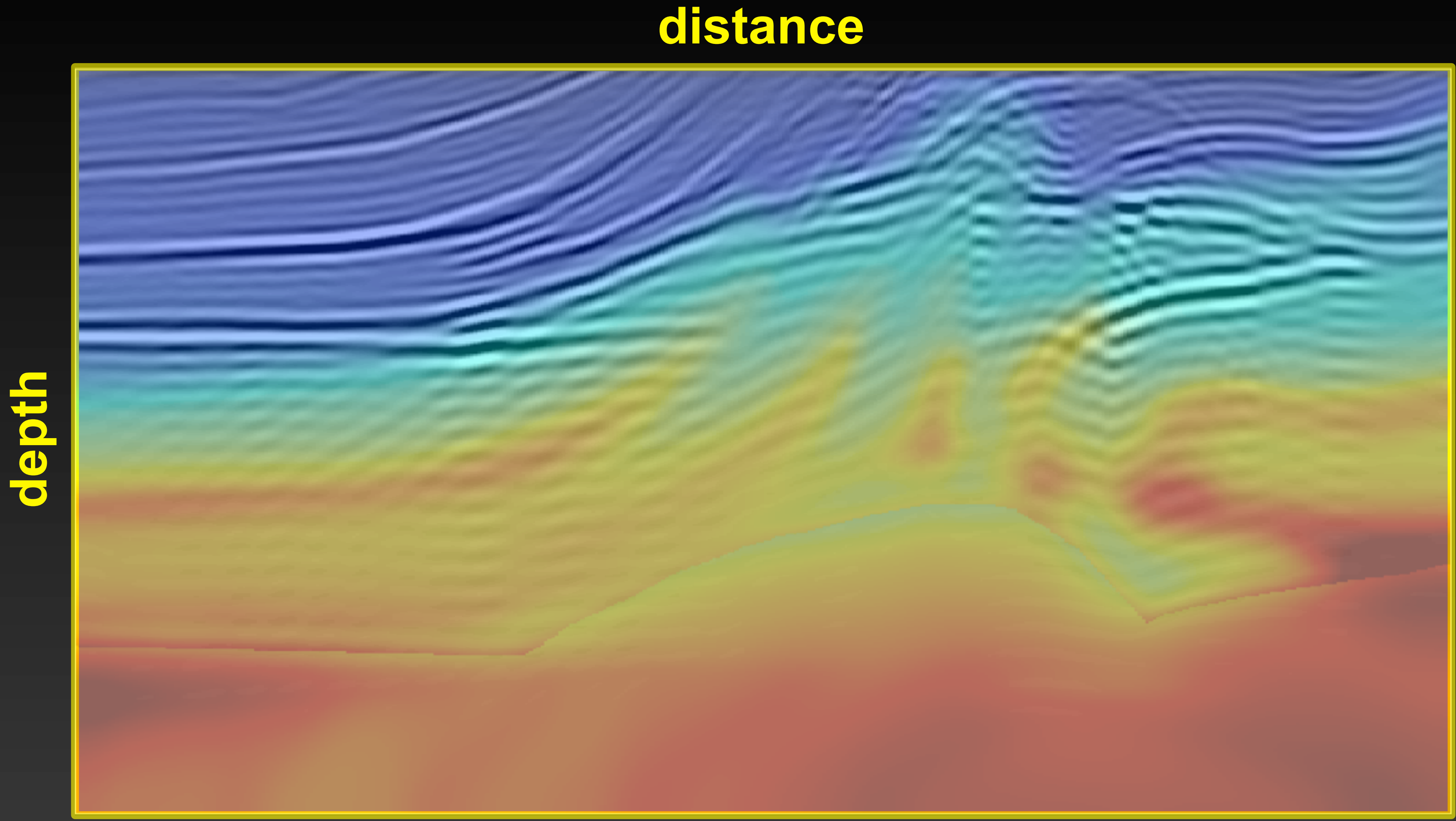
Exploding reflectors



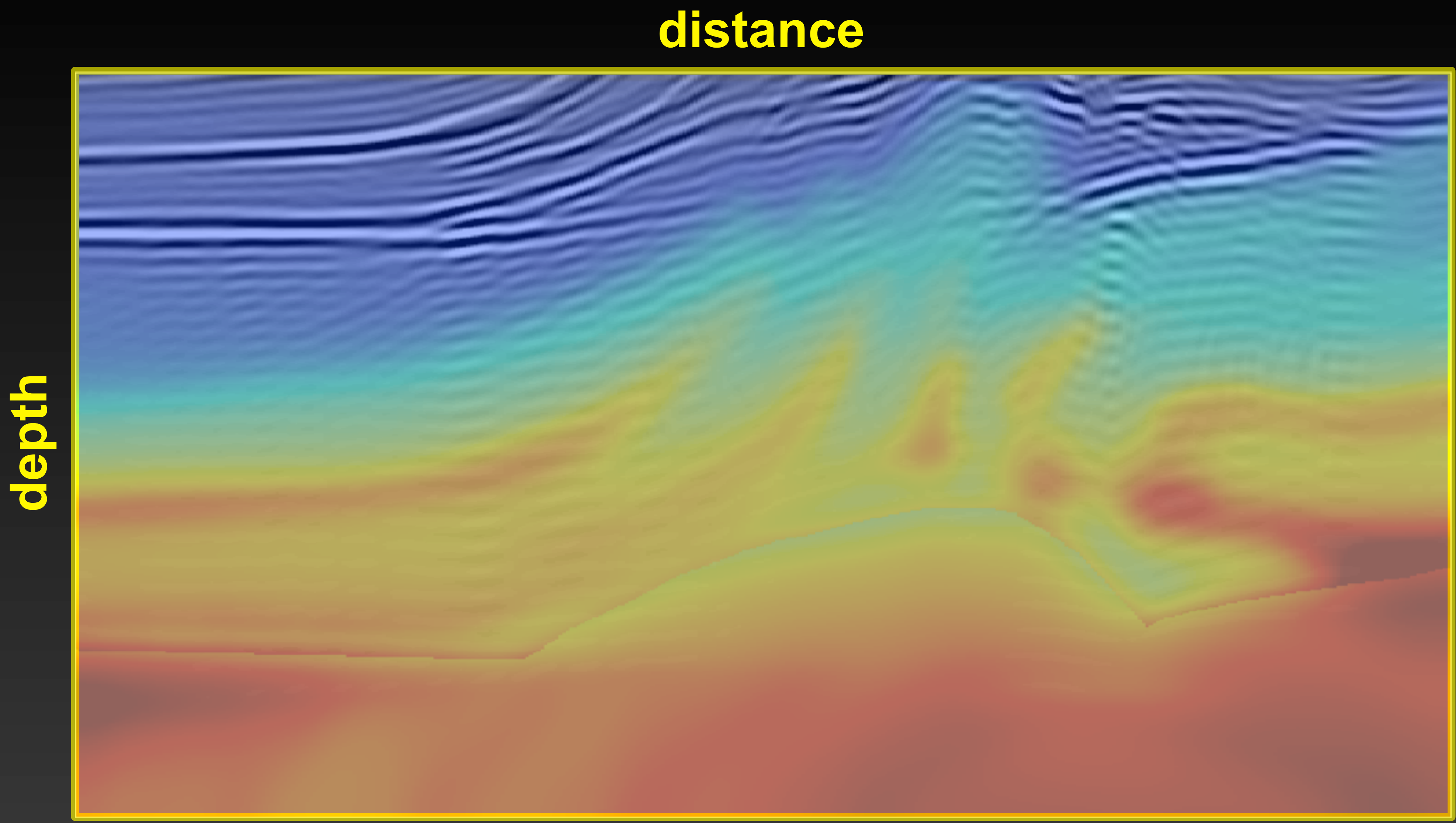
Exploding reflectors



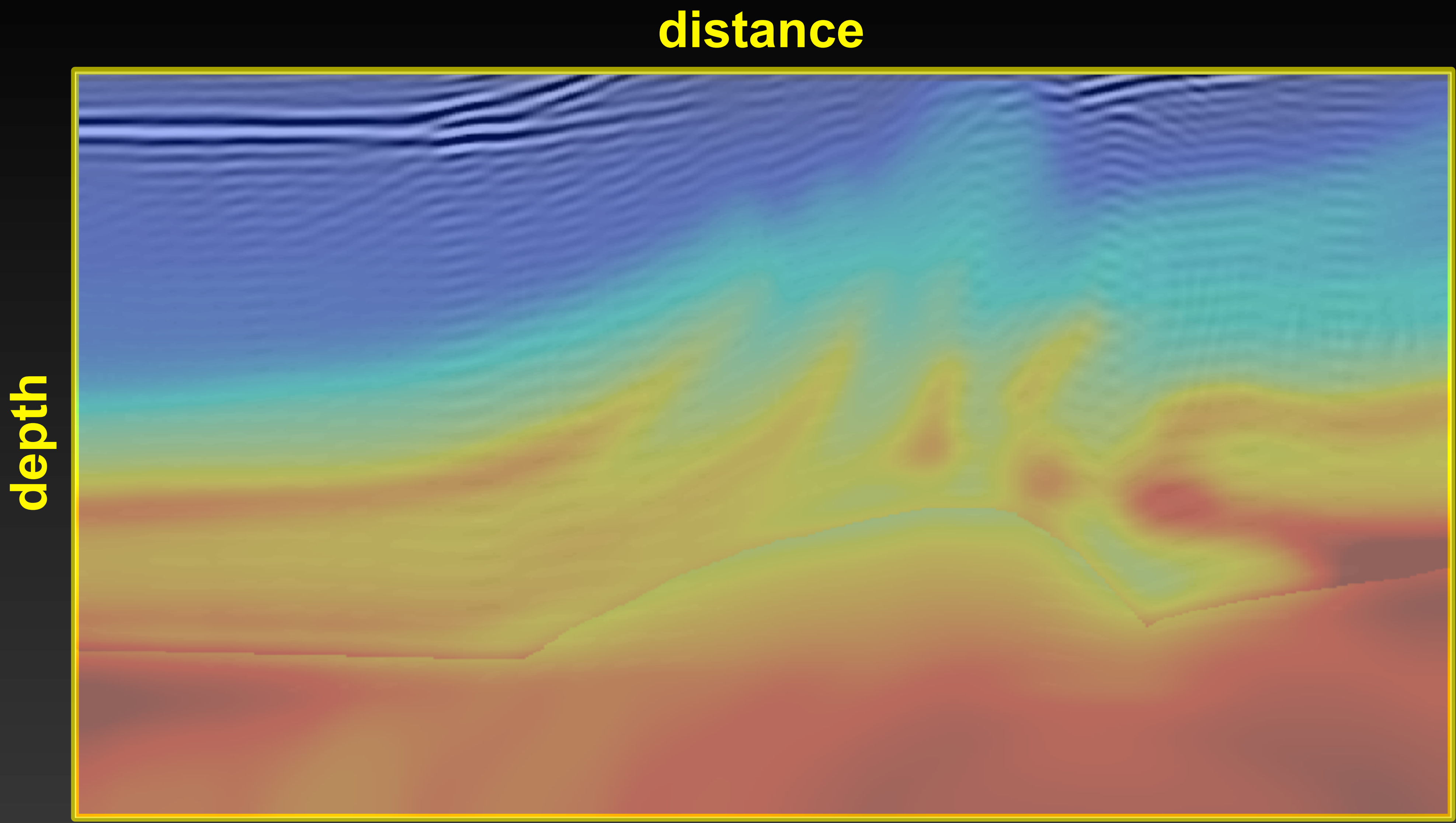
Exploding reflectors



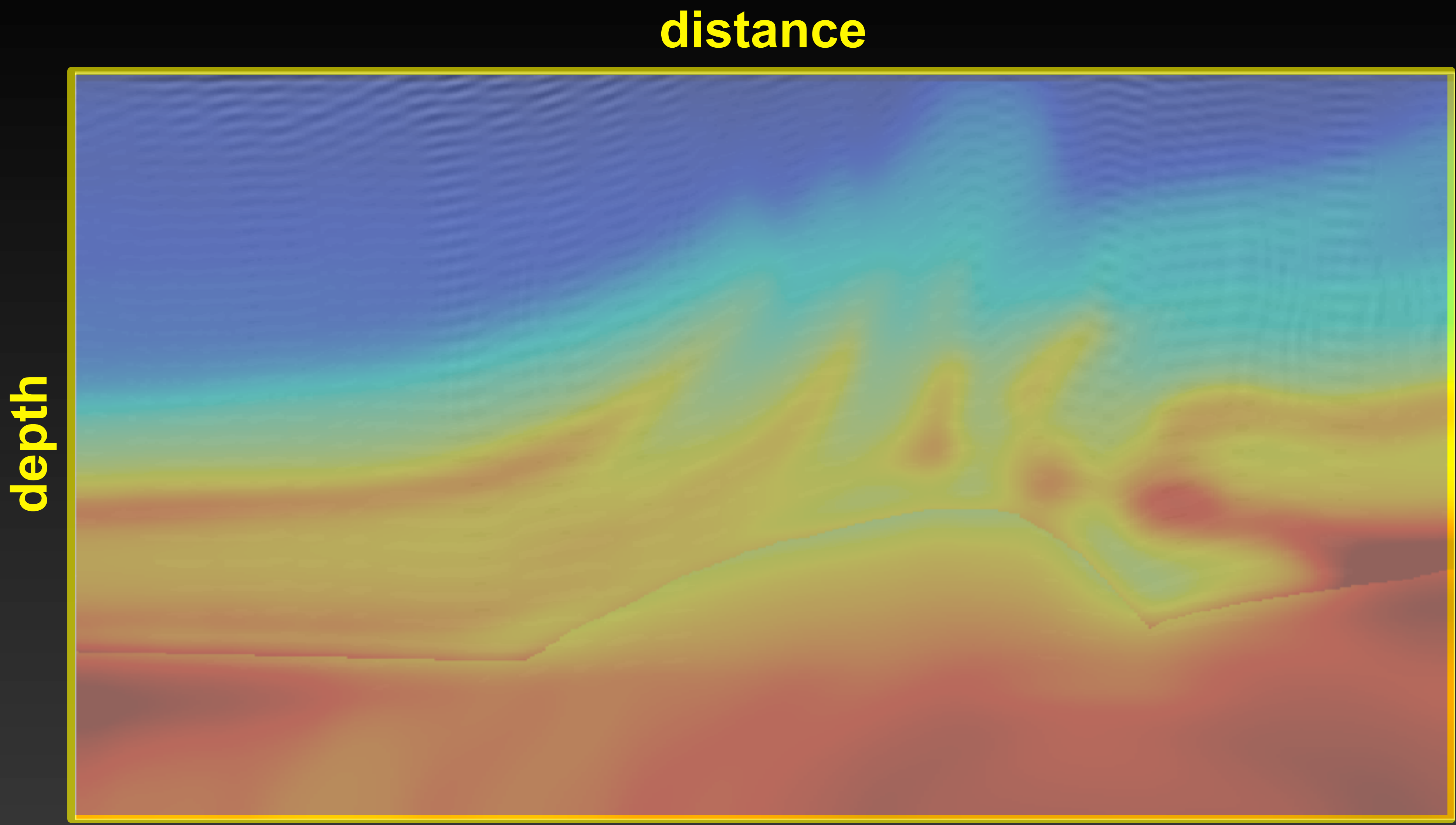
Exploding reflectors



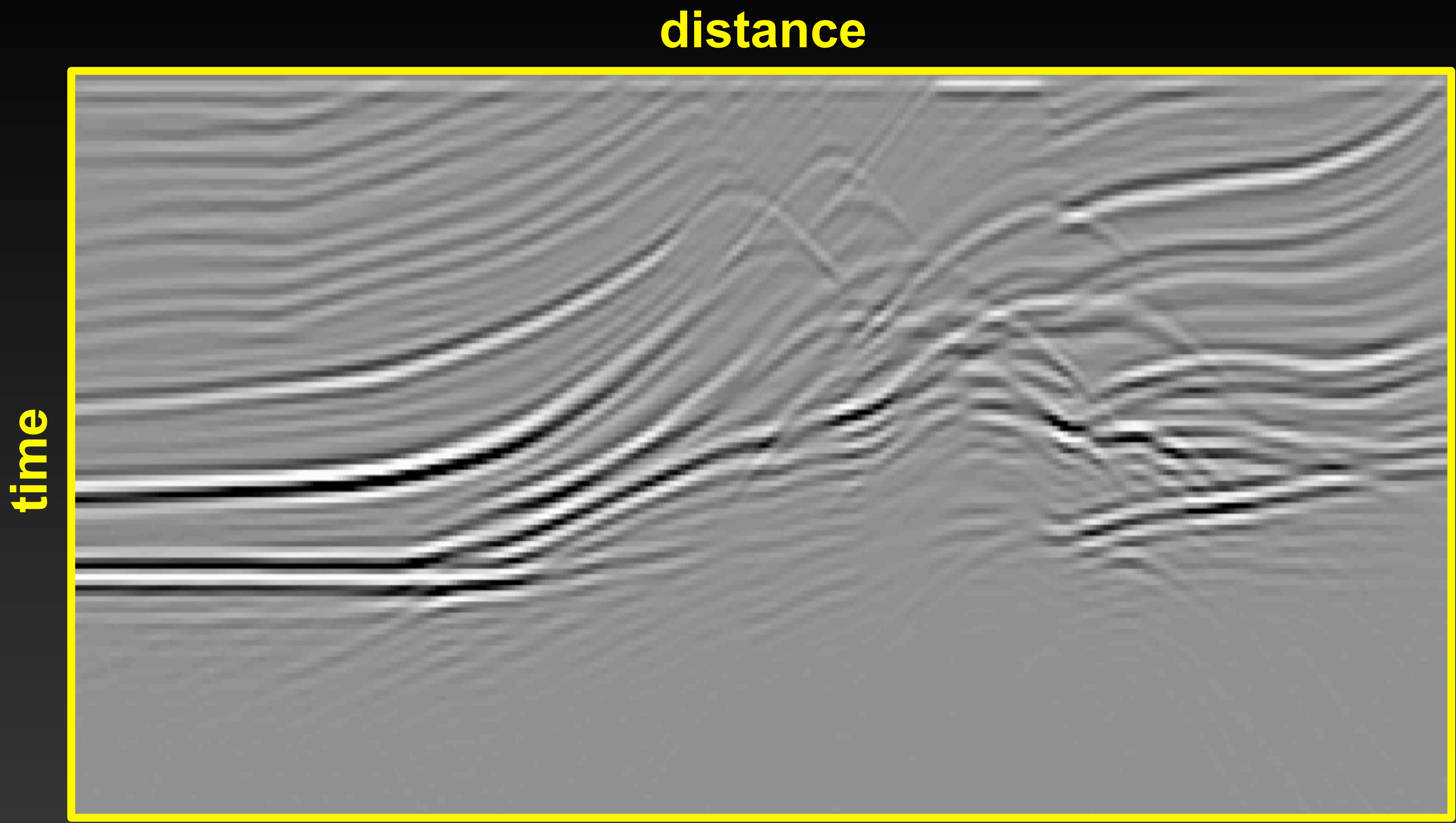
Exploding reflectors



Exploding reflectors



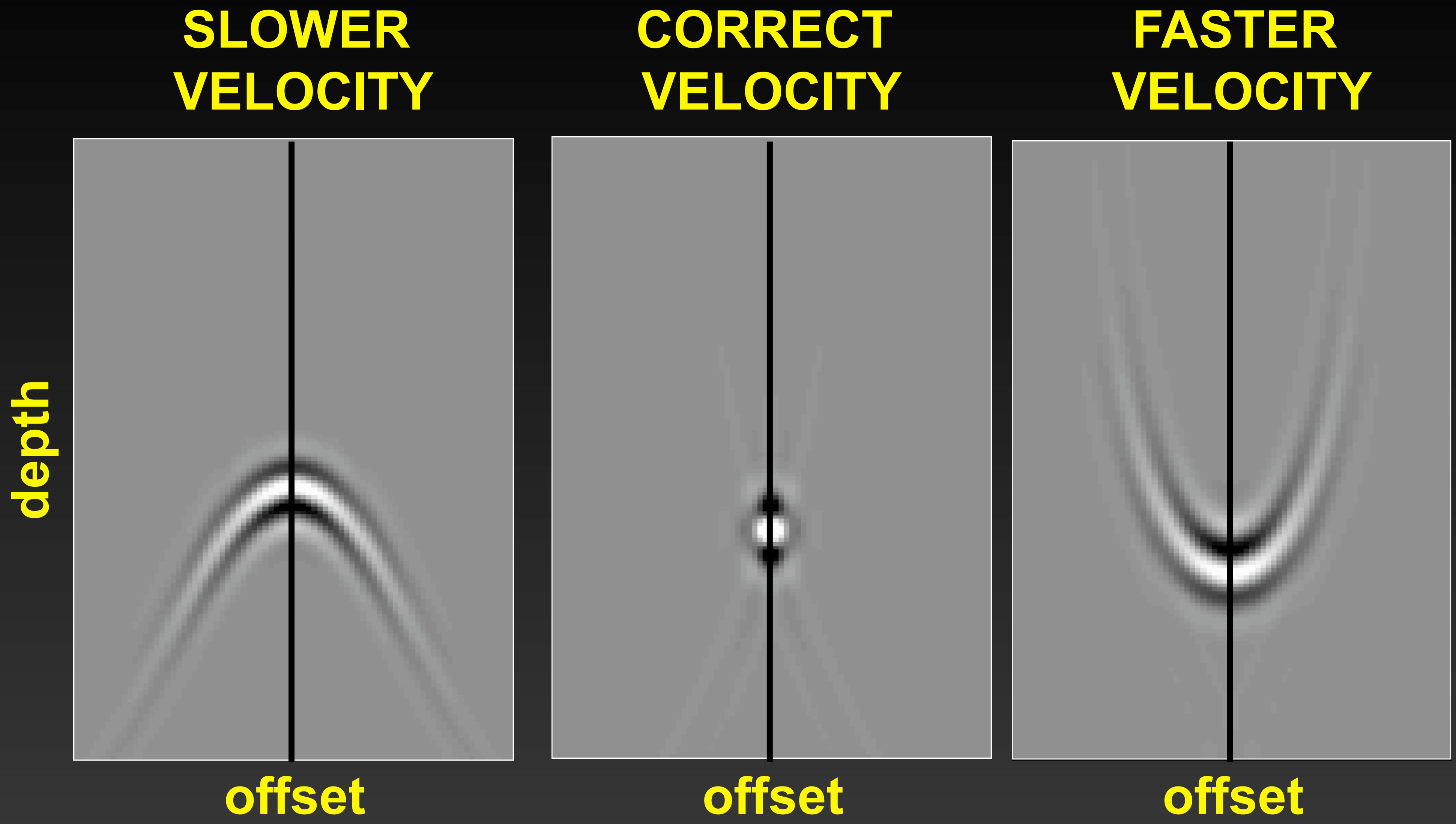
Zero-offset section



PERM

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

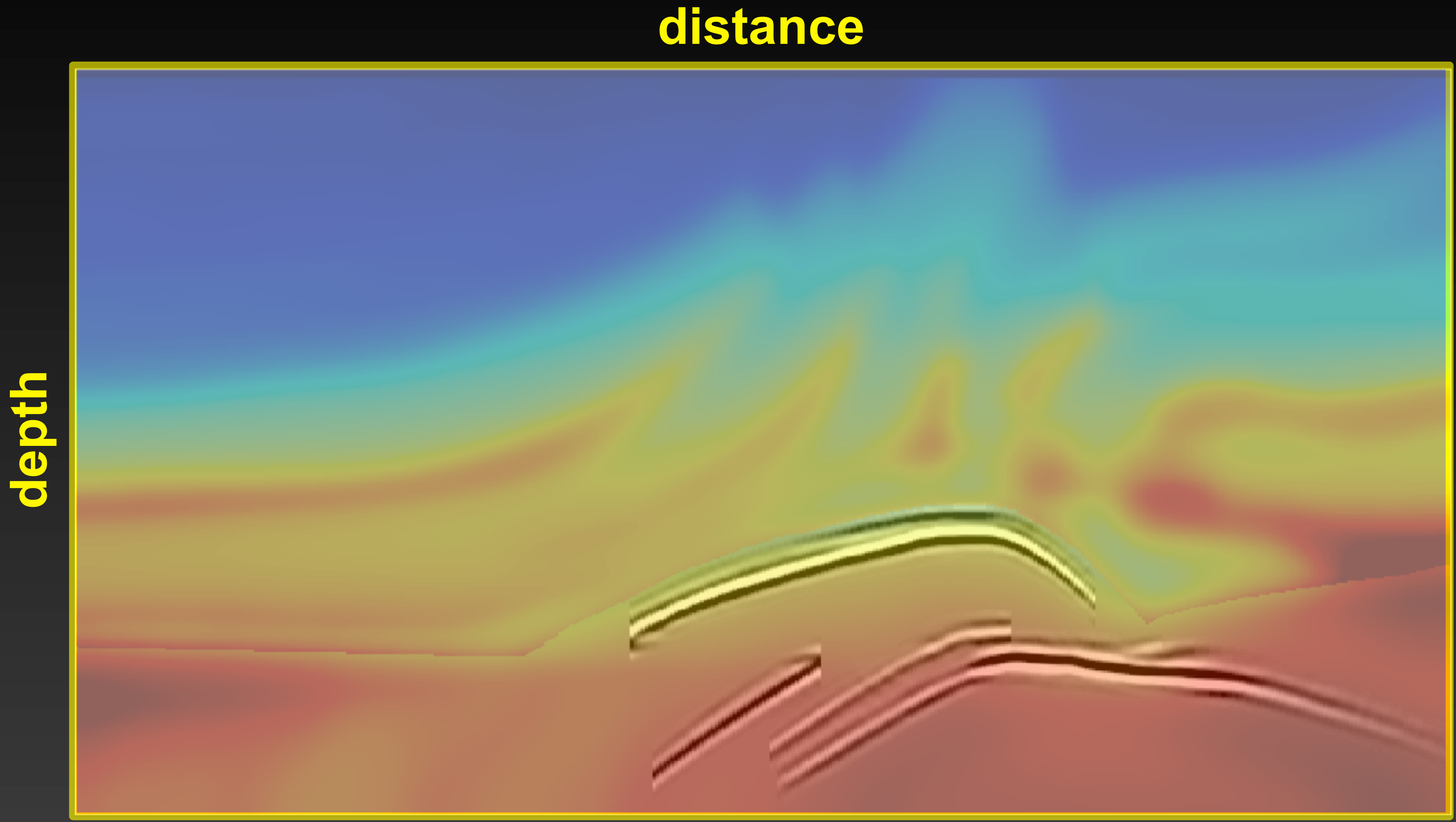
Subsurface-offset gathers



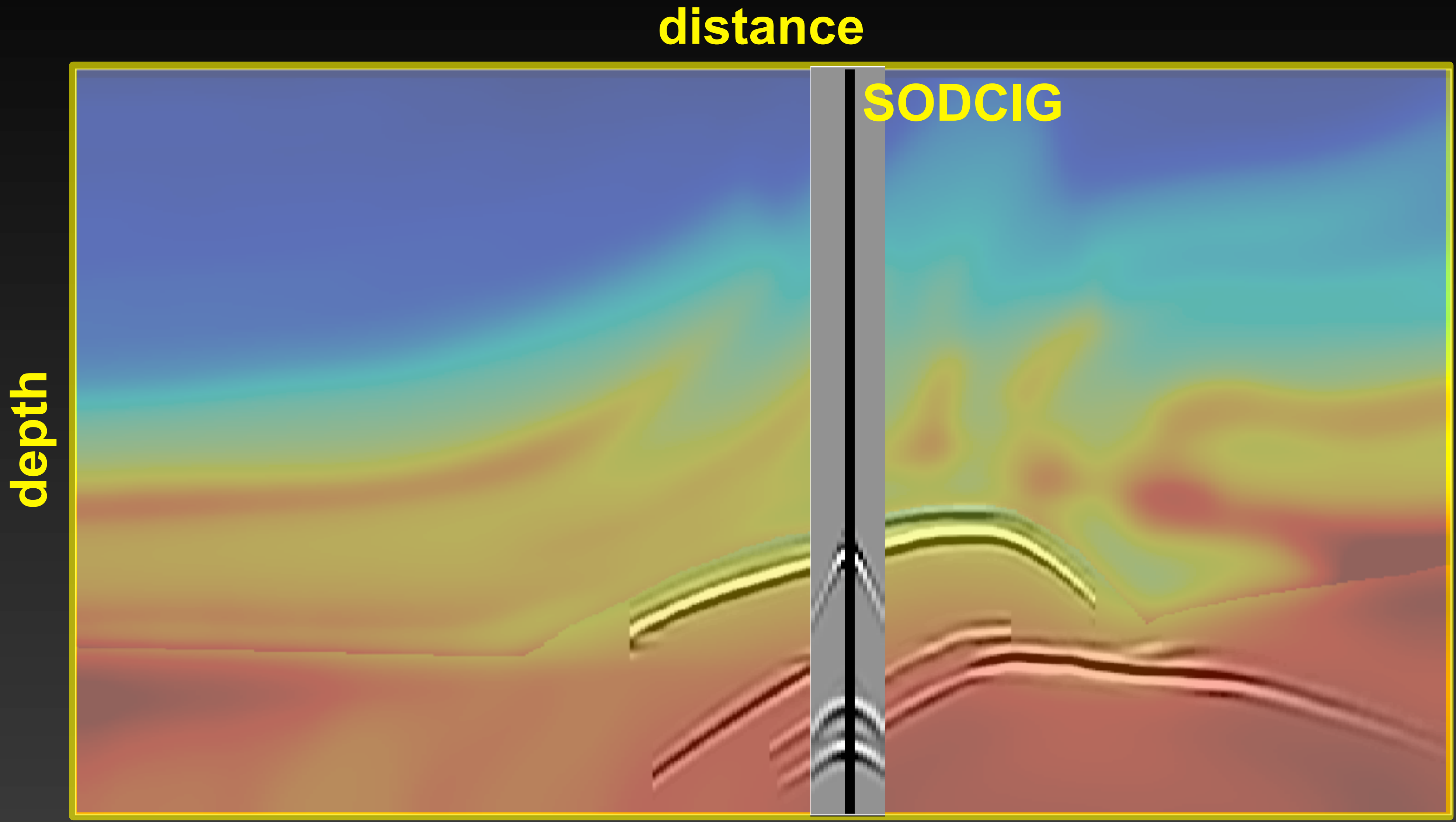
PERM

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

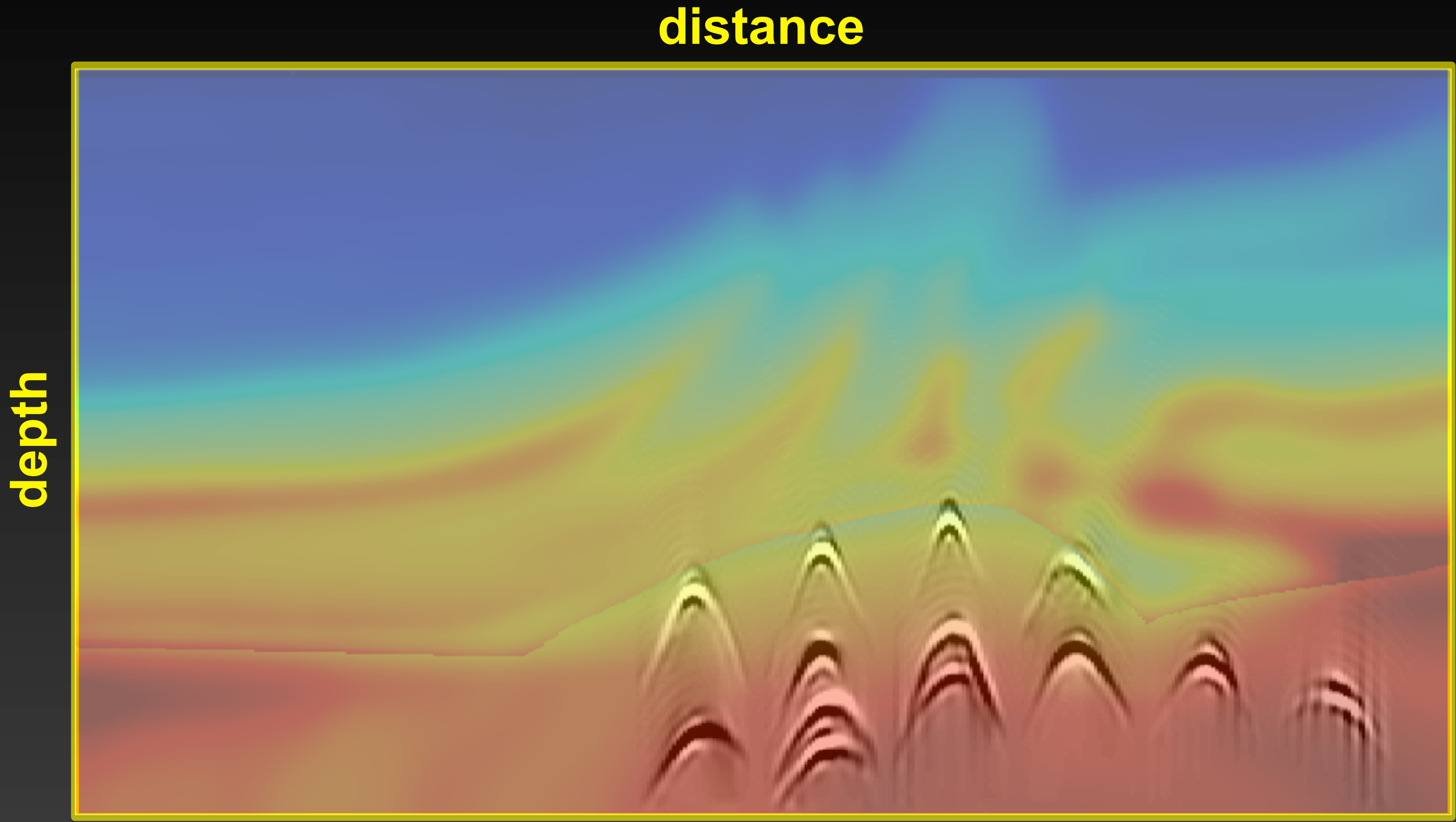
Modeling receiver wavefield



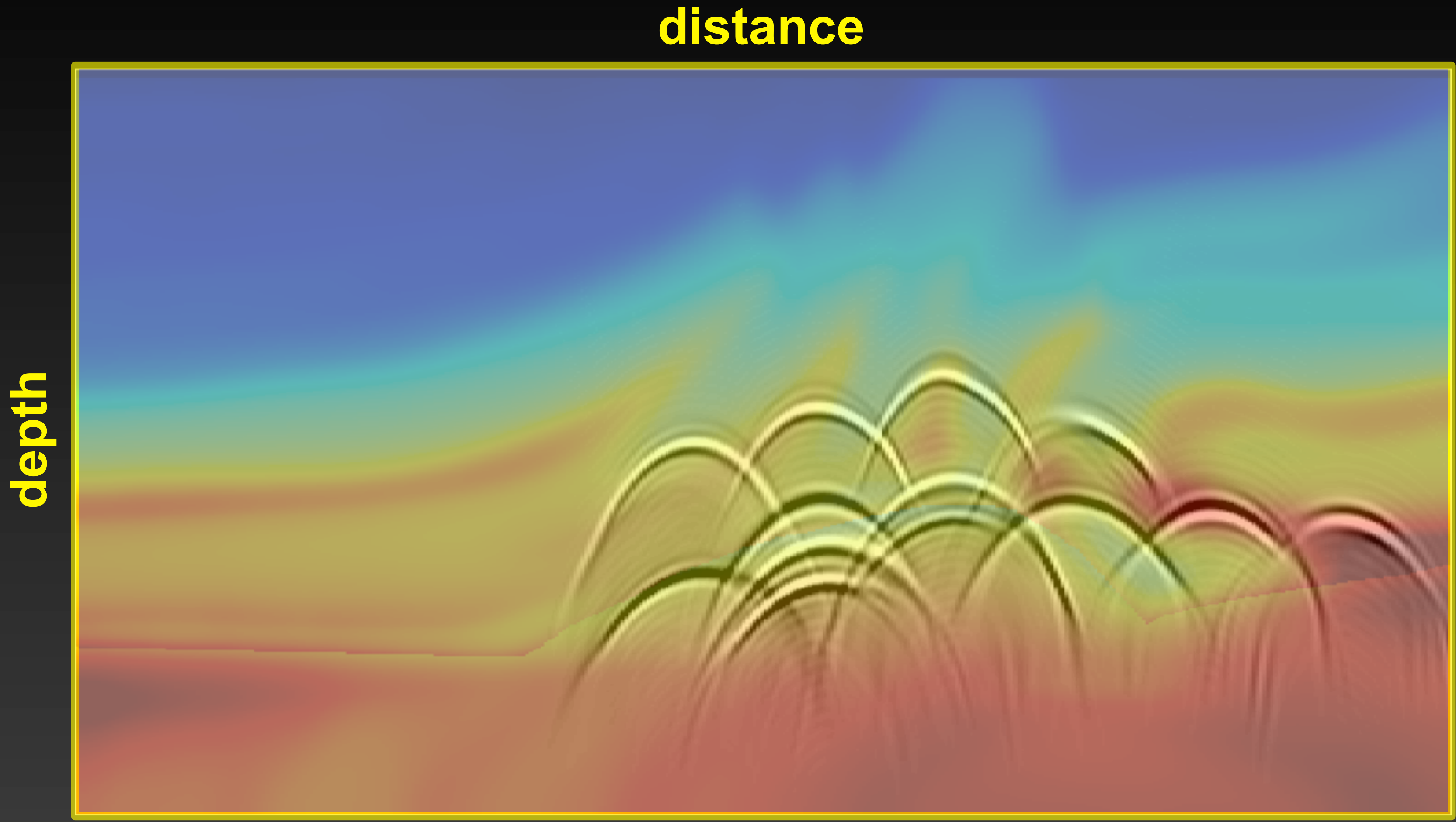
Modeling receiver wavefield



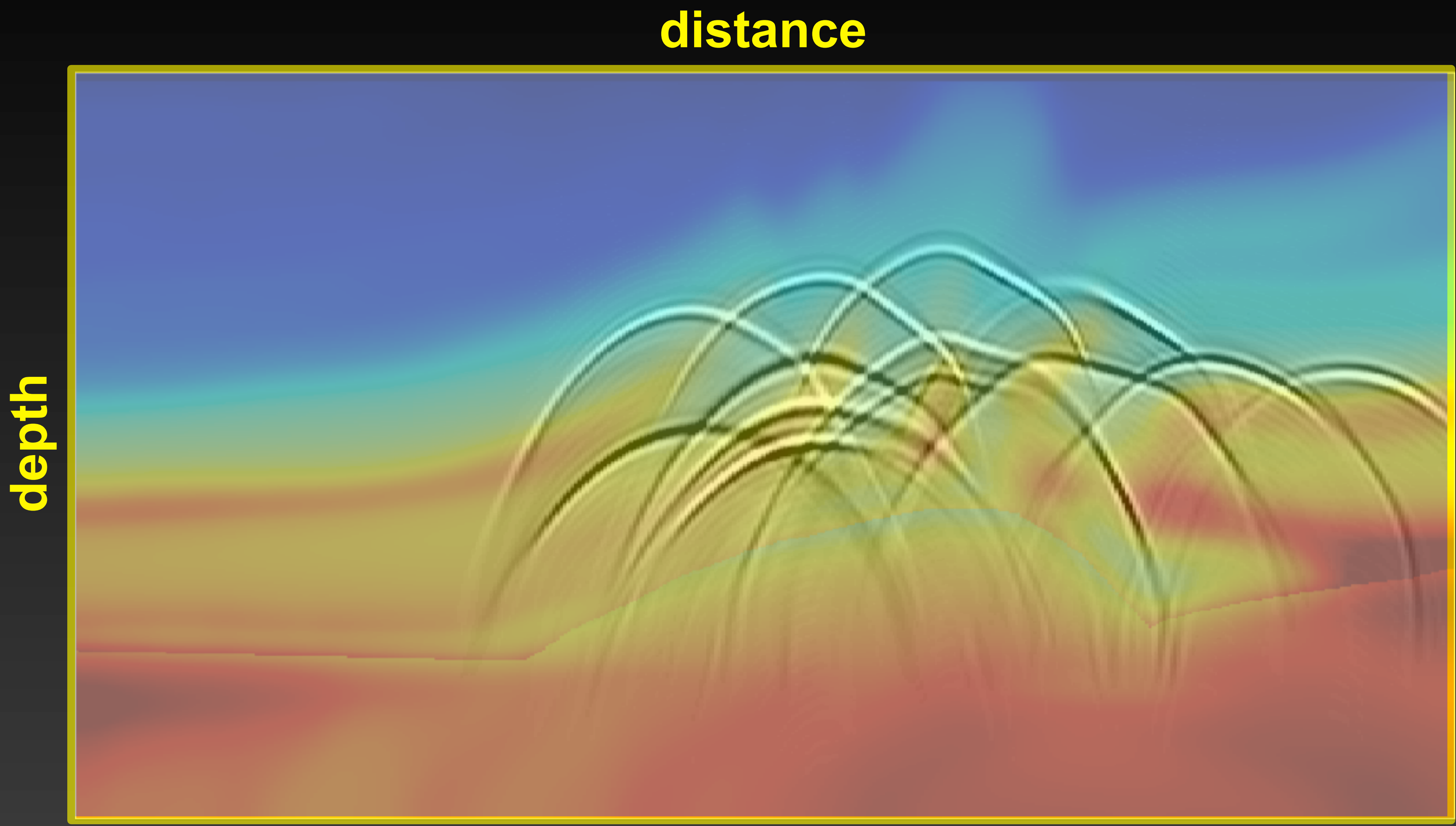
Modeling receiver wavefield



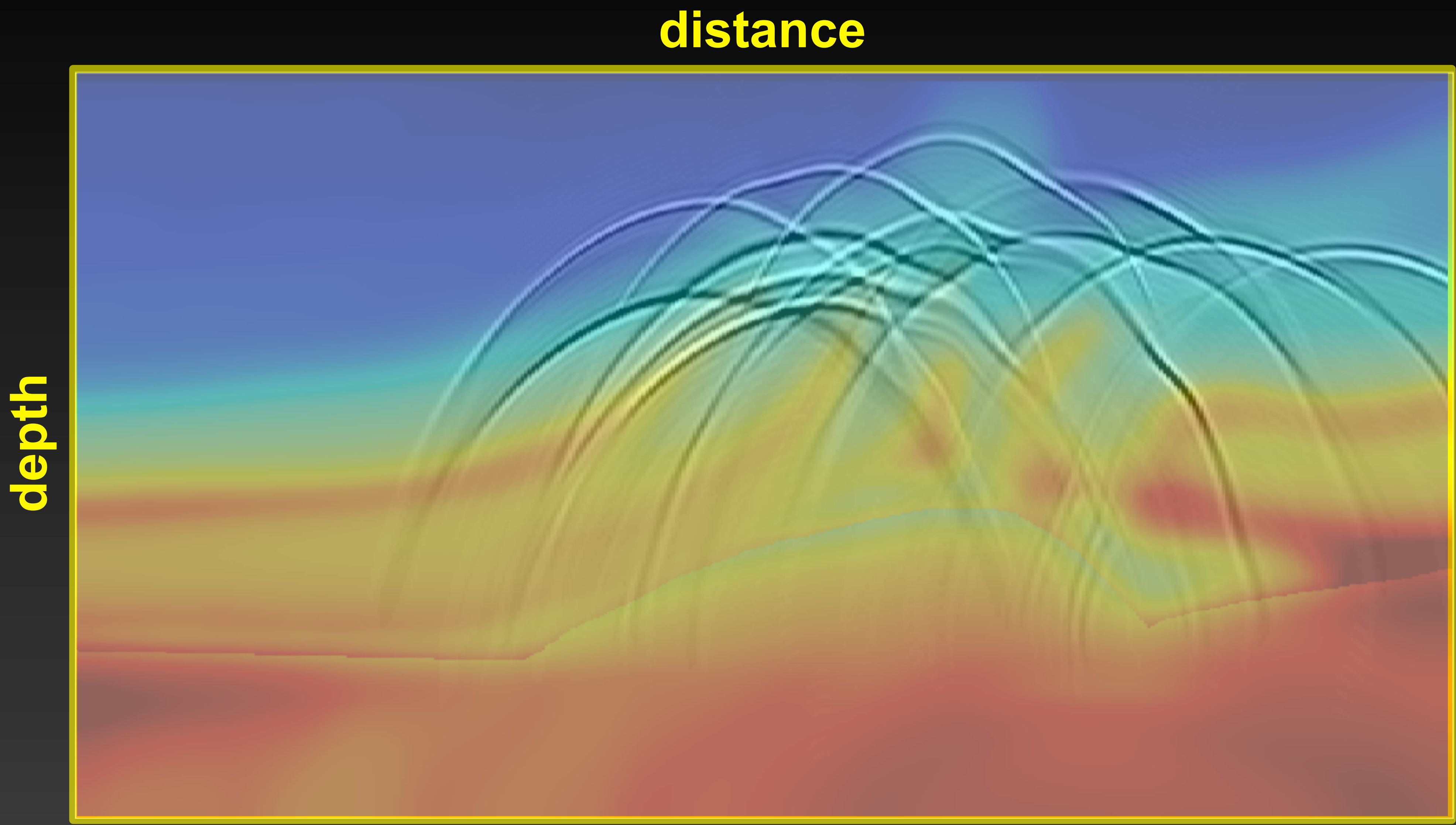
Modeling receiver wavefield



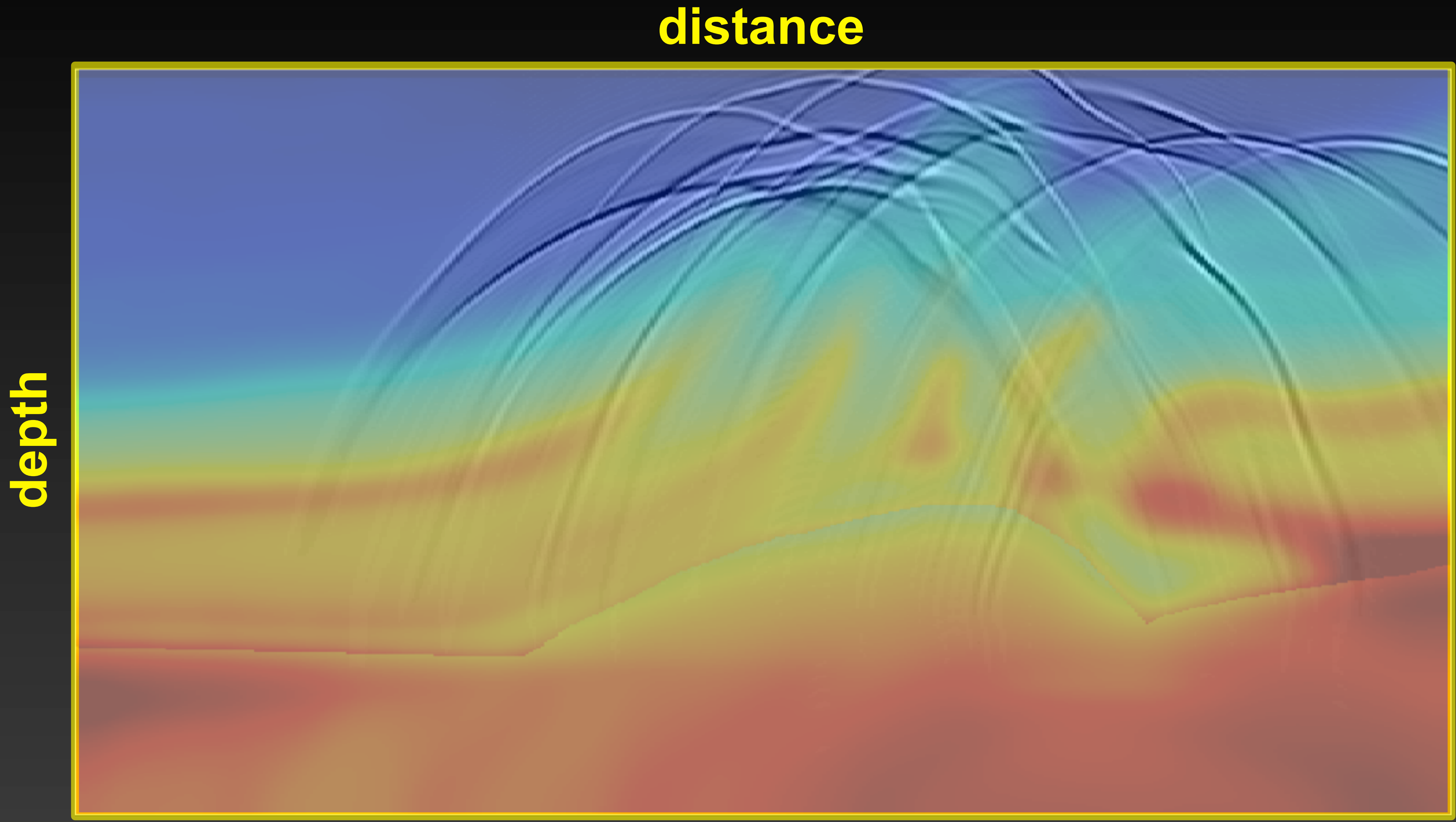
Modeling receiver wavefield



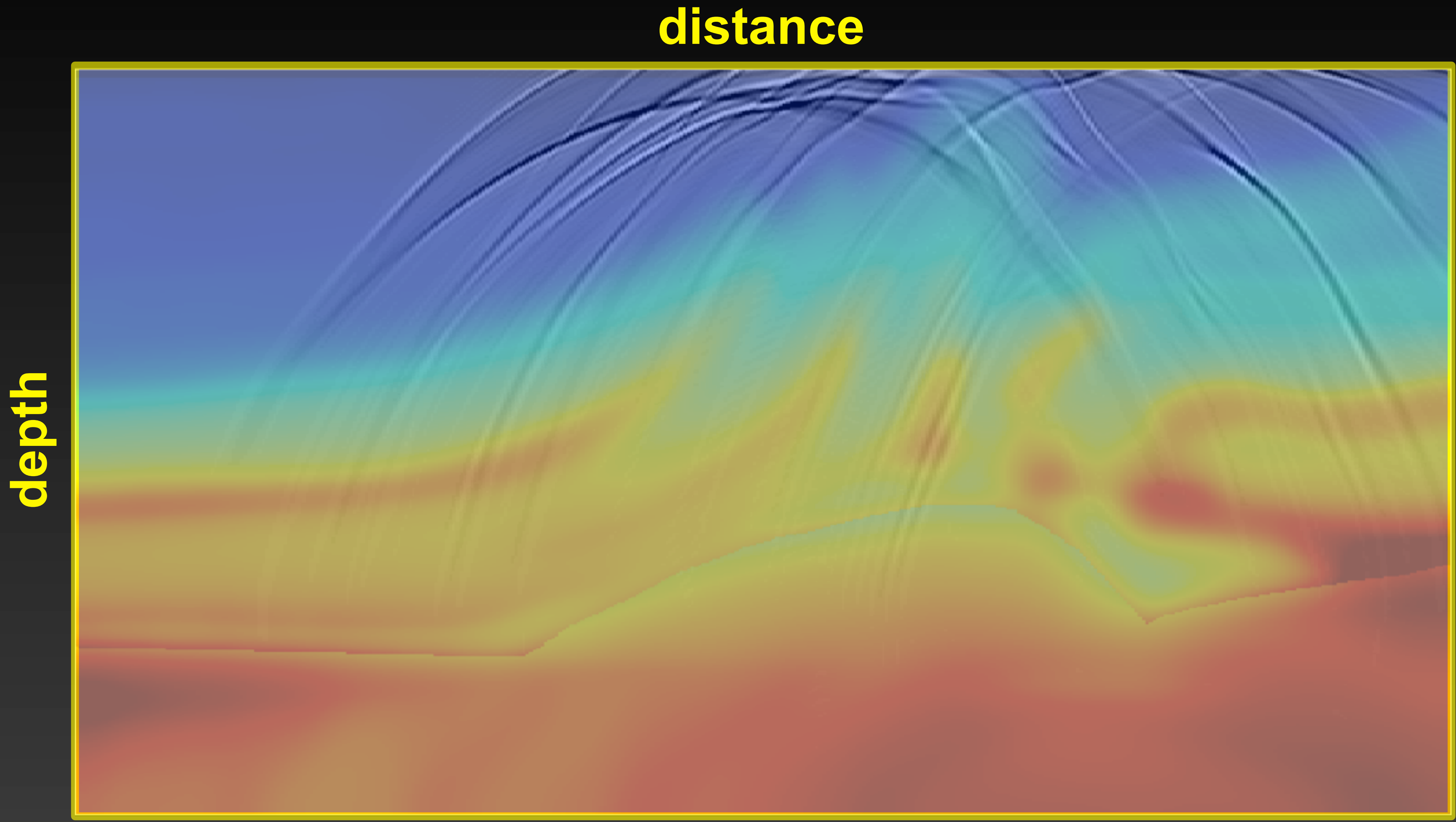
Modeling receiver wavefield



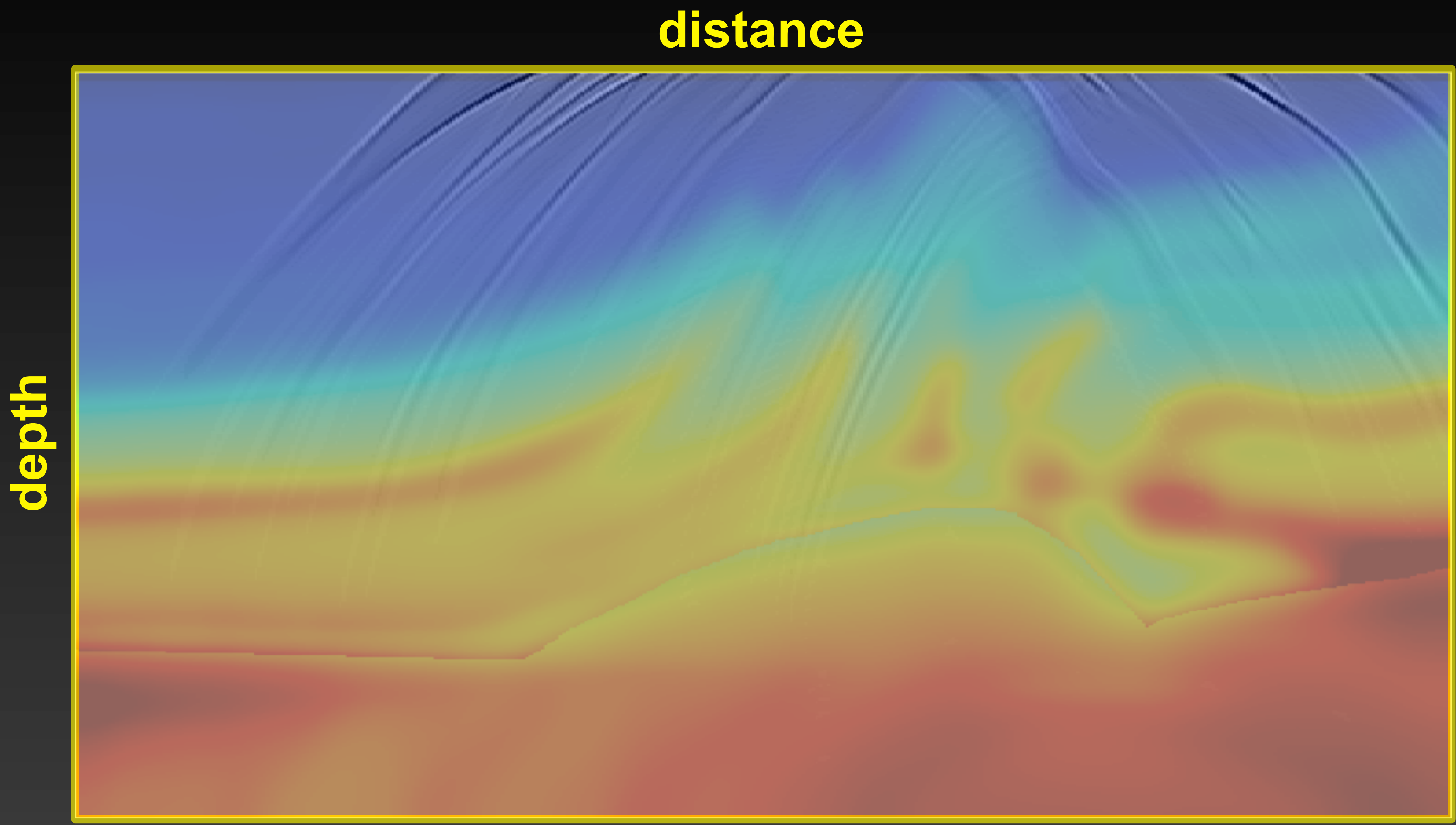
Modeling receiver wavefield



Modeling receiver wavefield

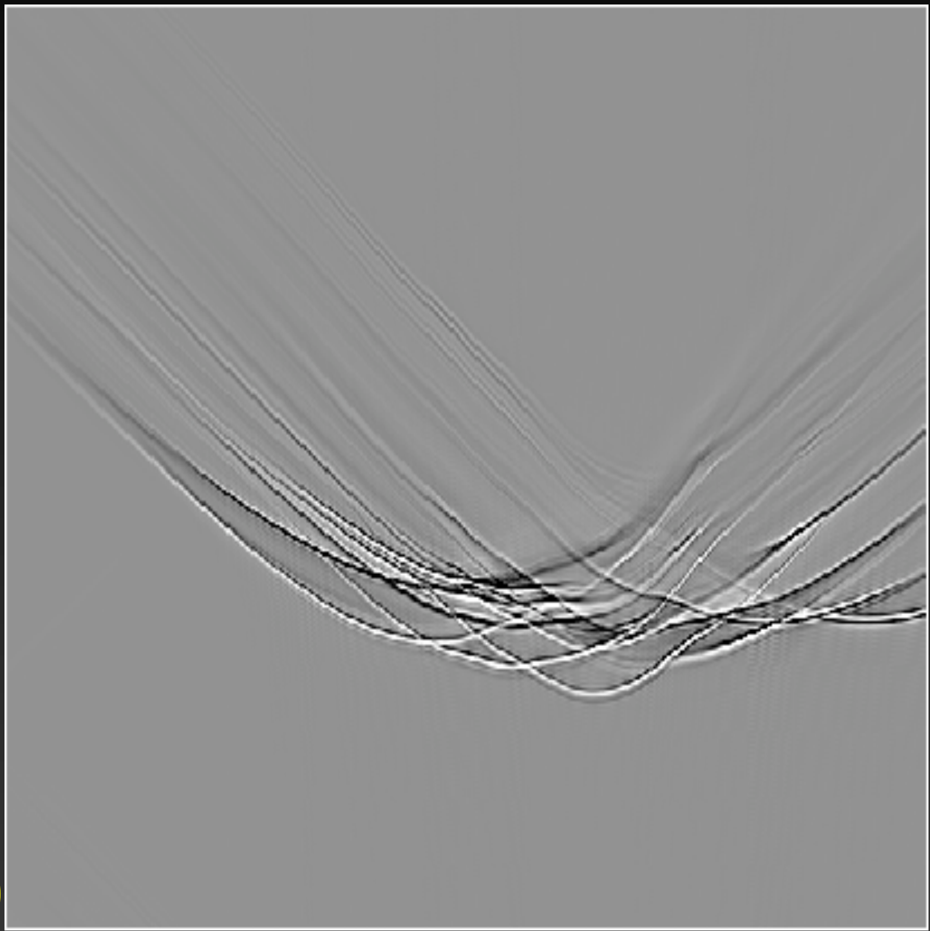


Modeling receiver wavefield

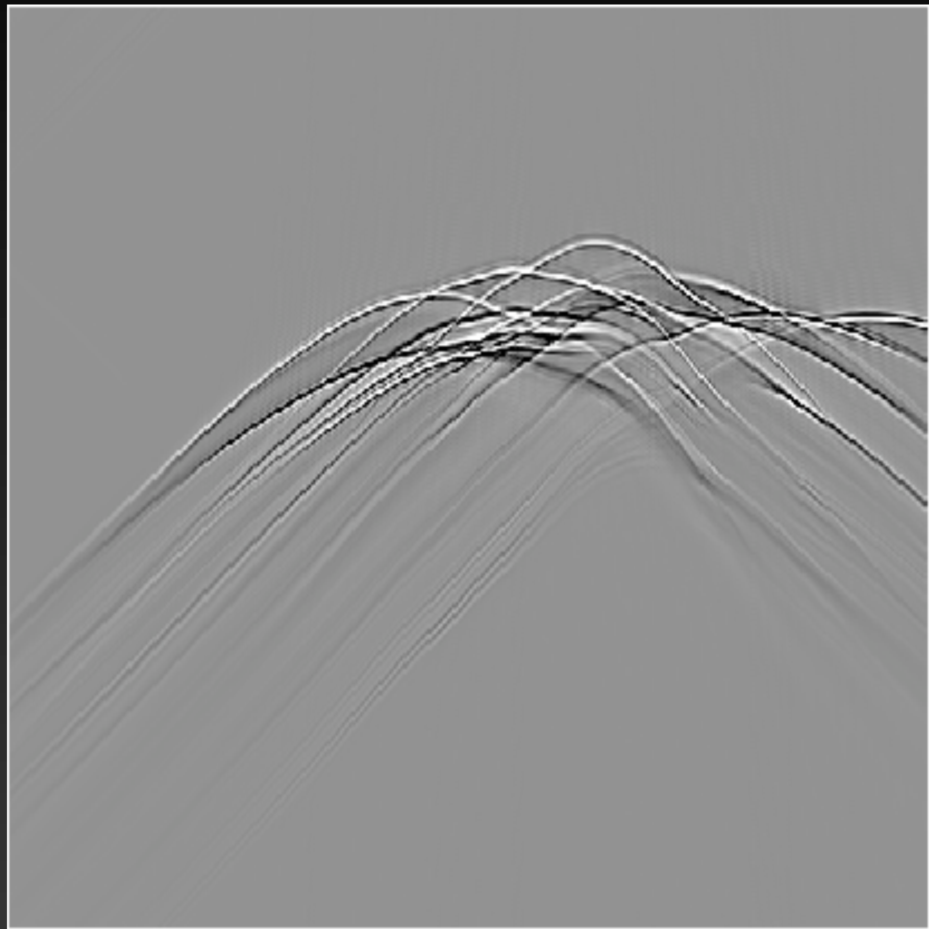


PERM data

Source



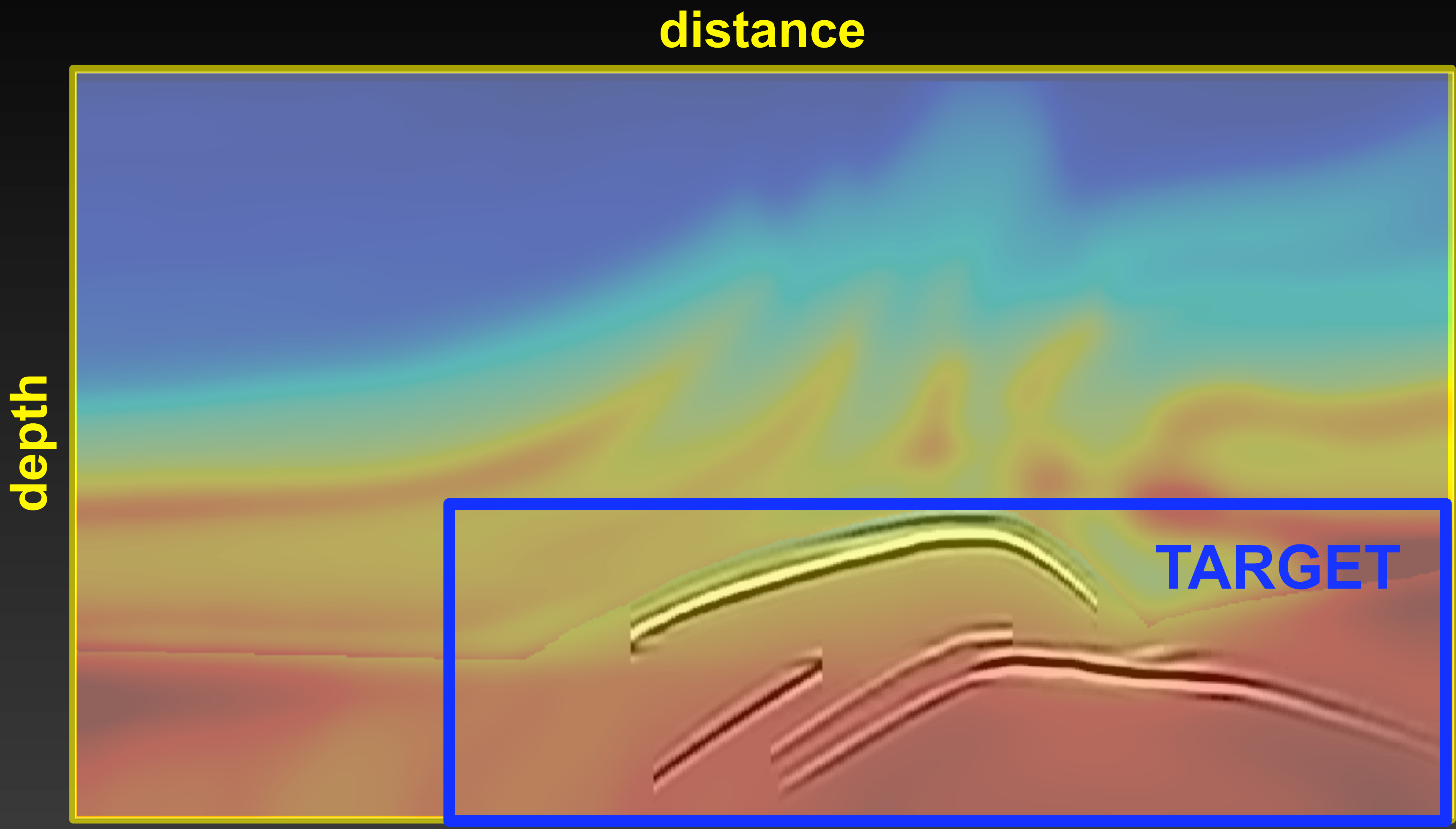
Receiver



PERM

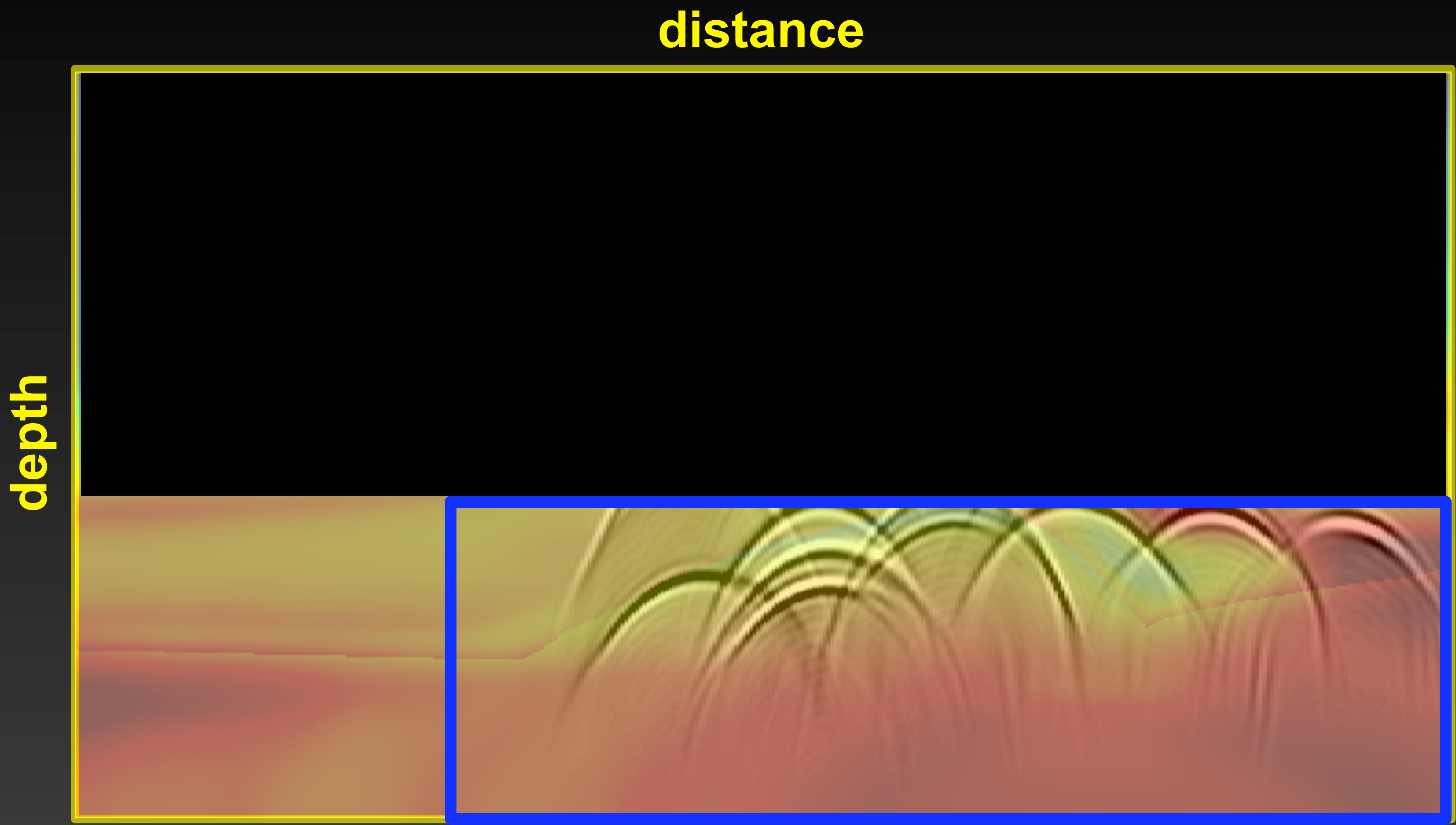
- **Generalizes the exploding-reflector model**
- **Uses selected reflectors as the initial conditions**
- **Uses a decorrelation distance to avoid crosstalk**
  - **Number of wavefields depends on the separation of SODCIGs**

Target-oriented strategy



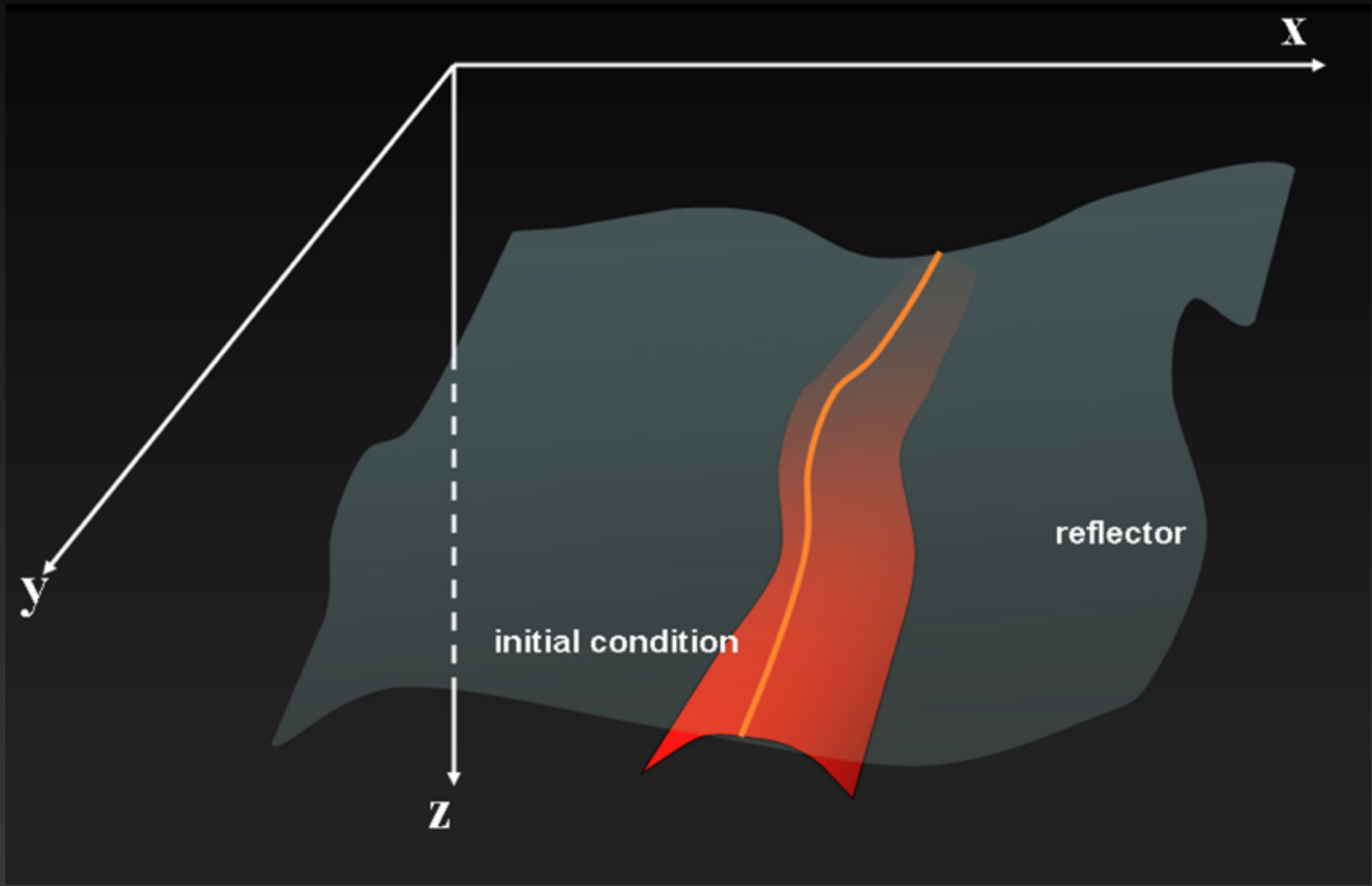
Target-oriented strategy

Wavefields collected at the top of the target



In 3D

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



Thesis content

✓ Chapter 2: Pre-stack exploding-reflector model

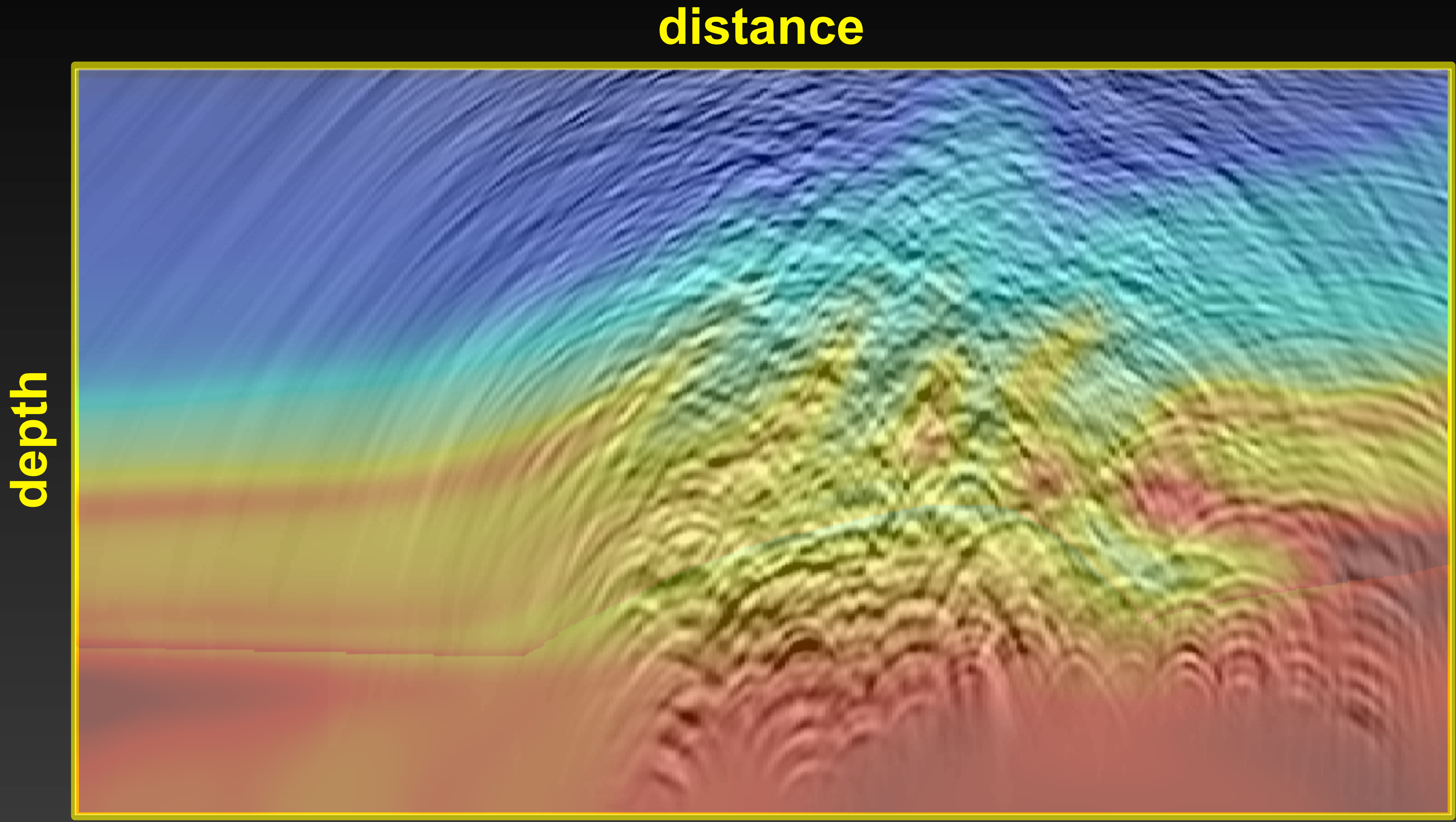
- Chapter 3: Image-space phase-encoded wavefields

- Chapter 4: MVA using image-space generalized sources

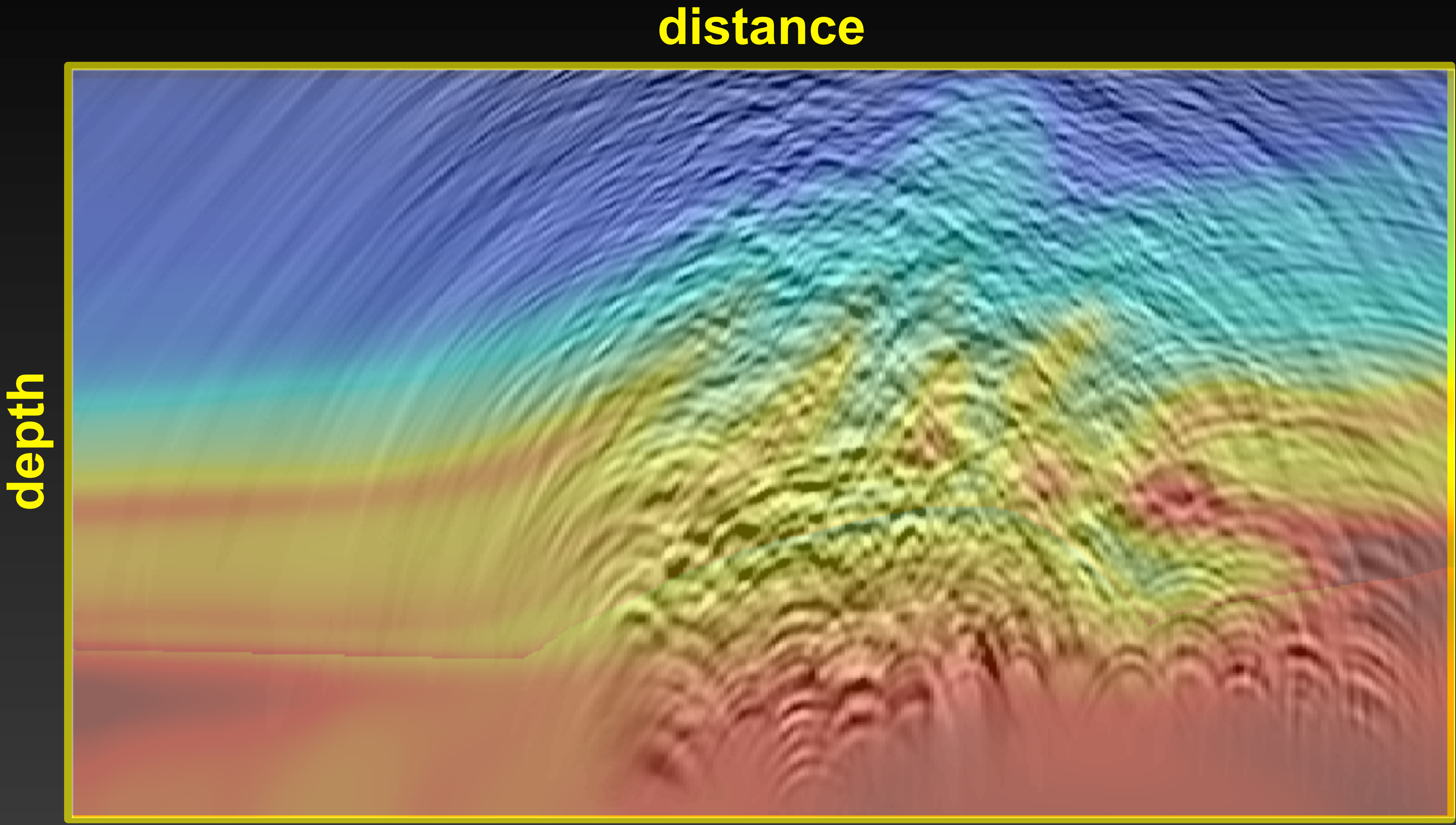
- Chapter 5: 3D-field data example

Further data reduction by phase-encoding the modeling experiments

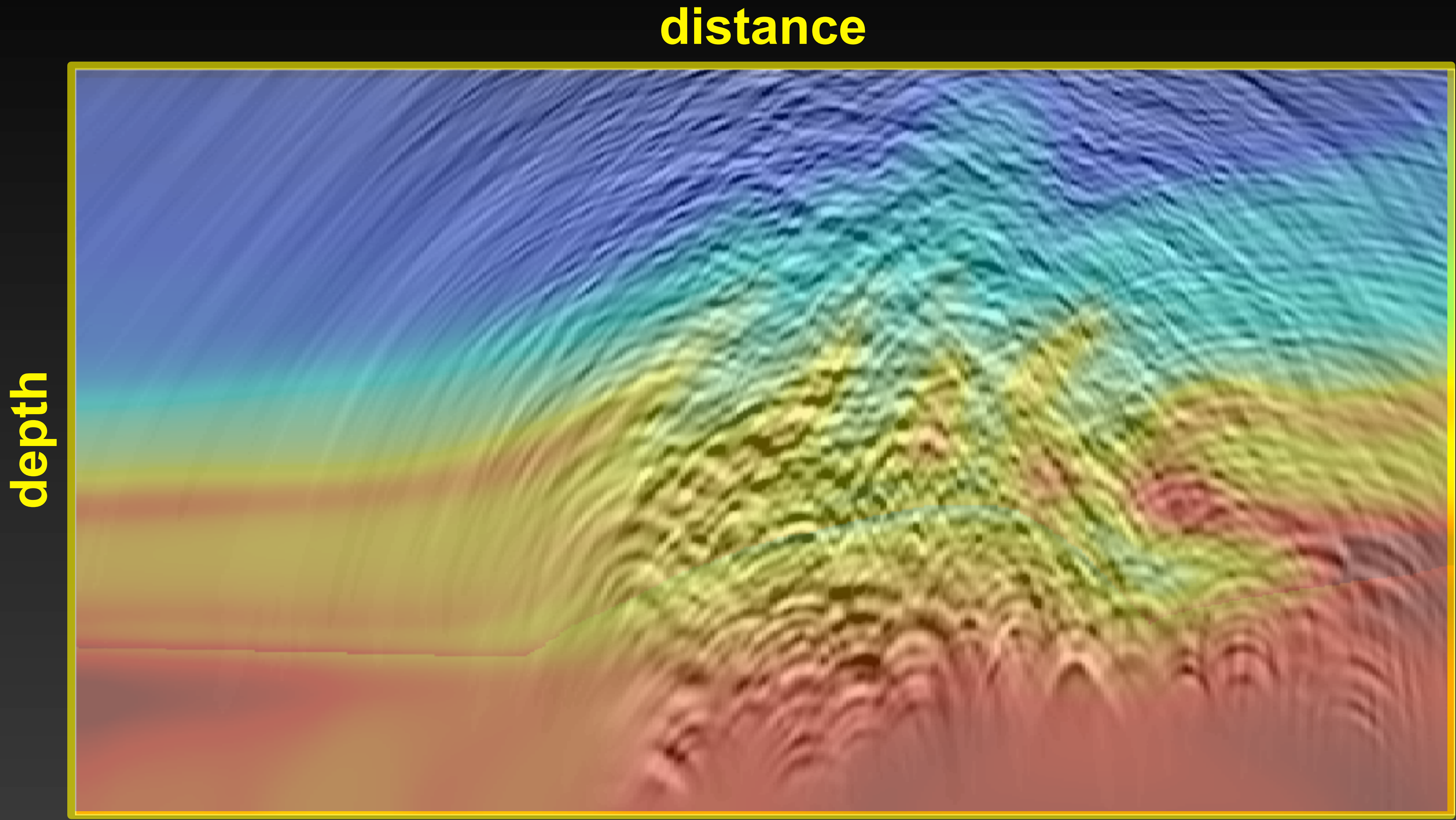
Phase-encoded receiver wavefield



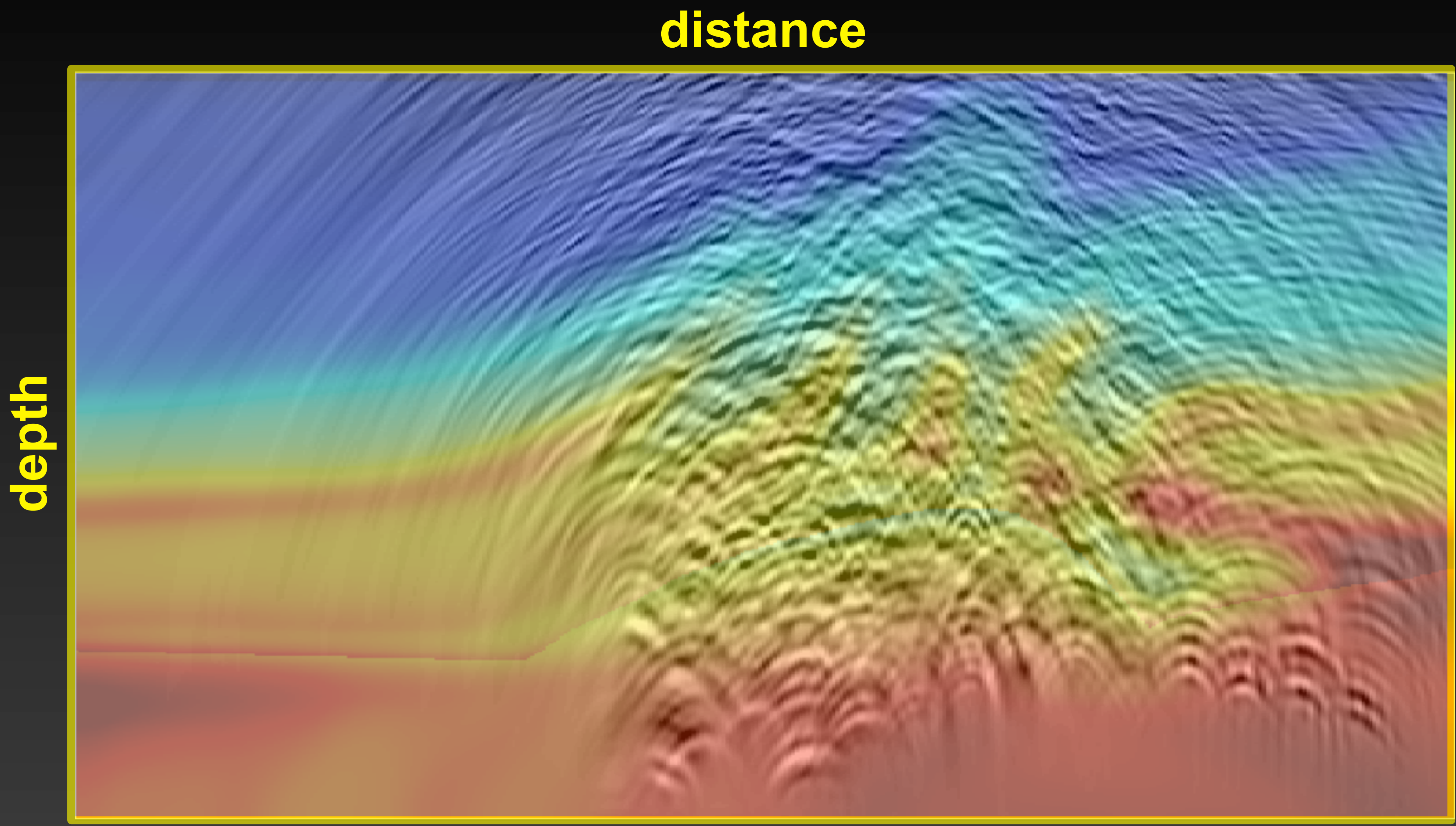
Phase-encoded receiver wavefield



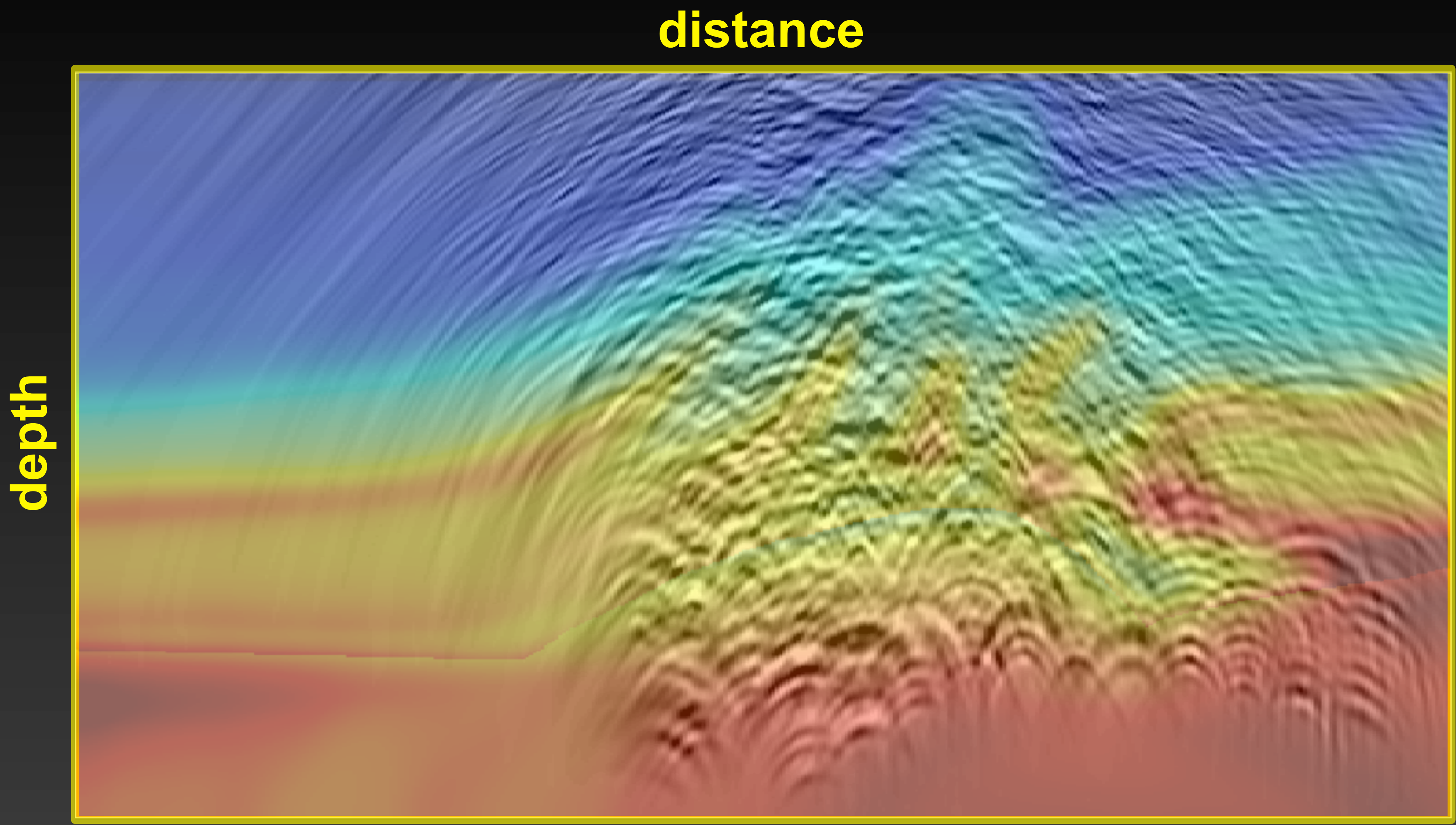
Phase-encoded receiver wavefield



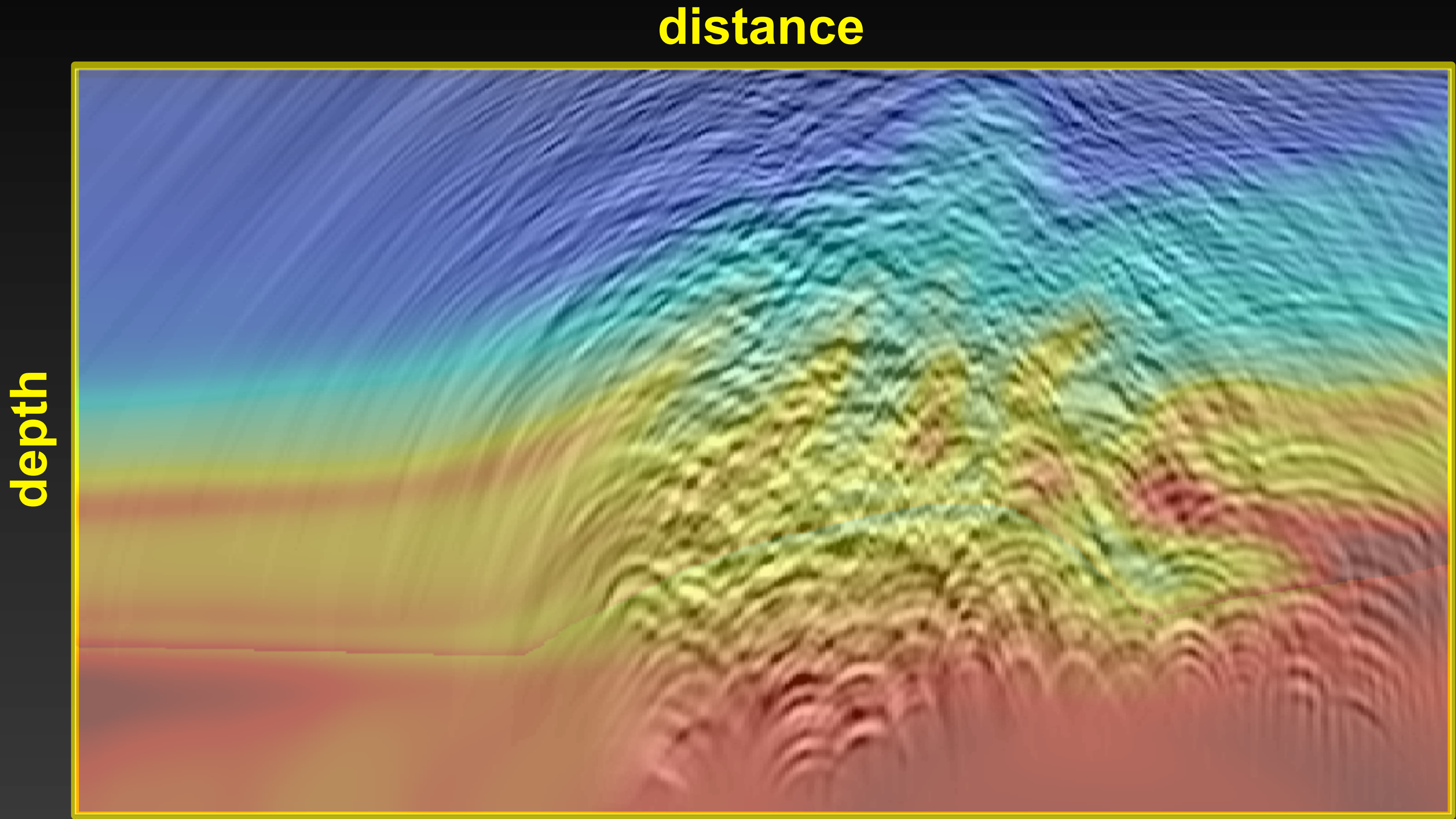
Phase-encoded receiver wavefield



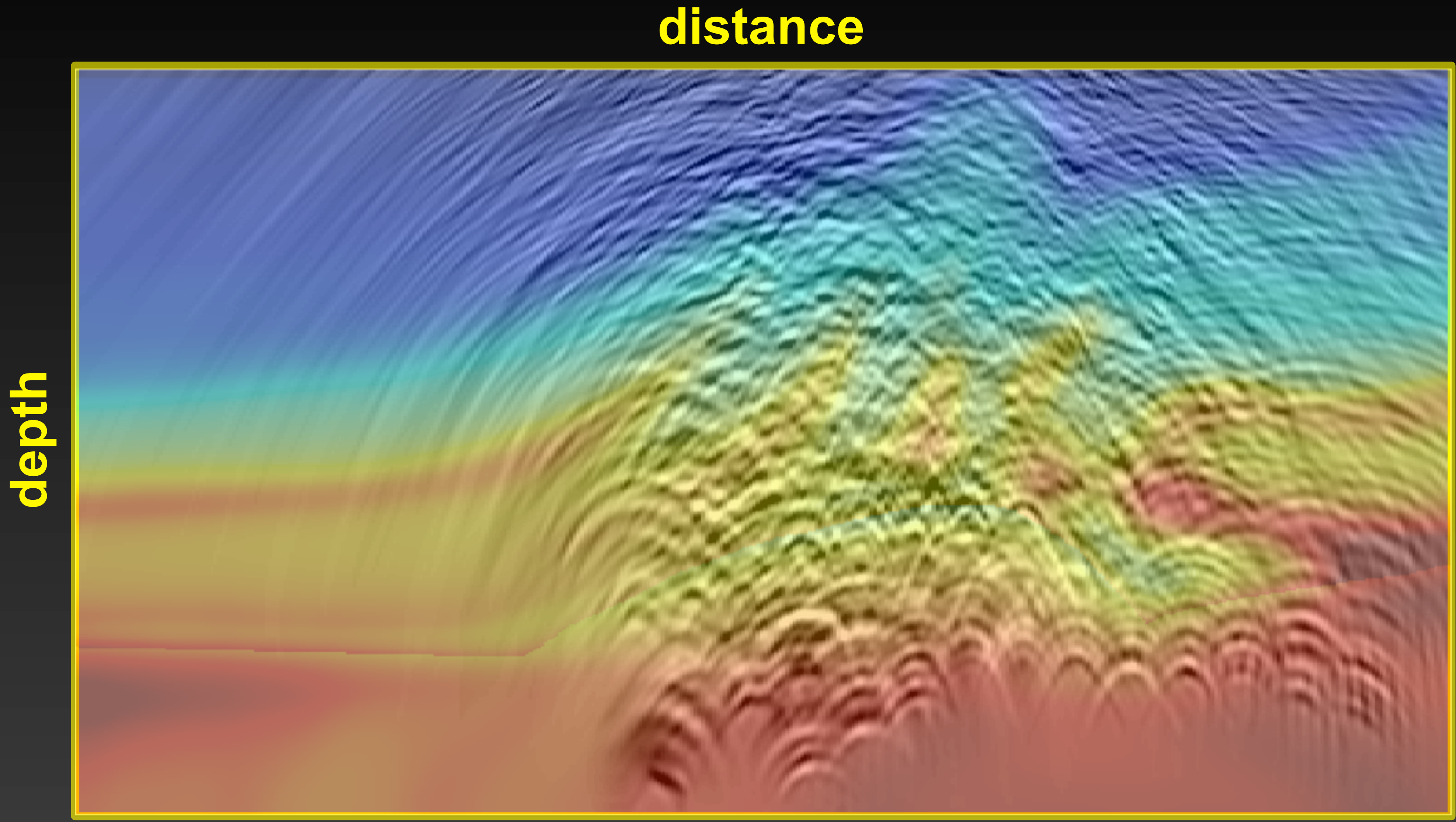
Phase-encoded receiver wavefield



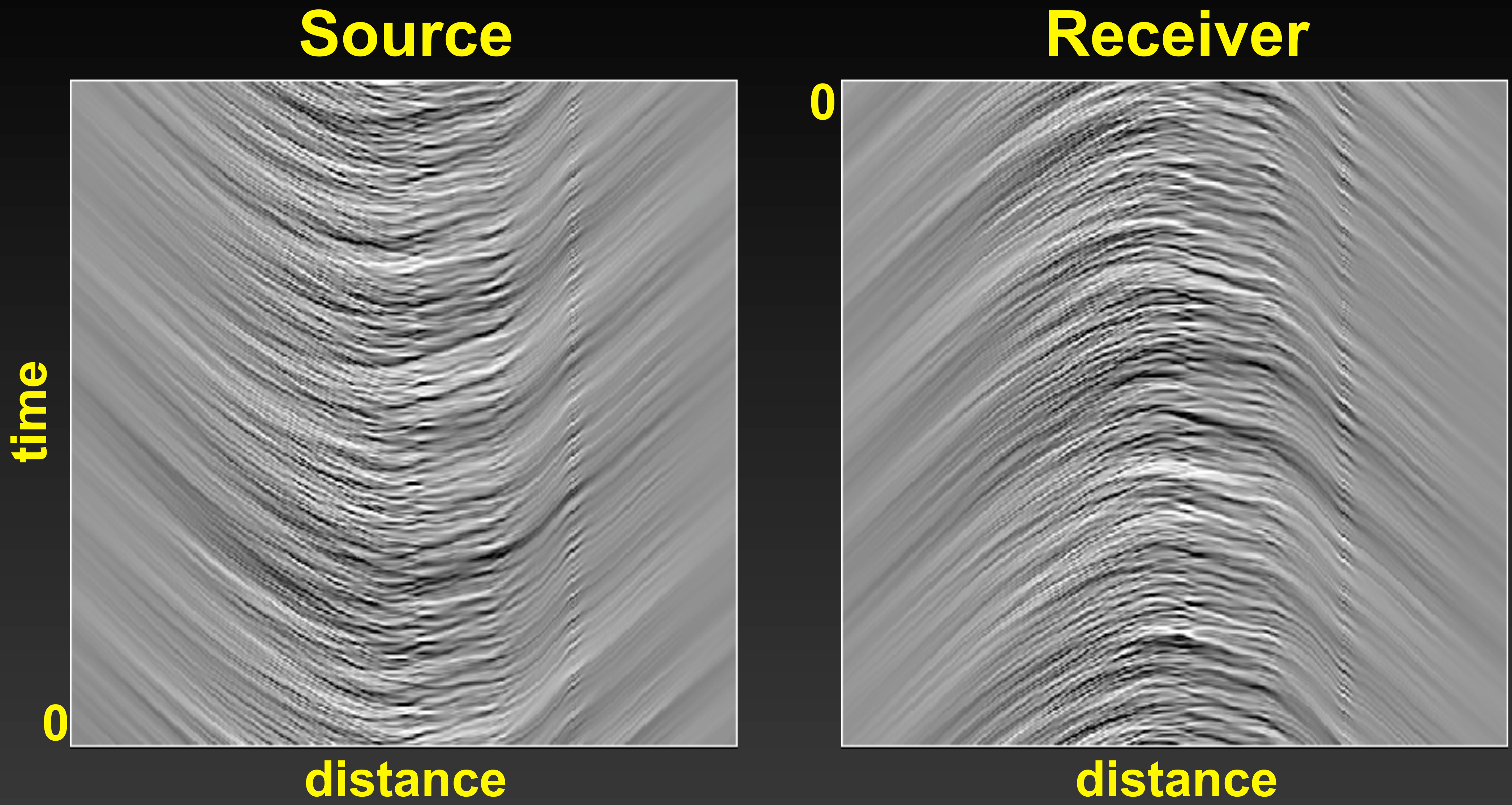
Phase-encoded receiver wavefield



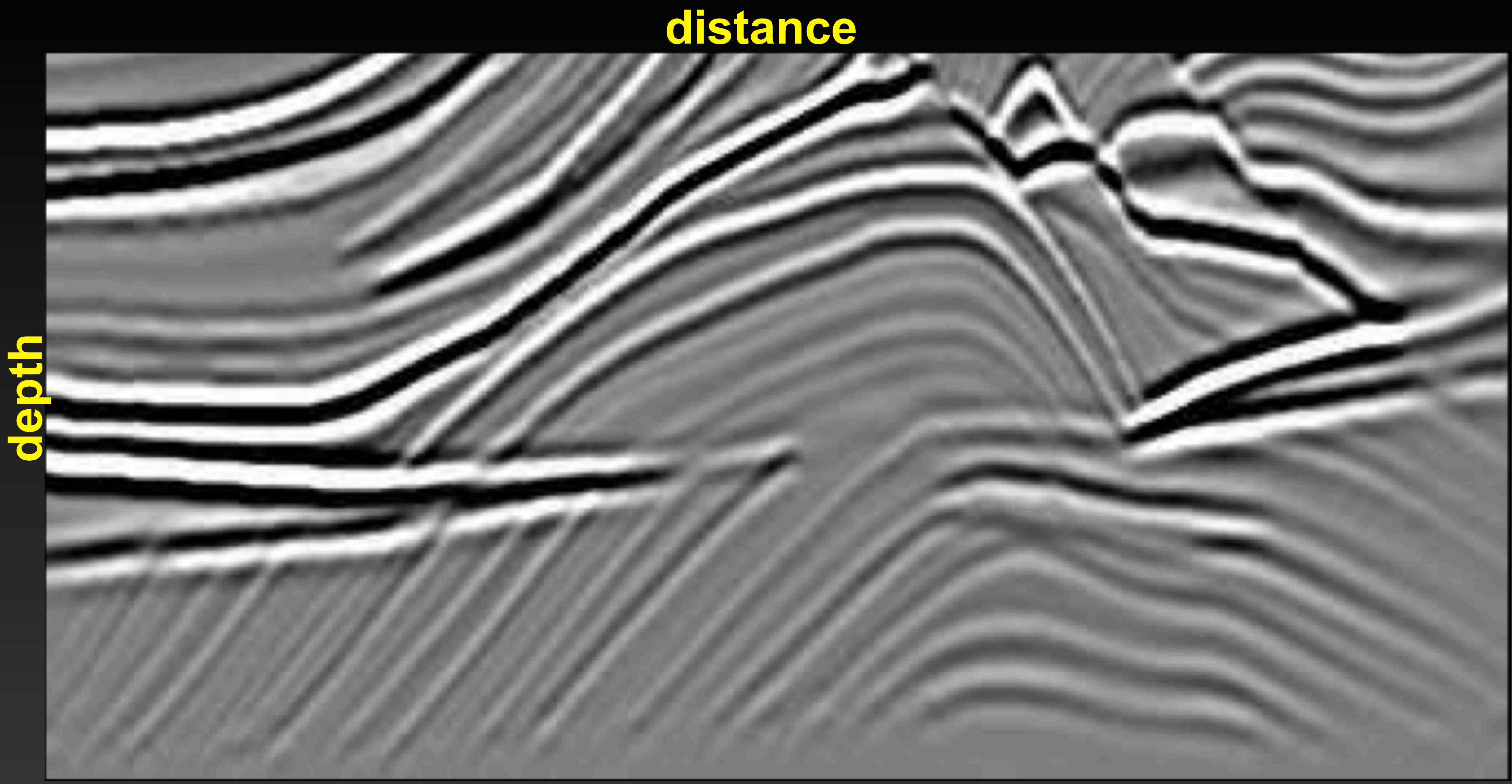
Phase-encoded receiver wavefield



ISPEW data



Migration of 375 shot profiles



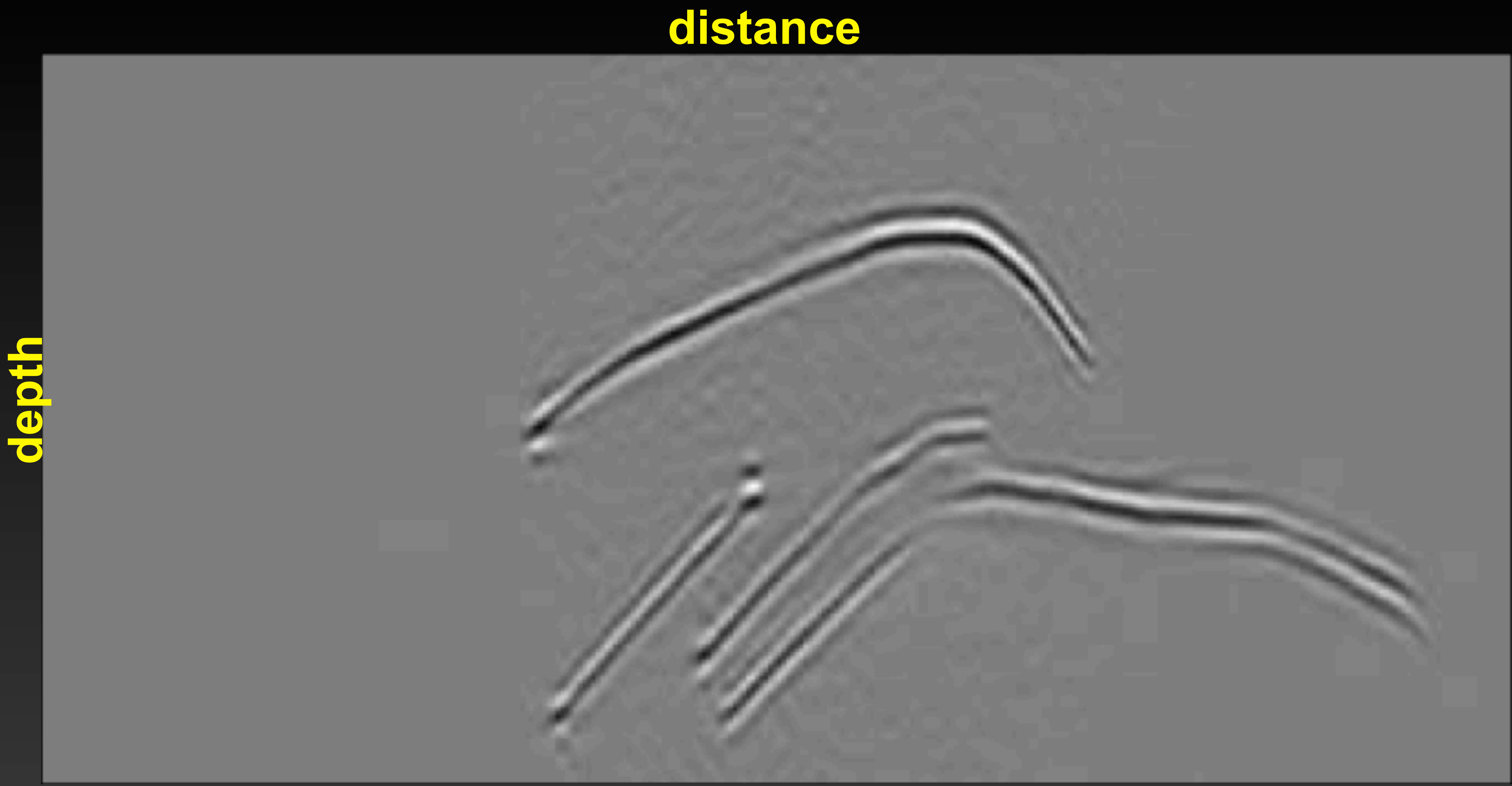
Selected reflectors

35 PERM migrated image

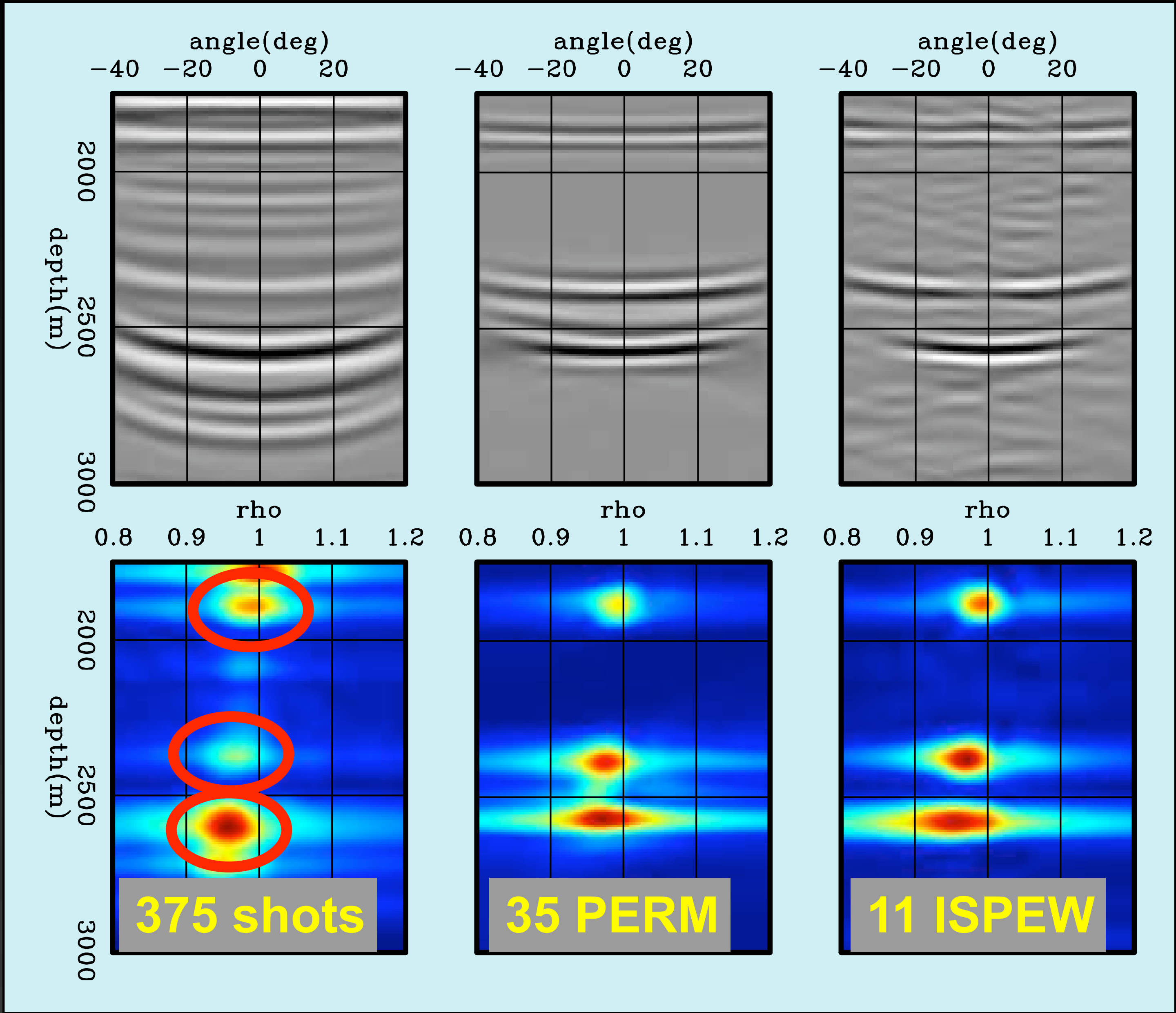
distance

depth

11 ISPEW migrated image



Velocity information



rho - curvature parameter

Thesis content

- ✓ Chapter 2: Pre-stack exploding-reflector model
- ✓ Chapter 3: Image-space phase-encoded wavefields
- Chapter 4: MVA using image-space generalized sources
- Chapter 5: 3D-field data example

Generalized-source domain ISWET

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

Generalized-source domain ISWET

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

- **Small number of wavefields**

Using image-space generalized-sources

- **Wavefields initiated at selected reflectors**

Using image-space generalized-sources

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

Using image-space generalized-sources

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

- **Easily solved in a target-oriented way**

Differential-semblance objective function

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

DSO operator (Symes and Carazzone, 1991)

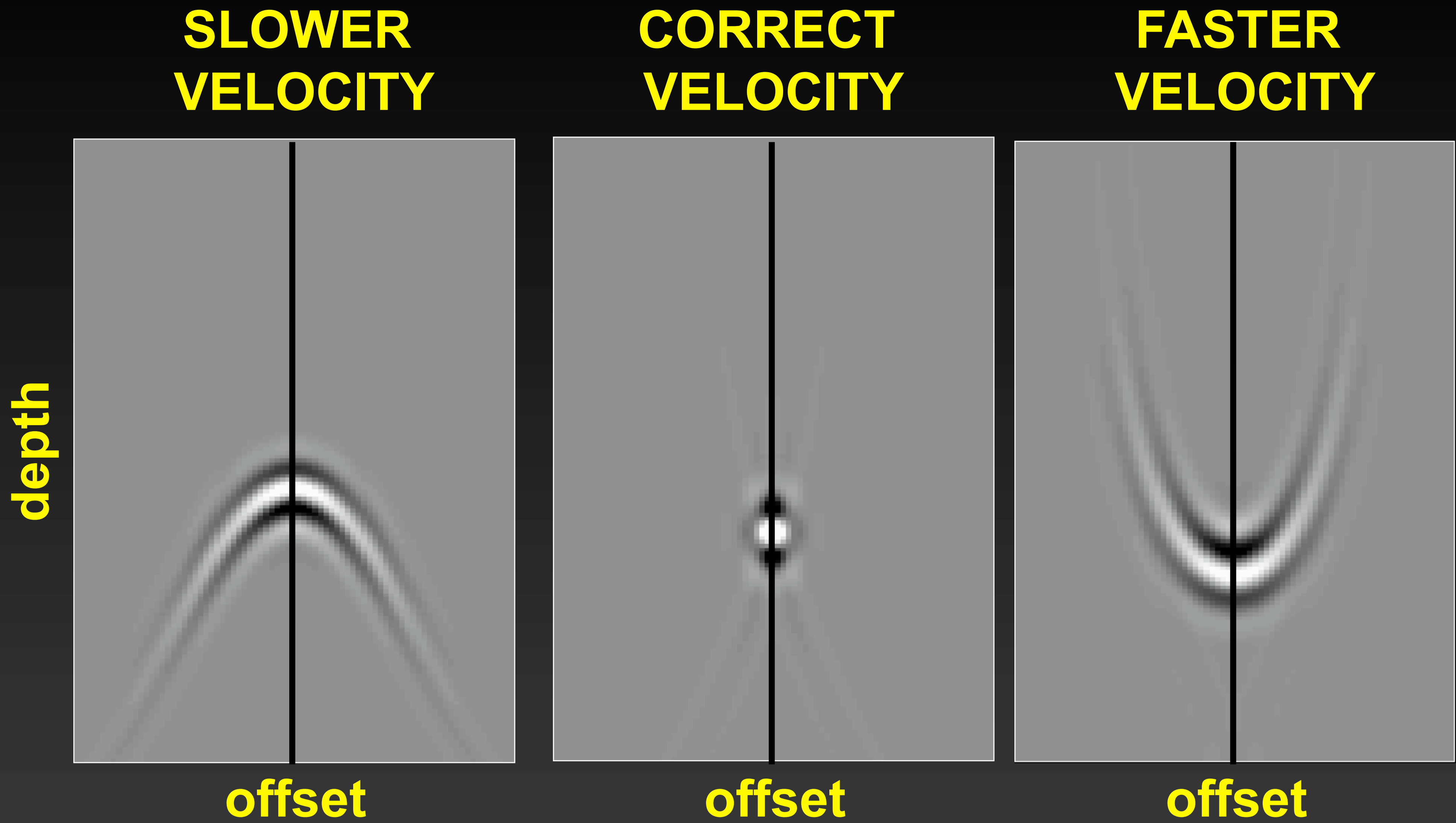
$J(s) =$ objective function

$\mathbf{h} =$ DSO operator

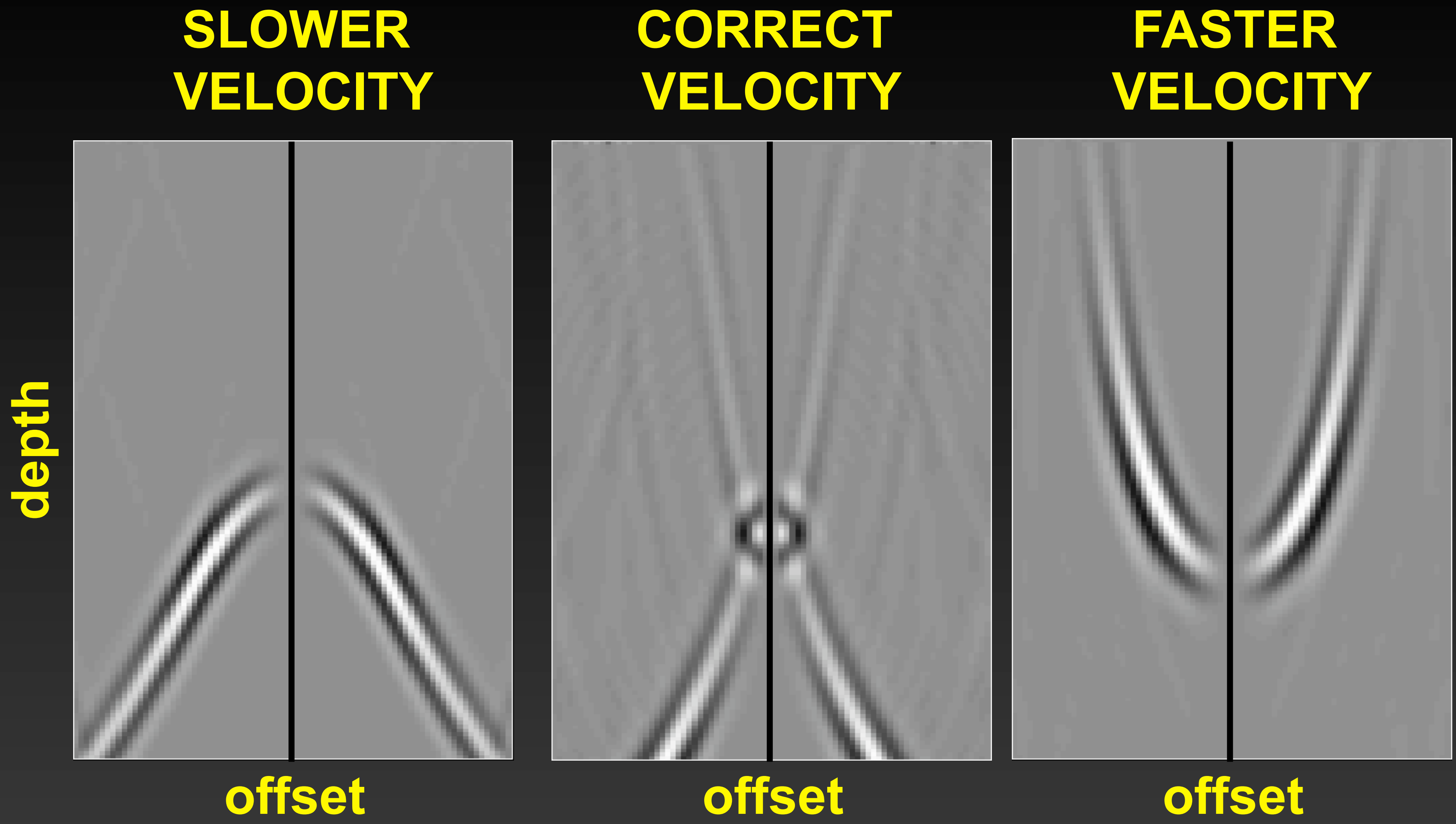
$\Delta \widetilde{I}(s) =$ perturbed image

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

DSO operator = $|h|$



DSO operator = $|h|$



DSO gradient

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

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

$J(s) =$ objective function

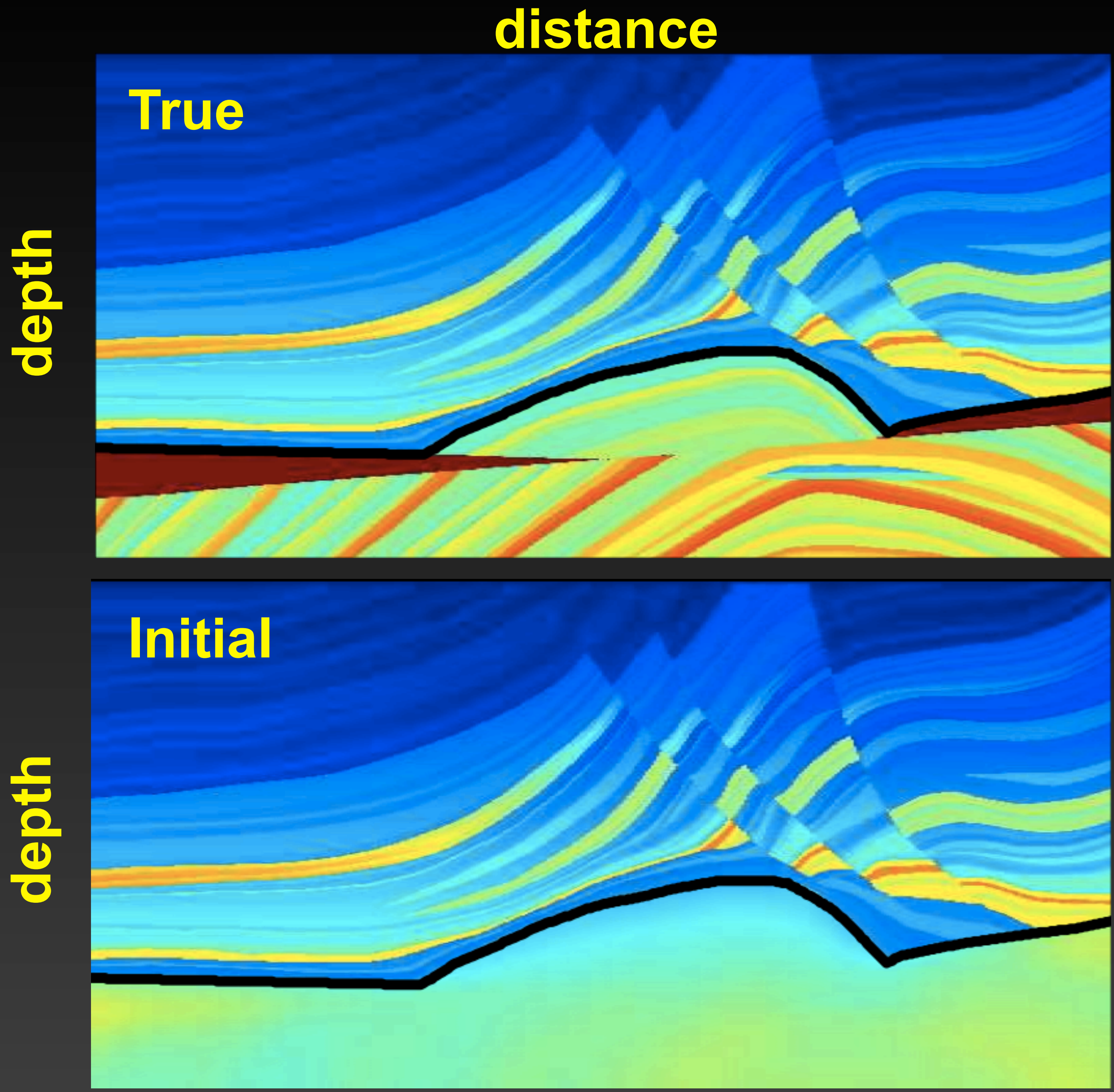
$\mathbf{h} =$ DSO operator

$s_o =$ current velocity

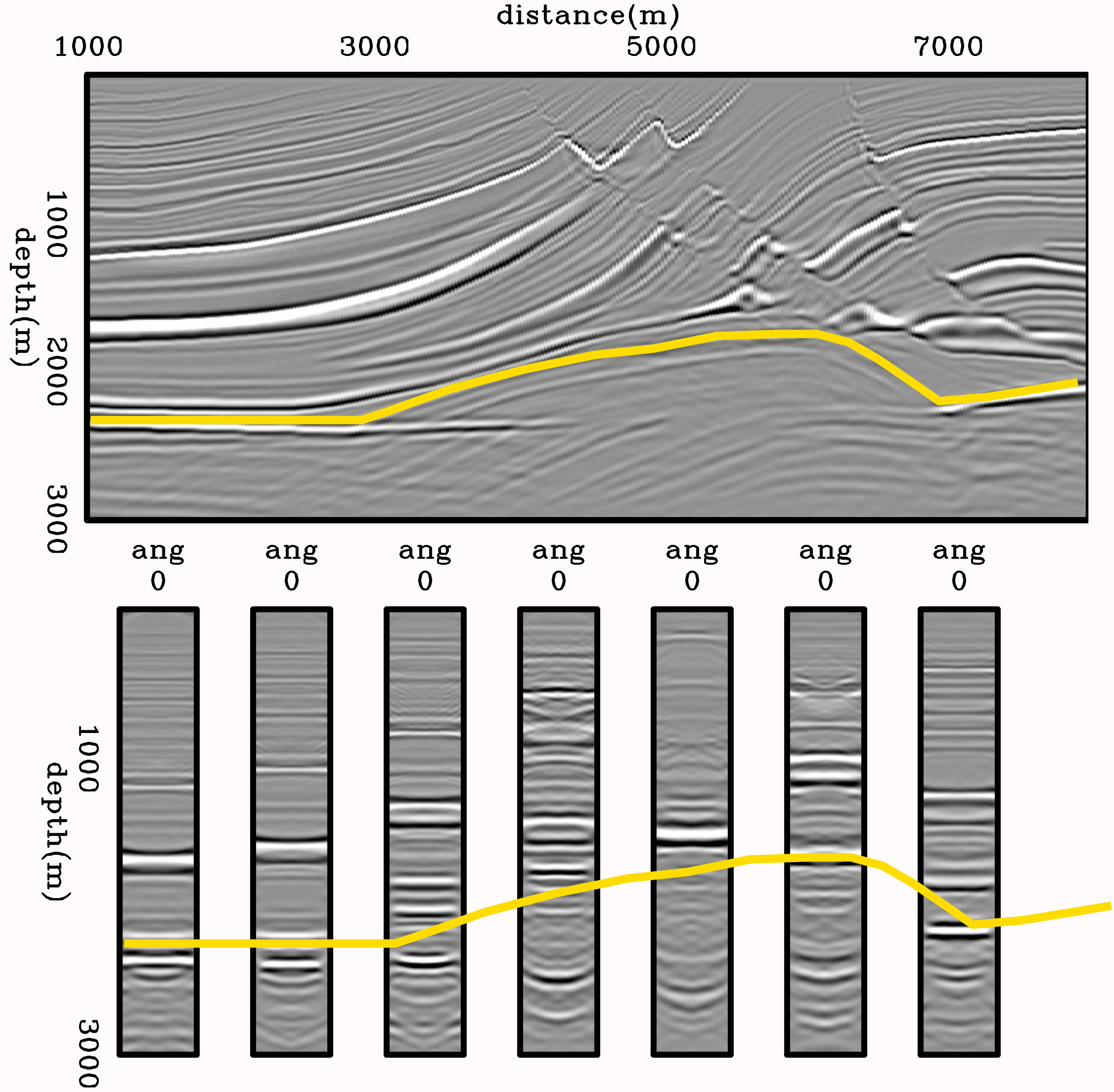
$\Delta\widetilde{I}(s) =$ perturbed image

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

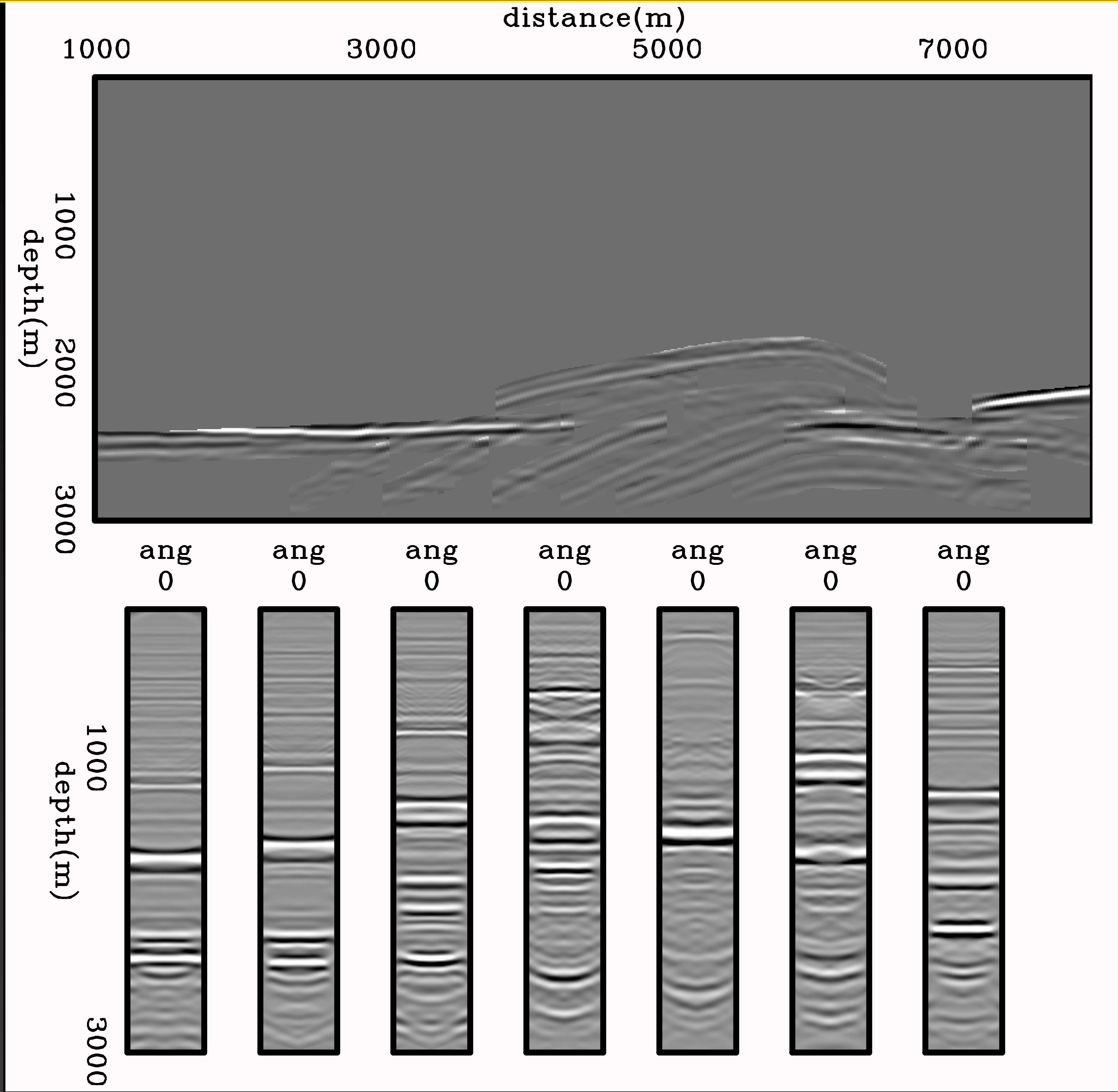
2D synthetic example



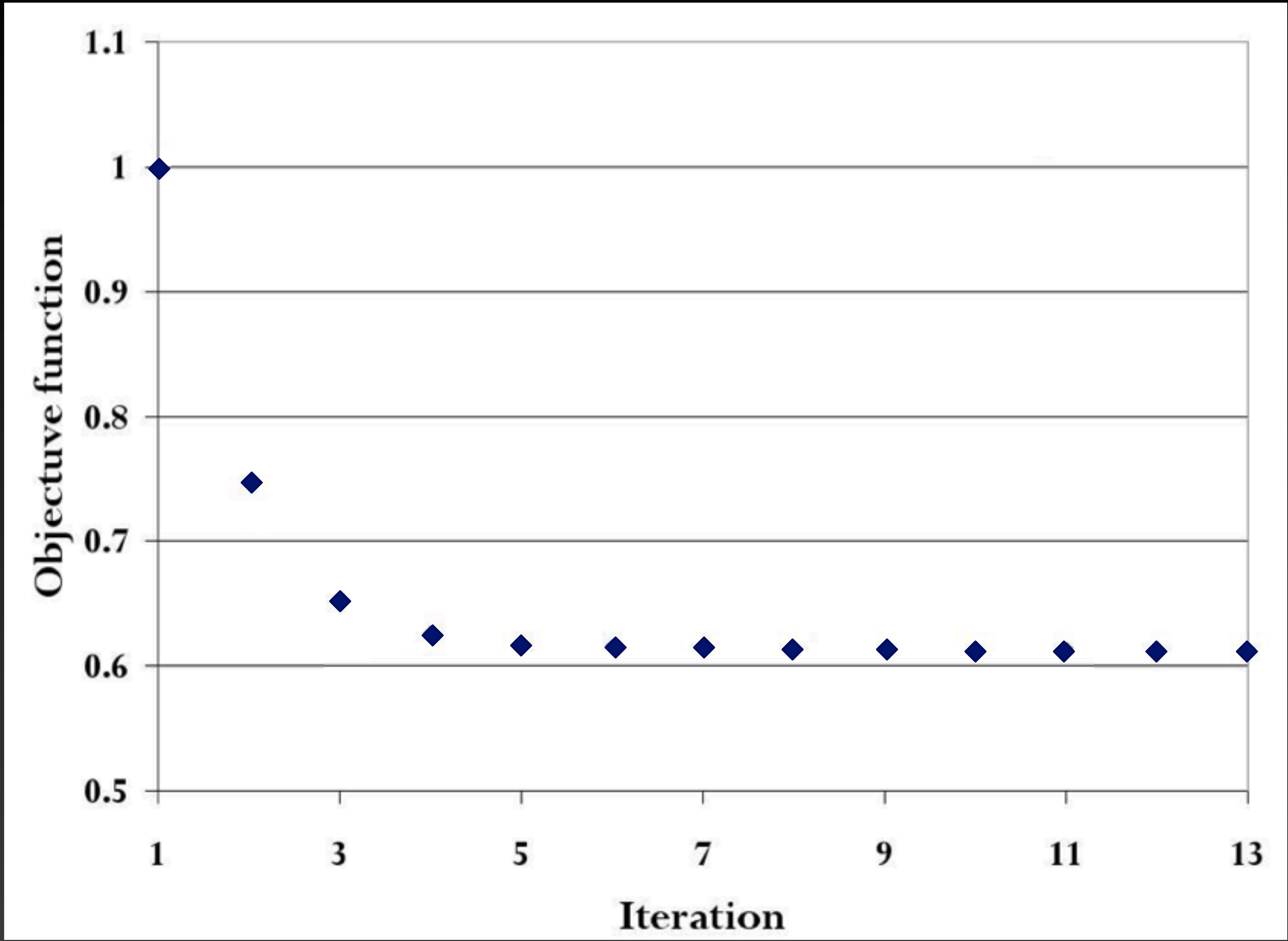
Initial image



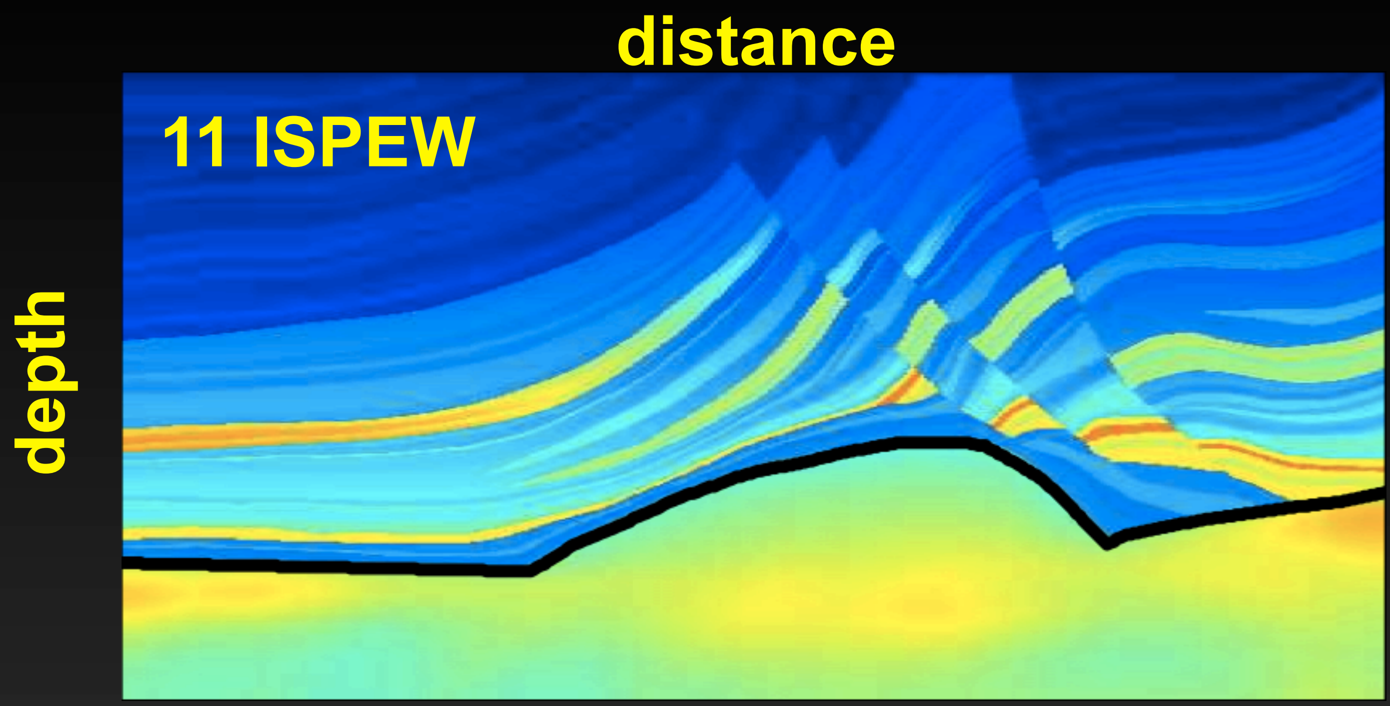
12 selected reflectors



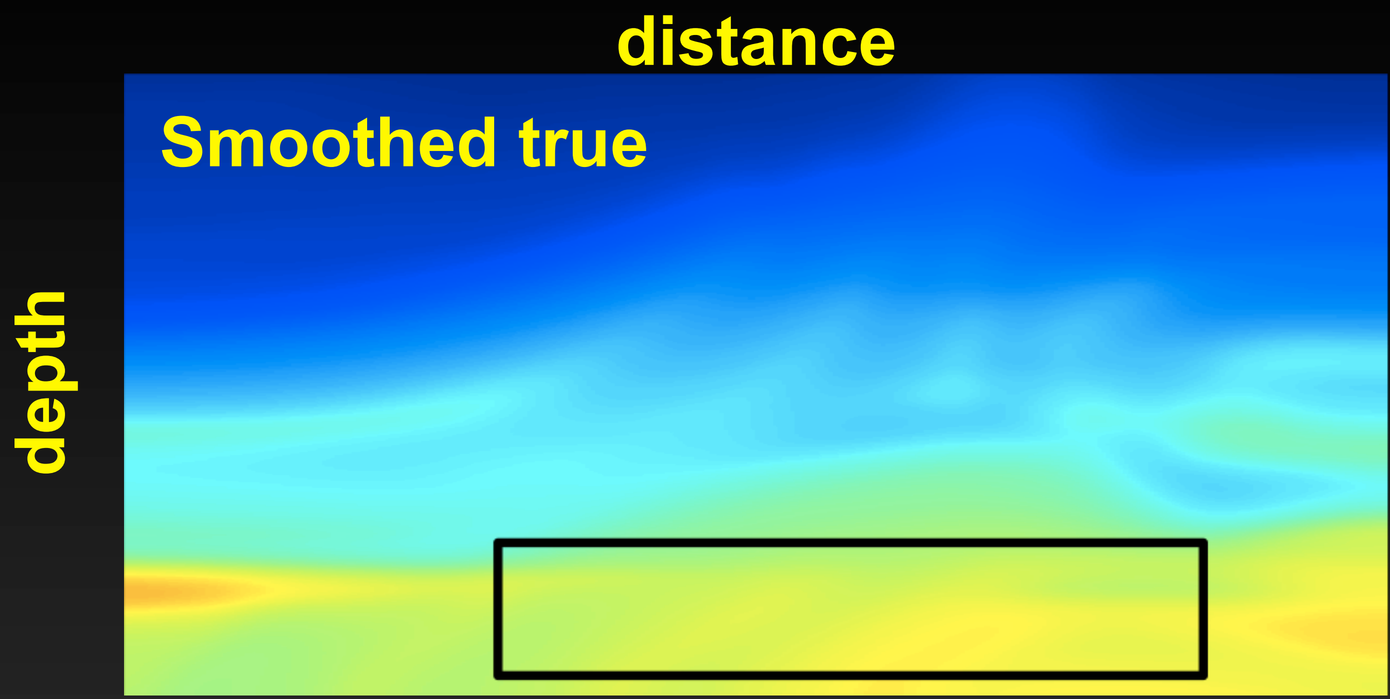
Evolution of the objective function

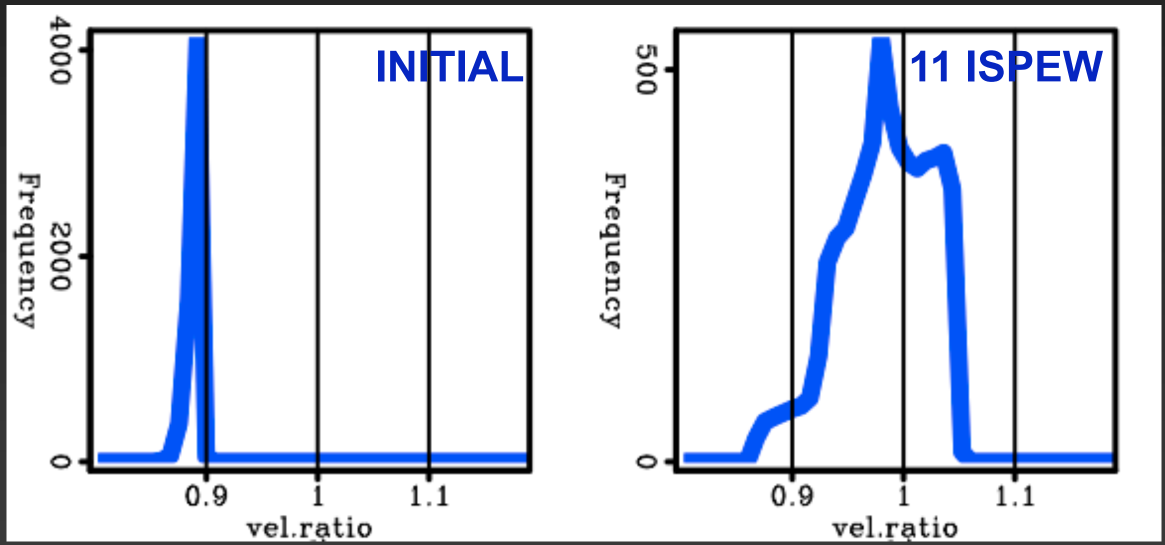


Optimized velocities

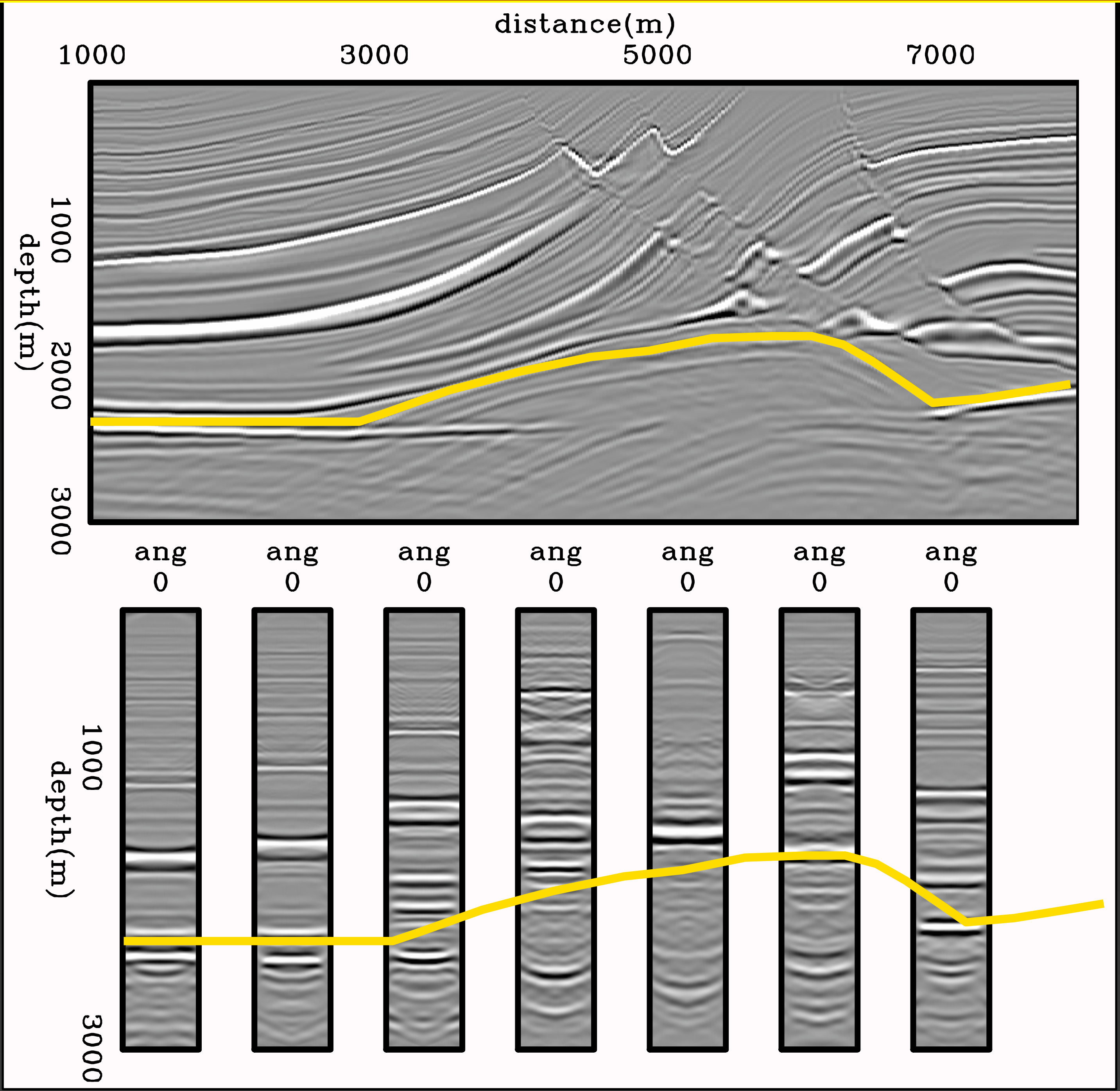


Velocity accuracy

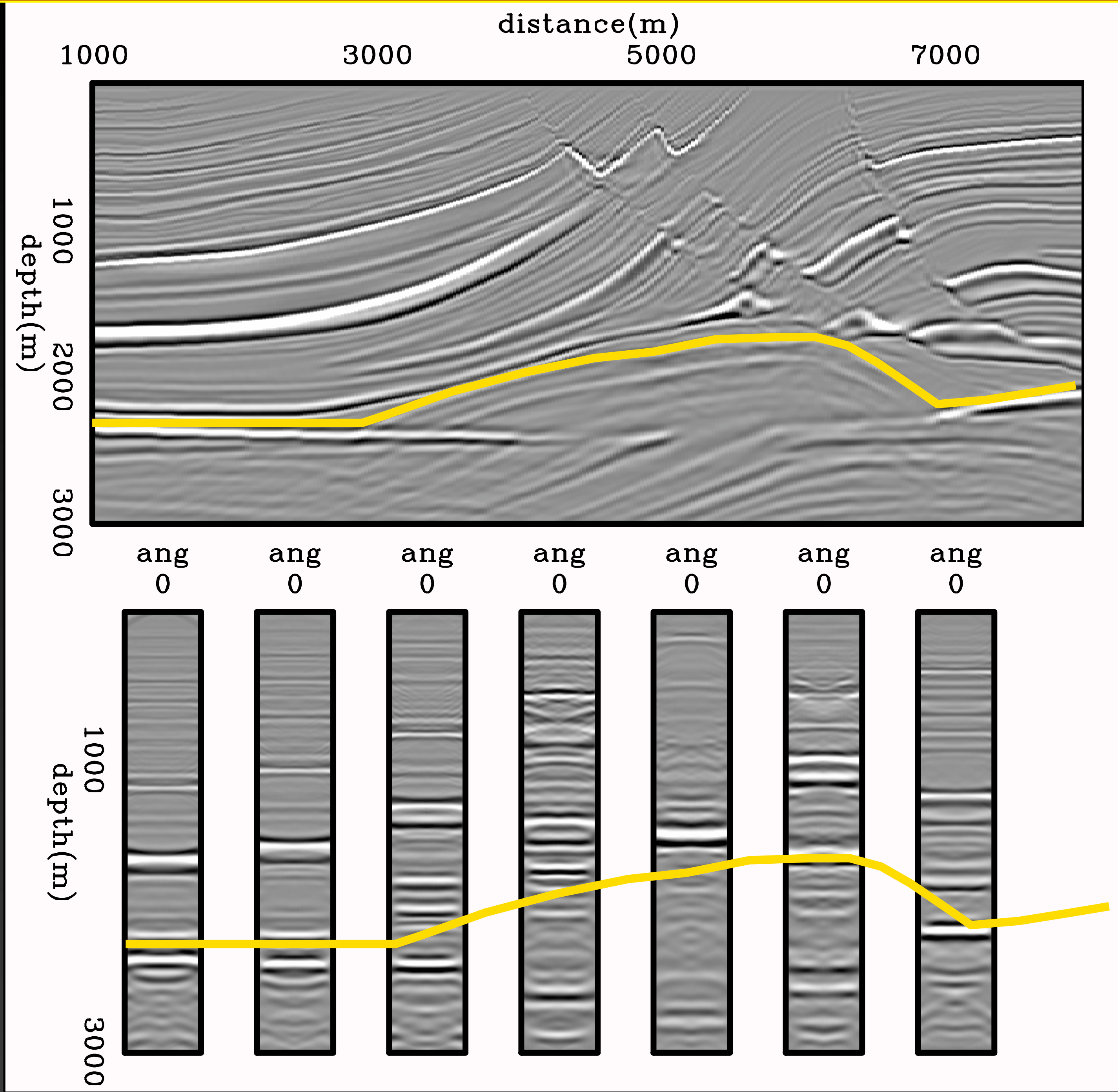




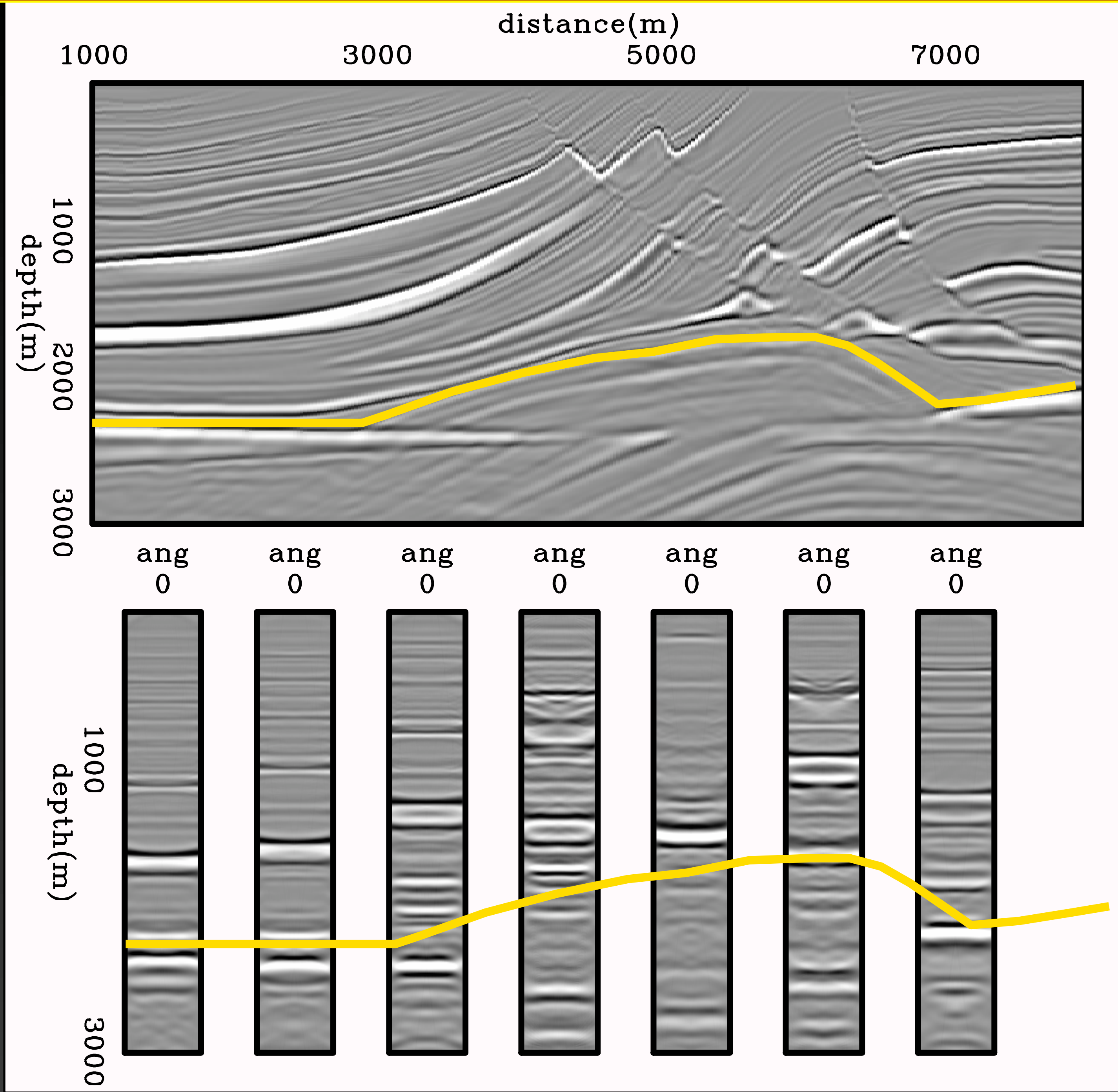
Initial image



Migration with optimized velocity



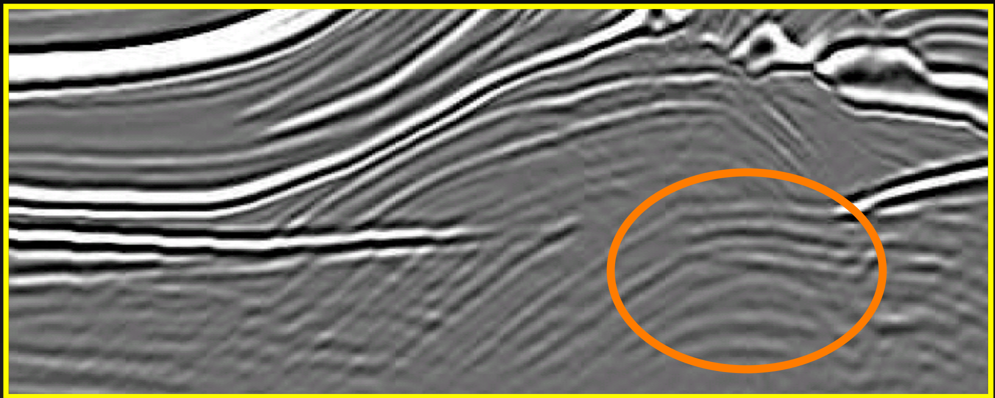
Migration with true velocity



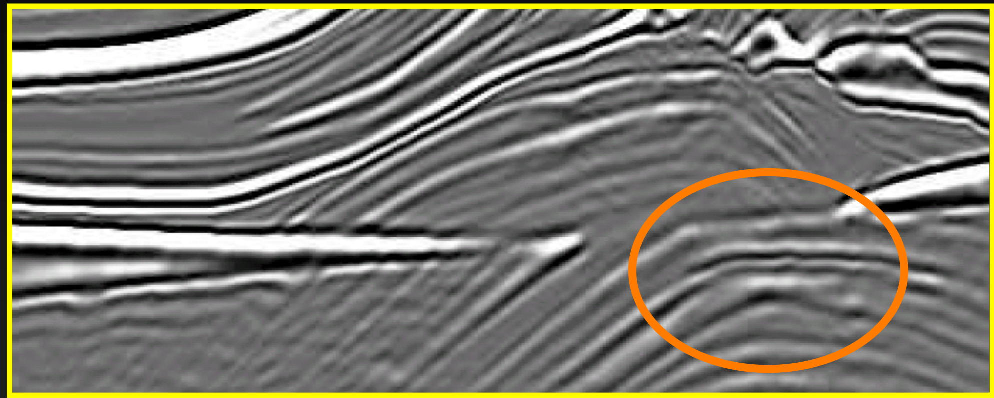
Computational gain

Initial x

z

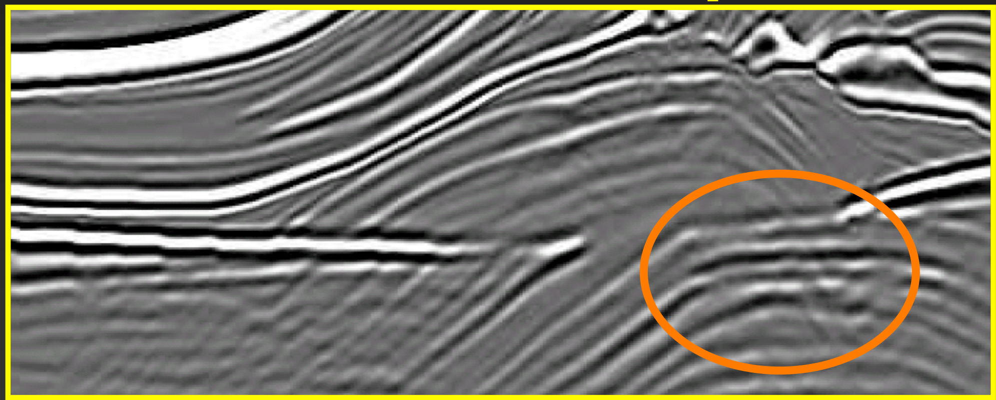


True x



Optimized

z

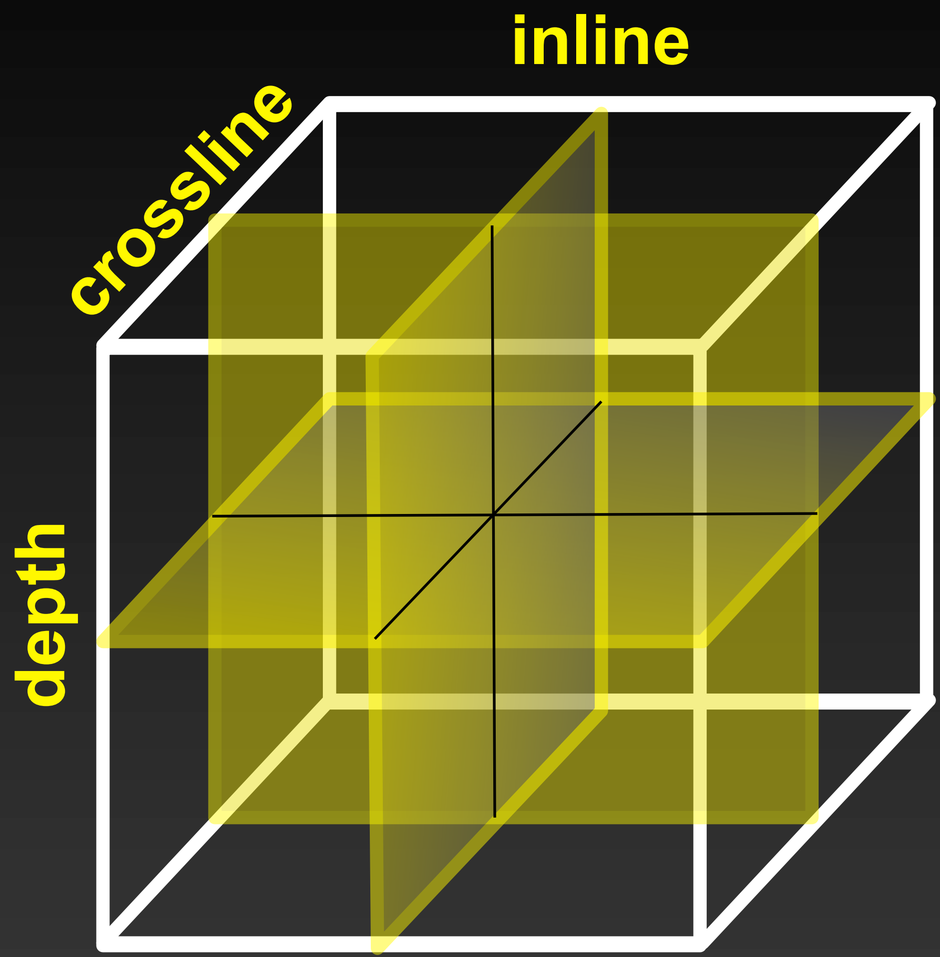


30x faster

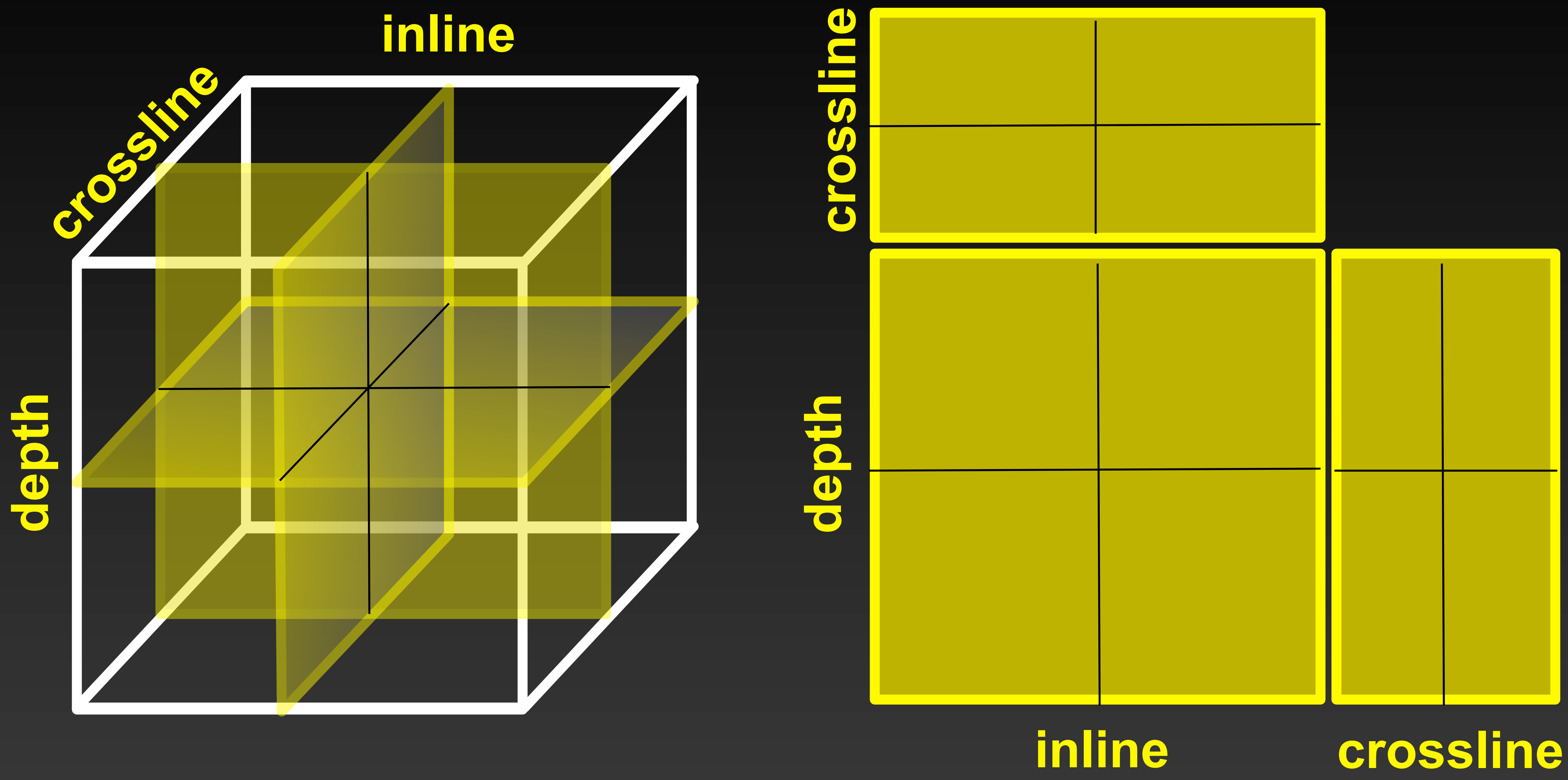
Thesis content

- ✓ Chapter 2: Pre-stack exploding-reflector model
- ✓ Chapter 3: Image-space phase-encoded wavefields
- ✓ Chapter 4: MVA using image-space generalized sources
- Chapter 5: 3D-field data example

3D views



3D views



3D-North Sea data example

- **Dimensions: 12 x 4 km**

3D-North Sea data example

- **Dimensions: 12 x 4 km**
- **Maximum offset: 3.6 km**

3D-North Sea data example

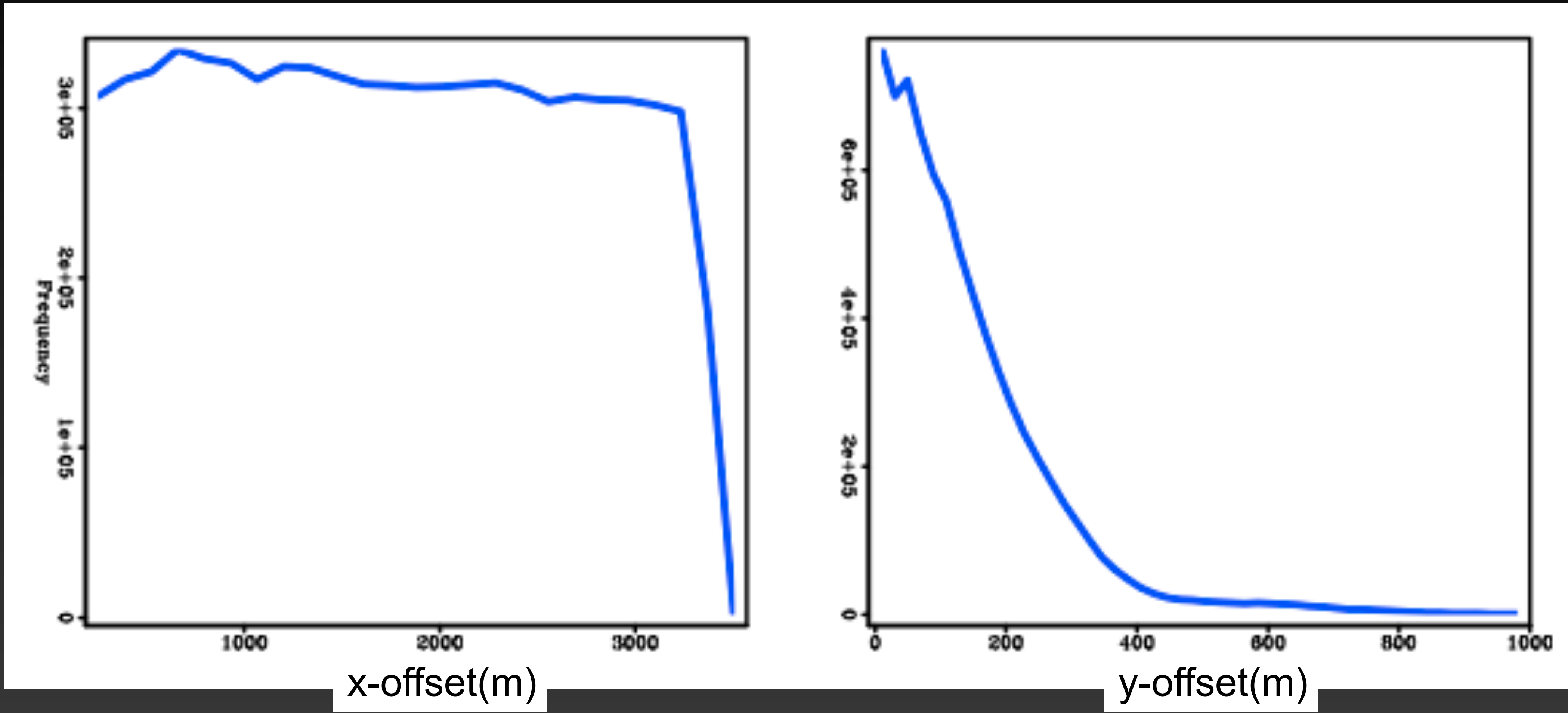
- Dimensions: 12 x 4 km
- Maximum offset: 3.6 km
- 30 ISPEW

Challenges

- Intense faulting, irregular salt body
  - interpretation inaccuracy

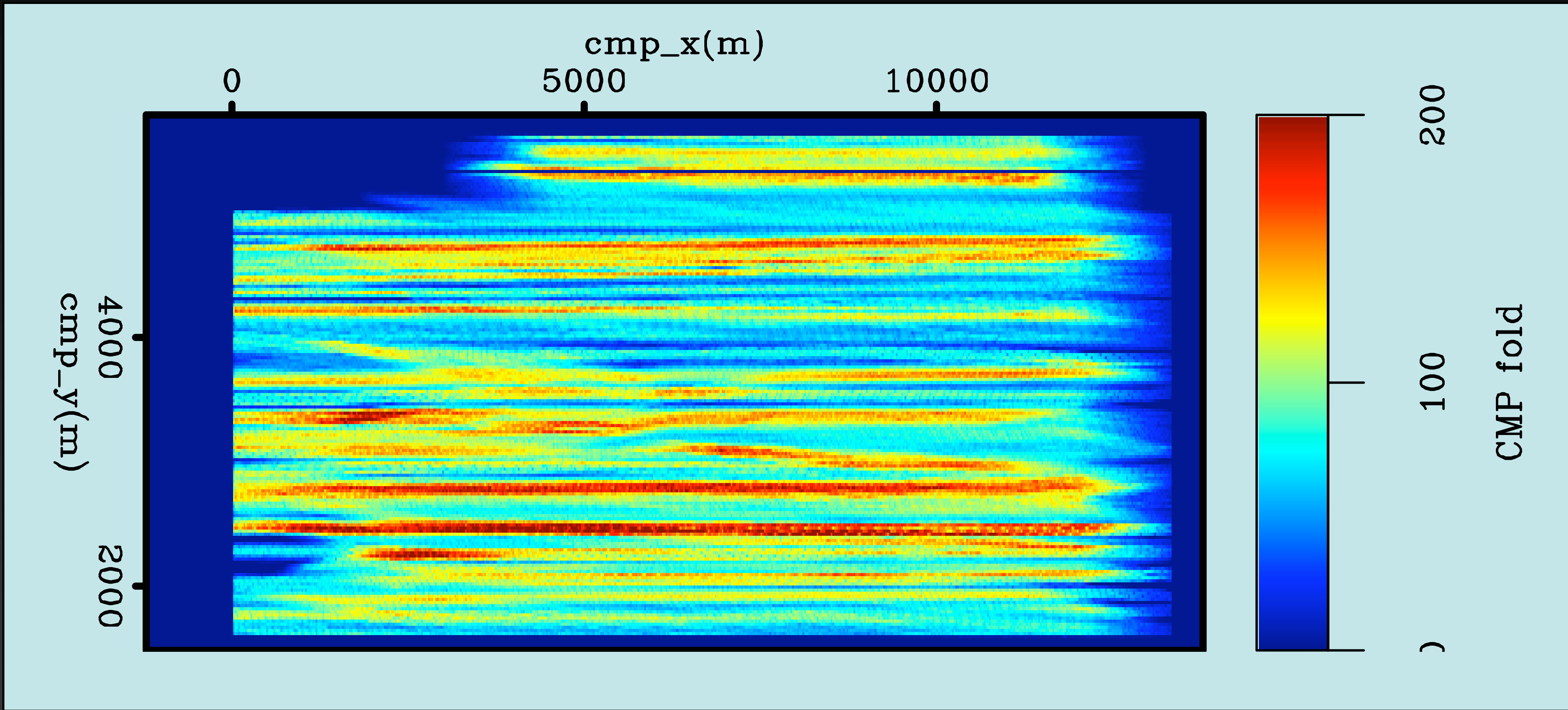
Challenges

- **Limited angular coverage and offsets**



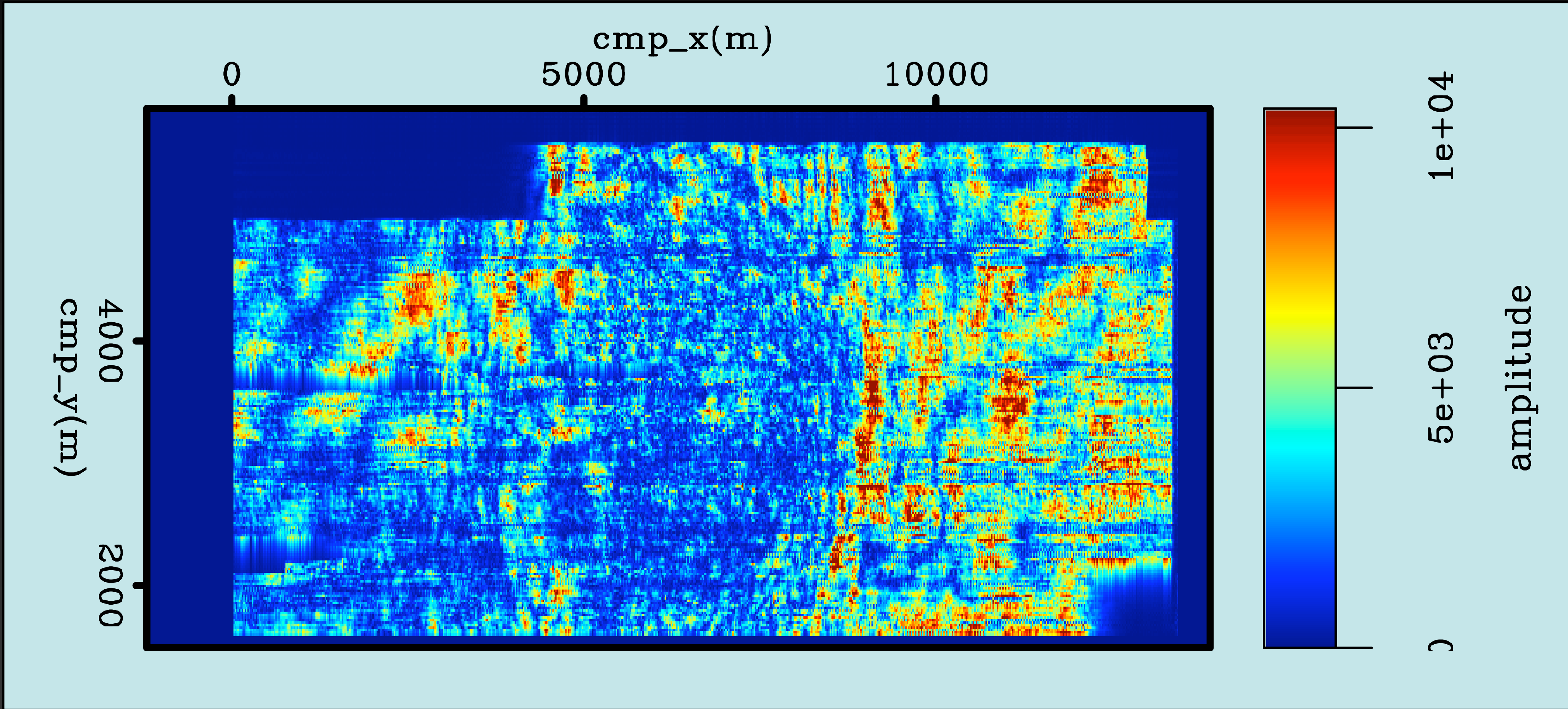
Challenges

- **Acquisition footprint**
  - **CMP fold**



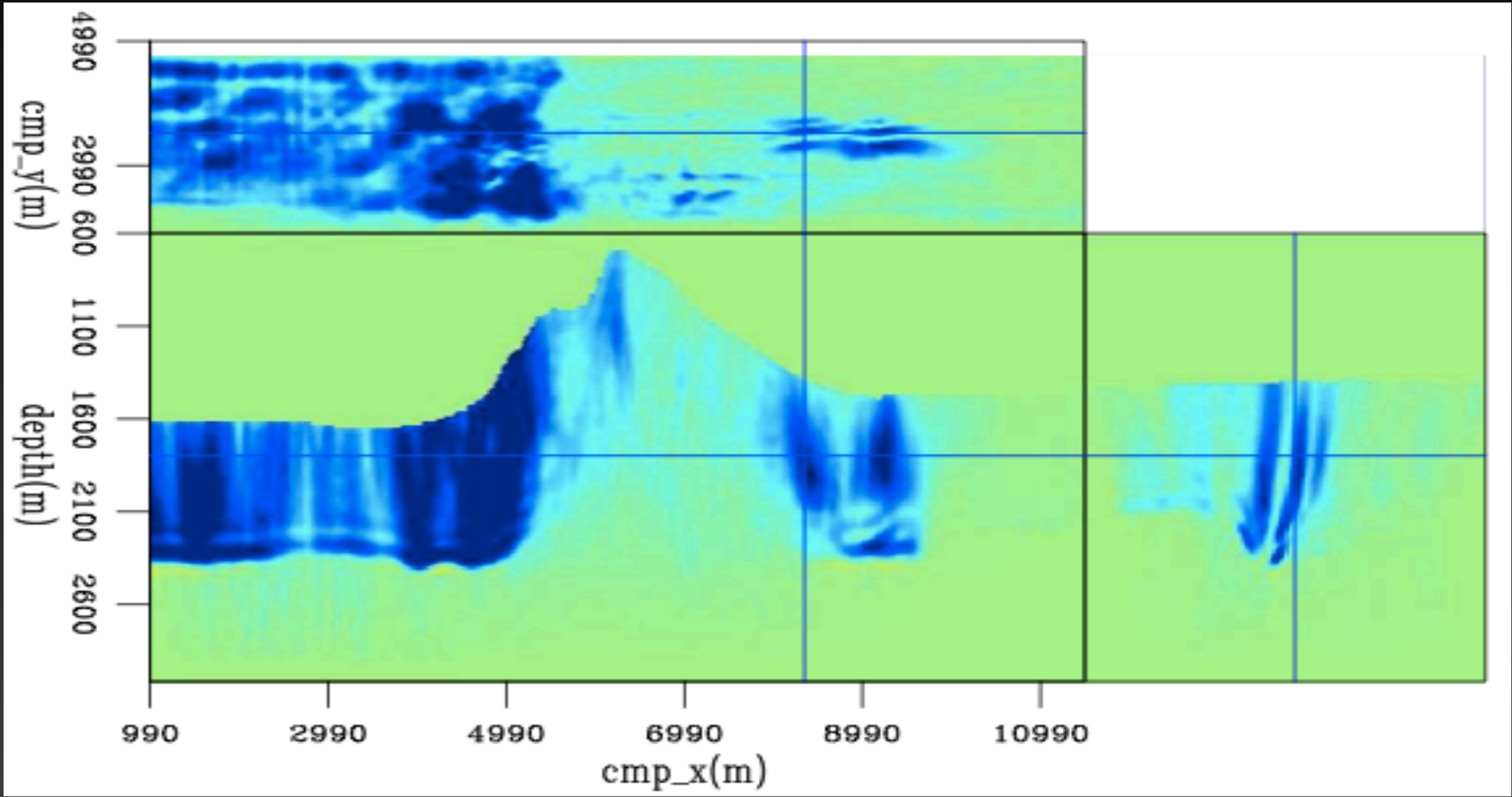
Challenges

- **Acquisition footprint**
  - **RMS amplitude map**

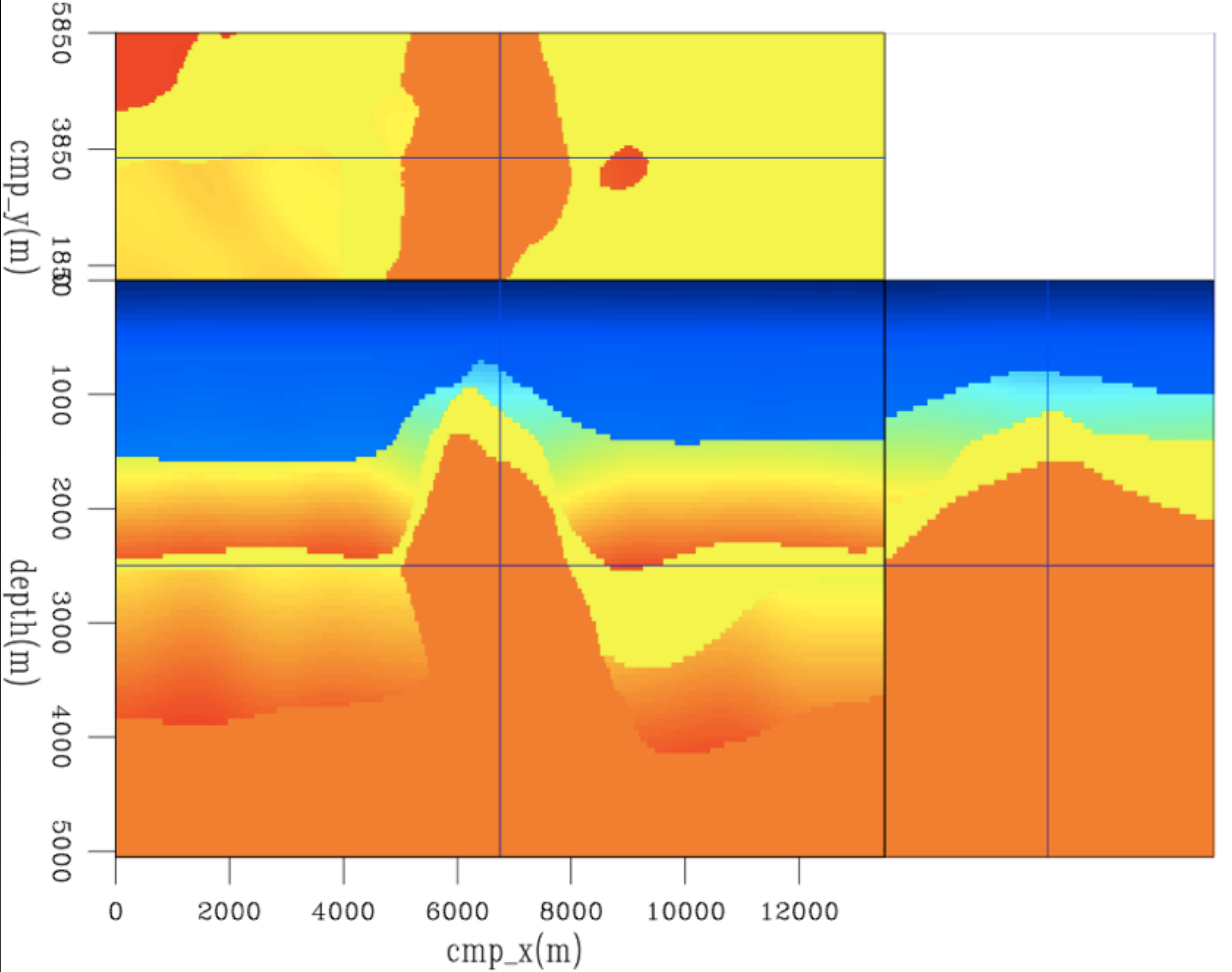


Challenges

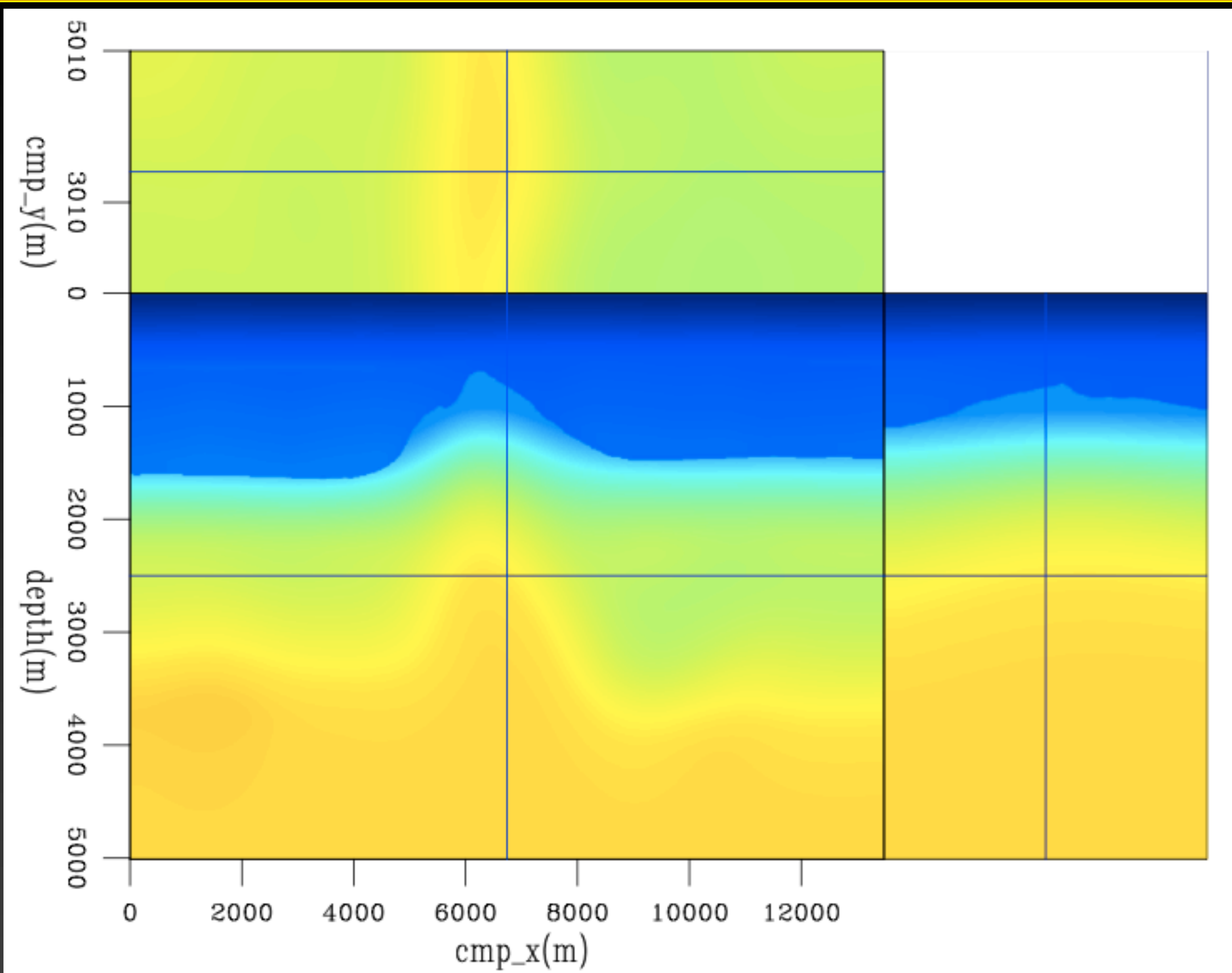
- **Acquisition footprint**
  - **deteriorates the gradient**



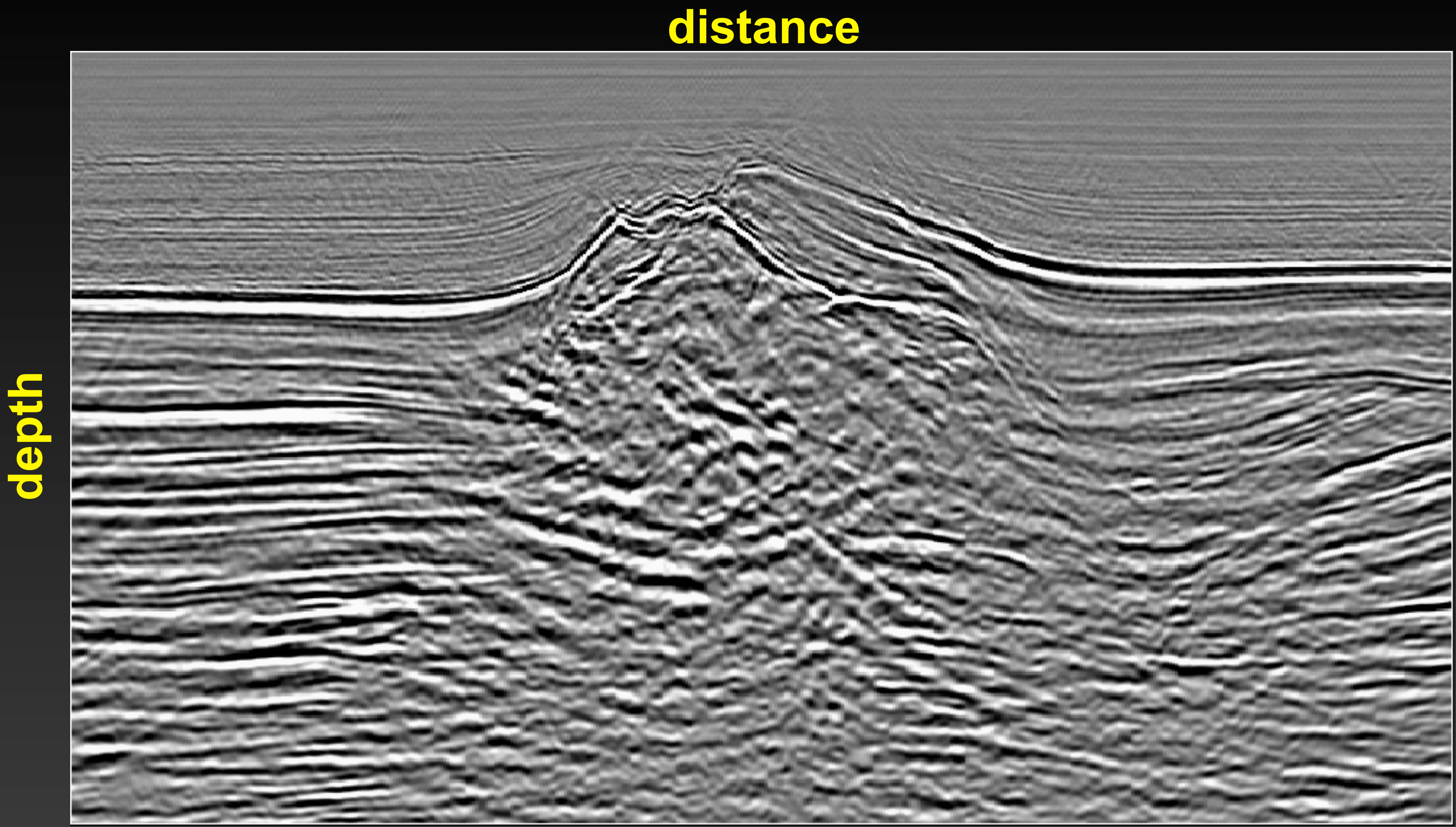
Original velocity model



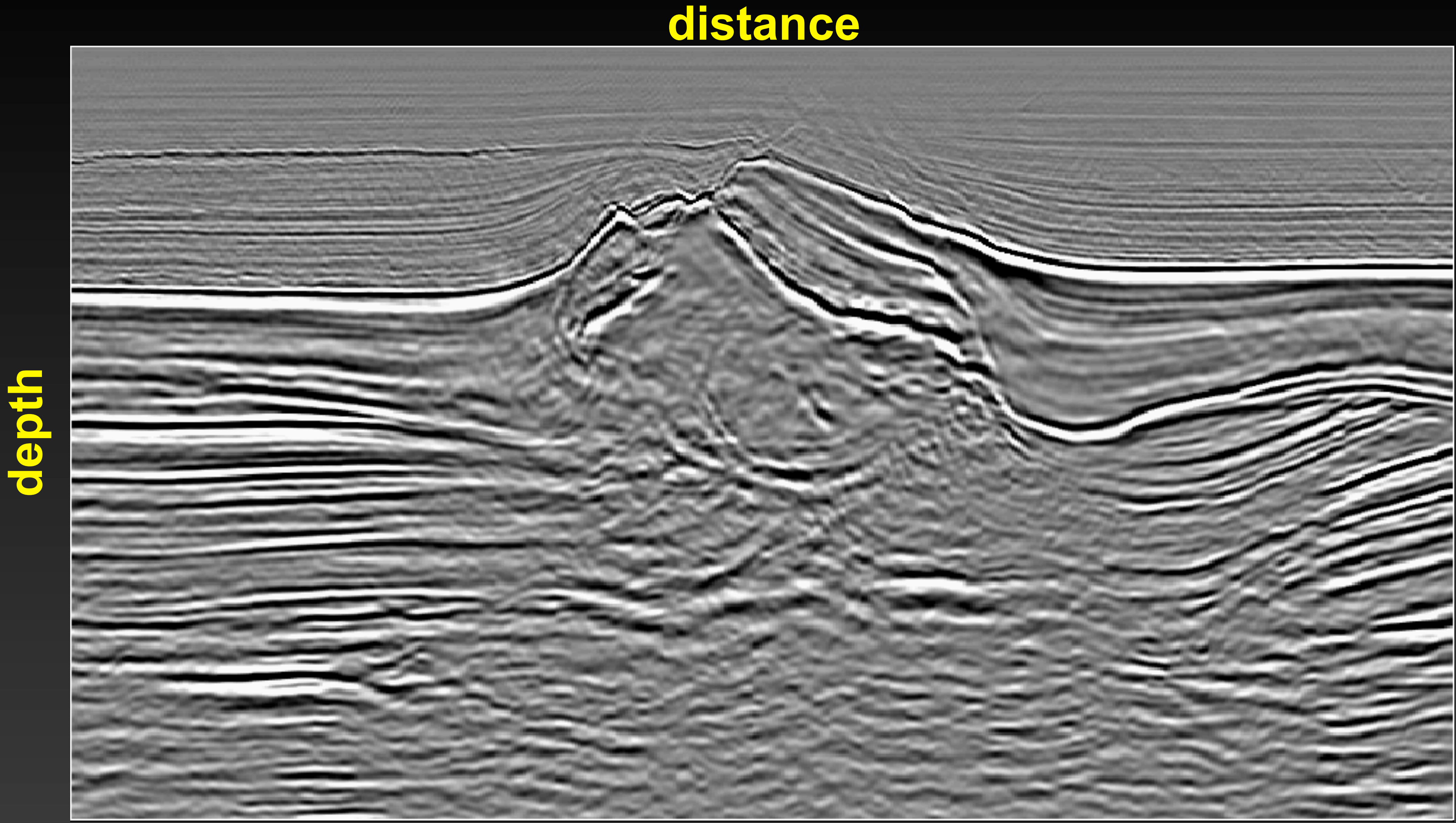
Initial velocity model



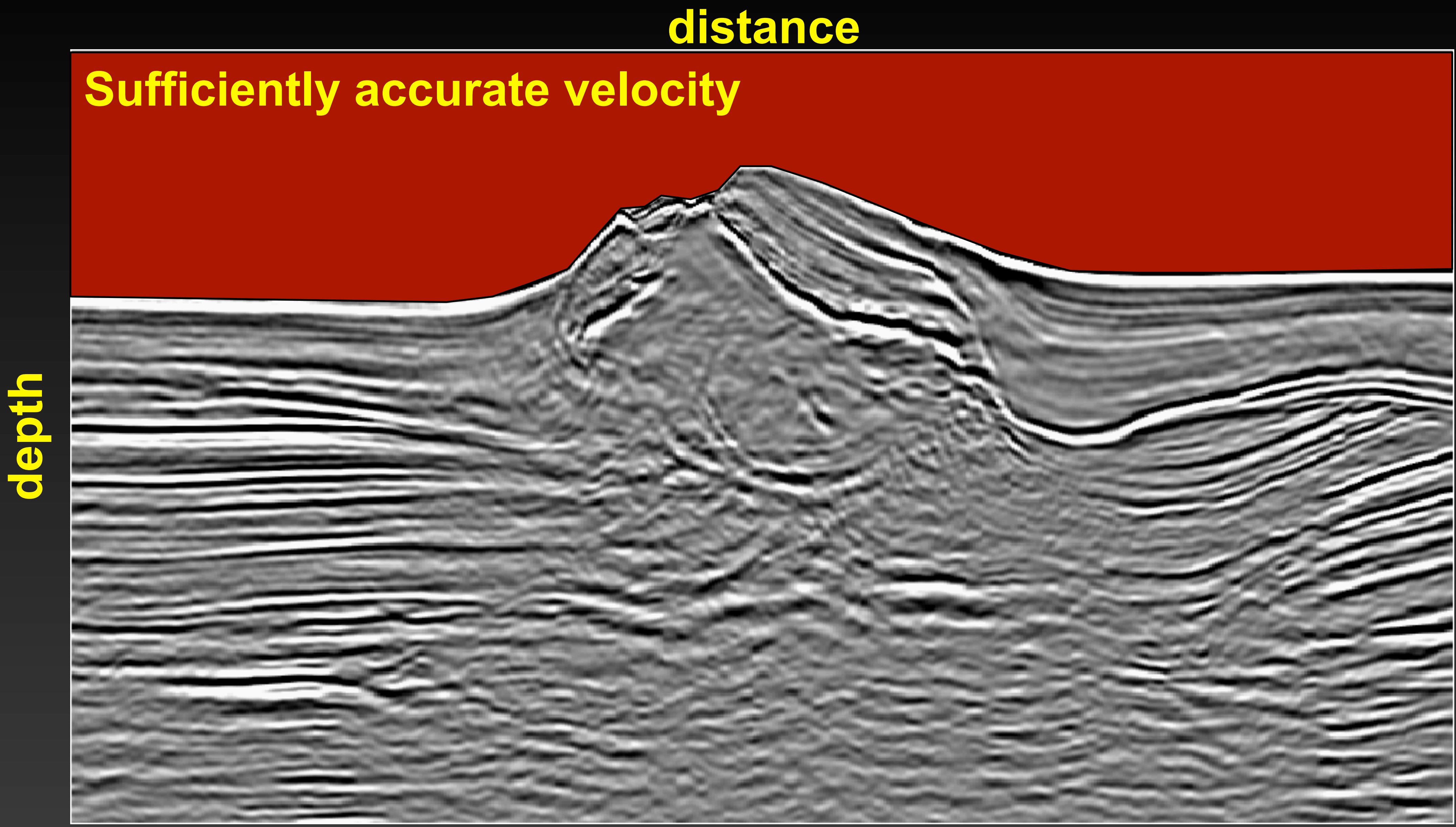
MVA strategy



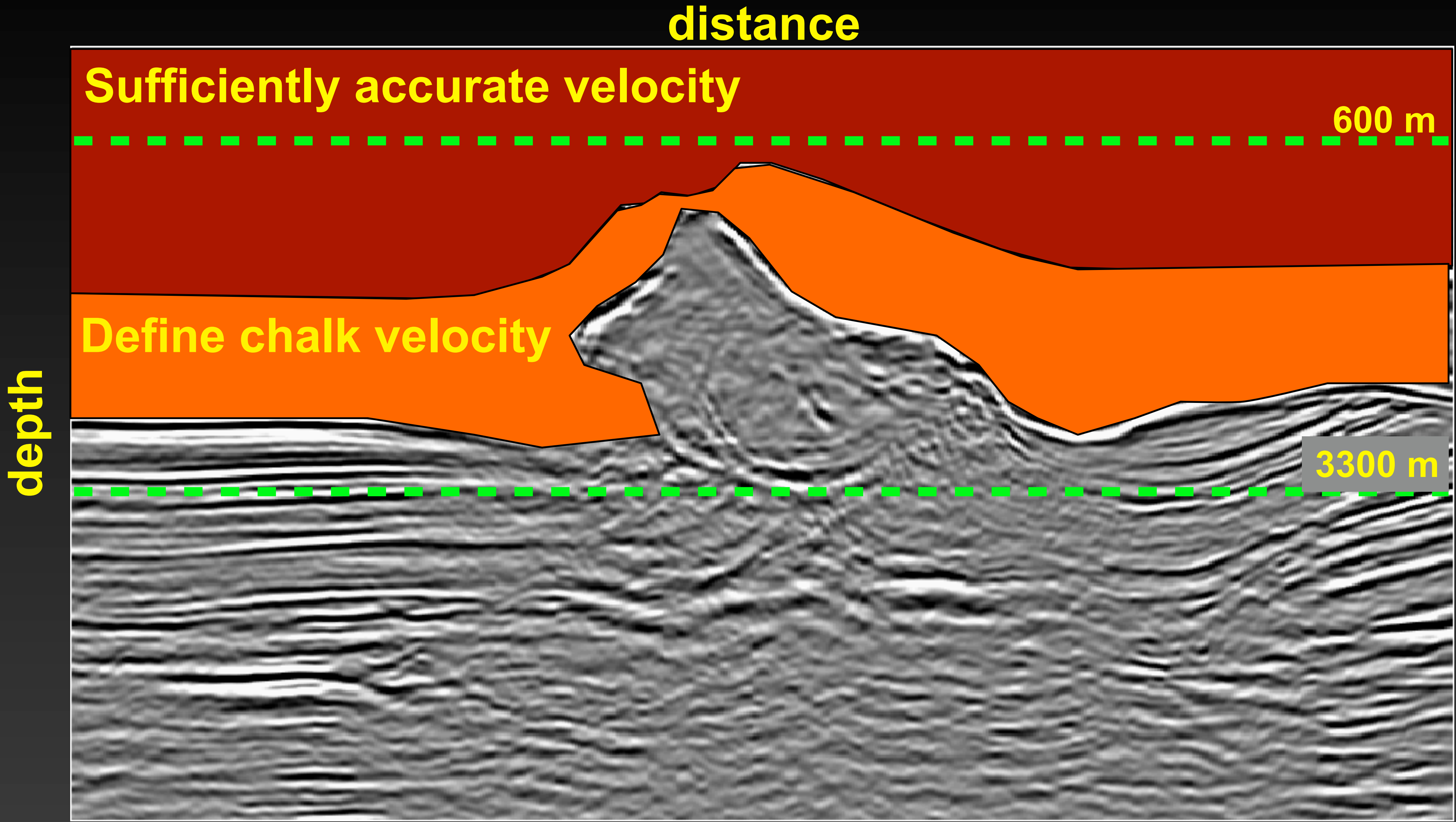
MVA strategy



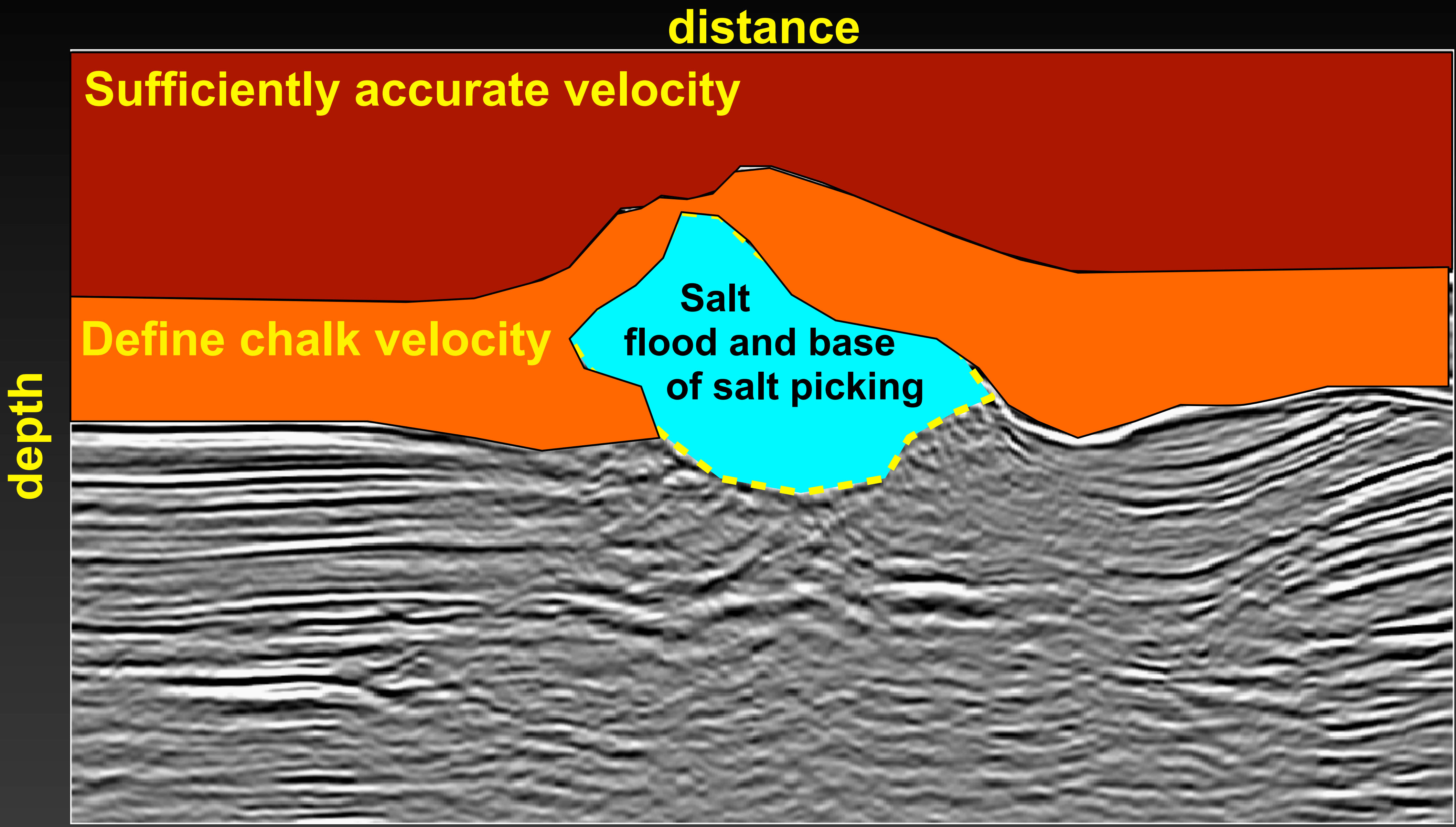
MVA strategy



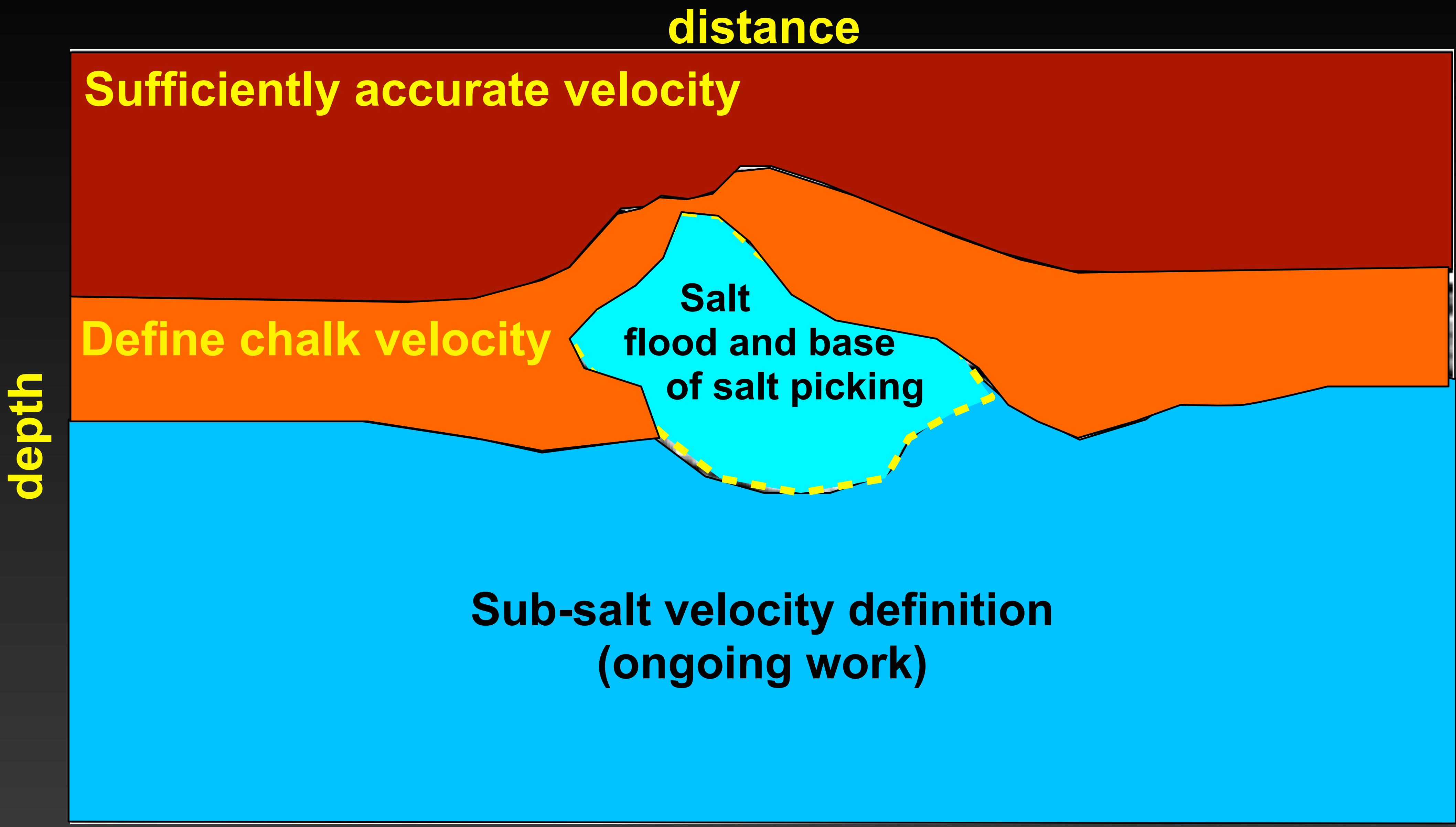
MVA strategy



MVA strategy



MVA strategy

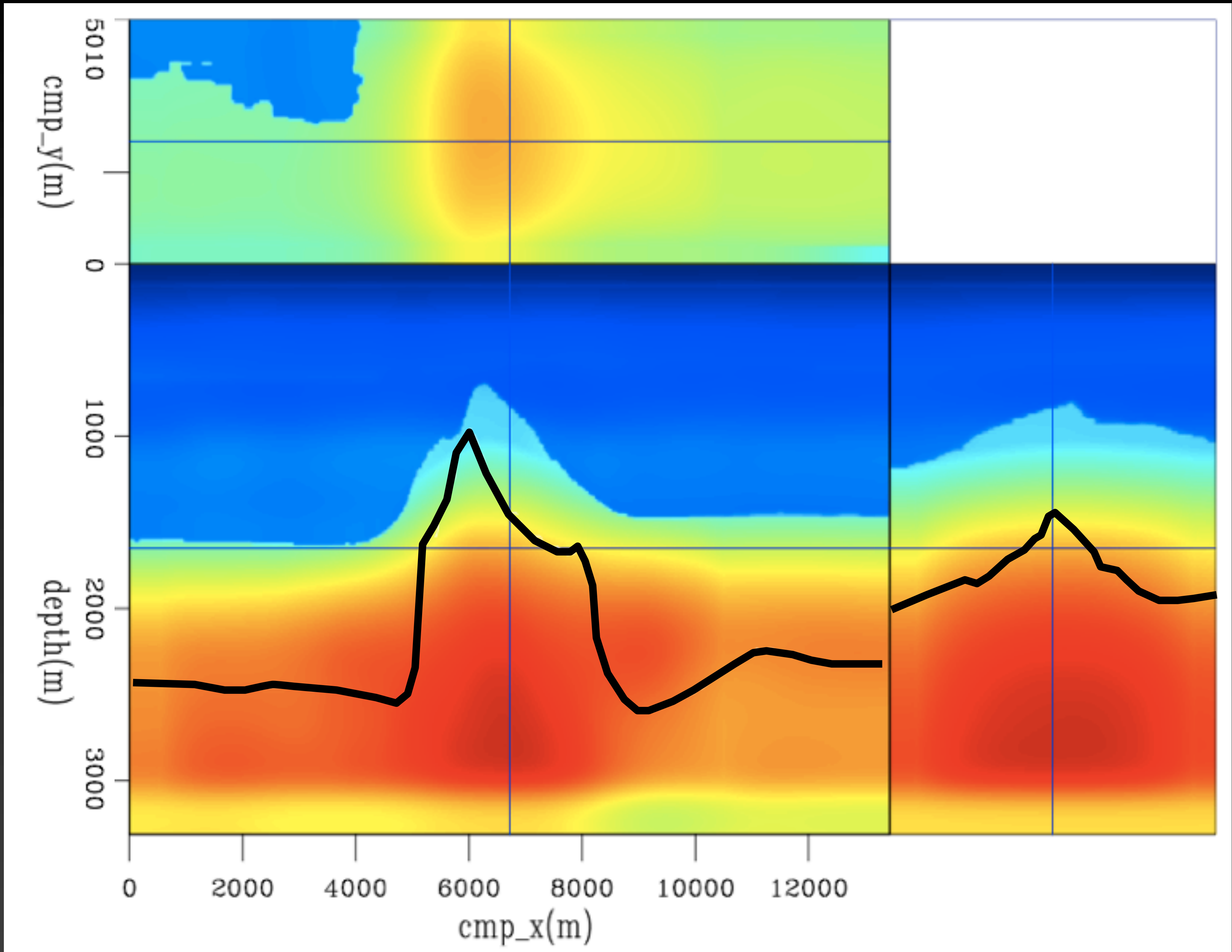


Chalk velocity optimization

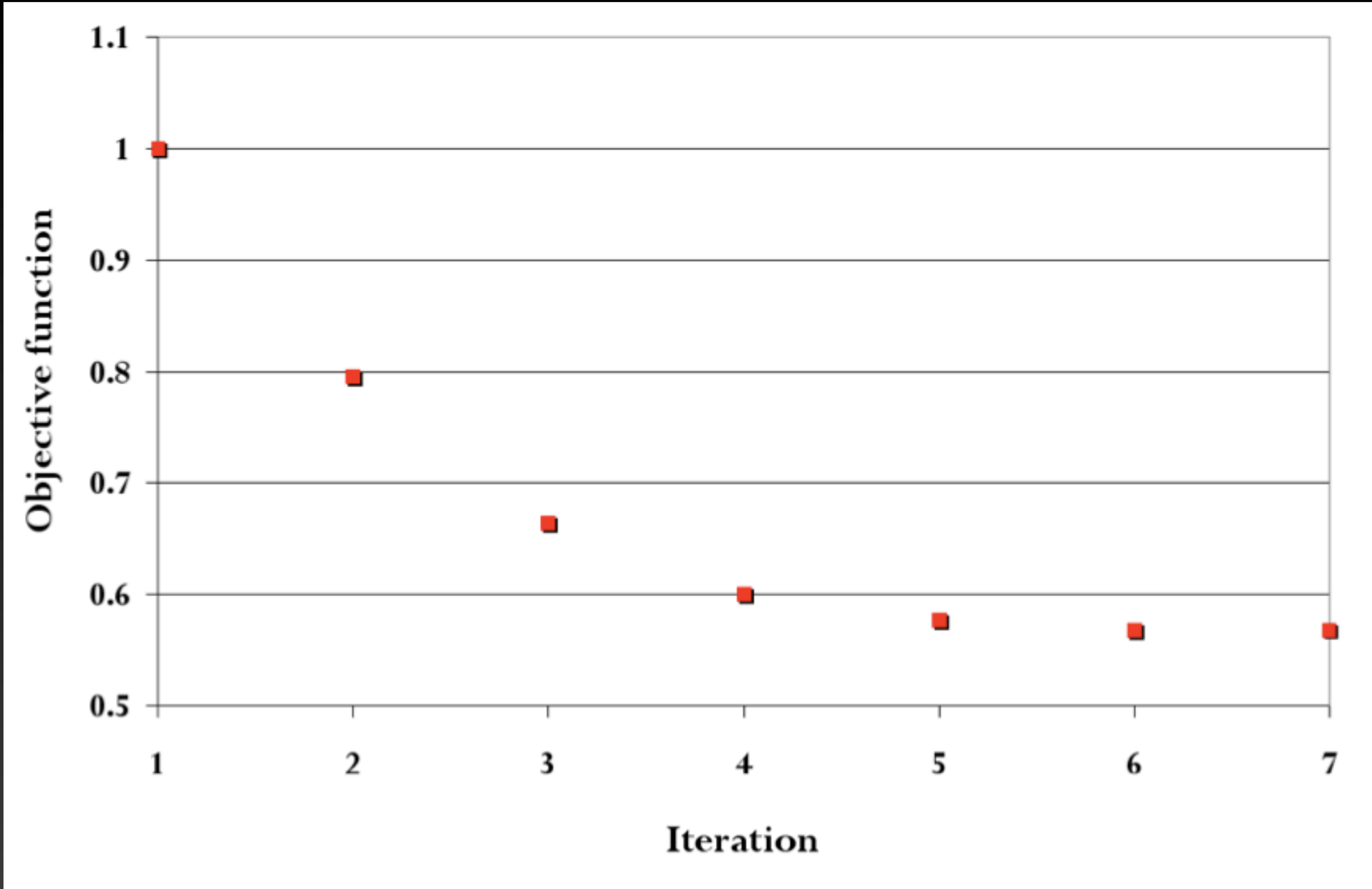
- Non-linear conjugate gradient
- Maximum of 10% velocity variation between iterations
- Two function evaluations per iteration
- CEES: 30 Dual Nehalem 5520, 24Gb RAM
  - Objective function: 20 min
  - Gradient: 40 min

CEES - Stanford Center for Computational Earth & Environmental Science

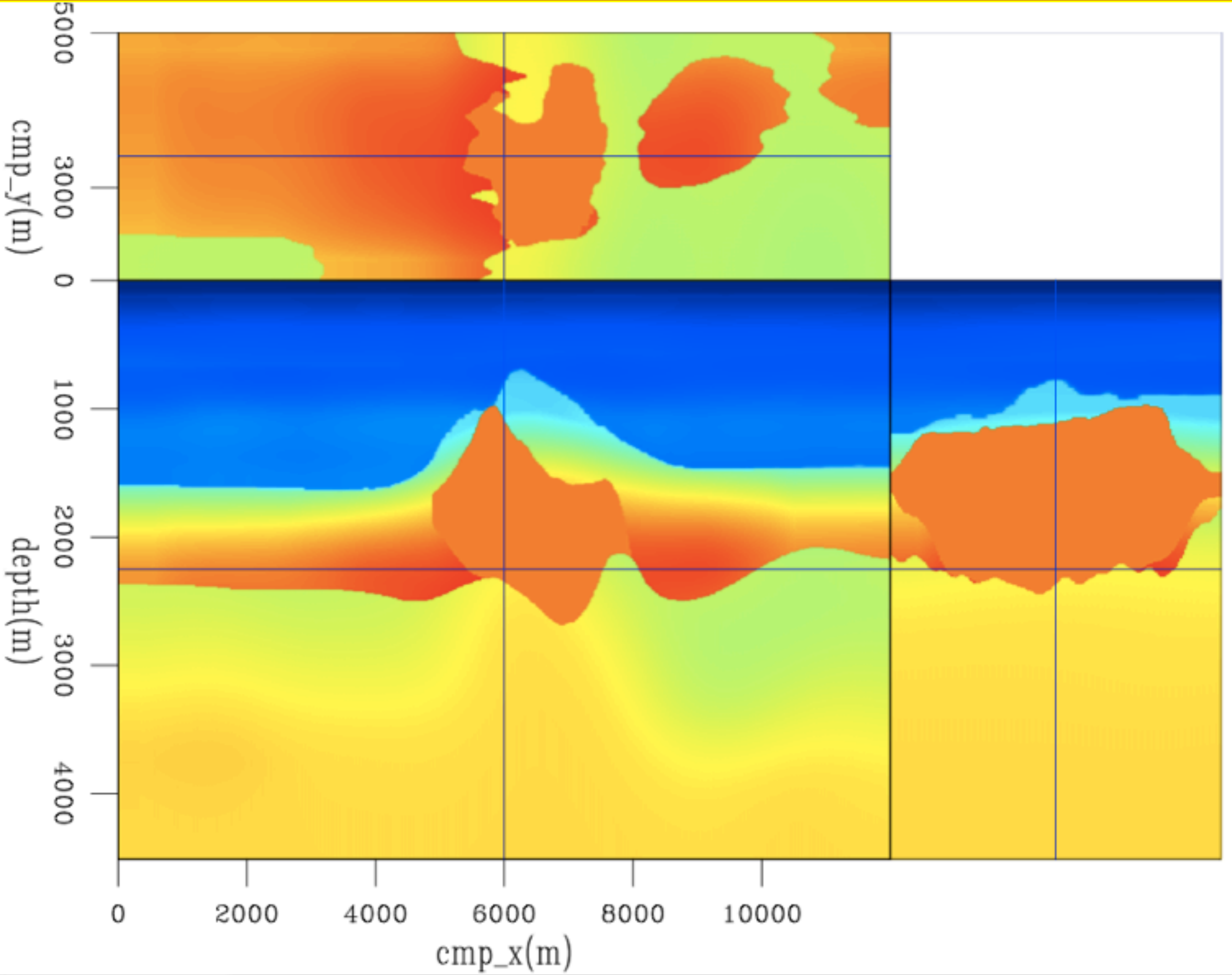
Optimized chalk velocity



Objective function

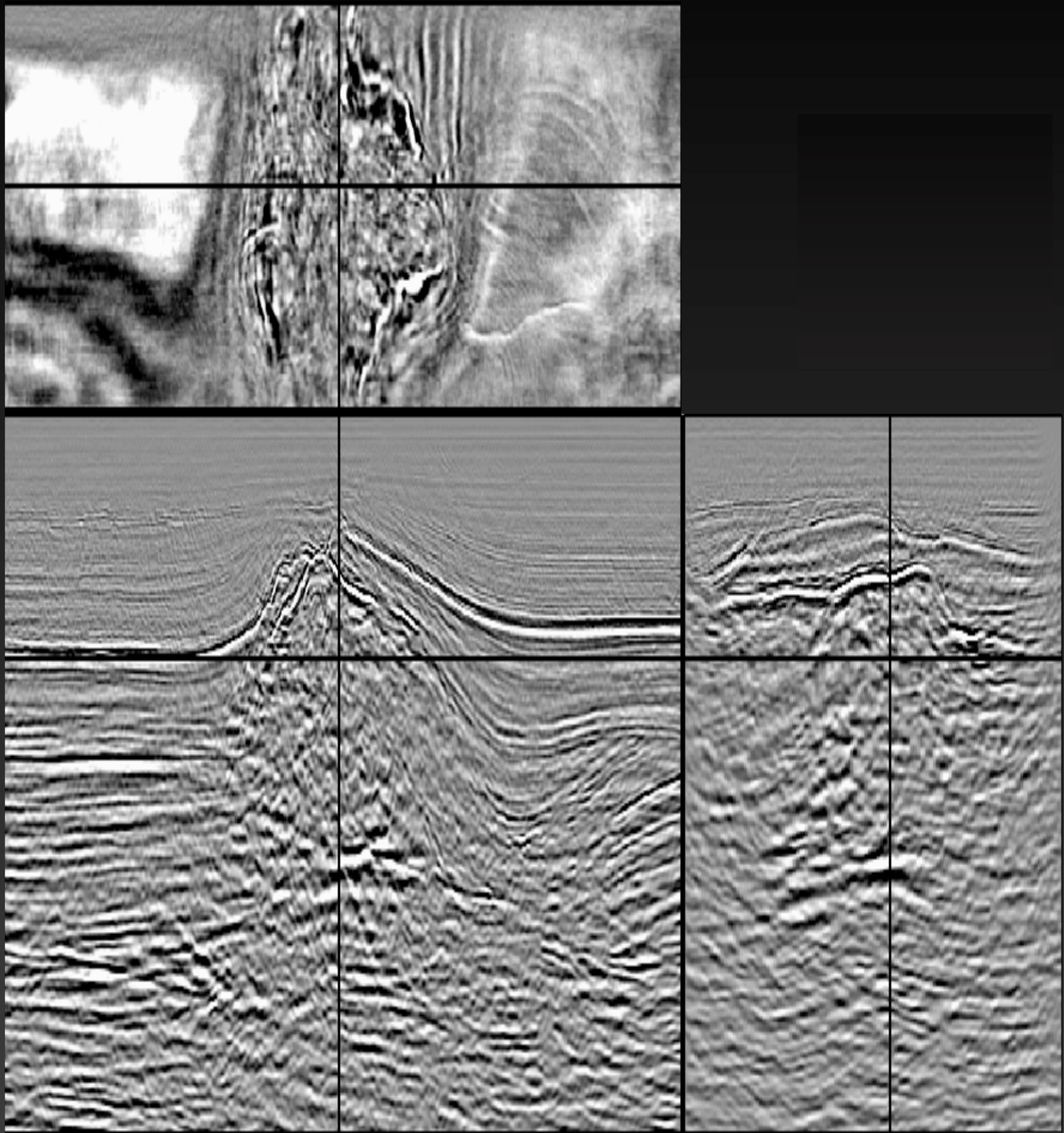


Velocity after salt body definition

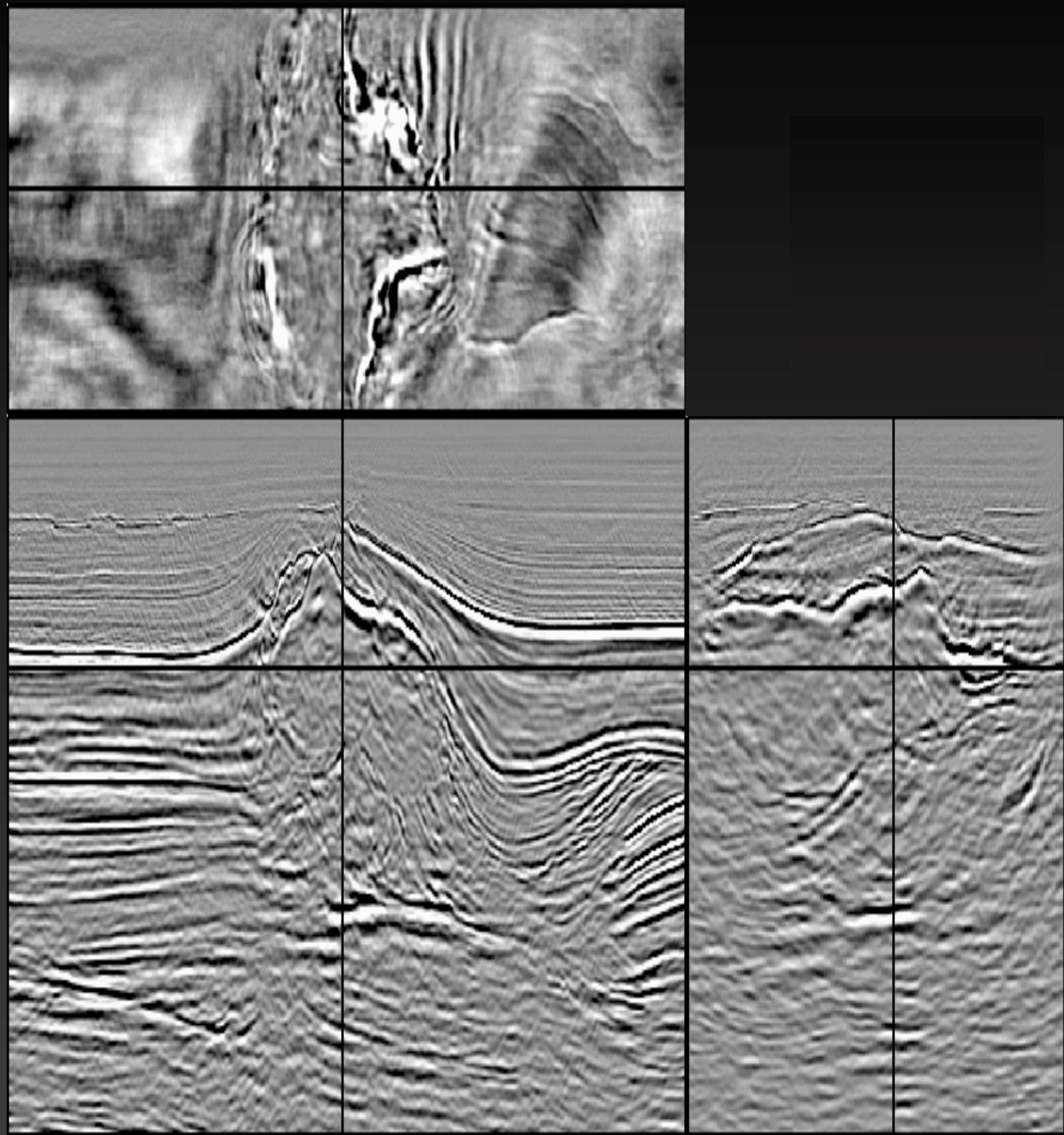


Better base of salt & focusing

Initial

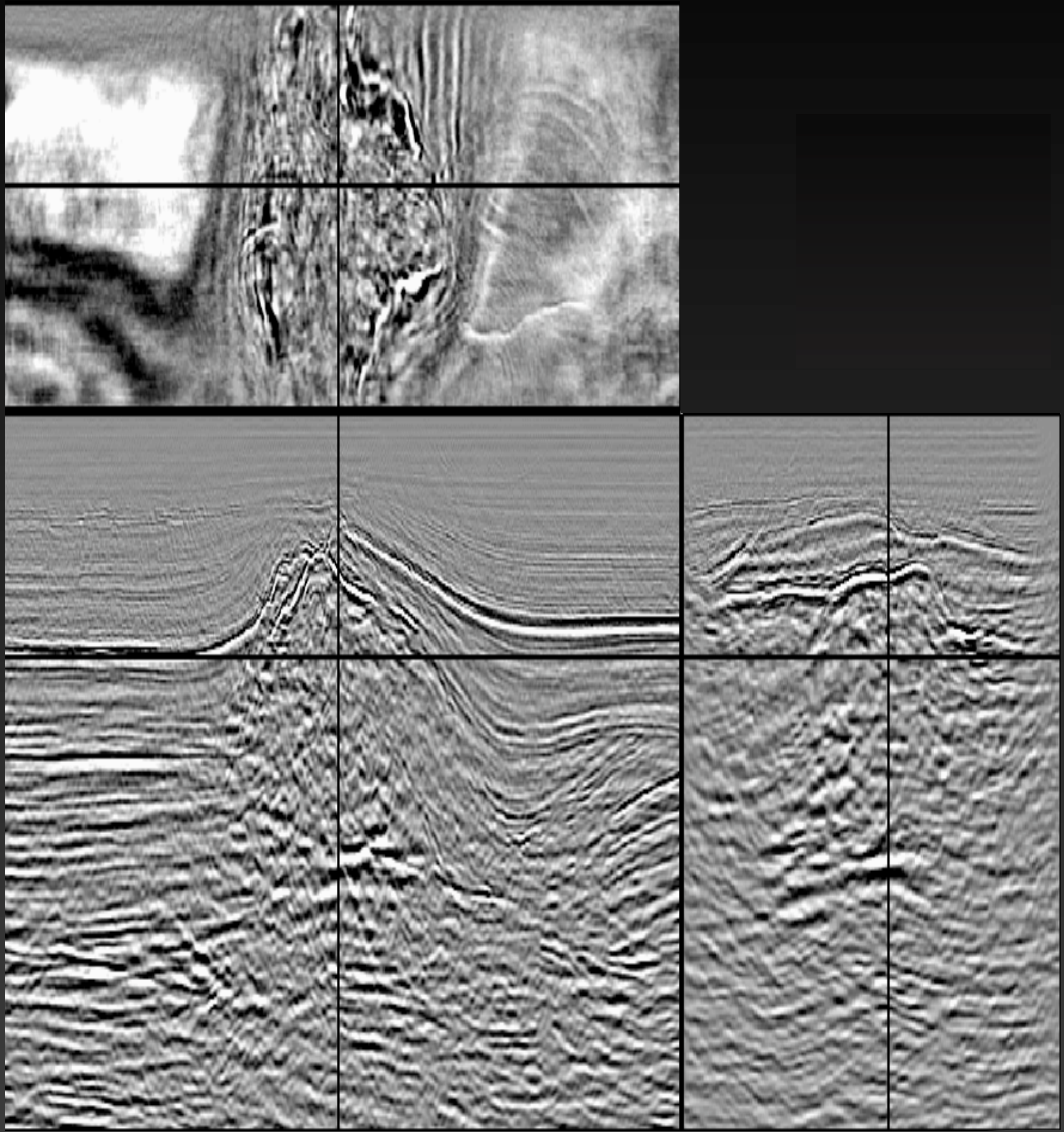


After salt body

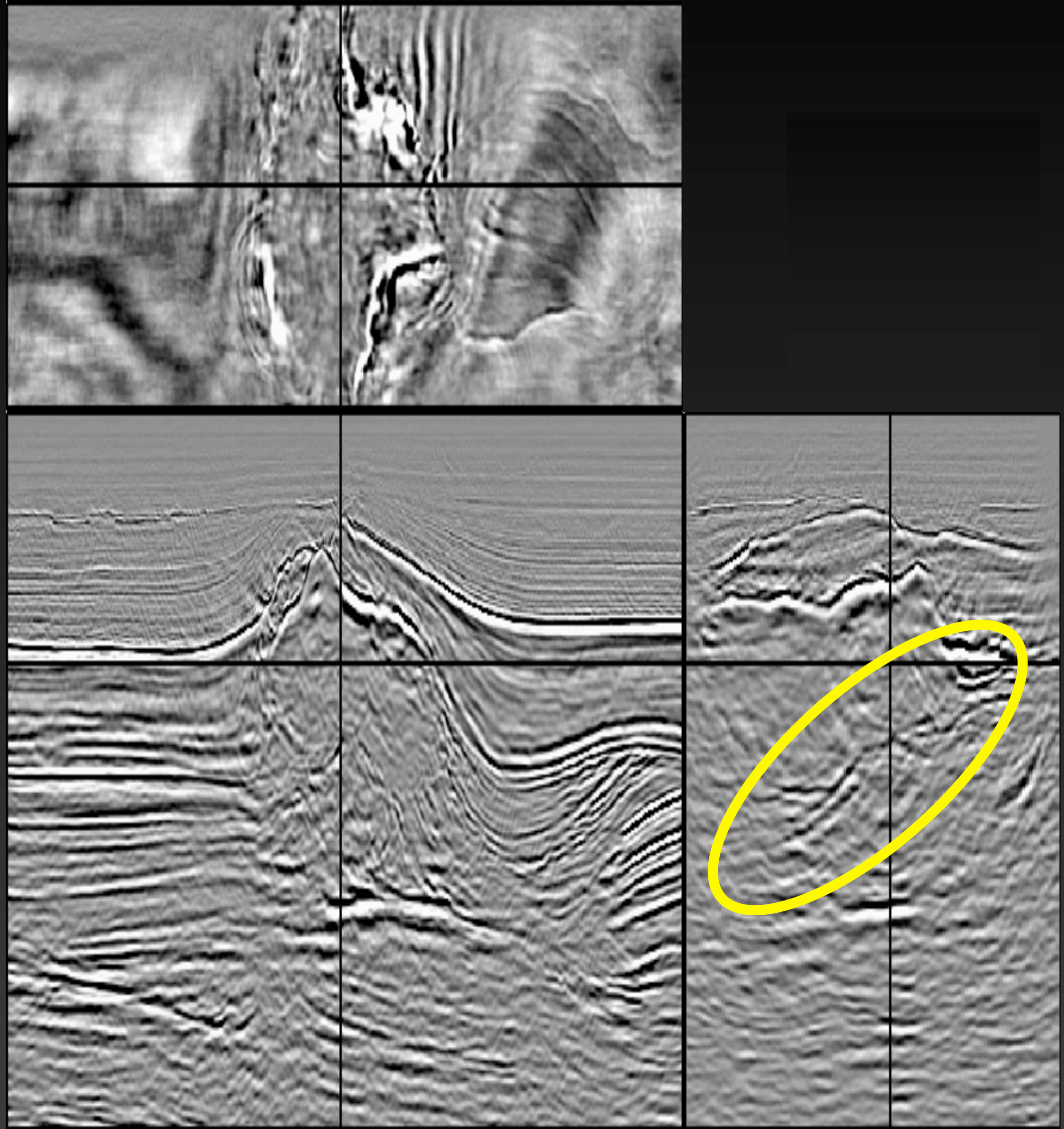


Better base of salt & focusing

Initial

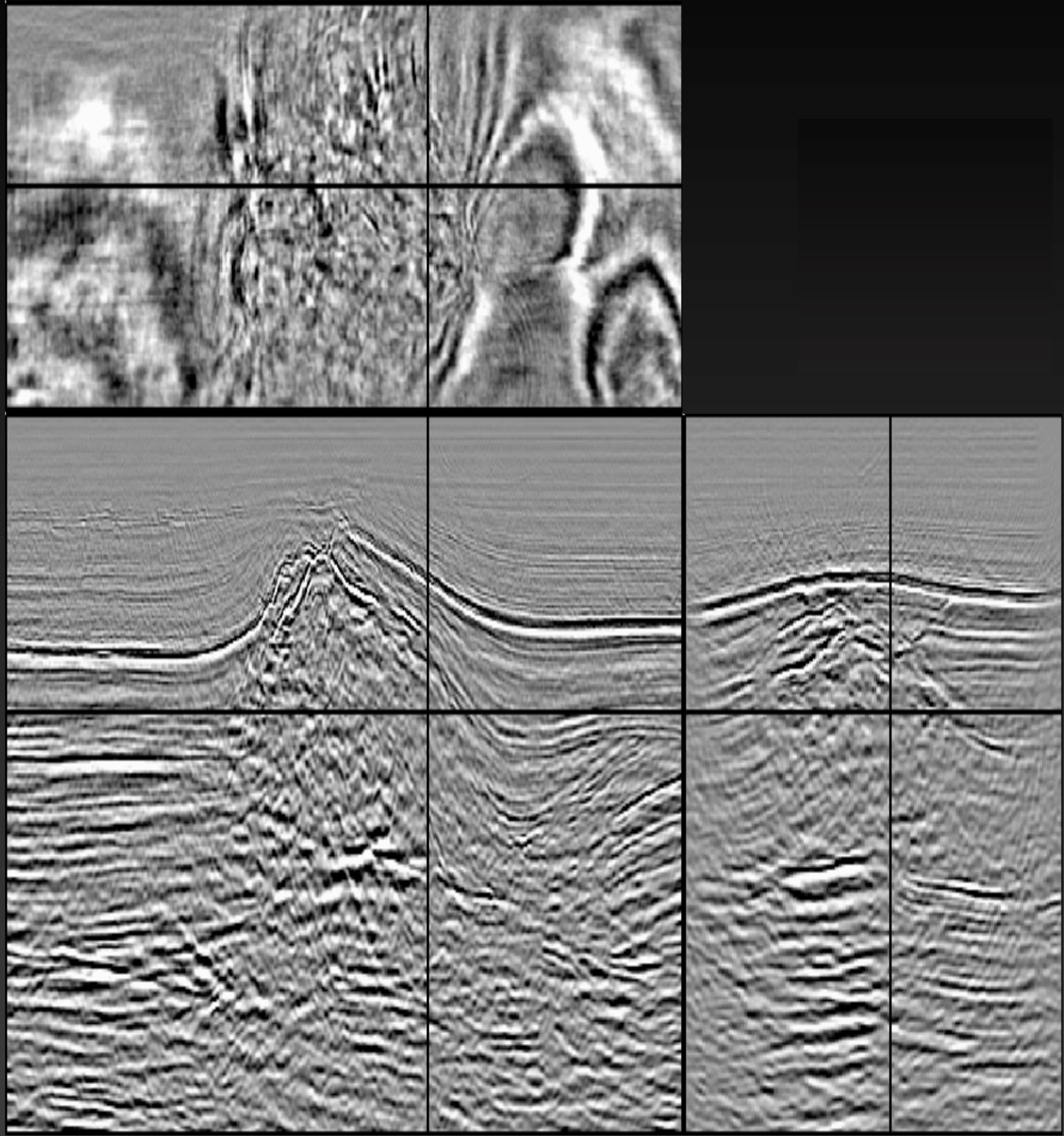


After salt body

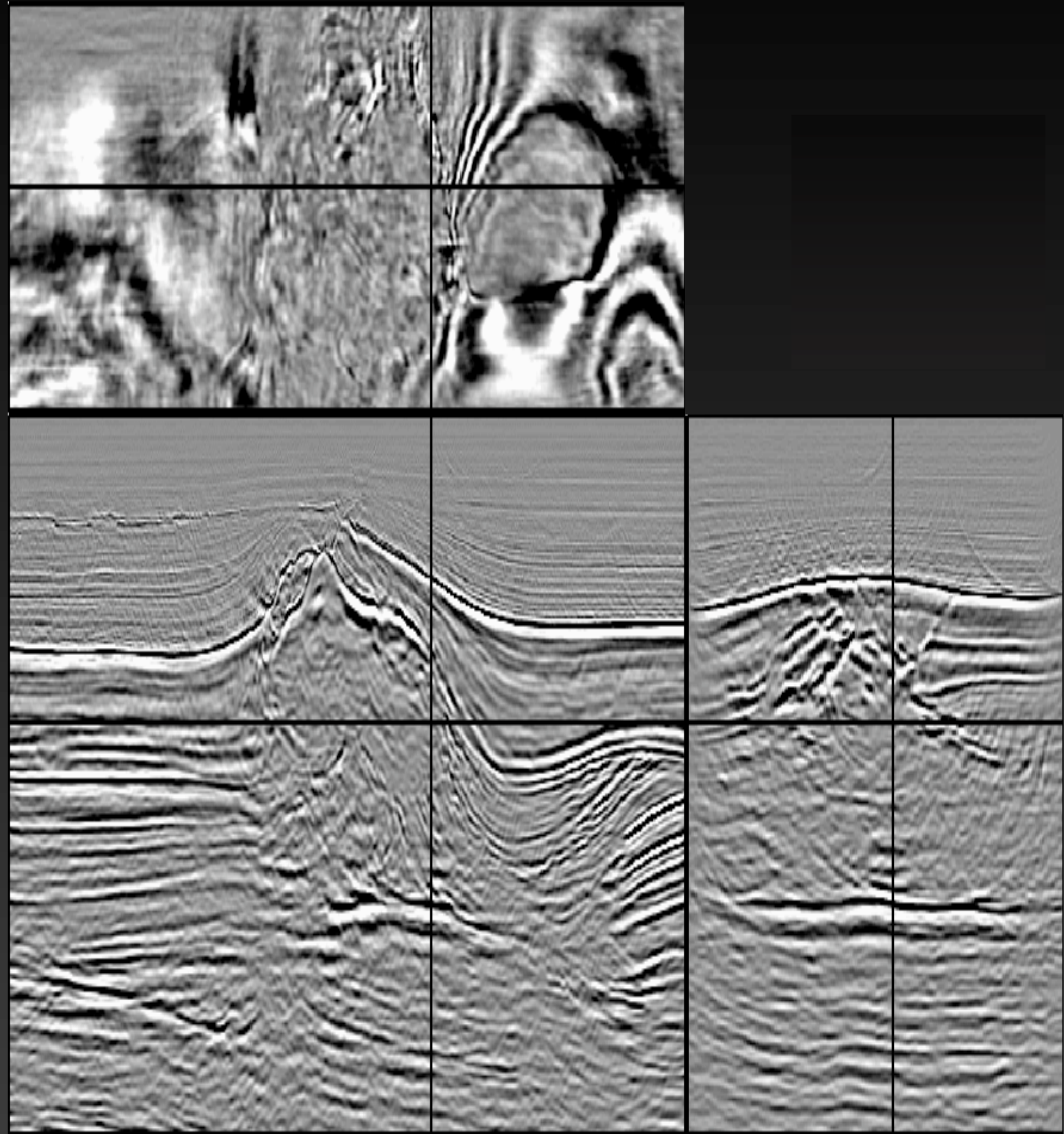


Continuous reflectors & better faults

Initial

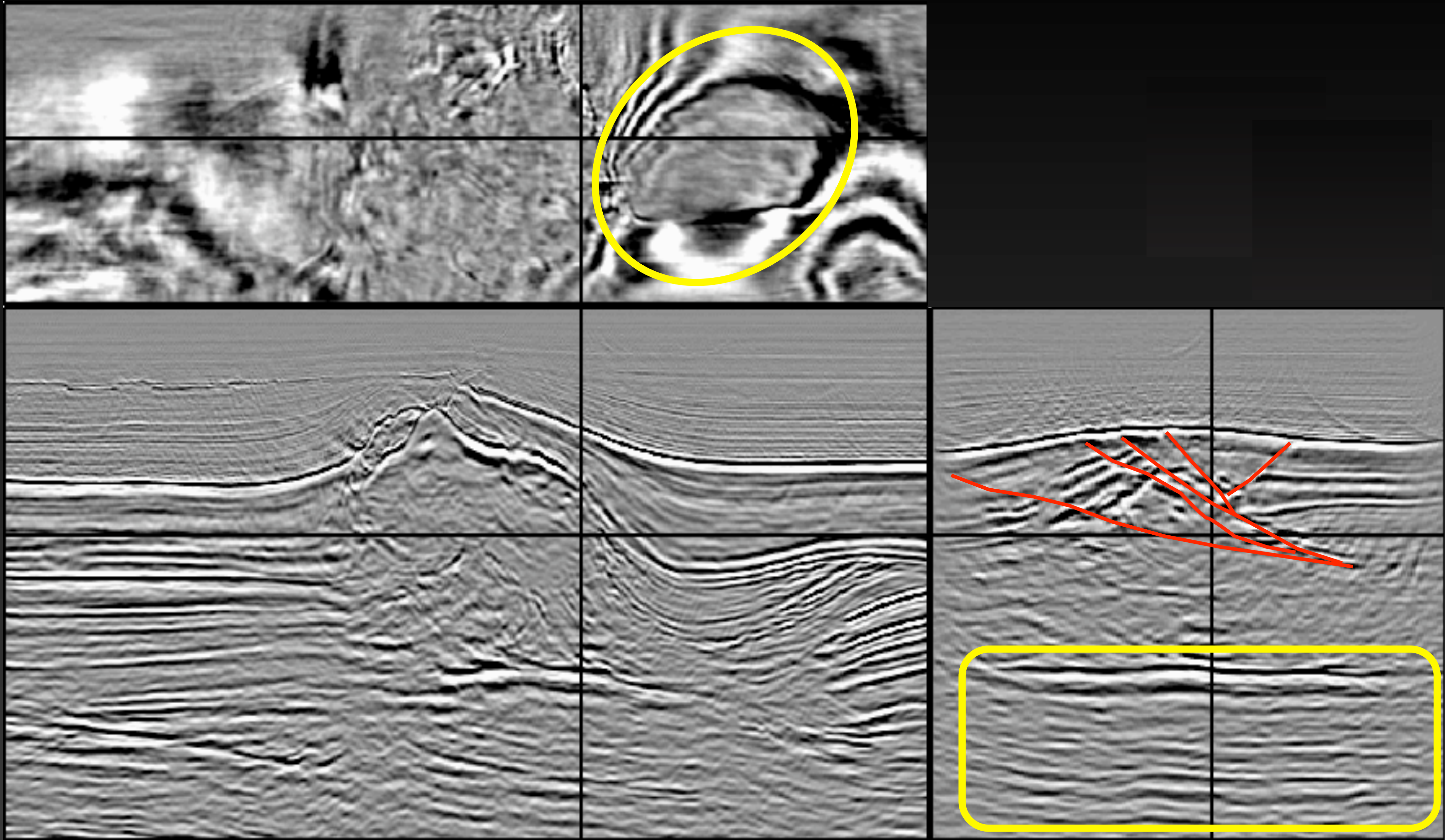


After salt body



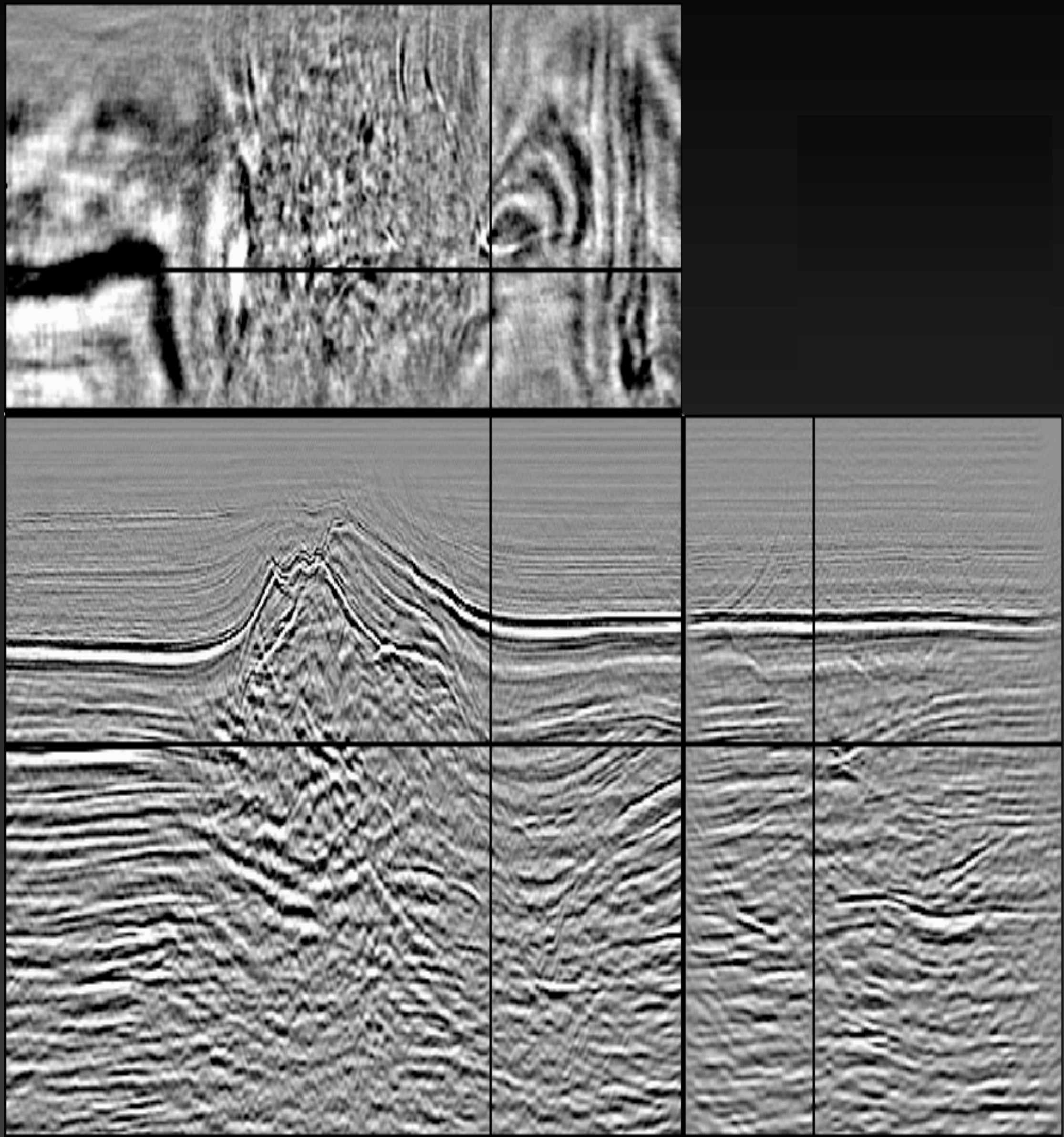
Continuous reflectors & better faults

After salt body

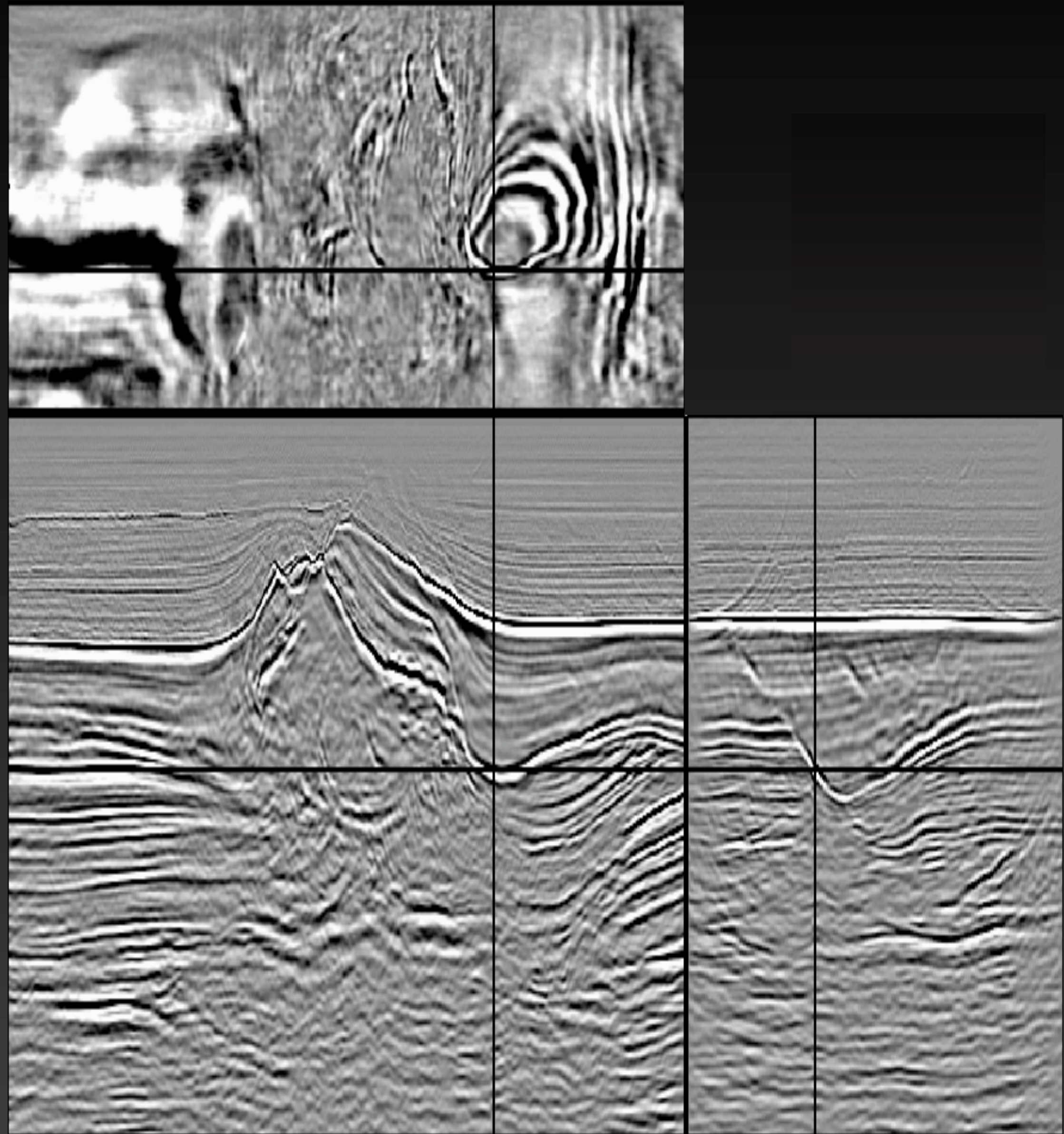


Better faults & focusing

Initial

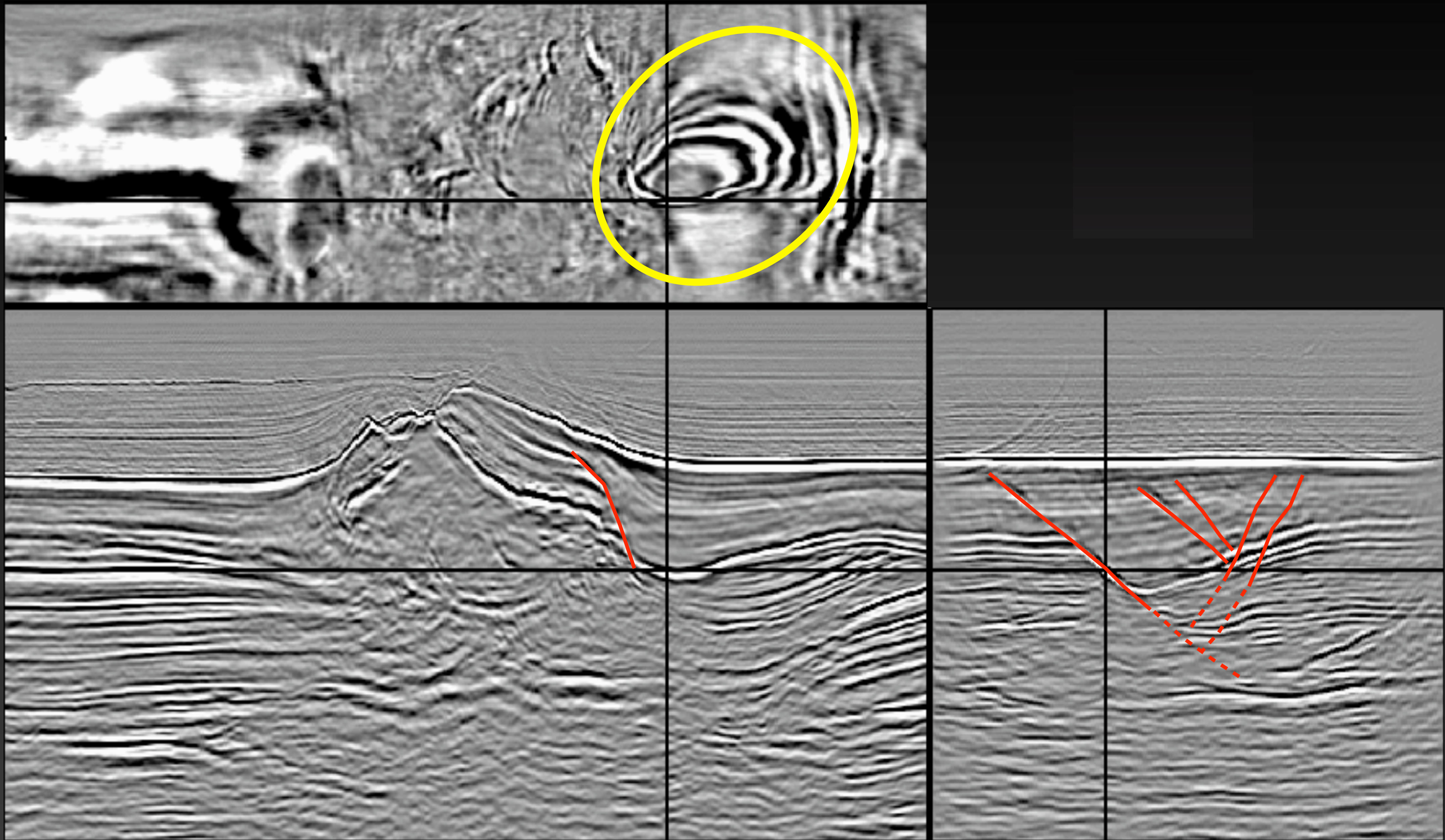


After salt body



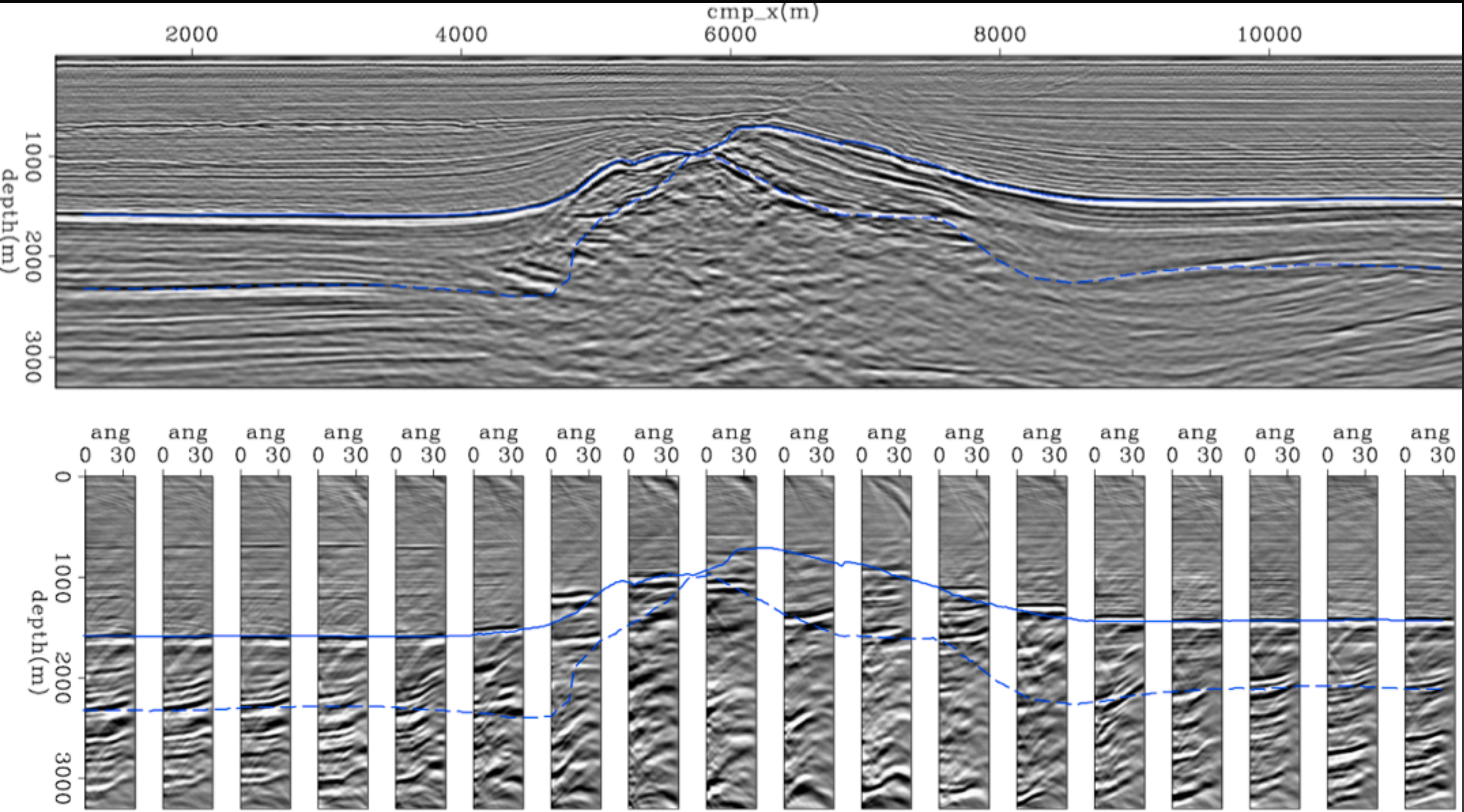
Better faults & focusing

After salt body



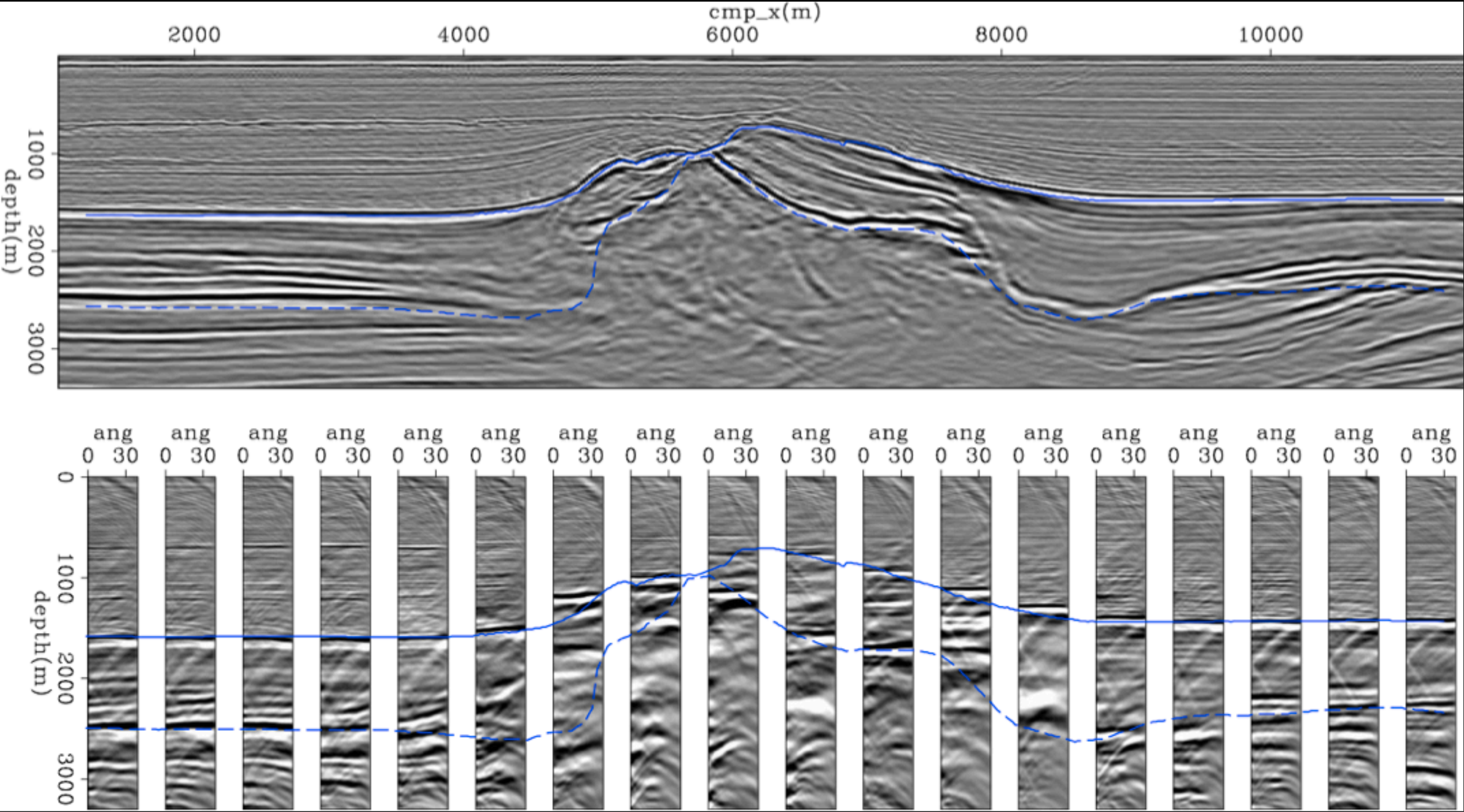
Comparisons: iline = 3200 m

Initial

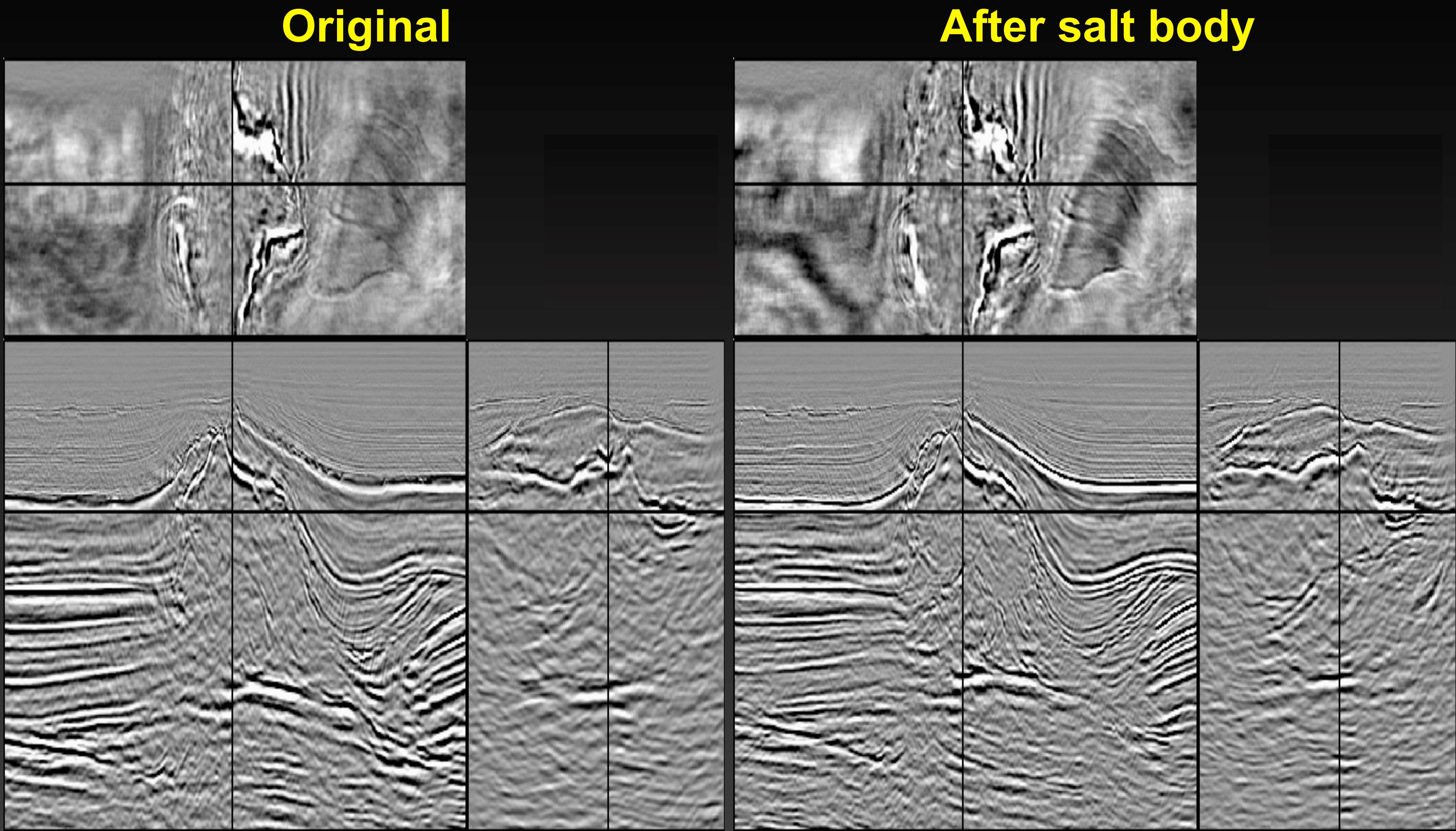


Flattened reflectors in the angle gathers

Chalk optimized velocity

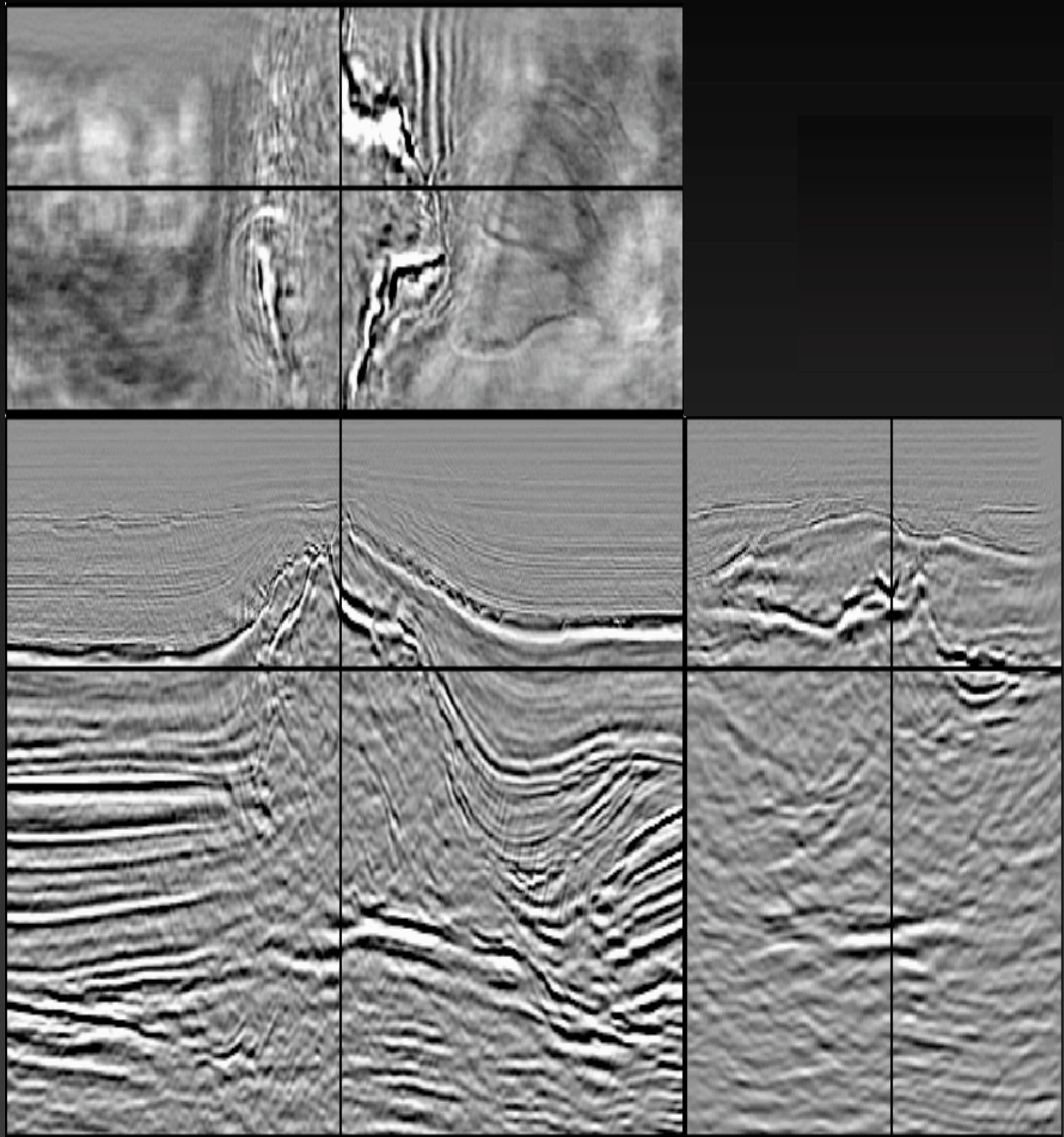


Better base of salt & focusing

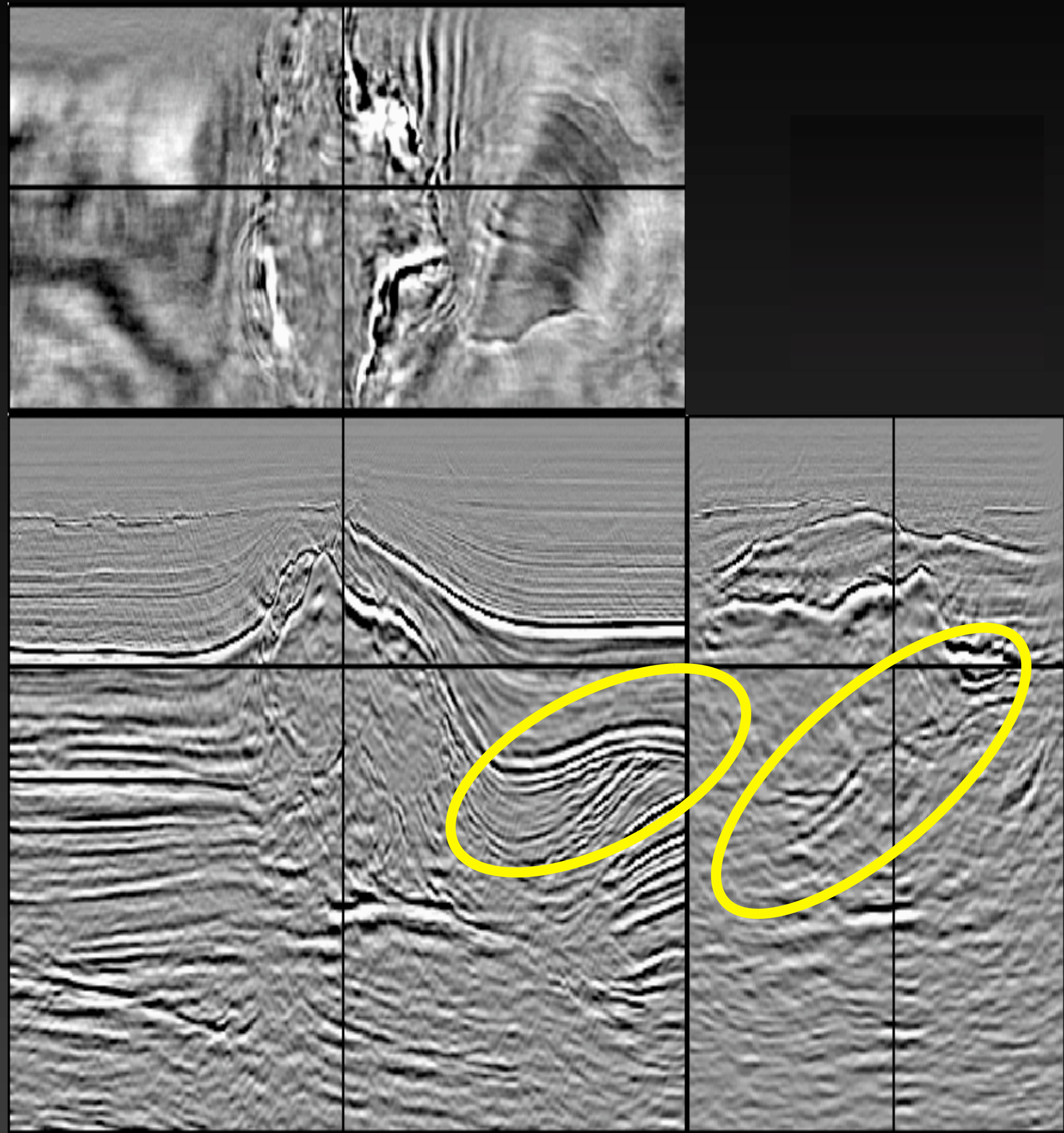


Better base of salt & focusing

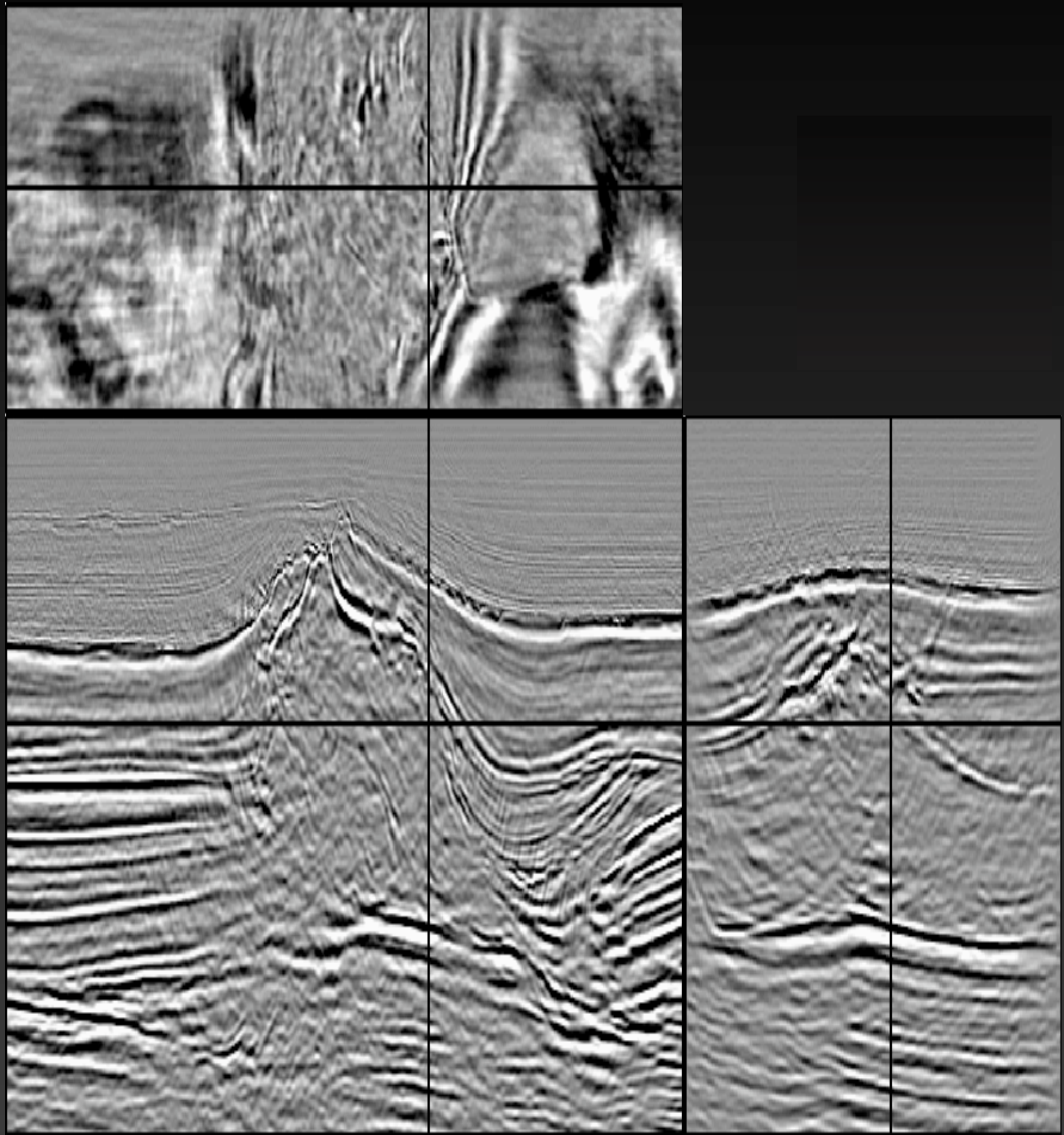
Original

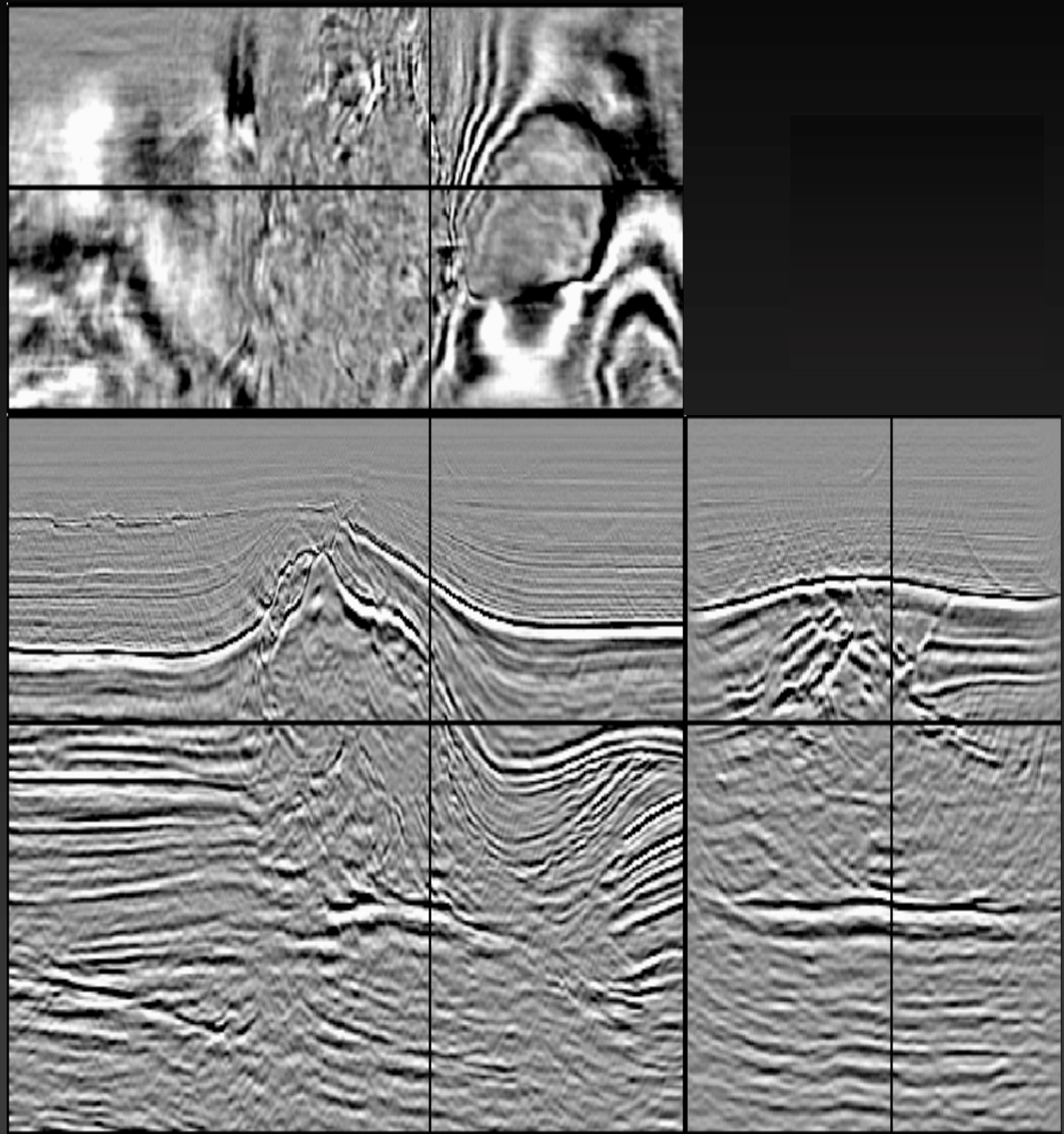


After salt body

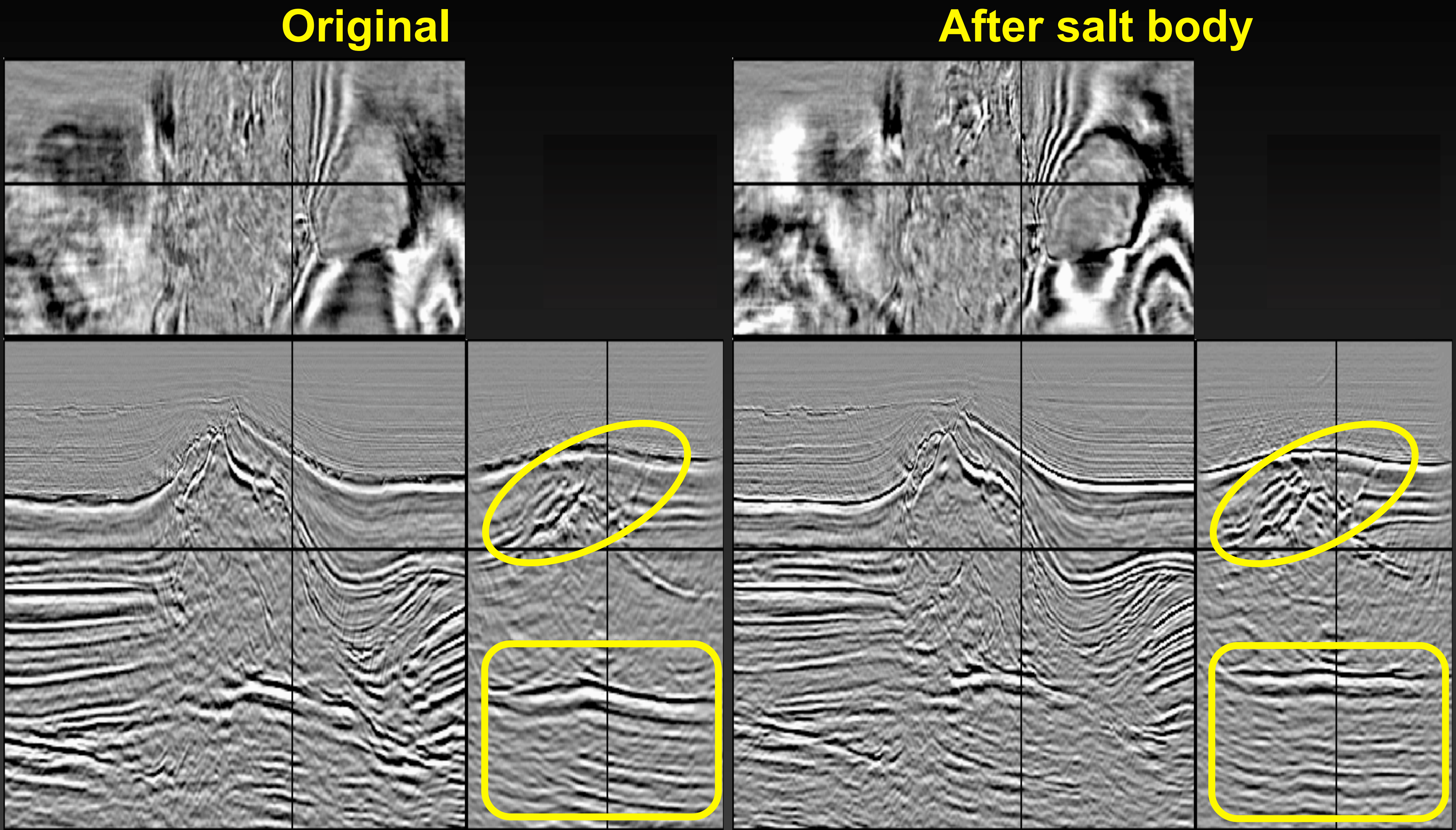


Better sub-salt reflectors & faults



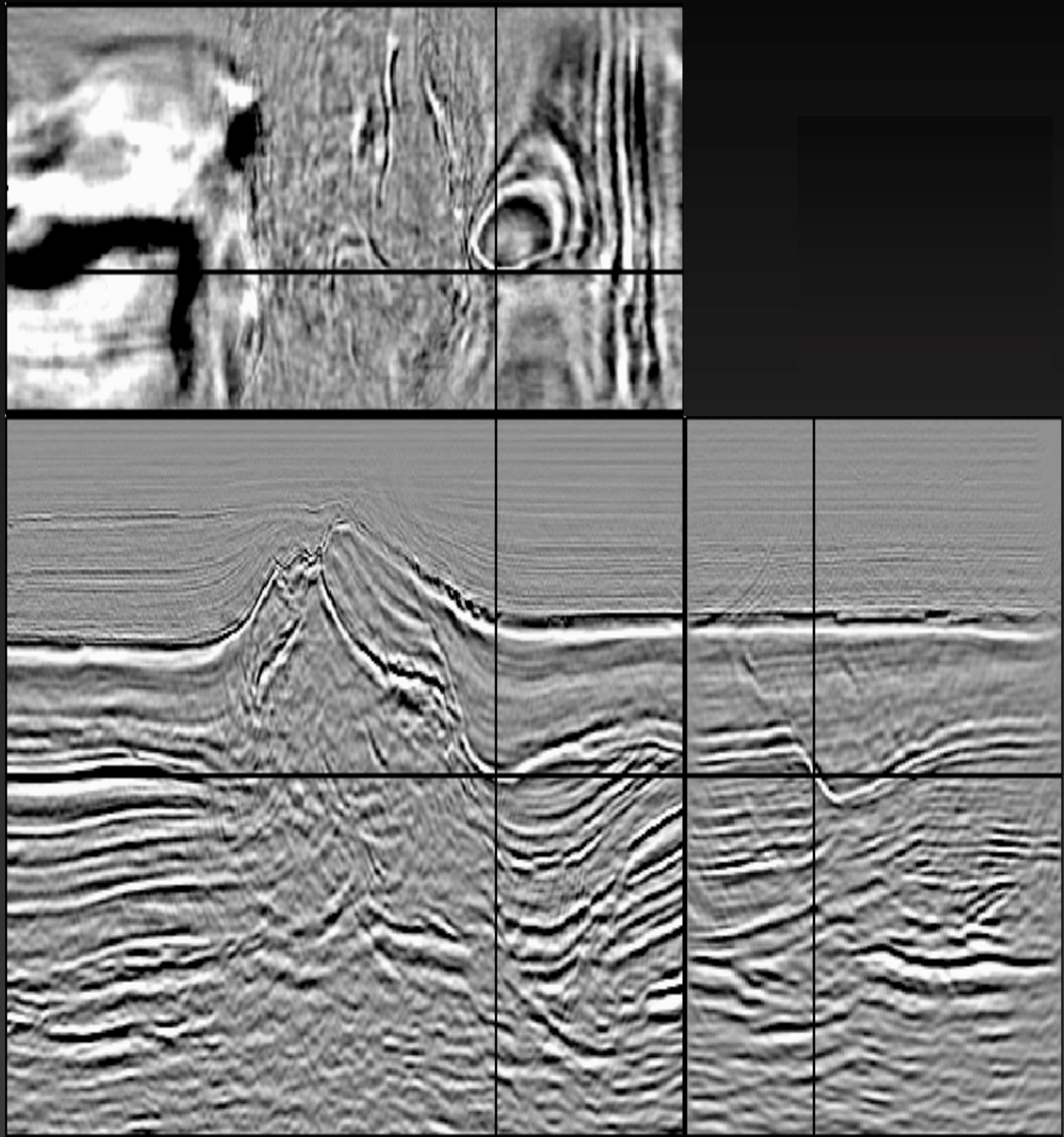


Better sub-salt reflectors & faults

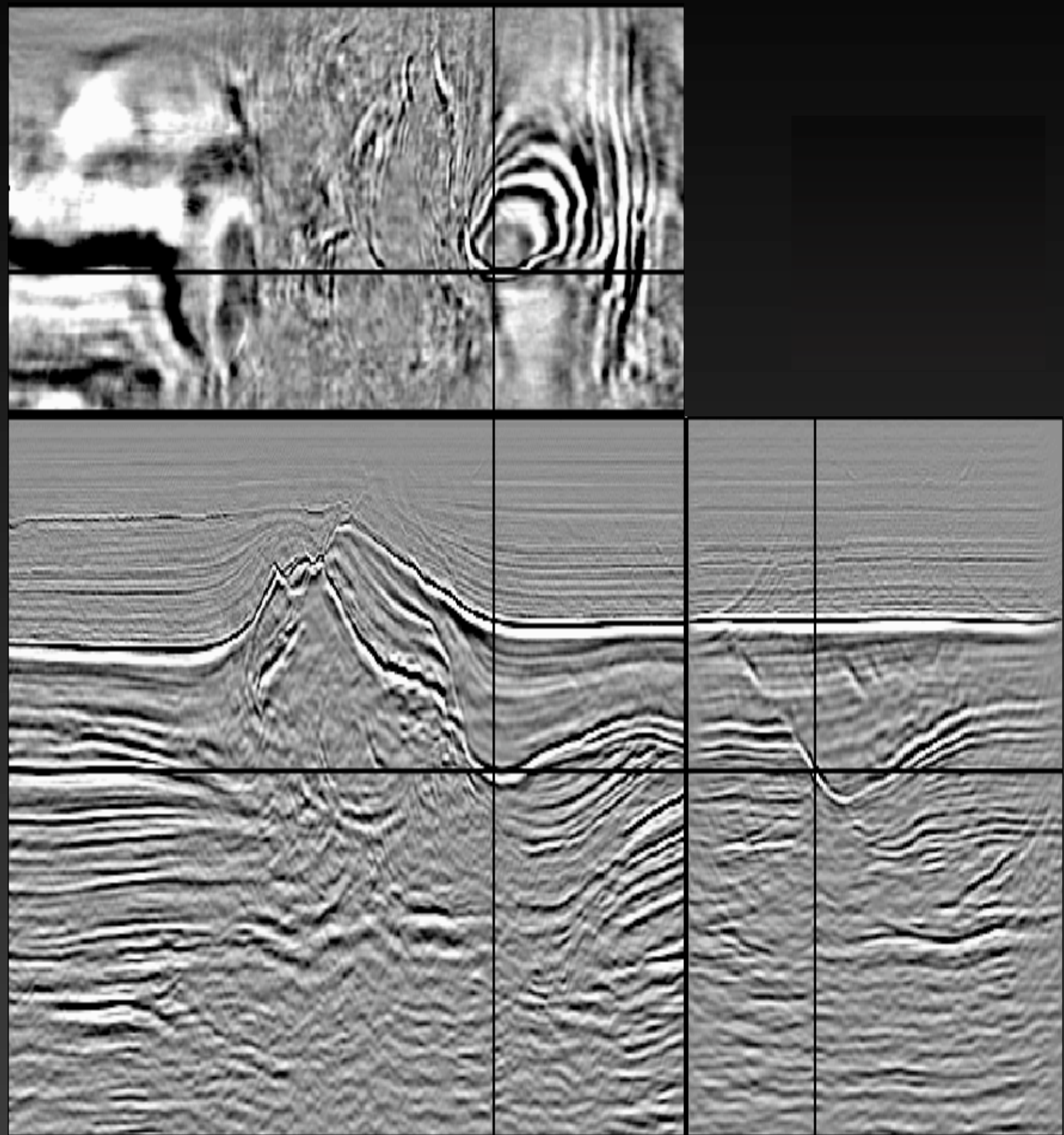


Better faults & focusing

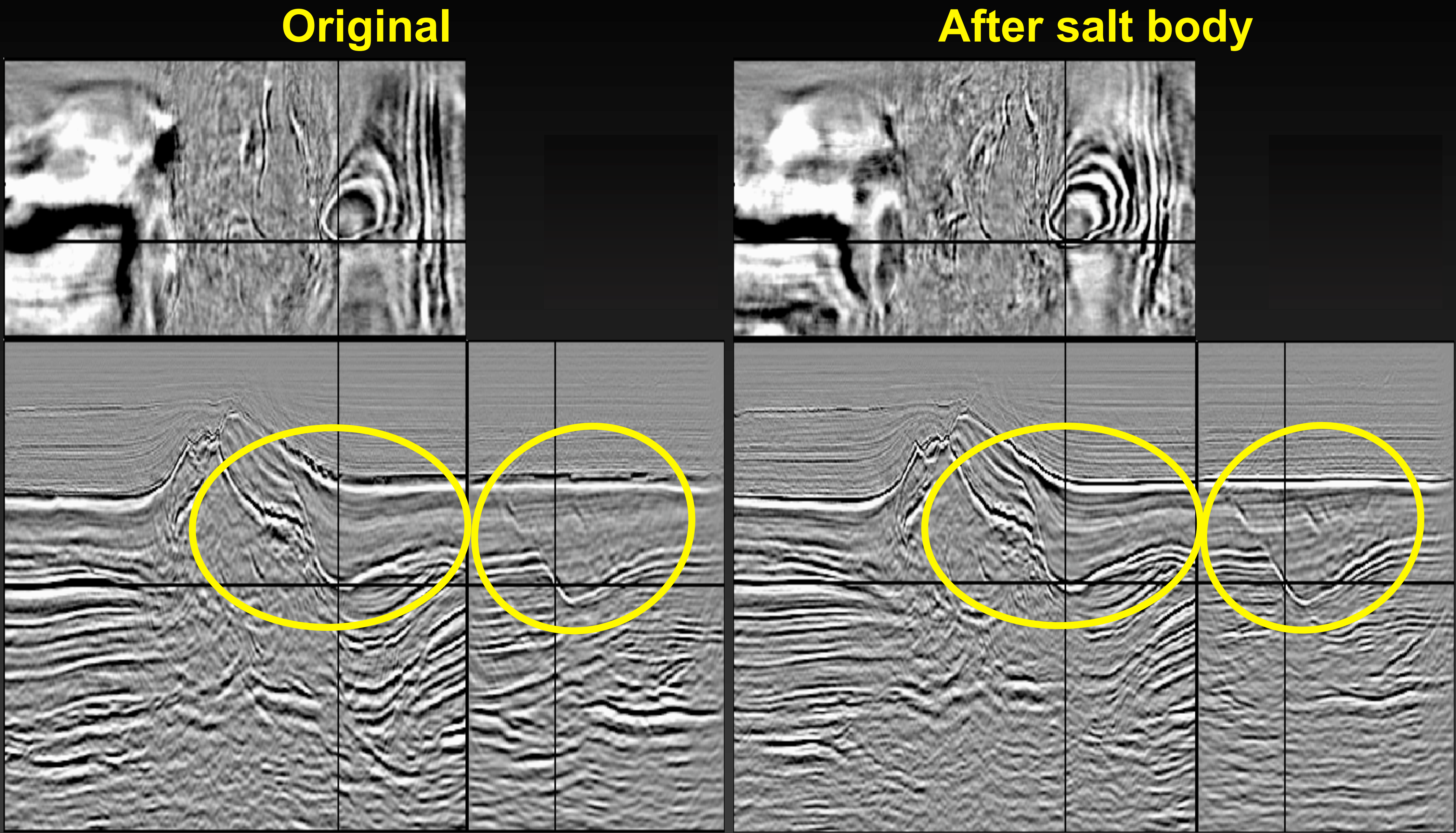
Original



After salt body



Better faults & focusing



Conclusions

- **Image-space generalized wavefields accelerate ISWET**
  - **reduced data size**
  - **target-oriented strategy**

Conclusions

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  - **reduced data size**
  - **target-oriented strategy**
- **Image-space generalized wavefields naturally incorporate a horizon-based strategy**

Conclusions

- Image-space generalized wavefields accelerate ISWET
  - reduced data size
  - target-oriented strategy

- Image-space generalized wavefields naturally incorporate a horizon-based strategy

- Image-space generalized wavefields yield accurate velocity updates

Conclusions

Image-space generalized wavefields enables the routine use of ISWET

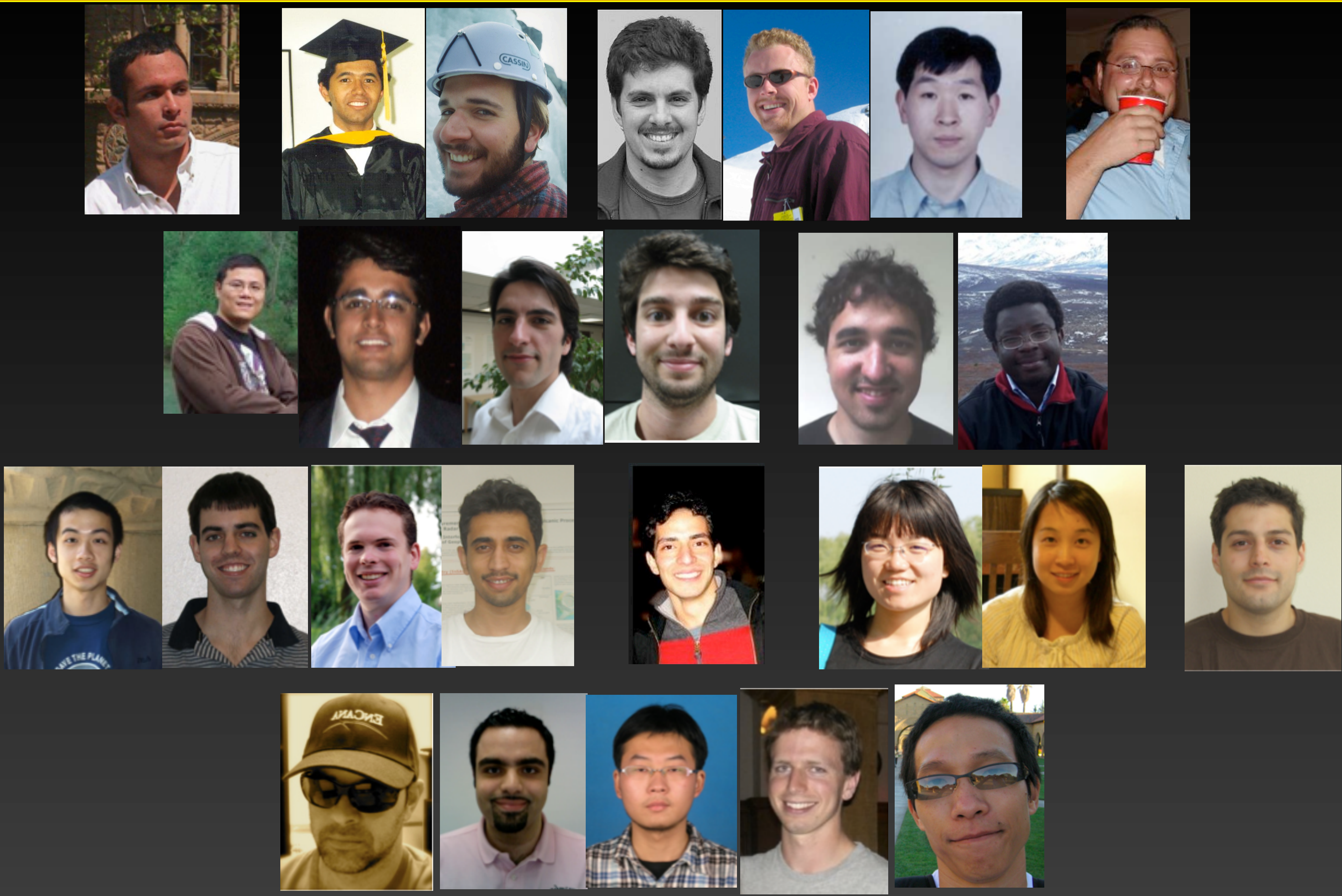
Thanks to

- **Petrobras** for providing all the necessary support
- **Biondo Biondi** for keeping me on track and for his constant encouragement
- **Jon Claerbout** for enlightening discussions
- **Bob Clapp** for always being steps ahead on defining SEP's computational needs
- **Tapan Mukerji** for chairing this defense
- **Jerry Harris** for always being in my committees

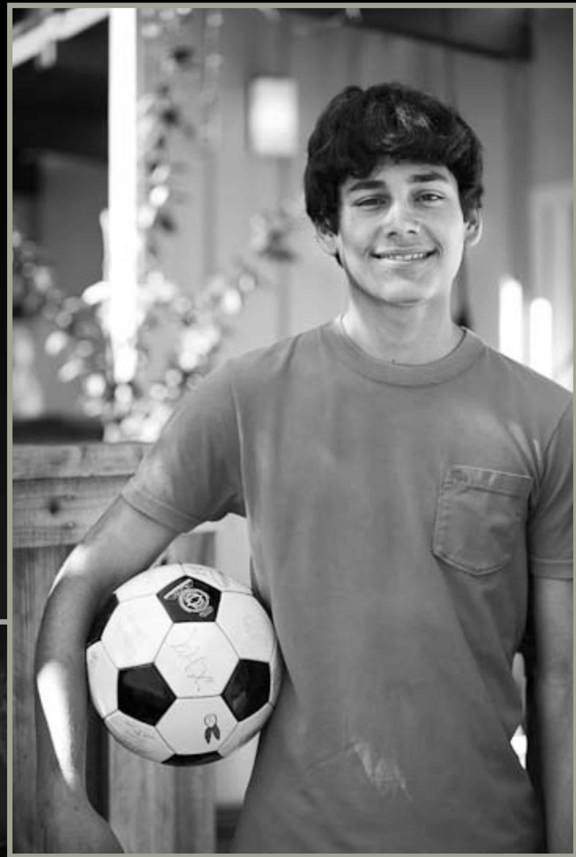
Thanks to

- **Diane Lau** for her unceasing effort to smoothly run SEP
- **Systems administrators** for taking care of our computers
- **TotalFinaElf** for providing the North Sea dataset

Thanks to

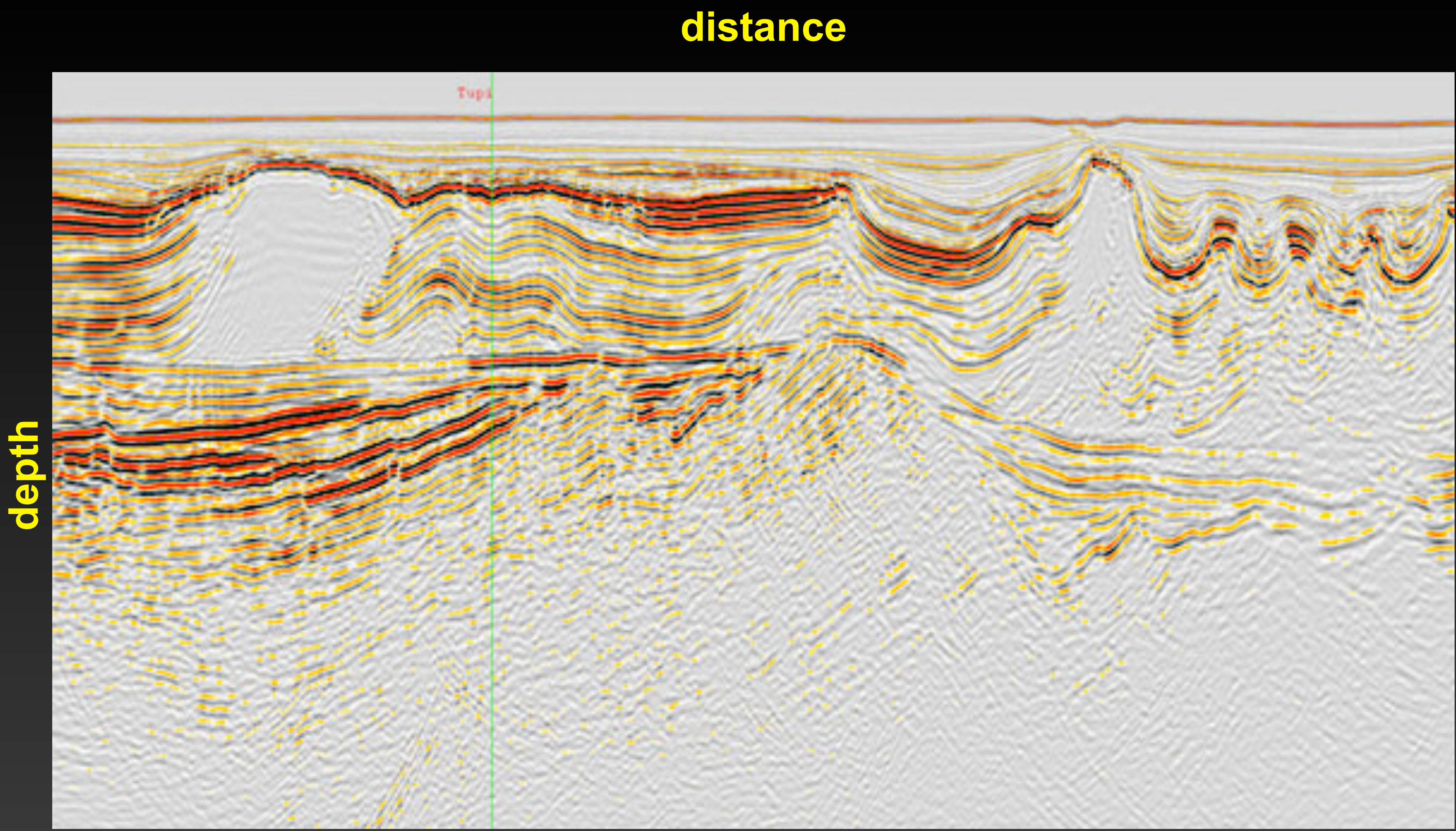



BMX



Thanks

STANFORD
EXPLORATION PROJECT



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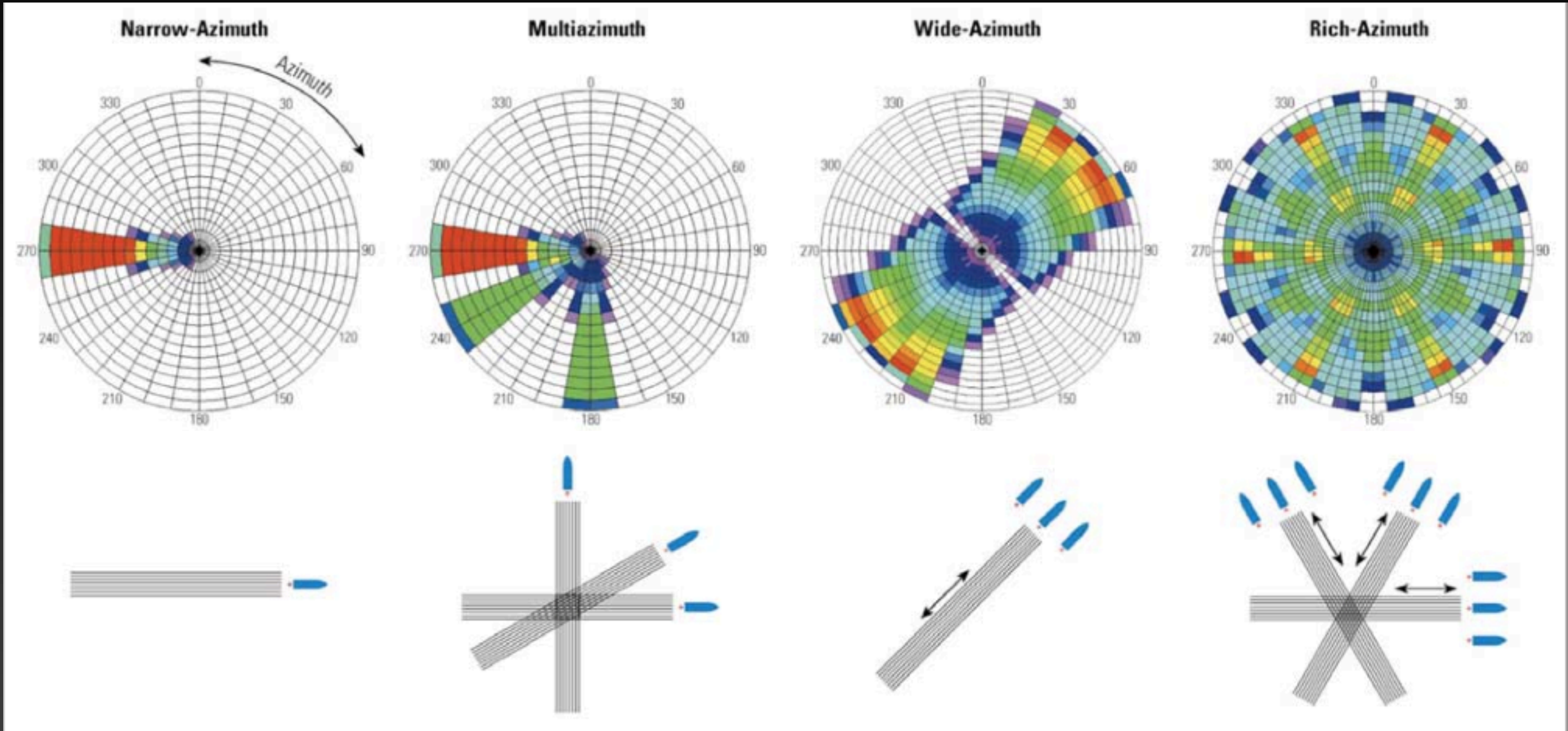
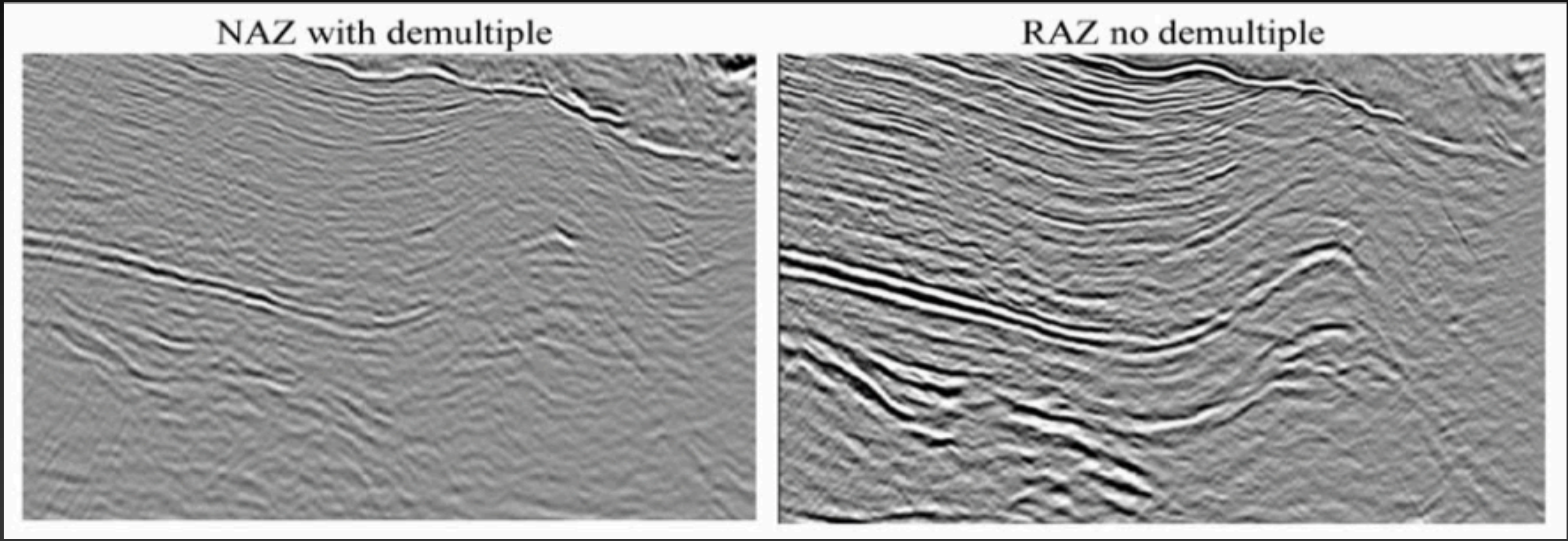
Acquisition



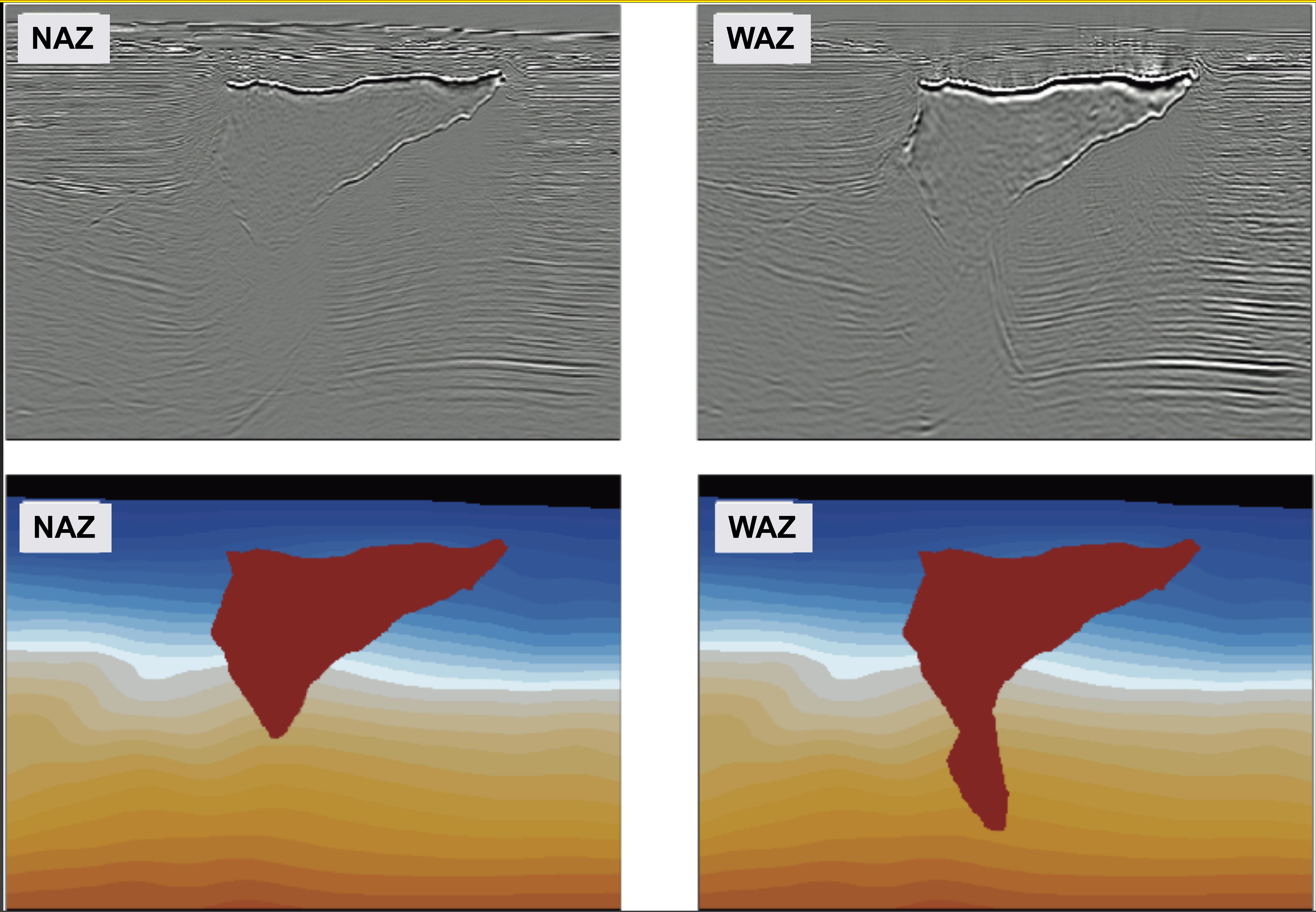
Kapoor et al., 2007

Acquisition

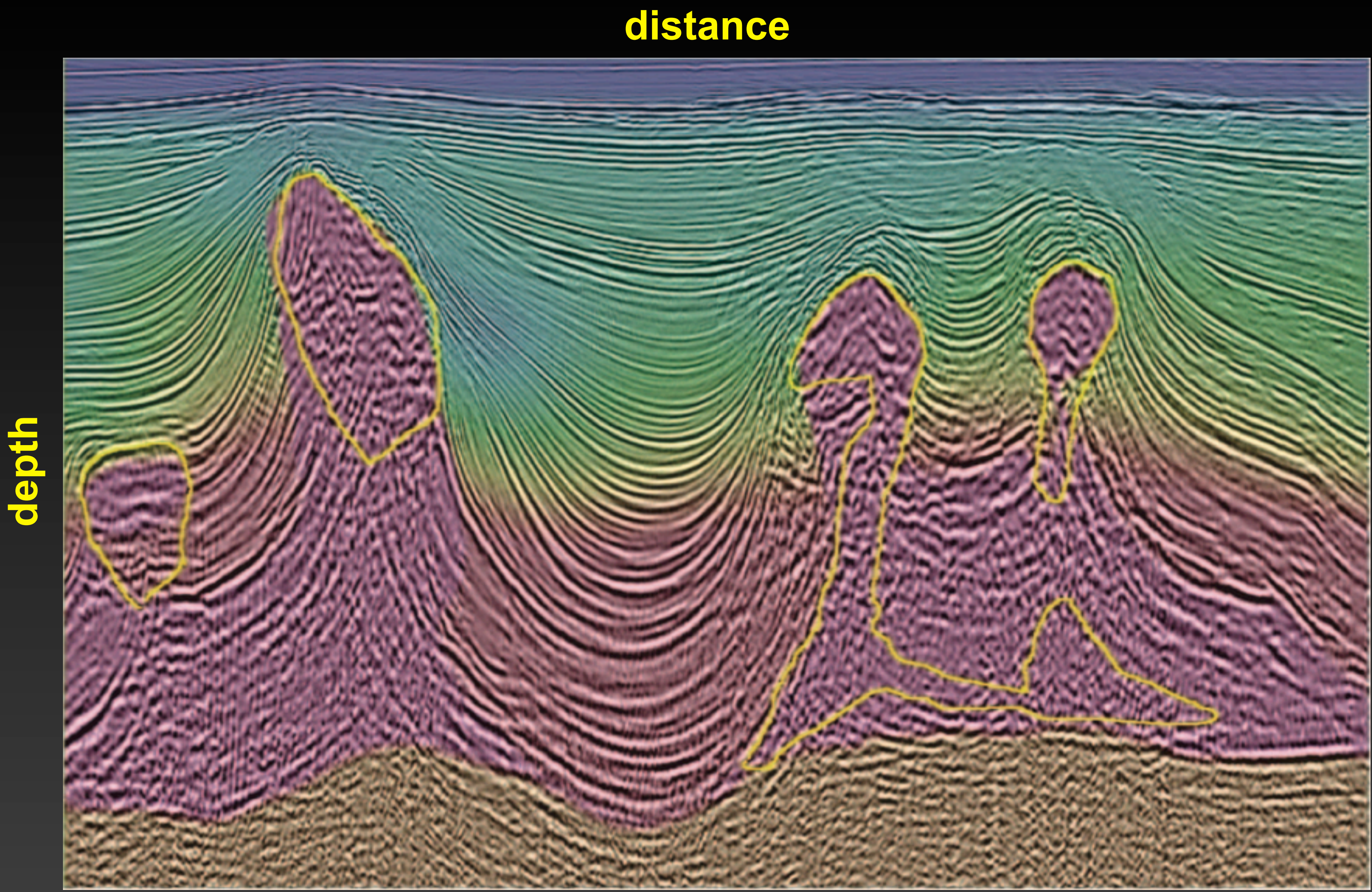


Kapoor et al., 2007

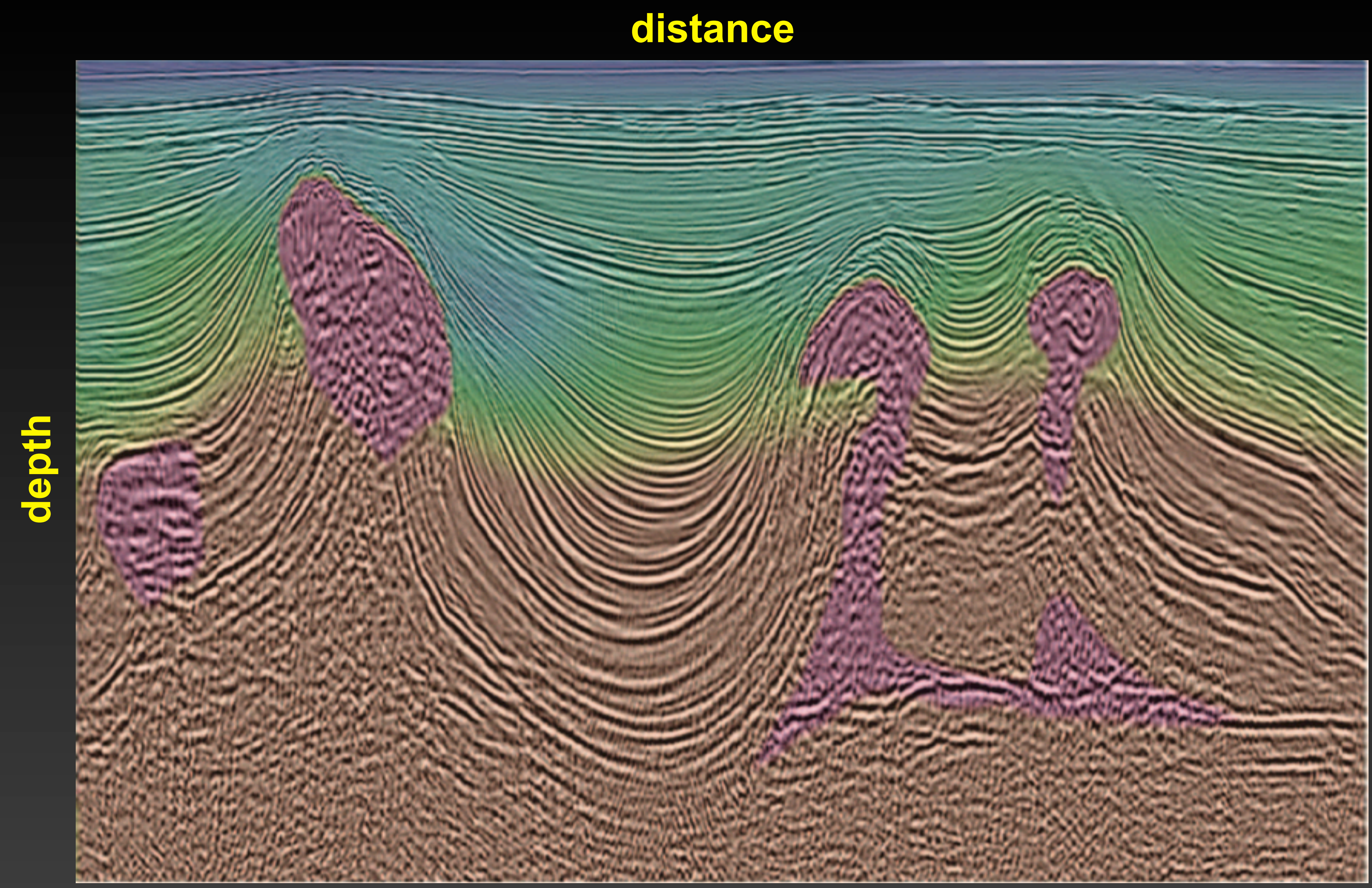
Acquitisision and velocity model



Xia et al., 2009

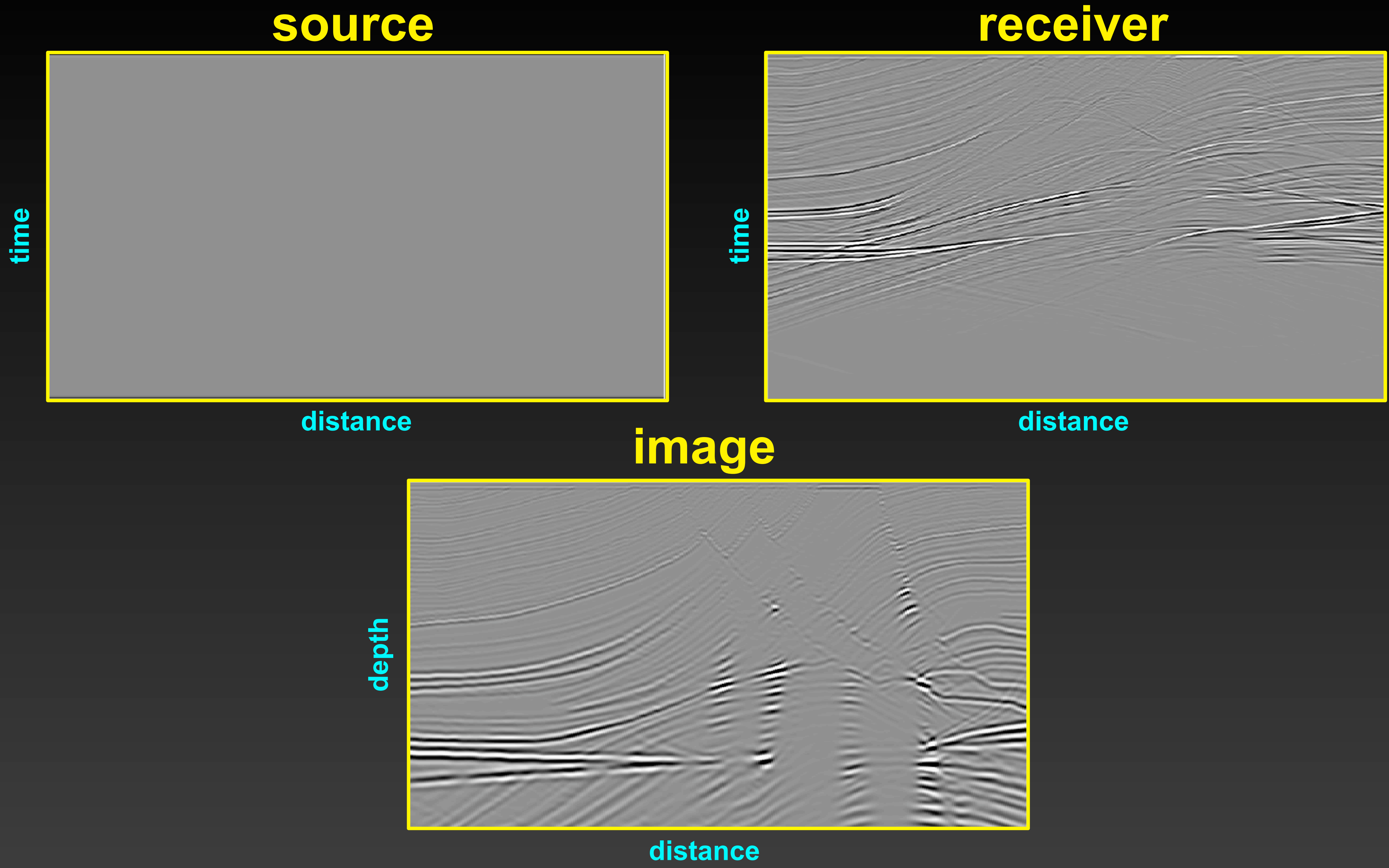


Li et al., 2009

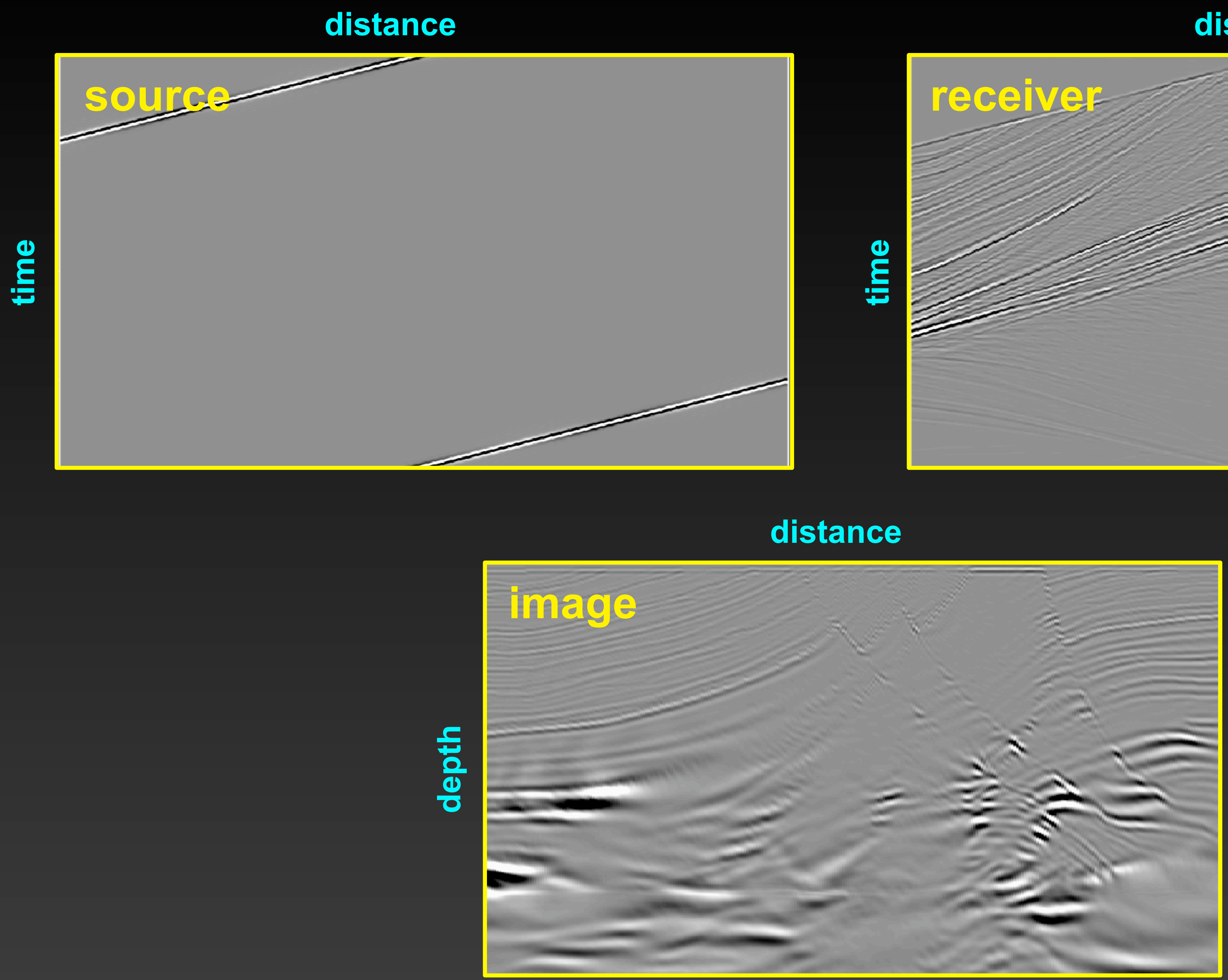


Li et al., 2009

Data-space: 0° plane wave

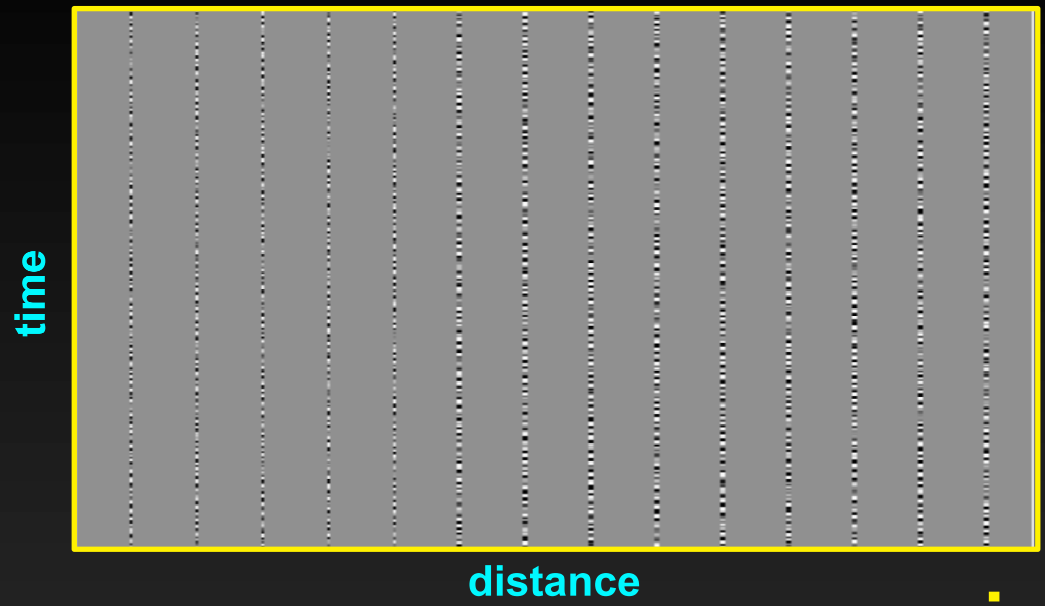


Data-space: plane waves

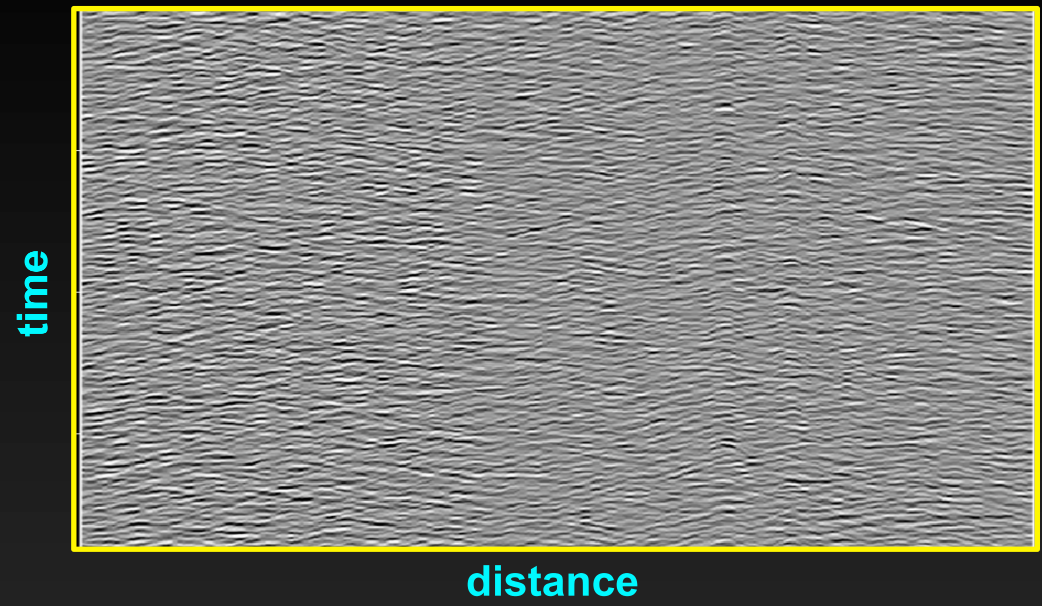


Data-space: random phases

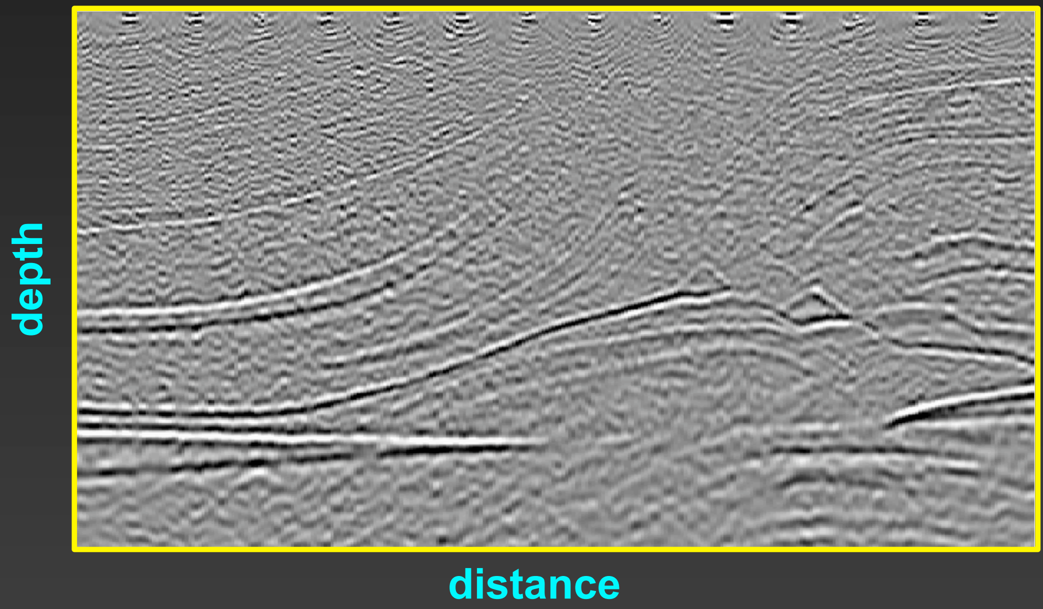
source



receiver



image



Data-space: controlled illumination

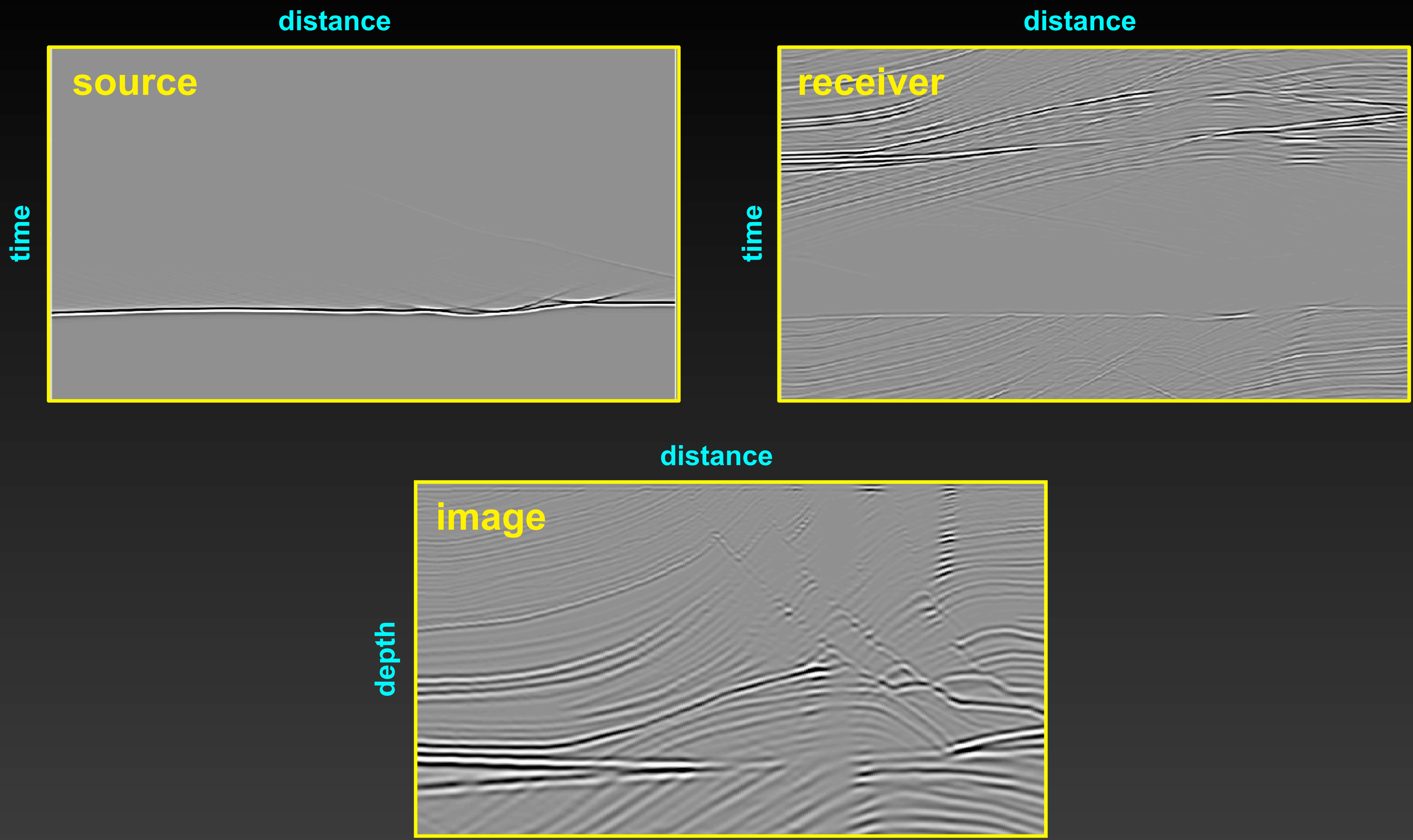


Image-space: prestack-exploding reflector

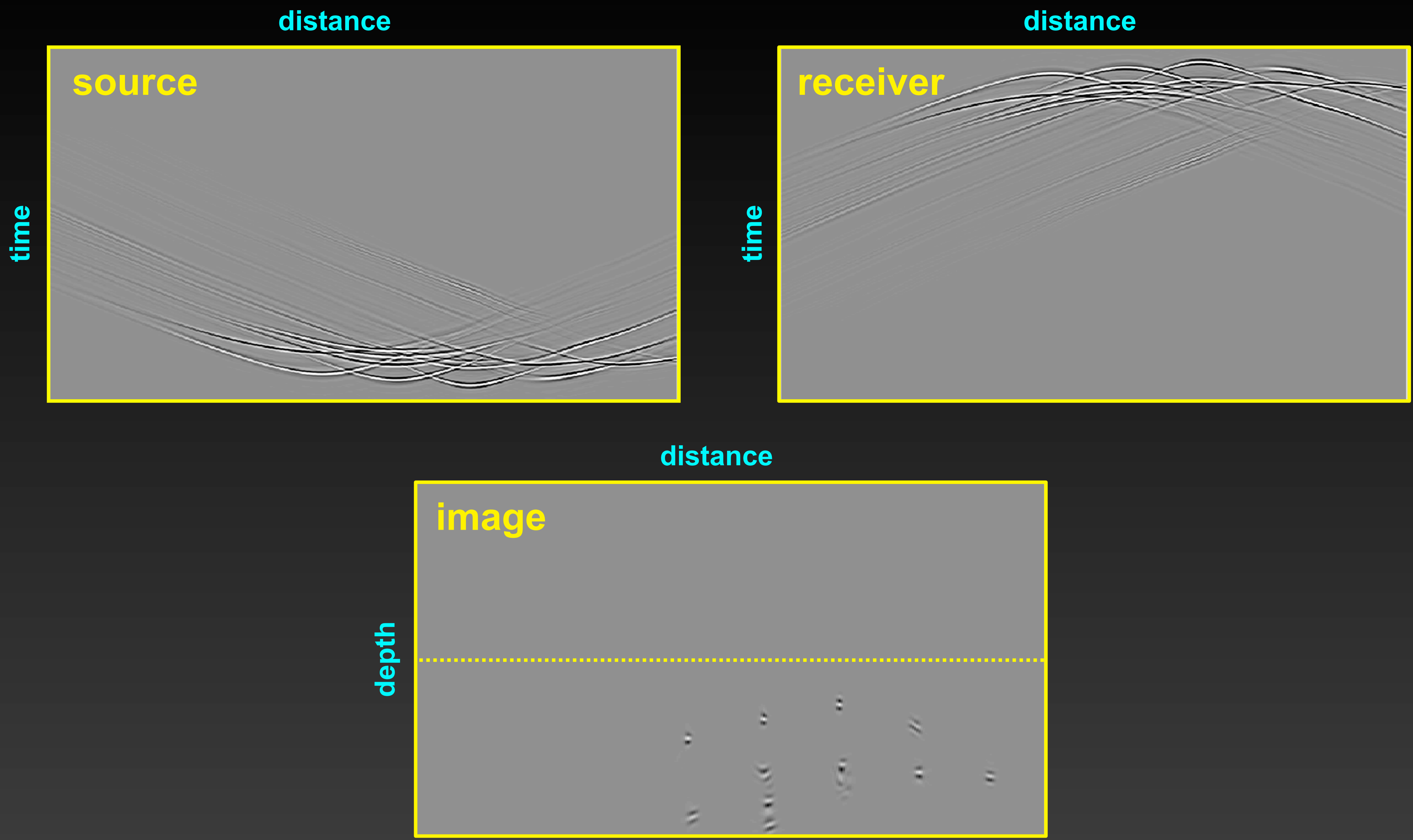
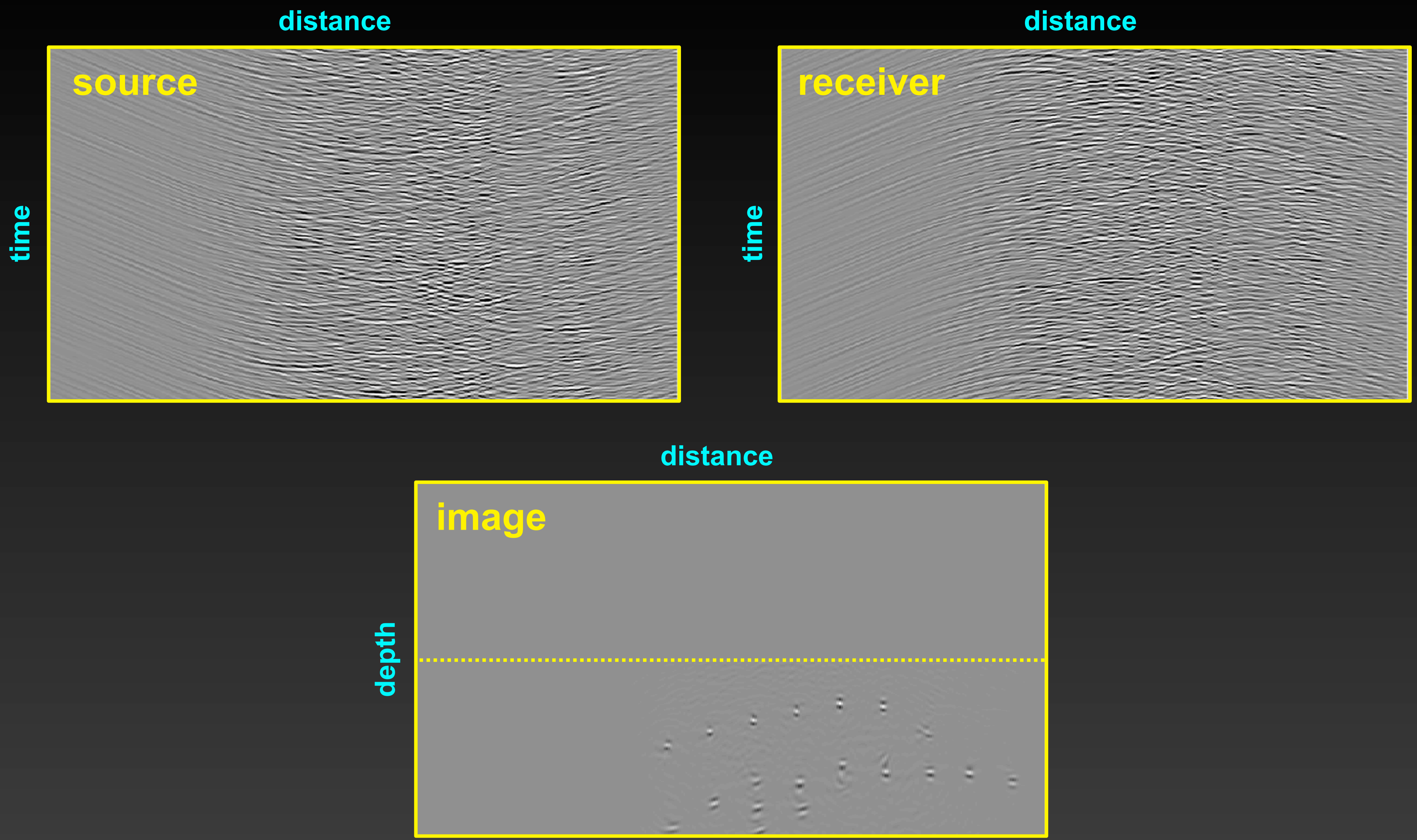
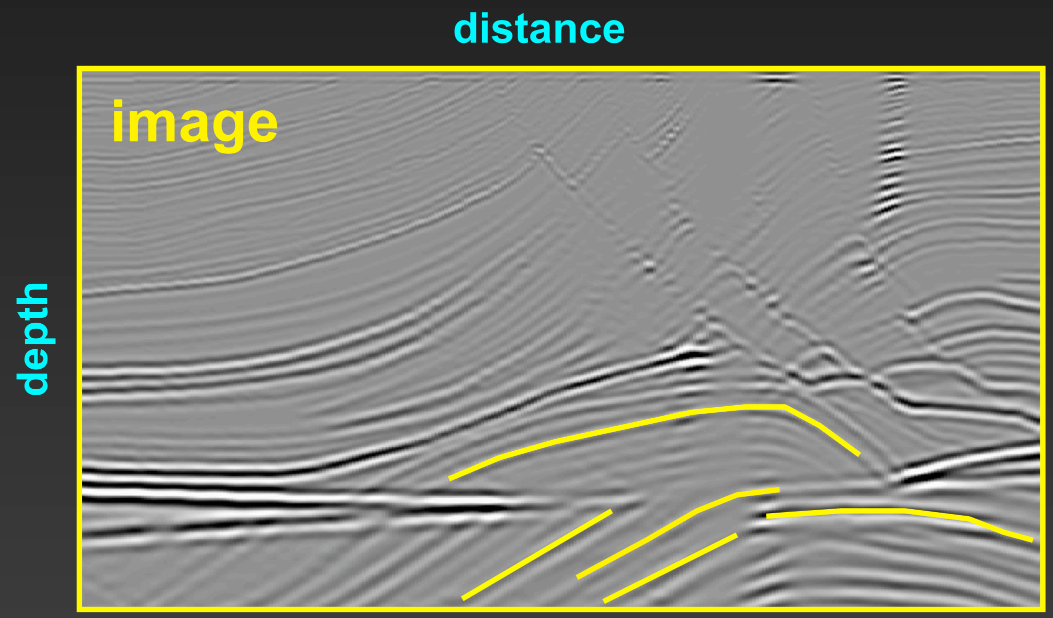


Image-space: random phases (ISPEW)

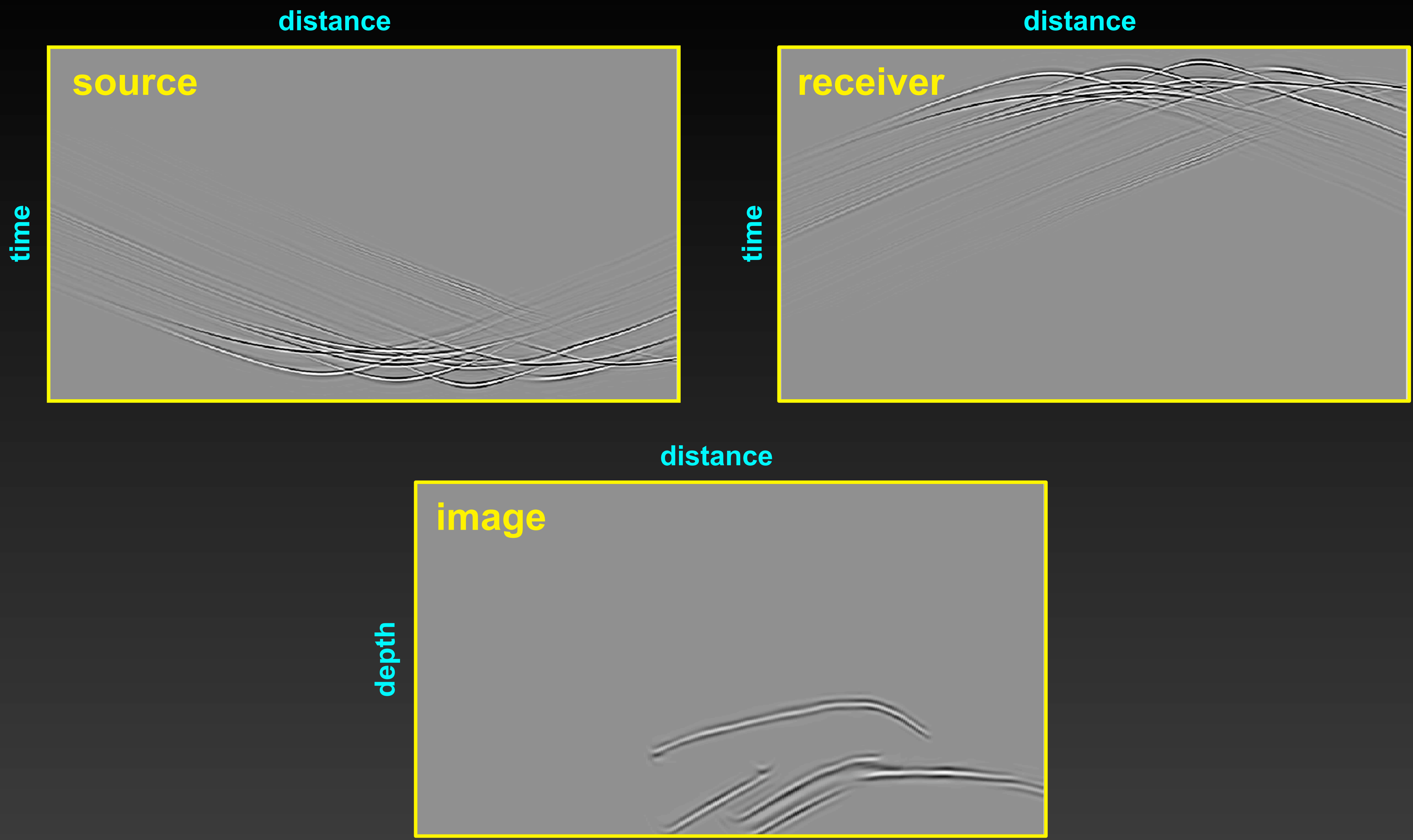


PERM

– **Models wavefields from selected reflectors**

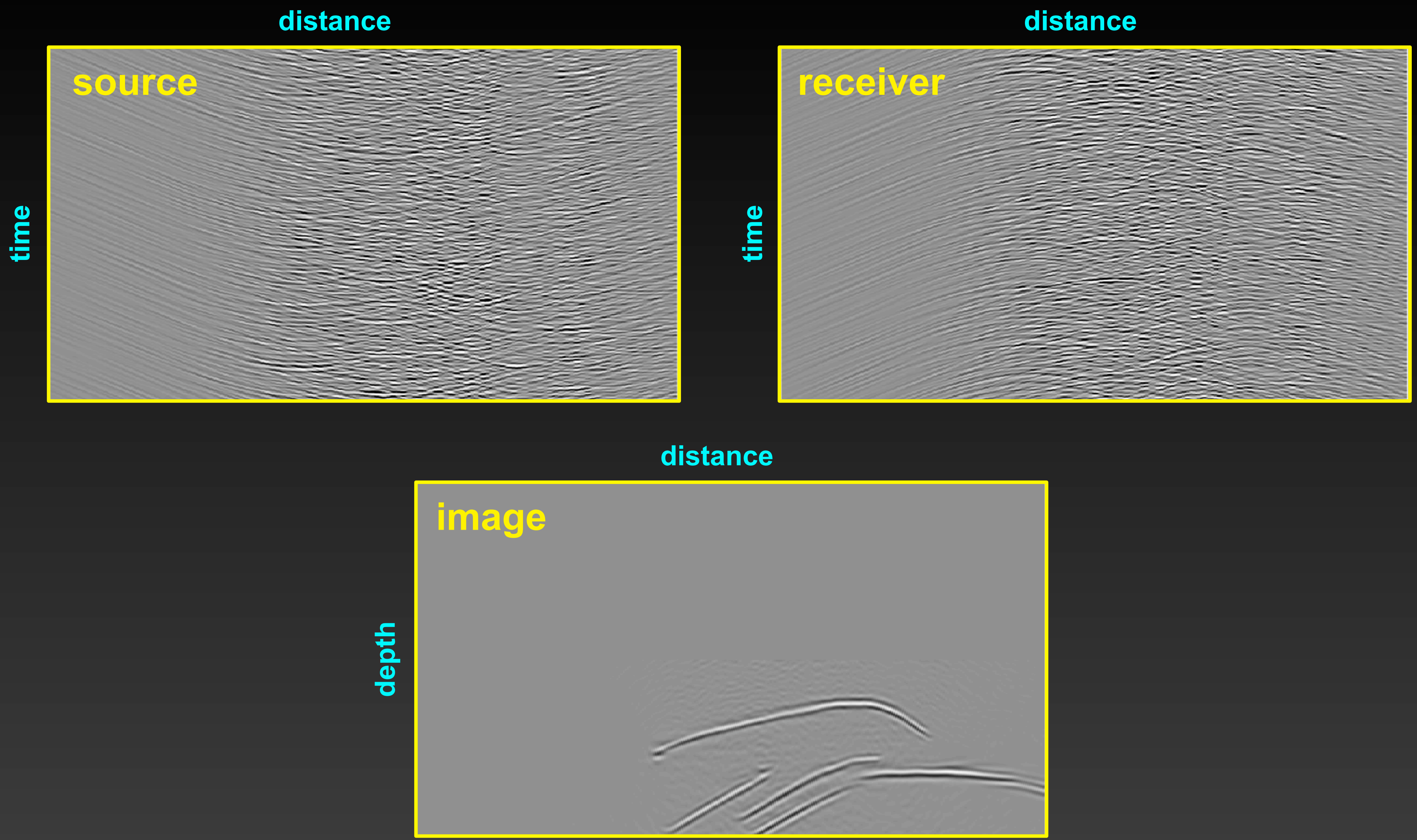


PERM



distance
time
source
distance
time
receiver
distance
depth
image

ISPEW


distance
source
time
distance
receiver
time
distance
image
depth

ISWET linearization

$$I(s) = \mathbf{F}[s]$$

$s = \text{slowness}$

$I = \text{image}$

ISWET linearization

$$I(s) = \mathbf{F}[s]$$

$$I(s) \approx I_o + \left.\frac{\partial I}{\partial s}\right|_{s=s_o} \Delta s$$

s = slowness

s_o = background slowness

Δs = slowness perturbation

I = image

I_o = background image

ISWET linearization

$$I(s) \approx I_o + \left.\frac{\partial I}{\partial s}\right|_{s=s_o} \Delta s$$

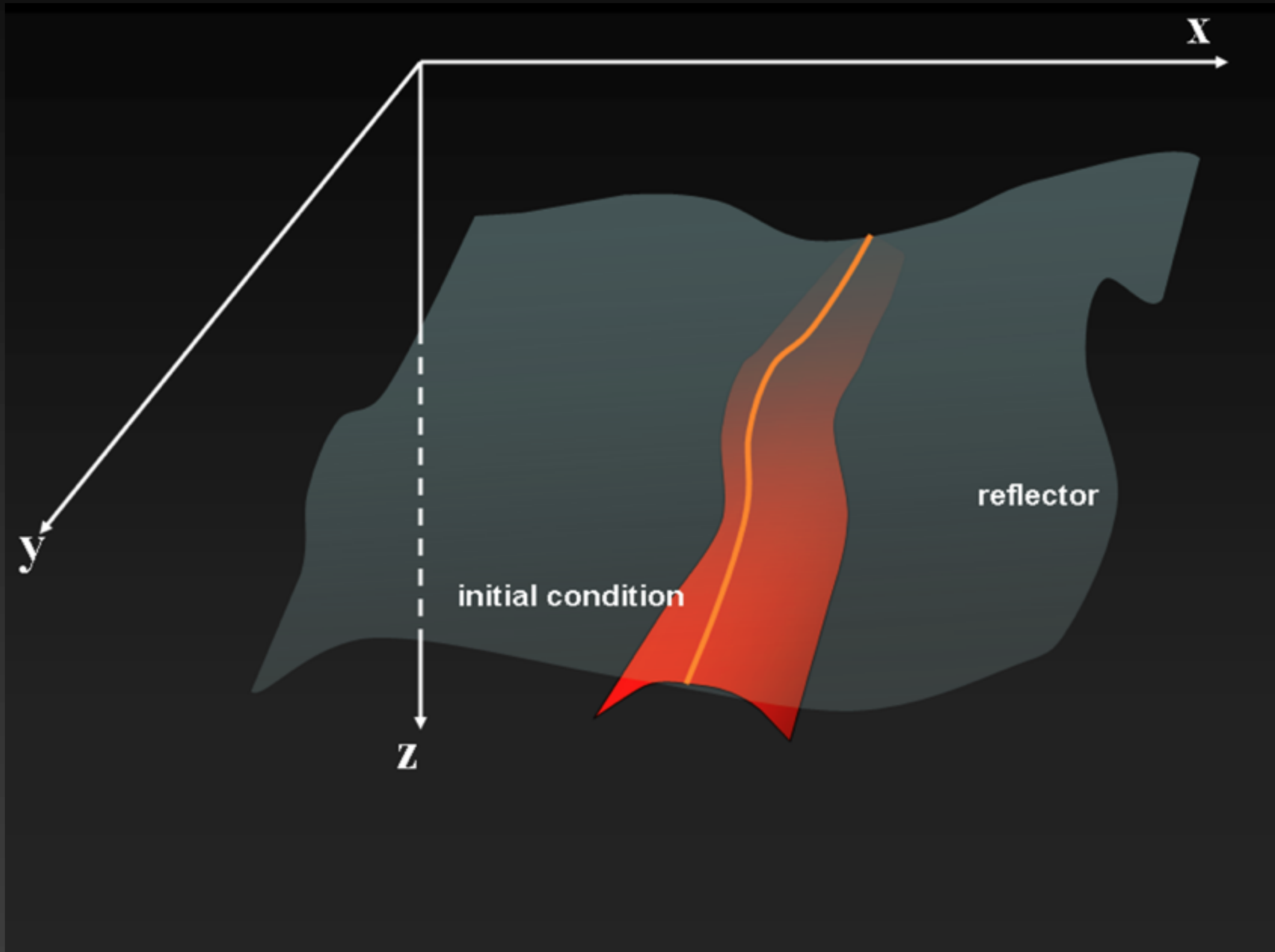
$$\Delta I(s) = \mathbf{T}\Delta s$$

s = slowness
s_o = background slowness
Δs = slowness perturbation
$\mathbf{T}$ = IS – tomographic operator

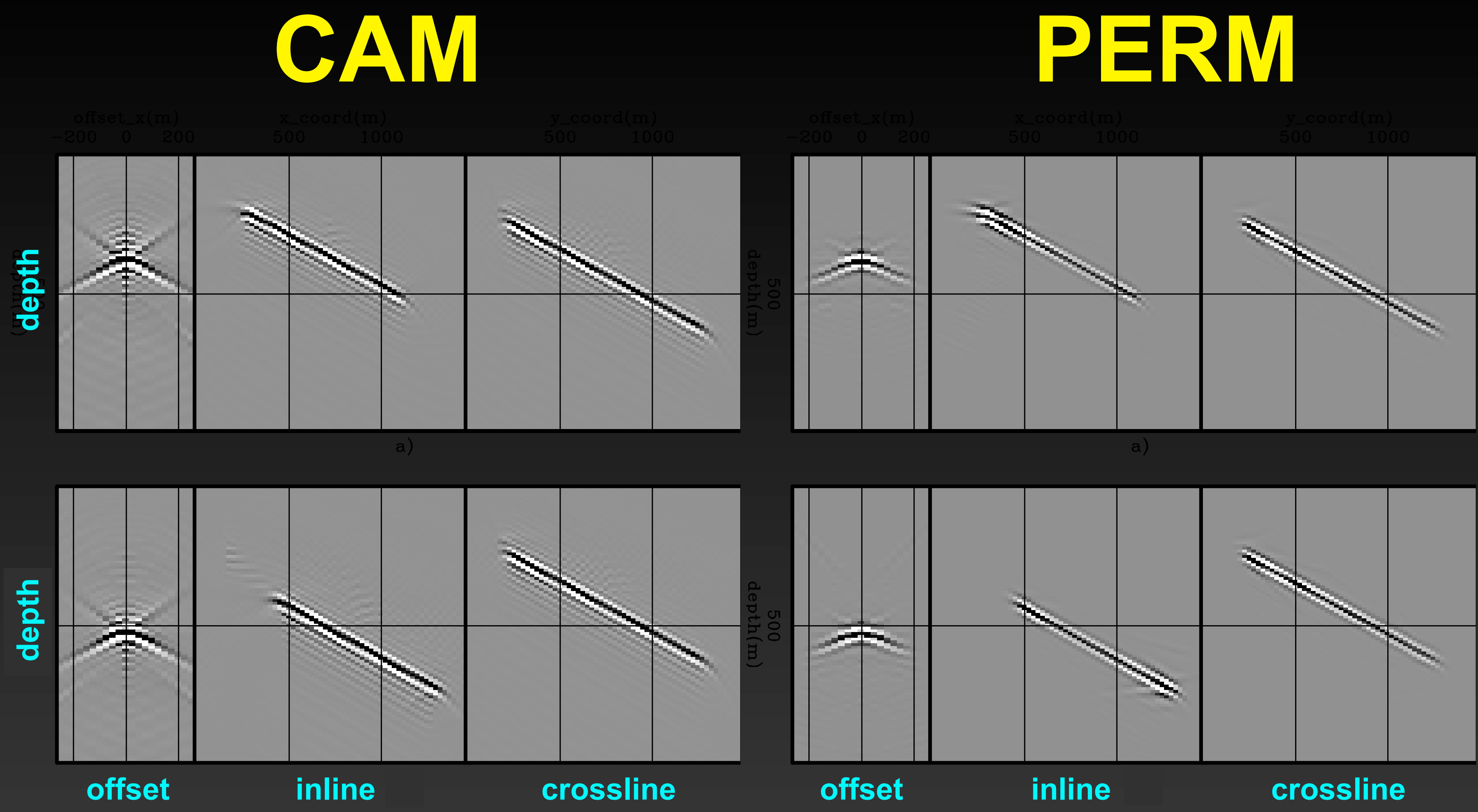
I = image
I_o = background image
ΔI = image perturbation

Using Common-azimuth migrated images

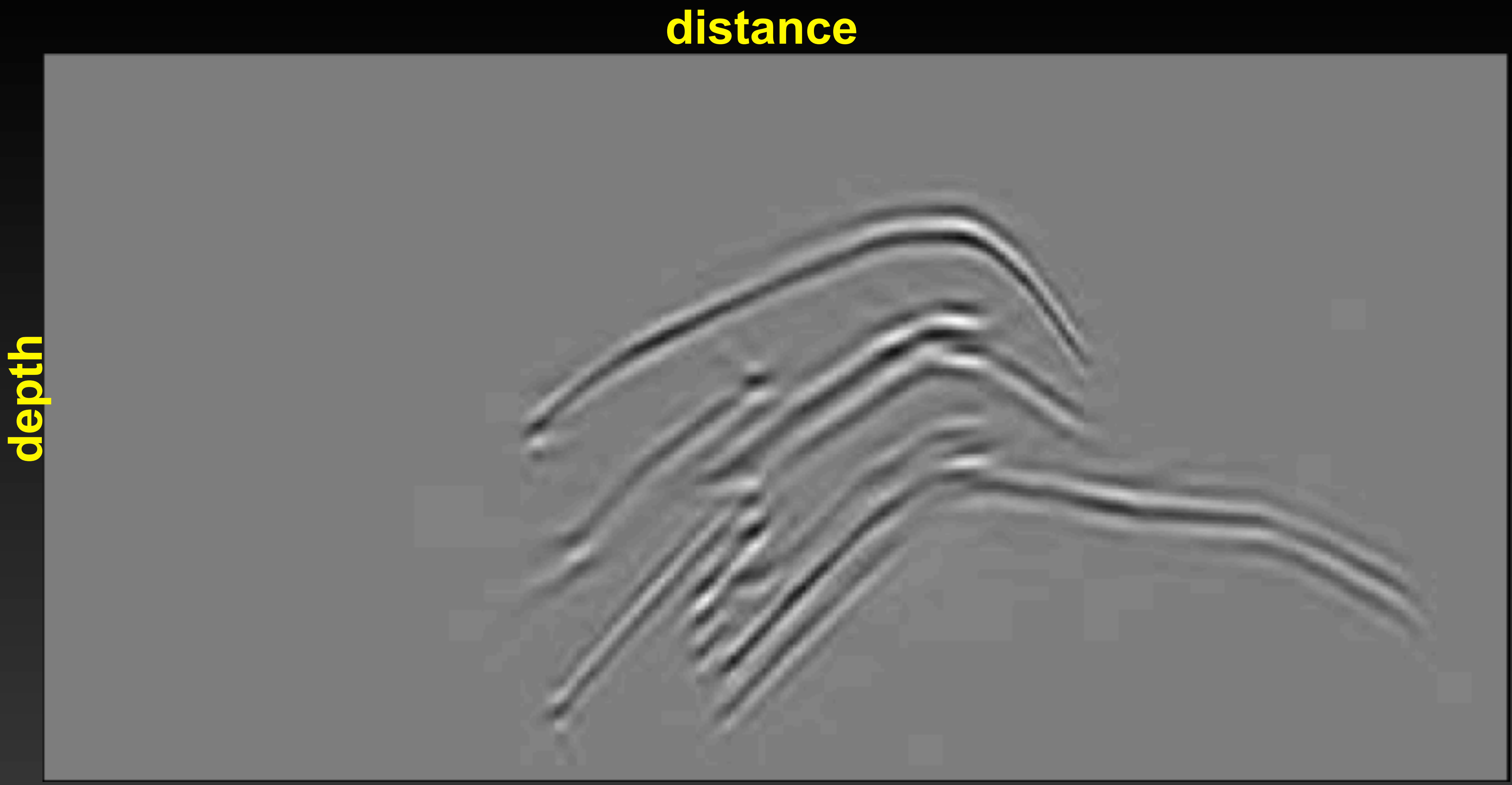
- **Less than 100 PERM wavefields**
  - **Only inline subsurface-offsets are computed**



Using CAM images as the initial conditions



35 PERM migrated image



ISPEW

Source wavefield

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

Receiver wavefield

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

$\Lambda =$ SSR operator

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

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

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

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

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

Image-space phase-encoded wavefields

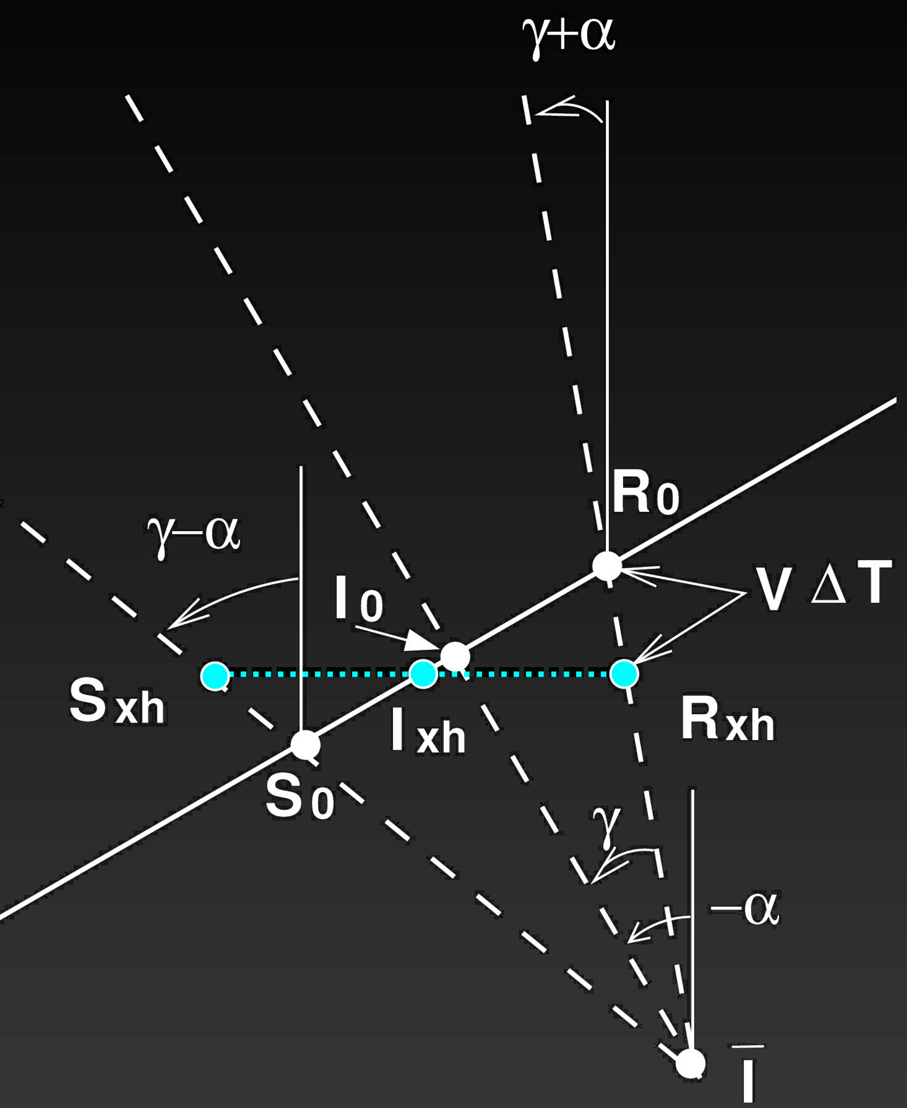
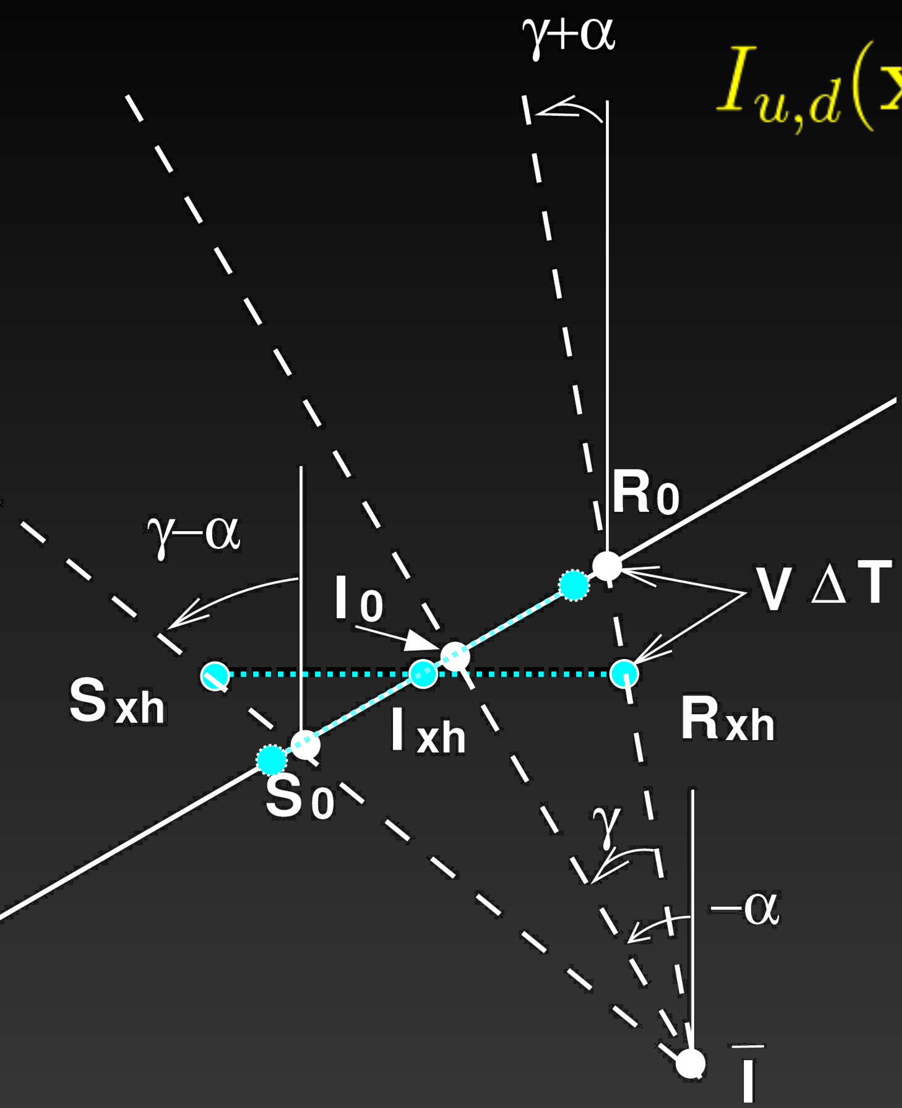


Image-space phase-encoded wavefields



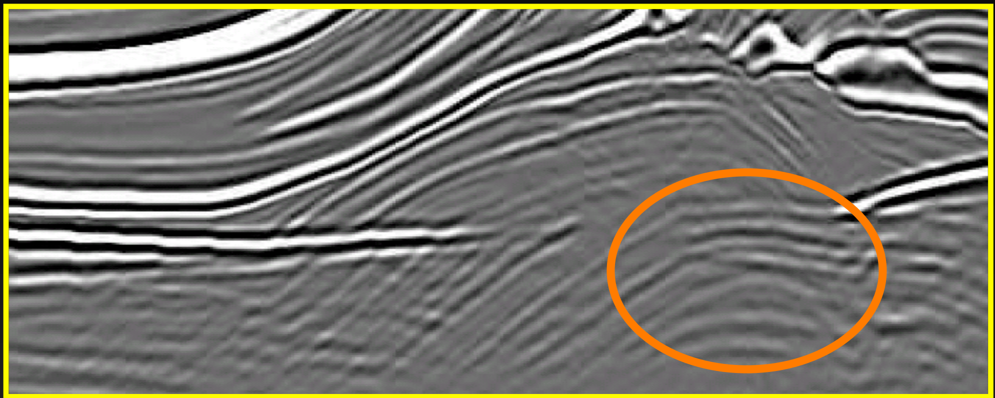
$$I_{u,d}(\mathbf{x},\mathbf{h}) = \iiint_{\alpha\gamma x'} \varrho I(\mathbf{x},\mathbf{h};x')dx'd\gamma d\alpha \Big|_{\zeta}$$

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

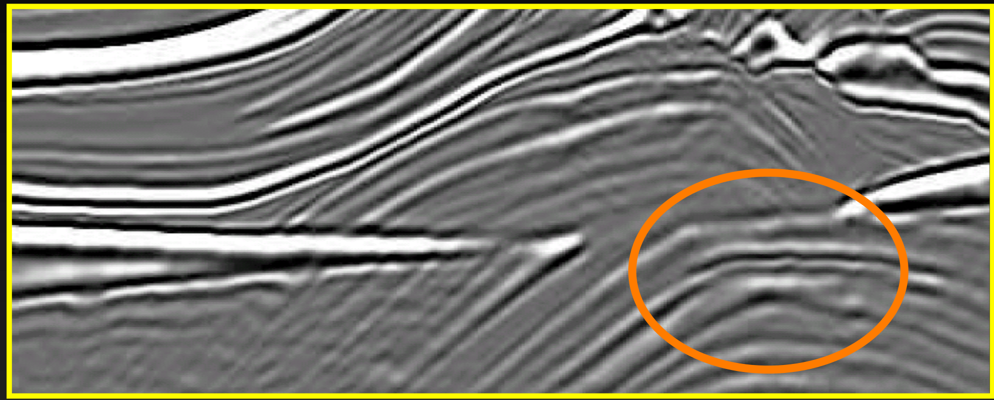
Motivation

Initial x

z

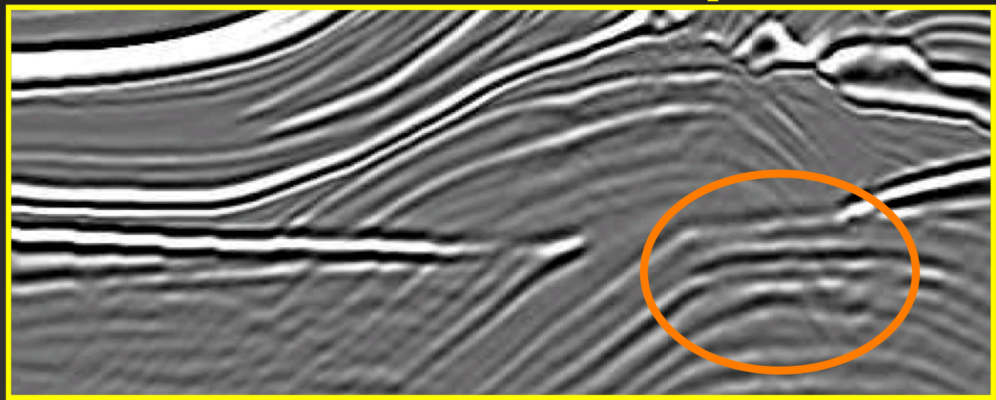


True x



Optimized

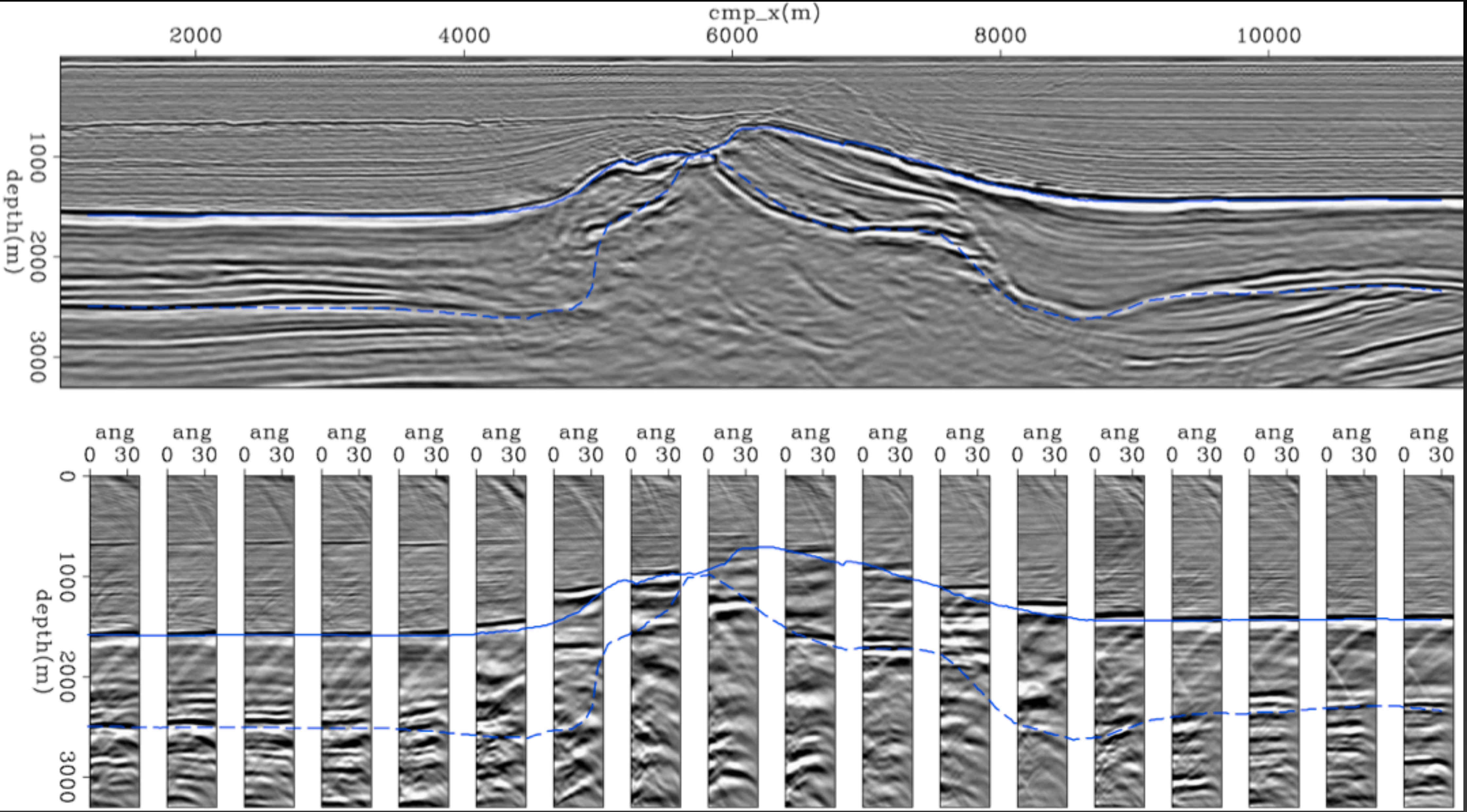
z



20x faster

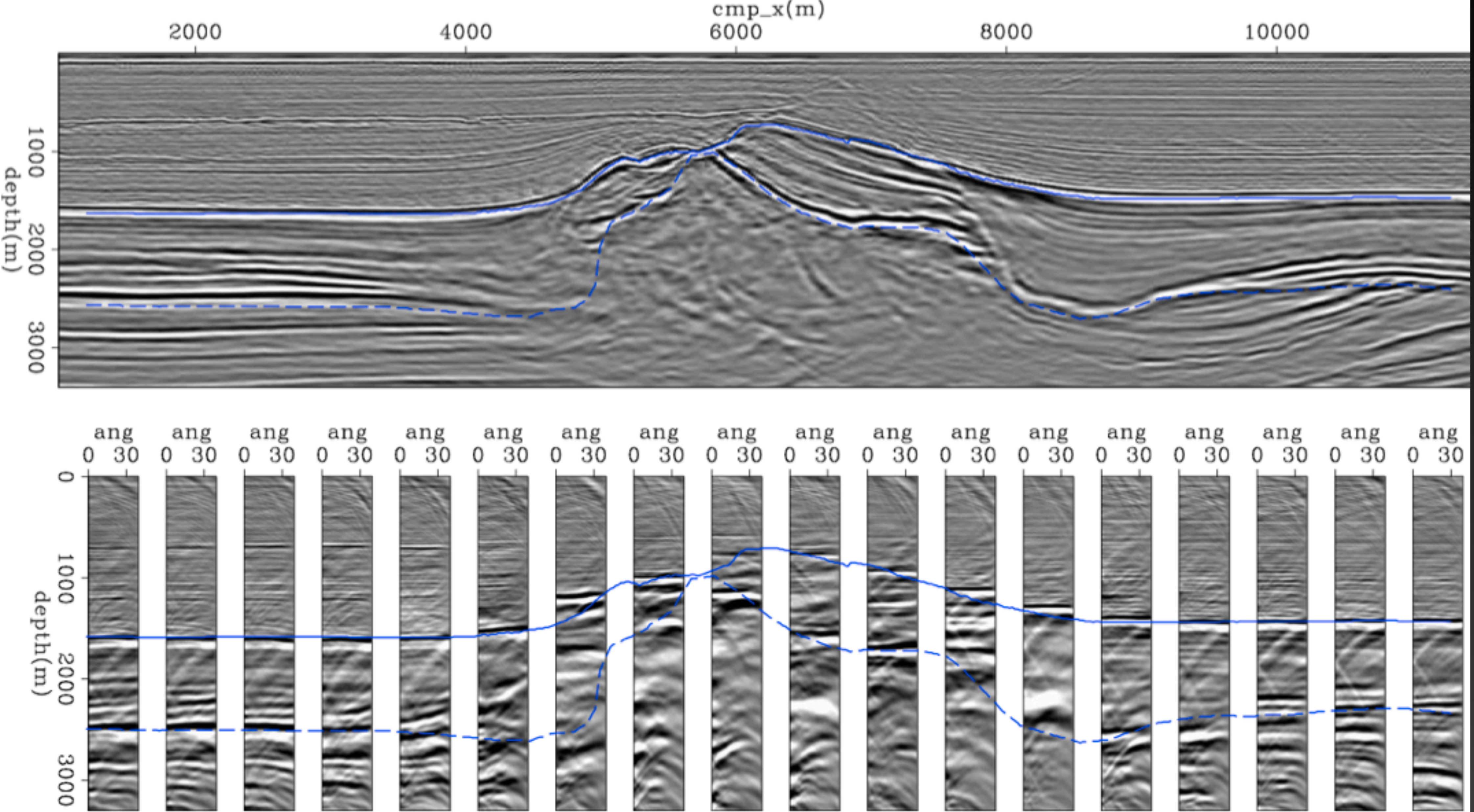
Comparisons: iline = 3200 m

IFP



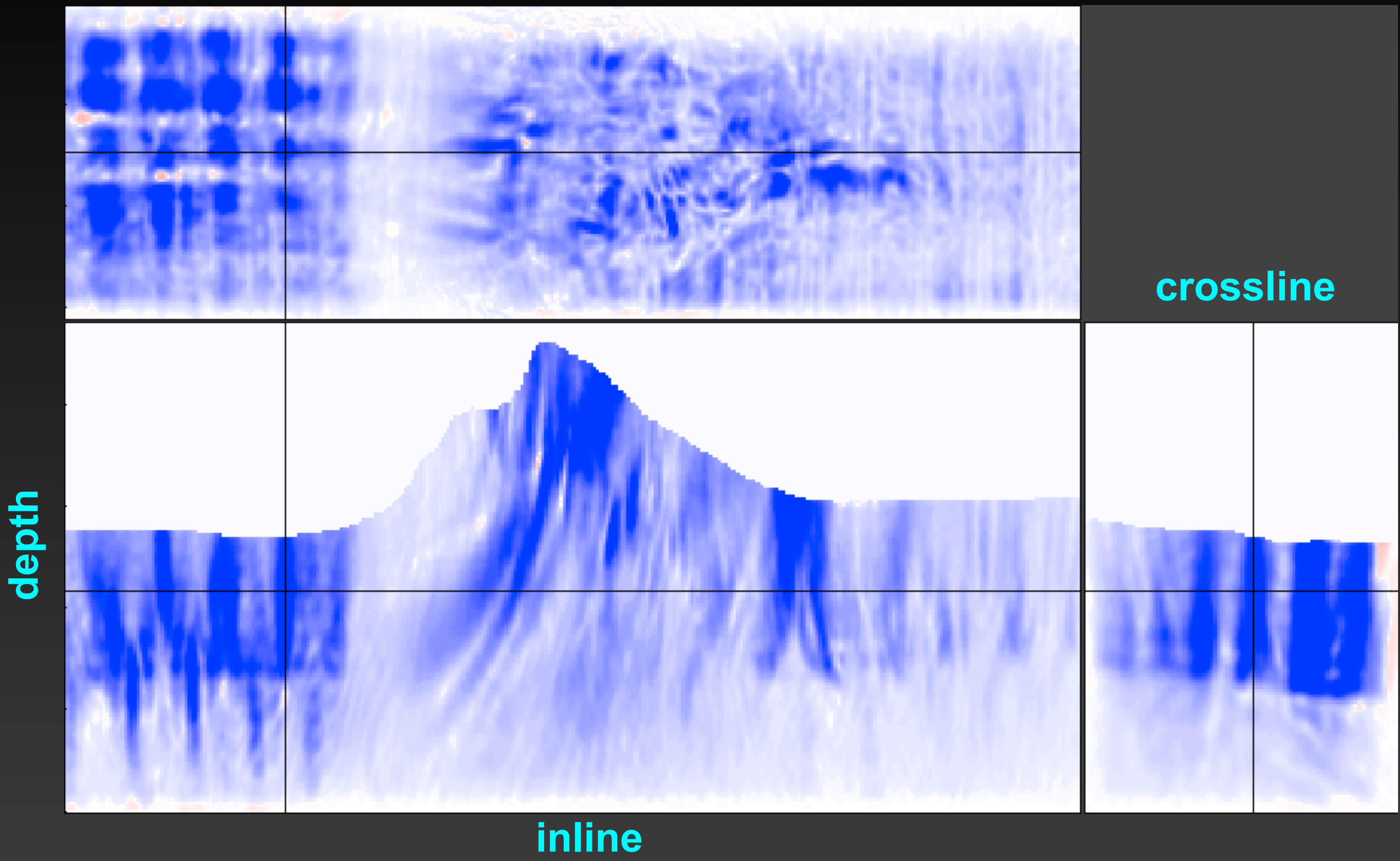
Comparisons: iline = 3200 m

Chalk optimized velocity



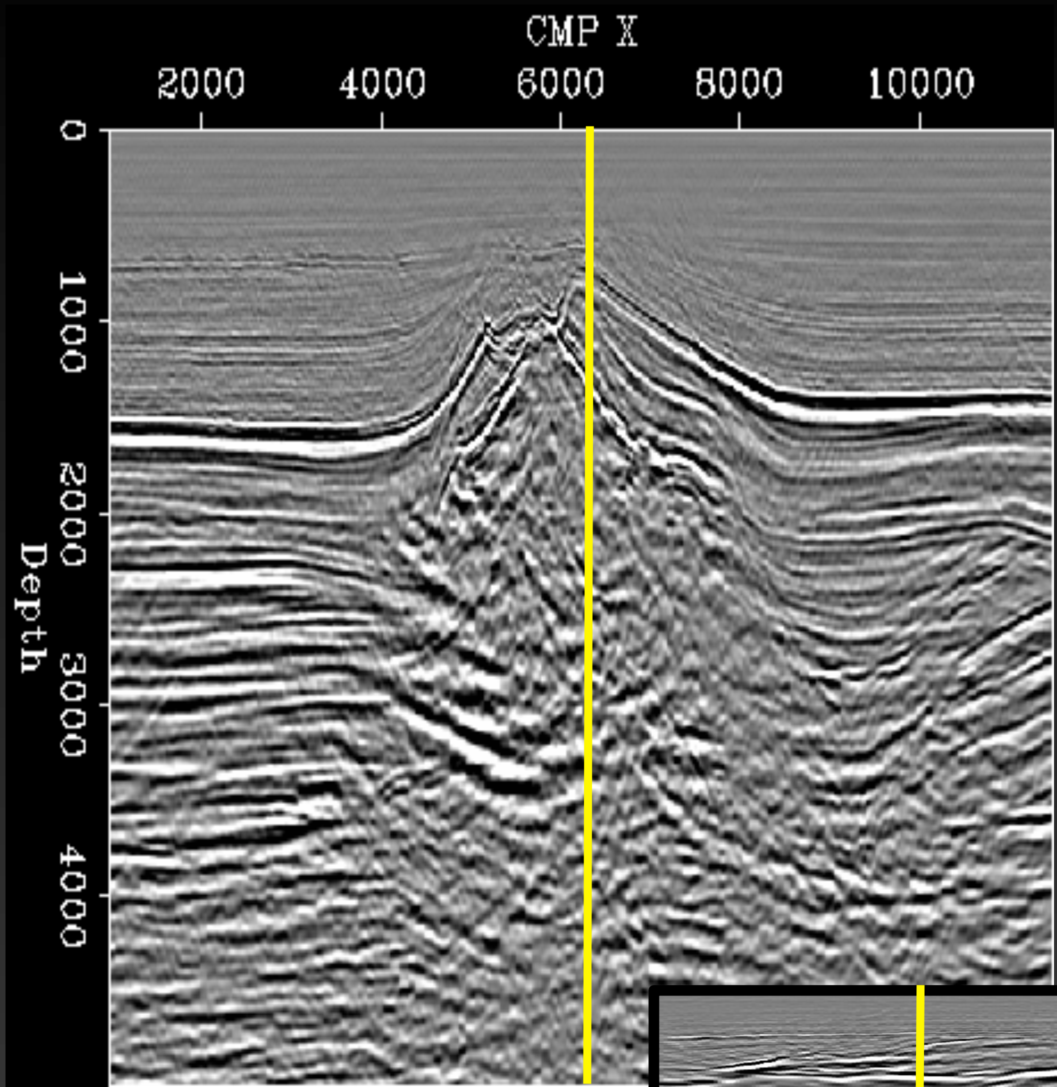
Potential for grid-tomography

Gradient with 1 pair of ISPEW

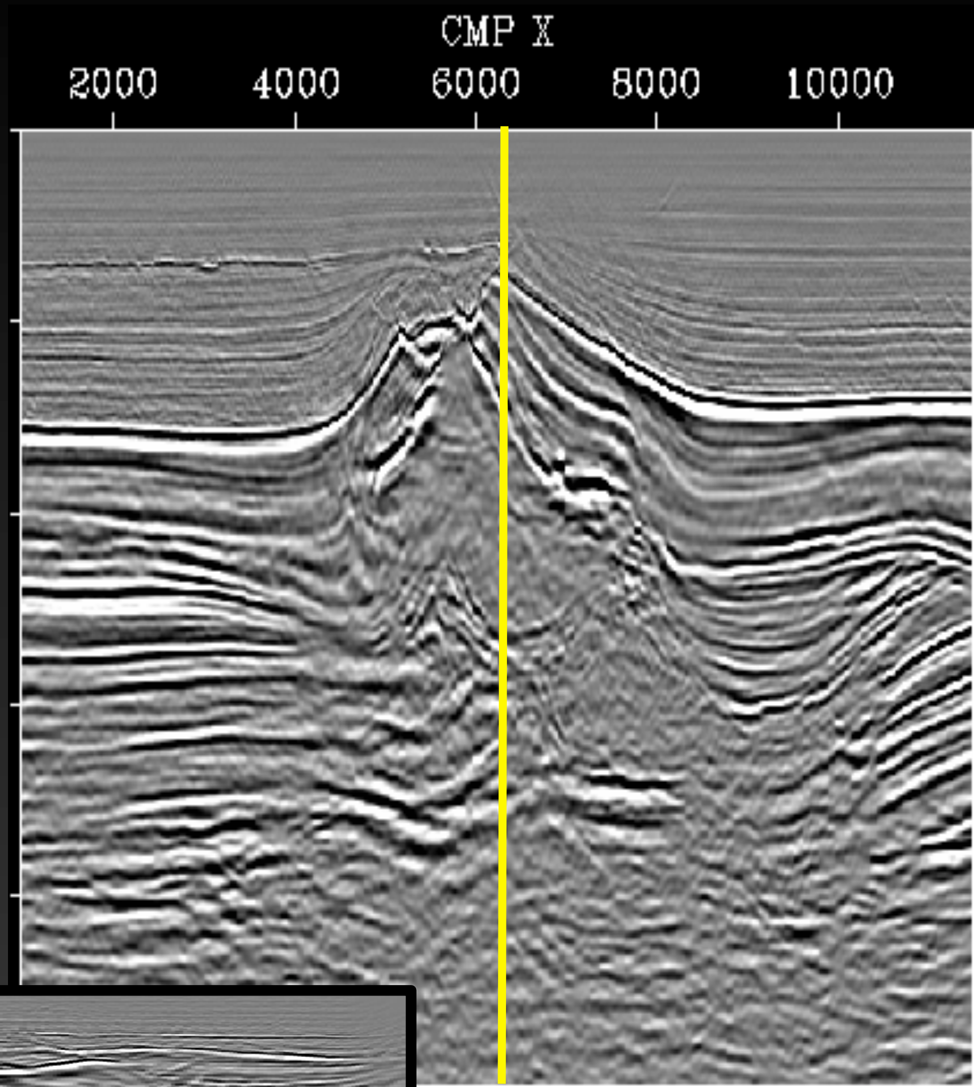


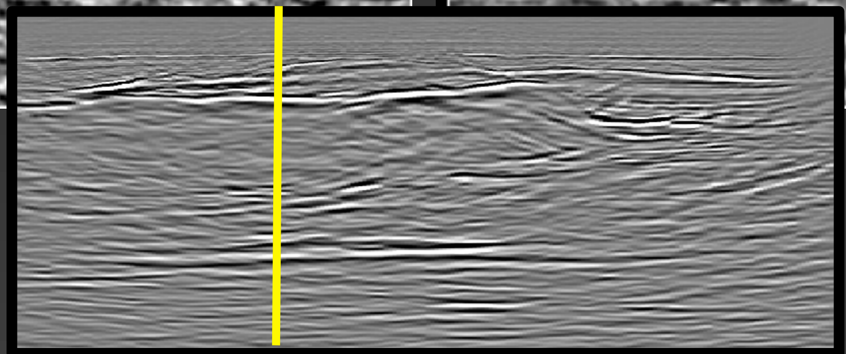
Comparisons: inline = 2900 m

Initial



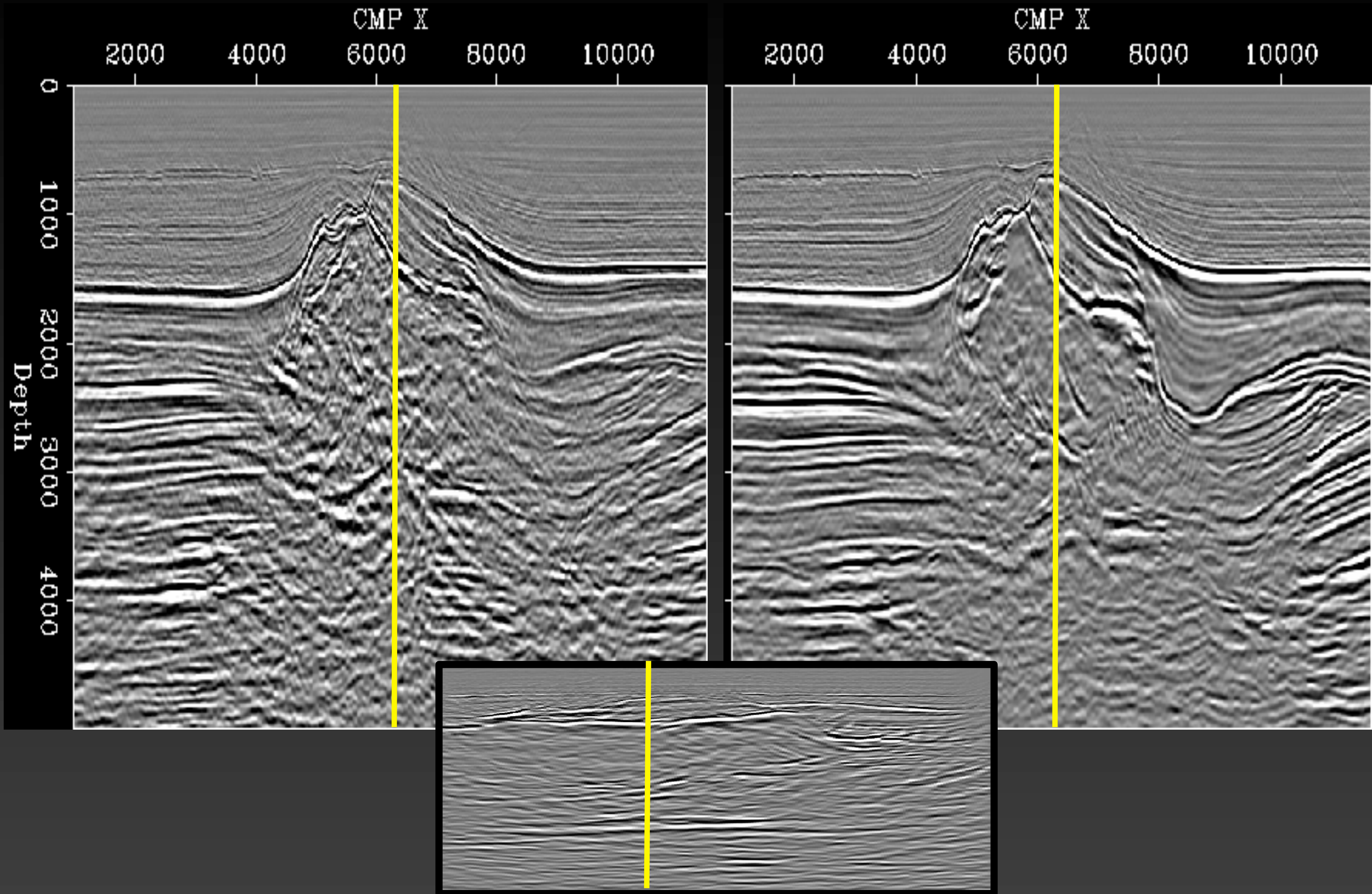
After salt body



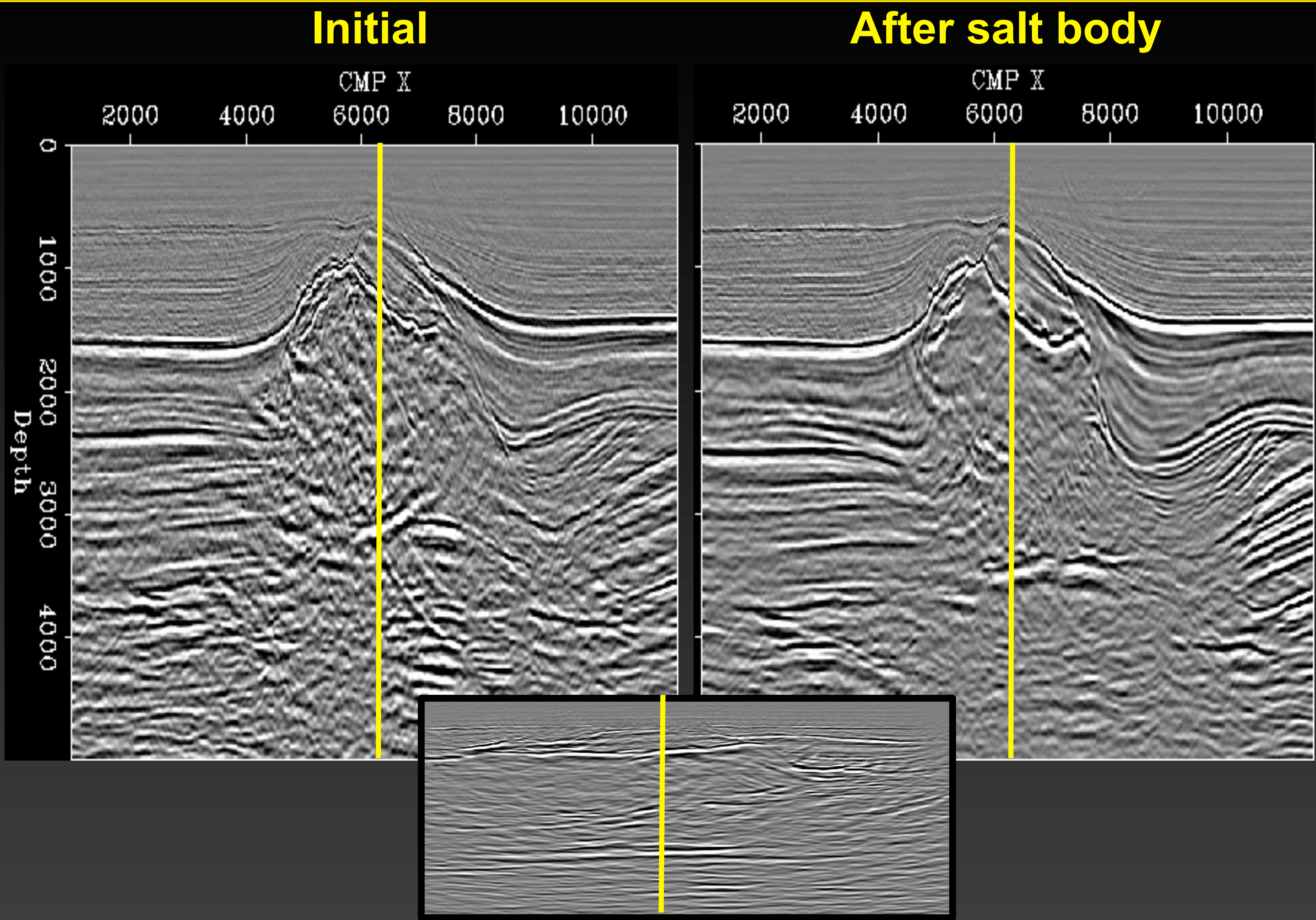


Comparisons: inline = 3200 m

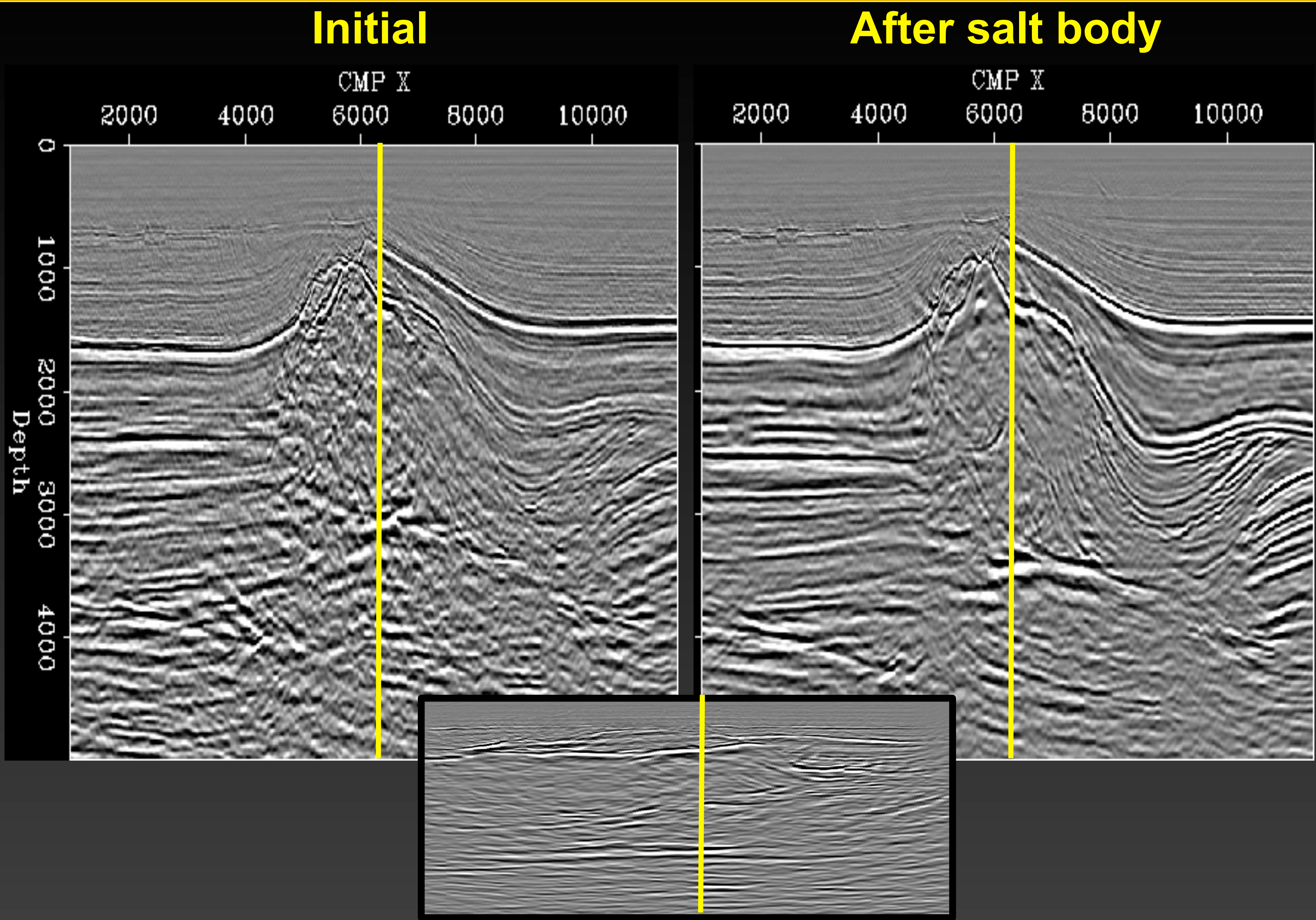
Initial | **After salt body**



Comparisons: inline = 3500 m

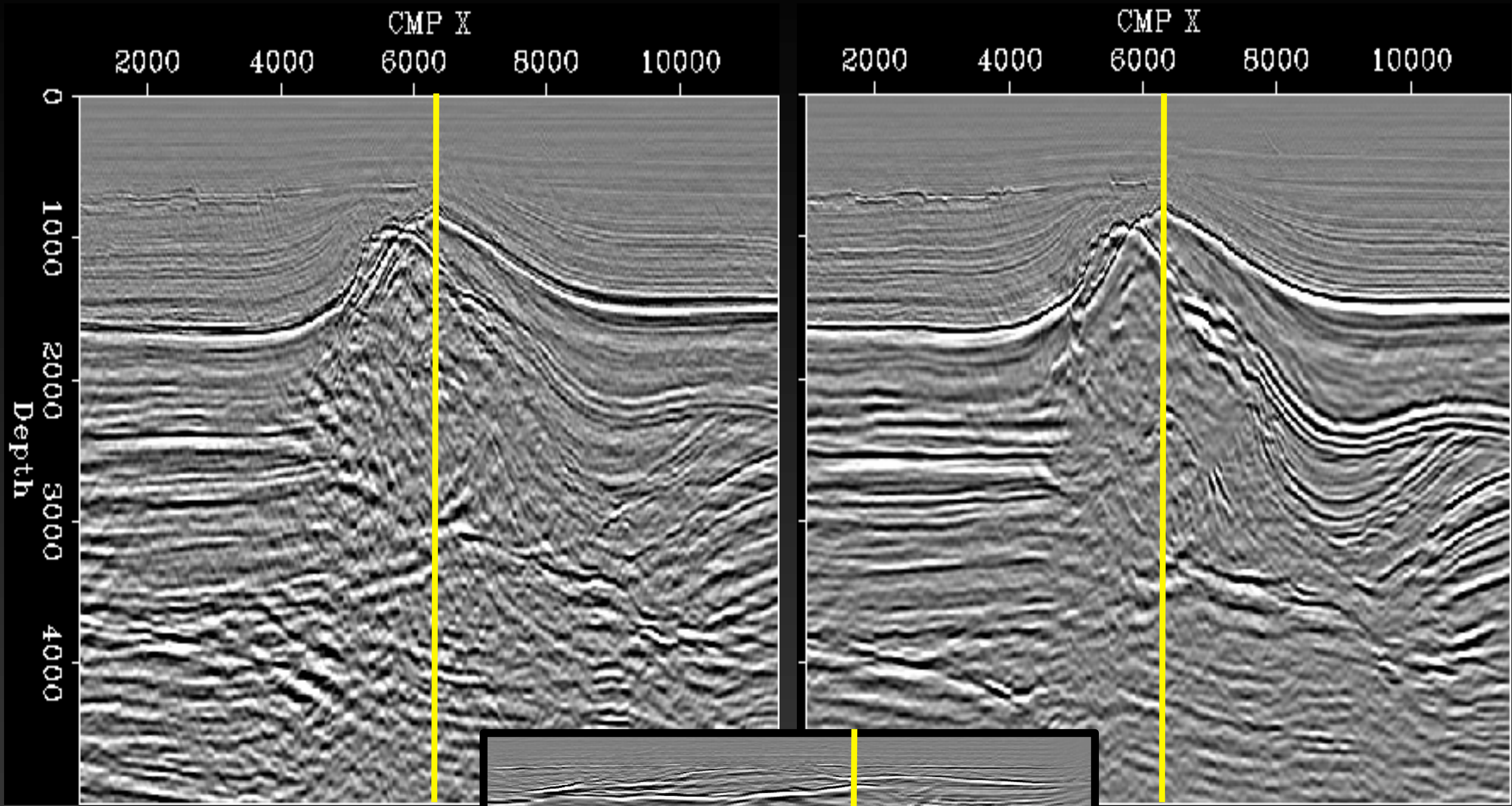


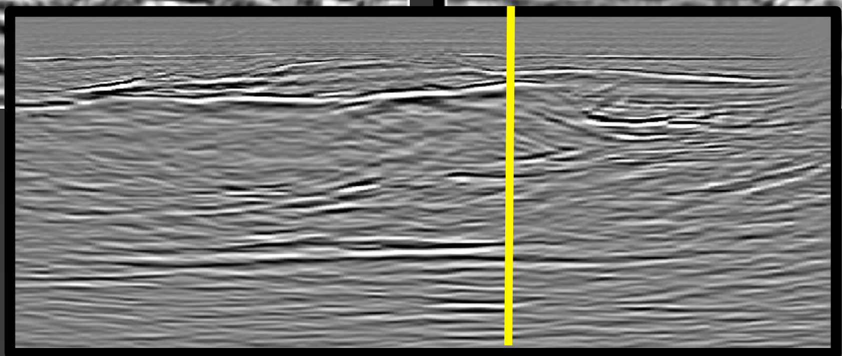
Comparisons: inline = 4000 m



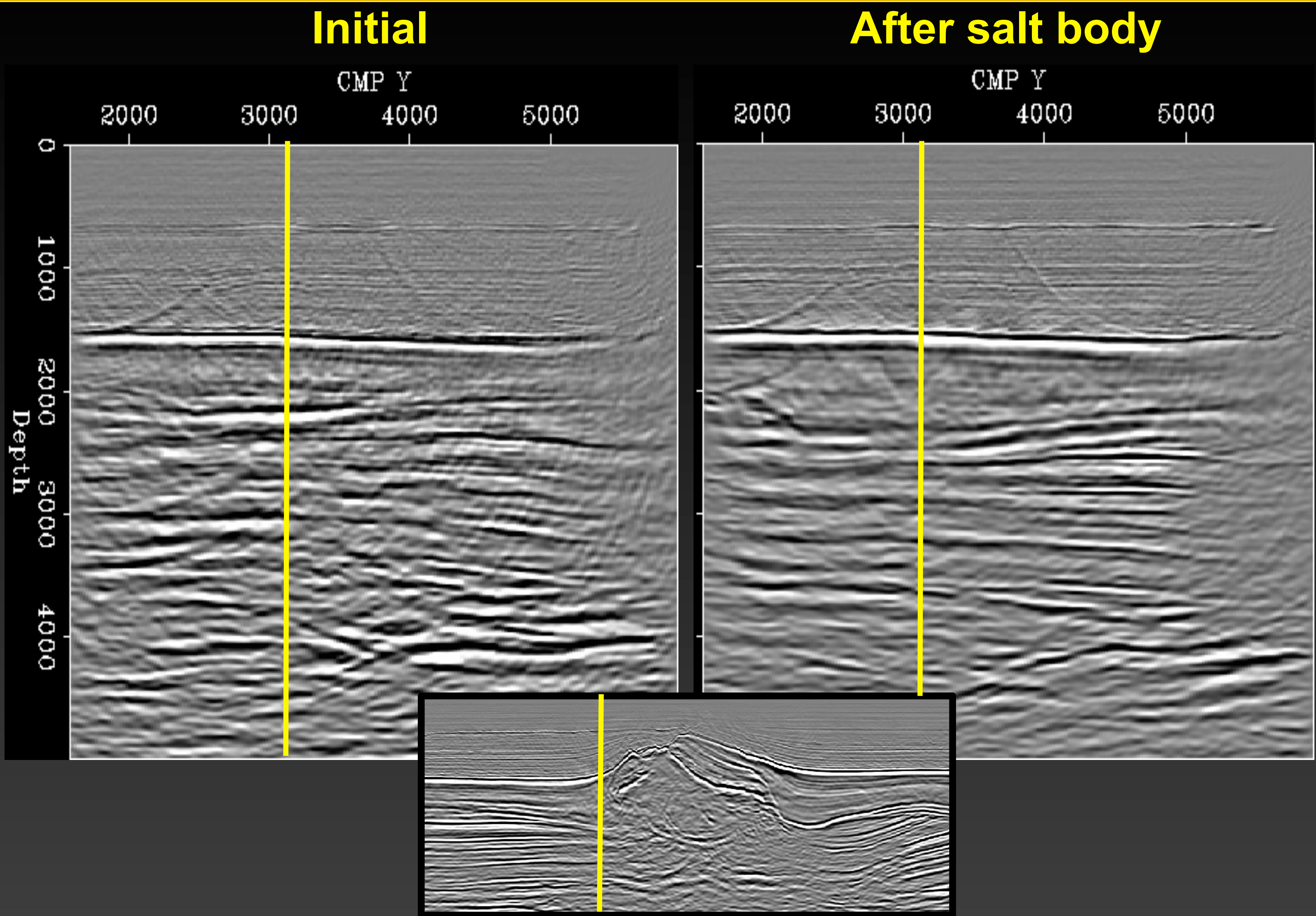
Comparisons: inline = 4200 m

Initial | **After salt body**

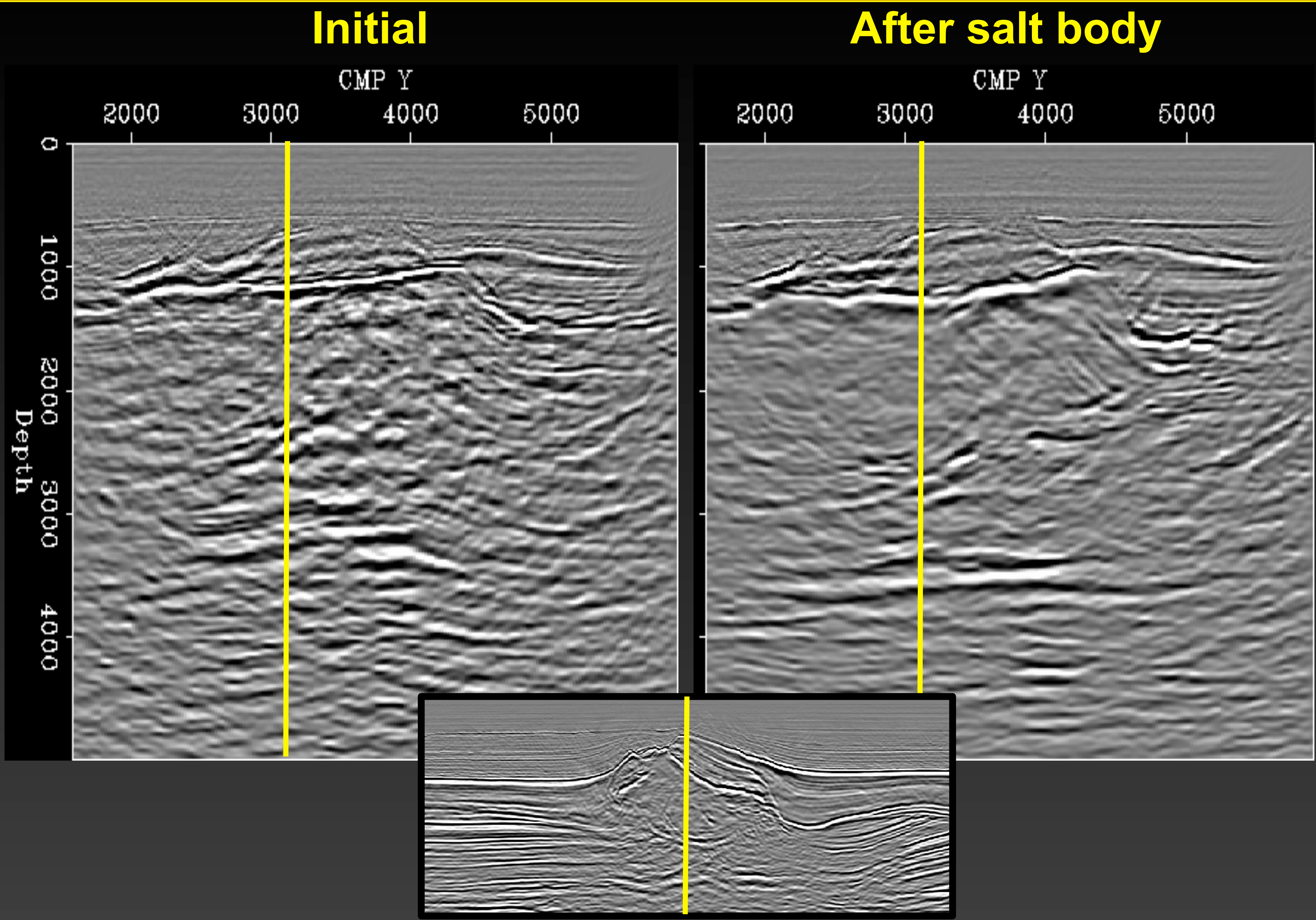




Comparisons: xline = 4400 m

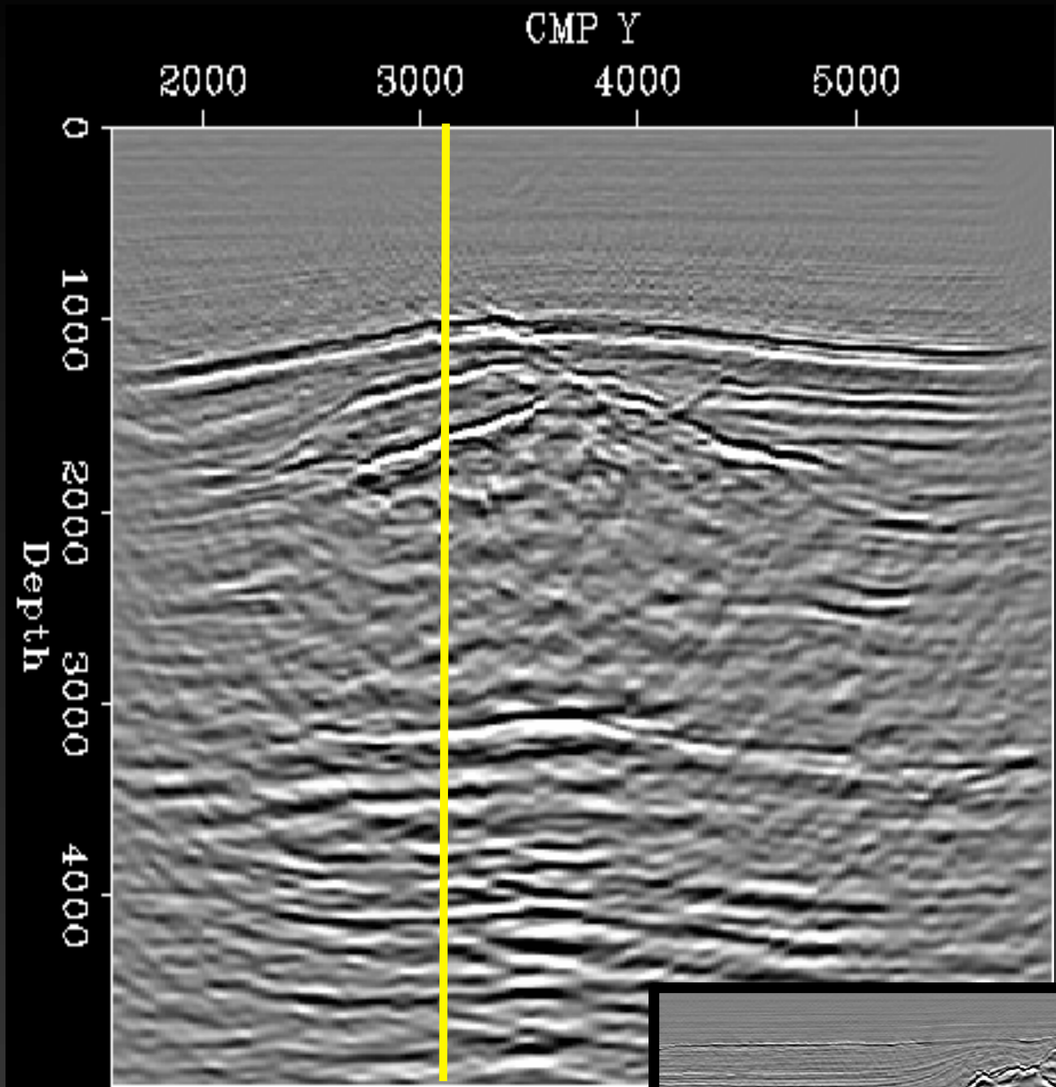


Comparisons: xline = 6100 m

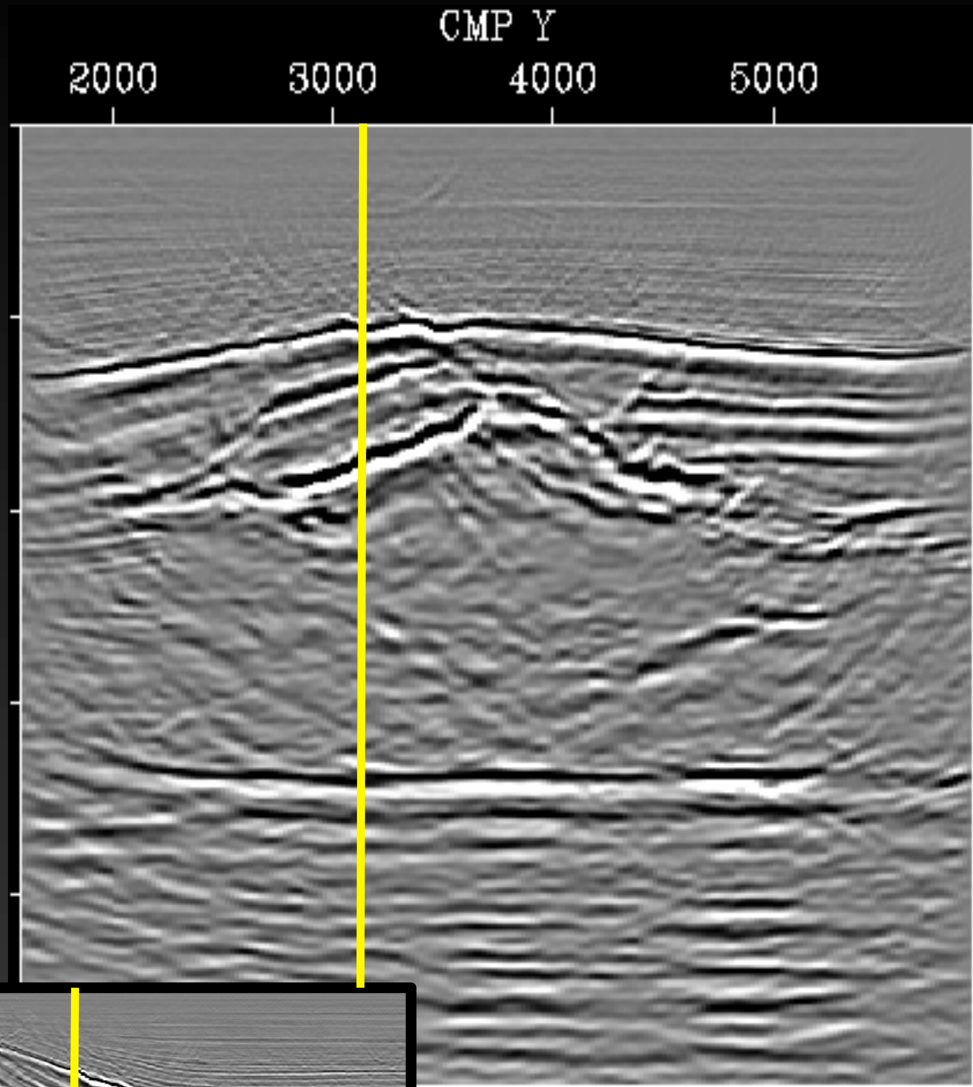


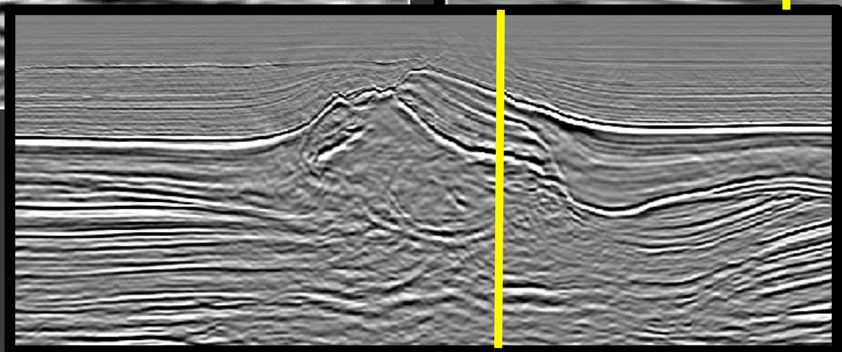
Comparisons: xline = 7300 m

Initial



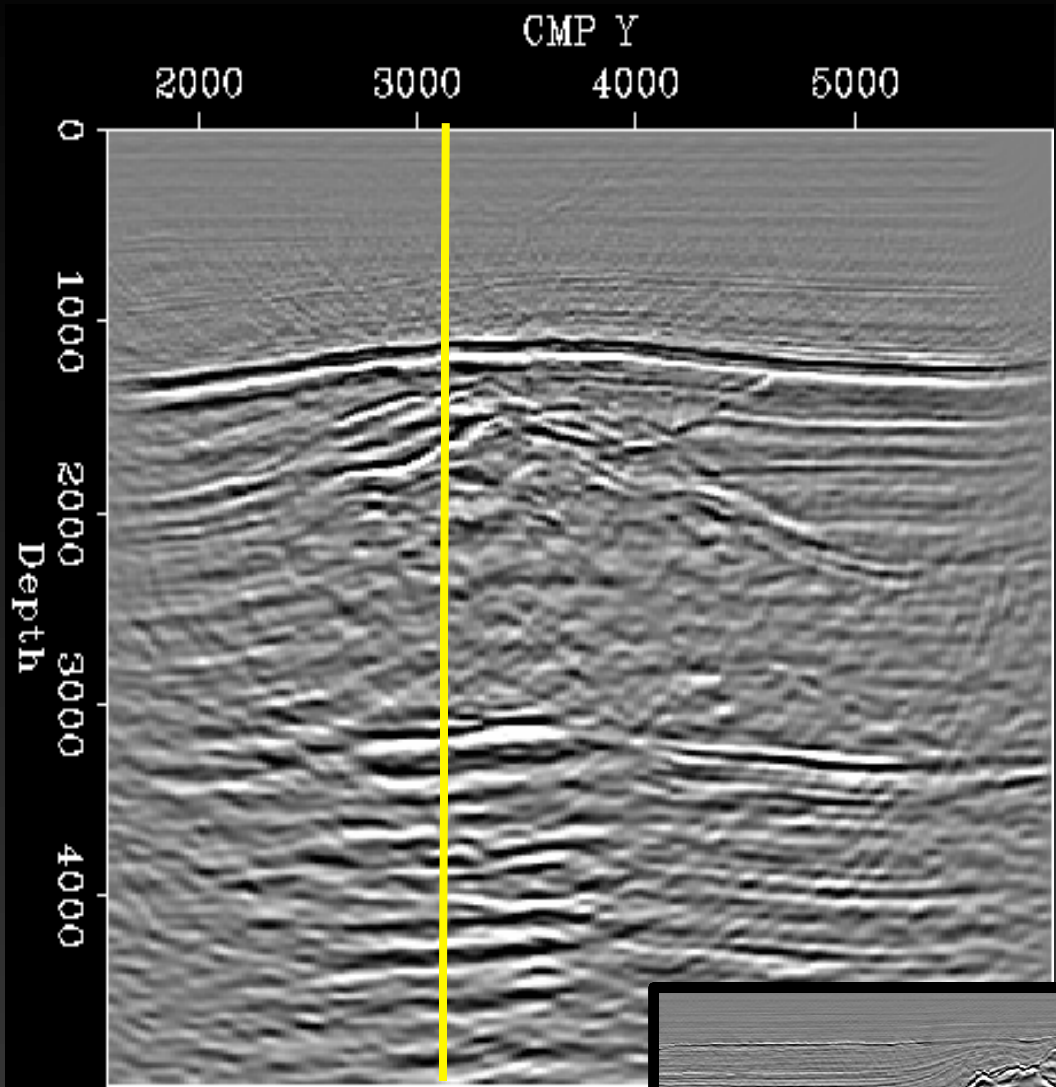
After salt body



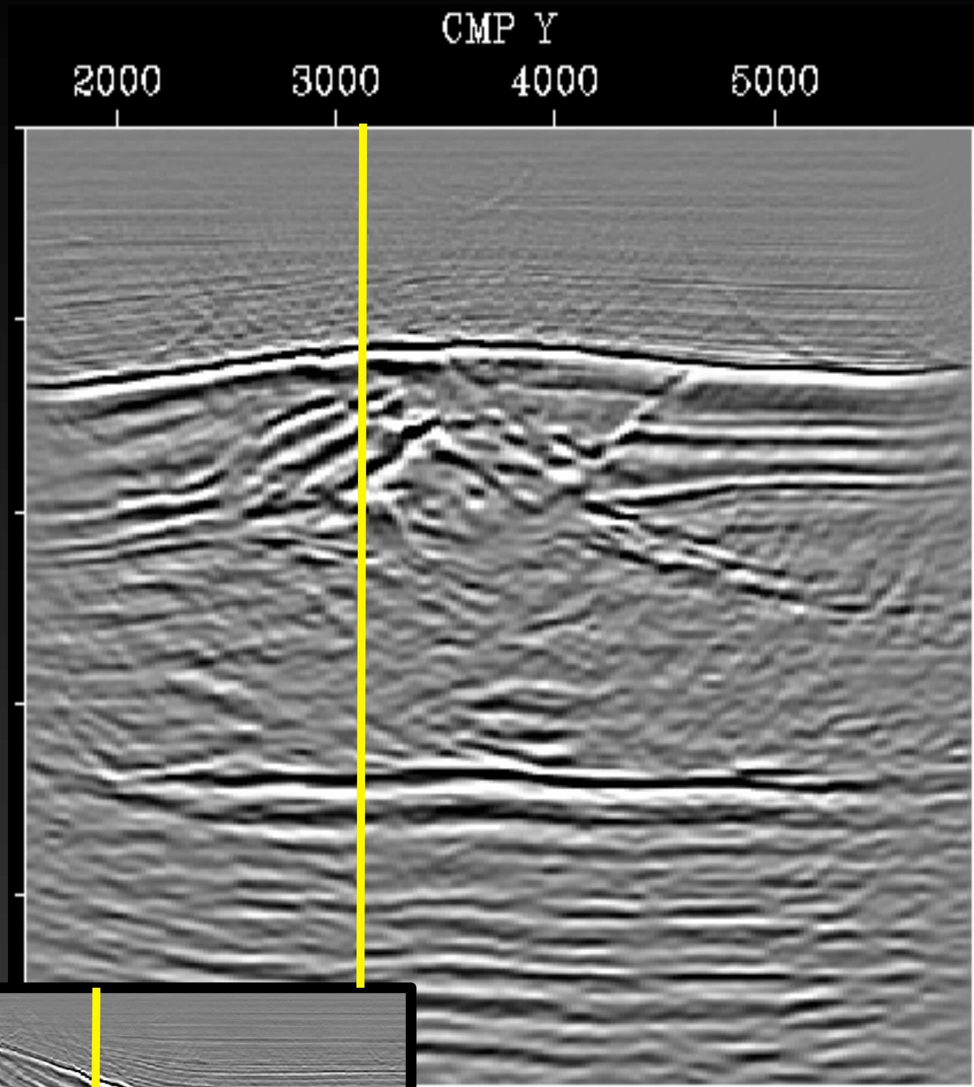


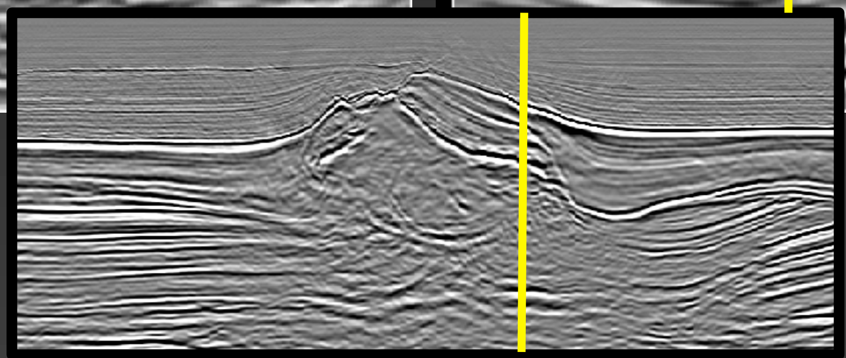
Comparisons: xline = 7600 m

Initial

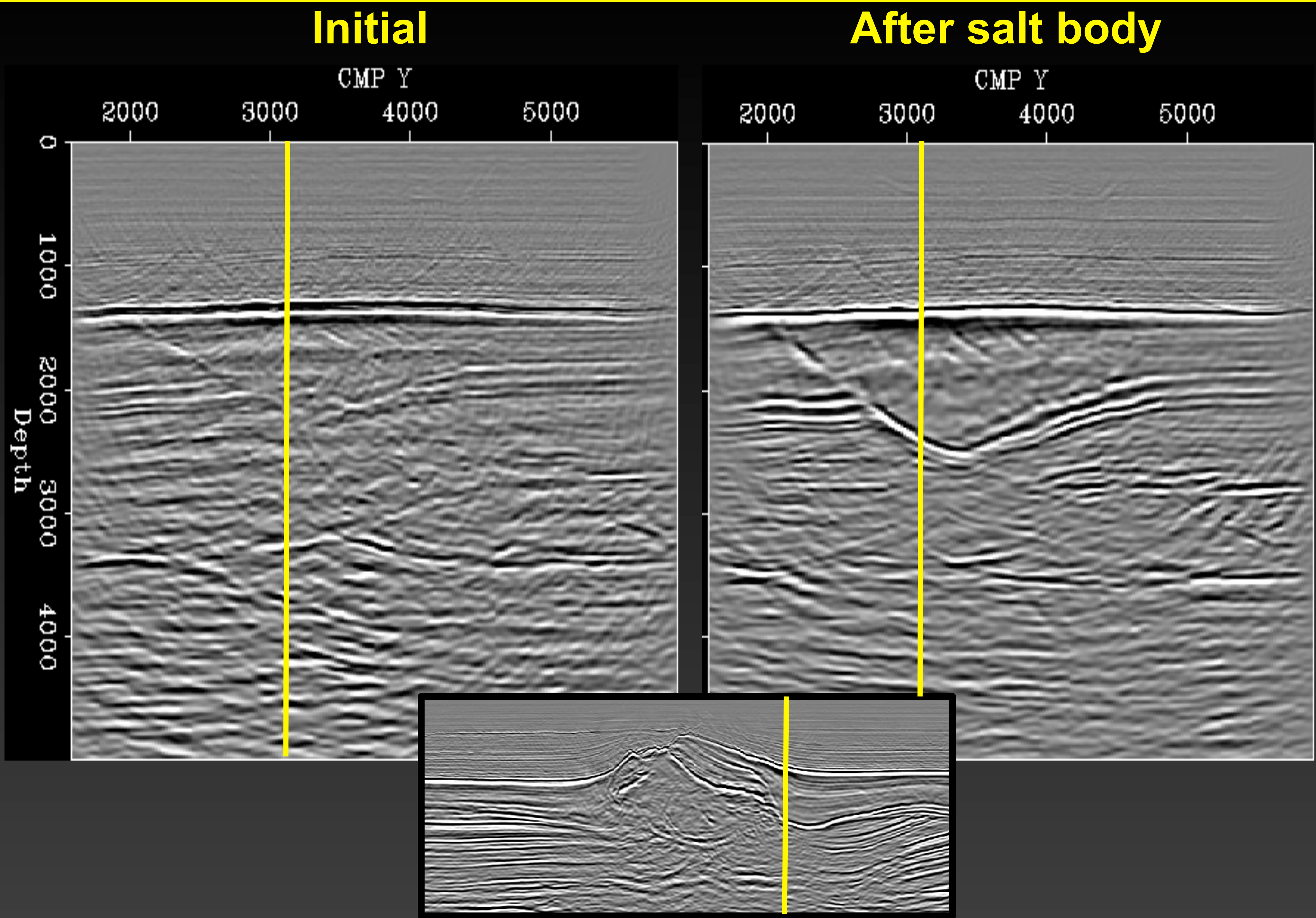


After salt body



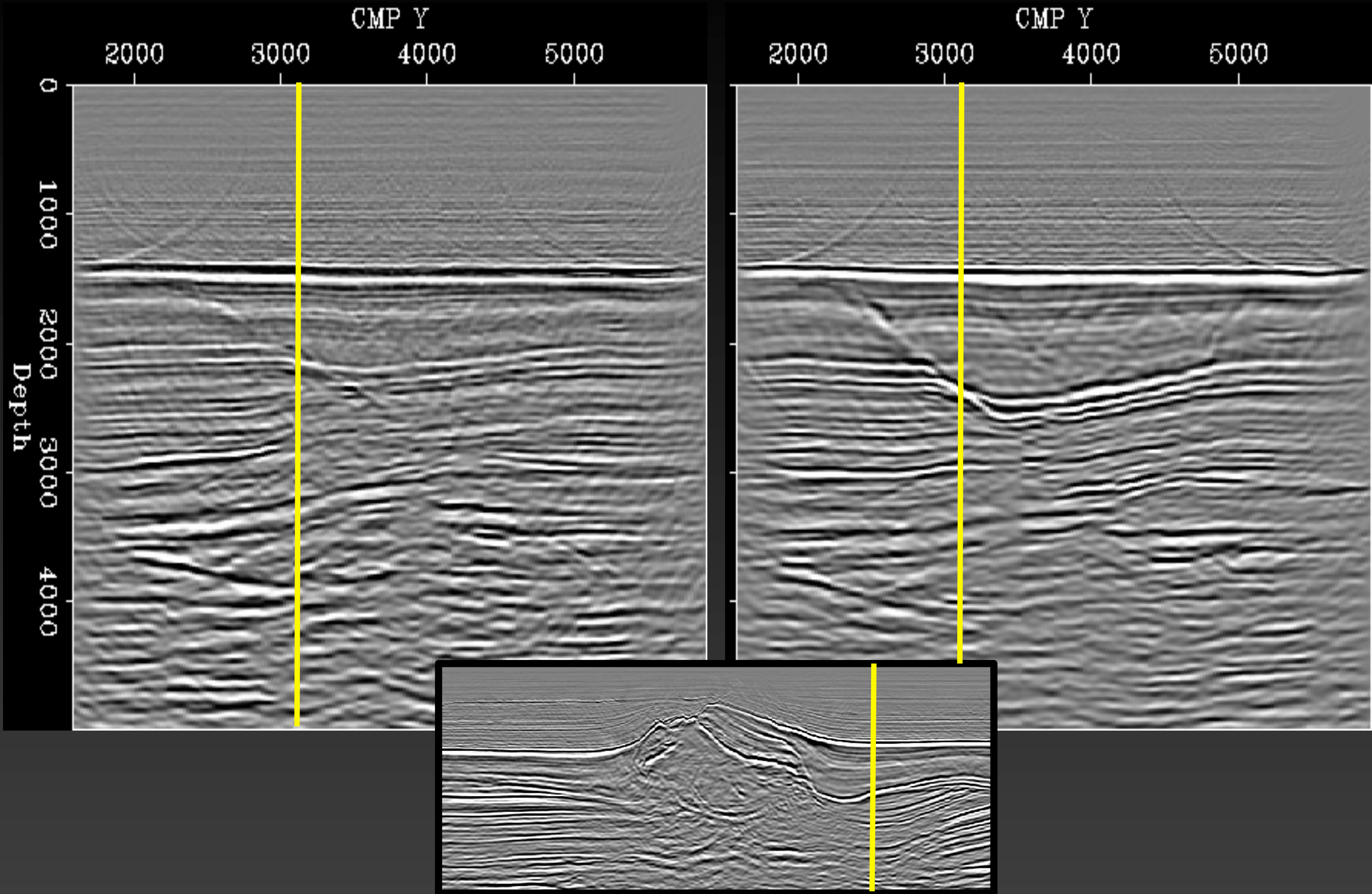


Comparisons: xline = 8200 m



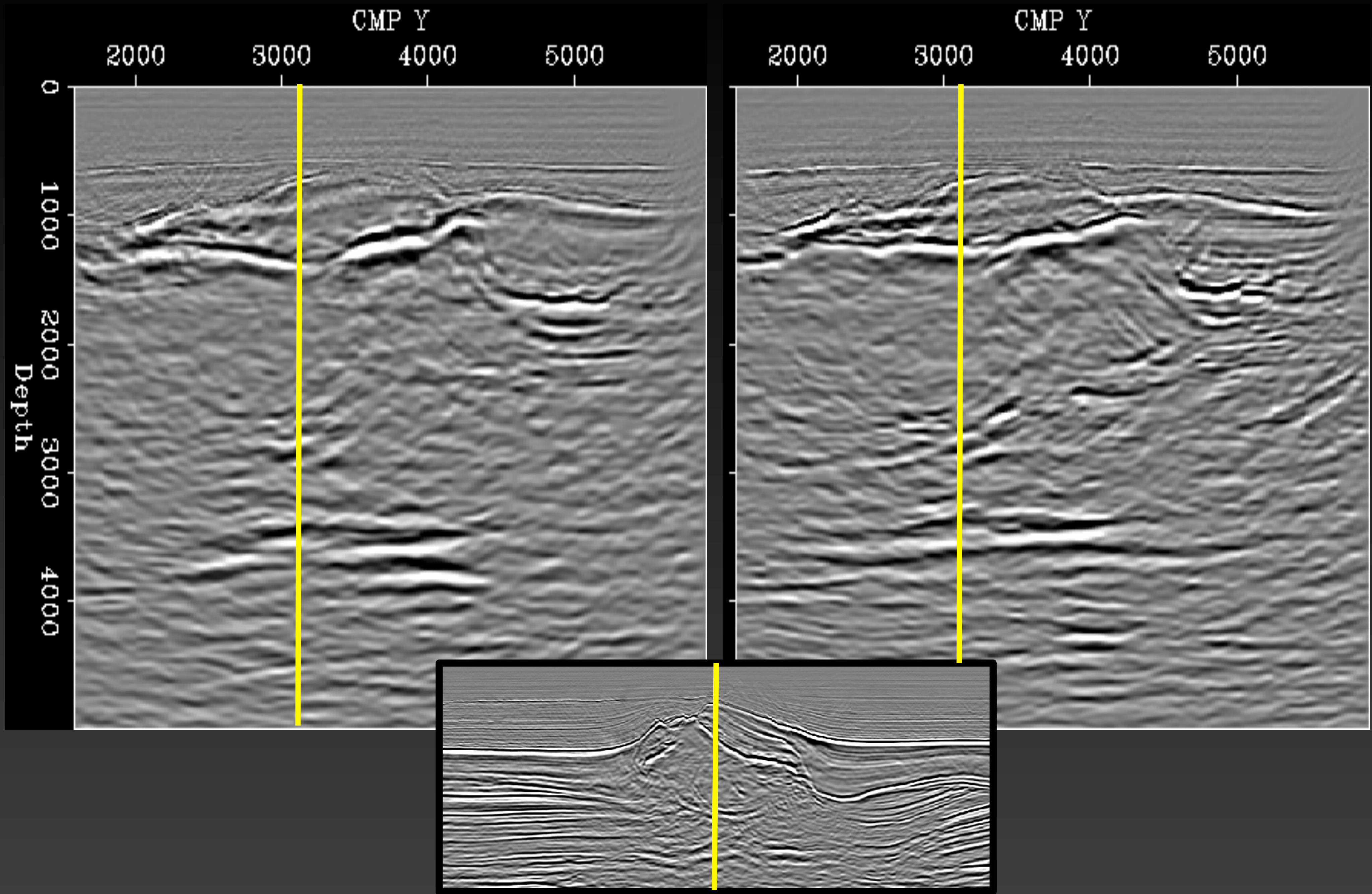
Comparisons: xline = 9300 m

Initial | **After salt body**



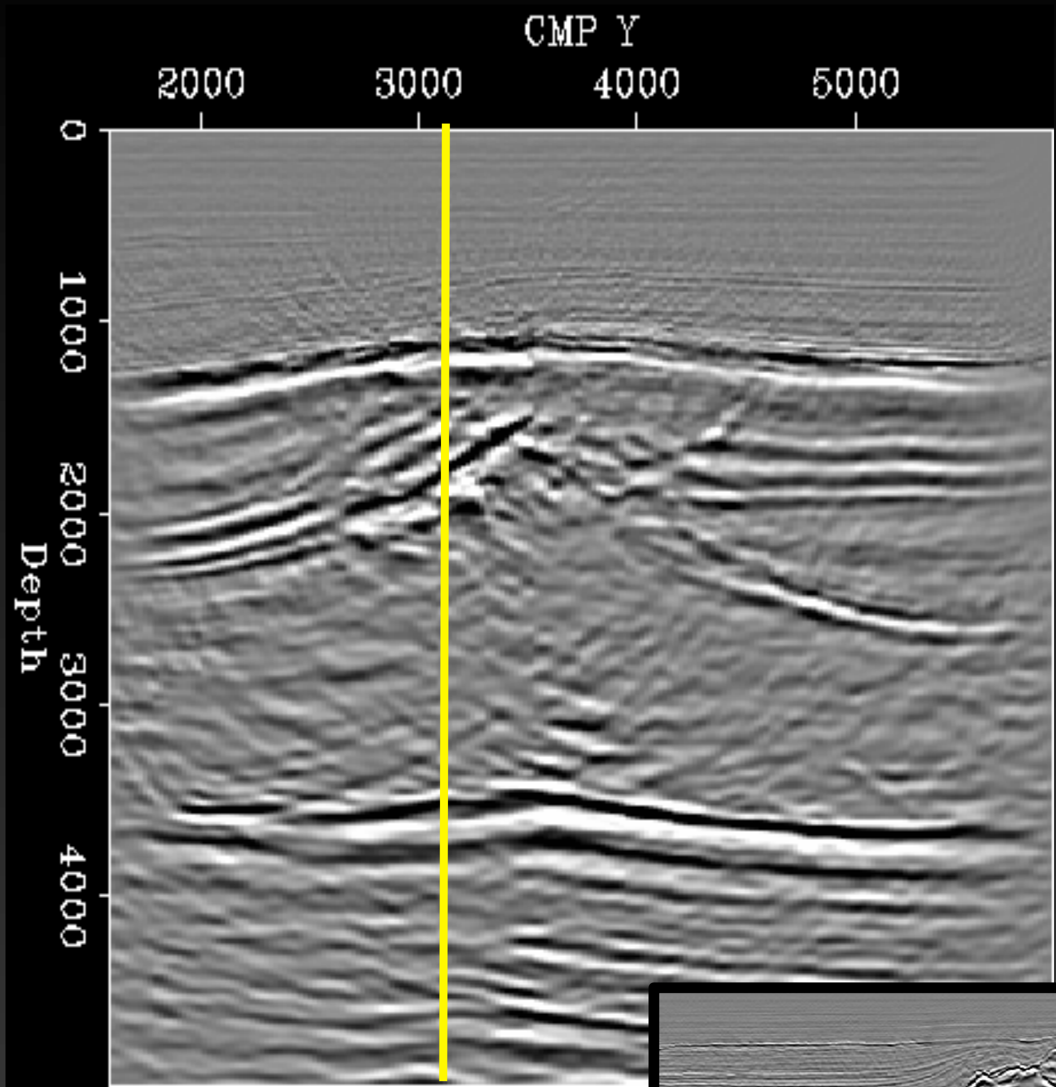
Comparisons: xline = 6100 m

Original | **After salt body**

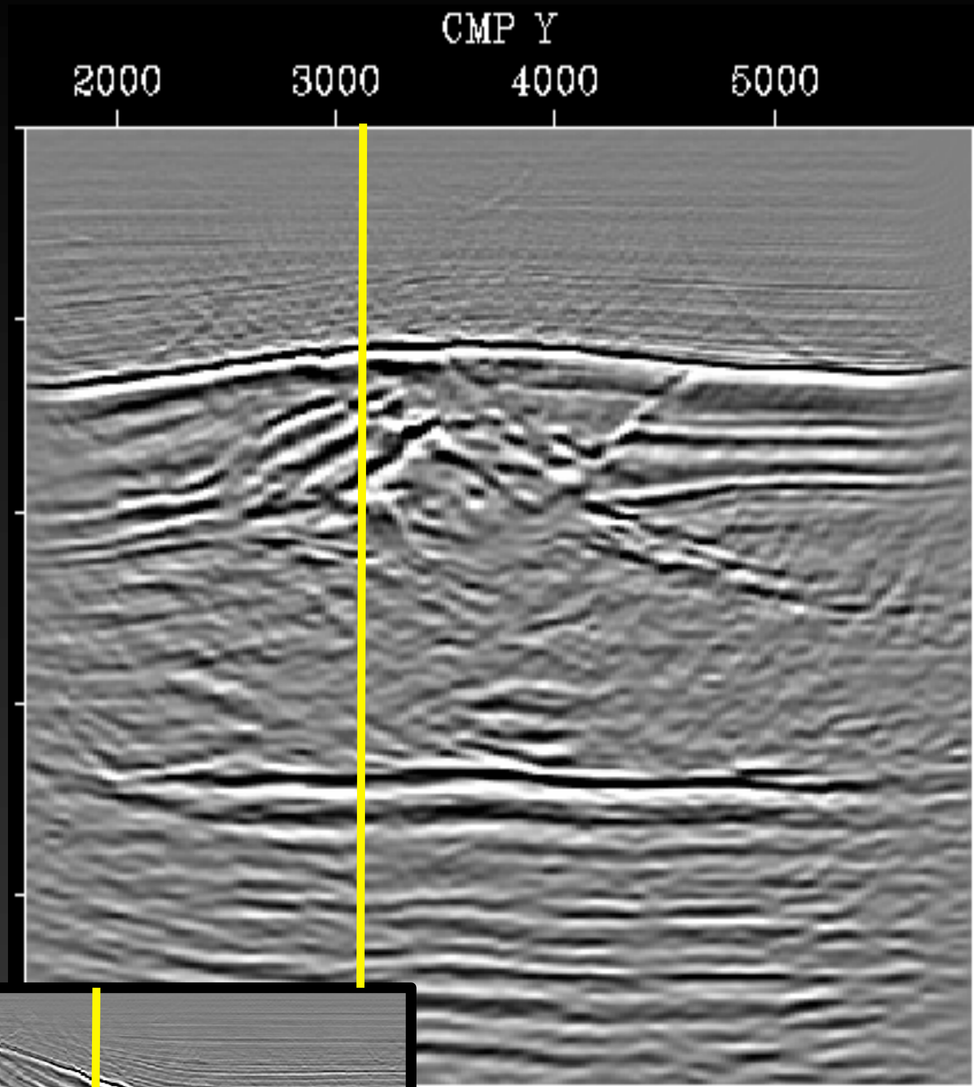


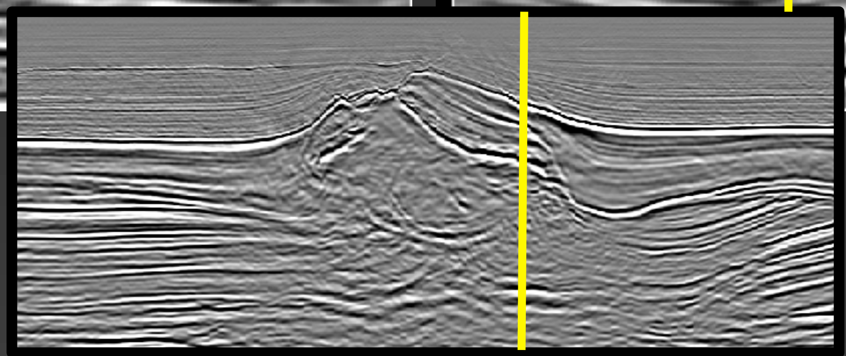
Comparisons: xline = 7600 m

Original



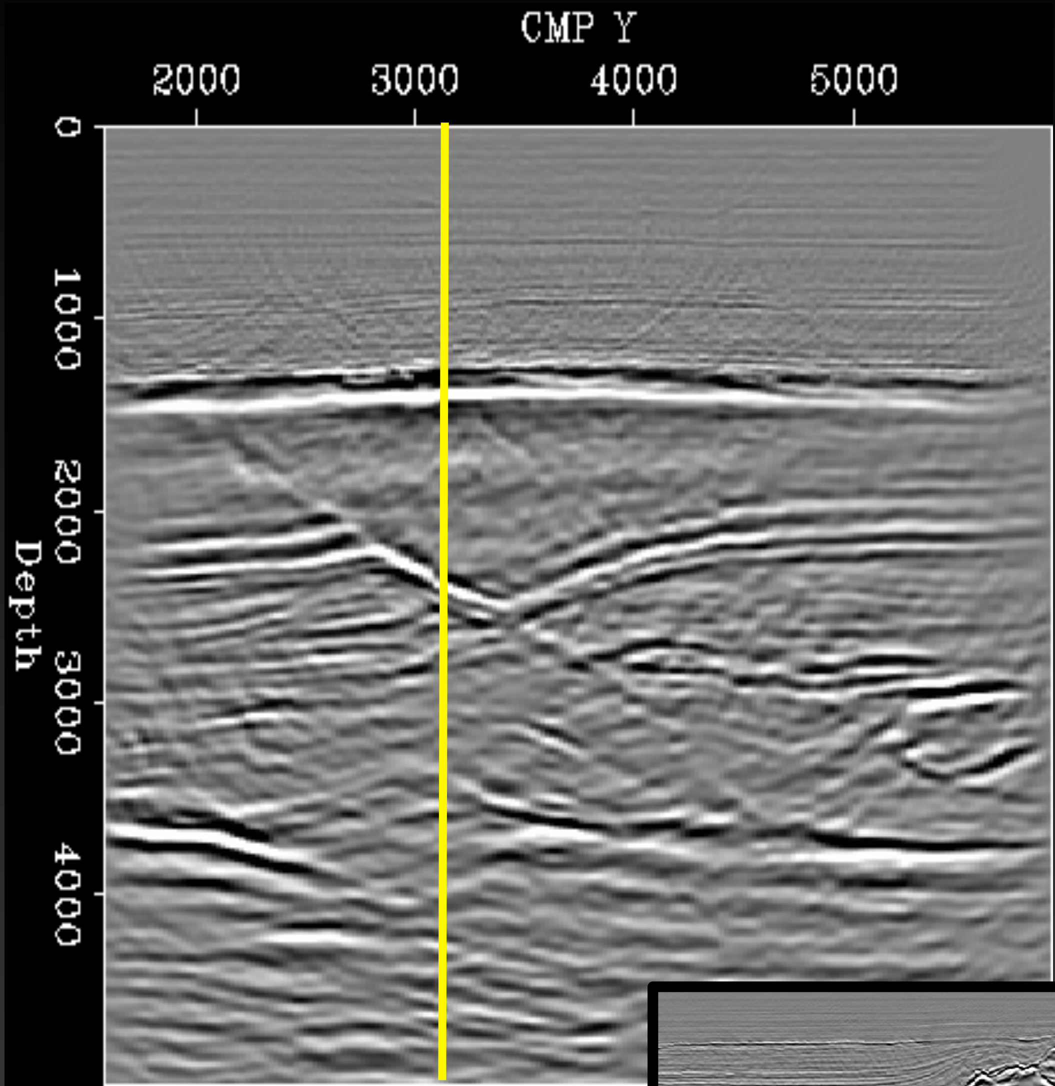
After salt body



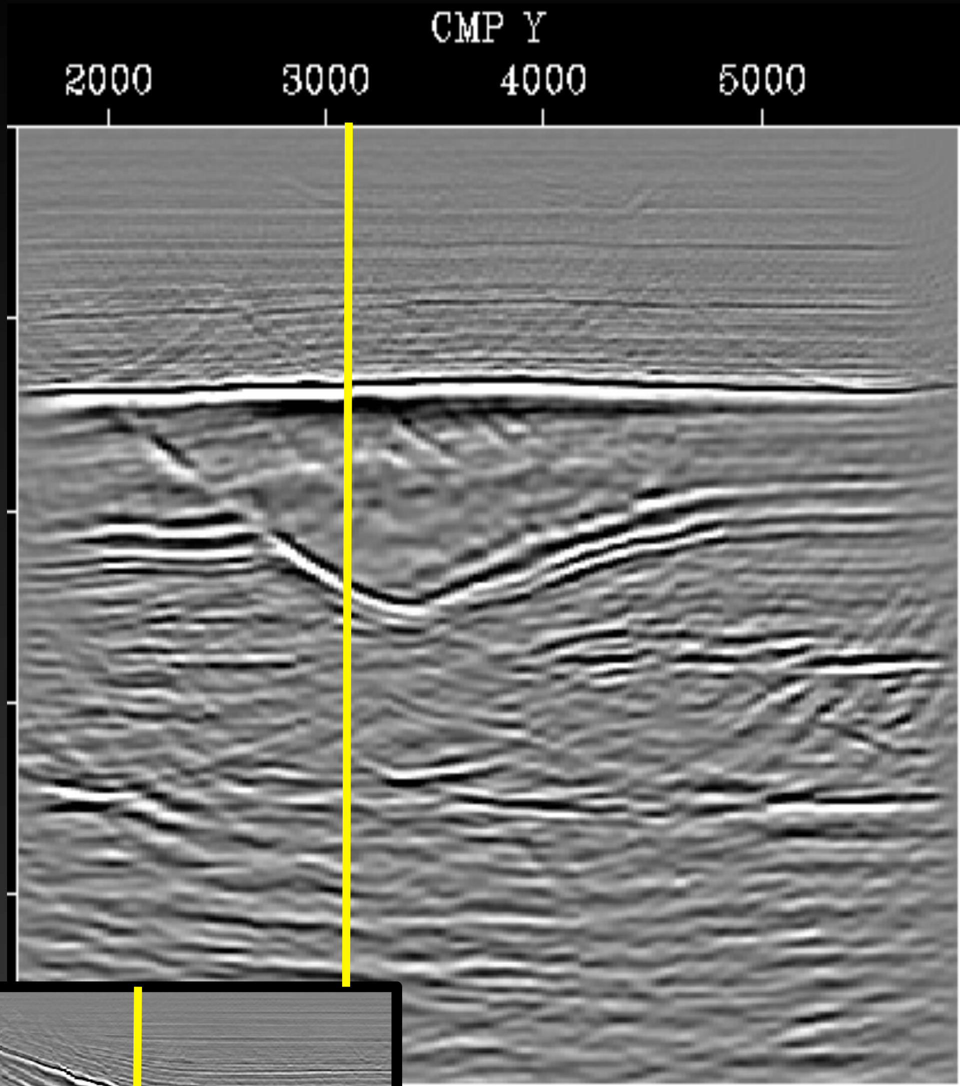


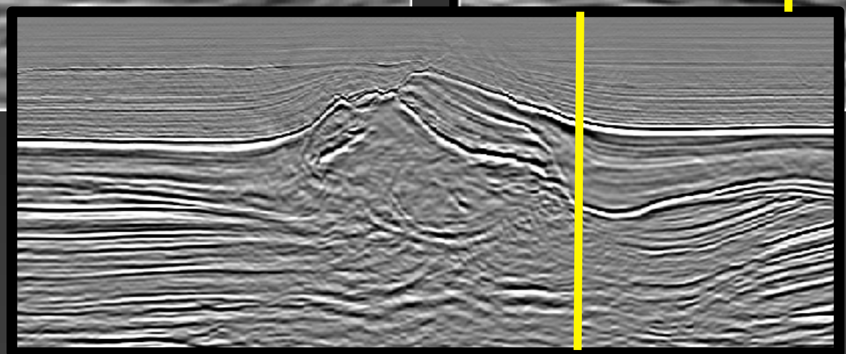
Comparisons: xline = 8200 m

Original



After salt body





Comparisons: xline = 9300 m

Original | **After salt body**