Wave-equation migration Q analysis

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Wave-equation migration Q analysis

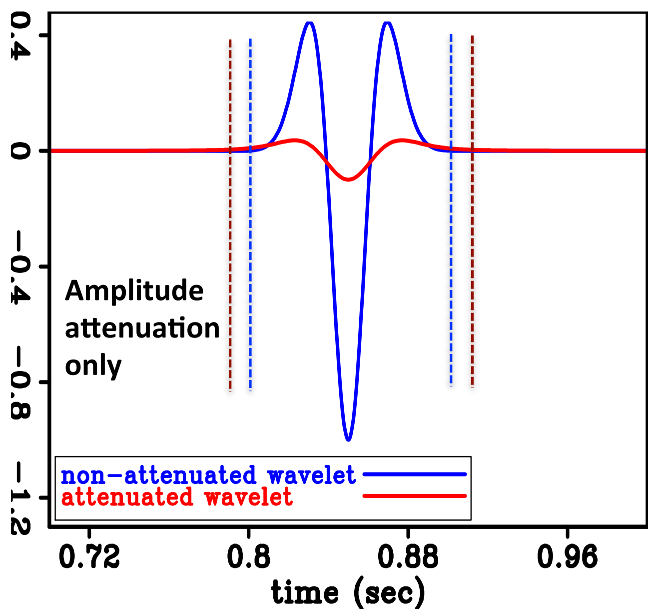
Quality factor that quantifies seismic attenuation

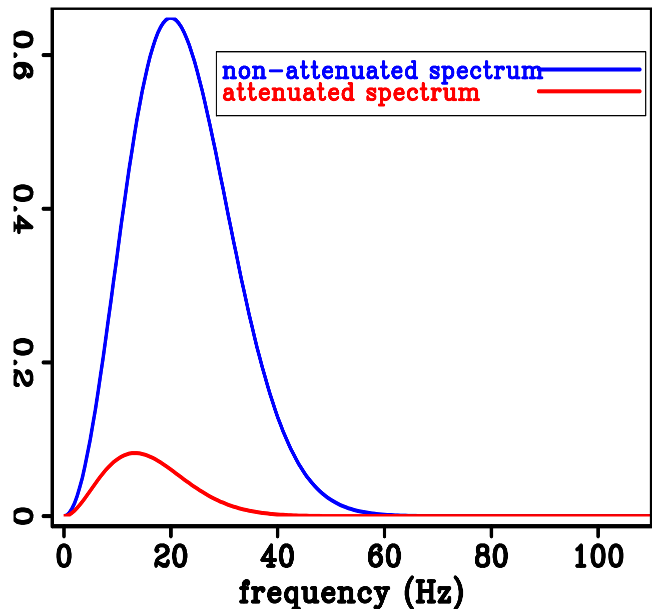
- Small Q means large attenuation
- Strong attenuation: Q ~ 10-50
- Nearly no attenuation: Q >5000

Effect of attenuation on amplitudes

Amplitudes

- The **higher** frequencies of a wave are attenuated more than its lower frequencies

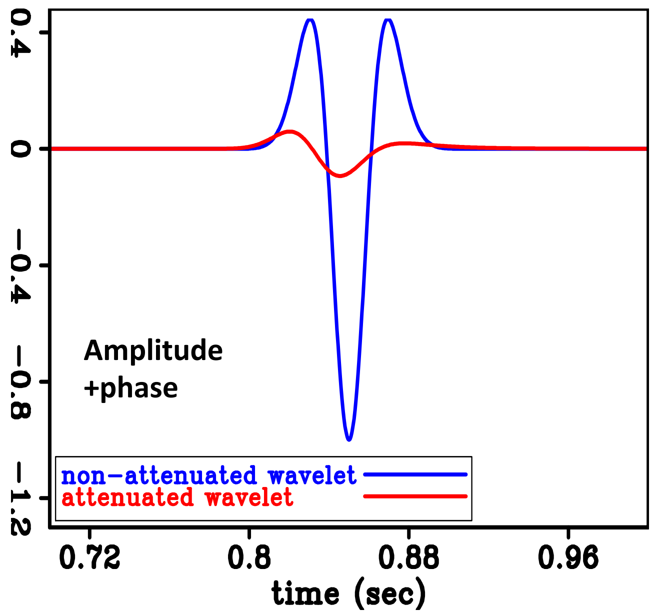


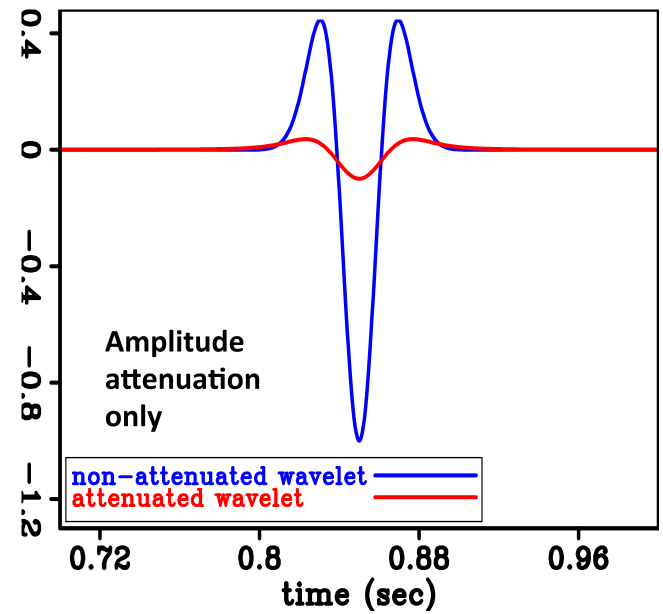


Effect of attenuation on phase

Phase

- The **higher** frequencies of a wave travel faster than its lower frequencies

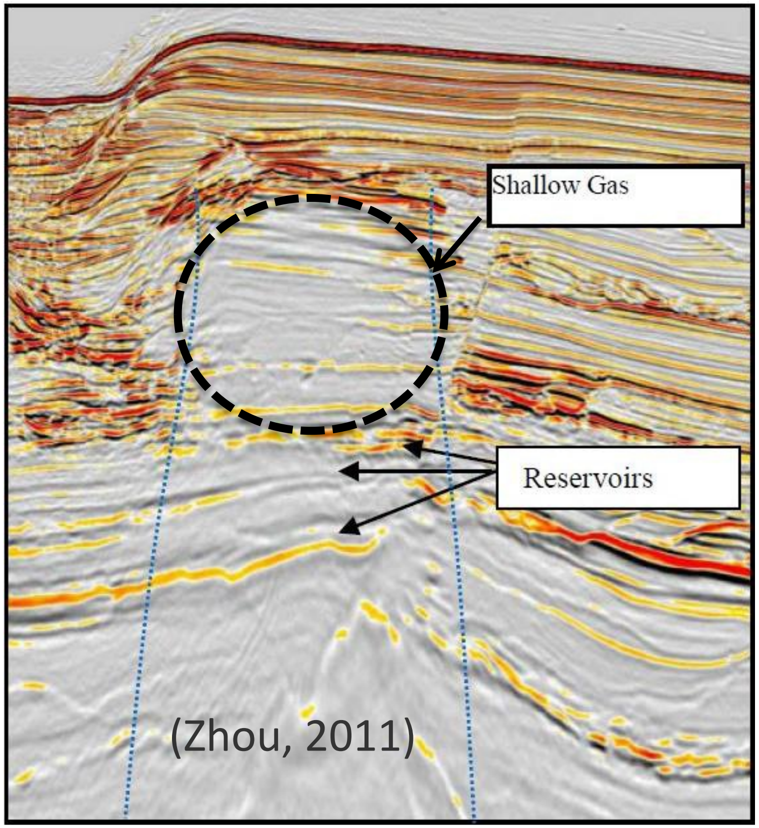




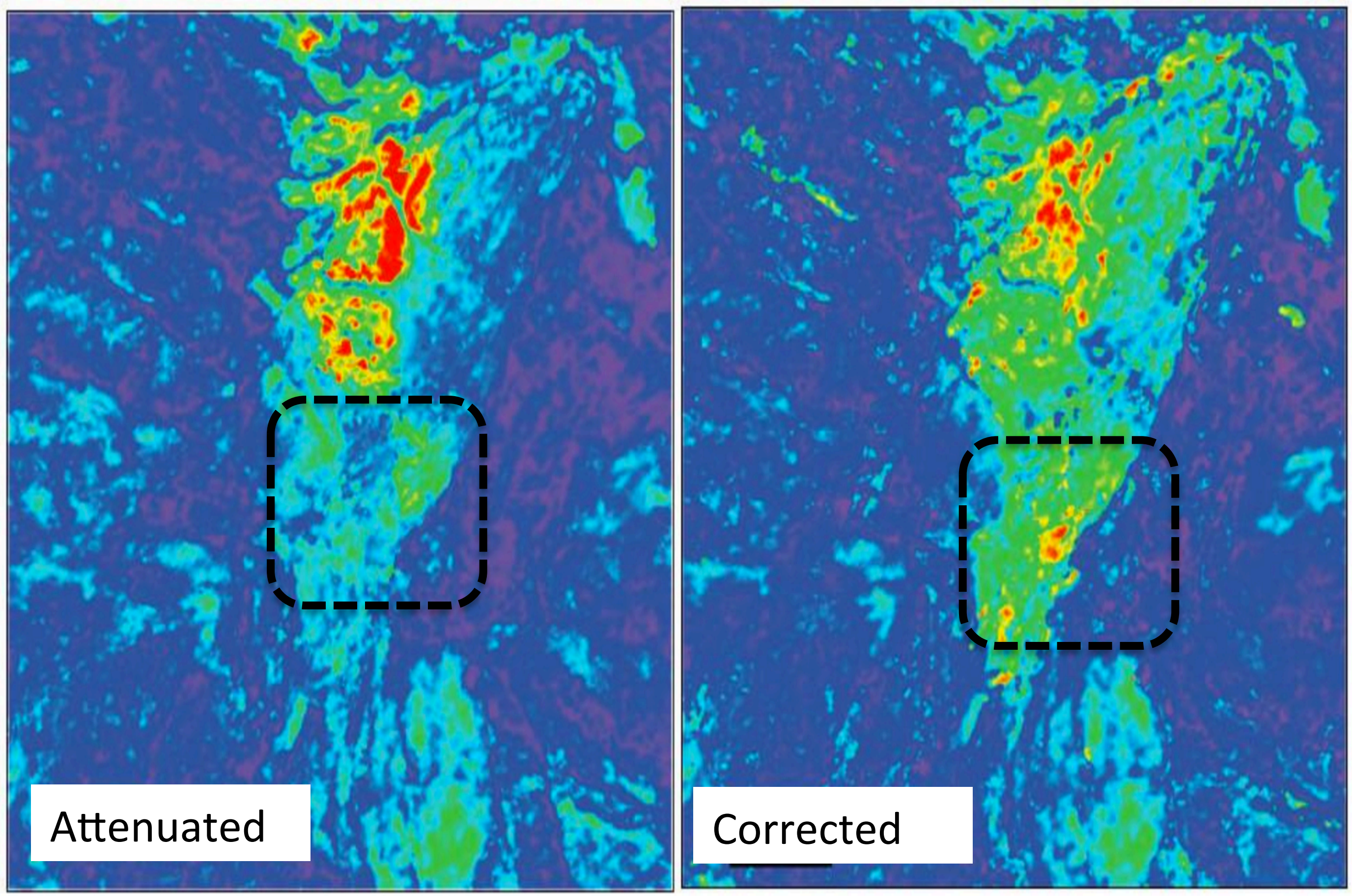
Effect of attenuation on image

- **Migration without Q compensation**
  - Damps amplitudes
  - Lowers resolutions
  - Disperses phases

- ***e.g.,* Gas trapped in sediments**
  - Degrades image quality
  - Makes identification and interpretation inaccurate

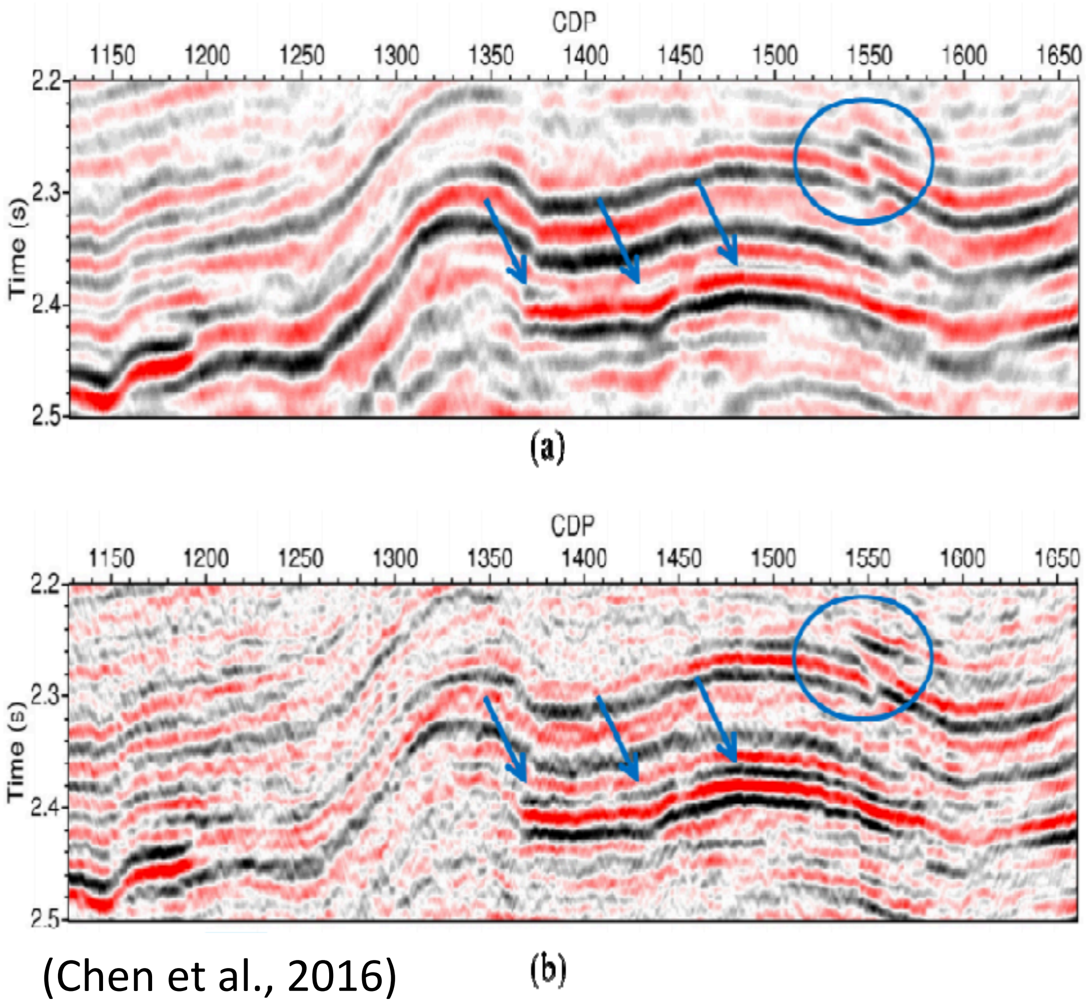


Effect of attenuation on reservoir characterization



(Francis, 2016)

Effect of attenuation on reservoir characterization



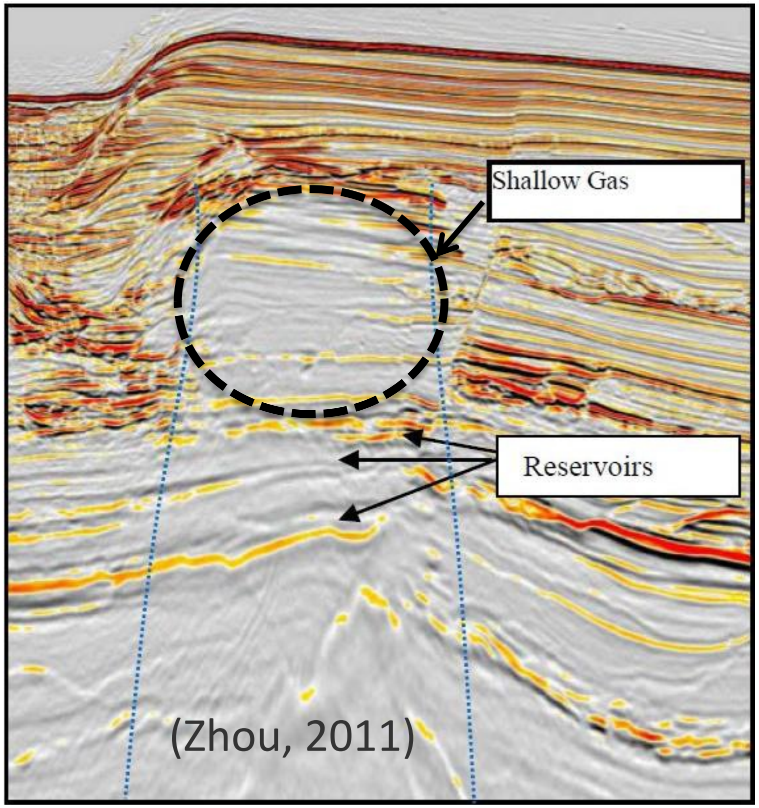
Attenuated

Corrected

(Chen et al., 2016)

Motivation

- **Goal of my study**
  - Target the attenuation caused by clouds/pockets
  - Understand and quantify the attenuation effects
  - Create and accurate Q model
  - Use the Q estimates to enhances seismic image quality



(Zhou, 2011)

Thesis chapters

- **Chapter 1:** Introduction
- **Chapter 2:** Wave-Equation Migration Q Analysis
- **Chapter 3:** Rock physics constrained WEMQA
- **Chapter 4:** Multi-parameter inversion of velocity and Q using wave-equation migration analysis
- **Chapter 5:** Field data application
- **Chapter 6:** Conclusions

Thesis chapters

- **Chapter 1:** Introduction
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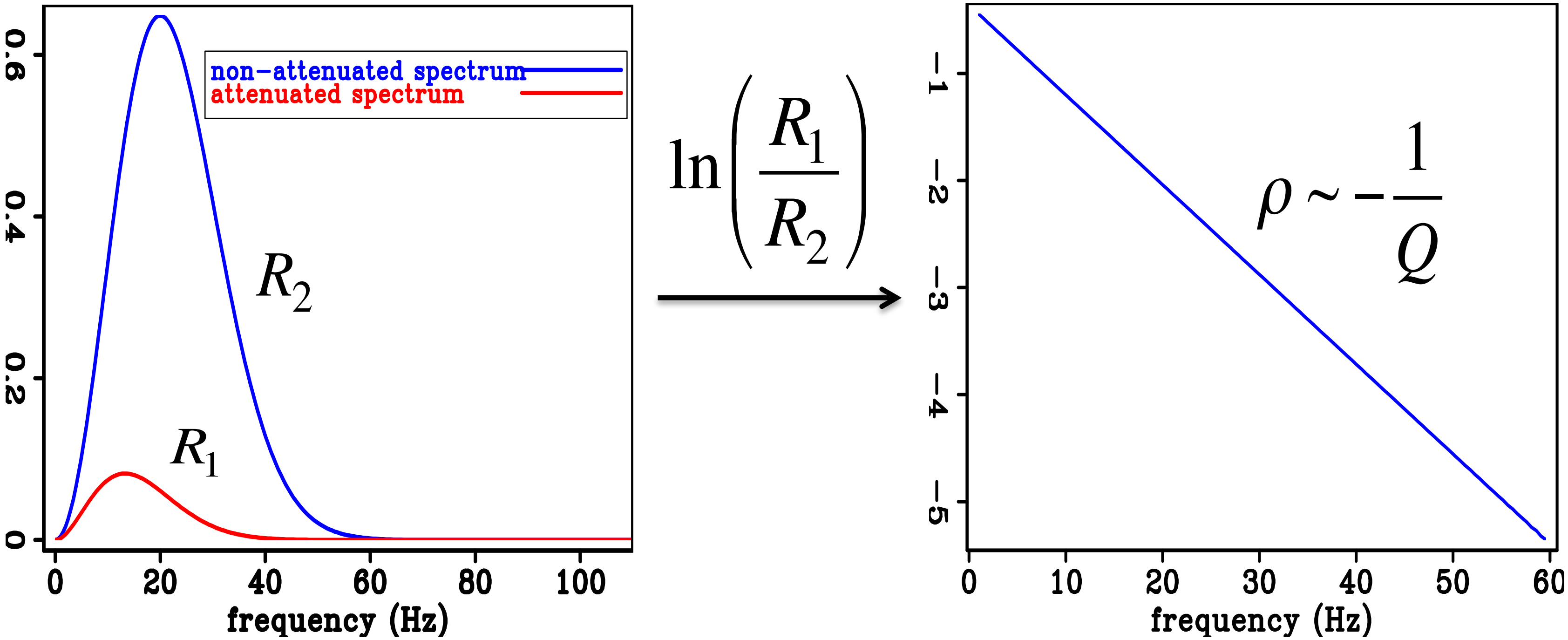
Outline

- Background
- Theory of wave-equation migration Q analysis
- Numerical examples
  - Synthetic examples
  - 3D field data examples
- Conclusions

Spectral ratio method

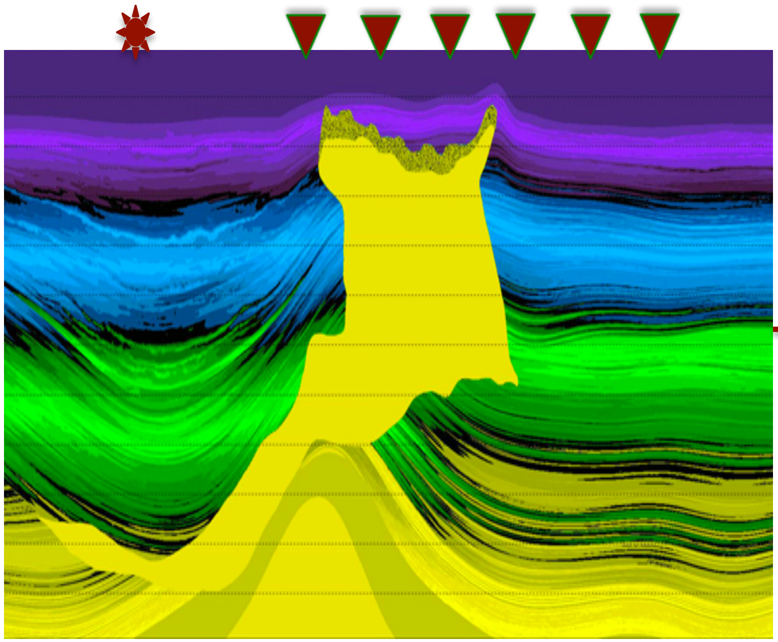


(Tonn, 1991)

Traditional approach

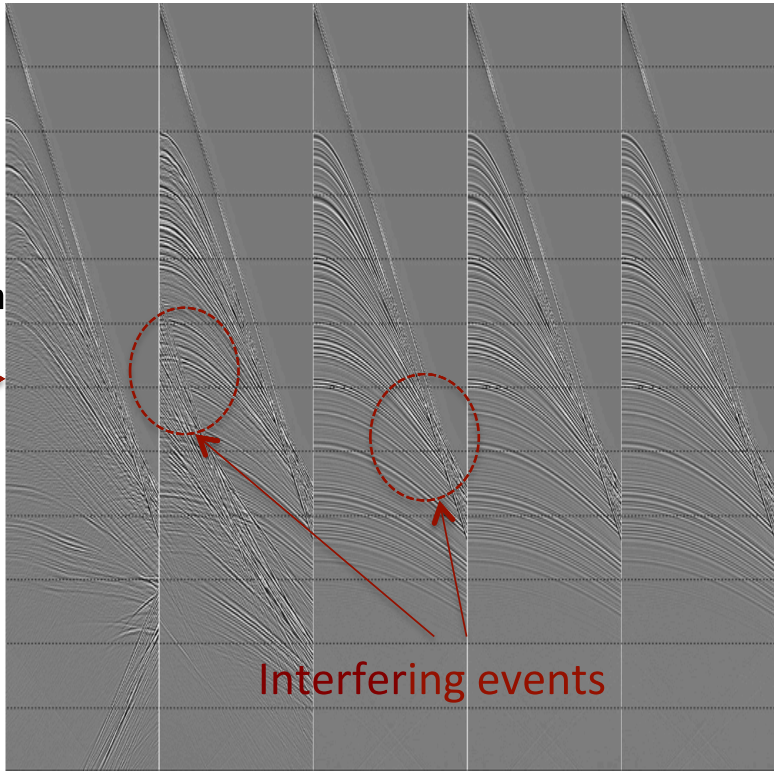
- Quantify attenuation effects in data space before seismic migration
- Update Q model using ray-based tomography

Traditional approach: data space



Recorded seismic data

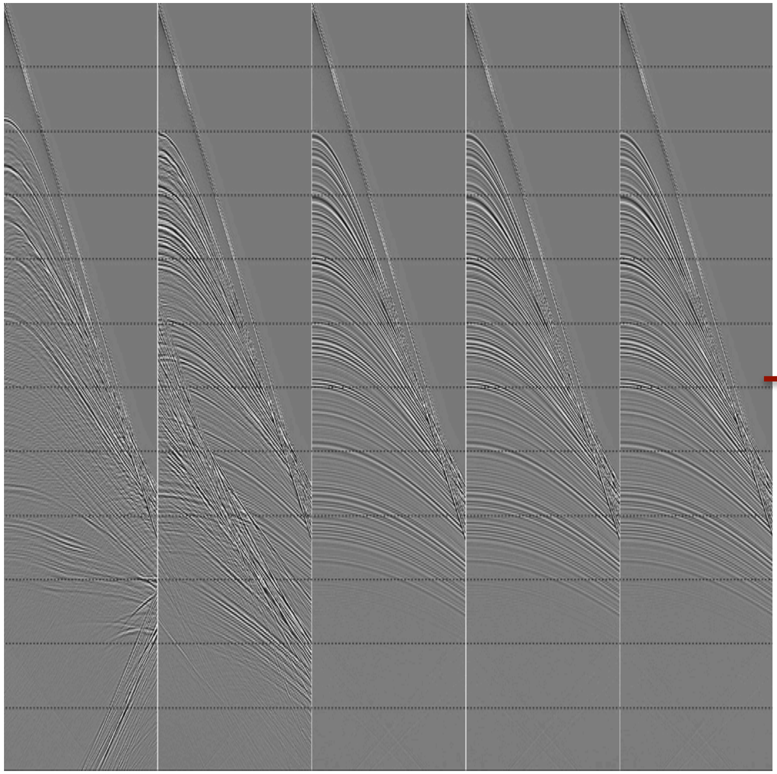
Seismic data: 5 shot gathers



Synthetic examples:
http://www.spectrumgeo.com/imaging-services/land-environment/depth-processing/pre-stack-depth-migration

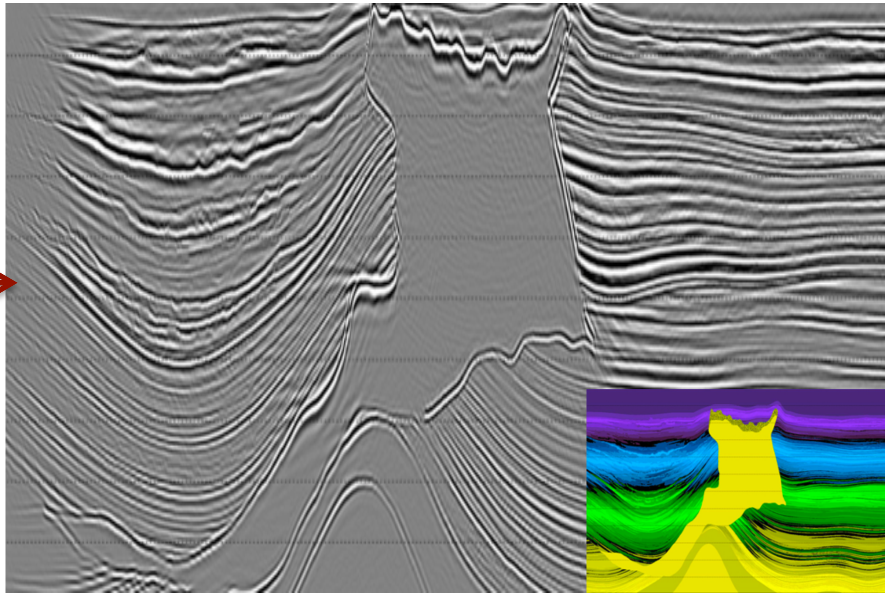
New approach: image domain

Seismic data: shot gathers



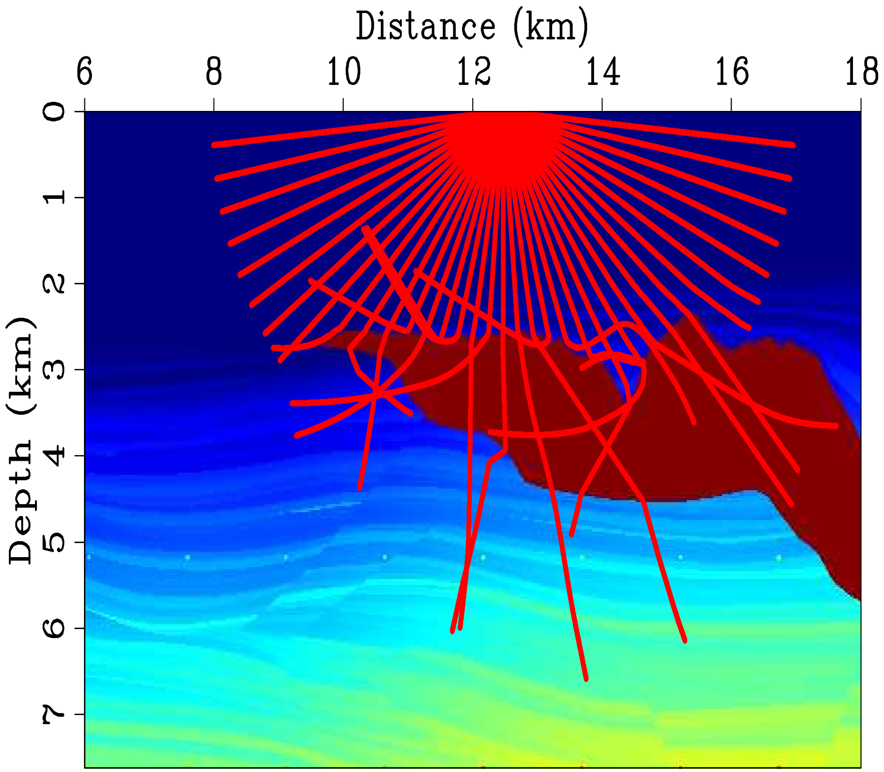
Seismic migration

Seismic migrated image



Synthetic examples:
http://www.spectrumgeo.com/imaging-services/land-environment/depth-processing/pre-stack-depth-migration

Traditional approach: ray-based tomography

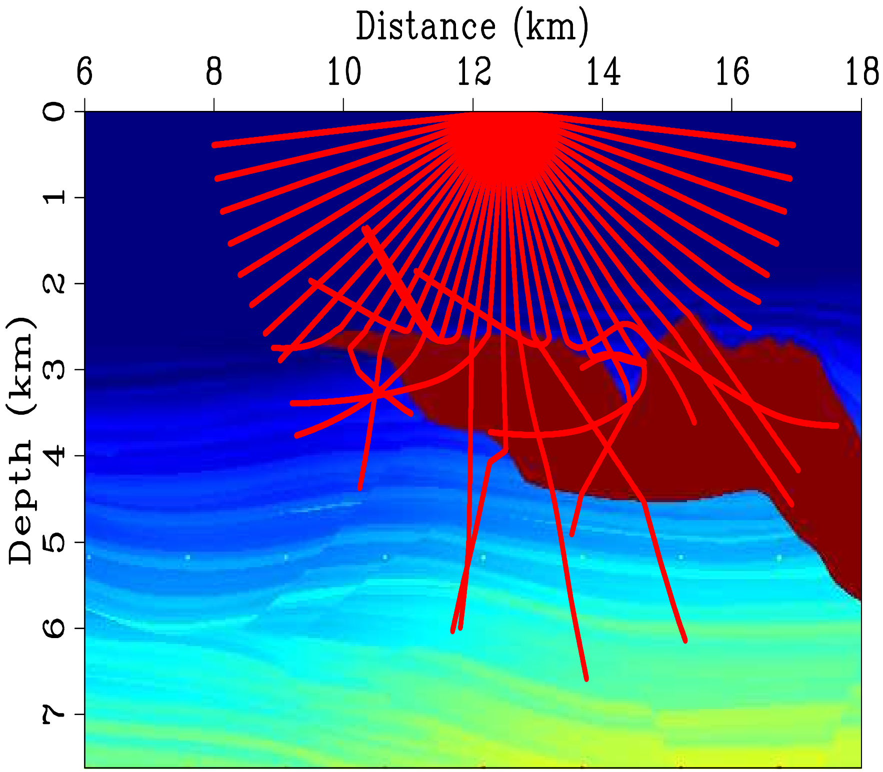


ray-based tomography

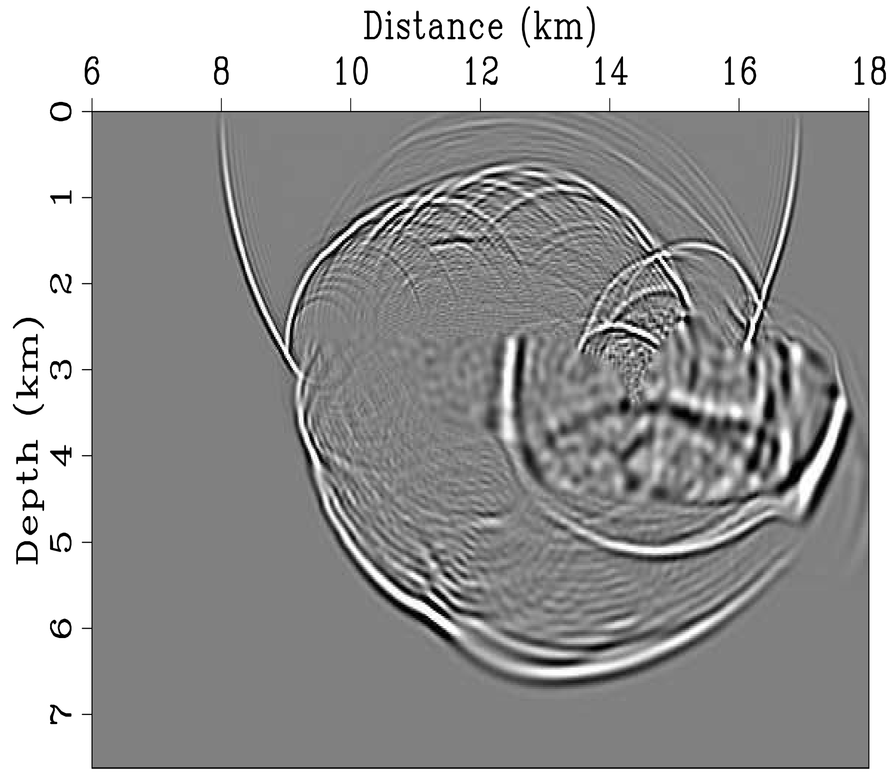
- High–frequency approximation
- Oversimplifies multi-pathing

(Tang, 2011)

New approach: wave-equation-based tomography



ray-based tomography



wave-equation-based tomography

(Tang, 2011)

New approach

- **Quantify attenuation effects in image space after seismic migration**
  - Suppresses the noise
  - Simplifies and focuses the events
  - Can be implemented in a target-oriented fashion

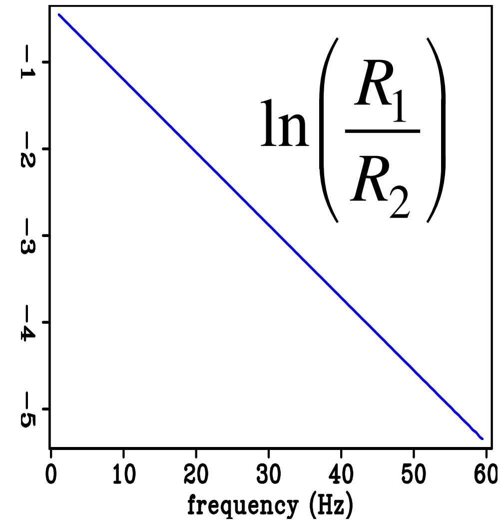
- **Update Q model using wave-equation based tomography**
  - Handle strong heterogeneities in the subsurface (e.g., salt body)
- **Wave-equation migration Q analysis (WEMQA)**

Objective function

- Define ρ as the effect of attenuation (**effect of Q**) on seismic **migrated images**

$$J = \frac{1}{2}\sum_{\mathbf{x}}\left|\rho\left(\mathbf{x};Q\right)\right|^2$$

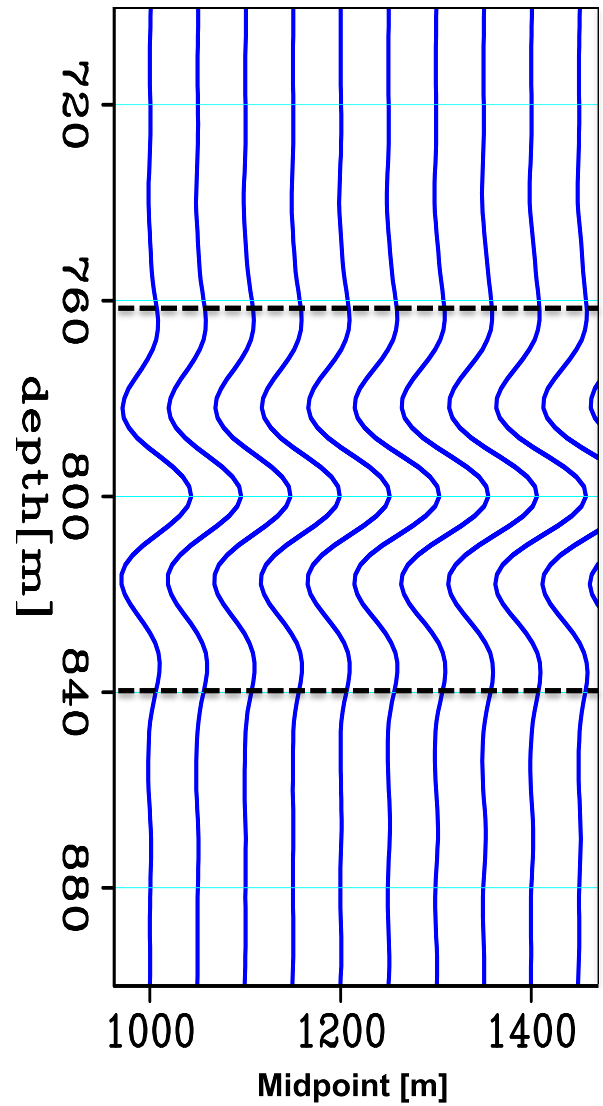
x is each a spatial location in the image space
Q is the current model for quality factor



Spectral ratio method

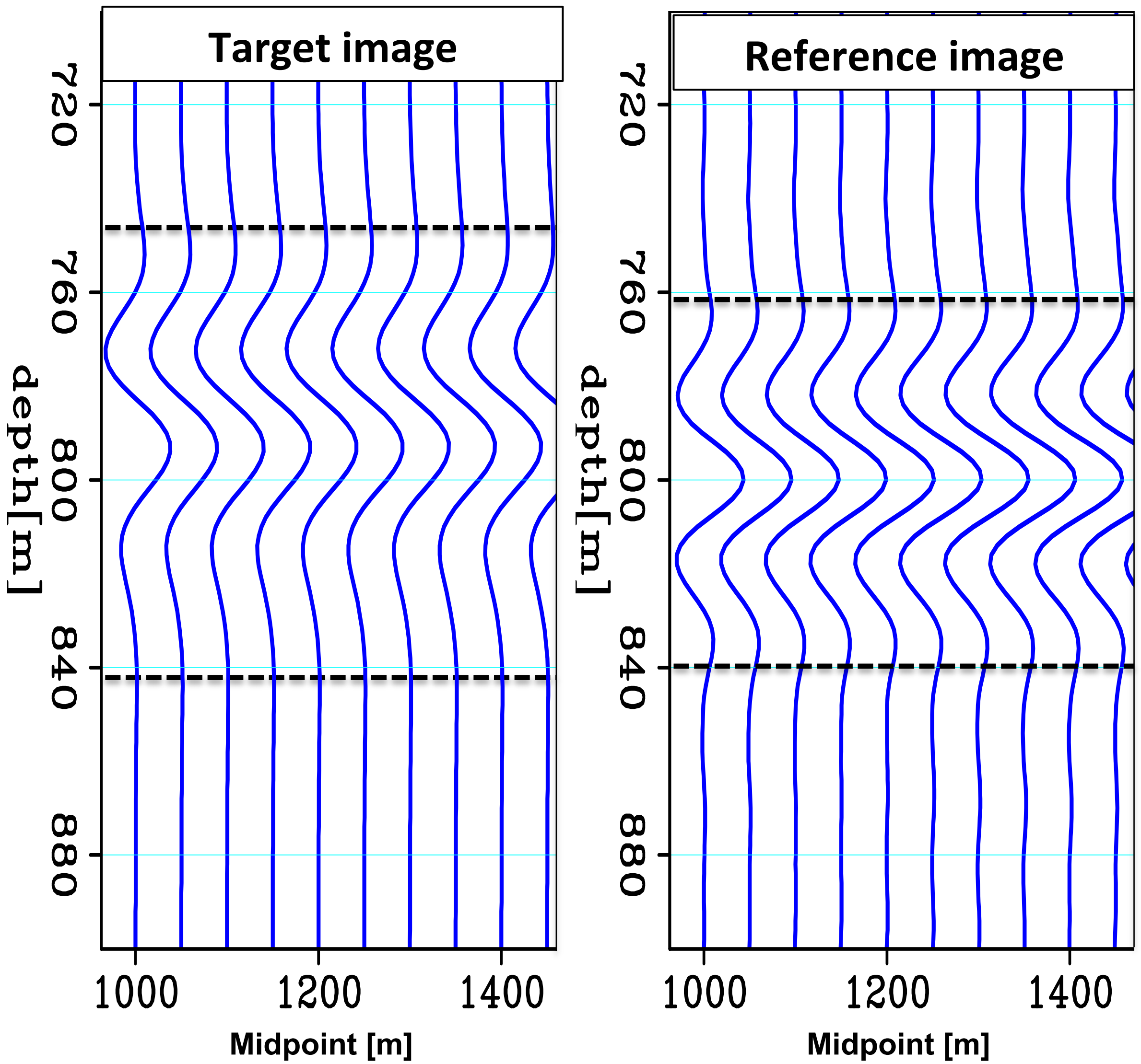
Reference migrated image

Reference image (spectrum R_2)
True model: Q_2=30
RMS amplitudes: 1.5
Events at z=800 m
Symmetric wavelets



Migrated image using inaccurate Q

Target image (spectrum R_1)
Current model:Q_1=10,000
RMS amplitudes: 0.13
Up-shifted events
Stretched wavelets

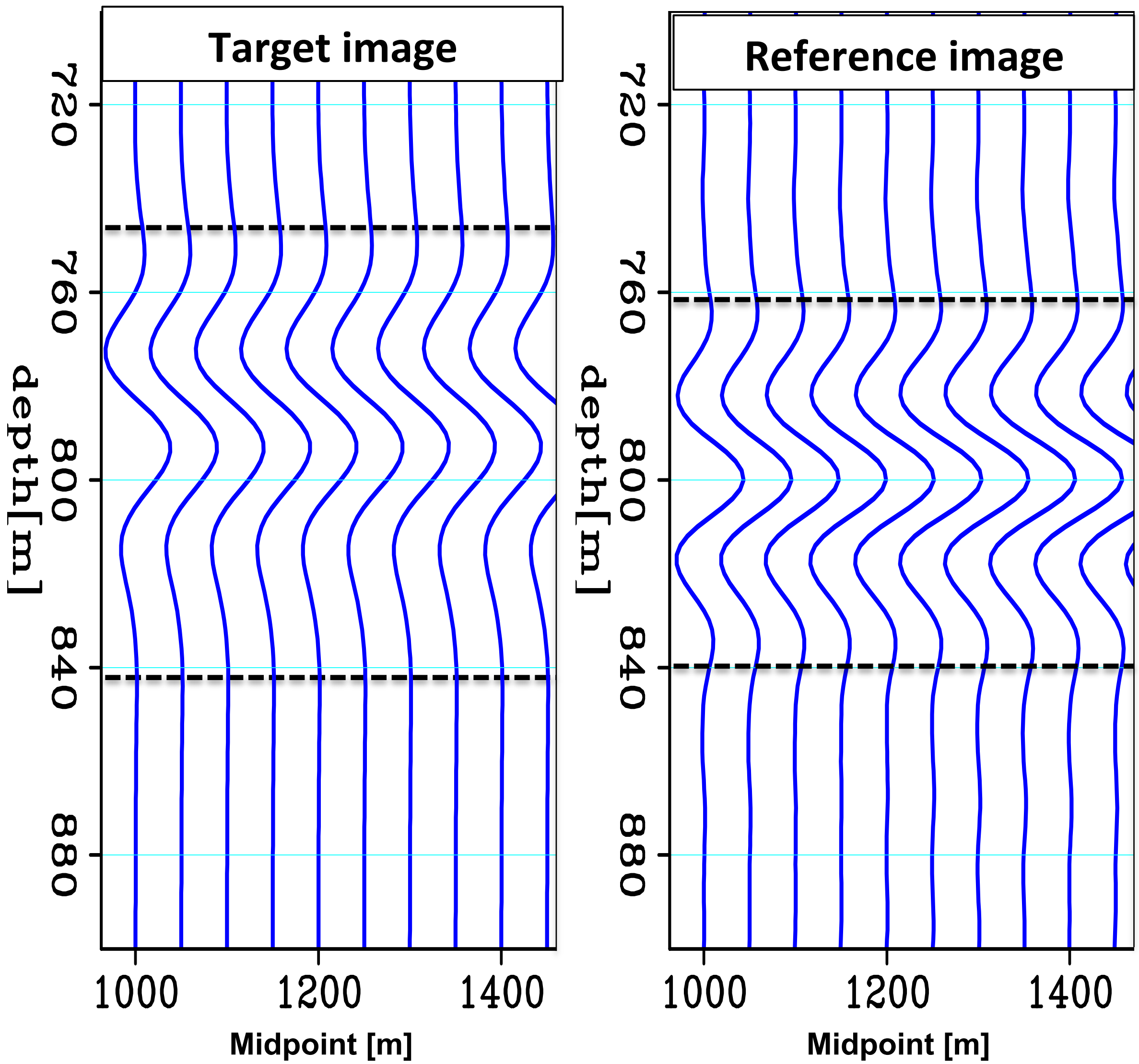


Migrated image using inaccurate Q

Under-compensated ($Q_1 > Q_2$)

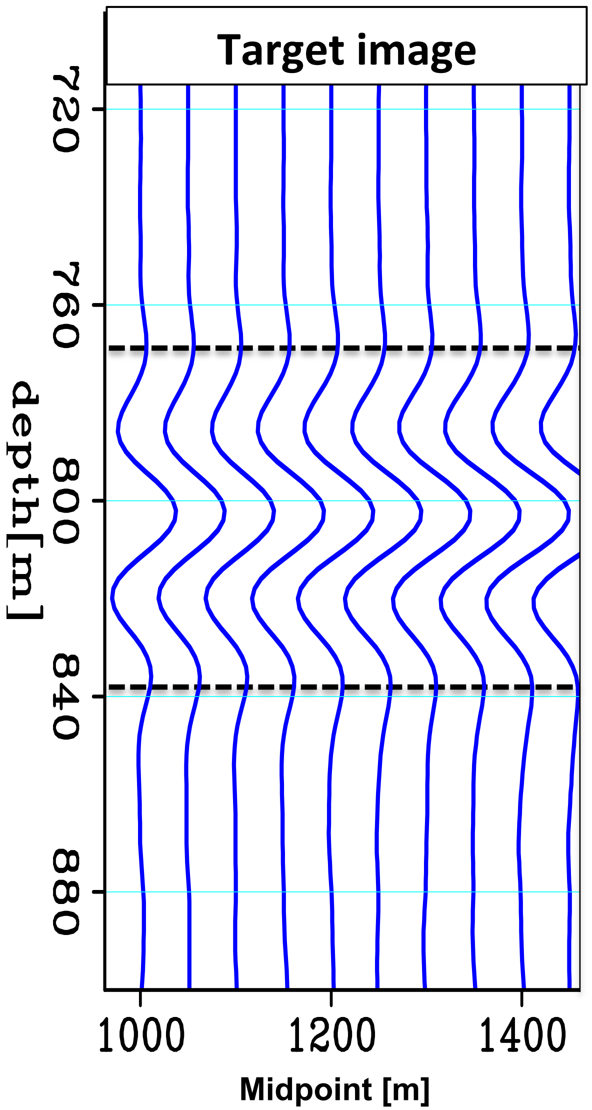
Higher frequencies are attenuated

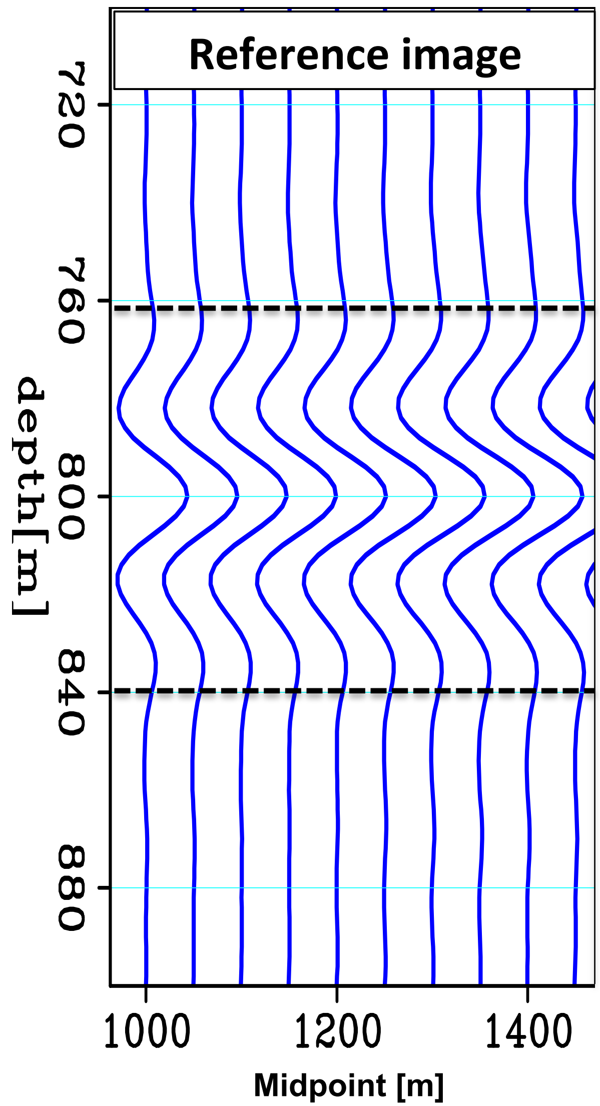
$\ln(R_1/R_2)$ => **$\rho<0$**



Migrated image using inaccurate Q

Target image (spectrum R_1)
Current model: Q_1=25
RMS amplitudes: 3.2
Down-shifted events
Squeezed wavelets



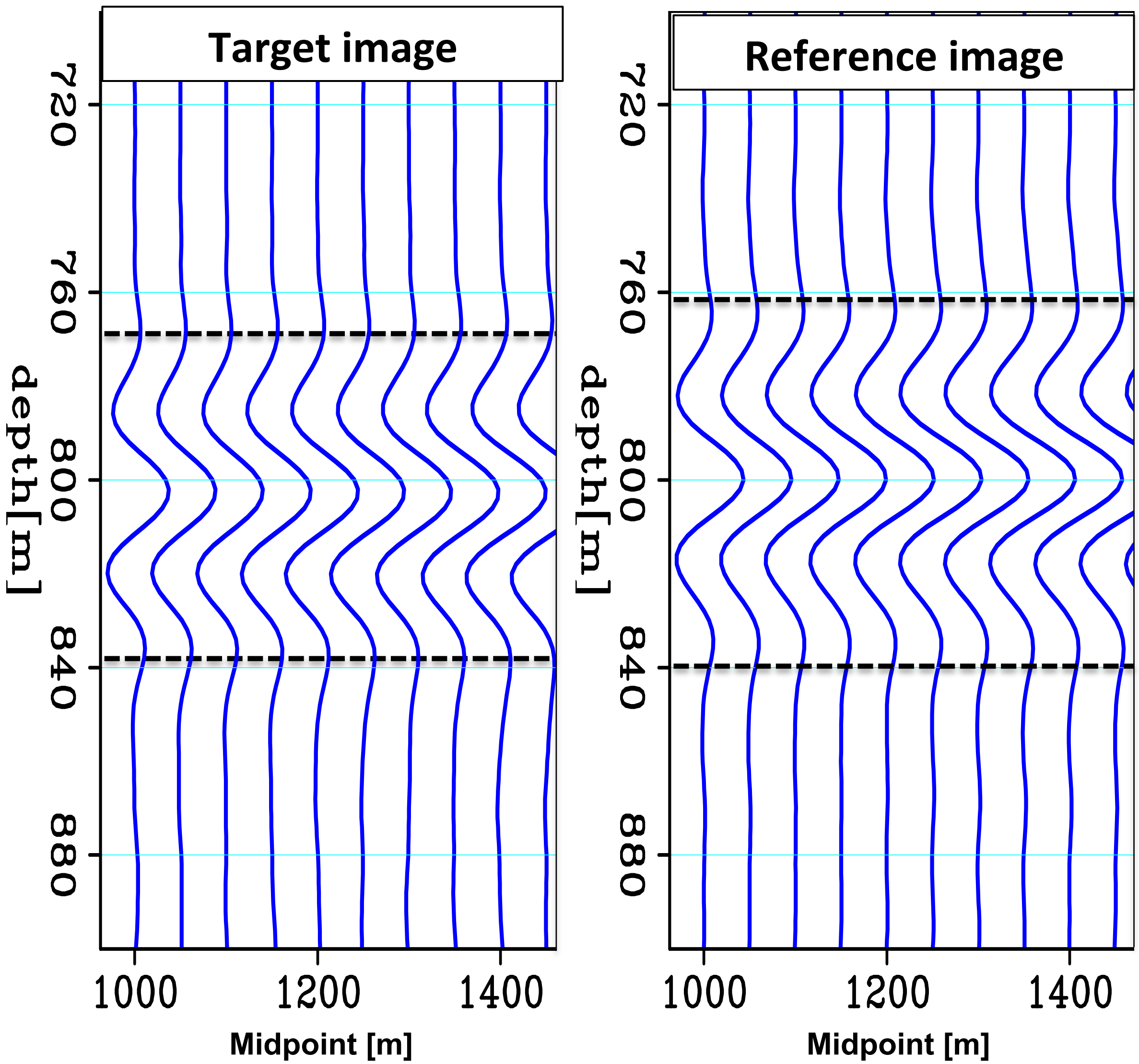


Migrated image using inaccurate Q

Over-compensated ($Q_1 < Q_2$)

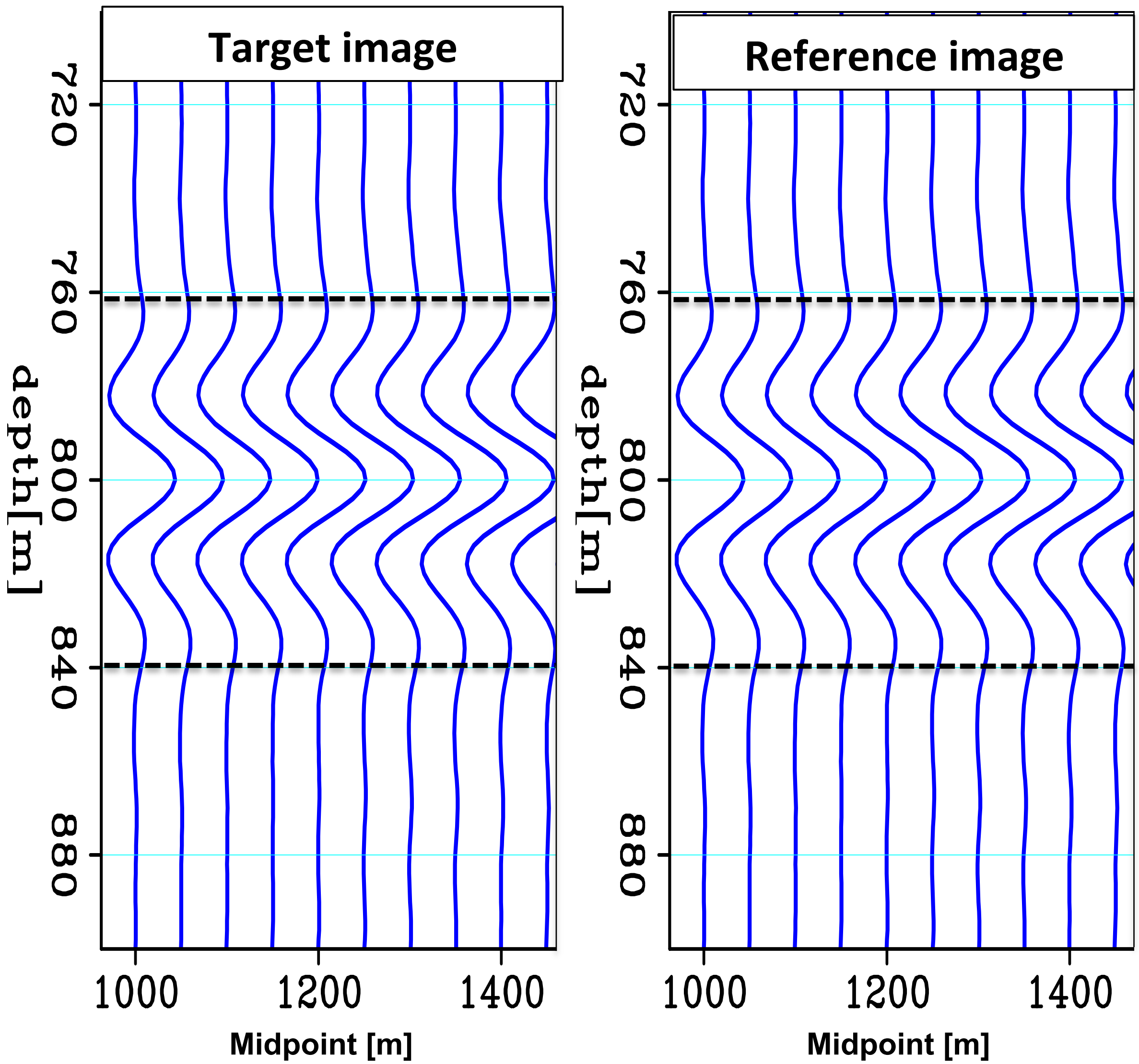
Higher frequencies are over-gained

$\ln(R_1/R_2)$ => **ρ>0**



Migrated image using inaccurate Q

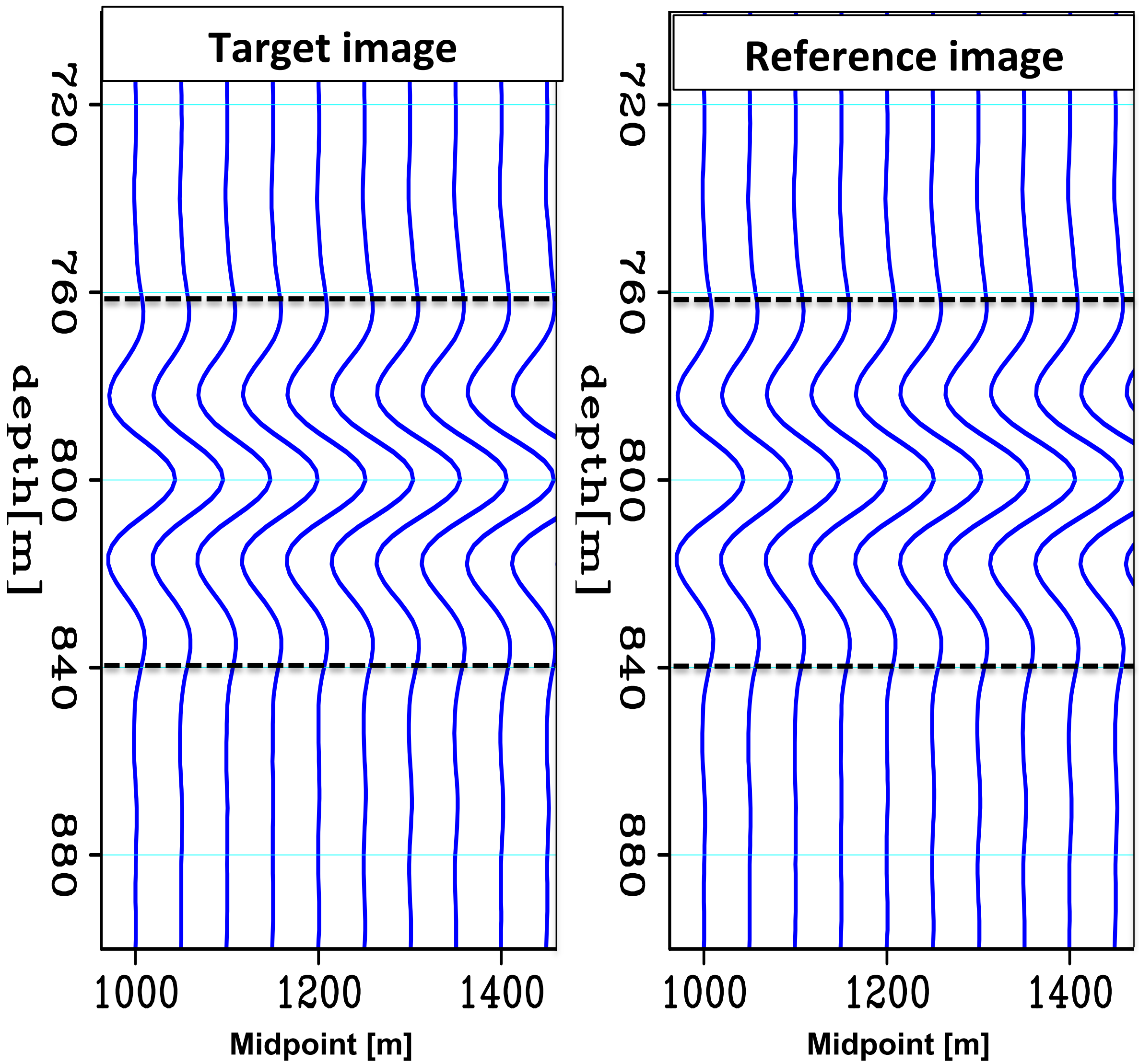
Target image (spectrum R_1)
Current model:Q_1=30
RMS amplitudes: 1.5
Non-shifted events
Non-deformed wavelets



Migrated image using inaccurate Q

Adequately-compensated ($Q_1 = Q_2$)

$\ln(R_1/R_2)$ => **ρ=0**



Spectral ratio method in image space

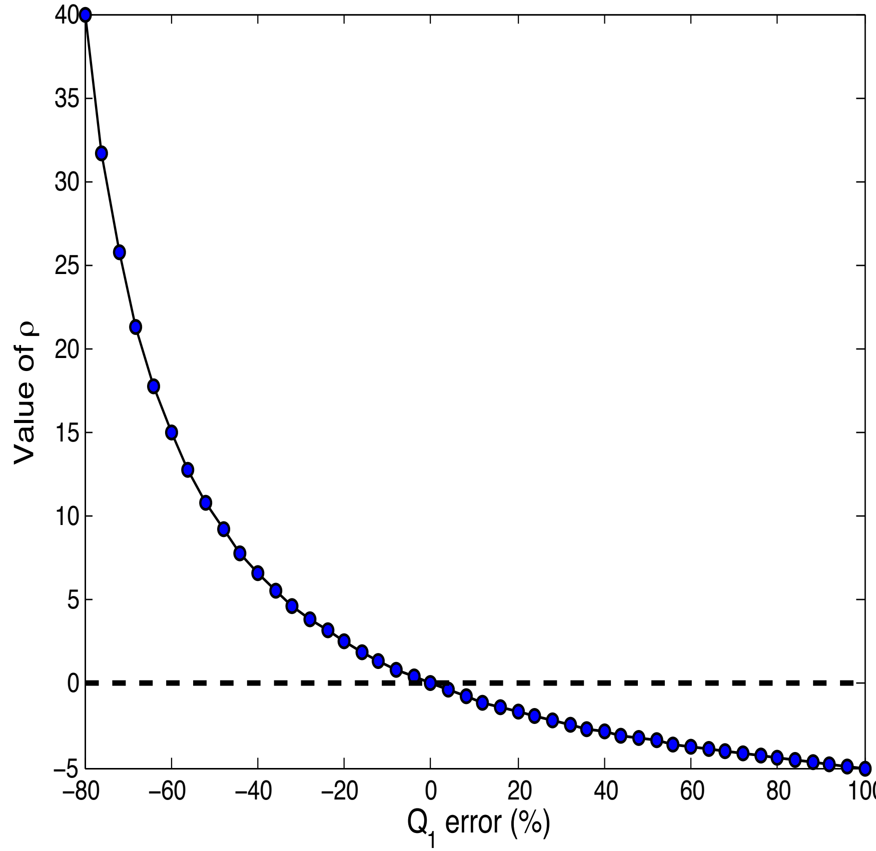
Objective function:

$$J = \frac{1}{2}\sum_{\mathbf{x}} \left| \rho(\mathbf{x}; Q) \right|^2$$

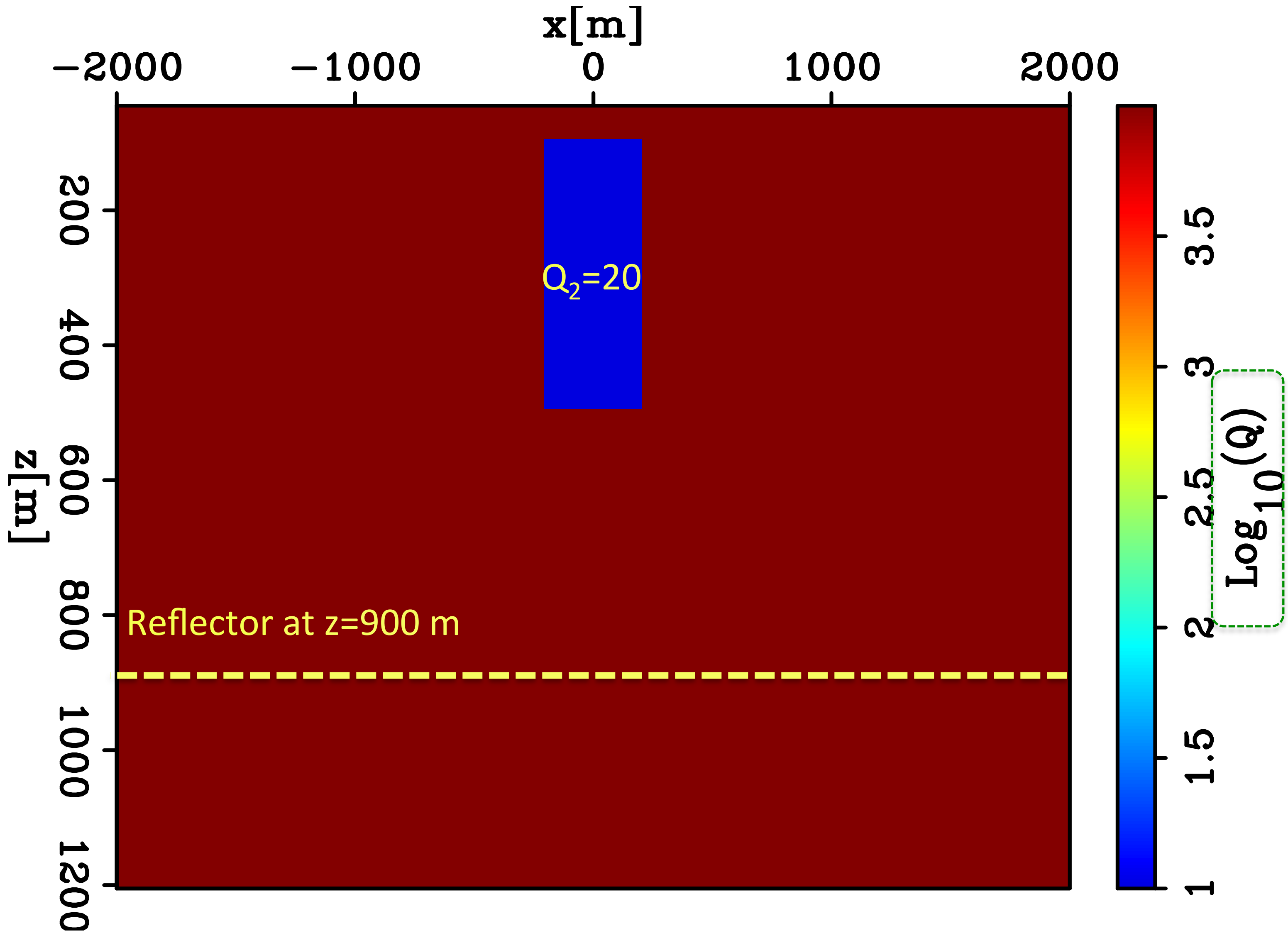
Slope

$$\ln\left(\frac{R_1}{R_2}\right)$$

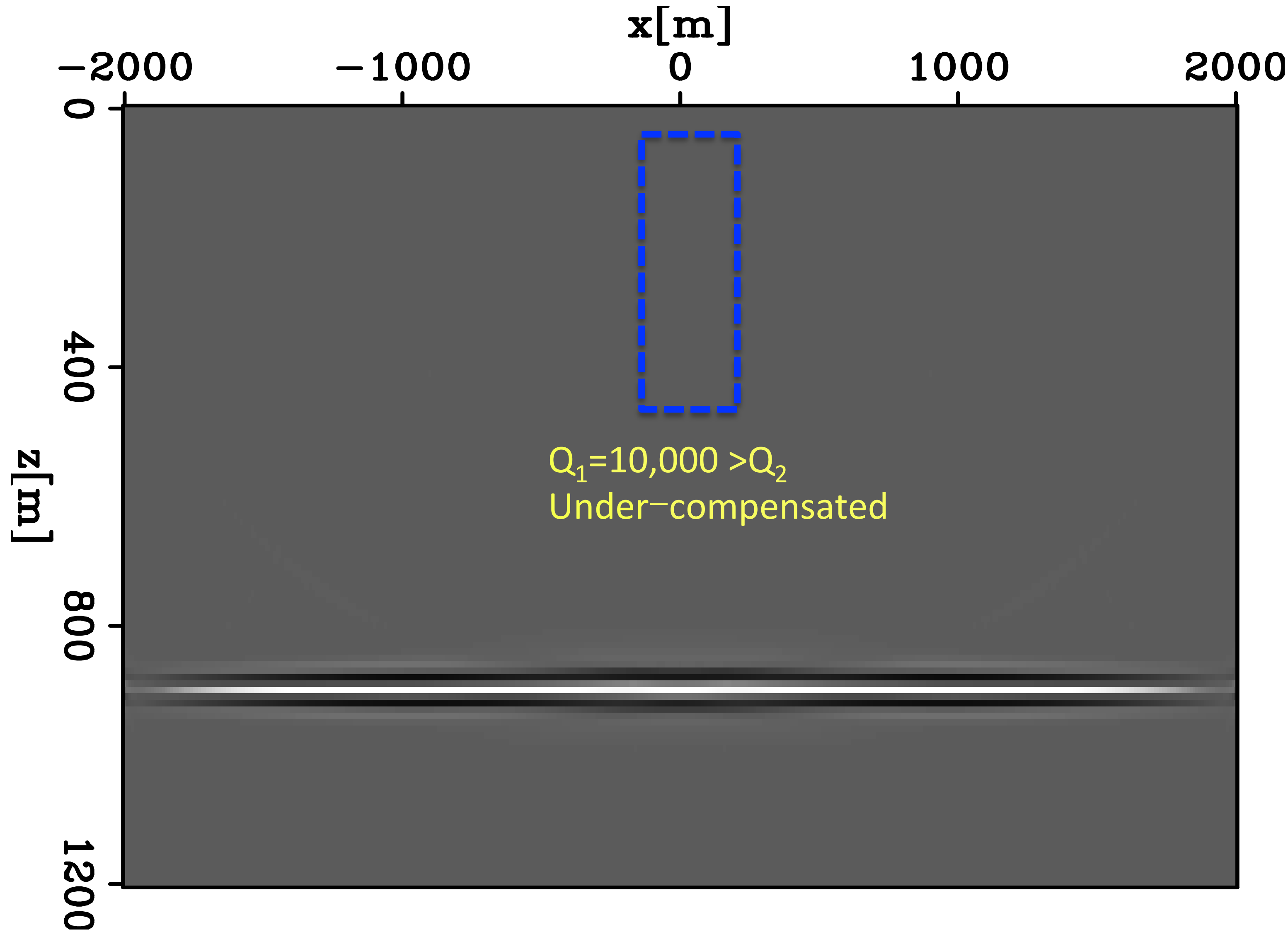
Reference spectrum



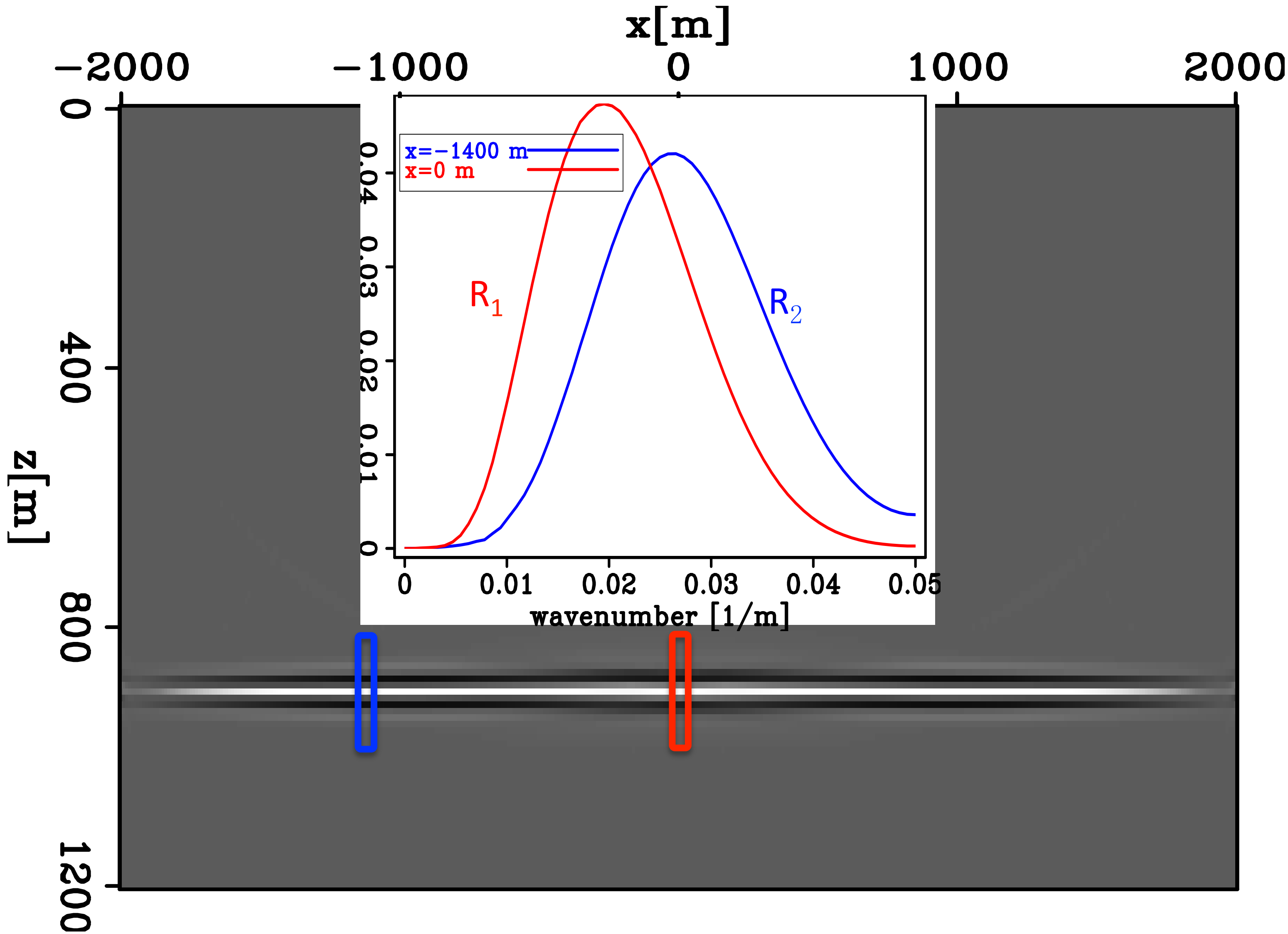
True Q model


x[m]
−2000
−1000
0
1000
2000
z[m]
200
400
600
800
1000
1200
Q2=20
Reflector at z=900 m
1
1.5
2
2.5
3
3.5
Log10(Q)

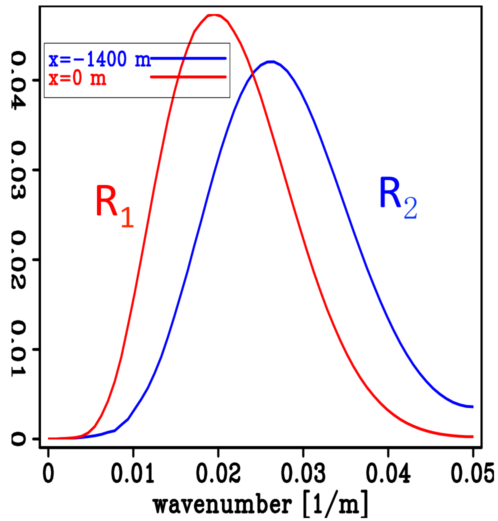
Attenuated image: migrated image at zero subsurface offset (stacked image)

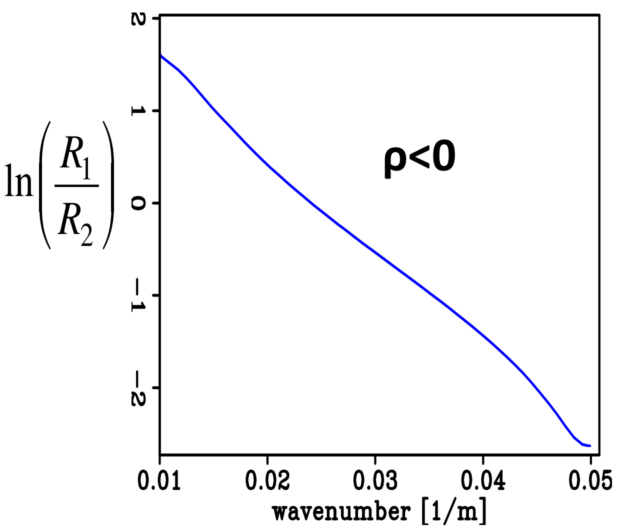


Stacked method



Stacked method

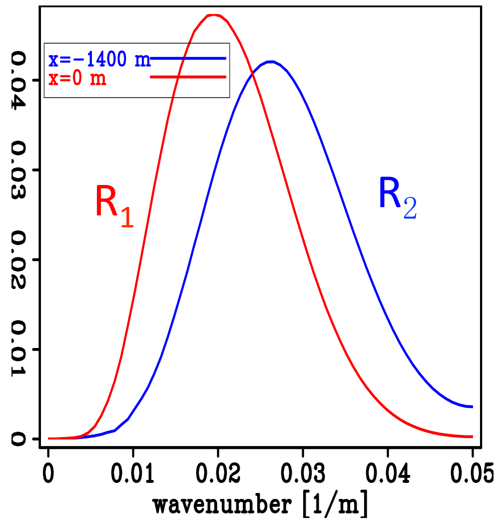


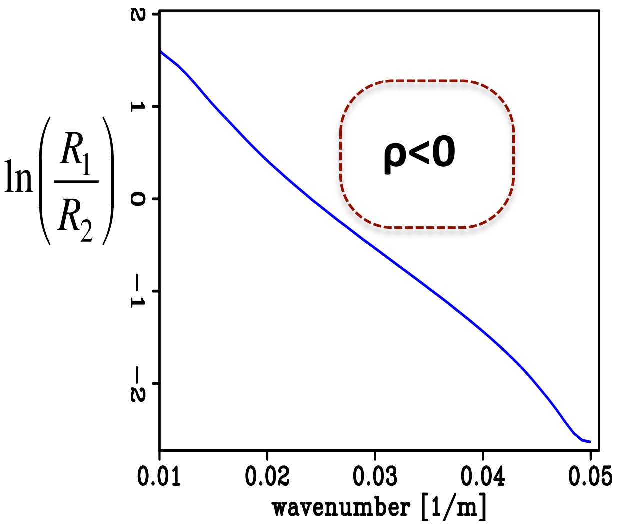


$$\ln\left(\frac{R_1(\mathbf{k}')}{R_2(\mathbf{k}')}\right) = \rho\left|\mathbf{k}'\right| + G_0$$

- Wavenumber domain

Stacked method

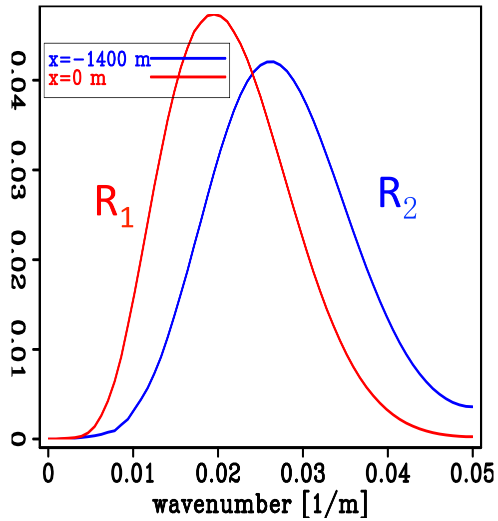


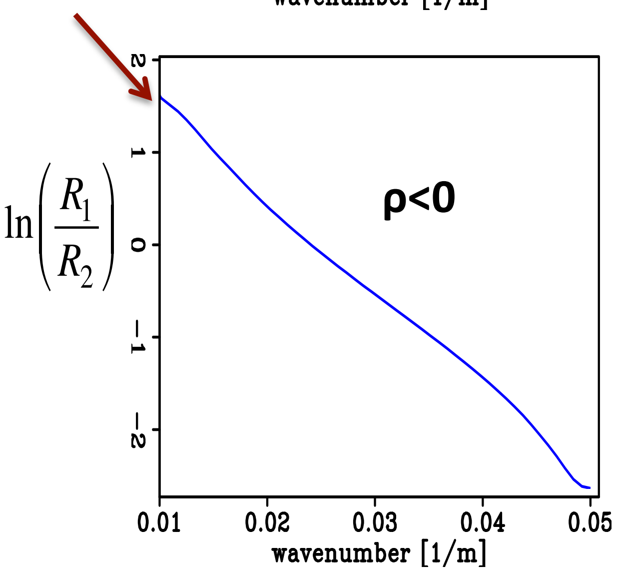


$$\ln\left(\frac{R_1(\mathbf{k}')}{R_2(\mathbf{k}')}\right) = \rho|\mathbf{k}'| + G_0$$

- Q_1=10,000 >Q_2
- The image is under-compensated (attenuated)
- ρ<0

Stacked method





$$\ln\left(\frac{R_1(\mathbf{k}')}{R_2(\mathbf{k}')}\right) = \rho|\mathbf{k}'| + G_0$$

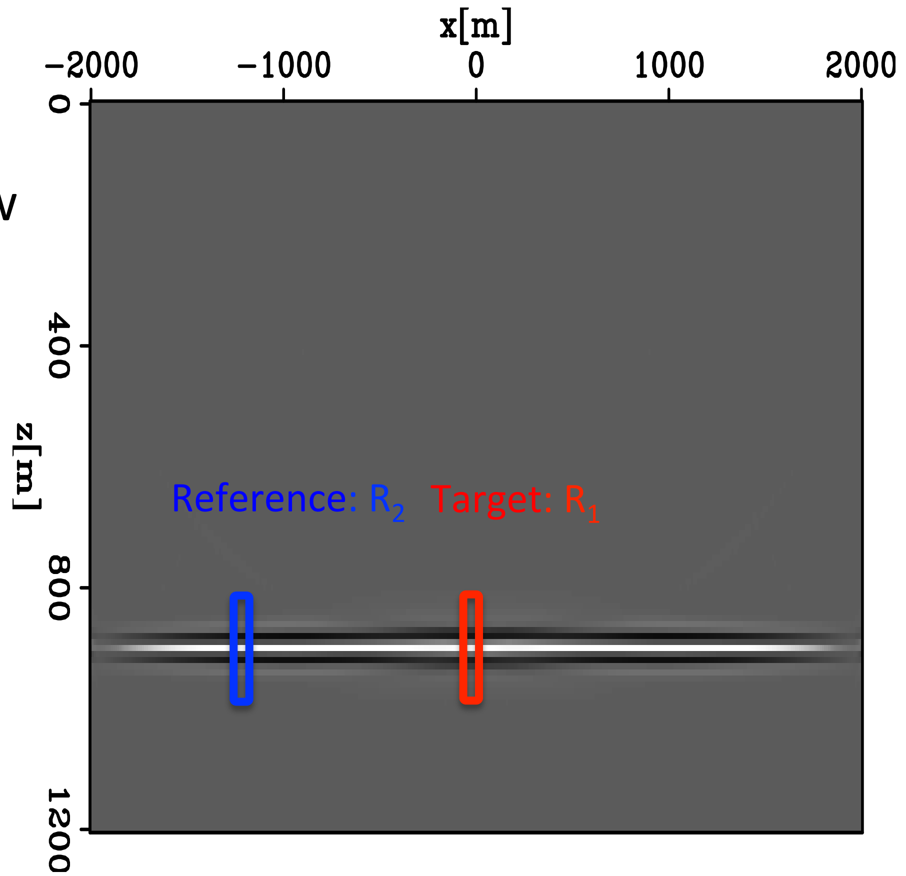
- Frequency-independent factors
  - Different illumination caused by acquisition limitations
  - Different reflection coefficients of different reflectors
  - Different geometrical spreading because of different wave-paths.

Stacked method

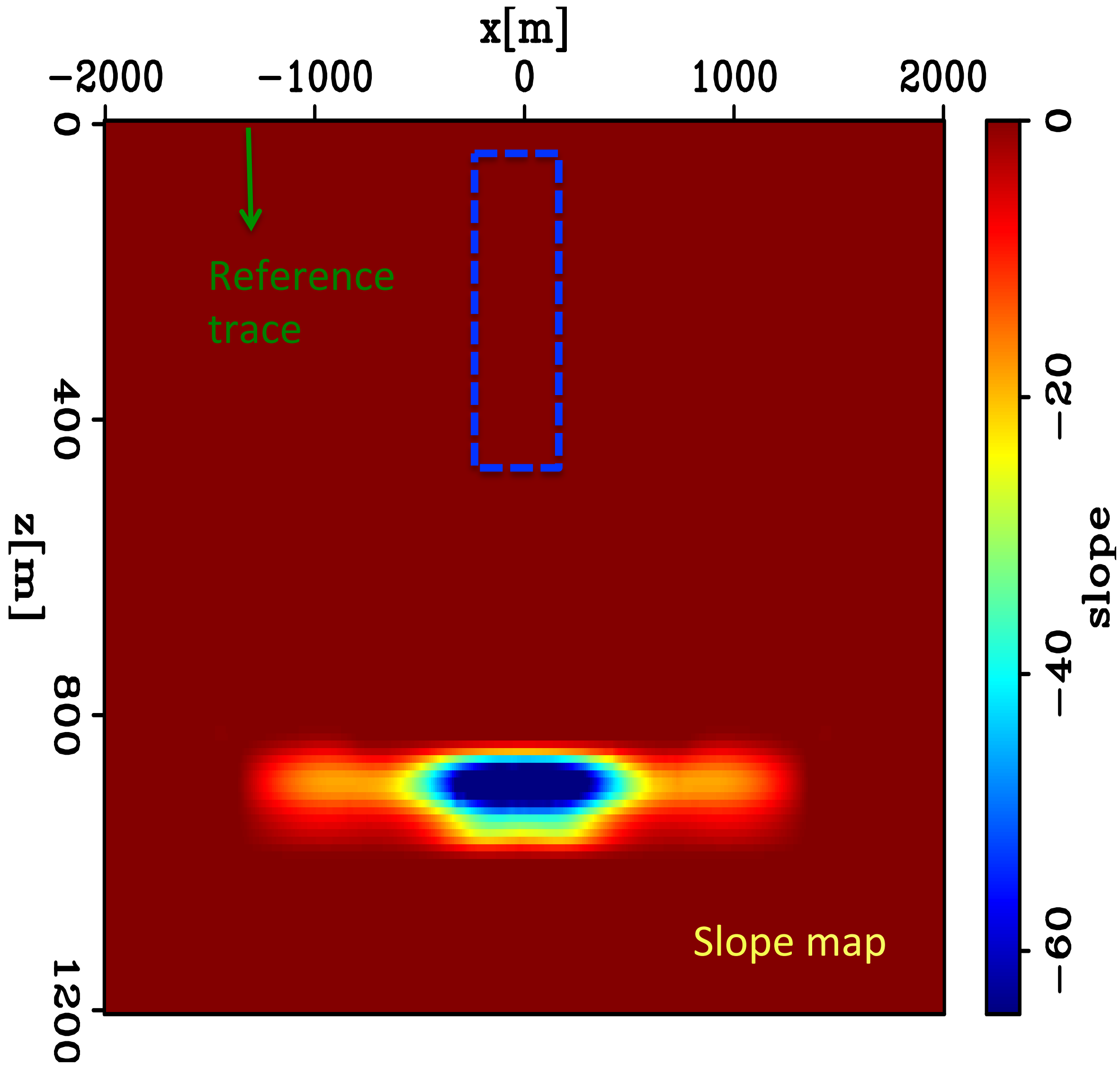
- Select one or more surface locations as reference traces
- At each image point x, I use a window of which the center is x
- Compare the windowed spectra for ρ: reference spectra and target spectra

$$\ln\left(\frac{R_1(\mathbf{k}')}{R_2(\mathbf{k}')}\right) = \rho|\mathbf{k}'| + G_0$$

- The windows are compared at the same depth



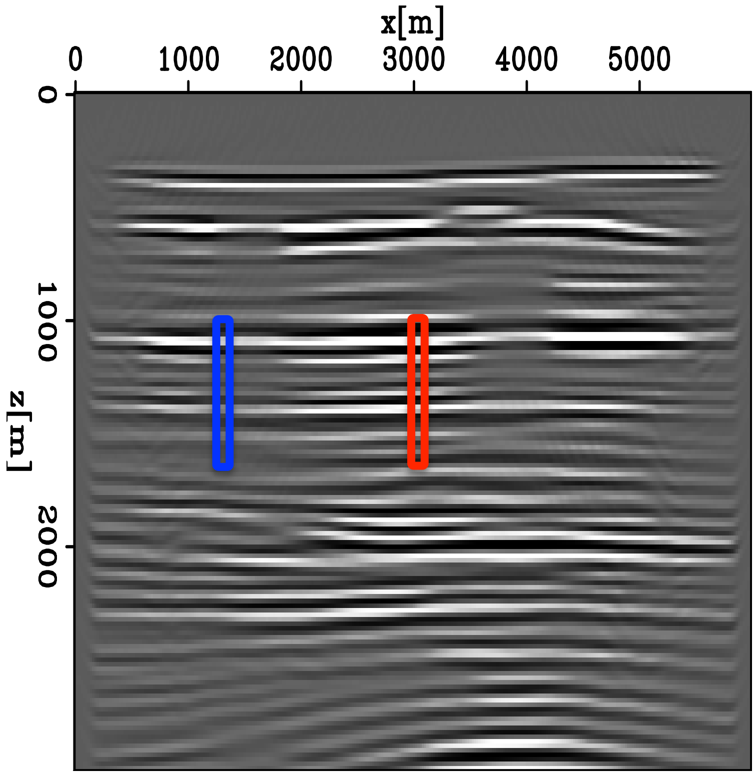
Stacked method



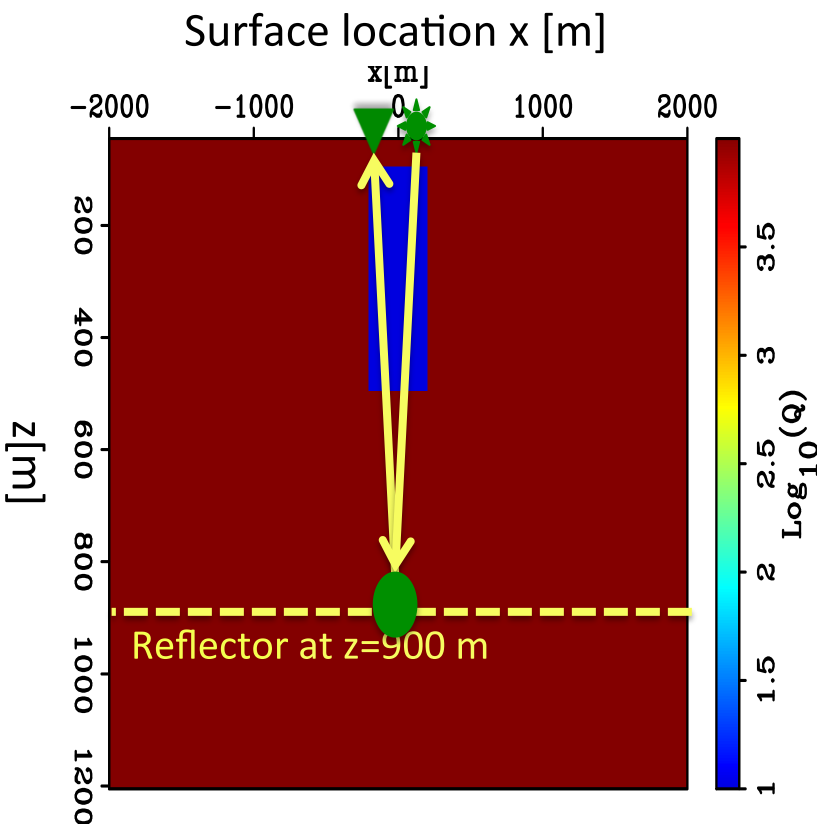
Red: non-attenuated regions
Blue: attenuated regions

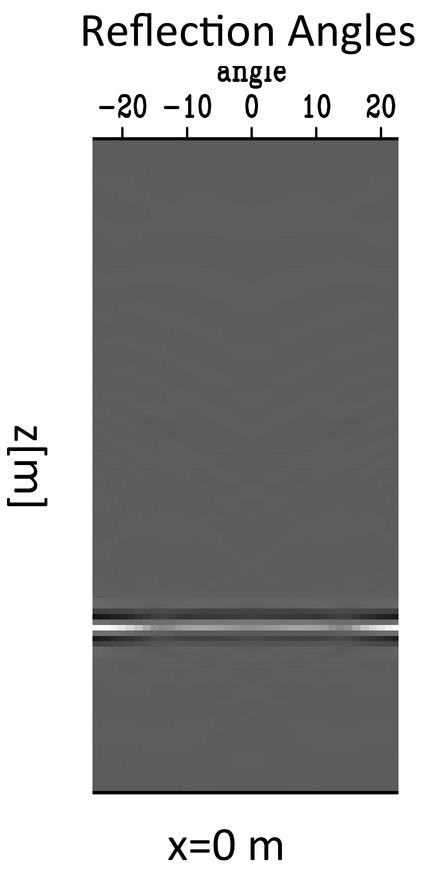
Stacked method

- **Stacked method using windows wide in depth**
  - The spectral variations caused by structure differences in each window are statistically the same
  - Does not represent the effect of Q on its image point
  - Mixes the Q effects from different reflection angles
- **Prestack method: angle domain common image gather (ADCIG)**

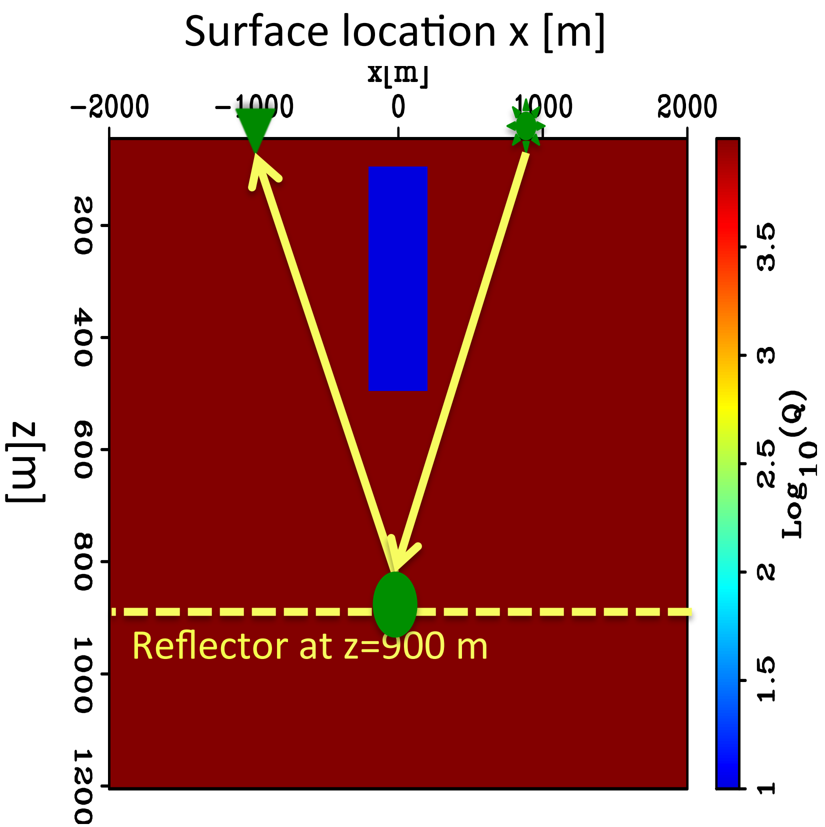


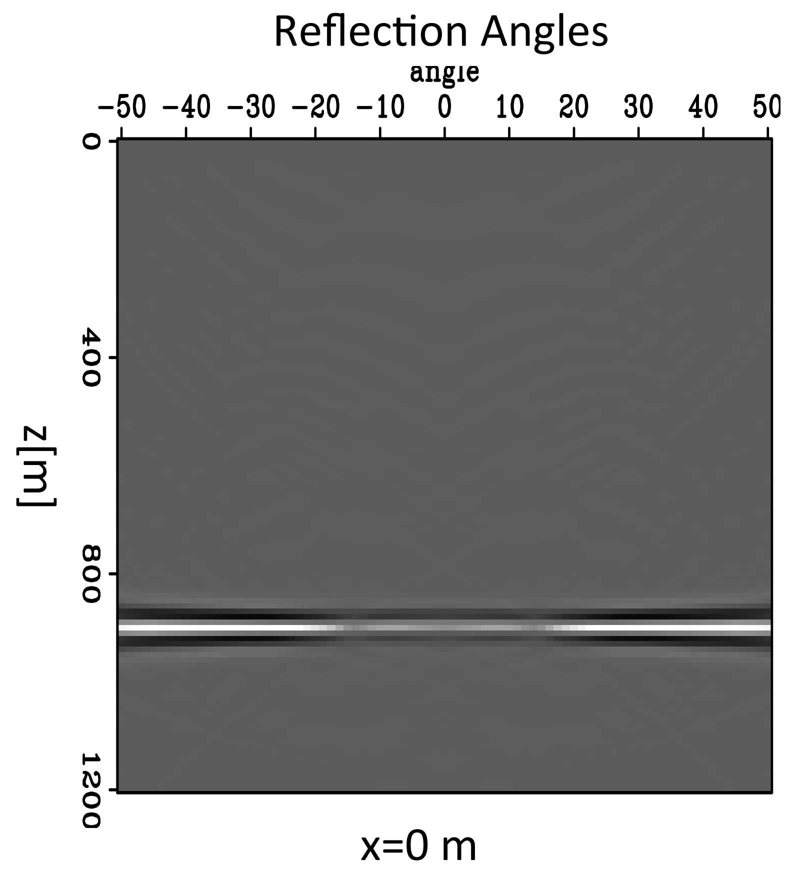
Prestack method: Angle domain common image gather (ADCIG)



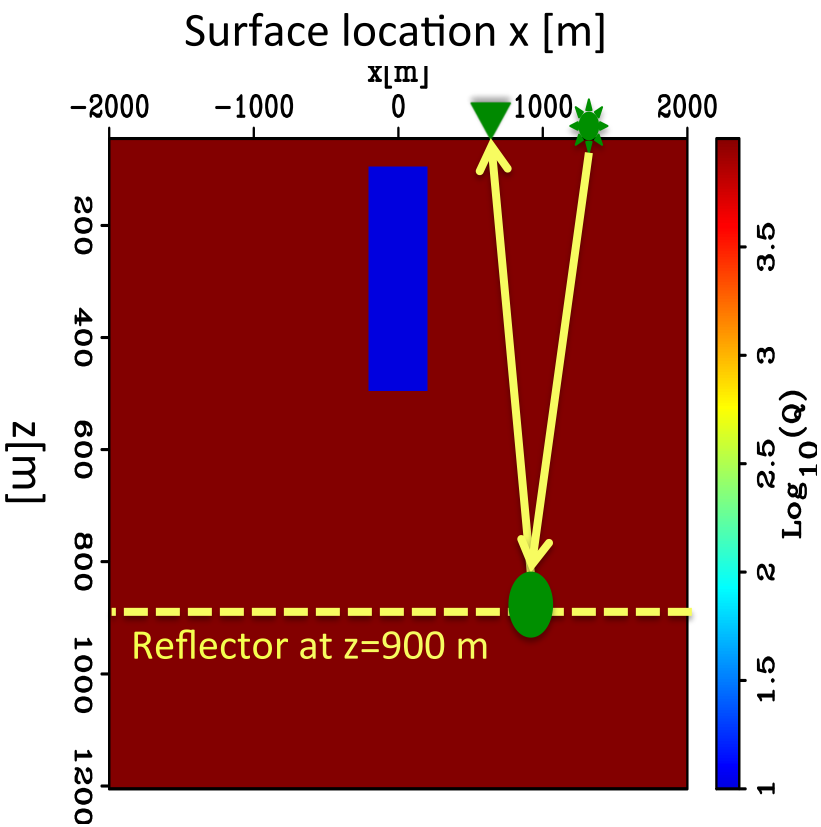


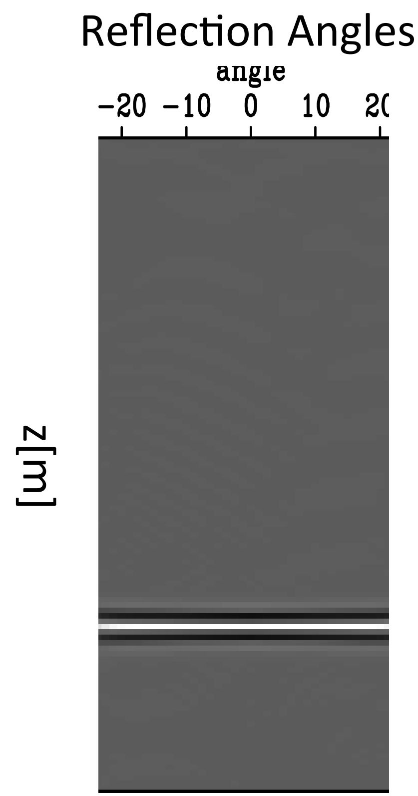
Prestack method: Angle domain common image gather (ADCIG)





Prestack method: Angle domain common image gather (ADCIG)

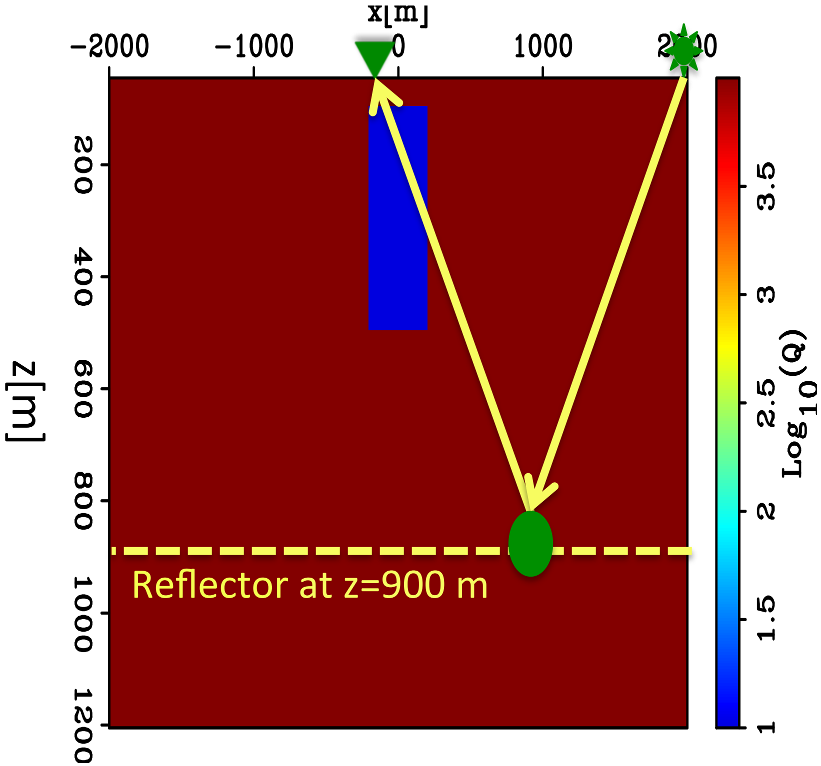




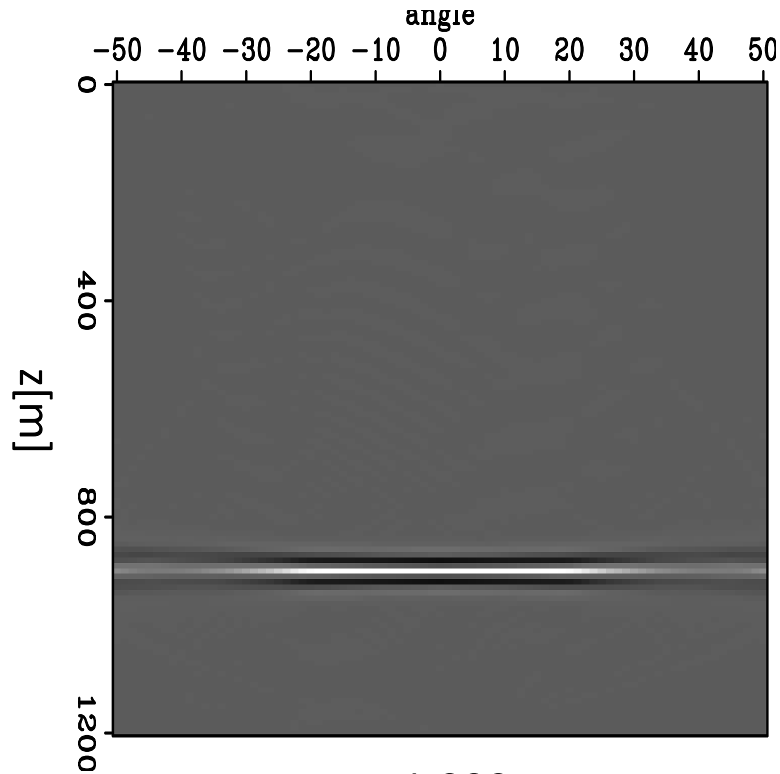
x=1,000 m

Prestack method: Angle domain common image gather (ADCIG)

Surface location x [m]



Reflection Angles



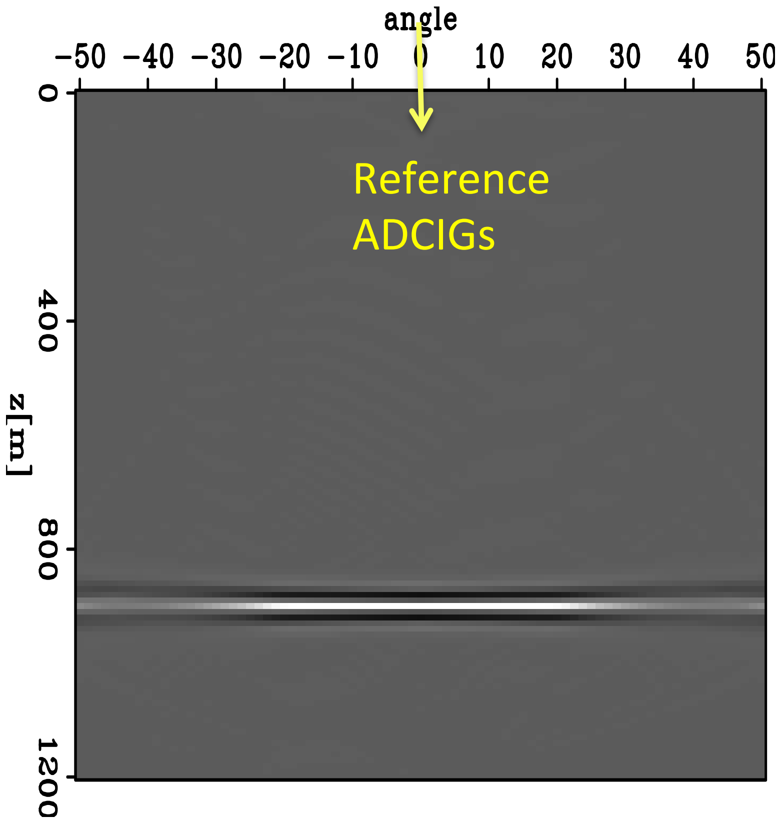
x=1,000 m

Prestack method: Angle domain common image gather (ADCIG)

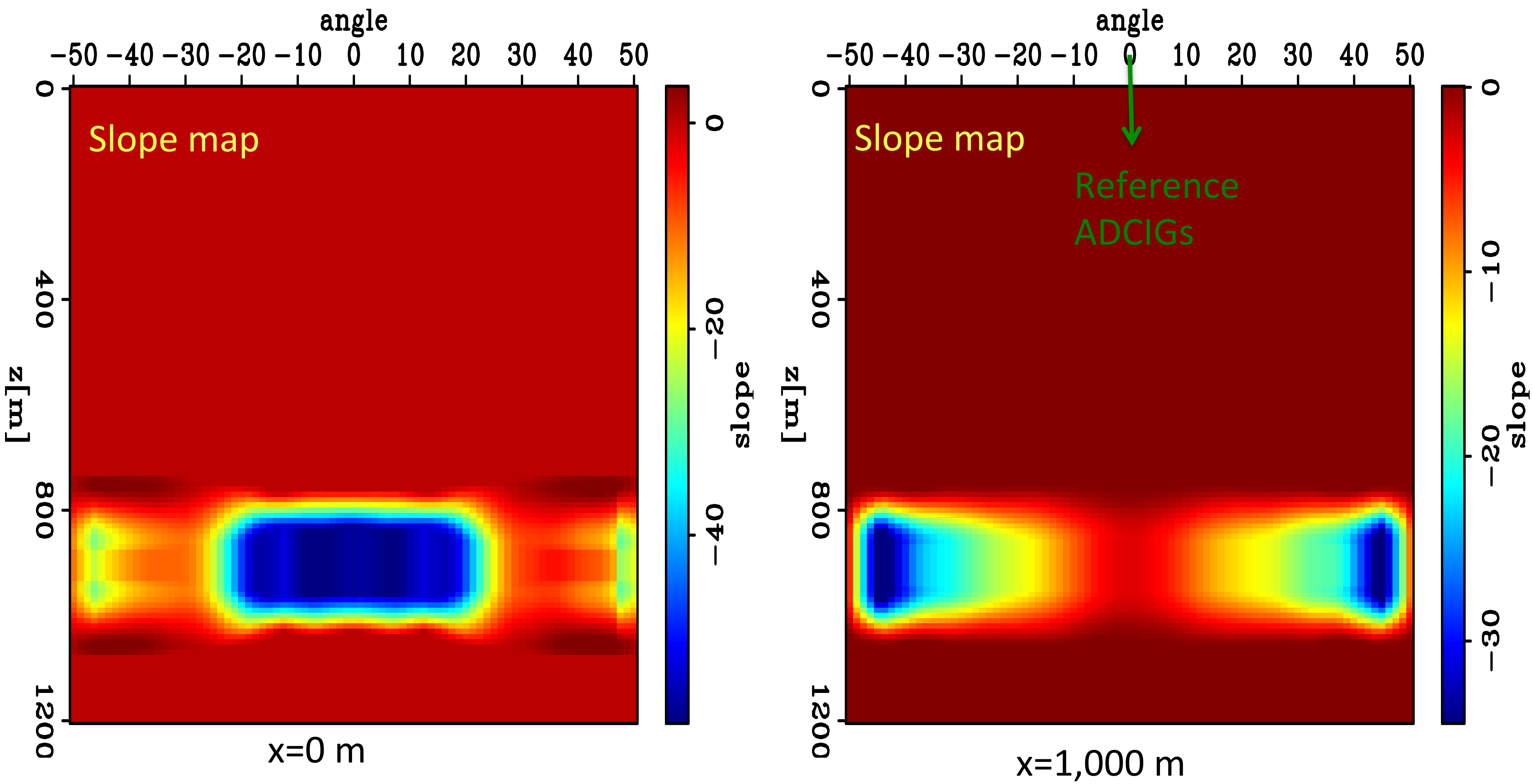
- Select near angles as the reference angles for each ADCIG
- Or select the reference ADCIGs
- Compare the windowed spectra for ρ: reference spectra and target spectra

$$\ln\left(\frac{R_1(\mathbf{k}')}{R_2(\mathbf{k}')}\right) = \rho|\mathbf{k}'| + G_0$$

- The windows are compared at the same depth

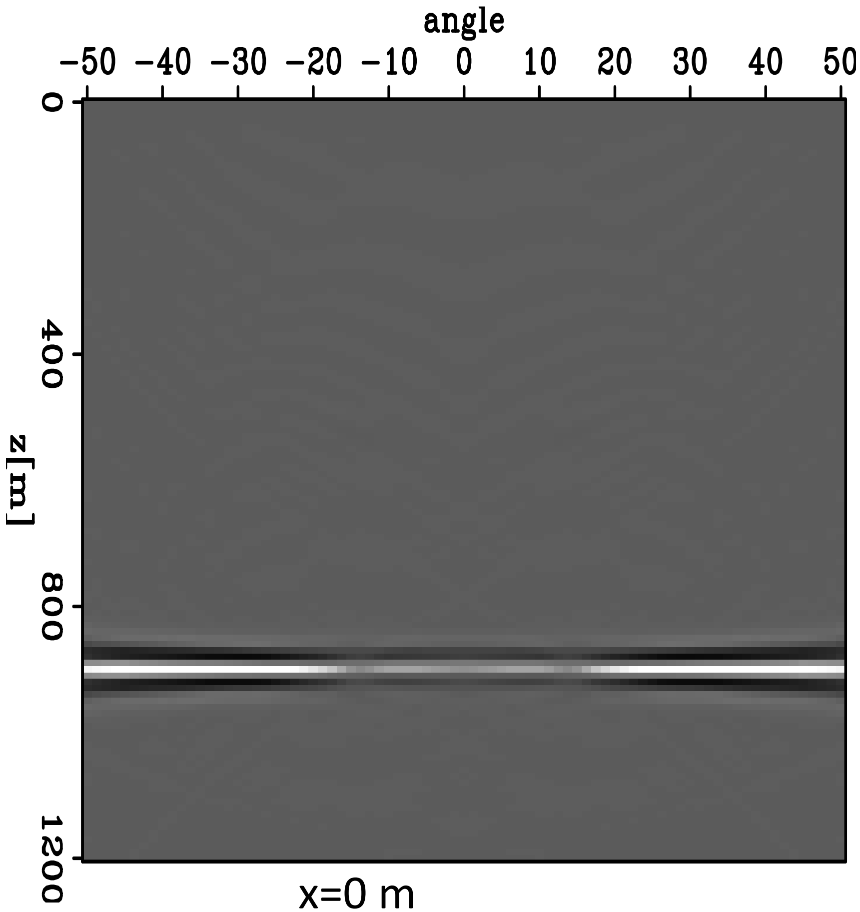


Prestack method: Angle domain common image gather (ADCIG)

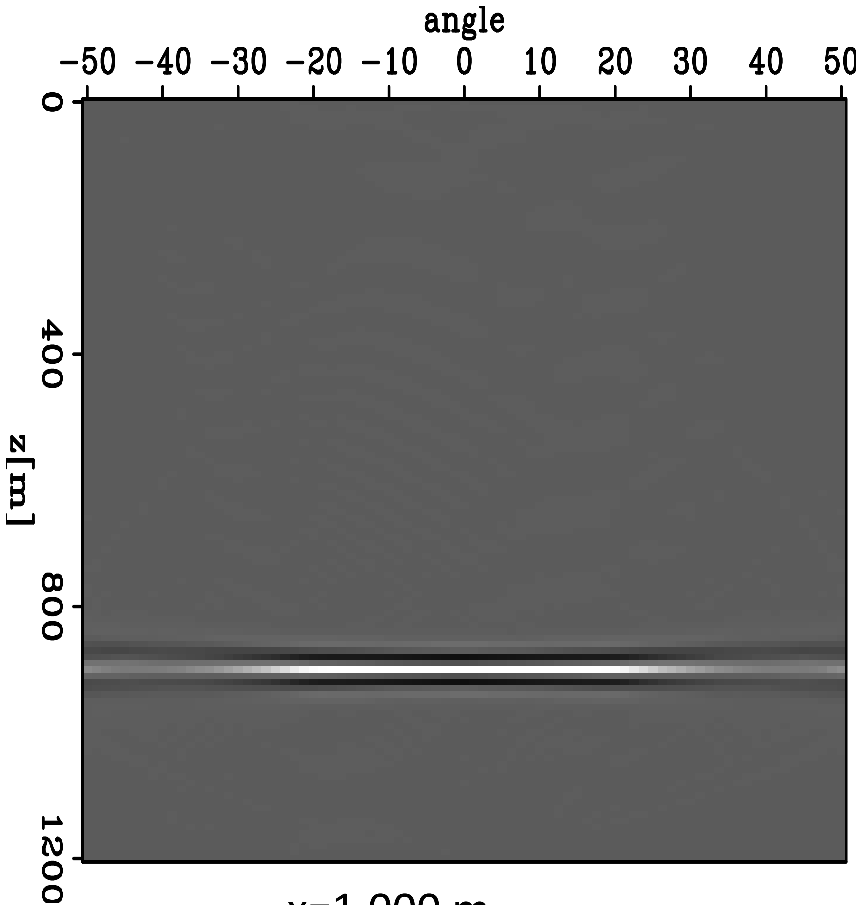


Red: non-attenuated regions
Blue: attenuated regions

Prestack method: Angle domain common image gather (ADCIG)



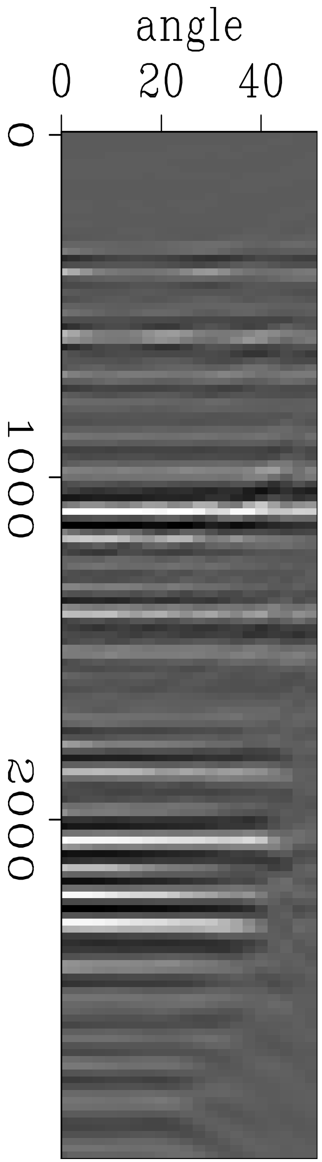
x=0 m



x=1,000 m

Prestack method

- **Prestack method using narrower windows in depth, If the velocity model is correct**
  - Improve results resolutions



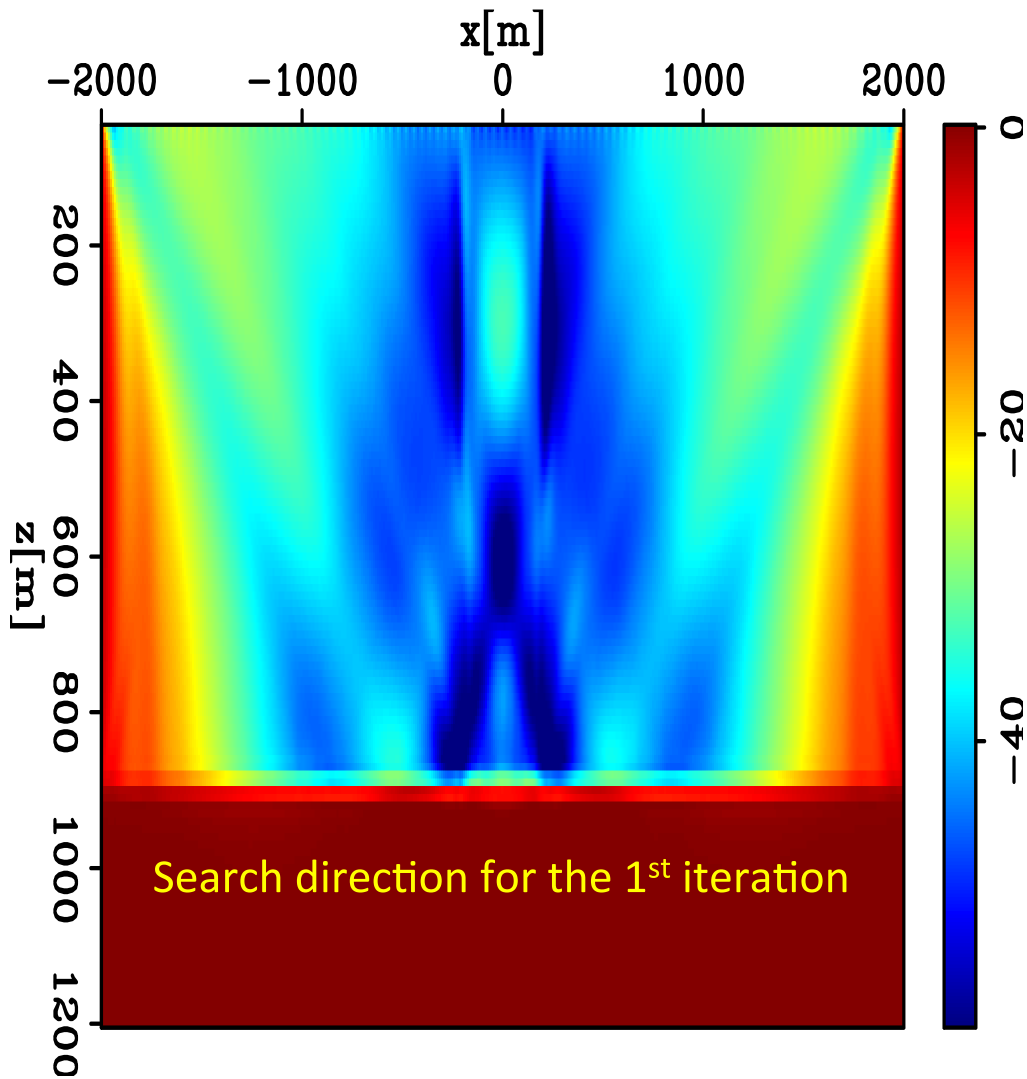
Q gradients

- **Gradients of the objective function with respect to Q**

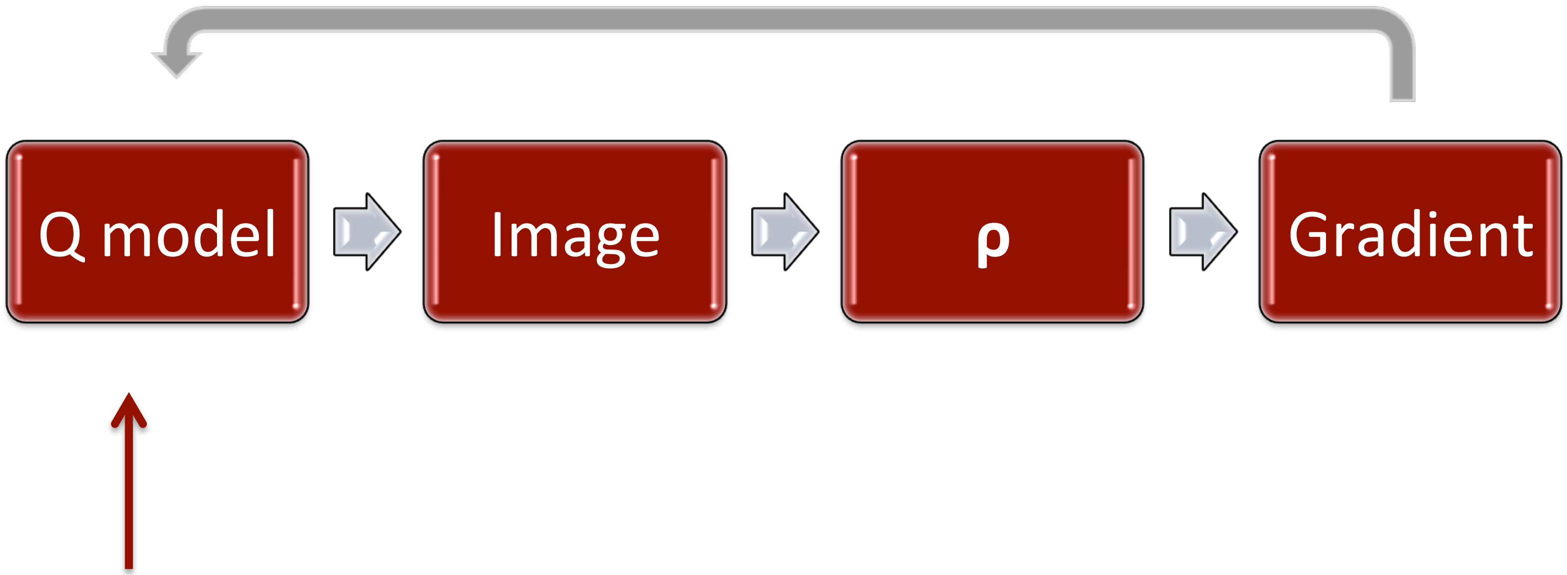
$$\left(\frac{\partial J}{\partial Q}\right)^{*} = \sum_{\mathbf{x}} \left(\frac{\partial \rho}{\partial Q}\right)^{*} \rho$$

- **Search direction for the 1st iteration**

$$-\left(\frac{\partial J}{\partial Q}\right)^{*}$$

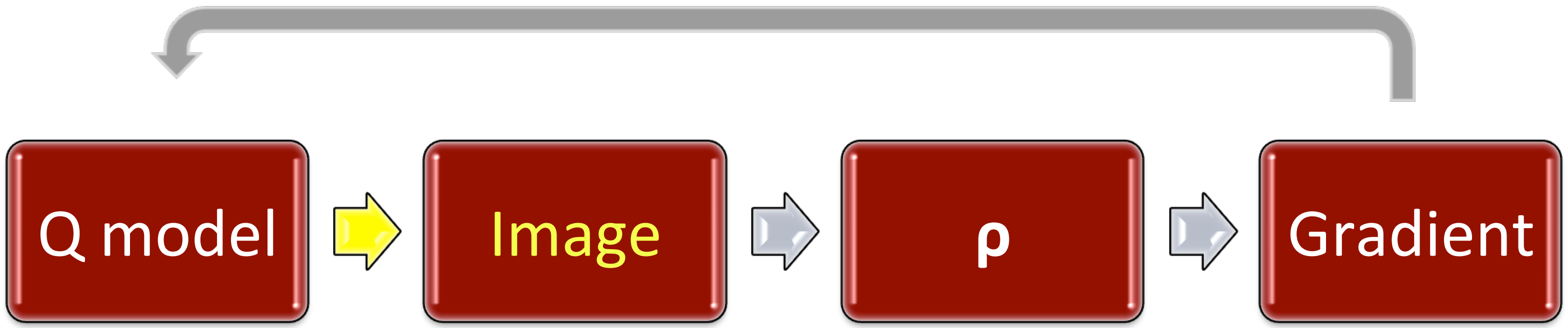


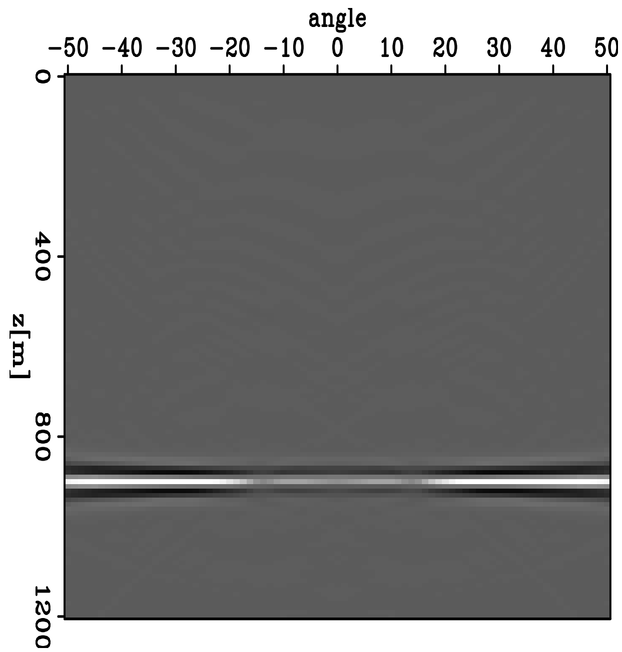
WEMQA workflow



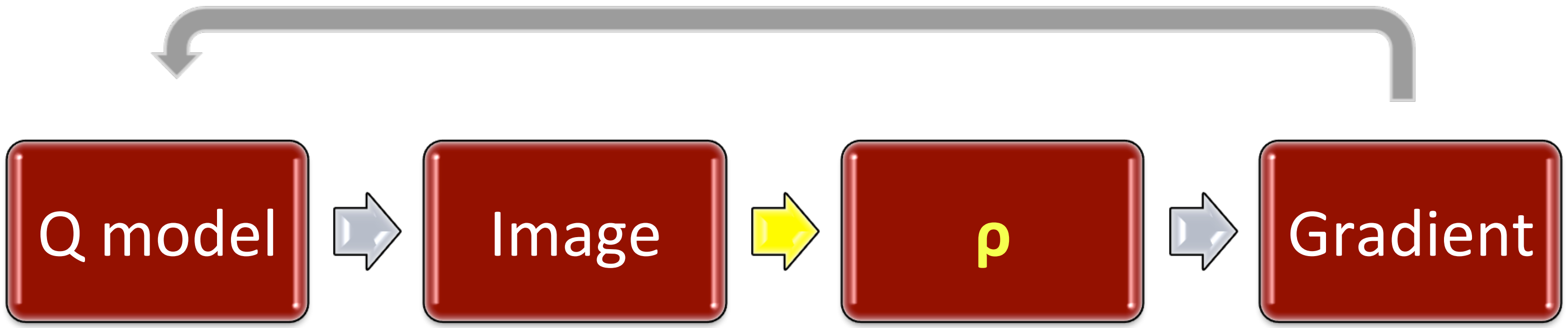
Initial Q (e.g., Q=10,000)

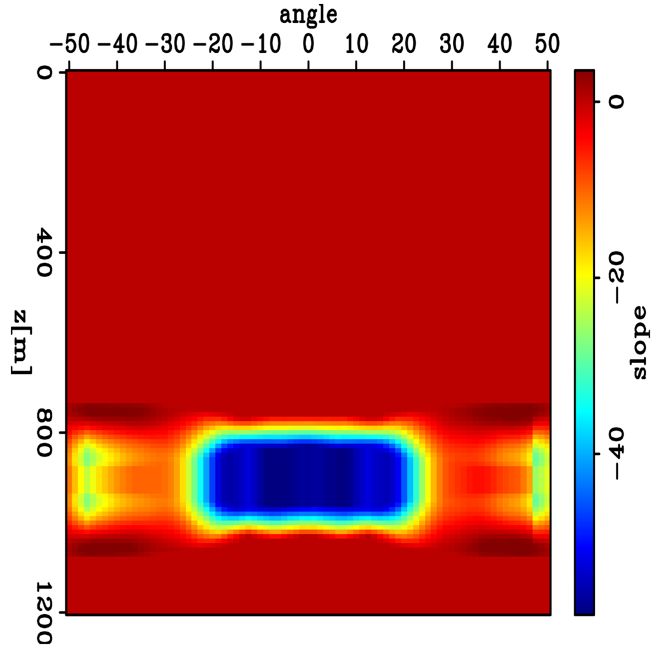
WEMQA workflow



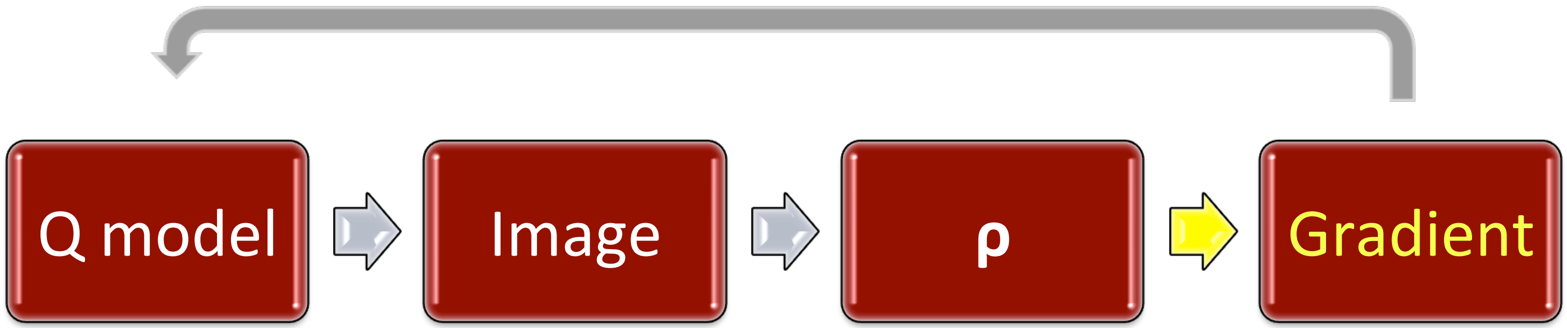


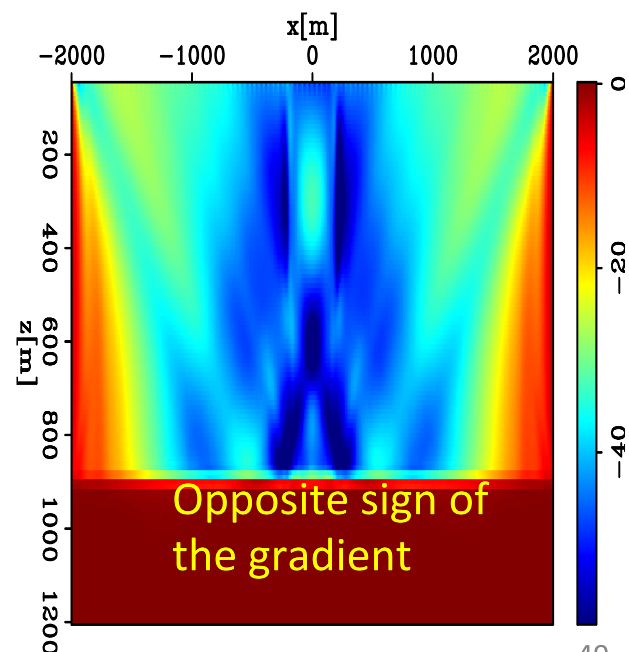
WEMQA workflow



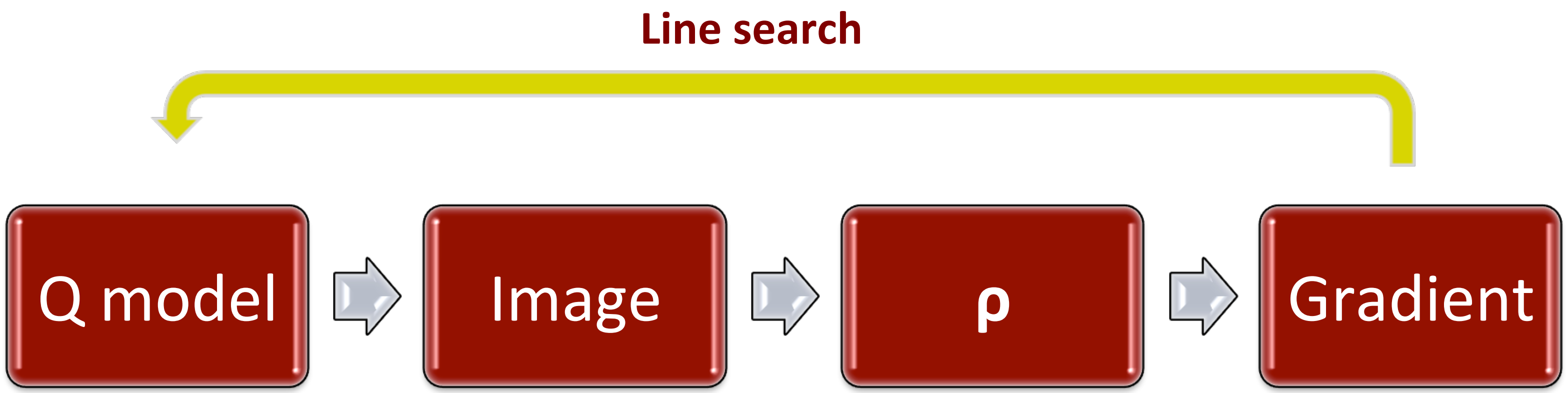


WEMQA workflow

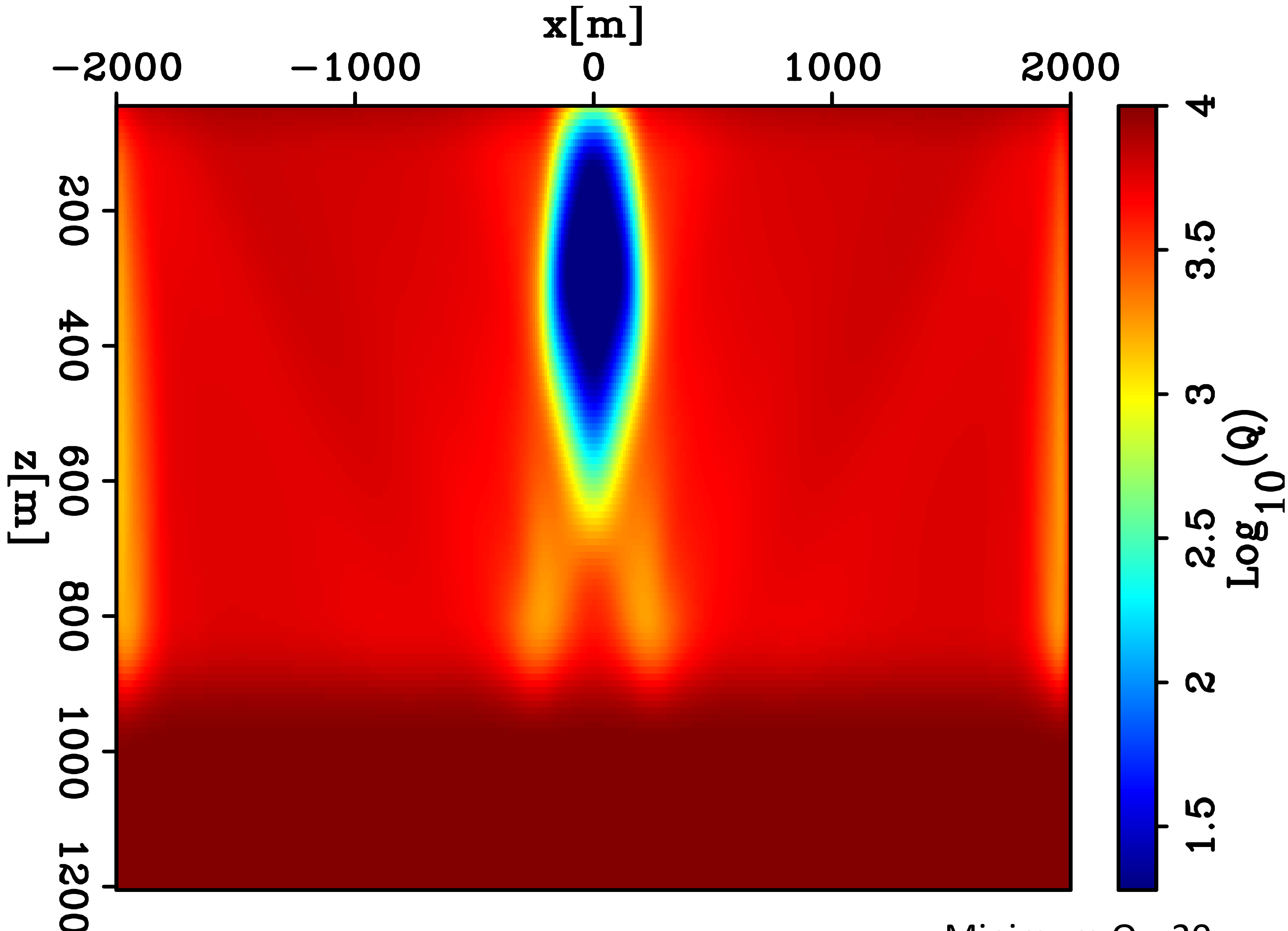




WEMQA workflow

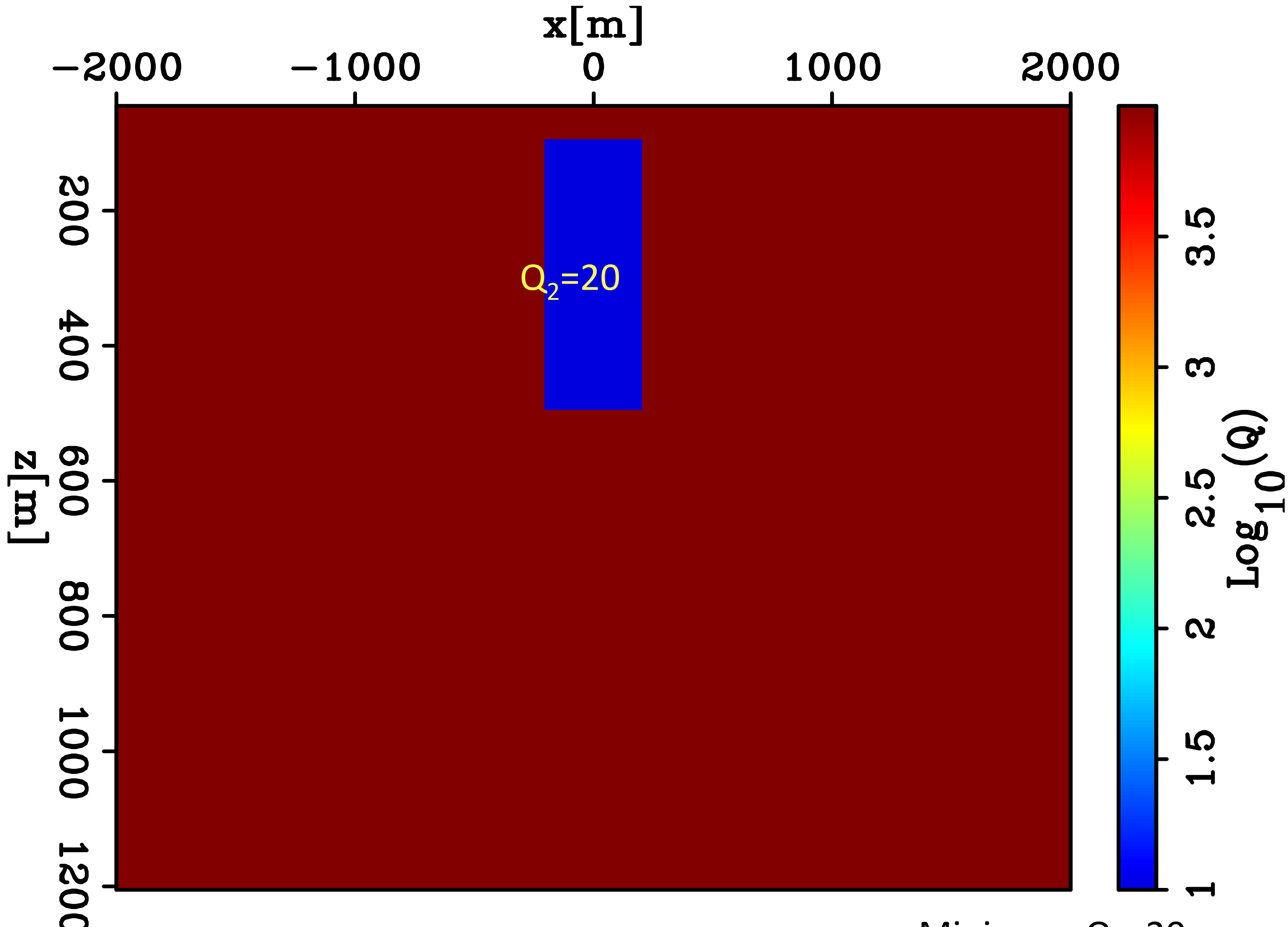


Inverted Q model using prestack method



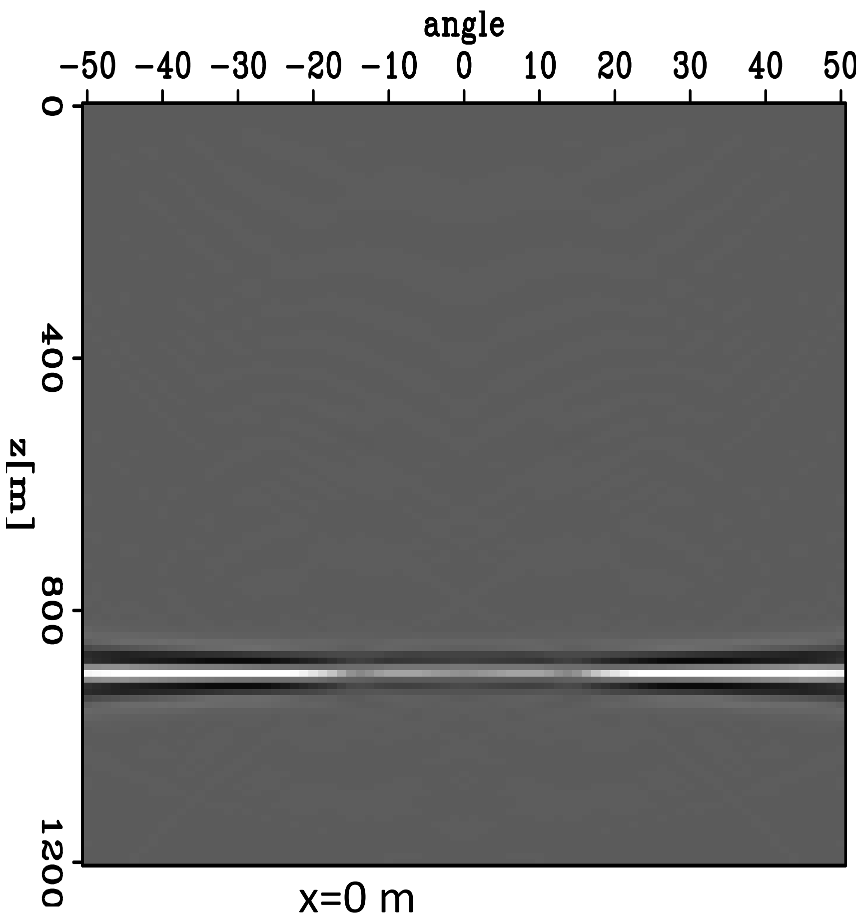
Minimum Q_1=20

True Q model

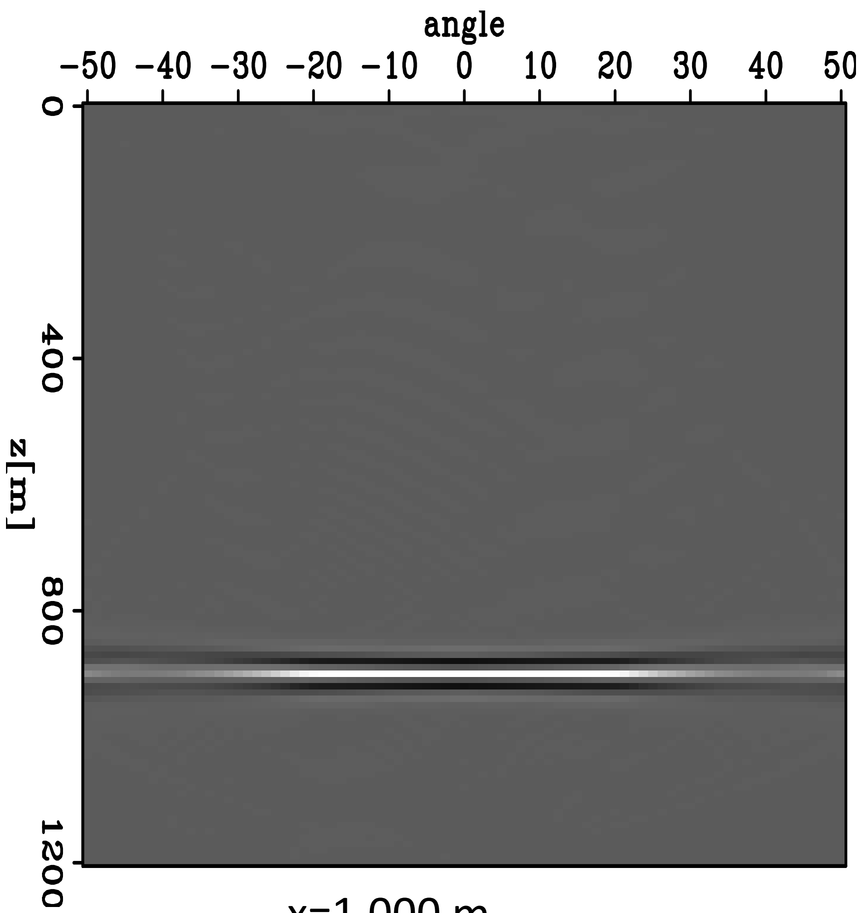


Minimum Q_2=20

ADCIG before Q compensation

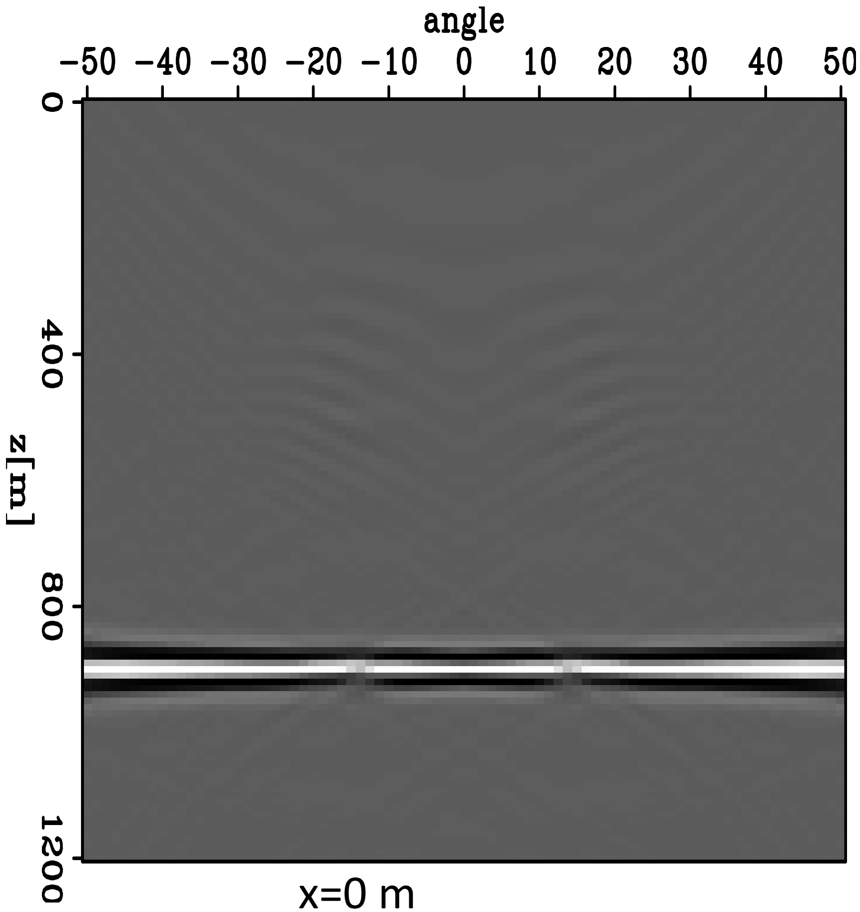


x=0 m

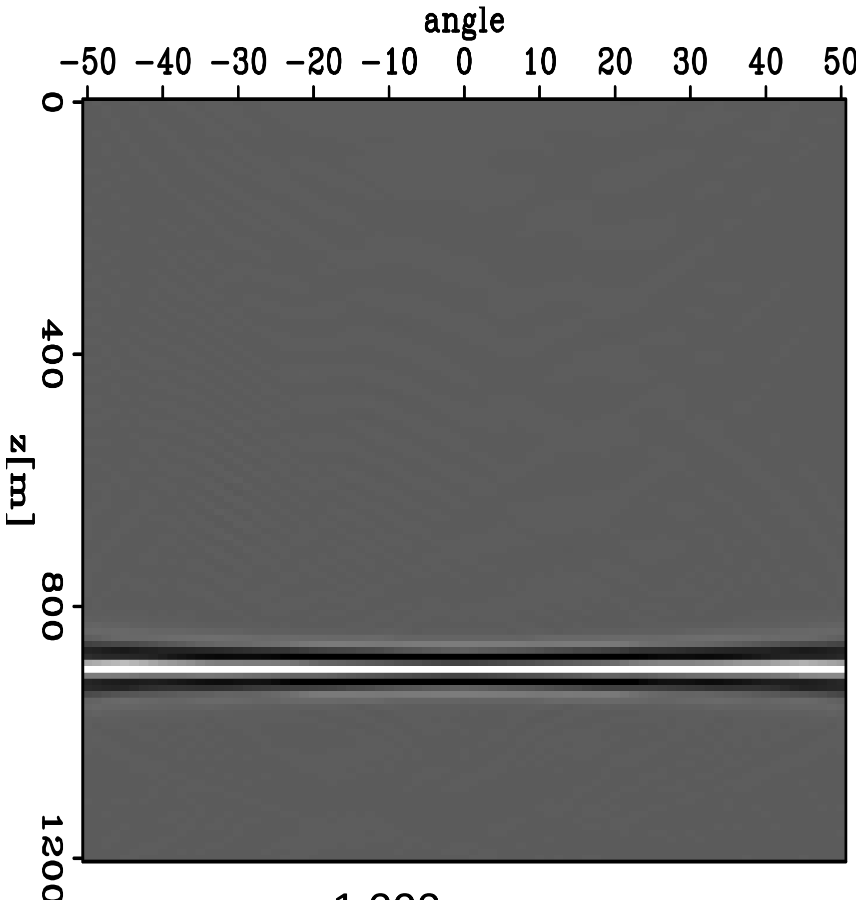


x=1,000 m

ADCIG after Q compensation

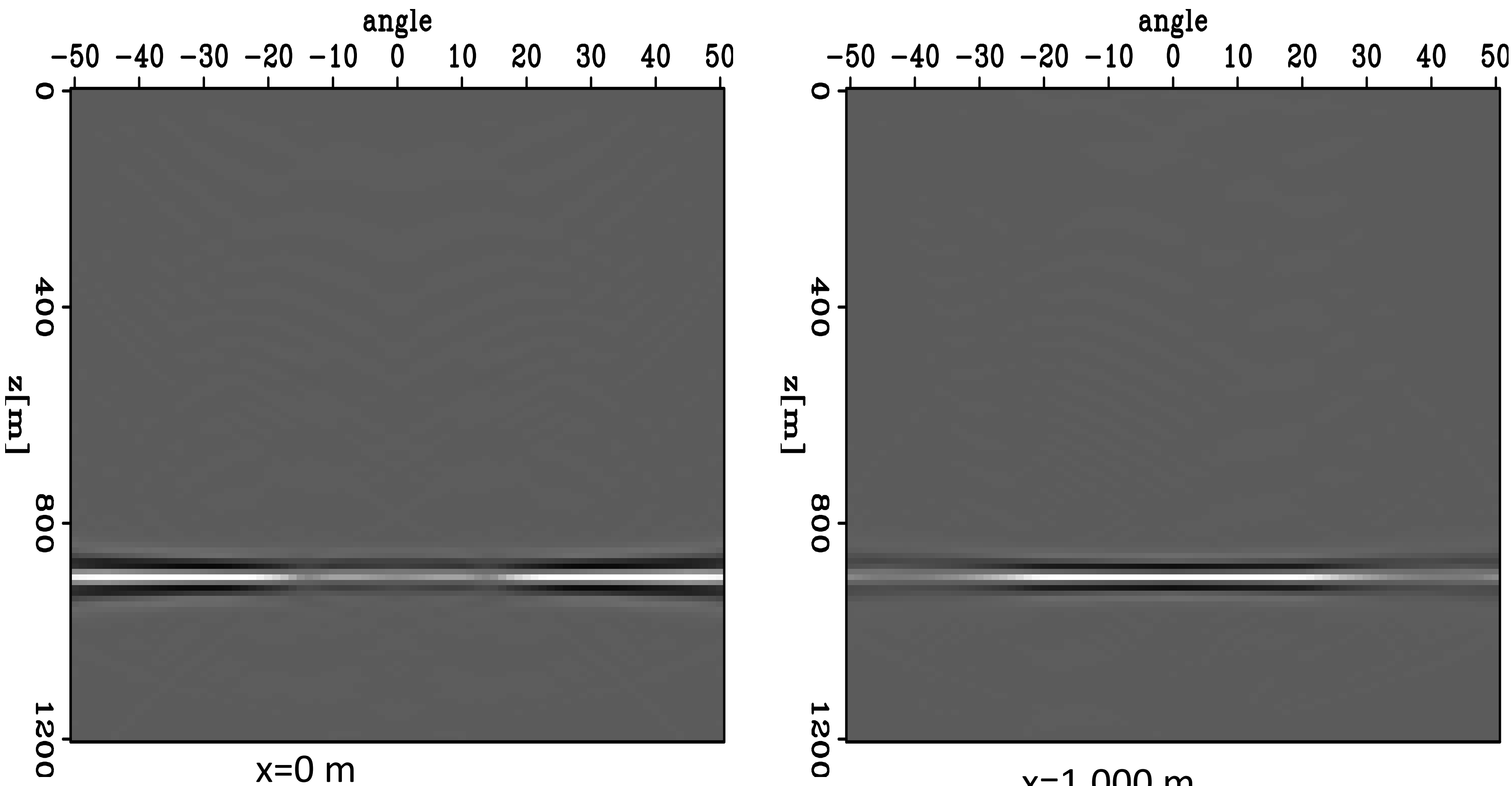


x=0 m



x=1,000 m

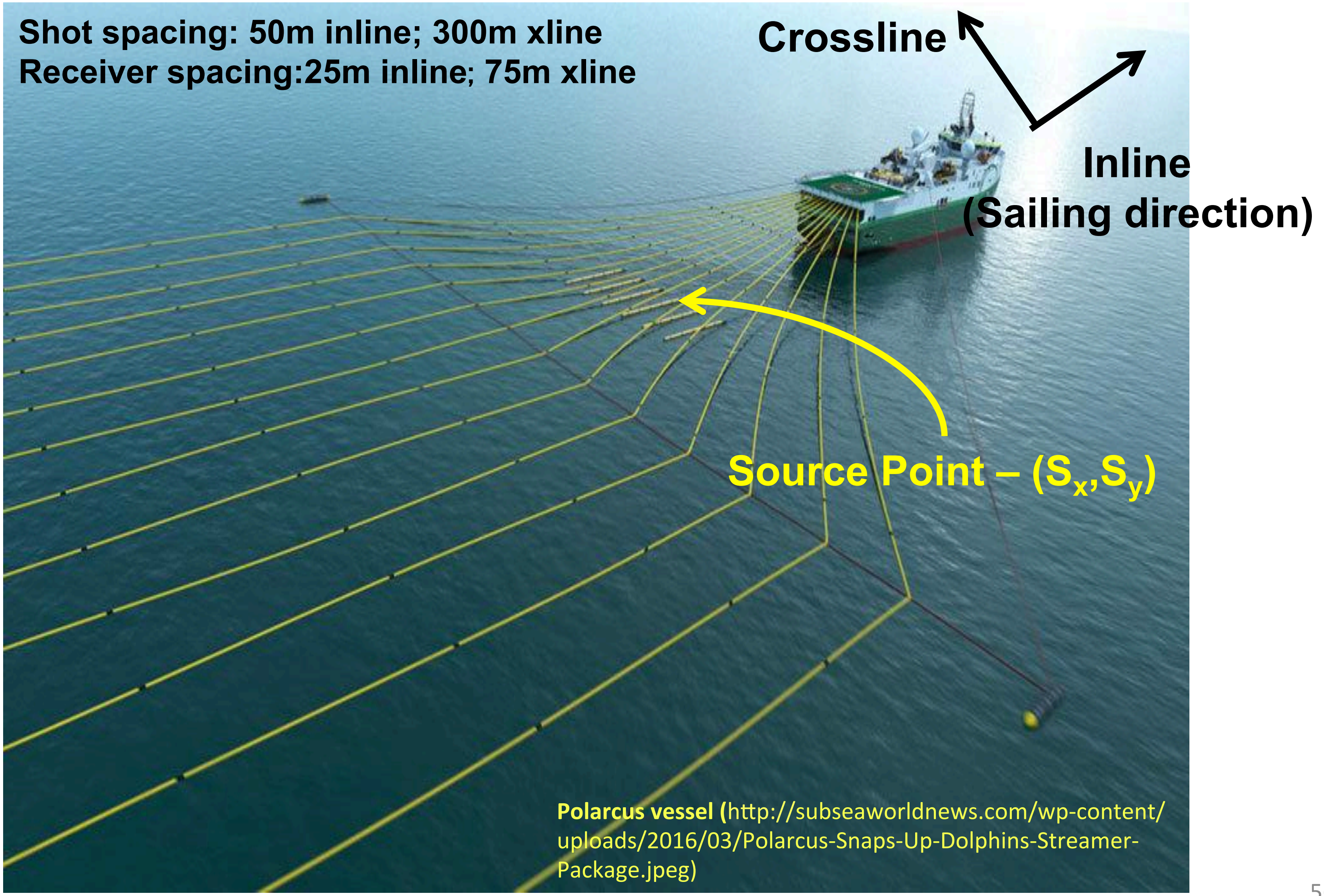
ADCIG before Q compensation



x=0 m

x=1,000 m

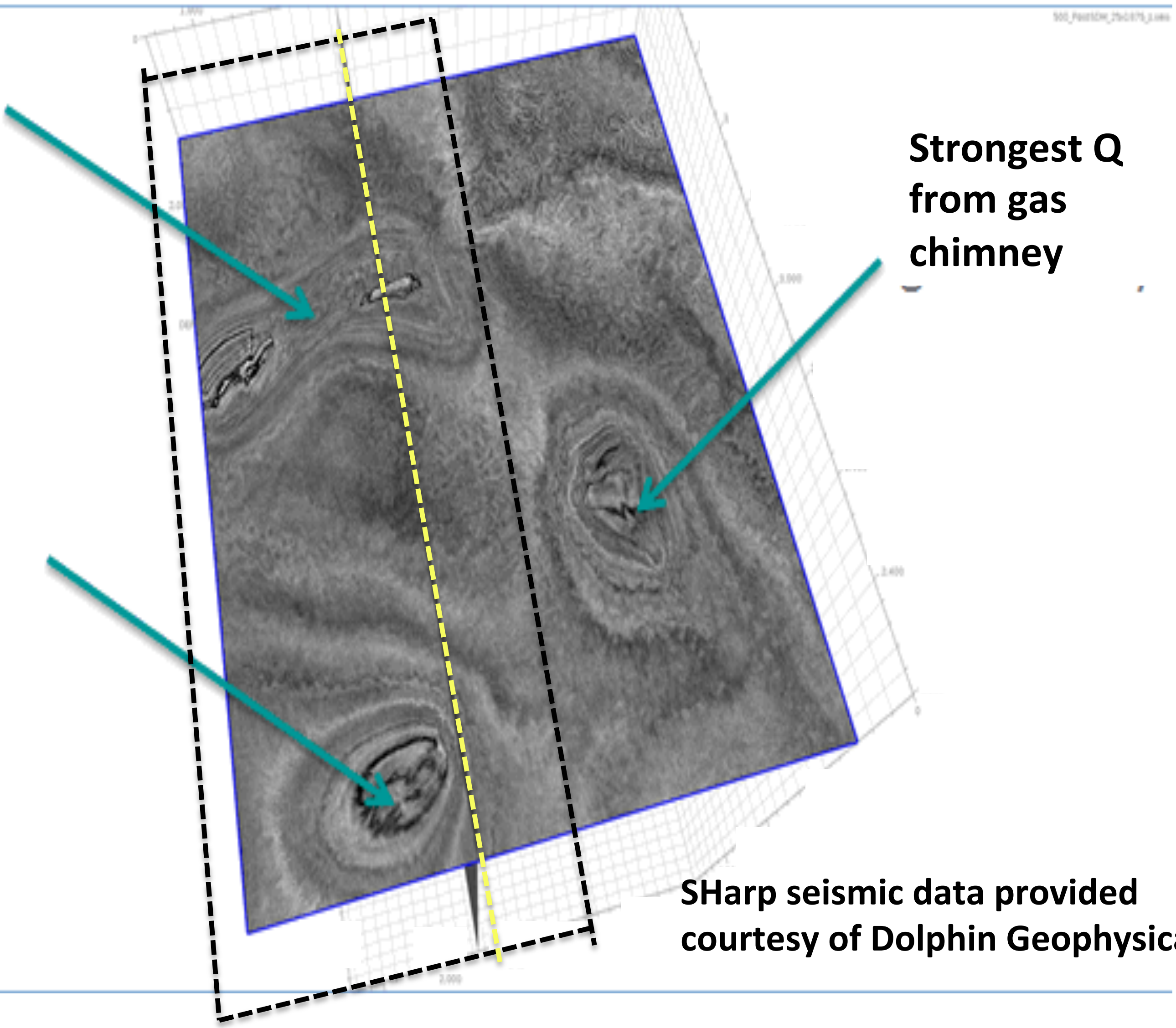
Field data application: streamer data



Depth slice that highlights anomalies

Channel with strong velocity drop

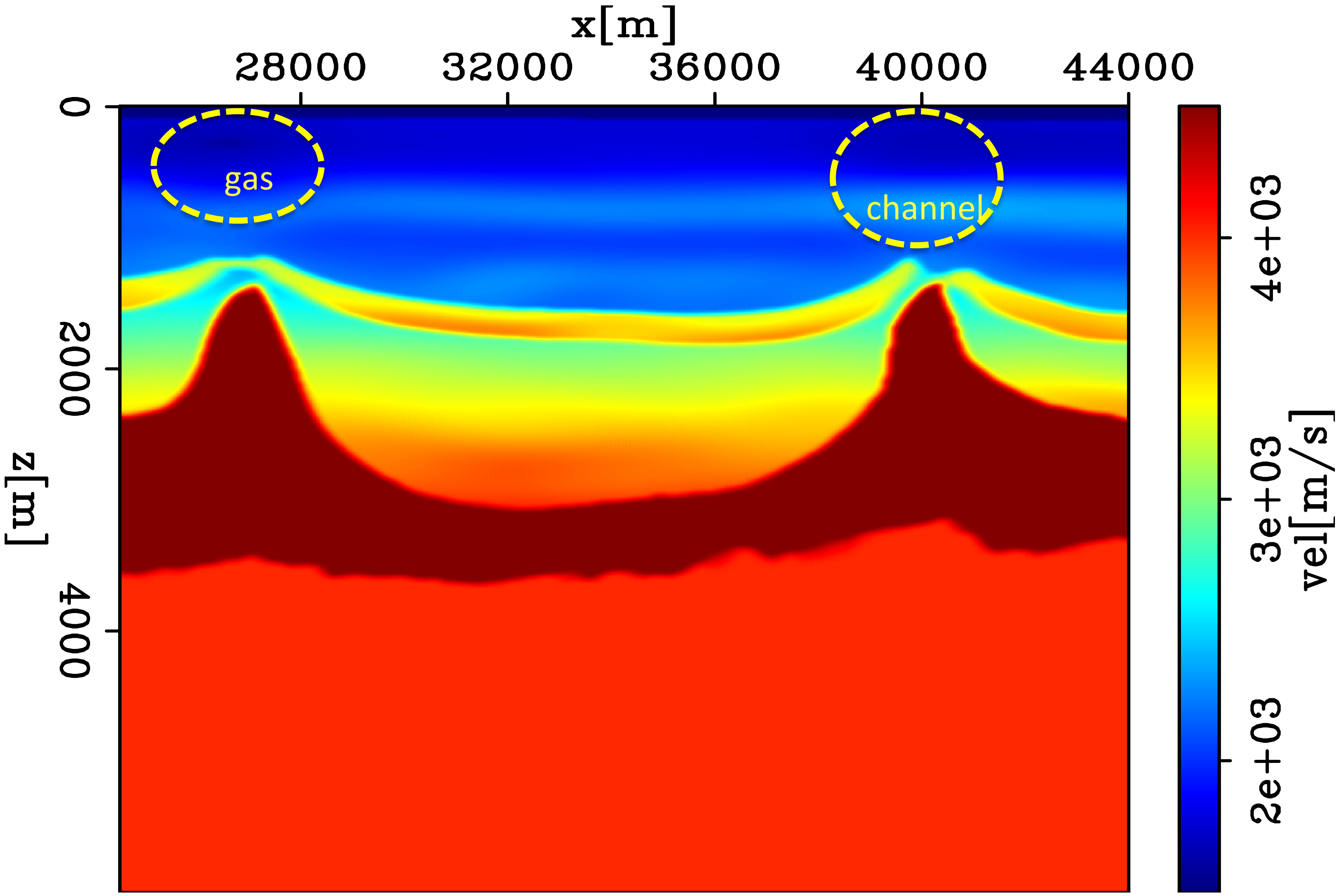
Strong Q from gas chimney



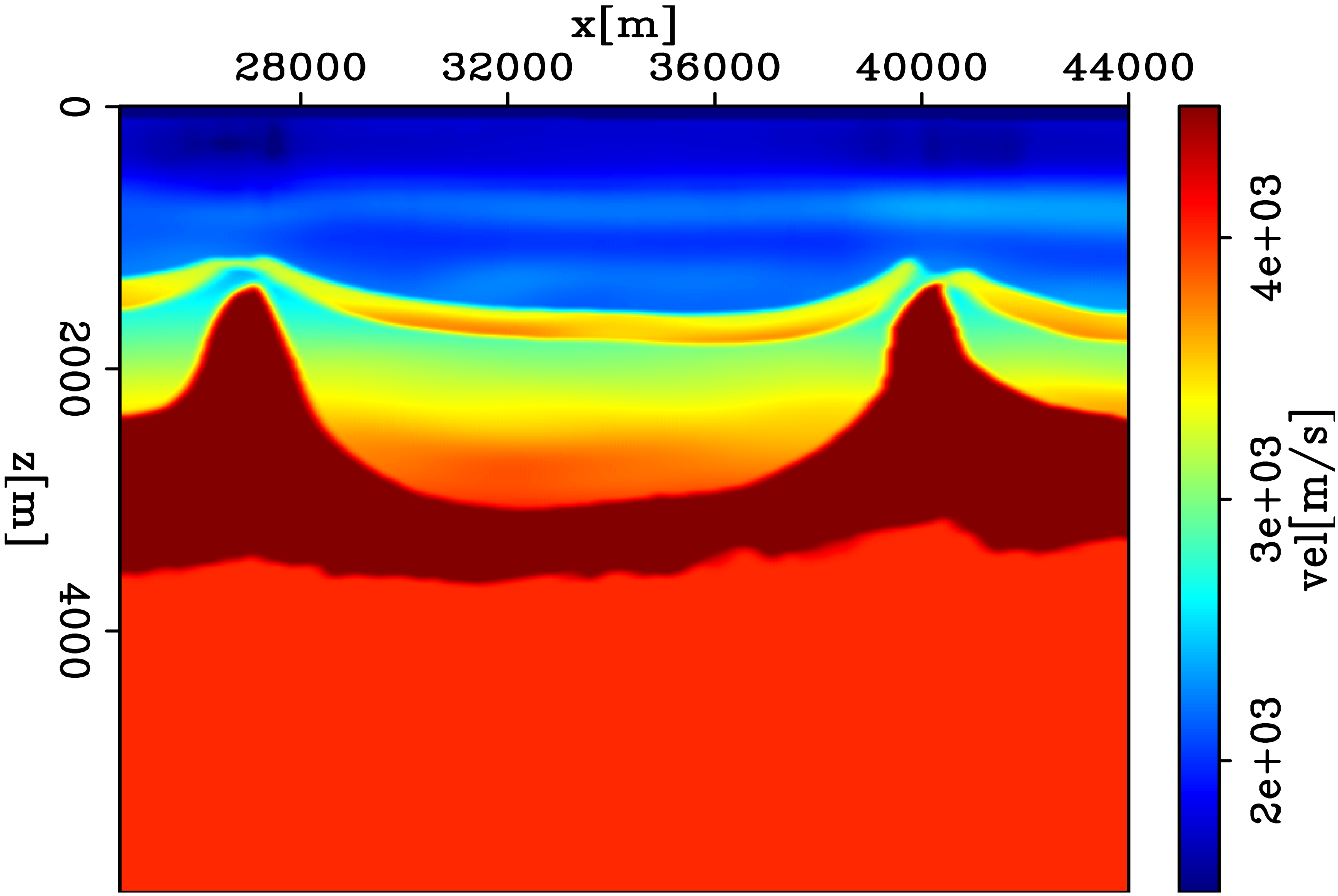
Strongest Q from gas chimney

SHarp seismic data provided courtesy of Dolphin Geophysical

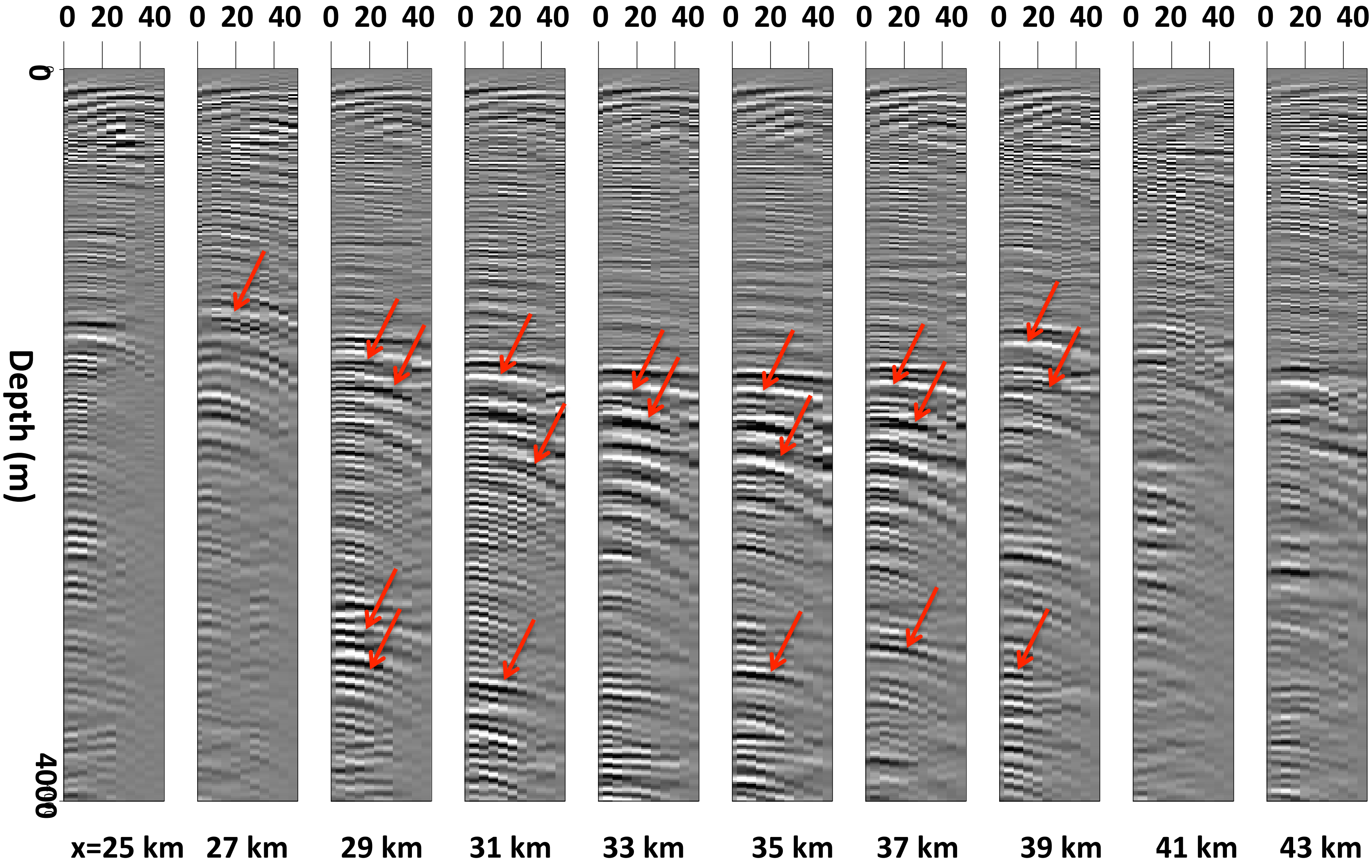
2D initial velocity



2D updated velocity

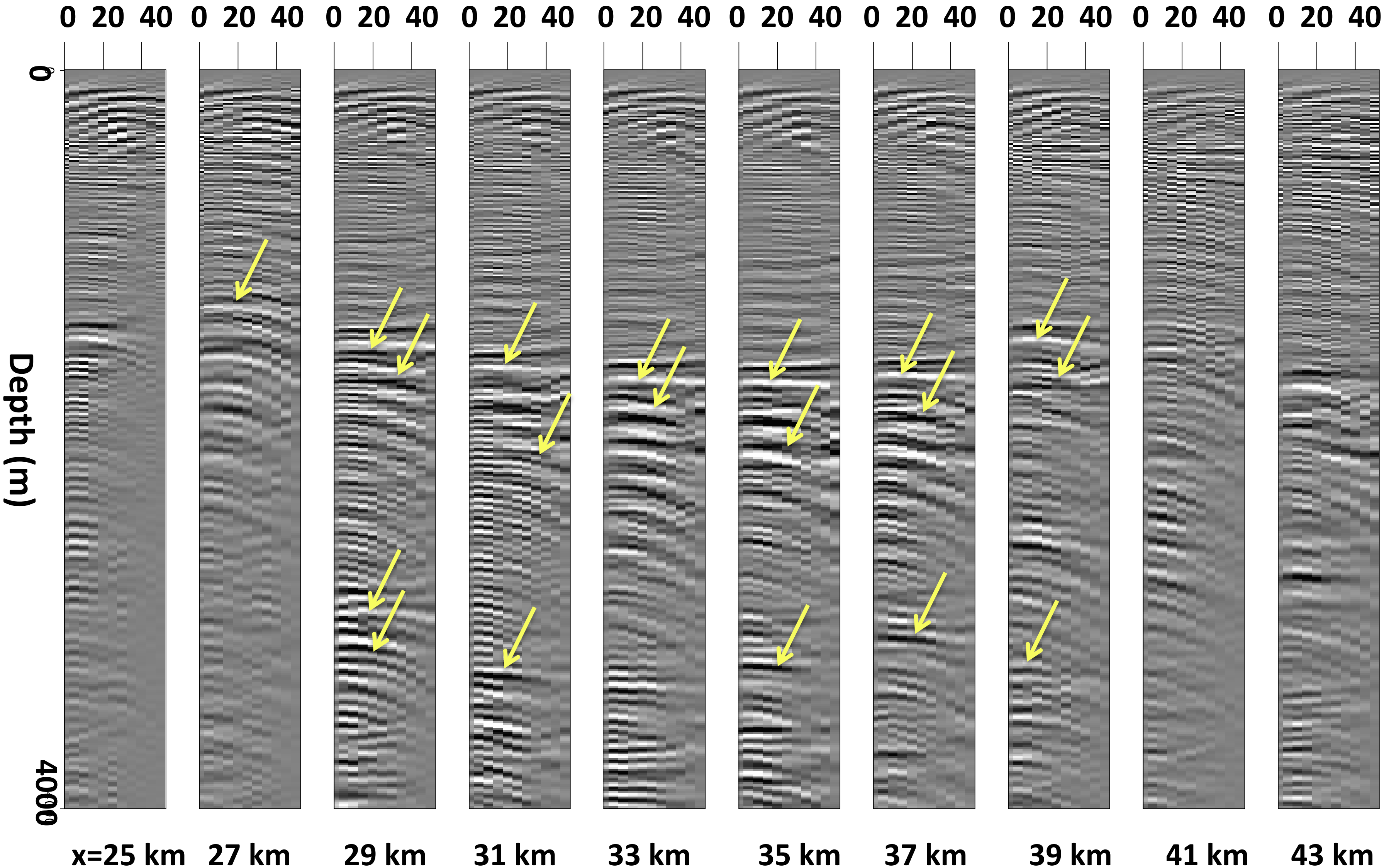


ADCIGs before velocity updating

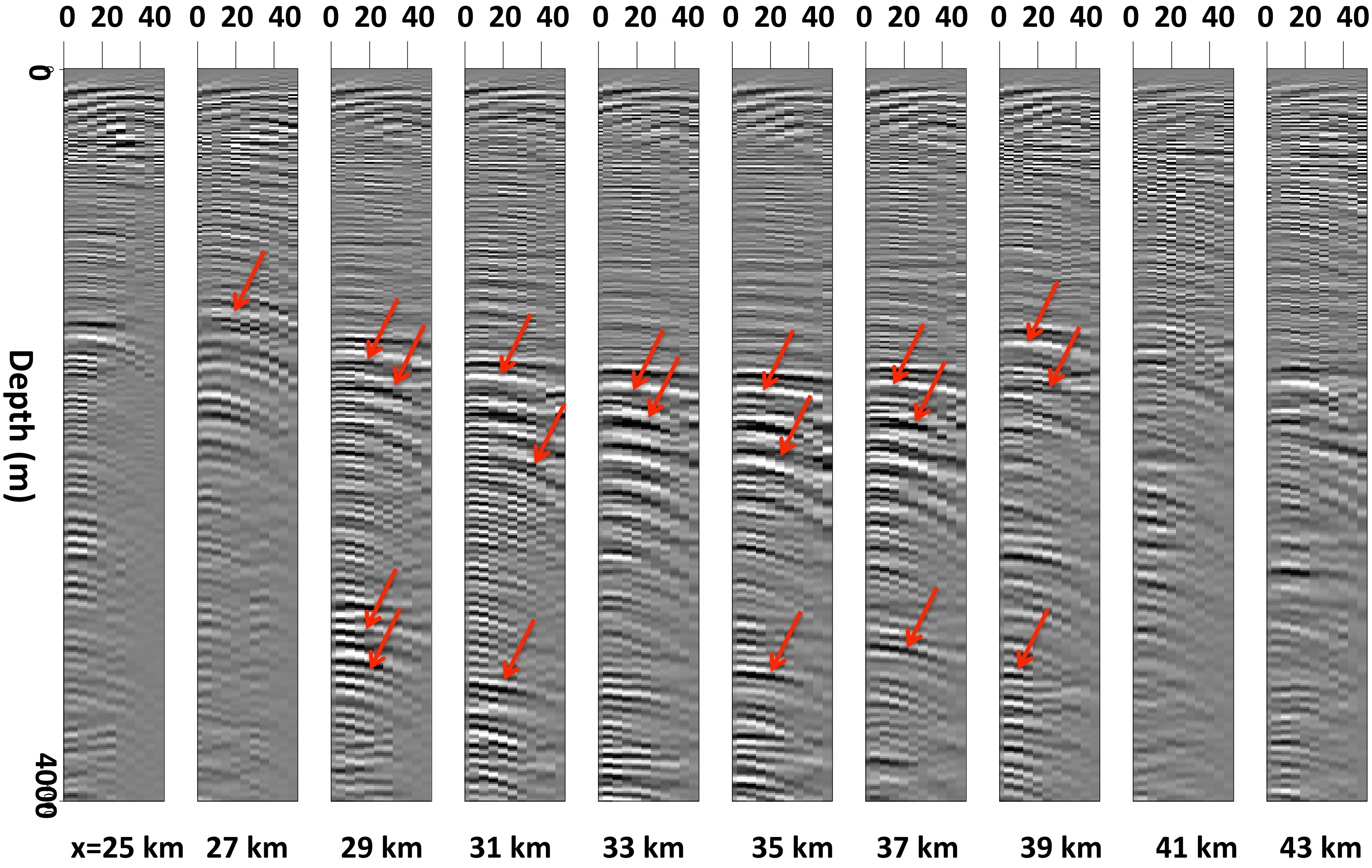


ADCIGs after velocity updating

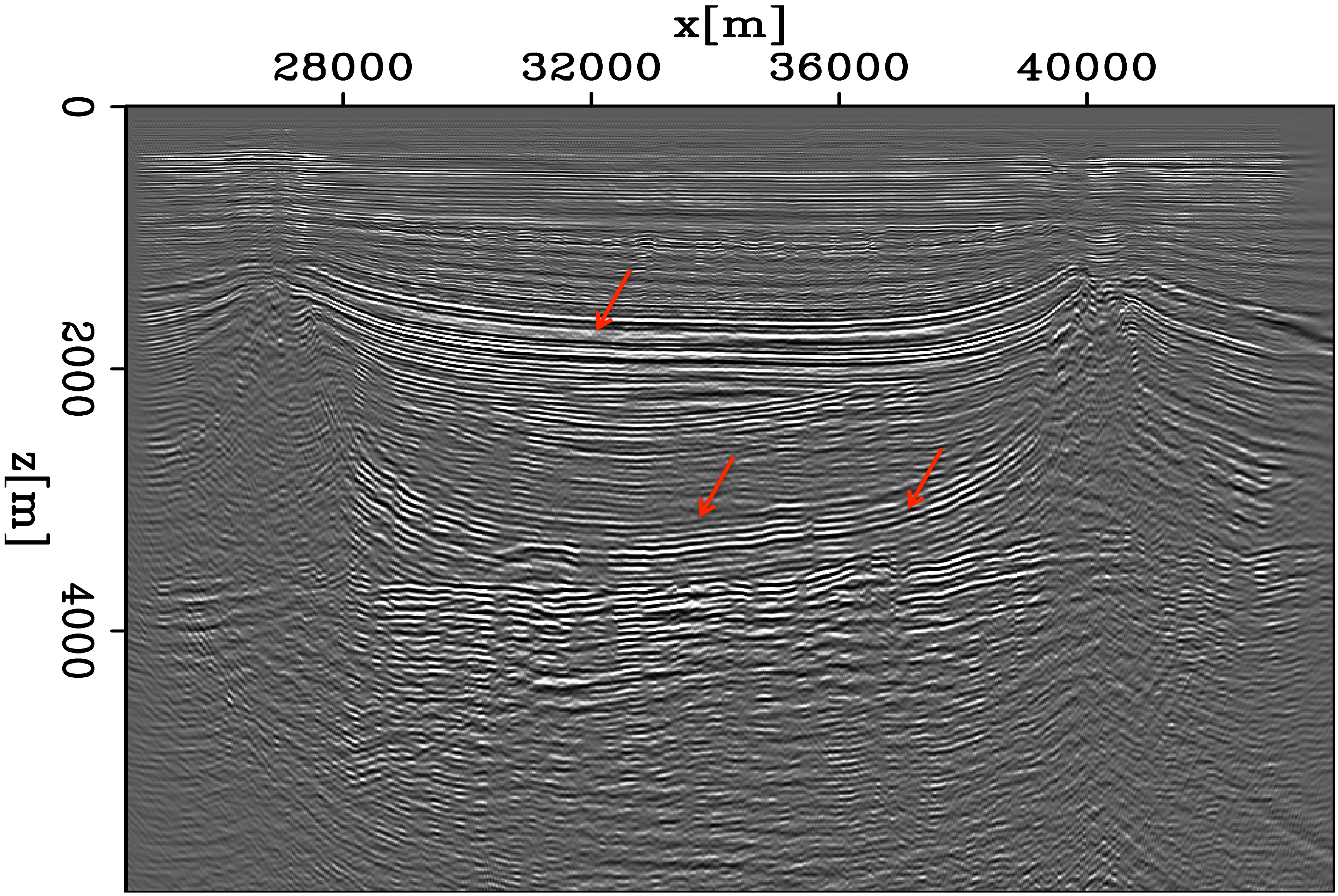
2D velocity estimation
2D one-way stacked WEMQA
2D one-way prestack WEMQA
3D one-way WEMVA and WEMQA



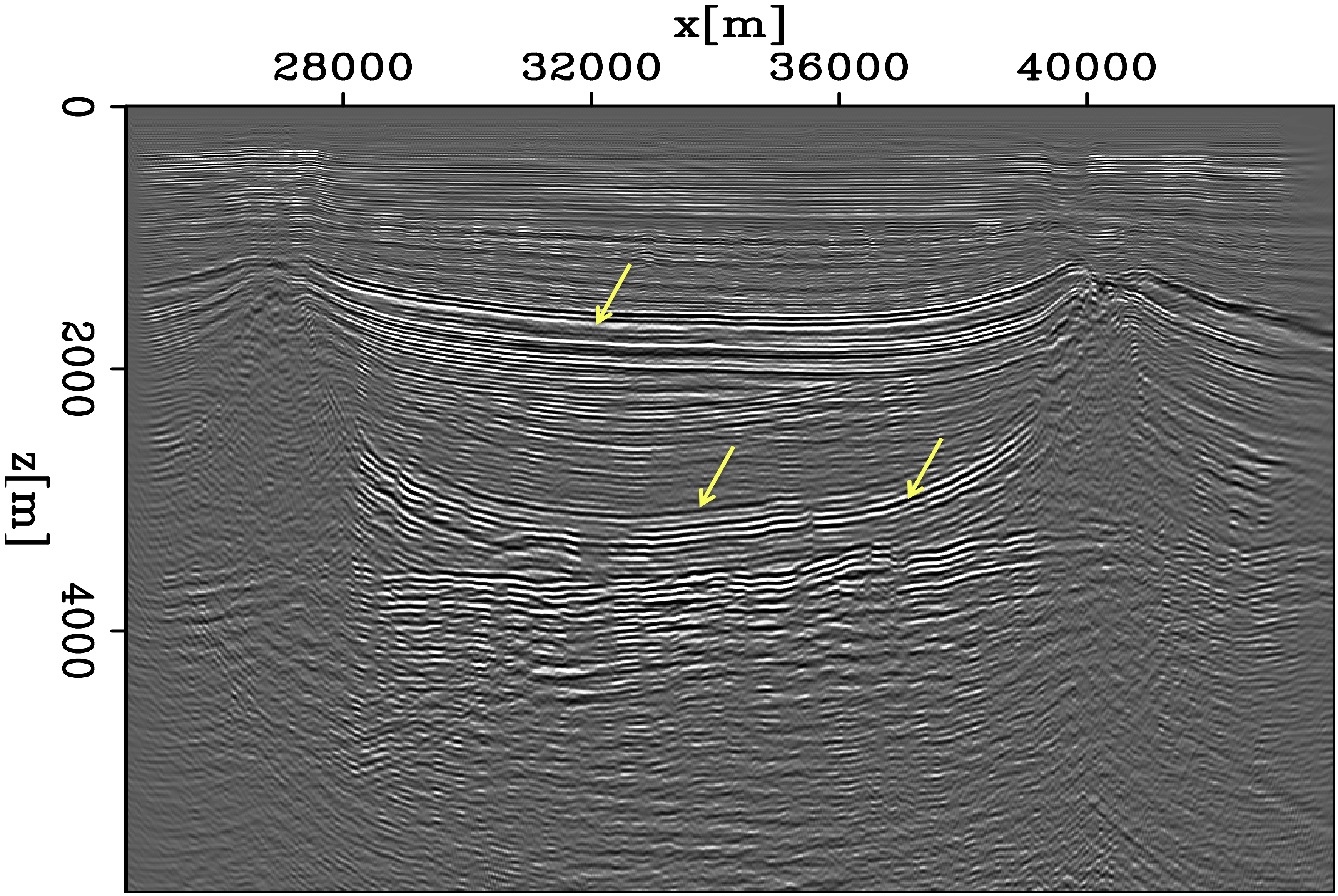
ADCIGs before velocity updating



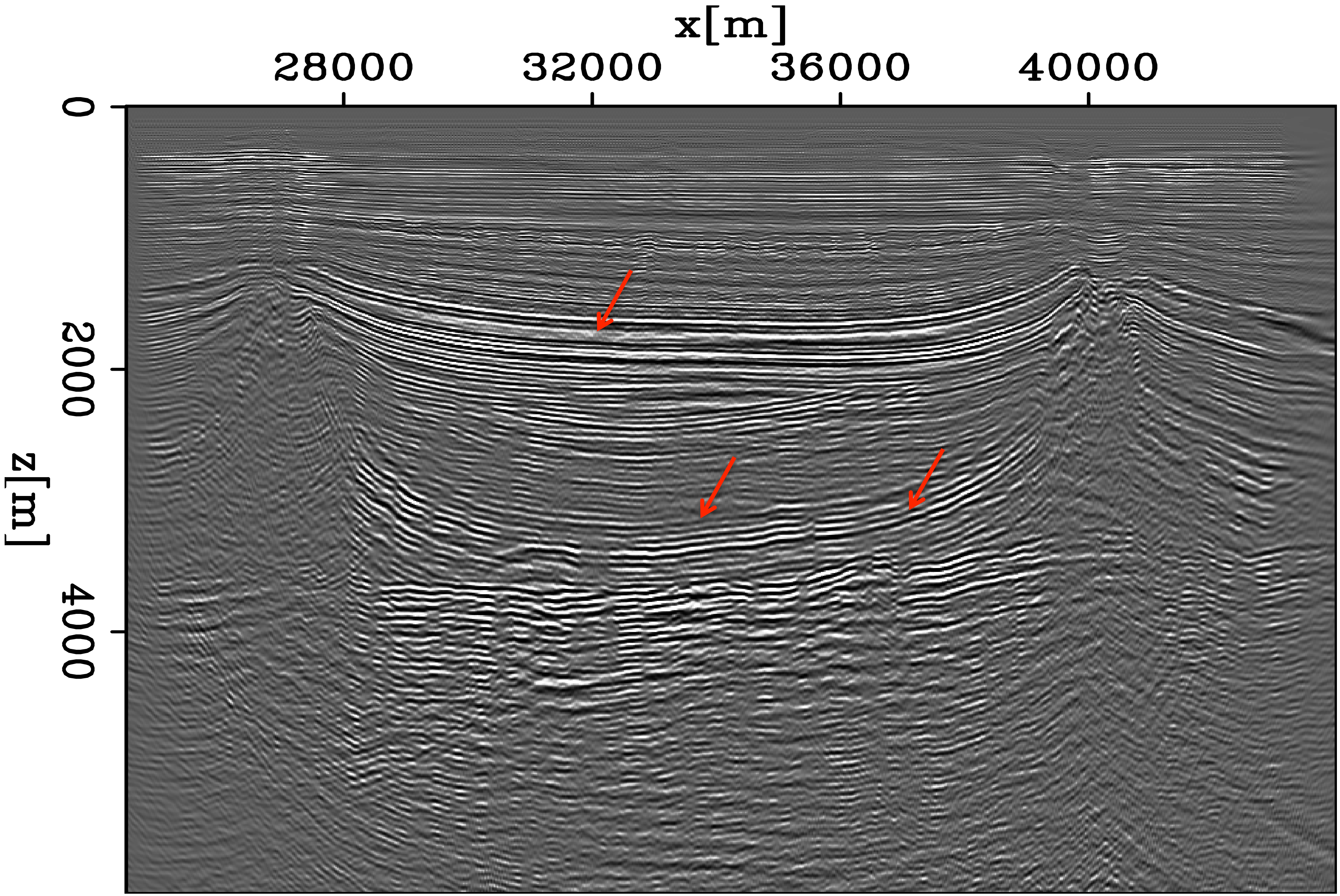
2D image before velocity updating



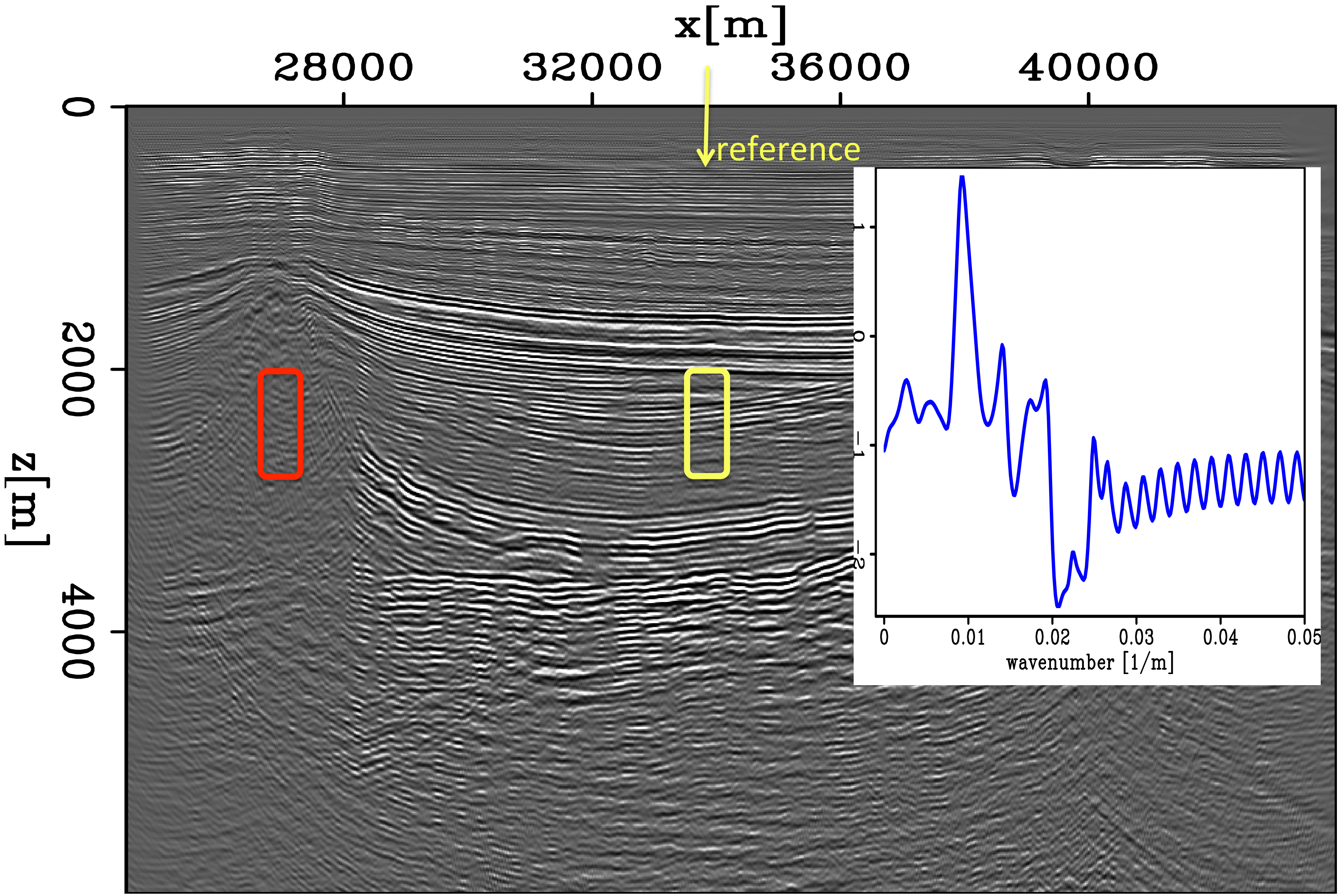
2D image after velocity updating



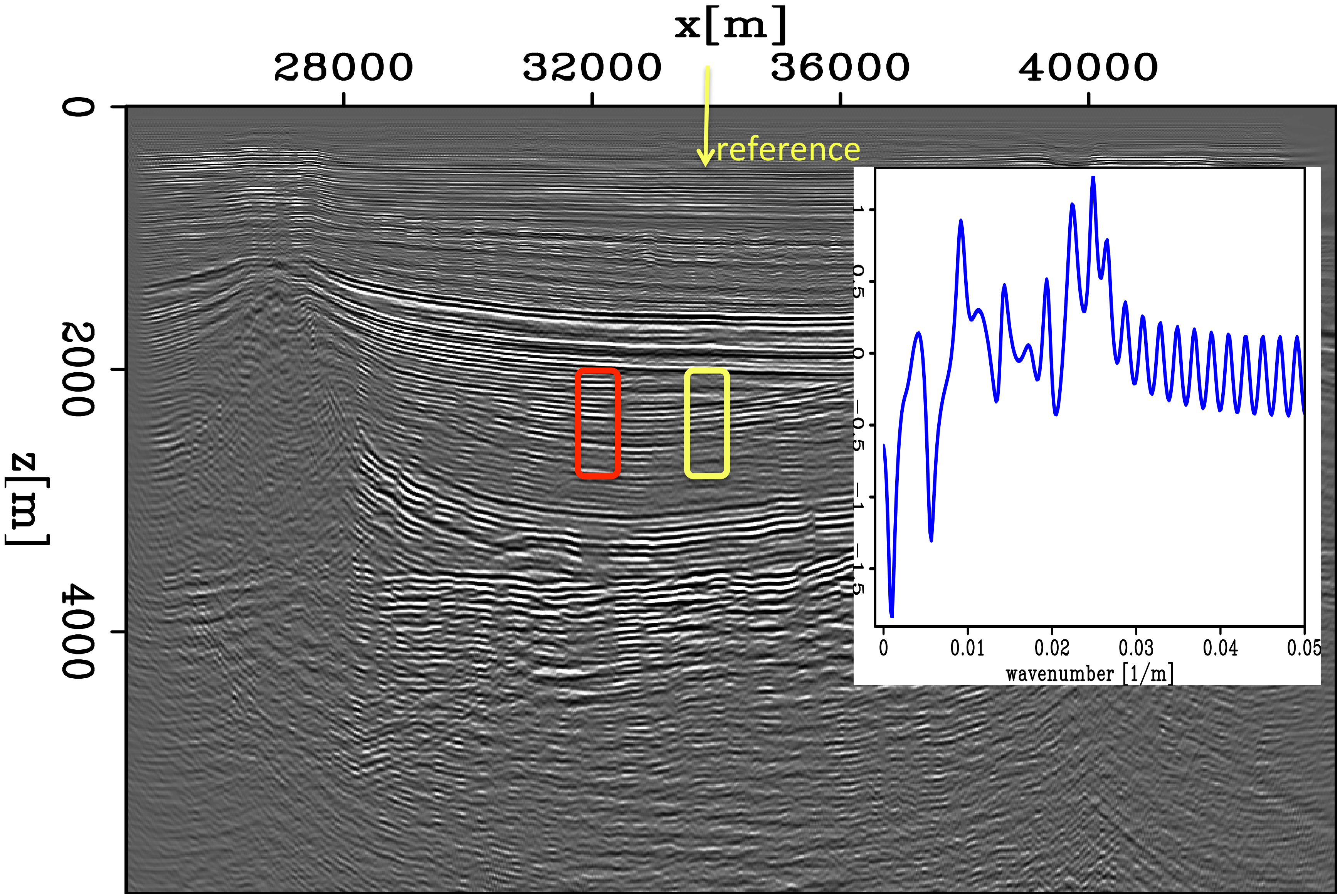
2D image before velocity updating



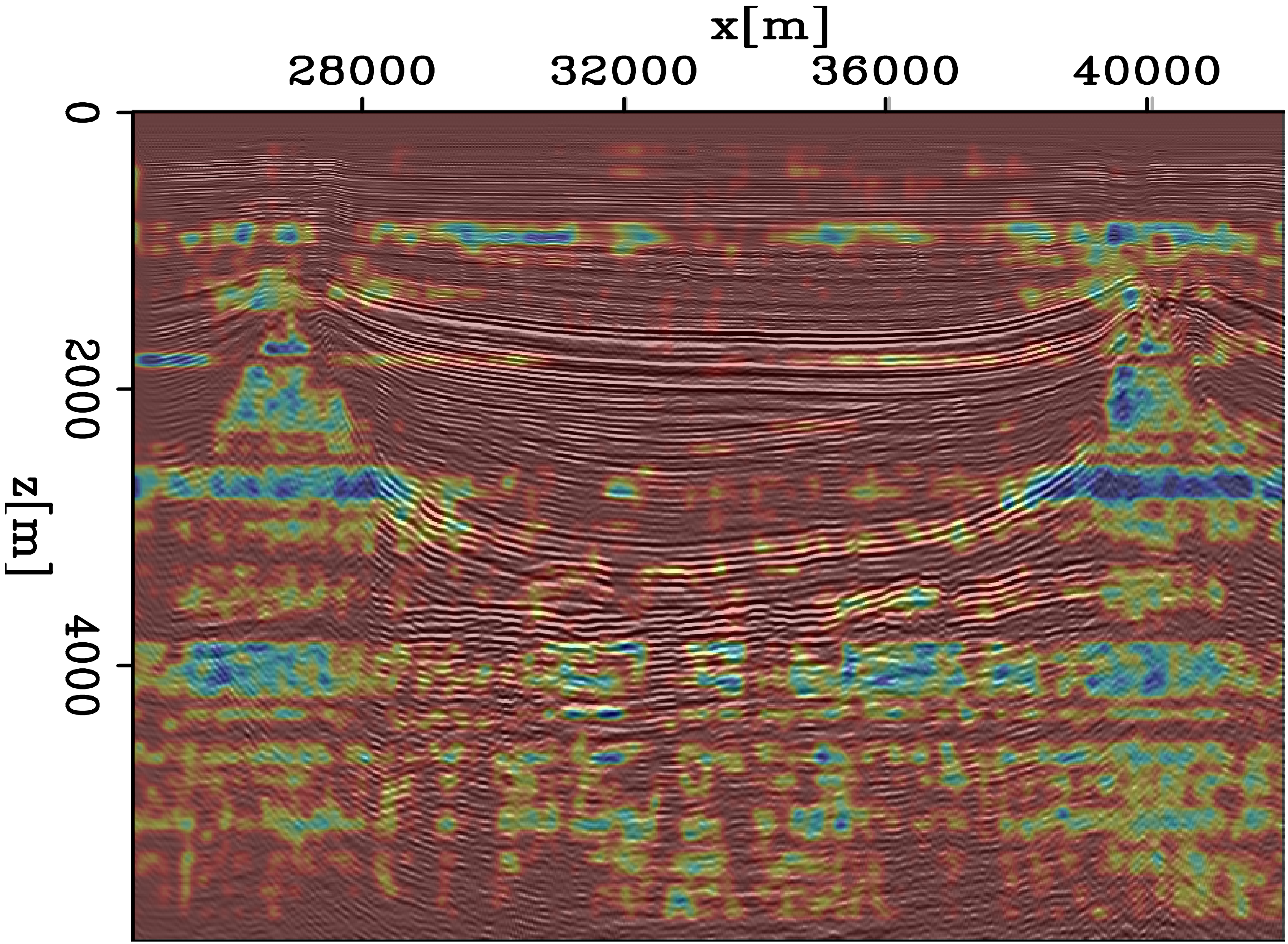
2D image before Q compensation



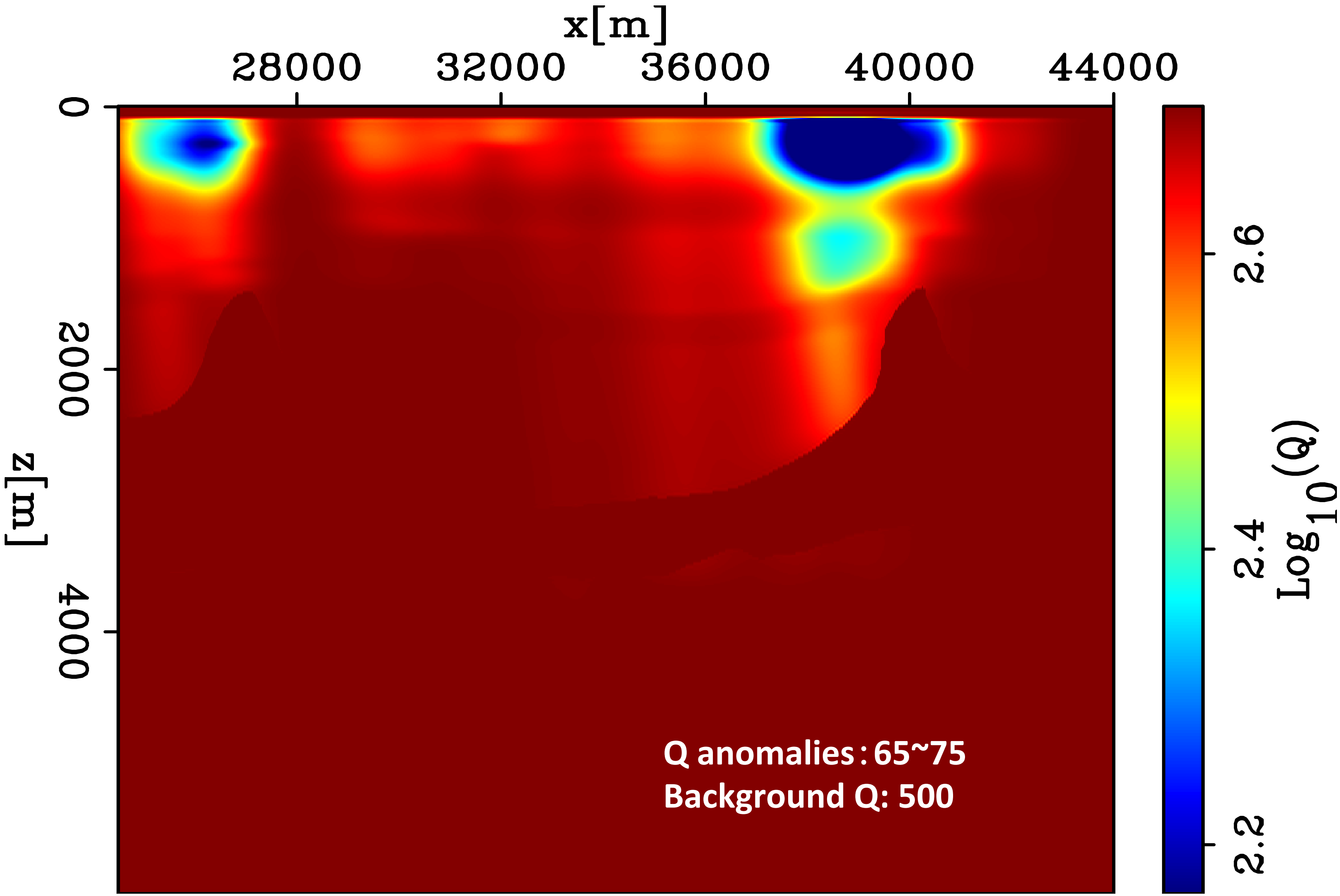
2D image before Q compensation



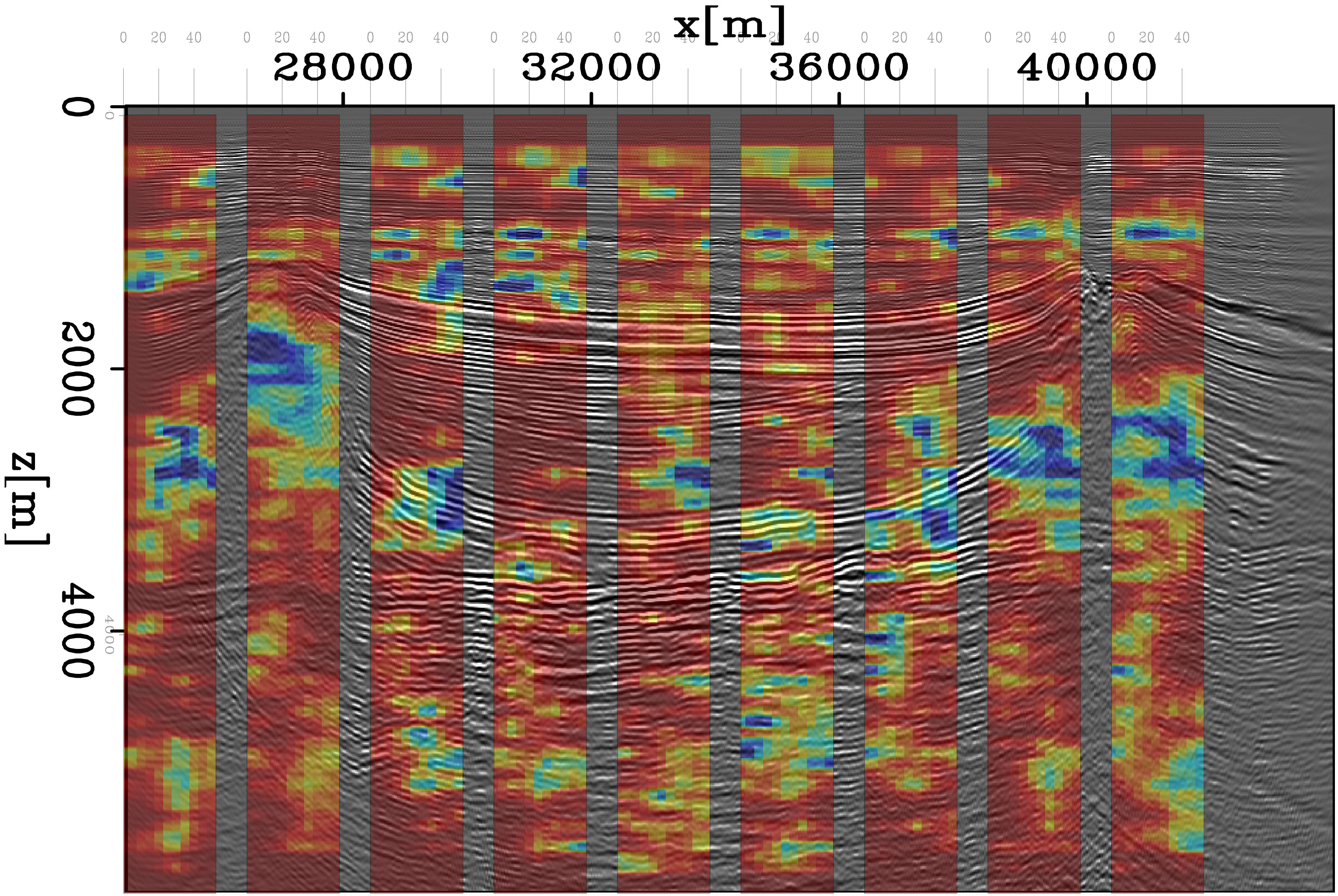
Slope of the stacked image



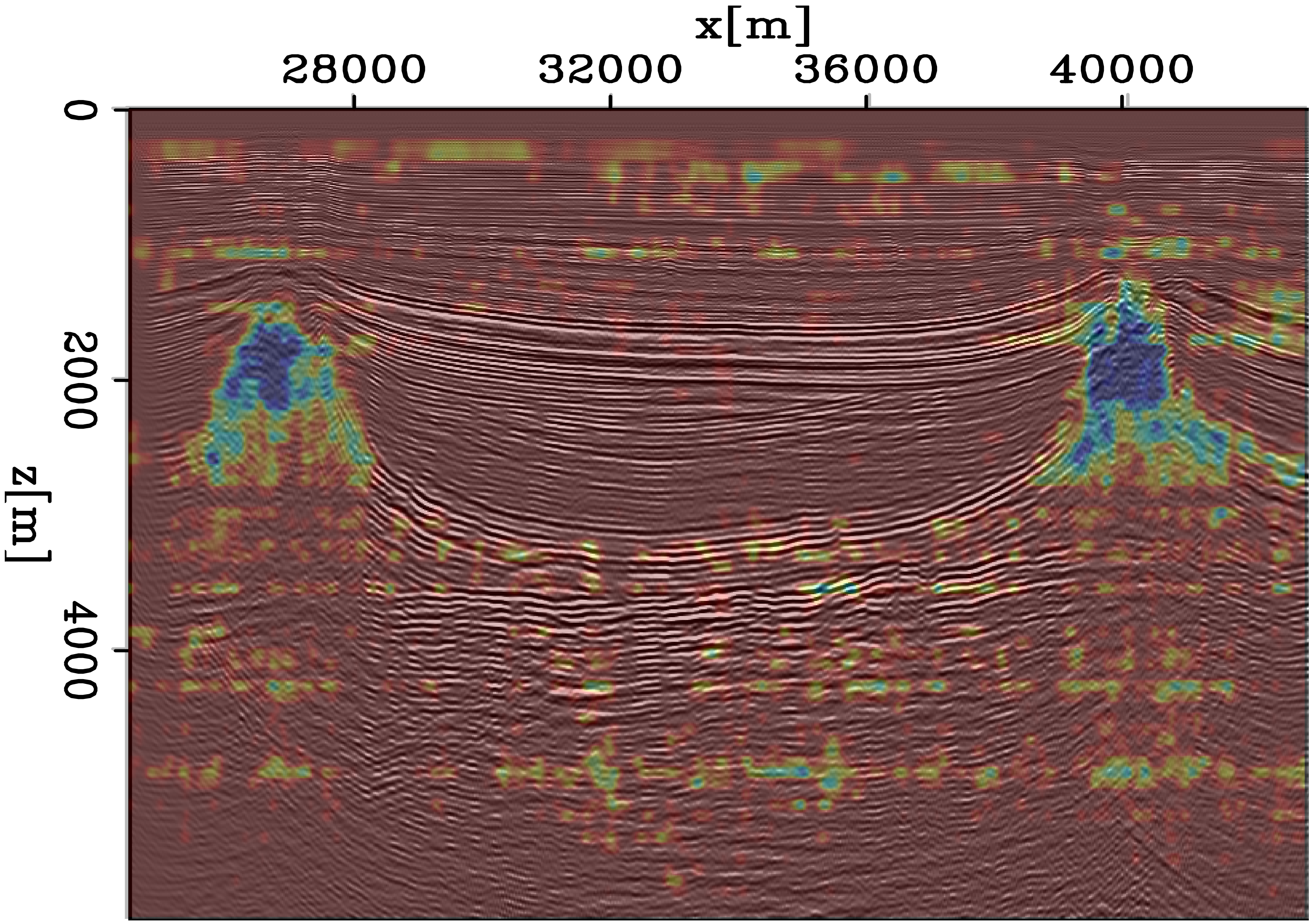
Inverted Q using stacked WEMQA



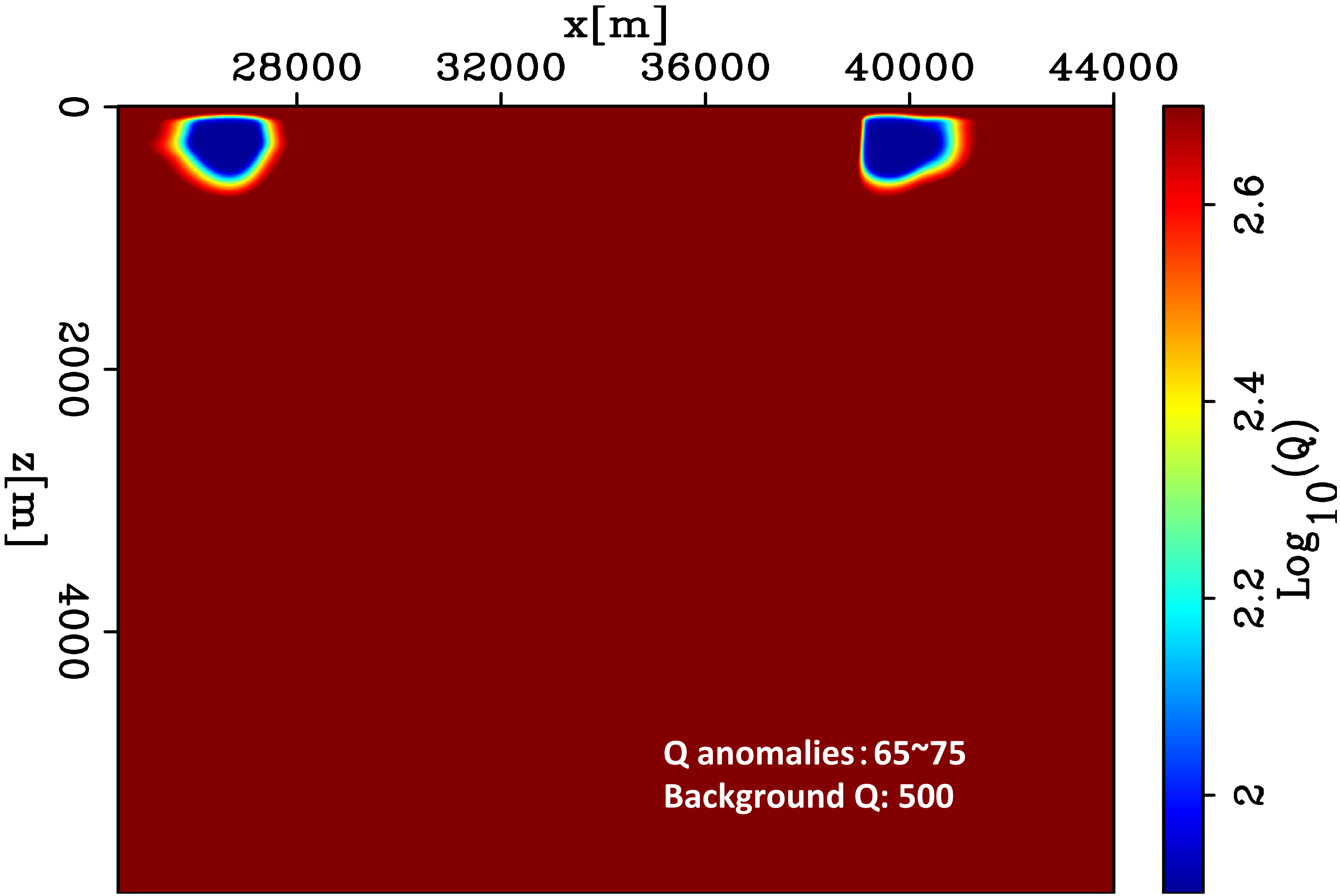
Slope of ADCIGs



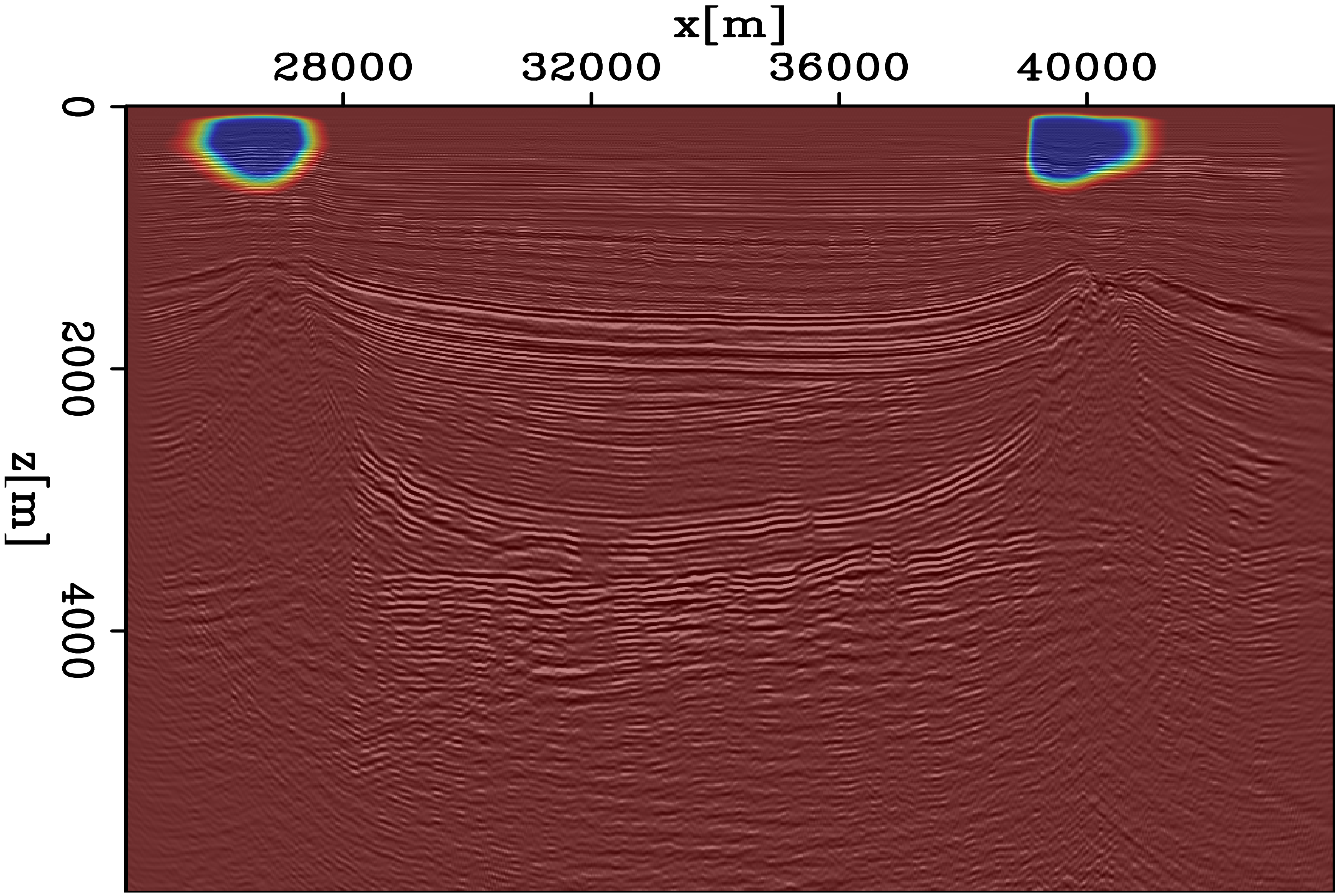
Slope of near angle image



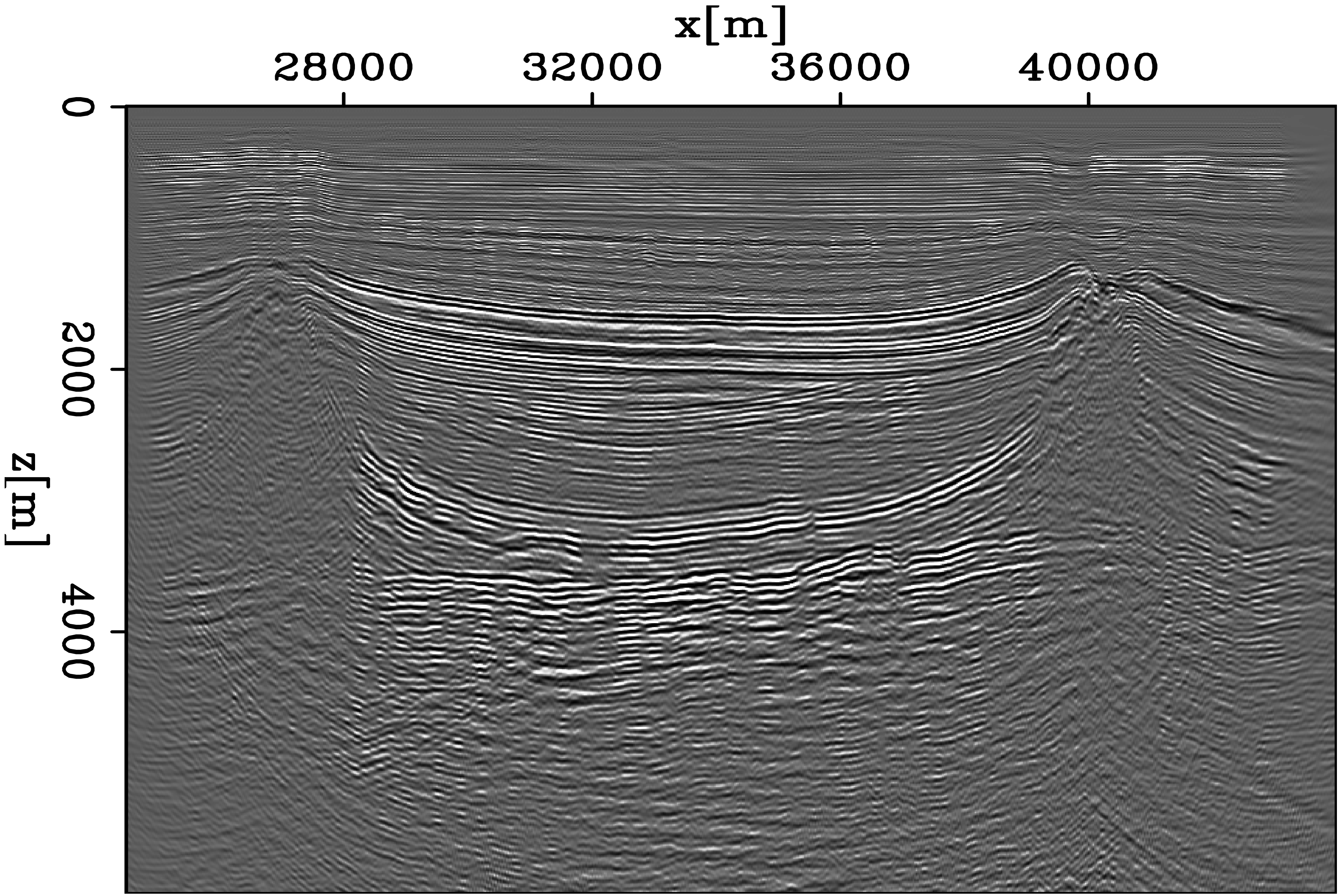
Inverted Q using prestack WEMQA



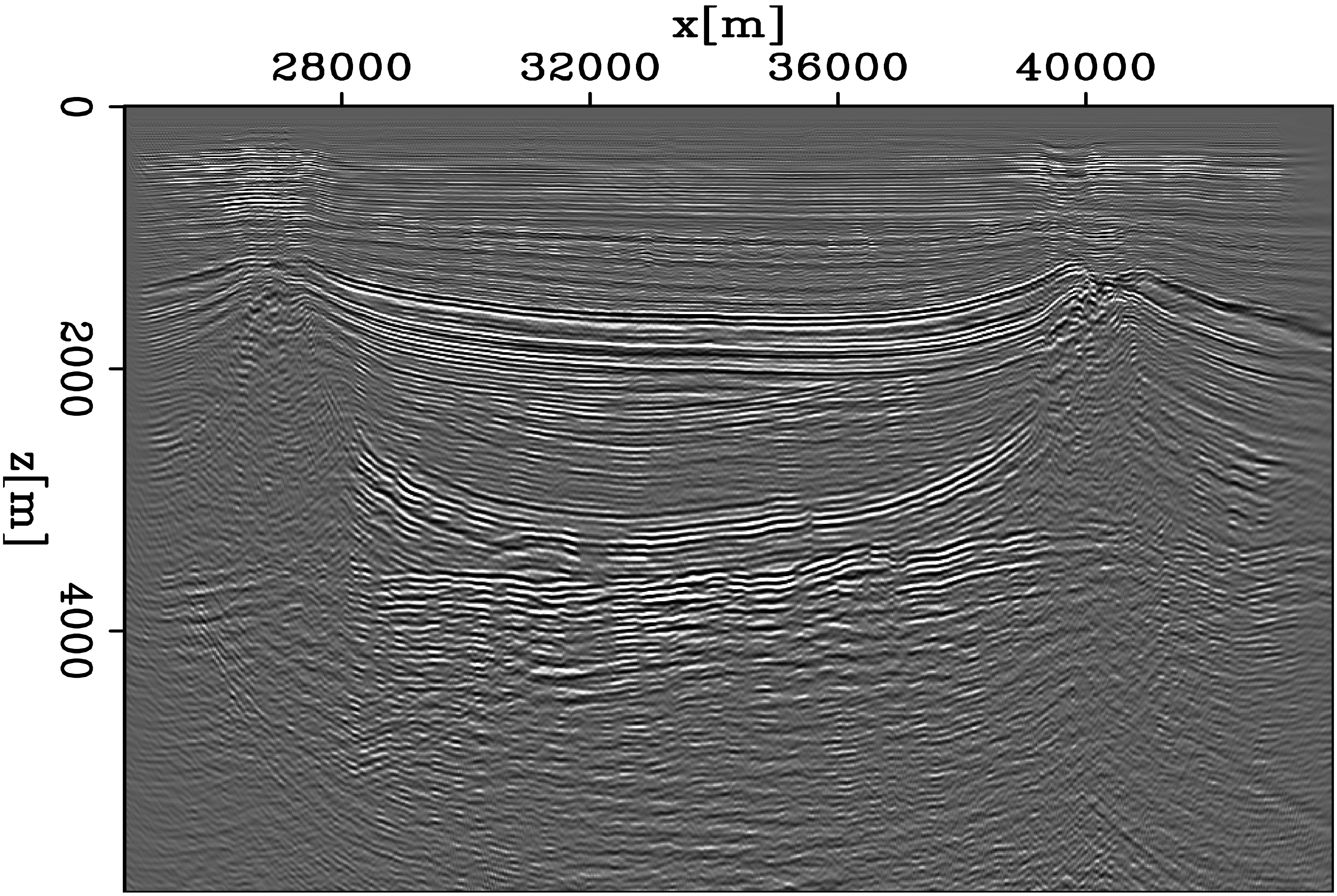
Inverted Q using prestack WEMQA



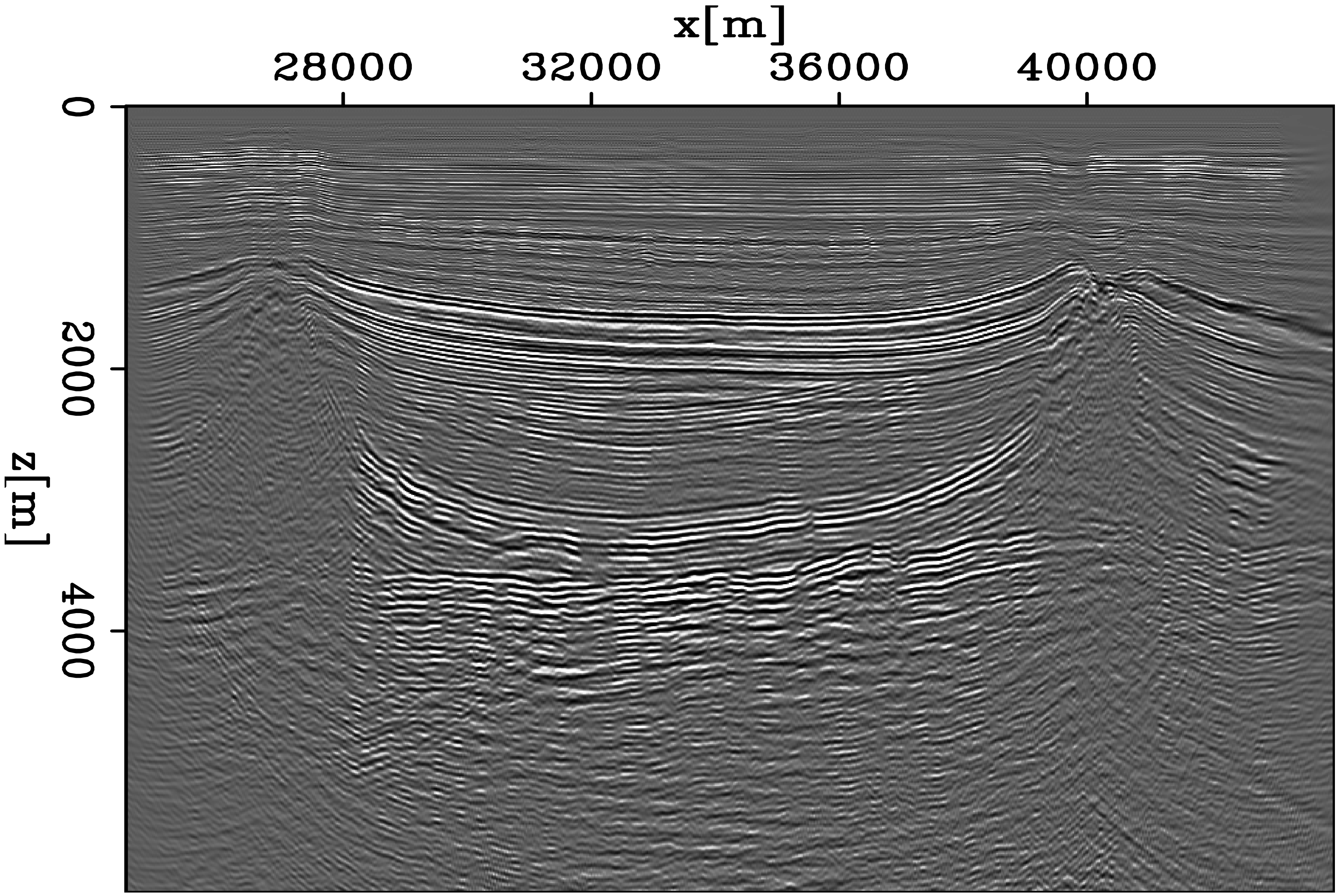
2D image before Q compensation



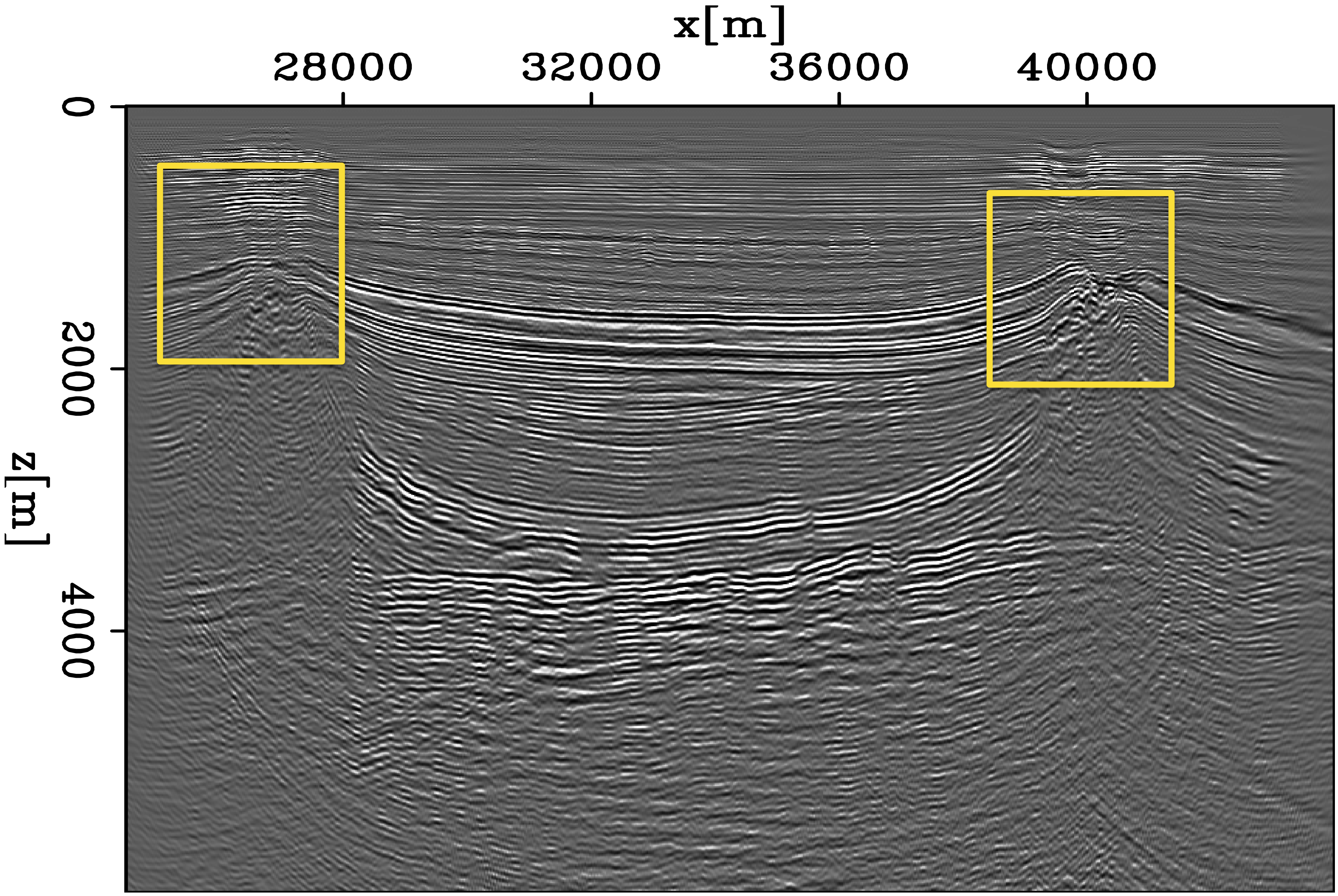
2D image after Q compensation



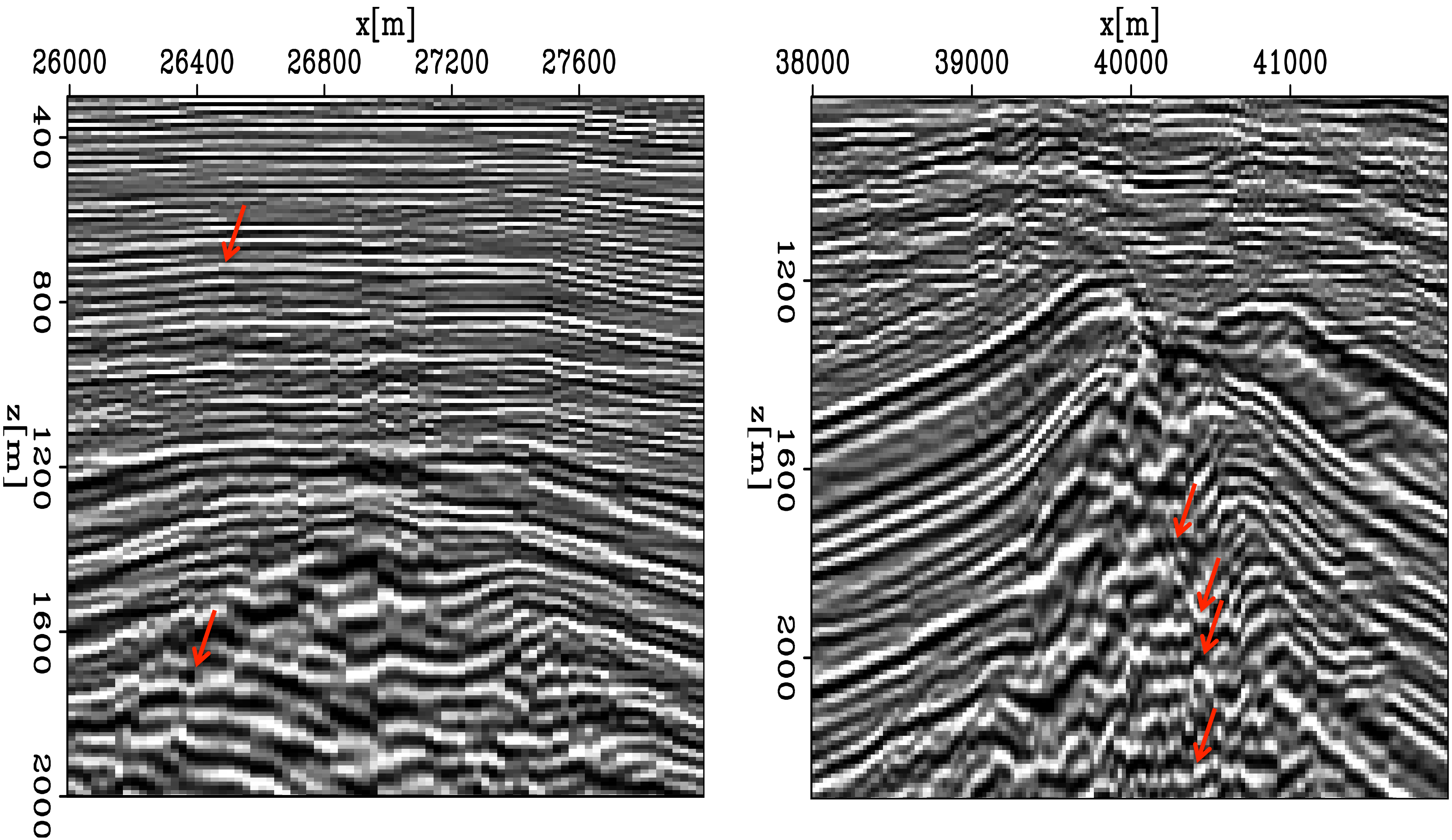
2D image before Q compensation



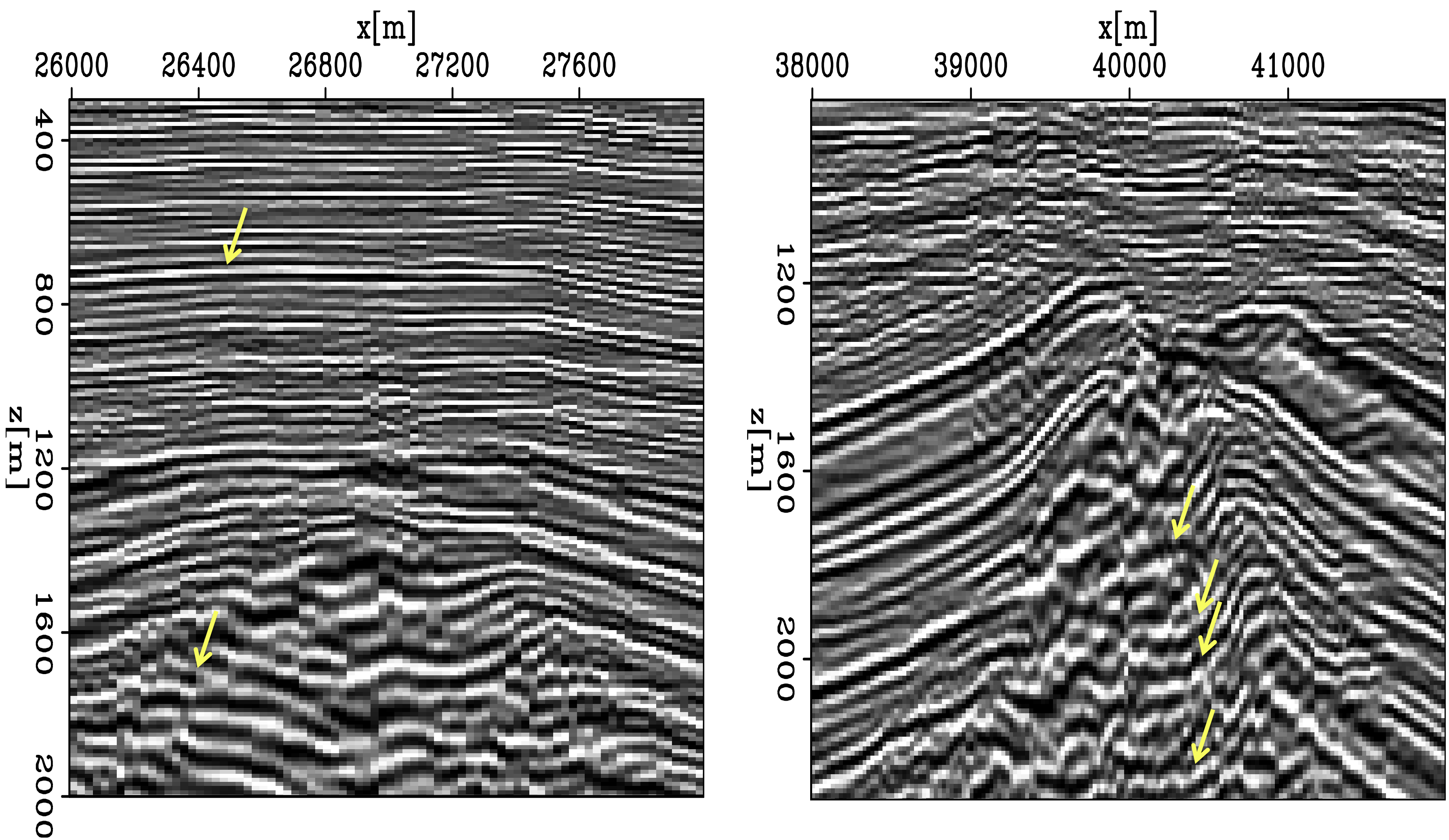
2D image after Q compensation



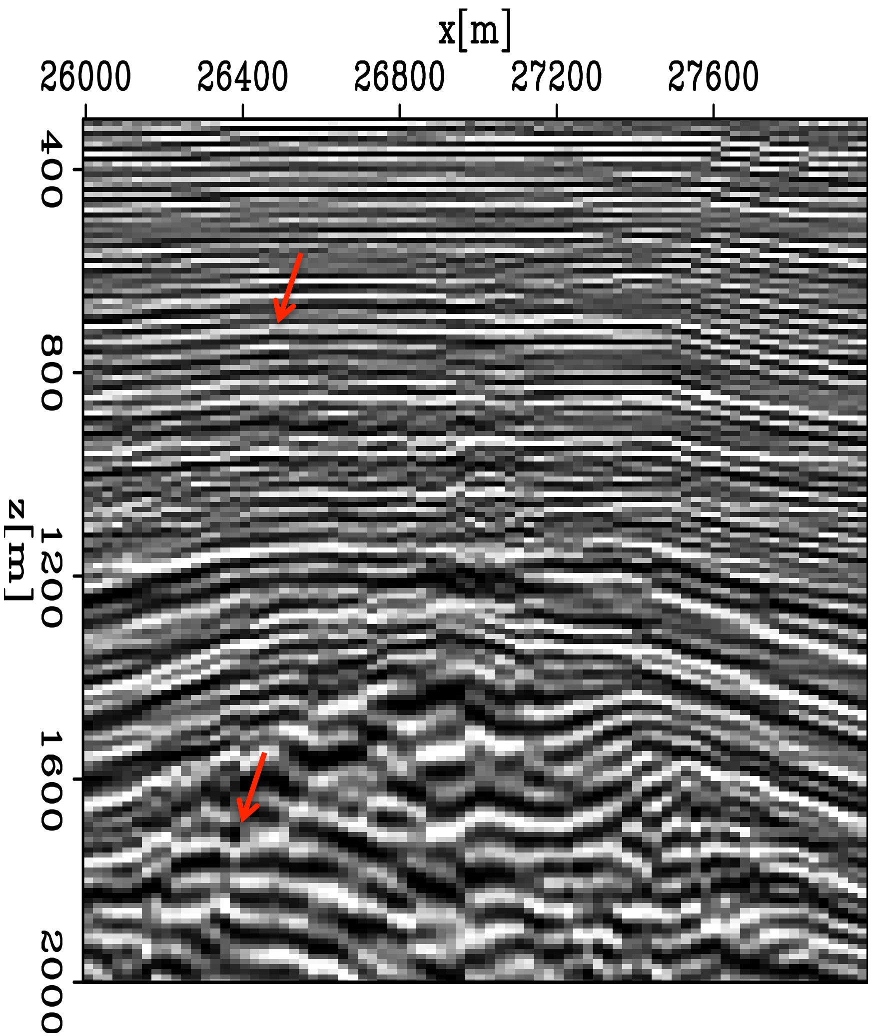
2D image before Q compensation: Automatic gain control (AGC) is applied

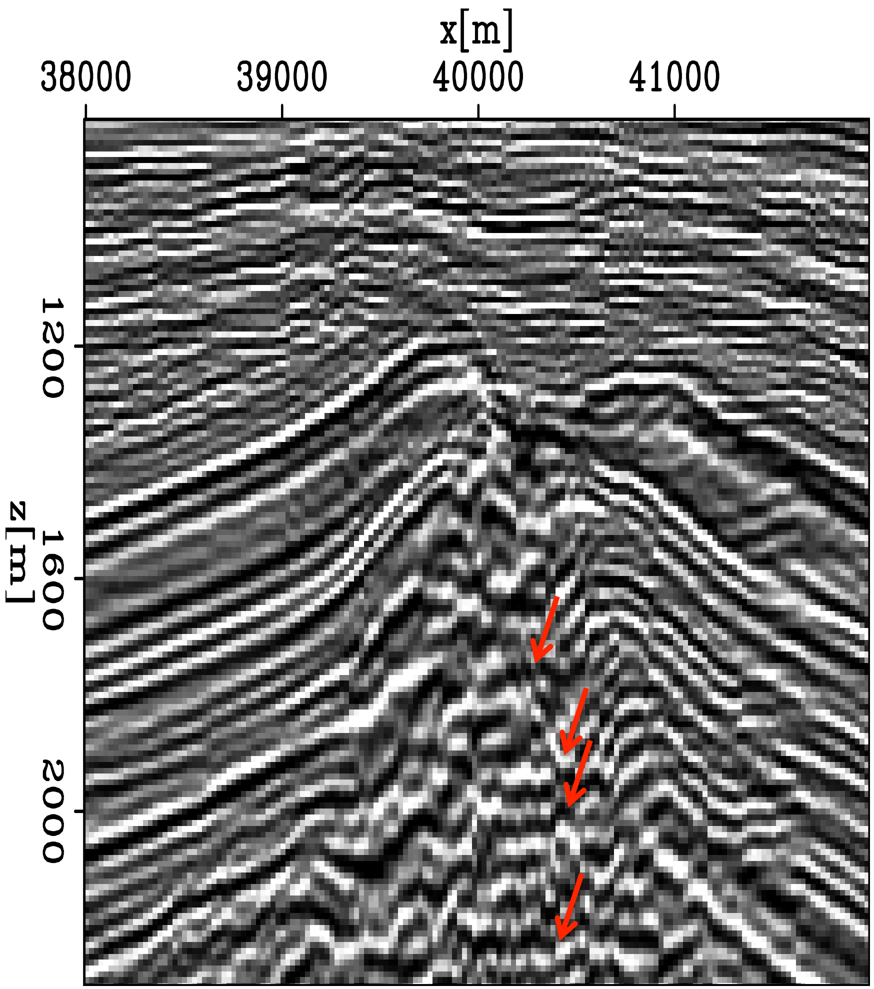


2D image after Q compensation: Automatic gain control (AGC) is applied

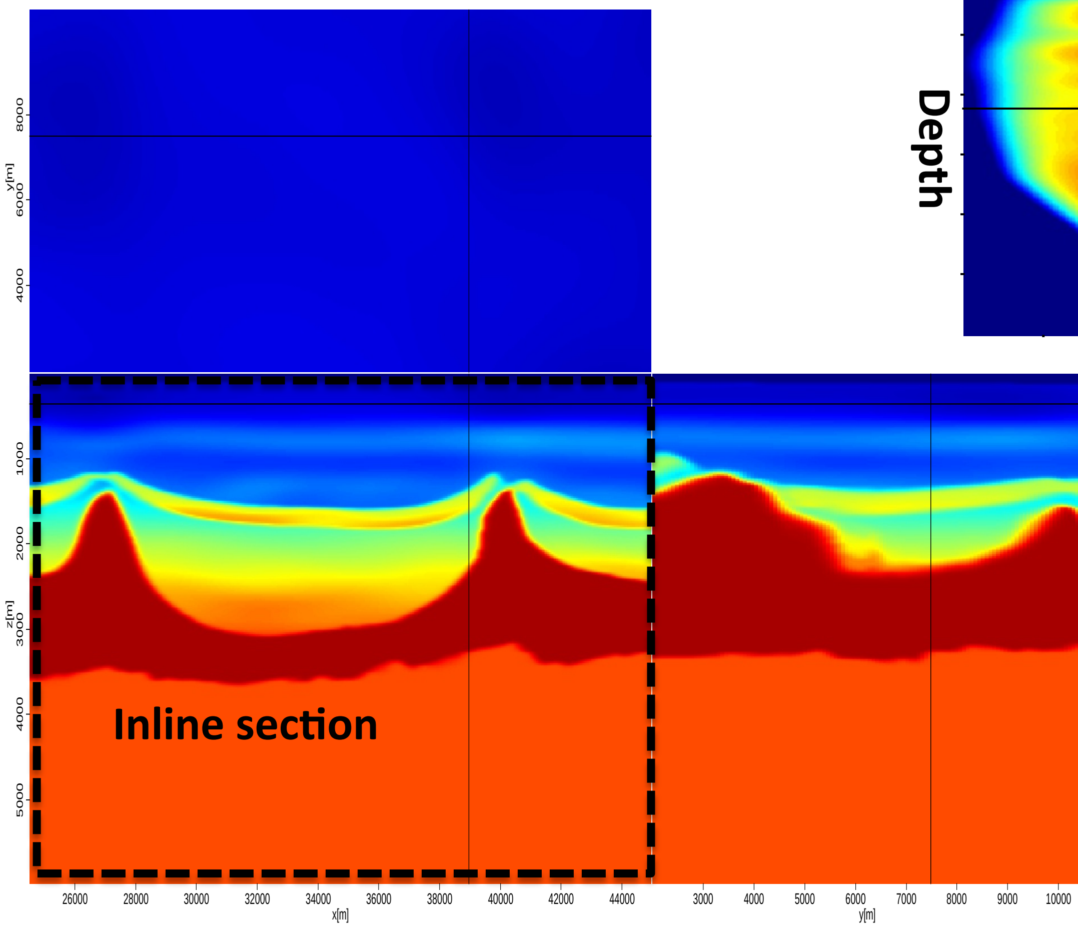


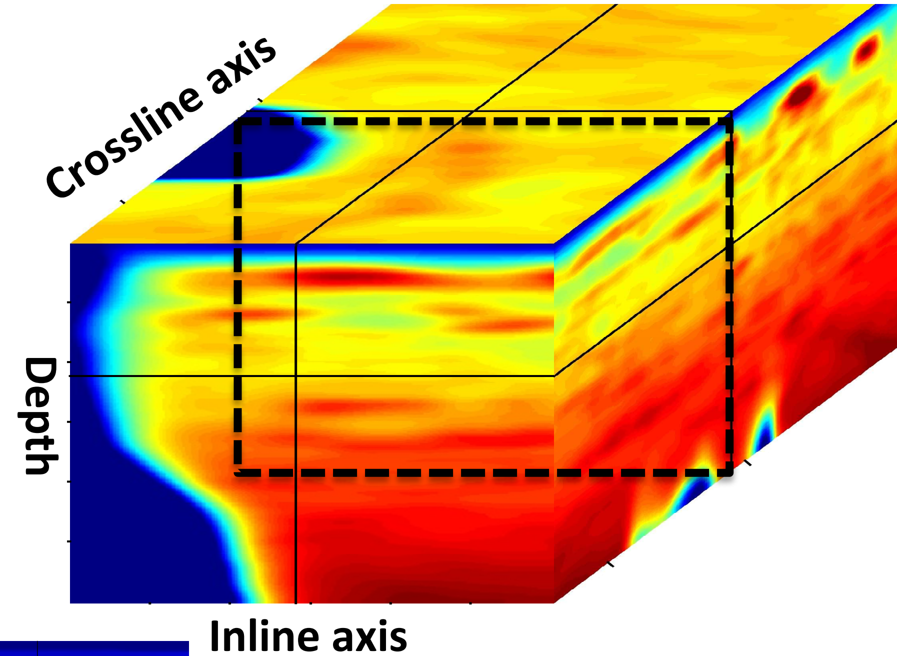
2D image before Q compensation: Automatic gain control (AGC) is applied



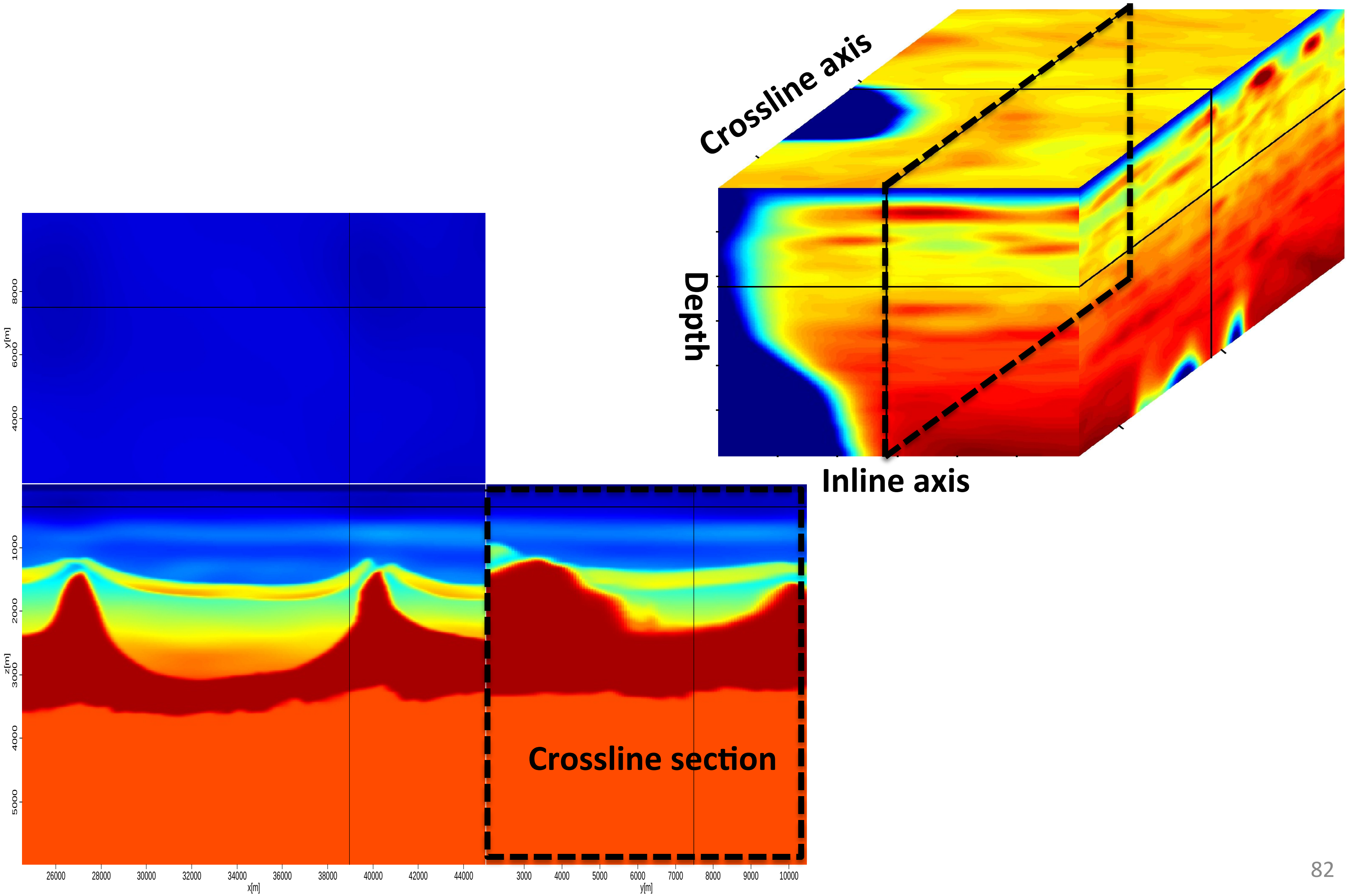


SEP 3D viewer: inline section

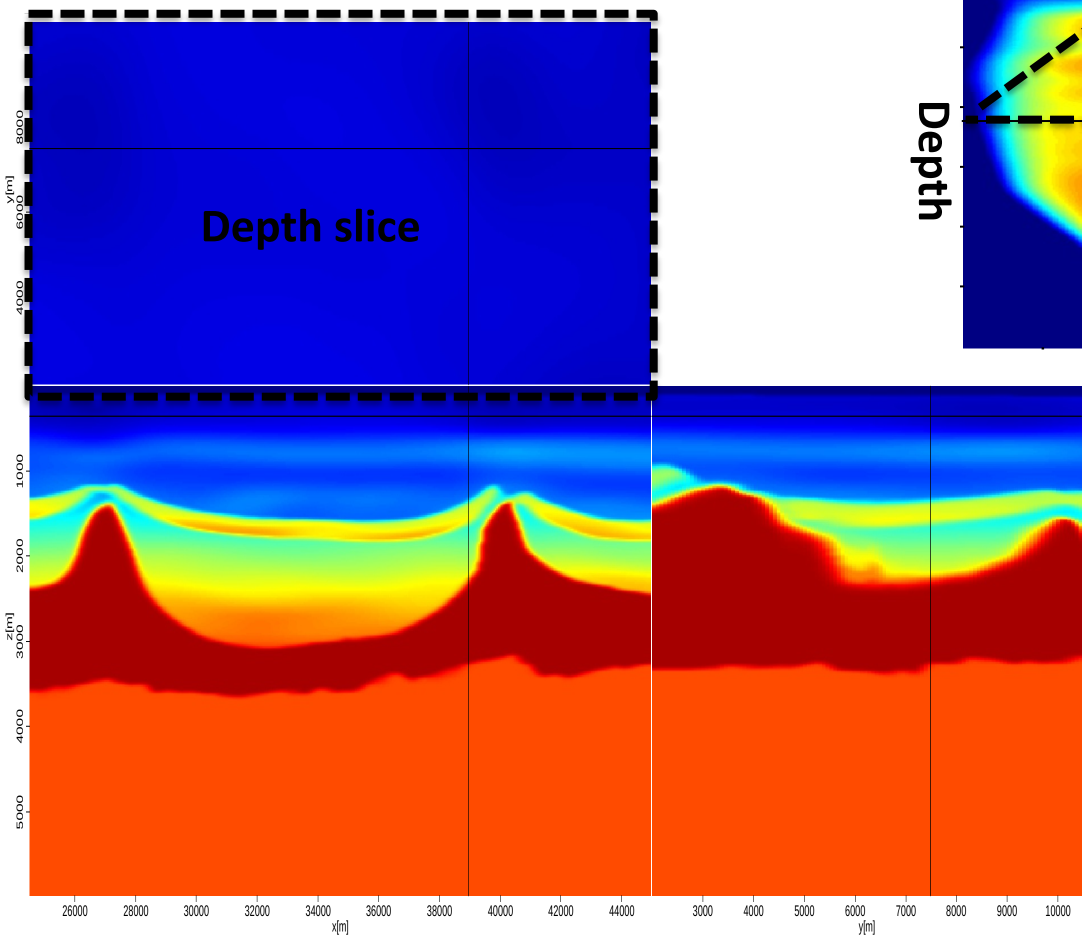


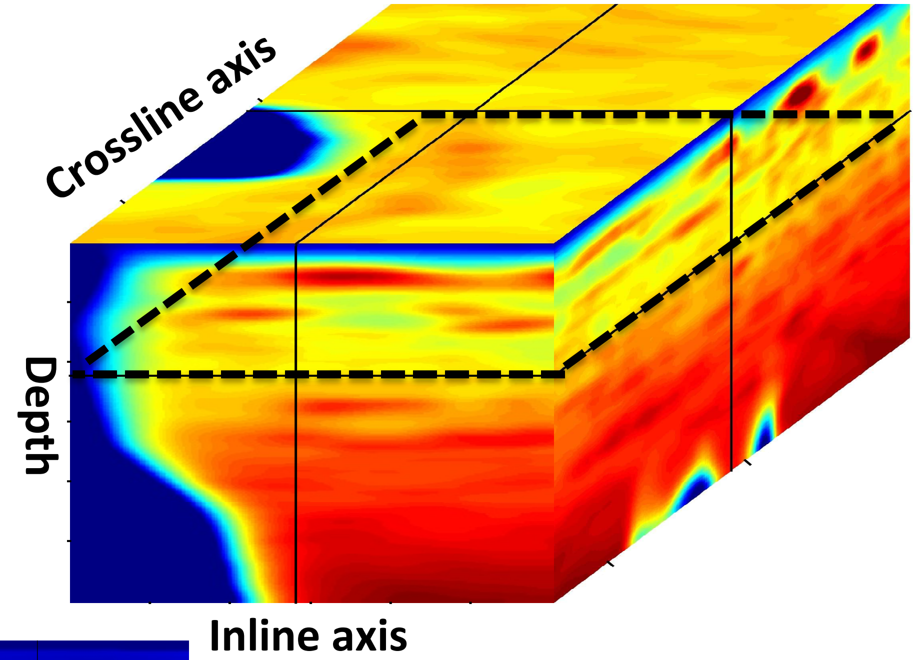


SEP 3D viewer: inline section

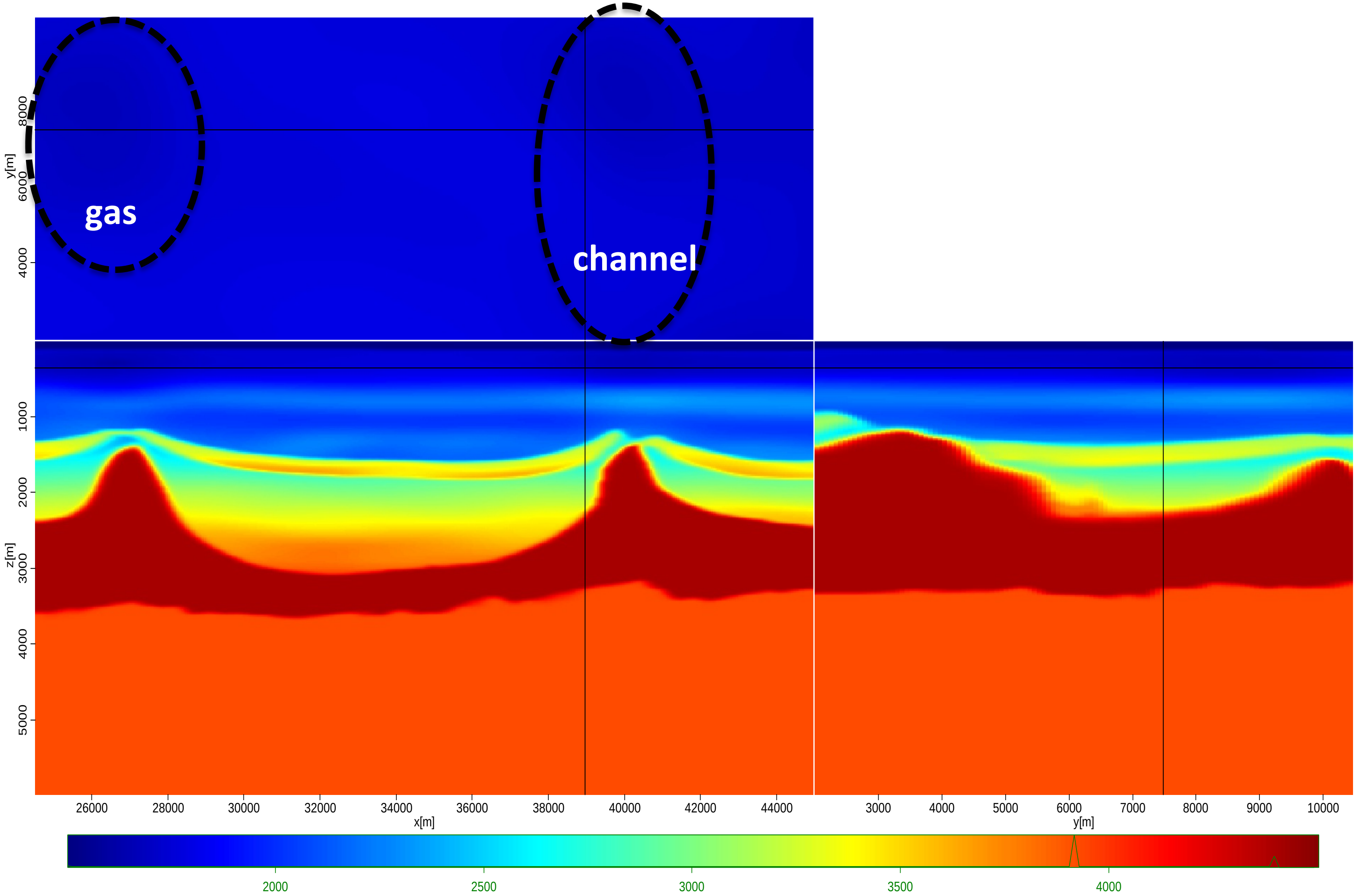


SEP 3D viewer: depth slice

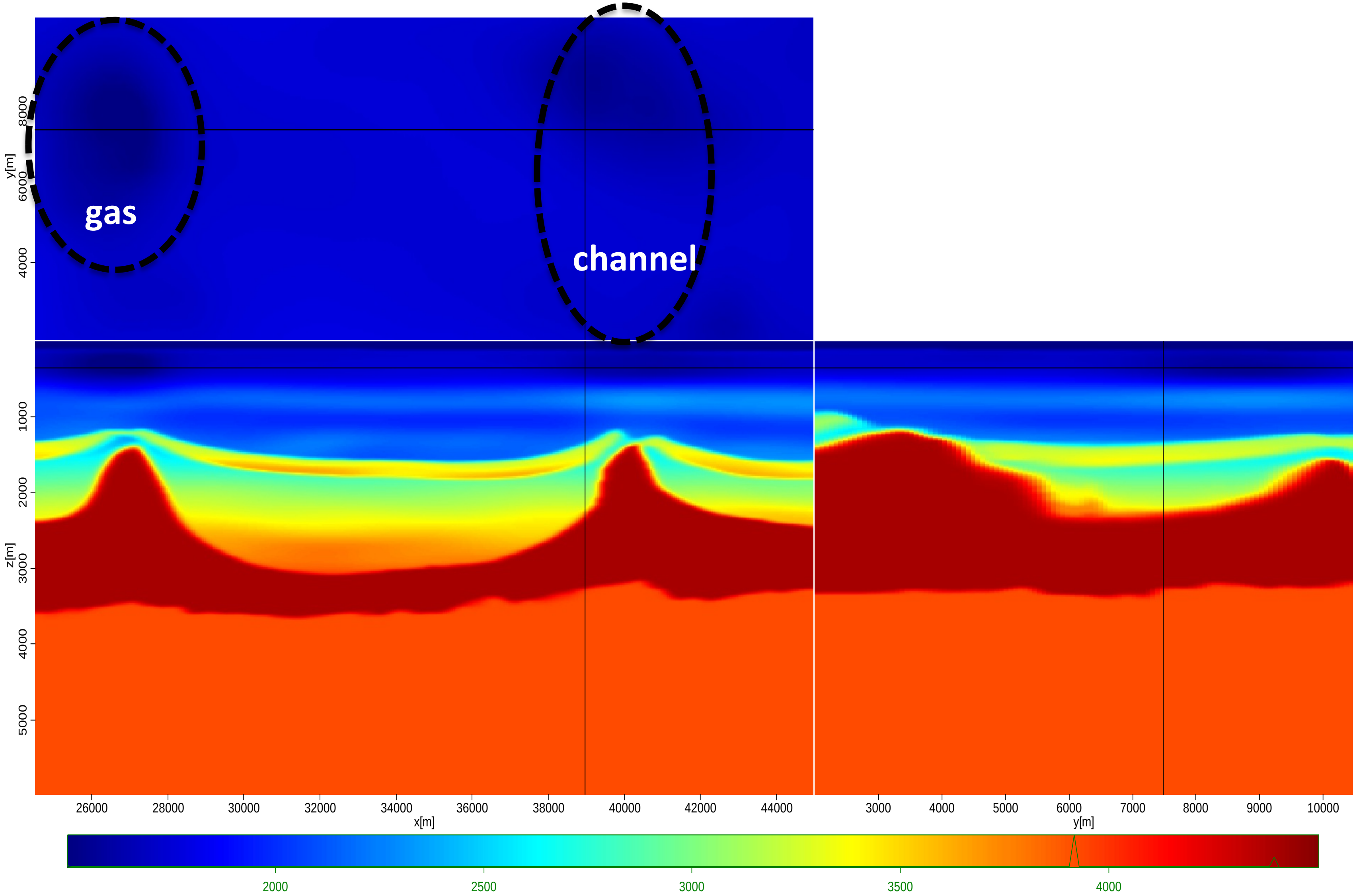




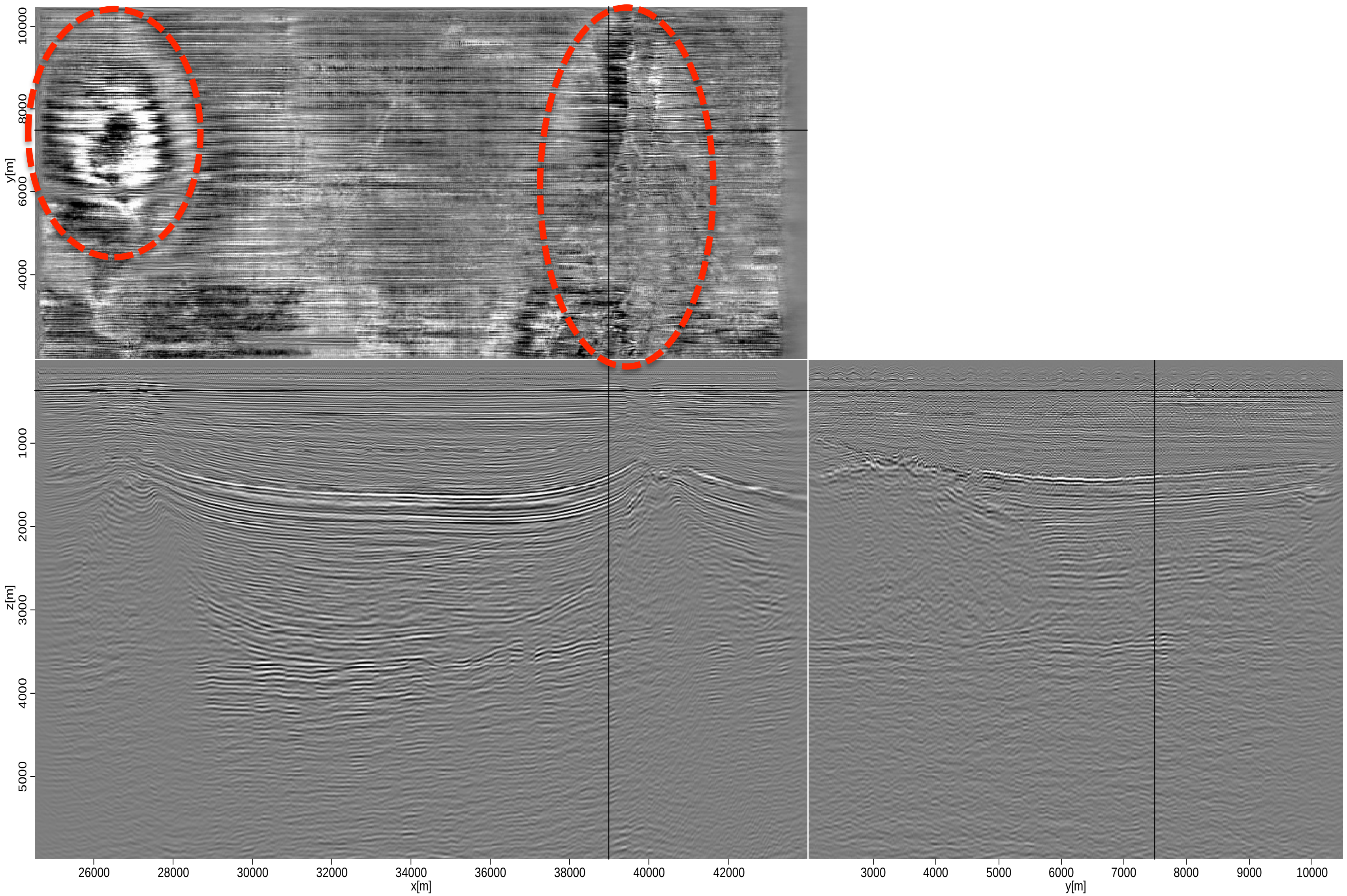
3D initial velocity



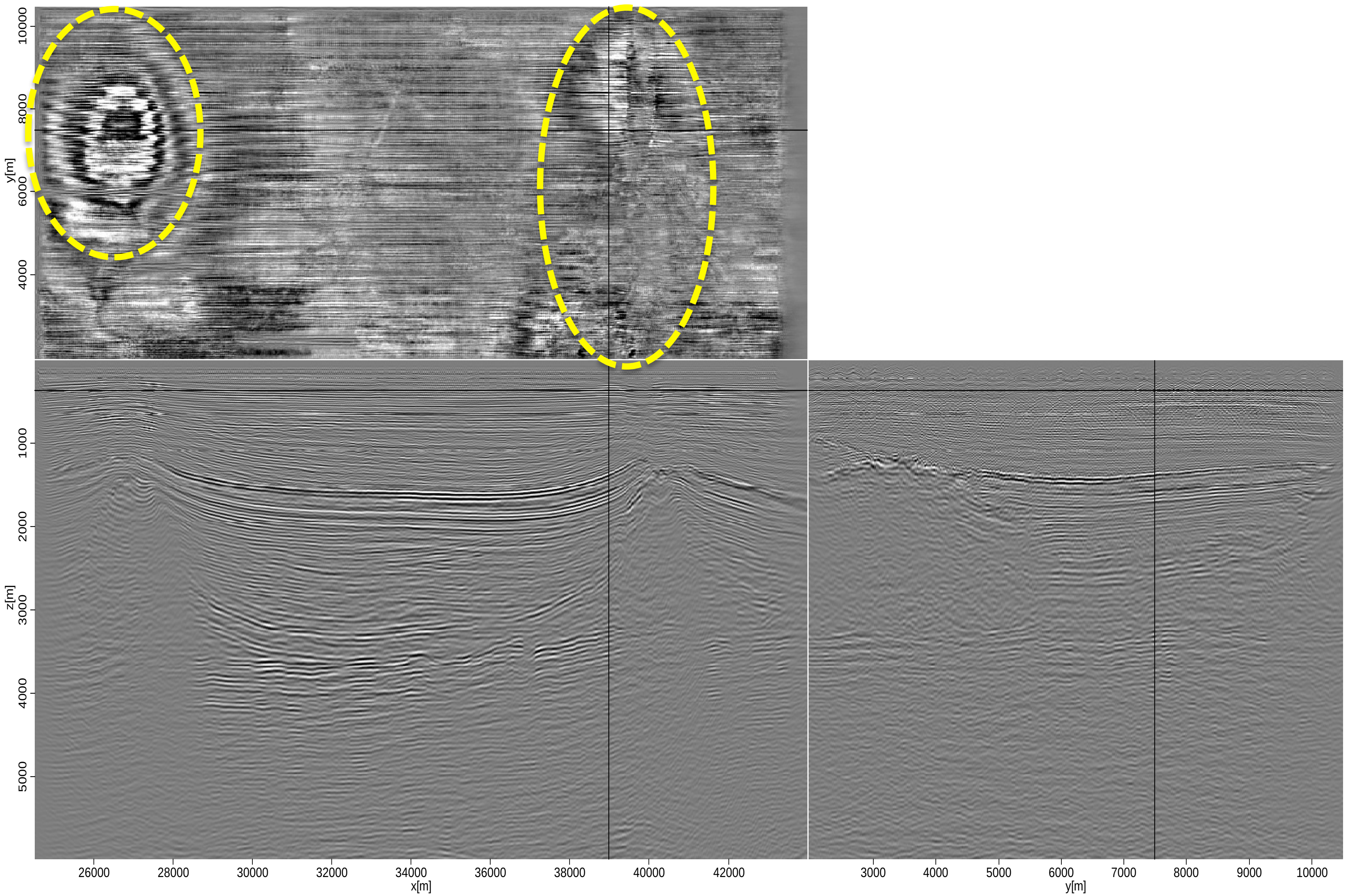
3D updated velocity



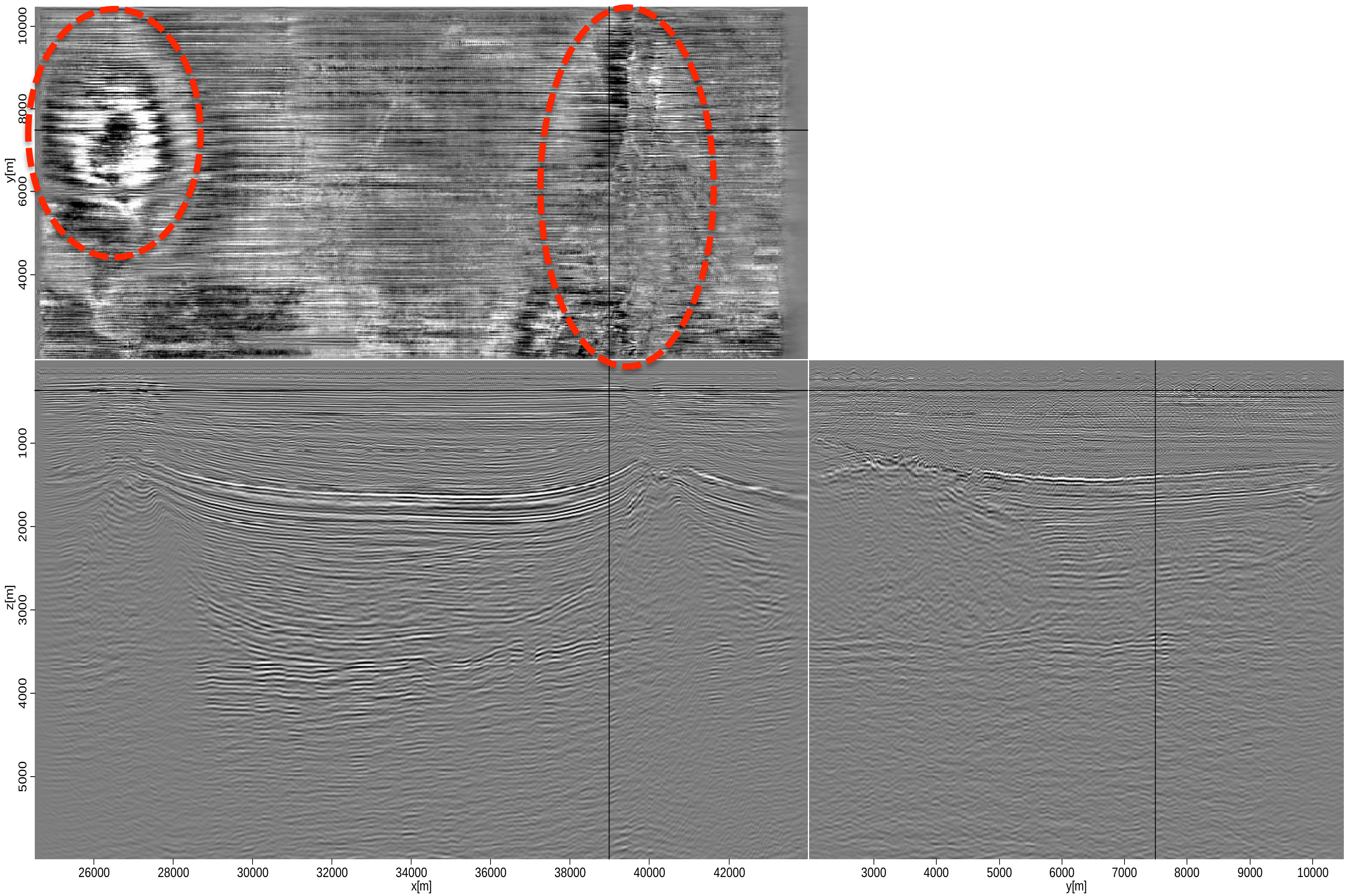
3D image before velocity updating



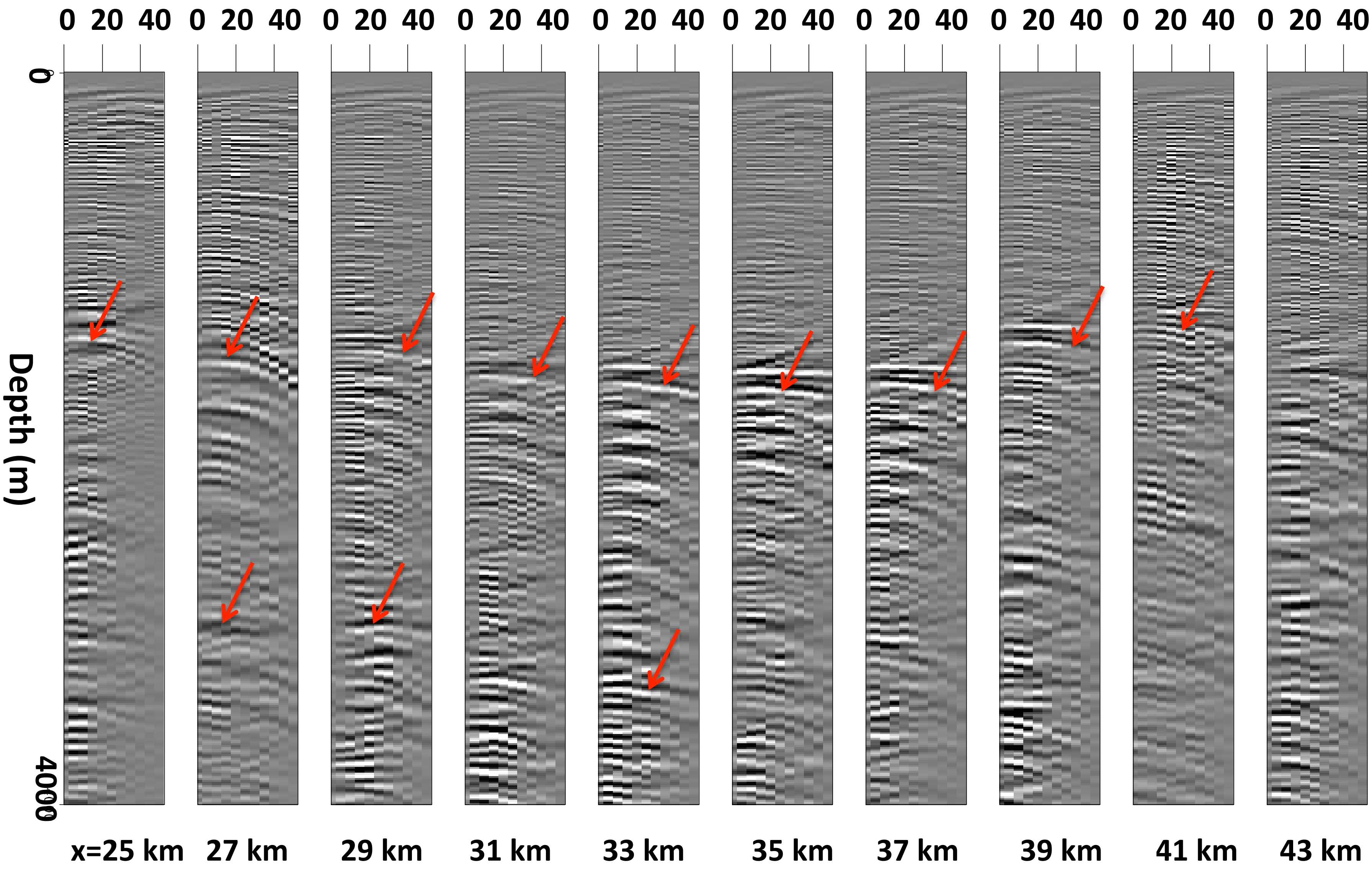
3D image after velocity updating



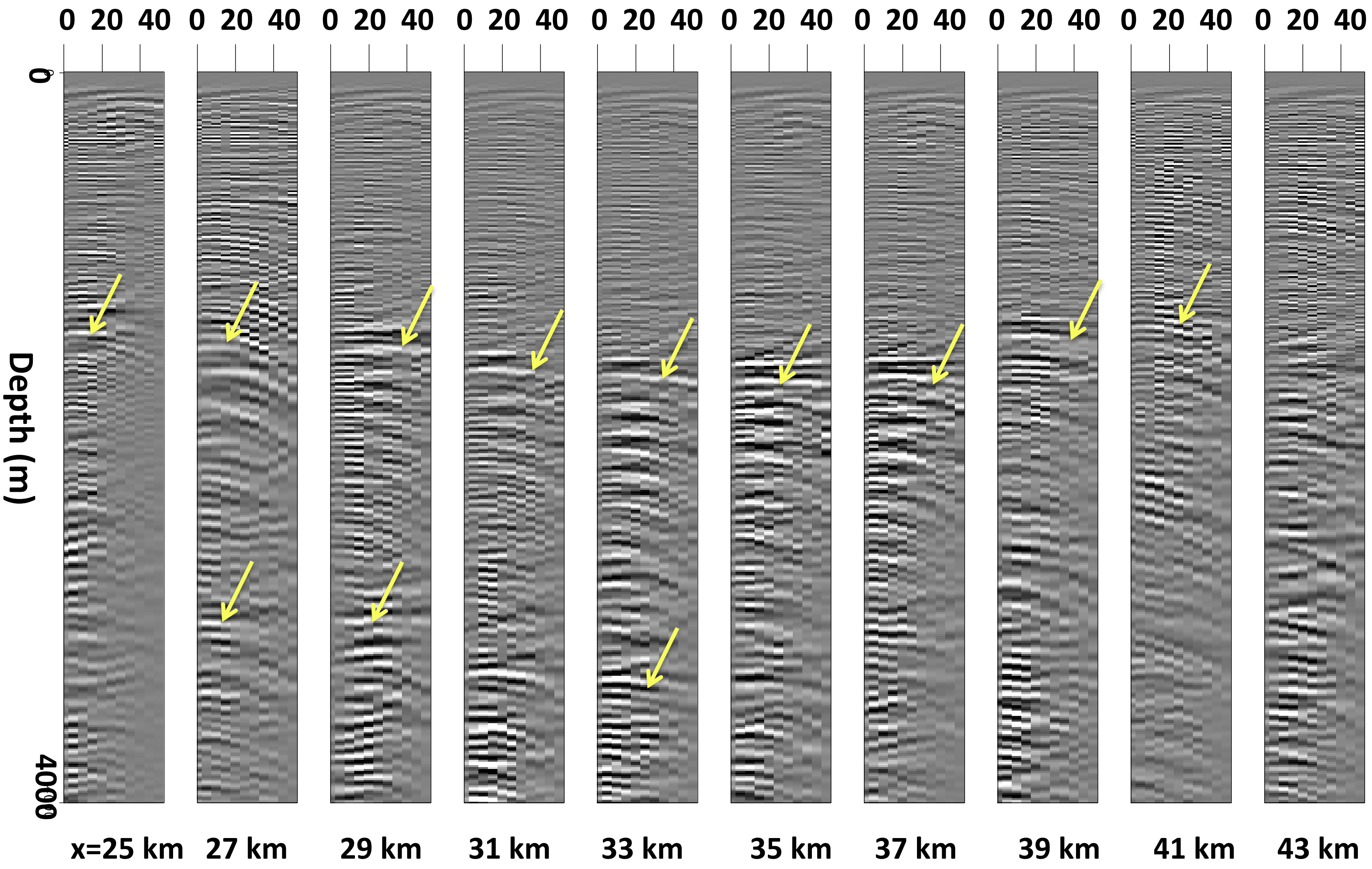
3D image before velocity updating



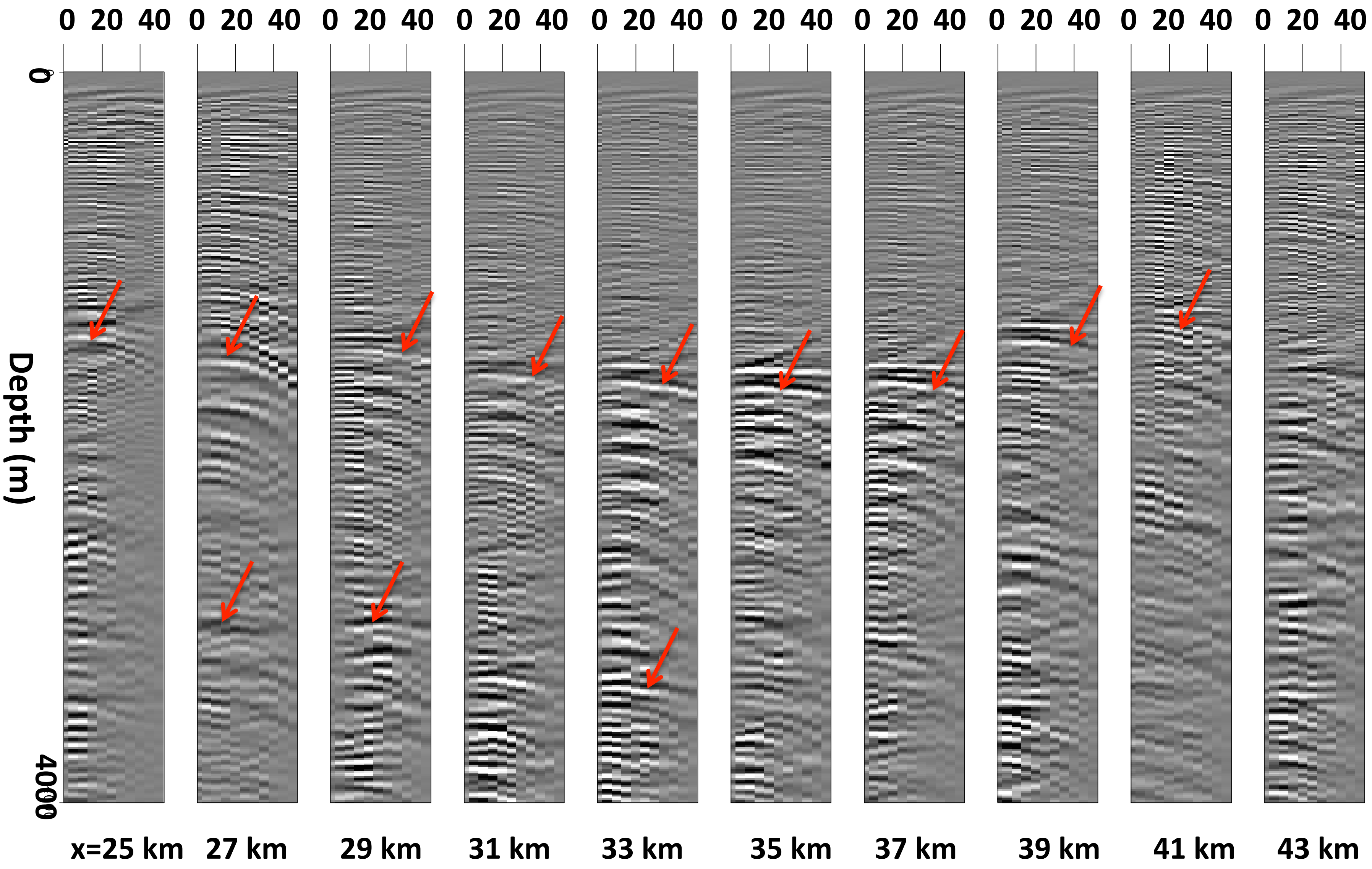
ADCIGs before velocity updating



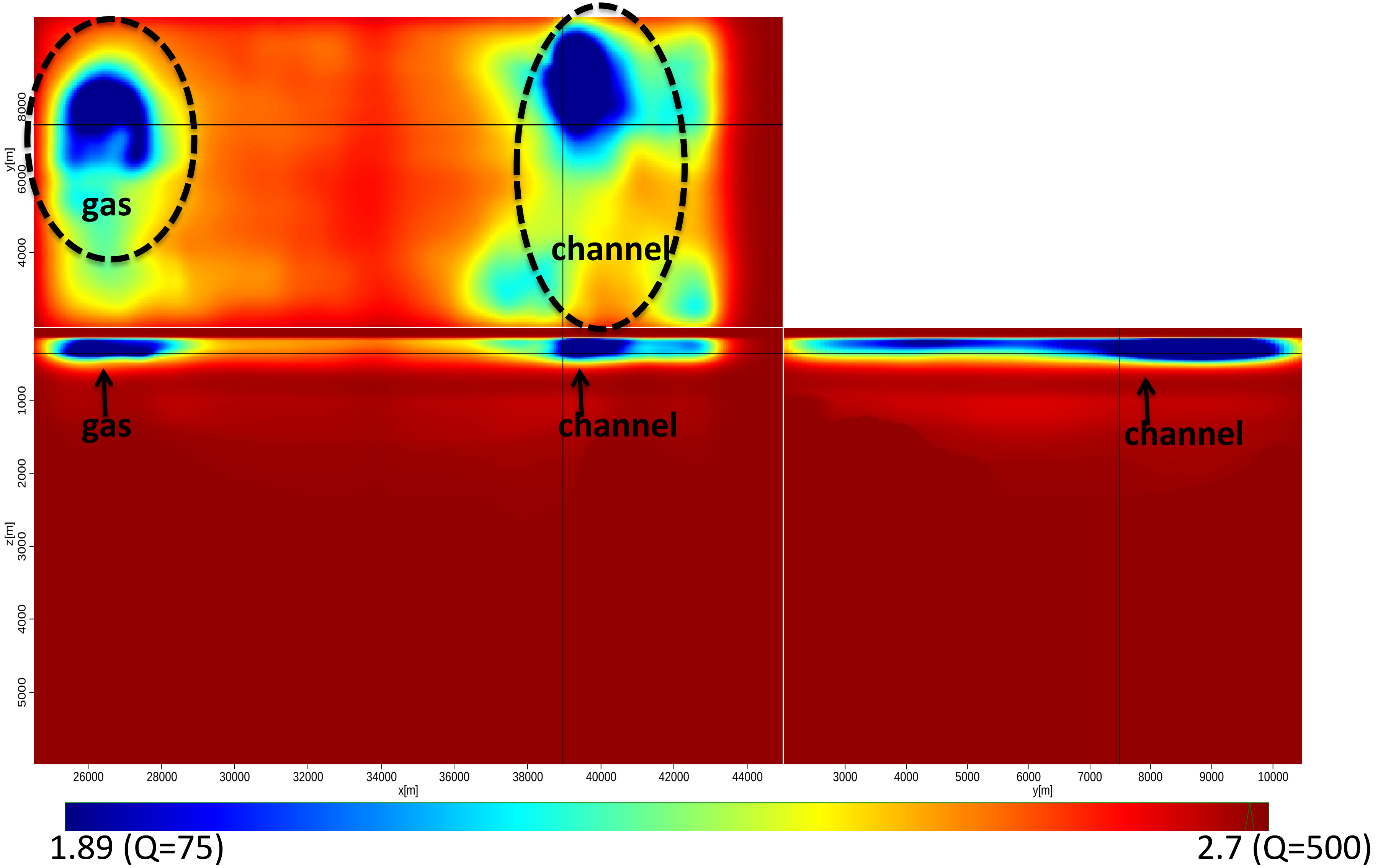
ADCIGs after velocity updating



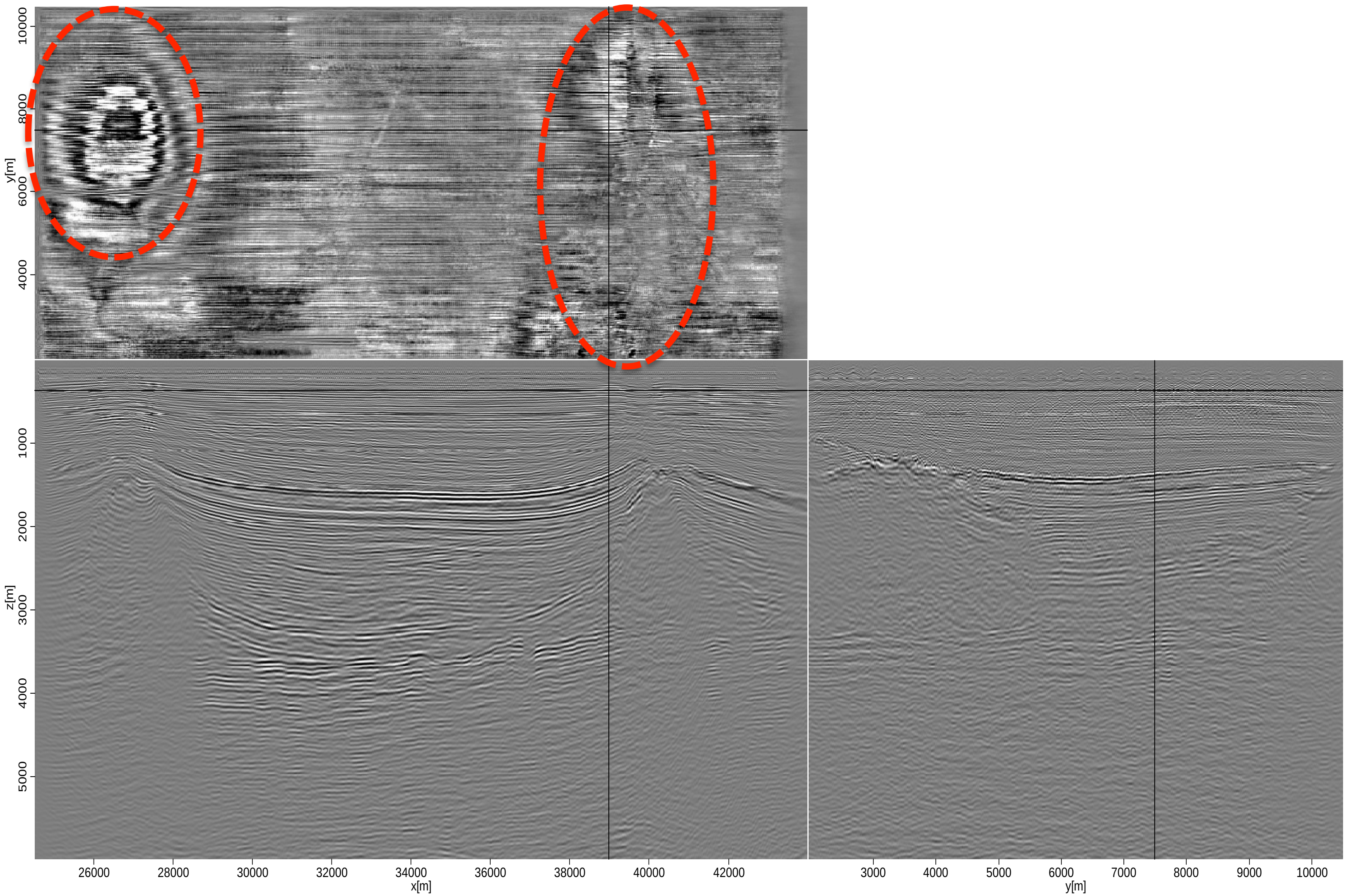
ADCIGs before velocity updating



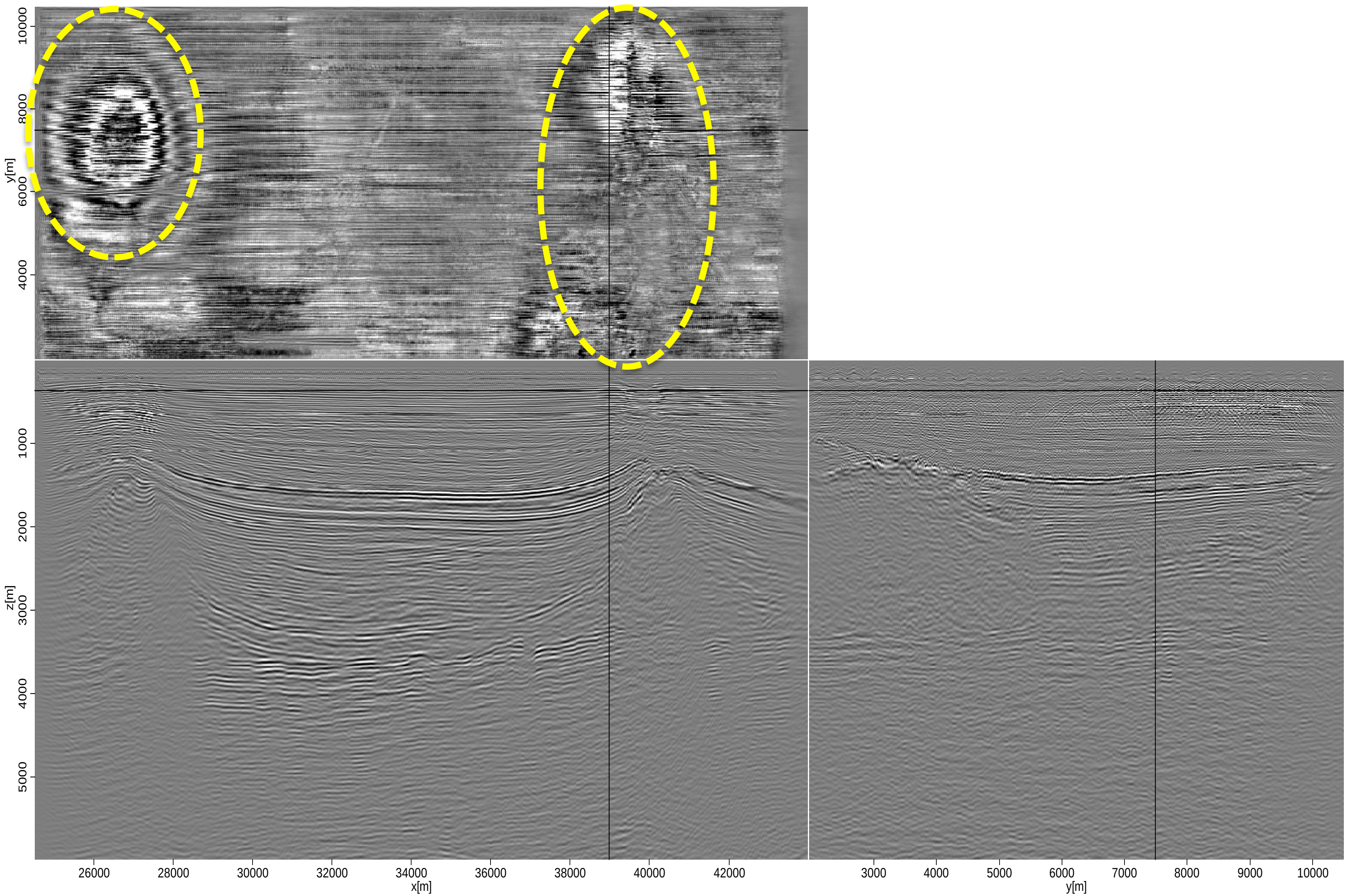
Inverted Q model using prestack WEMQA



3D image before Q compensation

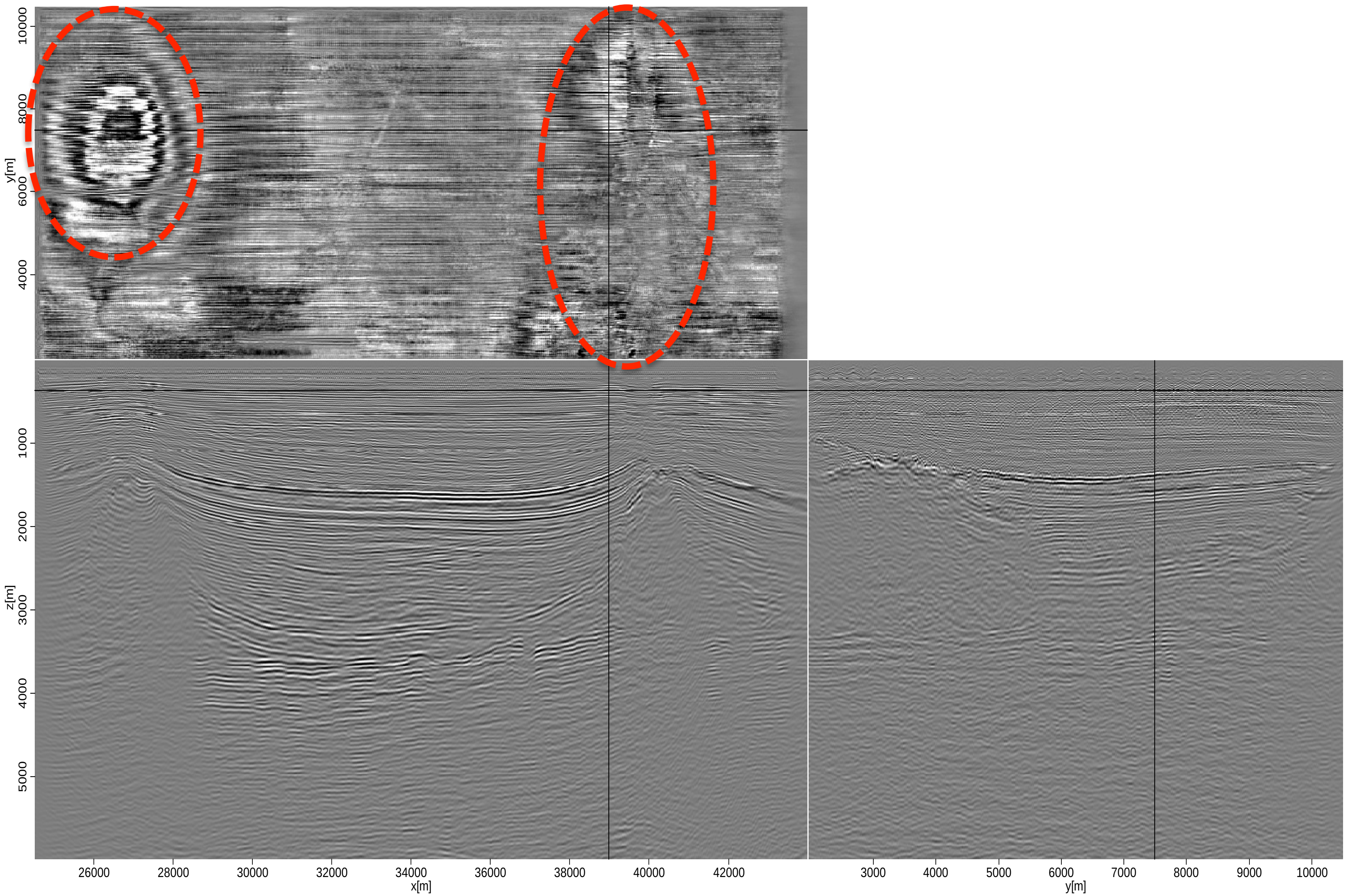


3D image after Q compensation

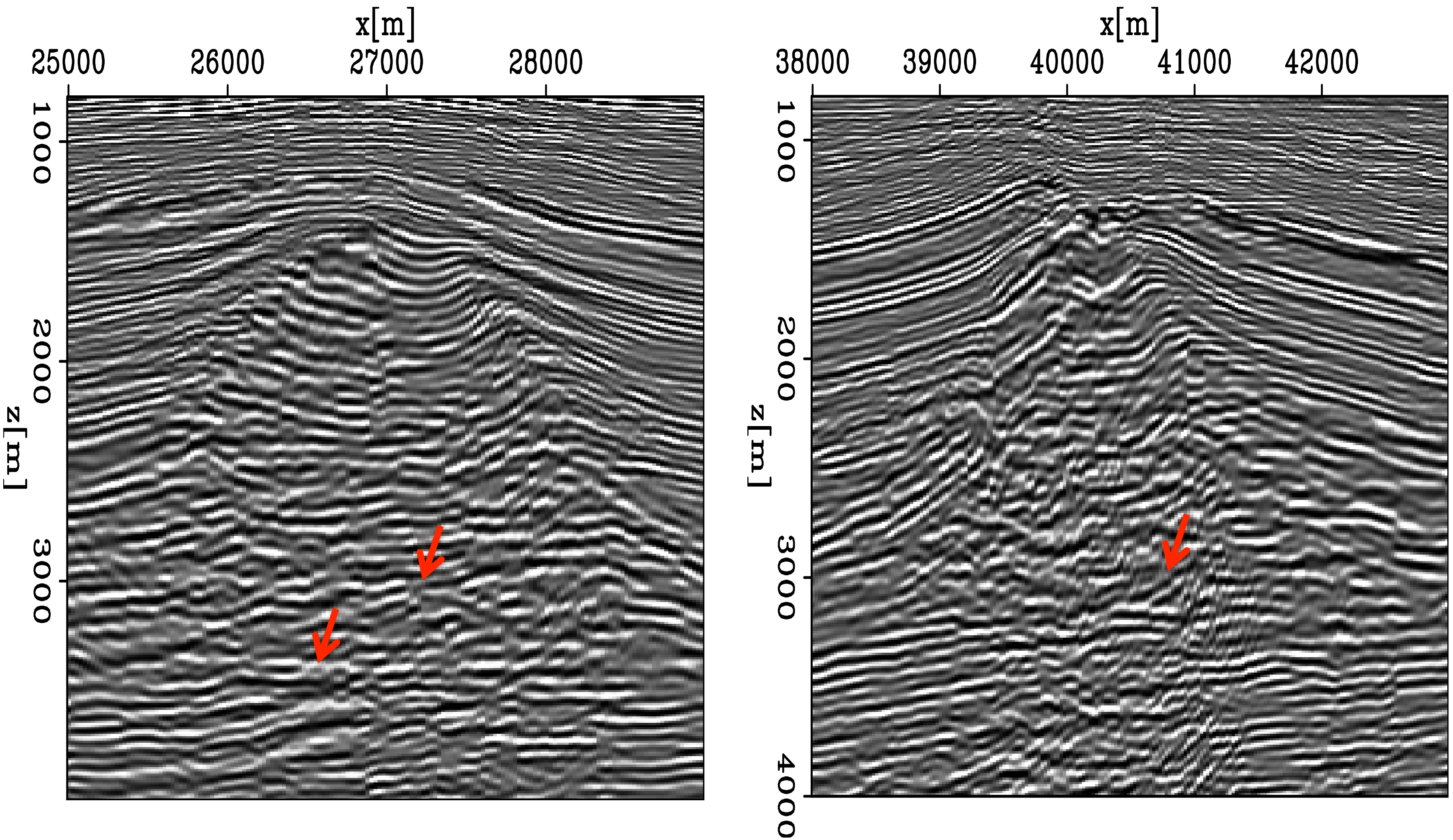


3D image before Q compensation

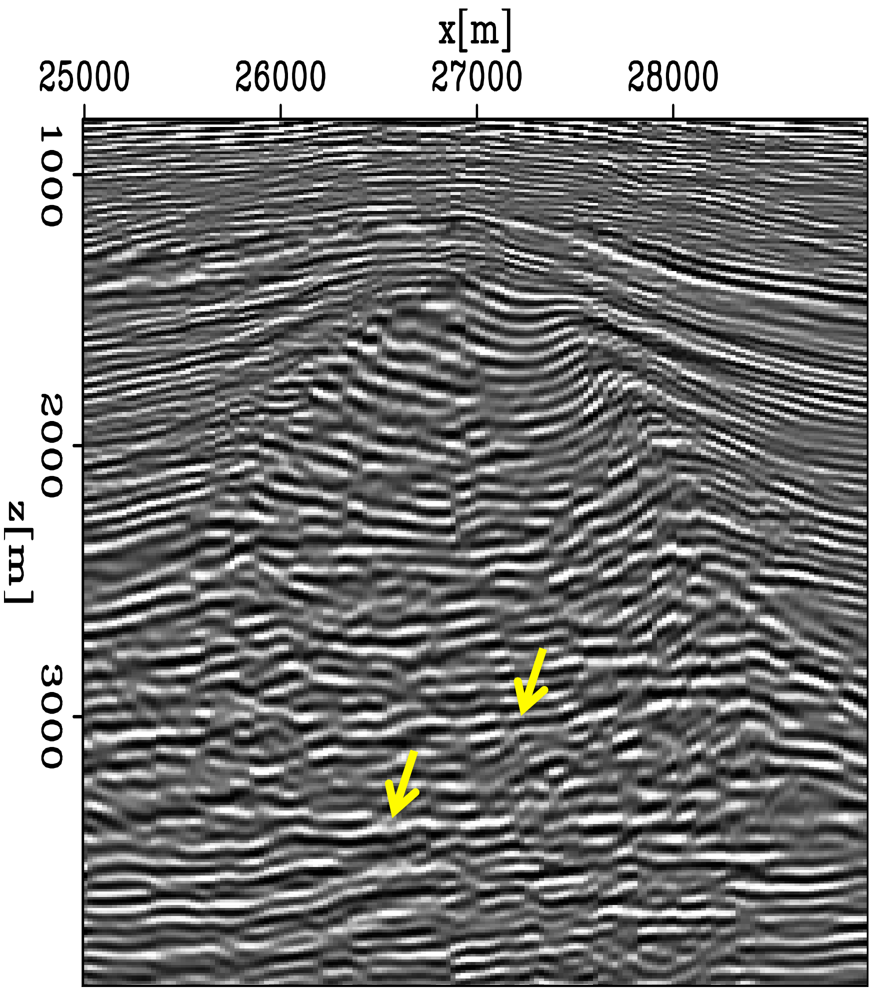
2D velocity estimation
2D one-way stacked WEMQA
2D one-way prestack WEMQA
3D one-way WEMVA and **WEMQA**

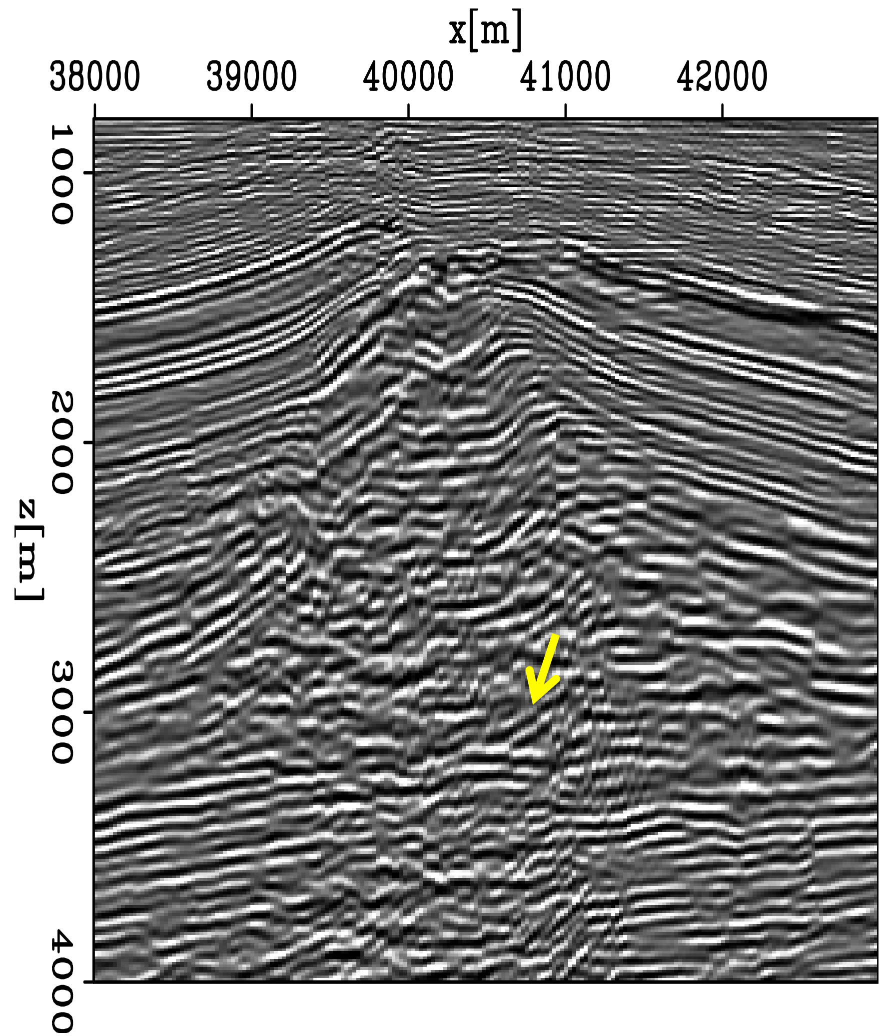


Zoomed-in image before Q compensation: Automatic gain control (AGC) is applied

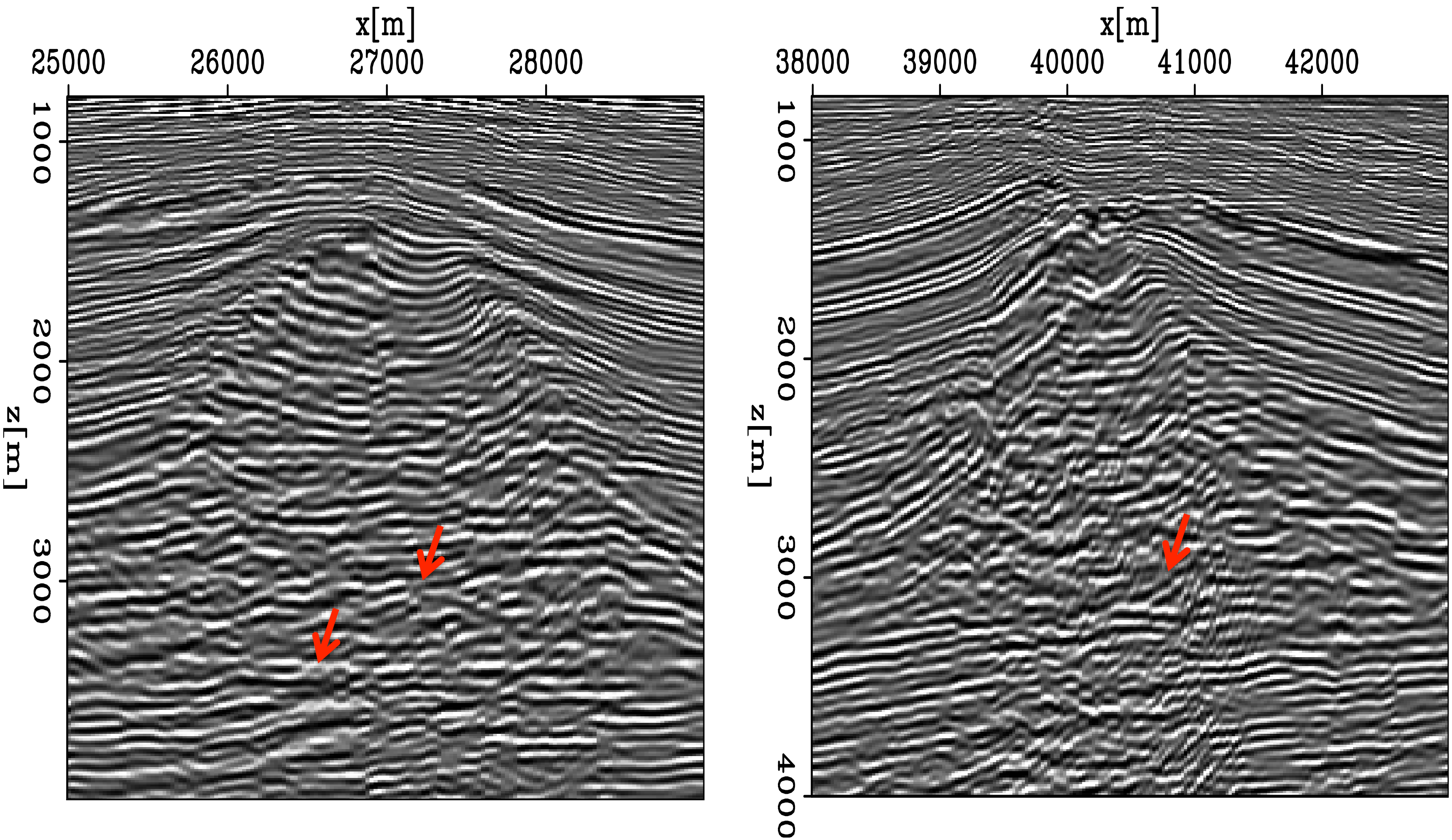


Zoomed-in image after Q compensation: Automatic gain control (AGC) is applied

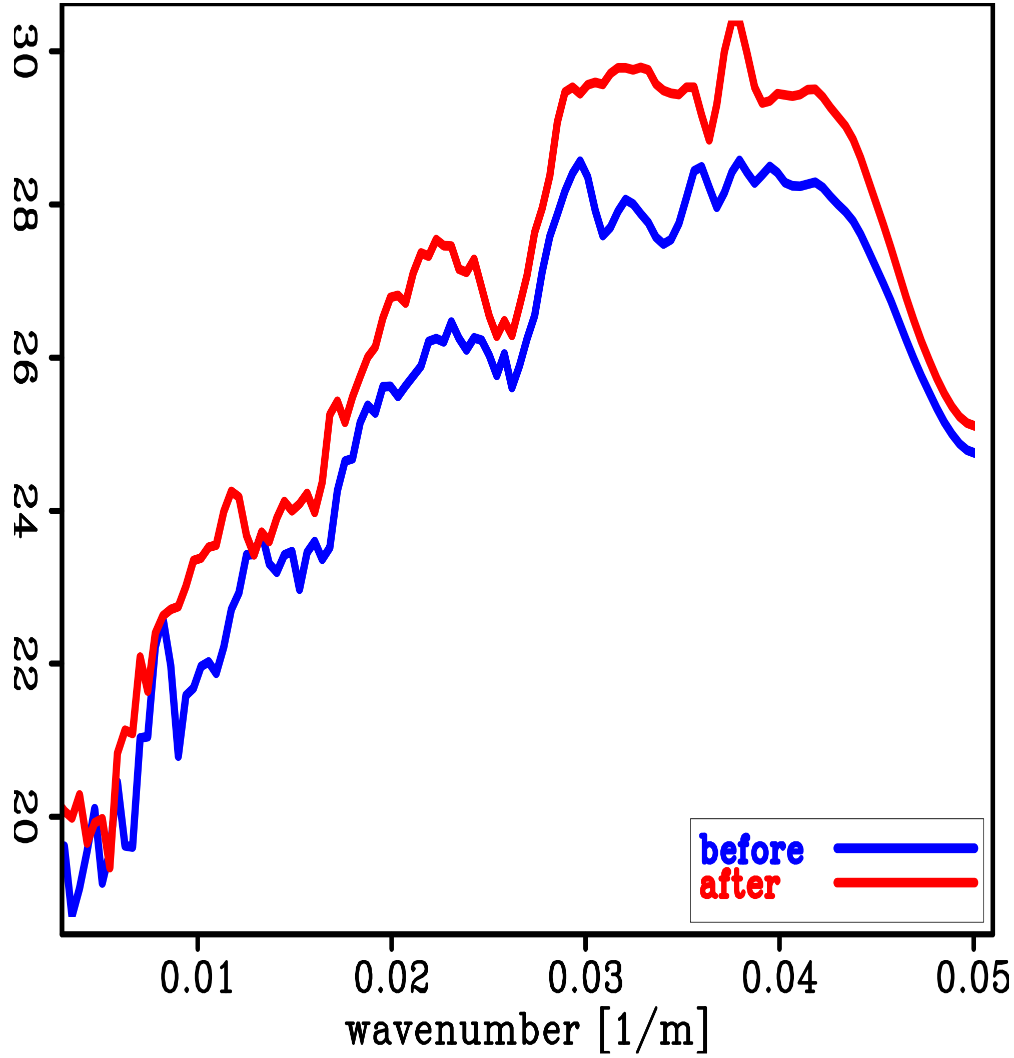




Zoomed-in image before Q compensation: Automatic gain control (AGC) is applied



3D image spectra



Conclusions I(壹)

- I have developed an inversion based method, WEMQA, to produce reliable Q models with two major features
  - Is performed in the image- space
  - Uses wave-equation-based Q tomography

Conclusions II(貳)

- Field application shows
  - The updated velocity shows regions around the gas and channel features, and makes the events in ADCIGs flatter.
  - The estimated Q anomalies for shallow gas and channel are consistent with Dolphin's interpretation.
  - The prestack WEMQA builds a higher resolution Q model than stacked WEMQA.

Conclusions III(叁)

- Field application shows
  - The migration compensation makes the seismic events below the anomalies clearly visible, with improved frequency content and phase coherency.
  - These improvements in image quality provide greater confidence for hydrocarbon exploration.

Acknowledgements

- **Thanks Dolphin Geophysical for providing us with this SHarp seismic data**
- **Thanks Shuki Ronen, Sergio Grion, Gareth Williams for their help with the data permisioon**

ThankQ and Q?