Constrained seismic tomography with data integration

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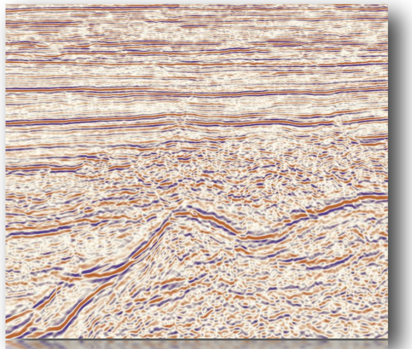
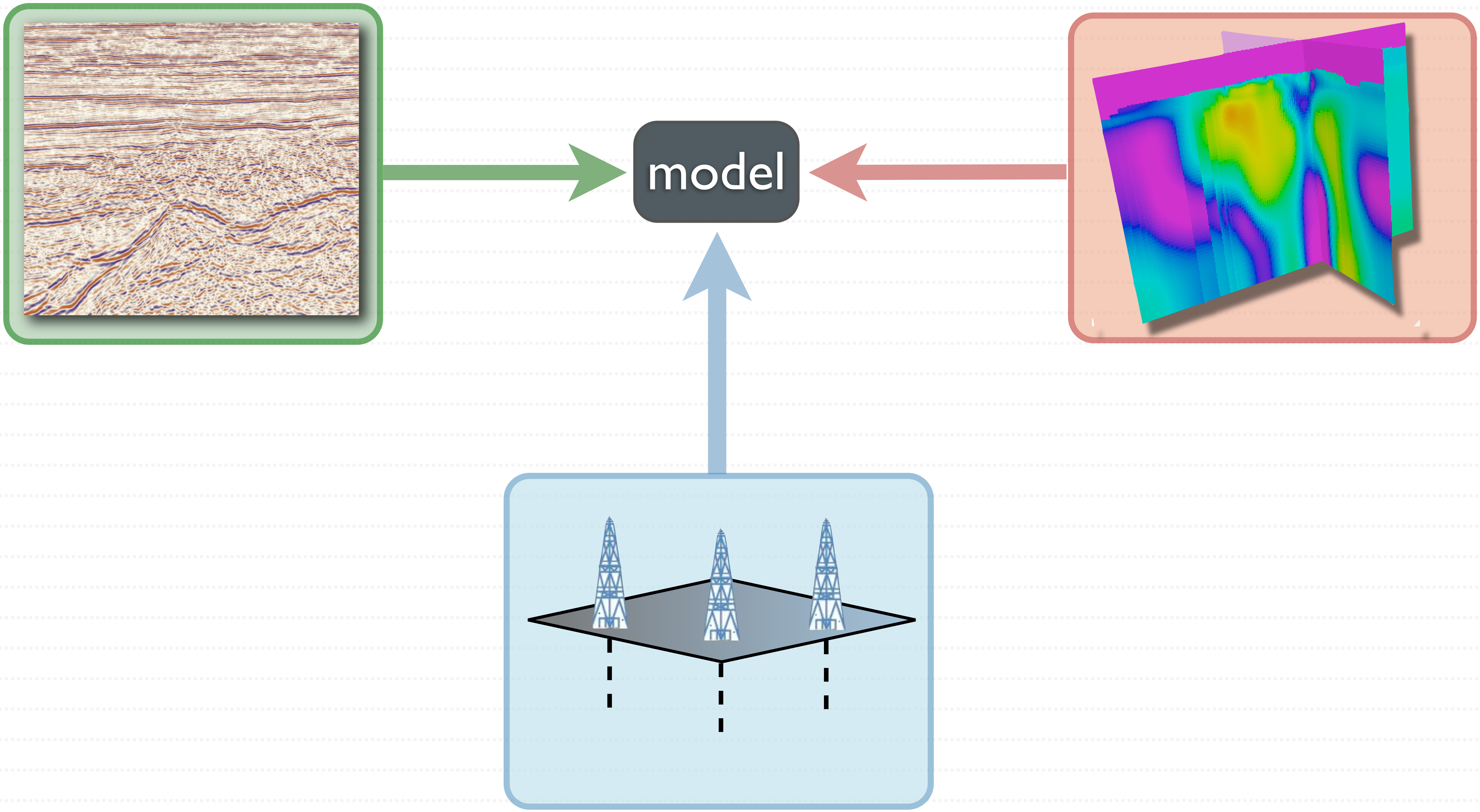


SEP 138, *P117-125*

SEP Annual Meeting
May 2009

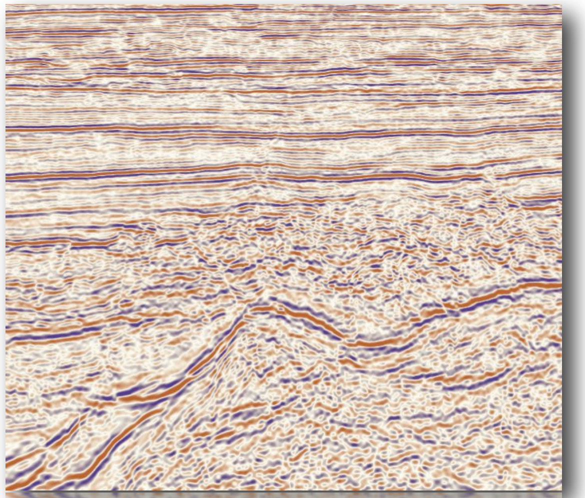
Motivation



Outline

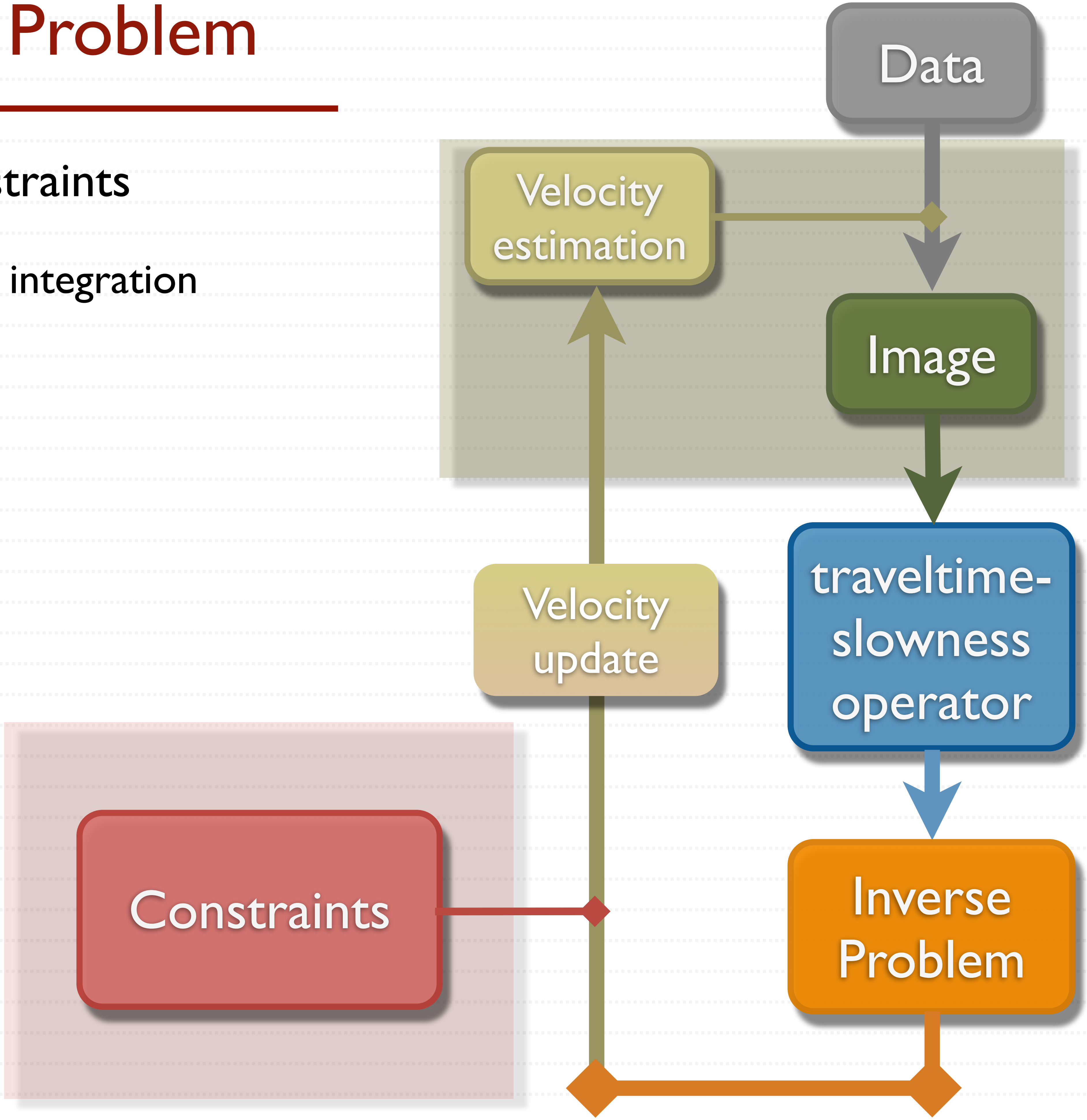
- Introduction
- Seismic tomography
- Geological constraints for velocity analysis
- Cross gradients function
- Results
- Future work:
  - Western Geco Dataset: Seismic & Resistivity

Introduction



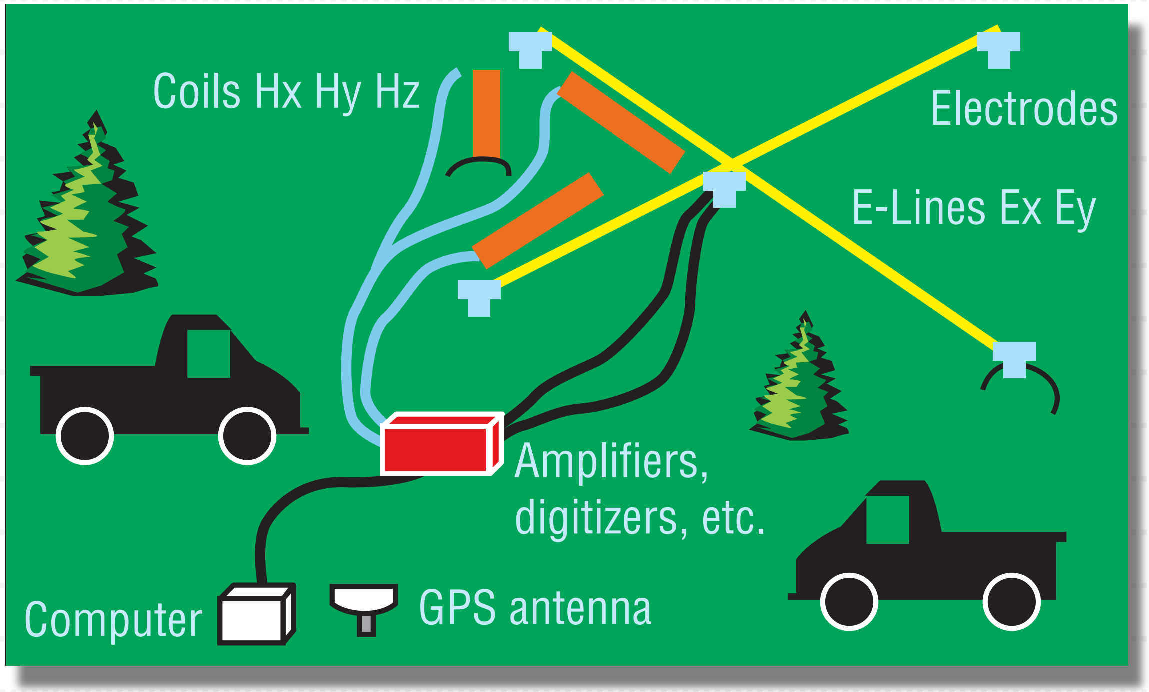
Tomography Problem

- Choices of constraints
  - Auxiliary data integration
  - Smoothness
  - Filters



Auxiliary data for P-wave velocity

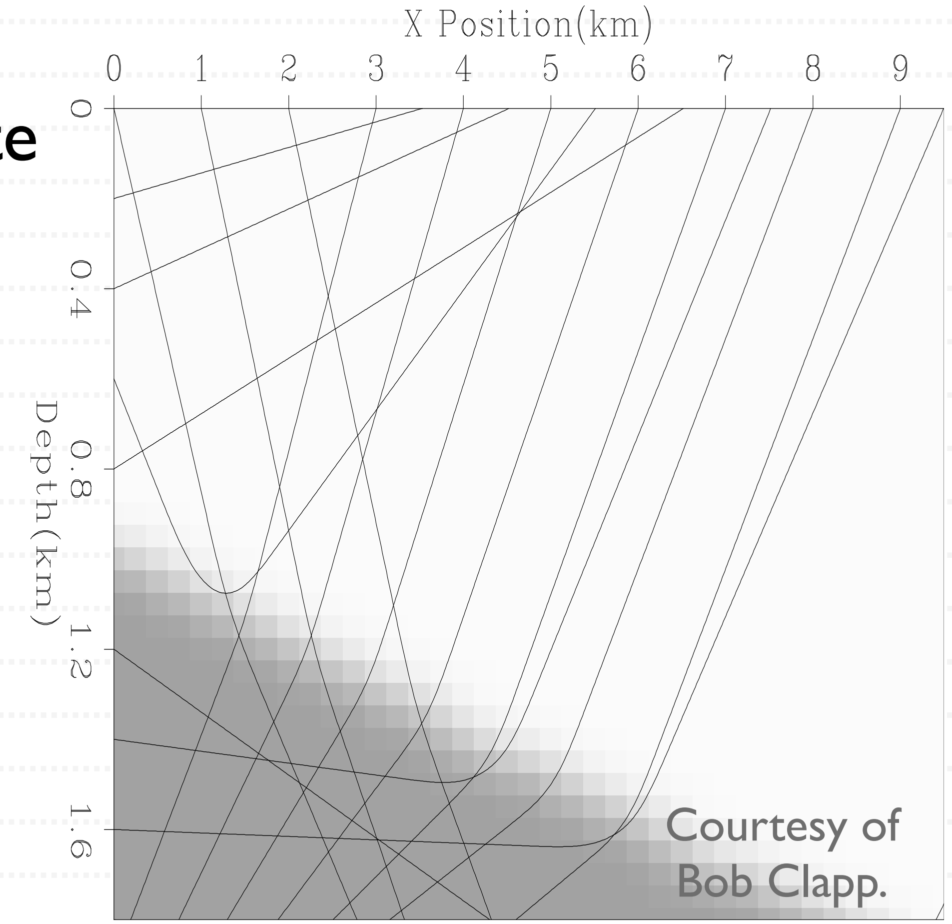
- Magnetotelluric (MT) Resistivity
  - Natural-source (electromagnetic method)
  - Insight into the resistivity structure as the main parameter
    - Low resolution
    - Insensitive to thin resistors
- Reflectivity
  - Sharp features
- S-wave velocity



Linearized tomography

- Travel time-slowness relation is $\mathbf{t} = \mathbf{T_{nl}}(\mathbf{s})$
  - model dependent
  - nonlinear
- Linearize operator
  - wrong initial ray paths
  - Linearize around new slowness estimate

$$
\begin{aligned}
\mathbf{t} &\approx \mathbf{T_{nl}}\ \mathbf{s_0} + \nabla \mathbf{T_{nl}}\ \Delta \mathbf{s} \\
\mathbf{t} &\approx \mathbf{t_0} + \mathbf{T_L}\ \Delta \mathbf{s} \\
\Delta \mathbf{t} &\approx \mathbf{T_L}\ \Delta \mathbf{s}
\end{aligned}
$$



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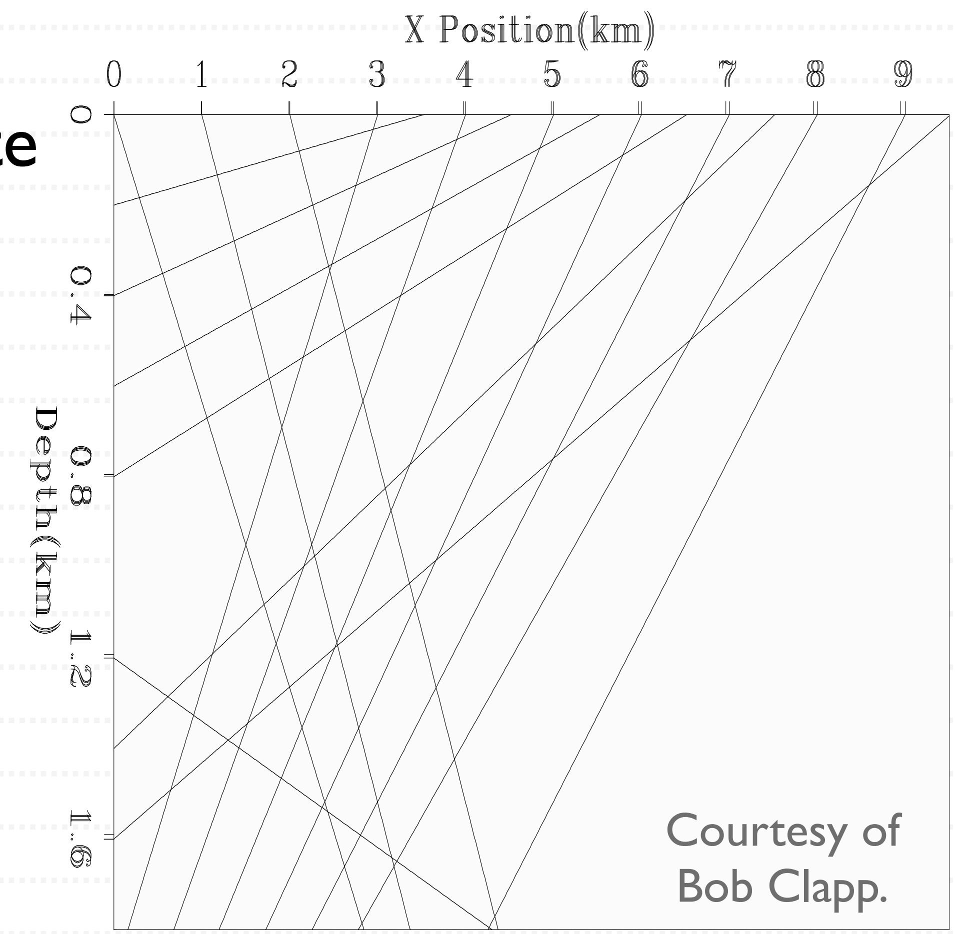
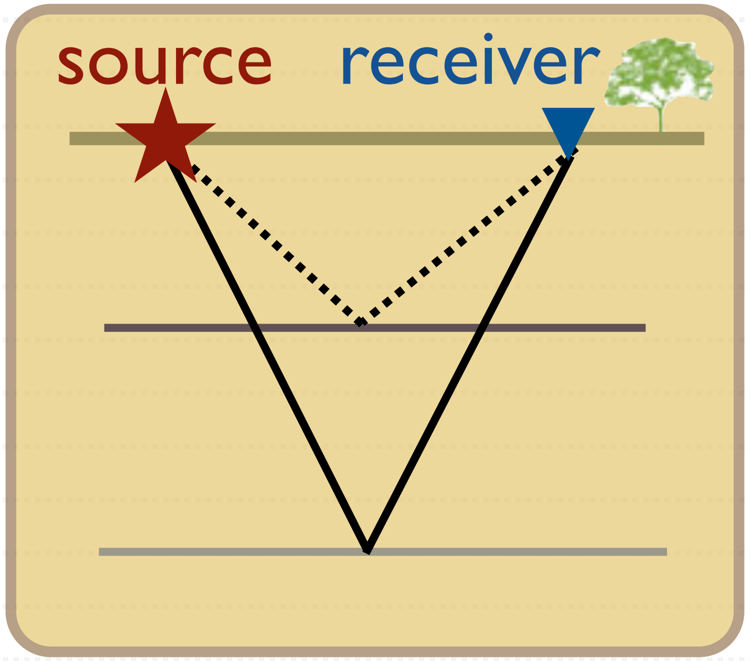


Courtesy of Bob Clapp.

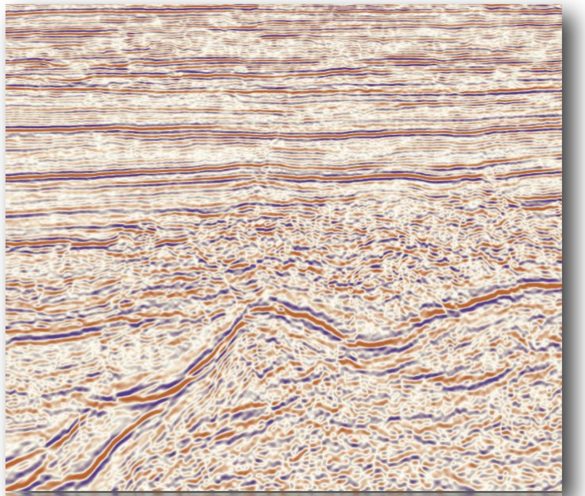
Tomography and null space

- shadow zones
  - lack of illumination or poor illumination (especially sub-salt regions)
- limited angle coverage
  - imposed by recording geometry
- resolution decreases with depth
  - velocity information is revealed with reflection angle.
- under-determined problem



$$\mathcal{Q}(\Delta \mathbf{s}) = ||\Delta \mathbf{t} - \mathbf{T}_0 \Delta \mathbf{s}||^2 + \epsilon^2 \; ||\mathbf{A}(s_0 + \Delta \mathbf{s})||^2$$

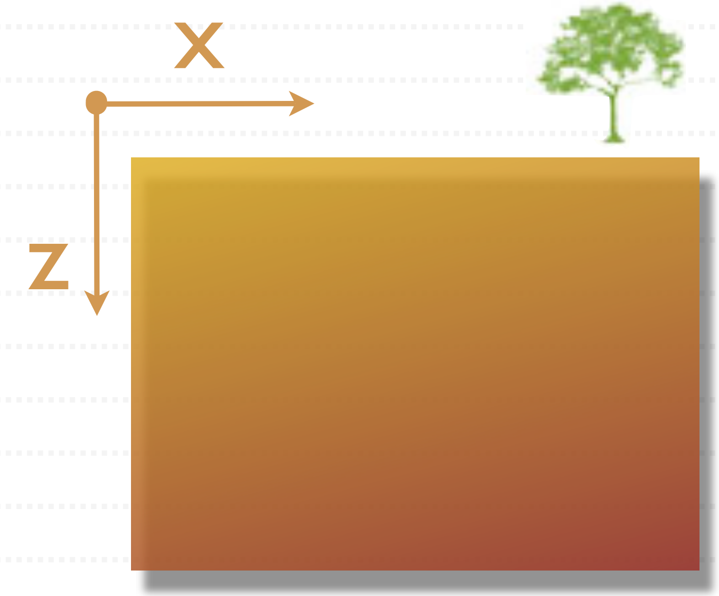
Cross-gradients function



Cross-gradient function [Gallardo & Meju 03]

- Structural similarity measurement

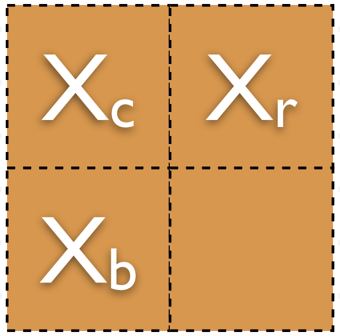
$$t(x, y, z) = ||\nabla m_{1n} \times \nabla m_{2n}||$$



- simplified 2-D definition

$$t(x, z) = \left|\left|\left(\frac{\partial m_{1n}}{\partial z}\frac{\partial m_{2n}}{\partial x}\right) - \left(\frac{\partial m_{1n}}{\partial x}\frac{\partial m_{2n}}{\partial z}\right)\right|\right|$$

  - Linearized on grids with finite difference approximations



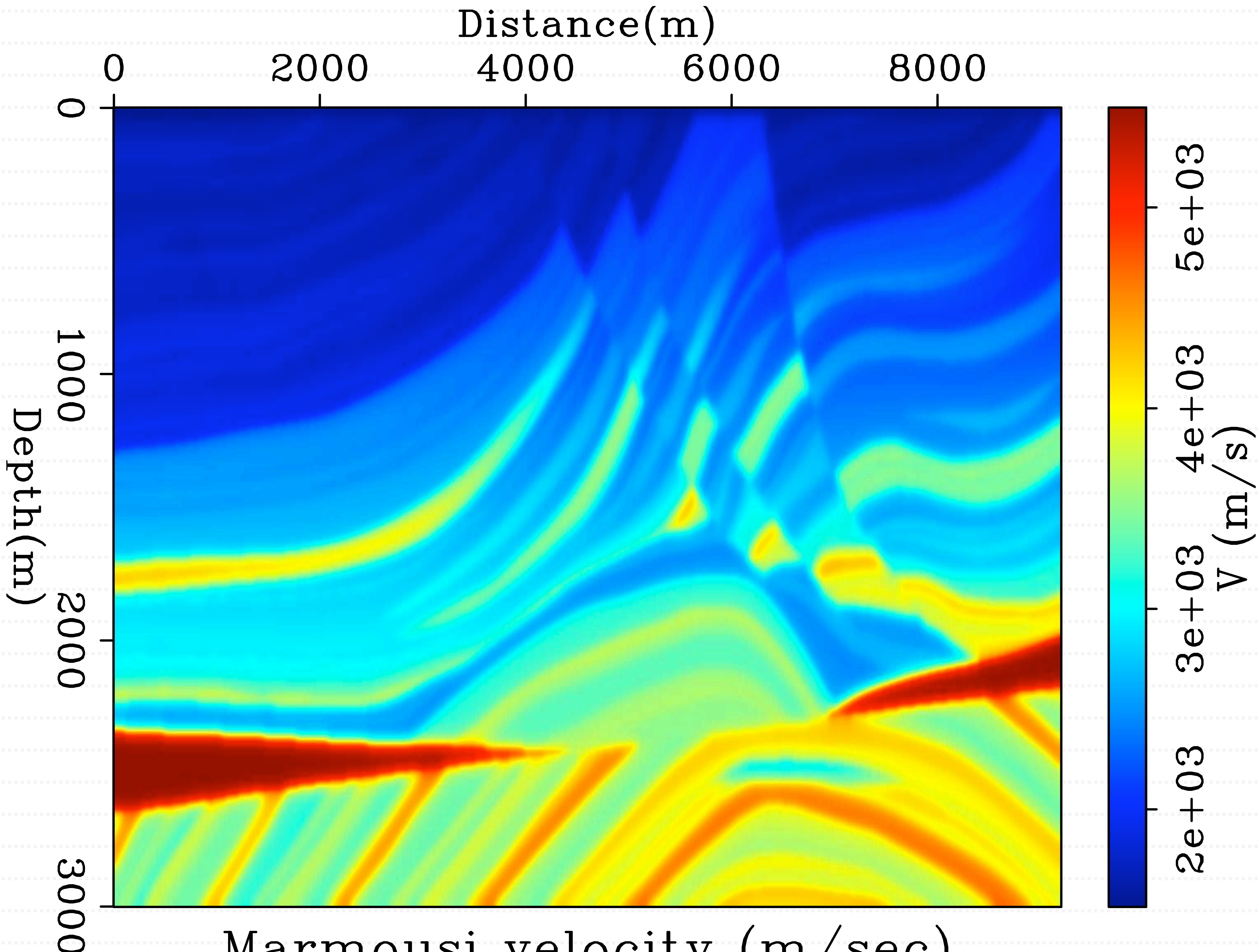
m_{1n} : normalized auxiliary field

m_{2n} : normalized main field

More on cross-gradient functions

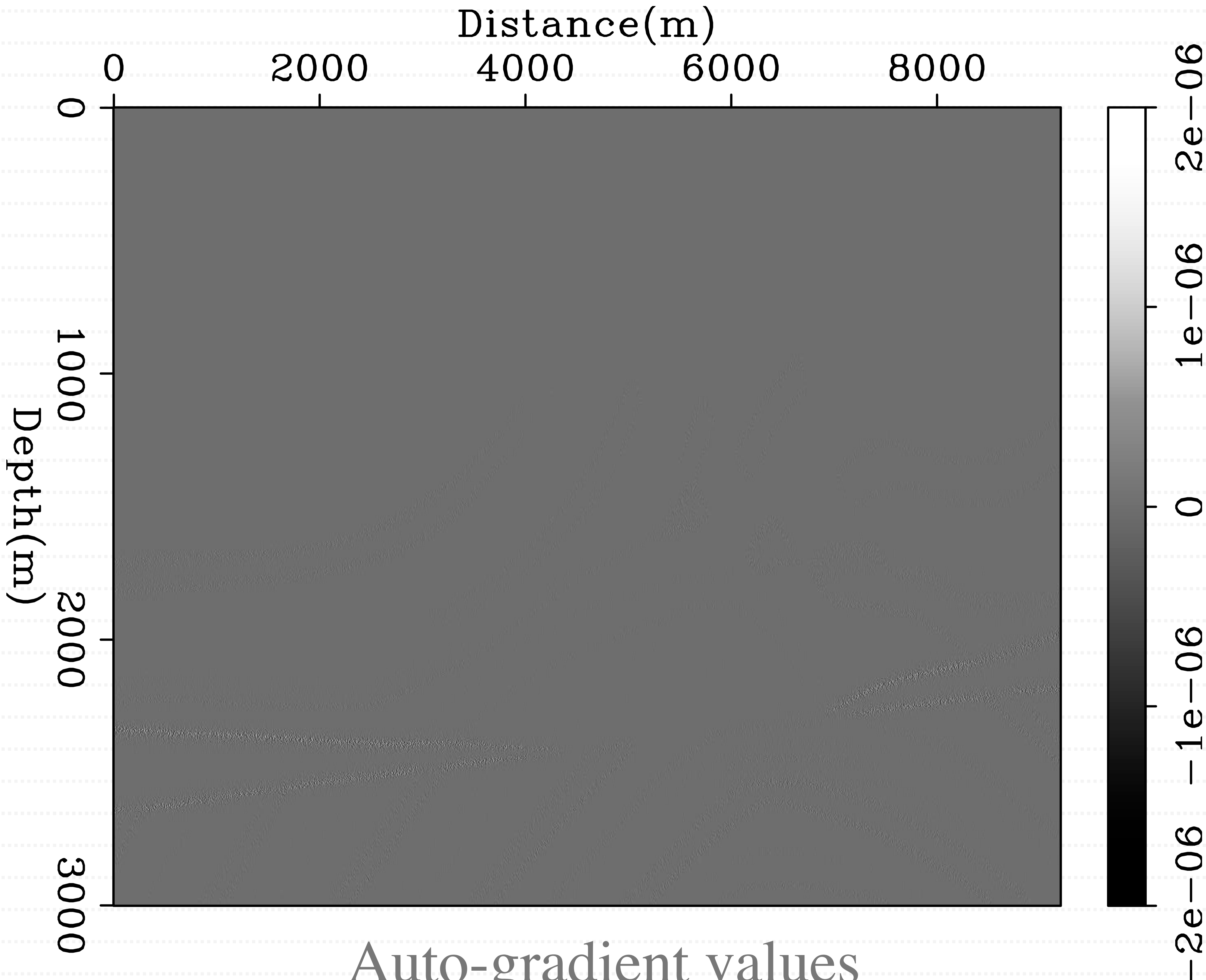
- Similar to covariance
- Sharp boundary improvements
- Accuracy for different field properties:
  - Difference in resolution
  - Structural complexity
- Velocity vs. resistivity
  - smooth velocity as resistivity

Marmousi model



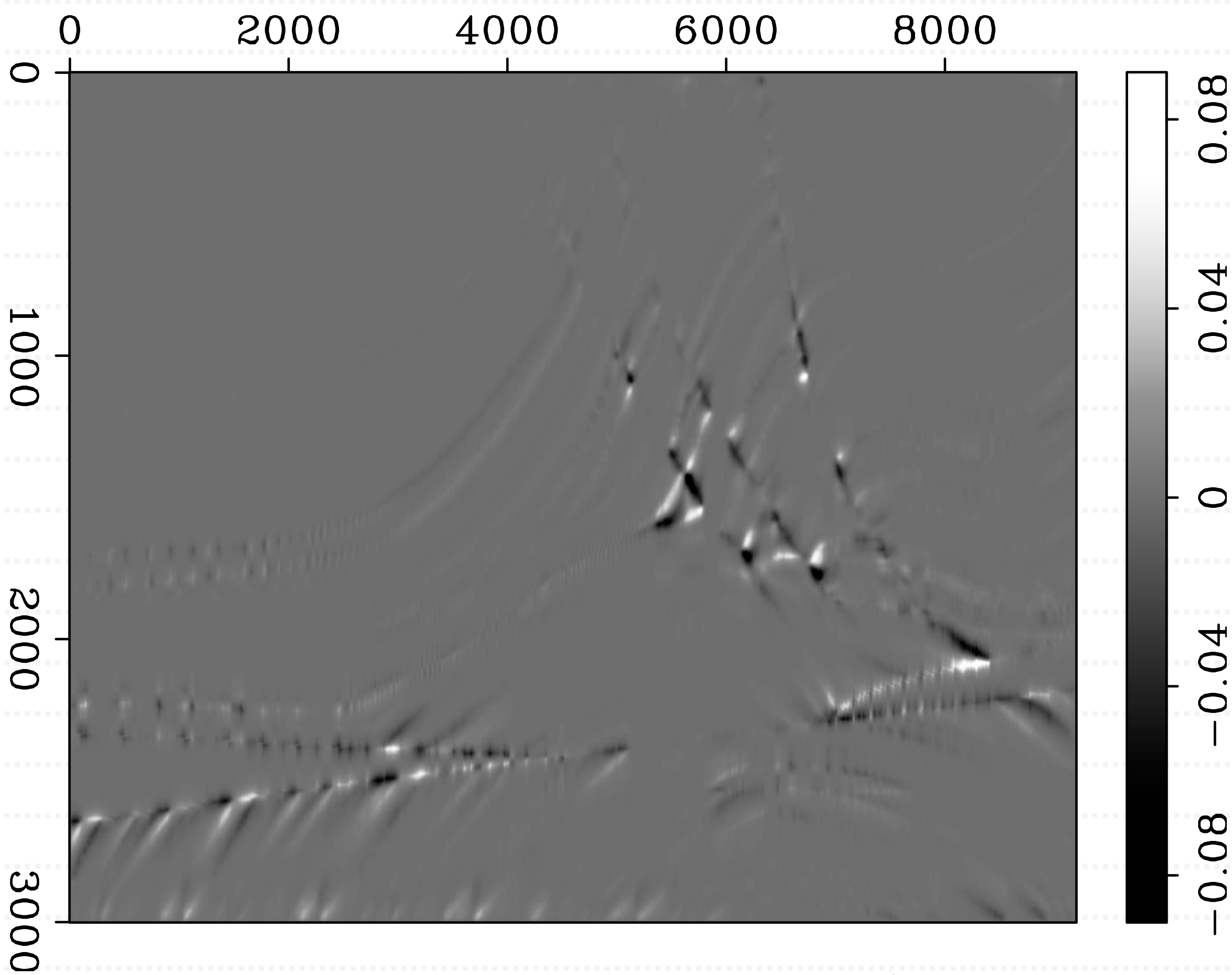
Marmousi velocity (m/sec)

Auto-gradient

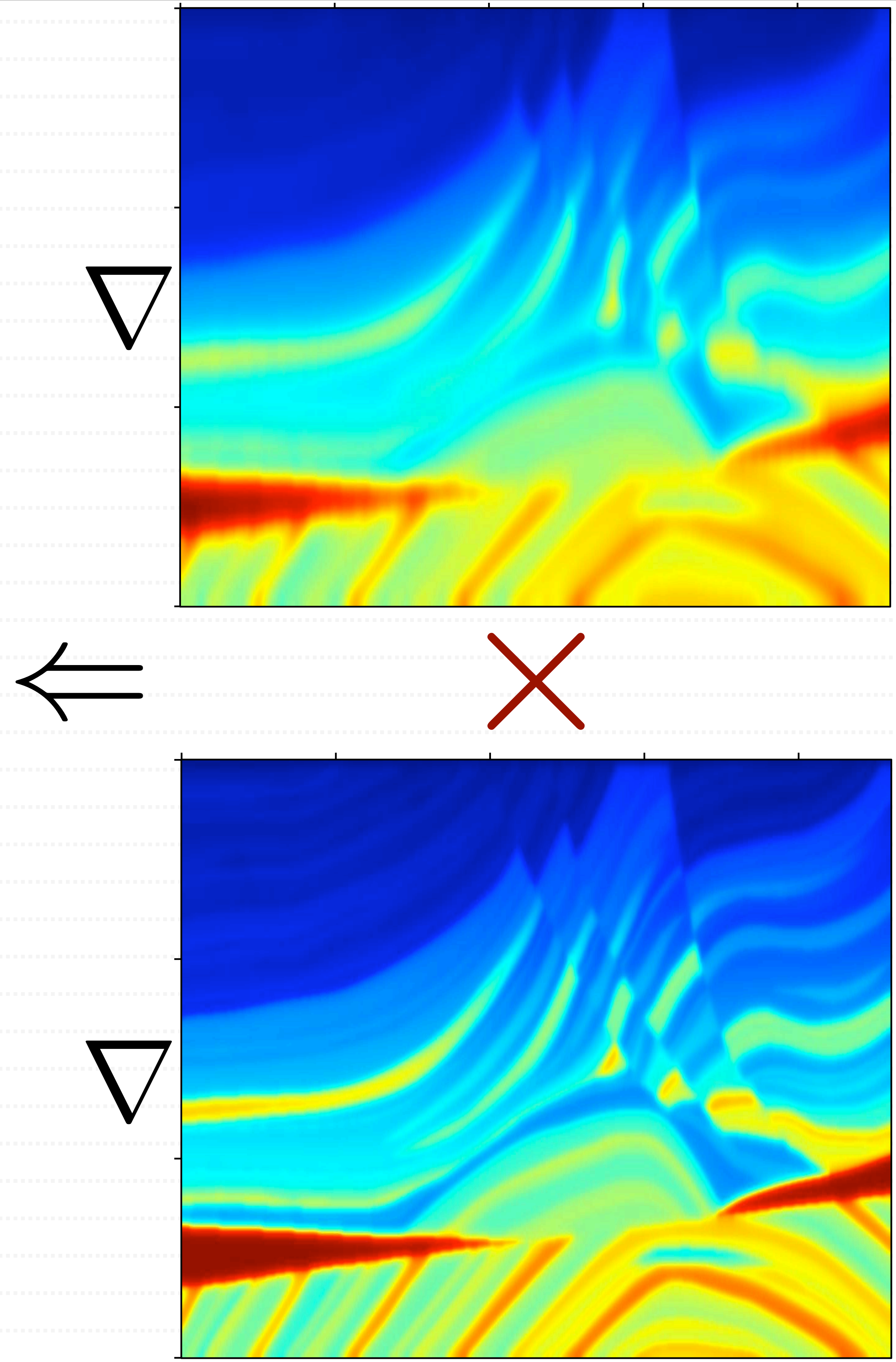


Auto-gradient values

Test 1: smooth velocity

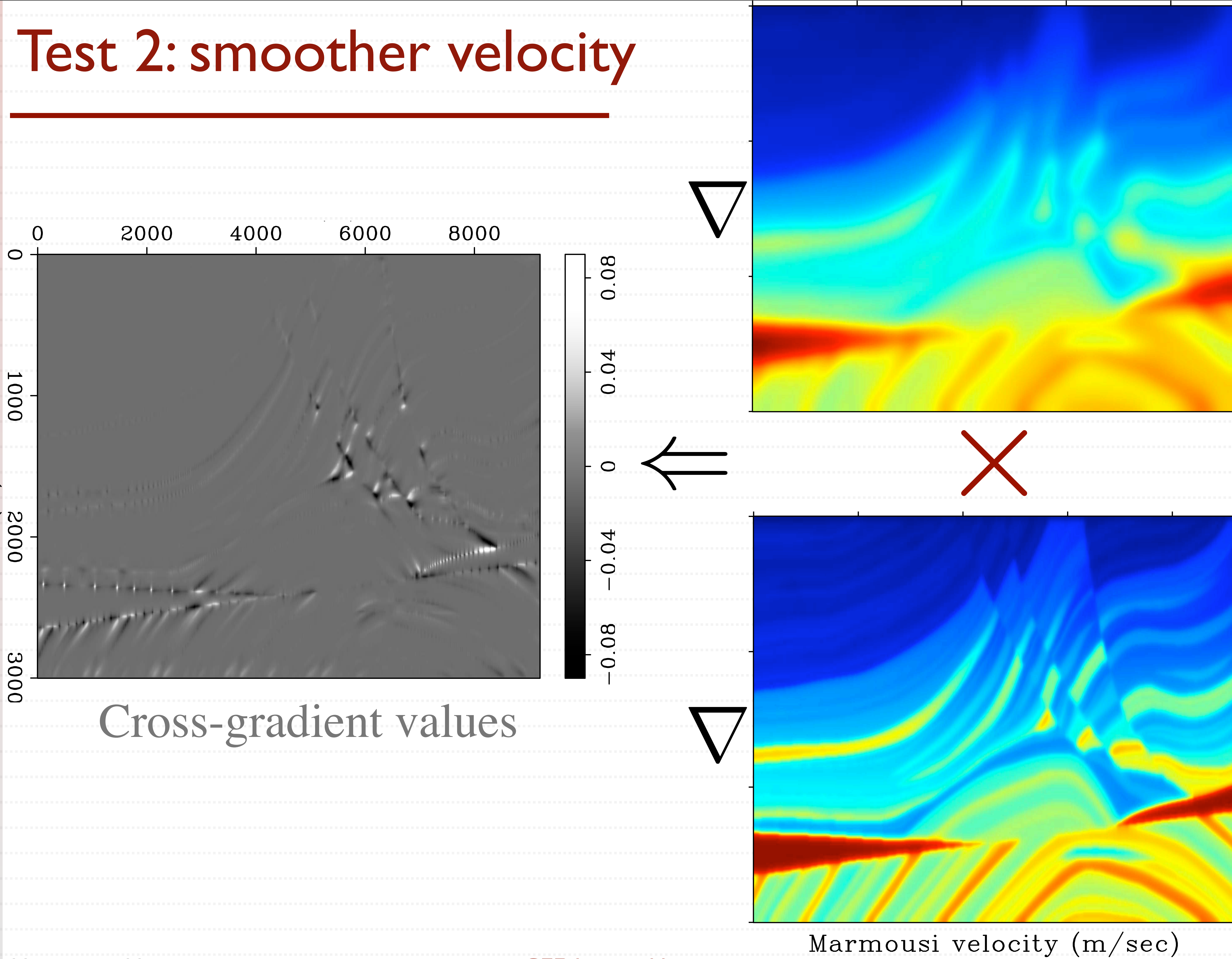


Cross-gradient values

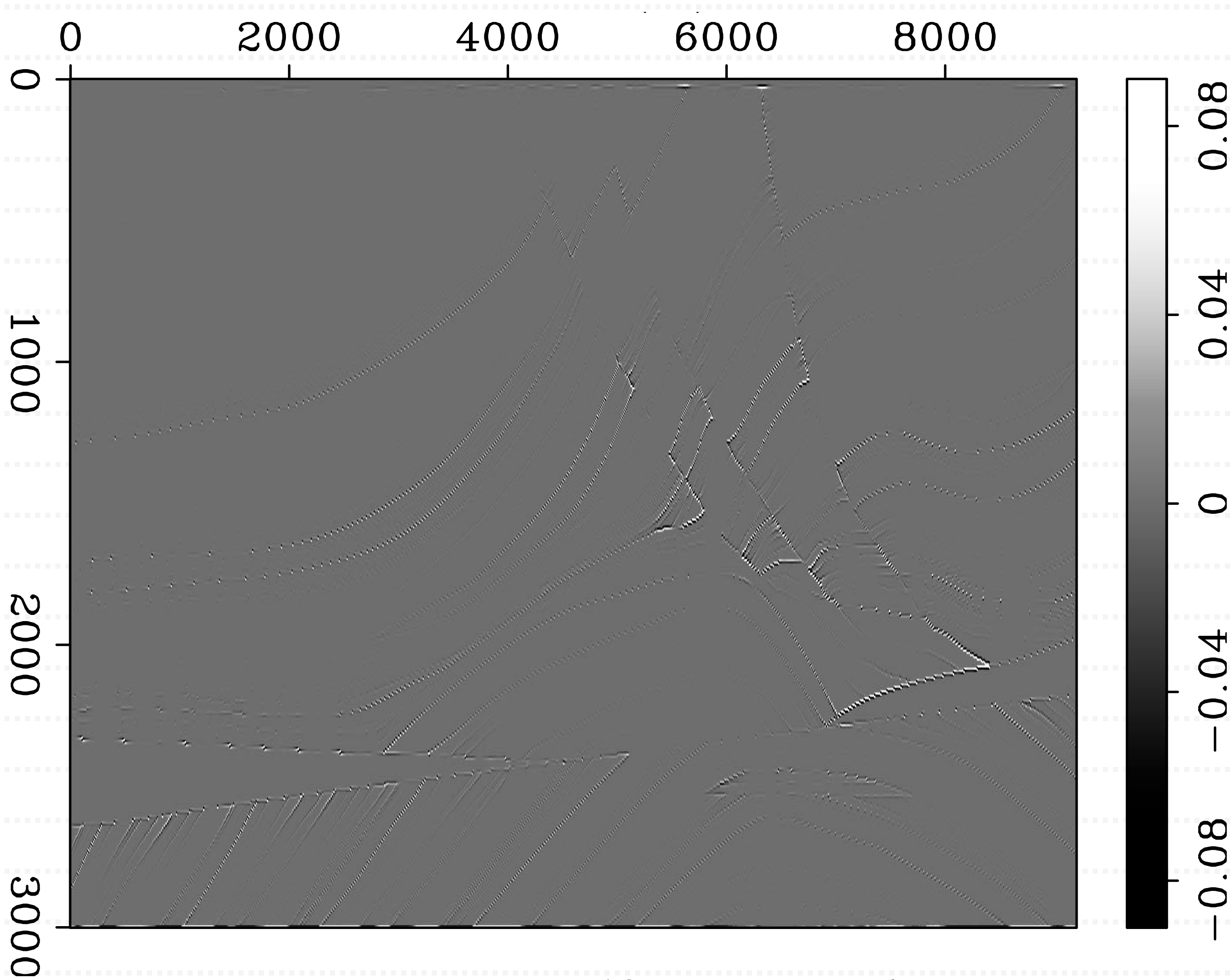


Marmousi velocity (m/sec)

Test 2: smoother velocity

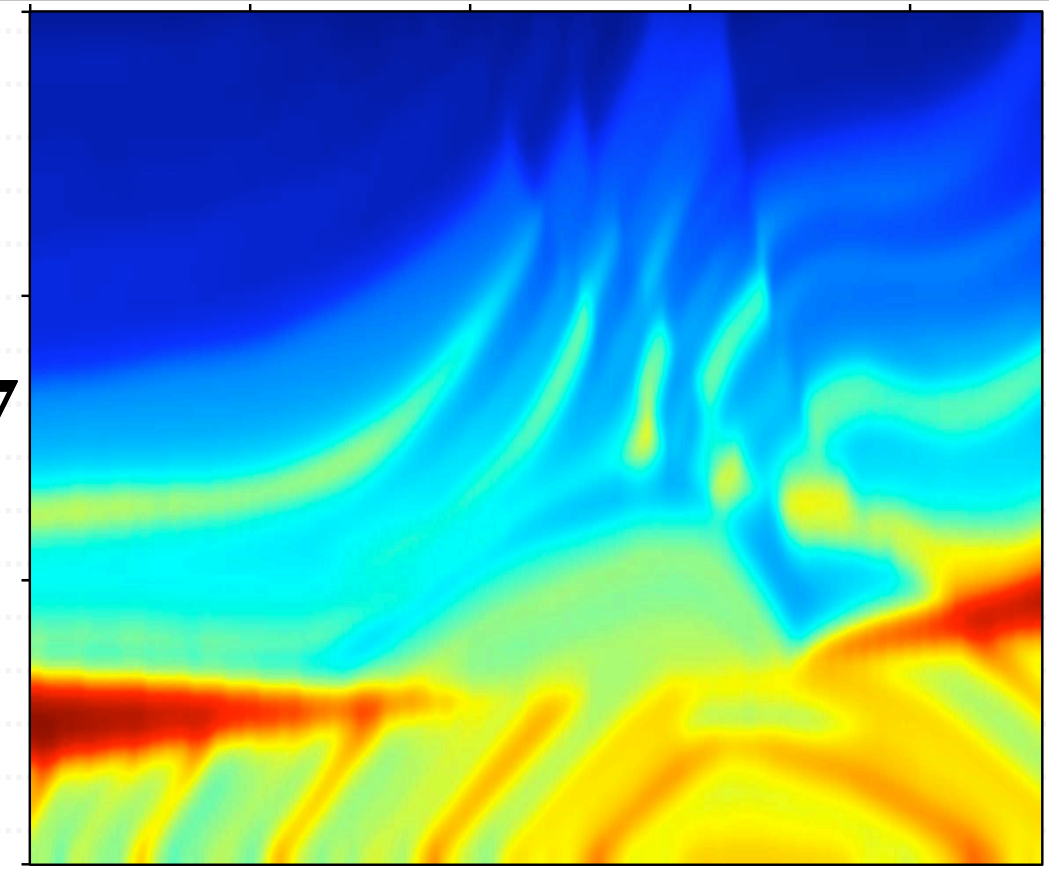


Test 3: reflectivity



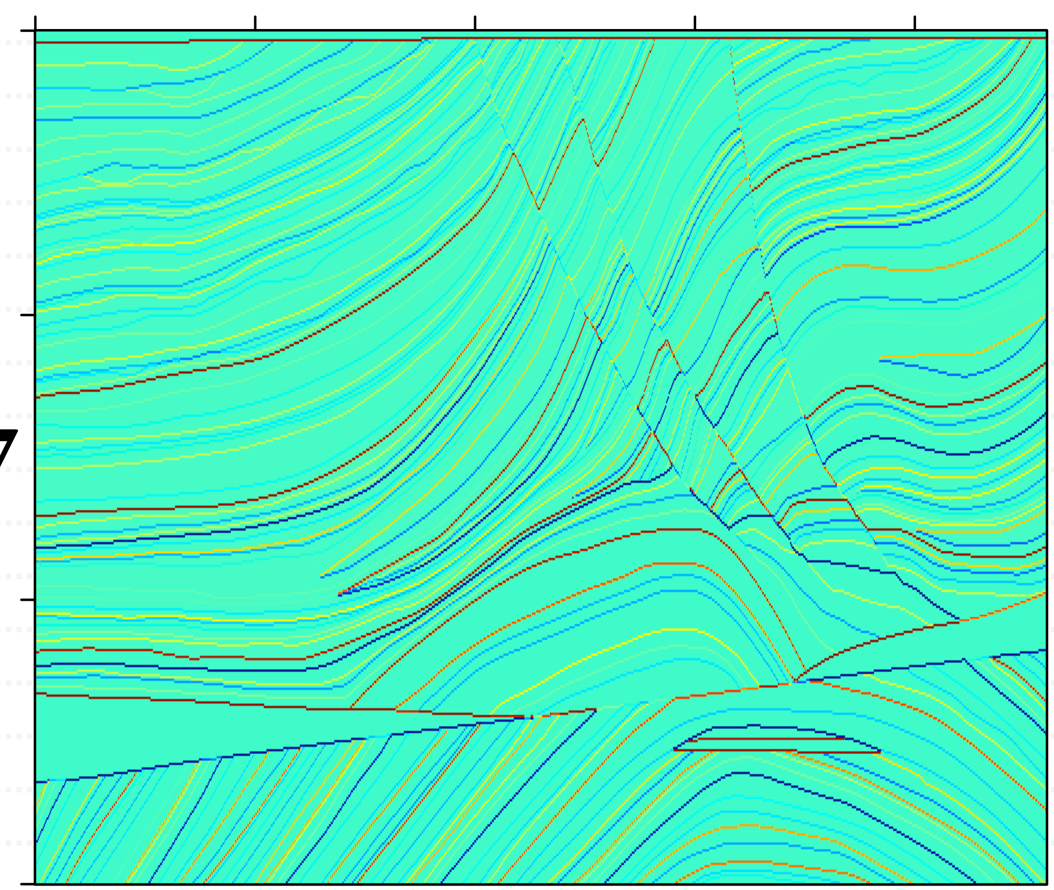
Cross-gradient values

$\Leftarrow$



∇

$\times$



∇

Velocity analysis with cross-gradient constraint

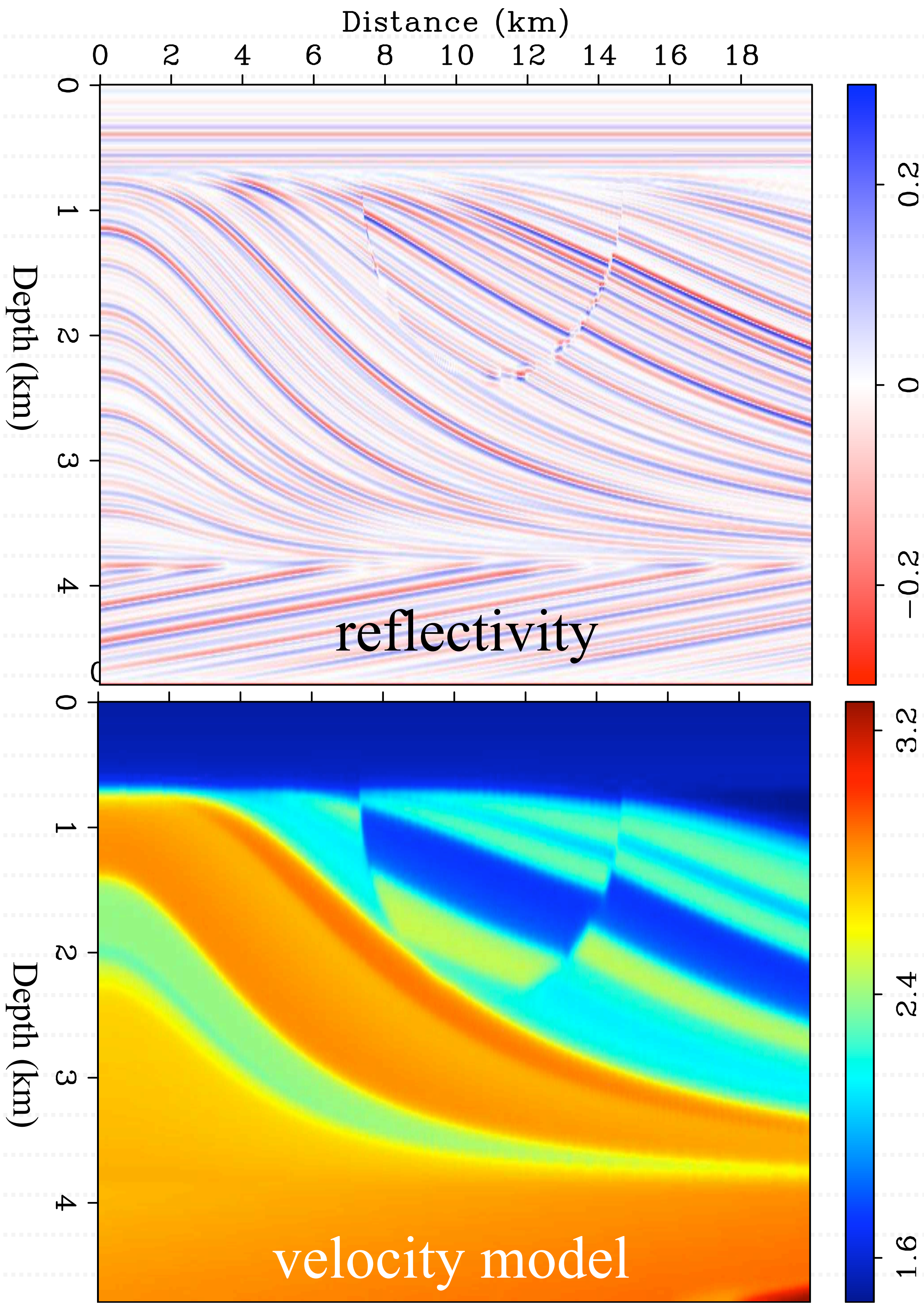
- Velocity analysis objective function

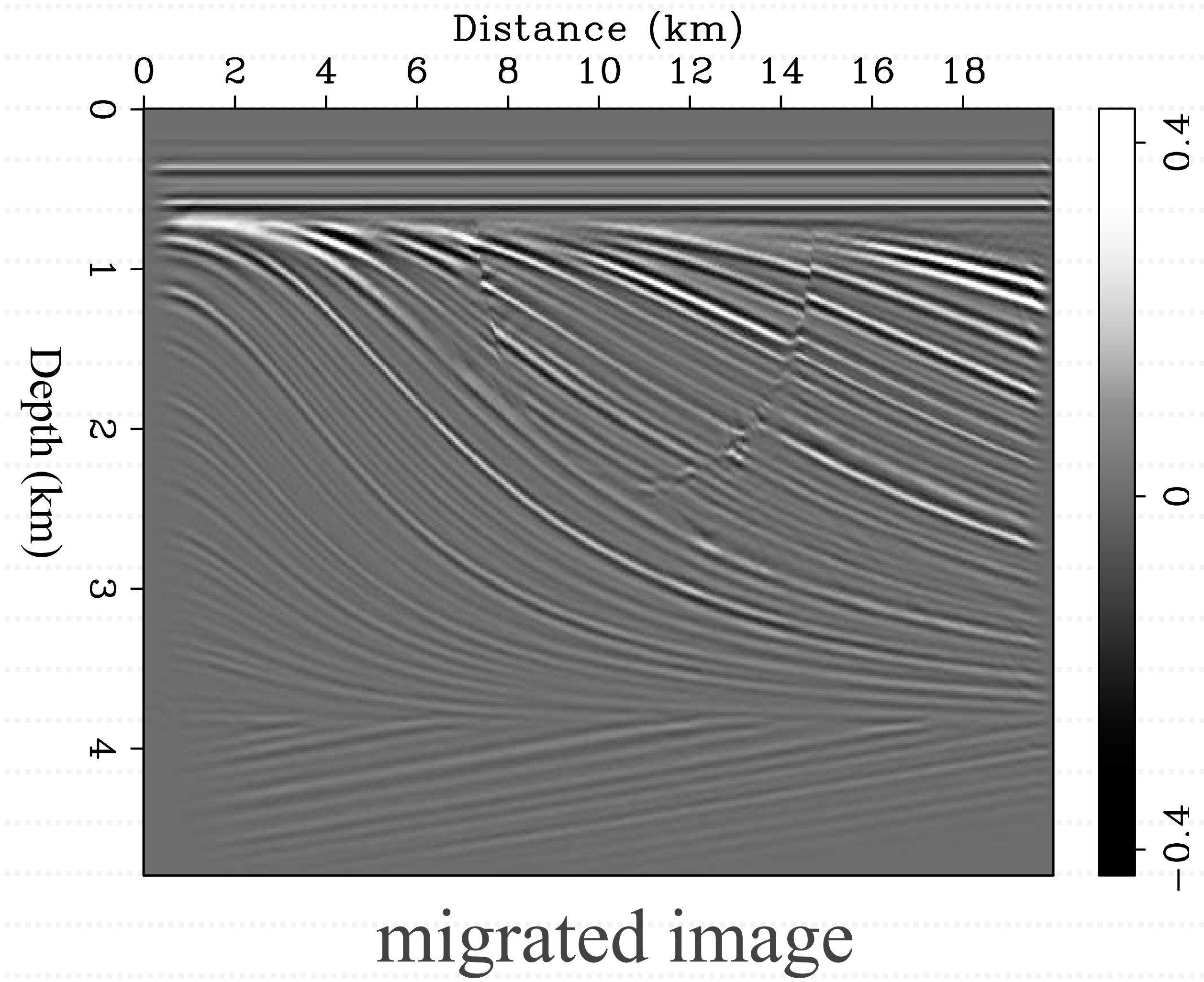
$$\mathcal{Q}(\Delta\mathbf{s}) = ||\Delta\mathbf{t} - \mathbf{T}_0\Delta\mathbf{s}||^2 + \epsilon^2 \, ||\mathbf{A}(s_0 + \Delta\mathbf{s})||^2$$

$$\mathcal{P}(\Delta\mathbf{s}) = ||\Delta\mathbf{t} - \mathbf{T}_L\Delta\mathbf{s}||^2 + \epsilon_1^2 \, ||\mathbf{A}(s_0 + \Delta\mathbf{s})||^2 + \epsilon_2^2 \, ||\mathbf{G}(r)(\mathbf{s}_0 + \Delta\mathbf{s})||^2$$

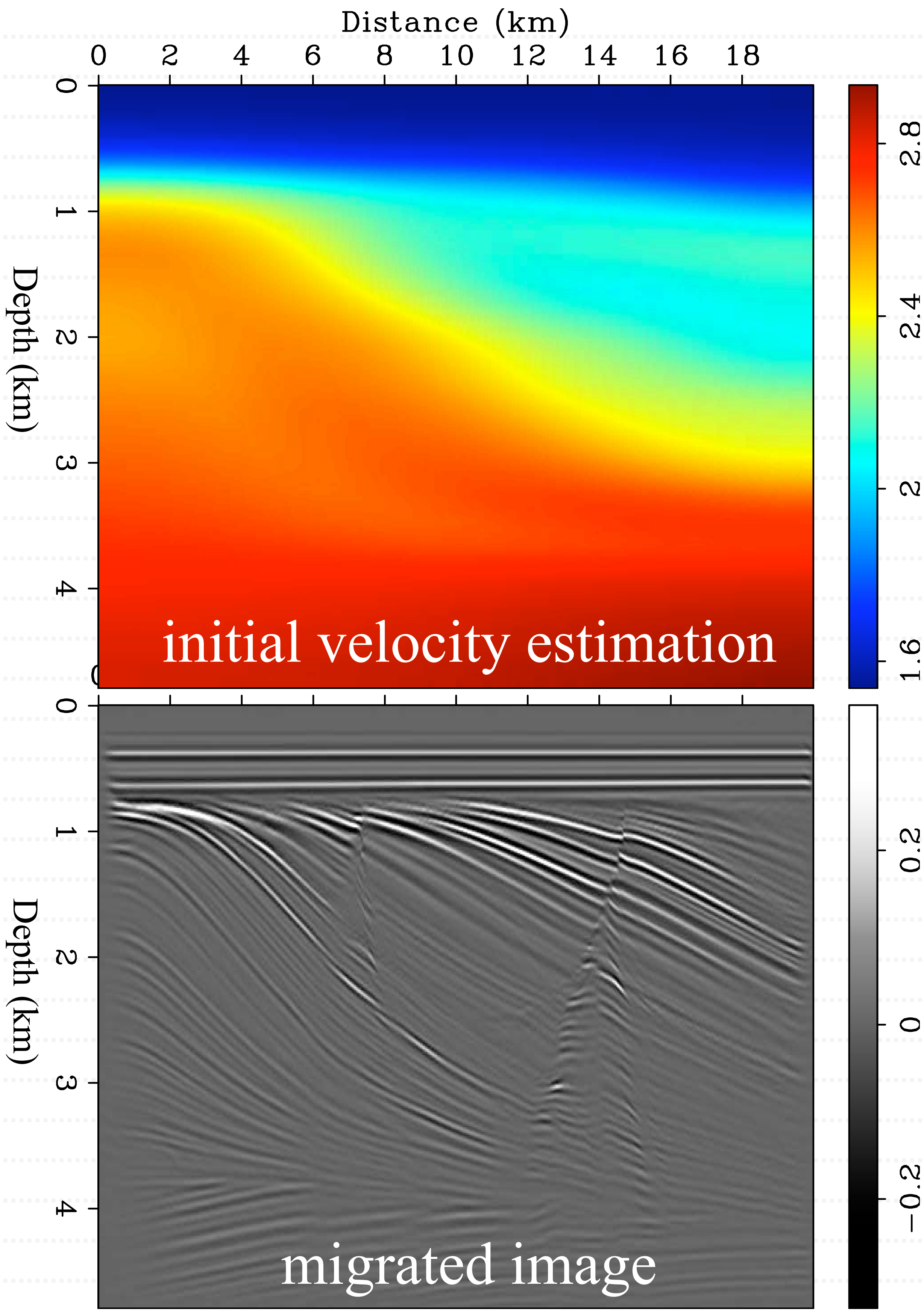
$\mathbf{T}_L$	:	linear approximation of tomography matrix	s	:	seismic slowness
$\mathbf{A}$	:	regularization operator	r	:	additional data
$\mathbf{G}(r)$	:	linear cross-gradients operator for given r	t	:	travel time

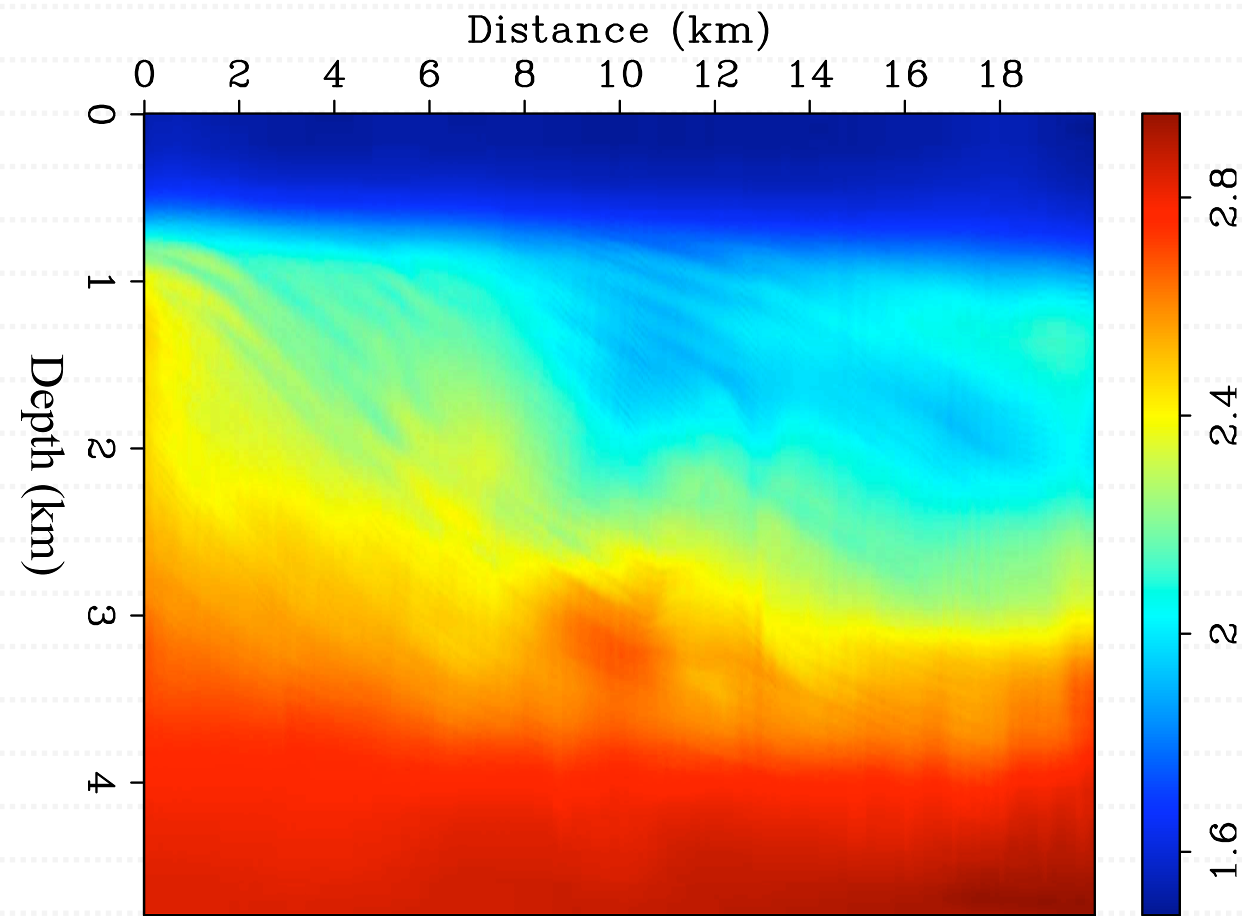
Synthetic model with semi-circular fault



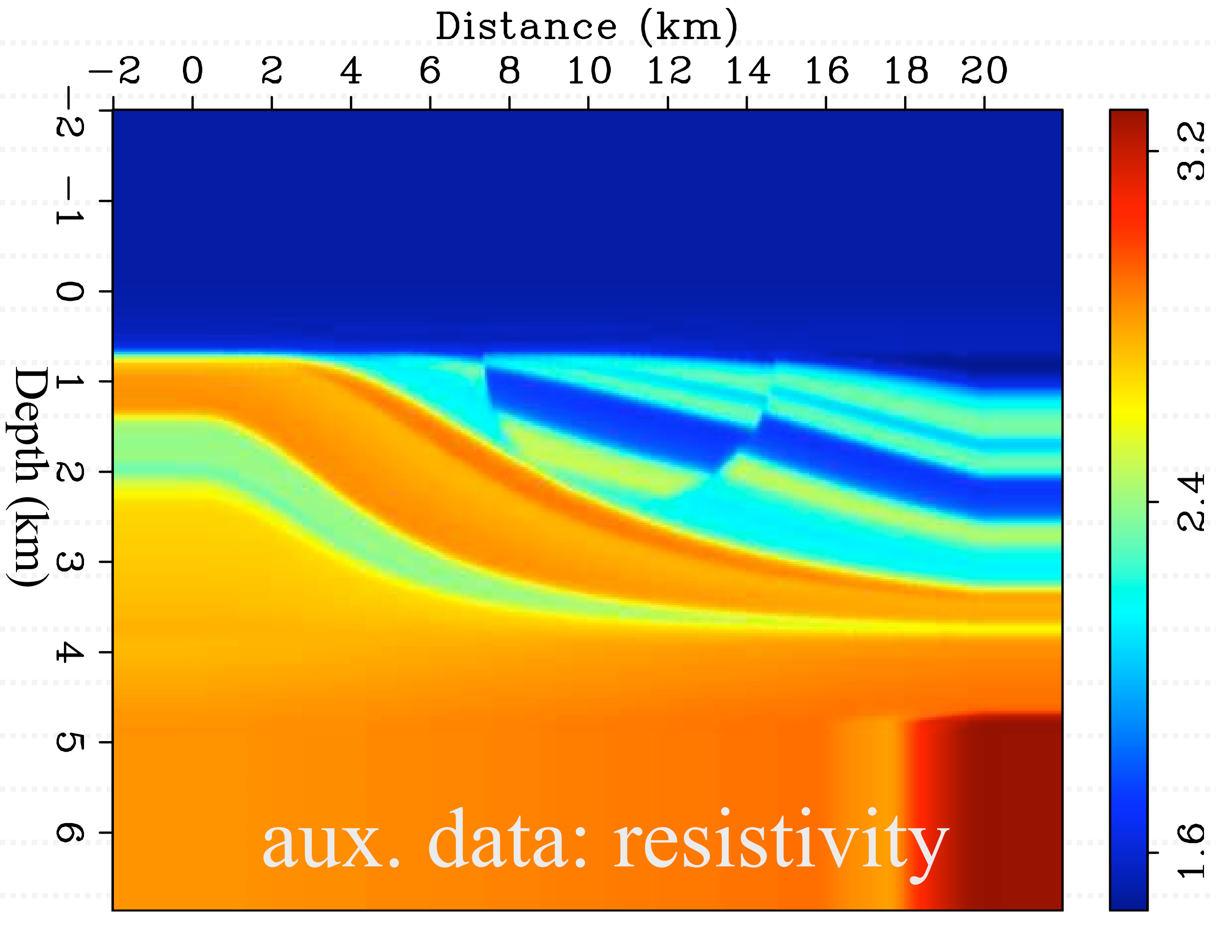


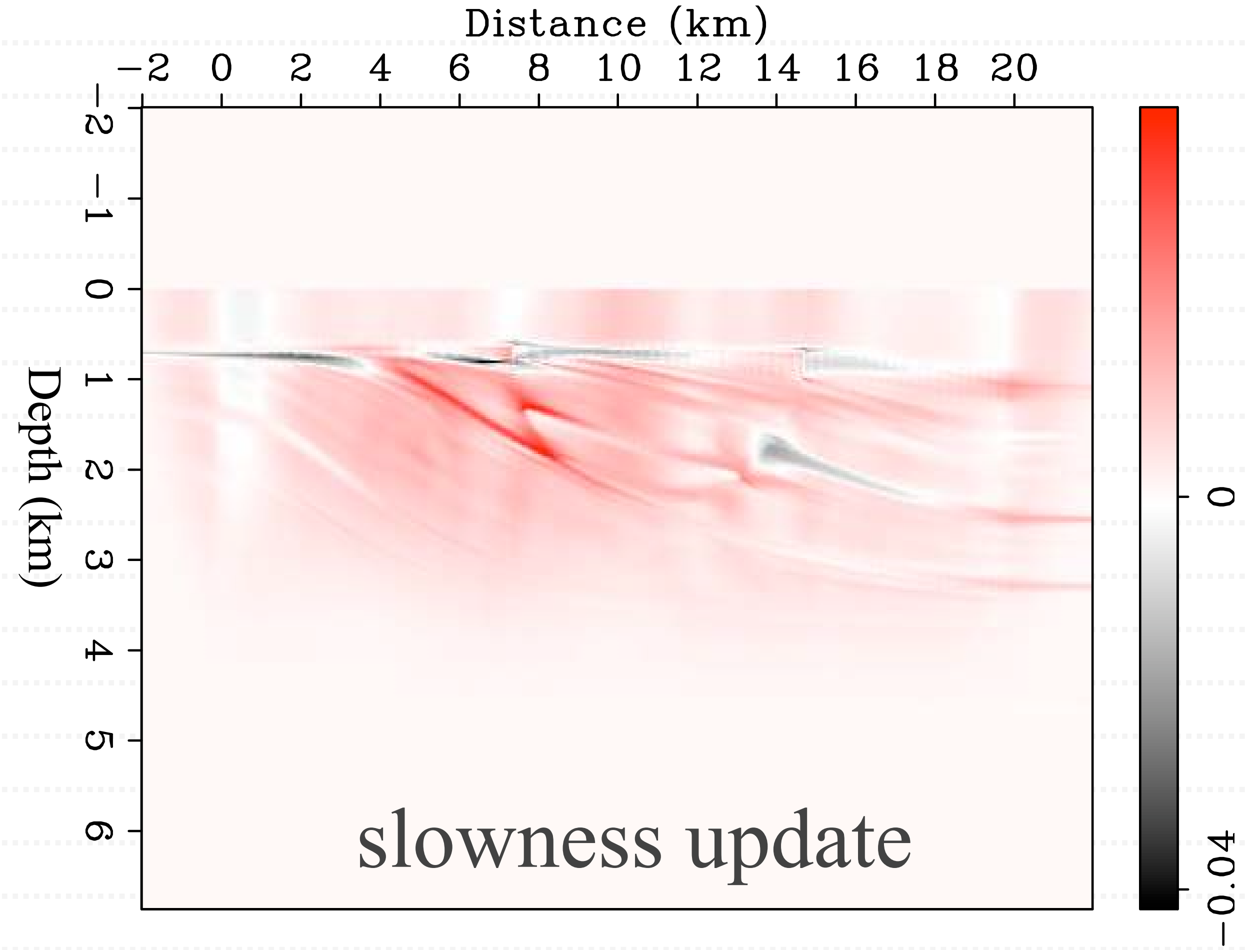
Velocity estimation with steering filters

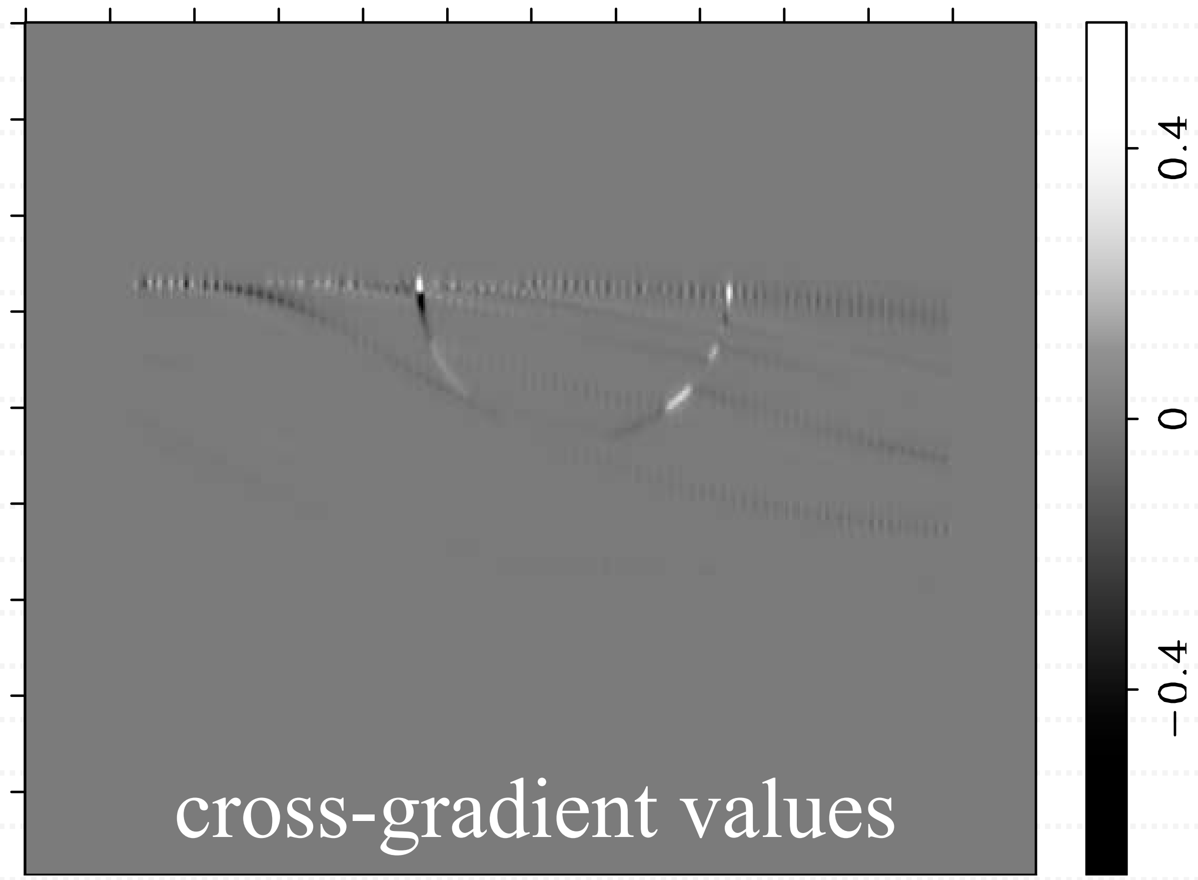


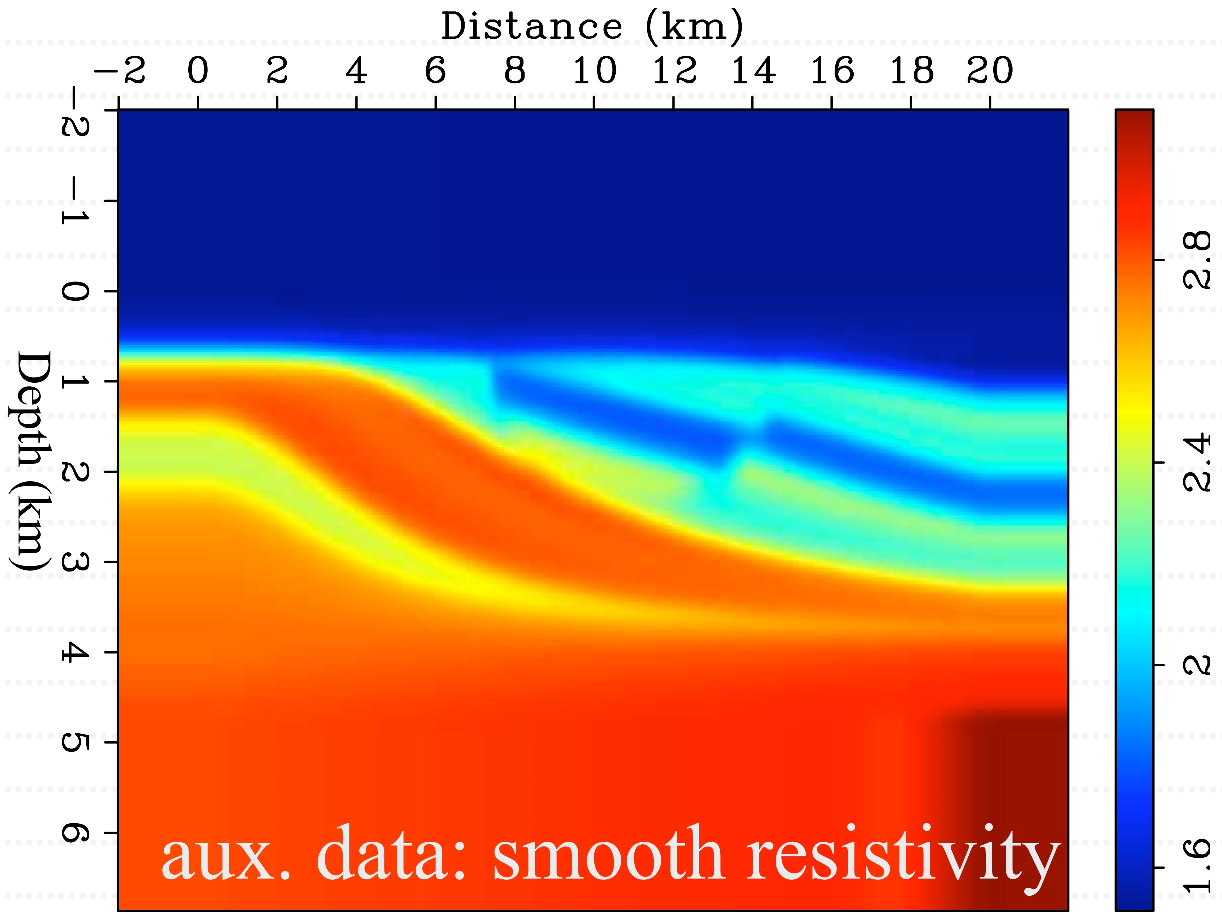


updated velocity

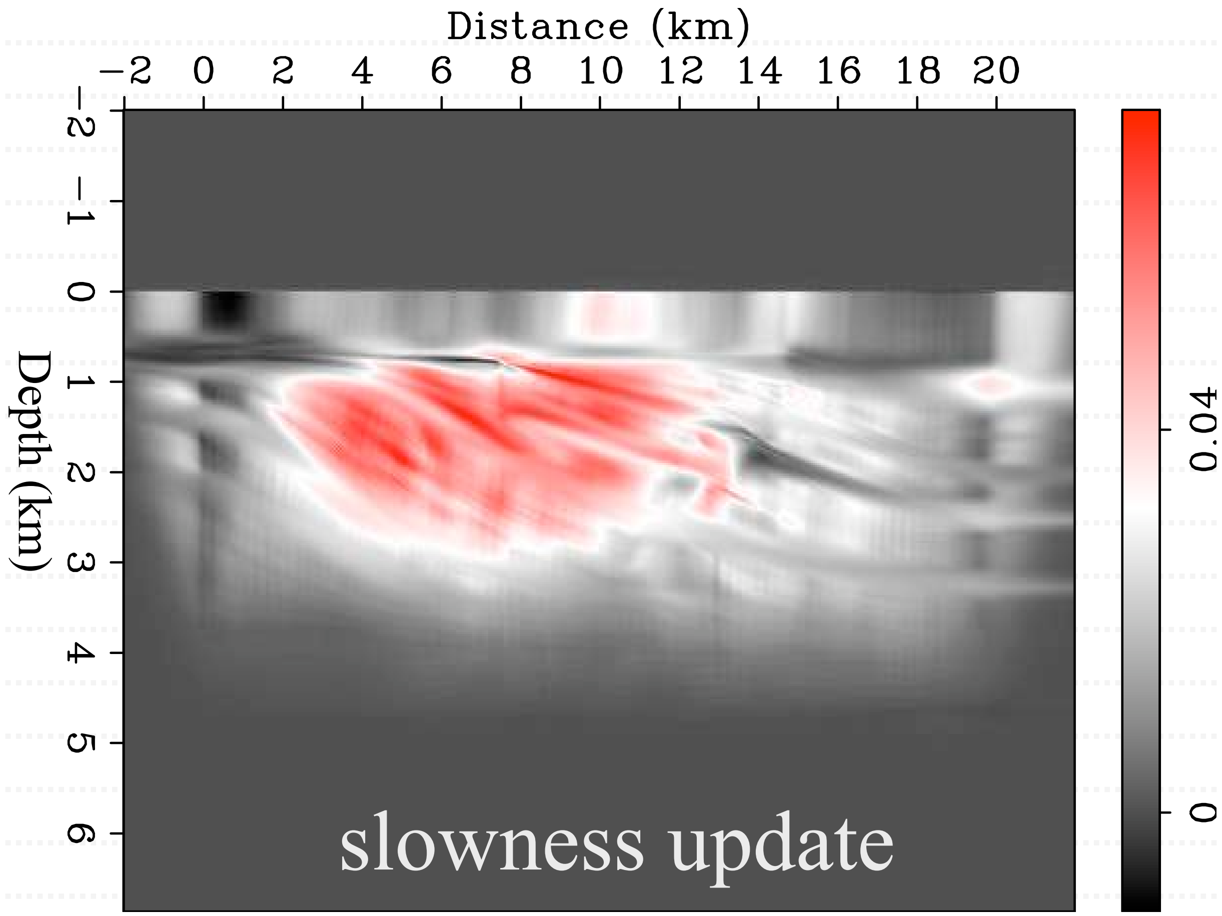

Distance (km)
−2 0 2 4 6 8 10 12 14 16 18 20
Depth (km)
−2 −1 0 1 2 3 4 5 6
3.2
2.4
1.6
aux. data: resistivity


Distance (km)
−2 0 2 4 6 8 10 12 14 16 18 20
Depth (km)
−2 −1 0 1 2 3 4 5 6
0
−0.04
slowness update

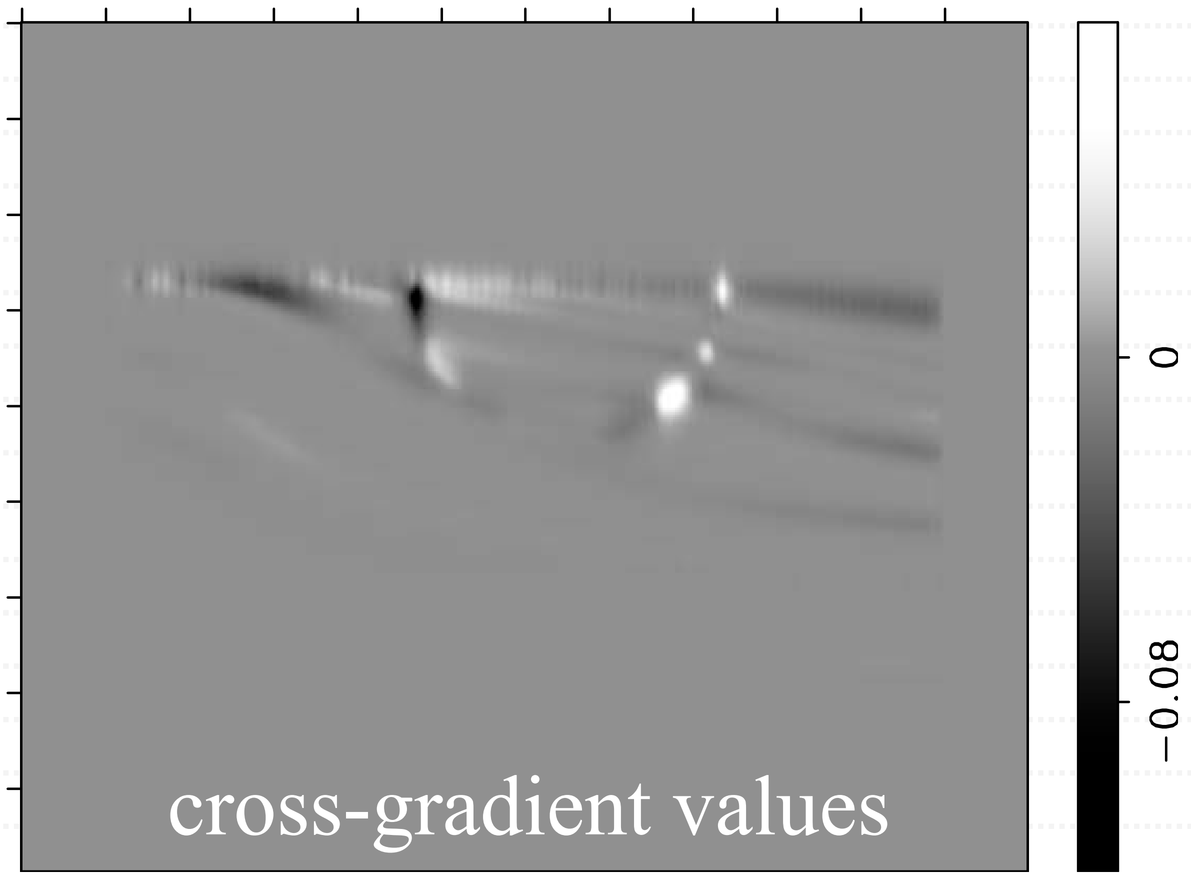

0.4
0
−0.4
cross-gradient values



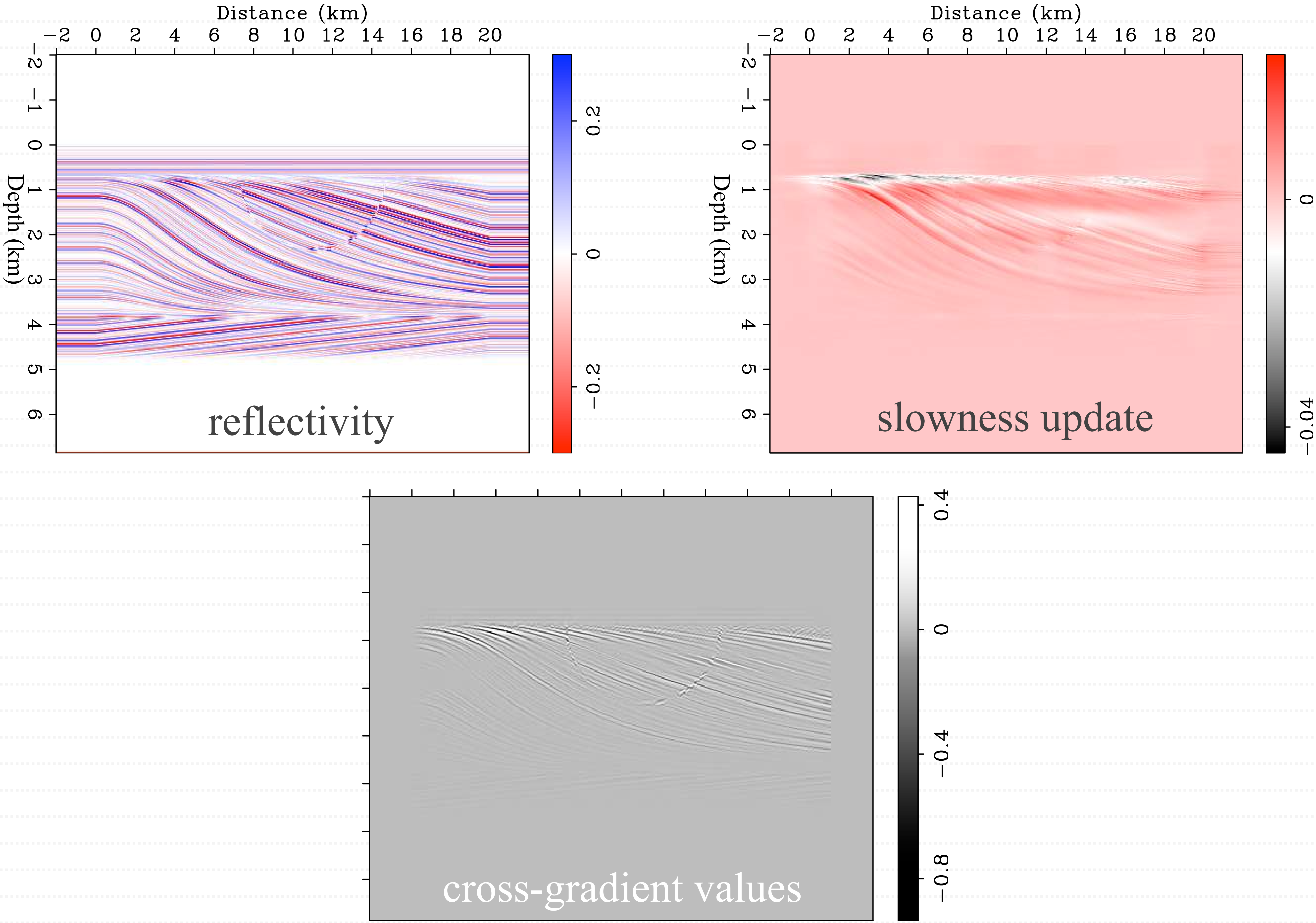
Distance (km)
−2 0 2 4 6 8 10 12 14 16 18 20
Depth (km)
−2 −1 0 1 2 3 4 5 6
aux. data: smooth resistivity
1.6 2 2.4 2.8



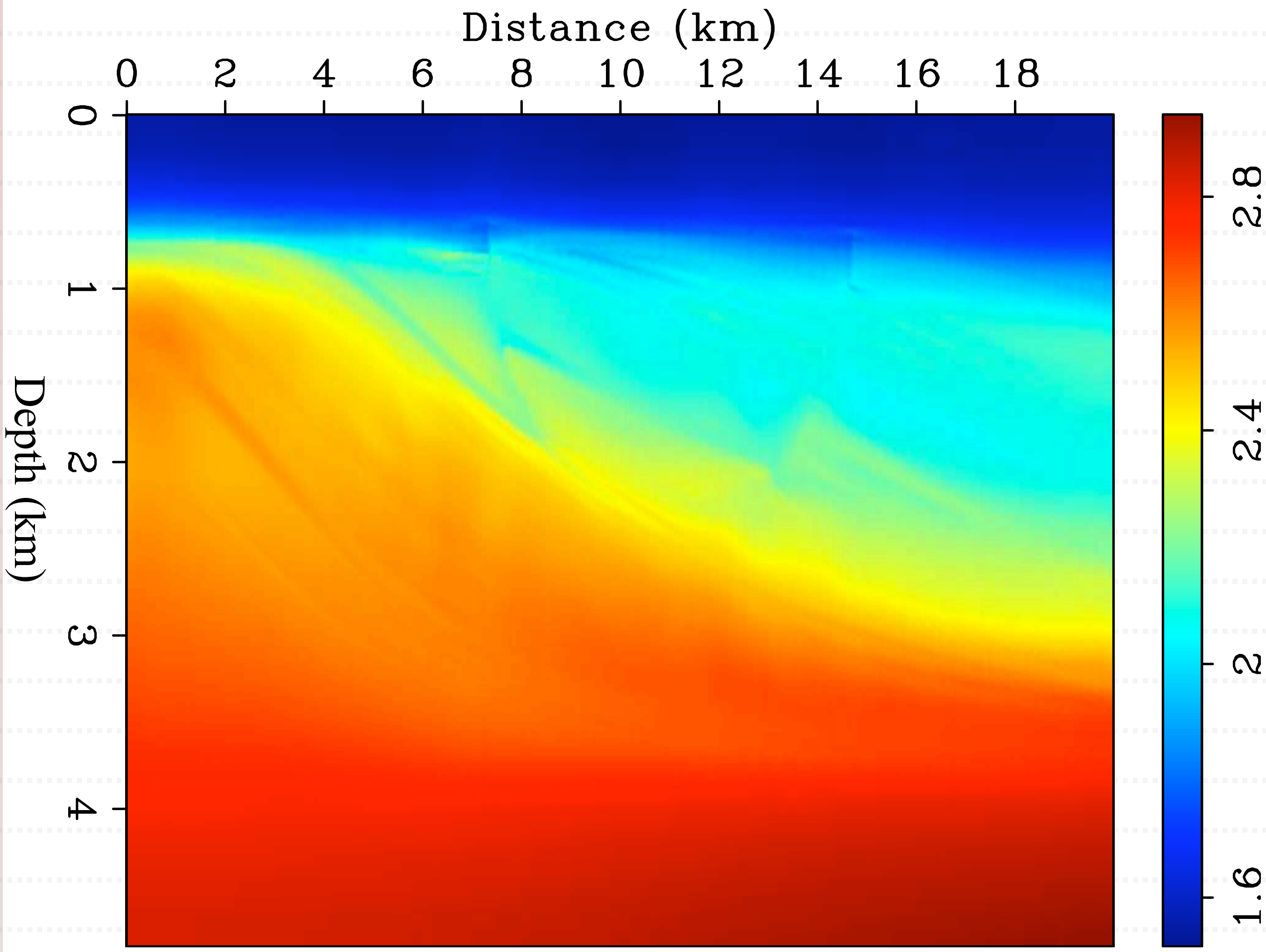
Distance (km)
−2 0 2 4 6 8 10 12 14 16 18 20
Depth (km)
−2 −1 0 1 2 3 4 5 6
slowness update
0 0.04



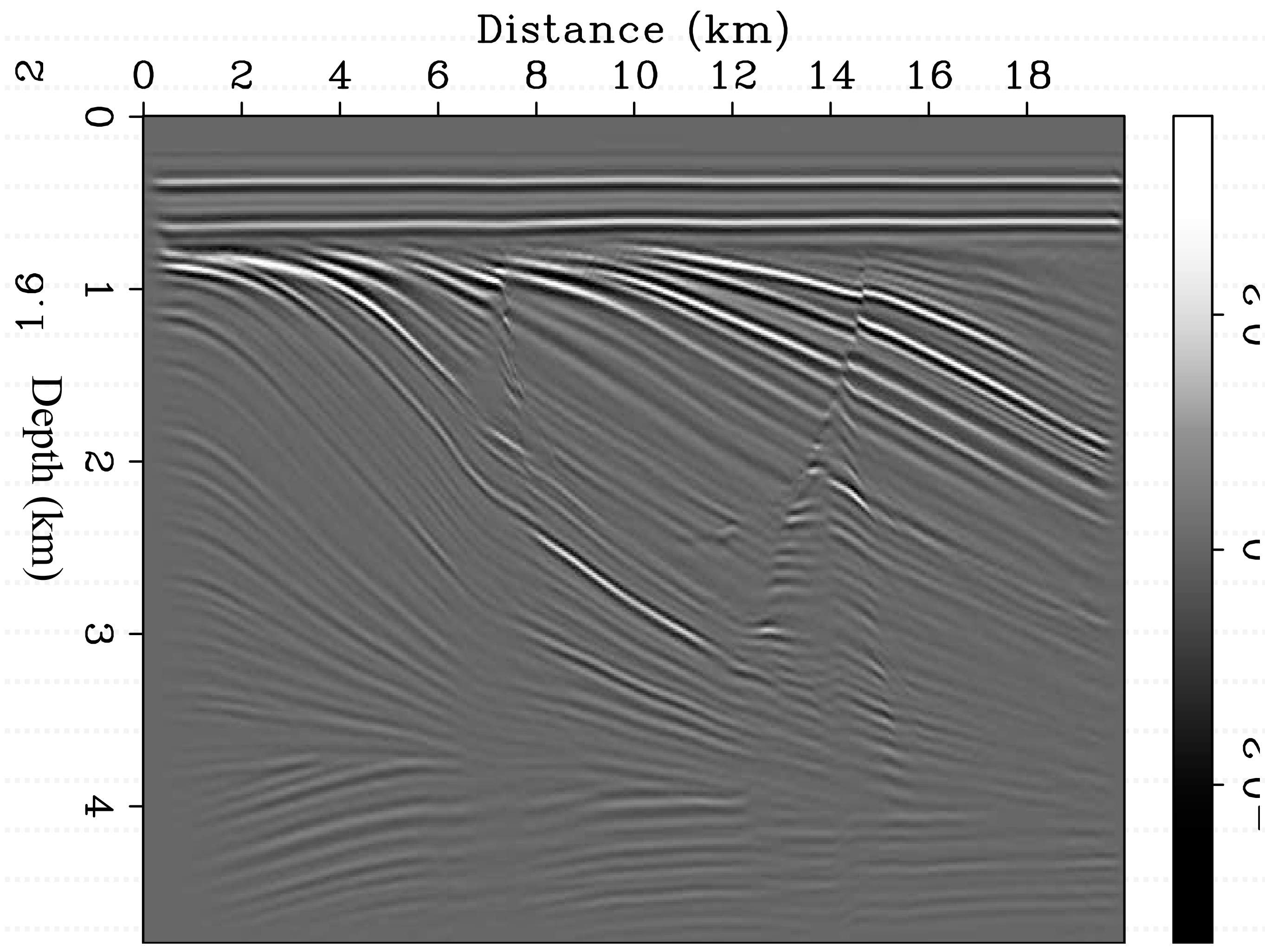
cross-gradient values
−0.08 0


Distance (km)
−2 0 2 4 6 8 10 12 14 16 18 20
Depth (km)
−2 −1 0 1 2 3 4 5 6
0.2
0
−0.2
reflectivity
Distance (km)
−2 0 2 4 6 8 10 12 14 16 18 20
Depth (km)
−2 −1 0 1 2 3 4 5 6
0
−0.04
slowness update
0.4
0
−0.4
−0.8
cross-gradient values

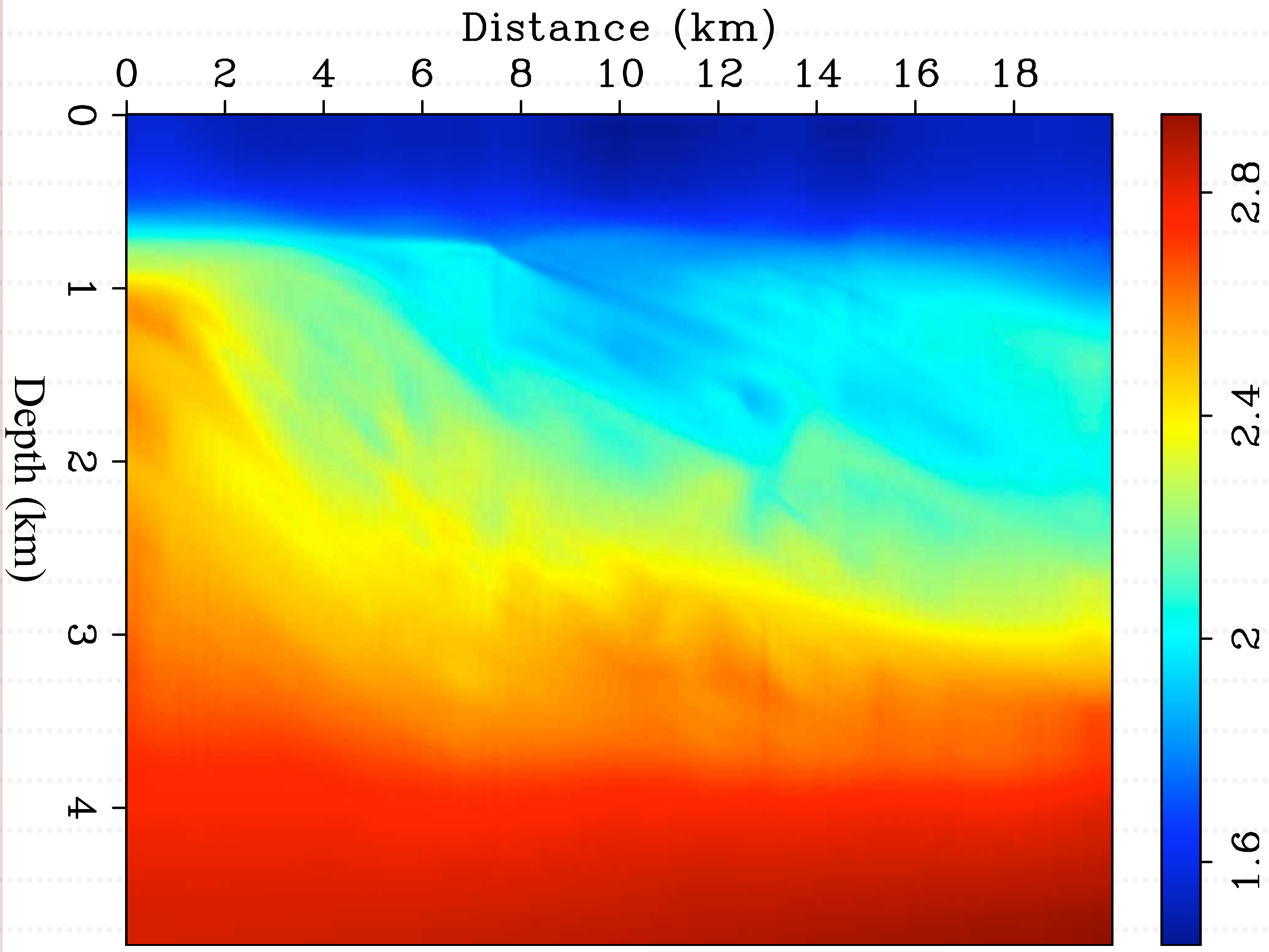
Velocity estimation with auxiliary data



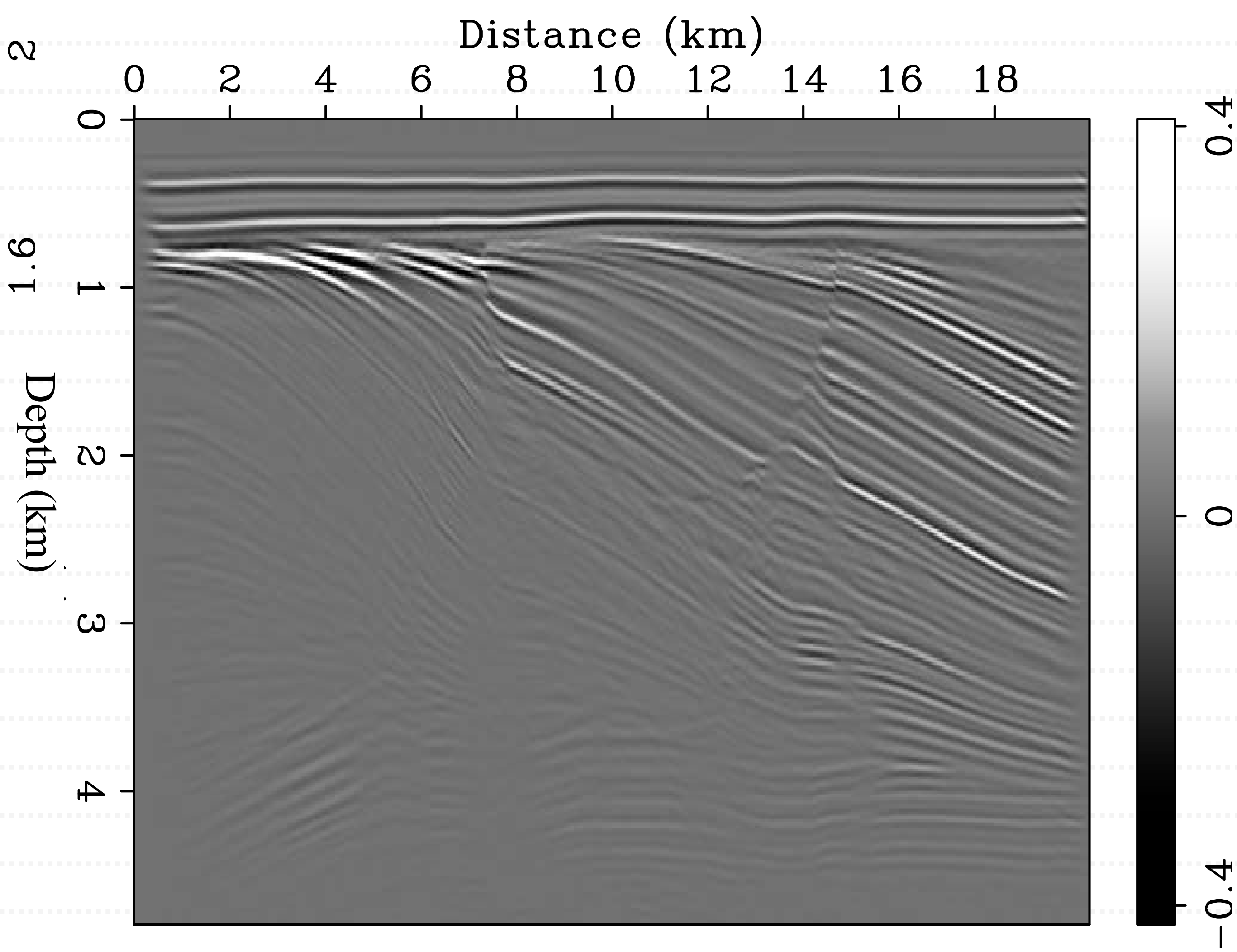
Updated velocity



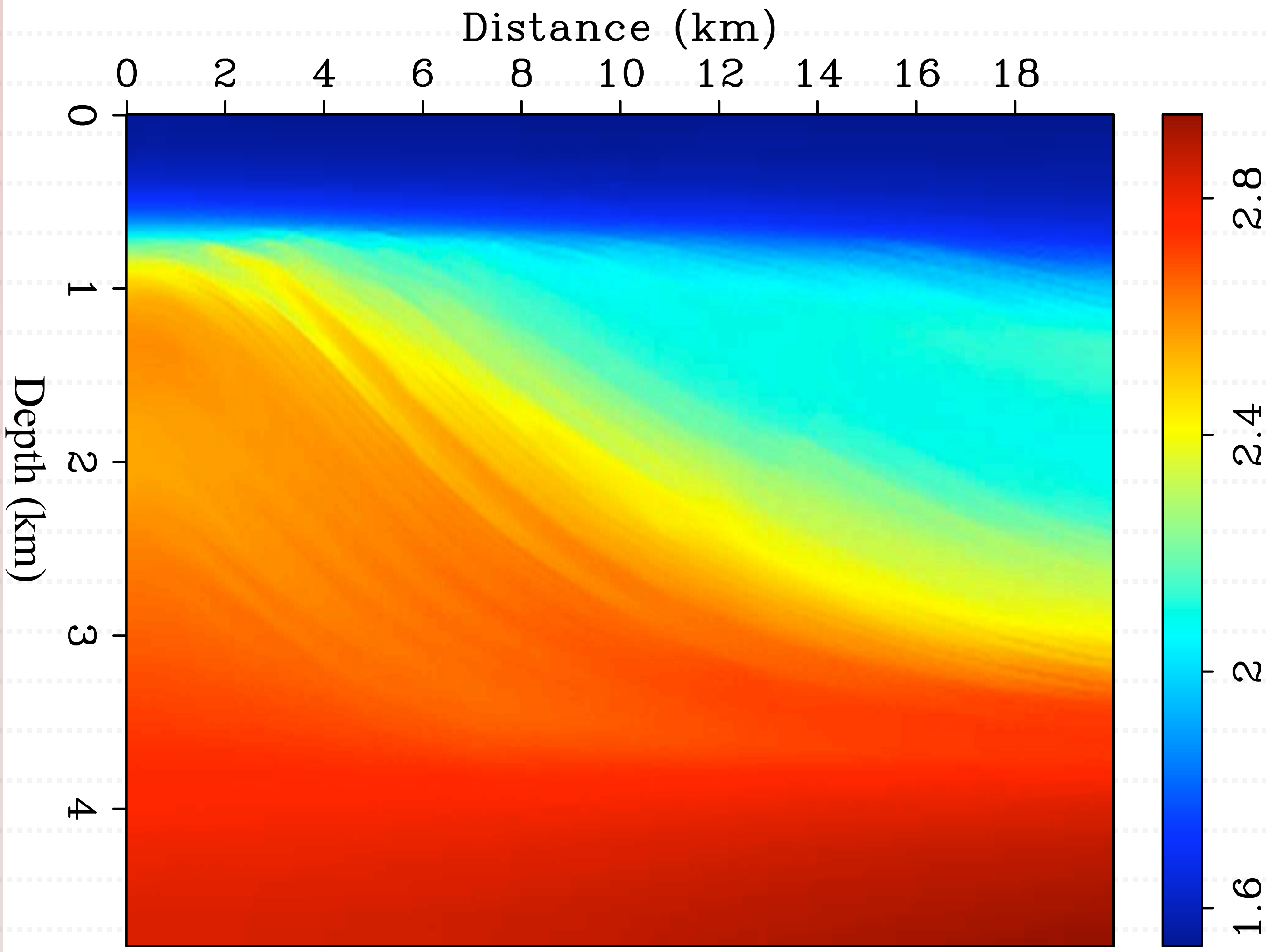
Velocity estimation with auxiliary data I



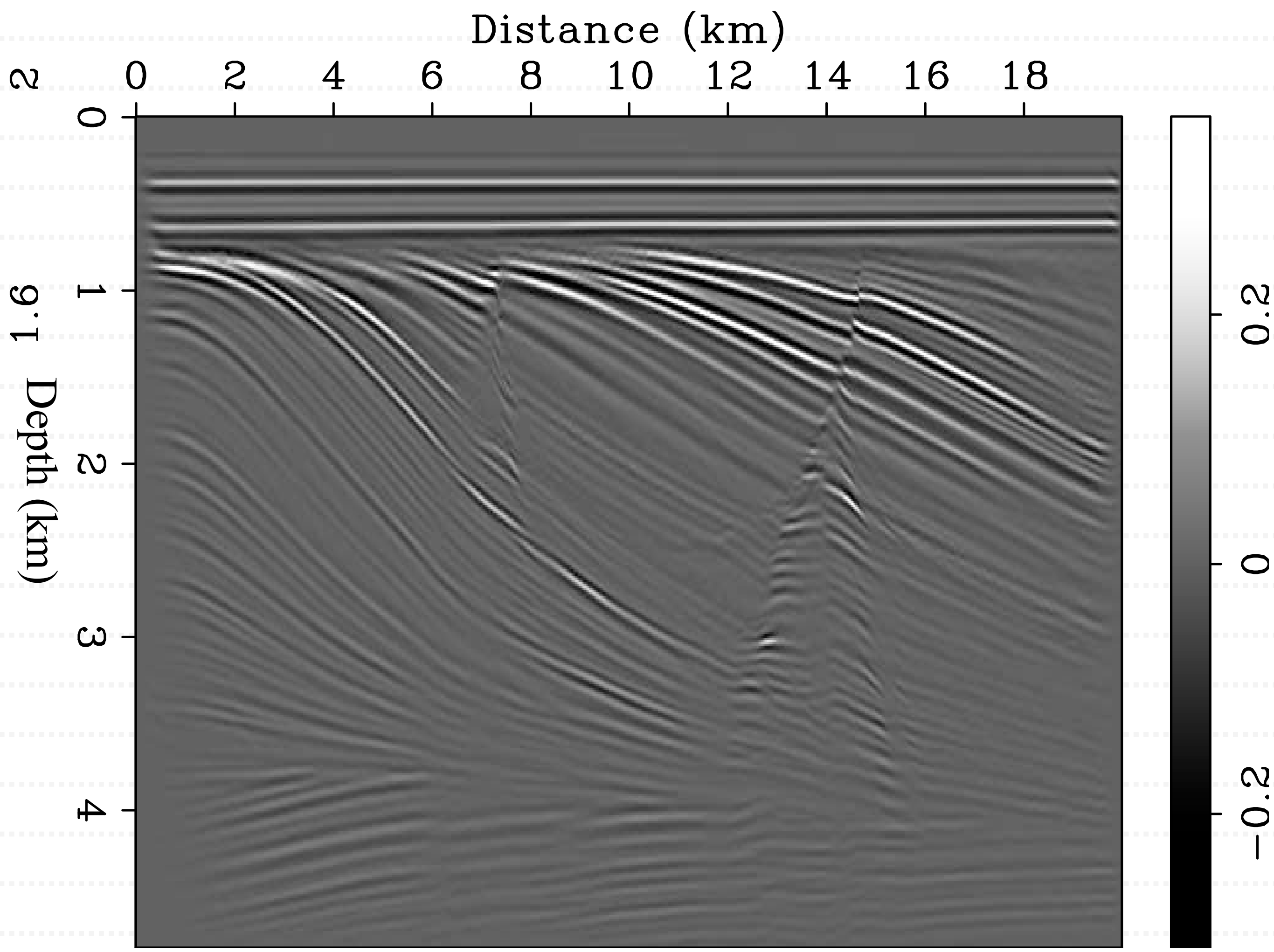
Updated velocity



Velocity estimation with auxiliary data 2



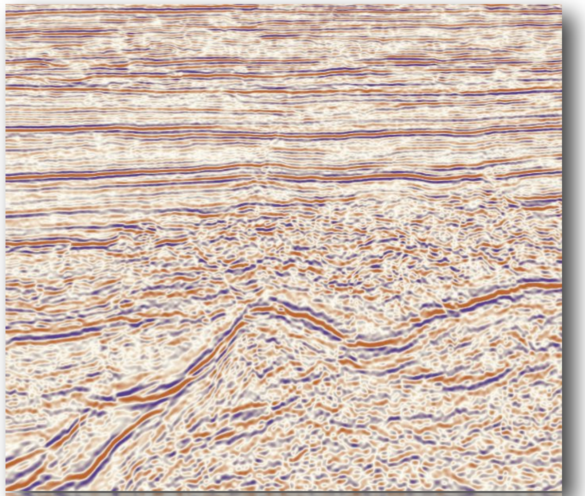
Updated velocity



Observations

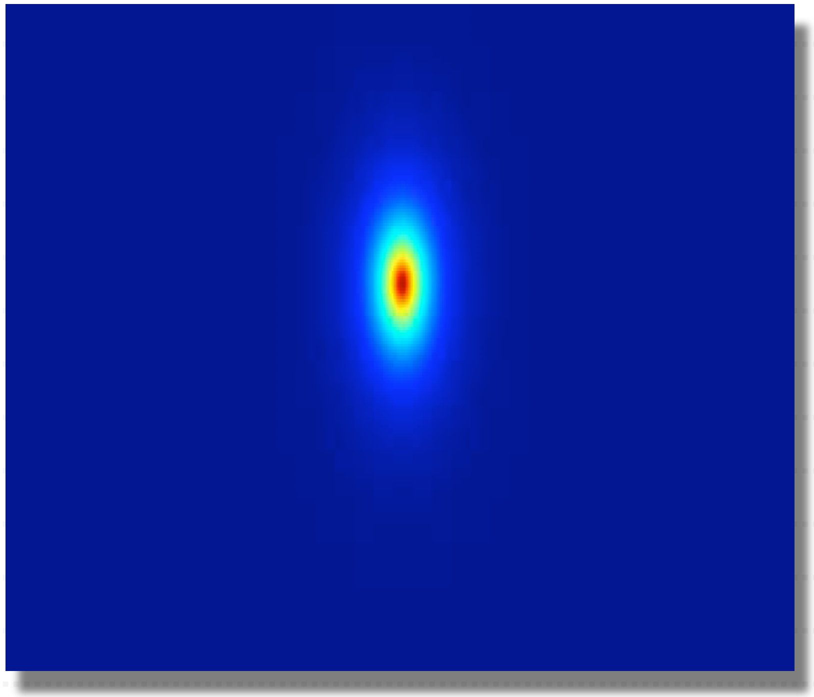
- Steering filters
  - Smooth and continuous velocity anomalies
- Cross-gradient functions
  - resolution of velocity update
  - Sharp boundaries
    - salt bodies, faults

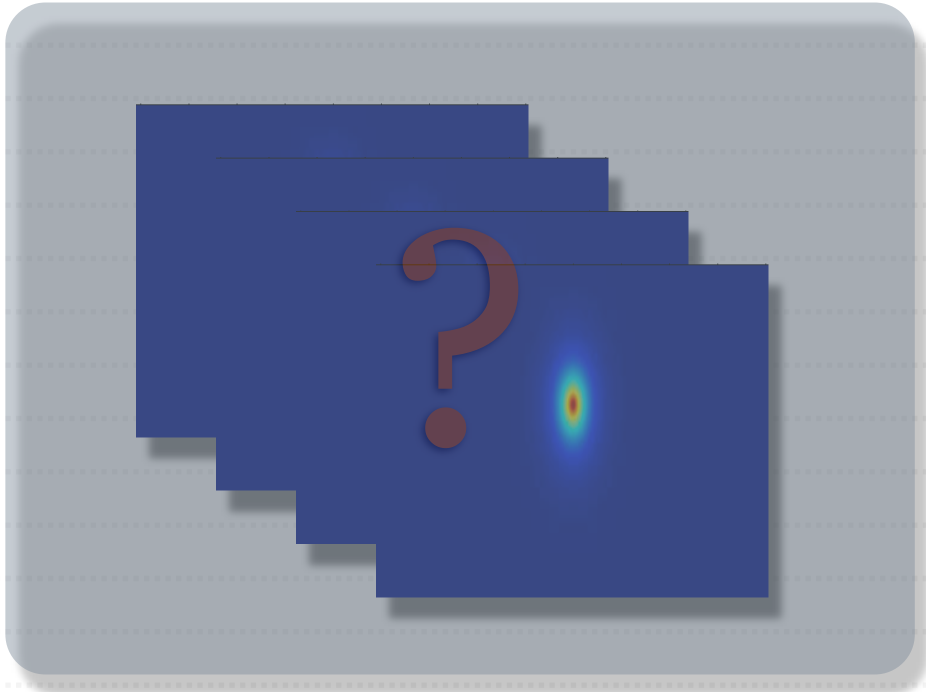
Next



Future work

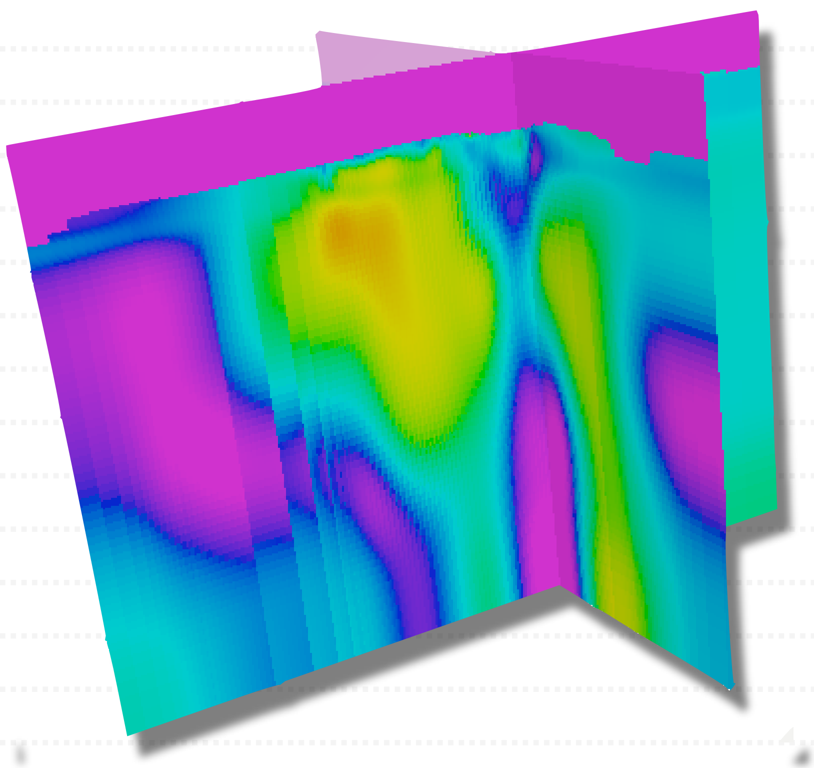
- Improved velocity-resistivity relations
- Apply to field data
- Integrate statistical uncertainty analysis



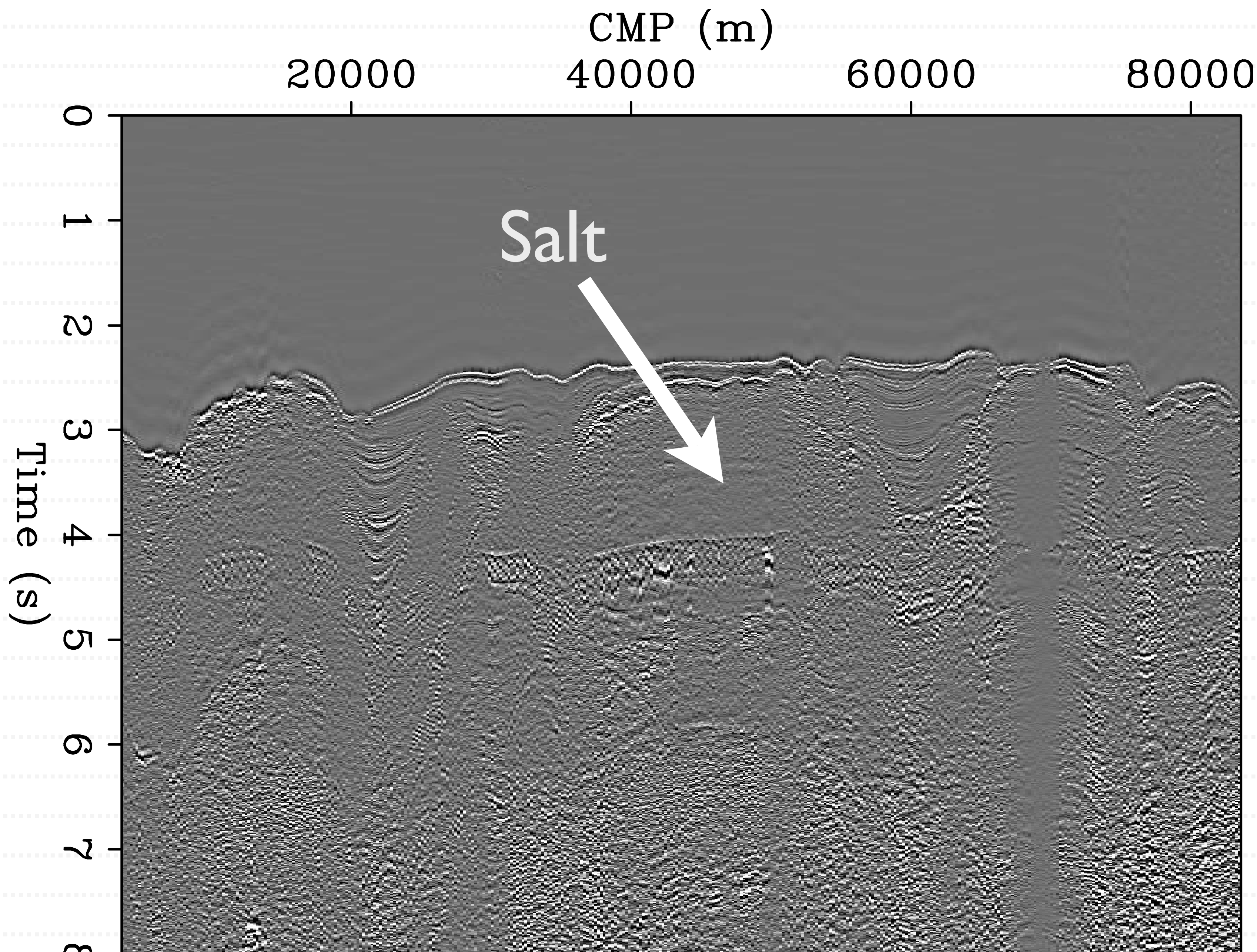


Field Data

- 3D cube of inverted resistivity
- Seismic Data



Courtesy of WesternGeco Co.



CMP gather

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- WesternGeco company

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