FWI from the West Coasts:
lessons learned from "Gulf of Mexico Imaging Challenges: What Can Full Waveform Inversion Achieve?"

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Dream team










Goals

- nonlinear Conjugate gradients
  - ***linear*** *anisotropic* smoothing of *gradients*
- *modified* Gauss-Newton
  - ***nonlinear*** "smoothing" of *gradients* with *anisotropic* curvelets

Acoustic FWI workflows with *minimal* parameters & user *intervention*... *Migration* was computationally *infeasible*.

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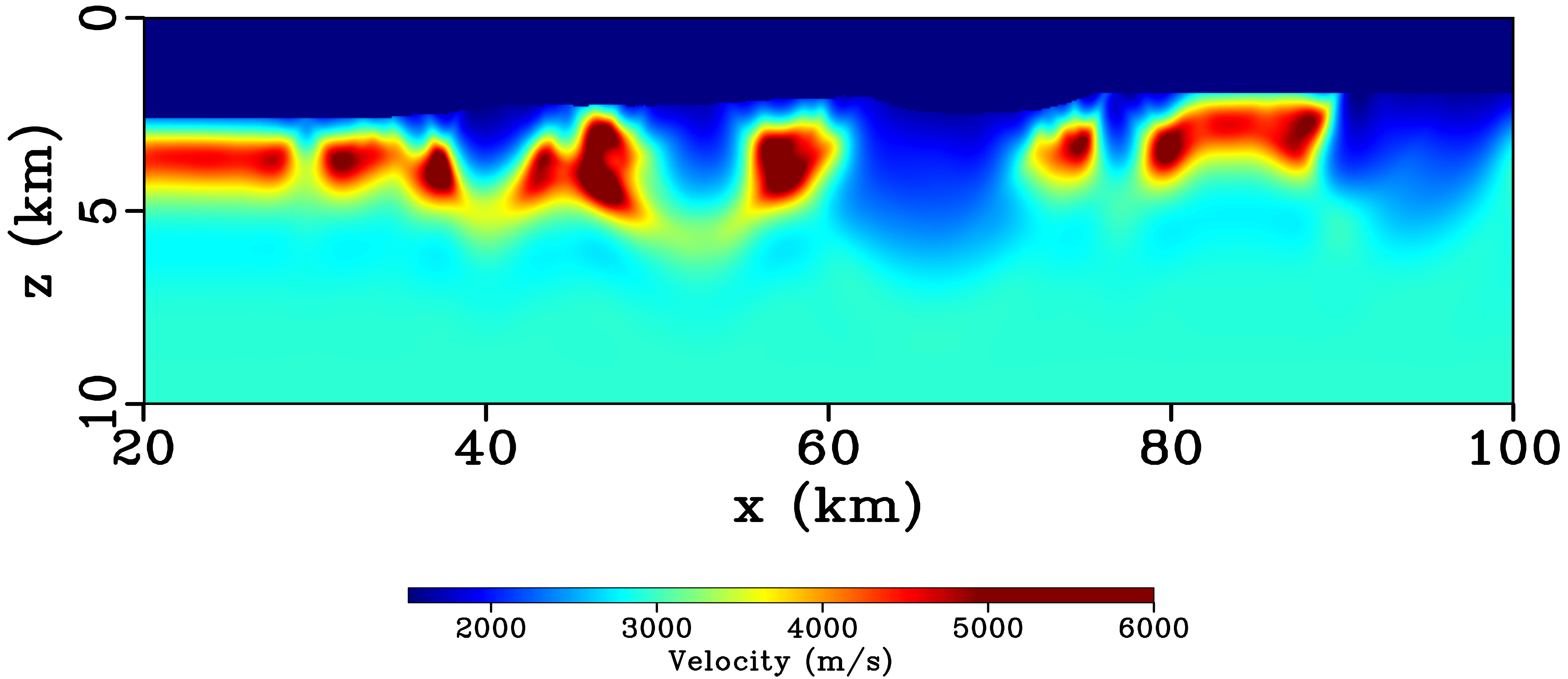
Preprocessing

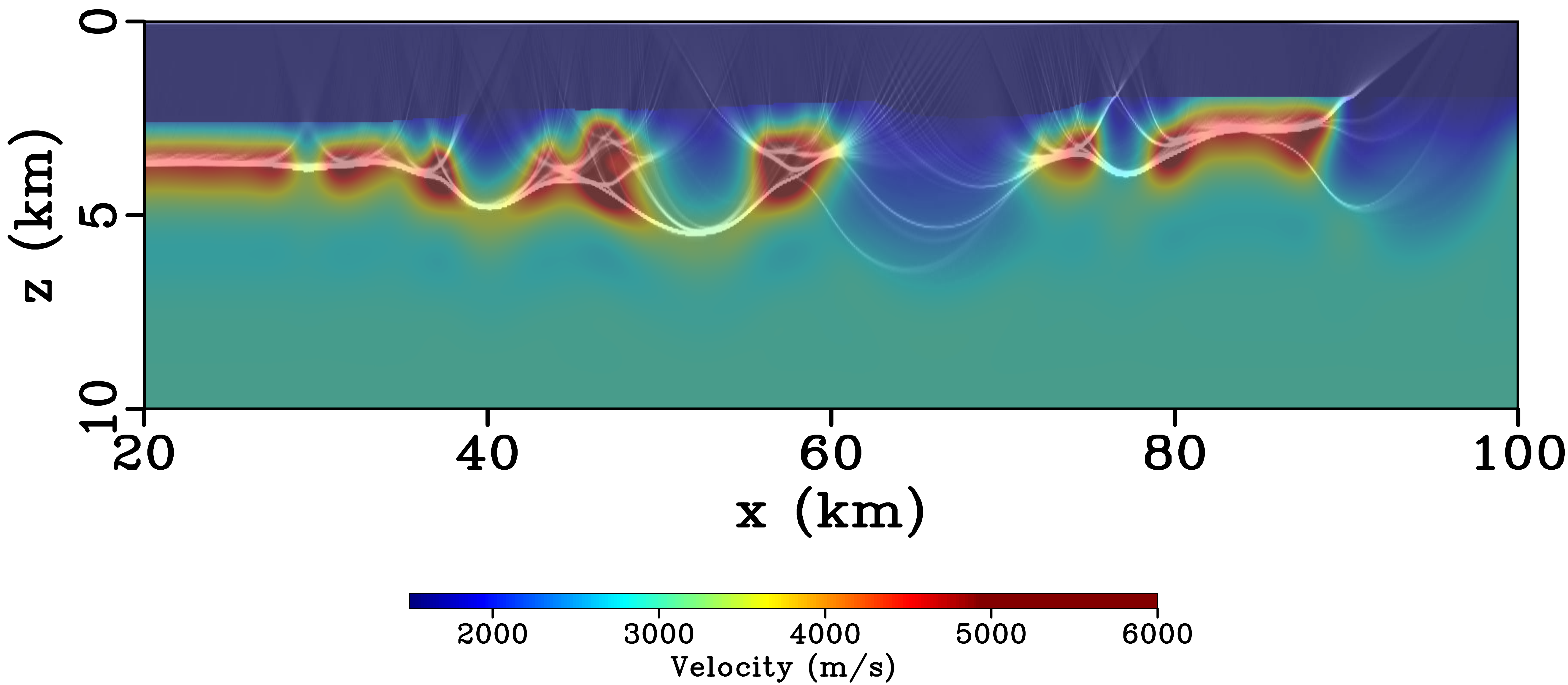
Travel-time *tomography* based on hand-picked *first* breaks ⟶ *initial velocity model*

Curvelet-denoising at selected *low*-frequencies ⟶ *improve SNR* for FWI

Initial model
[ray-based tomography]



Ray paths
[RMS traveltime misfit 11ms]



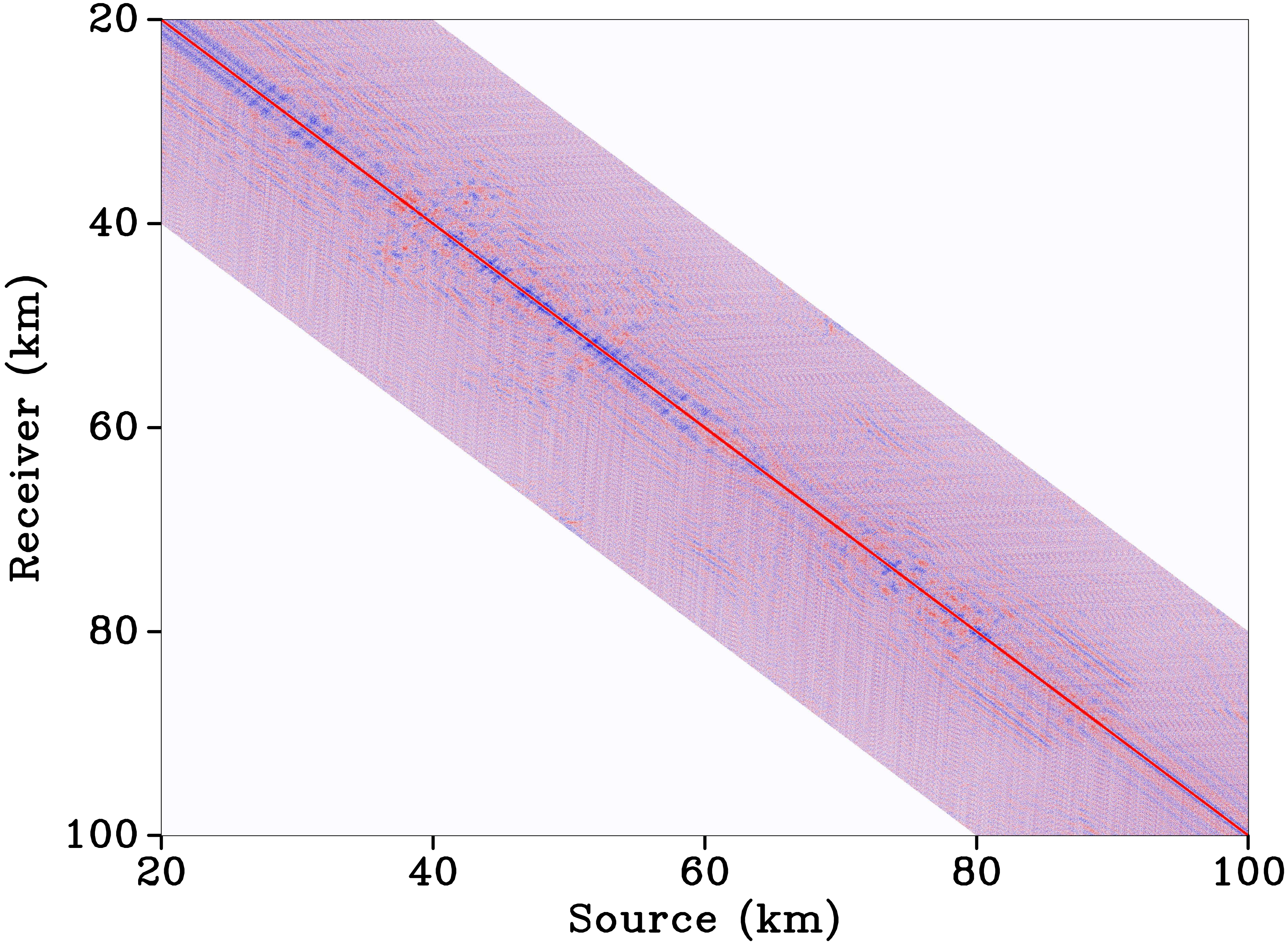
Denoising

Work on "frequency slices" in the *source*/*receiver* plane

Find *support* by *hand*-selected *thresholding* of *syntheses* curvelet coefficients

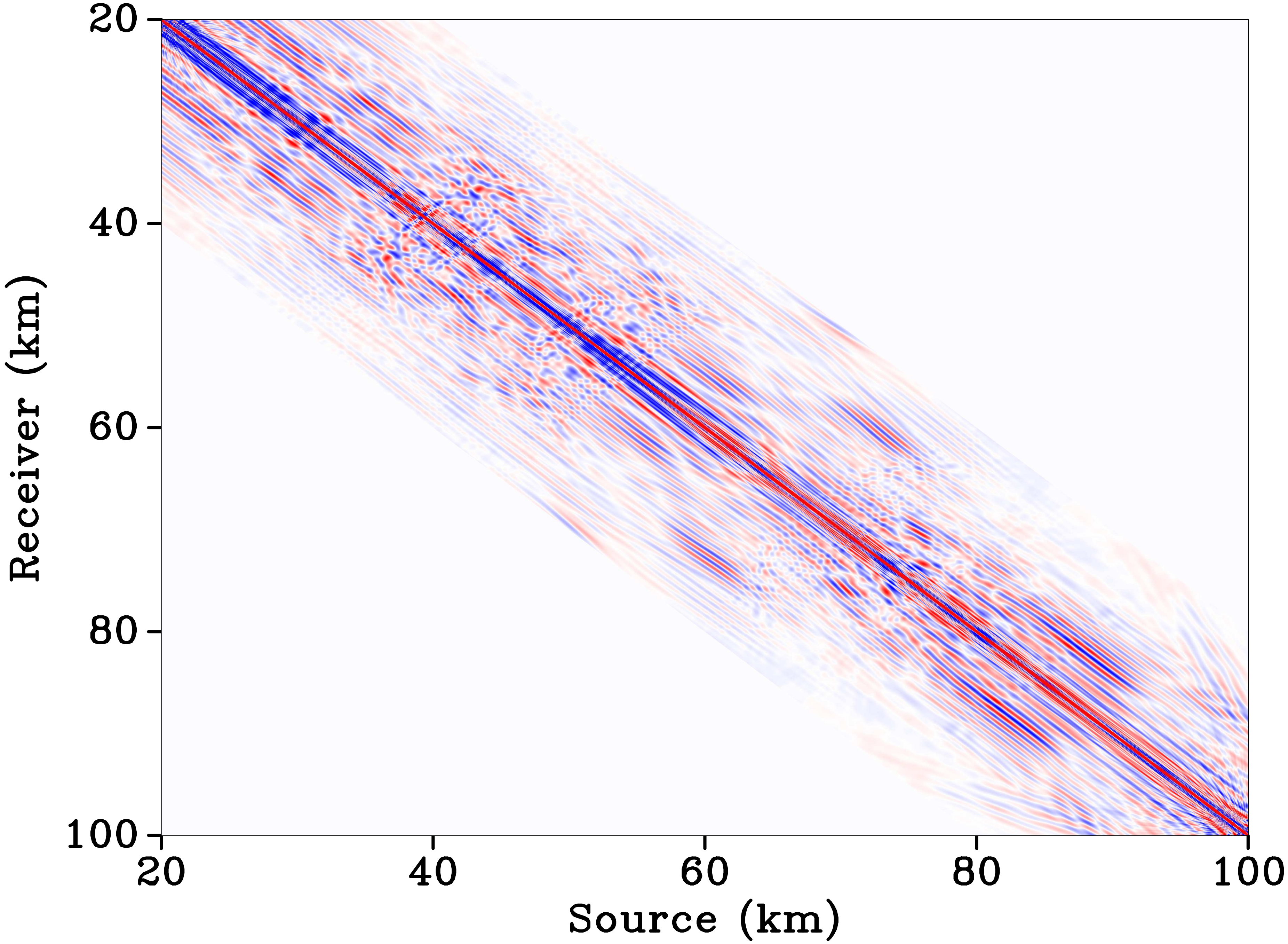
Followed by *debiasing* to restore *amplitudes*...

Before denoising
[real part at 2.0 Hz]



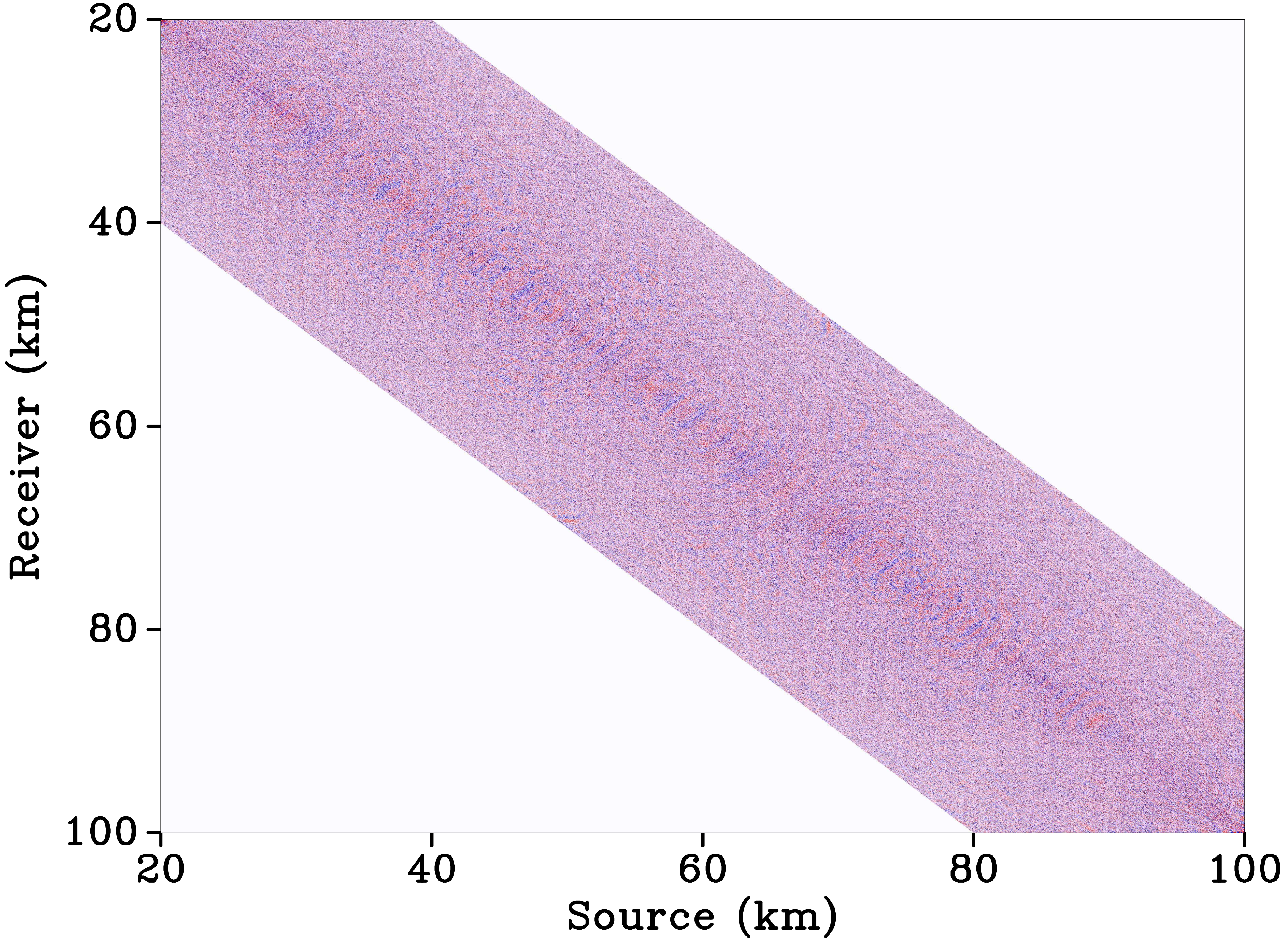
After denoising

[real part at 2.0 Hz]



Difference

[real part at 2.0 Hz]



Denoising

Removed mostly *incoherent* energy

Preserved amplitudes of the *coherent* events

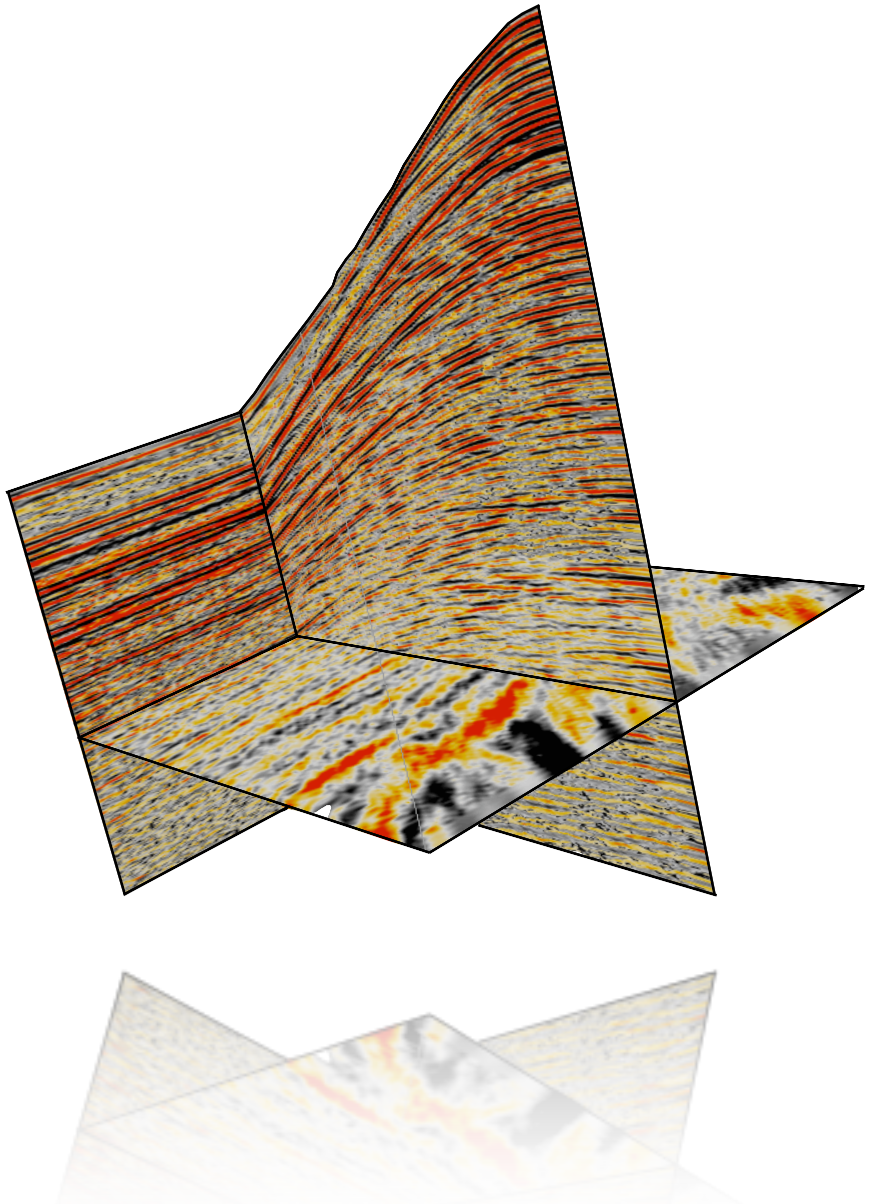
Improved data *quality* in the "eye ball" norm

Nonlinear Conjugate Gradients

Pratt, R.G., Shin, Changsoo and Hicks, G.J., 1998. Gauss-Newton and full Newton methods in frequency domain seismic waveform inversion. Geophysical Journal International, 133, 341-362.

Brenders, A. J. and Pratt, R. G., 2007. Full waveform tomography for lithospheric imaging: results from a blind test in a realistic crustal model, Geophysical Journal International, 168, 133-151

Takam Takougang, E. M. and Calvert, A. J., 2011. Application of waveform tomography to marine seismic reflection data from the Queen Charlotte Basin of western Canada, Geophysics,76, B1-B16



Methodology

Non-linear conjugate gradients (first order)

Scaling by *RMS* from (initial) *forward* model

Layer stripping with gradient & offset weights

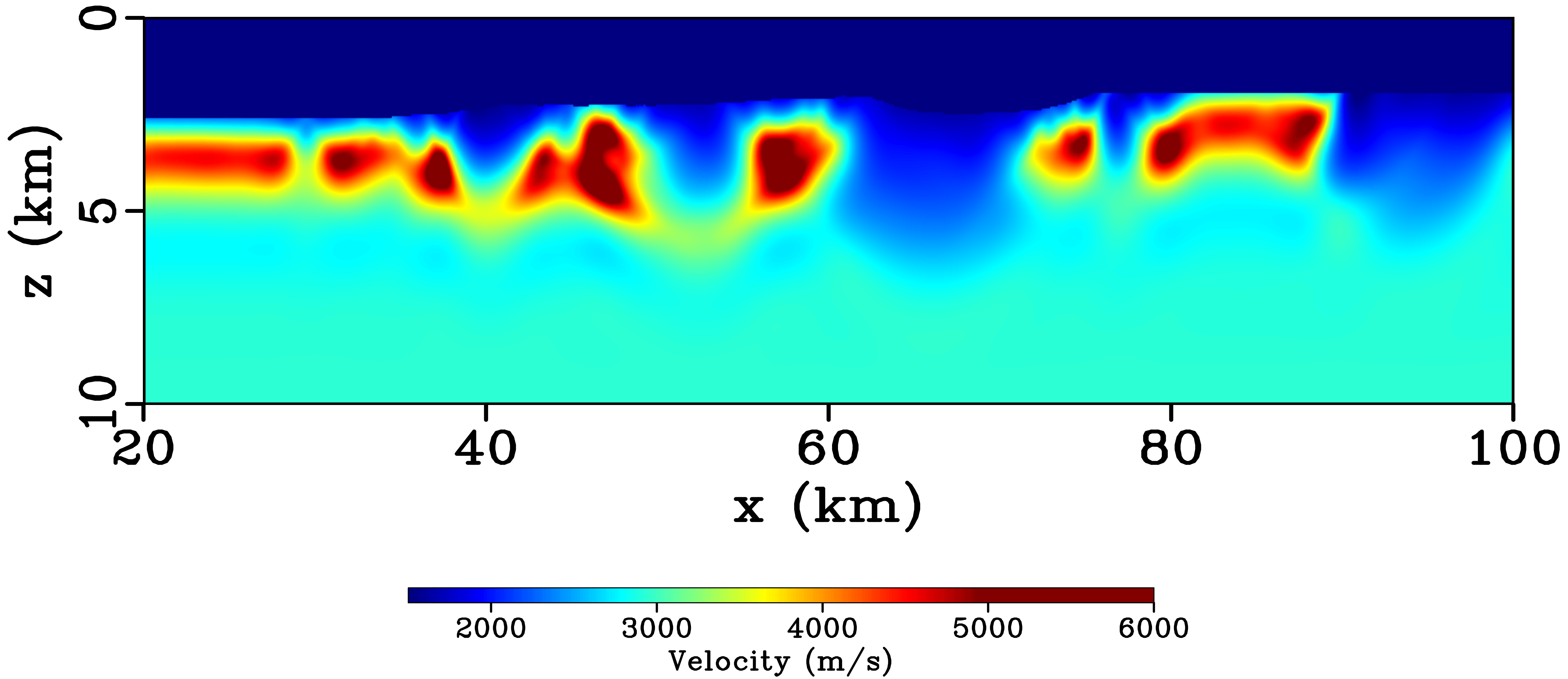
Two-staged inversion (40-80)% 3s window

- *phase* only 2–7 Hz

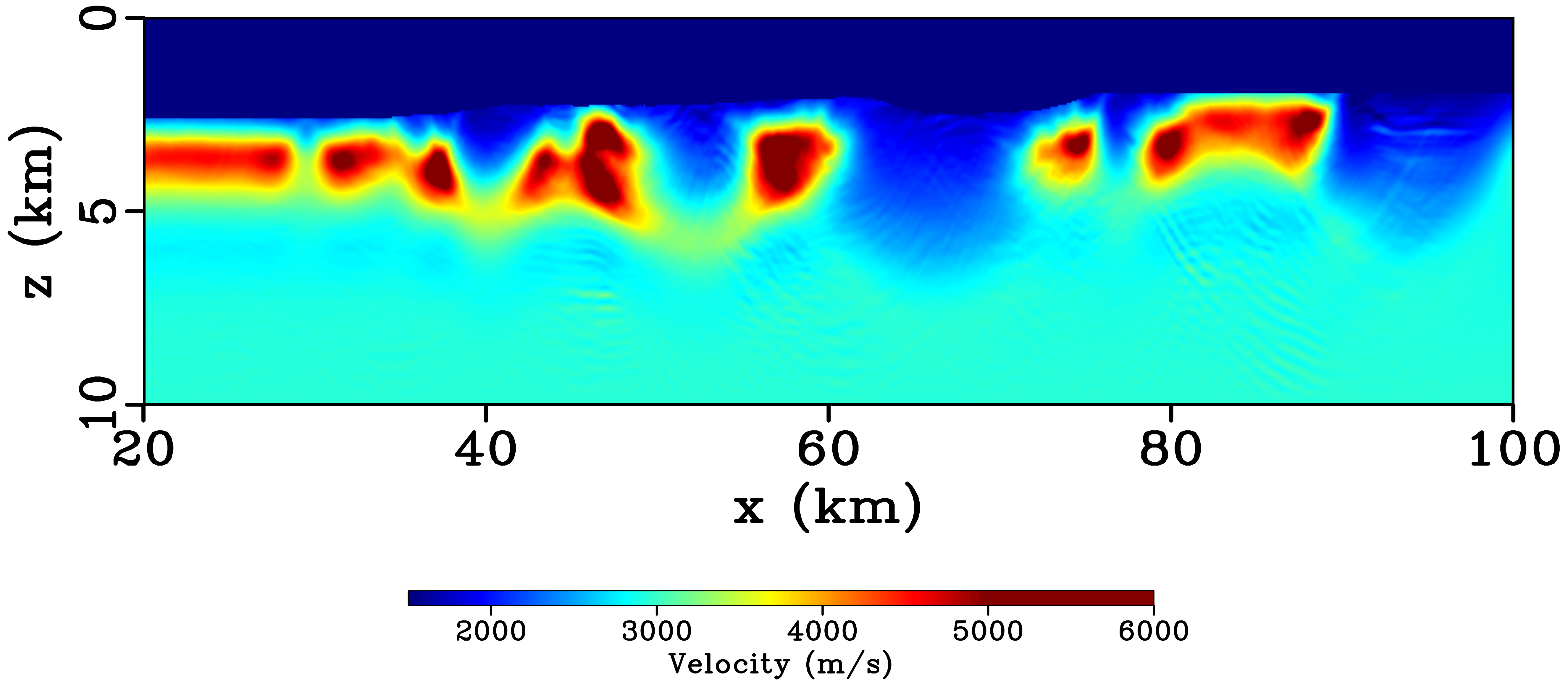
Anisotropic *smoothing* on *gradients*...

Initial model

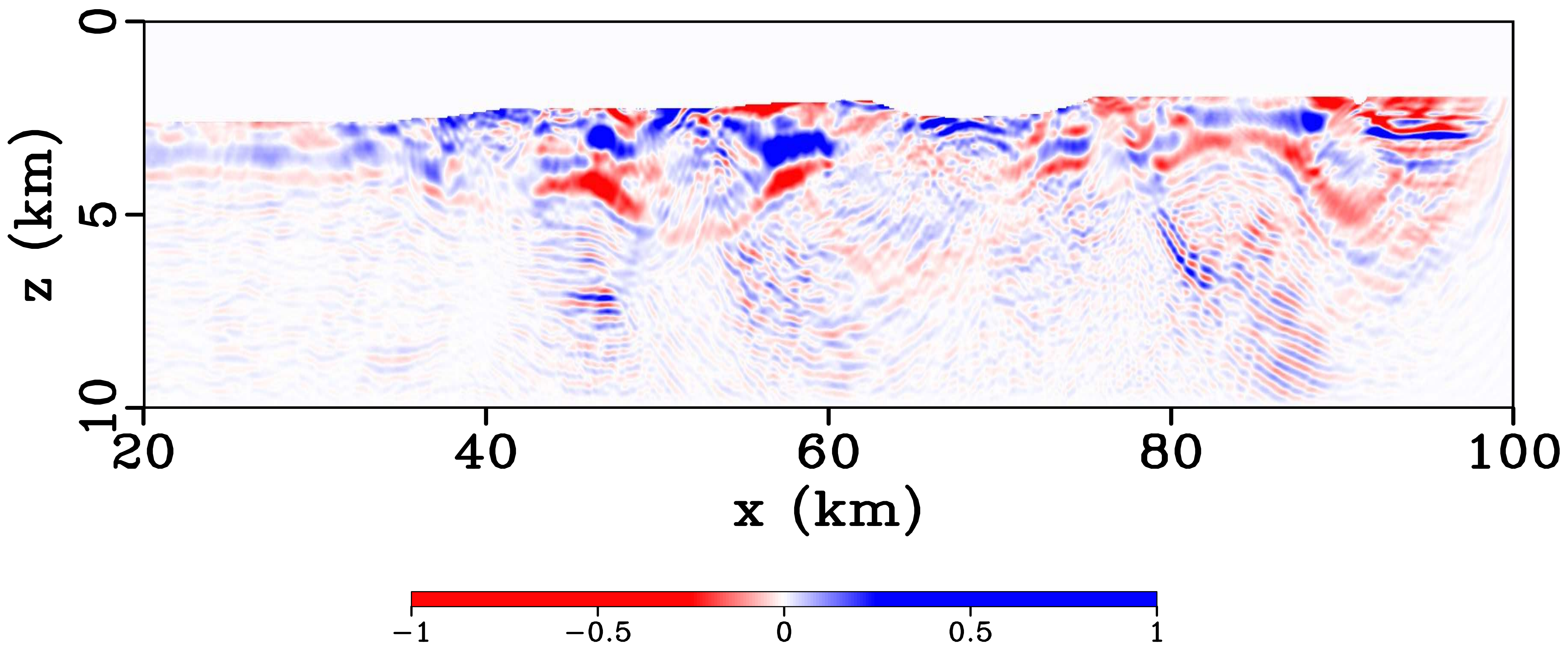
[ray-based tomography]



Final result
[w/o denoising]



Relative update $\Delta(V)/V$



Batched FWI with nuisance parameter estimation

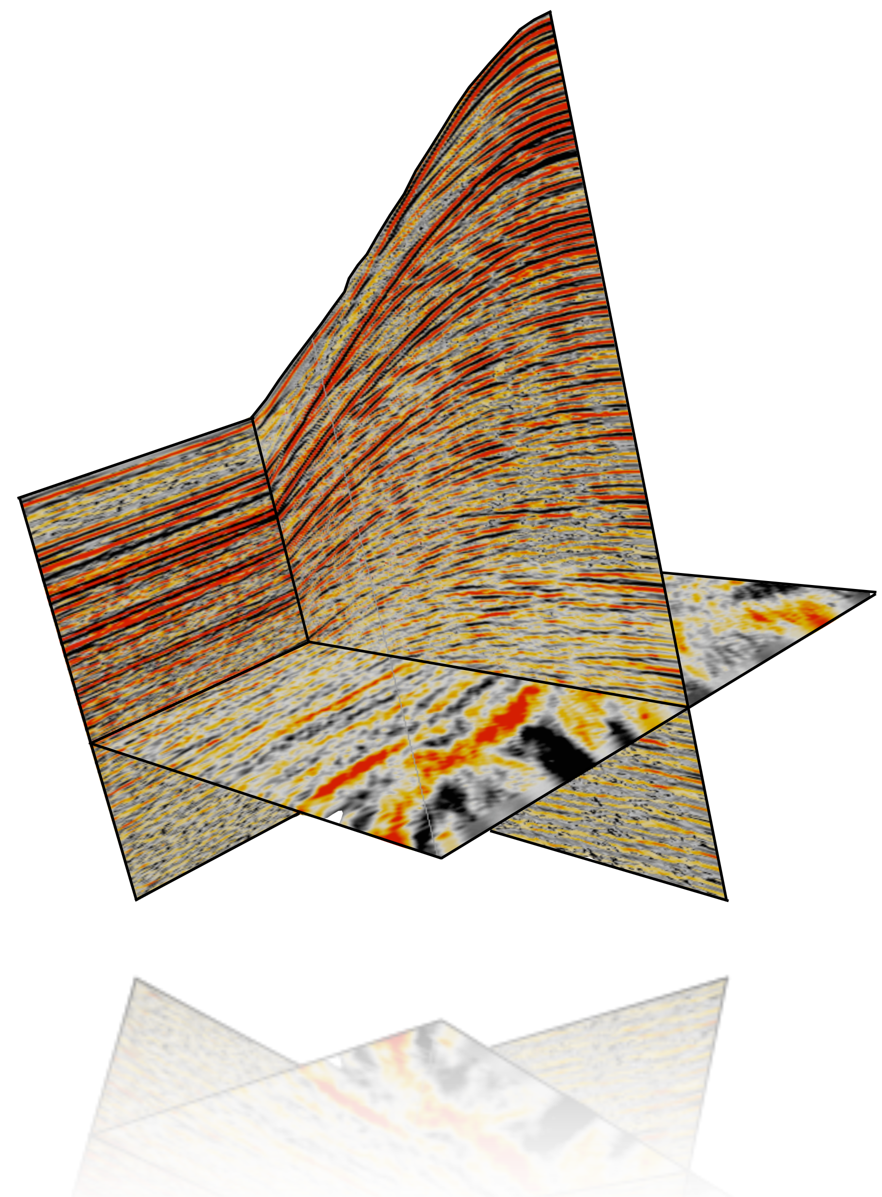
A.Y. Aravkin and T. van Leeuwen - Estimating nuisance parameters in inverse problems. Inverse Problems, 2012.

T. van Leeuwen and F.J. Herrmann - Fast waveform inversion without source encoding. Geophysical Prospecting, 2012

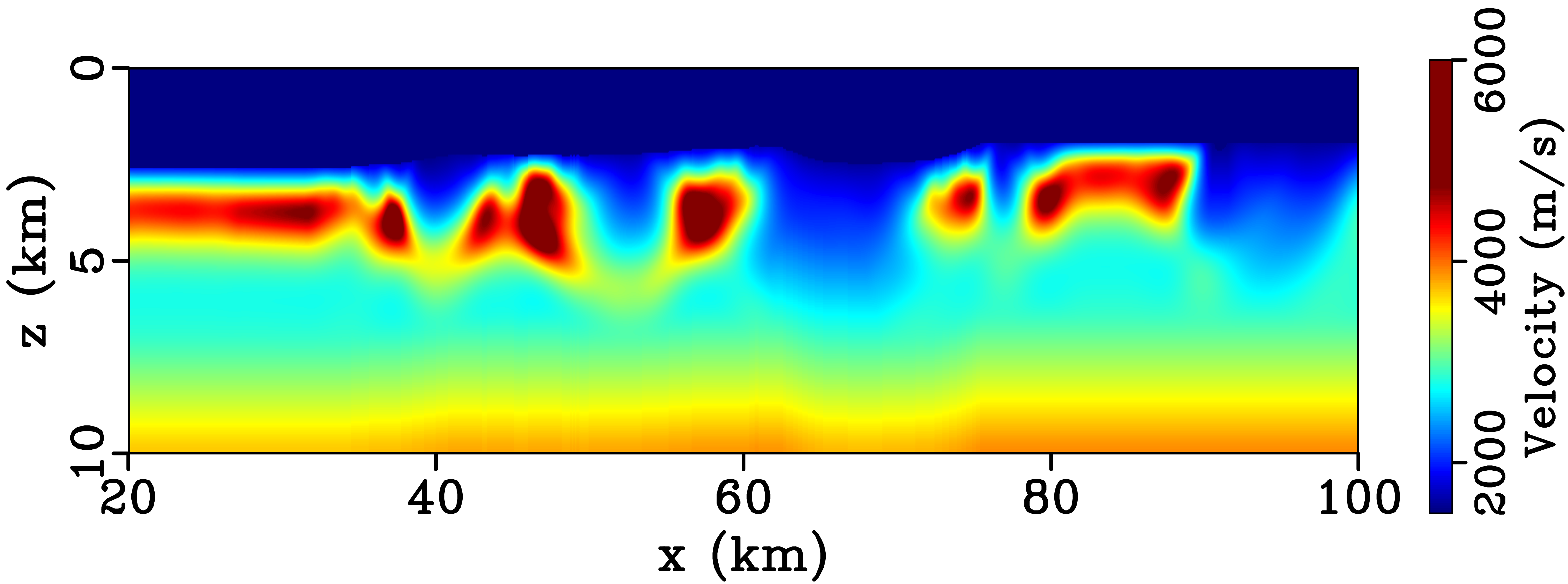
A. Aravkin, M.P. Friedlander, F.J. Herrmann and T. van Leeuwen - Robust inversion, dimensionality reduction and randomized sampling. Mathematical Programming, 2012.

Tristan van Leeuwen, “A parallel matrix-free framework for frequency-domain seismic modelling, imaging and inversion in Matlab”. 2012.

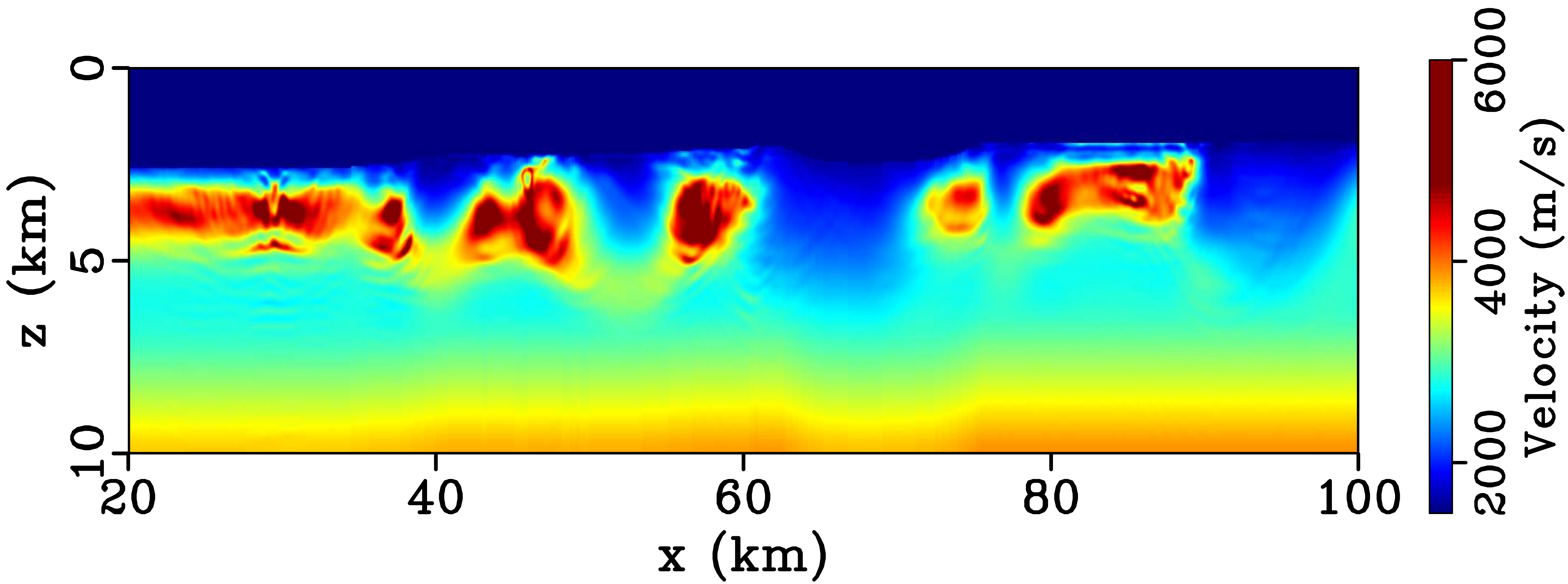
Tristan van Leeuwen and Felix J. Herrmann, “A parallel, object-oriented framework for frequency-domain wavefield imaging and inversion.”. 2012.



Input Model
[ray-based tomography + NMO]



Final result
[w/o denoising]

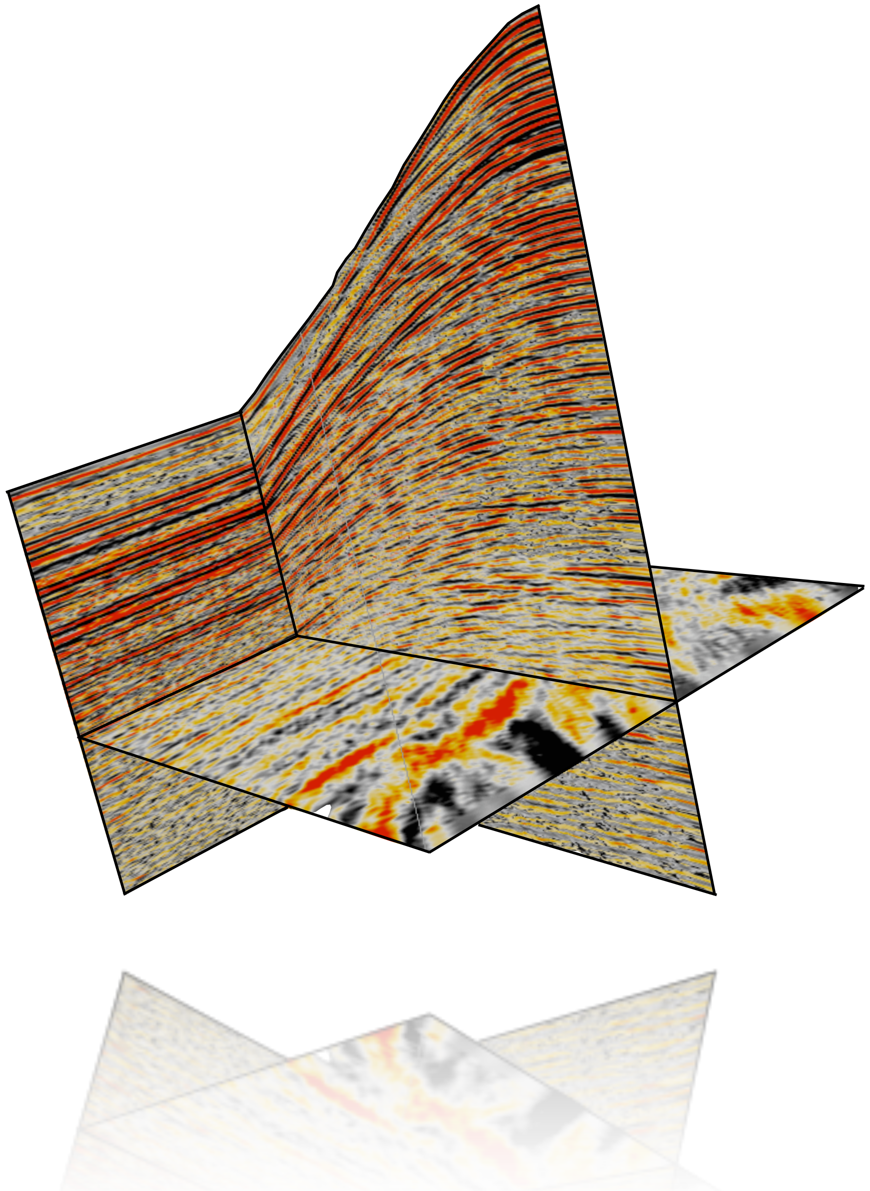


Modified Gauss-Newton

F. J. Herrmann, X. Li, A. Y. Aravkin, and T. van Leeuwen, “A modified, sparsity promoting, Gauss-Newton algorithm for seismic waveform inversion”, in Proc. SPIE, 2011, vol. 2011.

X. Li, F.J. Herrmann, A.Y. Aravkin and T. van Leeuwen - Fast randomized full waveform inversion with compressed sensing. Geophysics 77 (A13), 2012.

F.J. Herrmann, X. Li, A.Y. Aravkin, and T. van Leeuwen - A modified, sparsity-promoting, Gauss-Newton algorithm for seismic waveform inversion. Proc. SPIE 8138, 81380V (2011



Methodology

Modified Gauss-Newton:

- frequency continuation (7 bands 4 freqs, 2-5Hz)
- *rerandomized subsets* with *only* 600 shots
- 6 GN *iterations* per frequency *band*
- *preconditioning* of *Jacobian* by depth *weighting*
- *projection* of water *layer*

One-norm curvelet *regularized* gradients...

Algorithm

Result: Output estimate for the model $\mathbf{m}$

$k \longleftarrow 0$; $\mathbf{m}^k \longleftarrow \mathbf{m}_0$

while not converged **do**

$\{\underline{\mathbf{D}}^k, \underline{\mathbf{Q}}^k\} \longleftarrow \{\mathbf{D}\mathbf{W}^k, \mathbf{Q}\mathbf{W}^k\}$ with $\mathbf{W}^k \subset [\mathbf{e}_1, \cdots, \mathbf{e}_{n_s}]$

$\underline{\delta\mathbf{D}}^k \longleftarrow \underline{\mathbf{D}}^k - \boldsymbol{\mathcal{F}}[\mathbf{m}^k; \underline{\mathbf{Q}}^k]$ $\tau^k \longleftarrow \|\underline{\delta\mathbf{D}}^k\|_F \,/\, \|\mathbf{C}_2\nabla\boldsymbol{\mathcal{F}}^*[\mathbf{m}^k; \underline{\mathbf{Q}}^k]\underline{\delta\mathbf{D}}^k\|_\infty$

$\delta\mathbf{x} \leftarrow \arg\min_{||\mathbf{x}||_1 \leq \tau_k} \|\underline{\delta\mathbf{D}}^k - \nabla\boldsymbol{\mathcal{F}}[\mathbf{m}^k; \underline{\mathbf{Q}}^k]\mathbf{C}_2^H\mathbf{x}\|_F^2$

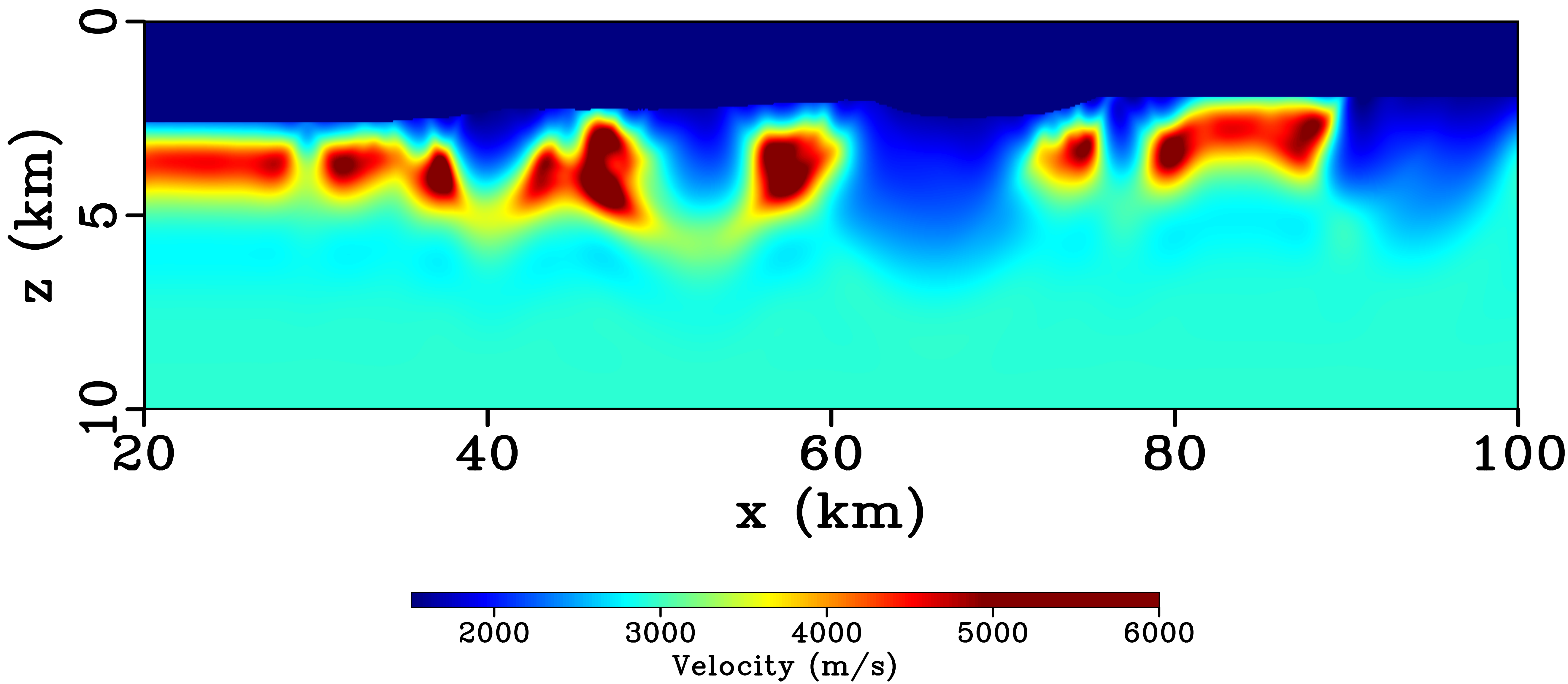
$\mathbf{m}^{k+1} \longleftarrow \mathbf{m}^k + \gamma^k \mathbf{C}_2^H \delta\mathbf{x}$

$k \longleftarrow k + 1$;

end

Algorithm 1: modified Gauss Newton with sparsity promotion

Initial model
[ray-based tomography]



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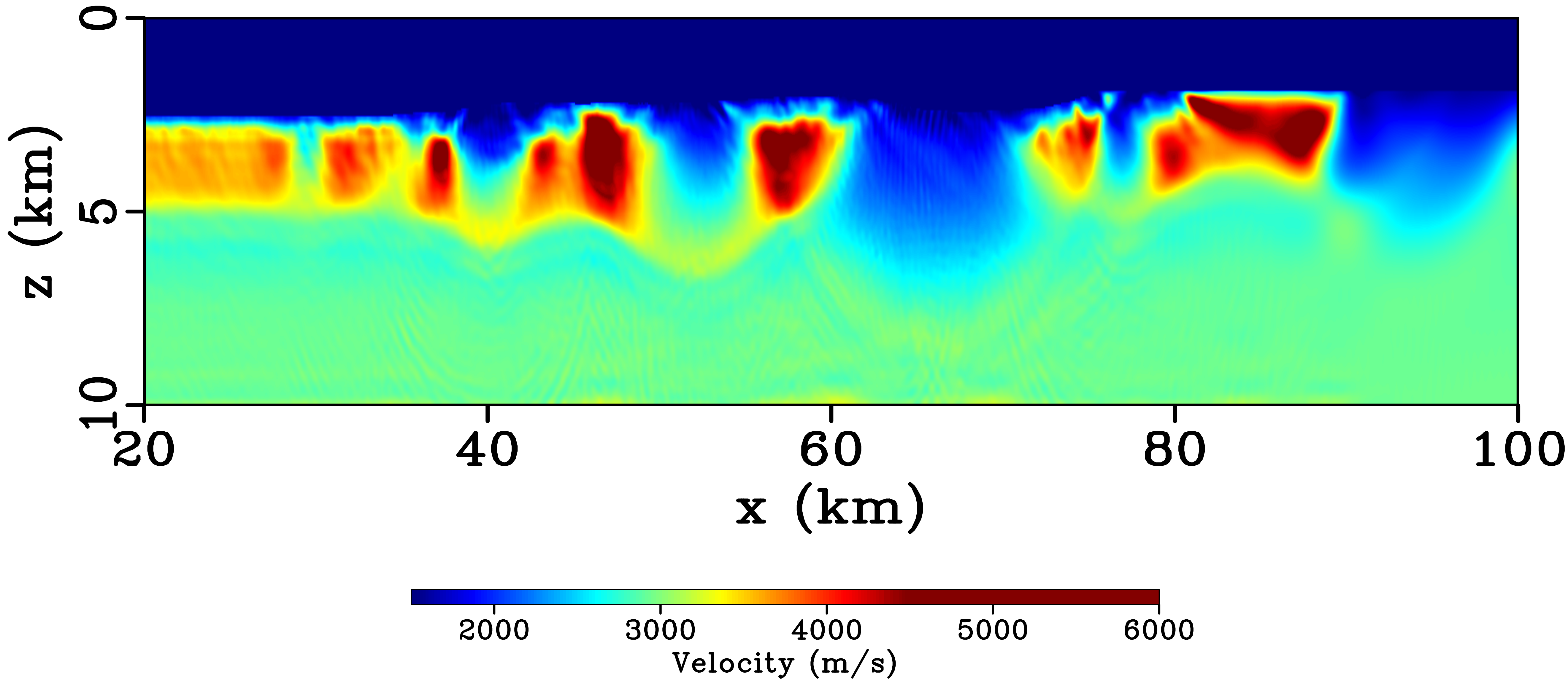
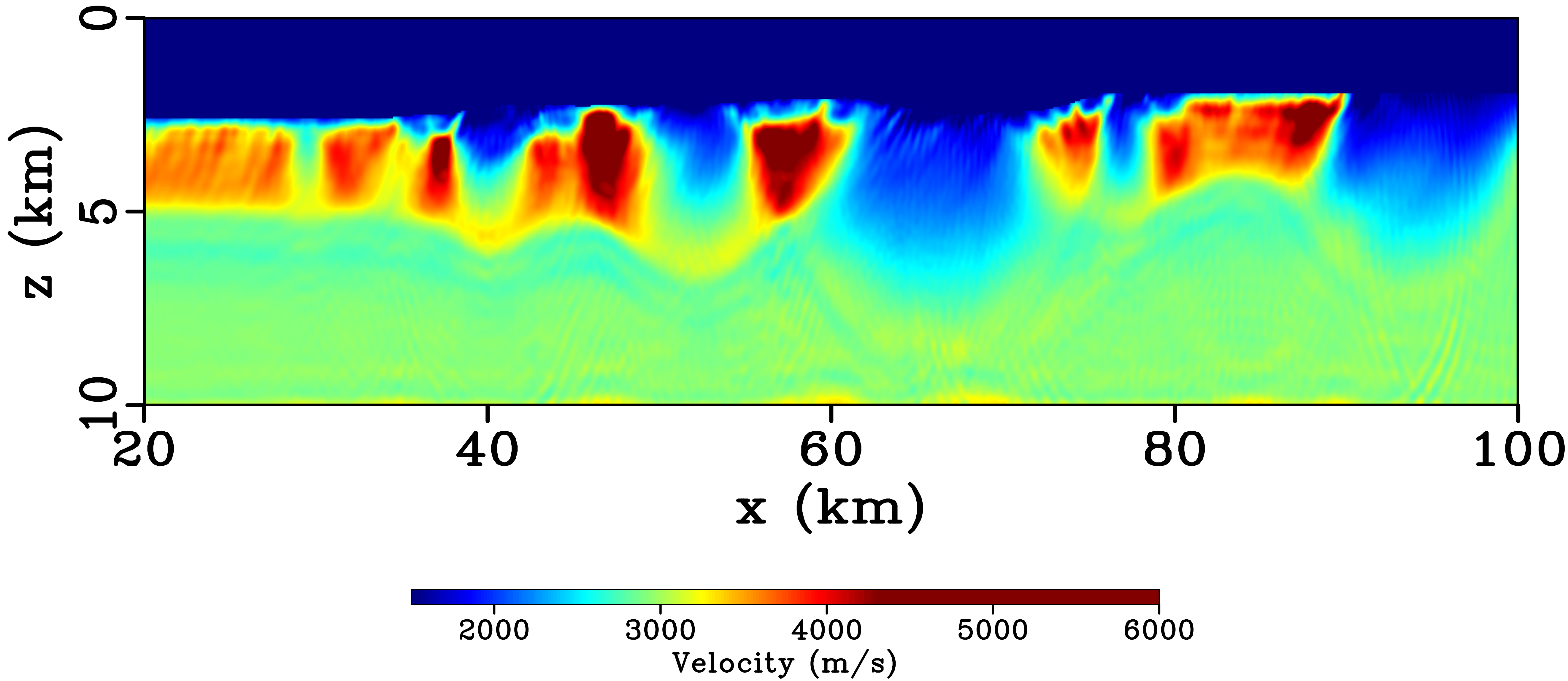
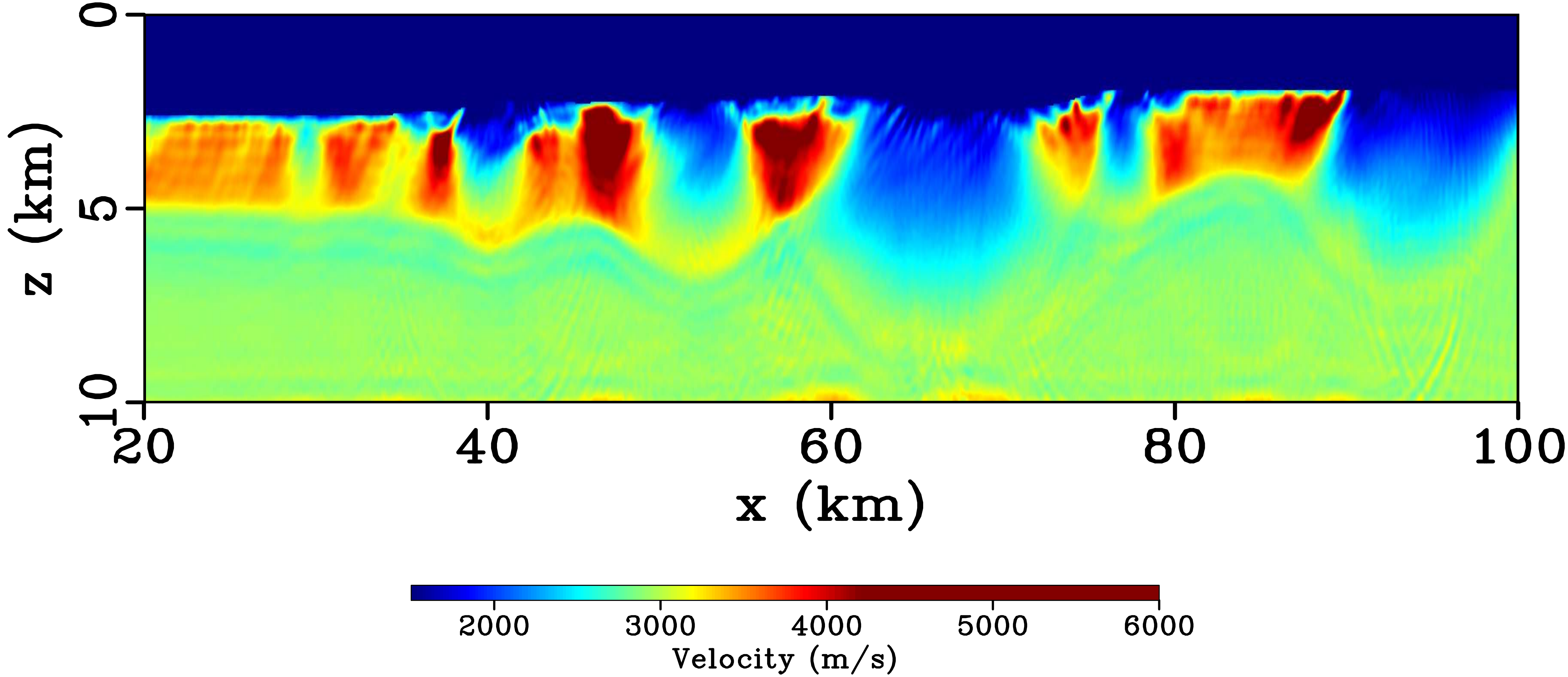
Final result submitted to workshop
[w/o denoising]



“Latest” final result
[w/o denoising]

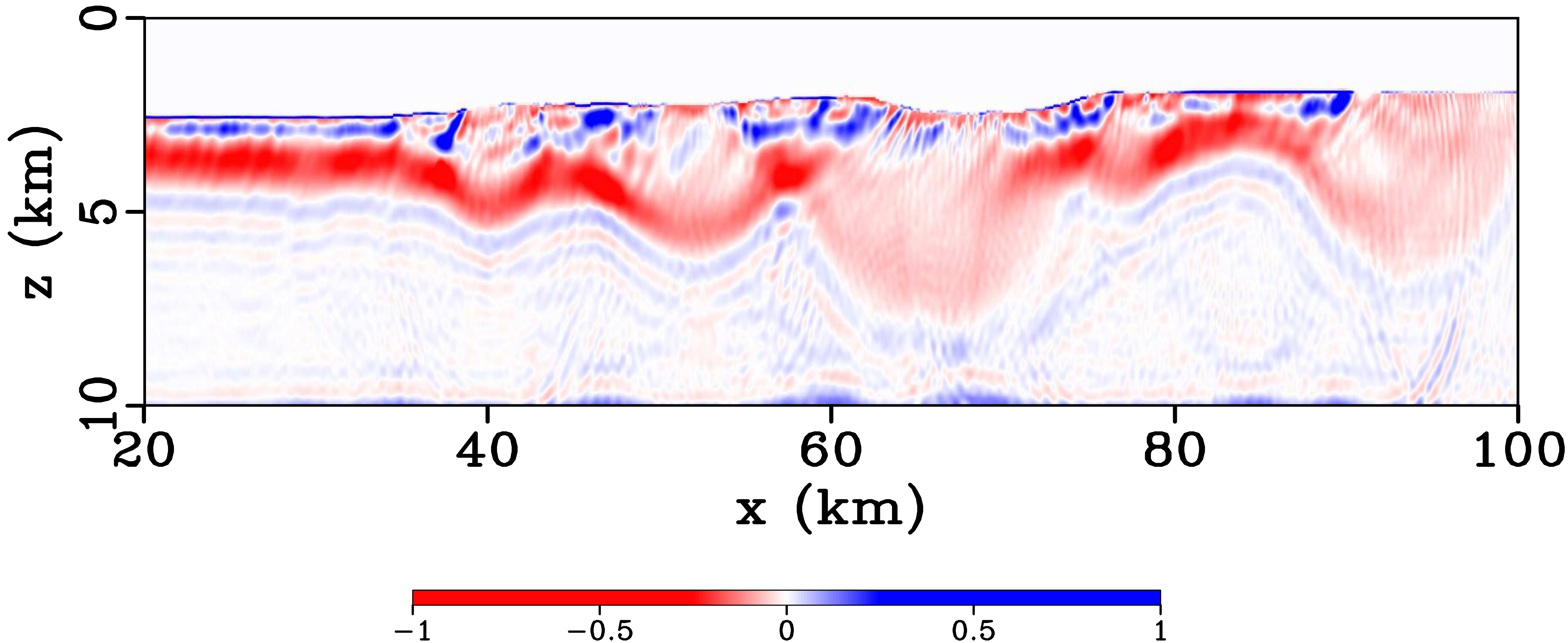


Final result
[w/ denoising]



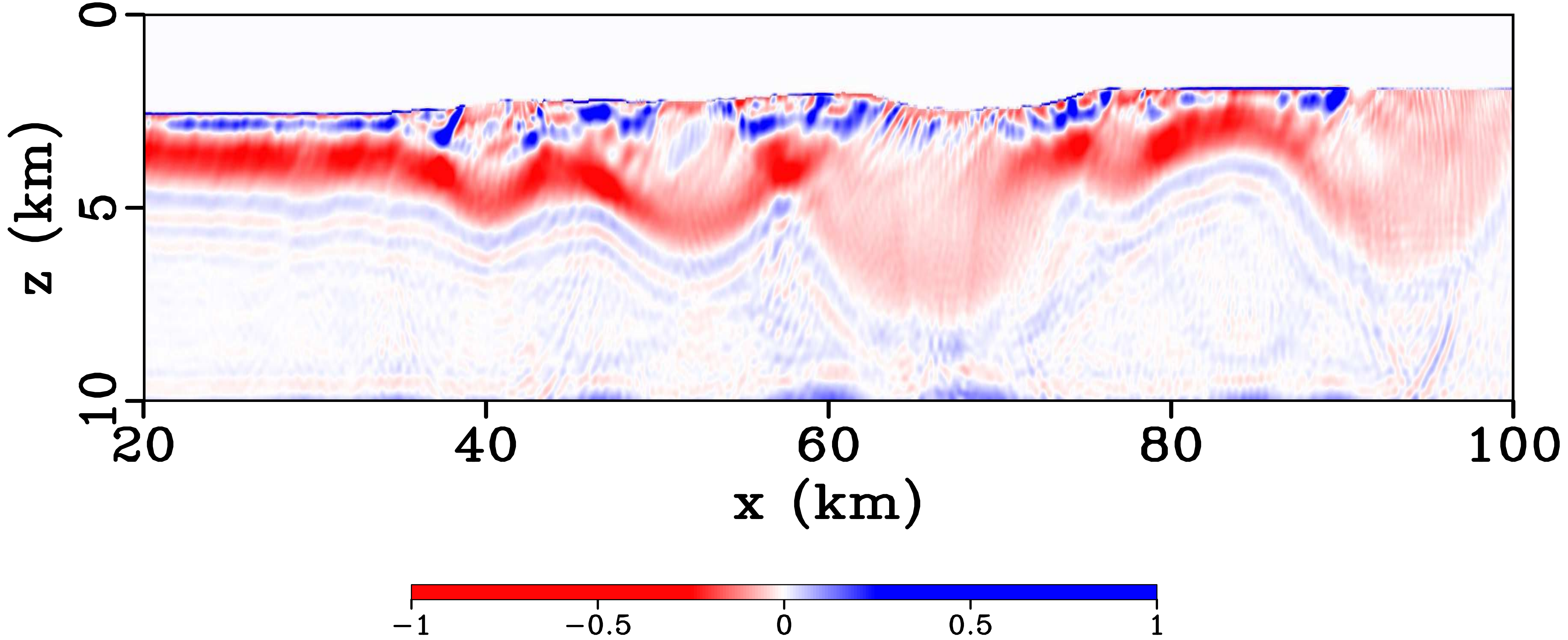
Relative update
[w/o denoising]

$$\Delta(V)/V$$

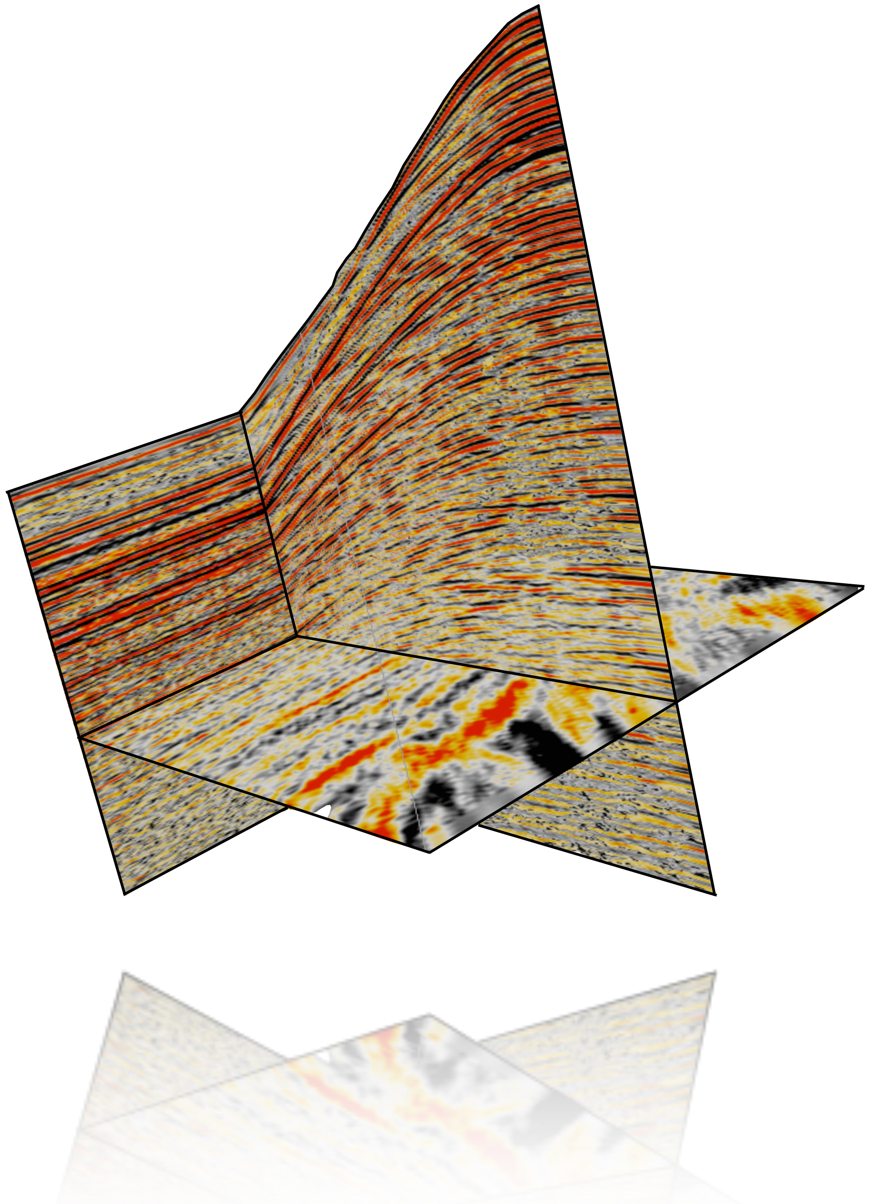


Relative update
[w/ denoising]

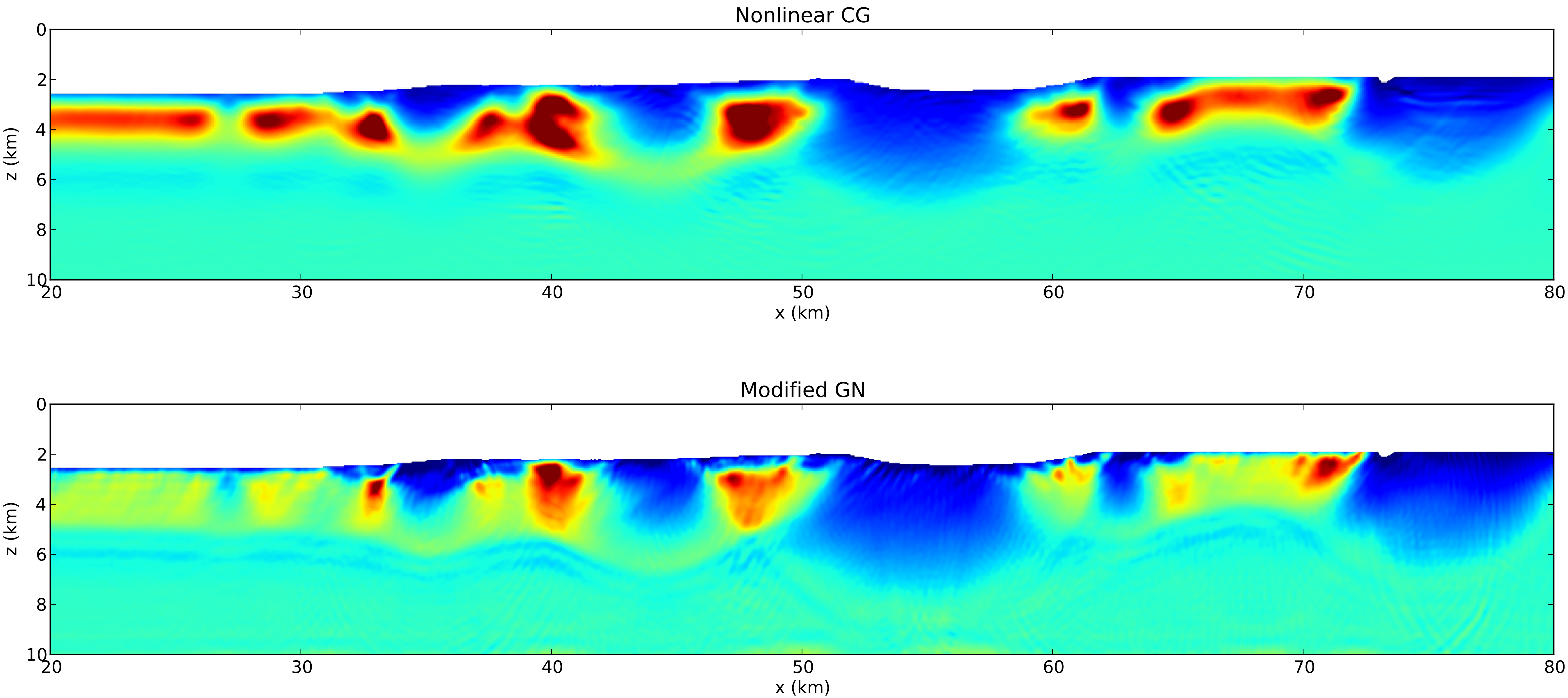
$\Delta(V)/V$



Lessons learned & road ahead



Comparison
[nonlinear CG versus modified GN]



Verdict

Modified Gauss-Newton is the winner:

- “clearly defined” topology @ top salt
- sharper edges @ the base of the salt
- little parameter settings and intervention (no layer stripping & offset continuation)

Good *starting* model for *elastic* inversion.

Why does this work?

Continuation method in

- frequency
- complexity (sparse to less sparse)

Sparse *nonlinear* approximations of updates

- contain "skeleton" of the singularities
- "concentrates on acoustic phases"

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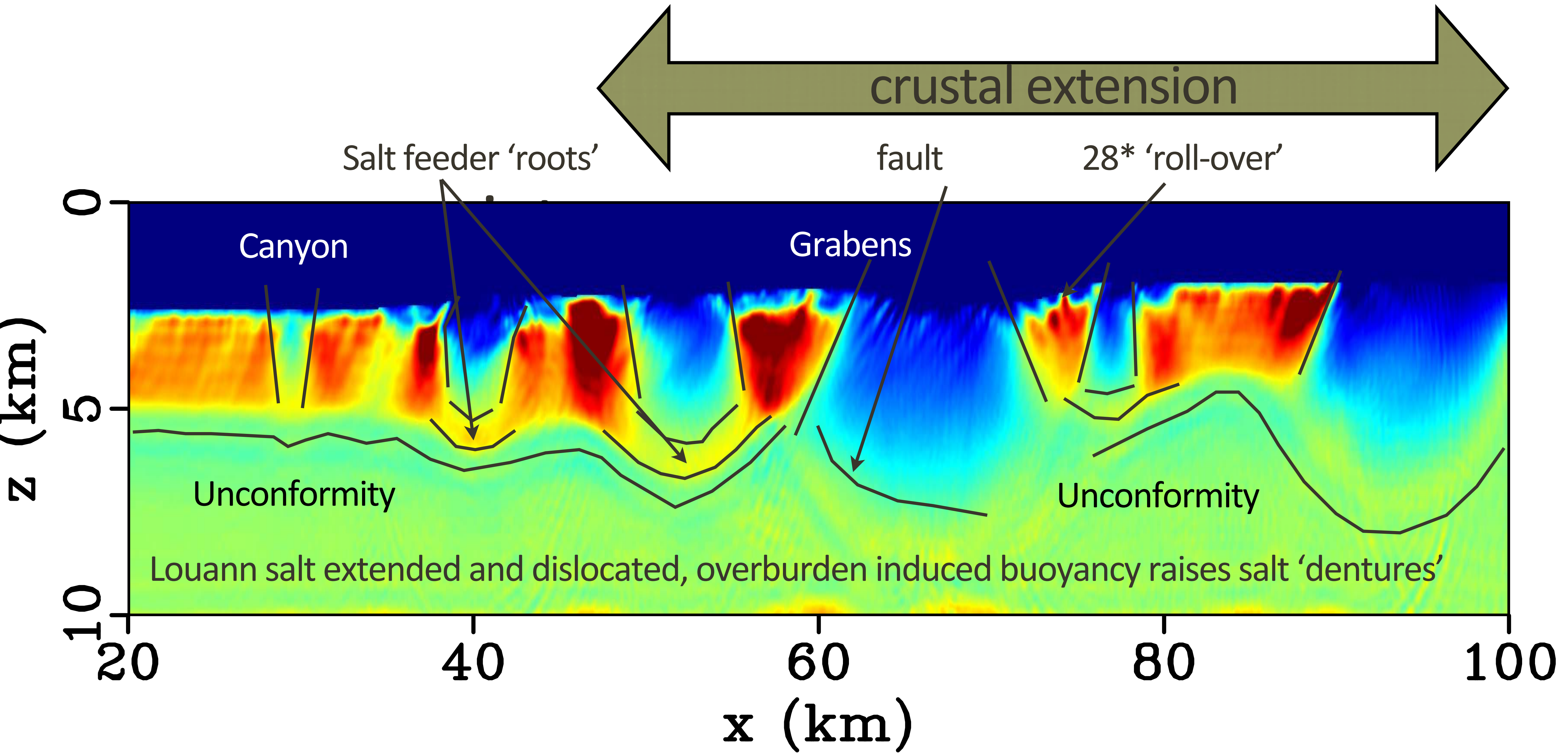
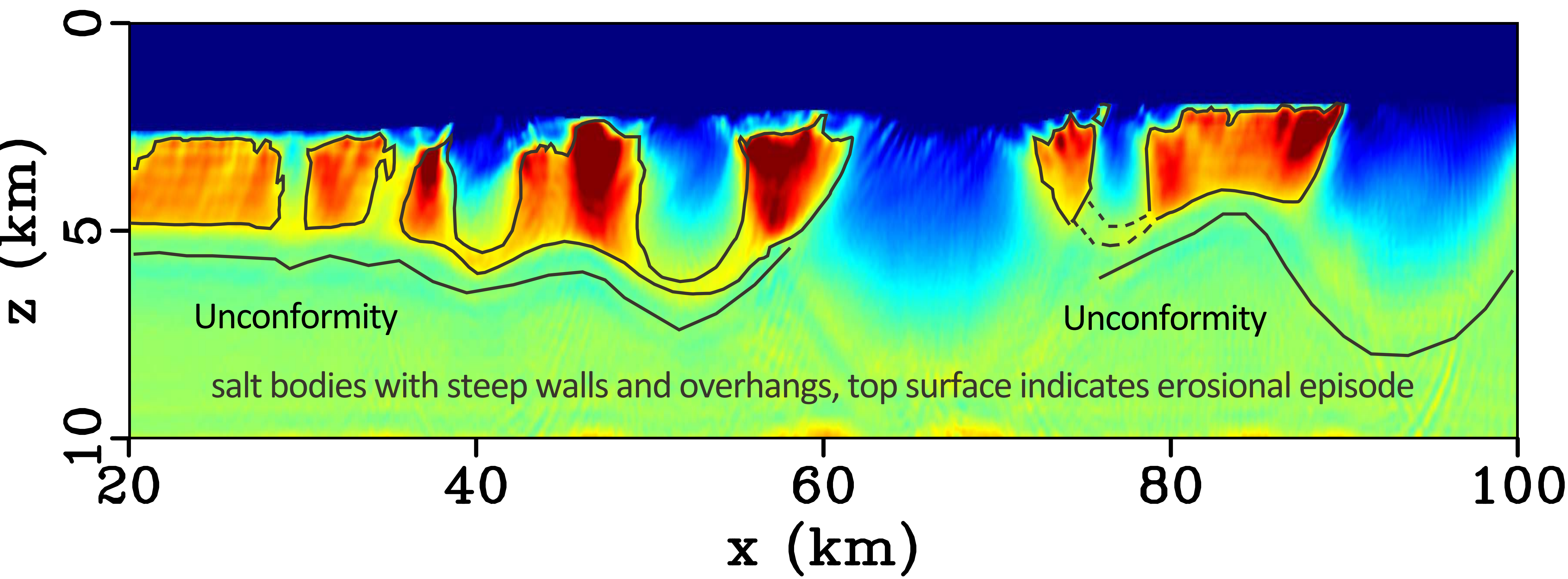
Interpretation

[Louann allochthonous salt]



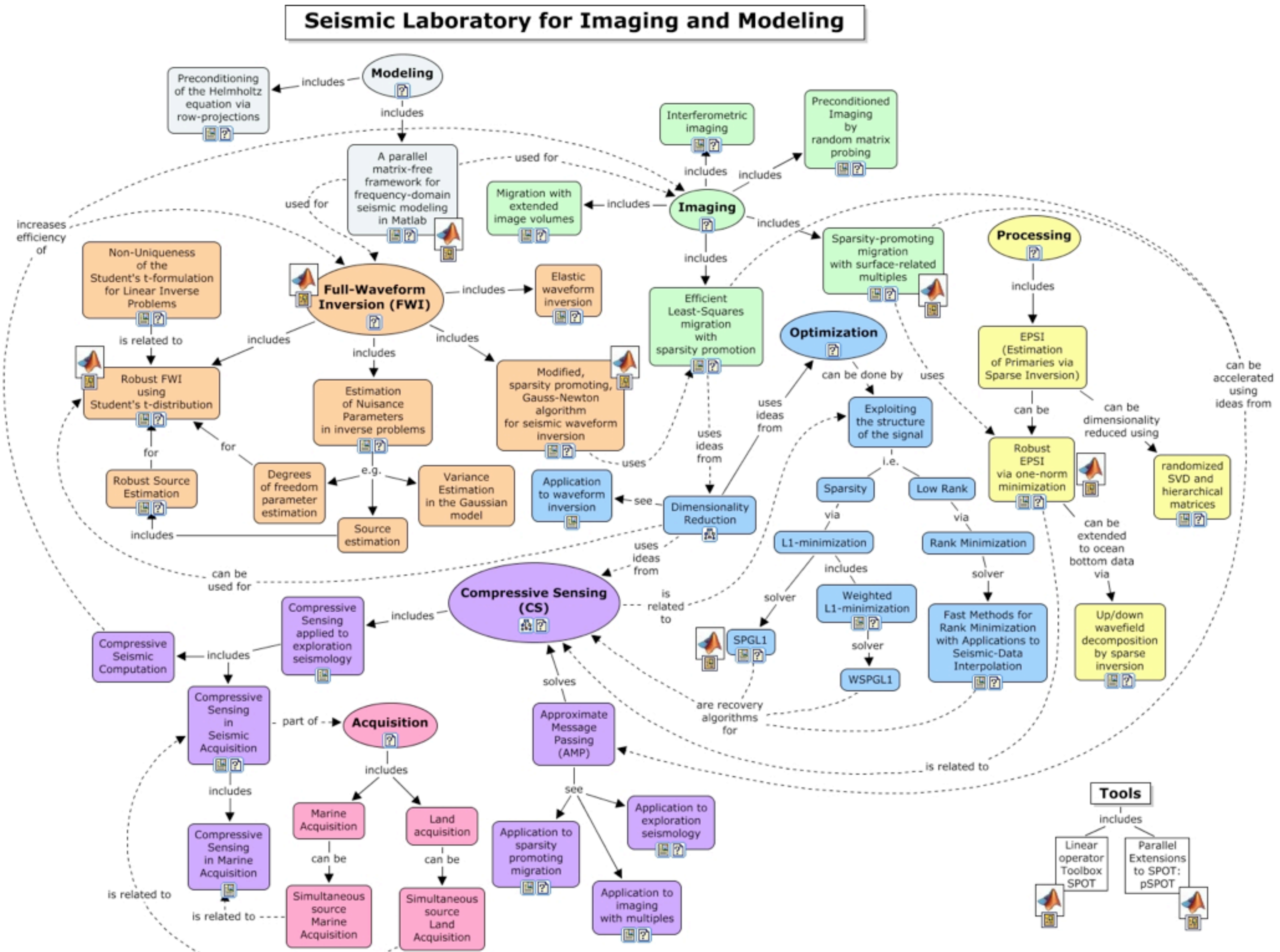
Interpretation

[top/bottom salt & unconformity]



Observations

	Nonlin. CG [phase]	Modified GN [amplitude]
Acoustic	mixed results	encouraging
Noise	?	important
Conditioning	involved	“simple”
Quality	smooth	sharp


Seismic Laboratory for Imaging and Modeling
Modeling
Preconditioning of the Helmholtz equation via row-projections
A parallel matrix-free framework for frequency-domain seismic modeling in Matlab
Full-Waveform Inversion (FWI)
Elastic waveform inversion
Non-Uniqueness of the Student's t-formulation for Linear Inverse Problems
Robust FWI using Student's t-distribution
Estimation of Nuisance Parameters in inverse problems
Modified, sparsity promoting, Gauss-Newton algorithm for seismic waveform inversion
Robust Source Estimation
Degrees of freedom parameter estimation
Variance Estimation in the Gaussian model
Source estimation
Imaging
Interferometric imaging
Preconditioned Imaging by random matrix probing
Migration with extended image volumes
Sparsity-promoting migration with surface-related multiples
Efficient Least-Squares migration with sparsity promotion
Processing
EPSI (Estimation of Primaries via Sparse Inversion)
Robust EPSI via one-norm minimization
randomized SVD and hierarchical matrices
Up/down wavefield decomposition by sparse inversion
Optimization
Exploiting the structure of the signal
Sparsity
Low Rank
L1-minimization
Rank Minimization
Weighted L1-minimization
SPGL1
WSPGL1
Fast Methods for Rank Minimization with Applications to Seismic-Data Interpolation
Application to waveform inversion
Dimensionality Reduction
Compressive Sensing (CS)
Compressive Sensing applied to exploration seismology
Compressive Seismic Computation
Compressive Sensing in Seismic Acquisition
Compressive Sensing in Marine Acquisition
Acquisition
Marine Acquisition
Land acquisition
Simultaneous source Marine Acquisition
Simultaneous source Land Acquisition
Approximate Message Passing (AMP)
Application to sparsity promoting migration
Application to exploration seismology
Application to imaging with multiples
Tools
Linear operator Toolbox SPOT
Parallel Extensions to SPOT: pSPOT
includes
used for
increases efficiency of
is related to
for
e.g.
uses
uses ideas from
see
can be done by
i.e.
via
solver
can be
can be dimensionality reduced using
can be accelerated using ideas from
can be extended to ocean bottom data via
can be used for
is related to
are recovery algorithms for
solves
part of
can be

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Acknowledgments

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Thank you

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