Imaging of complex structures by 3-D reflection seismic data

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IPRPI Workshop on Geophysical Imaging

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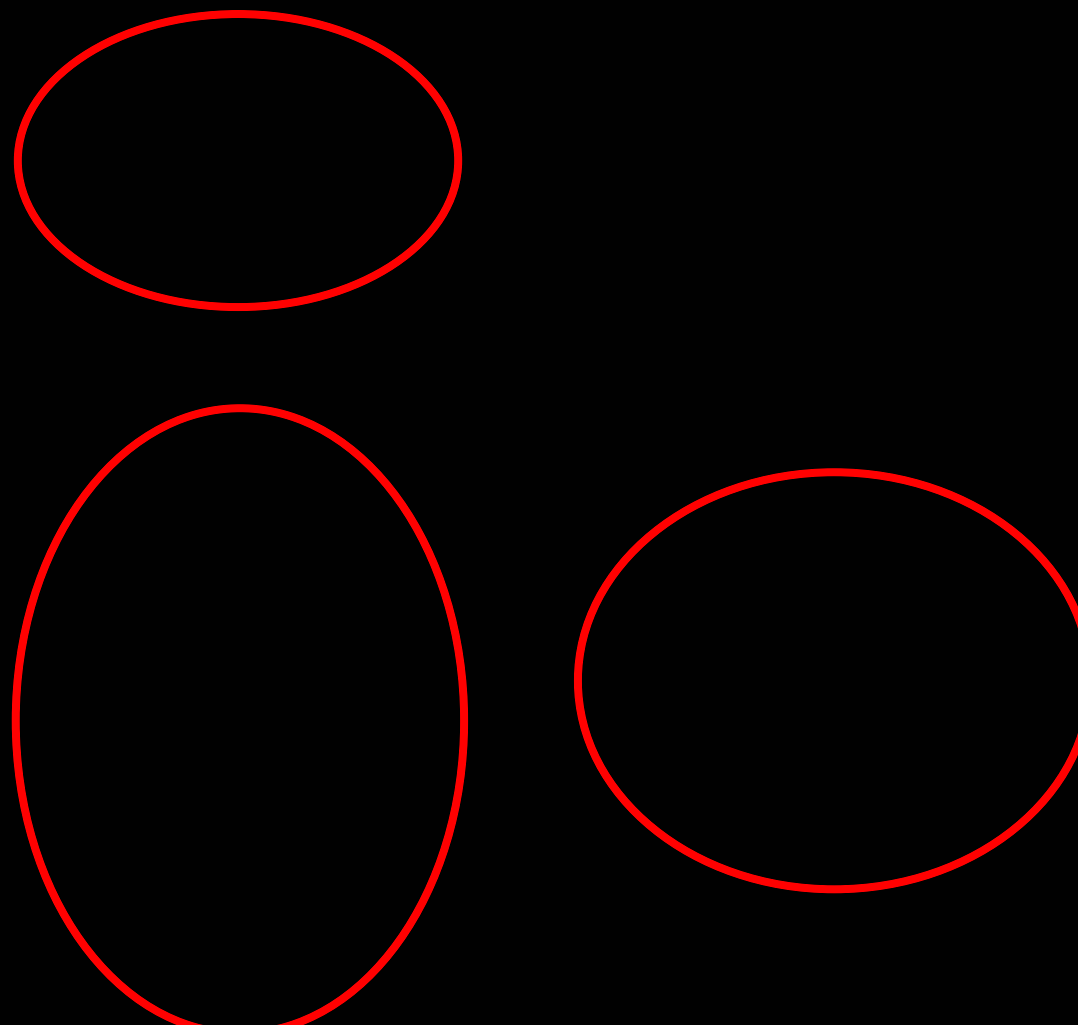
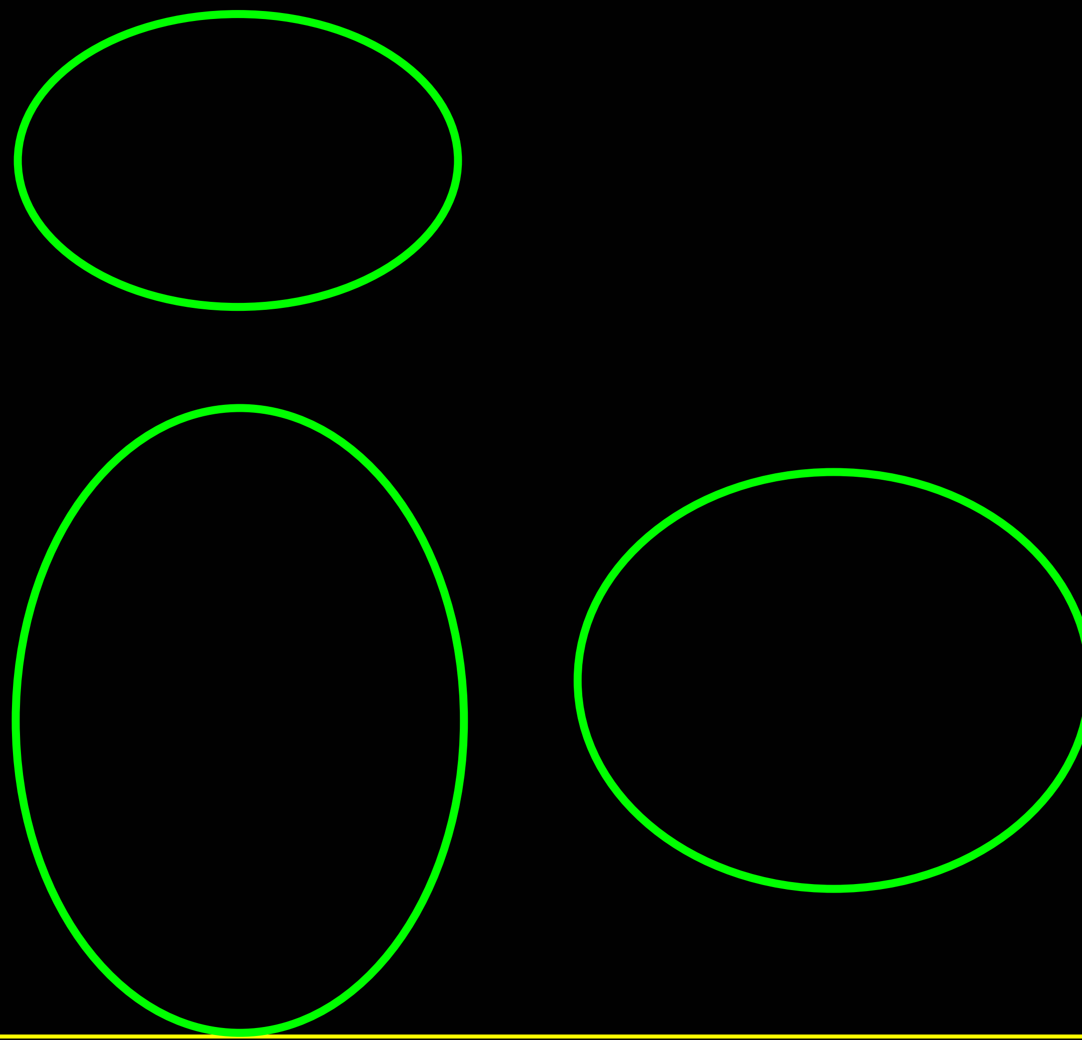
An example of imaging complex structures…

Deep Water GOM - Kirchhoff Mig.



Deep Water GOM – Wavefield-continuation Mig.



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Outline

- **Migration and complex wave propagation**
  - Wavefield continuation migration
  - Gaussian Beams and Coherent States migration
- **Migration => Iterative Regularized Inversion**
  - Normalized Migration
  - Iterative Wavefield Inversion with geophysical and geological constraints
- **Migration Velocity Analysis (MVA)**
  - Angle Domain Common Image Gathers (ADCIGs)
  - Ray tomography using ADCIGs
  - Wave-equation Migration Velocity Analysis

- **Routine**
- **Advanced**
- **Future?**

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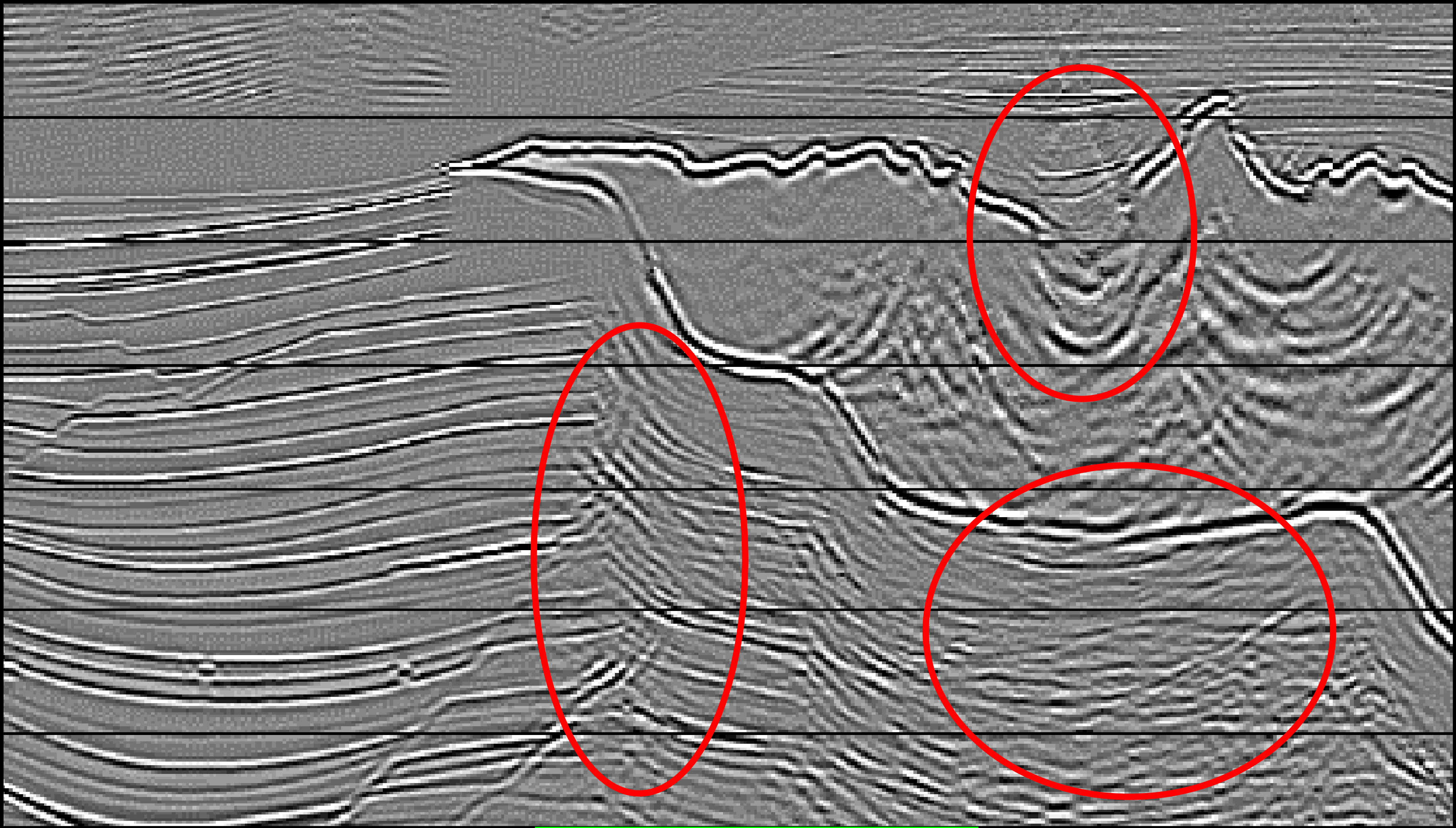
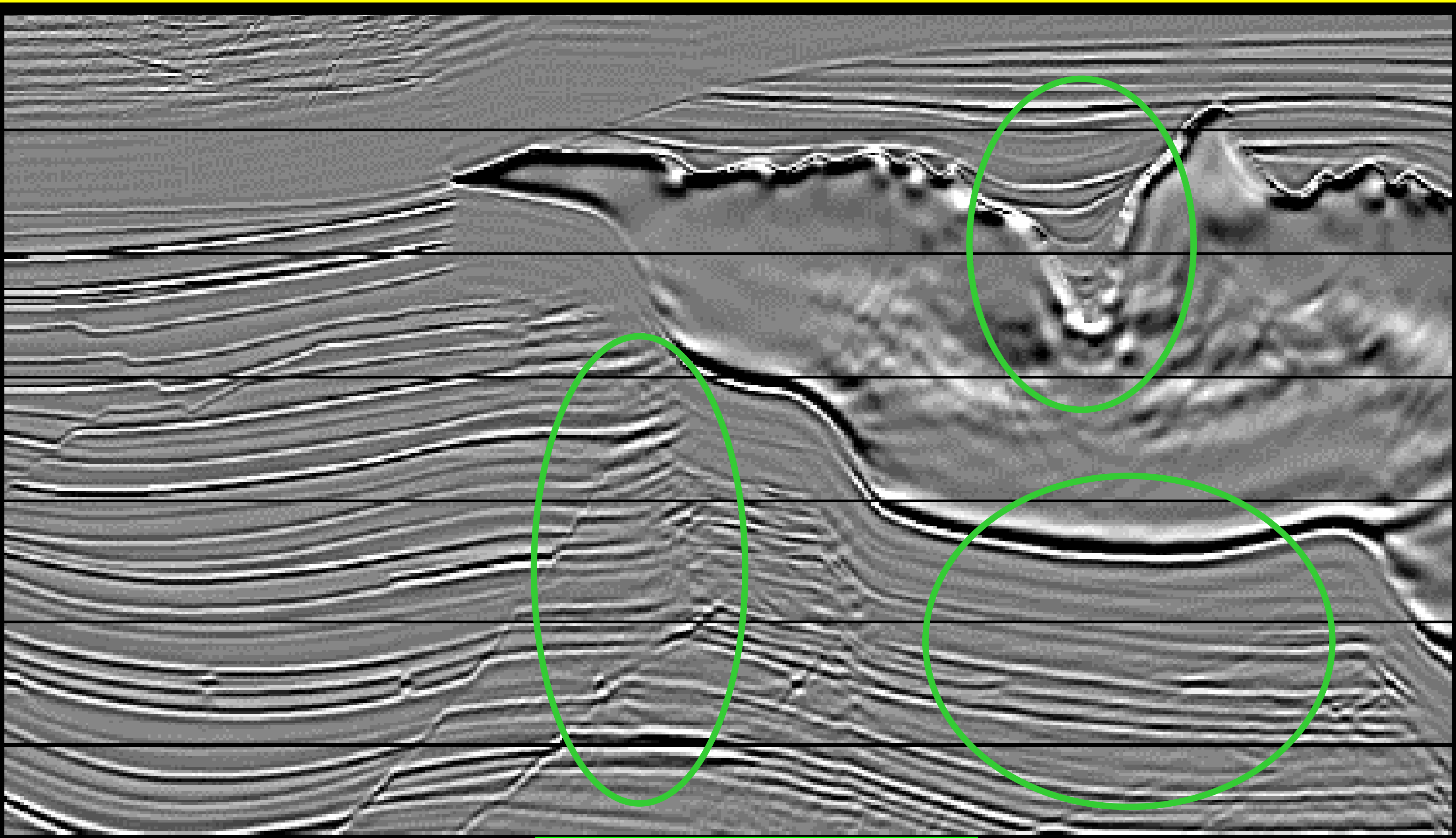
Sigsbee data - Kirchhoff



J. Paffenholz - SEG 2001

Sigsbee data - Wavefield continuation



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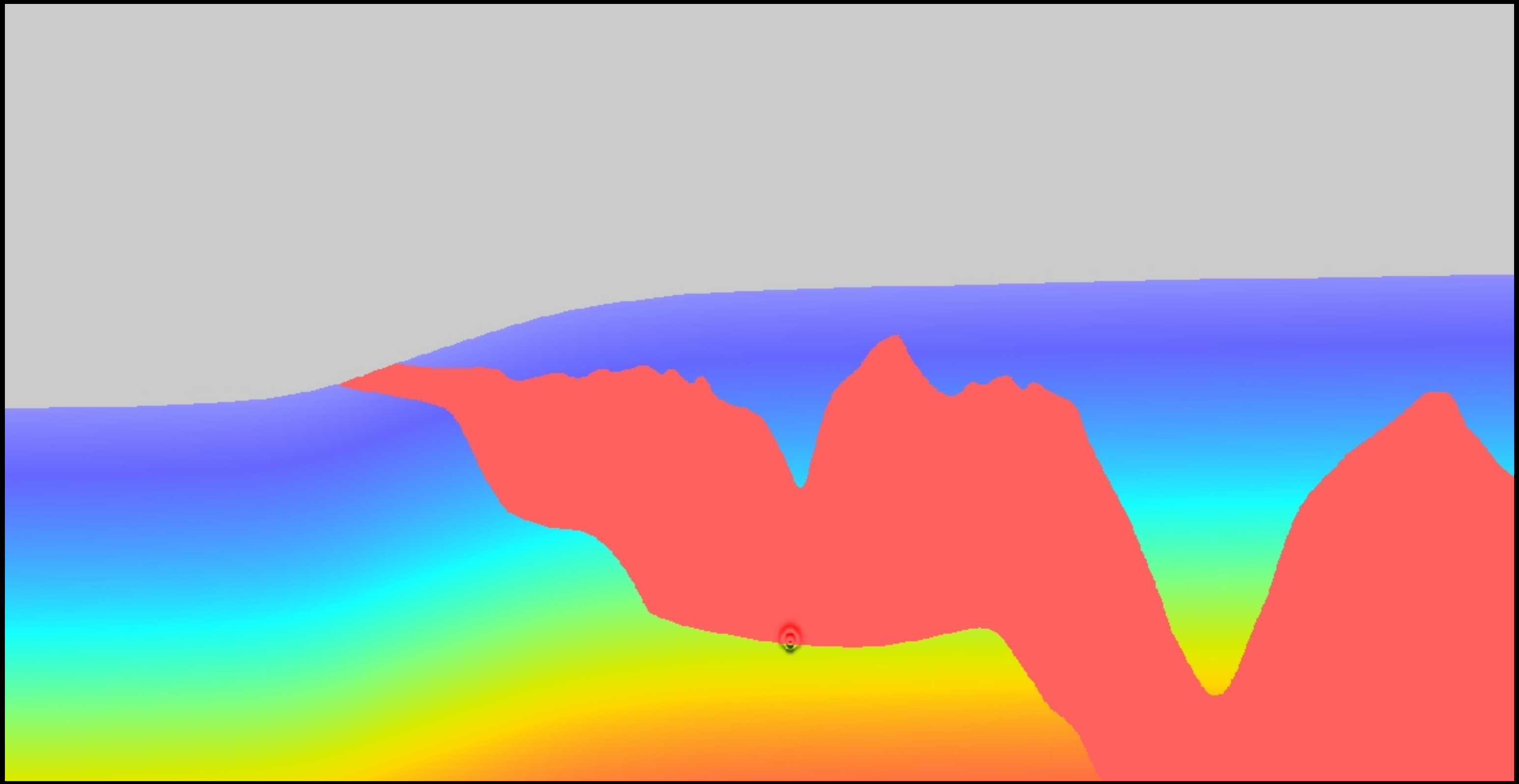
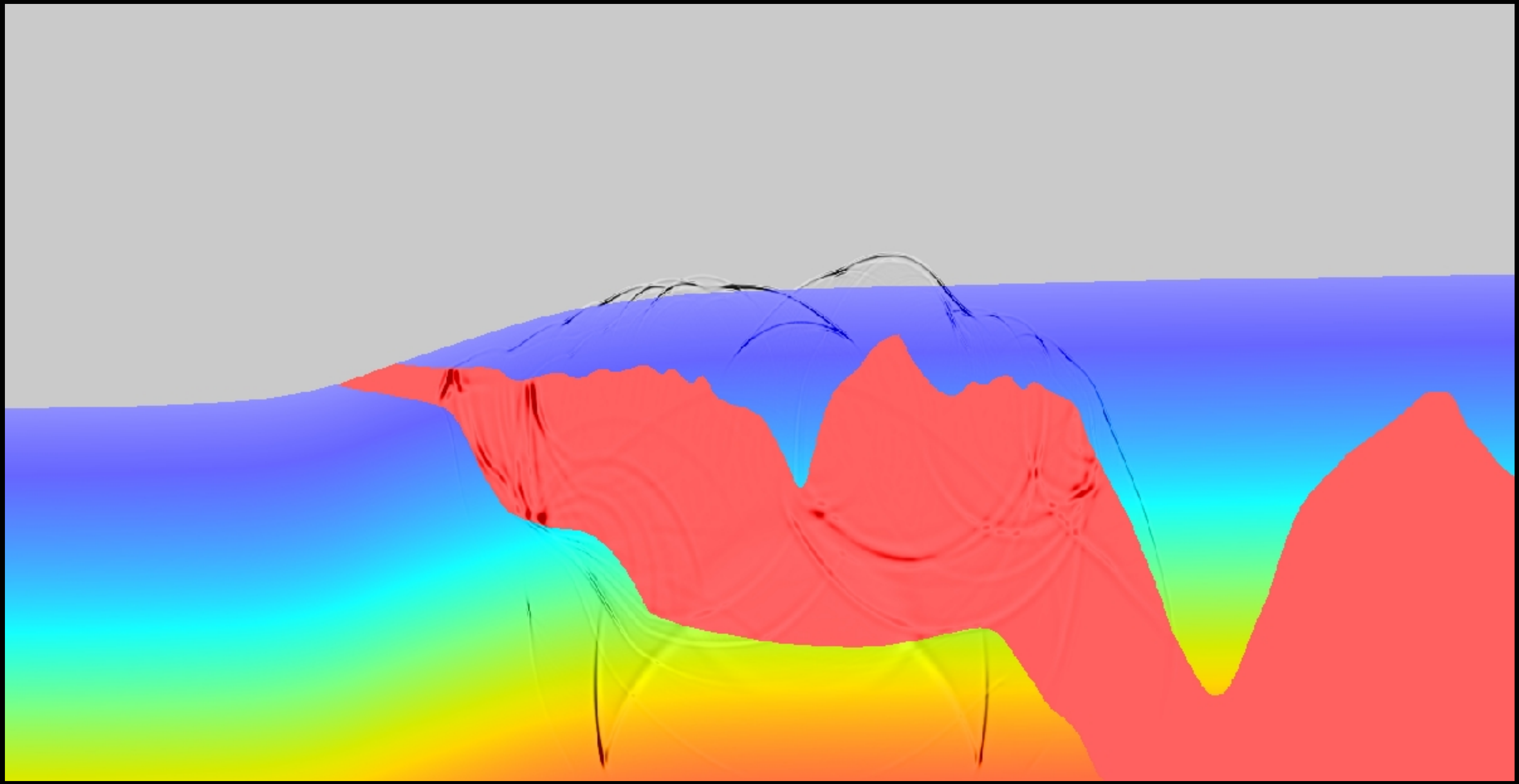
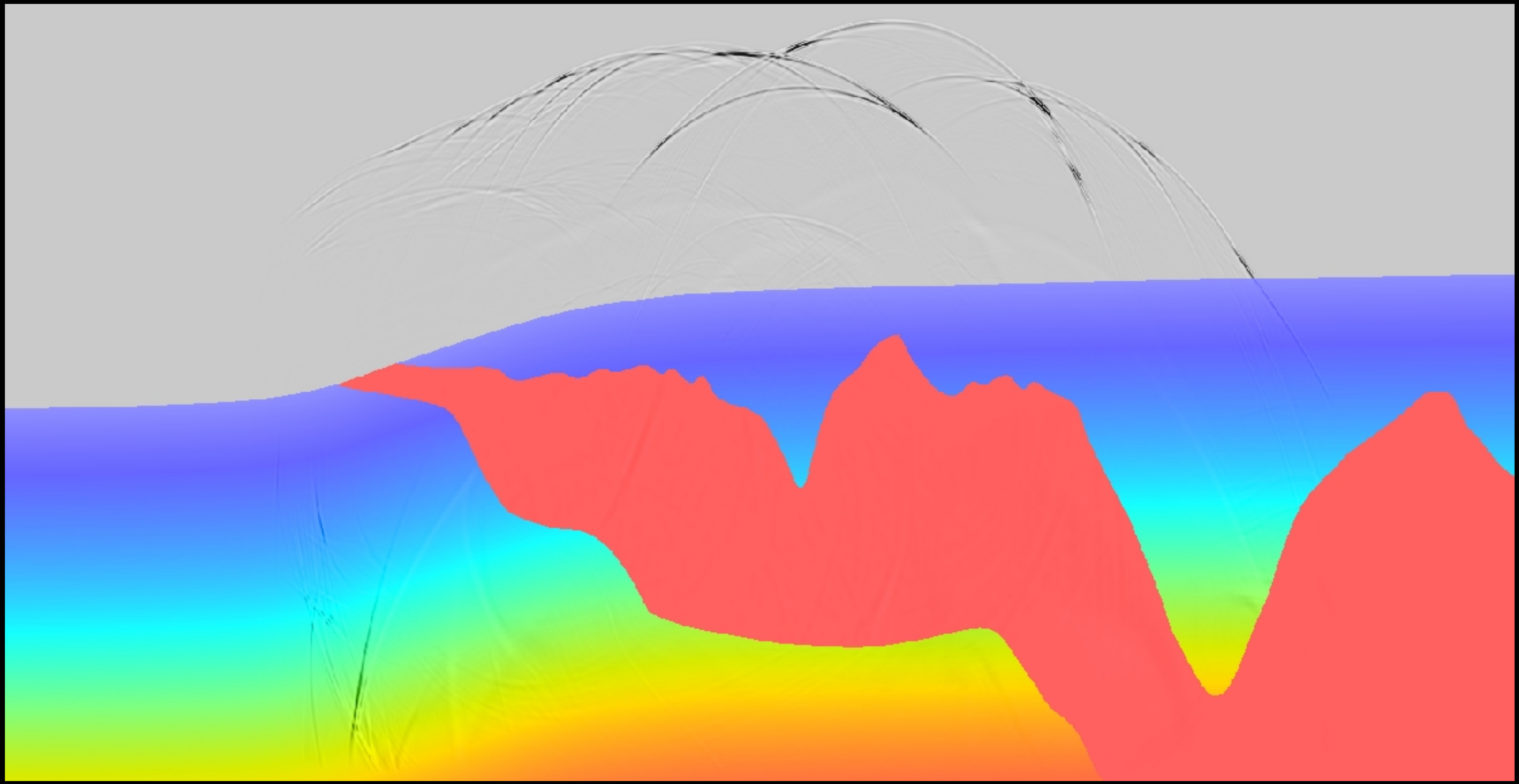
Sigsbee data - Wave modeling



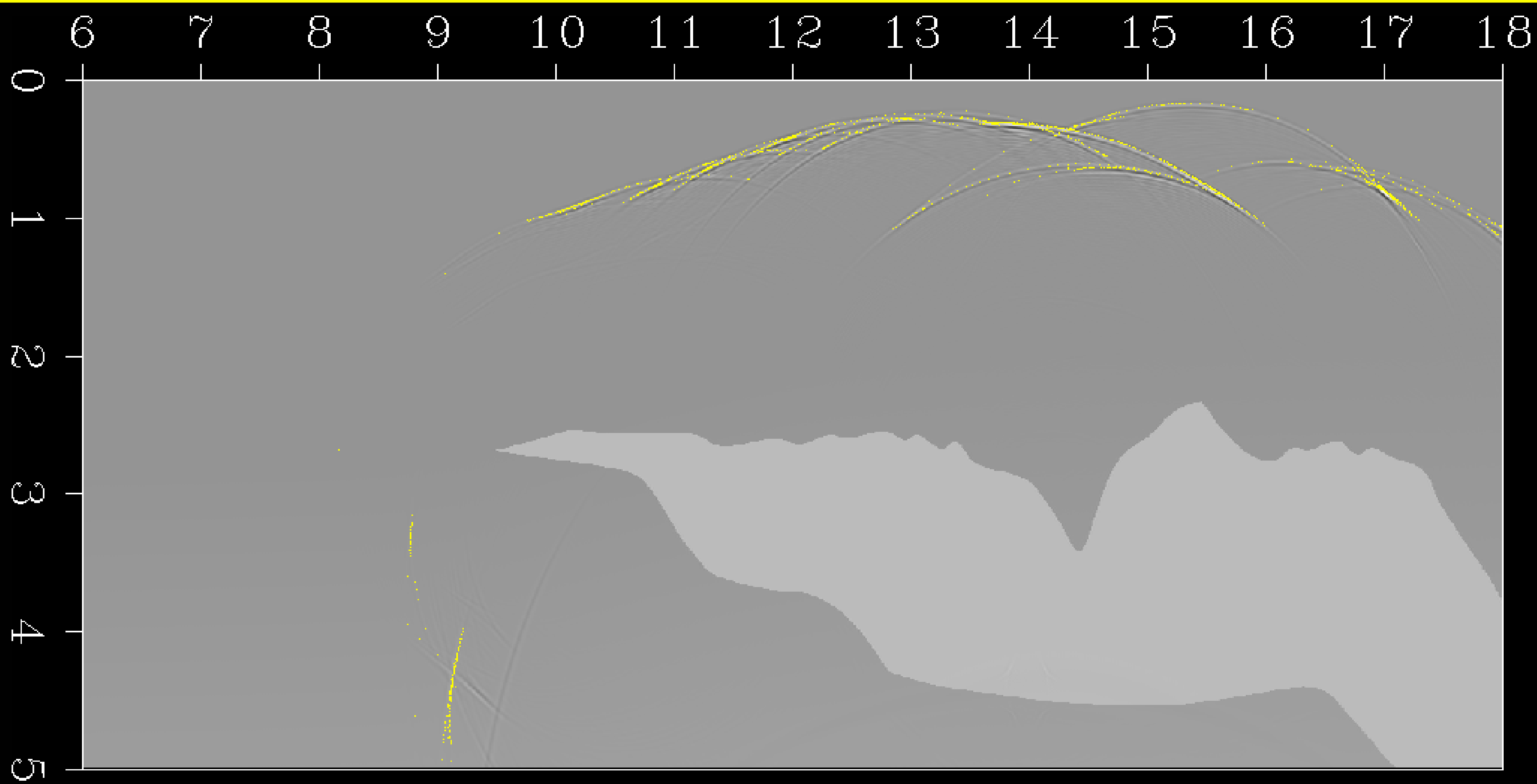
Sigsbee data - Wave modeling



Sigsbee data - Wave modeling



Sigsbee data - Wave modeling



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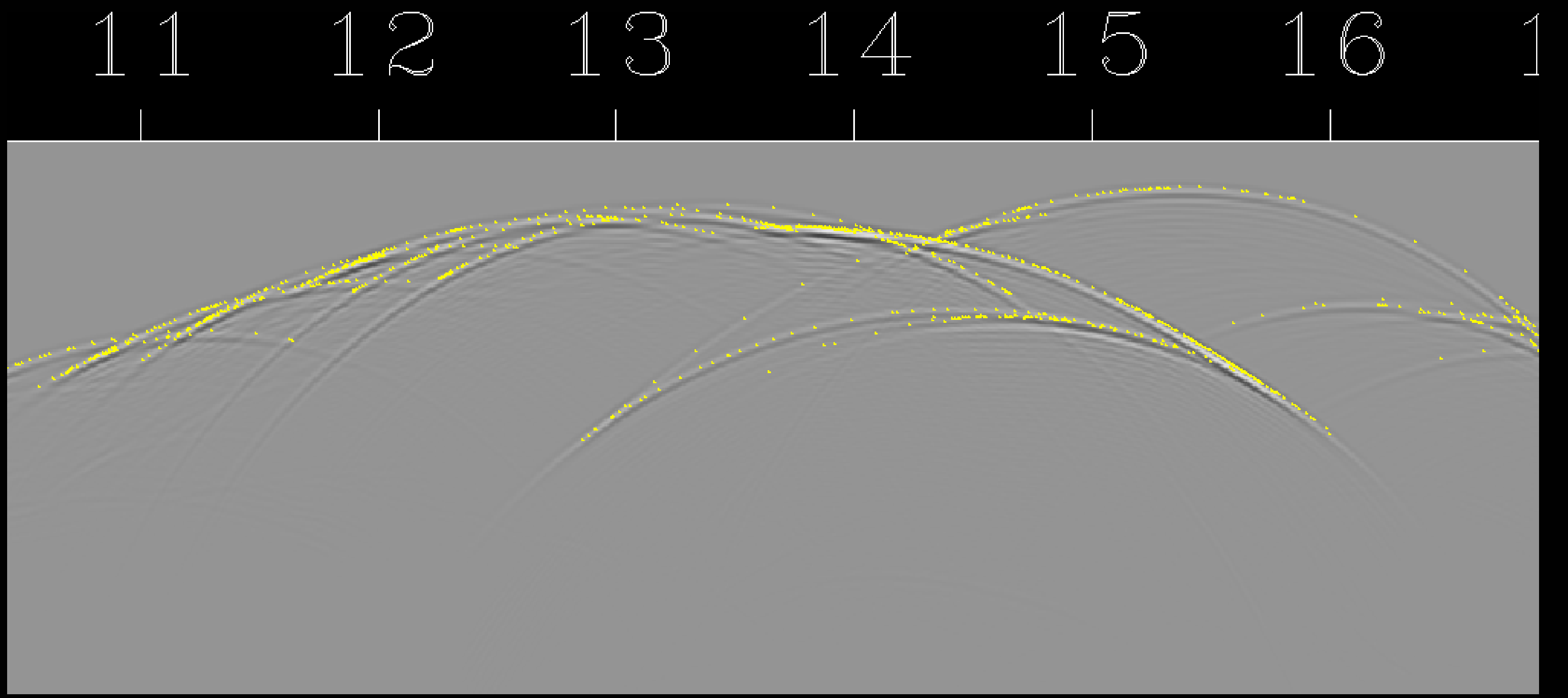
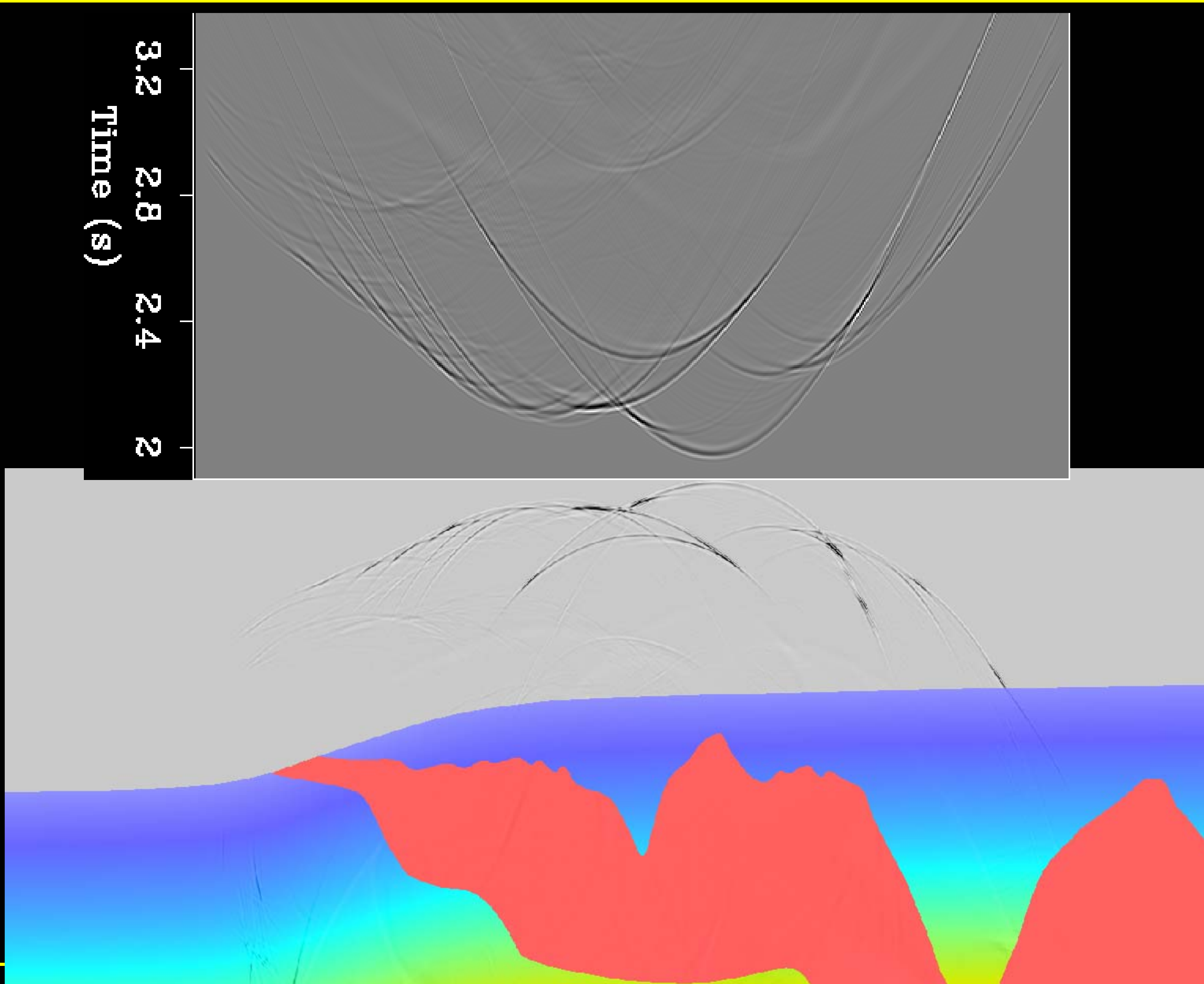
Sigsbee data - Wave modeling



Sigsbee data - Wave modeling



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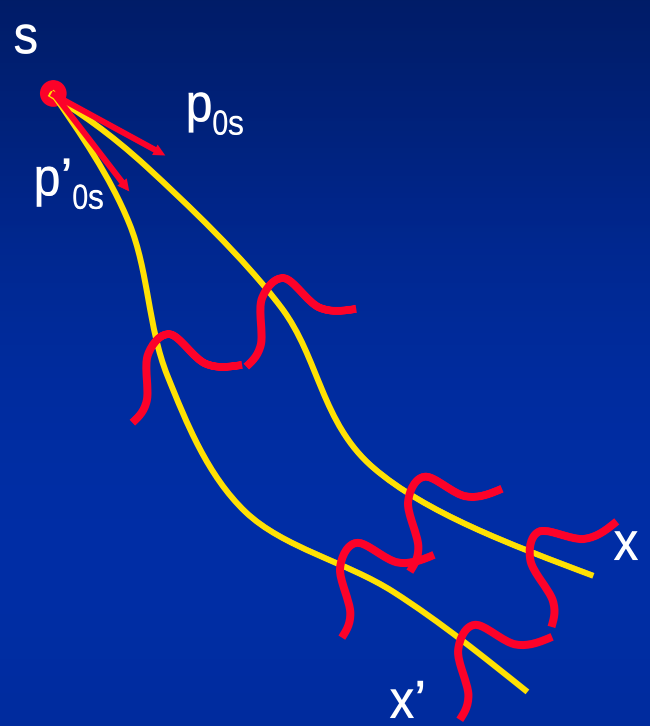
Superposition of Beams



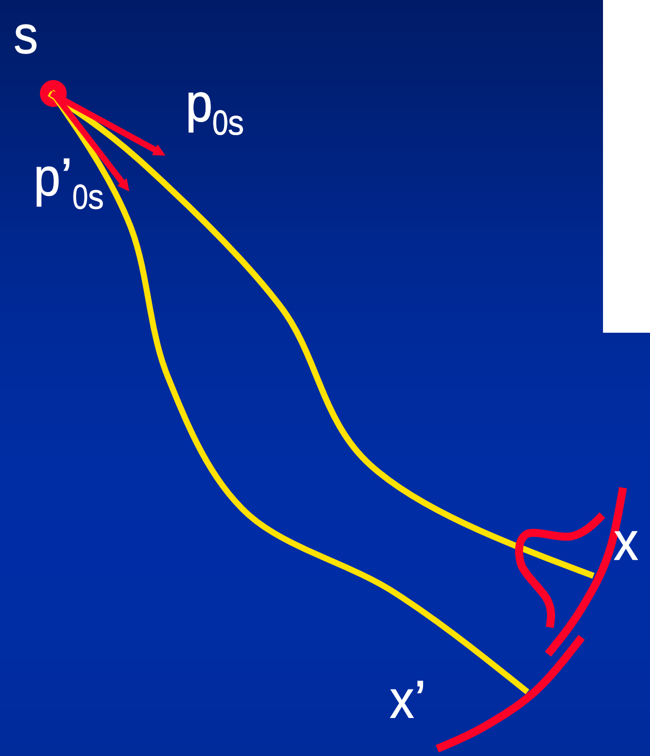
Solve wave equation by localizing initial wavefield in space and ray parameter (wavenumber)

Extrapolate and superimpose these solutions to form wavefield

If local solution is accurate and superposition is correct, accurate wavefield should result, including all arrivals, amplitudes, and phases

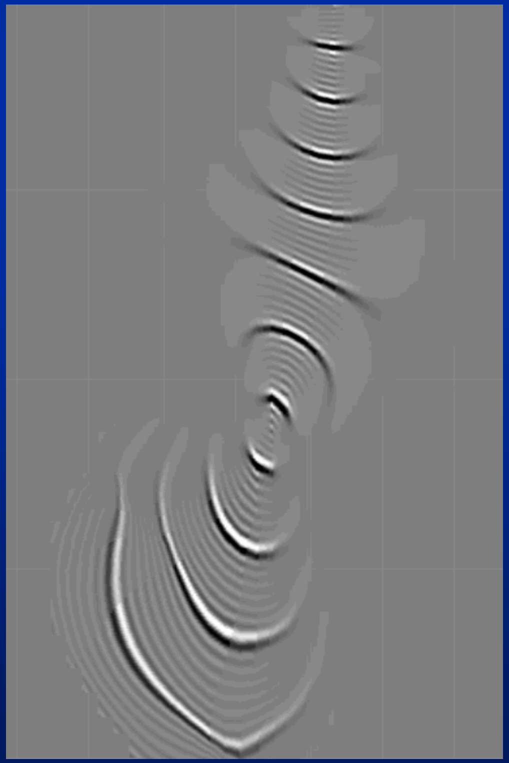
Uwe Albertin, WesternGeco

Gaussian Beam (Ray based)



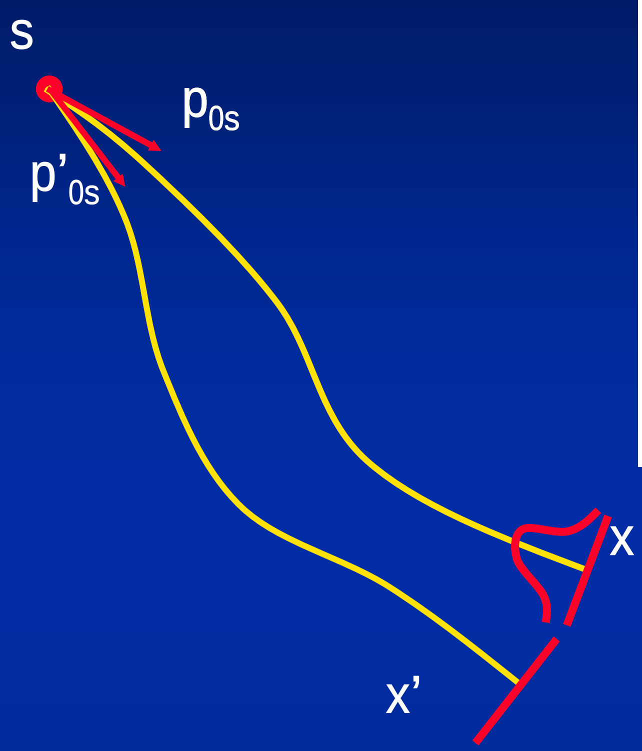
$$G(s,\mathbf{x}) \sim \int dp_{0s}\, u(s, p_{0s}, \sigma_s, n_s)$$

$$u = \left(\frac{v(\sigma_s)}{q(\sigma_s)}\right)^{1/2} \exp\left[i\omega\left(\tau(s,\sigma_s) + \frac{1}{2}\frac{p(\sigma_s)}{q(\sigma_s)} n_s^2\right)\right].$$



Cerveny, Popov, Psencik 1982
Hill, 1990, 2001
Kinneging et al 1989
White et al 1987
Hale 1992

Asymptotic Coherent State (Ray based)

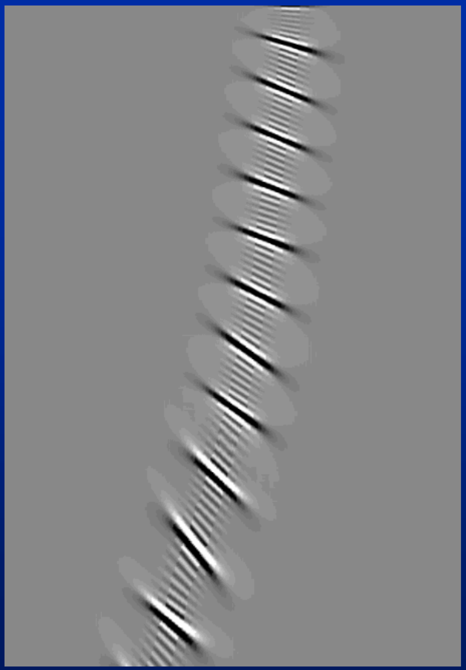


$$G(s,\mathbf{x}) \sim \int dp_{0s}\; u(s,p_{0s})$$

$$u(s,p_{0s}) \sim \left[\left|\frac{d\mathbf{p}}{dp_{0s}}\right|^2 \mu^2 + \Omega^2 \left|\frac{d\mathbf{x}}{dp_{0s}}\right|^2\right]^{1/4}$$

$$\exp\left[i\omega\left[\tau(s,\mathbf{x}(p_{0s})) - \mathbf{p}(p_{0s})\cdot(\mathbf{x}(p_{0s})-\mathbf{x})\right] - \frac{1}{2}\omega\Omega(\mathbf{x}(p_{0s})-\mathbf{x})^2\right]$$

Foster and Huang, 1991
Thompson, 2000
Albertin et al 2001



WesternGeco

Jun 17, 2001

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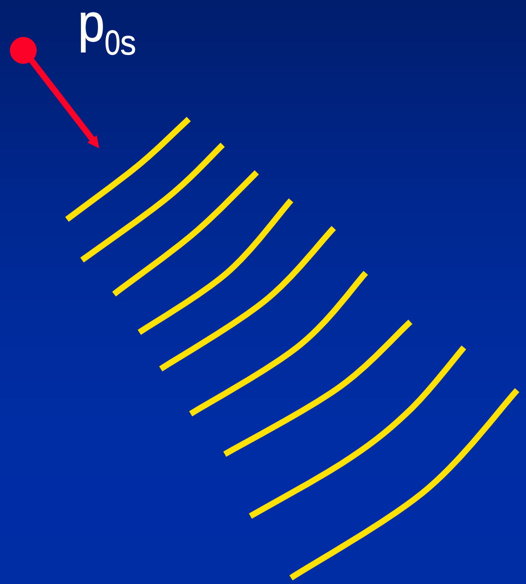
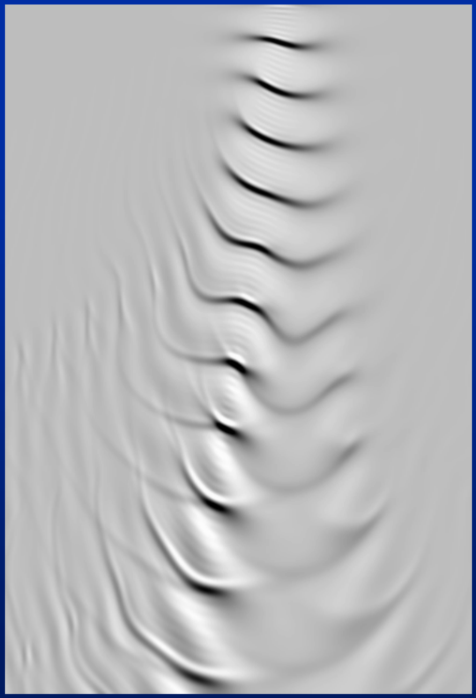
Wavefield-Extrapolated Coherent State



$$G(s,\mathbf{x}) \sim \int dp_{0s}\, u(s,p_{0s},\mathbf{x})$$

$$u(s,p_{0s},\mathbf{x}) \sim W\left[e^{-\frac{1}{2}\omega\Omega(x-x_0)^2} e^{-i\omega p_{0s}(x-x_0)}\right]$$



Foster and Huang 1991
Wu et al 2000
Albertin 2001

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Wavefield Extrapolated Zero-offset Impulse

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Asymptotic Coherent State Reconstruction

3 raytraced coherent states

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WesternGeco

Asymptotic Coherent State Reconstruction

Schlumberger Private

12 raytraced coherent states

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Asymptotic Coherent State Superposition

572 raytraced coherent states

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Wavefield Extrapolated Zero-offset Impulse

Schlumberger Private

Jun 17, 2001

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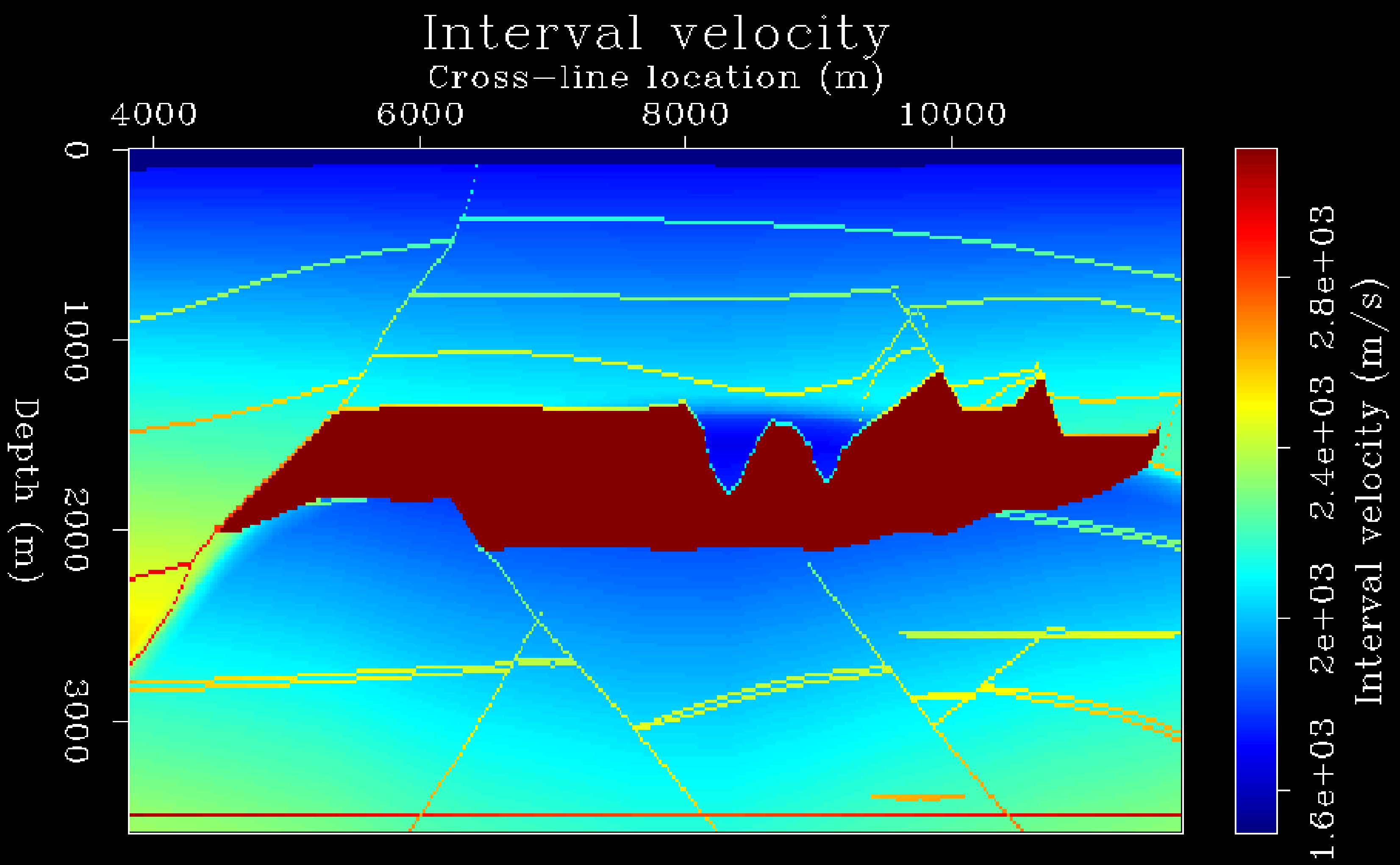
SEG/EAGE salt data set - Crossline



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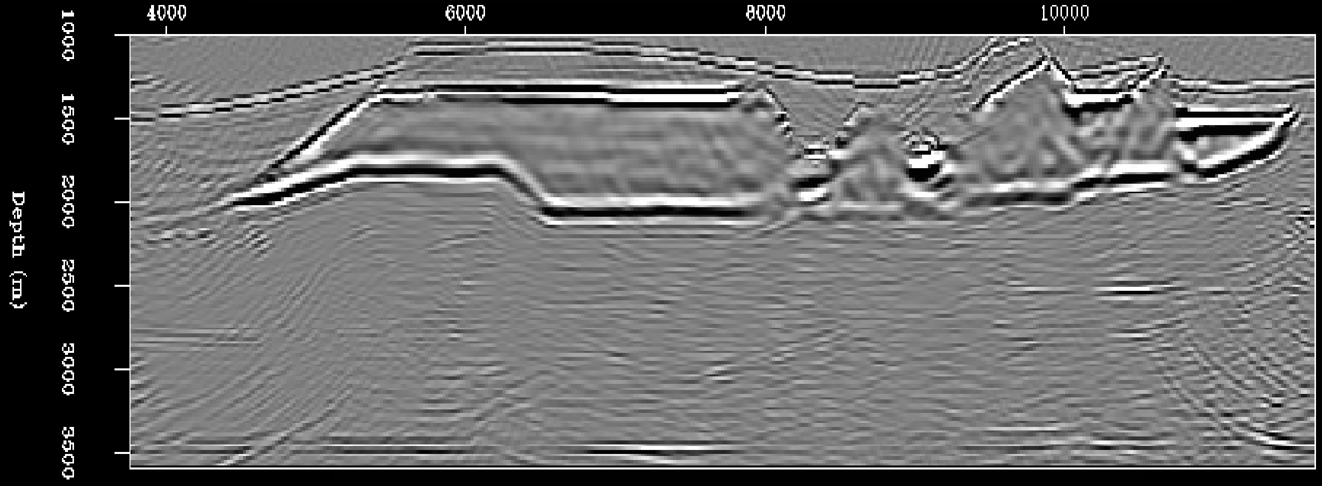
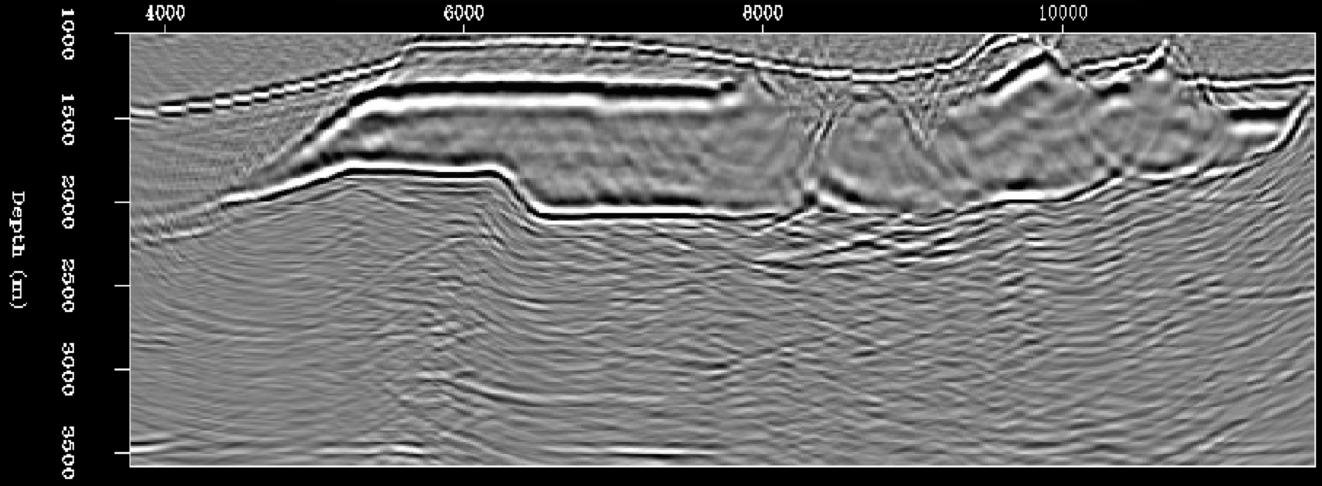
SEG/EAGE salt data set - Crossline

Wavefield-continuation migration



Kirchhoff migration



Beam Migration y=375

Schlumberger Private

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WesternGeco

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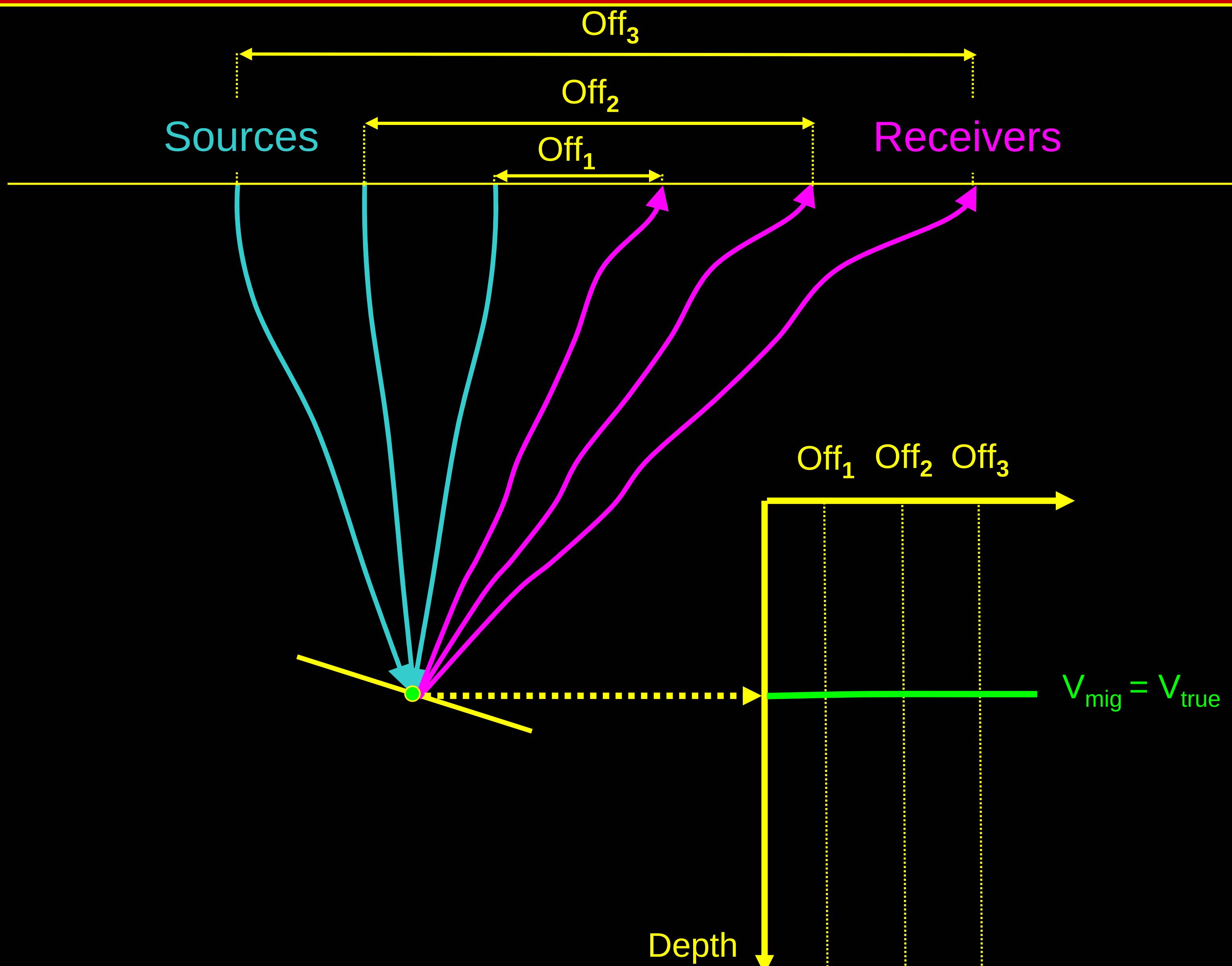
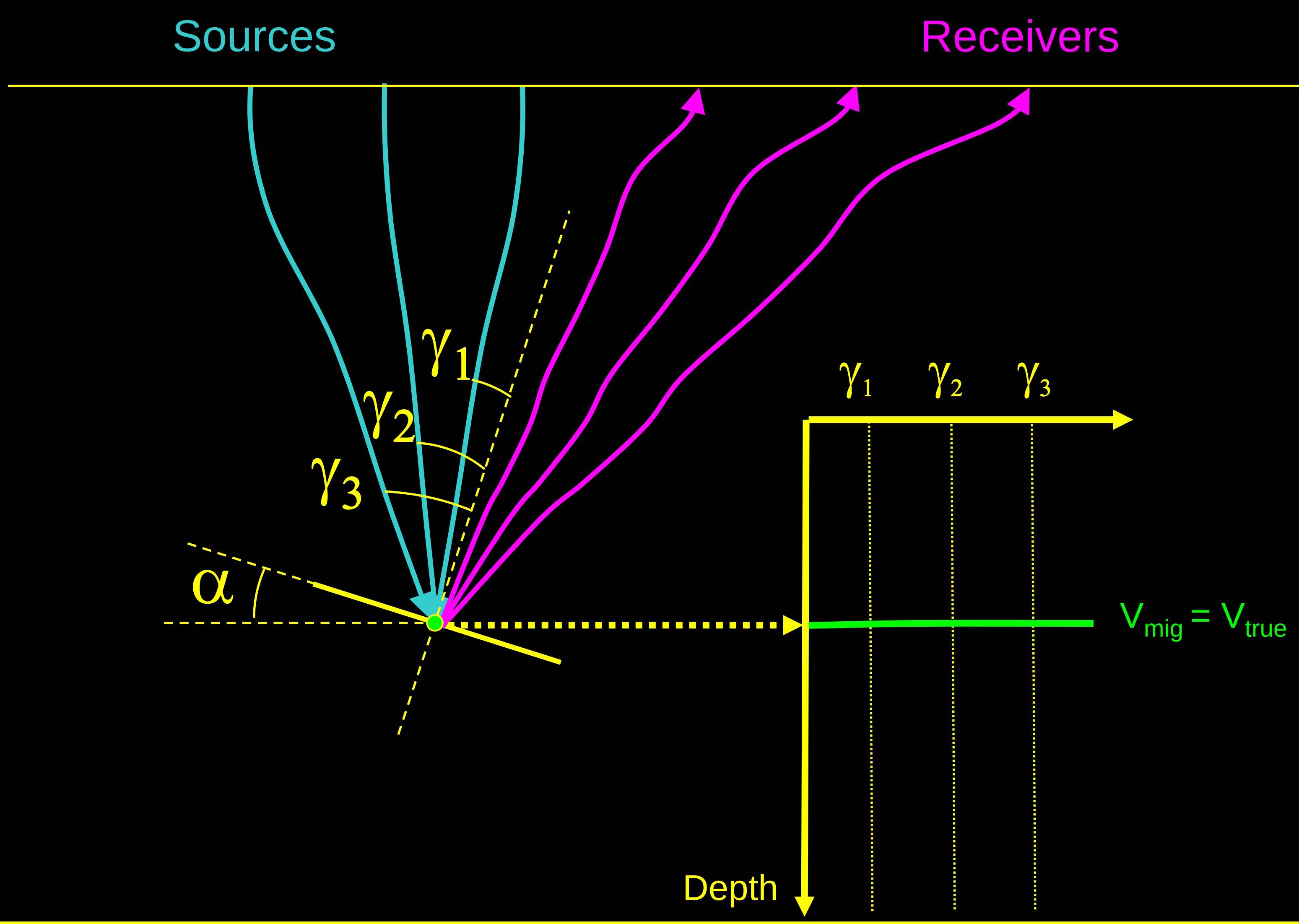
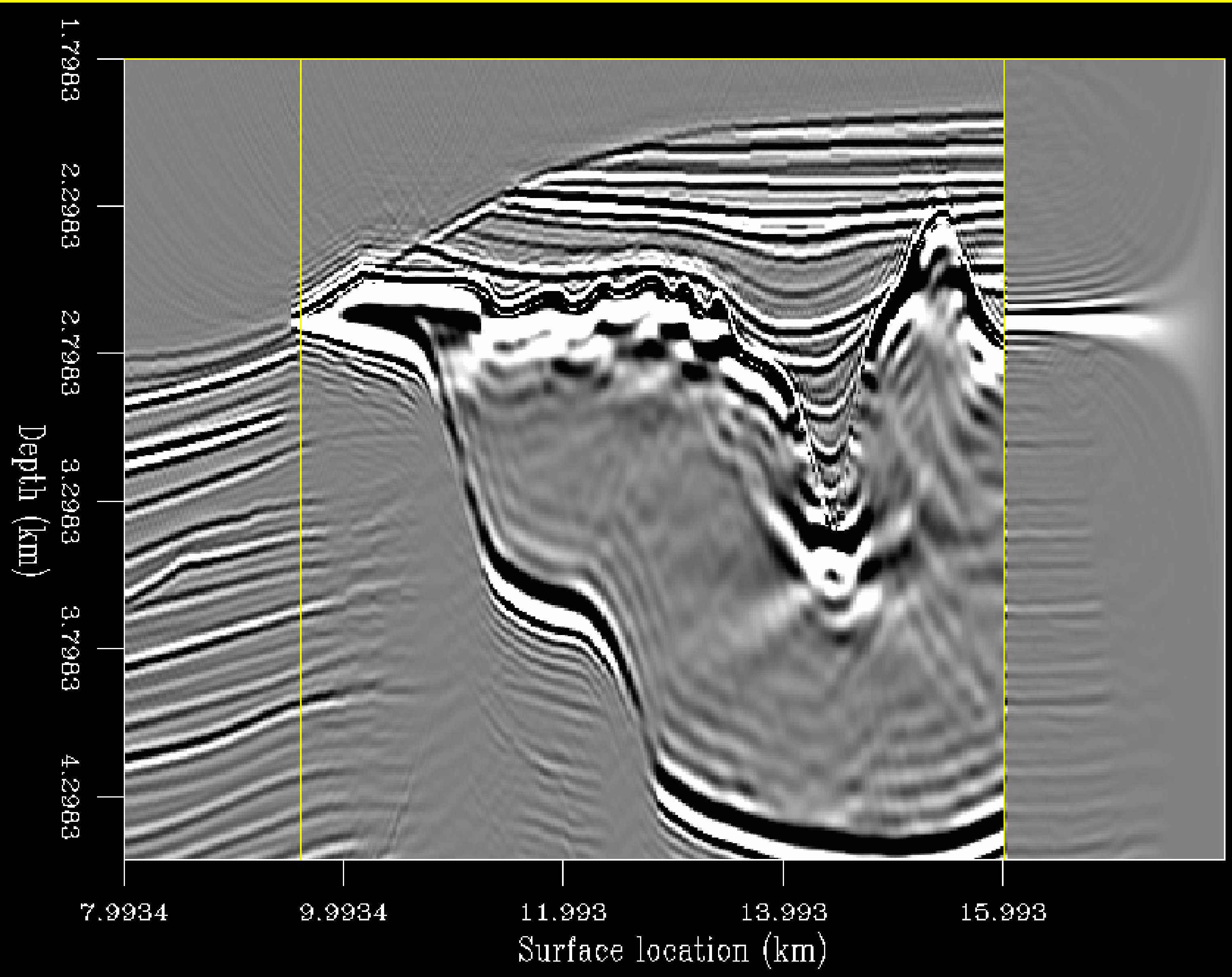
Offset Domain CIG (Kirchhoff)



Angle Domain CIG (wavefield continuation)



Sigsbee data - Well illuminated CIG



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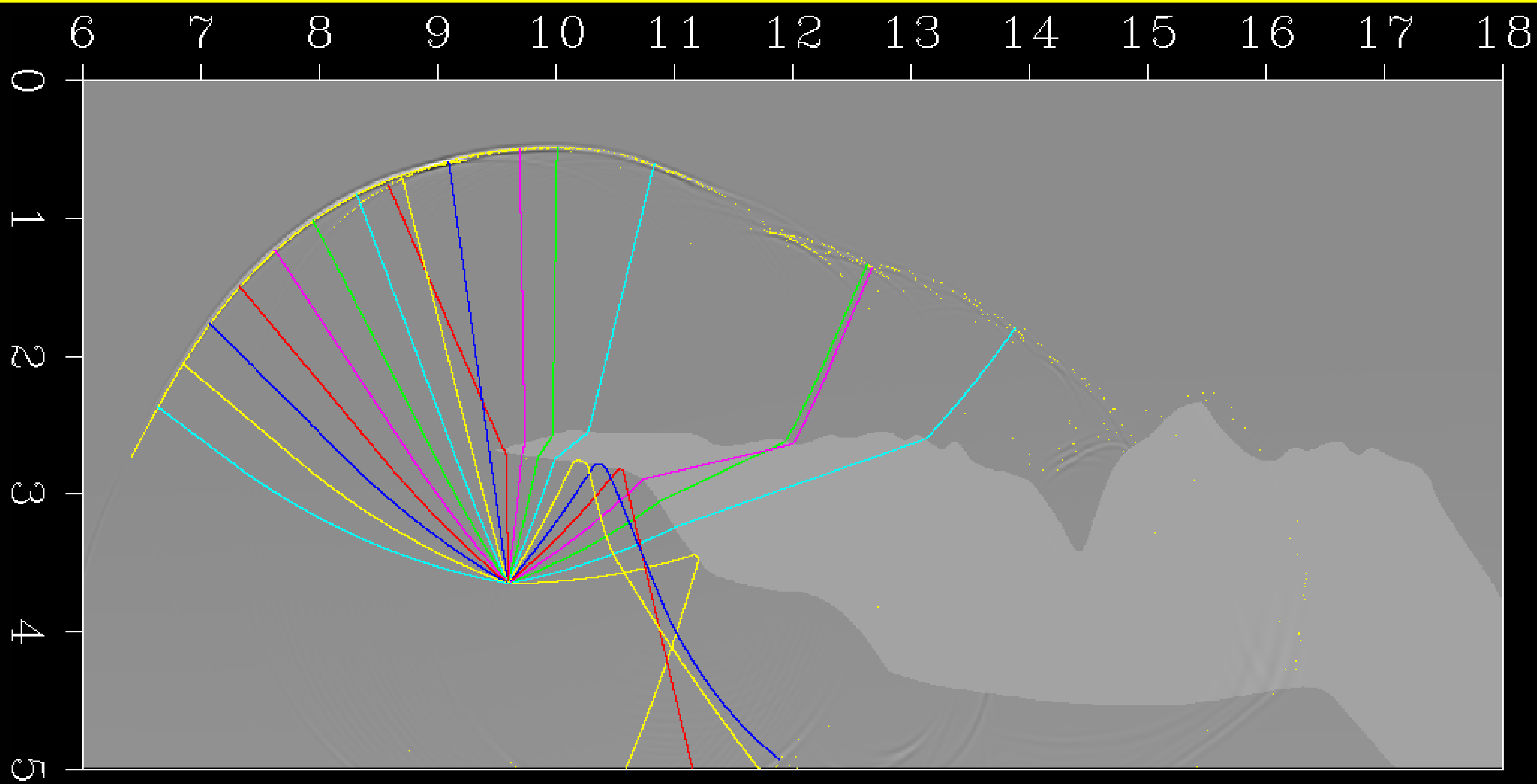
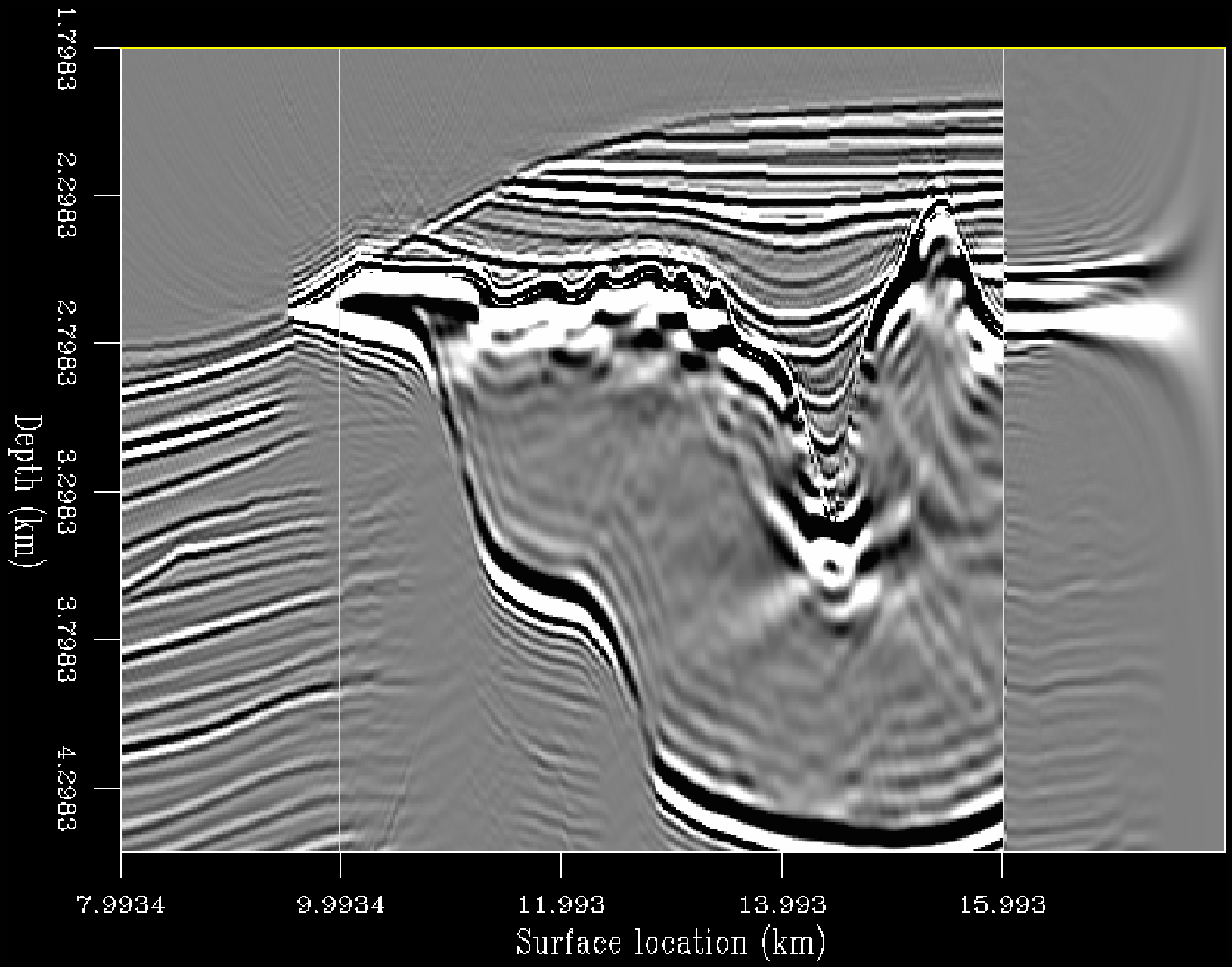


Sigsbee data - Partially illuminated CIG



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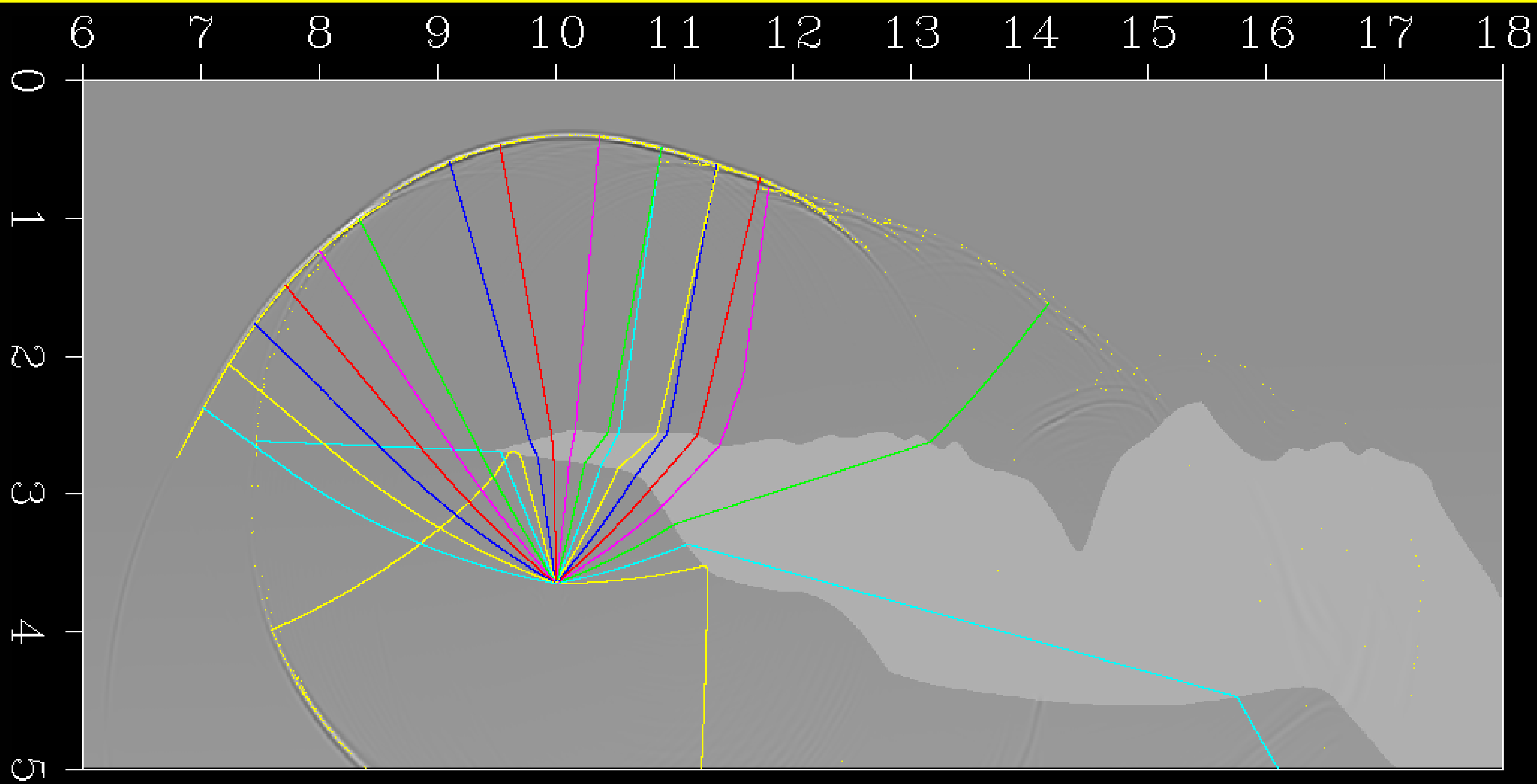

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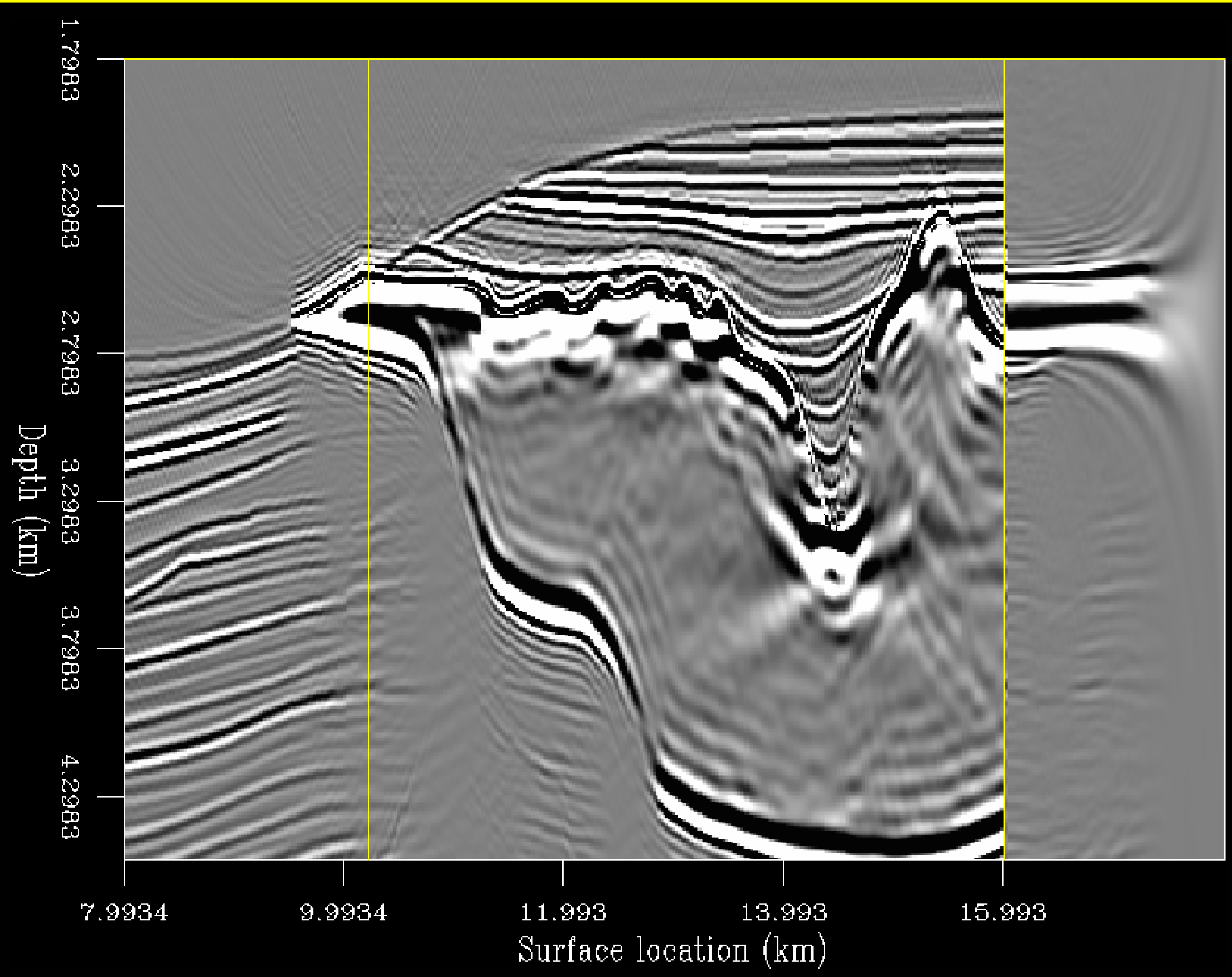
Sigsbee data - Poorly illuminated CIG



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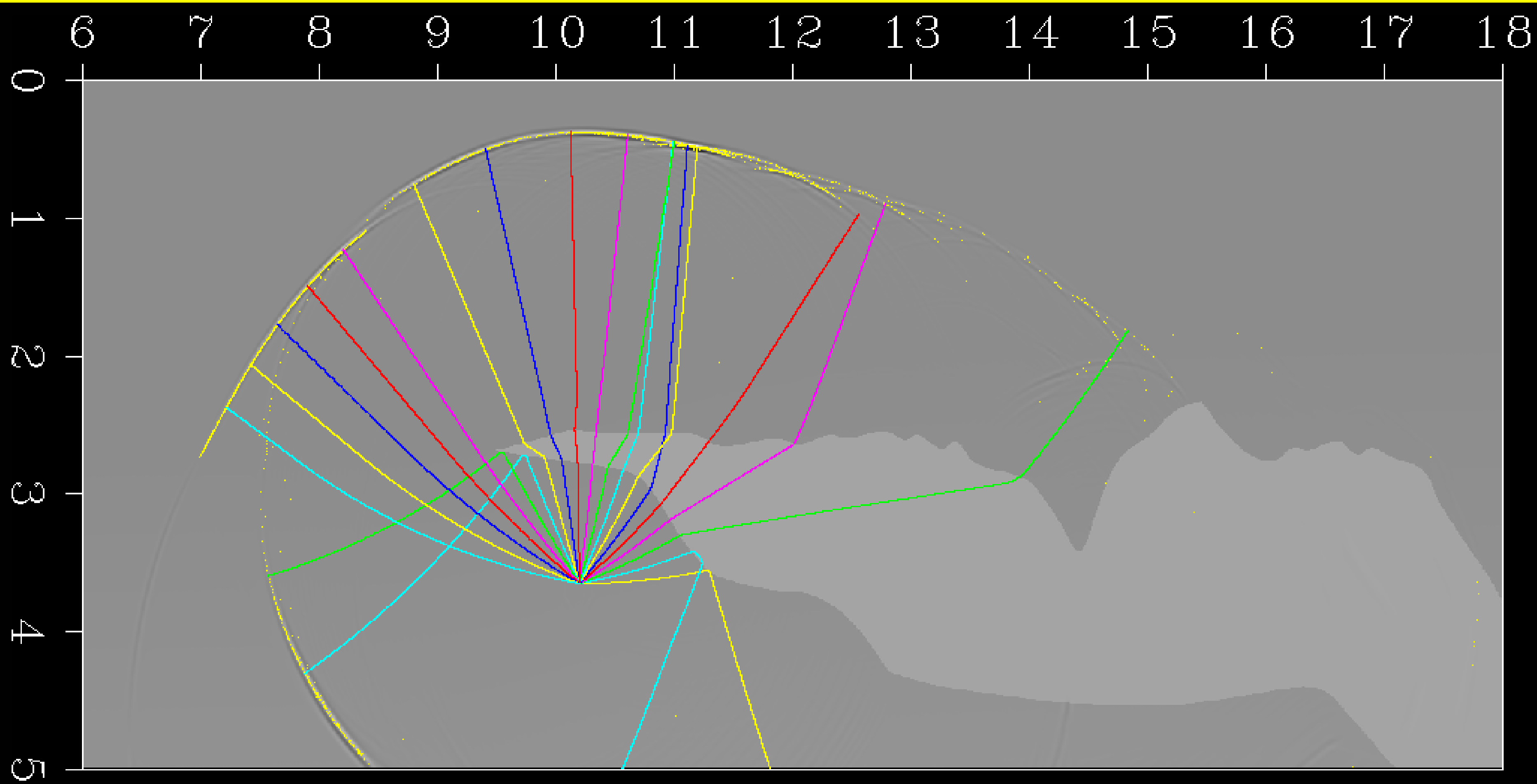
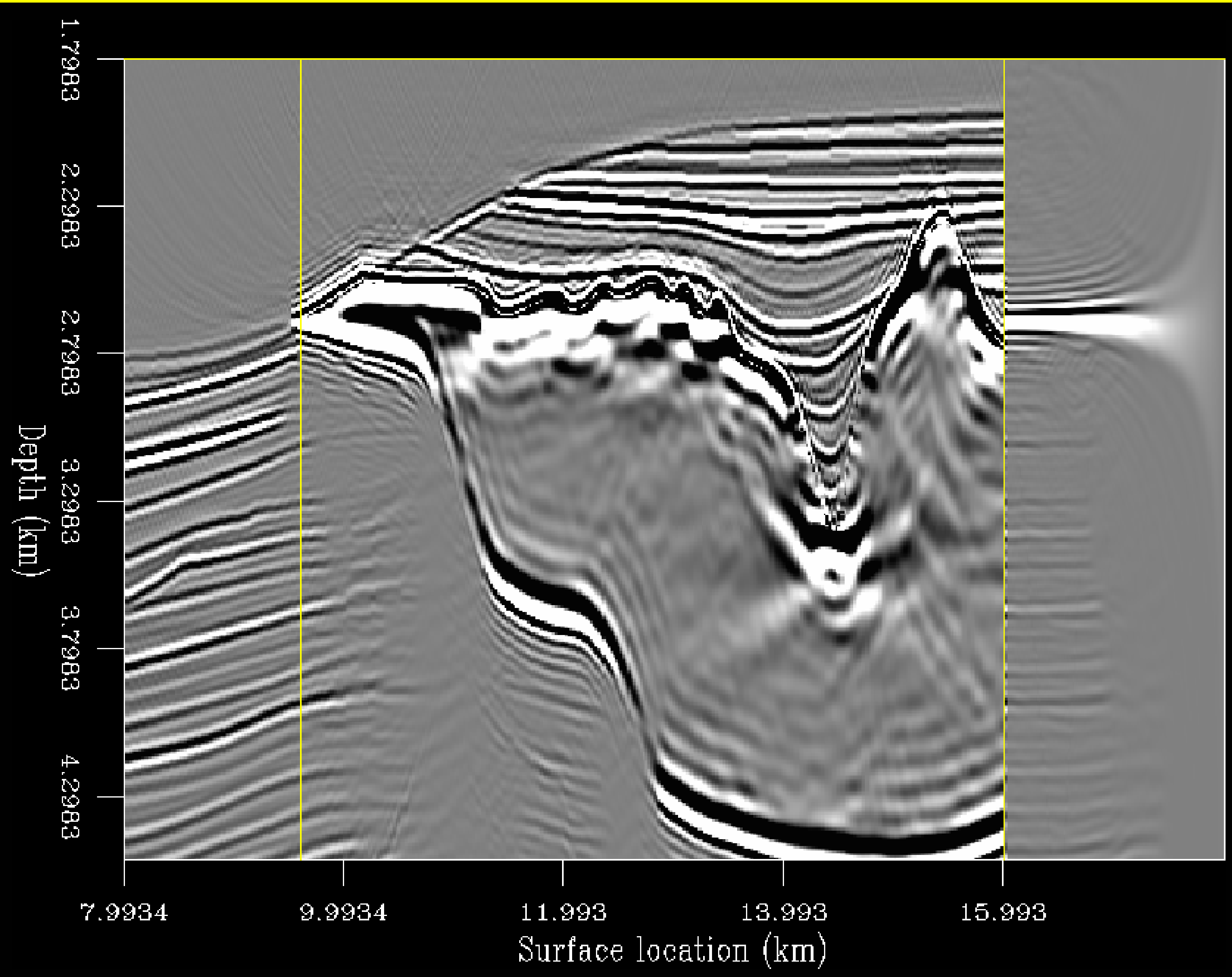


Sigsbee data - Well illuminated CIG



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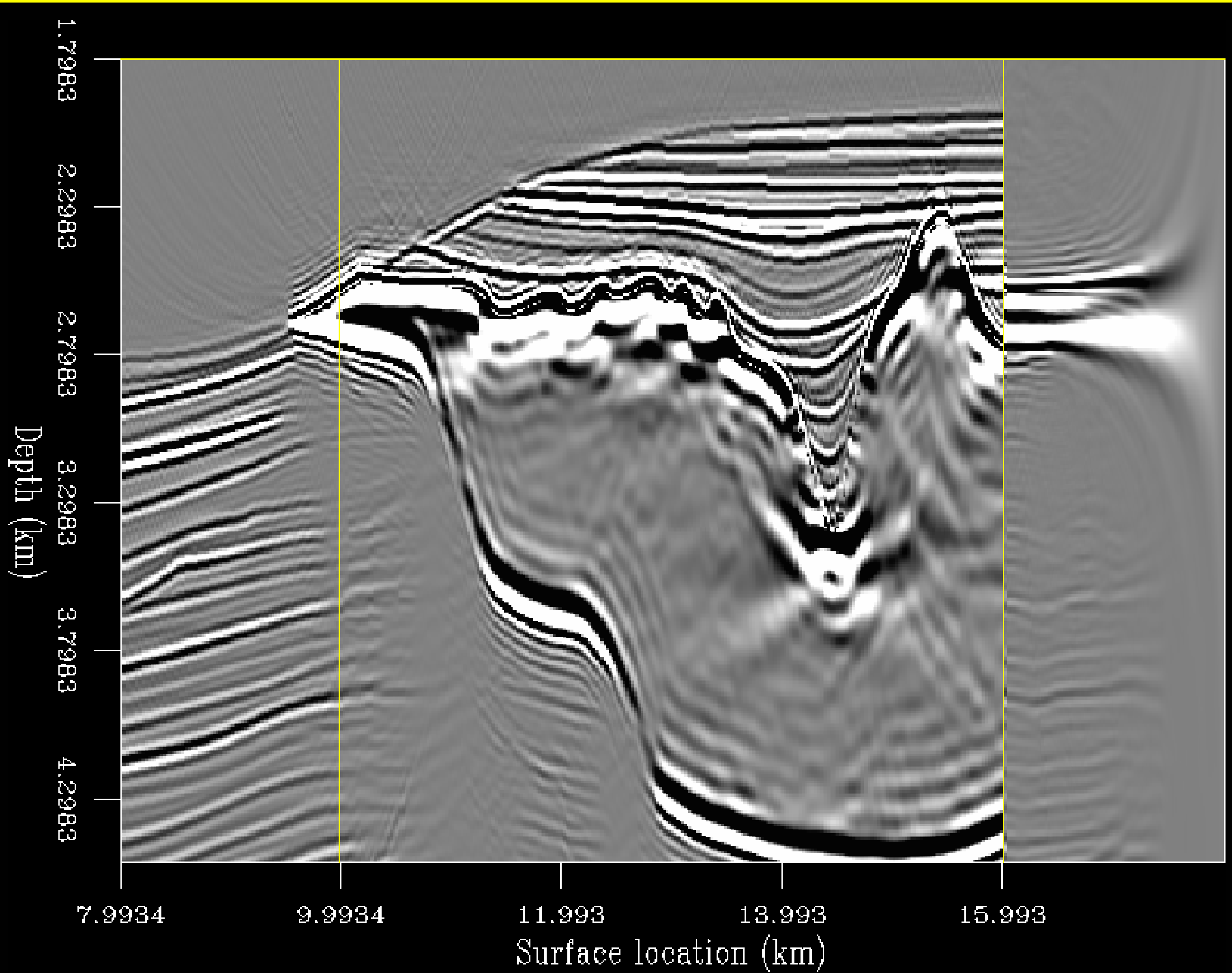
Sigsbee data - Partially illuminated CIG



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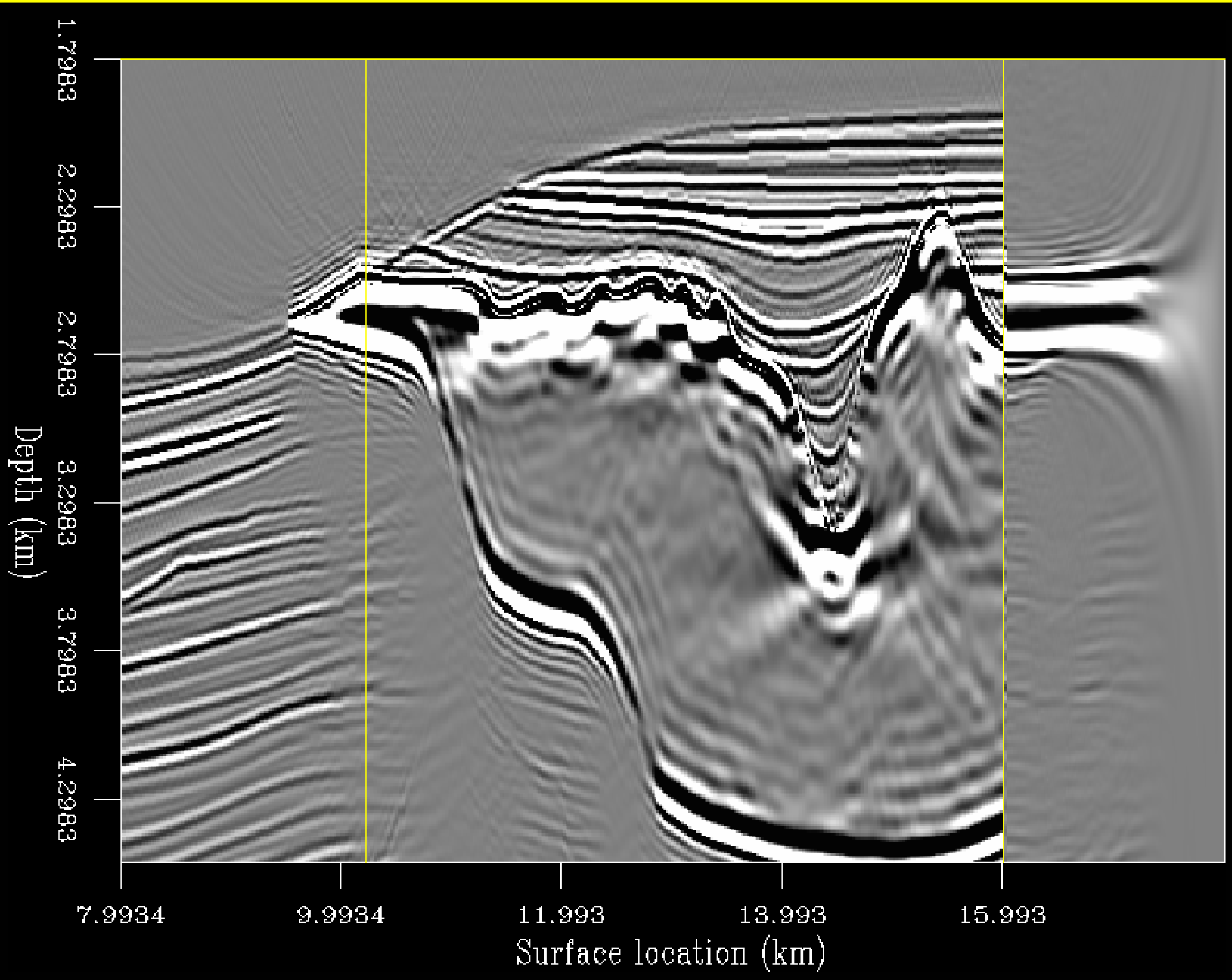

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Migration => Normalized Migration

- **Migration** $$m = \mathbf{L}^* d$$
- **Least-Squares Migration** $$m = \left(\mathbf{L}^* \mathbf{L}\right)^{-1} \mathbf{L}^* d$$
- **Normalized Migration** $$m = \mathbf{W}^{-1} \mathbf{L}^* d$$

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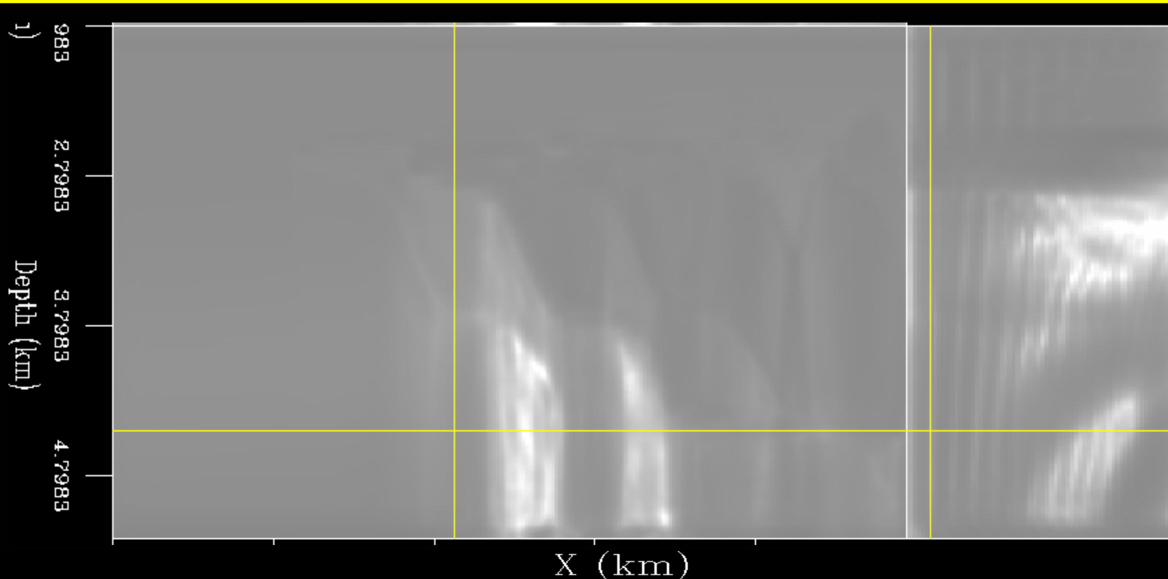
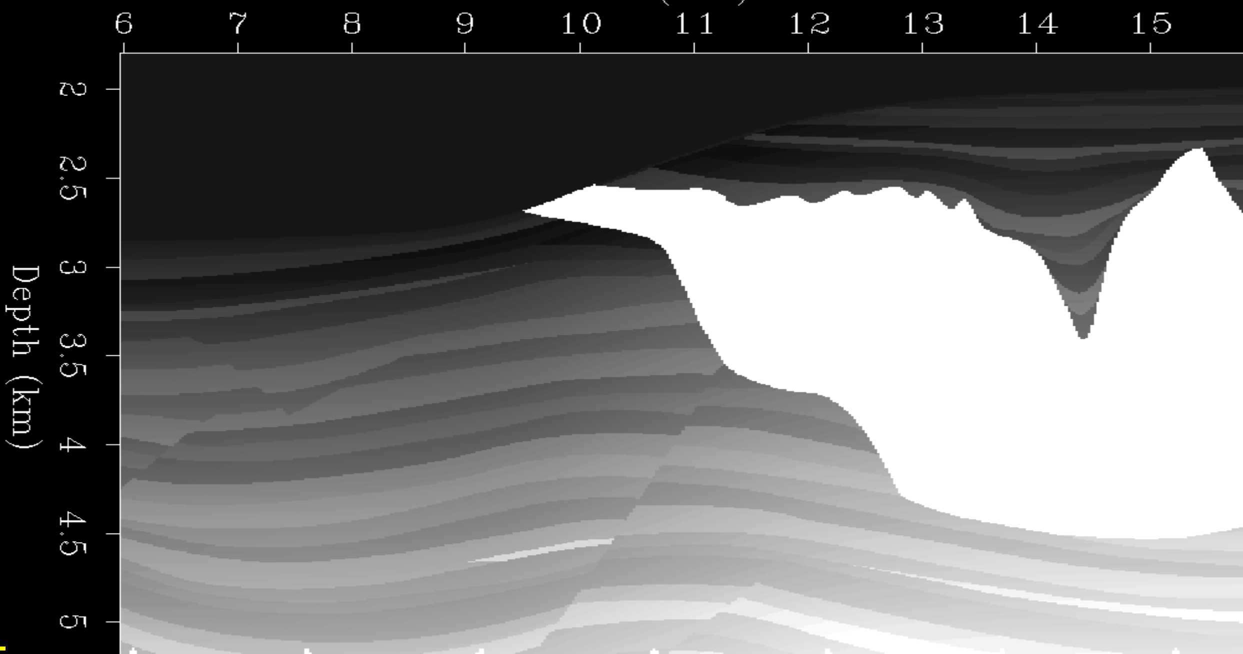
Normalized Migration



Normalization factor

W



Velocity model

Migration => Iterative Regularized Inversion

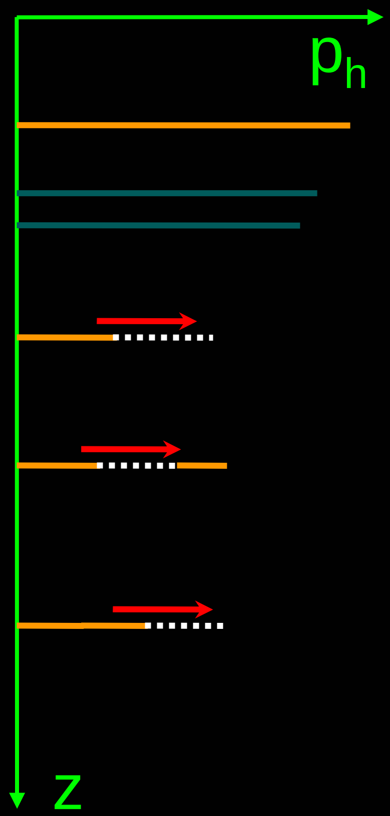
- **Least-Squares Migration**

$$m = \left(\mathbf{L}^{*}\mathbf{L}\right)^{-1}\mathbf{L}^{*}d$$

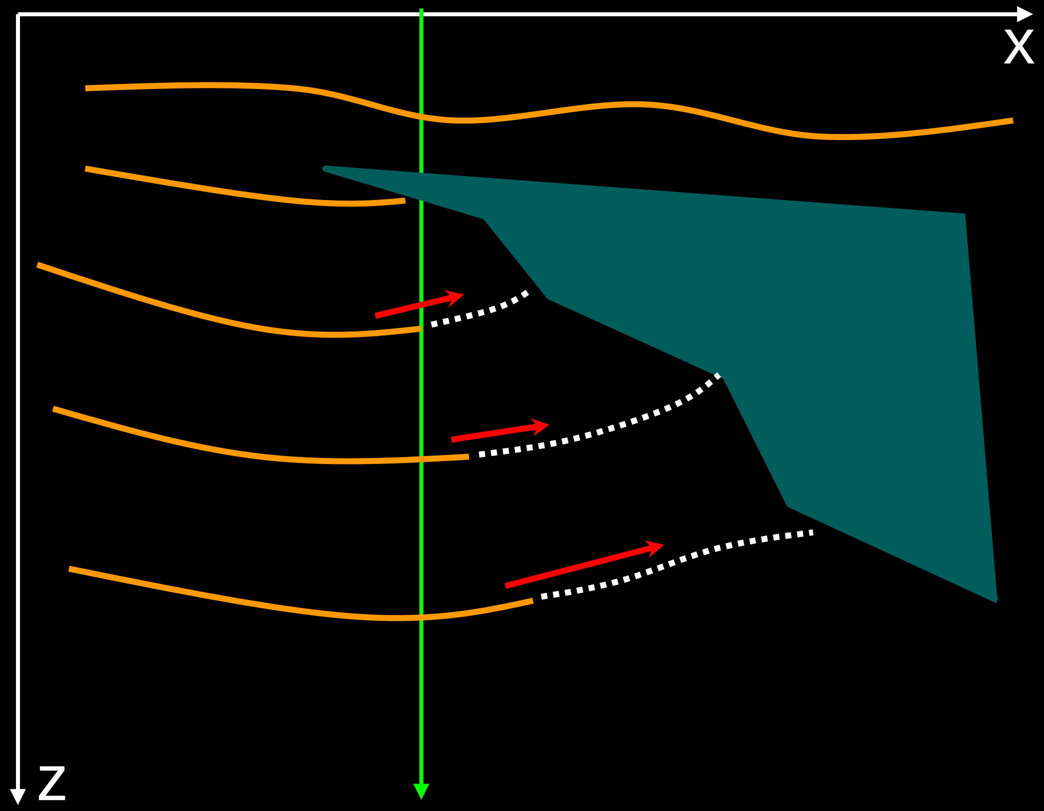
- **Iterative Regularized Inversion**

$$m = \left(\mathbf{L}^{*}\mathbf{L} + \varepsilon^{2}\mathbf{A}^{*}\mathbf{A}\right)^{-1}\mathbf{L}^{*}d$$

Regularization operator (A)



Geophysical regularization



Geological regularization

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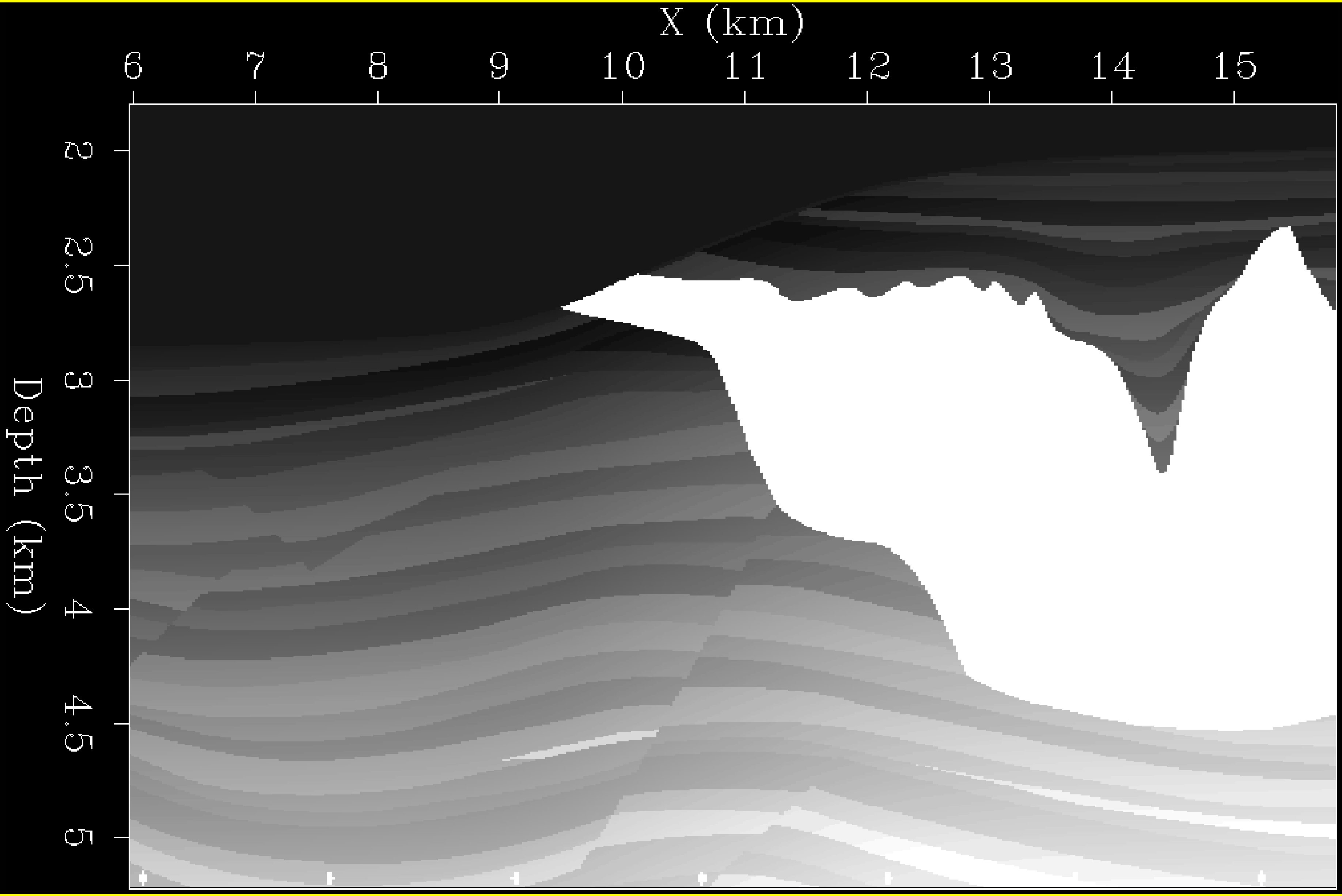
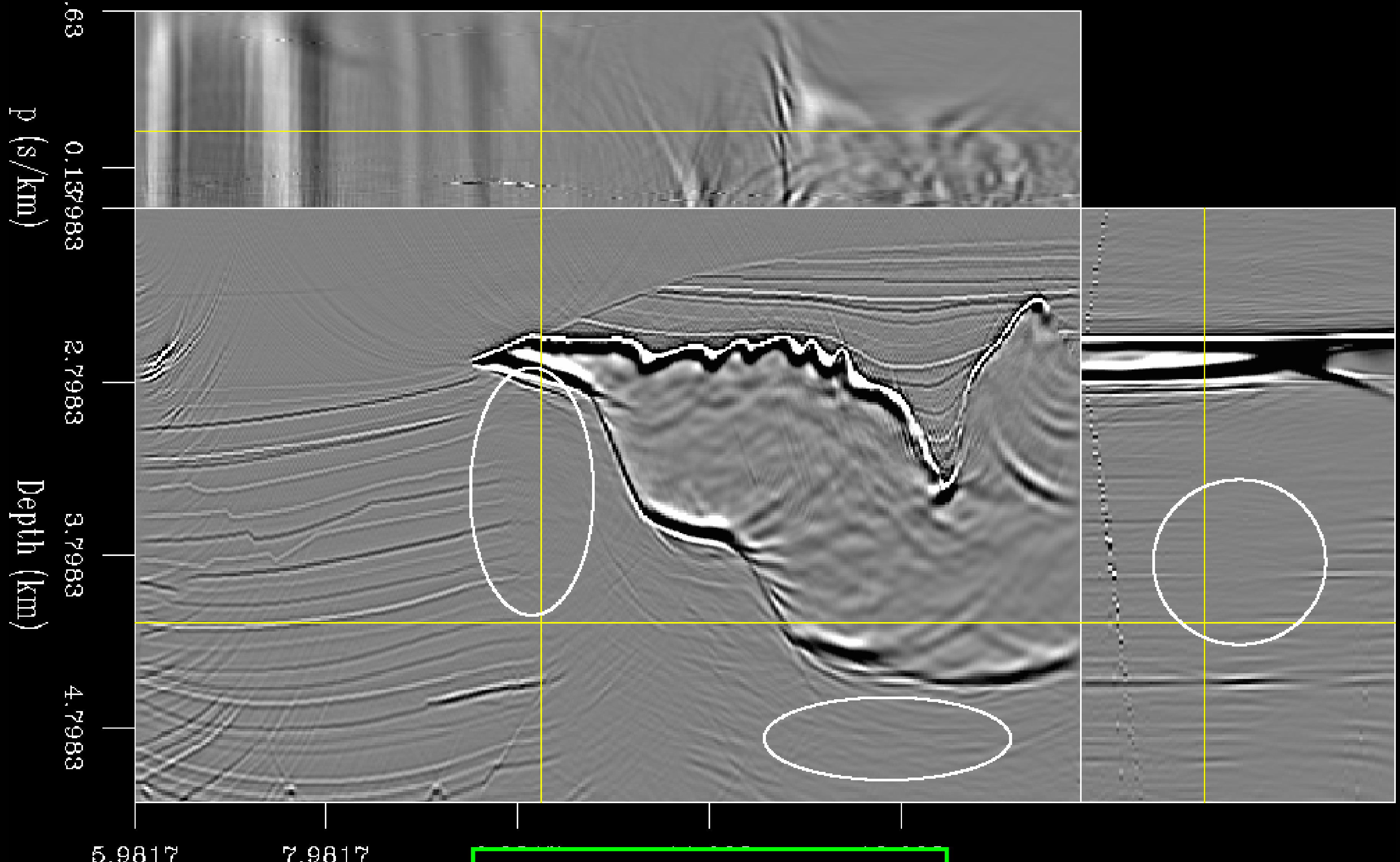
Layered velocity model

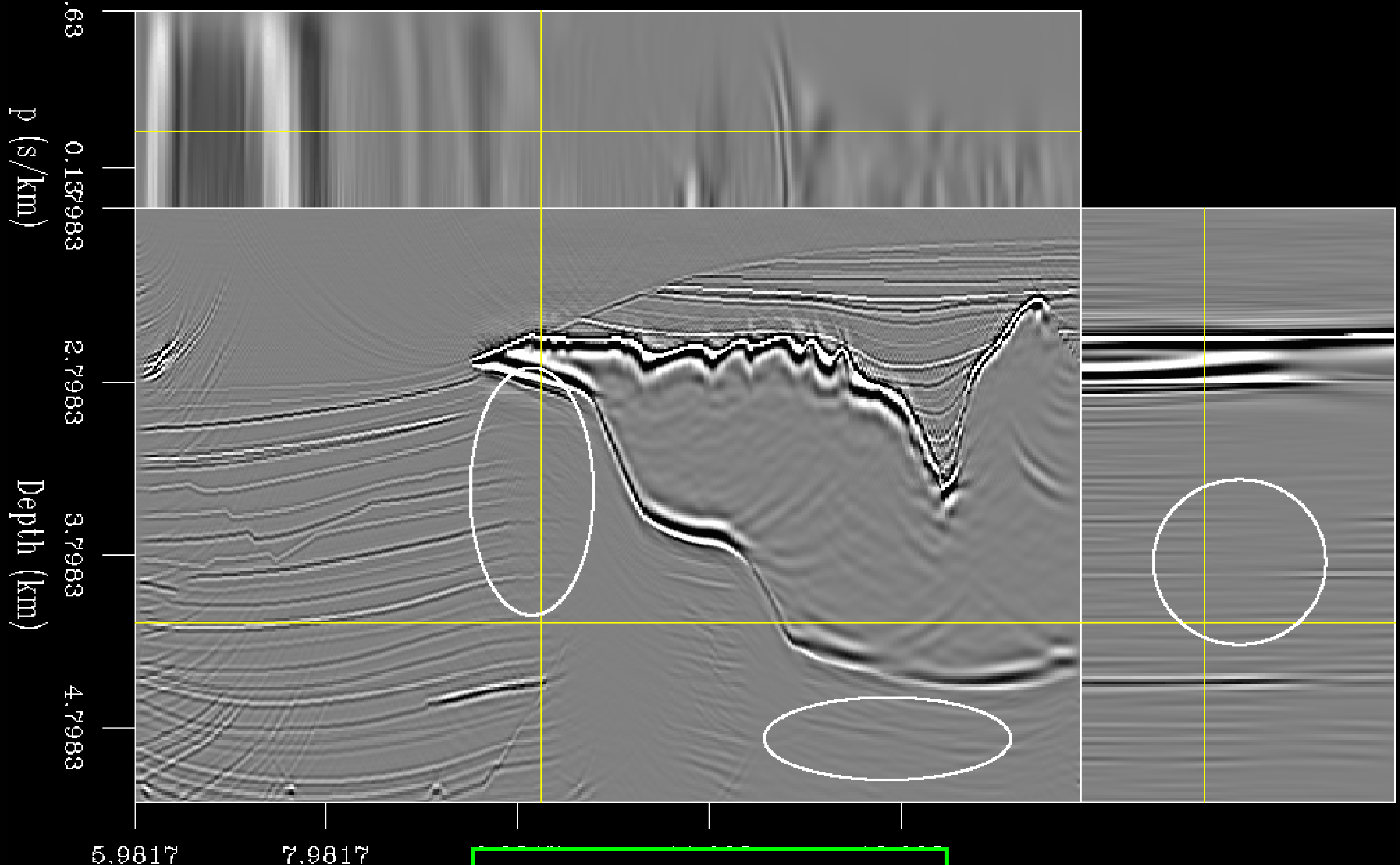


Migration



Courtesy of Marie Clapp (SEP)

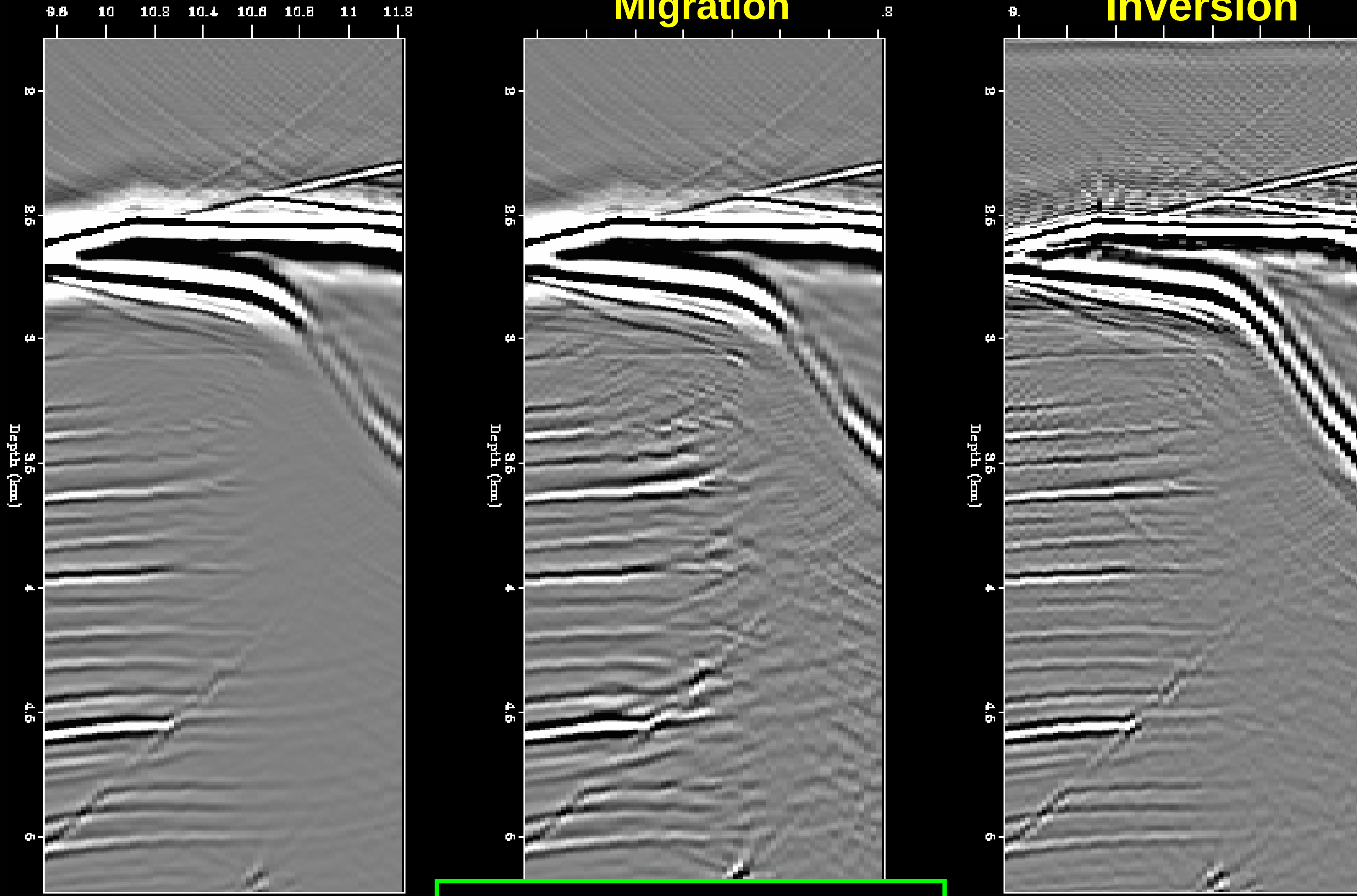
Inversion with Geophysical regularization



Courtesy of Marie Clapp (SEP)

Inversion with Geophysical regularization

Migration	Normalized Migration	Regularized Inversion



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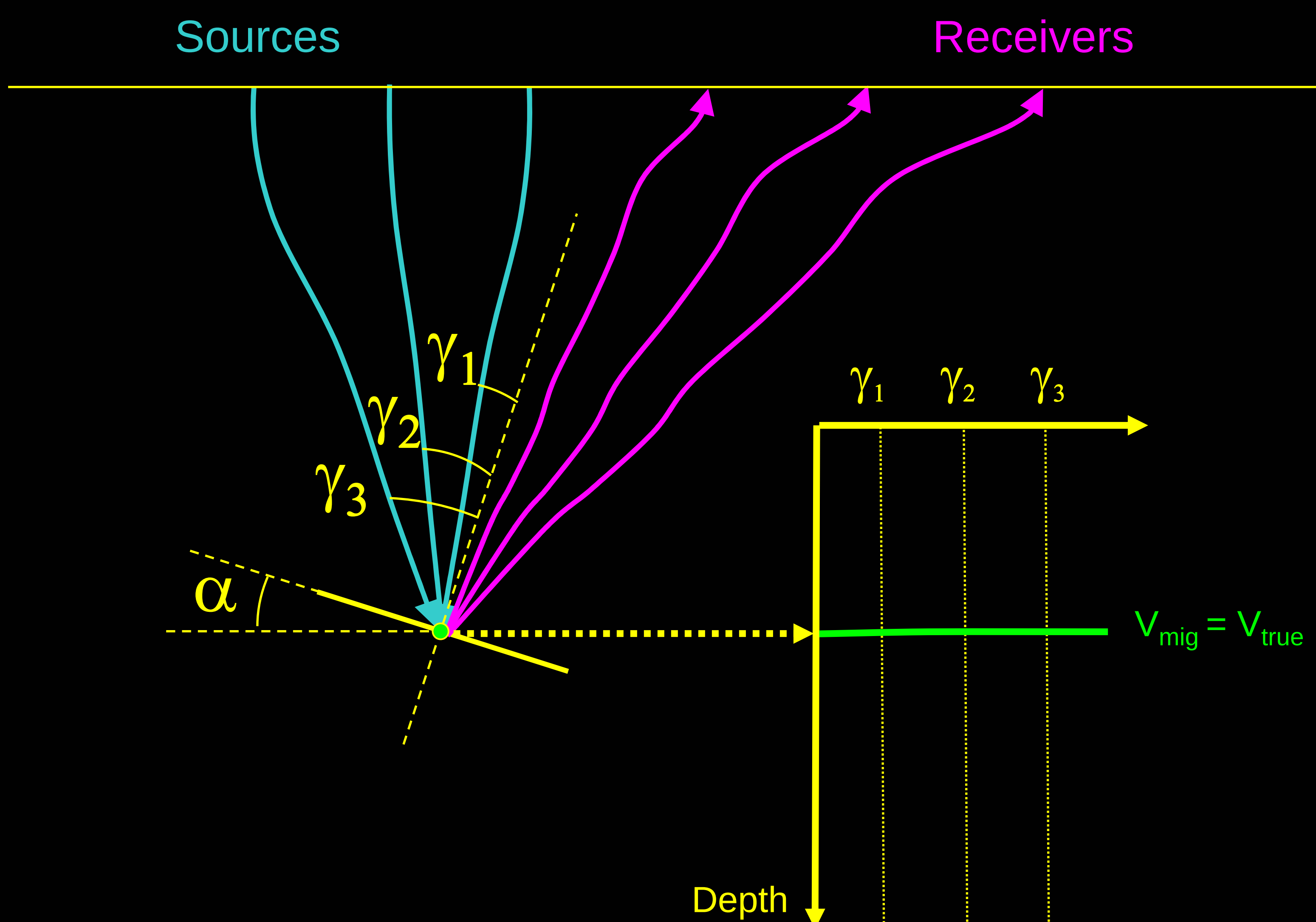
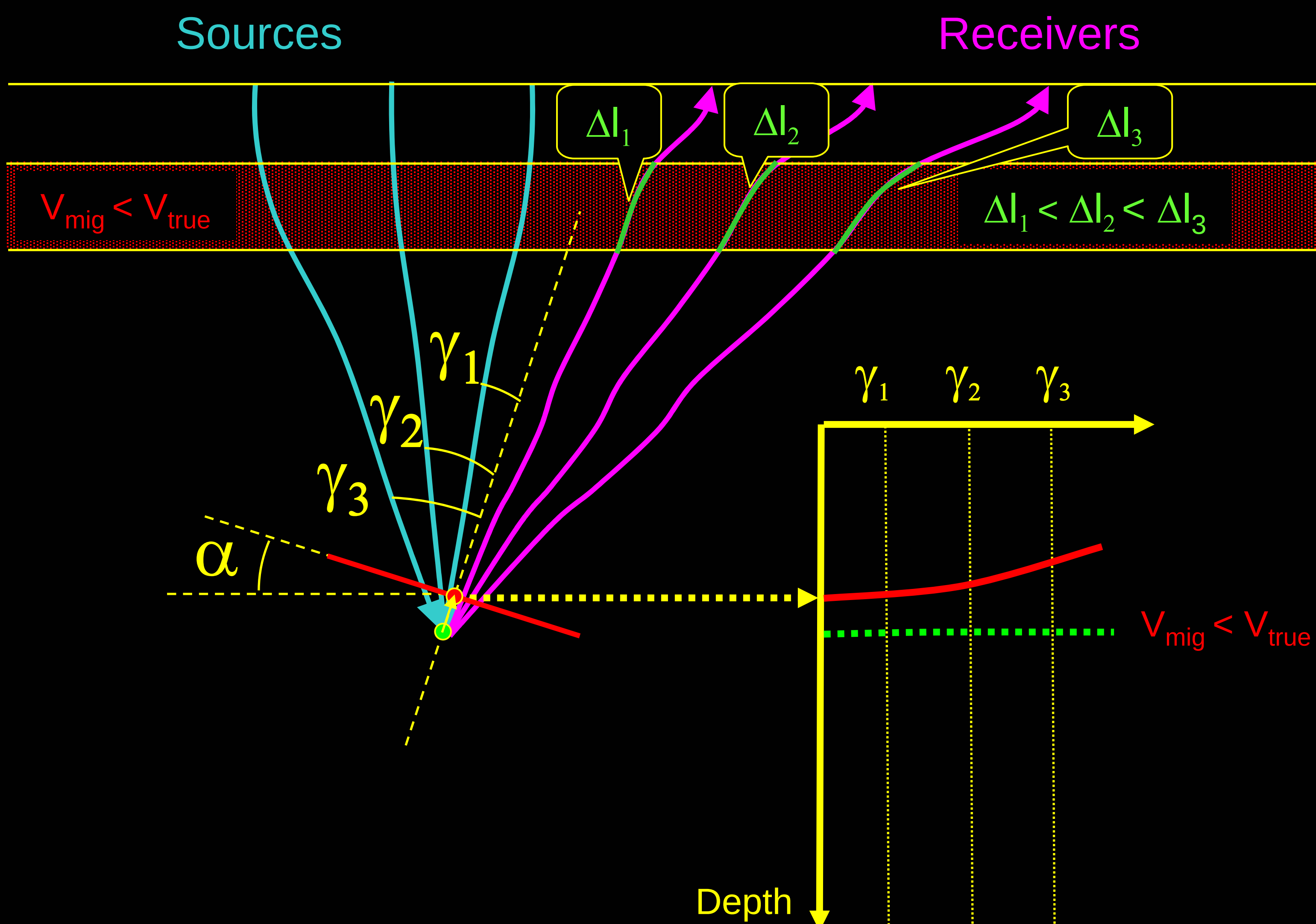
ADCIGs with correct velocity



ADCIGs and velocity errors



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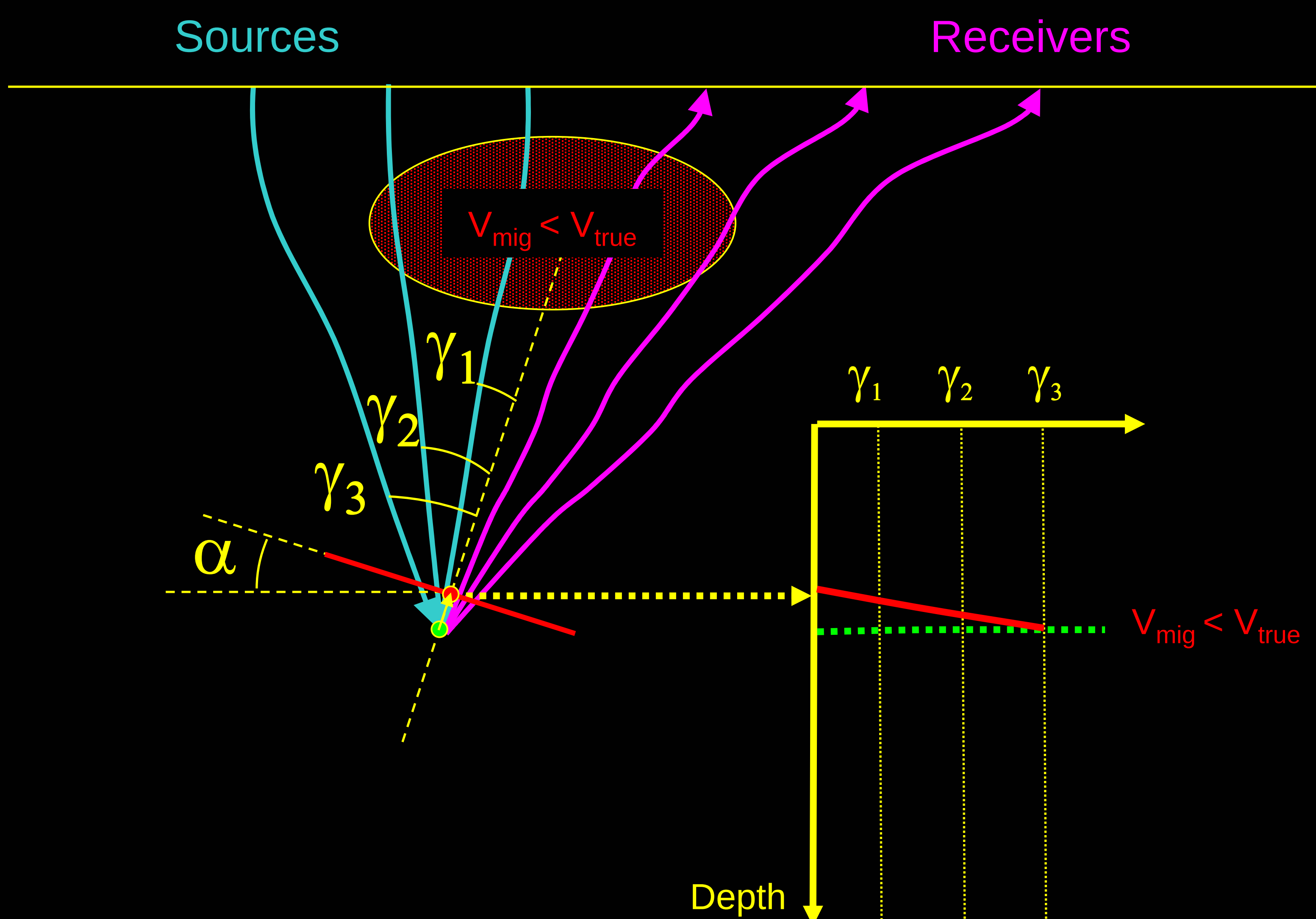
ADCIGs and local velocity errors



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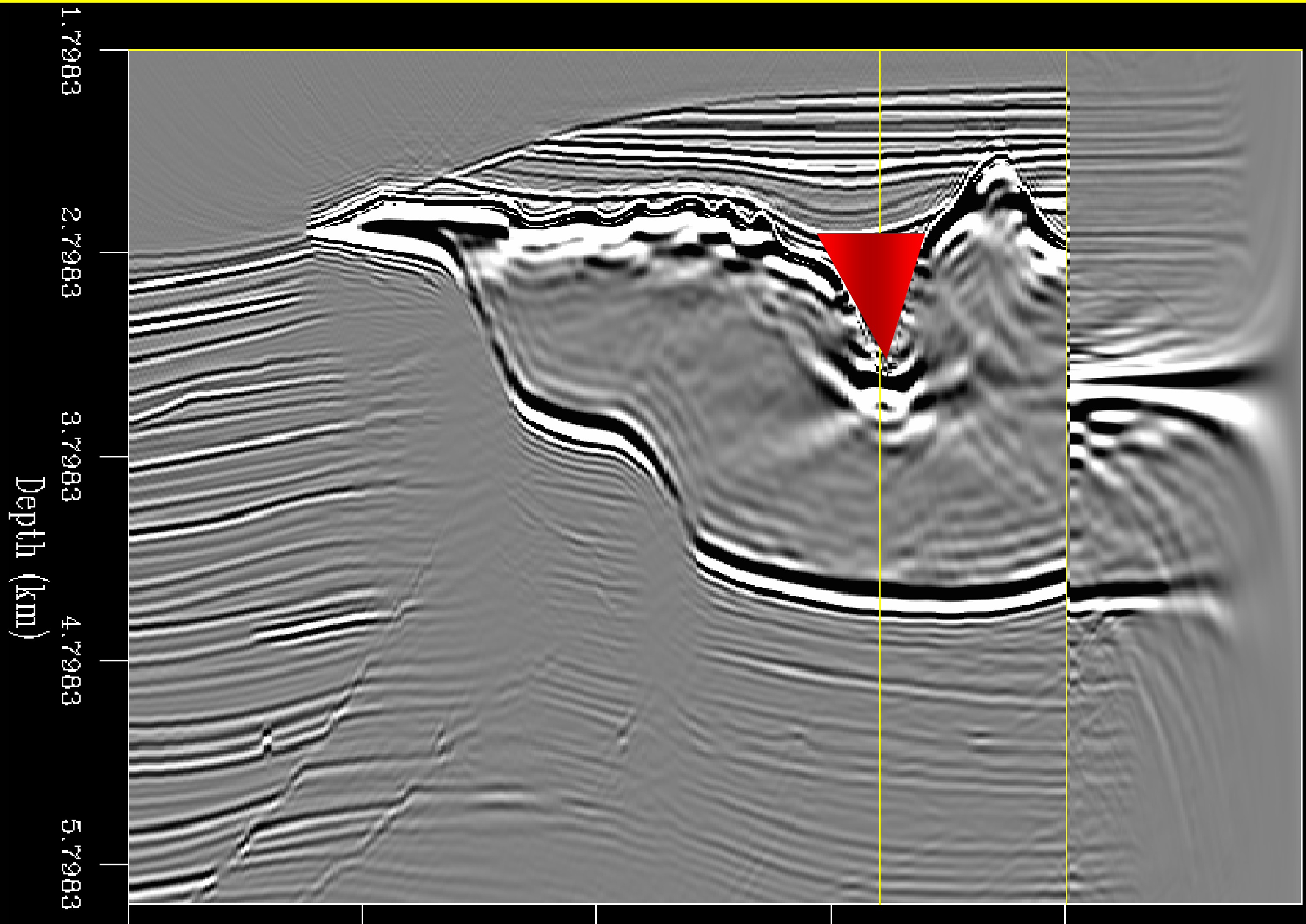
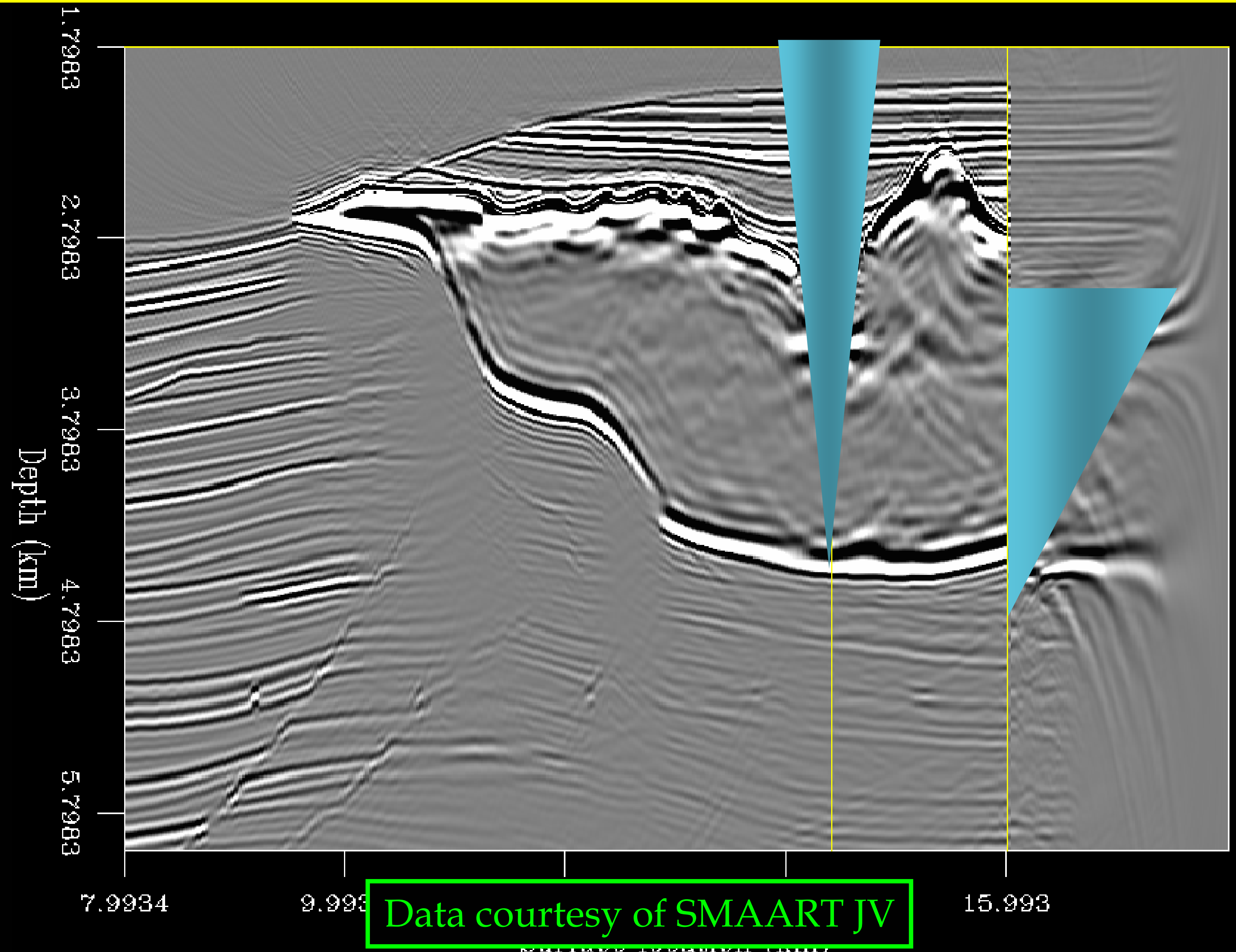
Sigsbee data - Correct velocity



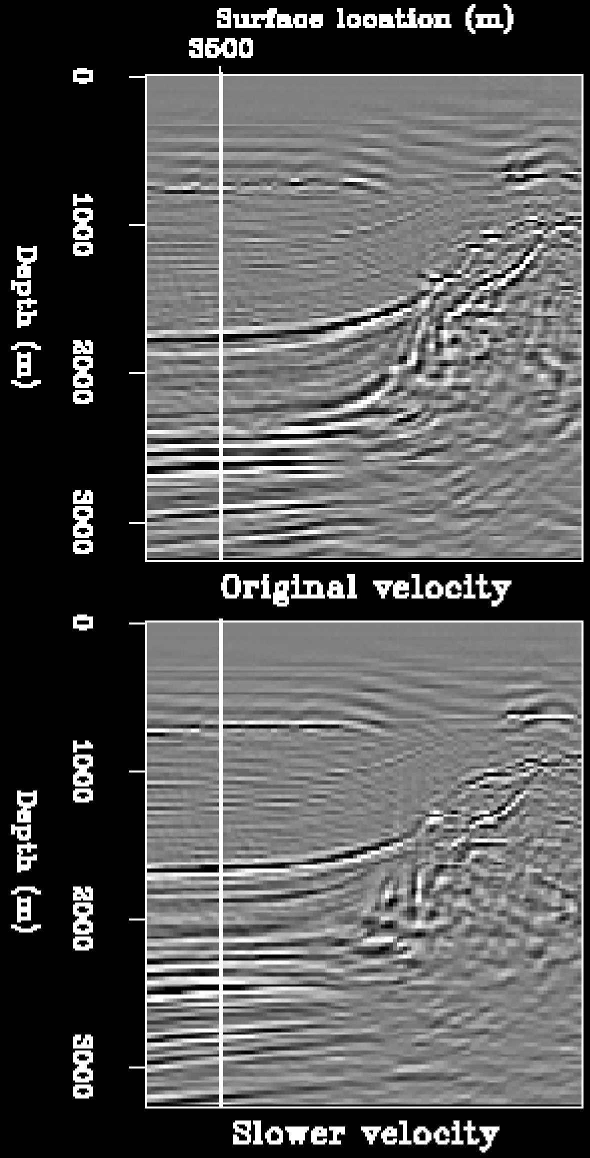
Data courtesy of SMAART JV

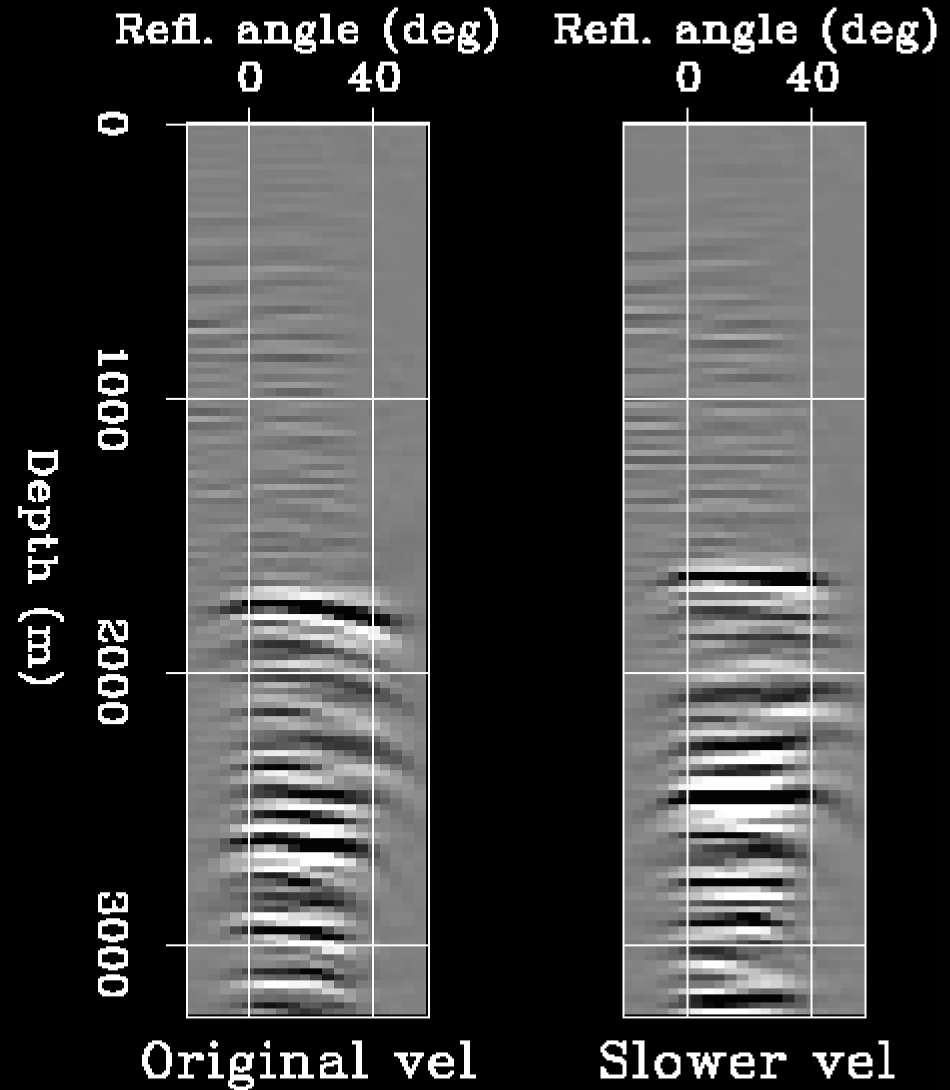
Sigsbee data - Wrong velocity



Data courtesy of SMAART JV

ADCIGs and velocity in simple structure





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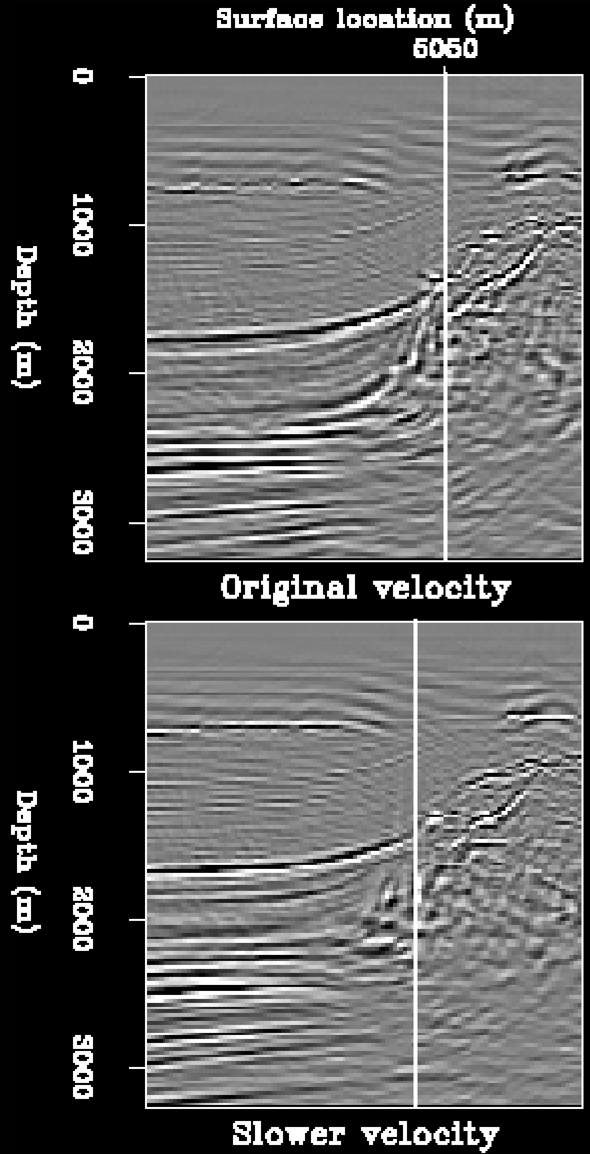
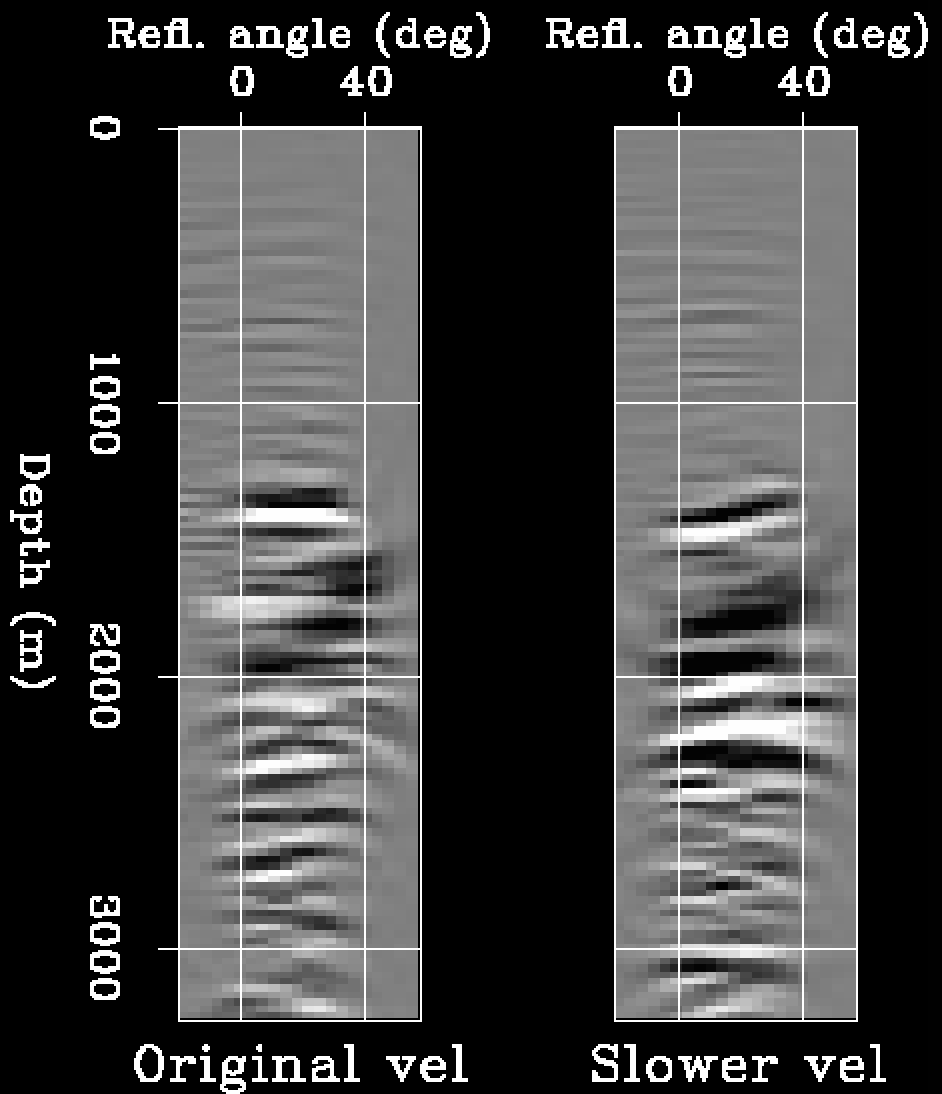
Velocity sensitivity of Angle-Domain DDCIGs





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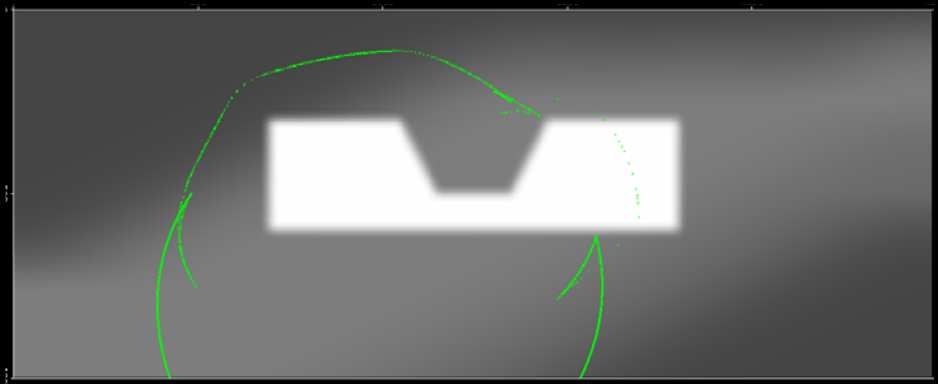
Migration ⇔ Migration Velocity Analysis



wavefronts

wavefields

- Kirchhoff migration
- traveltime tomography

- Wave-equation migration
- Wave-equation MVA

Courtesy of Paul Sava (SEP)

A tomography problem

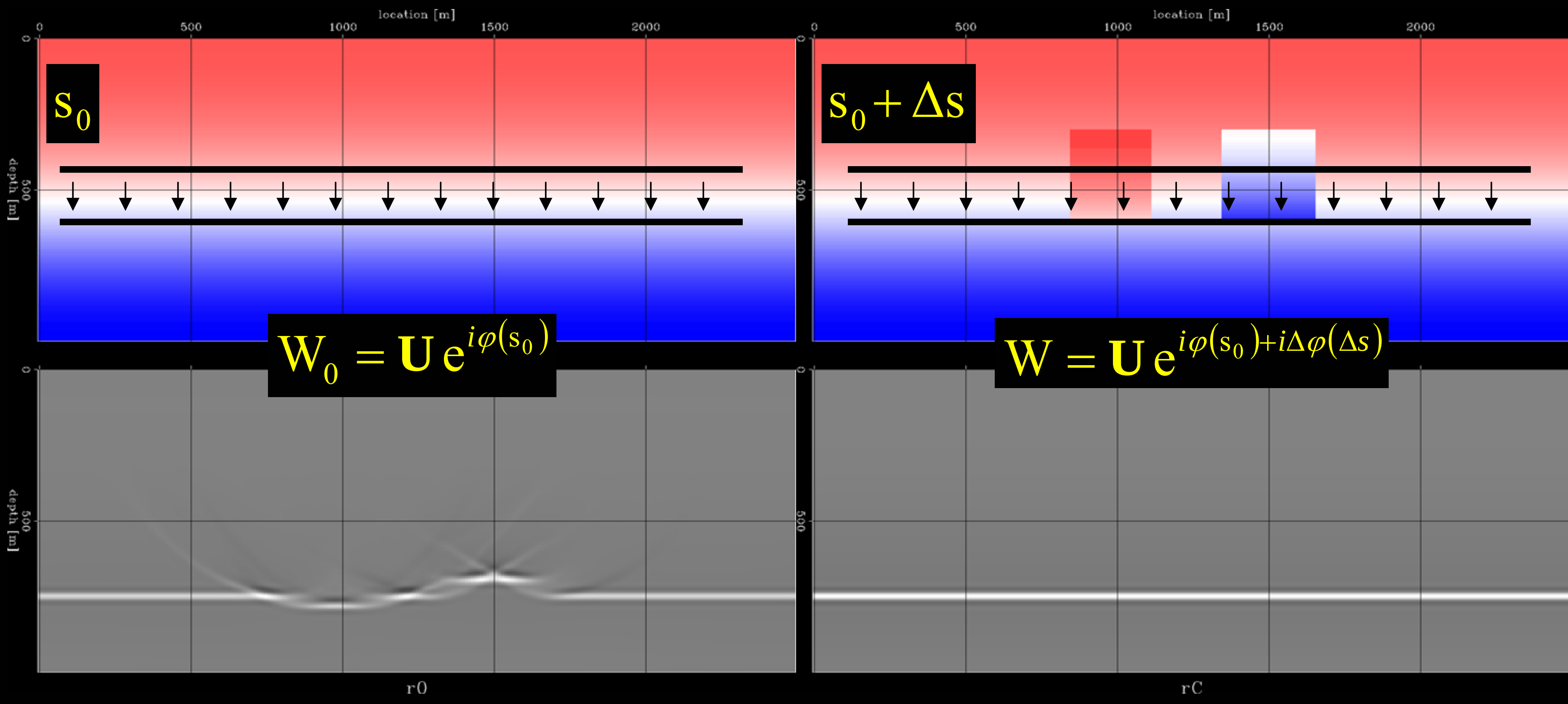
$$\min_{\Delta s} \left\| \Delta q - \mathbf{L}\Delta s \right\|$$

	Traveltime MVA	Wave-equation tomography	Wave-equation MVA
Δq	**Δt** **traveltime**	**Δd** **data**	**ΔR** **image**
L	**ray field**	**wavefield**	**wavefield**

Courtesy of Paul Sava (SEP)

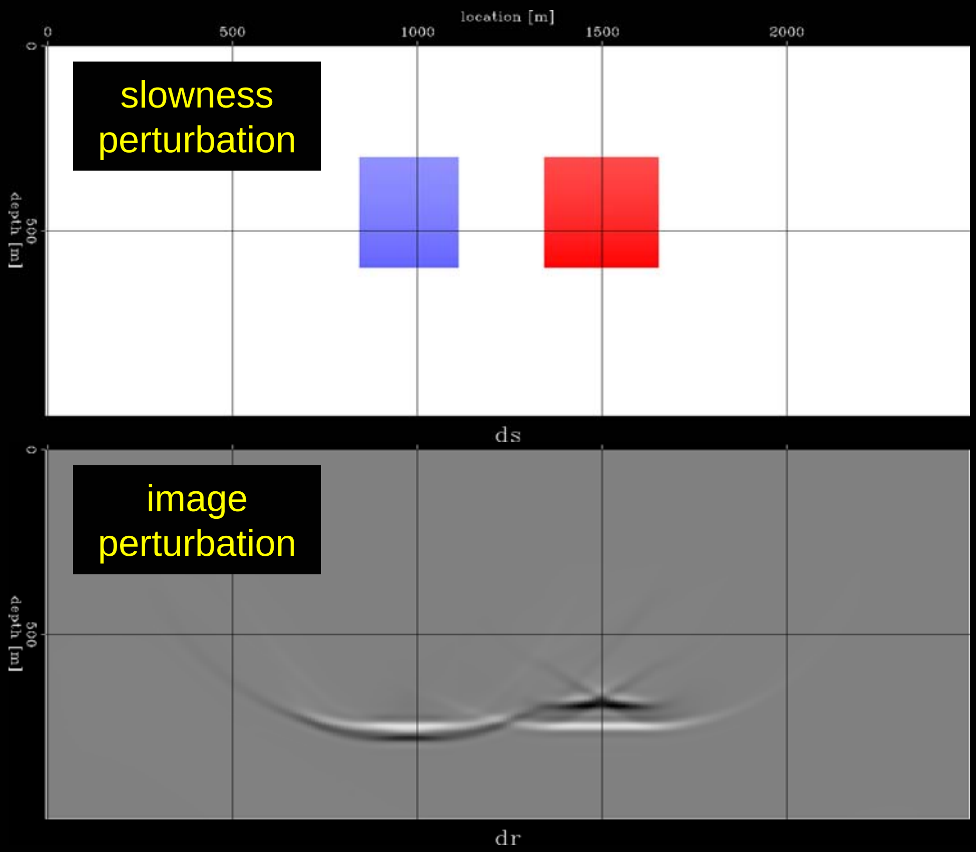
WEMVA: main idea

$$\Delta W = W - W_0$$



Courtesy of Paul Sava (SEP)

WEMVA: objective function



Linear WEMVA operator

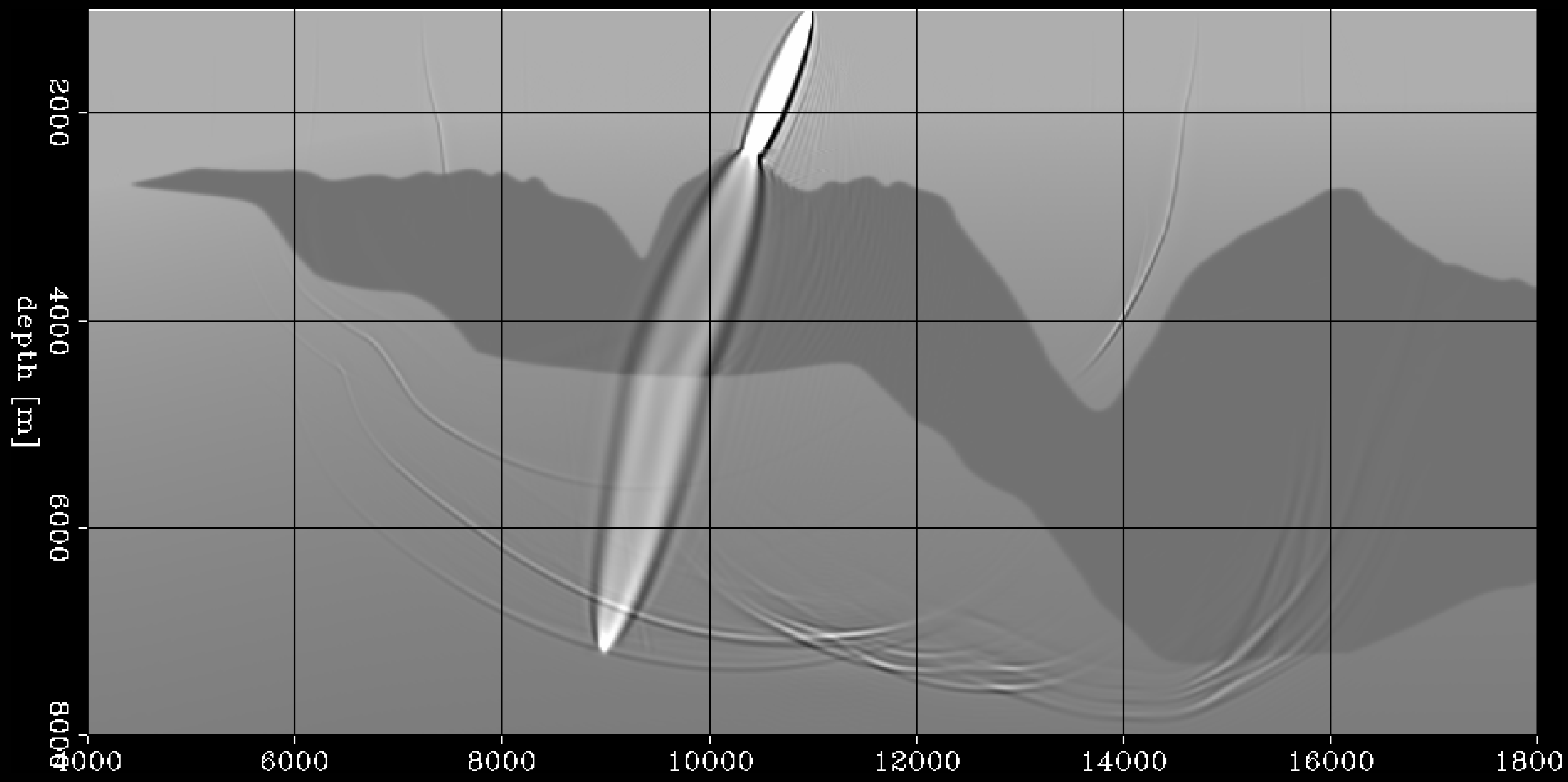
$$\min_{\Delta s} \left\| \Delta R - \mathbf{L} \Delta s \right\|$$

image perturbation (known)

slowness perturbation (unknown)

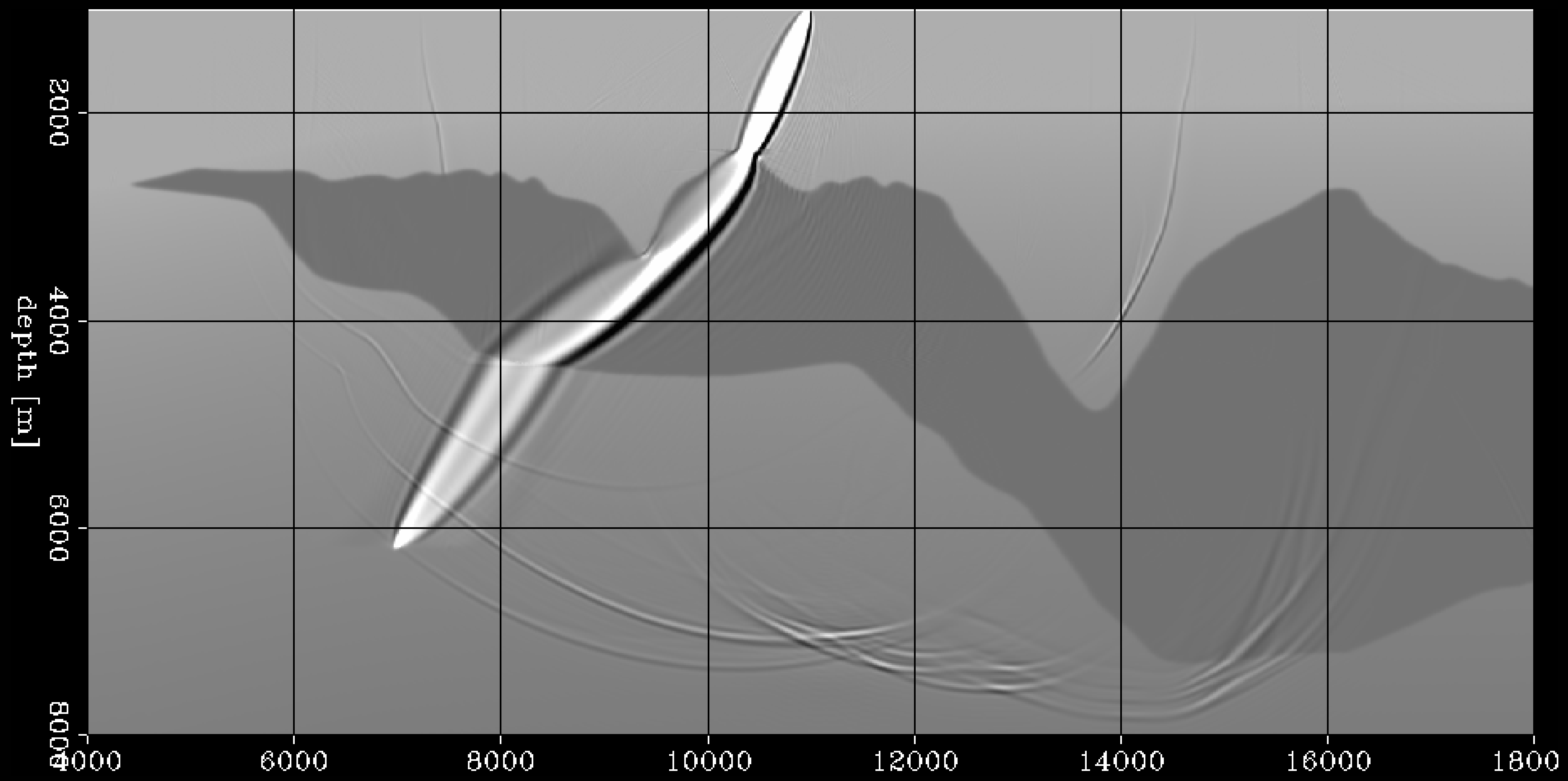
Courtesy of Paul Sava (SEP)

“Simple” wavepath with f=1⇔26 Hz



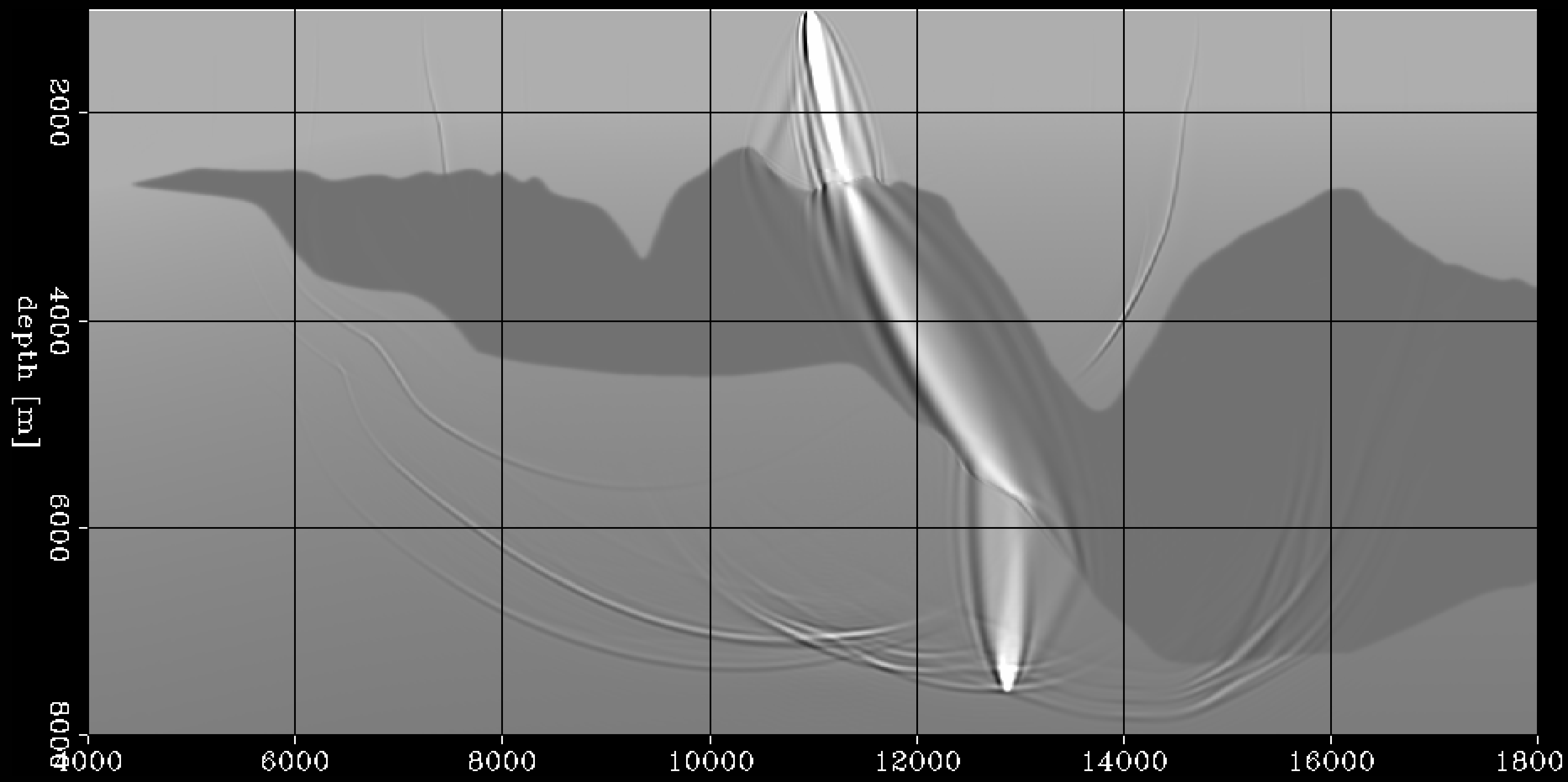
Courtesy of Paul Sava (SEP)

“Complex” wavepath with f=1⇔26 Hz



Courtesy of Paul Sava (SEP)

“Messy” wavepath with f=1⇔26 Hz



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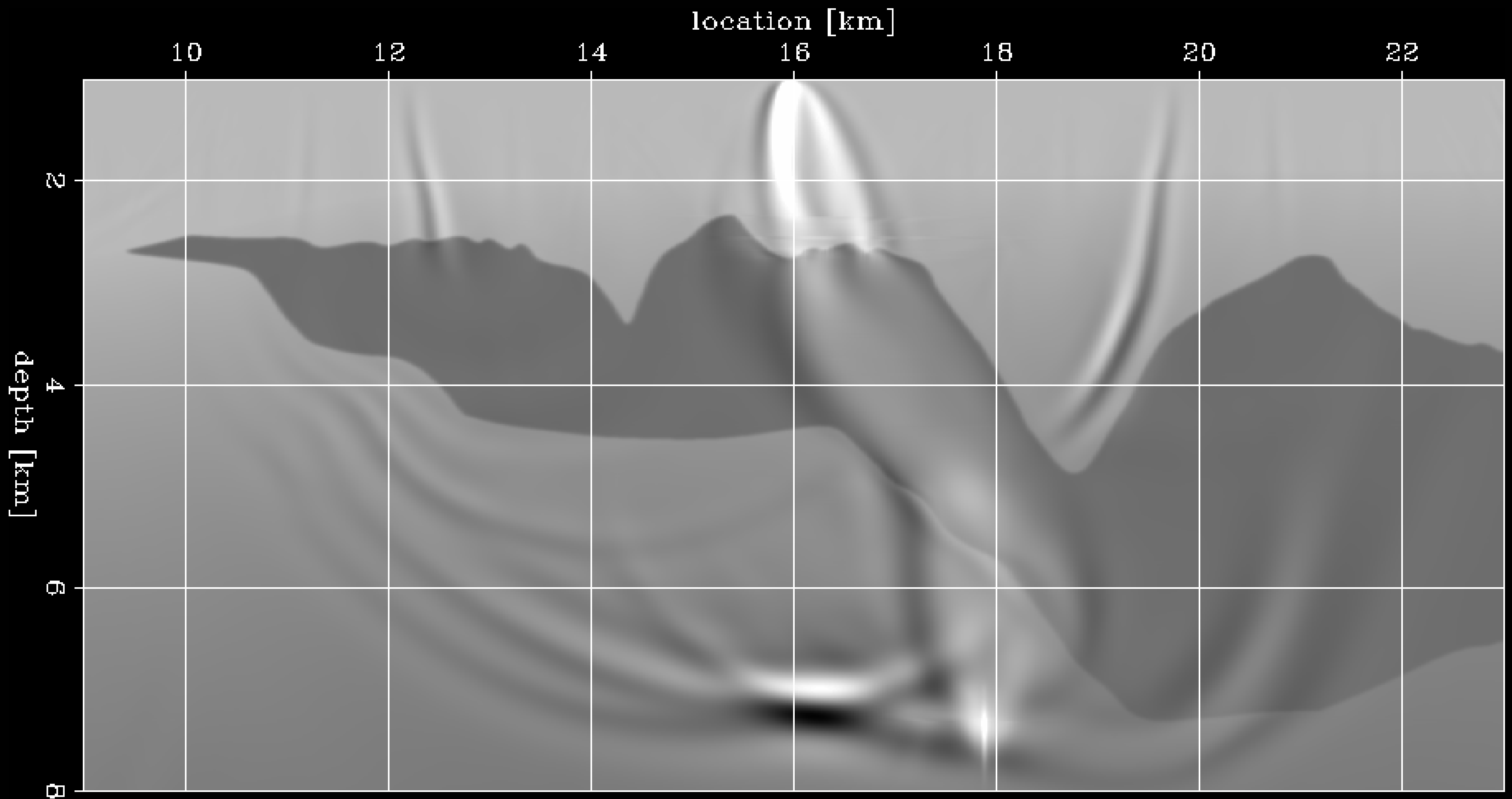
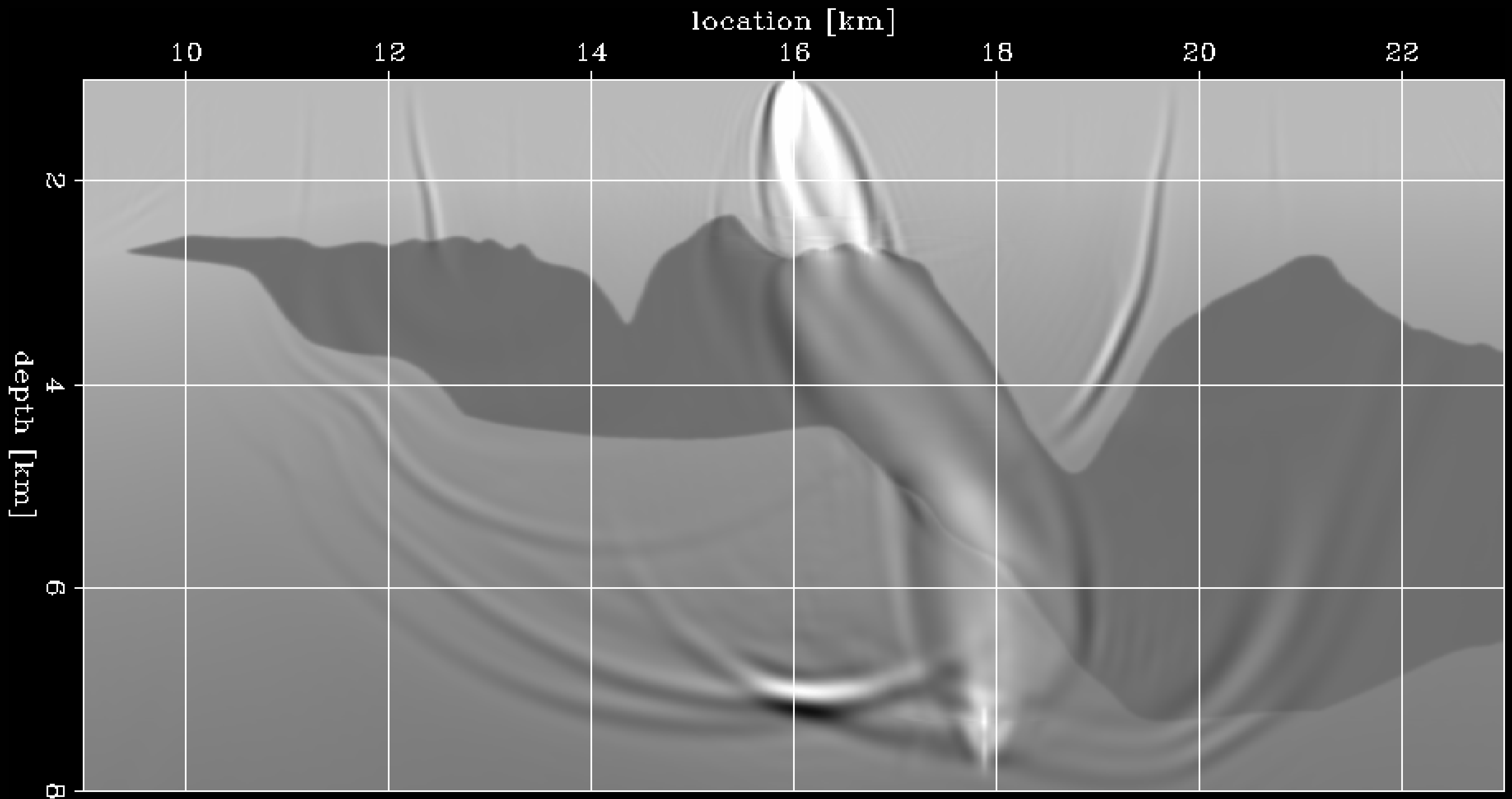
“Messy” wavepath with f=1⇔3 Hz



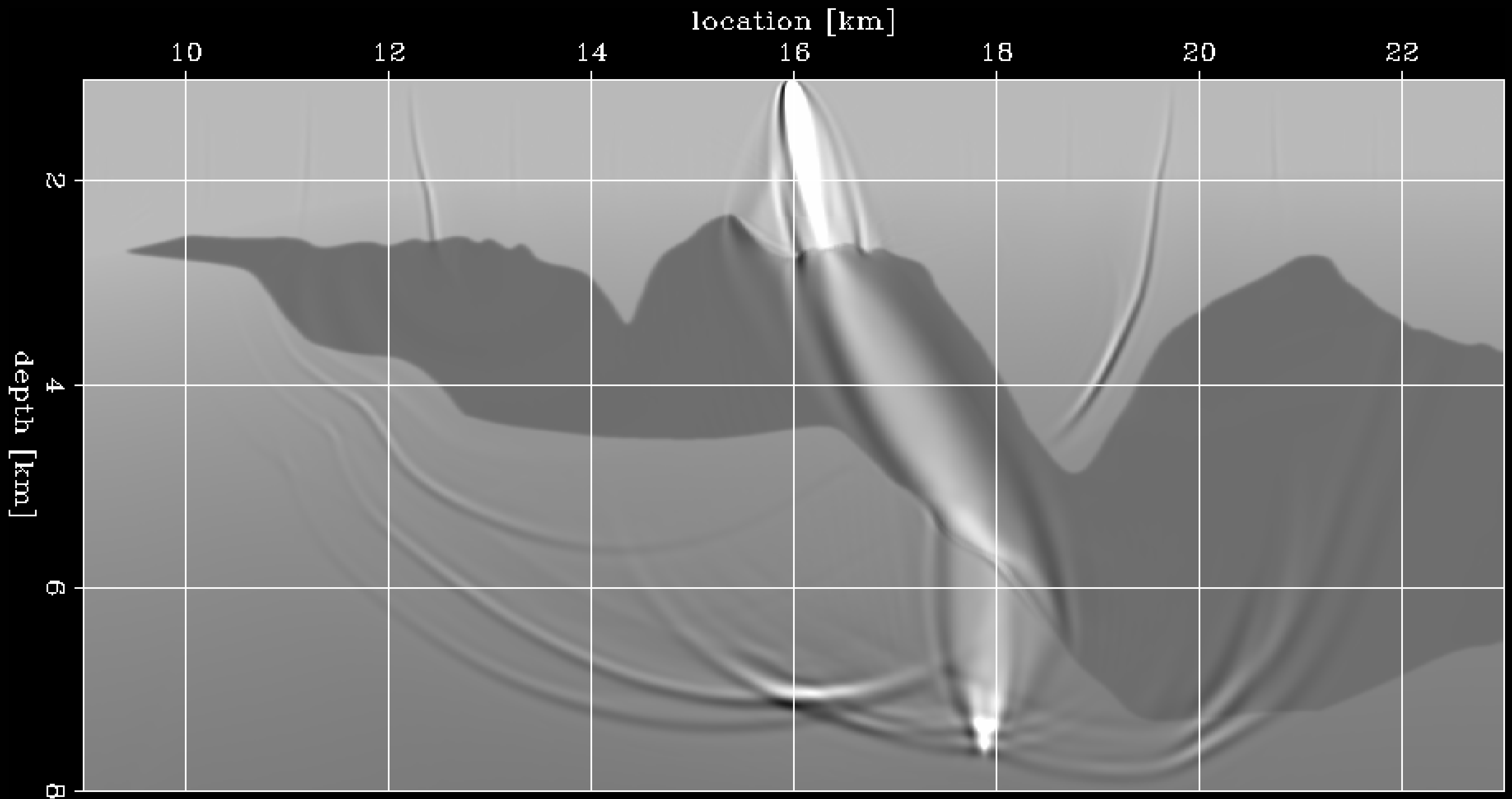
Courtesy of Paul Sava (SEP)

“Messy” wavepath with f=1⇔5 Hz



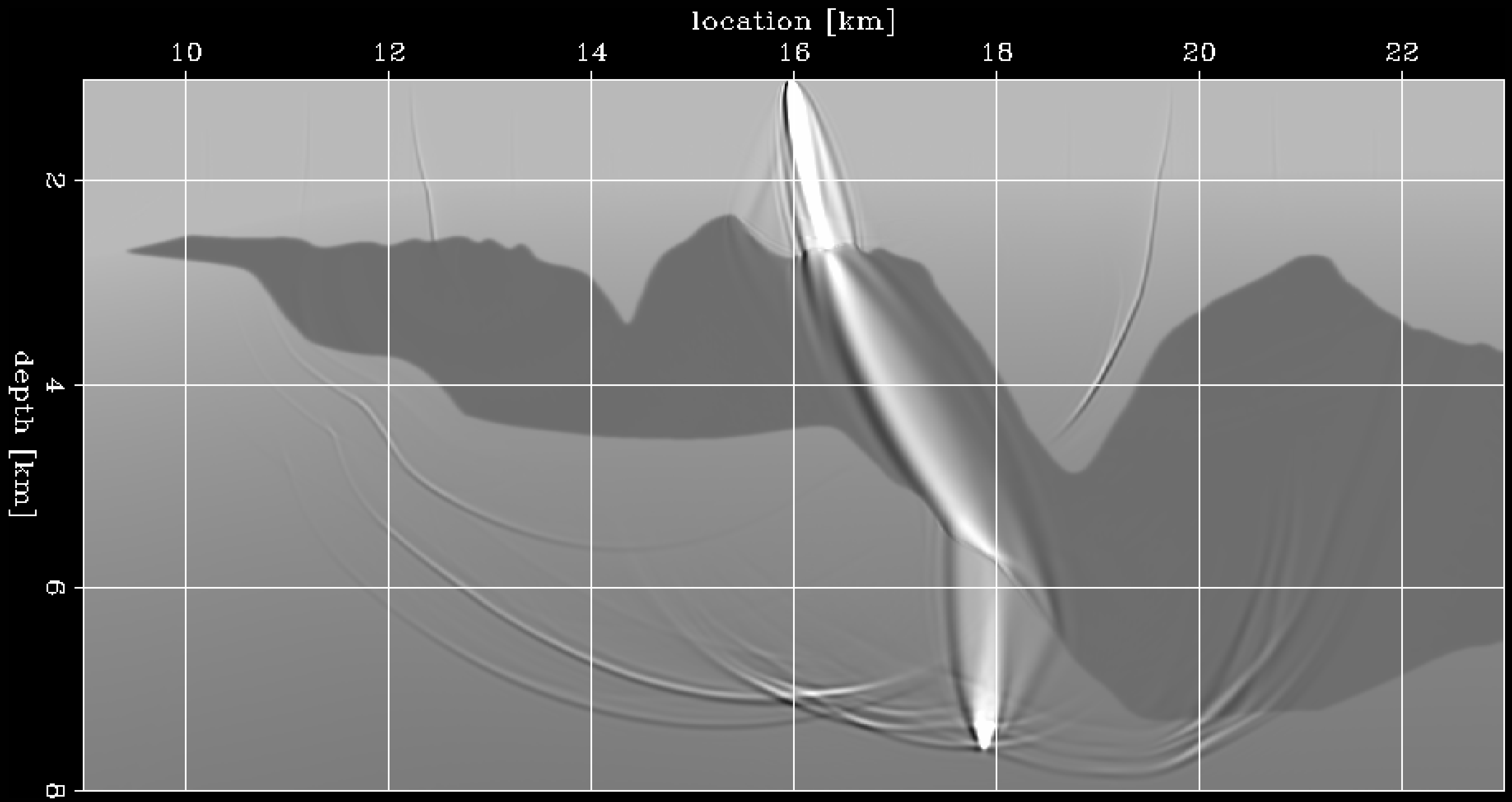
Courtesy of Paul Sava (SEP)

“Messy” wavepath with f=1⇔12 Hz



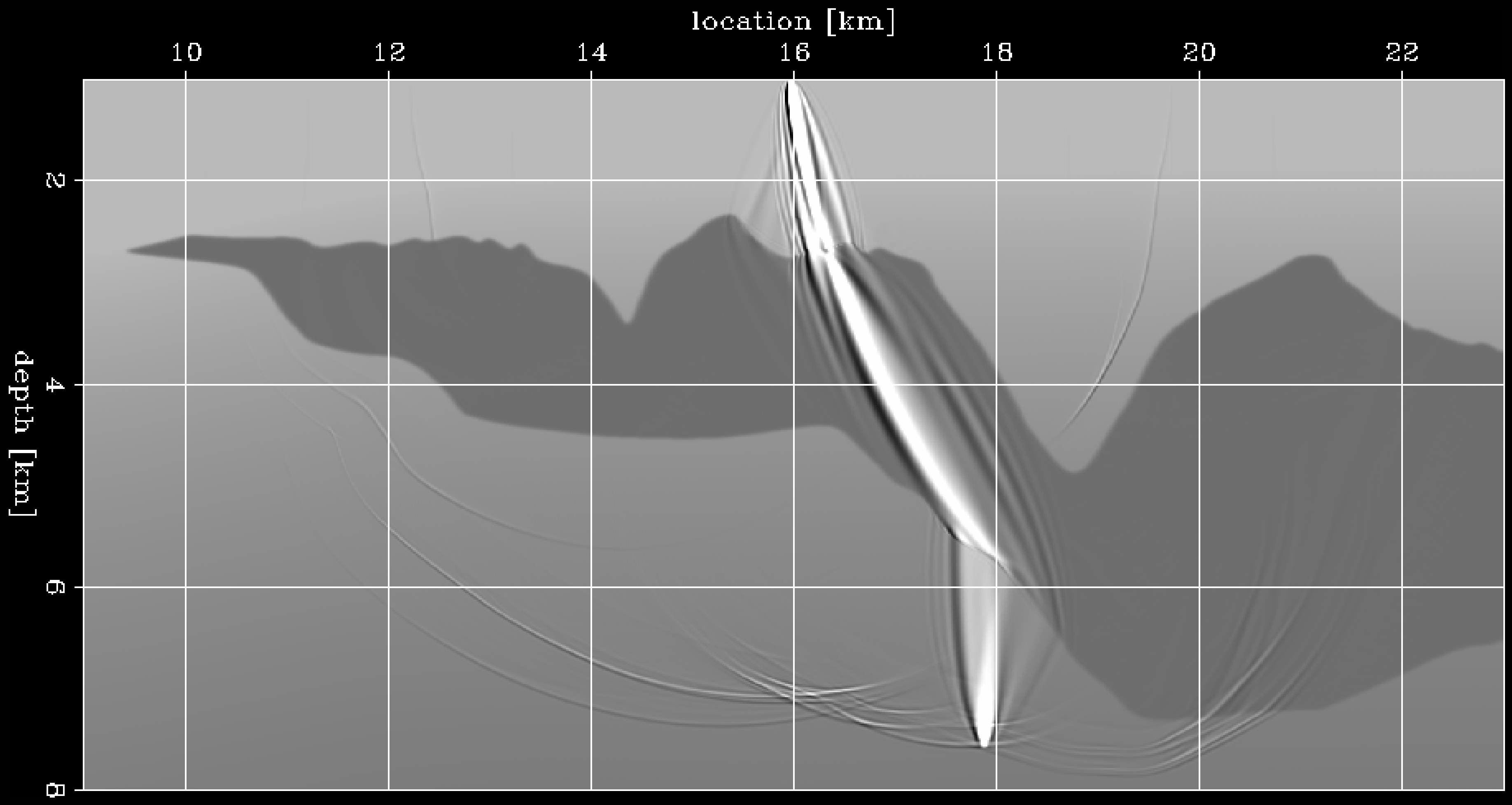
Courtesy of Paul Sava (SEP)

“Messy” wavepath with f=1⇔16 Hz



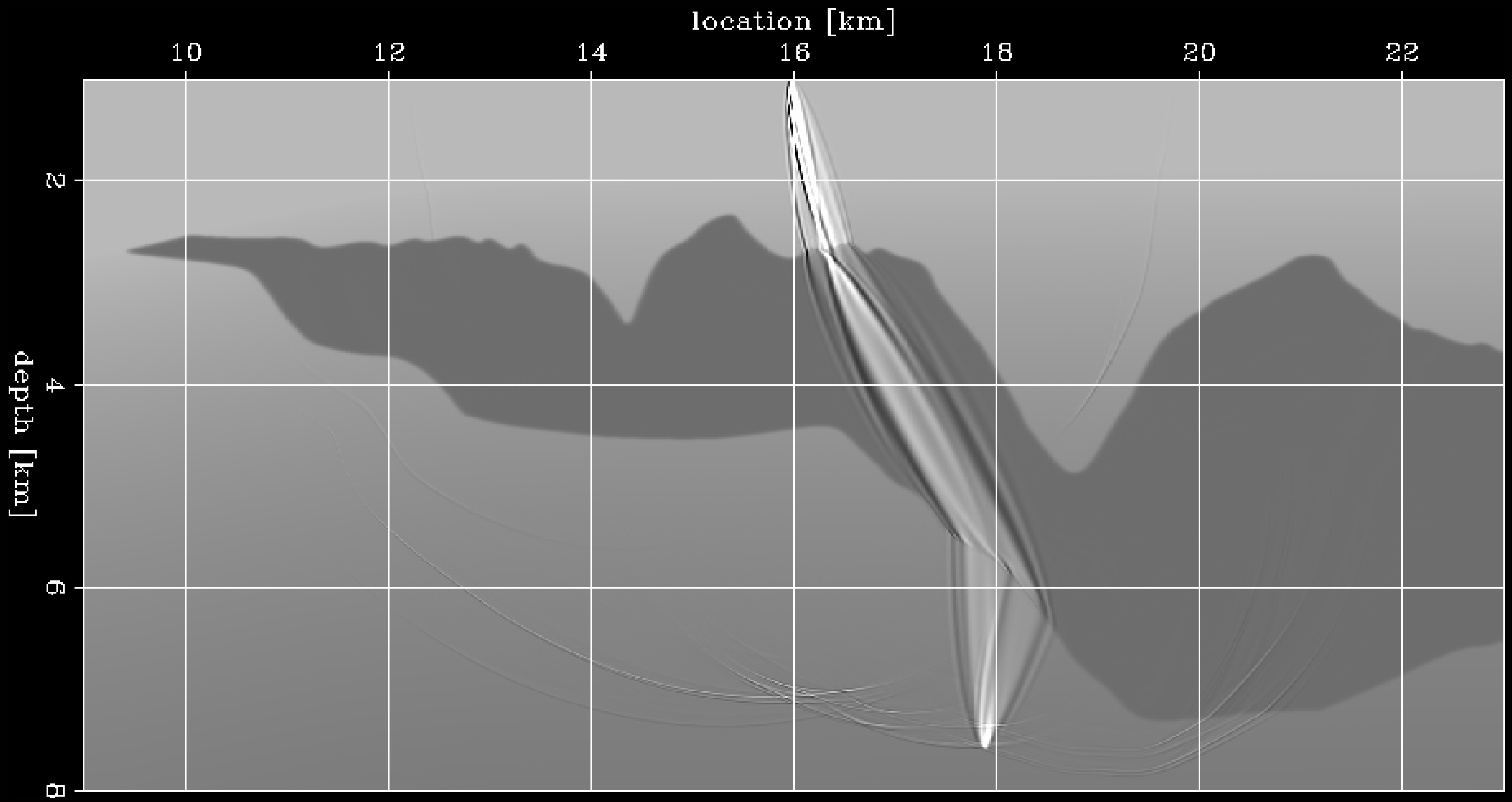
Courtesy of Paul Sava (SEP)

"Messy" wavepath with f=1⇔26 Hz



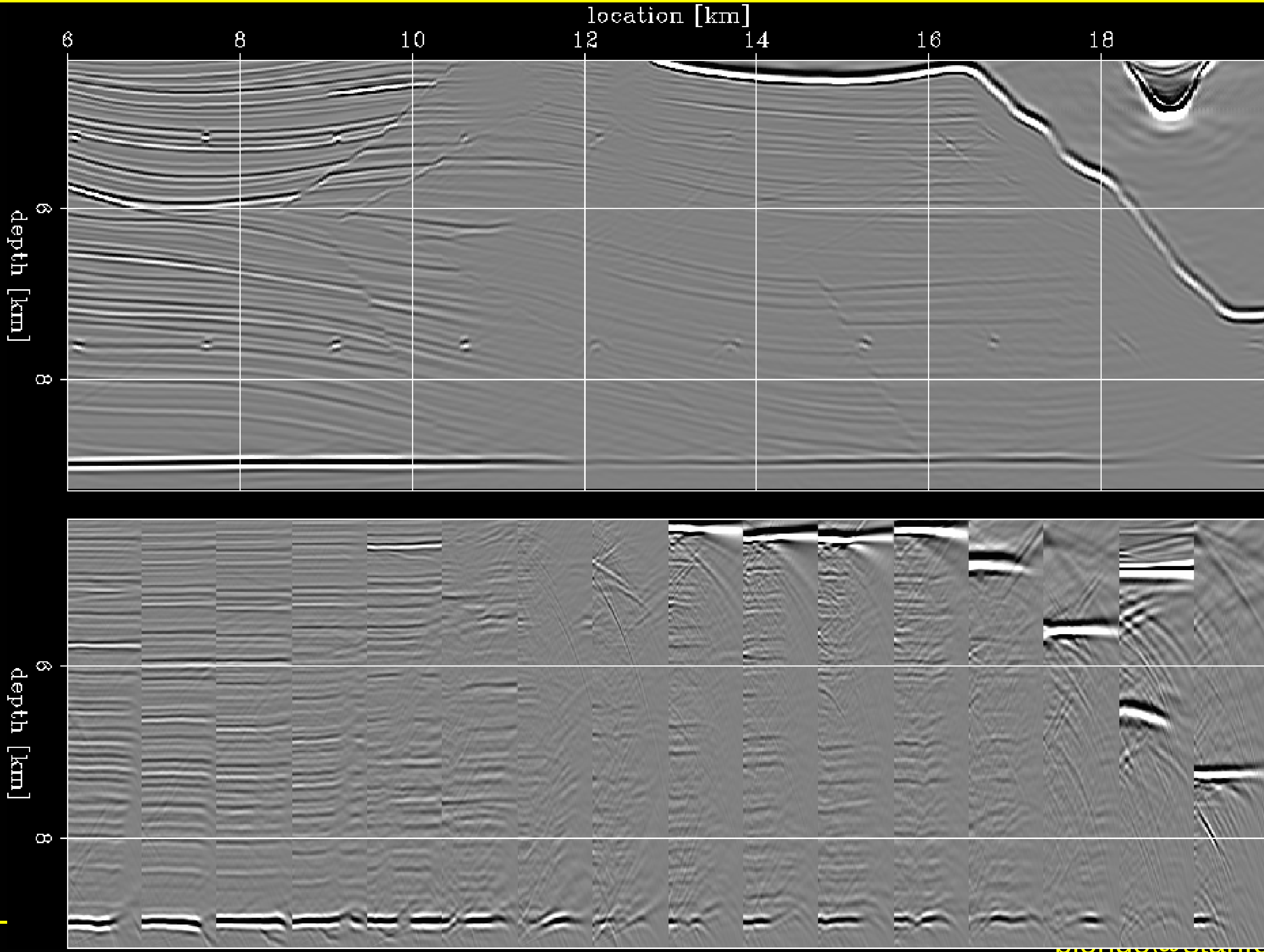
Courtesy of Paul Sava (SEP)

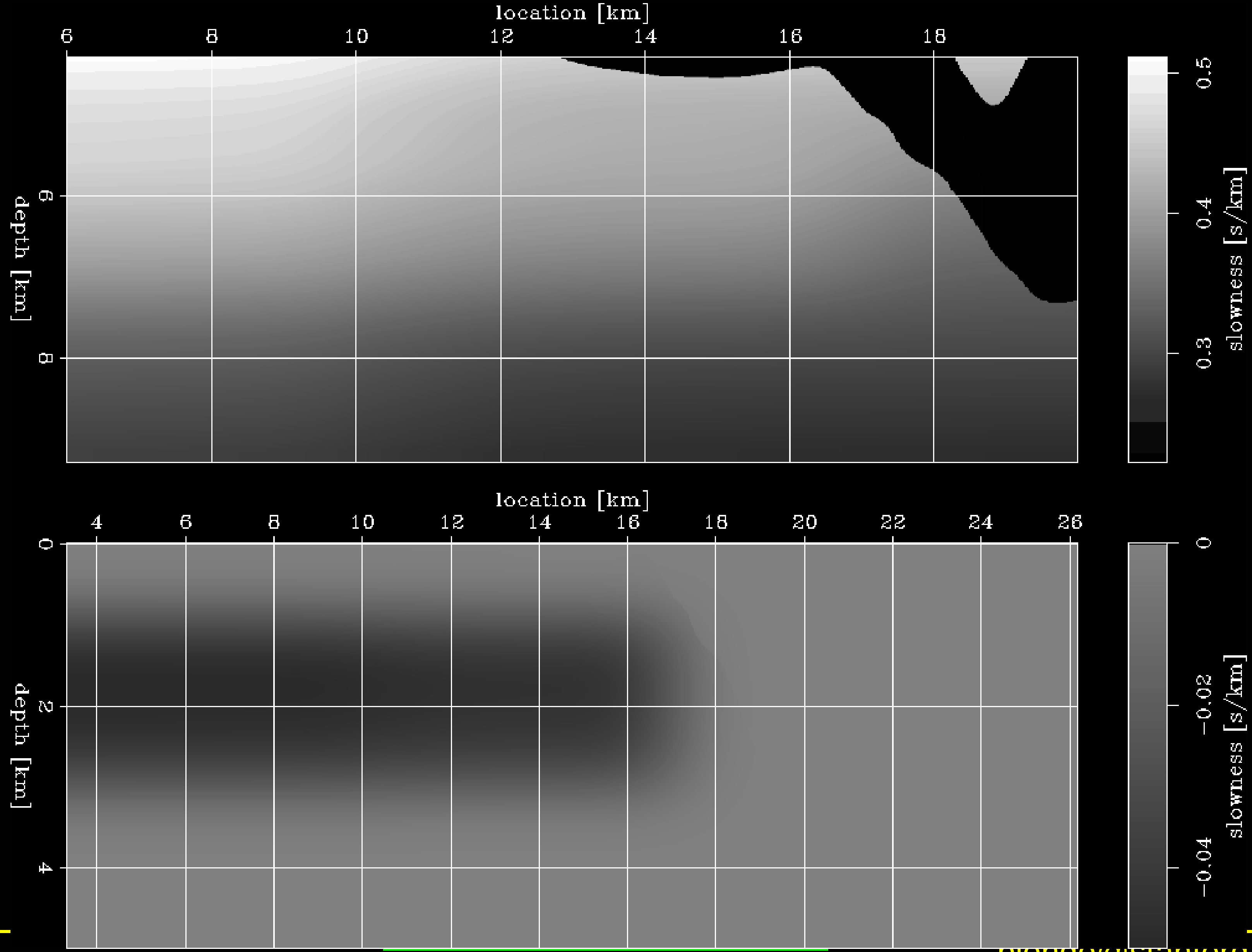
"Messy" wavepath with f=1⇔64 Hz



Courtesy of Paul Sava (SEP)

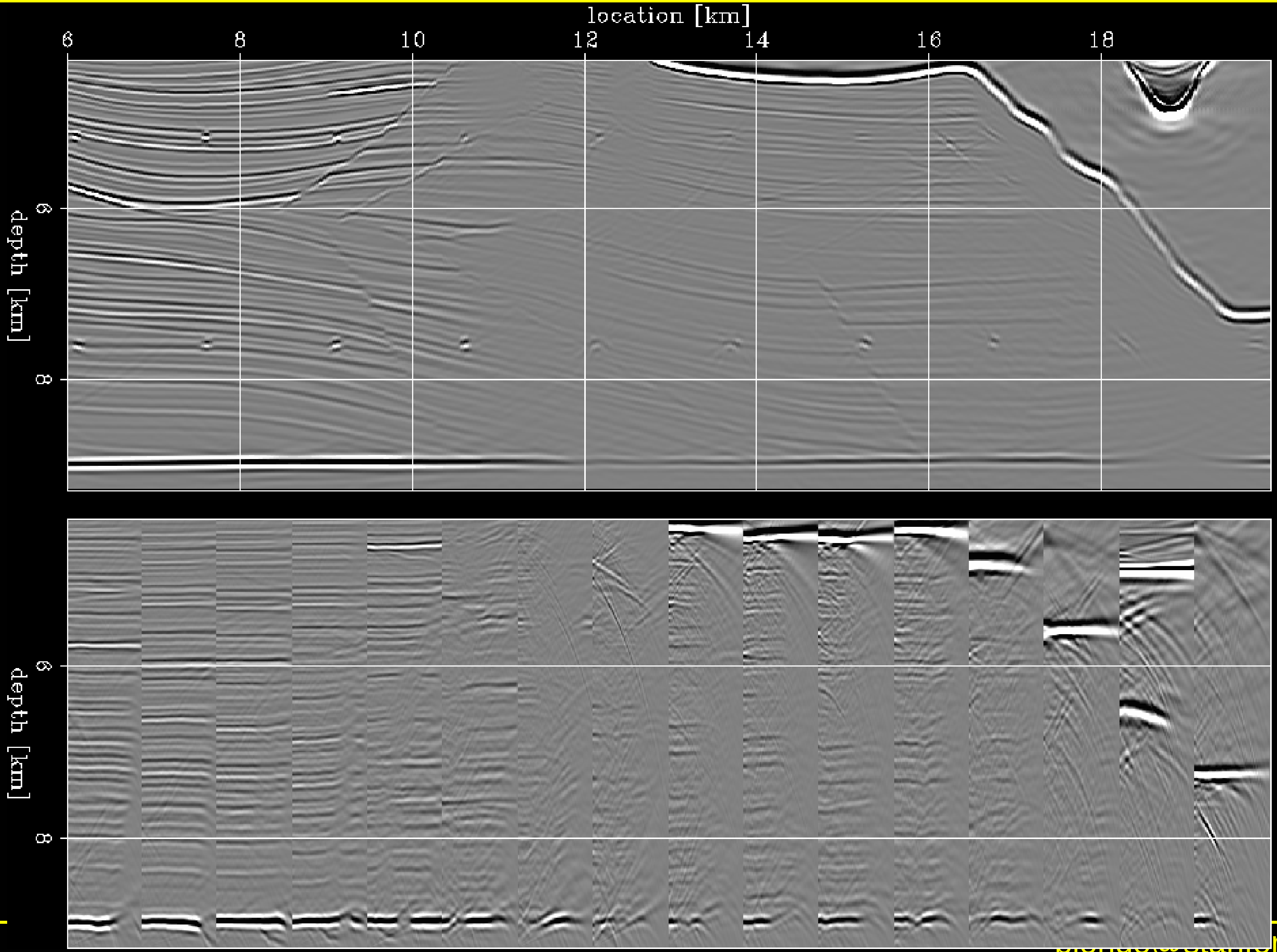
Migration and ADCIGs with correct velocity





location [km]
6
8
10
12
14
16
18
depth [km]
6
8
0.5
0.4
0.3
slowness [s/km]
location [km]
4
6
8
10
12
14
16
18
20
22
24
26
depth [km]
0
2
4
0
−0.02
−0.04
slowness [s/km]

Migration and ADCIGs with correct velocity



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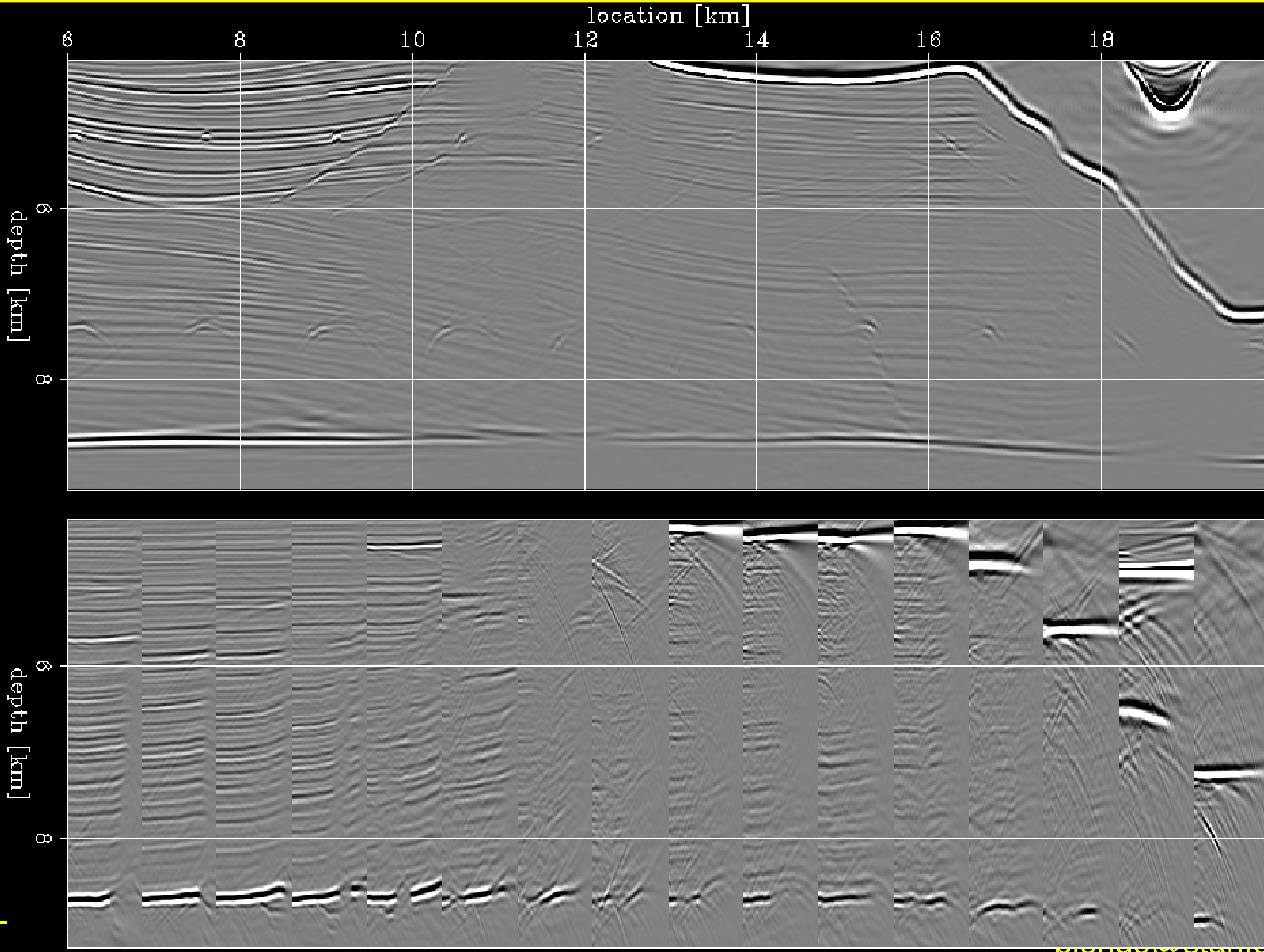
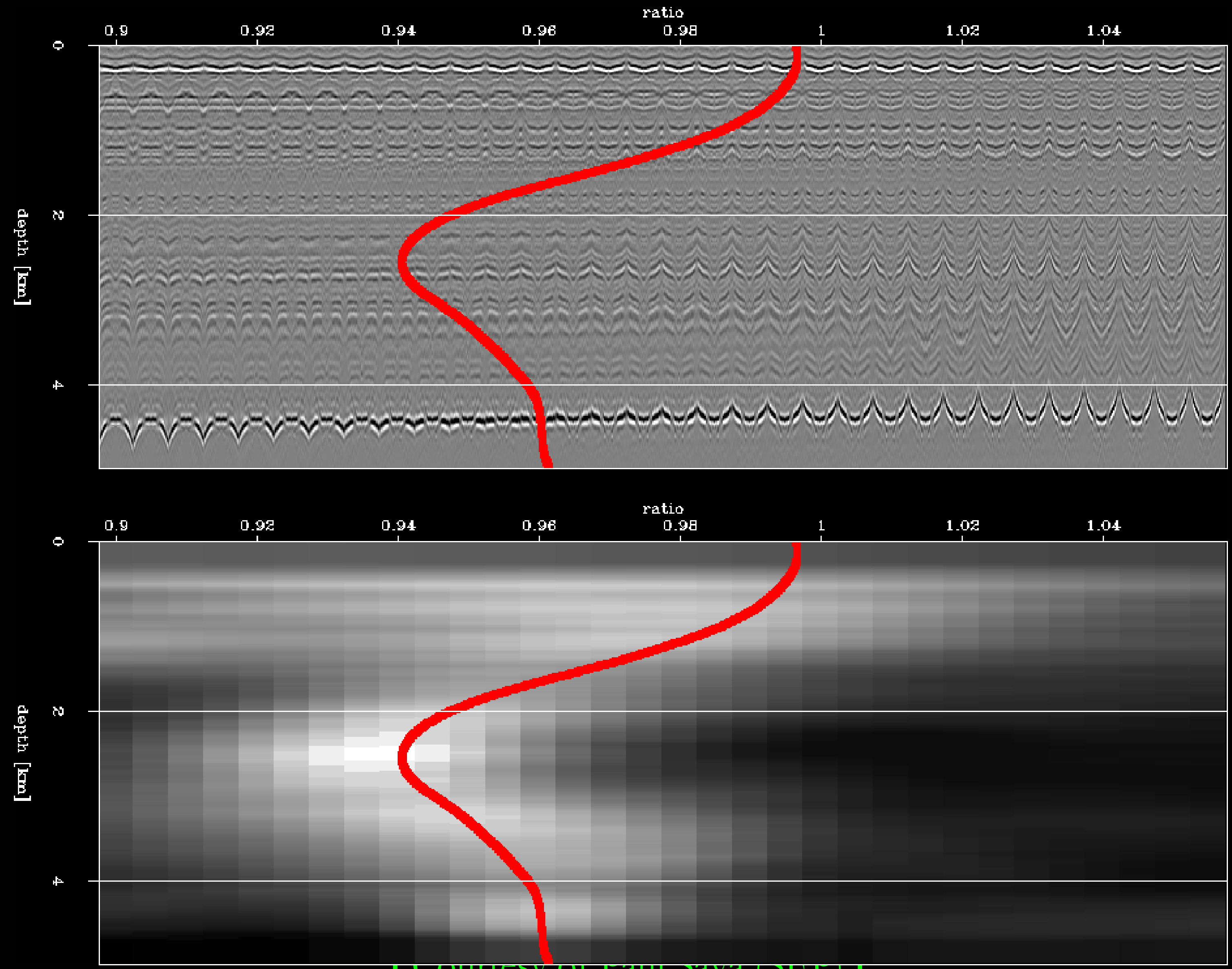
Migration and ADCIGs with initial velocity



Measuring velocity errors by residual migration



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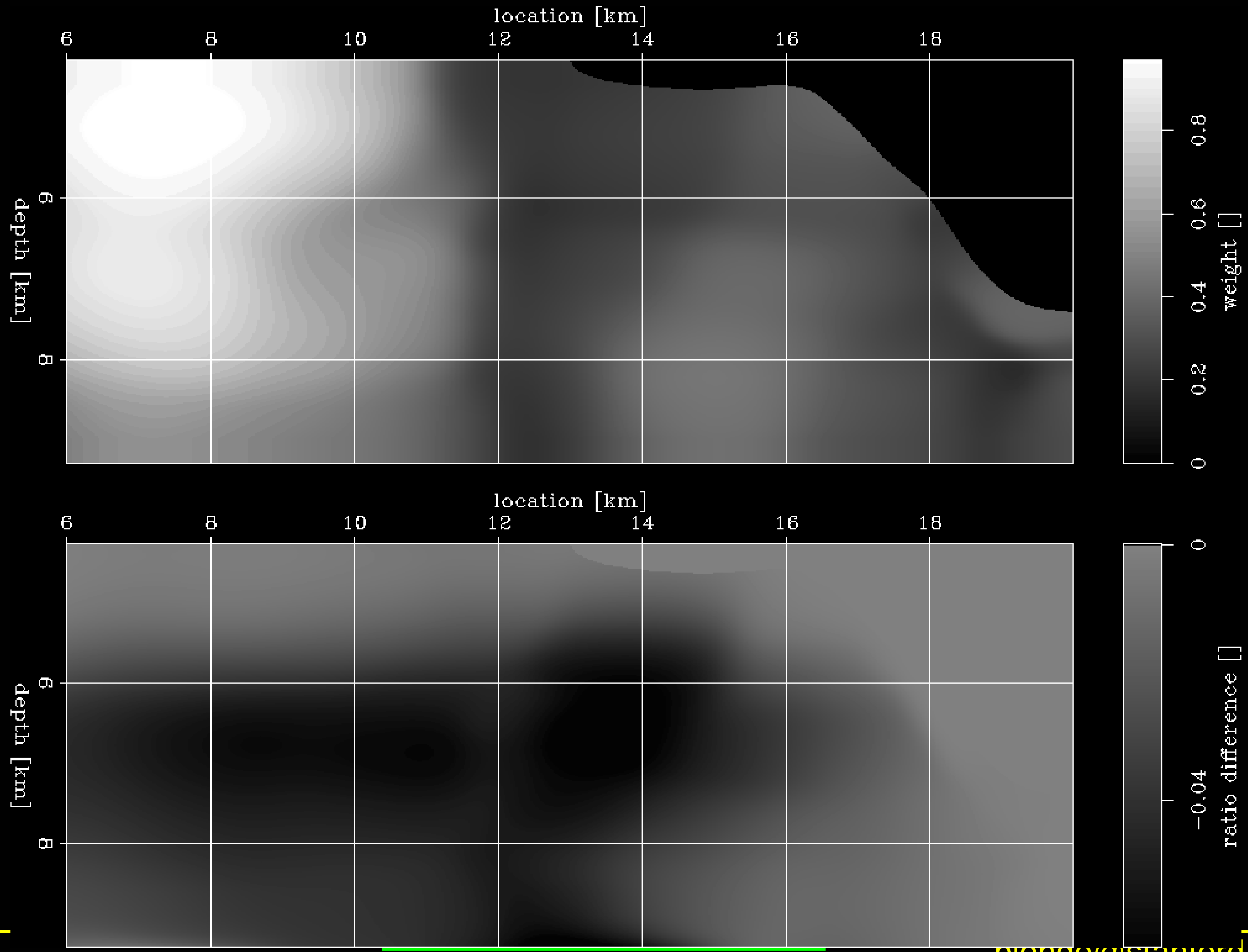
Reliability of measurements and velocity errors



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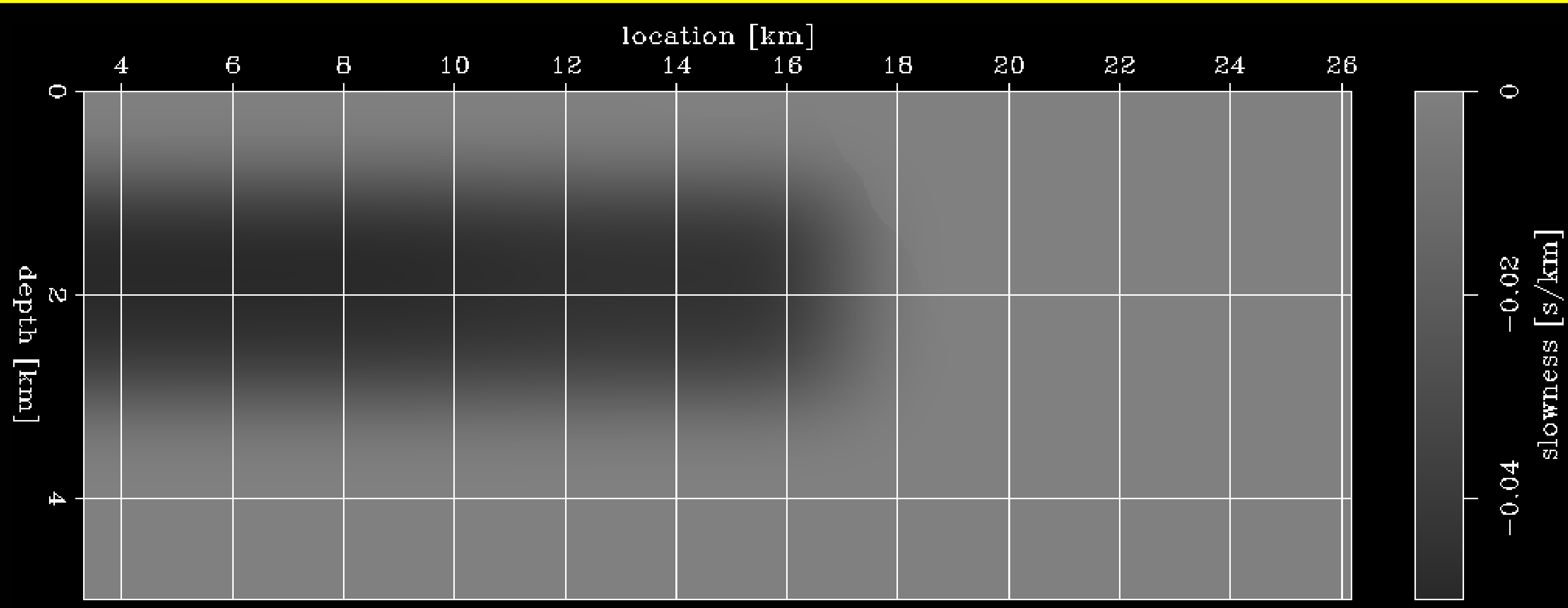
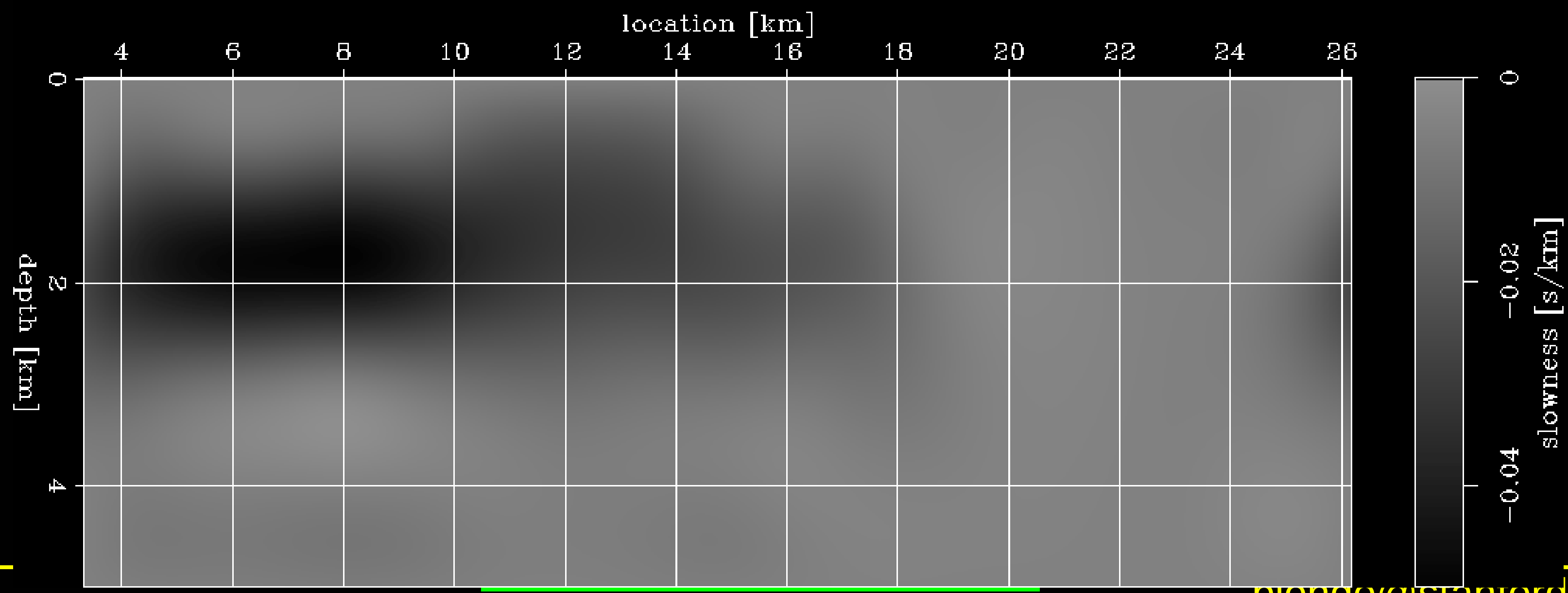
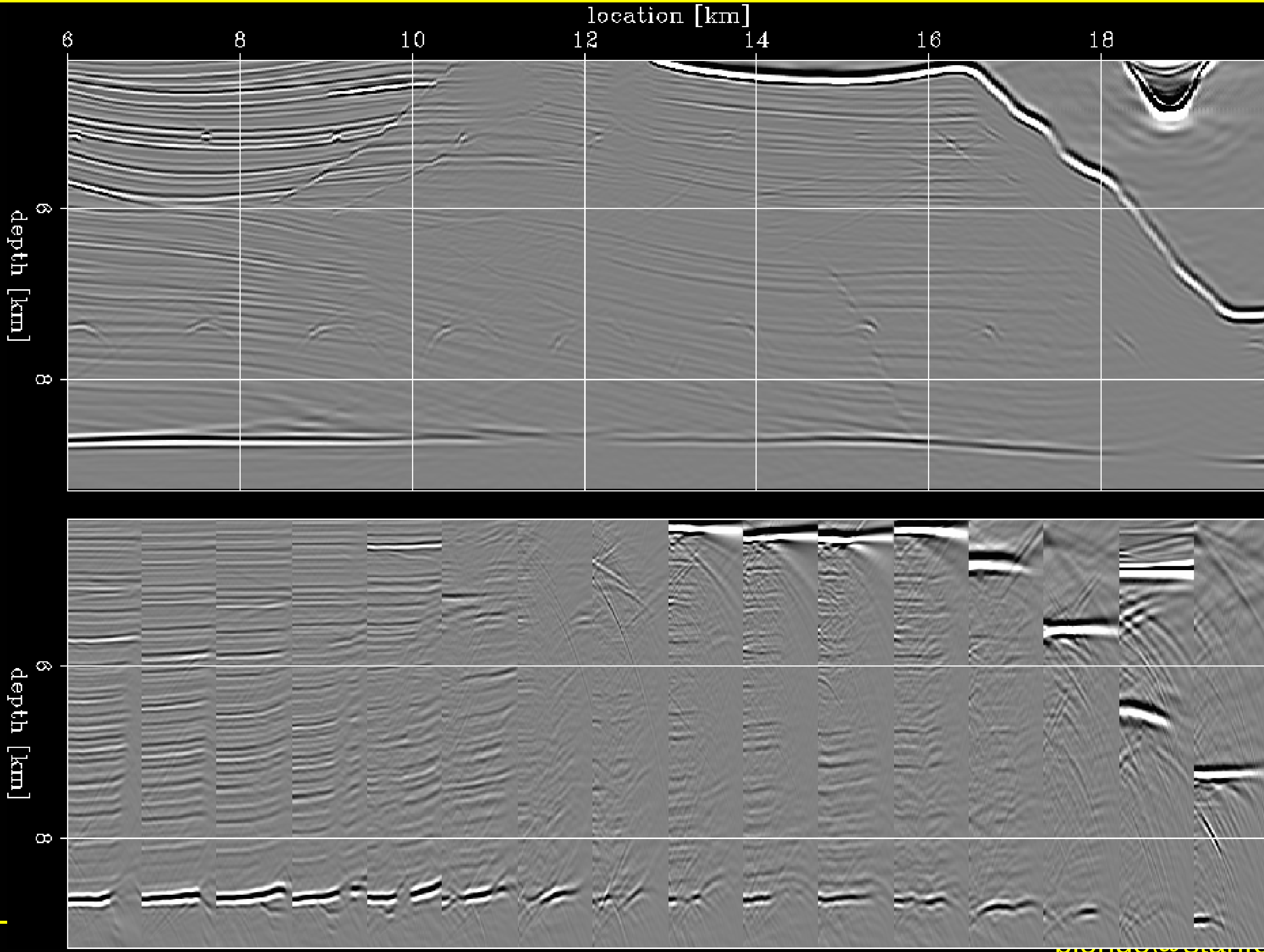
True and estimated velocity error

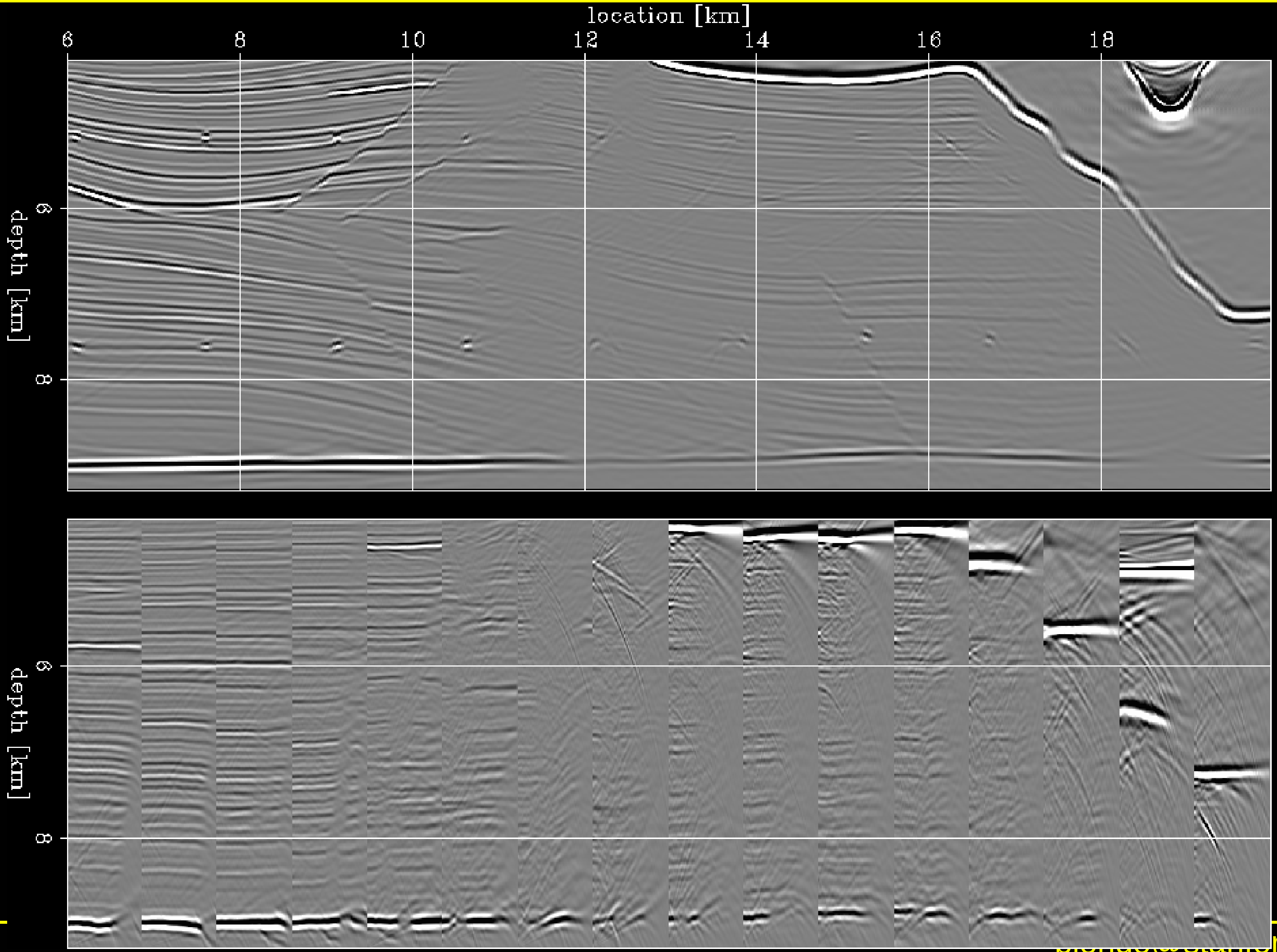




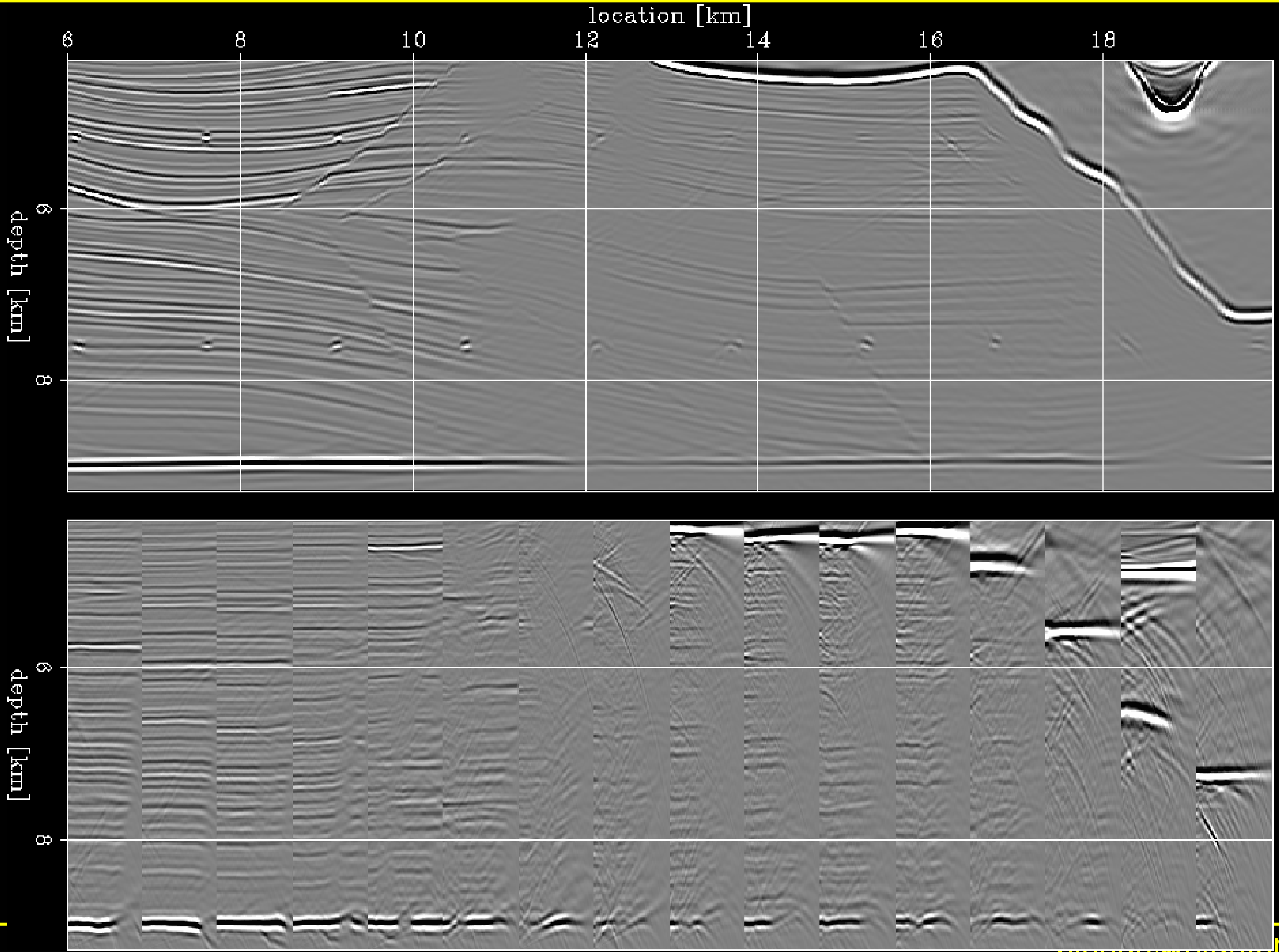
Migration and ADCIGs with initial velocity



Migration and ADCIGs with estimated velocity



Migration and ADCIGs with correct velocity



Conclusions

- Complex structures require accurate and expensive wavefield-continuation imaging operators.
- To image reflectors that are poorly illuminated we need to go beyond the application of the adjoint operator (migration) and move towards “intelligent” (regularized) inversion.
- Wavefield-continuation operators are beneficial not only for migration but also for velocity estimation.
- The estimation of holes in poorly illuminated reflectors and of velocity errors are tightly coupled problems.

Acknowledgments

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- Total for North Sea data set.
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