Seismic Attributes - from Interactive Interpretation to Machine Learning

Kurt J. Marfurt (The University of Oklahoma)

Geometric Attributes - Coherence

Geometric Attributes that map continuity, amplitude changes and textures

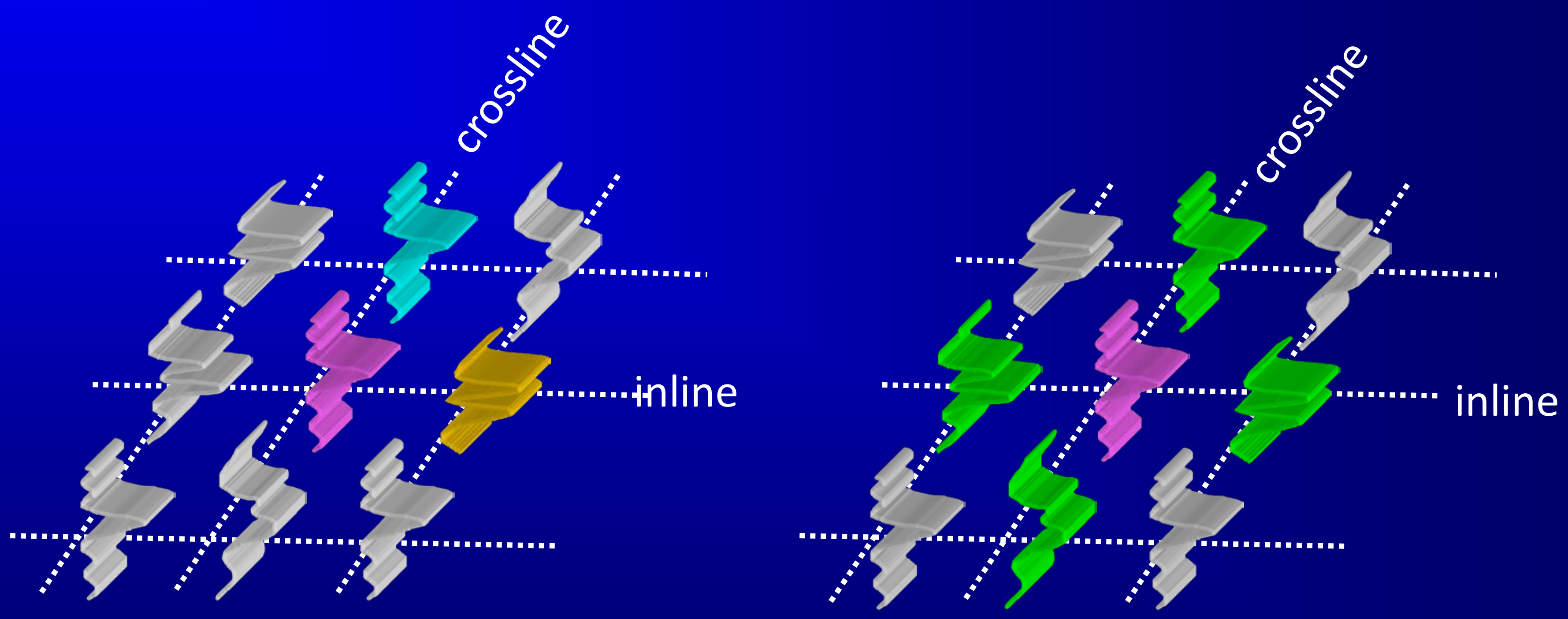
1. Coherence — Faults, channel edges, karst, dewatering
2. Amplitude gradients — Thin channels, fractures
3. GLCM textures — Chaotic vs. smooth reflector patterns

Coherence

After this section you will be able to:

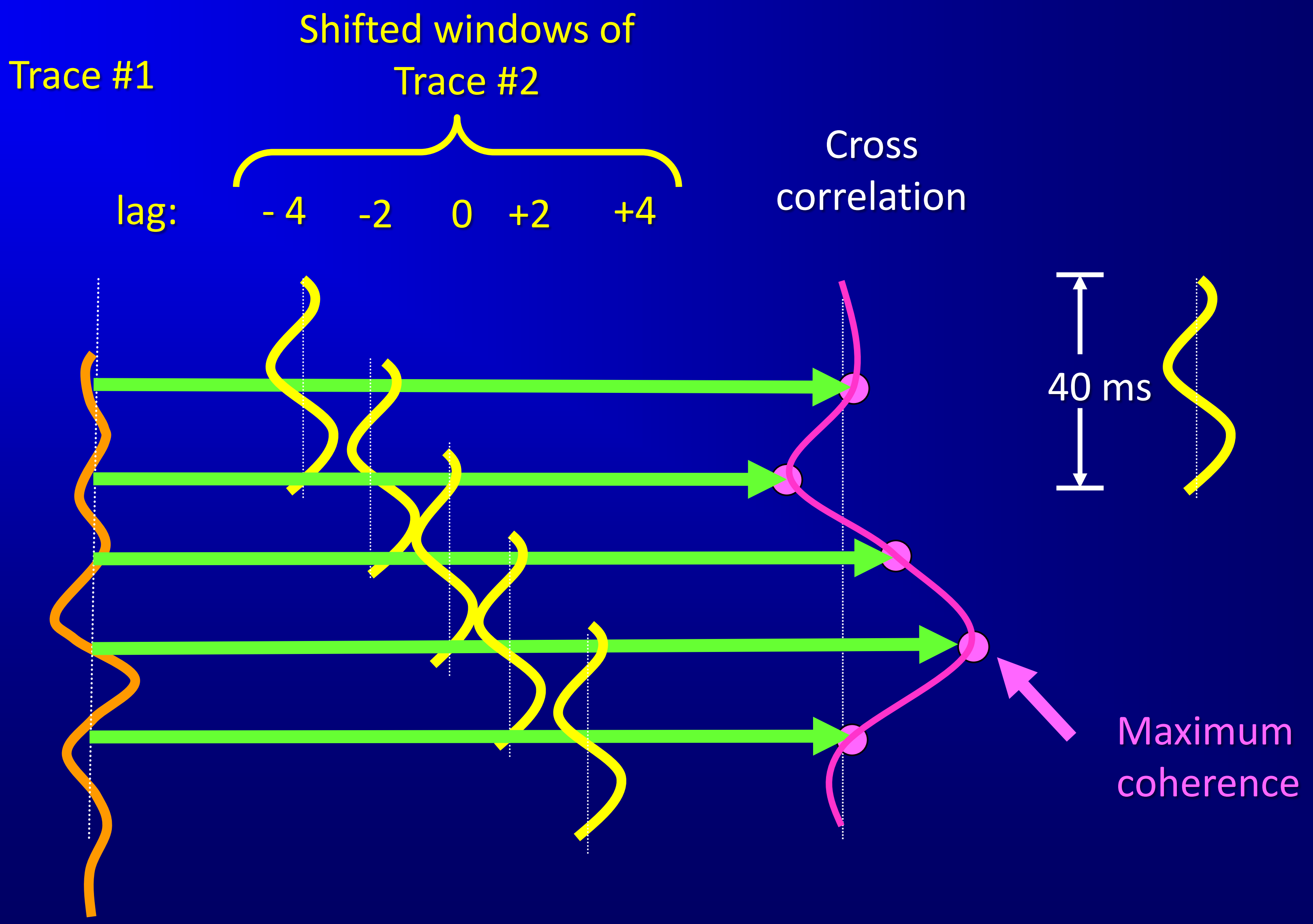
- Summarize the physical and mathematical basis of alternative seismic coherence algorithms,
- Evaluate the impact of spatial and temporal analysis window size on the resolution of geologic features, and
- Recognize artifacts due to algorithm design or due to limits in seismic data quality, seismic imaging, and/or geologic complexity.

Coherence compares the waveforms of neighboring traces



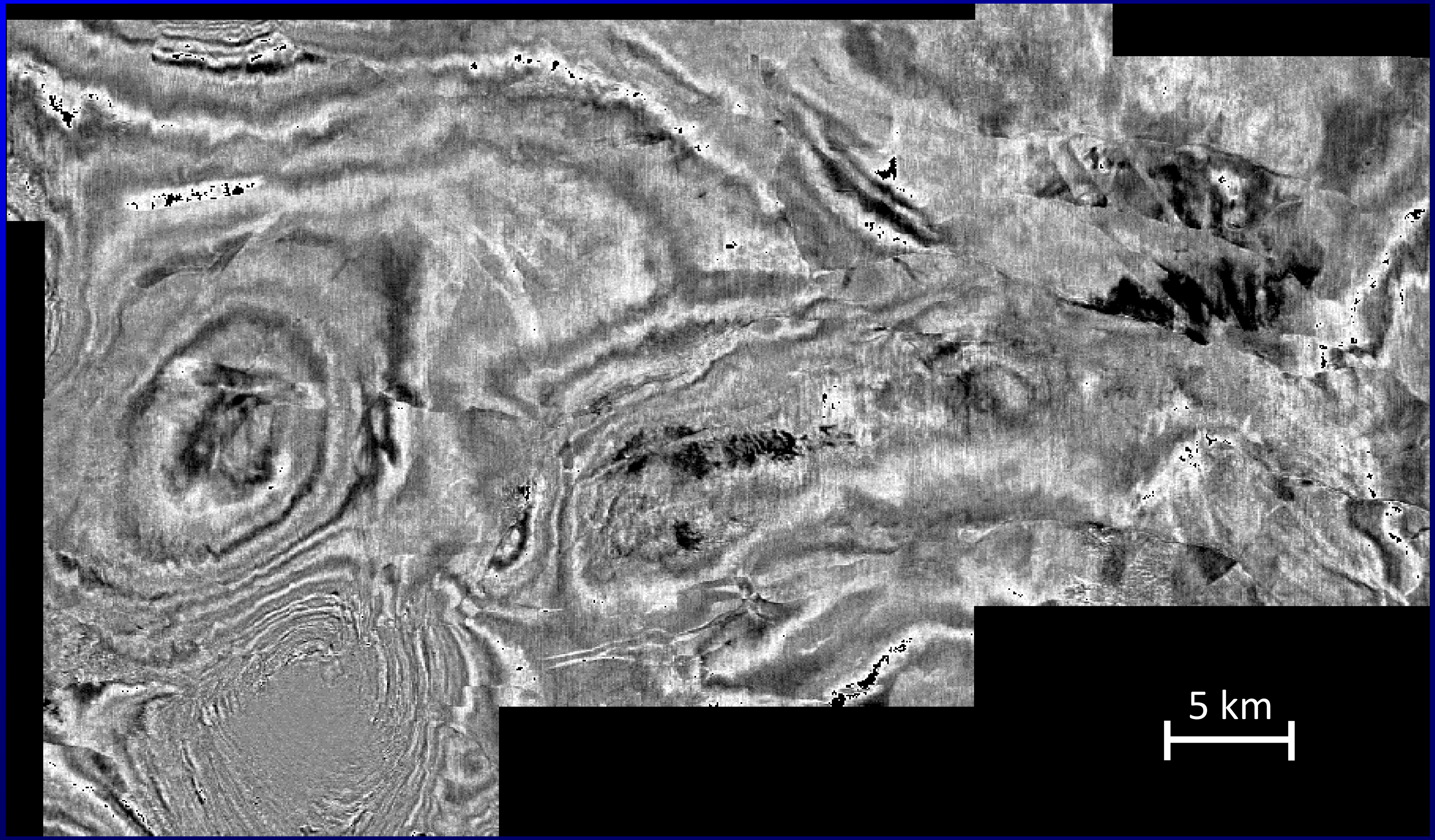
(Chopra and Marfurt, 2007)

Cross correlation of two traces



(Chopra and Marfurt, 2007)

Time slice through the seismic amplitude volume



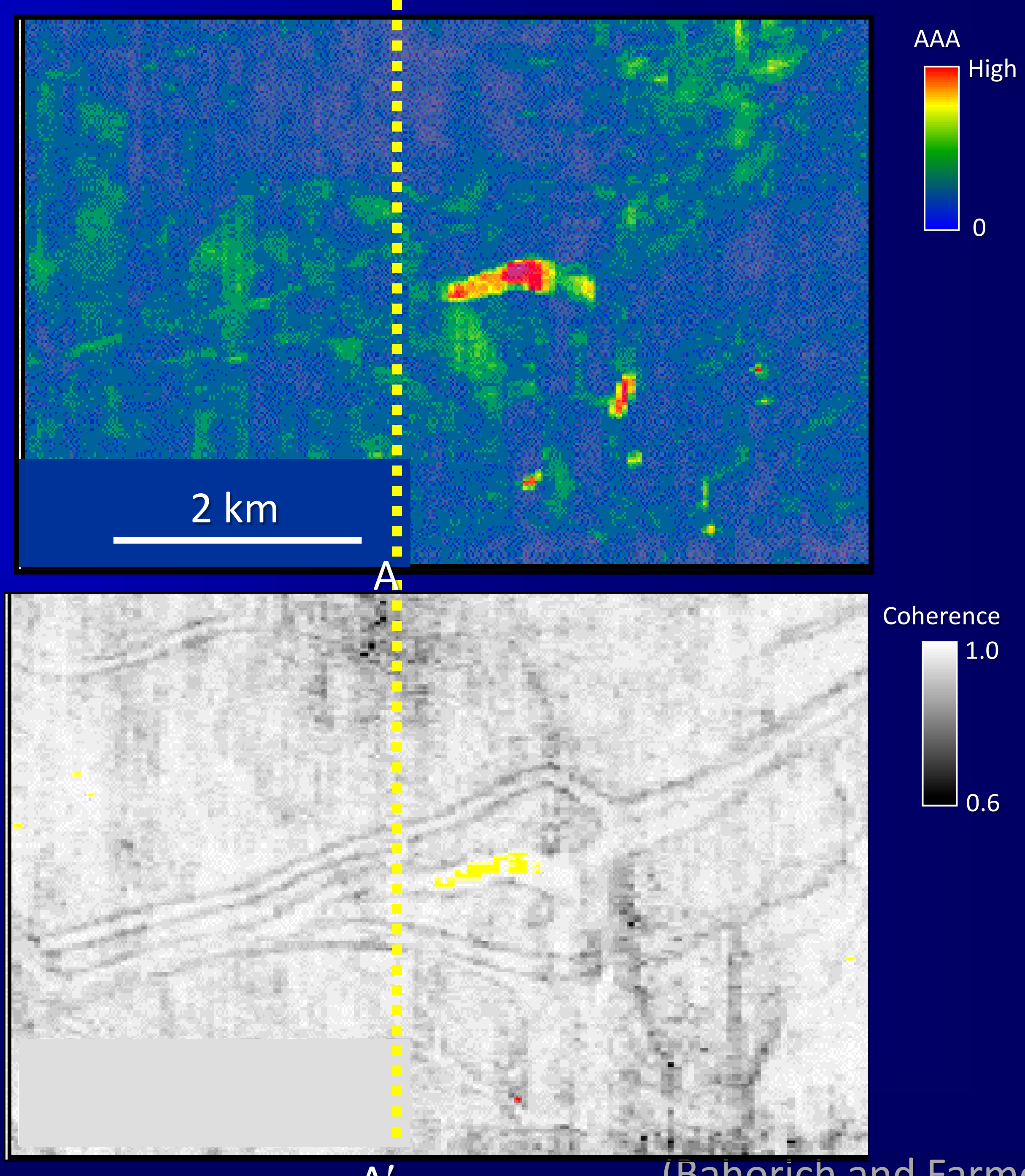
(Bahorich and Farmer, 1995)

Time slice through the coherence volume

(Bahorich and Farmer, 1995)

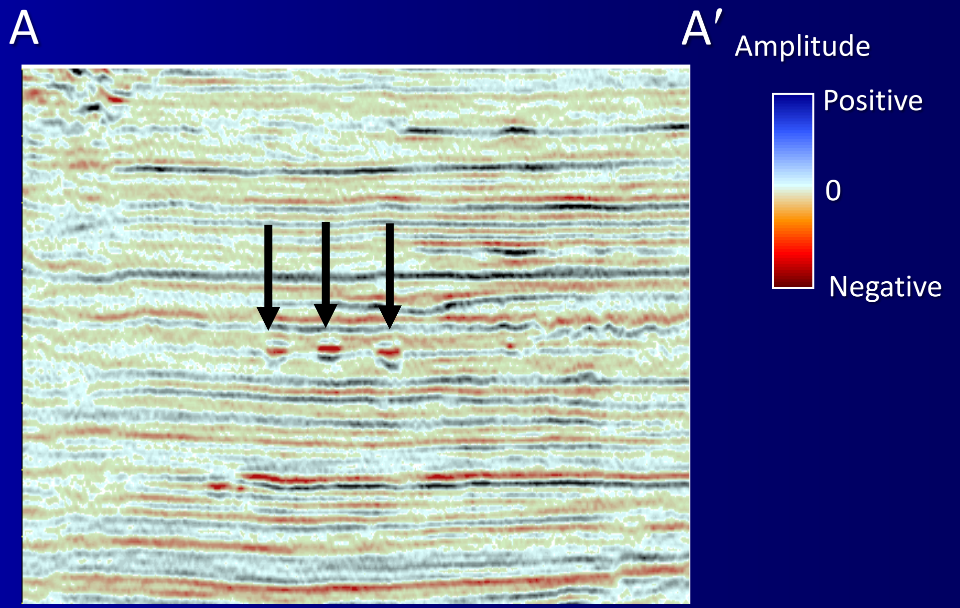
Time slice through
average absolute amplitude

Time slice through coherence
(initial crosscorrelation algorithm)

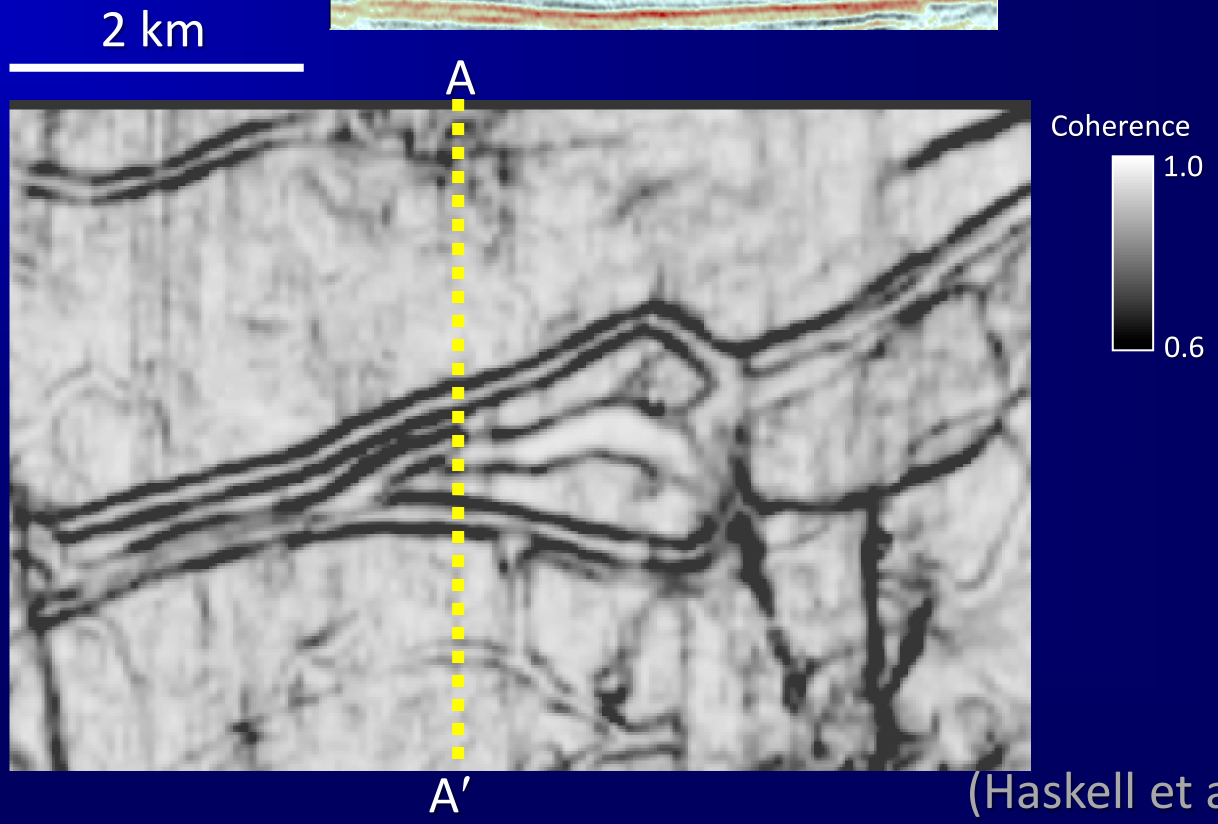


(Bahorich and Farmer, 1995)

Vertical slice through amplitude

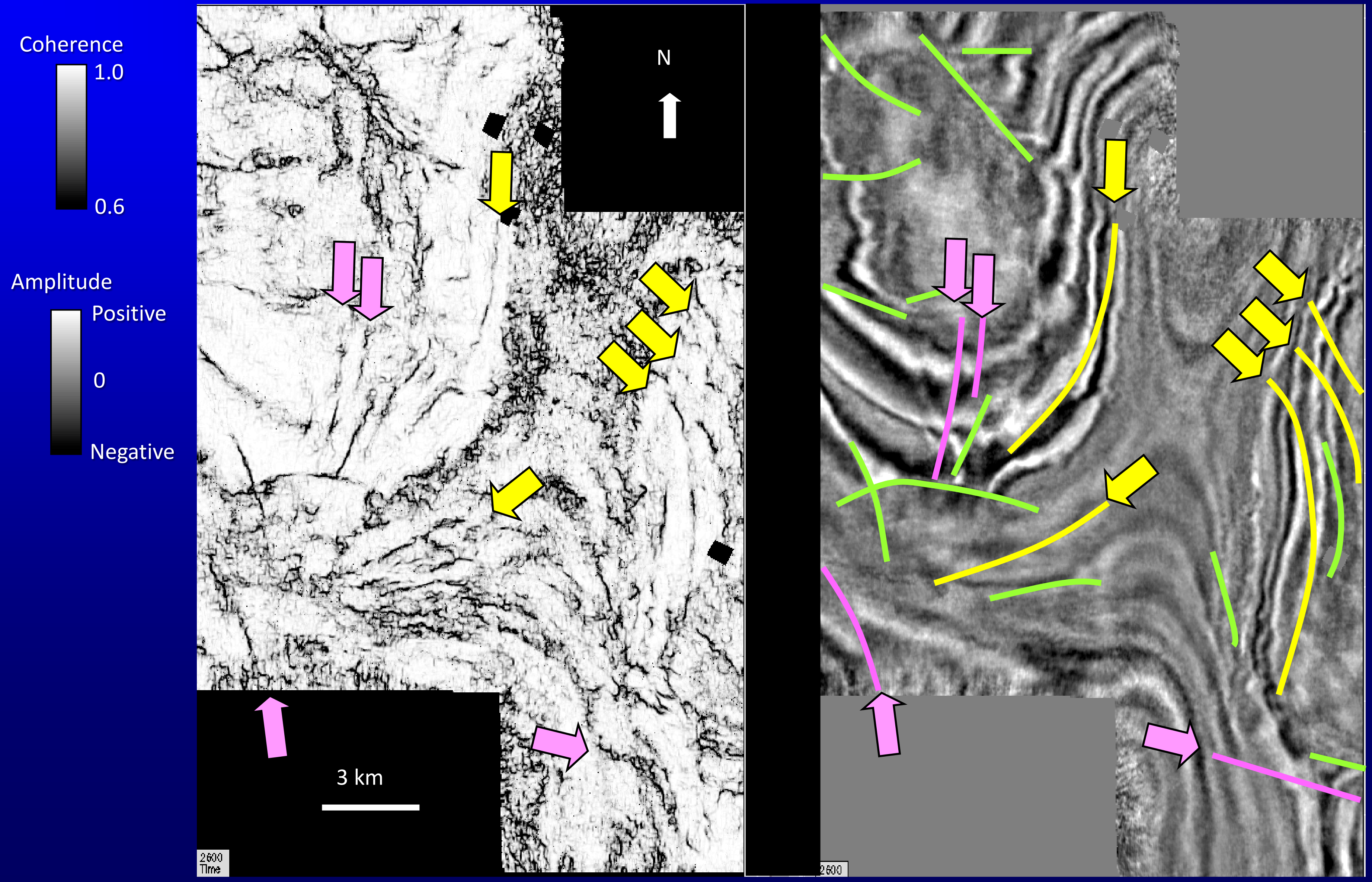


Time slice through coherence
(later semblance algorithm)



(Haskell et al. 1995)

Appearance of faults perpendicular and parallel to strike



Coherence

Amplitude

(Chopra and Marfurt, 2007)

Alternative measures of waveform similarity

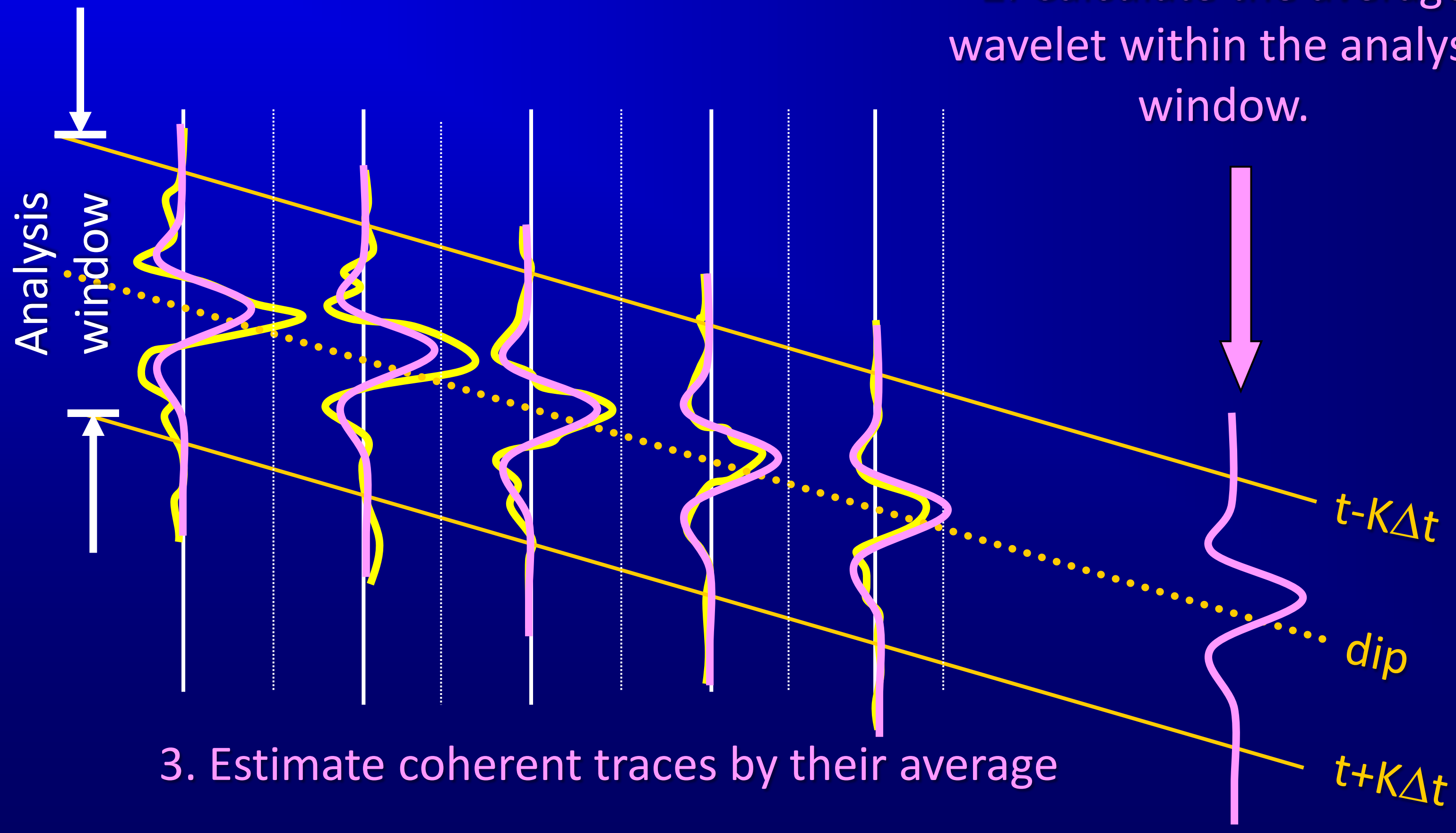
- Cross correlation — Waveform only
- Semblance, variance, and Manhattan distance similarity — Amplitude and waveform
- Sobel filter — Amplitude and waveform
- Eigenstructure and energy ratio similarity — Waveform only
- Gradient Structural Tensor “chaos” — Amplitude and waveform
- Plane-wave destructors — Amplitude and waveform

Semblance estimate of coherence

5. Coherence $\equiv \dfrac{\text{Energy of average trace}}{\text{Average energy of input traces}}$

1. Calculate energy of input traces

2. Calculate the average wavelet within the analysis window.



3. Estimate coherent traces by their average

4. Calculate energy of average traces

(Chopra and Marfurt, 2007)

Semblance estimate of coherence

$$c_s = \frac{\displaystyle\sum_{k=-K}^{+K}\left(\frac{1}{J}\sum_{j=1}^{J}[u(k\Delta t - px_j - qy_j)]\right)^2}{\displaystyle\sum_{k=-K}^{+K}\frac{1}{J}\left(\sum_{j=1}^{J}[u(k\Delta t - px_j - qy_j)]^2\right)}$$

Energy of the average trace

Average of the energy of all the traces

(Marfurt et al, 1998)

The 'Manhattan Distance: $r=|x-x_0|+|y-y_0|$

The "as the crow flies" (or Pythagorean) distance

$r=[(x-x_0)^2+(y-y_0)^2]/^{1/2}$

(New York City Archives)

Manhattan distance estimate of coherence

$$c_s = \frac{\sum_{k=-K}^{+K} \frac{1}{J} \left| \sum_{j=1}^{J} u(k\Delta t - px_j - qy_j) \right|}{\sum_{k=-K}^{+K} \frac{1}{J} \sum_{j=1}^{J} \left| u(k\Delta t - px_j - qy_j) \right|}$$

Absolute value of the average trace

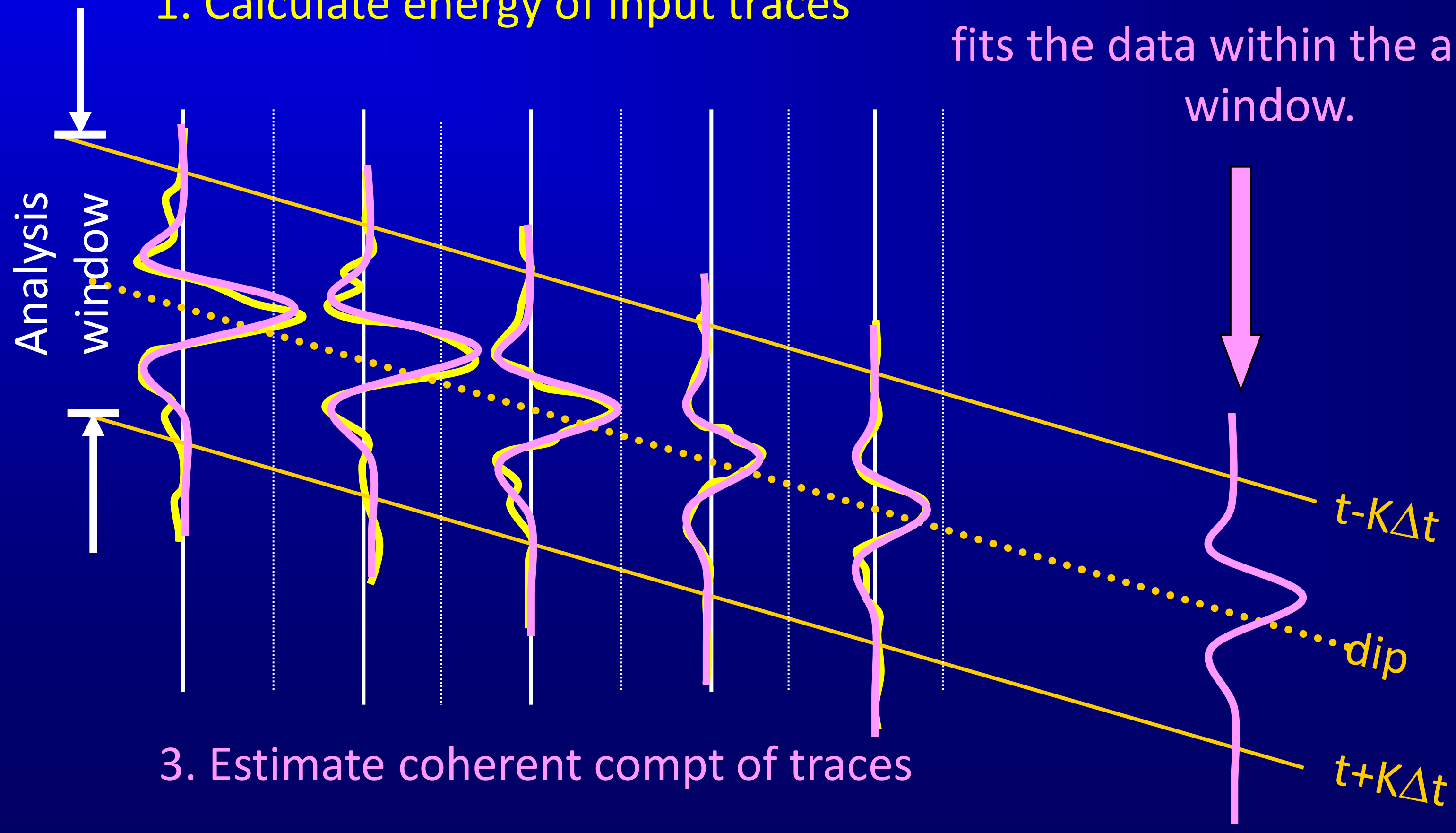
Average of the absolute value of all the traces

Eigenstructure estimate of coherence

5. Coherence $\equiv \dfrac{\text{Energy of coherent compt}}{\text{Energy of input traces}}$

1. Calculate energy of input traces

2. Calculate the wavelet that best fits the data within the analysis window.

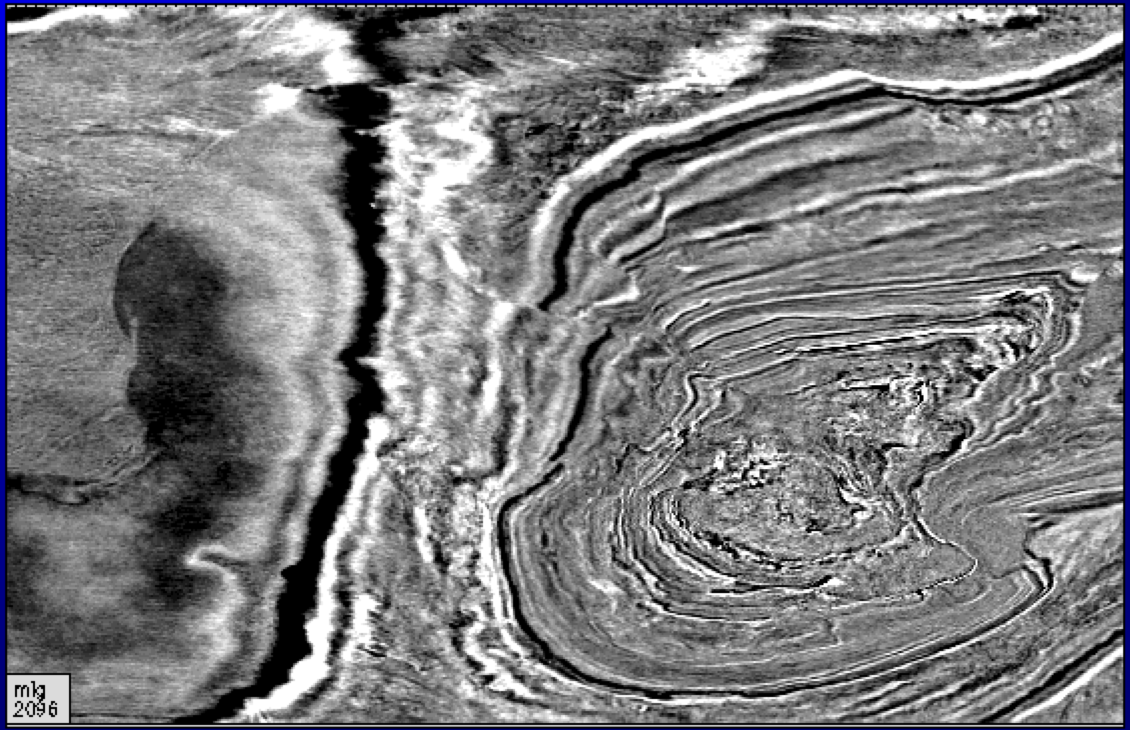


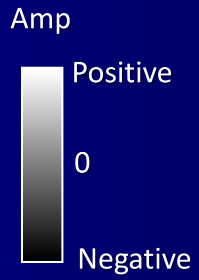
3. Estimate coherent compt of traces

4. Calculate energy of coherent compt of traces

Eigenstructure coherence:

Time slice through seismic

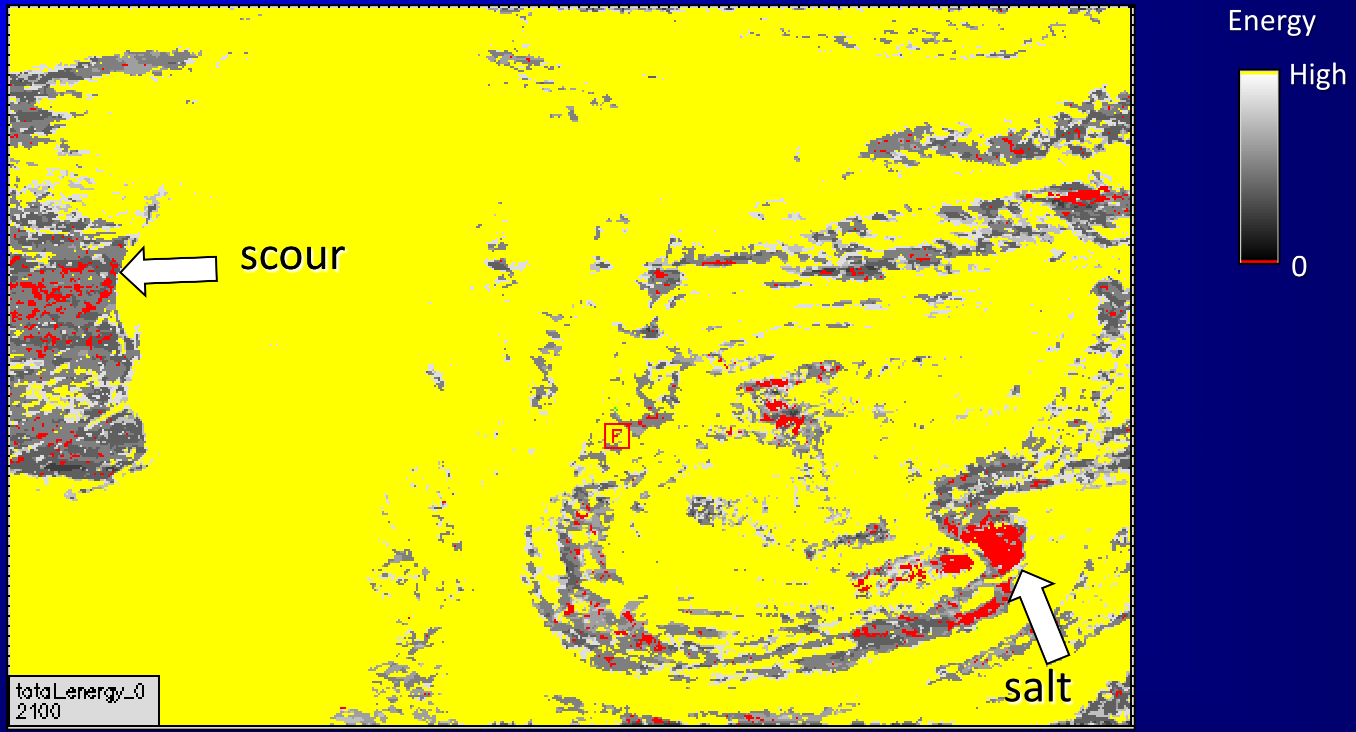




(Chopra and Marfurt, 2007)

Eigenstructure coherence:

Time slice through total energy in 9 trace, 40 ms window



(Chopra and Marfurt, 2007)

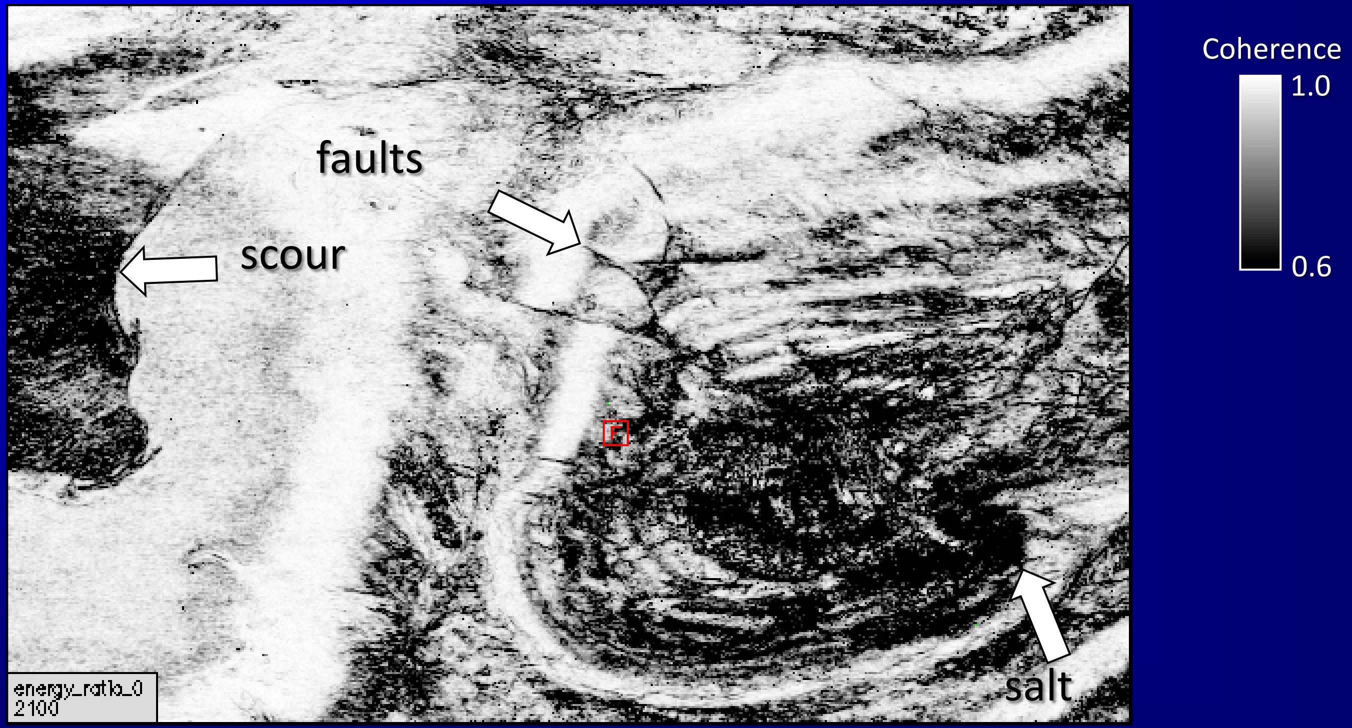
Eigenstructure coherence:

Time slice through coherent energy in 9 trace, 40 ms window

(Chopra and Marfurt, 2007)

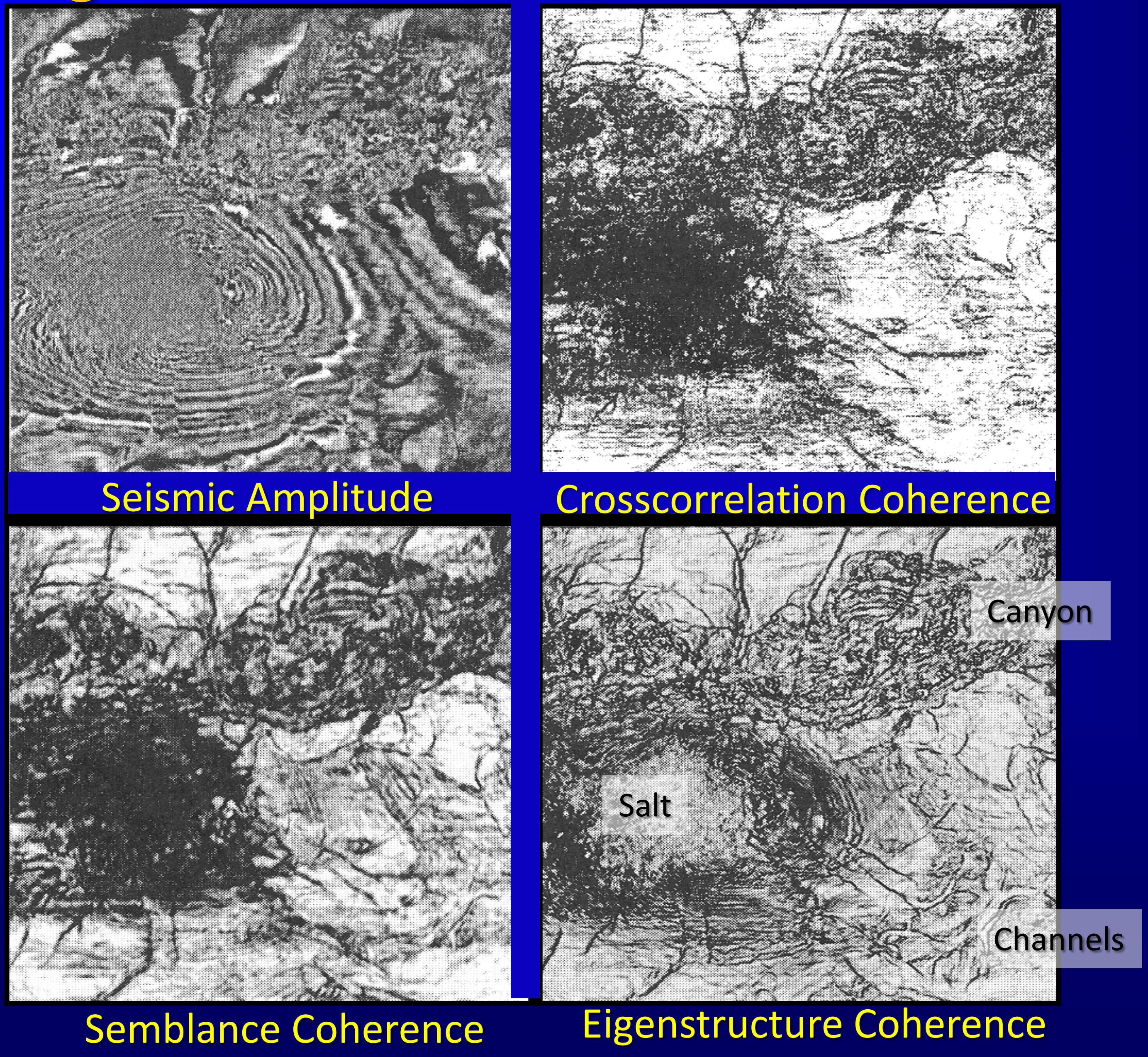
Eigenstructure coherence:

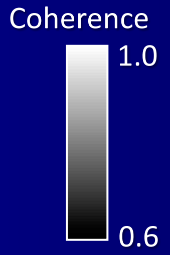
Time slice through ratio of coherent to total energy



(Chopra and Marfurt, 2007)

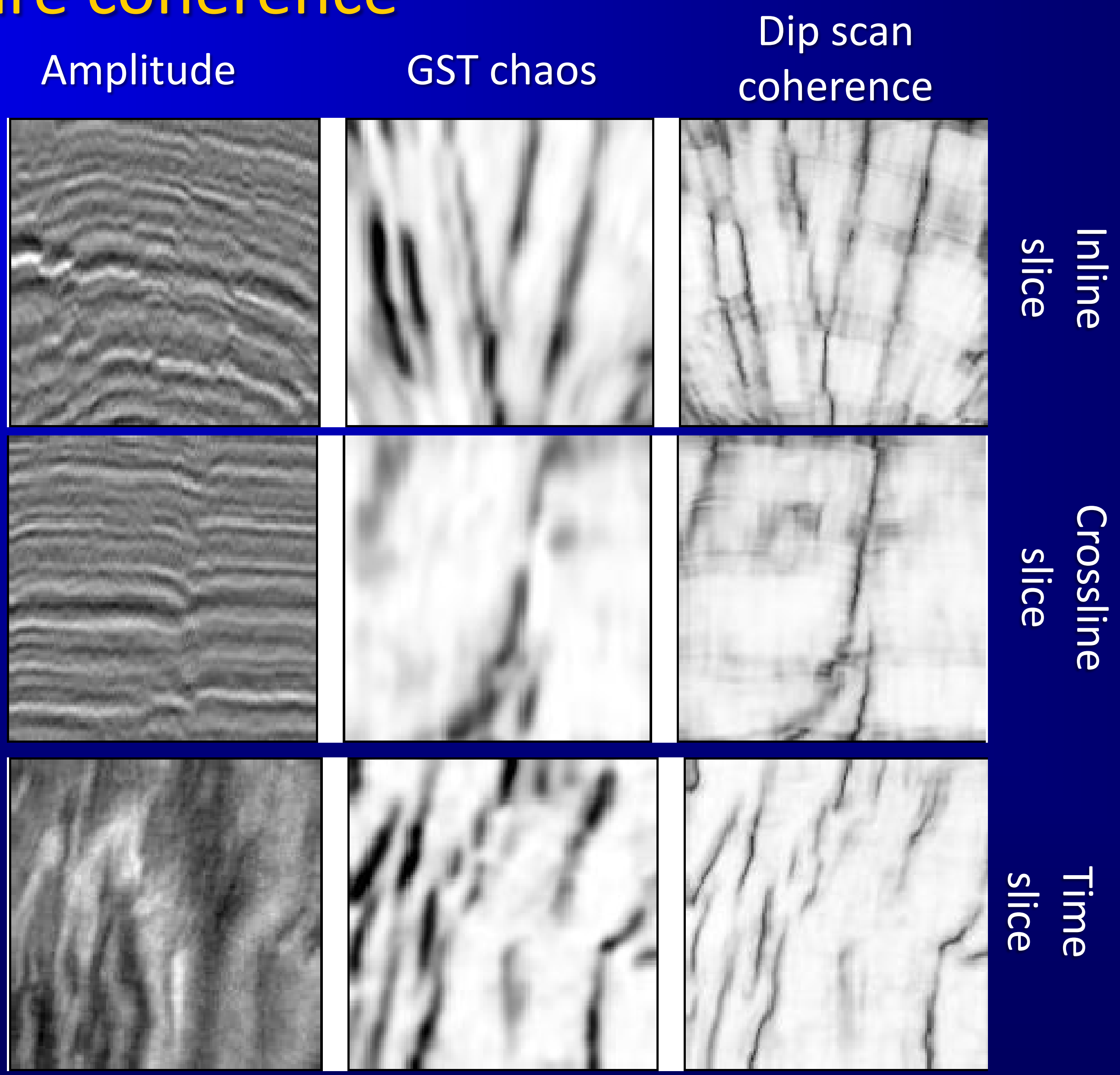
Coherence algorithm evolution





(Gersztenkorn and Marfurt, 1999)

Comparison of Gradient Structure Tensor and dip scan eigenstructure coherence

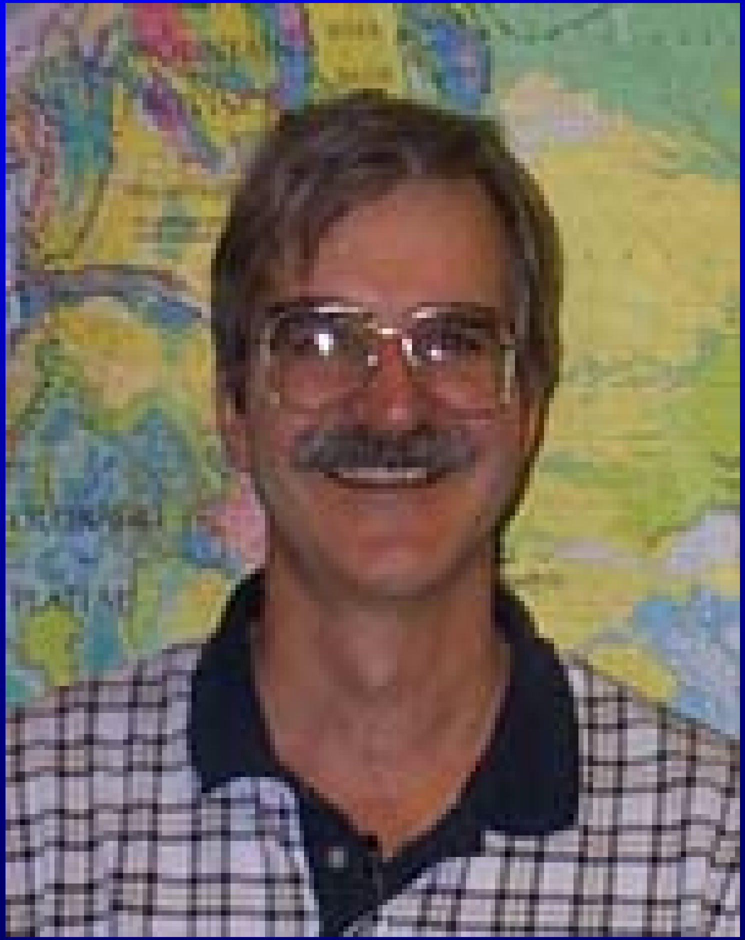


(Bakker, 2003)

Sobel edge detector

Numerical approximation to first derivative:

$$\frac{\partial u}{\partial x} = \lim_{\Delta x \to 0}\left[\frac{u(x+\Delta x) - u(x-\Delta x)}{2\Delta x}\right]$$

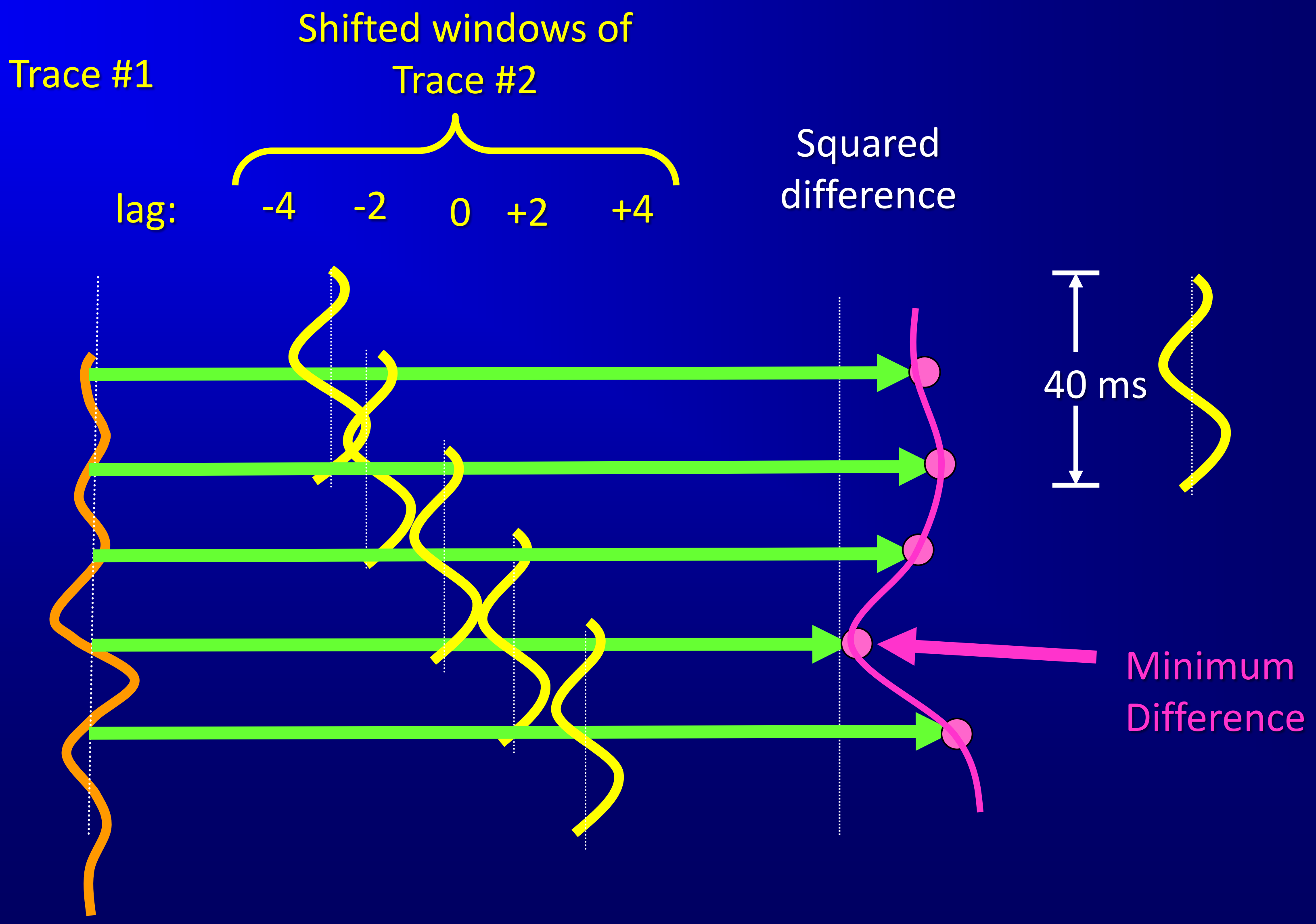


Input image, u

The Sobel filter: $[(du/dx)^2+(du/dy)^2]^{1/2}$

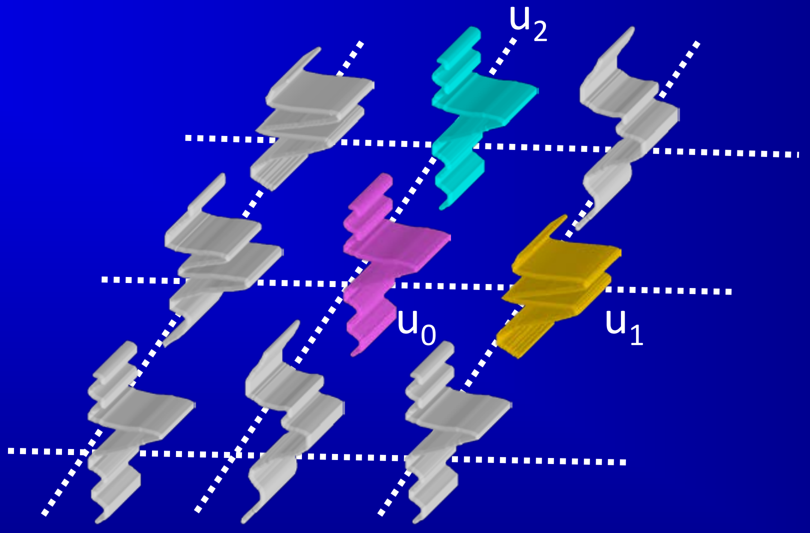
(Courtesy? of Saleh al Dossary)

Difference between 2 traces



(Luo et al., 1996)

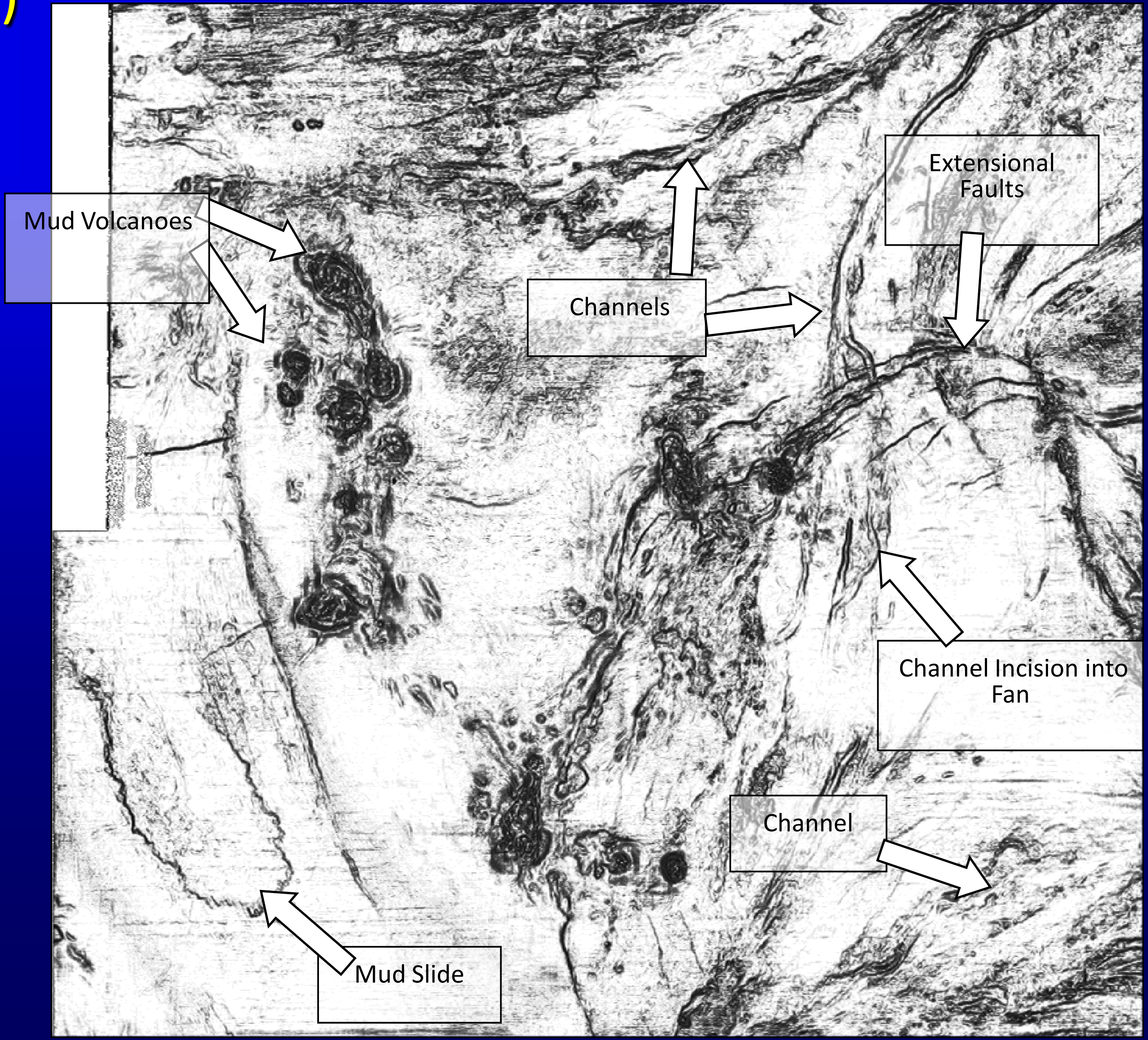
Chevron's original 'Edge' algorithm



$$e(t,\tau_x,\tau_y) = \frac{\left[\sum_{k=-K}^{+K}\left\{[u_0(t+k\Delta t)-u_1(t+k\Delta t-\tau_x)]^2+[u_0(t+k\Delta t)-u_2(t+k\Delta t-\tau_y)]^2\right\}\right]^{1/2}}{\left[\sum_{k=-K}^{+K}\left\{2[u_0(t+k\Delta t)]^2+[u_1(t+k\Delta t-\tau_x)]^2+[u_2(t+k\Delta t-\tau_y)]^2\right\}\right]^{1/2}}$$

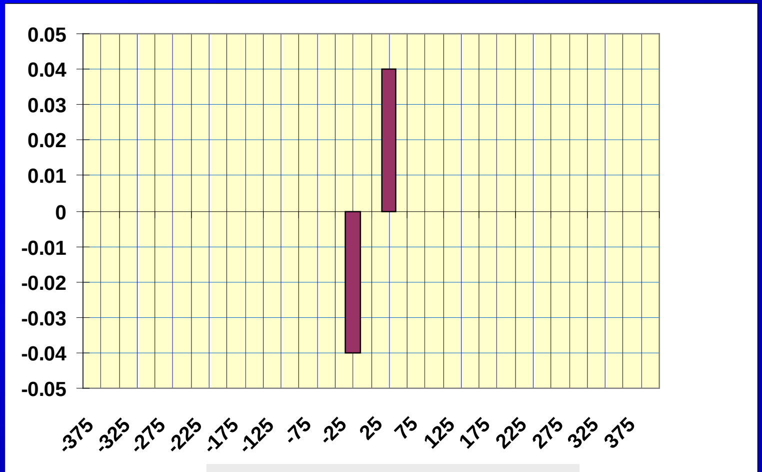
(Luo et al., 1996)

'Edge' horizon slice 200 ms below the water bottom (Offshore West Africa)

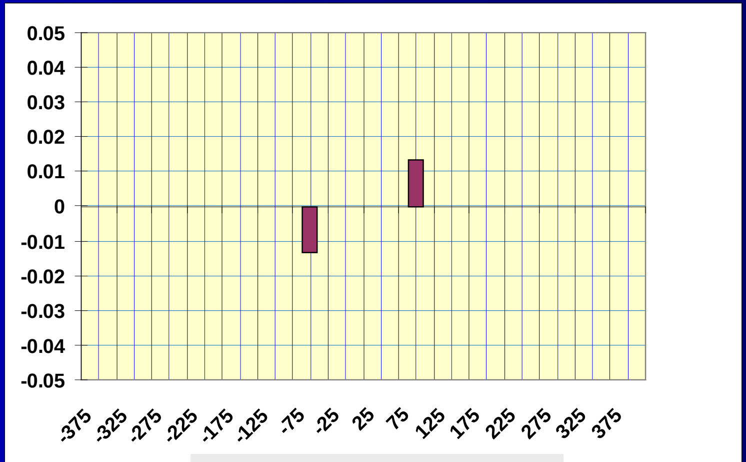


(Adeogba et al., 2005)

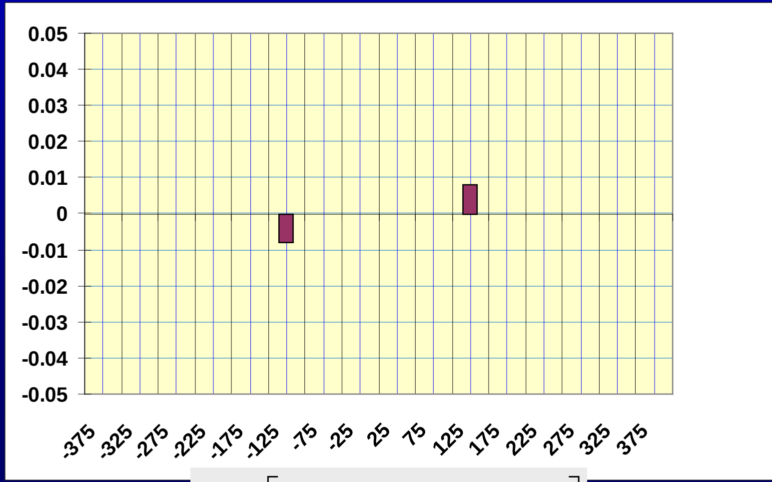
Which value of Δx should we use in a Sobel filter?



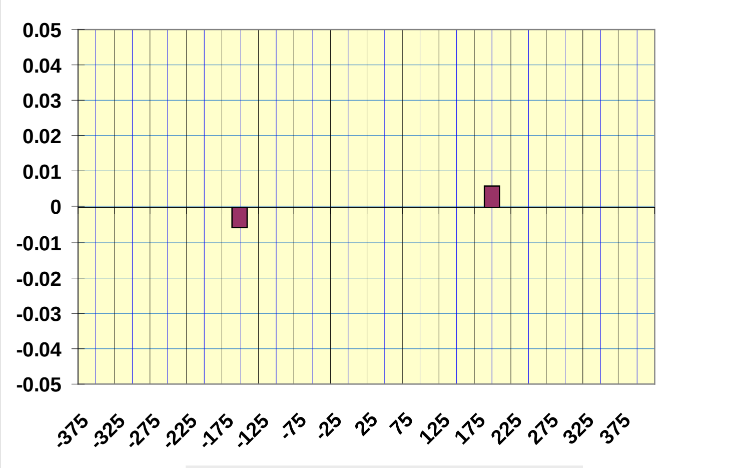
$$\frac{\partial u}{\partial x} \approx \left[\frac{u(x+25)-u(x-25)}{2(25)}\right]$$



$$\frac{\partial u}{\partial x} \approx \left[\frac{u(x+75)-u(x-75)}{2(75)}\right]$$

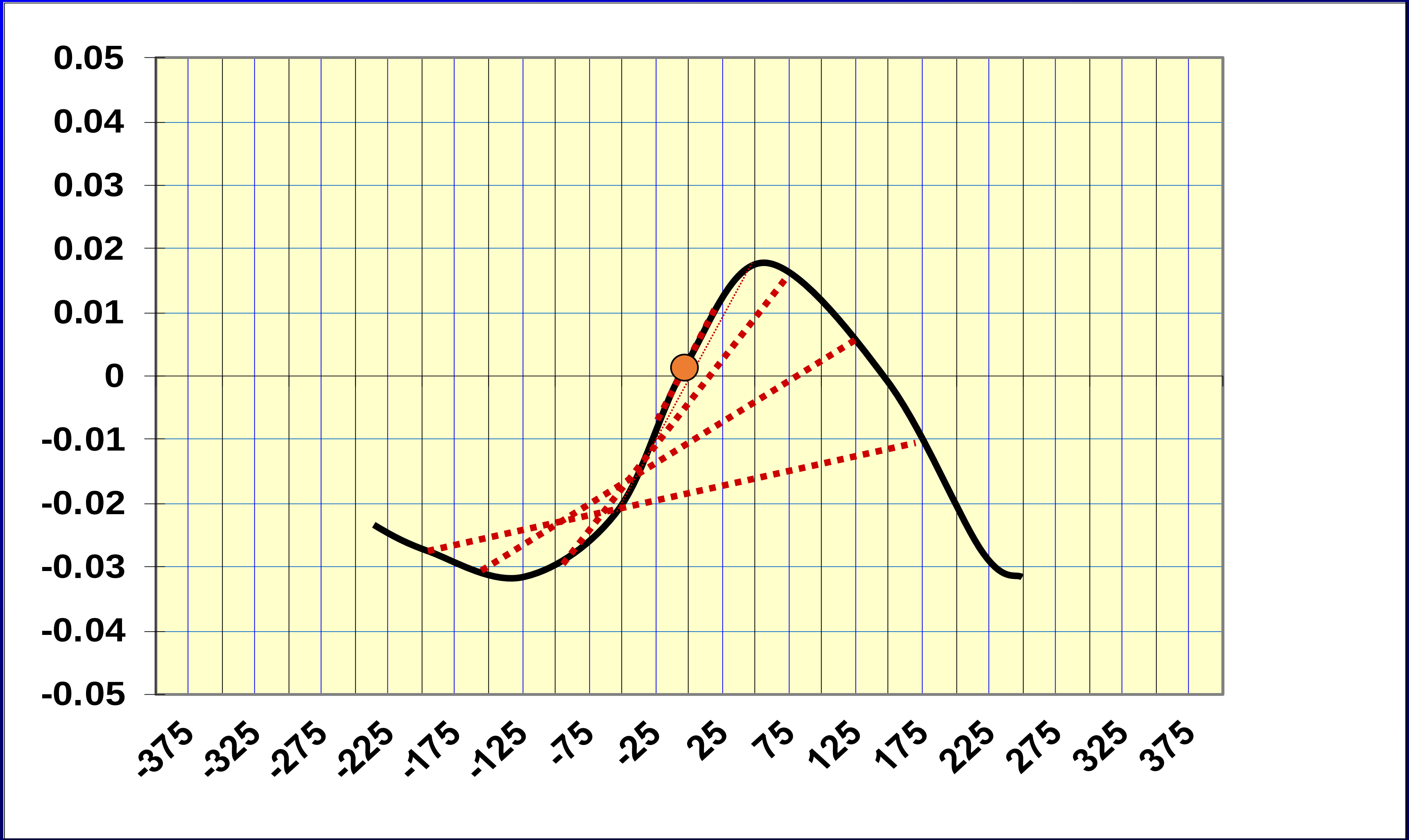


$$\frac{\partial u}{\partial x} \approx \left[\frac{u(x+125)-u(x-125)}{2(125)}\right]$$

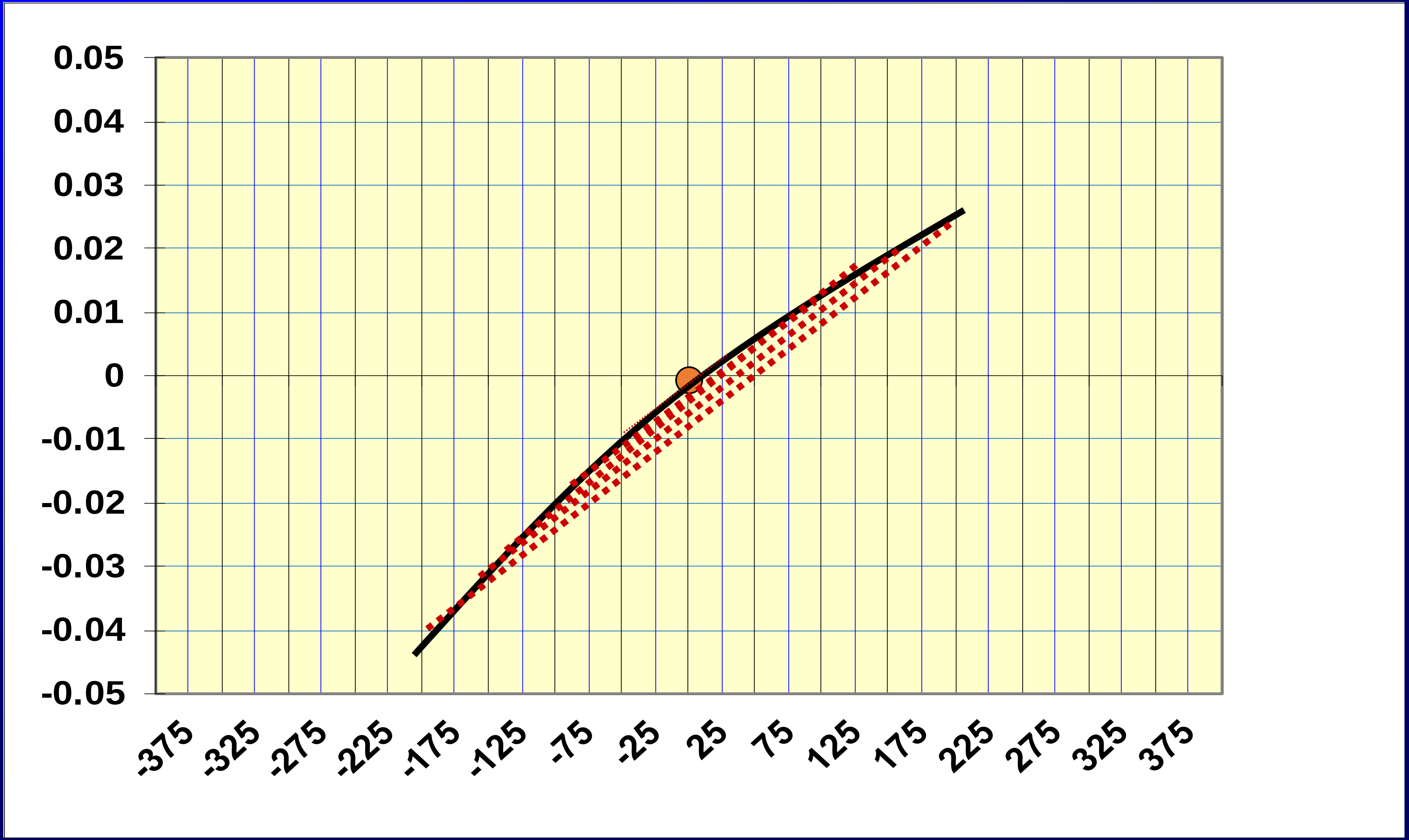


$$\frac{\partial u}{\partial x} \approx \left[\frac{u(x+175)-u(x-175)}{2(175)}\right]$$

Alternative choices of Δx provide different estimates of derivative

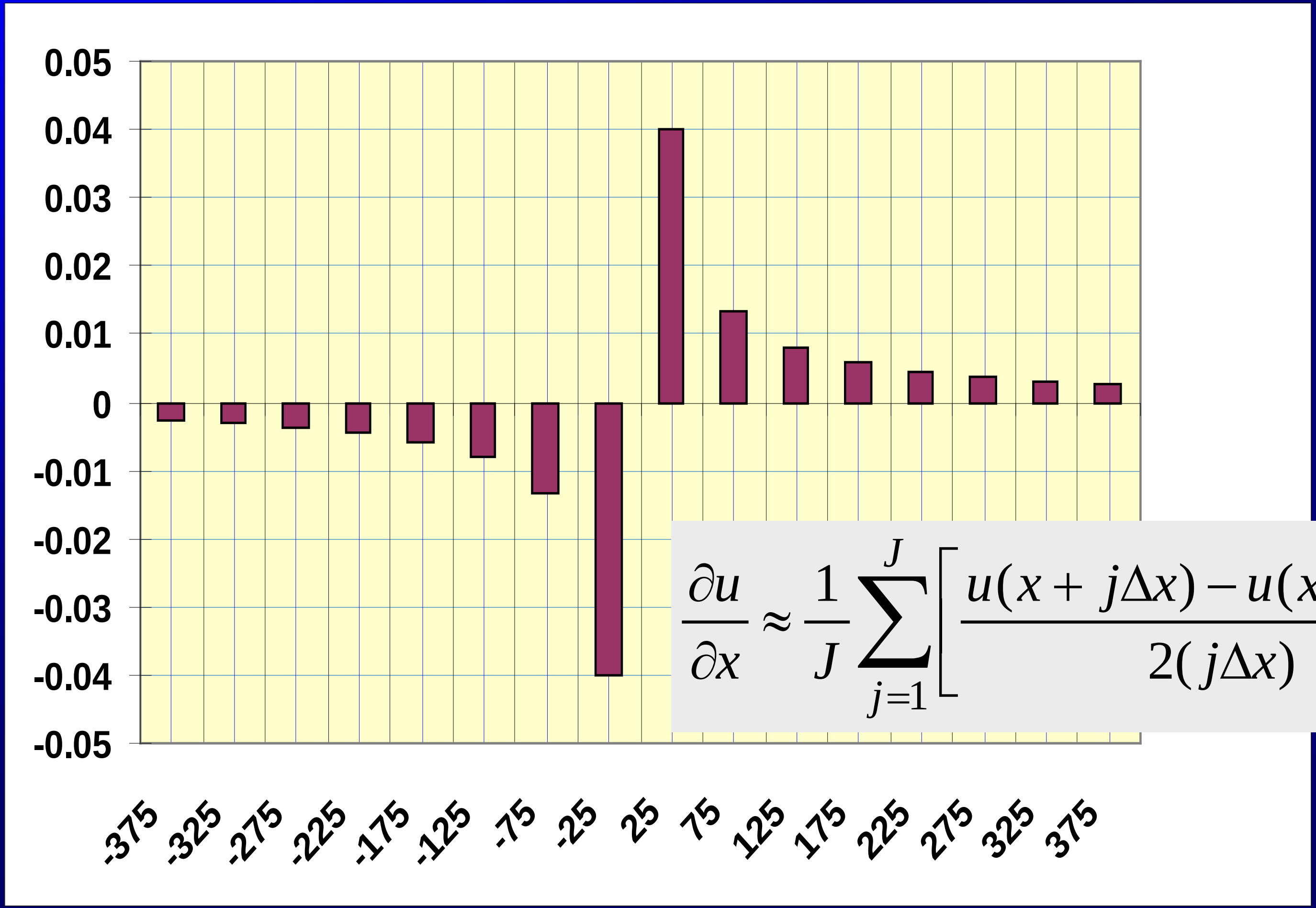


If the slope is long wavelength, estimates are similar



For long wavelength estimate, we could use all values of Δx!

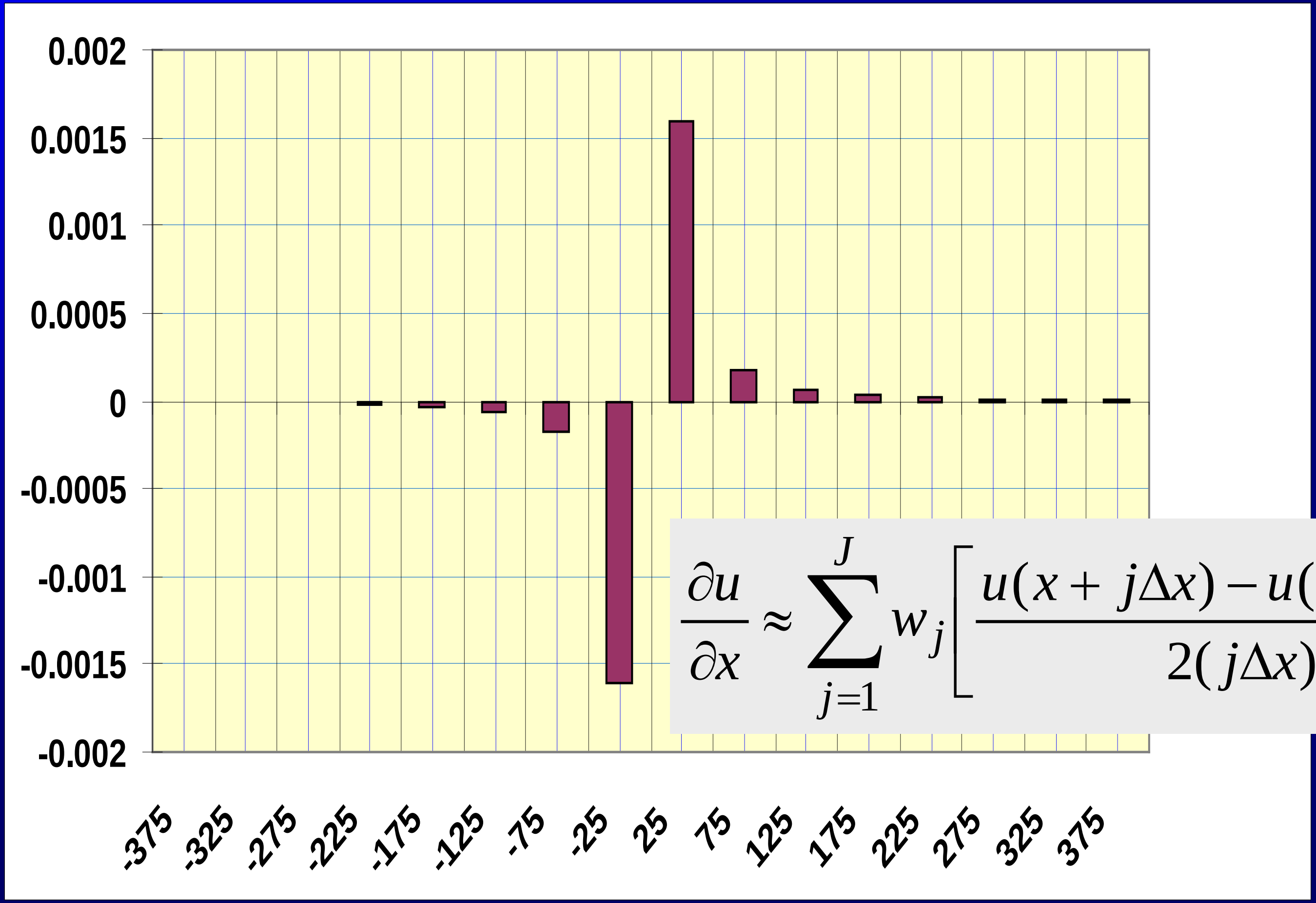
(Luo et al.'s (2003) Hilbert transform edge detector)



$$\frac{\partial u}{\partial x} \approx \frac{1}{J}\sum_{j=1}^{J}\left[\frac{u(x+j\Delta x)-u(x-j\Delta x)}{2(j\Delta x)}\right]$$

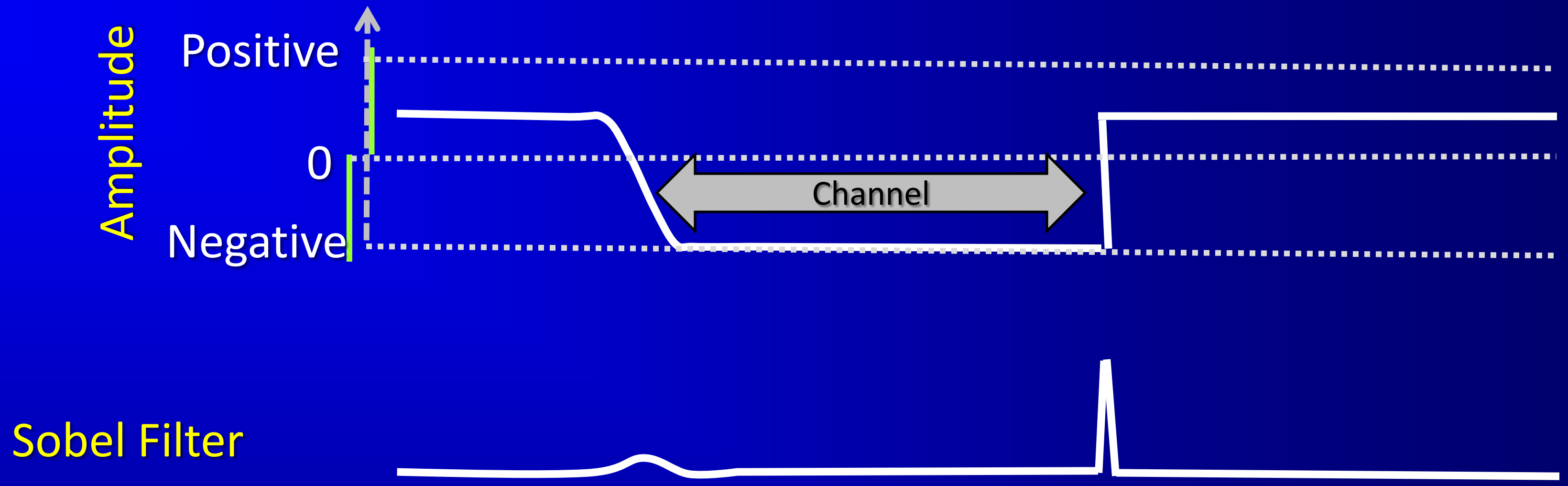
For a shorter wavelength estimate, we could "generalize" the Hilbert transform to vary as Sign(x)/x^2

(Luo et al.'s (2003) *Detect* algorithm)



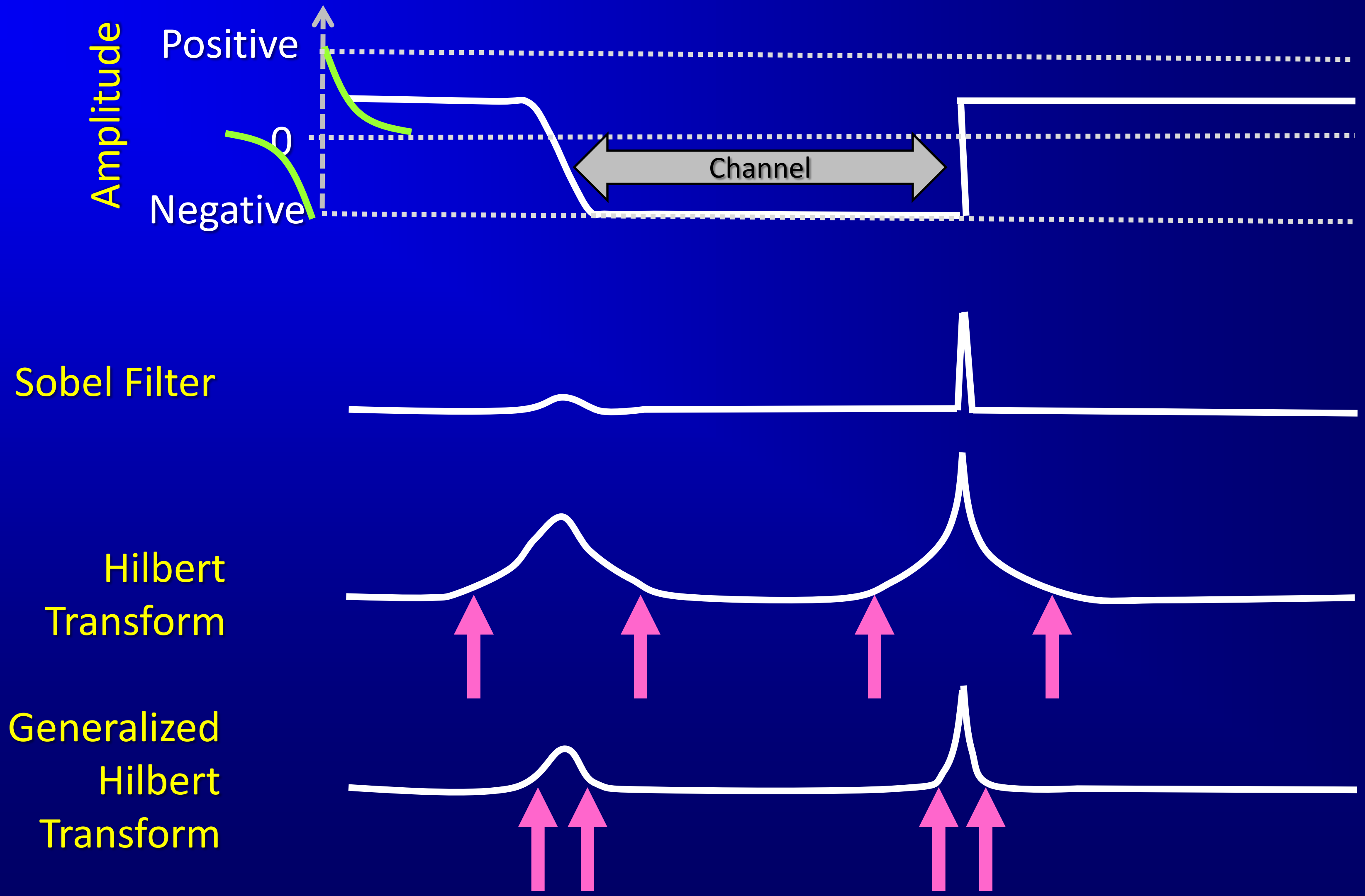
$$\frac{\partial u}{\partial x} \approx \sum_{j=1}^{J} w_j \left[\frac{u(x + j\Delta x) - u(x - j\Delta x)}{2(j\Delta x)} \right]$$

A ‘short wavelength’ edge detector



(Luo et al., 2003)

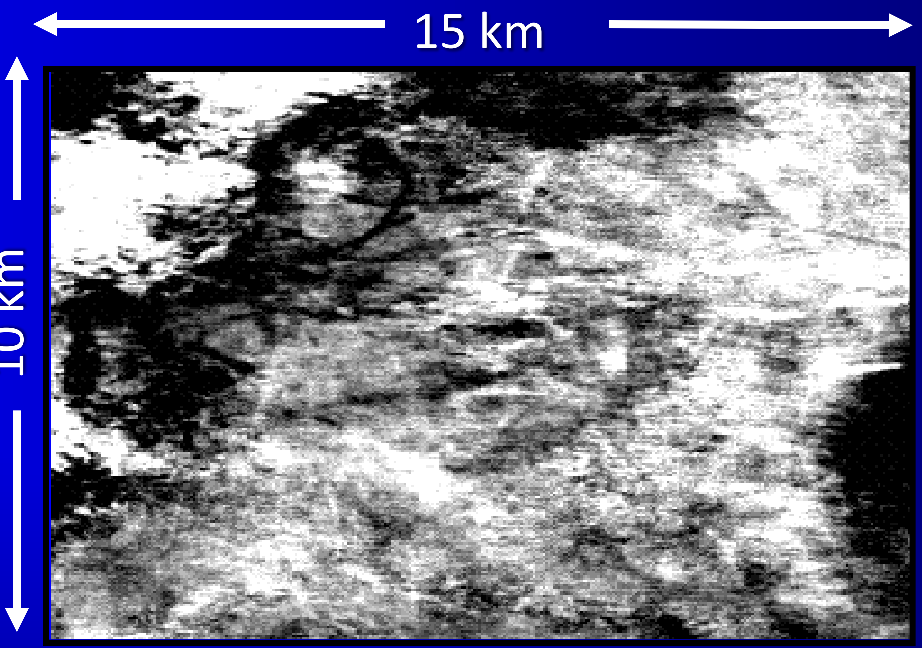
A ‘long wavelength’ edge detector



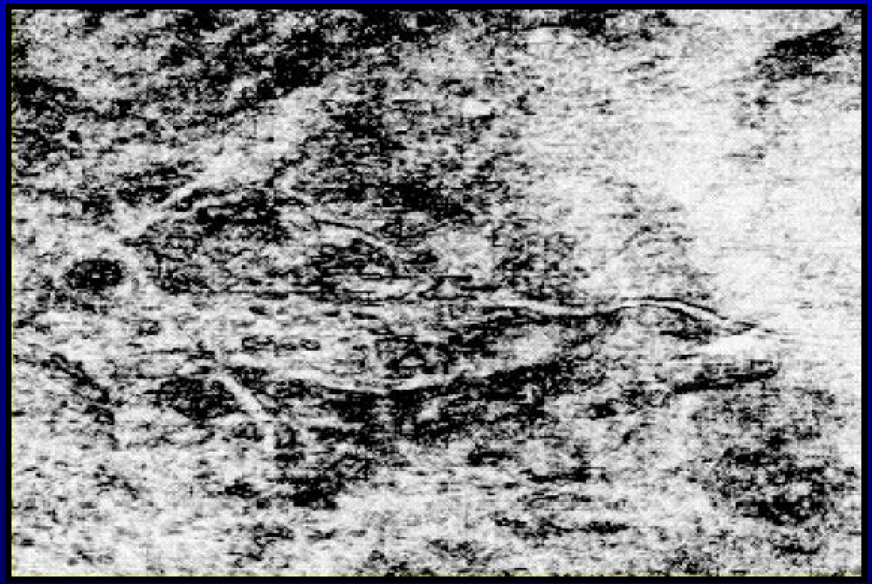
(Luo et al., 2003)

Saudi Arabia

(Time slice?)



Amplitude



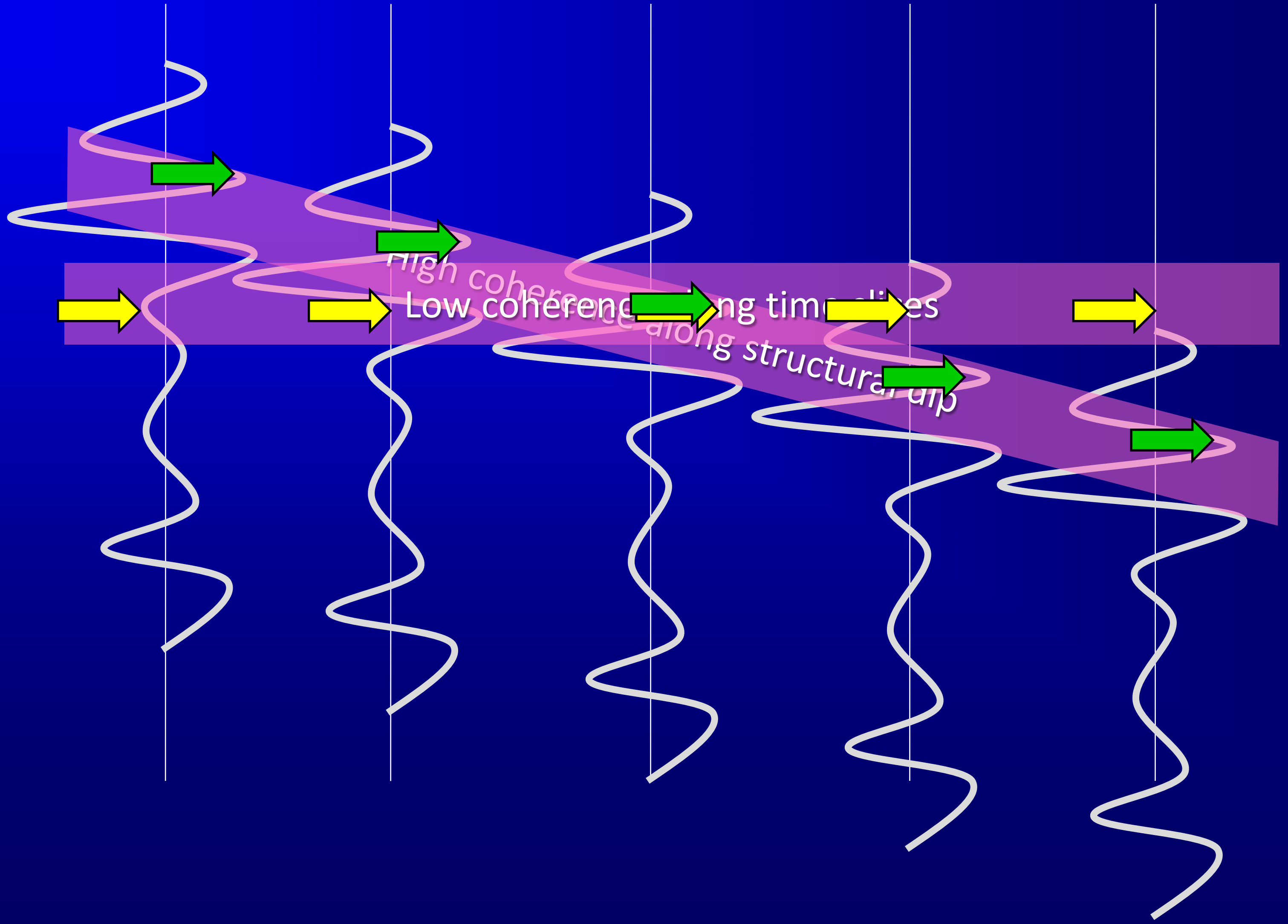
Eigenstructure coherence

Generalized Hilbert Transform

(Luo et al., 2003)

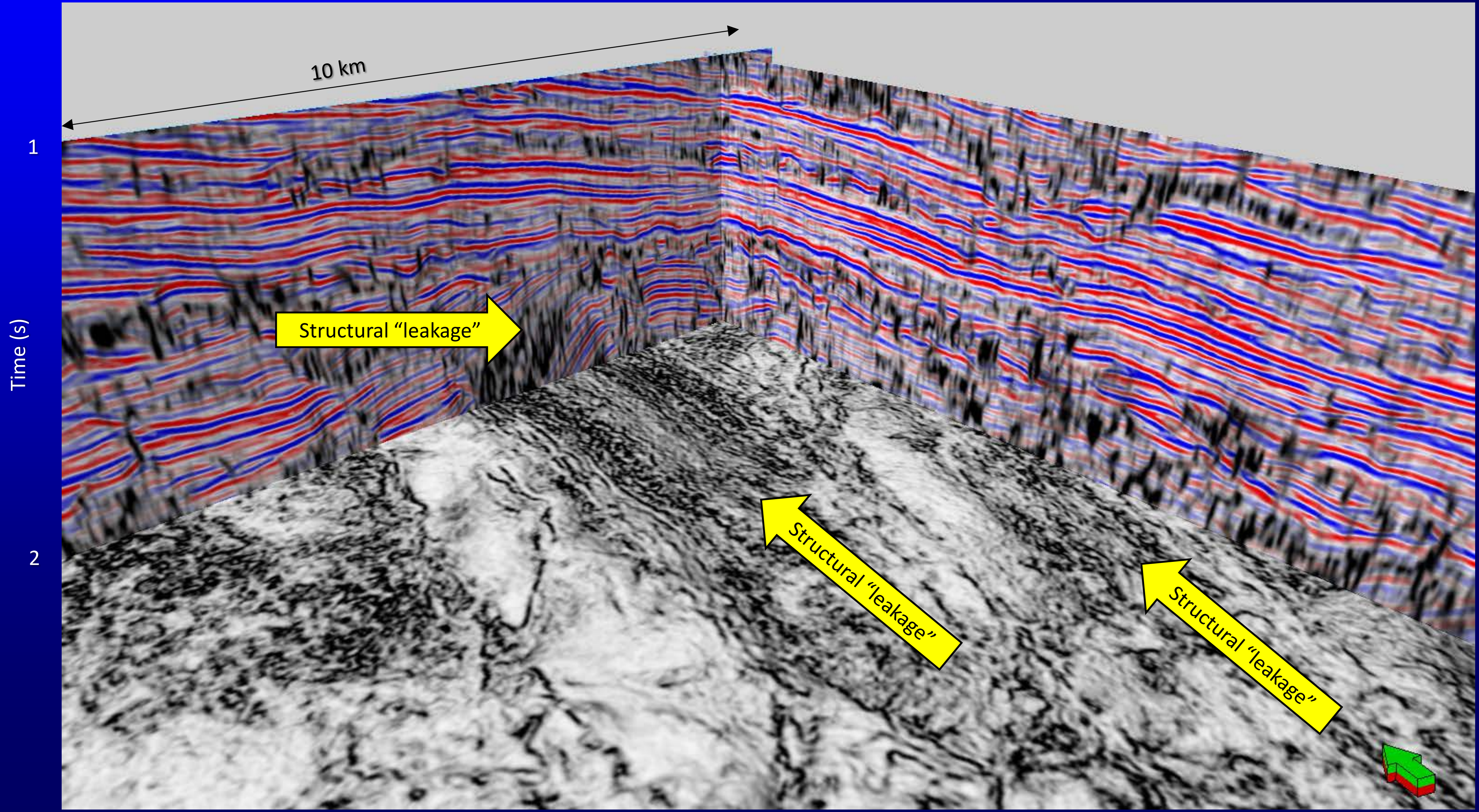
Pitfalls associated with blindly trusting default parameters

Not computing coherence along structure

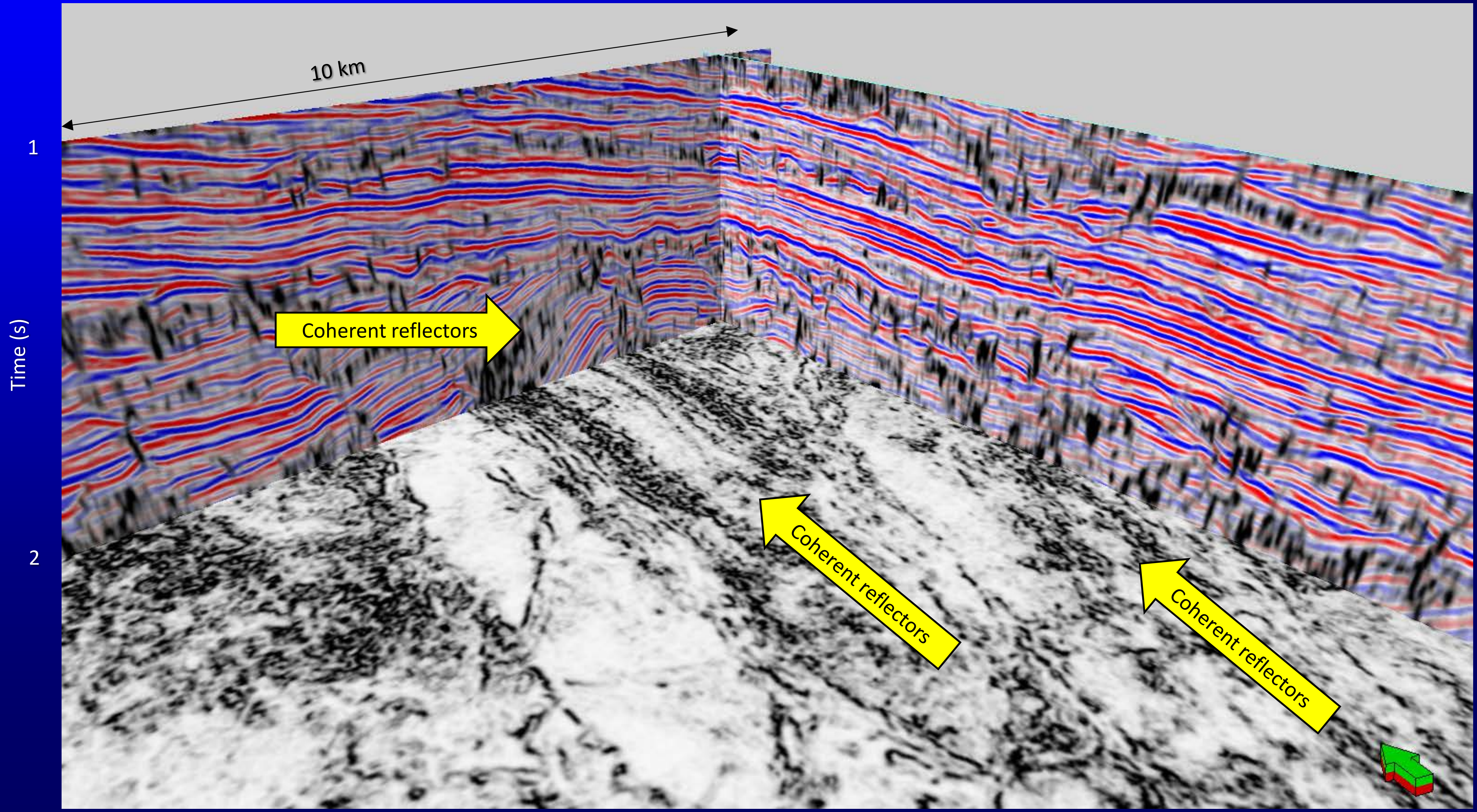


Pitfalls associated with blindly trusting default parameters

Pitfall: Computing coherence along (default) time slices



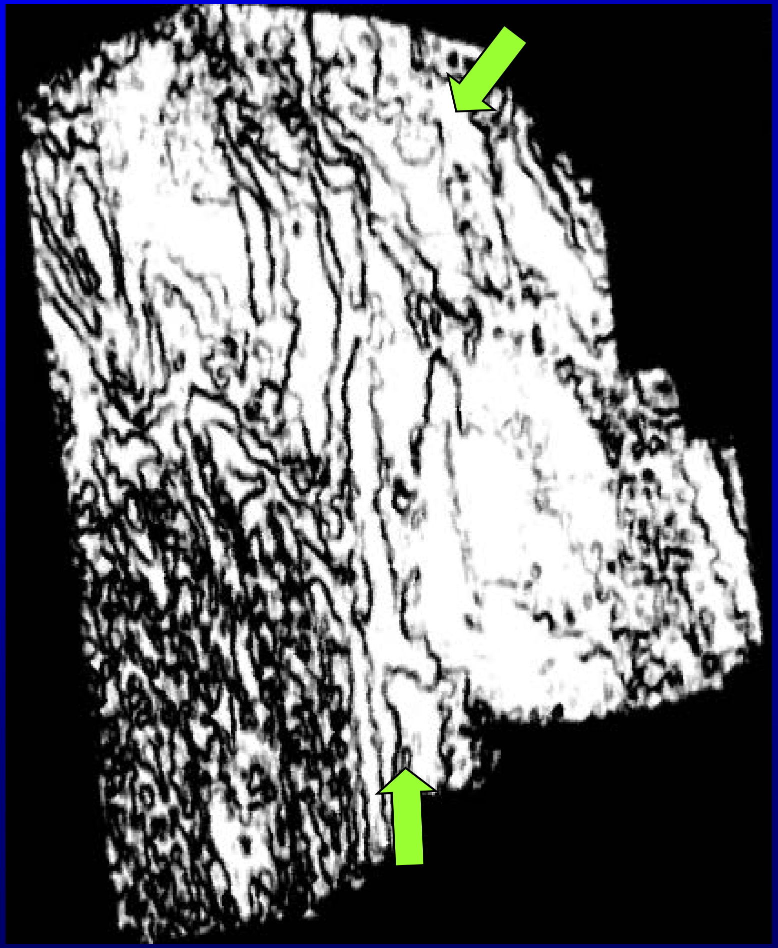
Pitfalls associated with blindly trusting default parameters
Solution: Compute coherence along structure



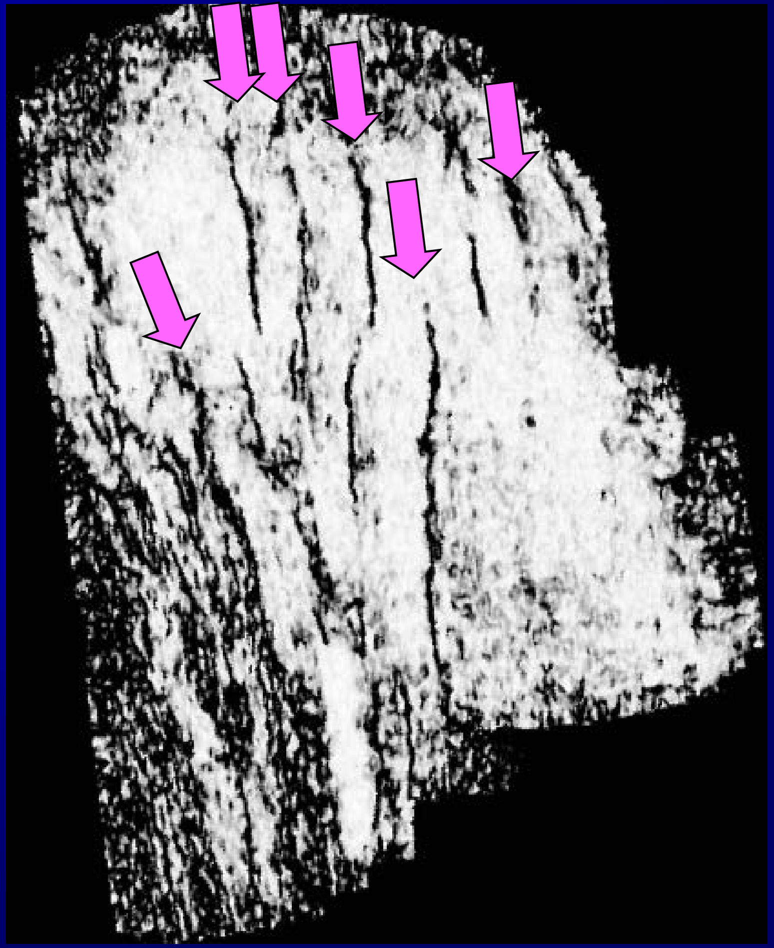
Pitfalls associated with blindly trusting default parameters

Pitfall: Computing coherence along (default) time slices

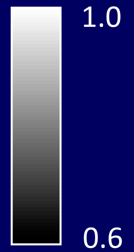
“Structural Leakage” resulting in contour artifacts



Coherence computed along a time slice



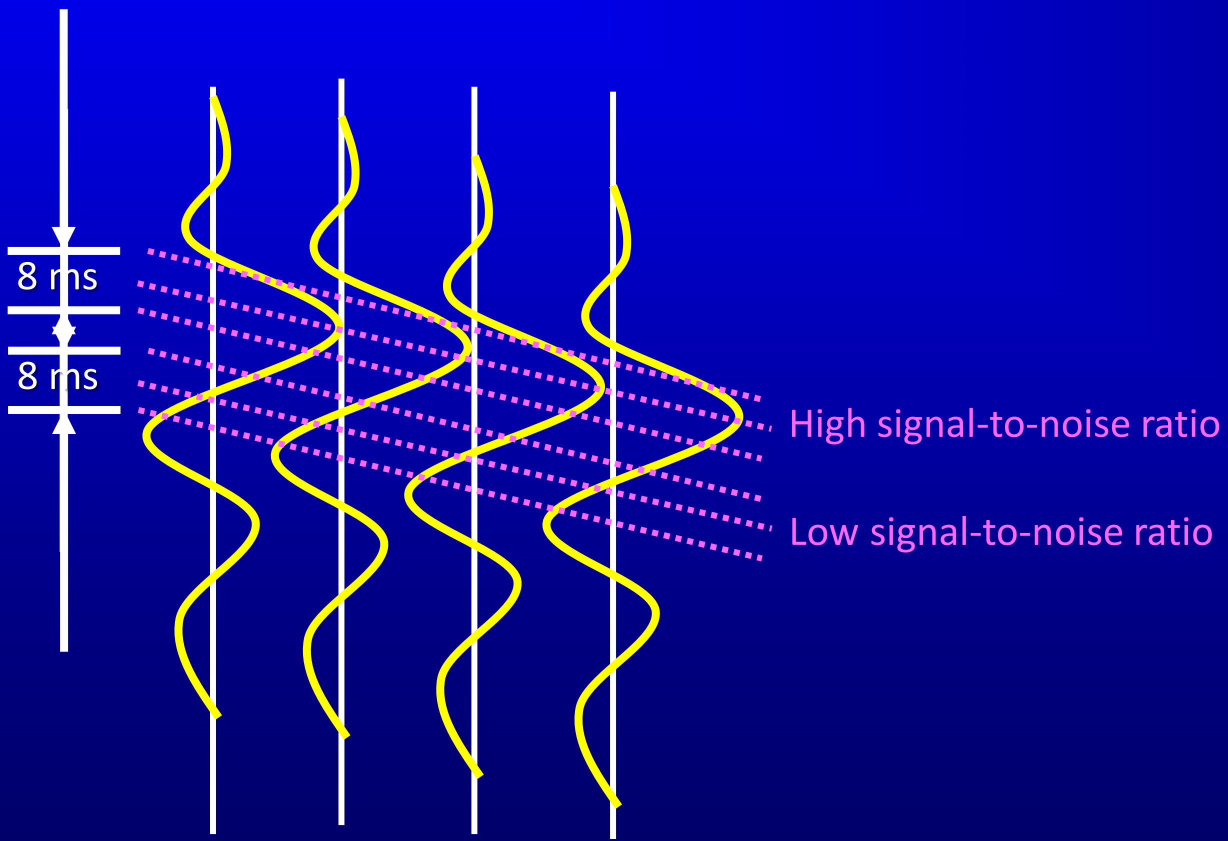
Coherence computed along structure

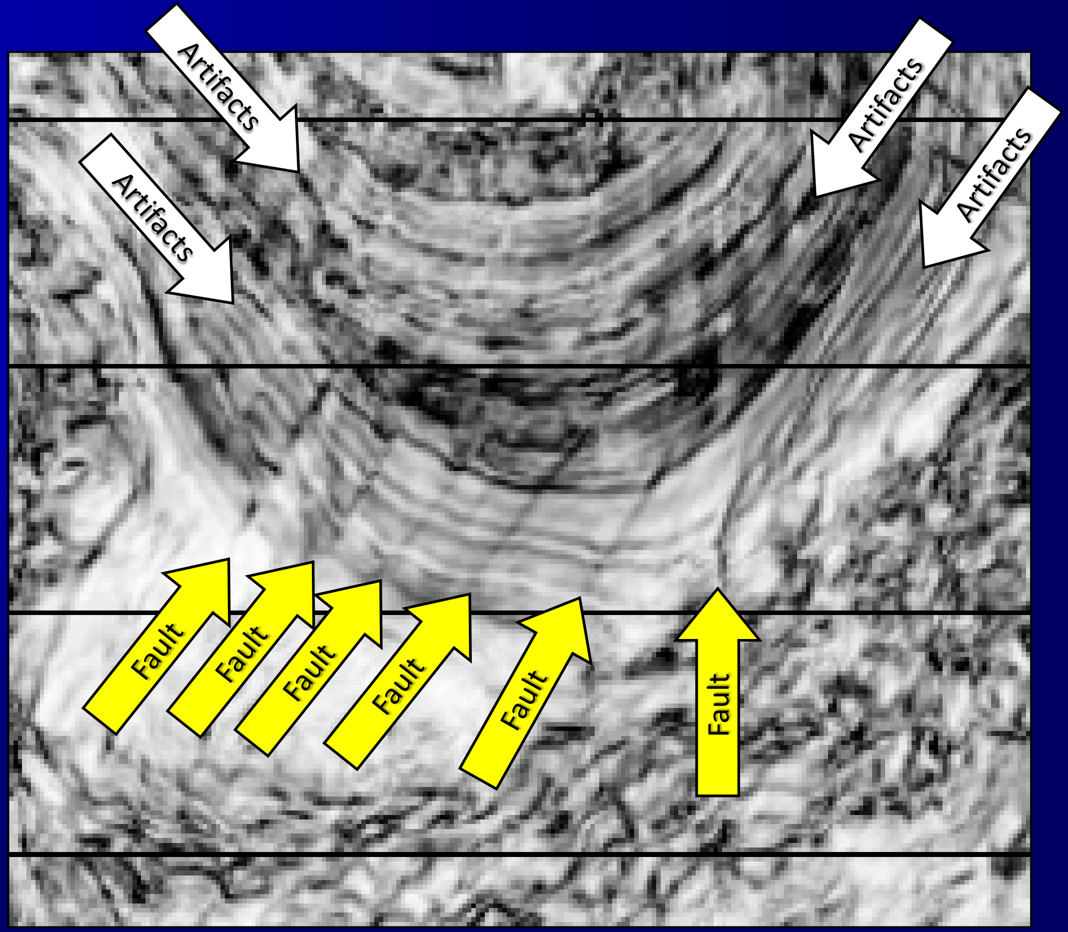


(Chopra and Marfurt, 2008)

Pitfalls and algorithm limitations:

Artifacts when using small windows about amplitude zero-crossings



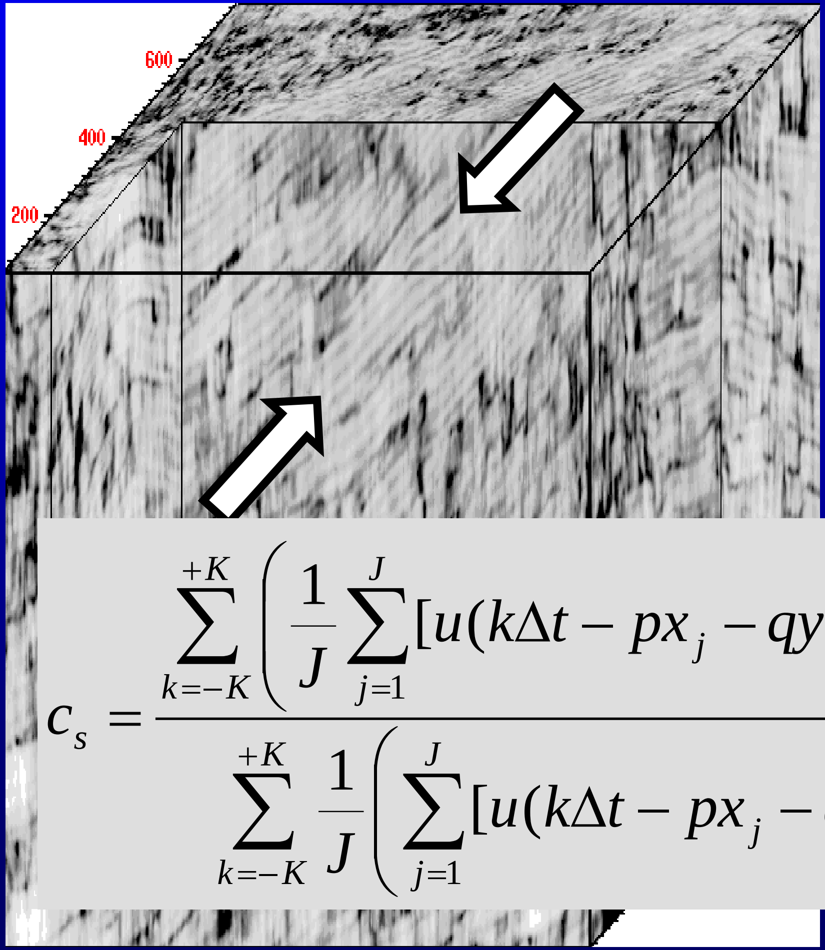


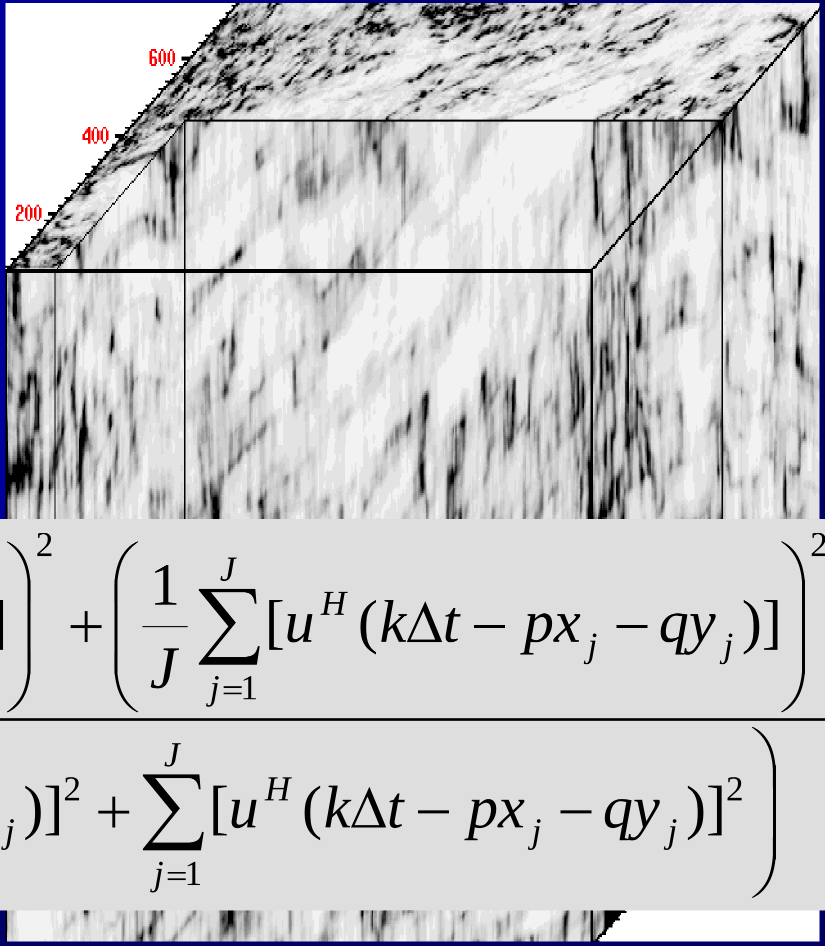
(Chopra and Marfurt, 2007)

Pitfalls and algorithm limitations:

Artifacts when using small windows about amplitude zero-crossings

Solution: Calculate the coherence of the analytic trace





$$c_s = \frac{\sum_{k=-K}^{+K}\left(\frac{1}{J}\sum_{j=1}^{J}[u(k\Delta t - px_j - qy_j)]\right)^2 + \left(\frac{1}{J}\sum_{j=1}^{J}[u^H(k\Delta t - px_j - qy_j)]\right)^2}{\sum_{k=-K}^{+K}\frac{1}{J}\left(\sum_{j=1}^{J}[u(k\Delta t - px_j - qy_j)]^2 + \sum_{j=1}^{J}[u^H(k\Delta t - px_j - qy_j)]^2\right)}$$

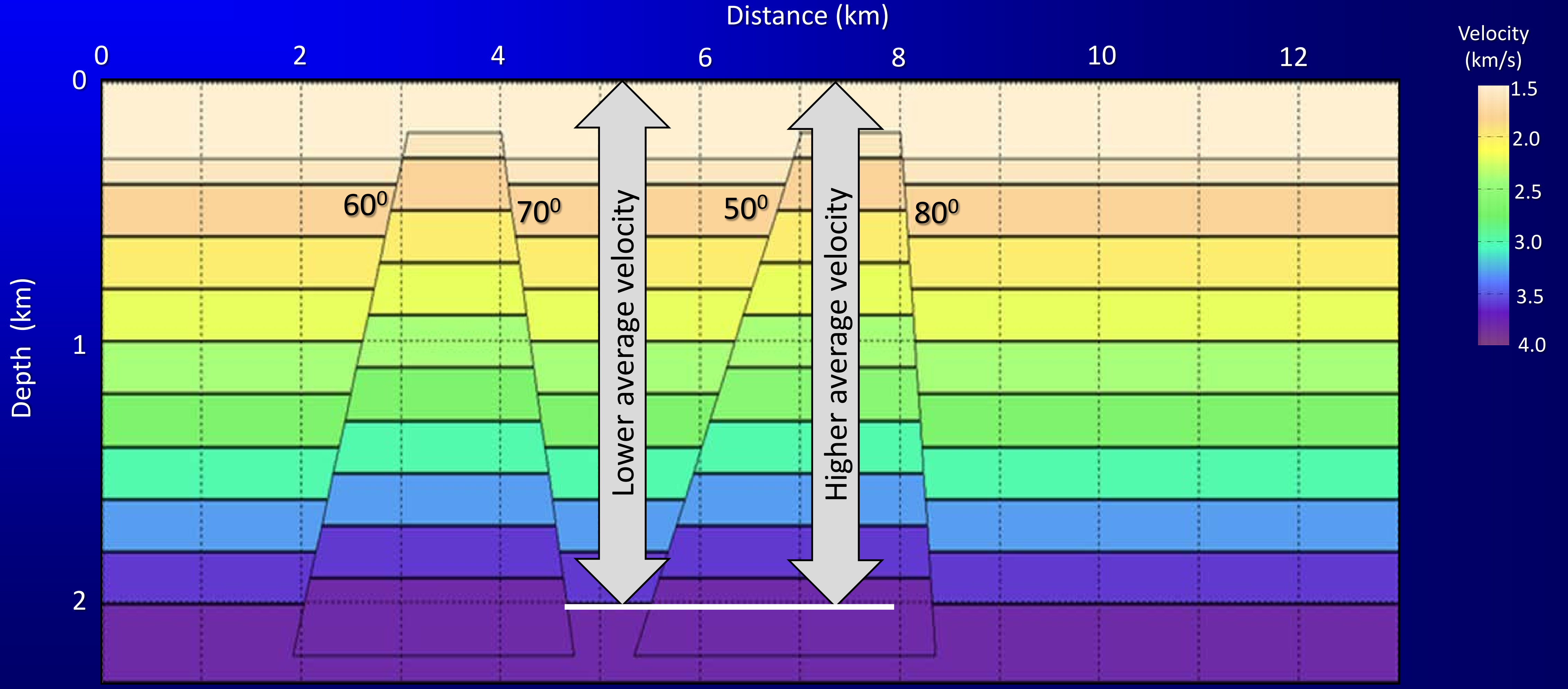
Coherence of real trace

Coherence of analytic trace

(Chopra and Marfurt, 2007)

Pitfalls and algorithm limitations:
Fault shadows and velocity pull-up and push-down

Generate finite difference synthetic shot gathers and migrate the results using an accurate velocity model



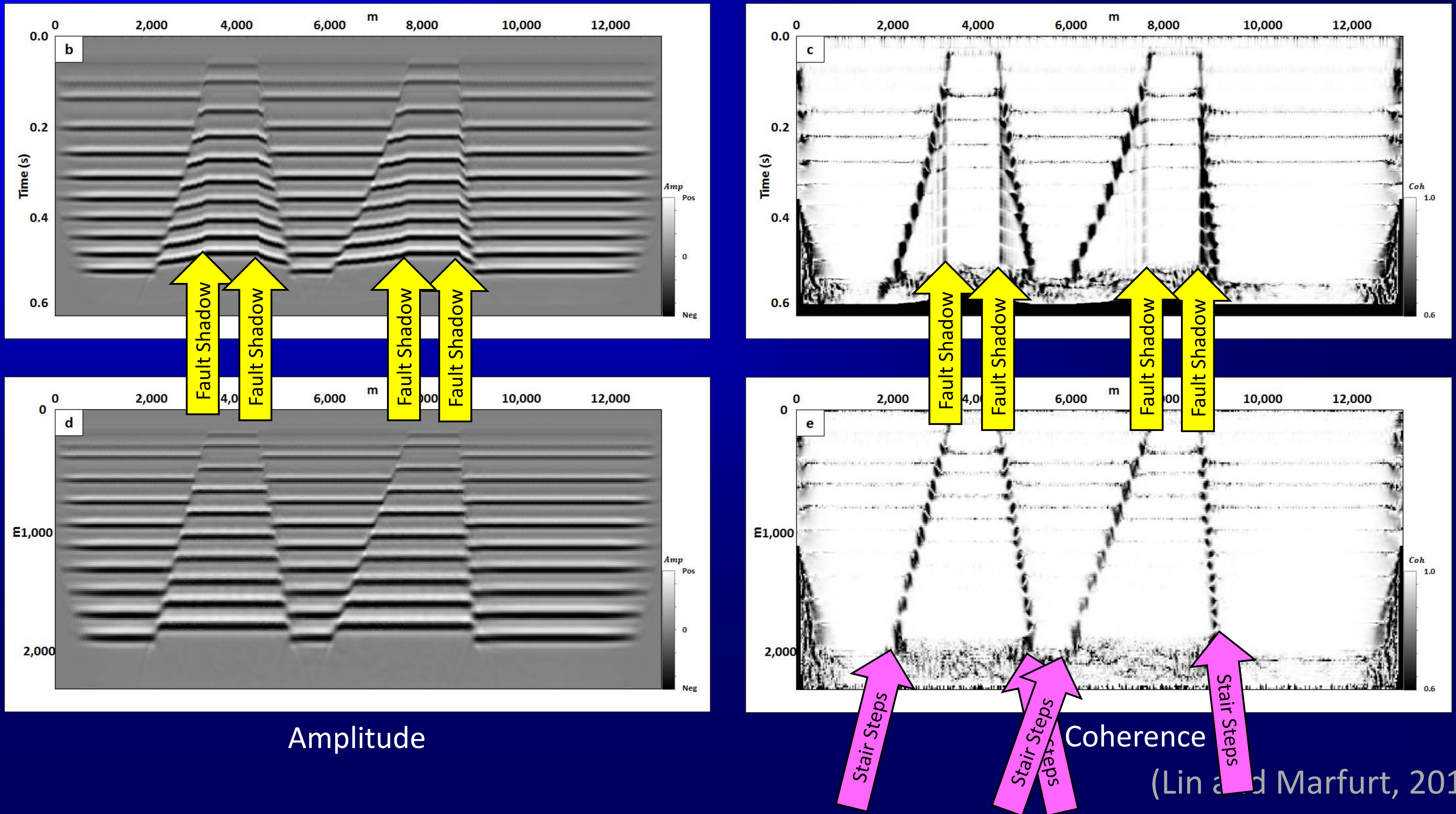
A simple model with four faults exhibiting different dips

(Lin and Marfurt, 2017)

Pitfalls and algorithm limitations:
Fault shadows and velocity pull-up and push-down

Prestack time-migrated

Prestack depth-migrated

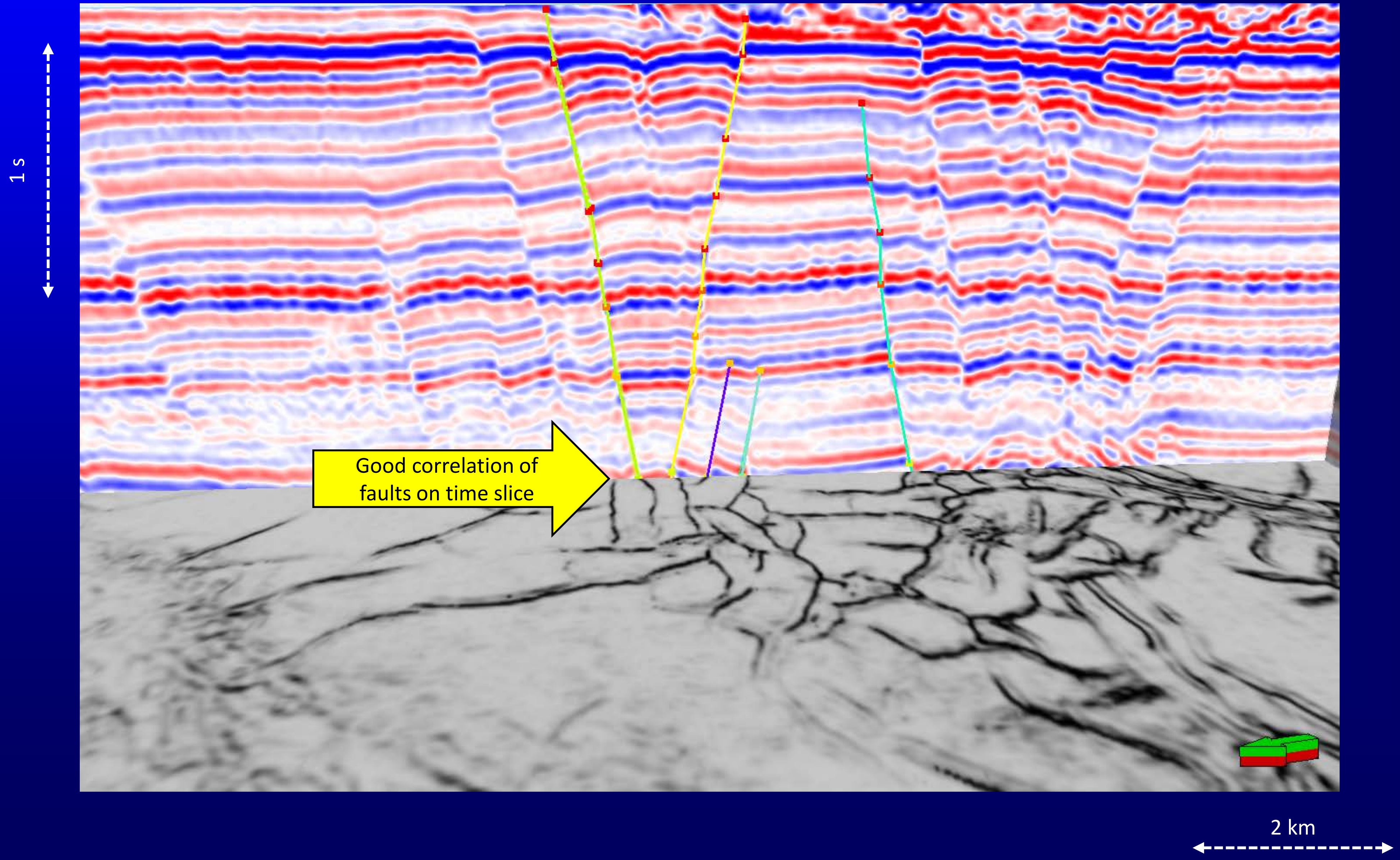


Amplitude

Coherence

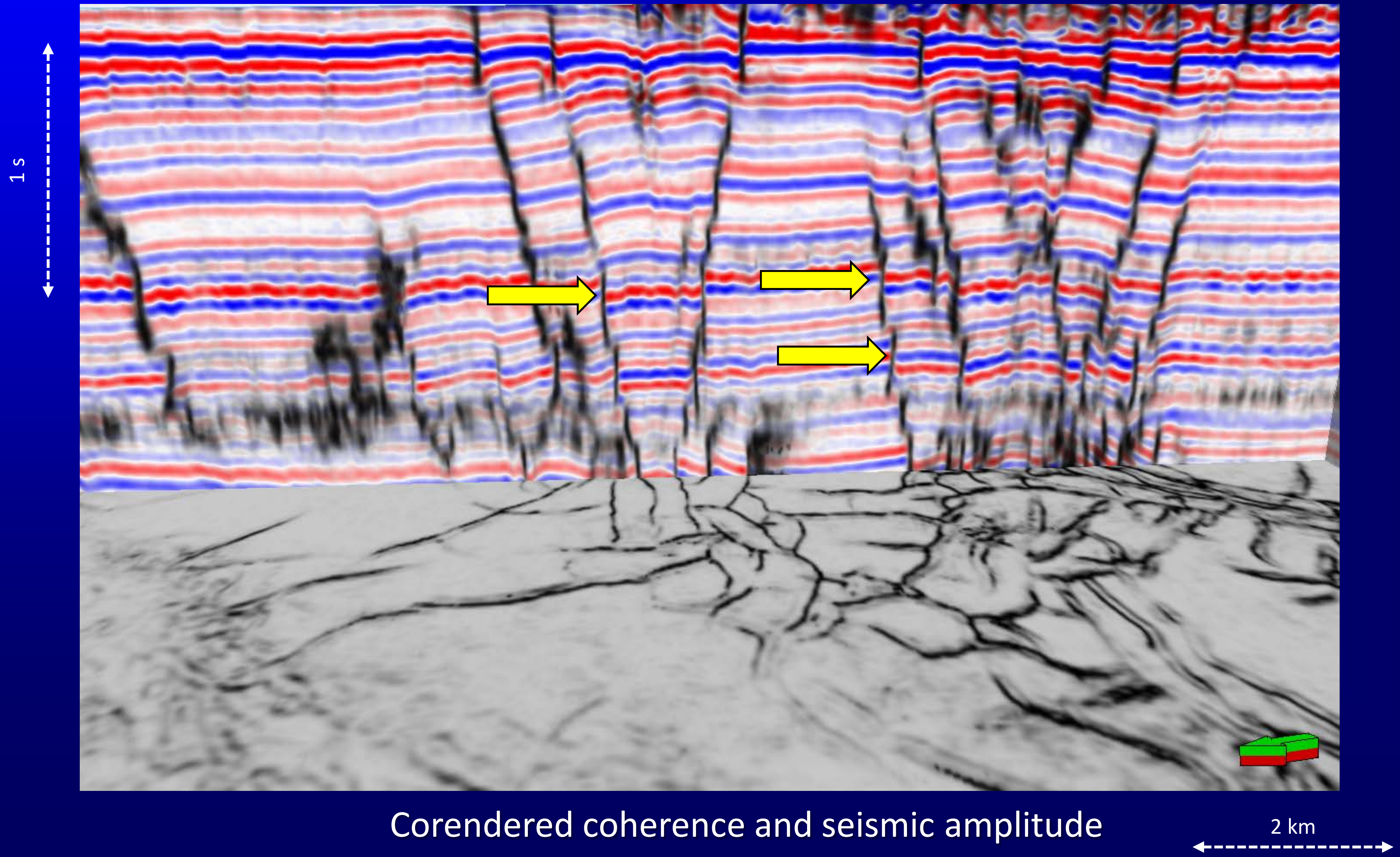
(Lin and Marfurt, 2017)

Pitfall: Coherence “stair step” effect



Pitfall: Coherence “stair step” effect

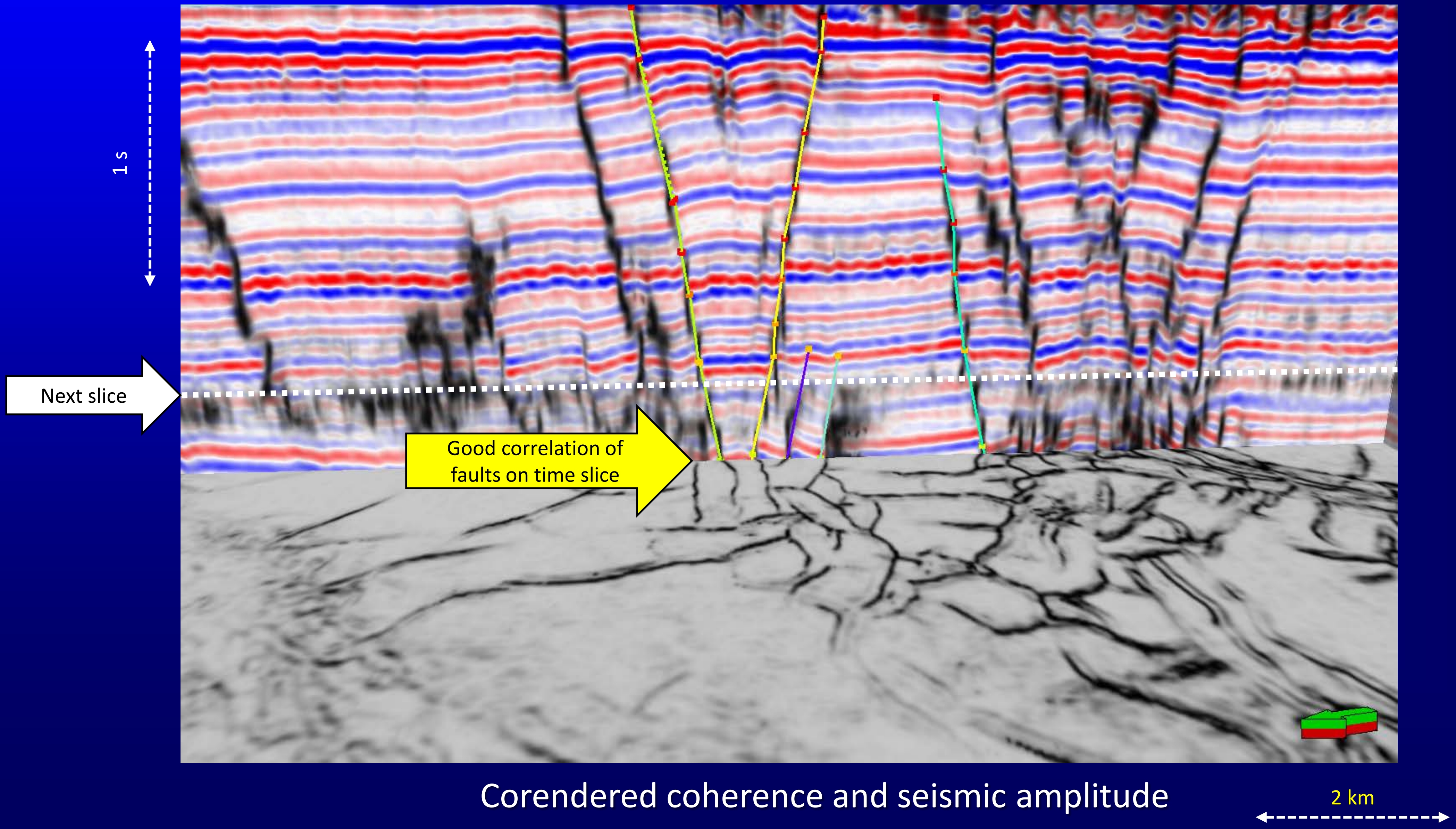
Discontinuities are perpendicular to the reflector, not parallel to the fault, and are the size of the wavelet



Corendered coherence and seismic amplitude

Pitfall: Coherence “stair step” effect

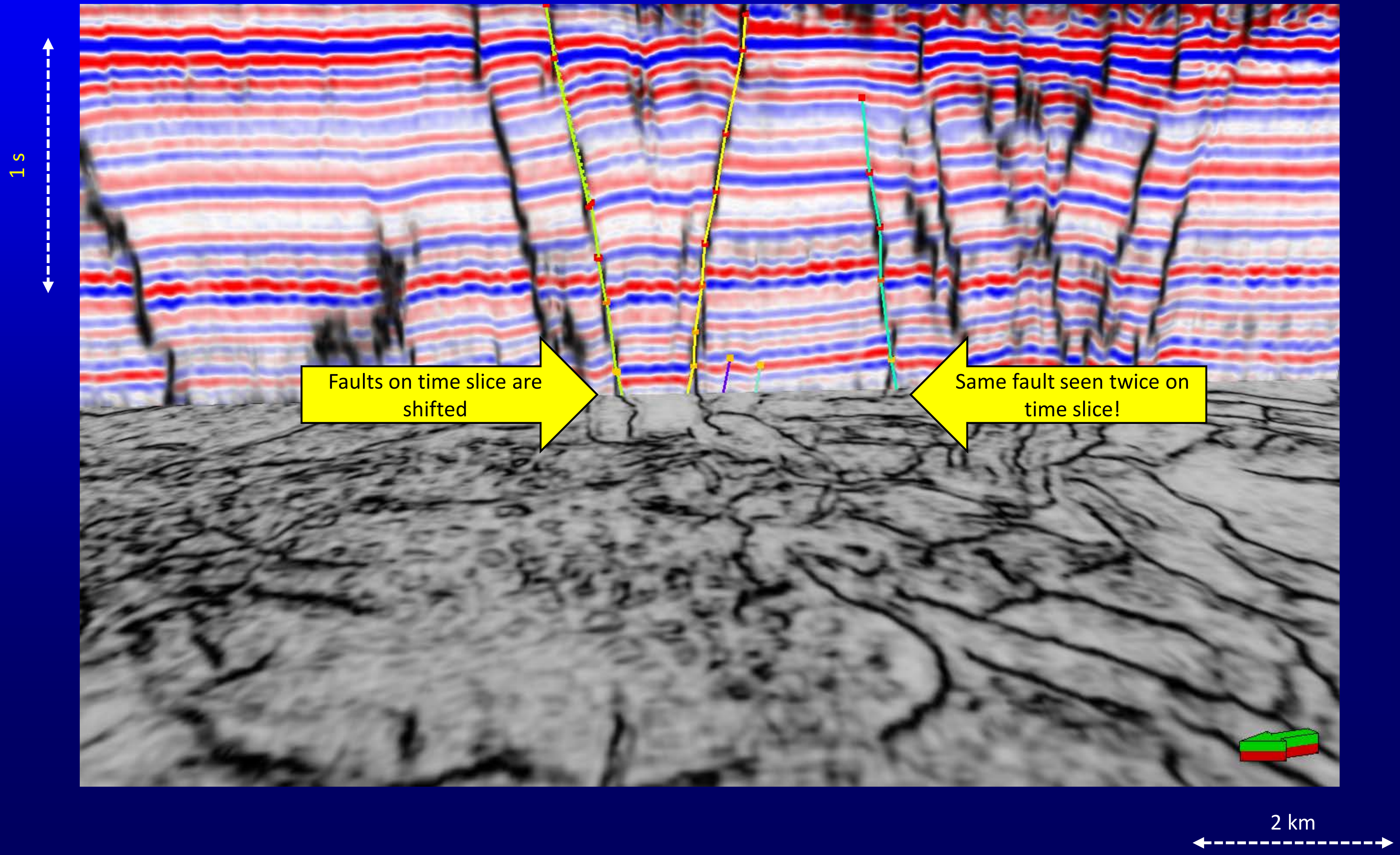
Coherence anomalies are well aligned at the peak of the reflector energy



Corendered coherence and seismic amplitude

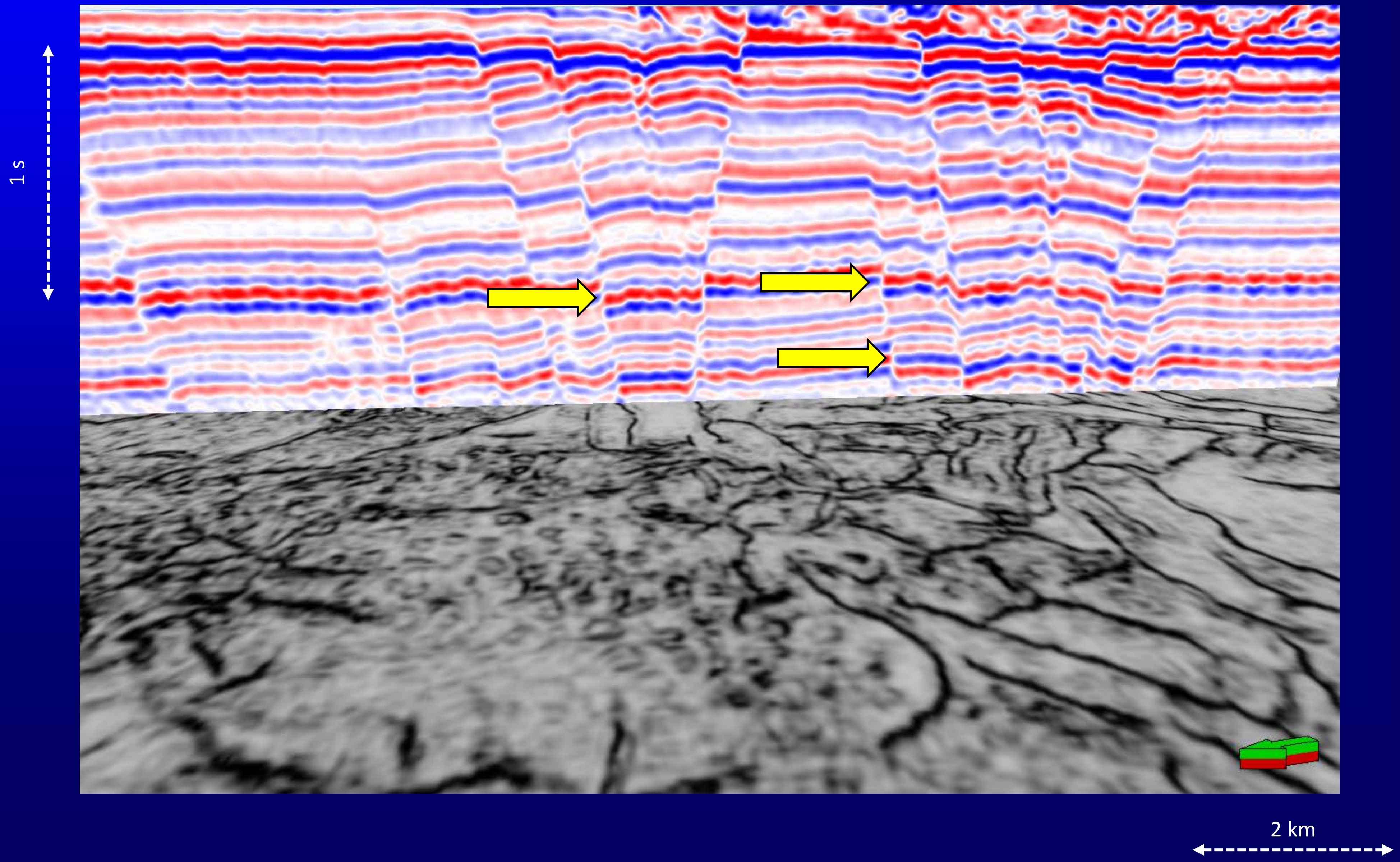
Pitfall: Coherence “stair step” effect

Coherence anomalies can be shifted with respect to the manually picked fault position

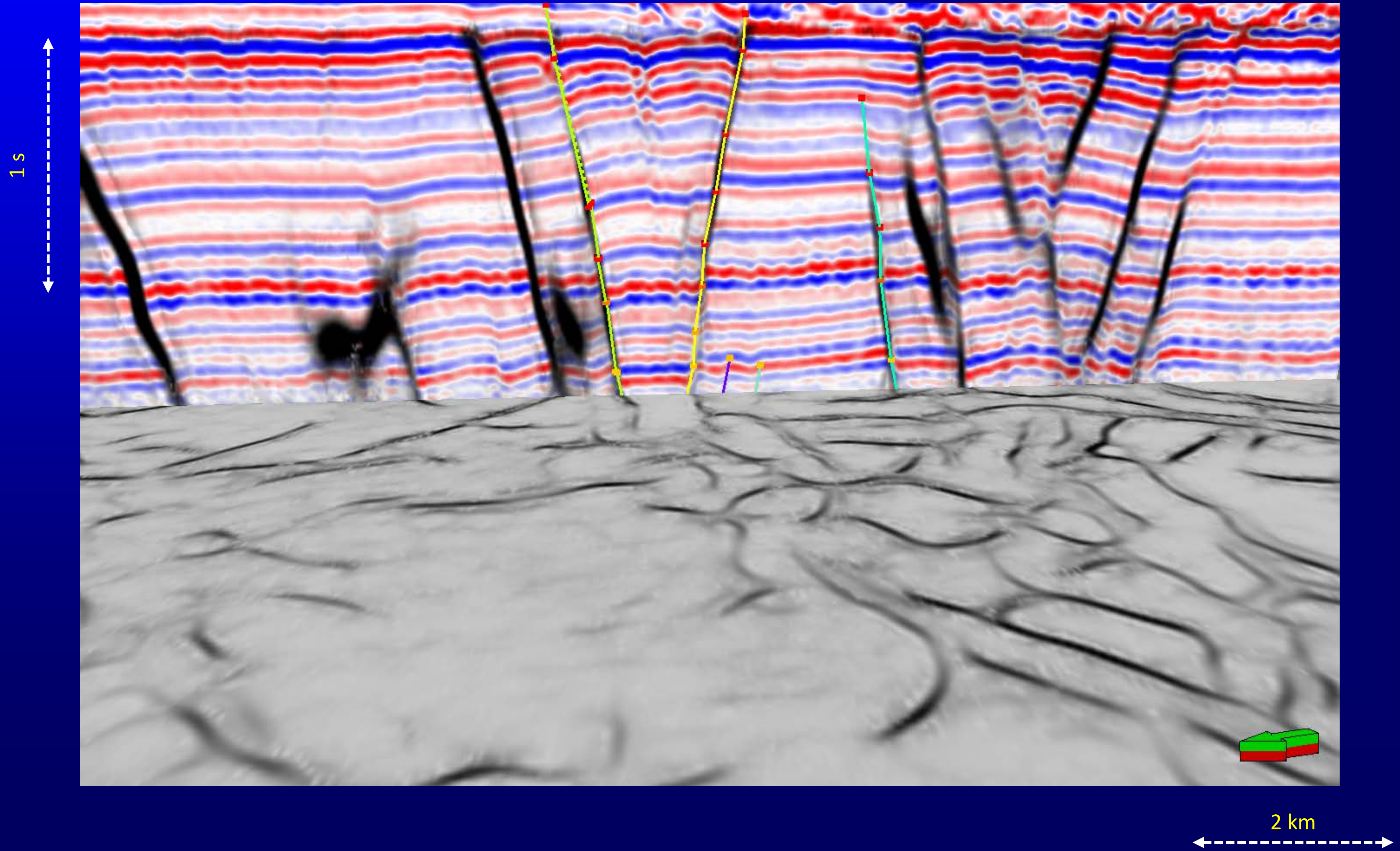


Pitfall: Coherence “stair step” effect

The stair steps are not due to coherence but are in the seismic data.

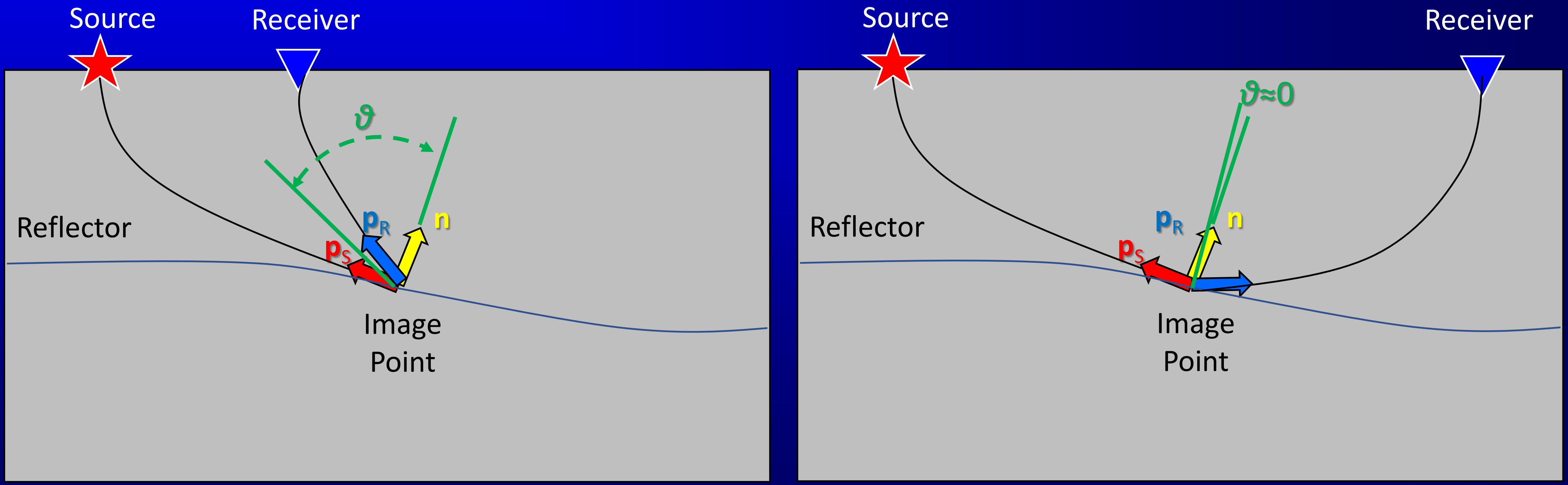


Partial solution: Apply weighted filters oriented along the local fault plane



A review of prestack seismic imaging

All source receiver pairs are weighted by cosϑ and summed to form an image.
The Snell's Law "obliquity factor" cosϑ results in wavelets oriented perpendicular to specular reflectors



Non-specular reflection: cosϑ<1

Specular reflection: cosϑ=1

(Lin and Marfurt, 2017)

Pitfalls and algorithm limitations:
Acquisition footprint

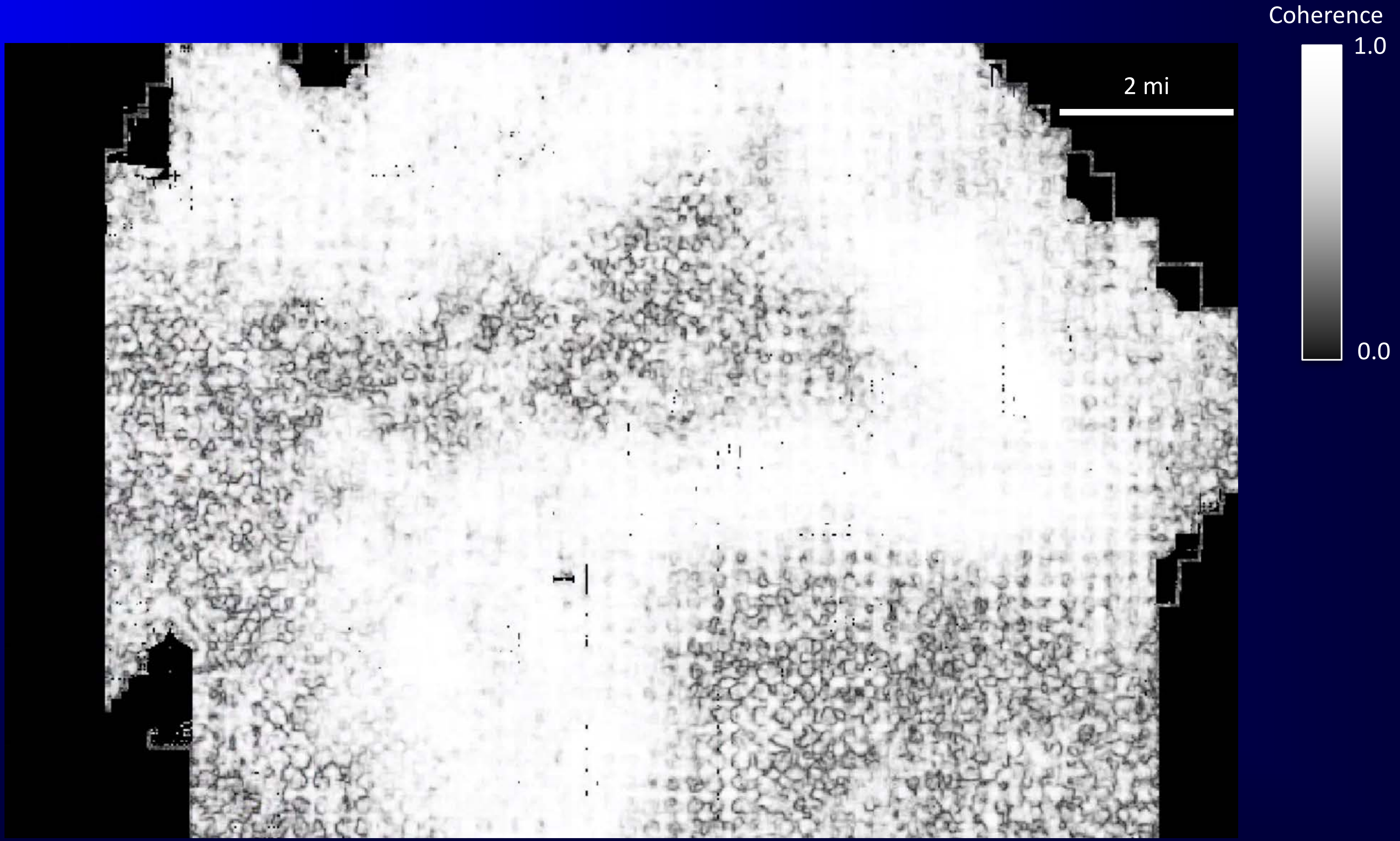
(Delaware Basin, NM, US)

Amplitude Slice (*t*= 0.45 s at Yates level)

(Alali et al., 2016)

Pitfalls and algorithm limitations:
Acquisition footprint

(Delaware Basin, NM, US)

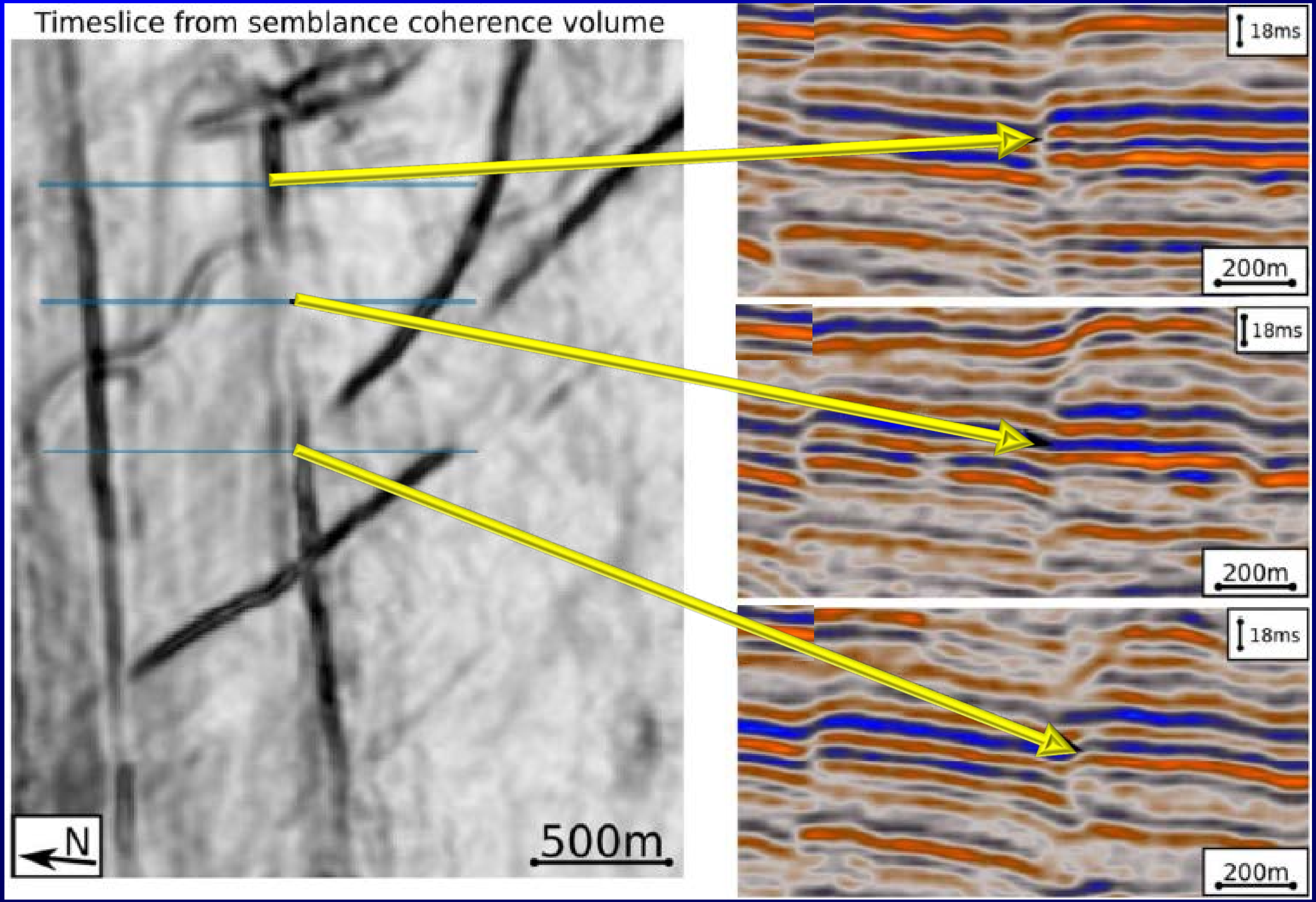


Coherence Slice (*t*= 0.45 s at Yates level)

(Alali et al., 2016)

Pitfalls and algorithm limitations:

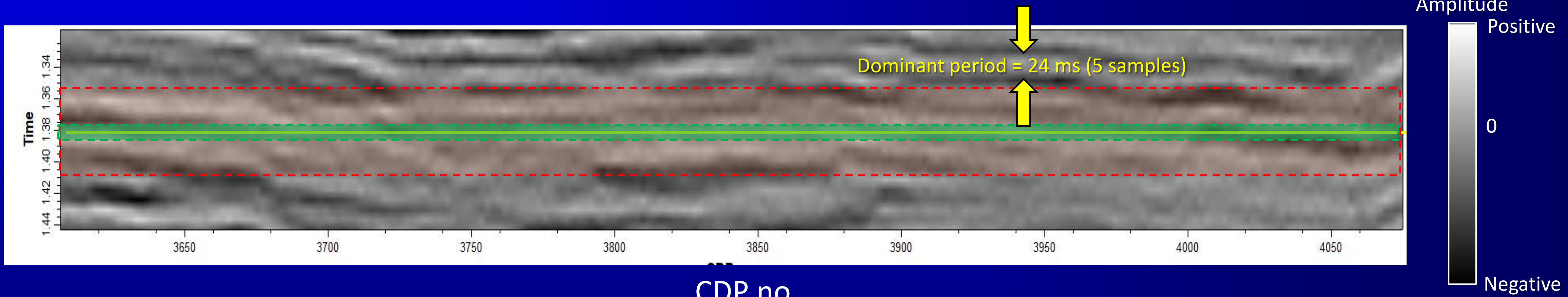
Faults that are easy to see on vertical sections but missed by coherence



(Libak et al., 2017)

Pitfalls and algorithm limitations:
Using a default analysis window size

Sample increment = 6 ms

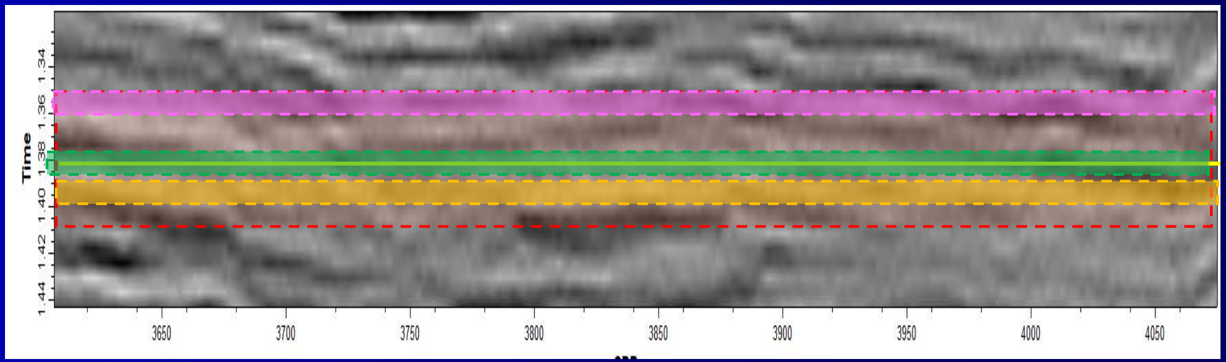


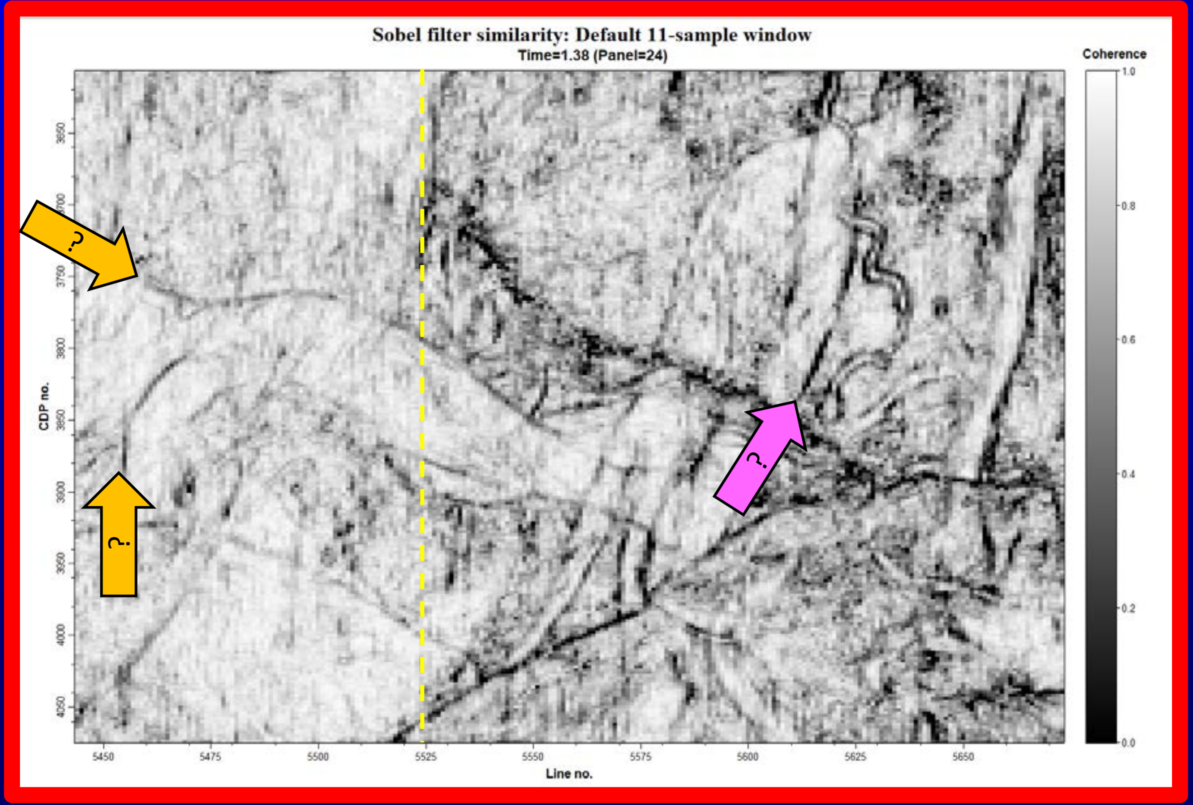
Default window size = 11 samples, or 60 ms

A smaller window size = 3 samples, or 12 ms

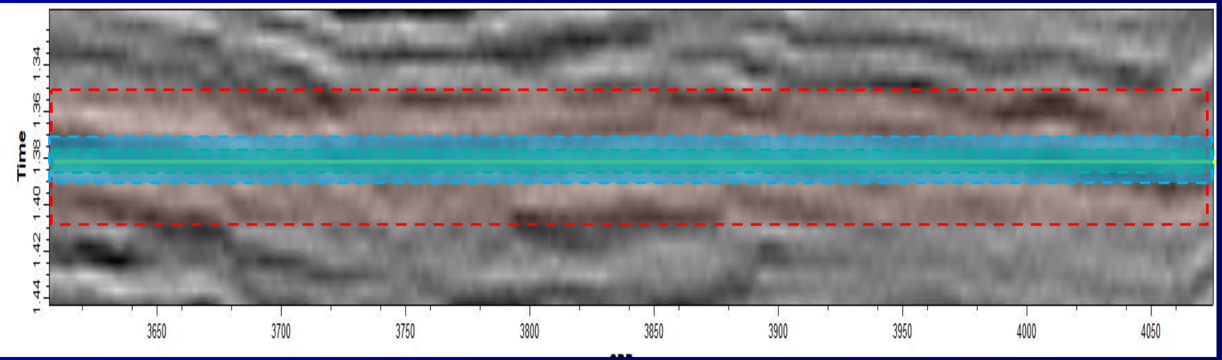
(Data courtesy Fairfield Industries)

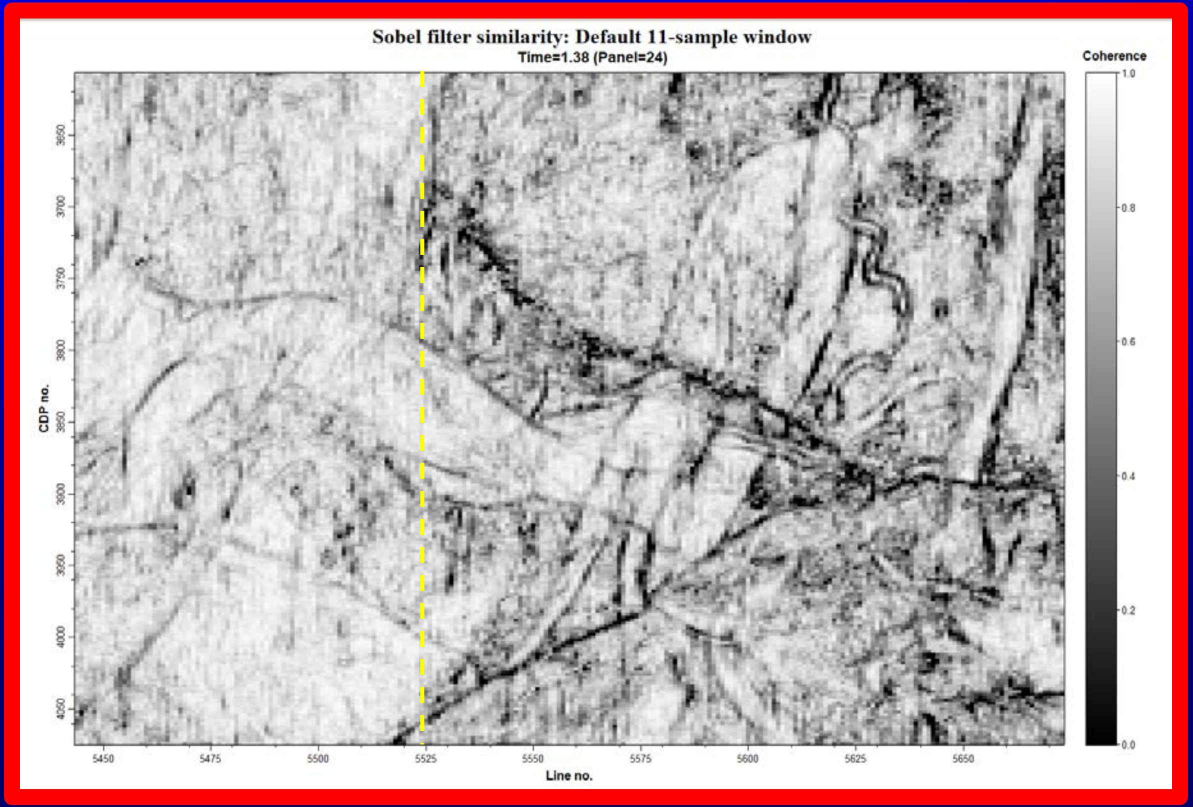
Pitfalls and algorithm limitations:
Using a default analysis window size

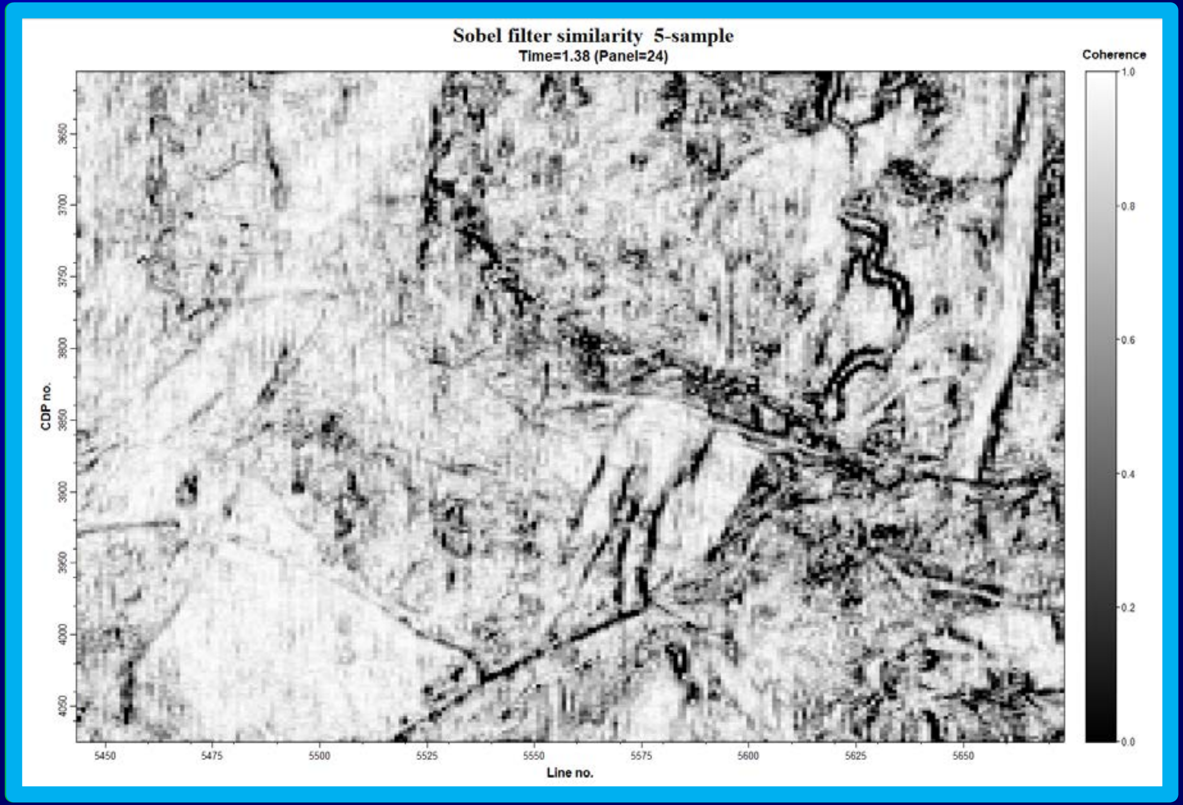




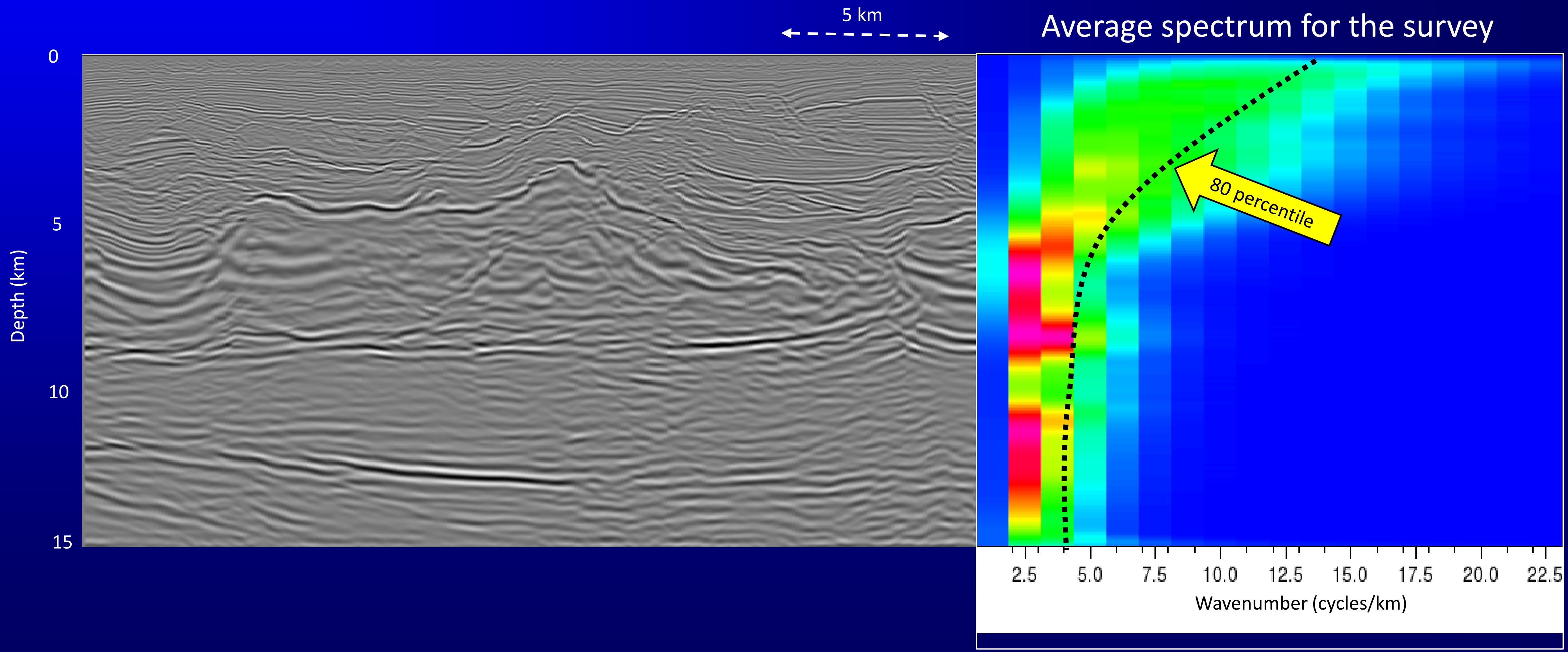
Pitfalls and algorithm limitations:
Using a default analysis window size







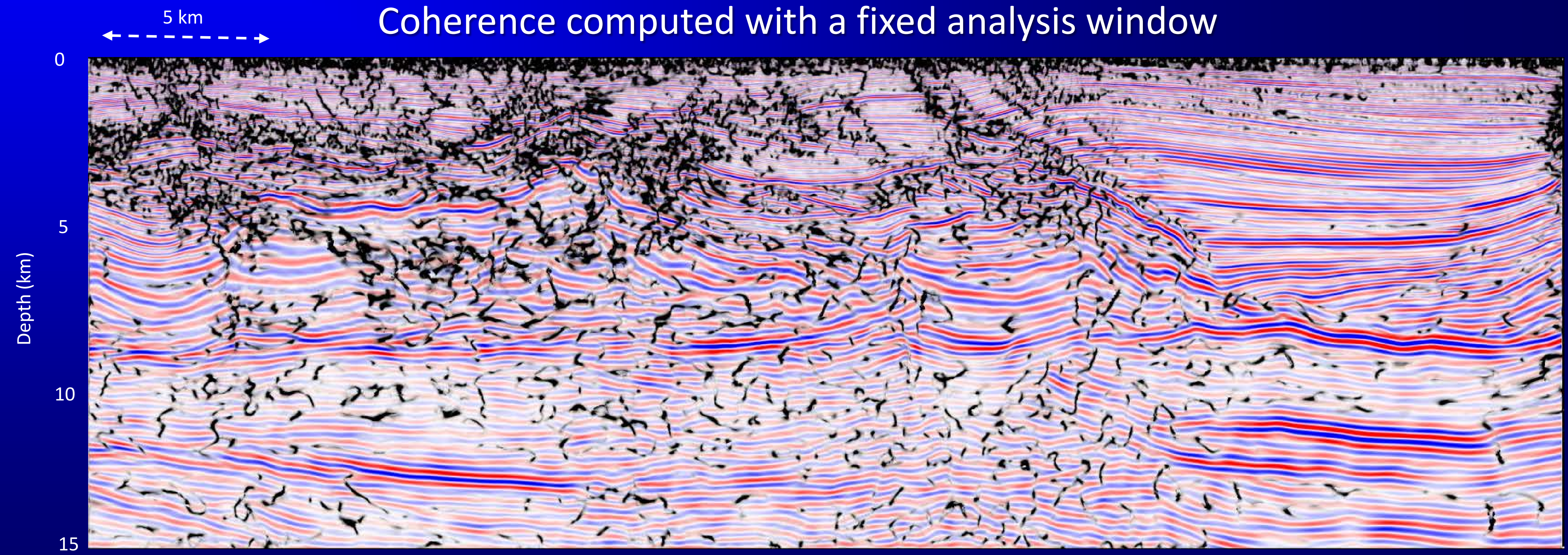
Pitfalls and algorithm limitations:
Using a single sized analysis window for depth-migrated data



Pitfalls and algorithm limitations:

Using a single sized analysis window for depth-migrated data

Coherence computed with a fixed analysis window



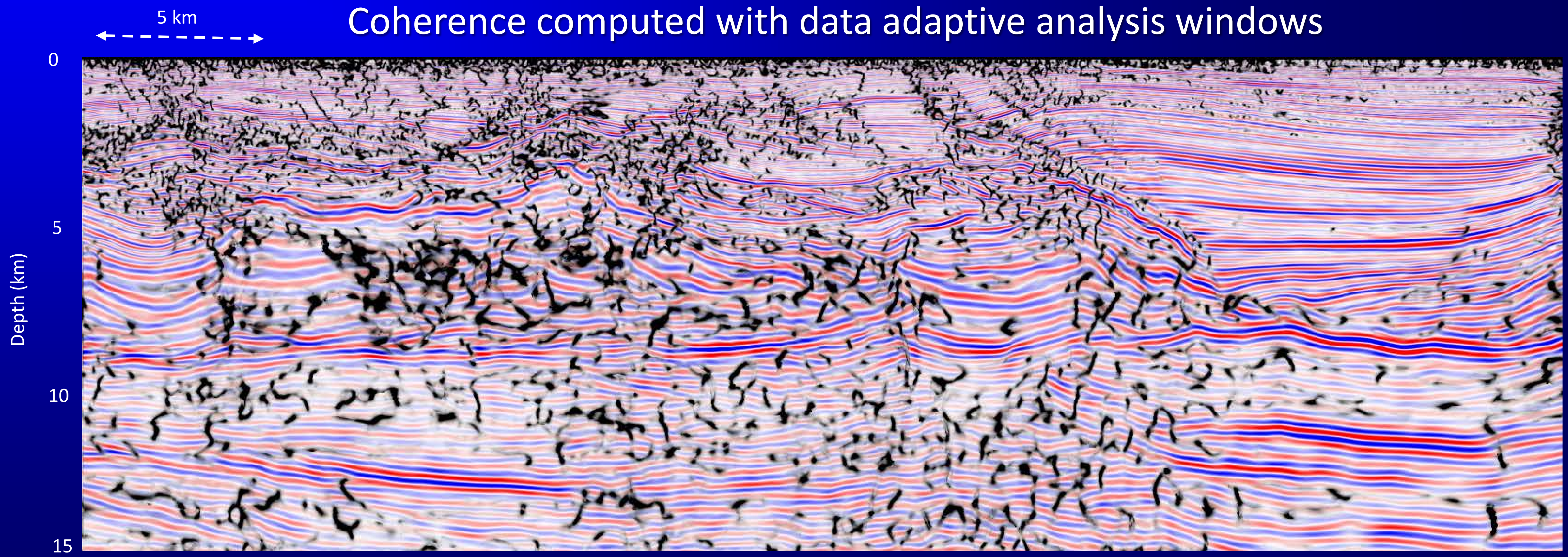
Fixed window = 50 m × 60 m × 50 m

Data grid: Δx=25 m, Δy=30 m, Δz=10 m

Pitfalls and algorithm limitations:

Using a single sized analysis window for depth-migrated data

Coherence computed with data adaptive analysis windows



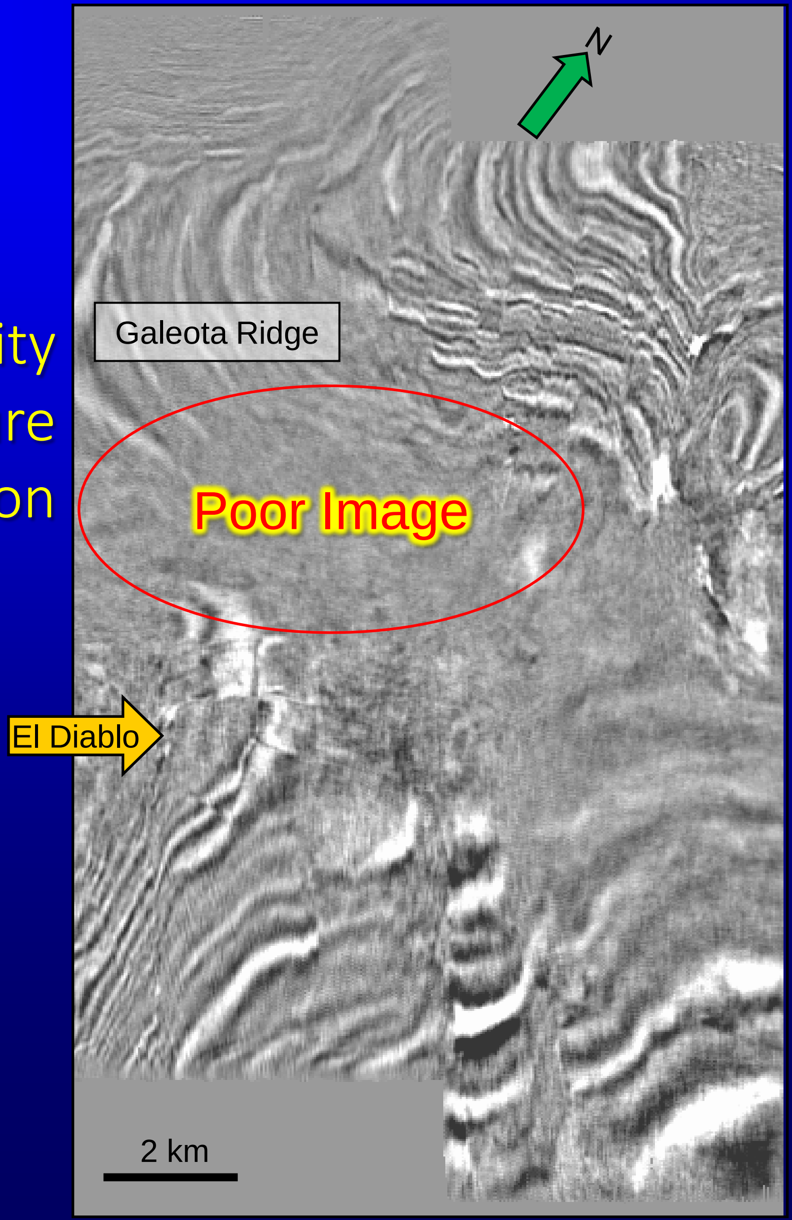
Multiple windows ranging from:

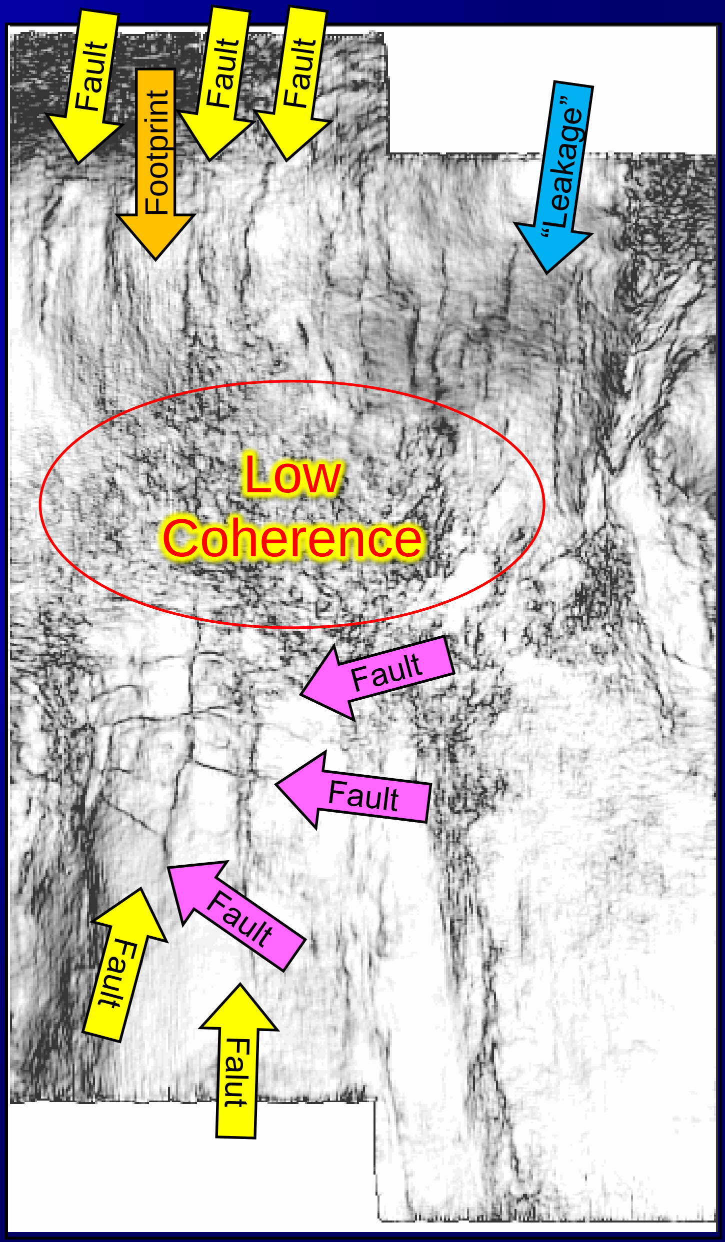
- 30 m × 30 m × 30 m in the shallower section, to
- 130 m × 130 m × 130 m in the deeper section

Data grid: Δx=25 m, Δy=30 m, Δz=10 m

Pitfalls and algorithm limitations:
Poor imaging

Inaccurate velocity due to pressure compartmentalization





(Marfurt and Alvez, 2015)

Figure 10

Coherence

In summary, coherence:

- Is an excellent tool for delineating geological boundaries (faults, lateral stratigraphic contacts, etc.),
- Allows accelerated evaluation of large data sets,
- Provides a quantitative estimate of fault/fracture presence,
- Often enhances stratigraphic information that is otherwise difficult to extract,
- Should always be calculated along structural dip, and
- Is a “local” algorithm- Faults that have drag, are poorly migrated, or separate two similar reflectors, or otherwise do not appear locally to be discontinuous, will not show up on coherence volumes.

In general:

- Stratigraphic features are best analyzed on horizon slices,
- Structural features are best analyzed on time slices, and
- Large vertical analysis windows can improve the resolution of vertical faults, but can smear dipping faults and mix stratigraphic features.