GPHY 5513
3D Seismic Interpretation

Zonghu Liao (China University of Petroleum)

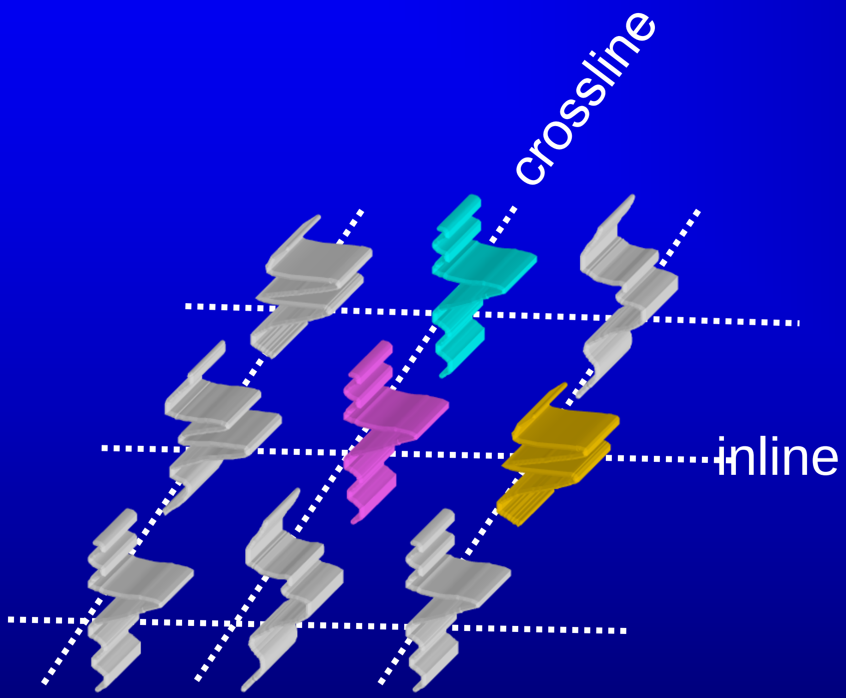
Coherence

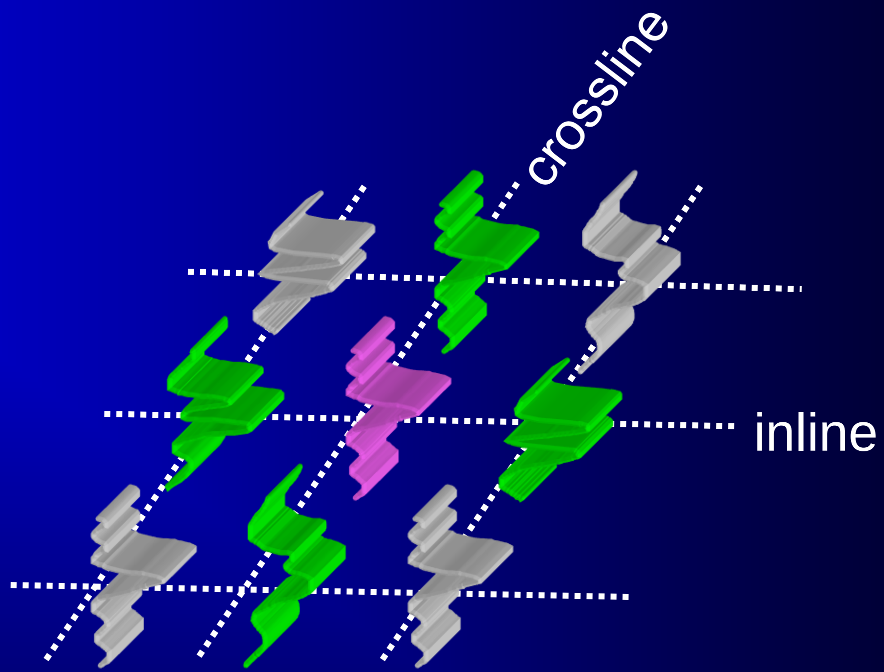
Coherence

After this section you will be able to:

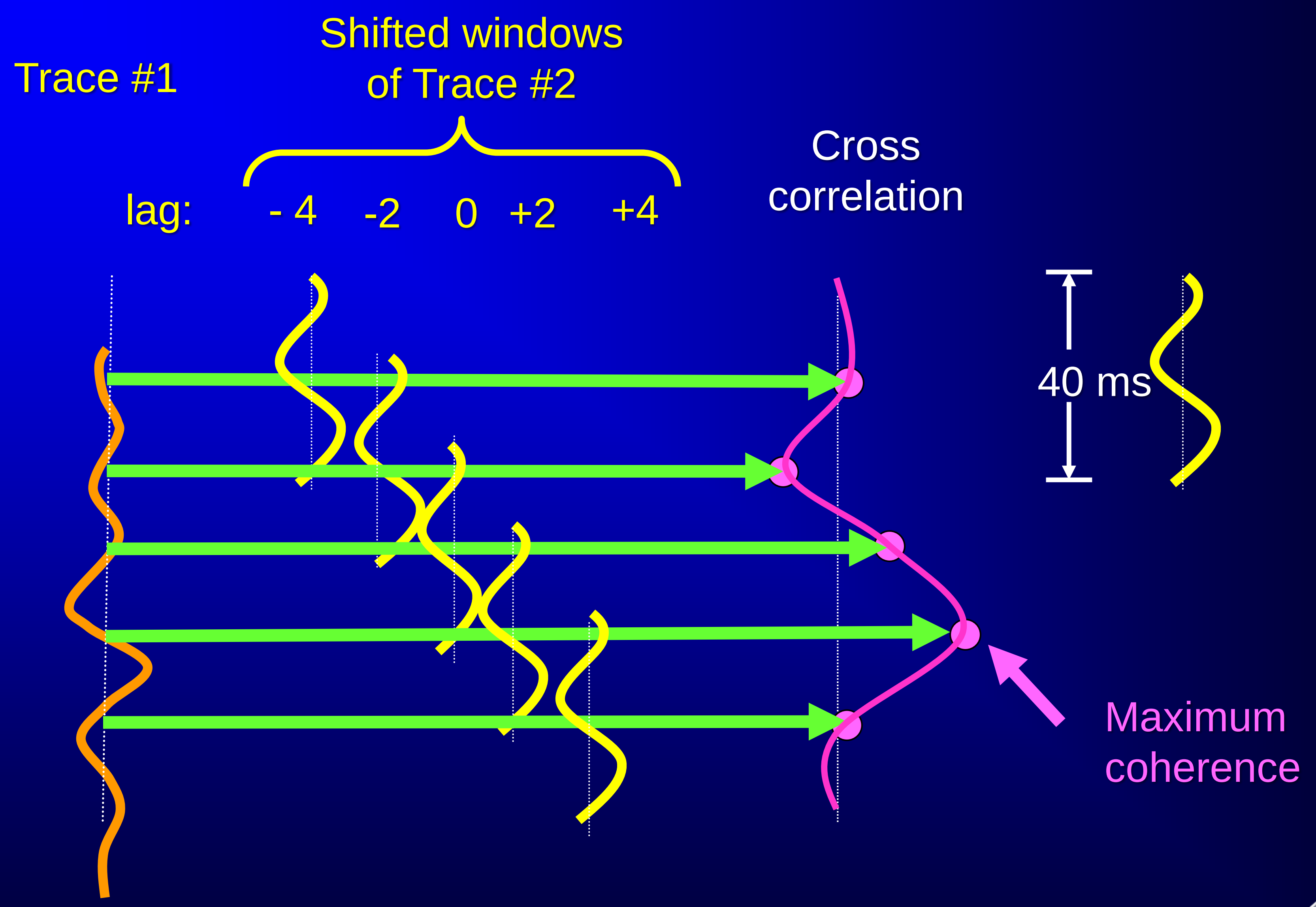
- Summarize the physical and mathematical basis of currently available seismic coherence algorithms,
- Evaluate the impact of spatial and temporal analysis window size on the resolution of geologic features,
- Recognize artifacts due to structural leakage and seismic zero crossings, and
- Apply best practices for structural and stratigraphic interpretation.

Coherence compares the waveforms of neighboring traces

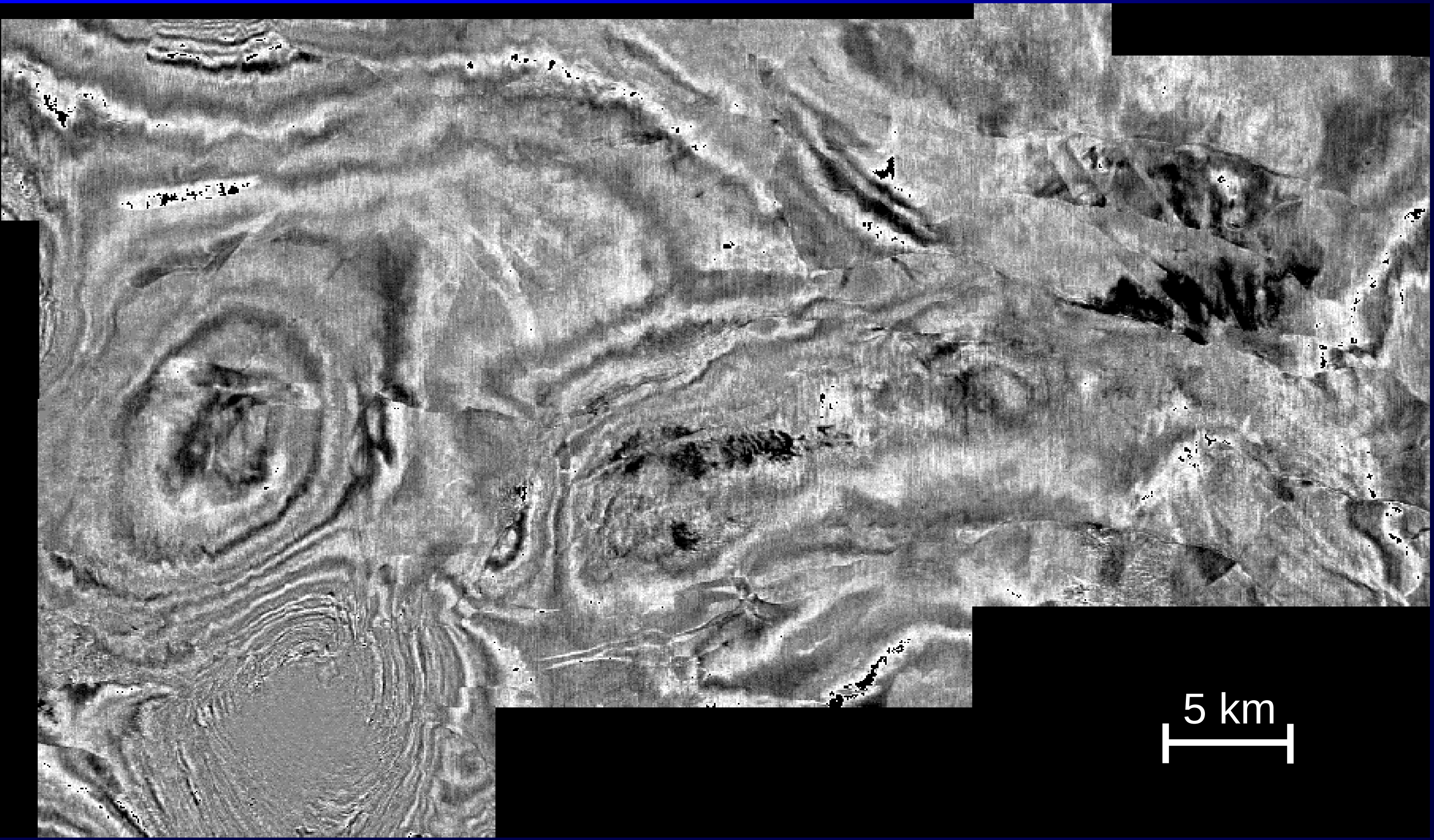




Cross correlation of 2 traces



Seismic Time Slice

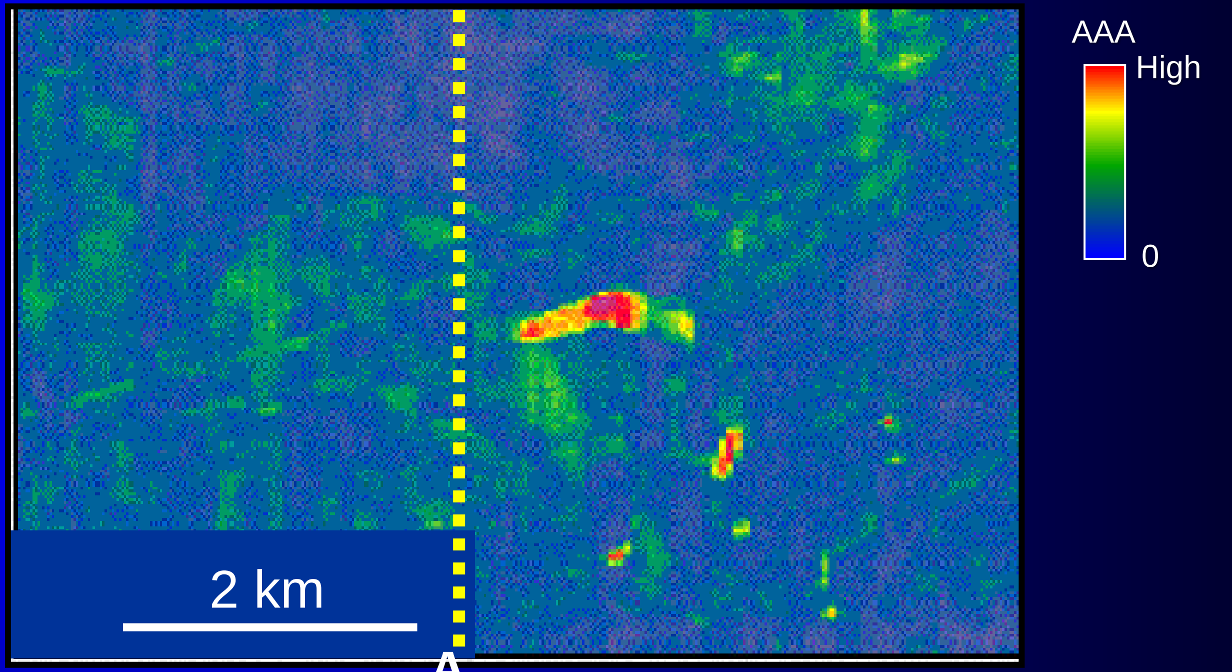


(Bahorich and Farmer, 1995)

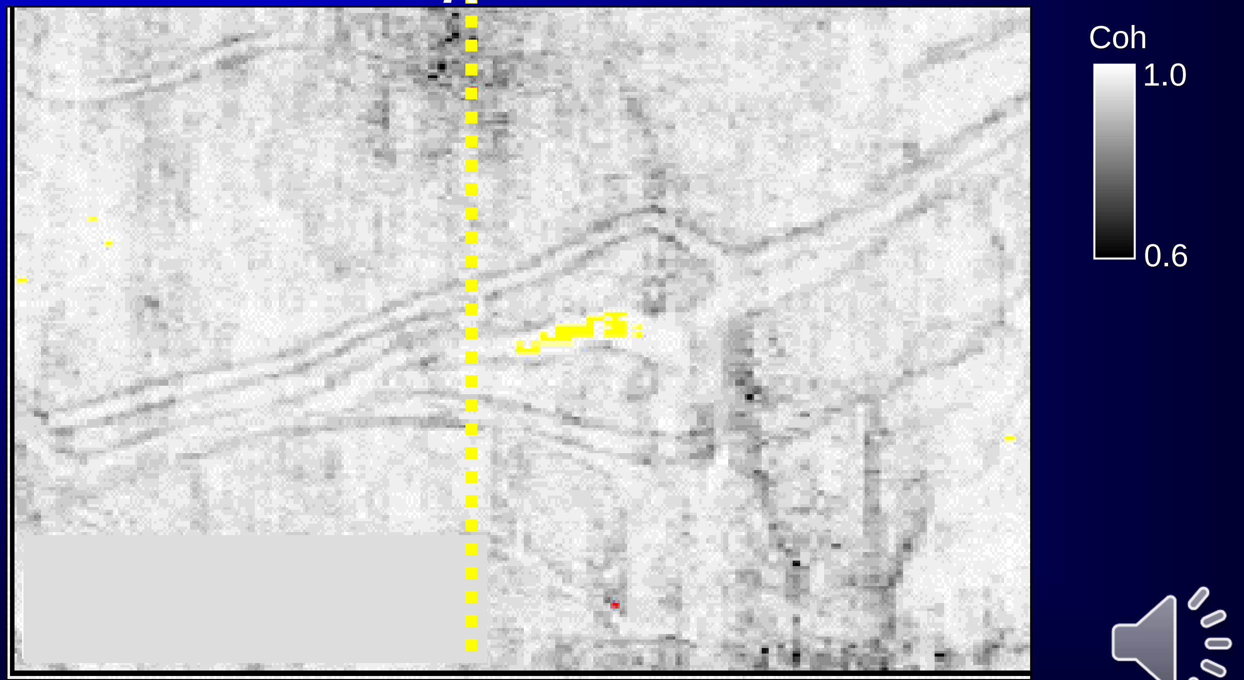
Coherence Time Slice

(Bahorich and Farmer, 1995)

Time slice through average absolute amplitude

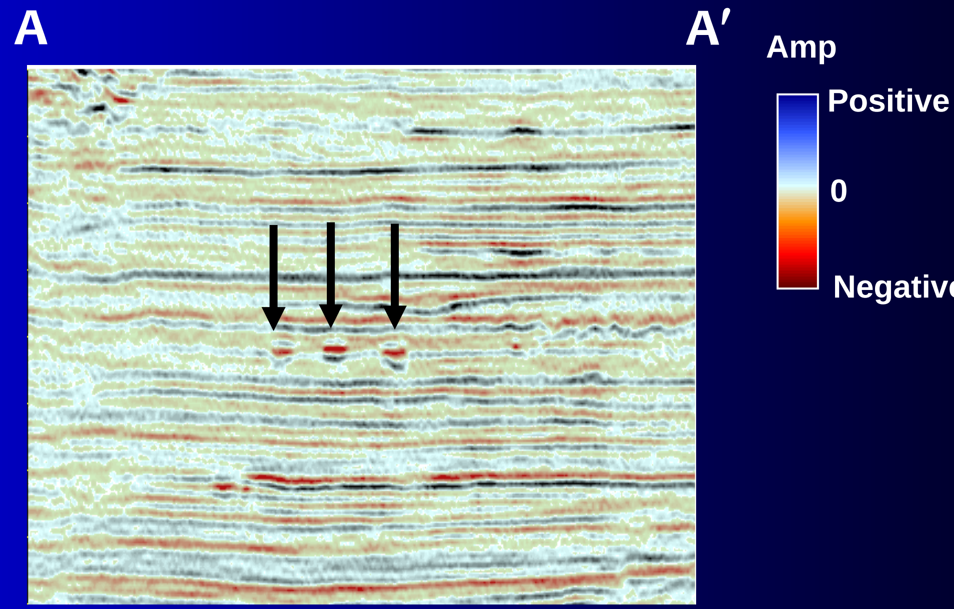


Time slice through coherence (early algorithm)

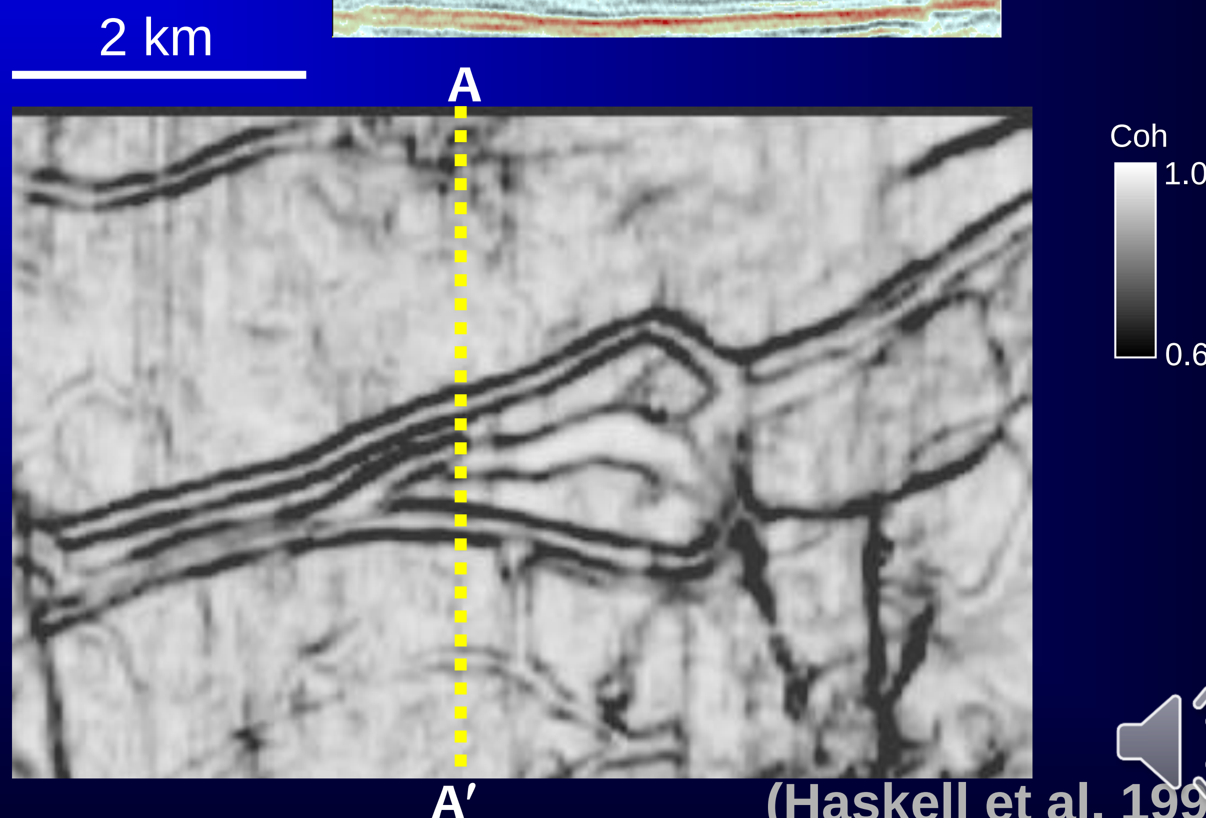


(Bahorich and Farmer, 1995)

Vertical slice through seismic

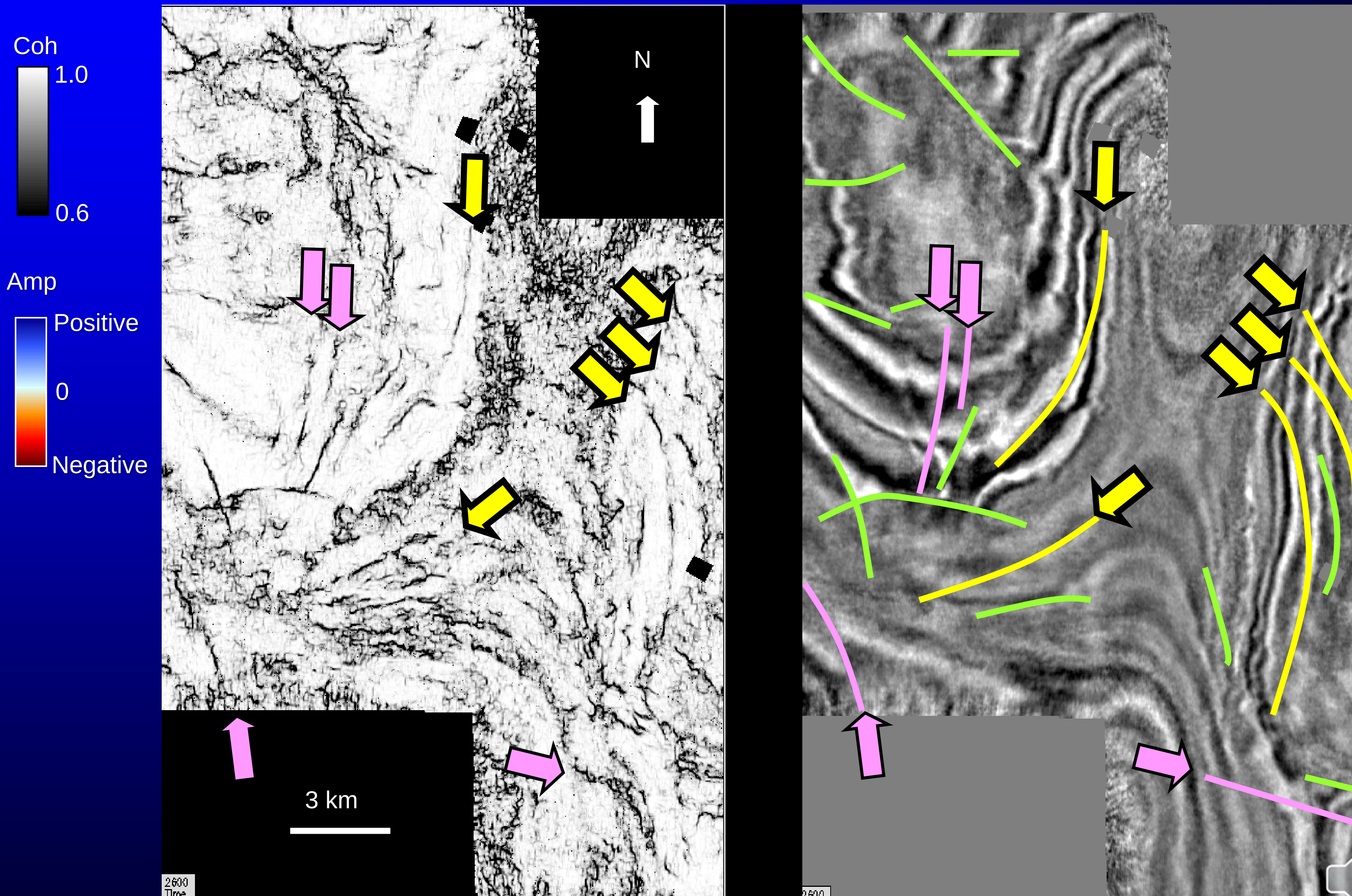


Time slice through coherence (later algorithm)



(Haskell et al. 1995)

Appearance faults perpendicular and parallel to strike



coherence seismic

Alternative measures of waveform similarity

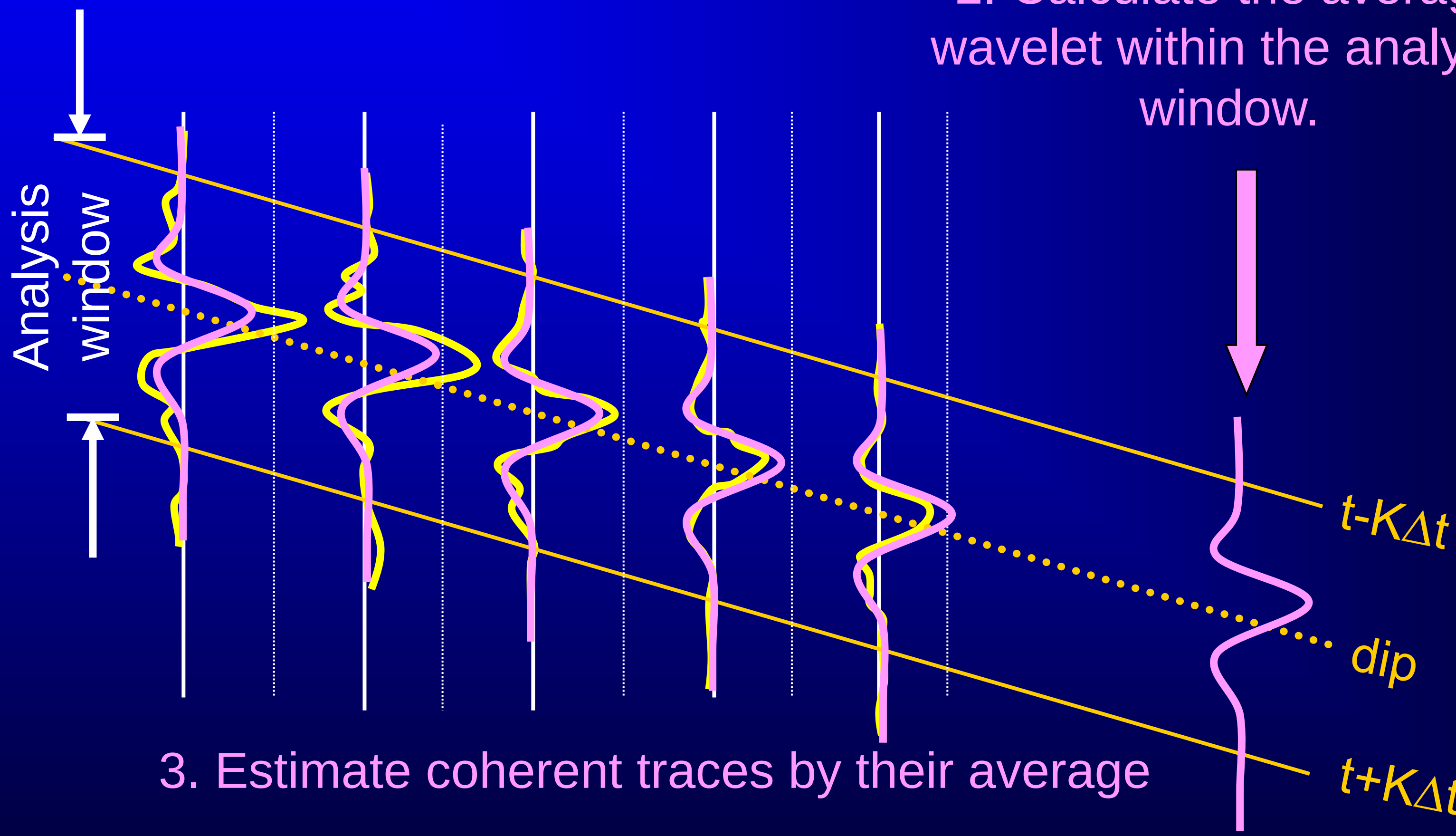
- cross correlation
- semblance, variance, and Manhattan distance
- eigenstructure
- Gradient Structural Tensors (GST)
- plane-wave destructors

Semblance estimate of coherence

5. coherence $\equiv \dfrac{\text{energy of average traces}}{\text{Average energy of input traces}}$

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

Semblance estimate of coherence

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

← Energy of the average trace

← Average of the energy of all the traces

(Marfurt et al, 1998)

Variance estimate of coherence

Statistical definition of variance

Classic definition of variance

"Fast" computation of variance

$$\sigma^2 \equiv \frac{1}{J}\sum_{j=1}^{J}\left(u_j - m\right)^2 = \frac{1}{J}\left[\sum_{j=1}^{J}\left(u_j{}^2\right) - m^2\right]$$

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

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

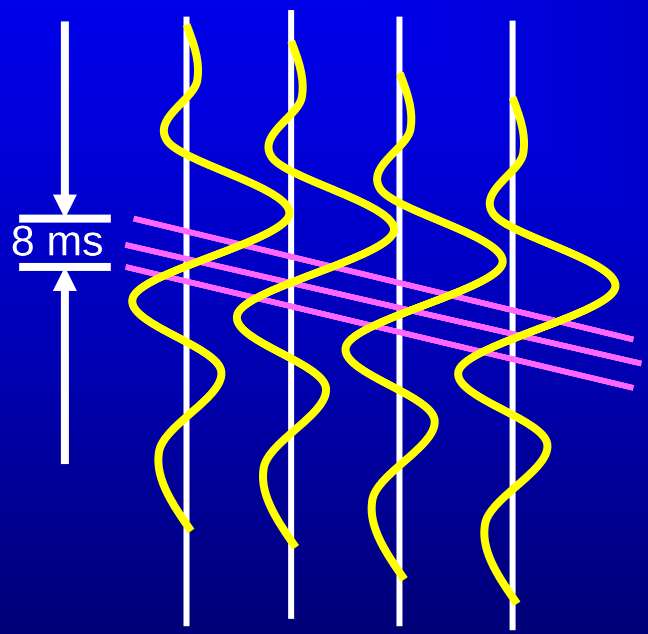
Manhattan distance estimate of coherence

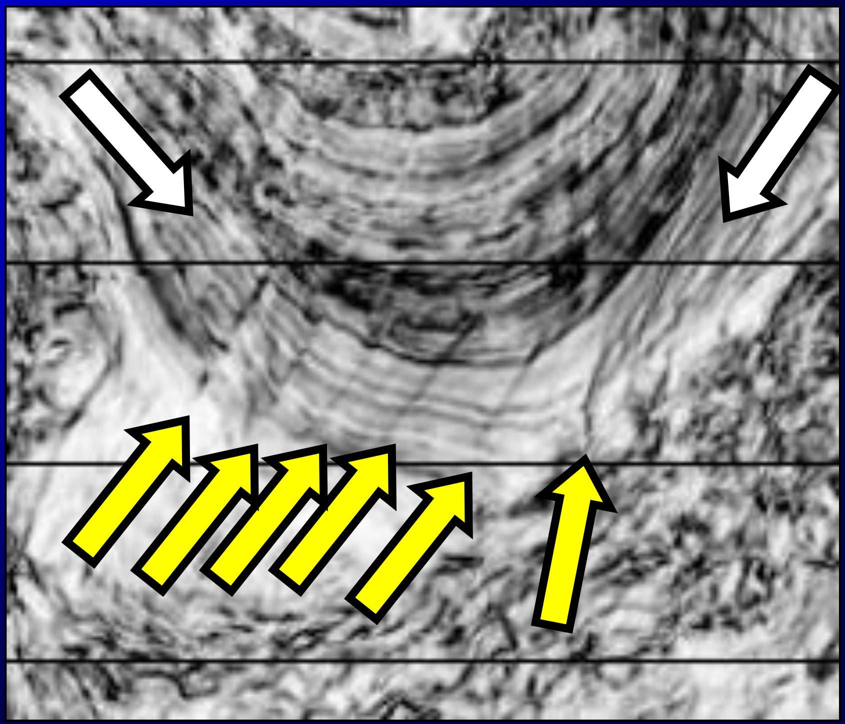
$$c_s = \frac{\sum_{k=-K}^{+K} \frac{1}{J} \left| \sum_{j=1}^{J} u(k\Delta t - px_j - qy_j) \right|}{\sum_{k=-K}^{+K} \frac{1}{J} \sum_{j=1}^{J} \left| u(k\Delta t - px_j - qy_j) \right|}$$

Absolute value of the average trace

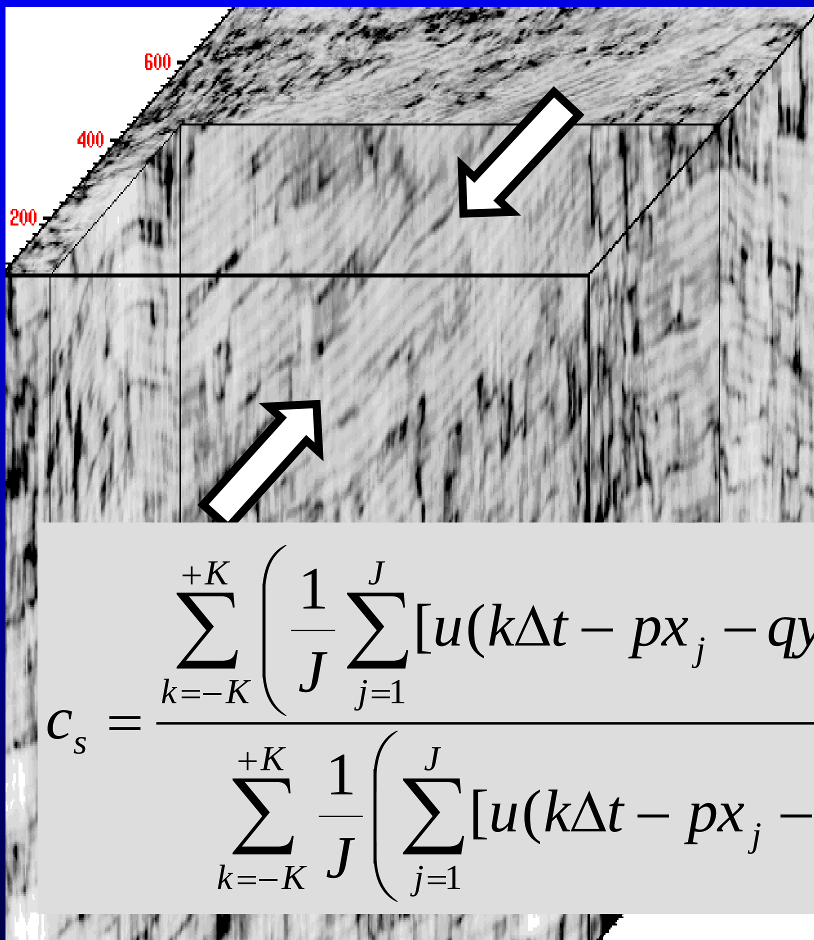
Average of the absolute value of all the traces

Pitfall: Banding artifacts near zero crossings

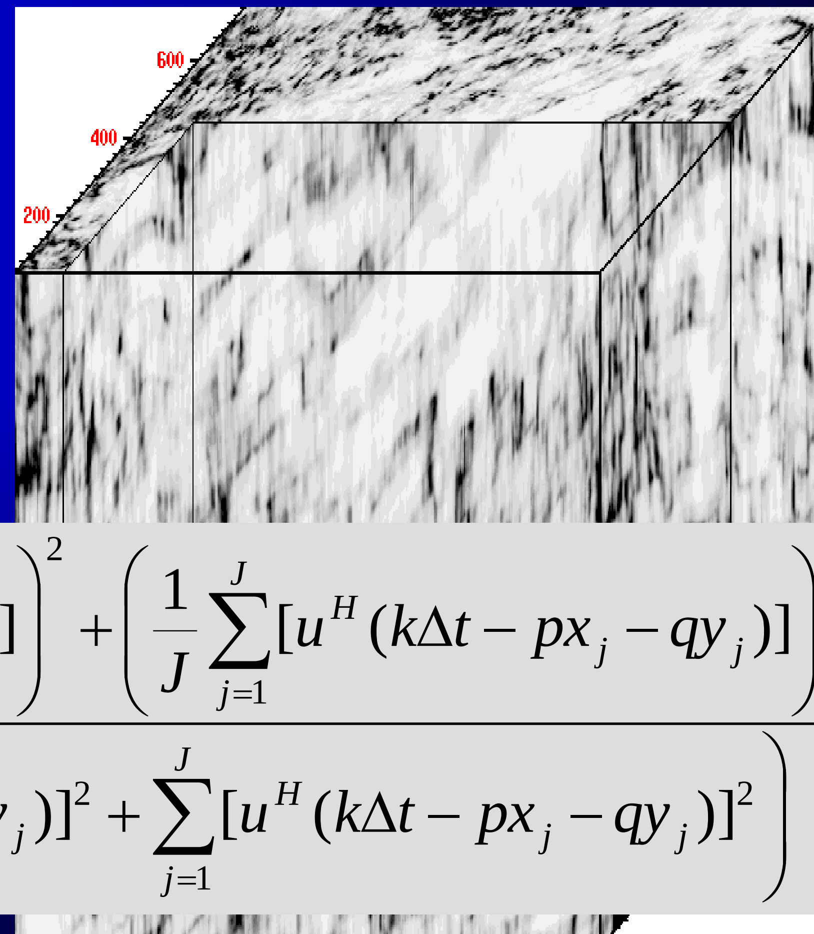




Solution: calculate coherence on the analytic trace



Coherence of real trace



Coherence of analytic trace

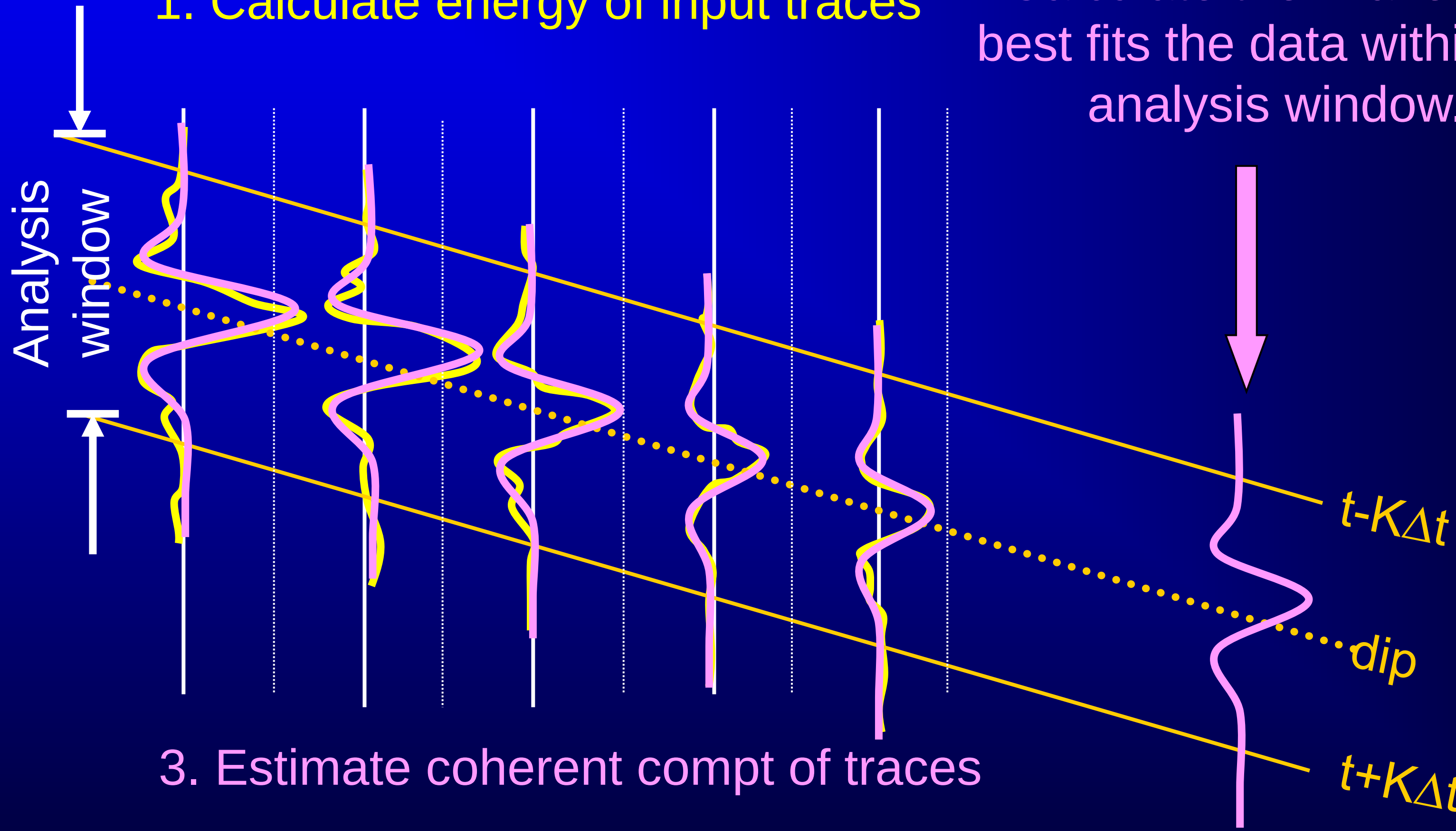
$$c_s = \frac{\sum_{k=-K}^{+K} \left(\frac{1}{J} \sum_{j=1}^{J} [u(k\Delta t - px_j - qy_j)] \right)^2 + \left(\frac{1}{J} \sum_{j=1}^{J} [u^H(k\Delta t - px_j - qy_j)] \right)^2}{\sum_{k=-K}^{+K} \frac{1}{J} \left(\sum_{j=1}^{J} [u(k\Delta t - px_j - qy_j)]^2 + \sum_{j=1}^{J} [u^H(k\Delta t - px_j -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

Eigenstructure estimate of coherence

5. coherence $\equiv \dfrac{\text{energy of coherent compt}}{\text{energy of input traces}}$

1. Calculate energy of input traces

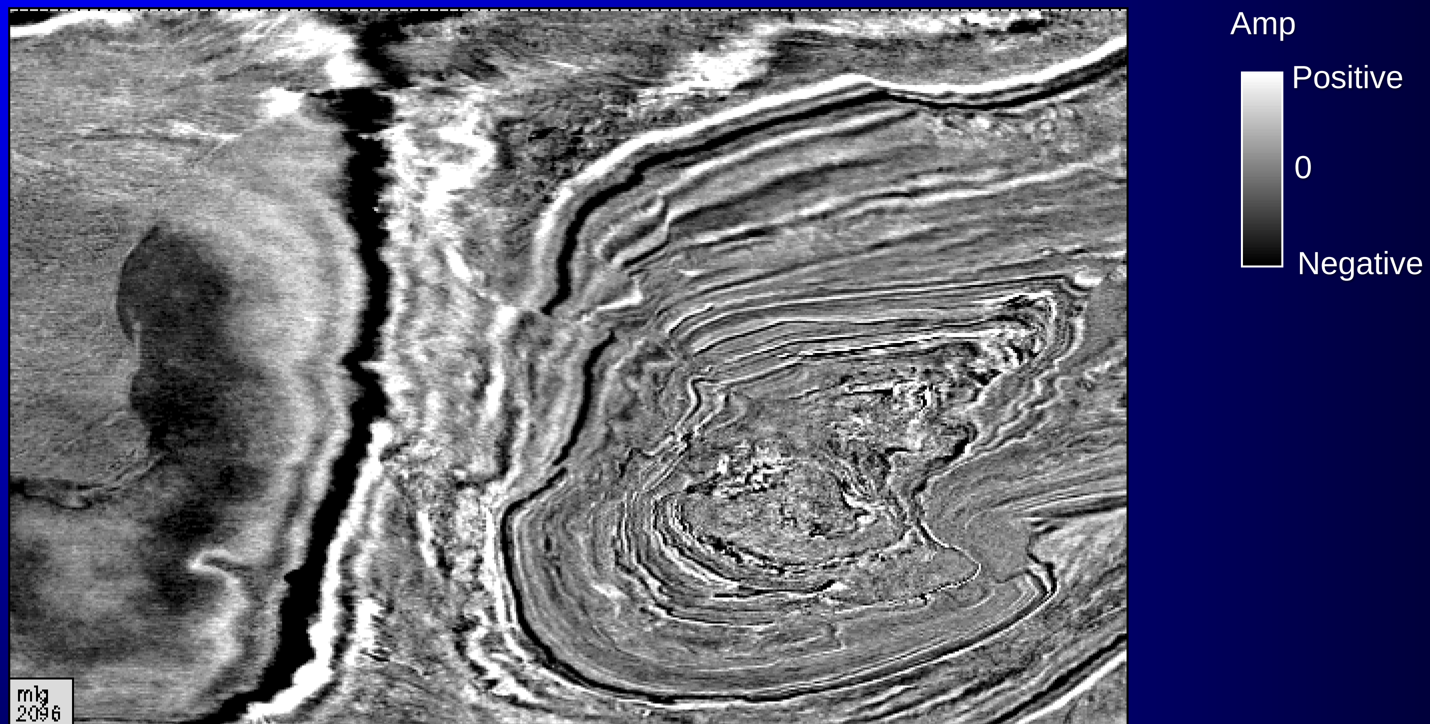
2. Calculate the wavelet that best fits the data within the analysis window.



3. Estimate coherent compt of traces

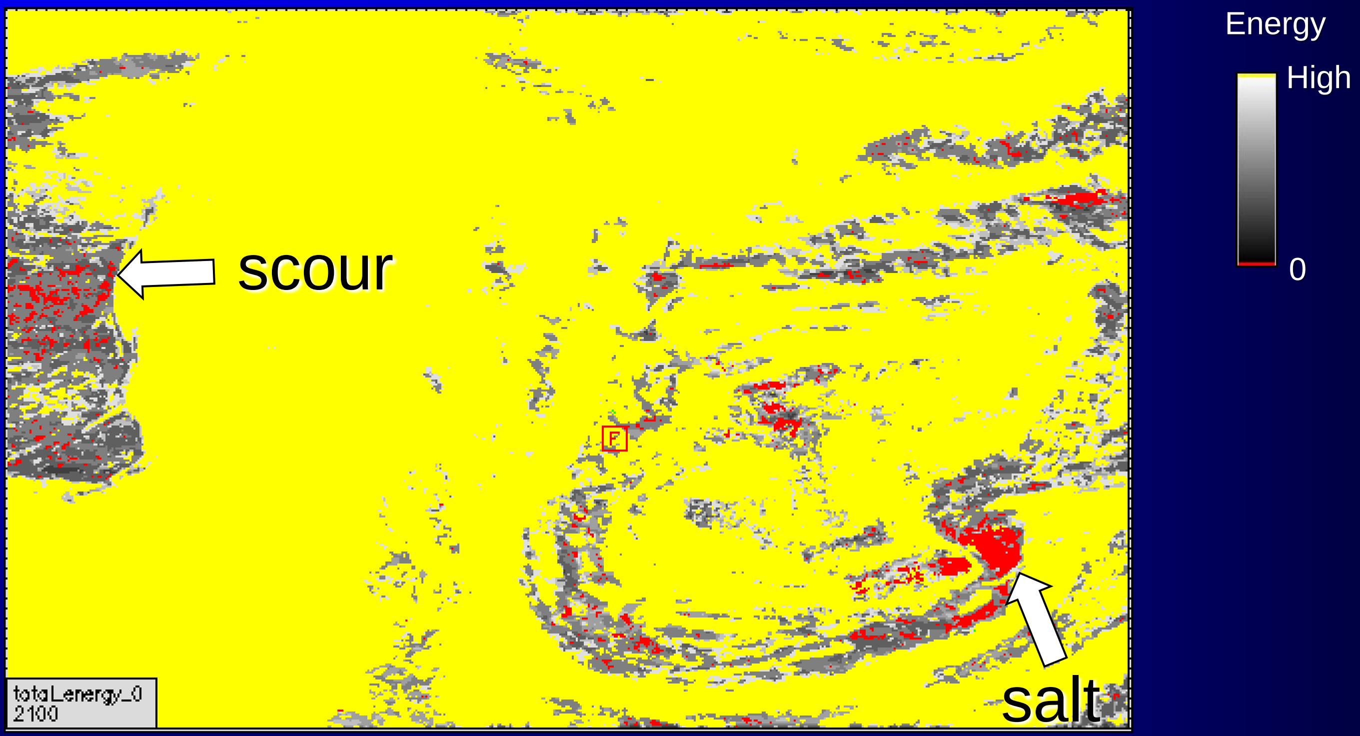
4. Calculate energy of coherent compt of traces

Eigenstructure coherence:
Time slice through seismic



Eigenstructure coherence:

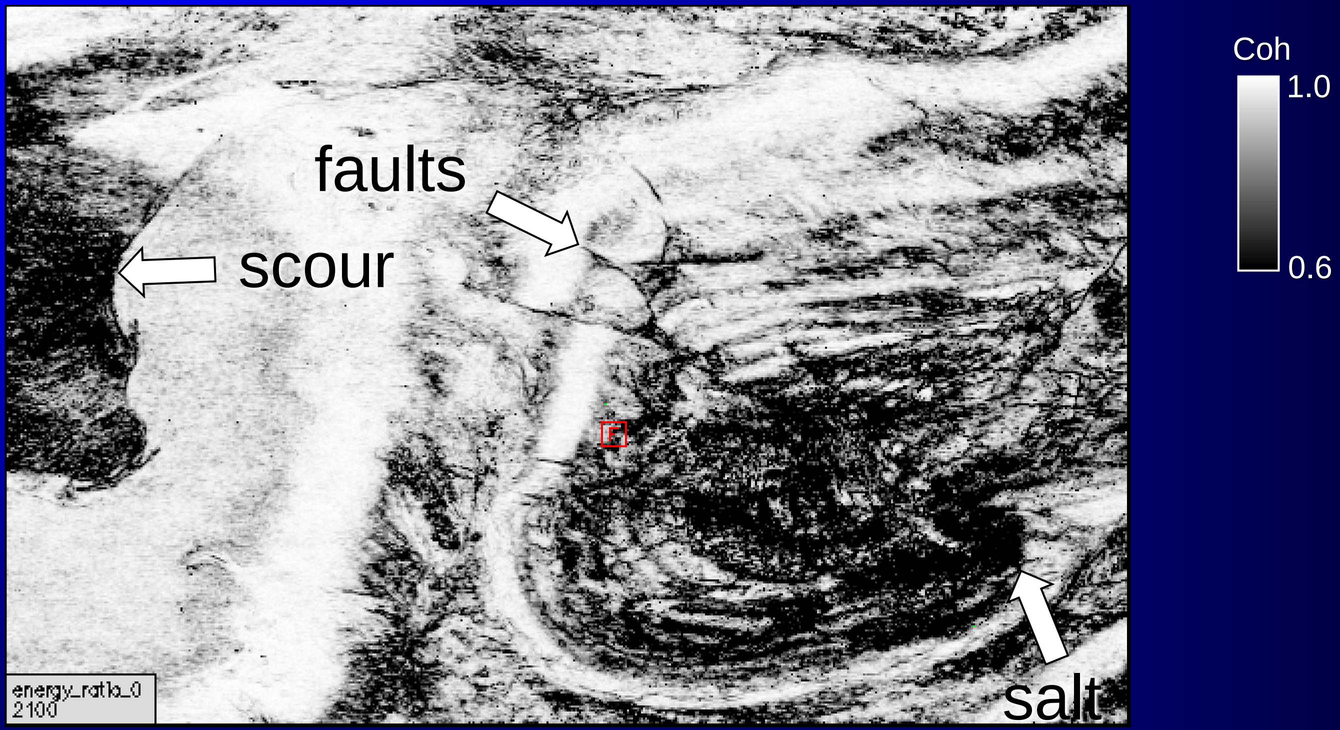
Time slice through total energy in 9 trace, 40 ms window



Eigenstructure coherence:

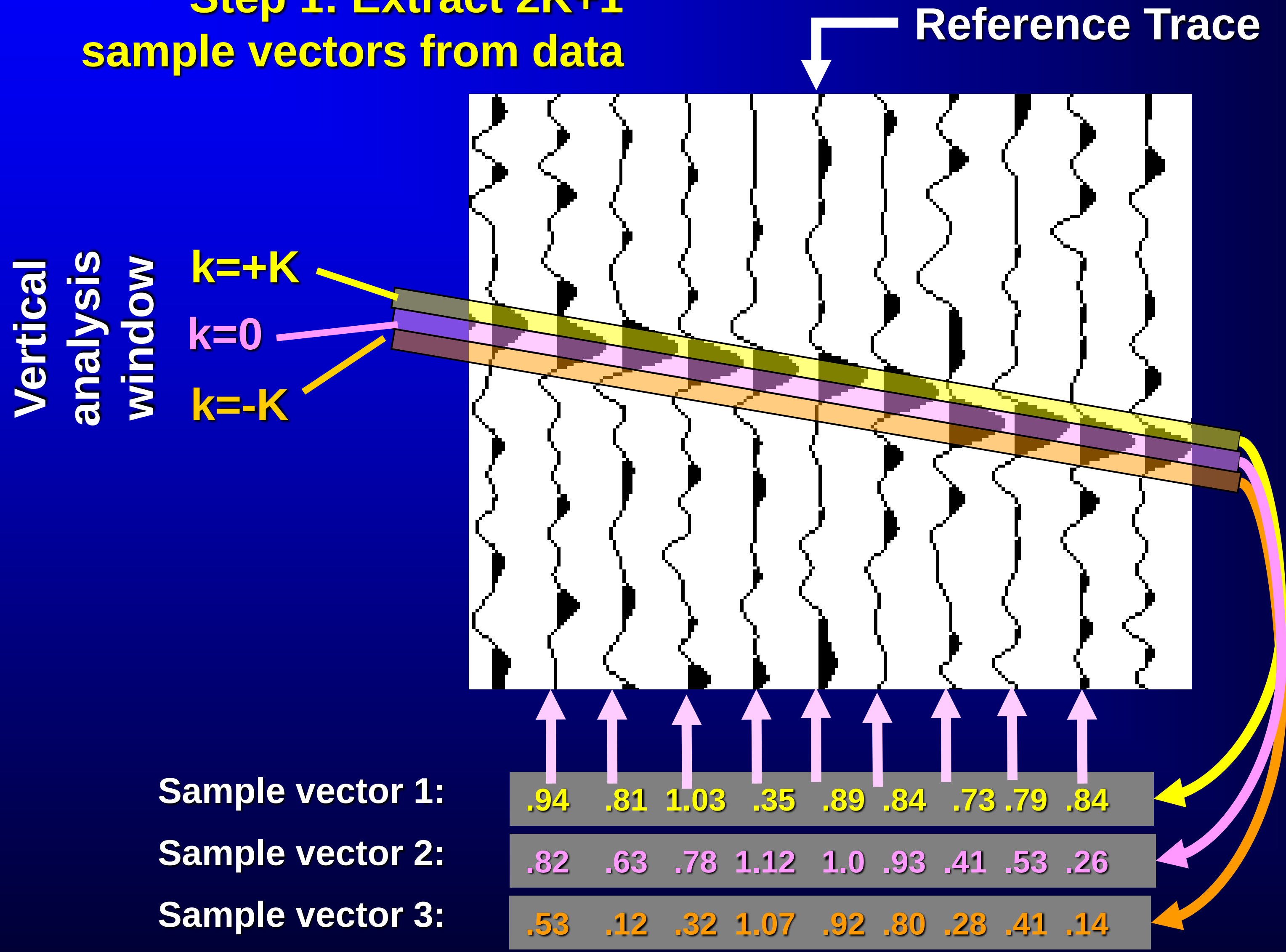
Time slice through coherent energy in 9 trace, 40 ms window

Eigenstructure coherence:
Time slice through ratio of coherent to total energy



Forming a covariance matrix

Step 1: Extract 2K+1 sample vectors from data



Forming a covariance matrix

Sample vector 1:	.94	.81	1.03	.35	.89	.84	.73	.79	.84
Sample vector 2:	..82	.63	.78	1.12	1.0	.93	.41	.53	.26
Sample vector 3:	.53	.12	.32	1.07	.92	.80	.28	.41	.14

Col #2

Col #8

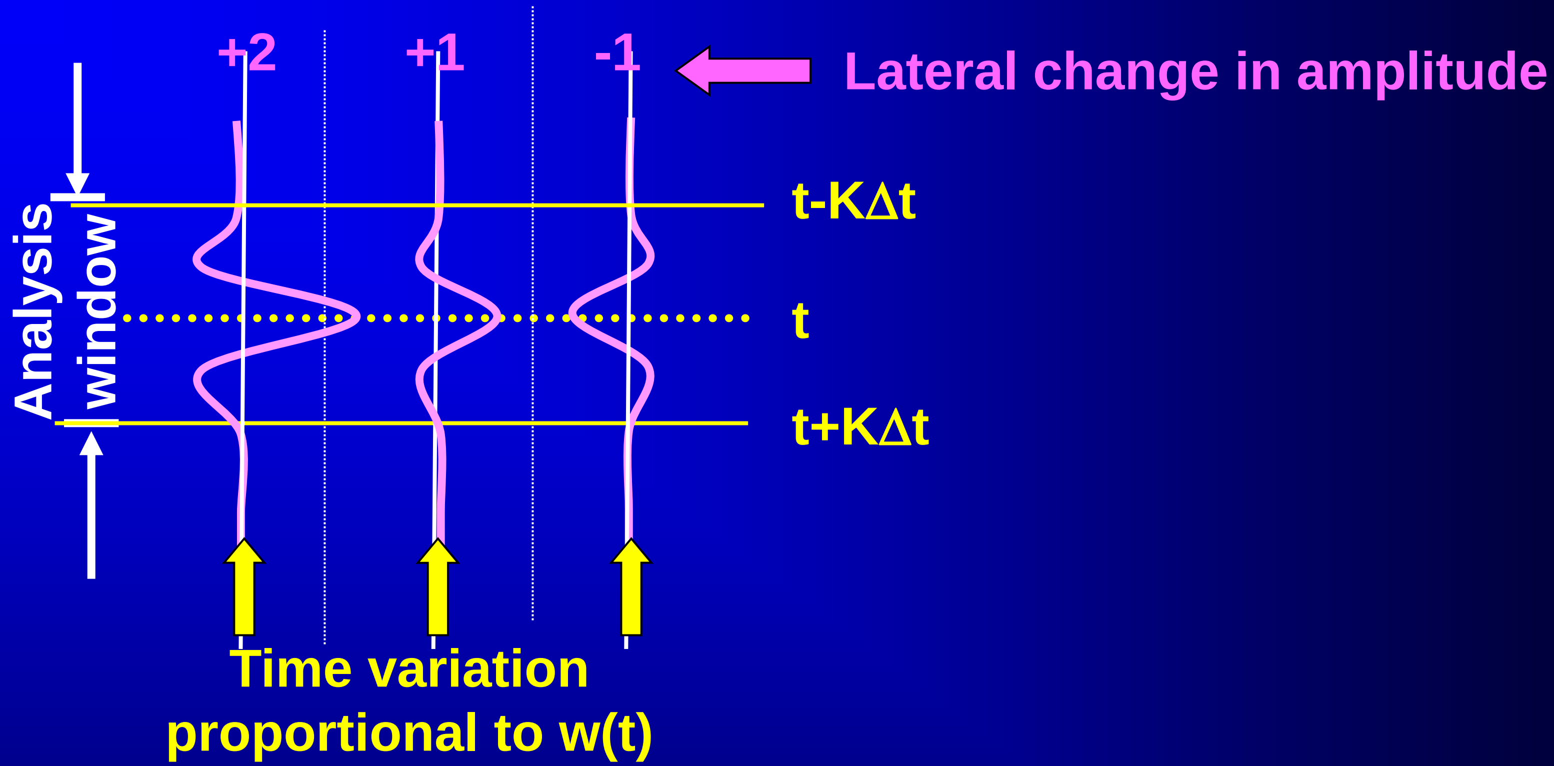
Step 2: Cross Correlate each column of the data matrix with itself and all other columns

$$C_{28} \equiv \begin{bmatrix} .81 & .63 & .12 \end{bmatrix} \begin{bmatrix} .79 \\ .53 \\ .41 \end{bmatrix}$$

Step 3: Copy result into corresponding entry of the data covariance matrix

$$\mathbf{C} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} & C_{17} & C_{18} & C_{19} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} & C_{27} & C_{28} & C_{29} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} & C_{37} & C_{38} & C_{39} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} & C_{47} & C_{48} & C_{49} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} & C_{57} & C_{58} & C_{59} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} & C_{67} & C_{68} & C_{69} \\ C_{71} & C_{72} & C_{73} & C_{74} & C_{75} & C_{76} & C_{77} & C_{78} & C_{79} \\ C_{81} & C_{82} & C_{83} & C_{84} & C_{85} & C_{86} & C_{87} & C_{88} & C_{89} \\ C_{91} & C_{92} & C_{33} & C_{94} & C_{95} & C_{96} & C_{97} & C_{98} & C_{99} \end{pmatrix}$$

Example of semblance coherence



$$c_s = \frac{\sum_{k=-K}^{+K}\left(\frac{1}{3}[2w(k\Delta t)+w(k\Delta t)-w(k\Delta t)\right)^2}{\sum_{k=-K}^{+K}\frac{1}{3}\left([+2w(k\Delta t)]^2+[+w(k\Delta t)]^2+[-w(k\Delta t)]^2\right)} = \frac{\left(\frac{4}{9}\right)}{\left(\frac{6}{3}\right)} = 0.33$$

Example of eigenstructure coherence

1. Form the 3x3 covariance matrix by cross-correlating each trace with itself and all other traces

$$\mathbf{C} = \sum_{k=-K}^{+K} \begin{pmatrix} (+2)w(k\Delta t)(+2)w(k\Delta t) & (+2)w(k\Delta t)(+1)w(k\Delta t) & (+2)w(k\Delta t)(-1)w(k\Delta t) \\ (+1)w(k\Delta t)(+2)w(k\Delta t) & (+1)w(k\Delta t)(+1)w(k\Delta t) & (+1)w(k\Delta t)(-1)w(k\Delta t) \\ (-1)w(k\Delta t)(+2)w(k\Delta t) & (-1)w(k\Delta t)(+1)w(k\Delta t) & (-1)w(k\Delta t)(-1)w(k\Delta t) \end{pmatrix}$$

Simplify to obtain

$$\mathbf{C} = \sum_{k=-K}^{+K} w^2(k\Delta t) \begin{pmatrix} +4 & +2 & -2 \\ +2 & +1 & -1 \\ -2 & -1 & +1 \end{pmatrix} \equiv E \begin{pmatrix} +4 & +2 & -2 \\ +2 & +1 & -1 \\ -2 & -1 & +1 \end{pmatrix}$$

where:

$$E \equiv \sum_{k=-K}^{+K} w^2(k\Delta t)$$

2. Guess at the first eigenvector, $\mathbf{v}^{(1)}$, that solves the equation:

$$\mathbf{C}\mathbf{v}^{(1)} = \lambda_1 \mathbf{v}^{(1)}$$

I claim $\mathbf{v}^{(1)}$ is proportional to the amplitude of the coherent part of the trace:

$$\mathbf{v}^{(1)} = \begin{pmatrix} +2 \\ +1 \\ -1 \end{pmatrix}$$

Let's test this claim:

$$E\begin{pmatrix} +4 & +2 & -2 \\ +2 & +1 & -1 \\ -2 & -1 & +1 \end{pmatrix}\begin{pmatrix} +2 \\ +1 \\ -1 \end{pmatrix} = E\begin{pmatrix} +12 \\ +6 \\ -6 \end{pmatrix} = 6E\begin{pmatrix} +2 \\ +1 \\ -1 \end{pmatrix} = \lambda_1\begin{pmatrix} +2 \\ +1 \\ -1 \end{pmatrix}$$

, which indicates:

$$\lambda_1 = 6E$$

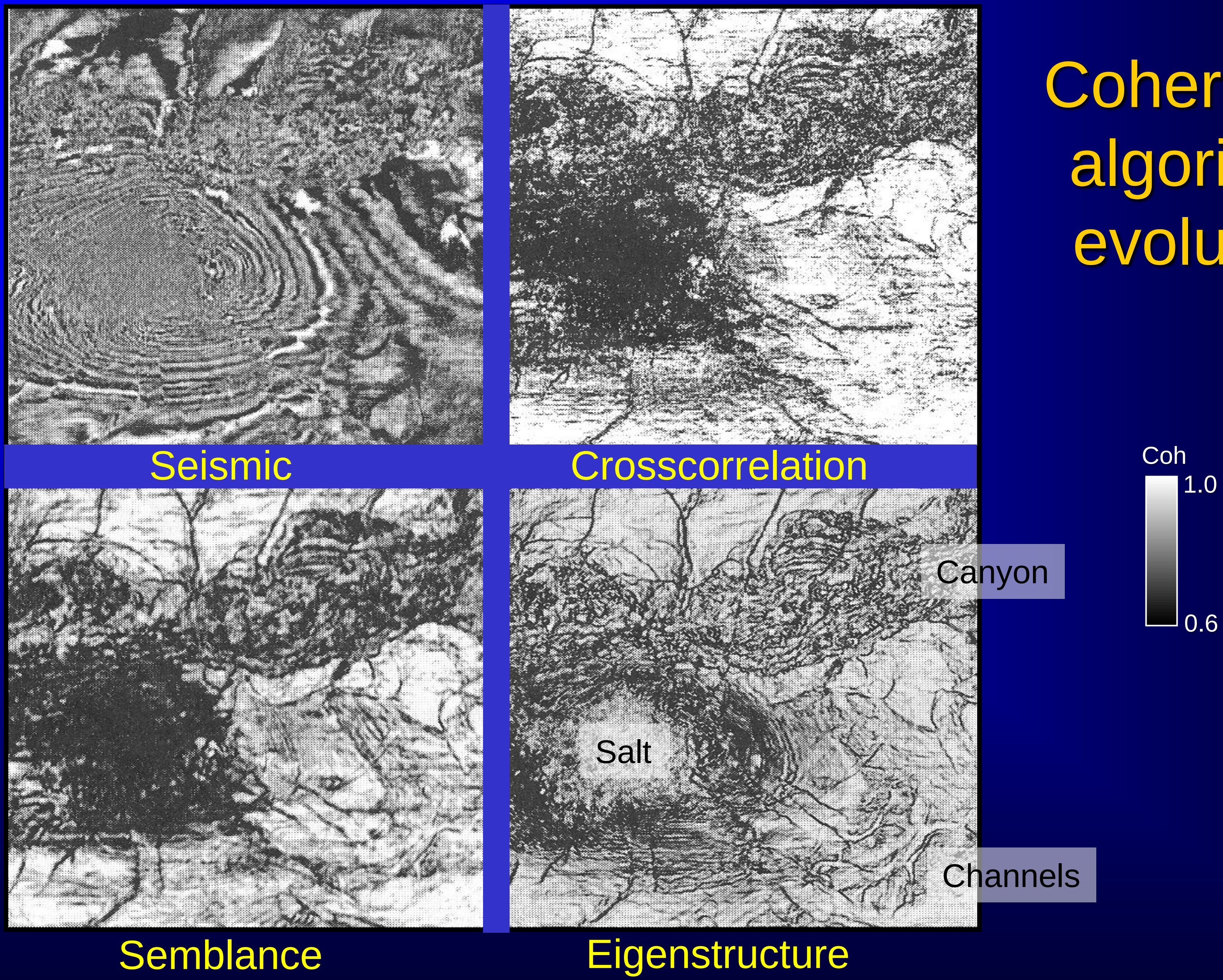
To calculate coherence, we need the sum of the diagonal of the covariance matrix, C:

$$\sum_{j=1}^{3} C_{jj} = C_{11} + C_{22} + C_{33} = E(4+1+1) = 6E$$

We can now form the eigenstructure estimate of coherence, c_e:

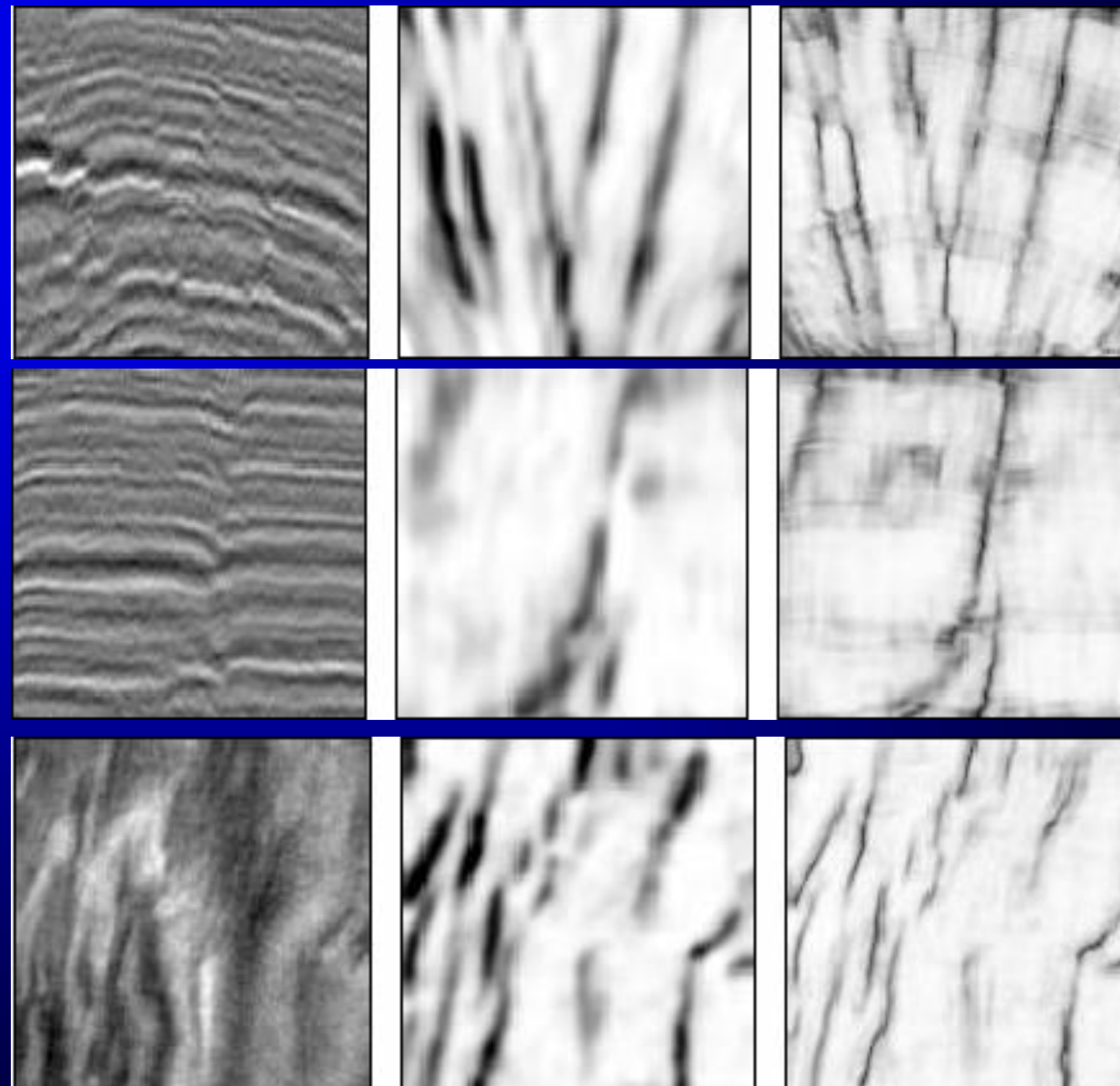
$$c_e \equiv \frac{\lambda_1}{\sum_{j=1}^{3} C_{jj}} = \frac{6E}{6E} = 1$$

Coherence algorithm evolution



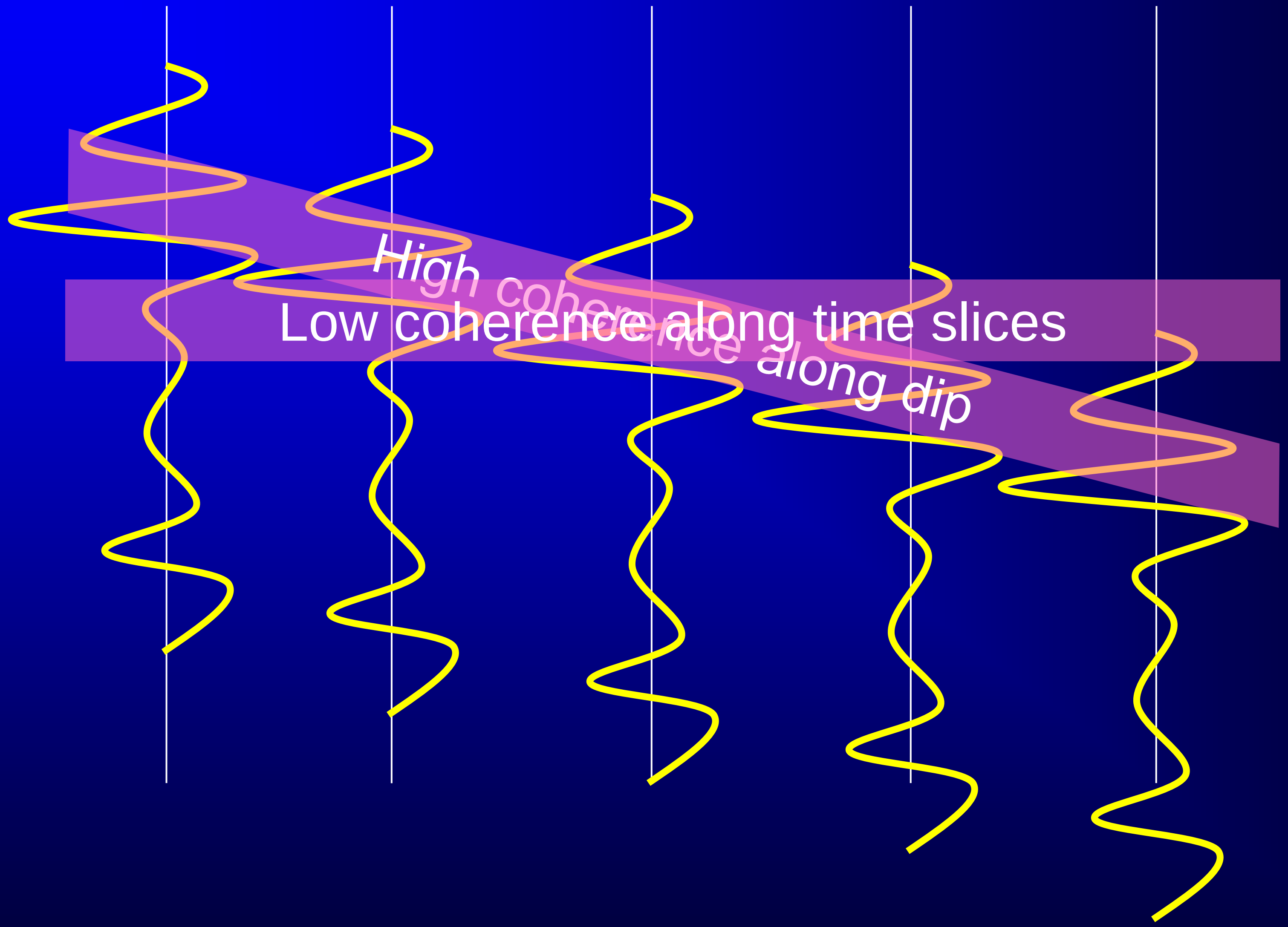
(Gersztenkorn and Marfurt, 1999)

Comparison of Gradient Structure Tensor and dip scan eigenstructure coherence

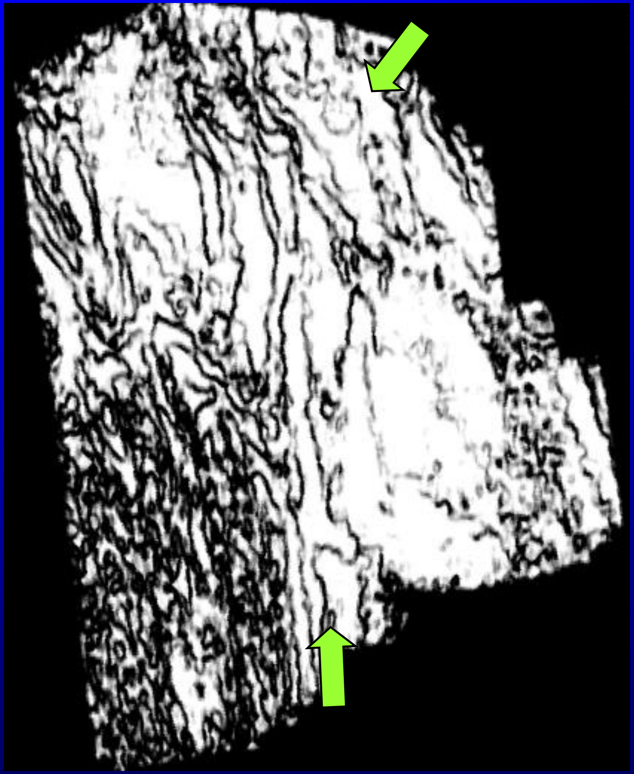


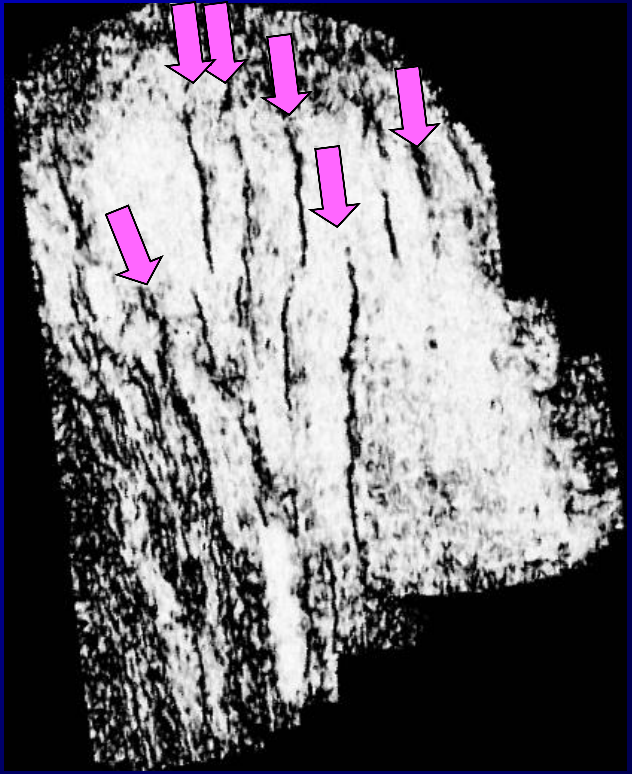
(Bakker, 2003)

Importance of computing coherence along structural dip



Coherence artifacts due to an 'efficient' calculation without search for structure





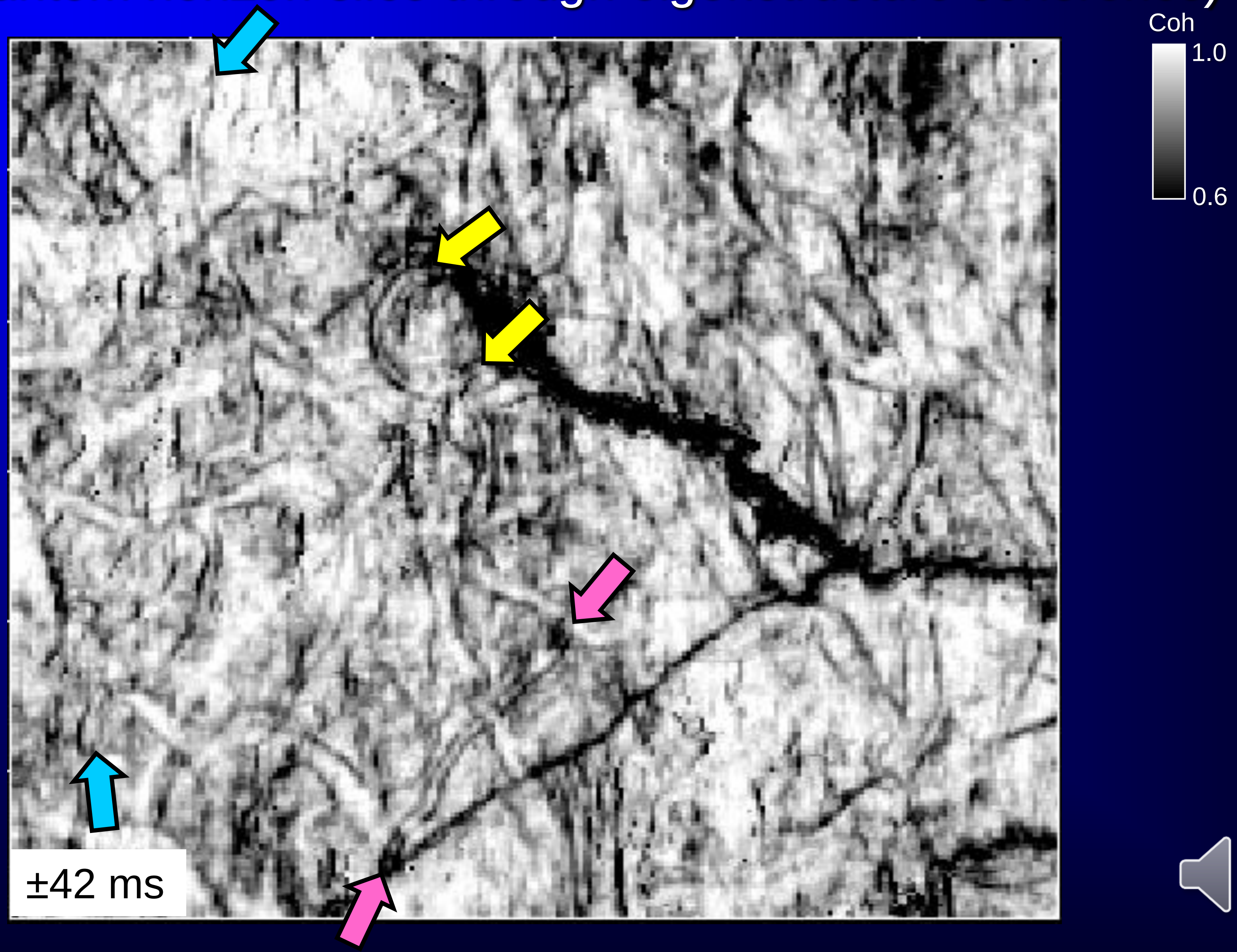
Coherence computed along a time slice

Coherence computed along structure

(Chopra and Marfurt, 2008)

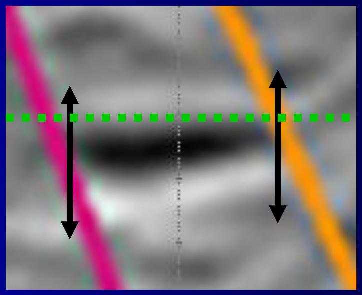
Impact of vertical analysis window

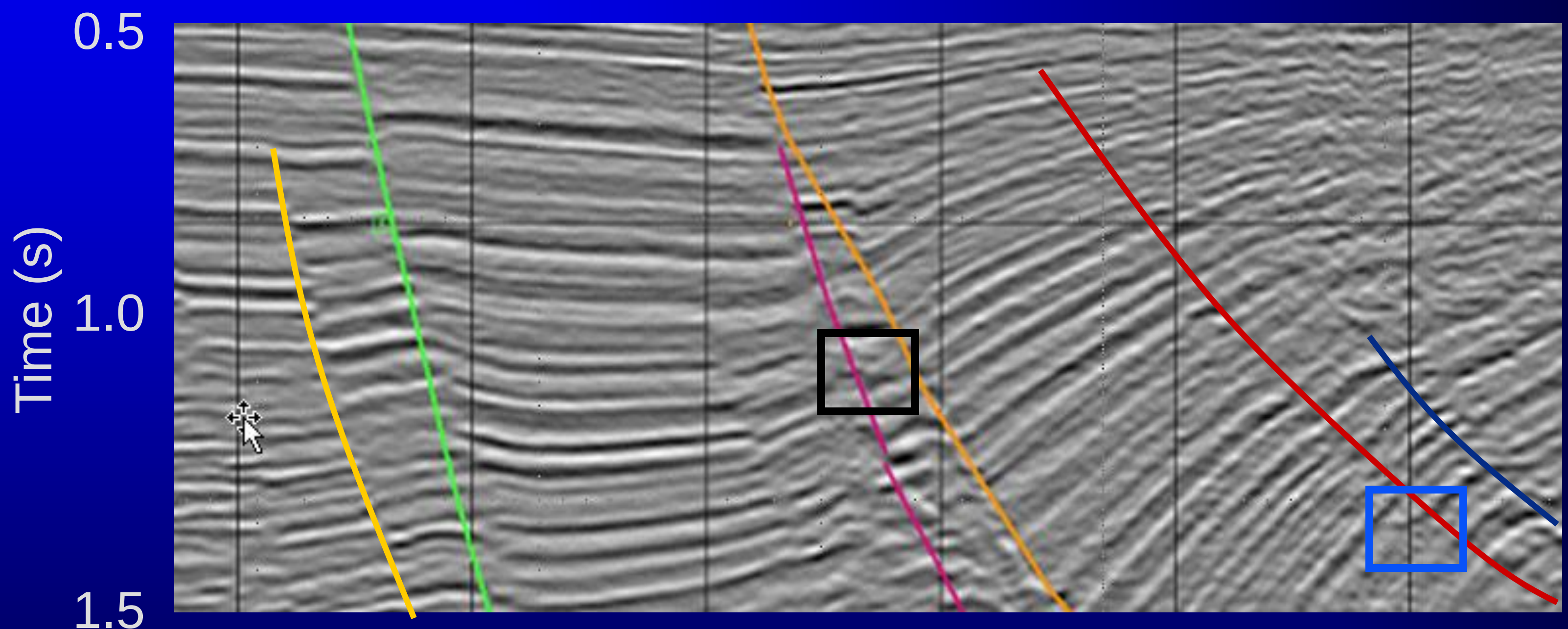
(phantom horizon slice through eigenstructure coherence)



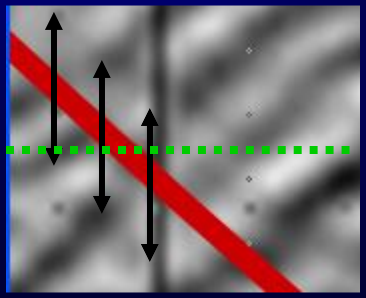
Impact of vertical analysis window

Fault on coherence green time slice is shifted by a stronger, deeper event





Steeply dipping faults will not only be smeared by long coherence windows, but may appear more than once!



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 quantitative estimate of fault/fracture presence,
• Often enhances stratigraphic information that is otherwise difficult to extract,
• Should always be calculated along dip – either through algorithm design or by first flattening the seismic volume to be analyzed, and
• Algorithms are local - 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 smears dipping faults and mixes stratigraphic features.