ConocoPhillips SCHOOL OF GEOLOGY & GEOPHYSICS The University of Oklahoma

GPHY 5513
3D Seismic Interpretation

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Volumetric Dip and Azimuth

Geometric Attributes

1. Dip magnitude and dip azimuth — Input for other attributes
2. Coherence — Faults, channel edges, karst, dewatering
3. Amplitude gradients — Thin channels, fractures
4. Seismic textures — Mass transport complexes, diagentic alteration
5. Curvature and reflector shape — Folds and flexures, compaction, collapse features
6. Reflector rotation — Wrench faults, syntectonic deposition
7. Reflector convergence — Angular unconformities, clinoforms

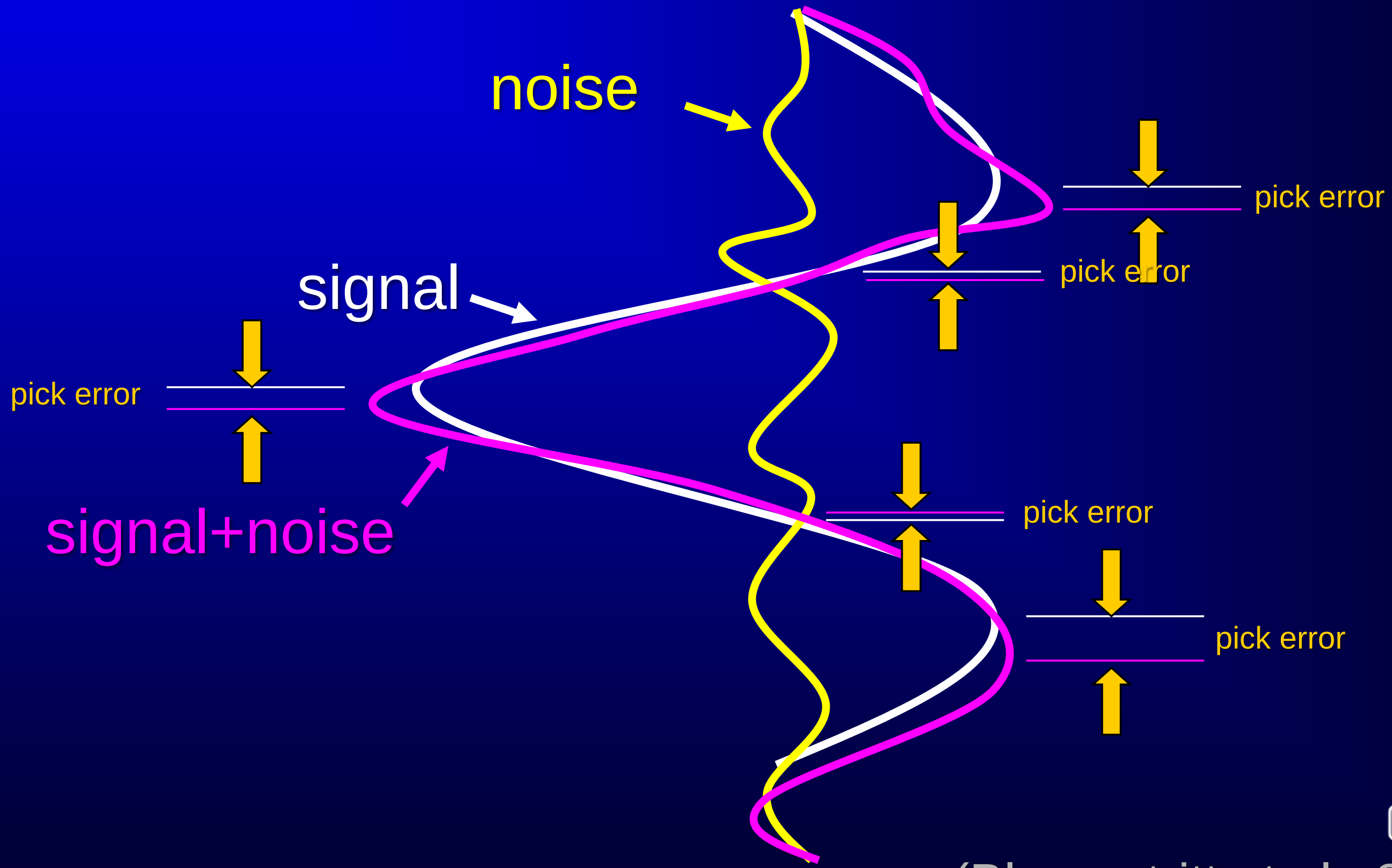
Volumetric dip and azimuth

After this section you will be able to:

- Evaluate alternative algorithms to calculate volumetric dip and azimuth in terms of accuracy and lateral resolution,
- Interpret shaded relief and apparent dip images to delineate subtle structural features, and
- Apply composite dip/azimuth/seismic images to determine how a given reflector dips in and out of the plane of view.

Dip computed from picked maps:

Zero-crossing picks are less sensitive to noise than peaks or troughs

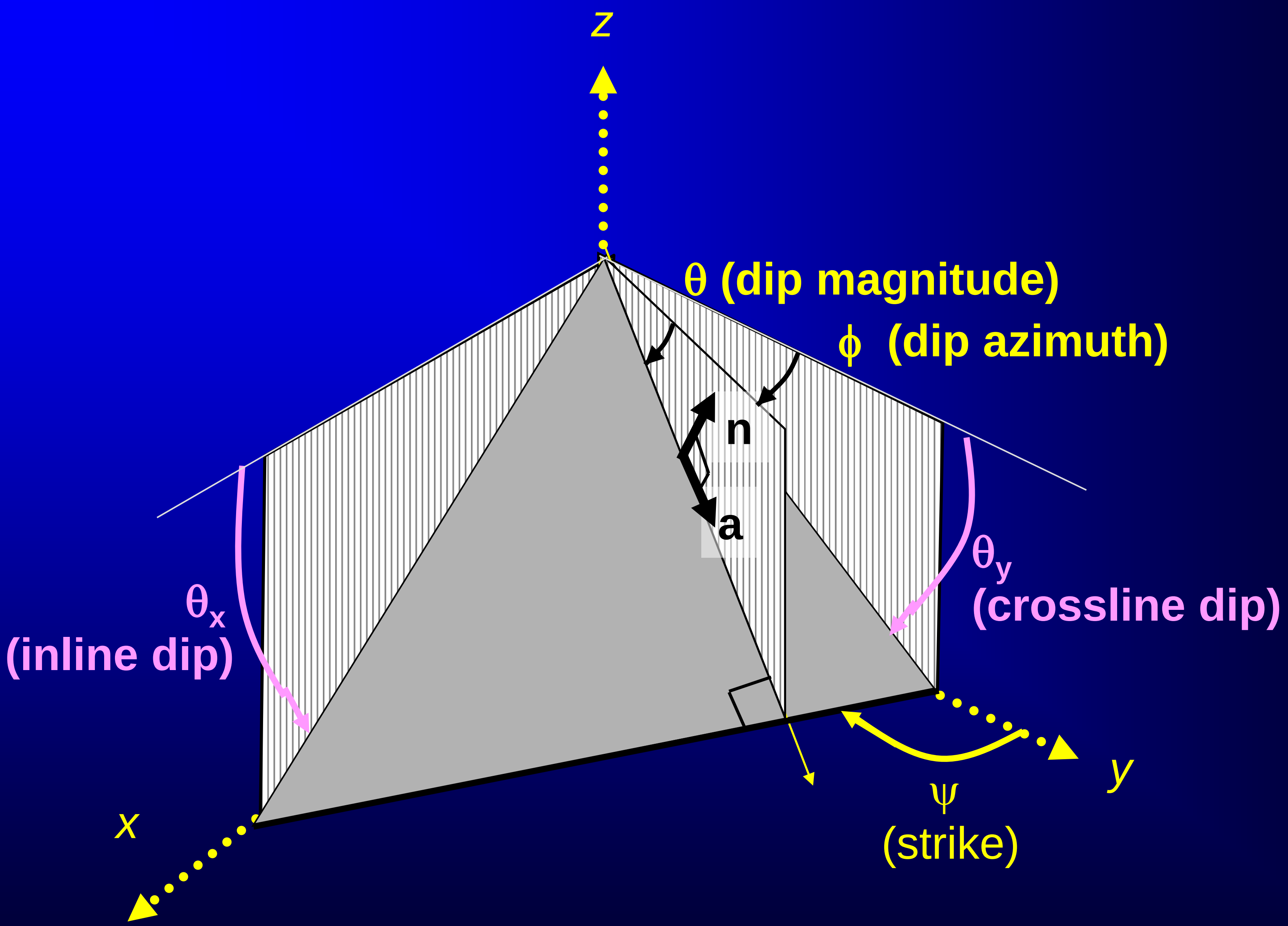


(Blumentritt et al., 2005)

Alternative volumetric measures of reflector dip and azimuth

1. 3D Complex trace analysis
2. Gradient Structure Tensor (GST)
3. Plane-wave destructor
4. Discrete scans for dip of most coherent reflector

Definition of reflector dip



(Marfurt, 2006)

1. 3D Complex Trace Analysis (Instantaneous Dip/Azimuth)

Hilbert transform

Instantaneous phase

$$\phi = \mathrm{ATAN2}(d^H, d)$$

Instantaneous frequency

$$\omega = 2\pi f = 2\pi \frac{\partial \phi}{\partial t} = 2\pi \frac{\frac{\partial d^H}{\partial t} d - \frac{\partial d}{\partial t} d^H}{d^2 + \left(d^H\right)^2}$$

Instantaneous in line wavenumber

$$k_x = \frac{\partial \phi}{\partial x} = \frac{\frac{\partial d^H}{\partial x} d - \frac{\partial d}{\partial x} d^H}{d^2 + \left(d^H\right)^2}$$

Instantaneous cross line wavenumber

$$k_y = \frac{\partial \phi}{\partial y} = \frac{\frac{\partial d^H}{\partial y} d - \frac{\partial d}{\partial y} d^H}{d^2 + \left(d^H\right)^2}$$

Instantaneous apparent dips

$$p = \frac{k_x}{\omega}; q = \frac{k_y}{\omega}$$

$$s = \sqrt{p^2 + q^2}$$

$$\psi = ATAN2(q,p)$$

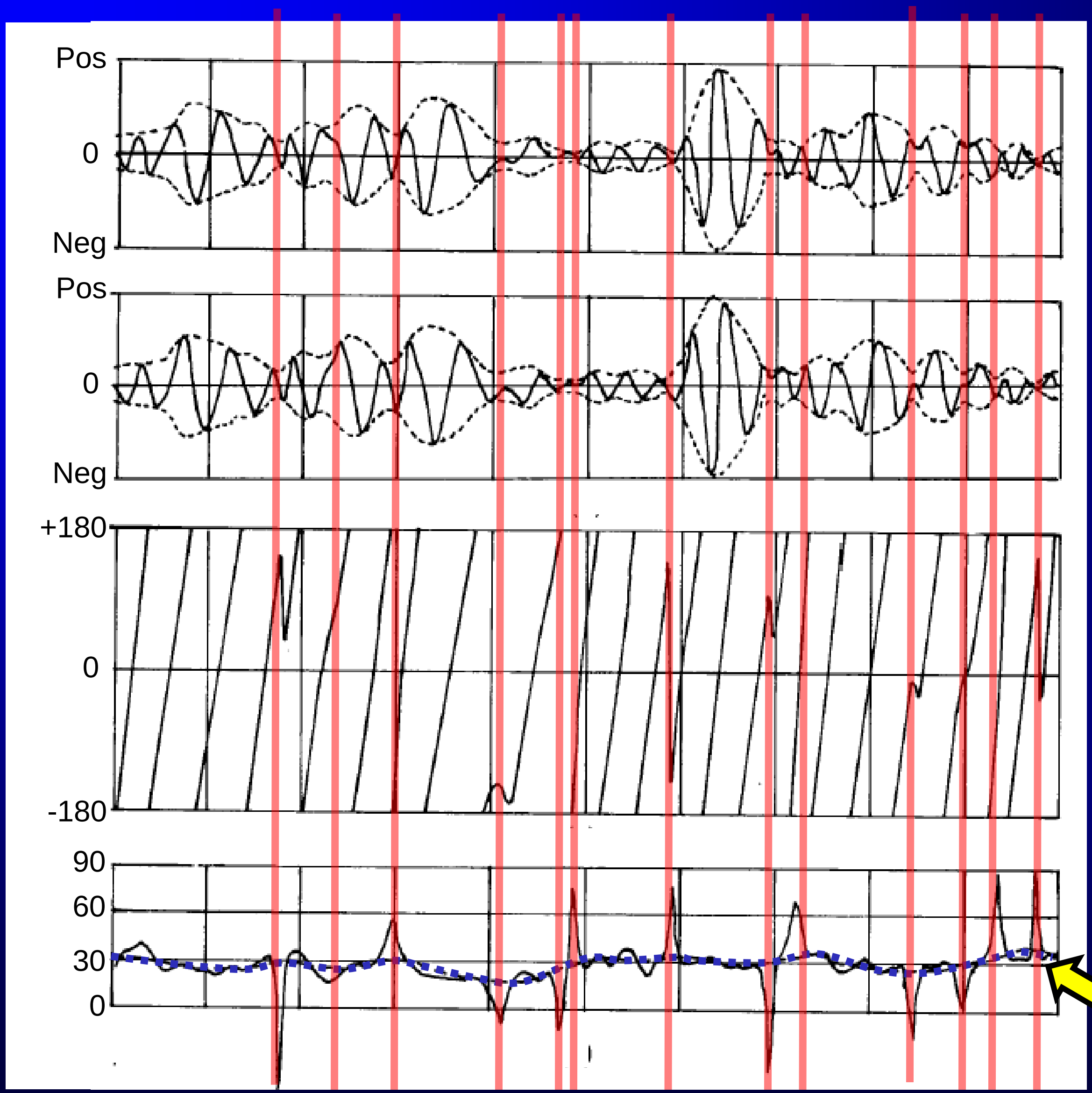
The analytic trace

Original data (real component)

Quadrature (imaginary component)

Phase

Frequency (Hz)



d(t)

$d^H(t)$

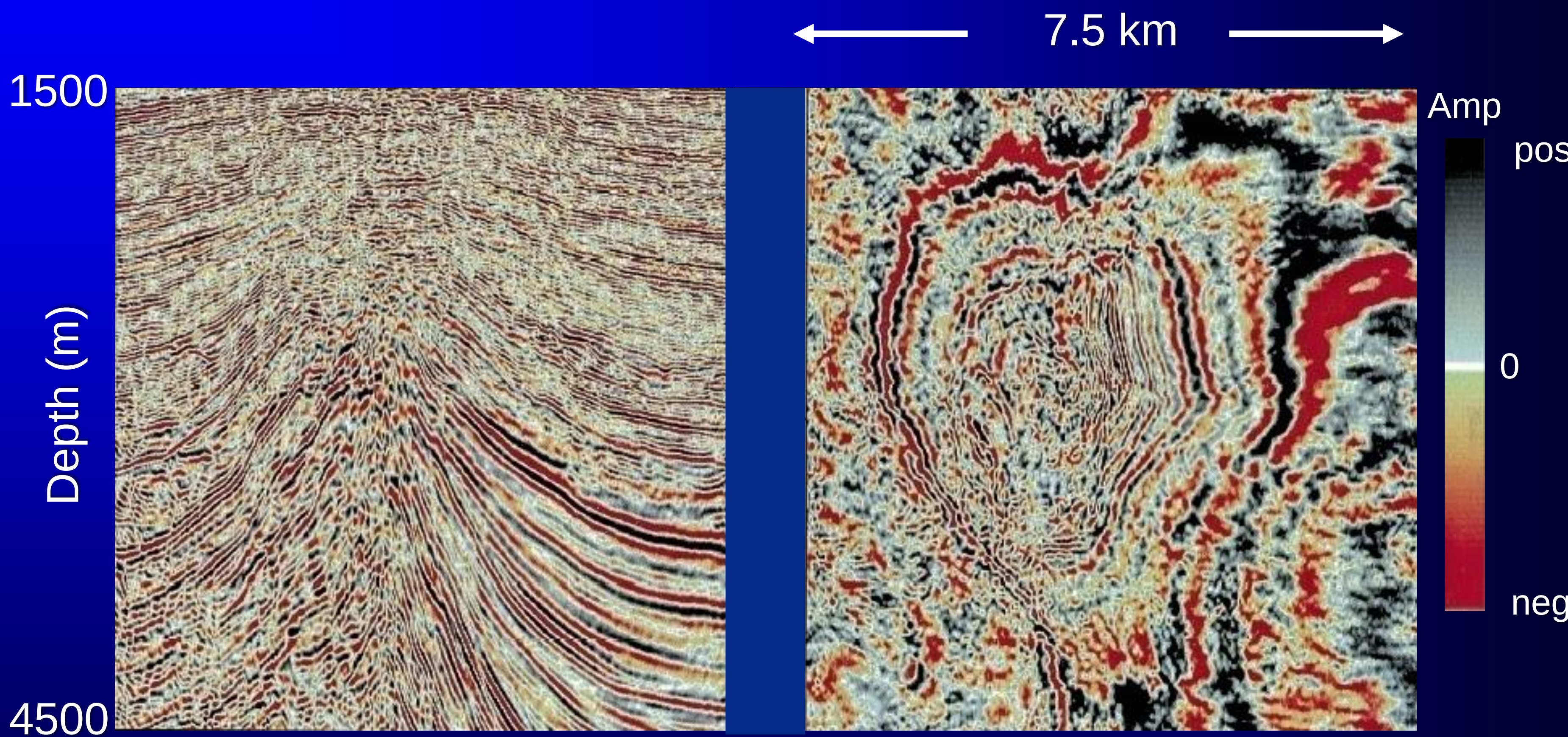
$\phi(t) = \mathrm{ATAN2}[d^H(t), d(t)]$

$$\bar{f}_n \equiv \frac{\sum_{k=-K}^{K} e_{n+k} f_{n+k}}{\sum_{k=-K}^{K} e_{n+k}}$$

Weighted-average frequency

(Taner et al., 1979)

Seismic data



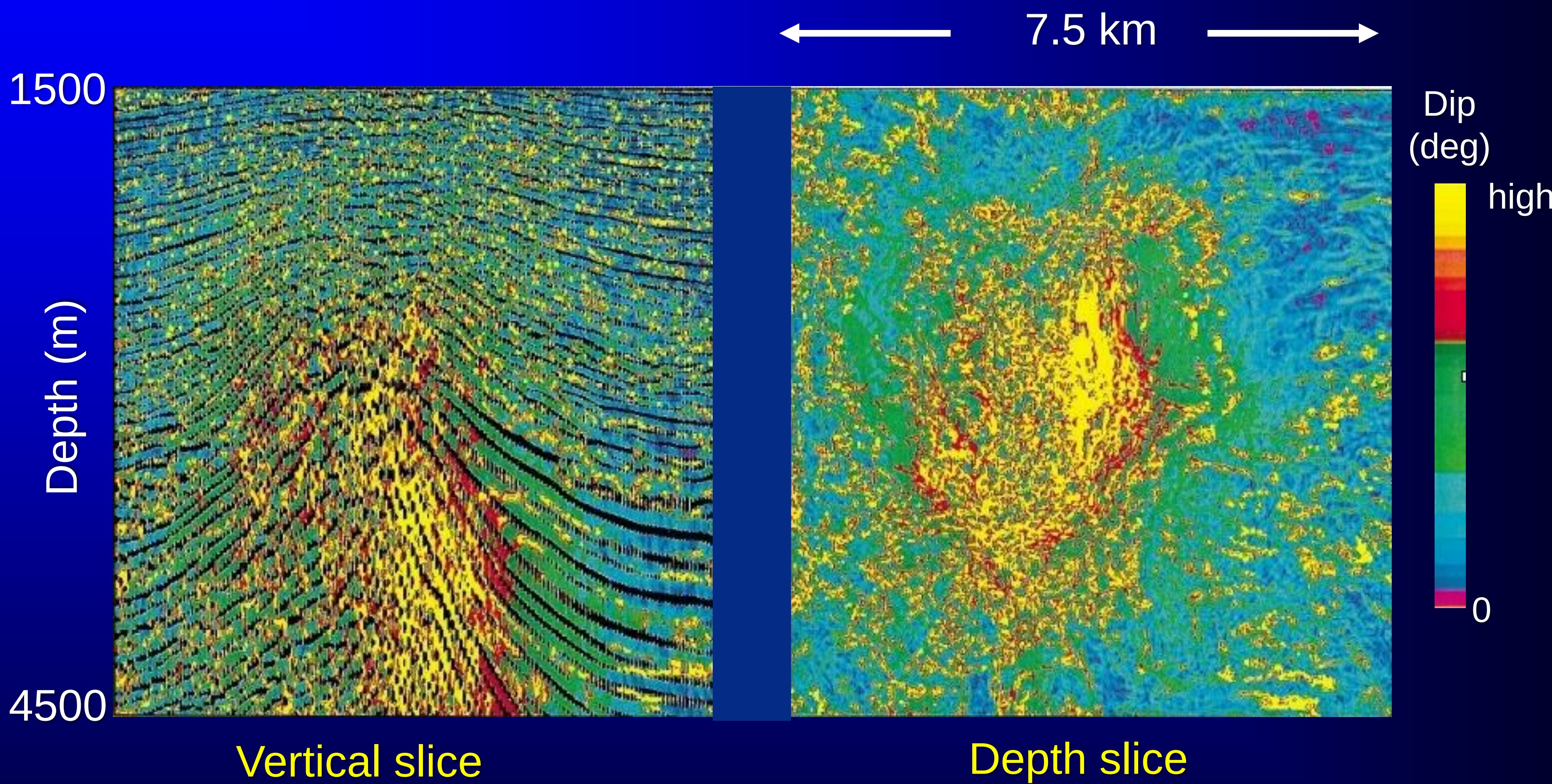
Vertical slice

Depth slice

(Barnes, 2000)

Instantaneous dip magnitude (sensitive to errors in ω, k_x and k_y!)

$$s = \sqrt{p^2 + q^2}$$

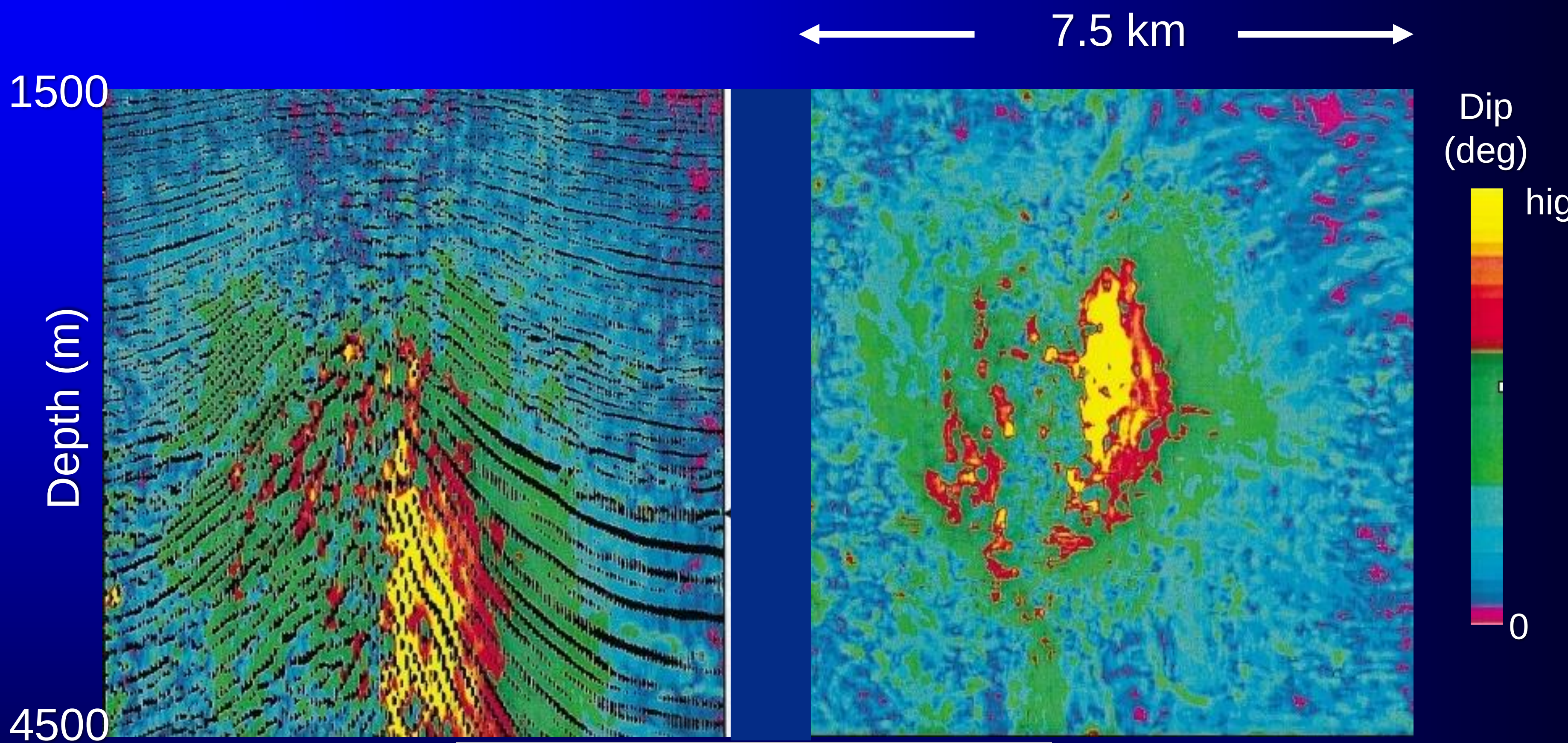


(Barnes, 2000)

Weighted average dip magnitude

(5 crossline by 5 inline by 7 sample window)

$$\bar{s} = \sqrt{\left(\frac{\bar{k}_x}{\bar{\omega}}\right)^2 + \left(\frac{\bar{k}_y}{\bar{\omega}}\right)^2}$$



Vertical slice

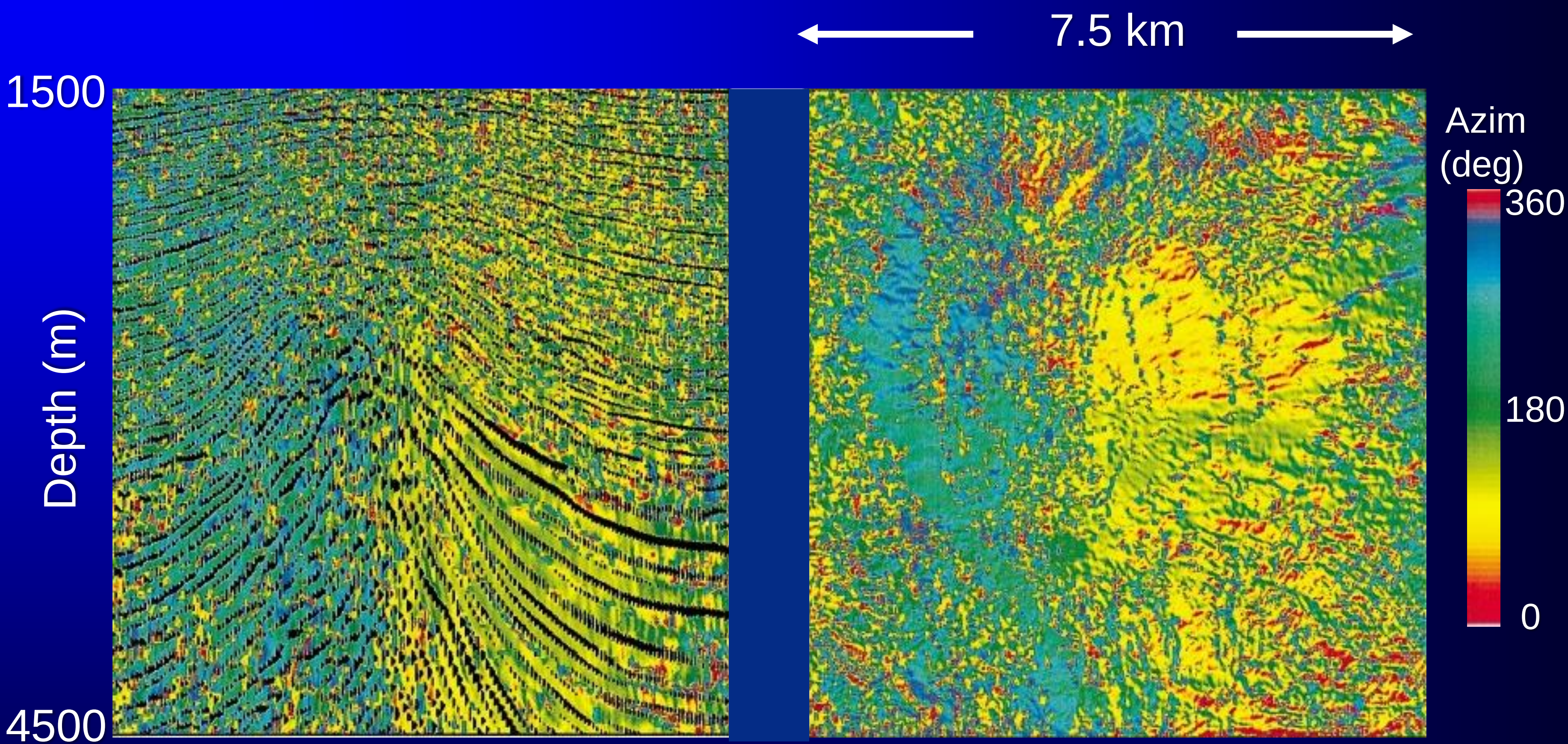
Depth slice

$$\bar{\omega}_{rst} \equiv \frac{\sum_{l=-L}^{+L}\sum_{k=-K}^{+K}\sum_{j=-J}^{+J} e_{r+j,s+k,t+l}\,\omega_{r+j,s+k,t+l}}{\sum_{l=-L}^{+L}\sum_{k=-K}^{+K}\sum_{j=-J}^{+J} e_{r+j,s+k,t+l}}$$

(Barnes, 2000)

Instantaneous dip azimuth

$$\psi = ATAN2(q, p)$$



Vertical slice

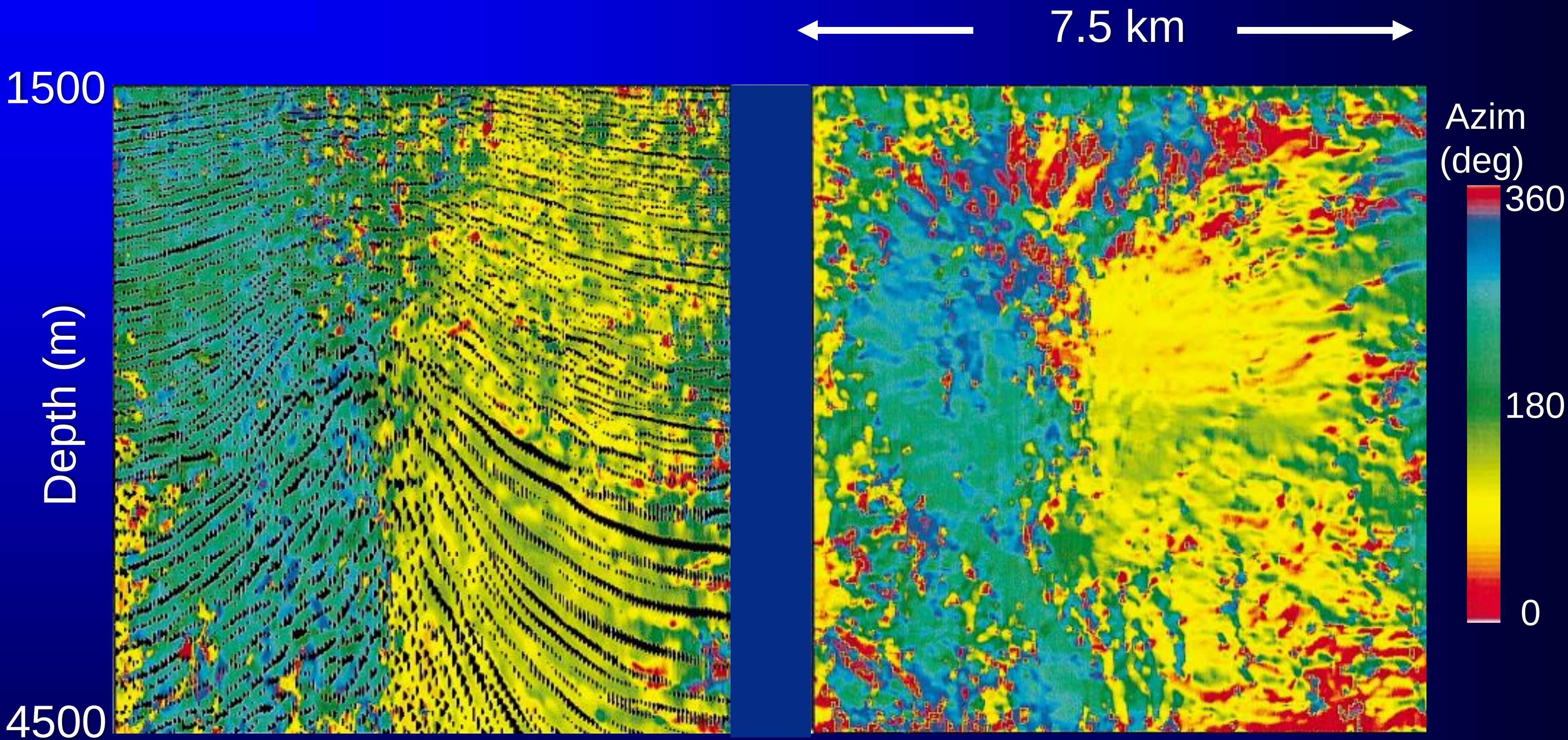
Depth slice

(Barnes, 2000)

Weighted average dip azimuth

(5 crossline by 5 inline by 7 sample window)

$$\bar{\psi} = \mathrm{ATAN2}\left(\frac{\overline{k_y}}{\bar{\omega}}, \frac{\overline{k_x}}{\bar{\omega}}\right)$$



Vertical slice

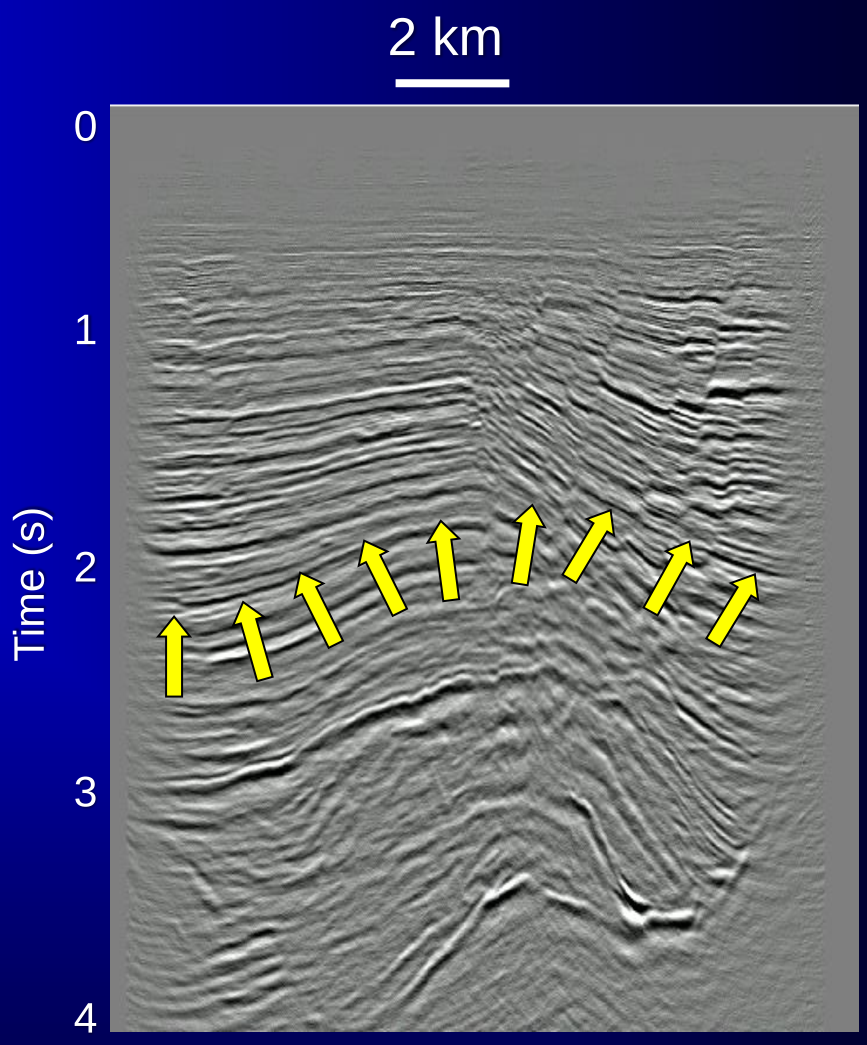
Depth slice

(Barnes, 2000)

2. Gradient Structure Tensor (GST)

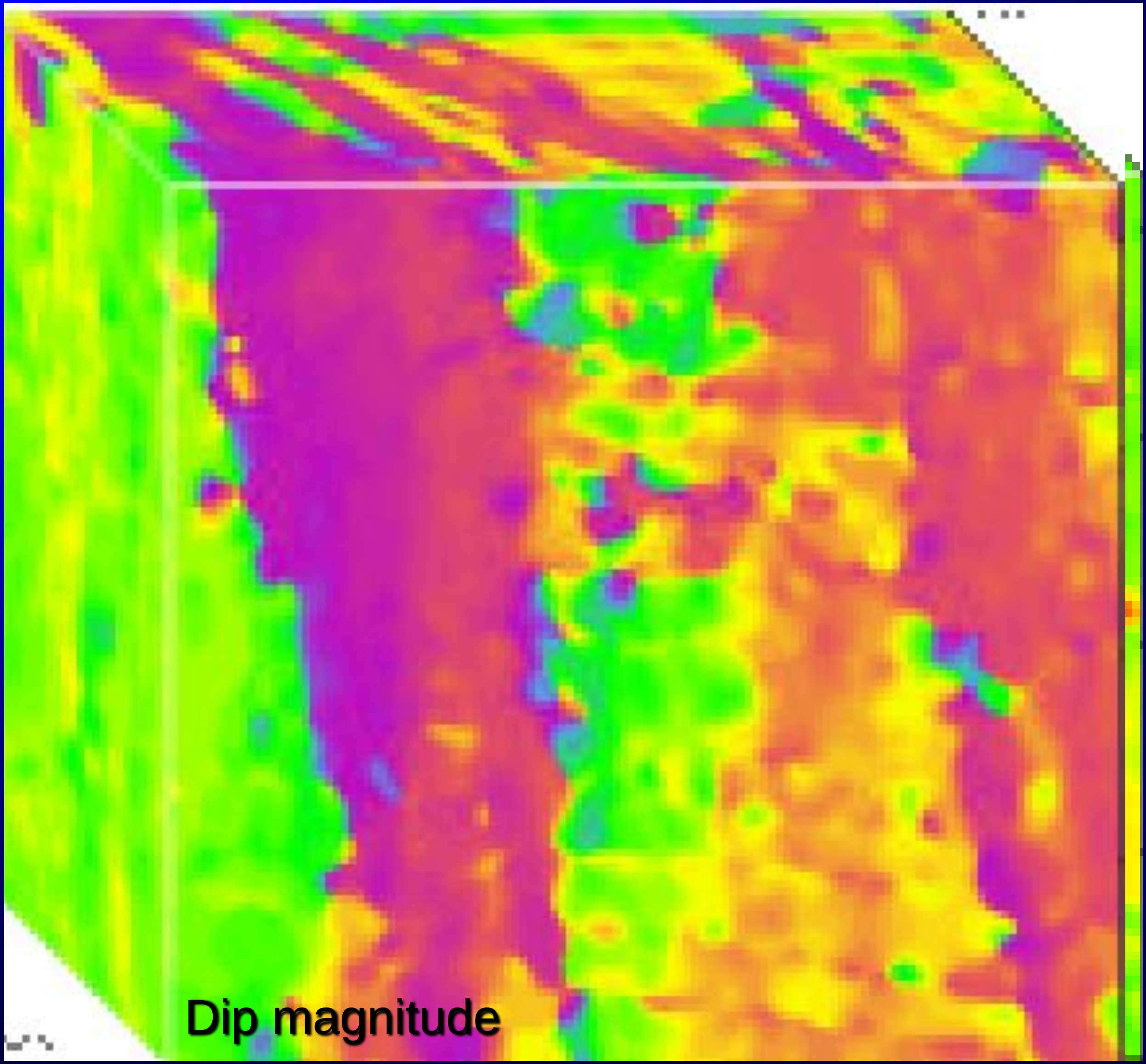
$$\mathbf{T}_{GS} = \begin{bmatrix} \left\langle \frac{\partial u}{\partial x}\frac{\partial u}{\partial x} \right\rangle & \left\langle \frac{\partial u}{\partial y}\frac{\partial u}{\partial x} \right\rangle & \left\langle \frac{\partial u}{\partial z}\frac{\partial u}{\partial x} \right\rangle \\ \left\langle \frac{\partial u}{\partial x}\frac{\partial u}{\partial y} \right\rangle & \left\langle \frac{\partial u}{\partial y}\frac{\partial u}{\partial y} \right\rangle & \left\langle \frac{\partial u}{\partial z}\frac{\partial u}{\partial y} \right\rangle \\ \left\langle \frac{\partial u}{\partial x}\frac{\partial u}{\partial z} \right\rangle & \left\langle \frac{\partial u}{\partial y}\frac{\partial u}{\partial z} \right\rangle & \left\langle \frac{\partial u}{\partial z}\frac{\partial u}{\partial z} \right\rangle \end{bmatrix}$$

The eigenvector of the T_{GS} matrix points in the direction of the maximum amplitude gradient



(Bakker et al, 2003)

2. Gradient Structure Tensor (GST)



(Randen et al., 2000)

3. Plane-wave destructor

Predict a trace s_j, from a neighboring trace along an unknown inline dip, *p*:

$$s_j(t) \approx s_{j-1}(t + px) \equiv P^{(x)}_{j,j-1}(p)\, s_{j-1}(t)$$

Minimize the squared error, ε^2, along the inline dip direction, *p*:

$$\|\boldsymbol{\varepsilon}\|^2 \equiv \sum_{j=2}^{J} \left\| s_j - s_{j-1}(t + px) \right\|^2 = \|\mathbf{Ds}\|^2$$

$$\mathbf{D} = \begin{bmatrix} \mathbf{I} & 0 & 0 & \cdots & 0 \\ -\mathbf{P}_{1,2} & \mathbf{I} & 0 & \cdots & 0 \\ 0 & -\mathbf{P}_{2,3} & \mathbf{I} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & -\mathbf{P}_{N-1,N} & \mathbf{I} \end{bmatrix}$$

(Fomel, 2008)

3. Plane-wave destructor (using Marfurt’s inelegant math)

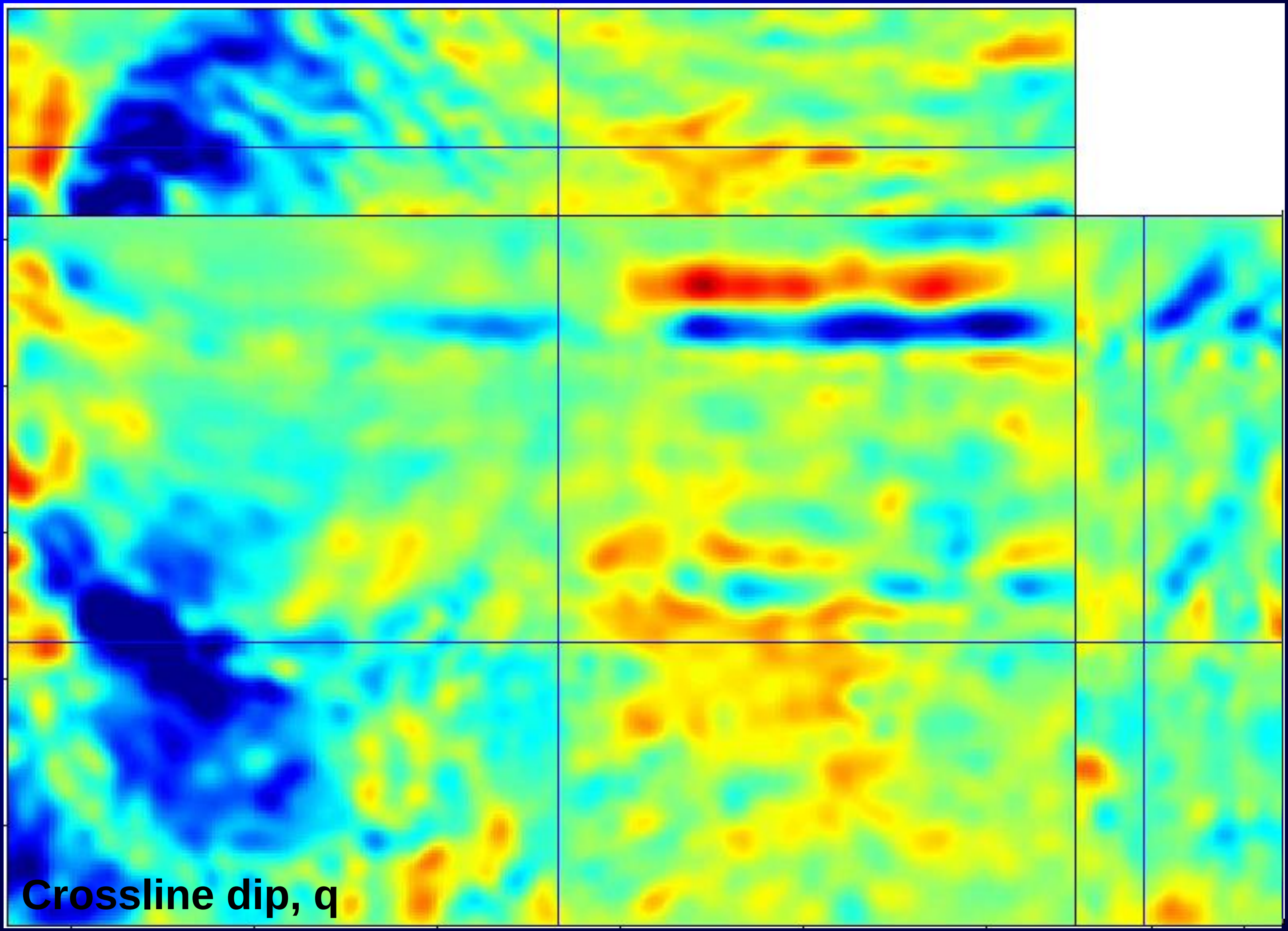
1. Predict (interpolate) the adjacent trace at unknown sample *t+px* using a simple 3-point parabola

$$
\begin{aligned}
s_j(t+px) \approx\ & s_{j-1}(t) \\
& + \frac{s_{j-1}(t+\Delta t) - s_{j-1}(t+\Delta t)}{2\Delta t}(px) \\
& + \frac{s_{j-1}(t+\Delta t) - 2s_{j-1}(t) + s_{j-1}(t+\Delta t)}{(\Delta t)^2}(px)^2
\end{aligned}
$$

2. Minimize the predicted error by minimizing the objective function with respect to *p*.

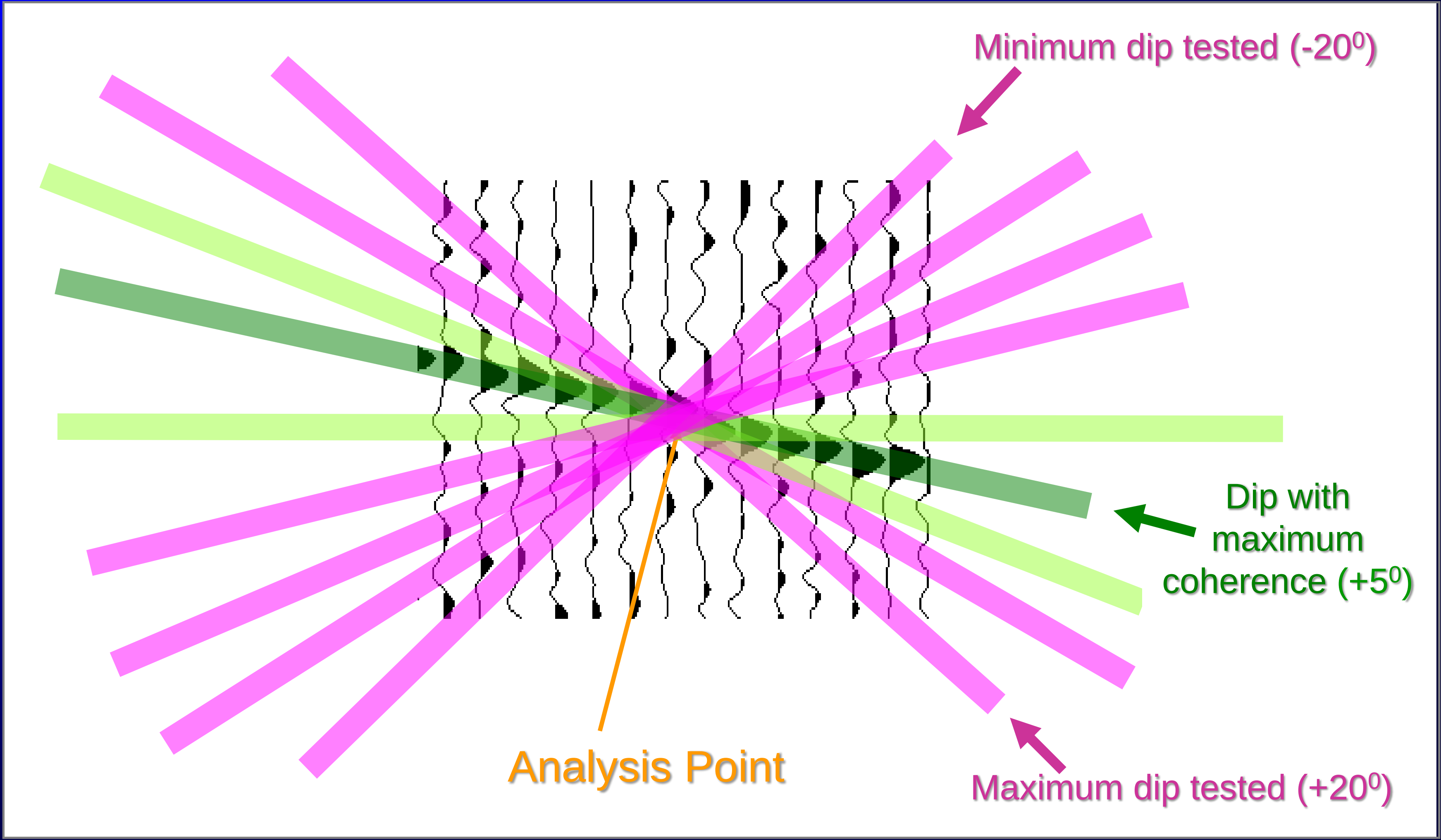
(Fomel, 2008)

3. Plane-wave destructor



(Fomel, 2008)

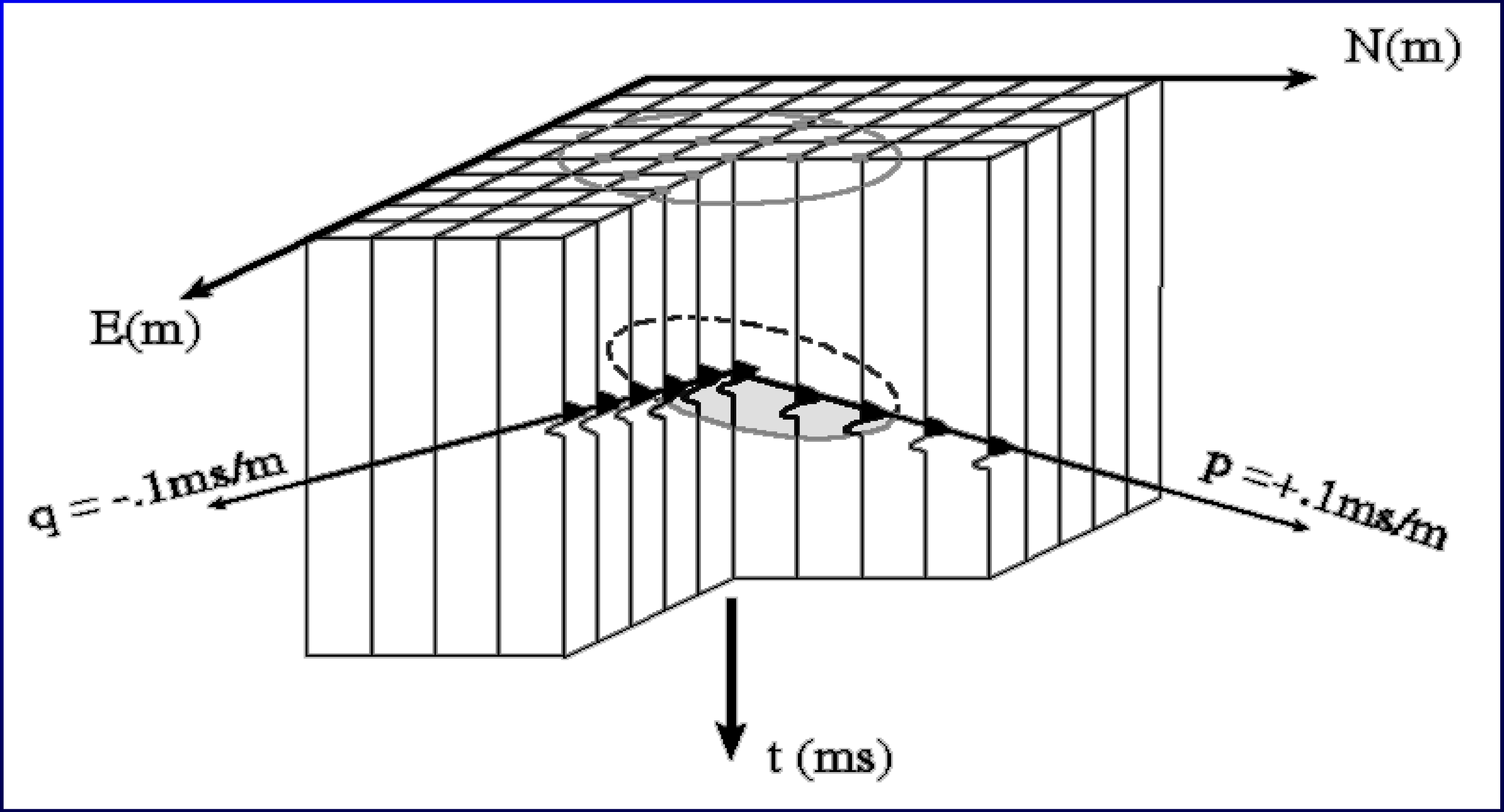
4. Discrete scans for dip of most coherent reflector



Instantaneous dip = dip with highest coherence

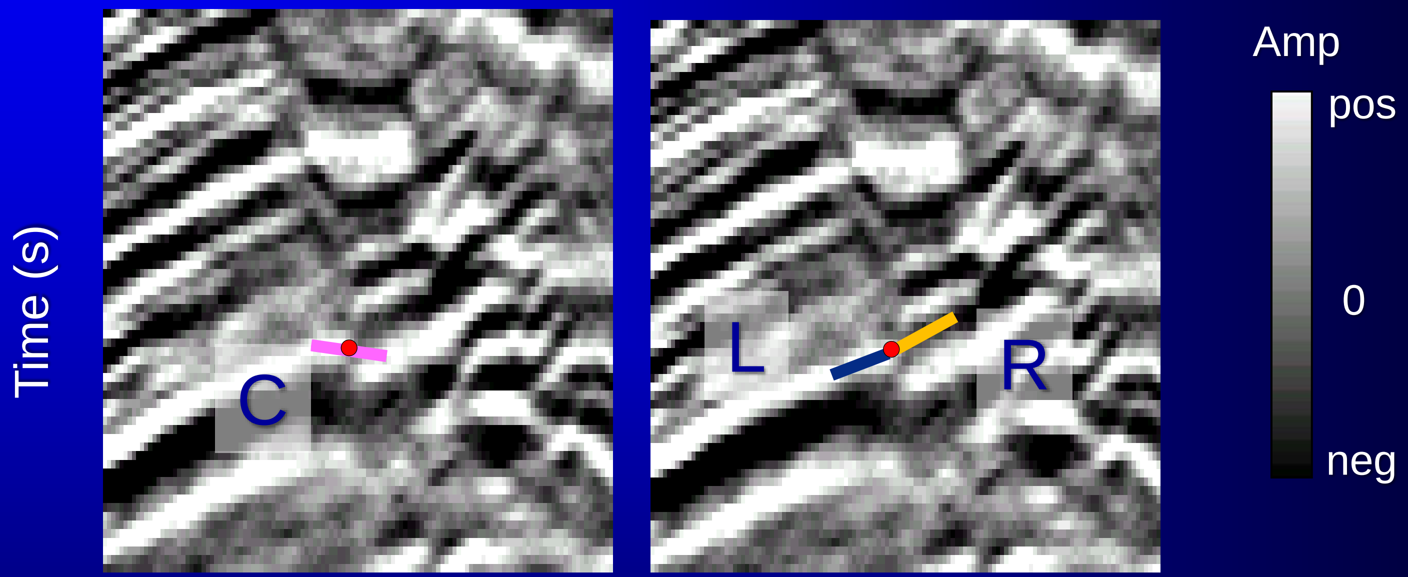
(Marfurt et al, 1998)

3D estimate of coherence and dip/azimuth



(Marfurt et al, 1998)

Searching for dip in the presence of faults

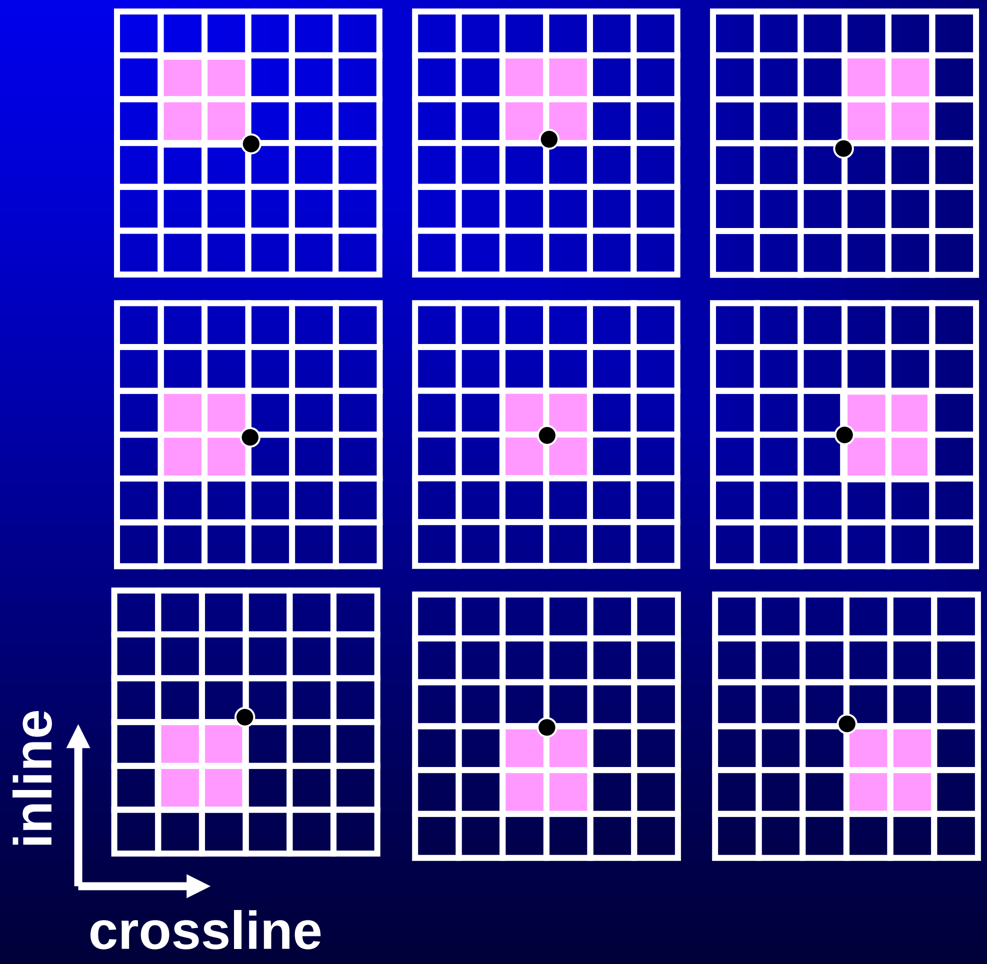


Single window search

Multi-window search

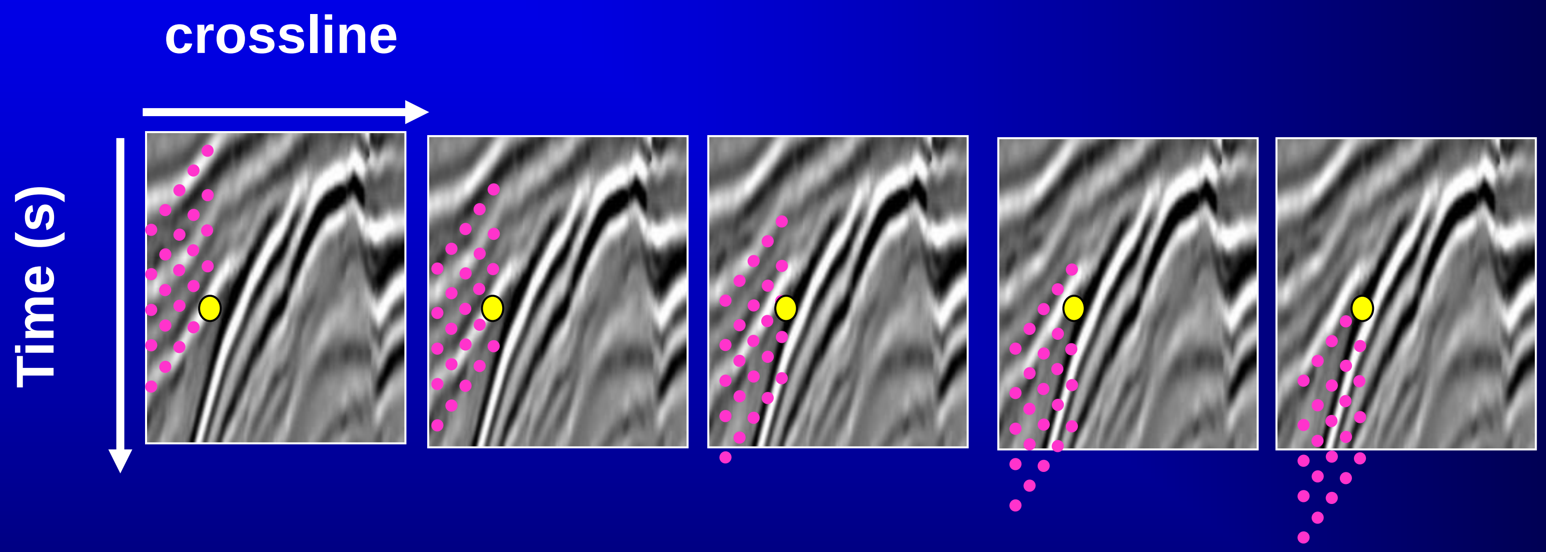
(Marfurt, 2006)

Search for the most coherent window containing the analysis point

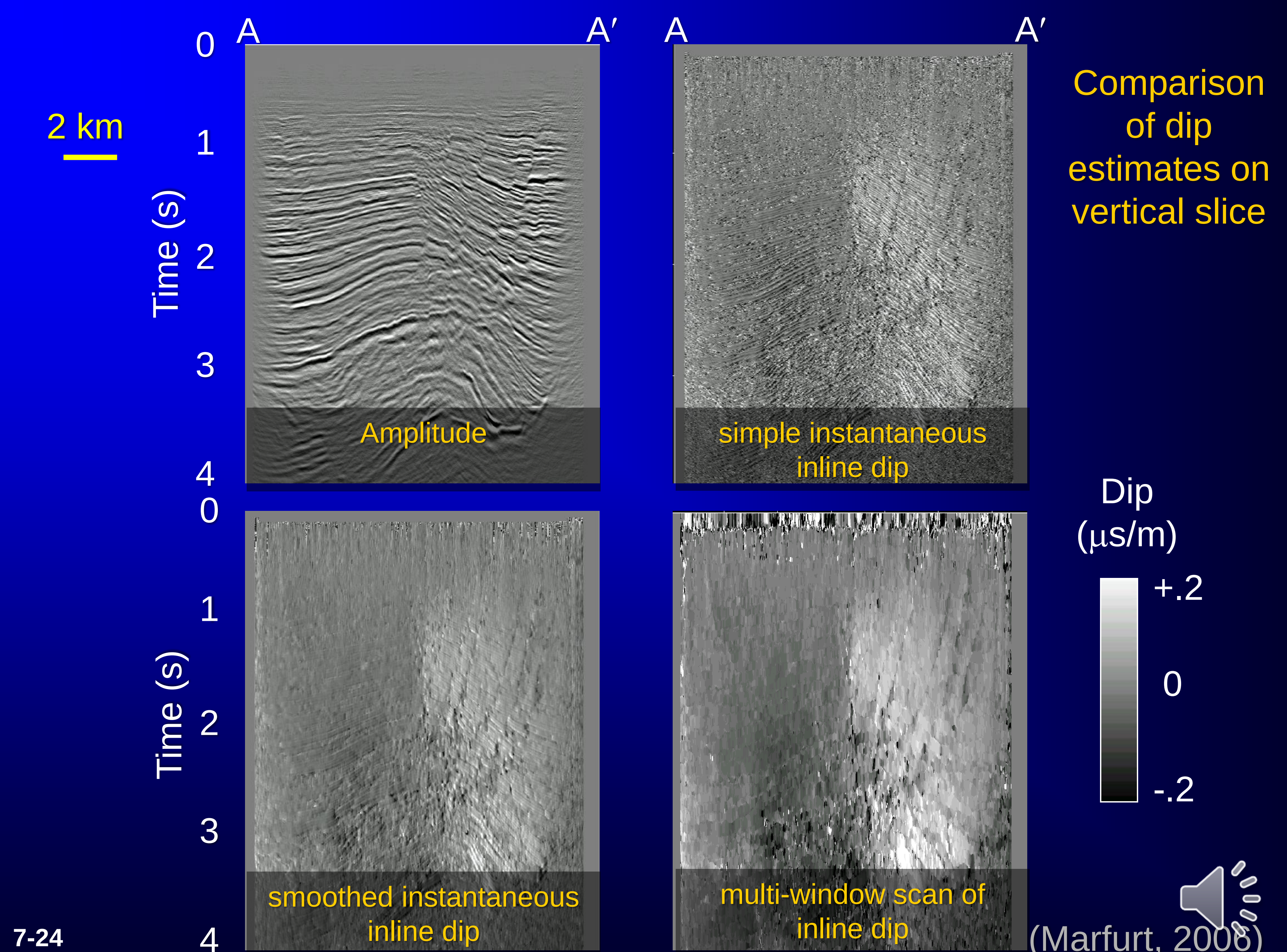


(Marfurt, 2006)

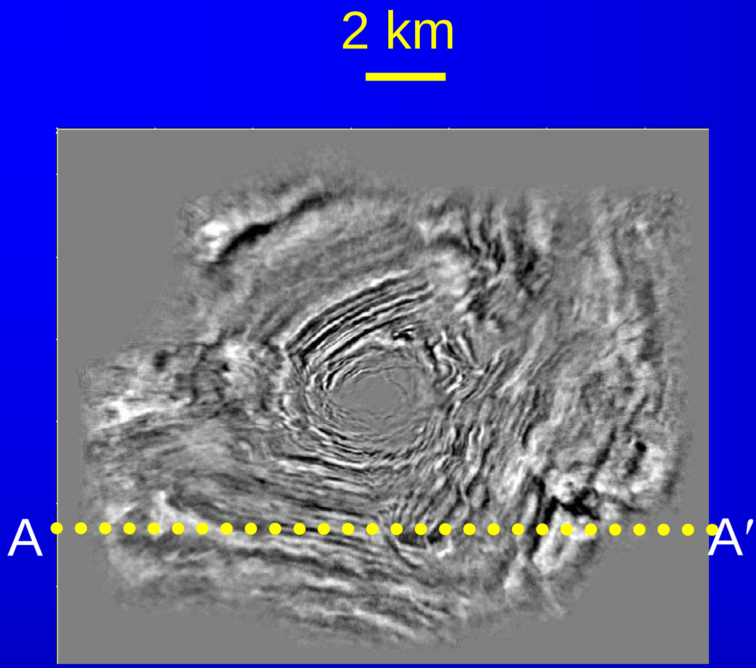
Search for the most coherent window containing the analysis point



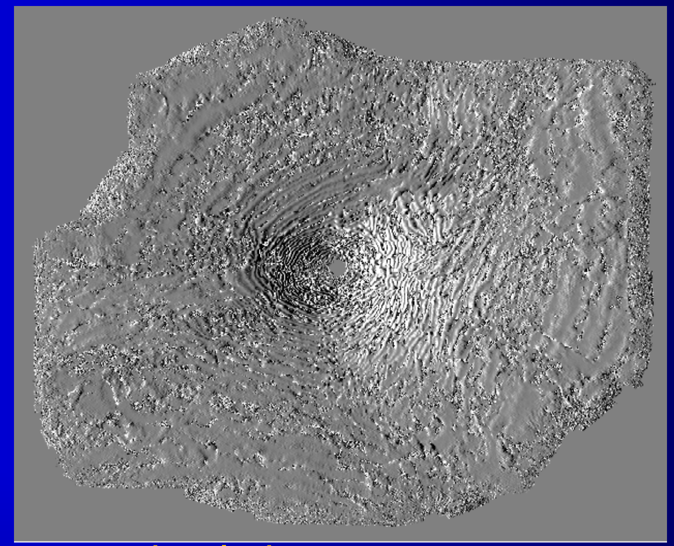
(Marfurt, 2006)


Comparison of dip estimates on vertical slice
2 km
A
A′
Time (s)
0
1
2
3
4
Amplitude
simple instantaneous inline dip
smoothed instantaneous inline dip
multi-window scan of inline dip
Dip (μs/m)
+.2
0
-.2
(Marfurt, 2006)

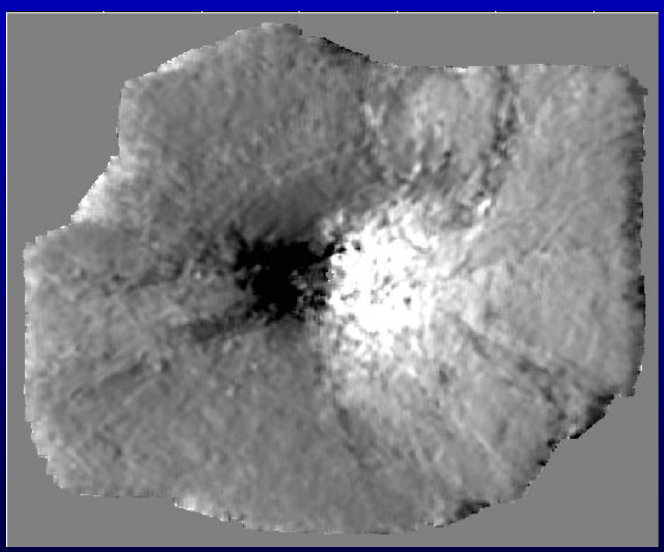
Comparison of dip estimates on time slice (t=1.0 s)



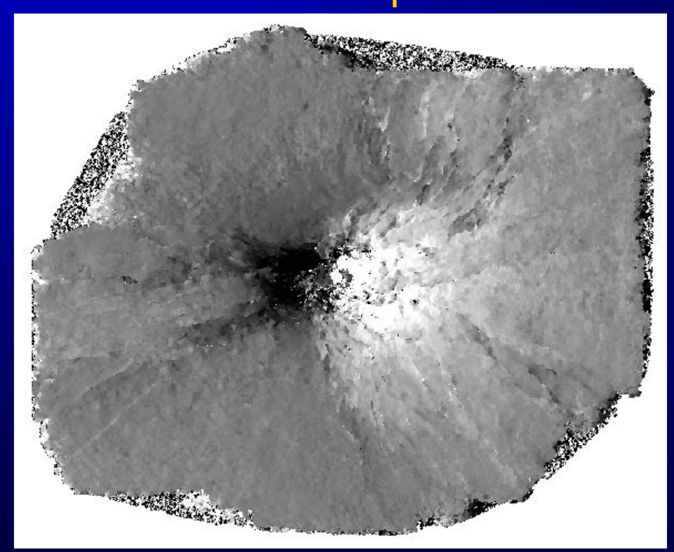
Amplitude



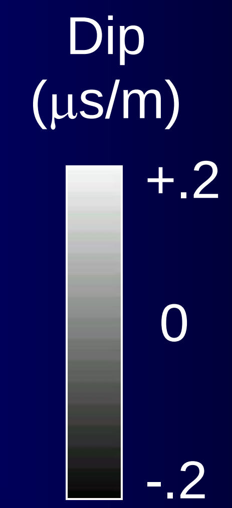
simple instantaneous inline dip



smoothed instantaneous inline dip

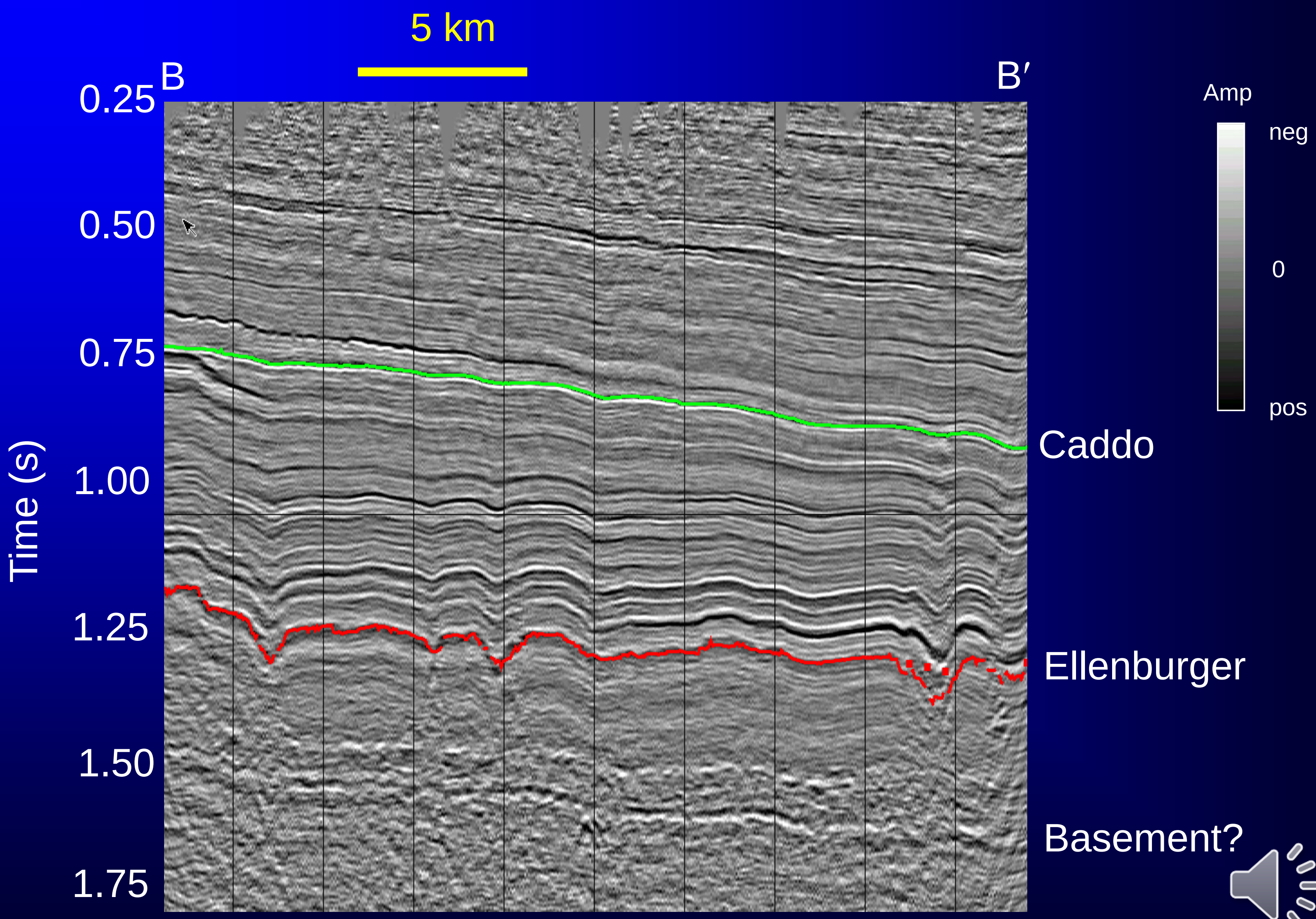


multi-window scan of inline dip

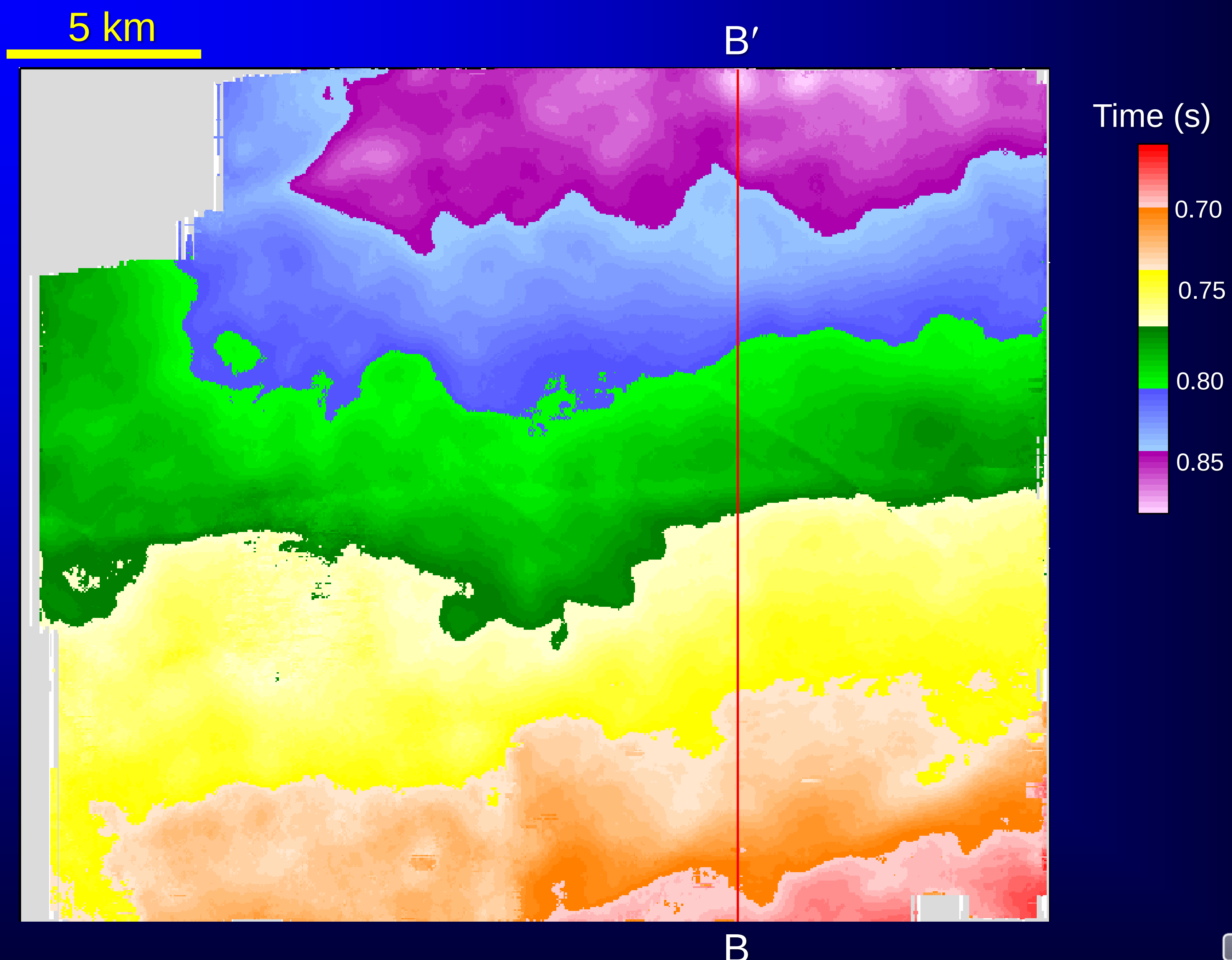


(Marfurt, 2006)

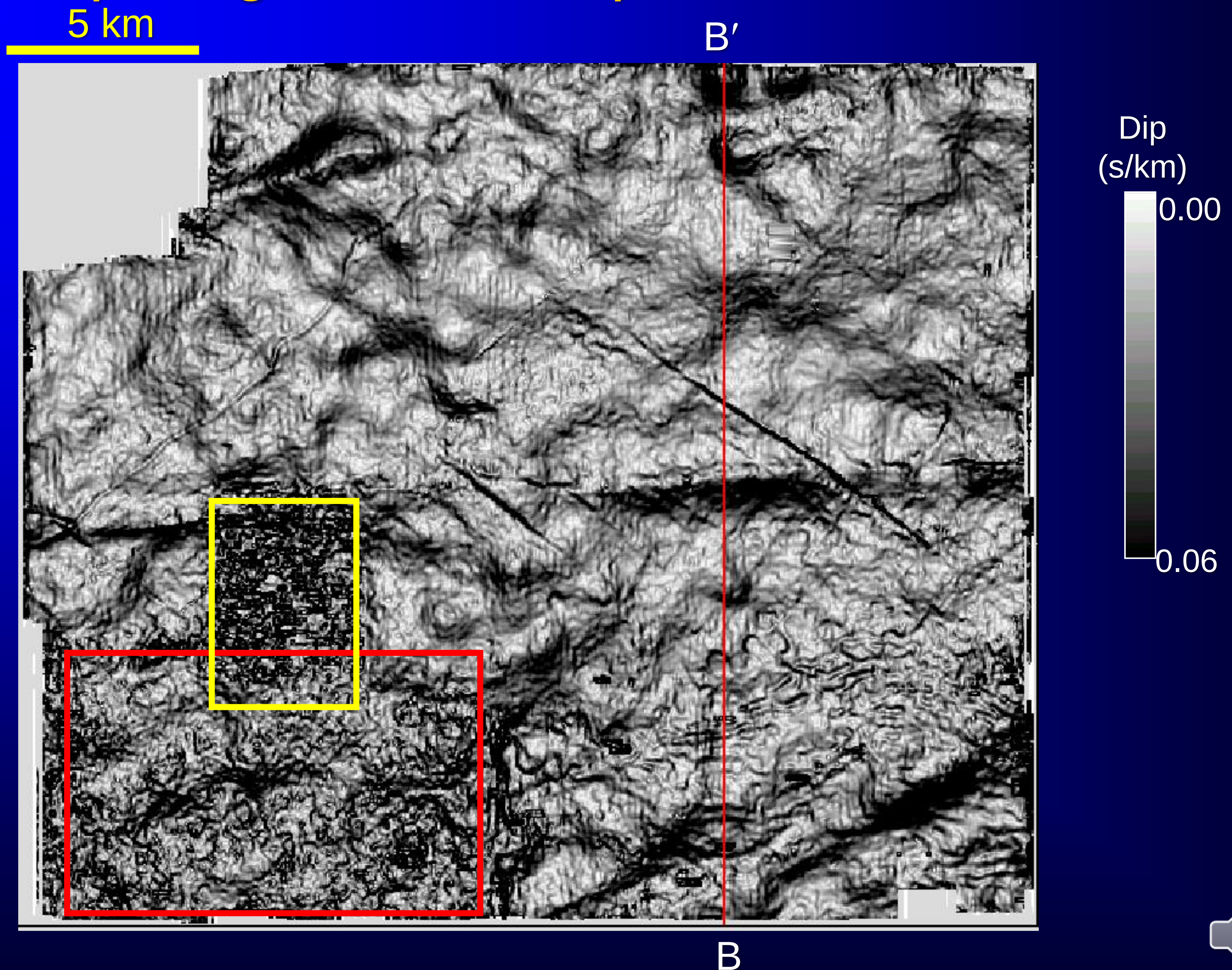
Vertical Slice through Seismic



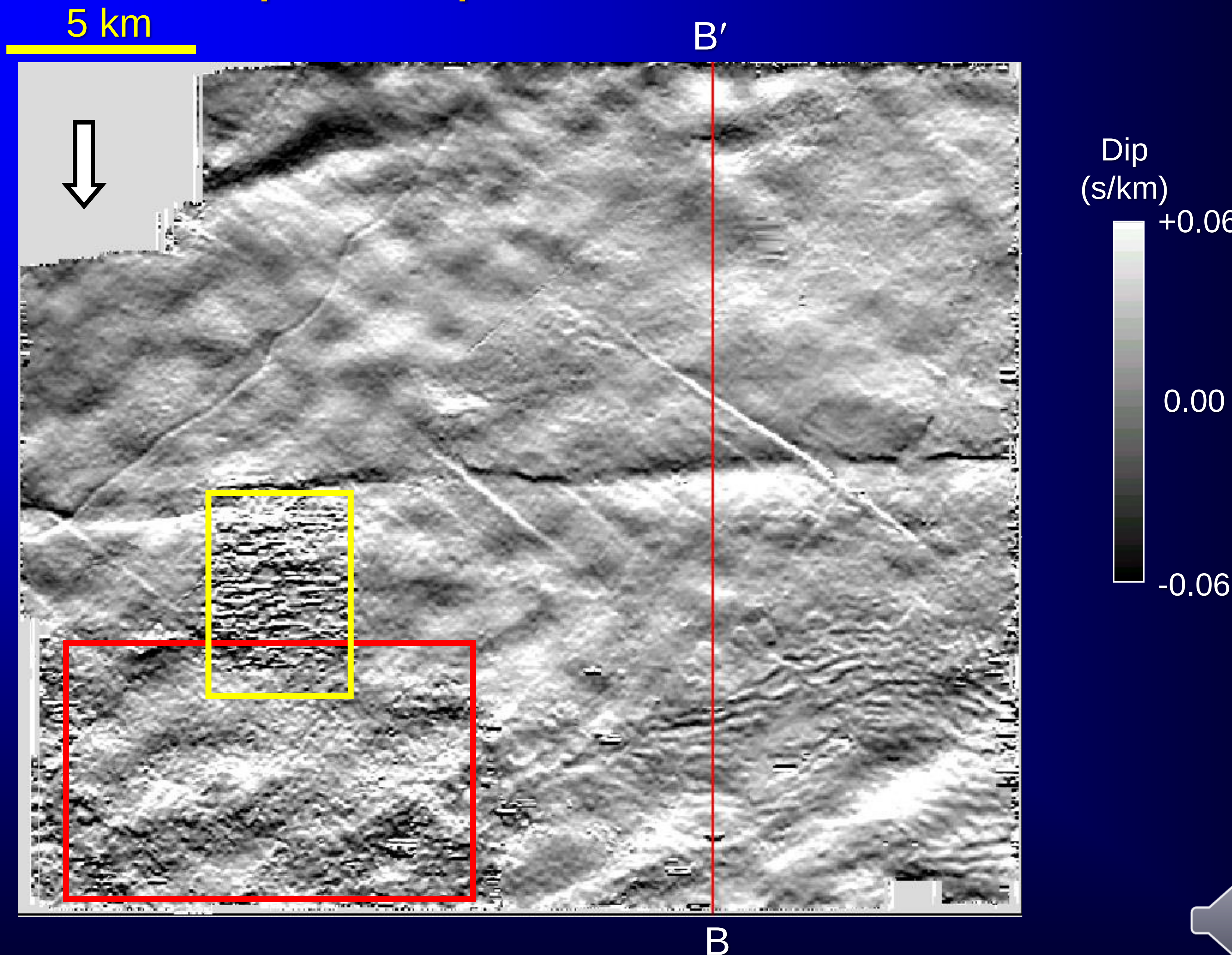
Time/structure of Caddo horizon



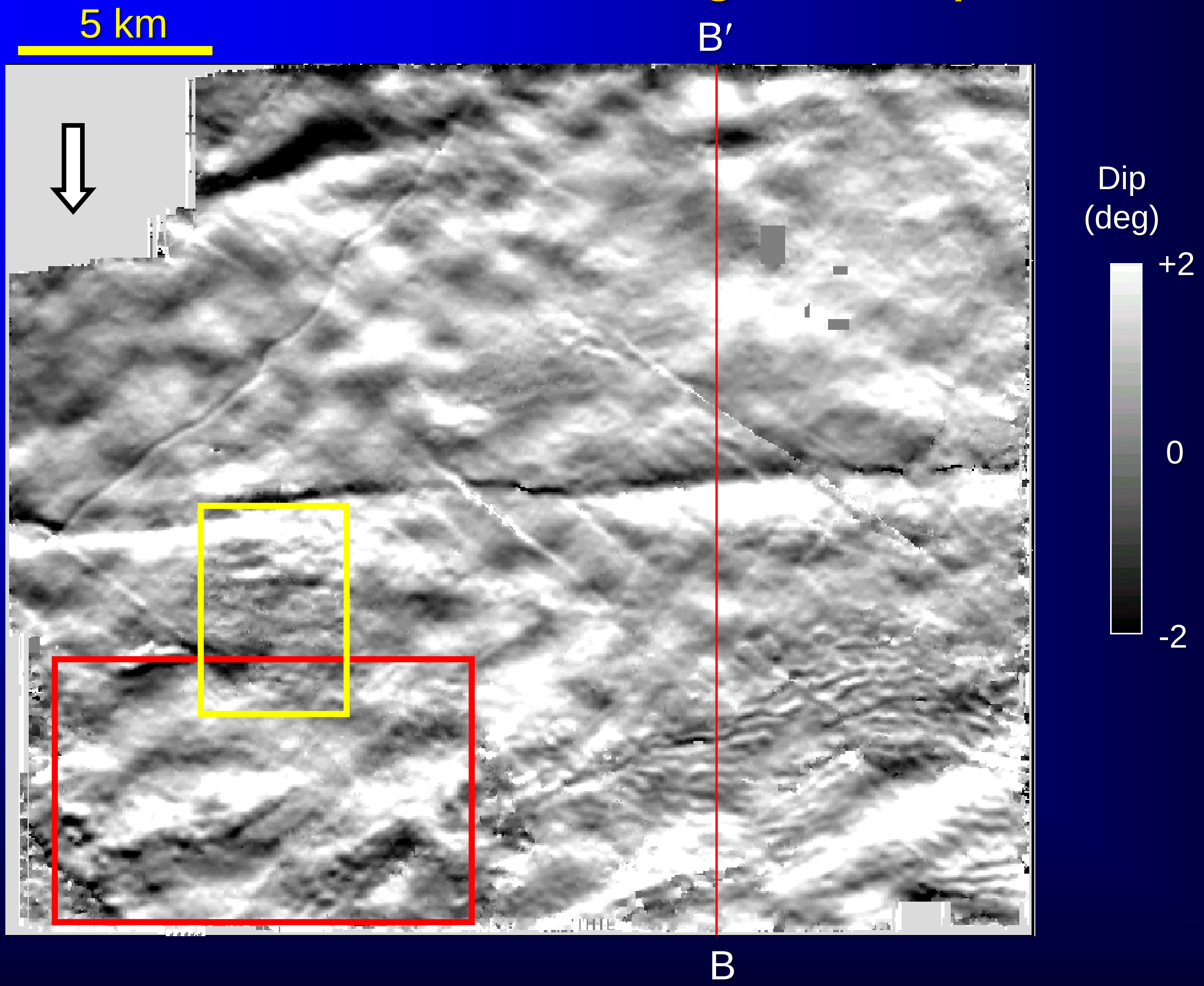
Dip magnitude from picked Caddo horizon



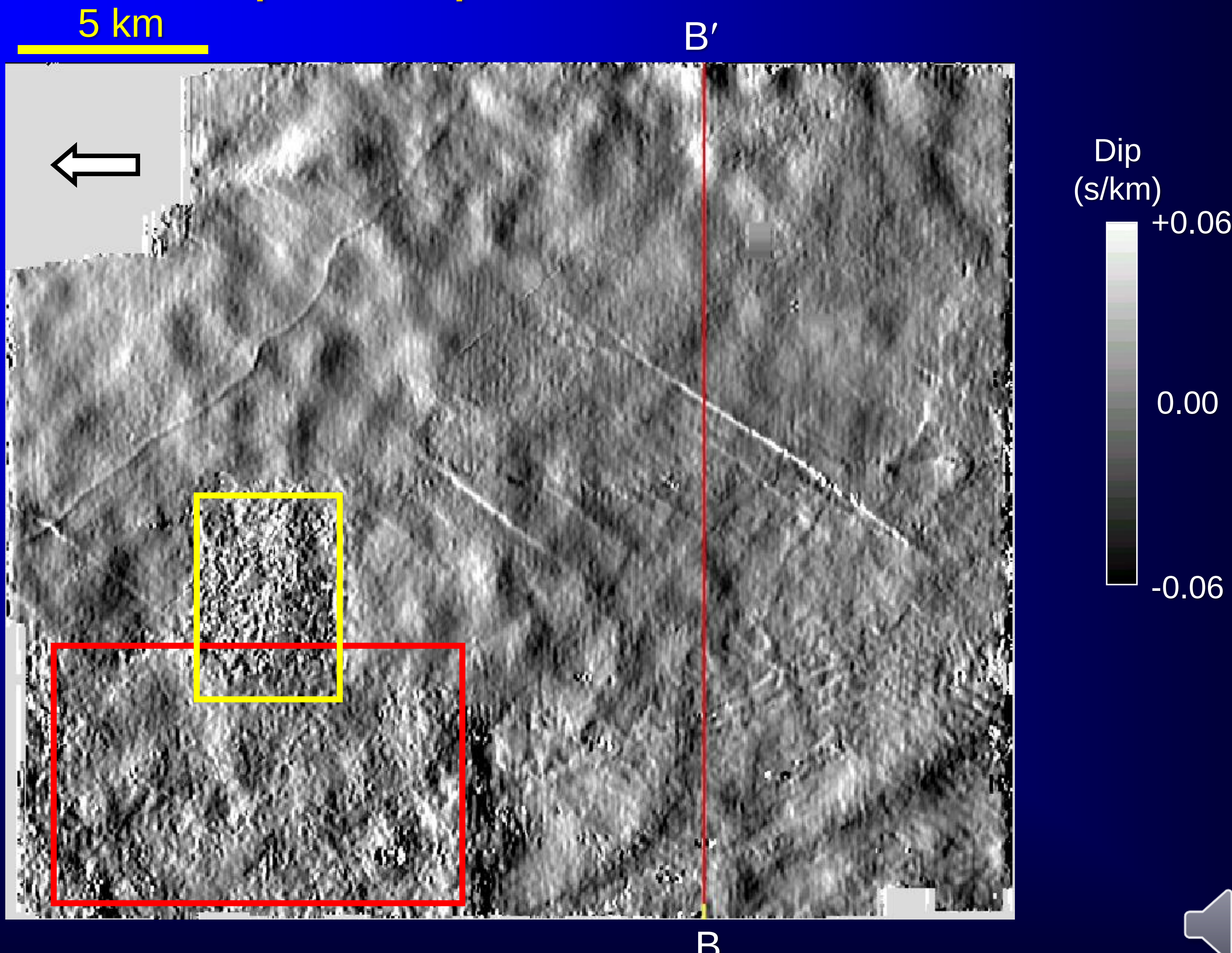
NS dip from picked Caddo horizon



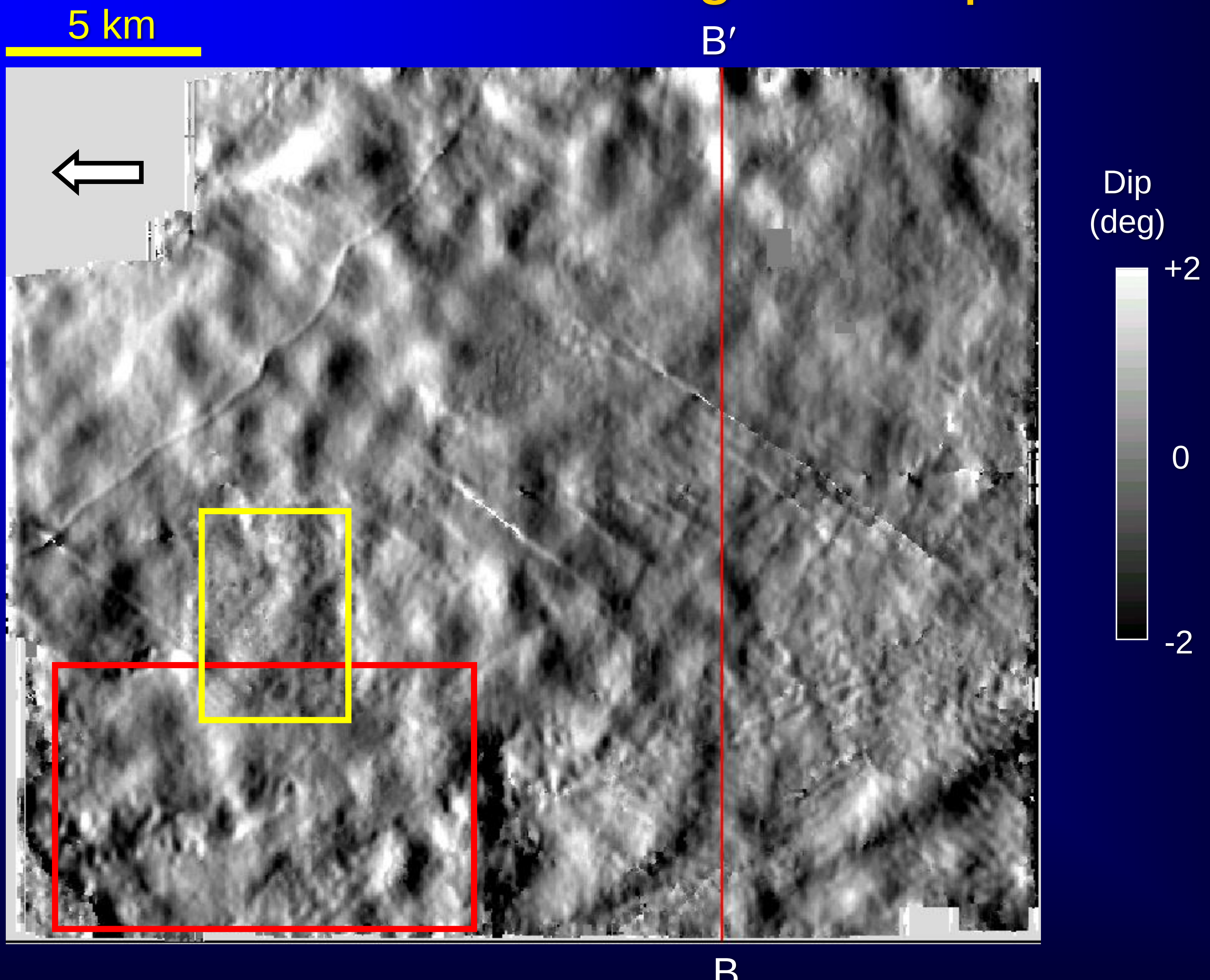
Caddo horizon slice through NS dip volume



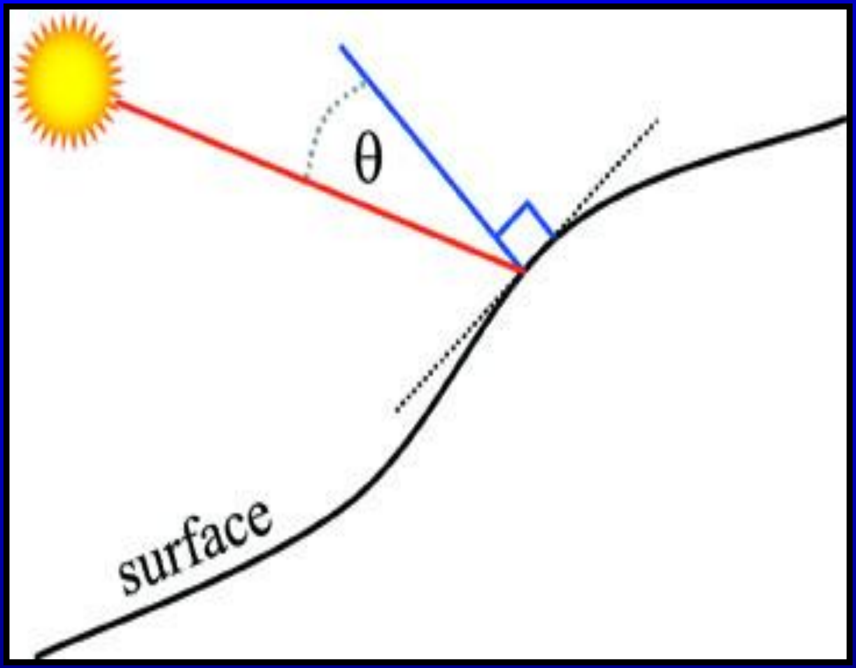
EW dip from picked Caddo horizon



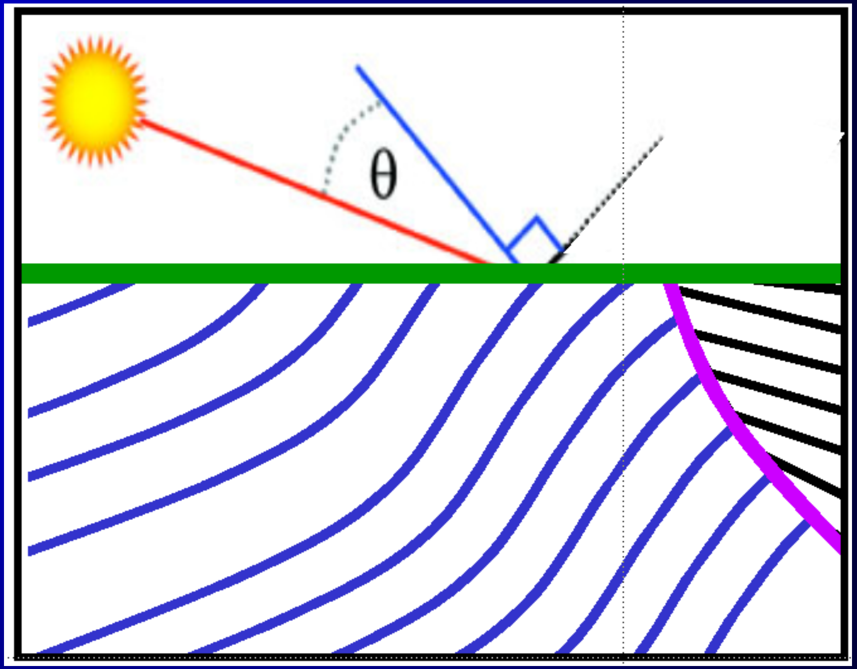
Caddo horizon slice through EW dip volume



Shaded illumination



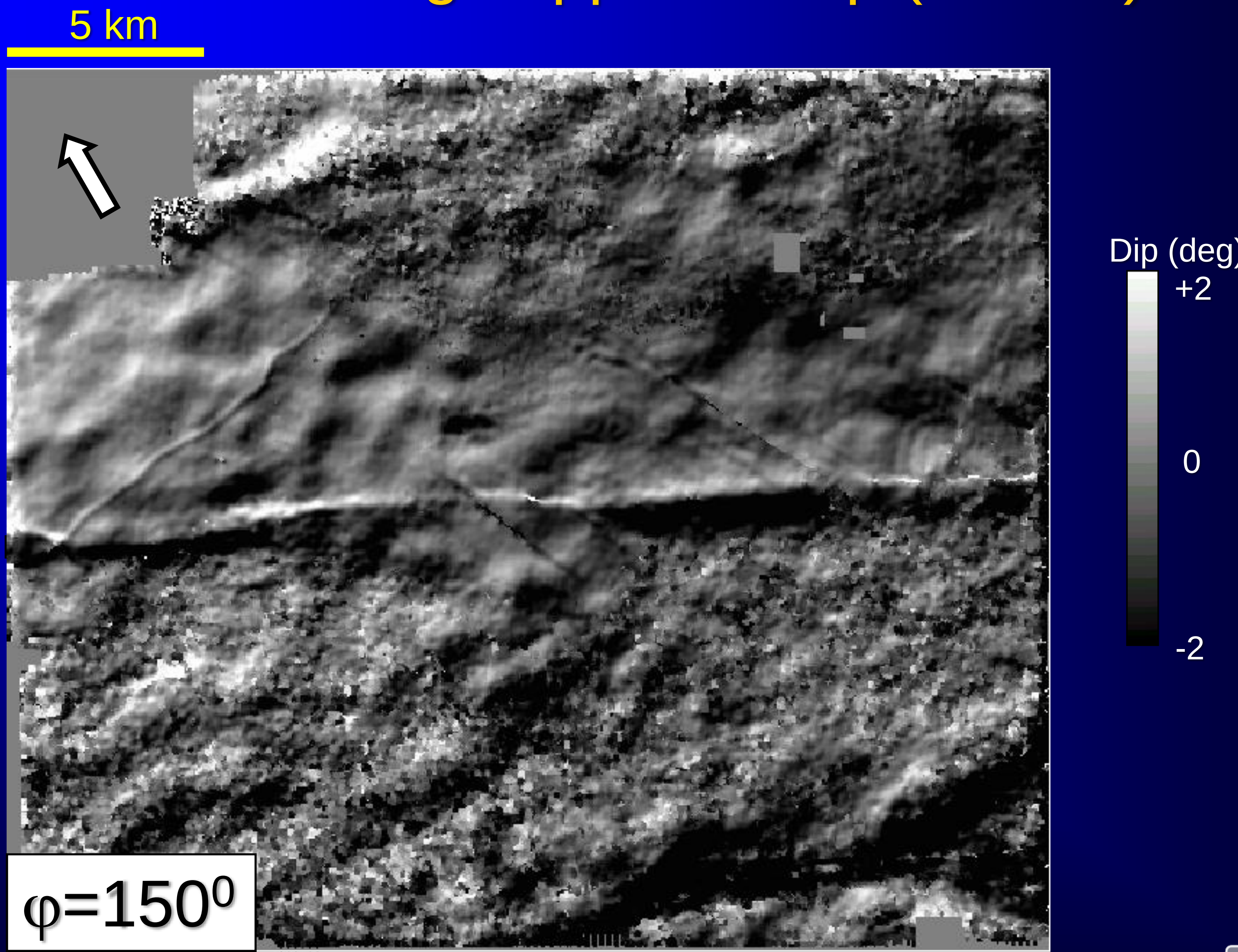
on a surface



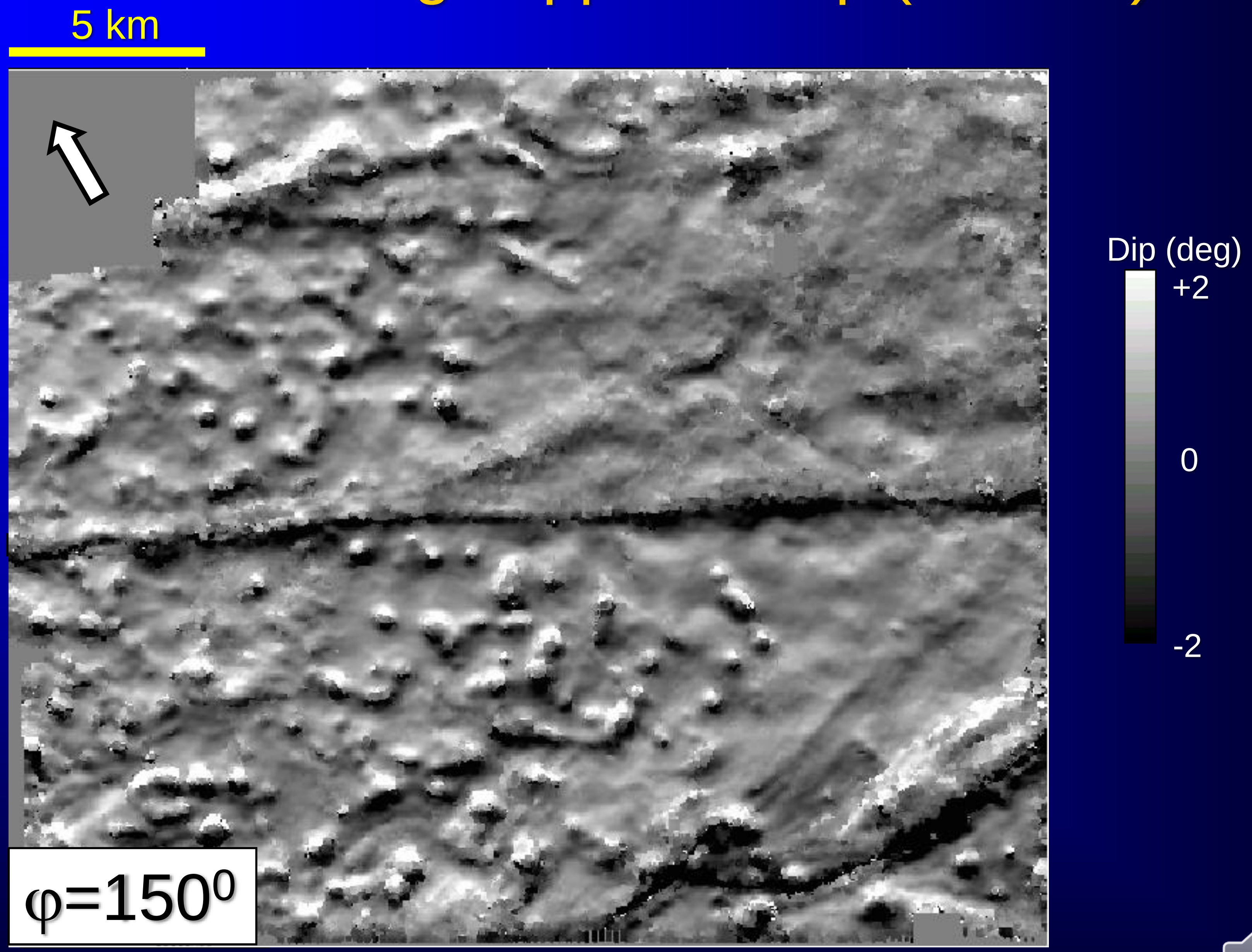
on a time slice through
dip and azimuth volumes

(after Barnes, 2002)

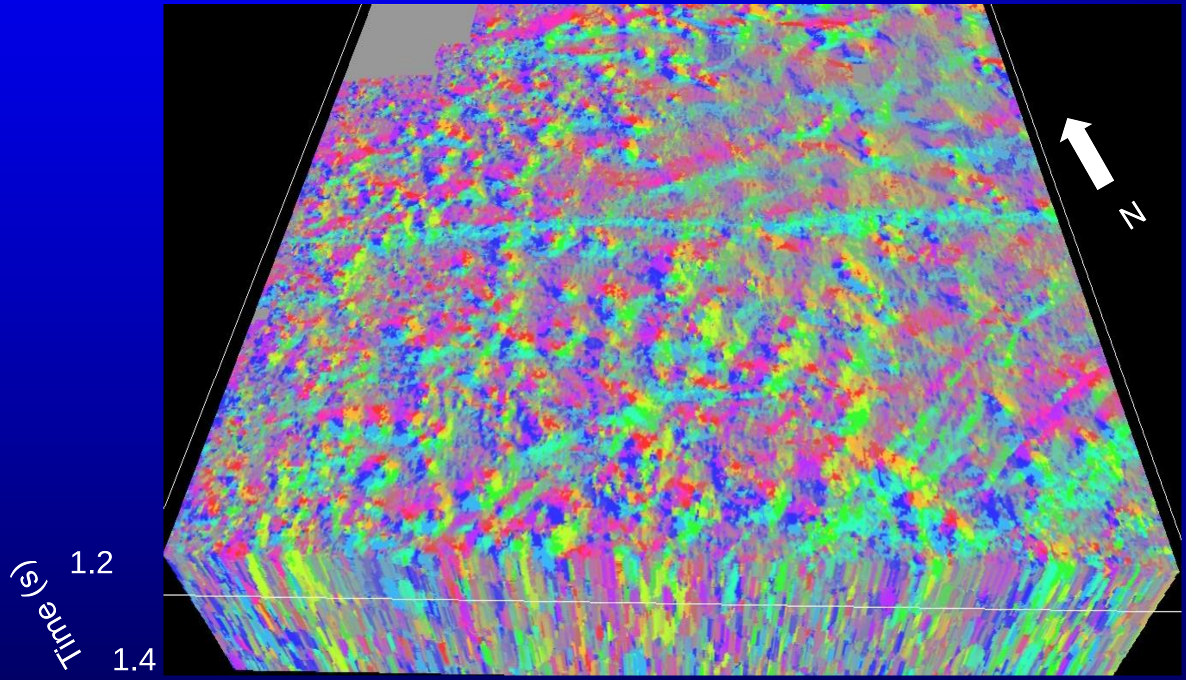
Time slices through apparent dip (t=0.8 s)

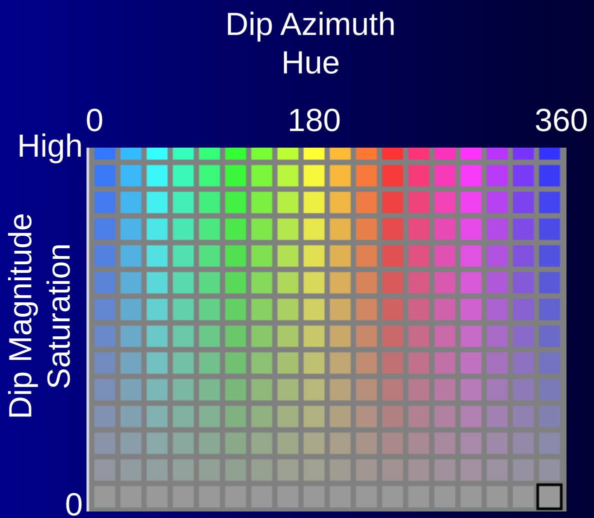


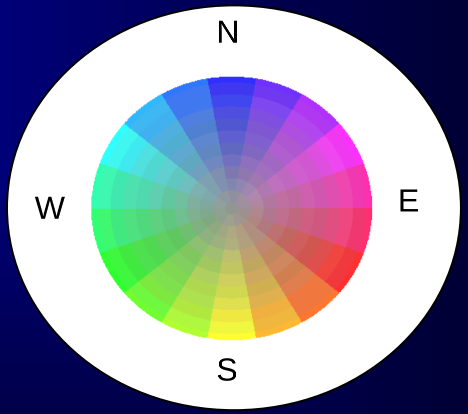
Time slices through apparent dip (t =1.2 s)



Volumetric visualization of reflector dip and azimuth



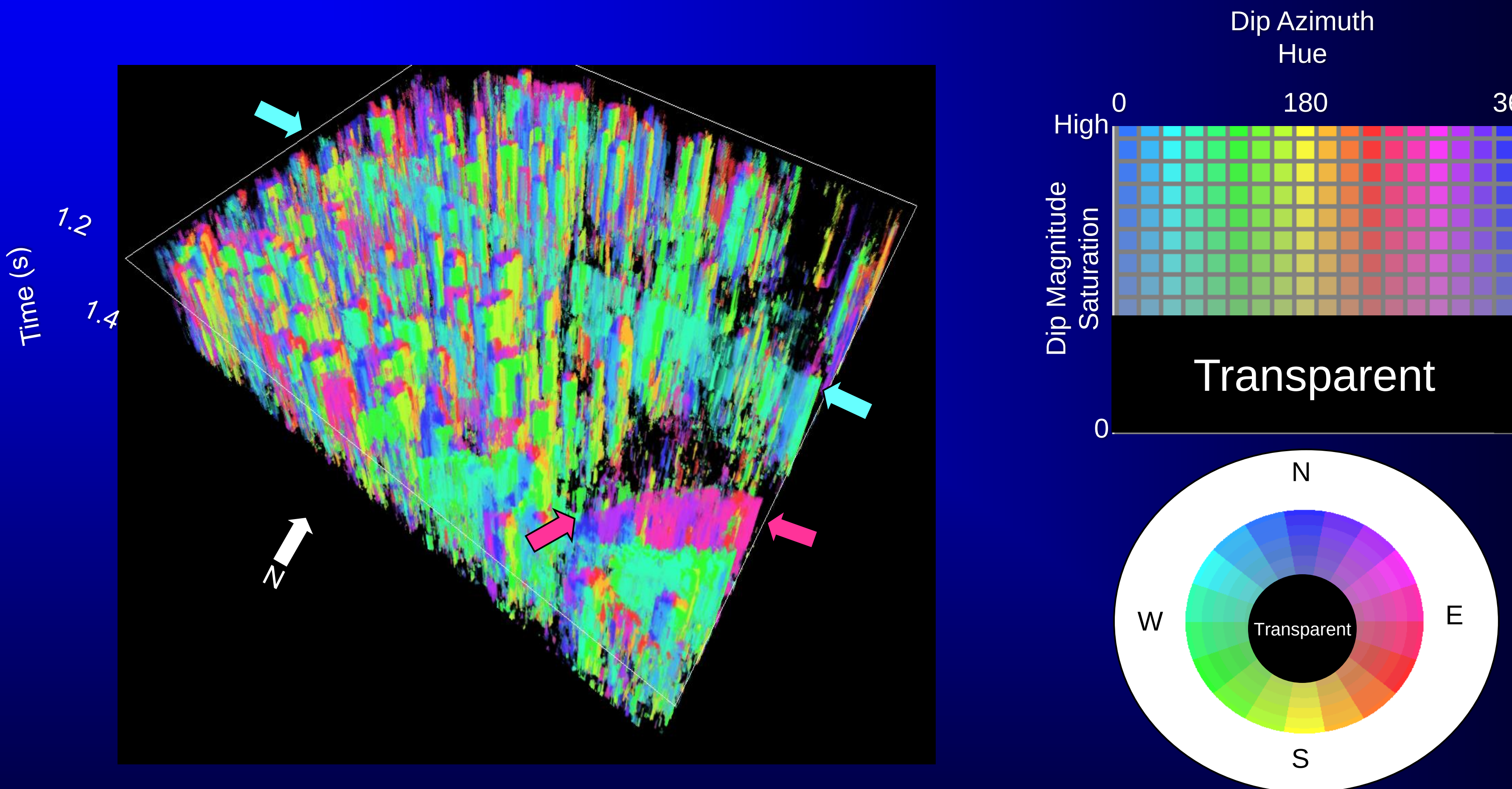




(c)

(Guo et al., 2008)

Volumetric visualization of reflector dip and azimuth



(Guo et al., 2008)

Volumetric Dip and Azimuth

In Summary:

- Dip and azimuth estimated using a vertical window in general provide more robust estimates than those based on picked horizons

- Dip and azimuth volumes form the basis for volumetric curvature, coherence, amplitude gradients, seismic textures, and structurally-oriented filtering

- Dip and azimuth are the key components for computer-aided 3D seismic stratigraphy

- Dip and azimuth will suffer from fault shadow and other velocity pull-up and push-down artifacts