Seismic Attributes - from Interactive Interpretation to Machine Learning

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Color and Multiattribute Display

Multiattribute display

After this section you should be able to:

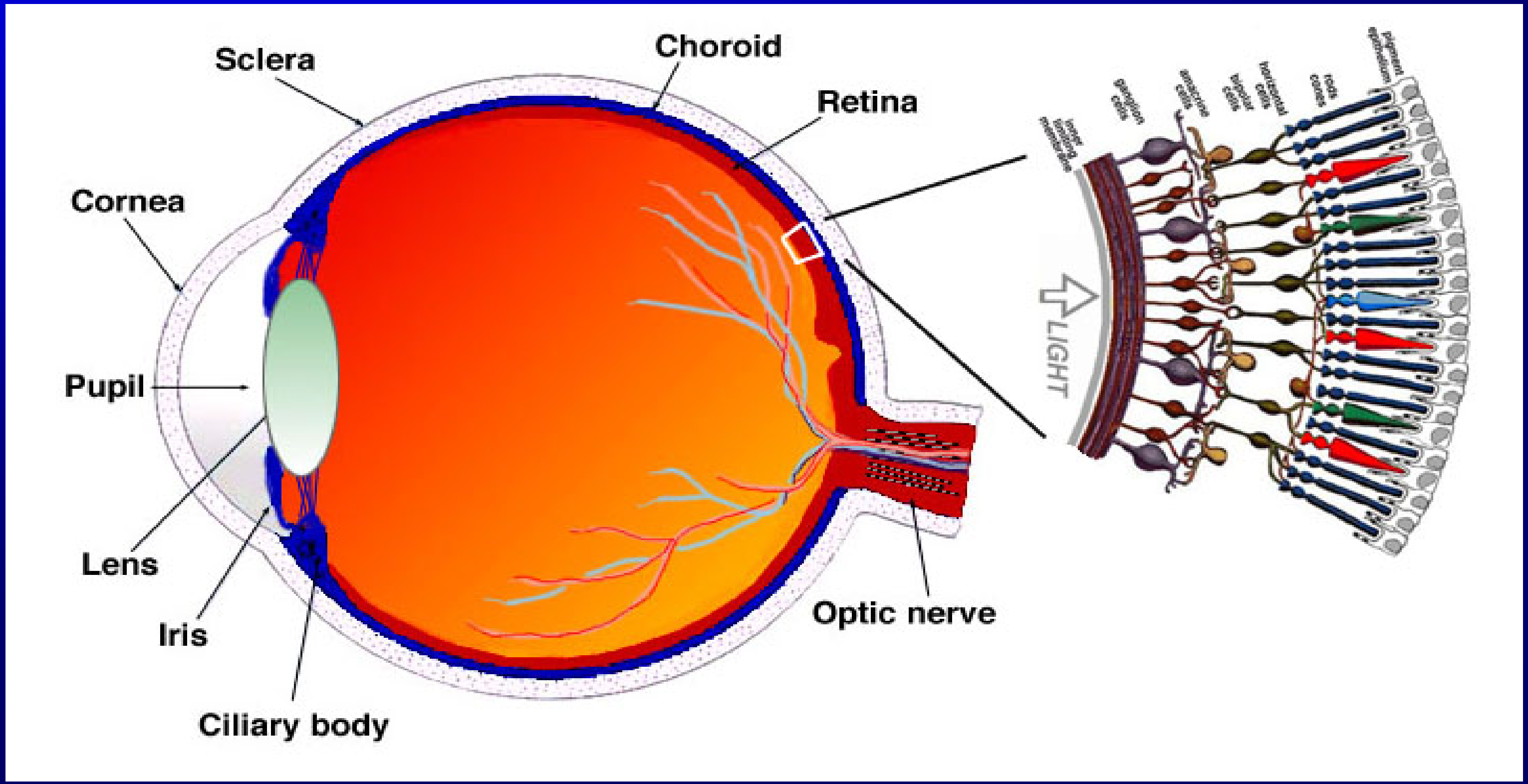
- Identify good and bad color display practices,
- Display multiple attributes in a single image, and
- Apply color schemes that allow you to effectively communicate these features to others.

Color perception: Humans

Cone and Rod receptors

Cone: 3 types, each being sensitive to a different range of wavelengths

Rod: for night vision, sensitive to a broad range of light intensities



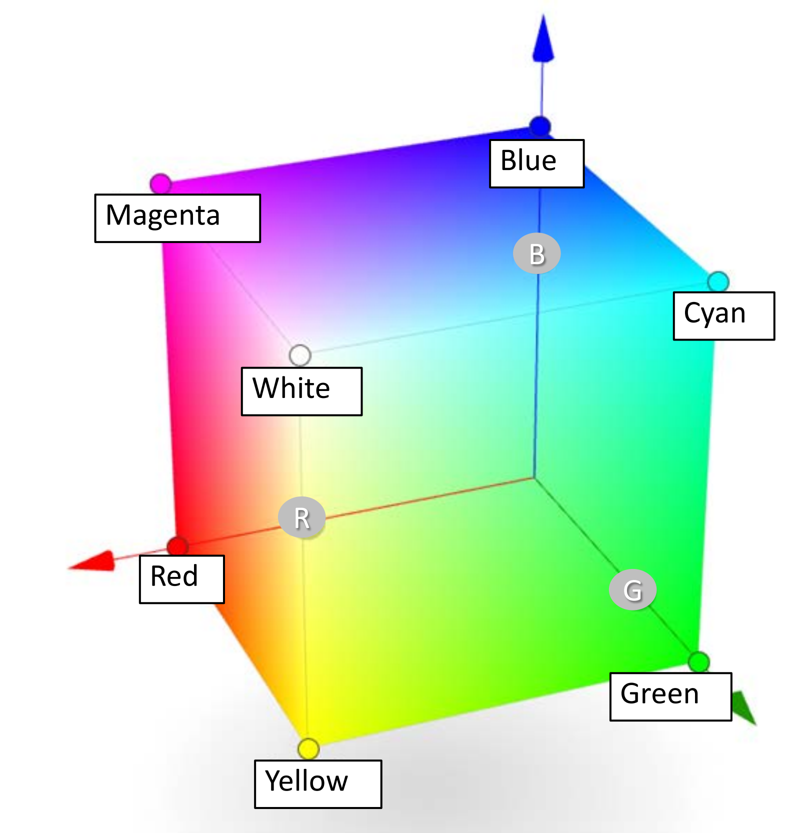
(Thomson and Macpherson, 2017)

Color perception: Men vs. women

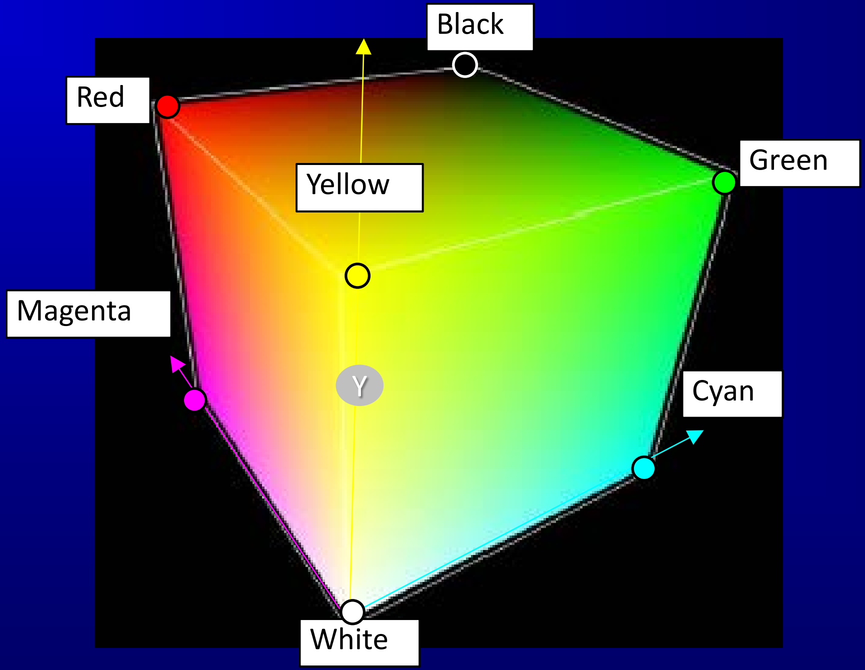
(email communication on 10/18/2011. Origin unknown)

Alternative color models

The additive RGB color model
Mixes light

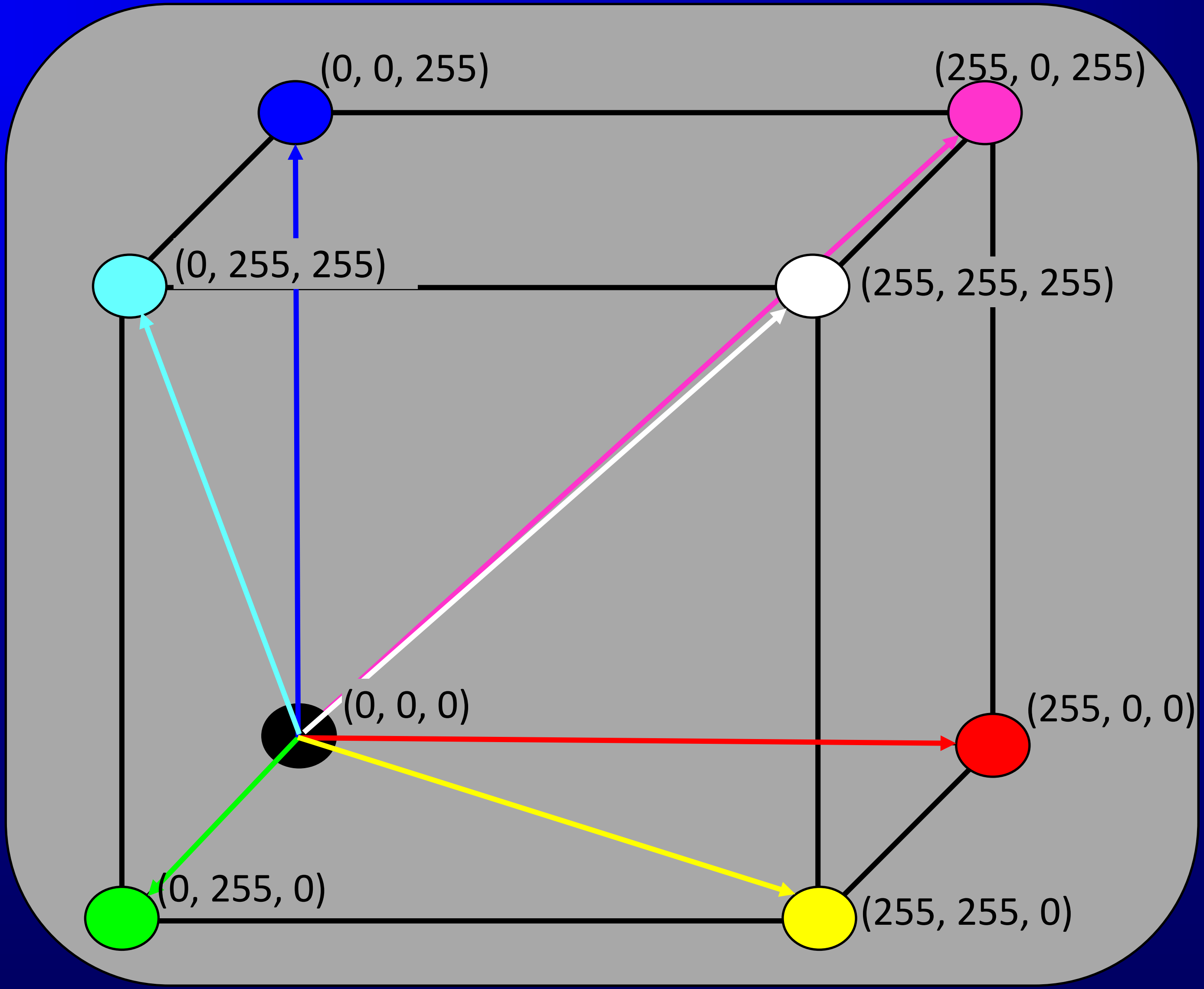


The subtractive CMY color model
Mixes pigment



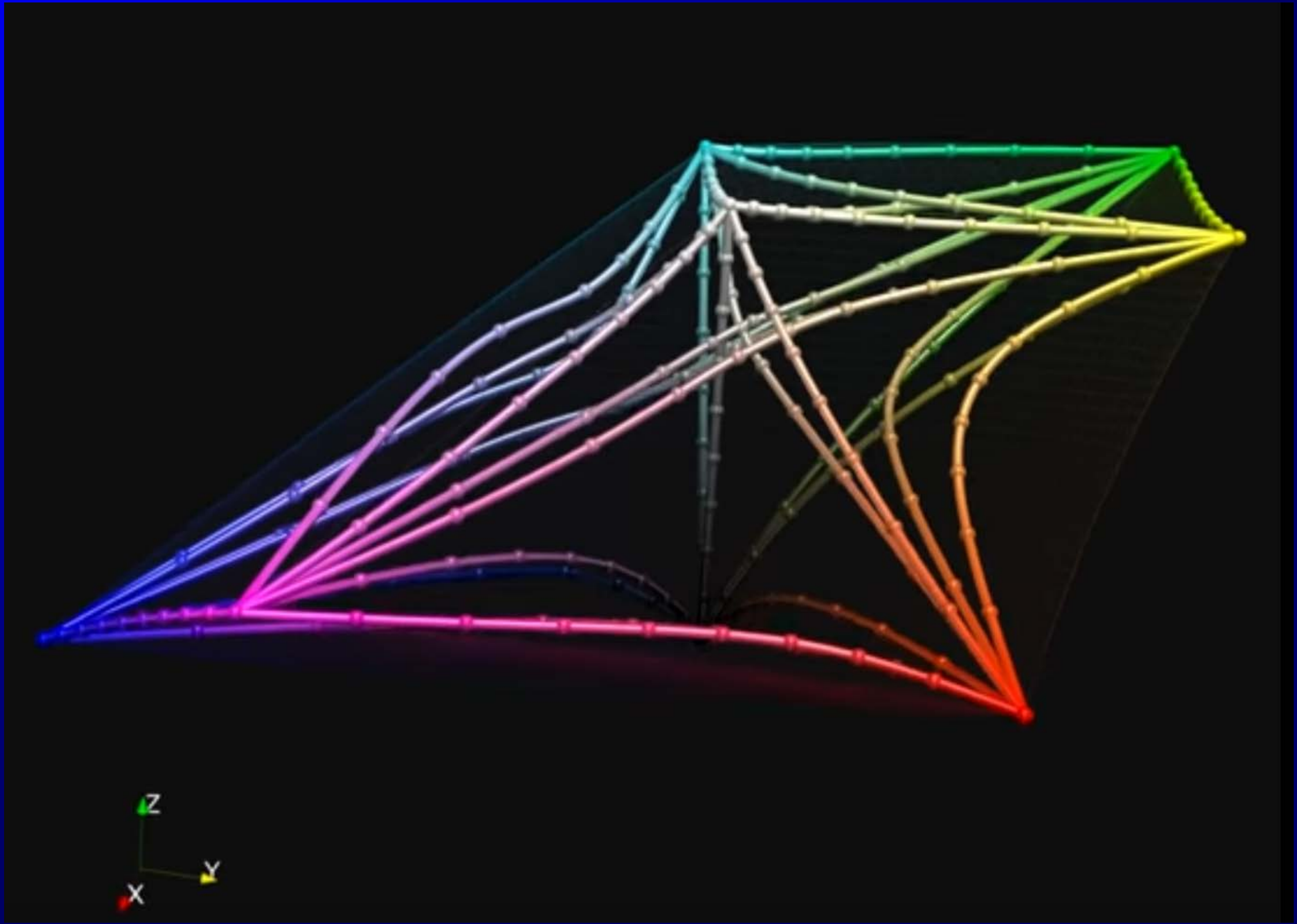
(Chopra and Marfurt, 2021)

Defining 24-bit color on a computer



(Chopra and Marfurt, 2021)

A very recent (2022) color model based on human perception



https://youtu.be/E-9wCFby5XE

Color Depth (the number of colors)

16,777,216 colors
R=256,G=256,B=256
(24-bit color)

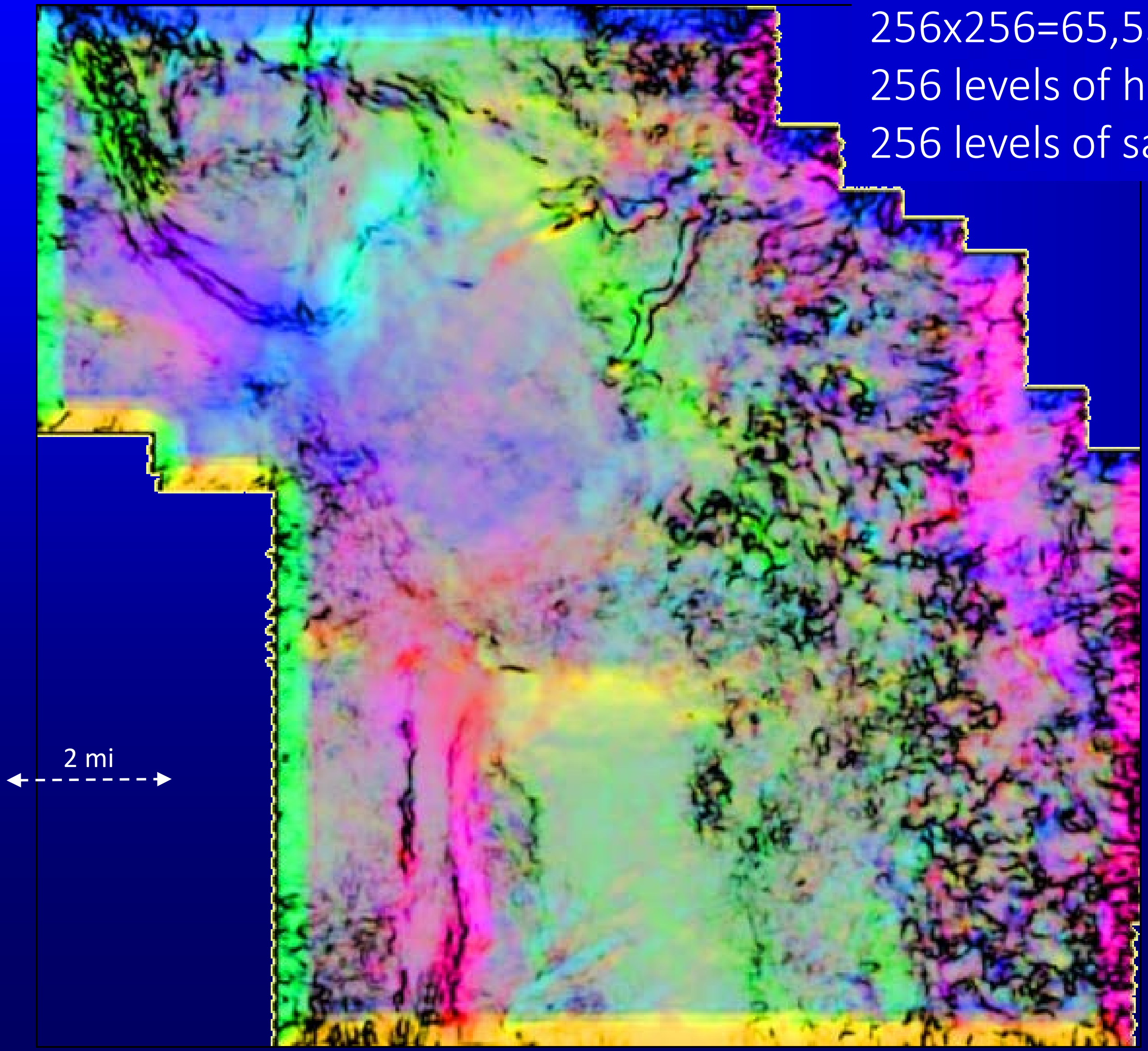
4096 colors
R=16,G=16,B=16

216 colors
R=6,G=6,B=6

Only a few interpretation packages provide 24-bit color. Most are still limited to 8-bit color (256 colors)

(Dao and Marfurt, 2011)

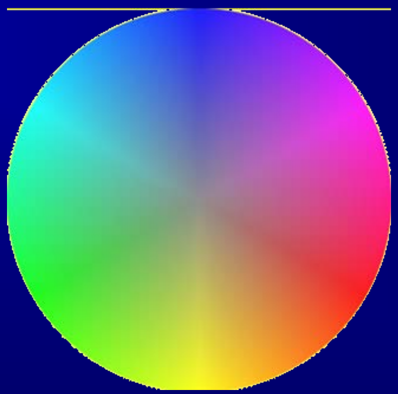
Color depth – how many colors are enough?



256x256=65,536 colors
256 levels of hue
256 levels of saturation

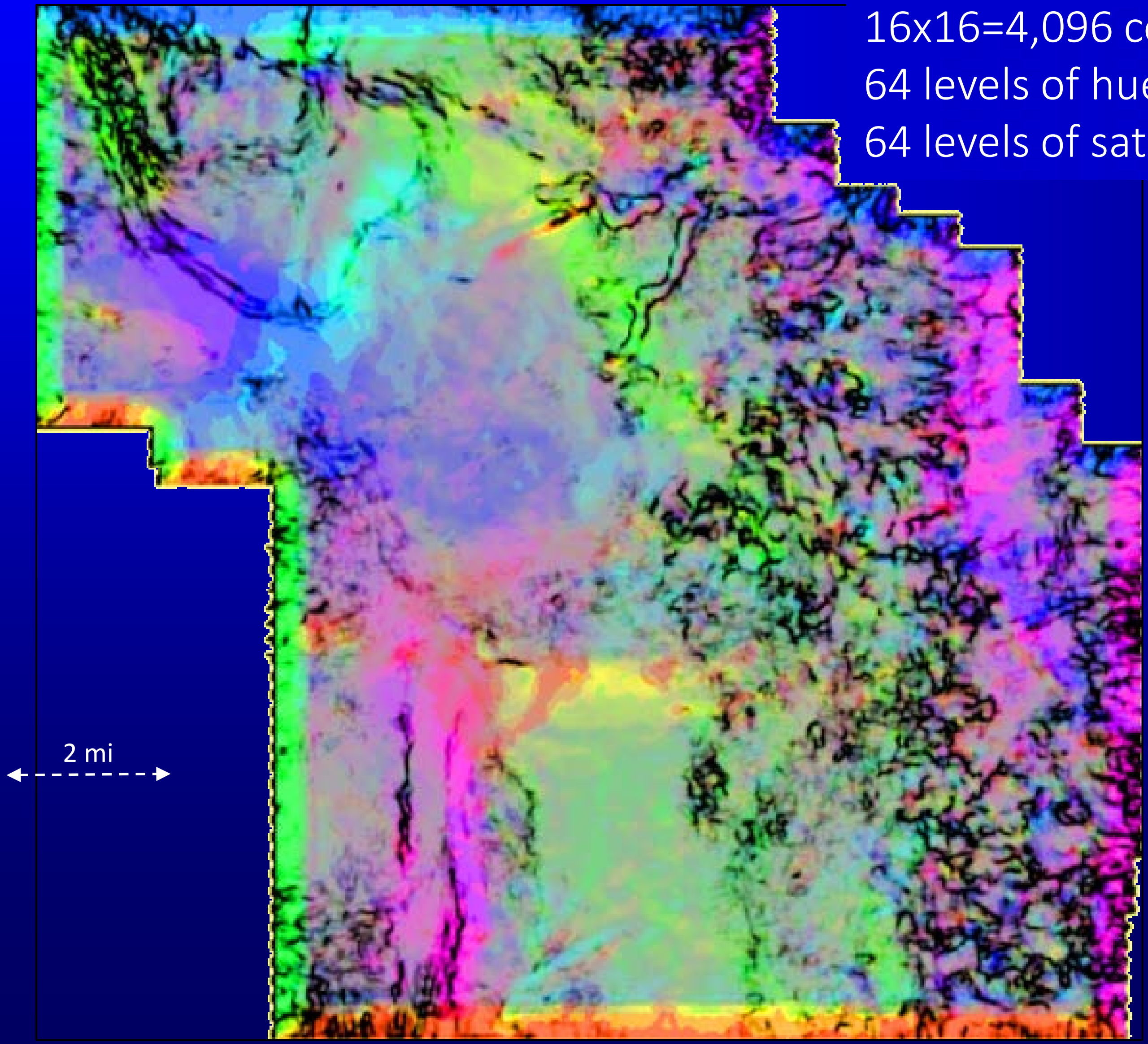
Reflector convergence
(magnitude vs. azimuth)

(Central Basin Platform, Texas)



(Dao and Marfurt, 2011)

Color depth – how many colors are enough?



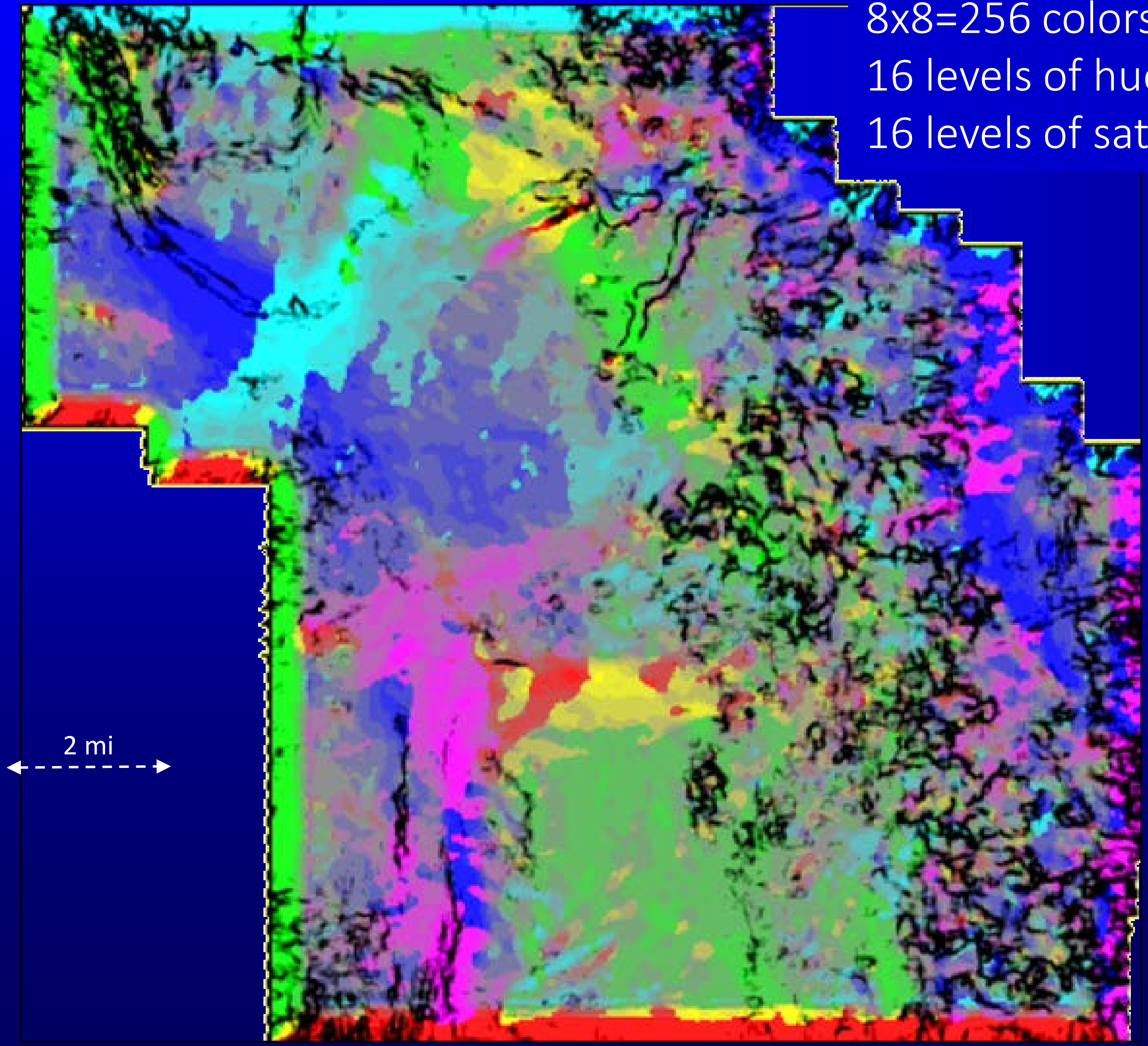
16x16=4,096 colors
64 levels of hue
64 levels of saturation

Reflector convergence
(magnitude vs. azimuth)

(Central Basin Platform, Texas)

(Dao and Marfurt, 2011)

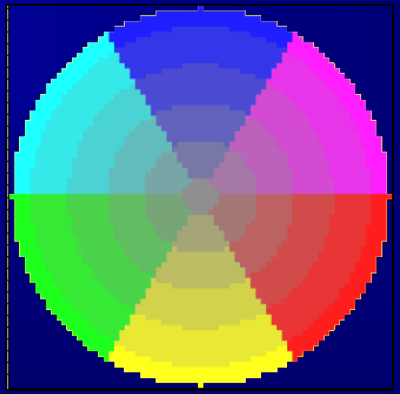
Color depth – how many colors are enough?



8x8=256 colors
16 levels of hue
16 levels of saturation

Reflector convergence
(magnitude vs. azimuth)

(Central Basin Platform, Texas)

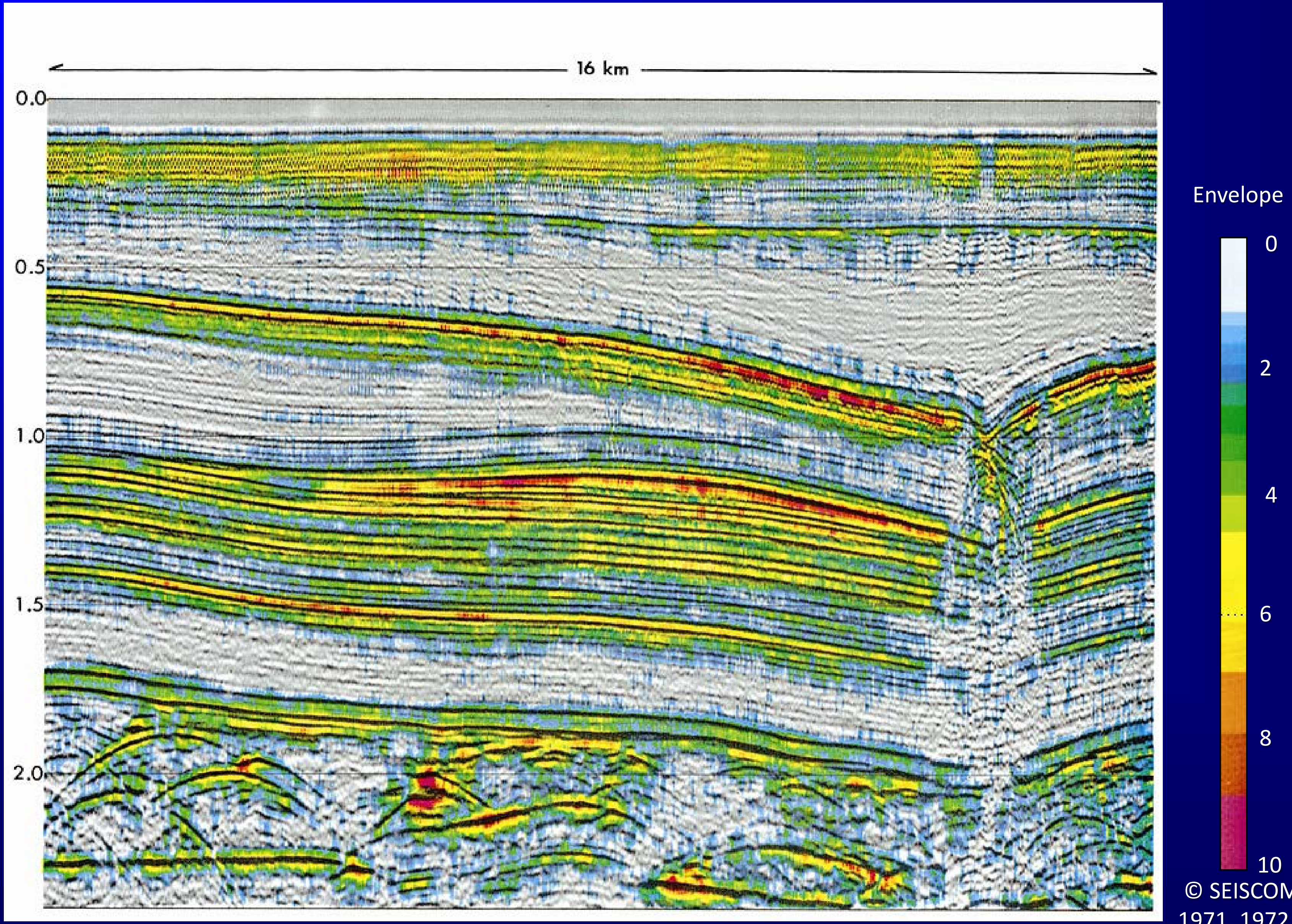


(Dao and Marfurt, 2011)

Multiattribute display tools

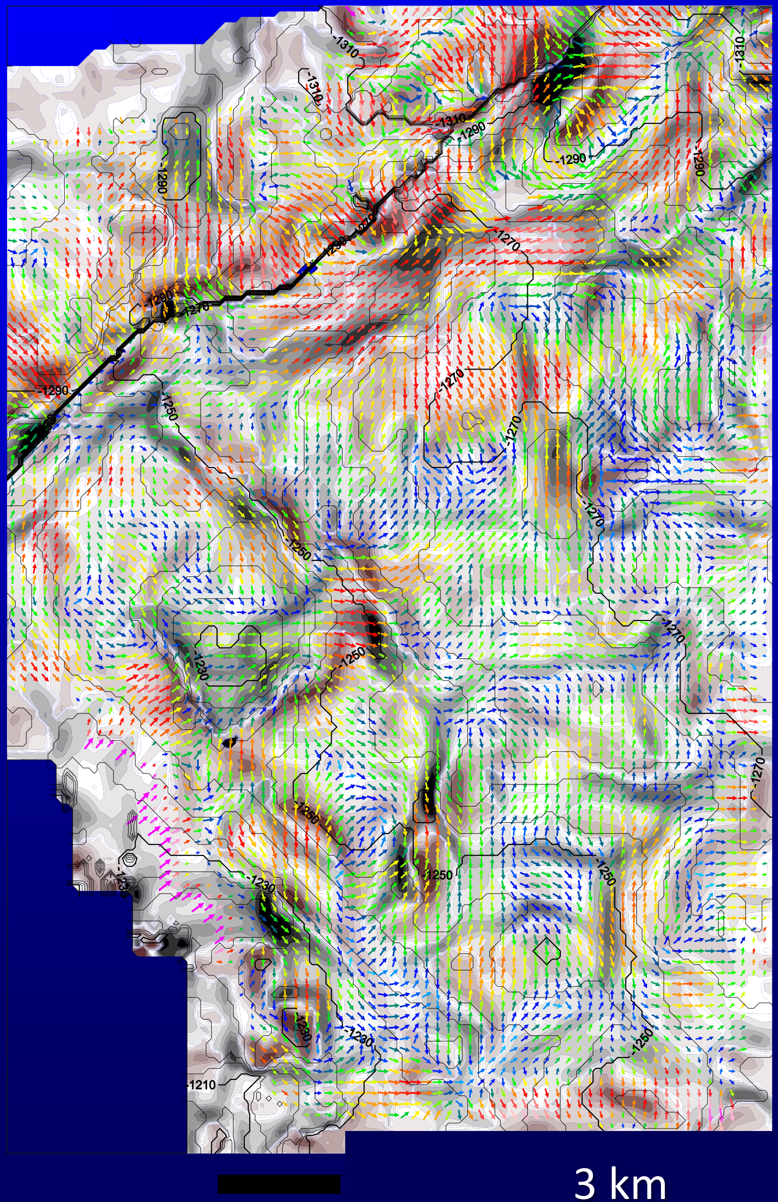
- Overplotting
- RGB- and CMY-blended (“stacked”) images
- HLS color modulated images
- Color blending/transparency/opacity
- Bump maps

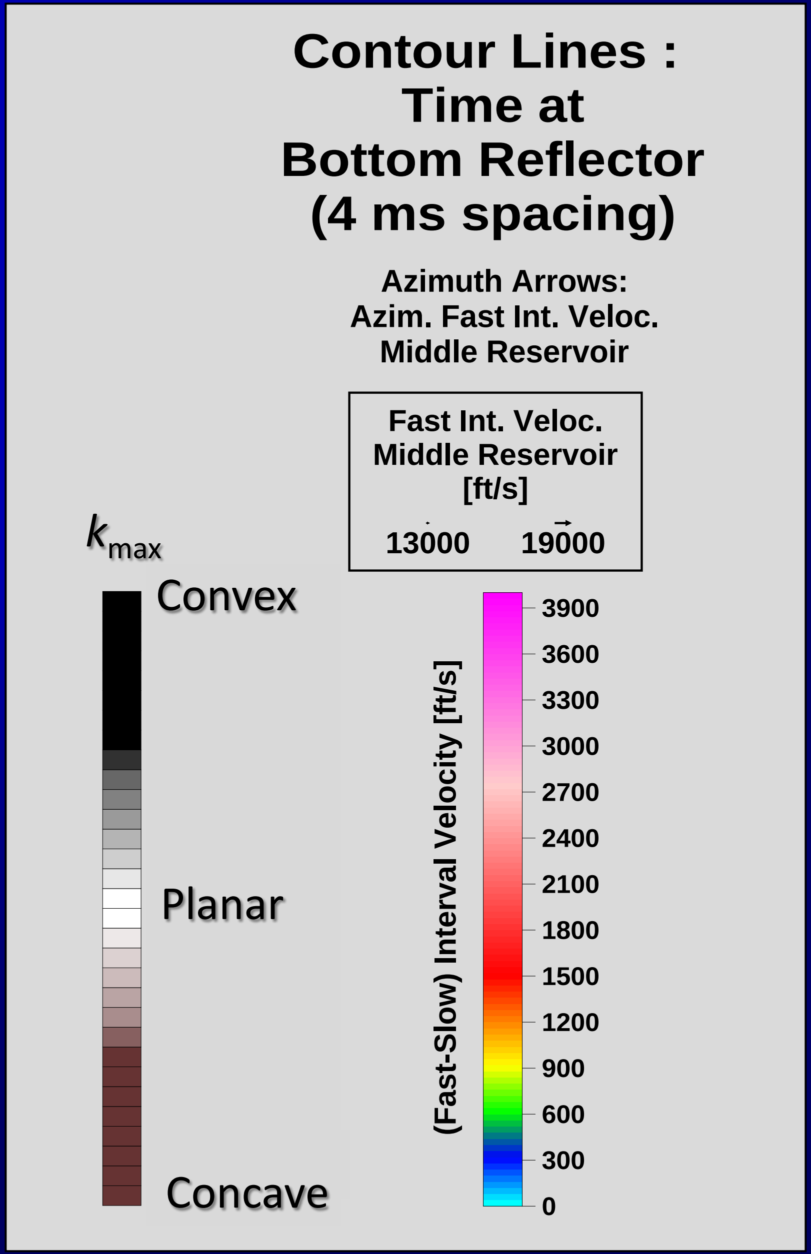
Multiattribute display using overlays



(Anstey, 2005)

Multiattribute display of vector data using color icons



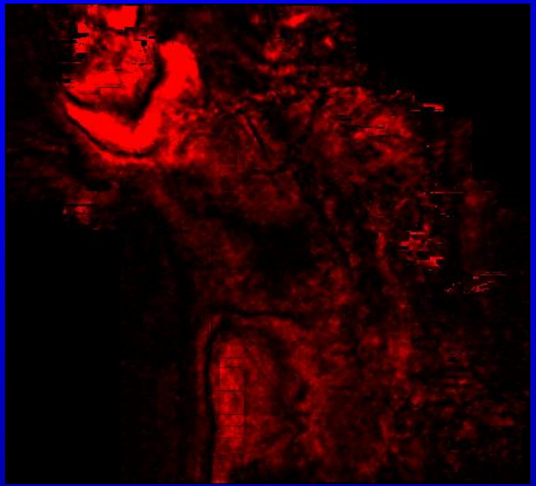


(Simon, 2005)

Multiattribute display tools

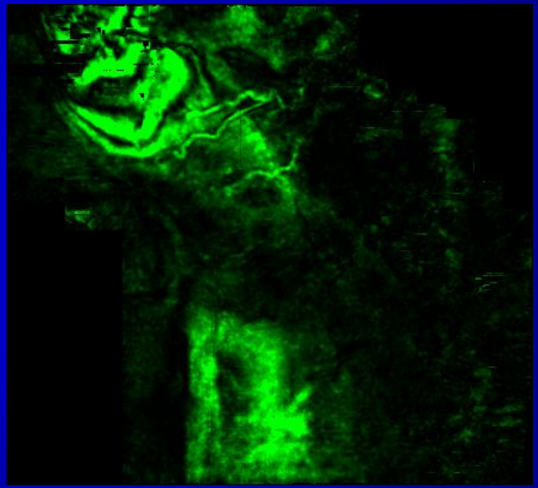
- Overplotting
- RGB- and CMY-blended ("color stacked") images
- HLS color modulated images
- Color blending/transparency/opacity
- Bump maps

RGB color stack



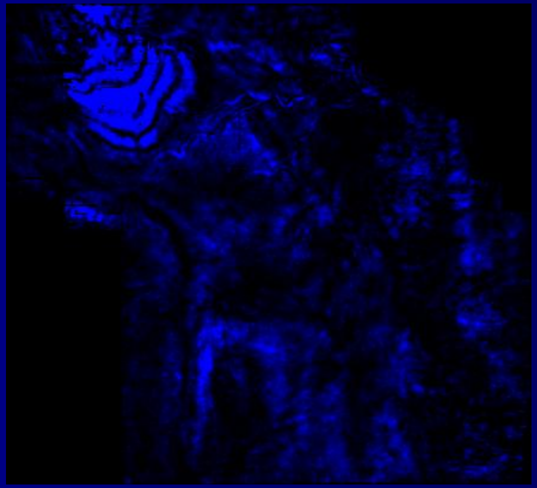
Red=16 Hz

+



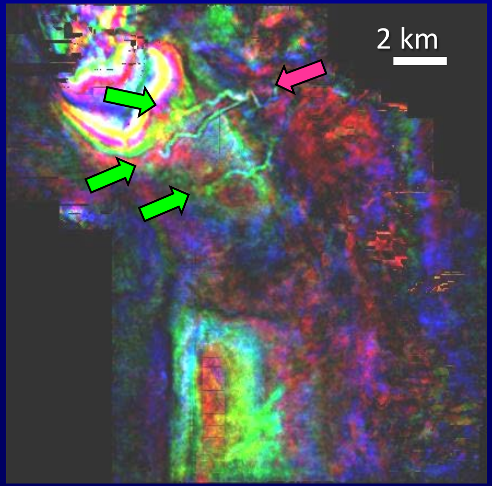
Green=32 Hz

+



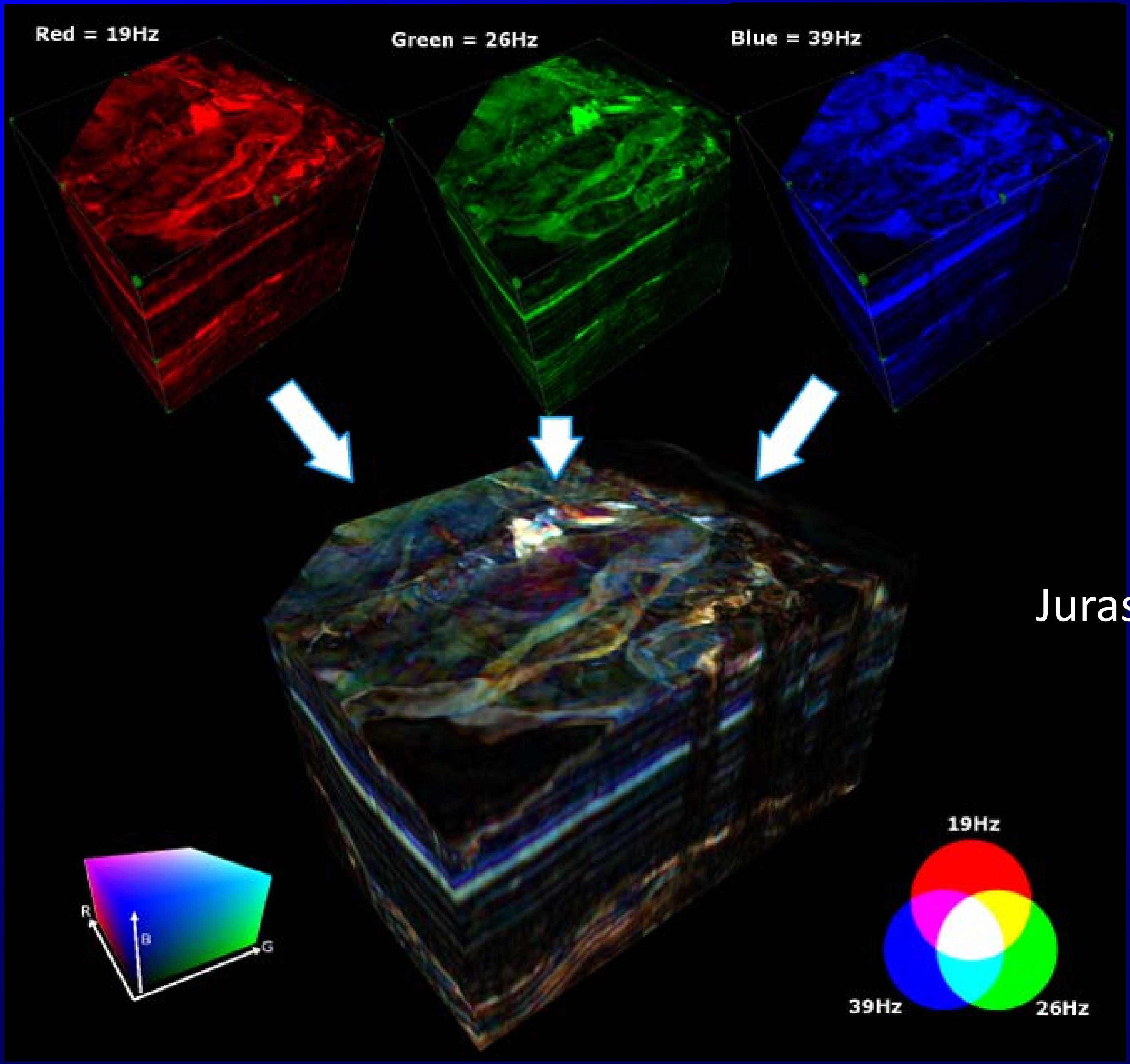
Blue=48 Hz

=



(Guo and Marfurt, 2007)

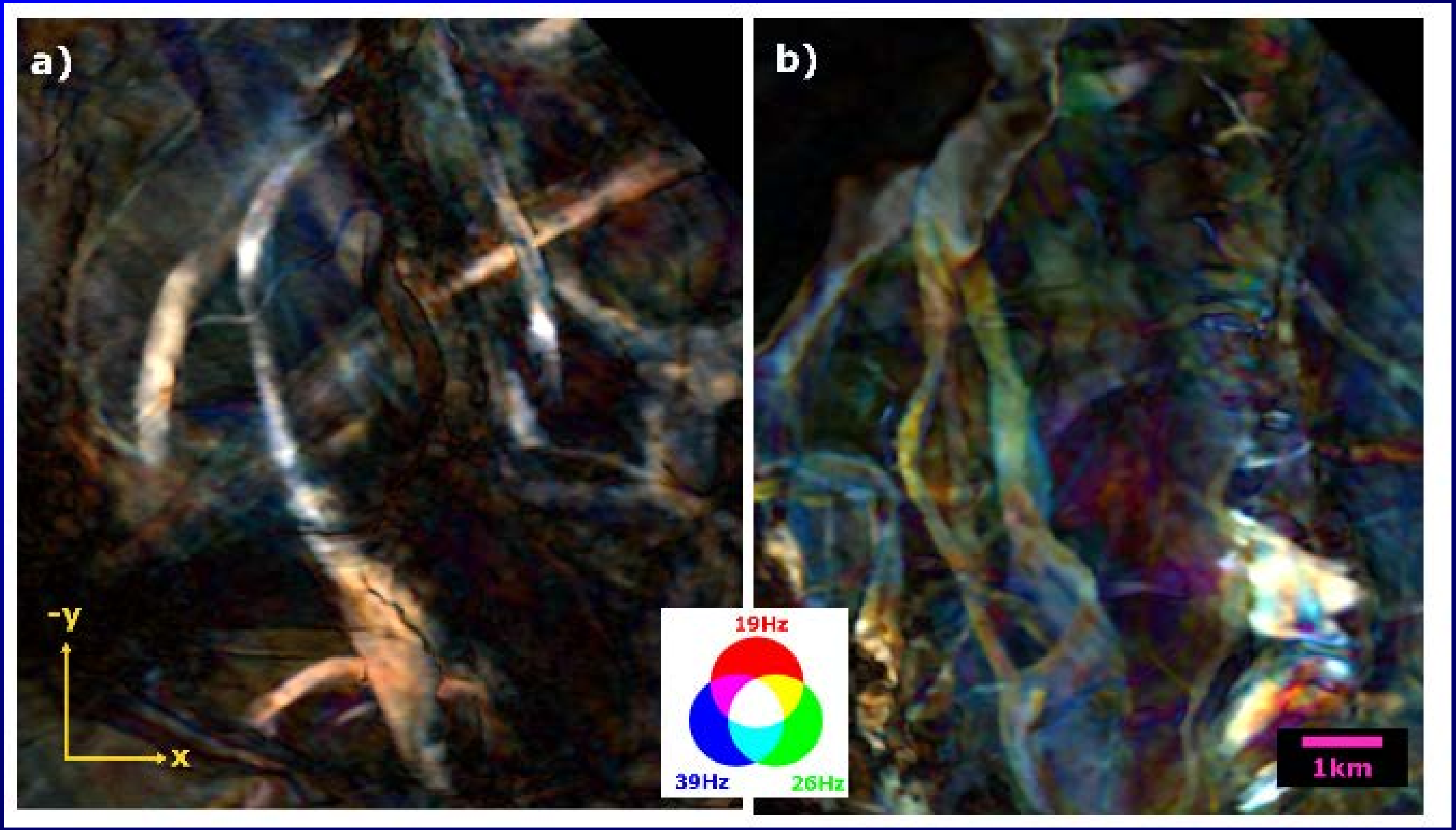
RGB color stack



Jurassic Channels

(McArdle et al., 2011)

RGB color stack

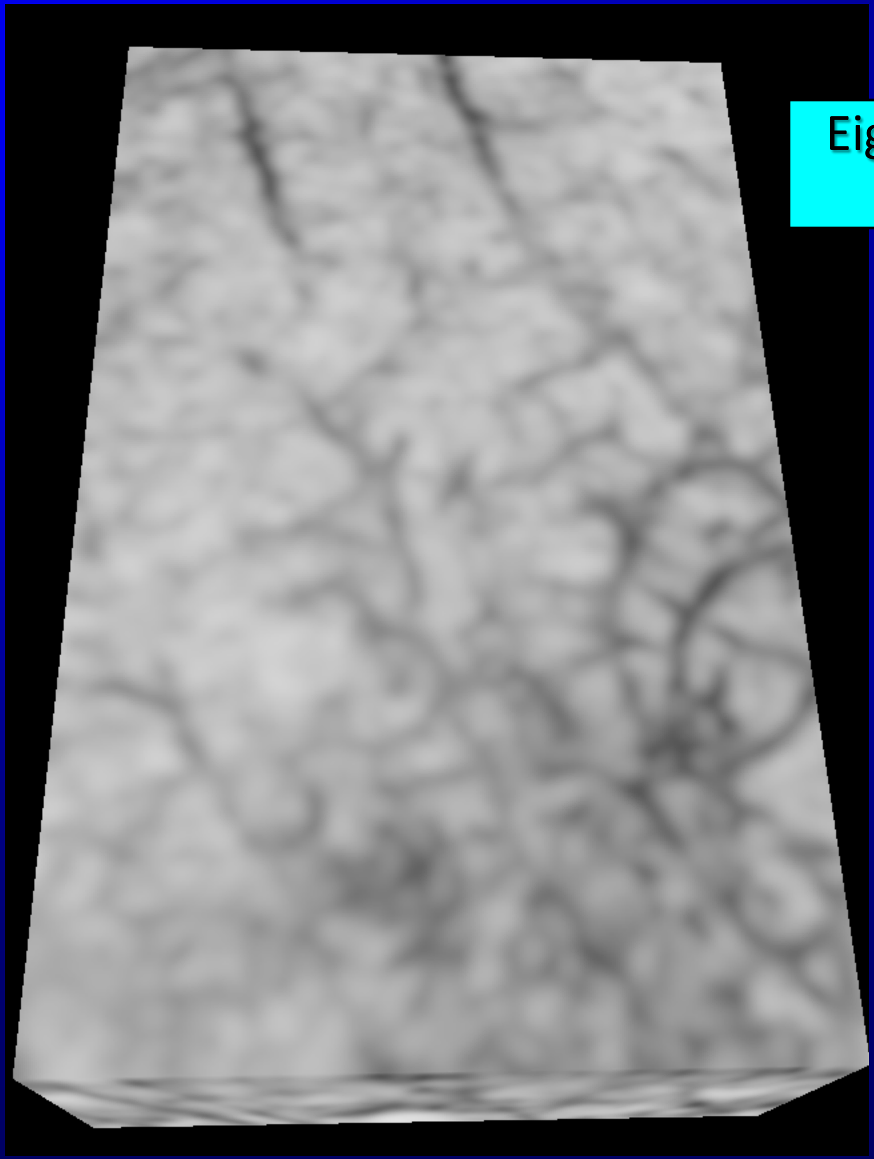


Triassic Horizon Slice

Jurassic Horizon Slice

(McArdle et al., 2011)

CMY color stack



Eigenvalues of gradient structure tensor

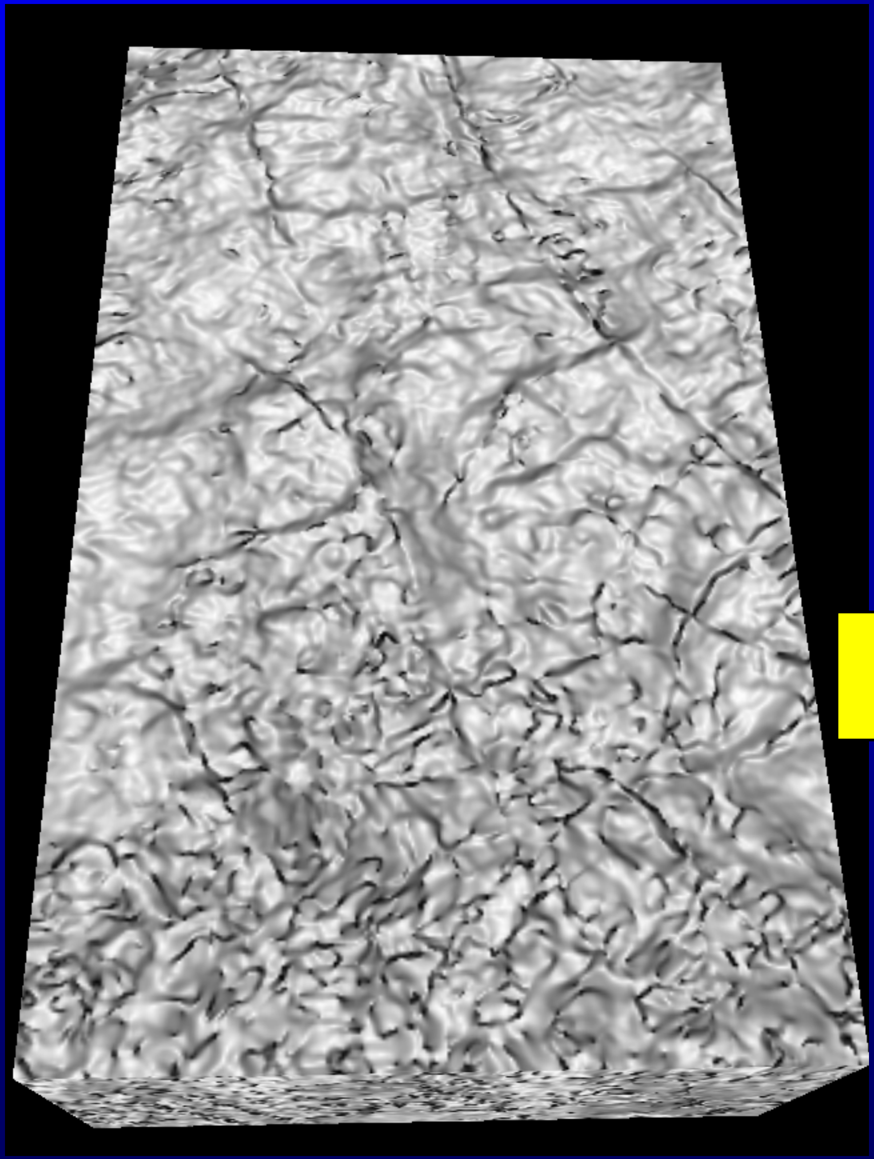
(Courtesy ffA)

CMY color stack

Semblance

(Courtesy ffA)

CMY color stack

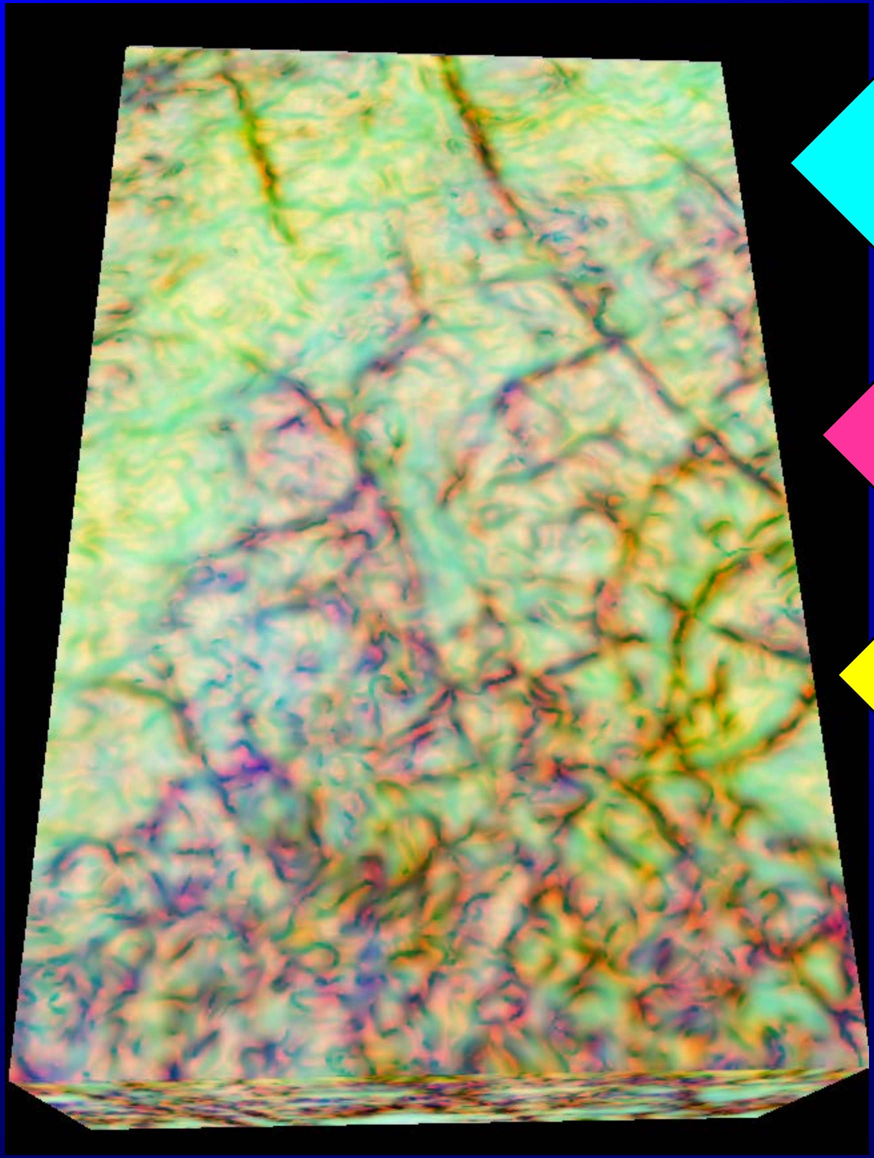


Dip Magnitude

3a-23

(Courtesy ffA)

CMY color stack



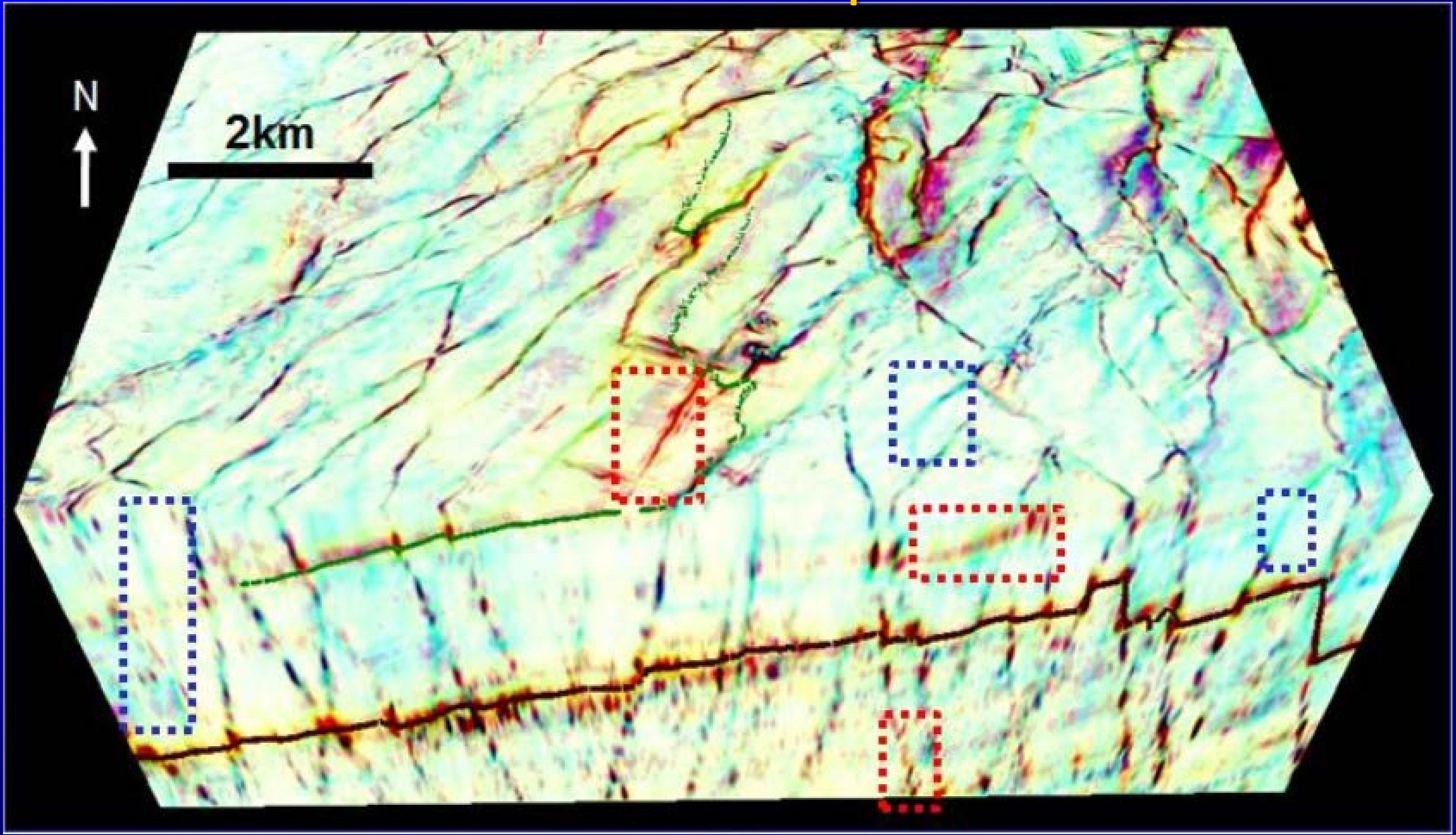
Eigenvalues of gradient structure tensor

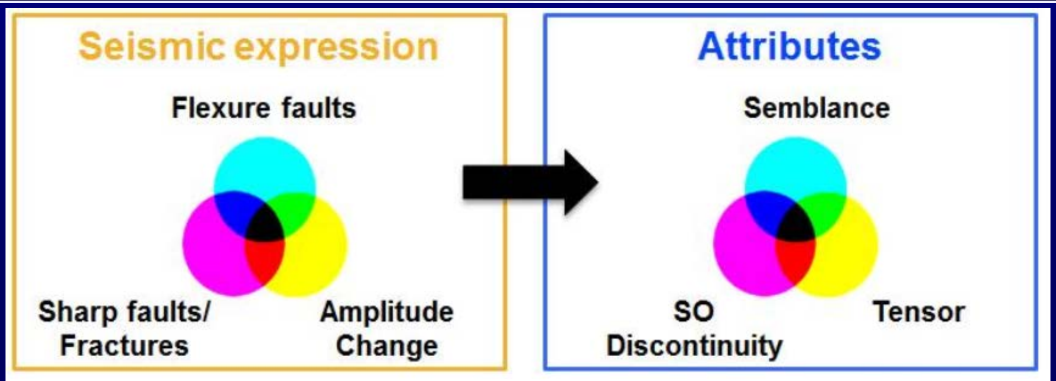
Semblance

Dip Magnitude

(Courtesy ffA)

CMY color stack – Australia data example





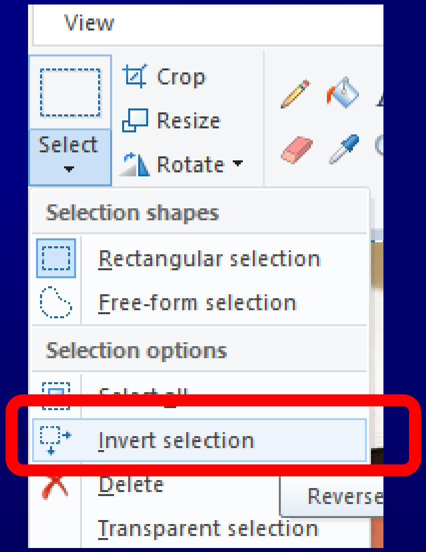
(Payton et al., 2014)

Computing the “negative” of a photo using Microsoft Paint

An RGB image

A CMY image=(255,255,255)-RGB image

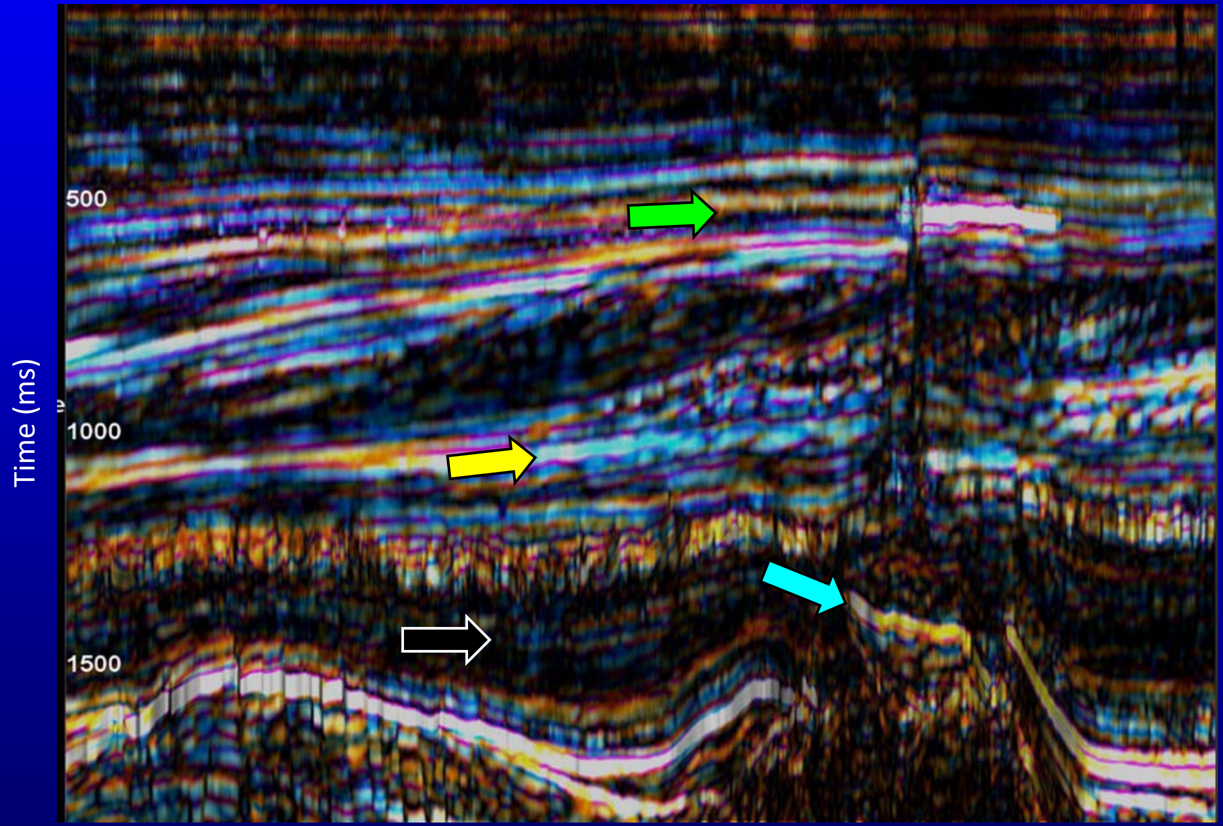
	R	G	B
White	255	255	255
- Blue	0	0	255
= Yellow	255	255	0



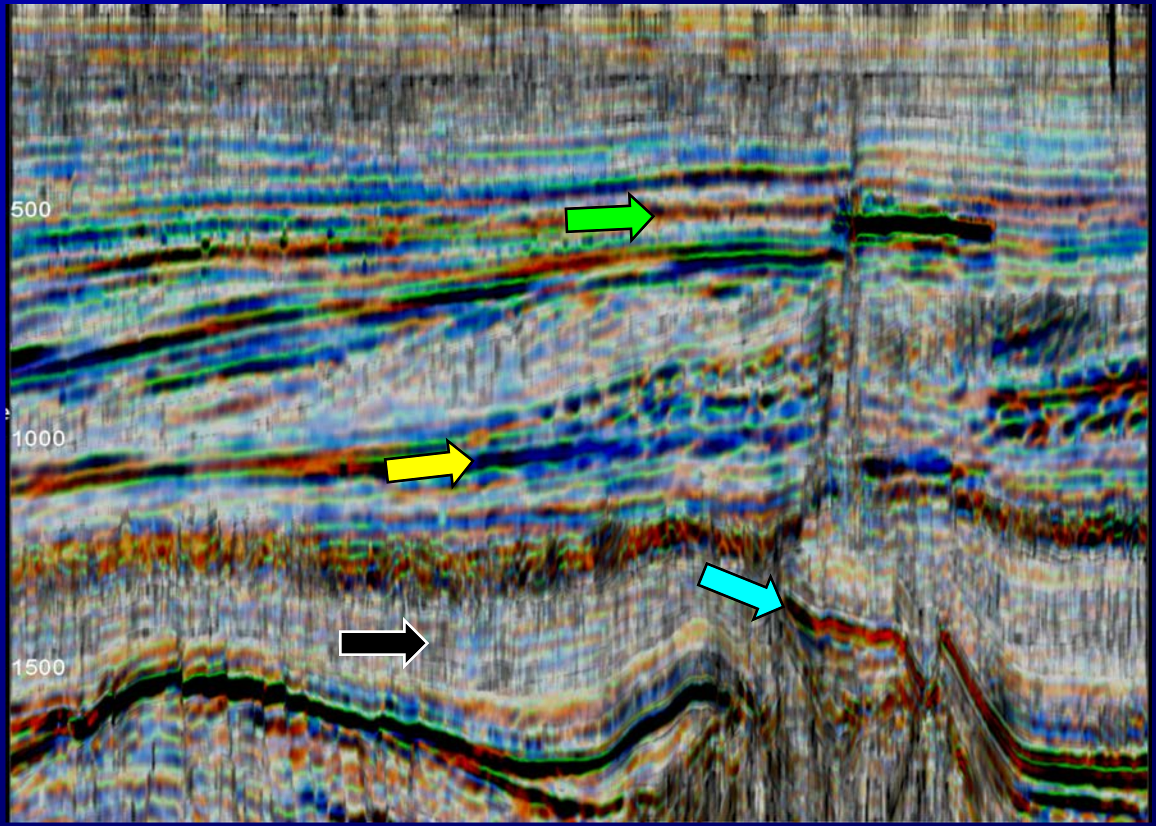
(Chopra and Marfurt, 2021)

Emphasizing low amplitude RGB anomalies by converting to CMY

An RGB image



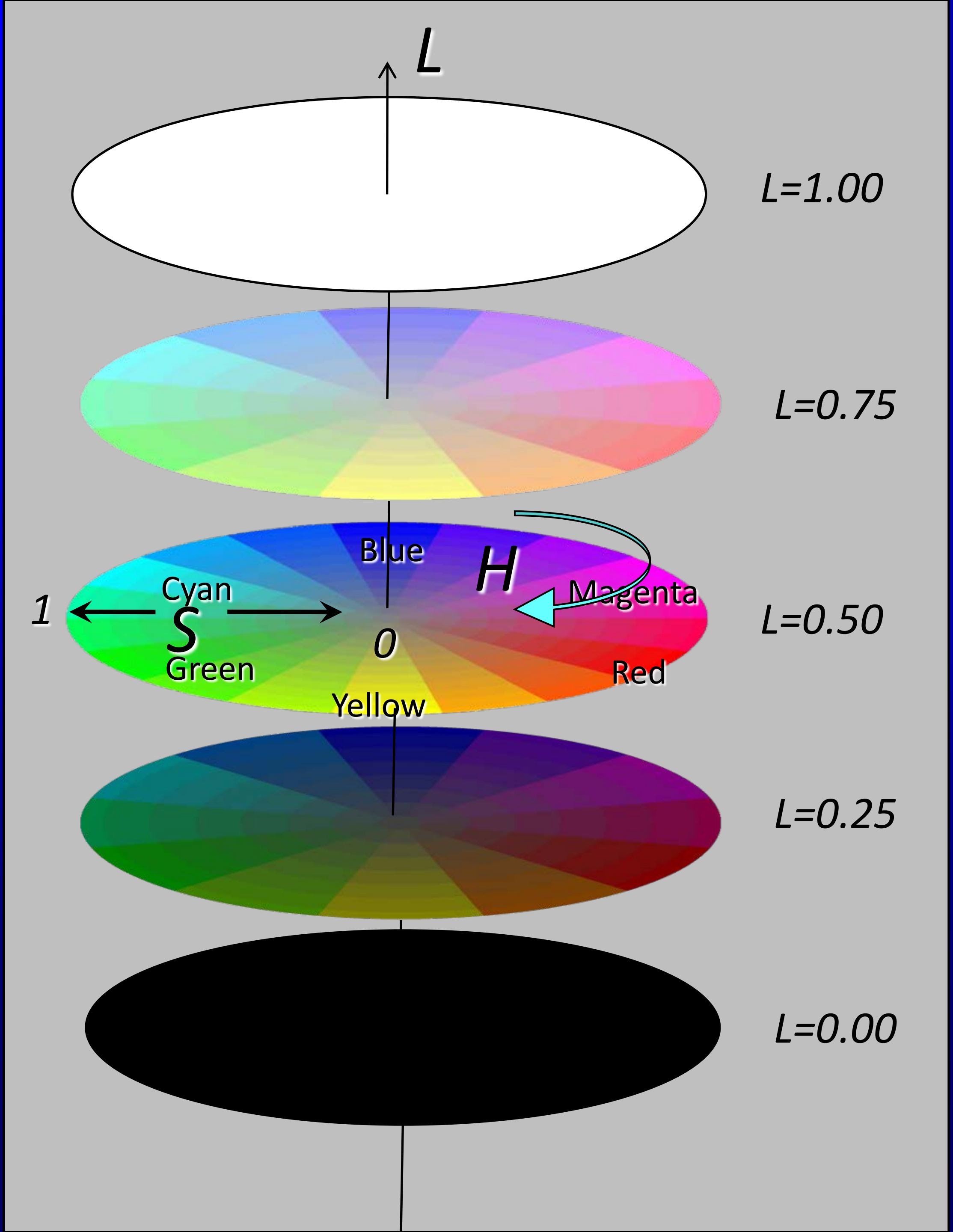
A CMY image=(255,255,255)-RGB image



(PetroExplorers and dGB Earth Sciences)

Multiattribute display tools

- Overplotting
- RGB- and CMY-blended (“stacked”) images
- HLS color modulated images
- Color blending/transparency/opacity
- Bump maps



The HLS color model

Hue: the wavelength contrast aspect of color

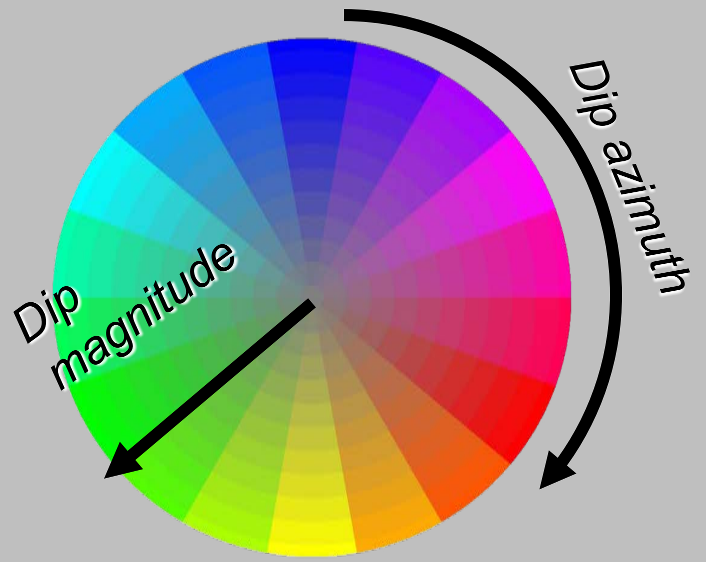
Lightness: the level of illumination

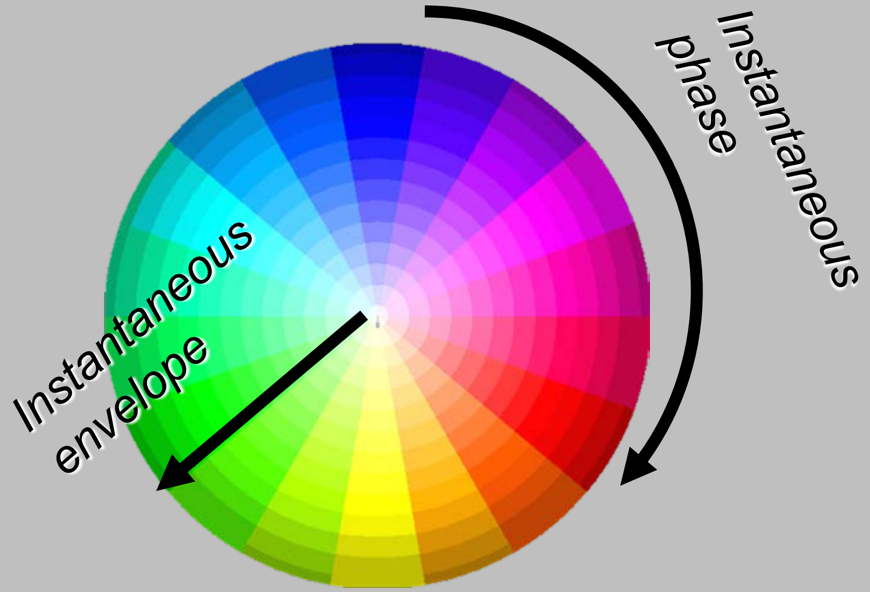
Saturation: the degree to which the hue differs from neutral gray

(Chopra and Marfurt, 2007)

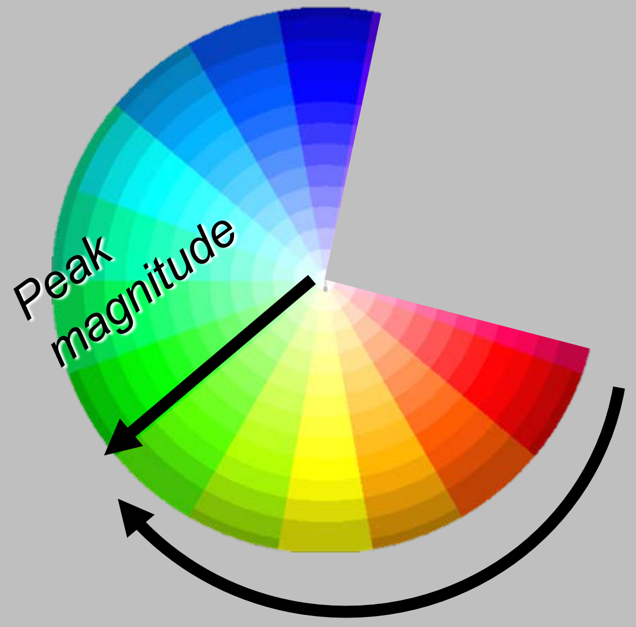
Examples of 2D color bars

Cyclical



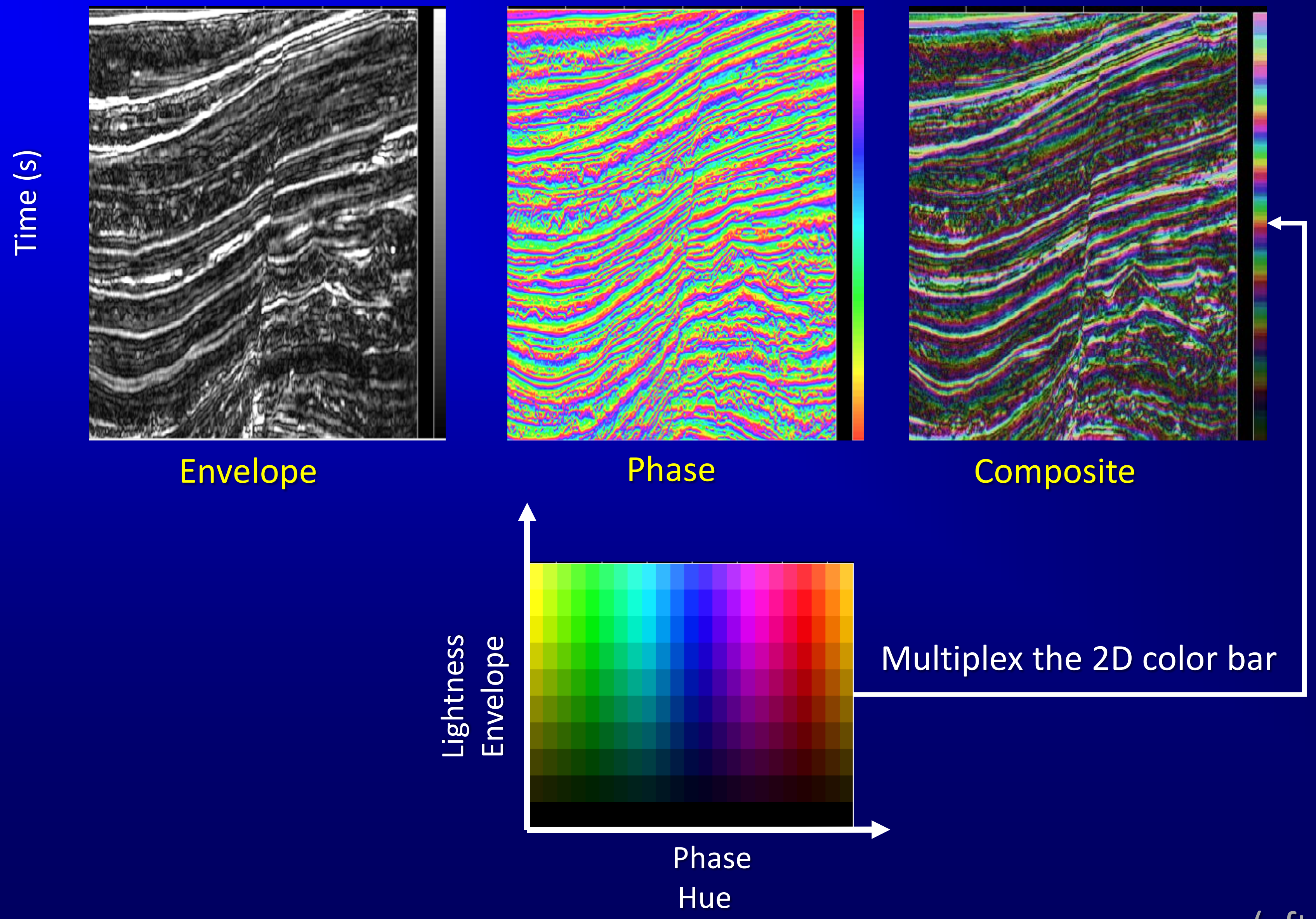


Non-Cyclical



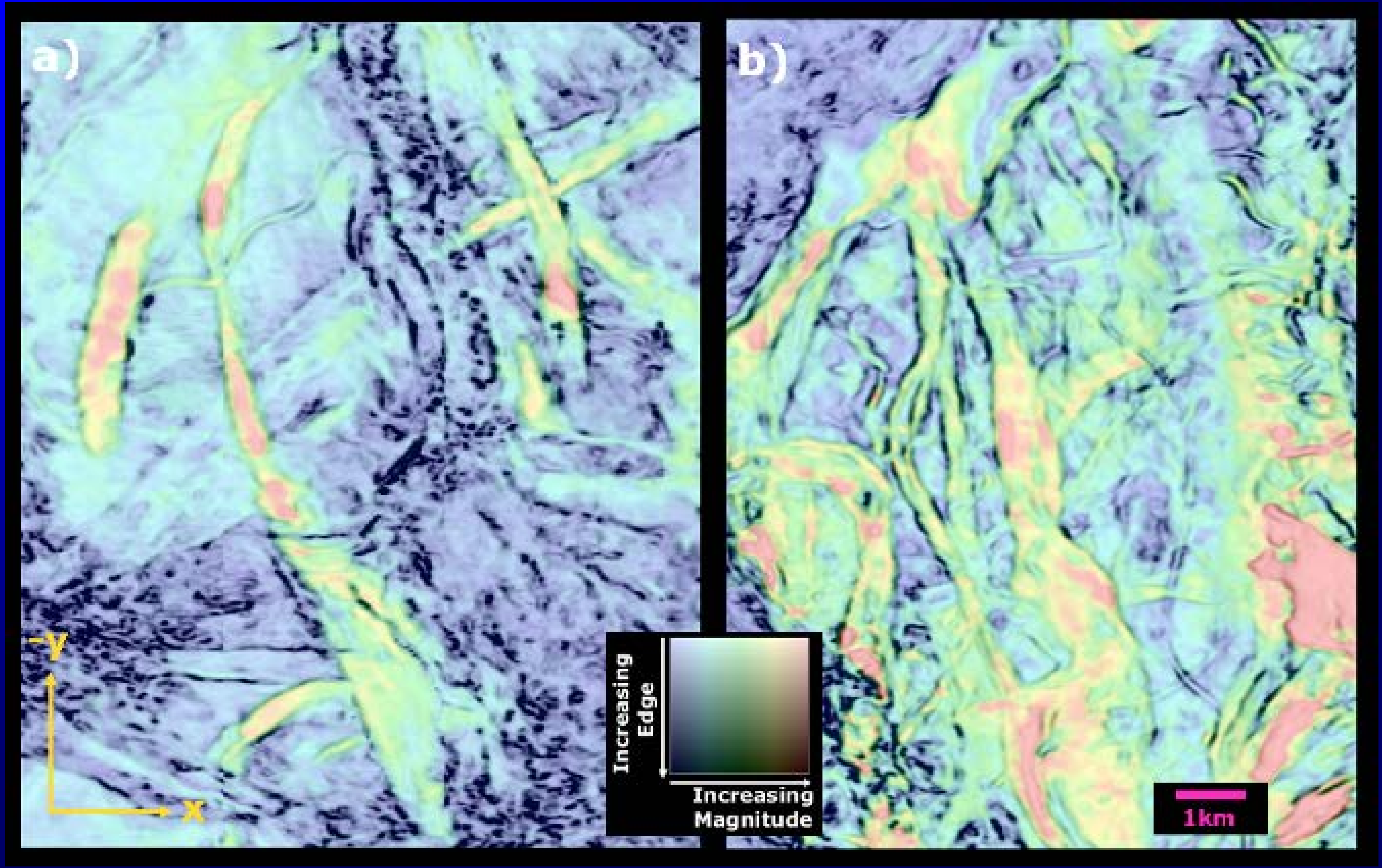
(Chopra and Marfurt, 2007)

Multiattribute display using 2D color tables



(after Knobloch, 1982)

Multiattribute display using 2D color tables



Modulating envelope by coherence

(McArdle et al., 2011)

Multiattribute display tools

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Alpha Blending of 2 or 3 images

Each image has R, G, and B components, which can be thought of as vectors, a, b, and c

$$\mathbf{a} = \begin{pmatrix} a_R \\ a_G \\ a_B \end{pmatrix} \quad \mathbf{b} = \begin{pmatrix} b_R \\ b_G \\ b_B \end{pmatrix} \quad \mathbf{c} = \begin{pmatrix} c_R \\ c_G \\ c_B \end{pmatrix}$$

Blending a and b:

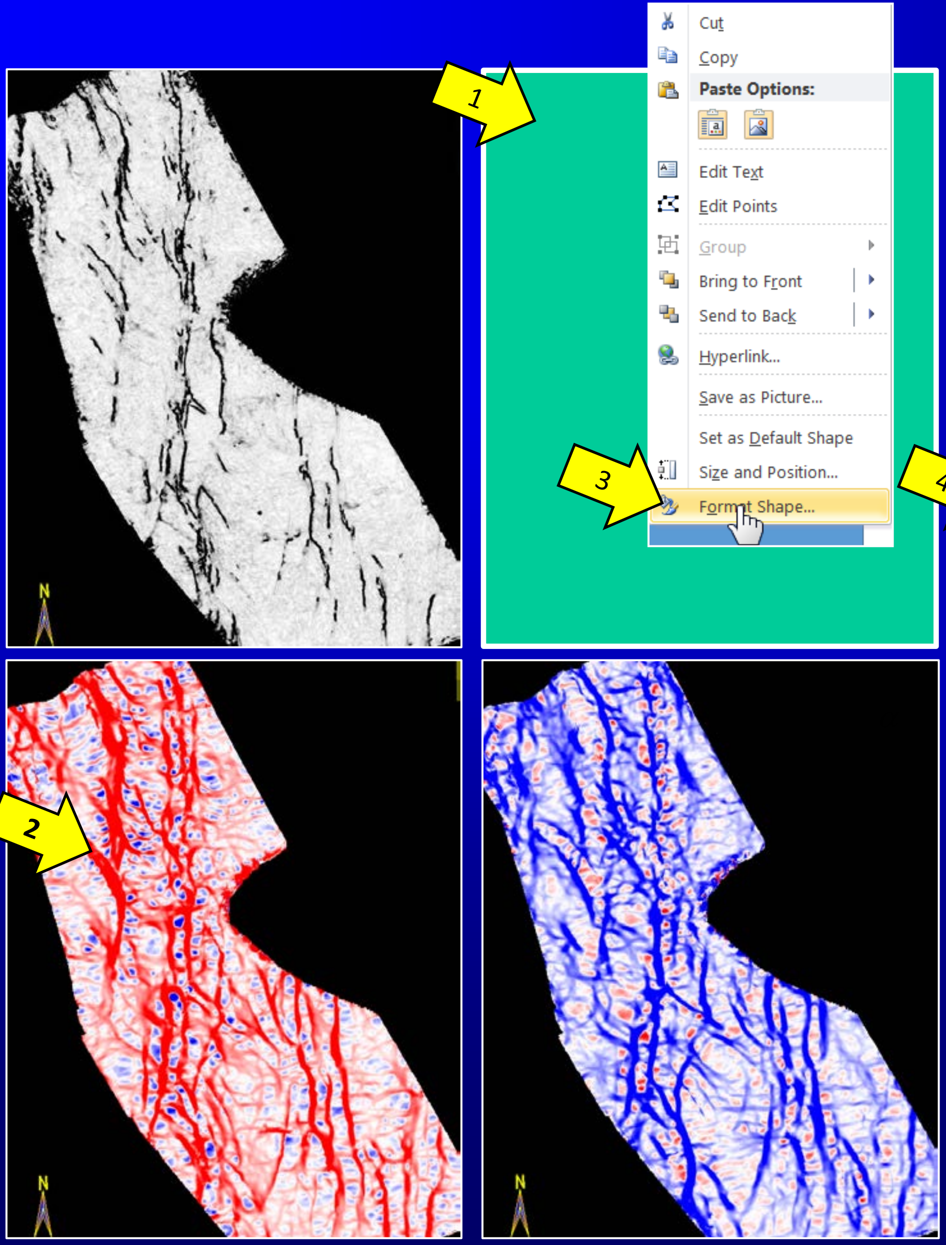
$$\begin{pmatrix} f_R \\ f_G \\ f_B \end{pmatrix} = (1-\alpha)\begin{pmatrix} a_R \\ a_G \\ a_B \end{pmatrix} + \alpha\begin{pmatrix} b_R \\ b_G \\ b_B \end{pmatrix}$$

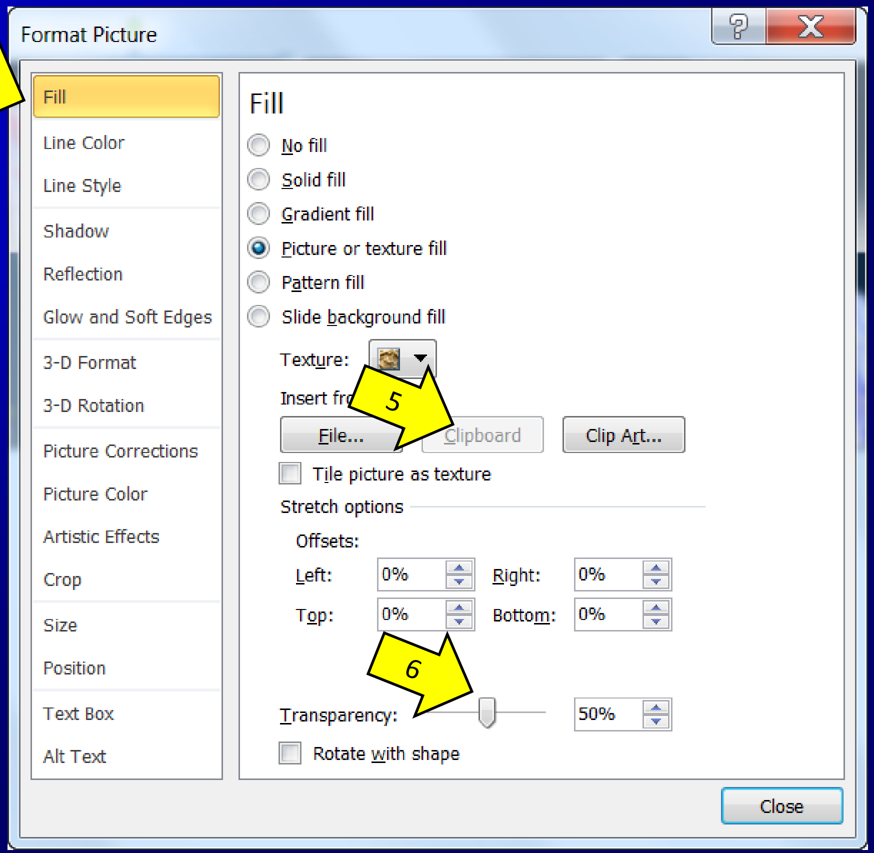
Blending a , b, and c:

$$\begin{pmatrix} g_R \\ g_G \\ g_B \end{pmatrix} = (1-\beta)\begin{pmatrix} f_R \\ f_G \\ f_B \end{pmatrix} + \beta\begin{pmatrix} c_R \\ c_G \\ c_B \end{pmatrix} = (1-\beta)(1-\alpha)\begin{pmatrix} a_R \\ a_G \\ a_B \end{pmatrix} + (1-\beta)\alpha\begin{pmatrix} b_R \\ b_G \\ b_B \end{pmatrix} + \beta\begin{pmatrix} c_R \\ c_G \\ c_B \end{pmatrix}$$

(Marfurt, 2015)

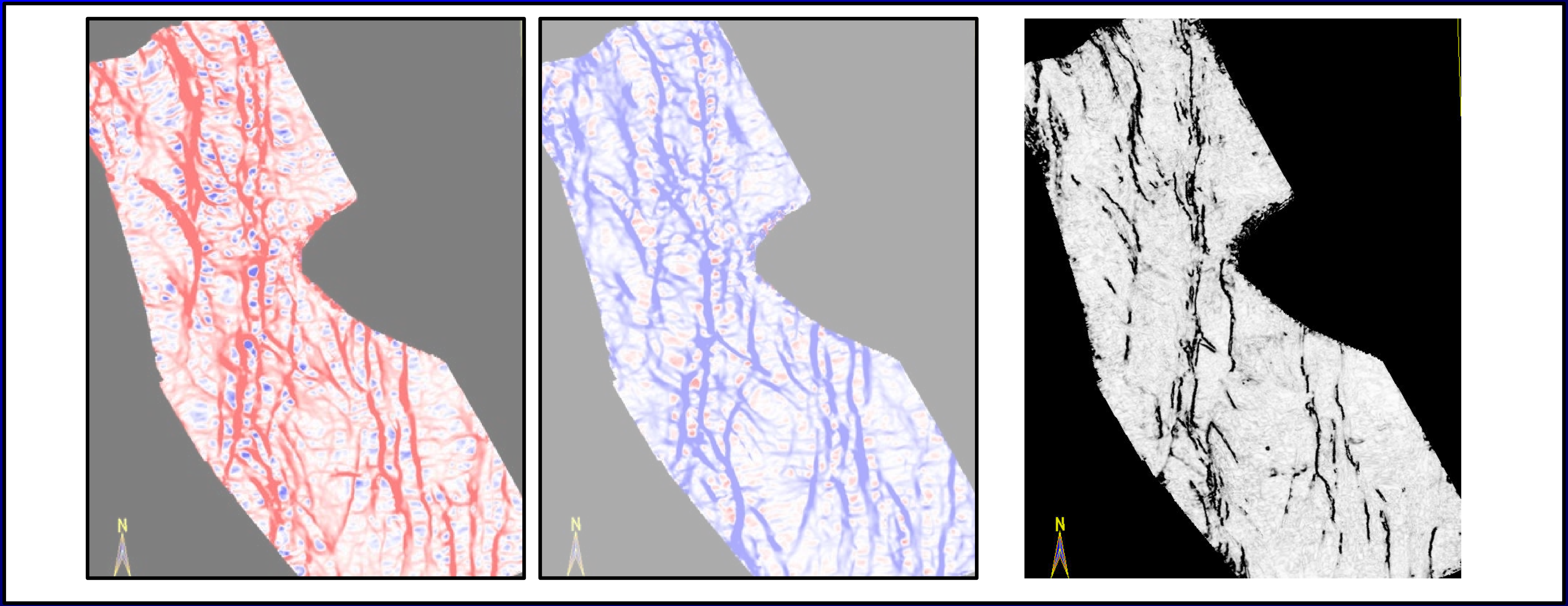
Using Transparency in PowerPoint





(Marfurt, 2015)

Using Transparency in PowerPoint



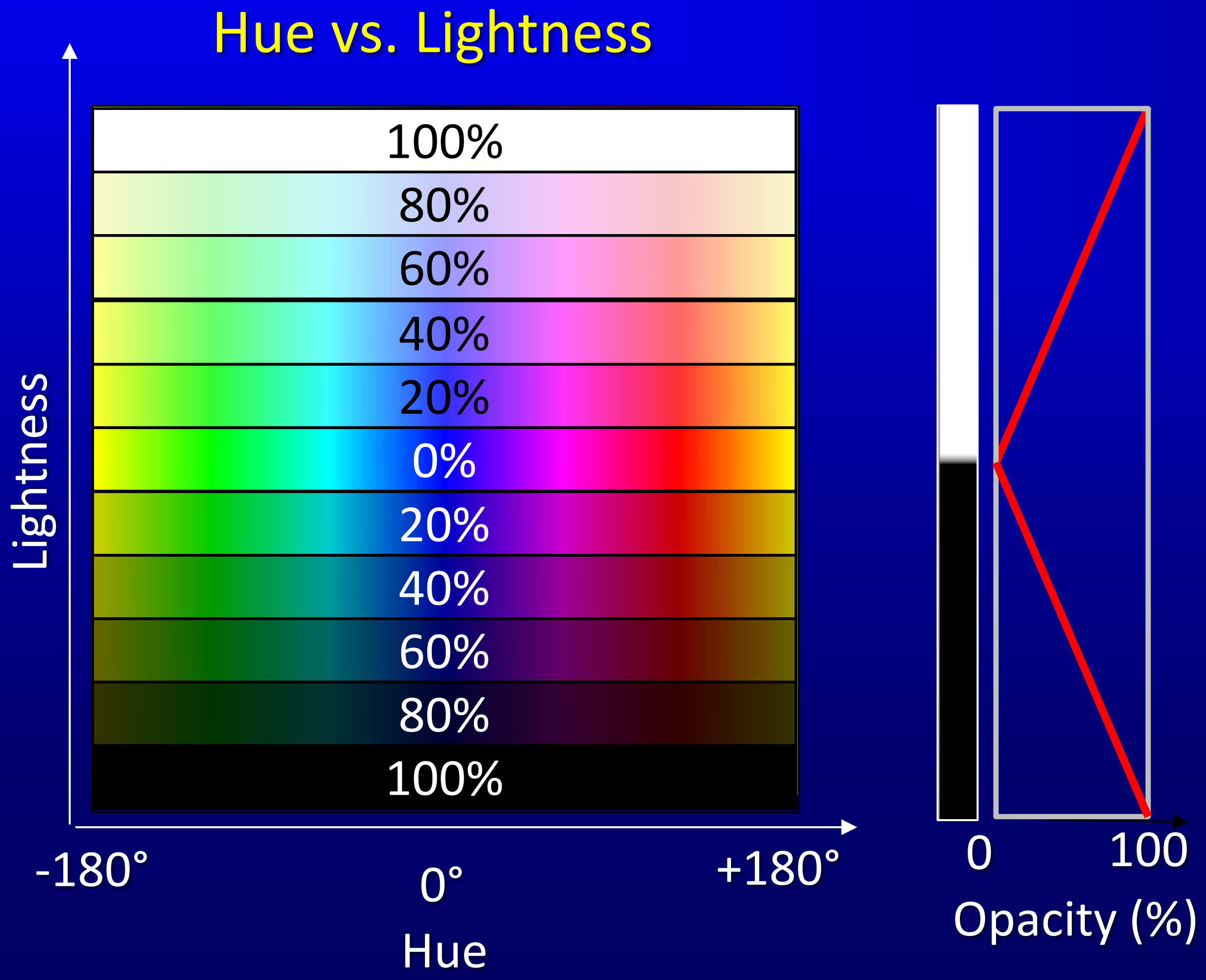
50% transparent k_1 on top of opaque gray background

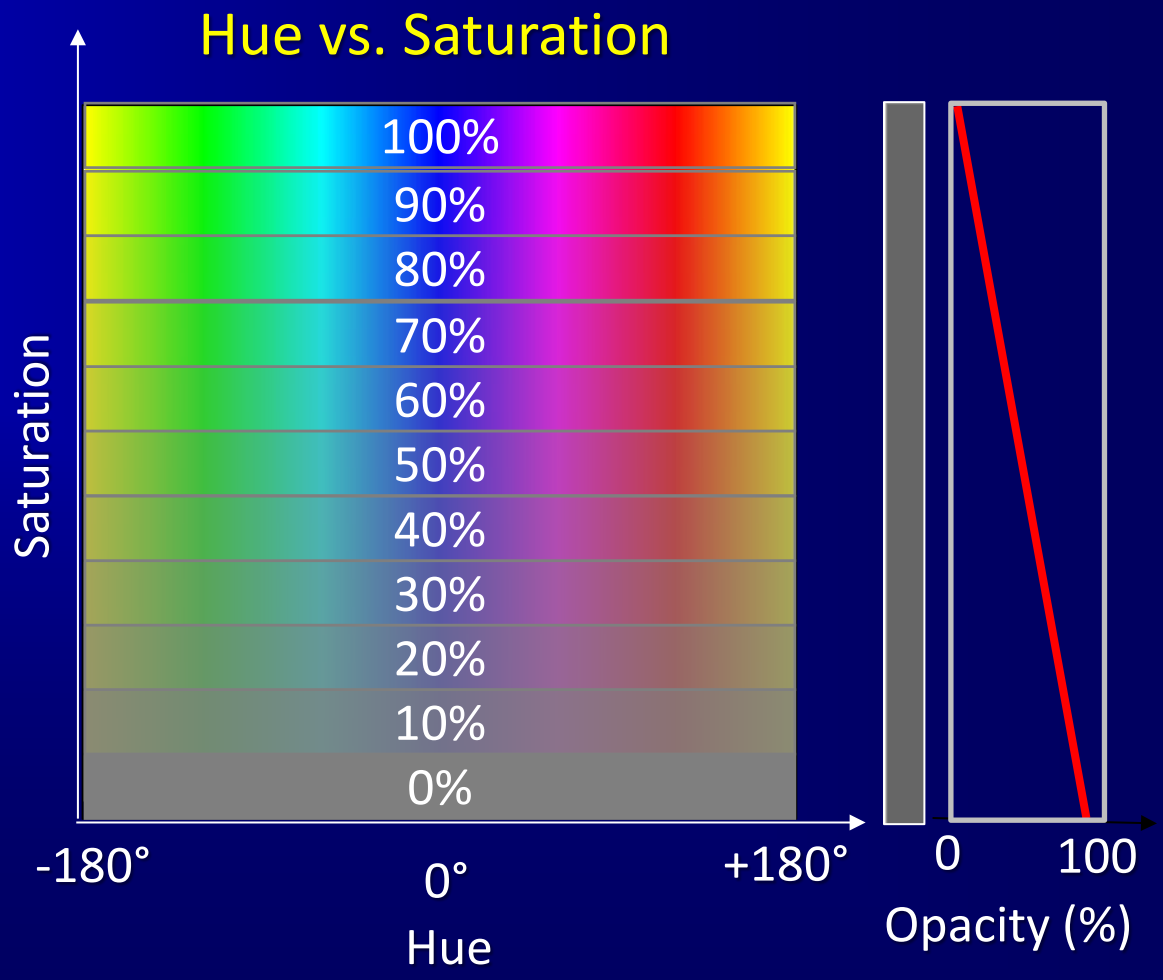
67 % transparent k_2 on top of opaque gray background

Transparent k_1 and k_2 on top of opaque coherence

(Marfurt, 2015)

Replicating the HLS color model by blending monochrome gray, black, and white color bars.

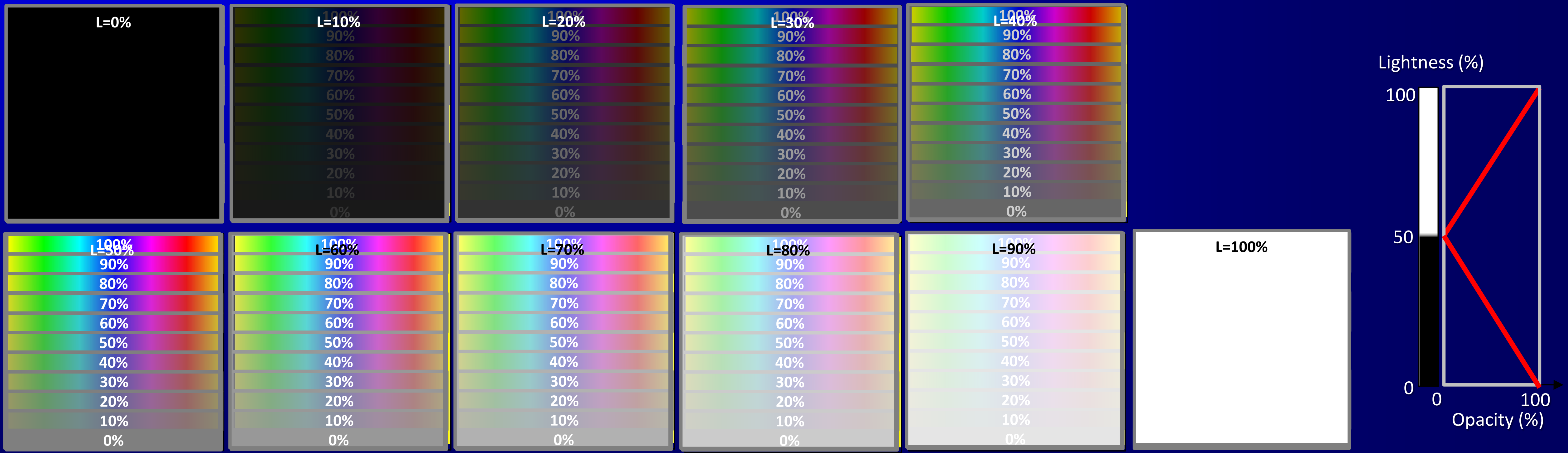




(Marfurt, 2015)

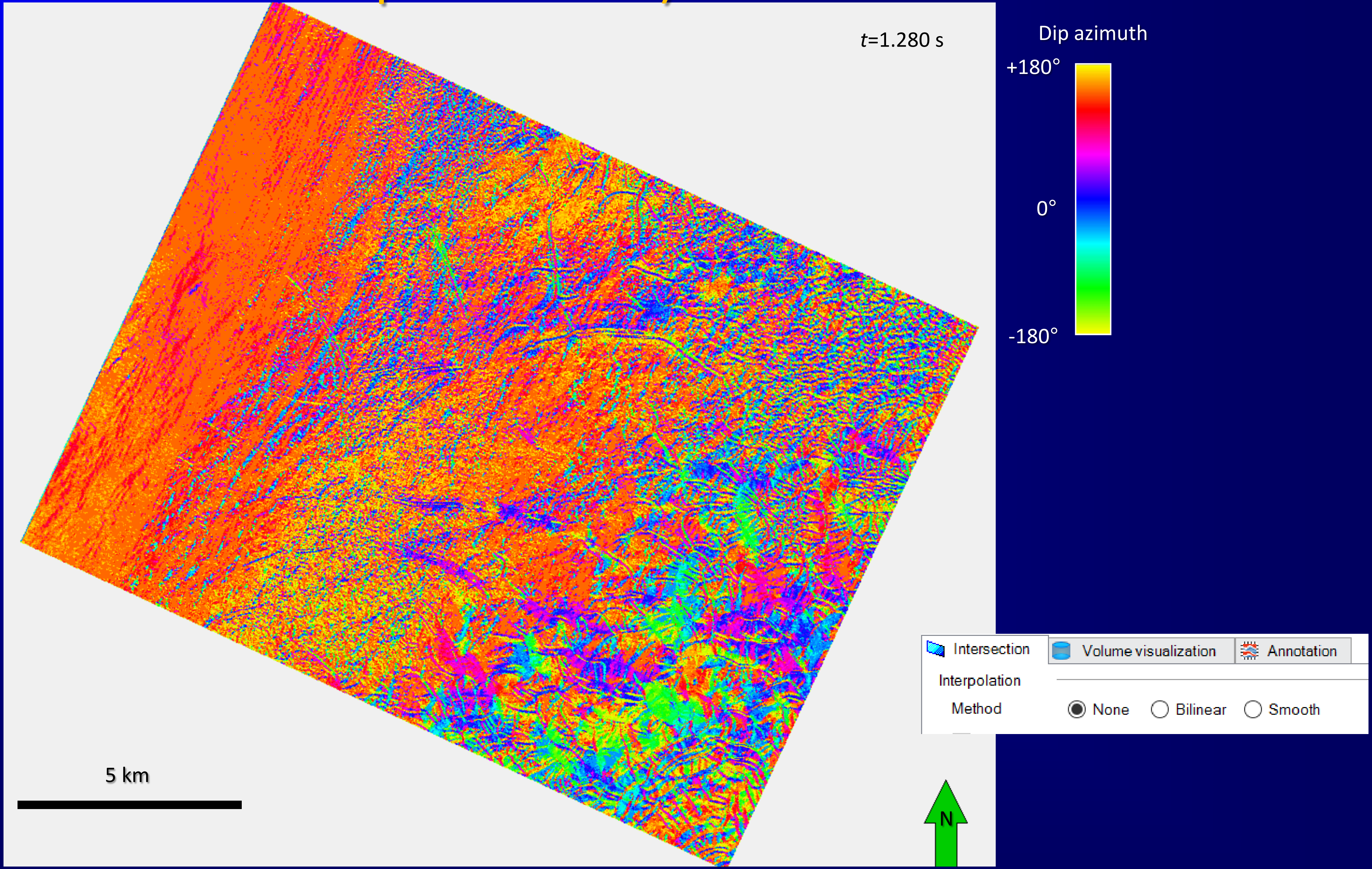
Replicating the HLS color model by blending monochrome gray, black, and white color bars.

Hue vs. Lightness vs. Saturation



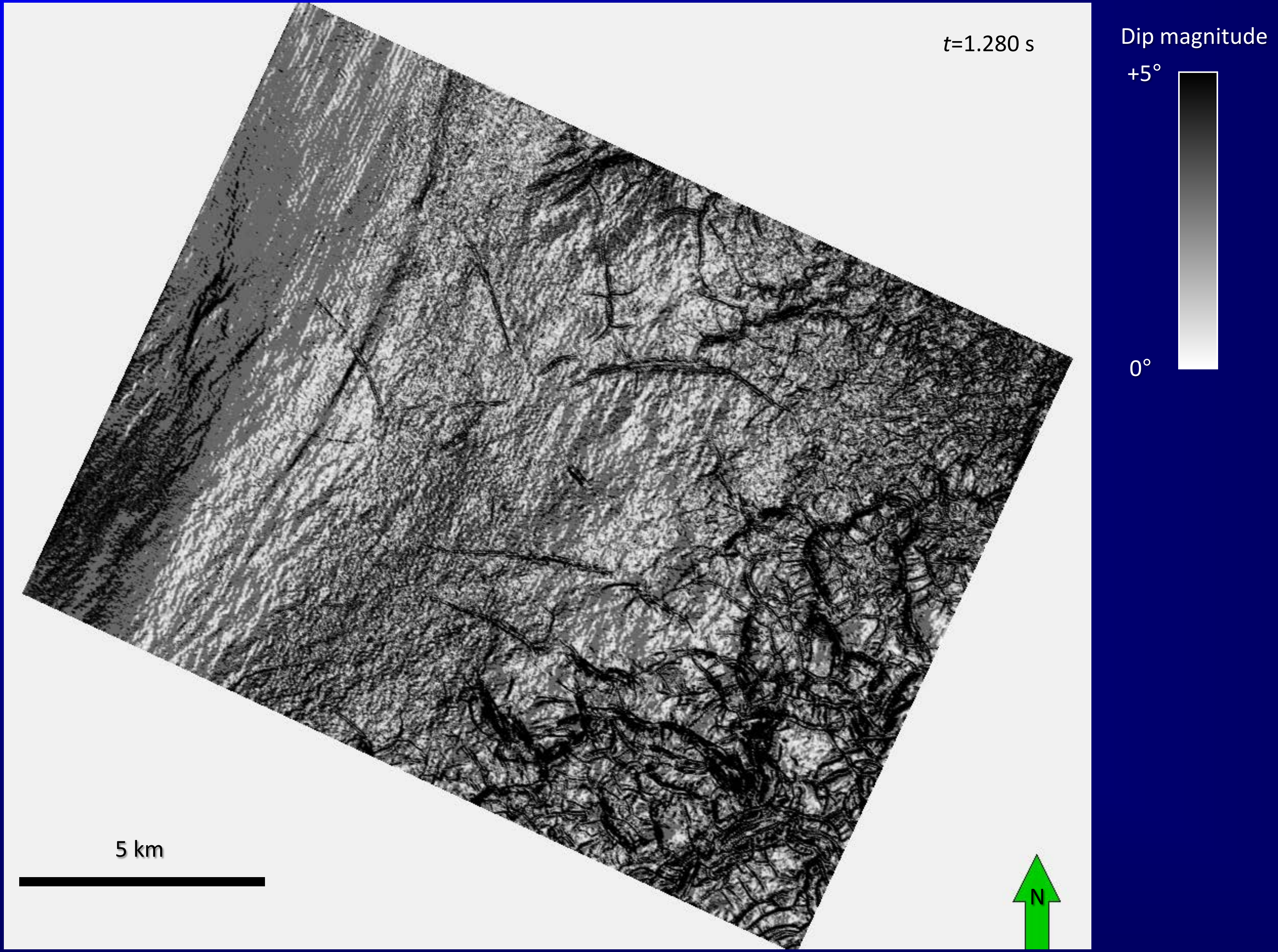
(Marfurt, 2015)

Dip azimuth (with smooth interpolation off)



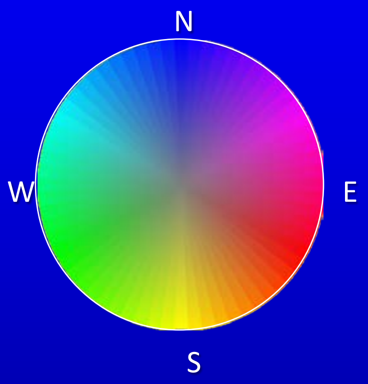
(Marfurt, 2018)

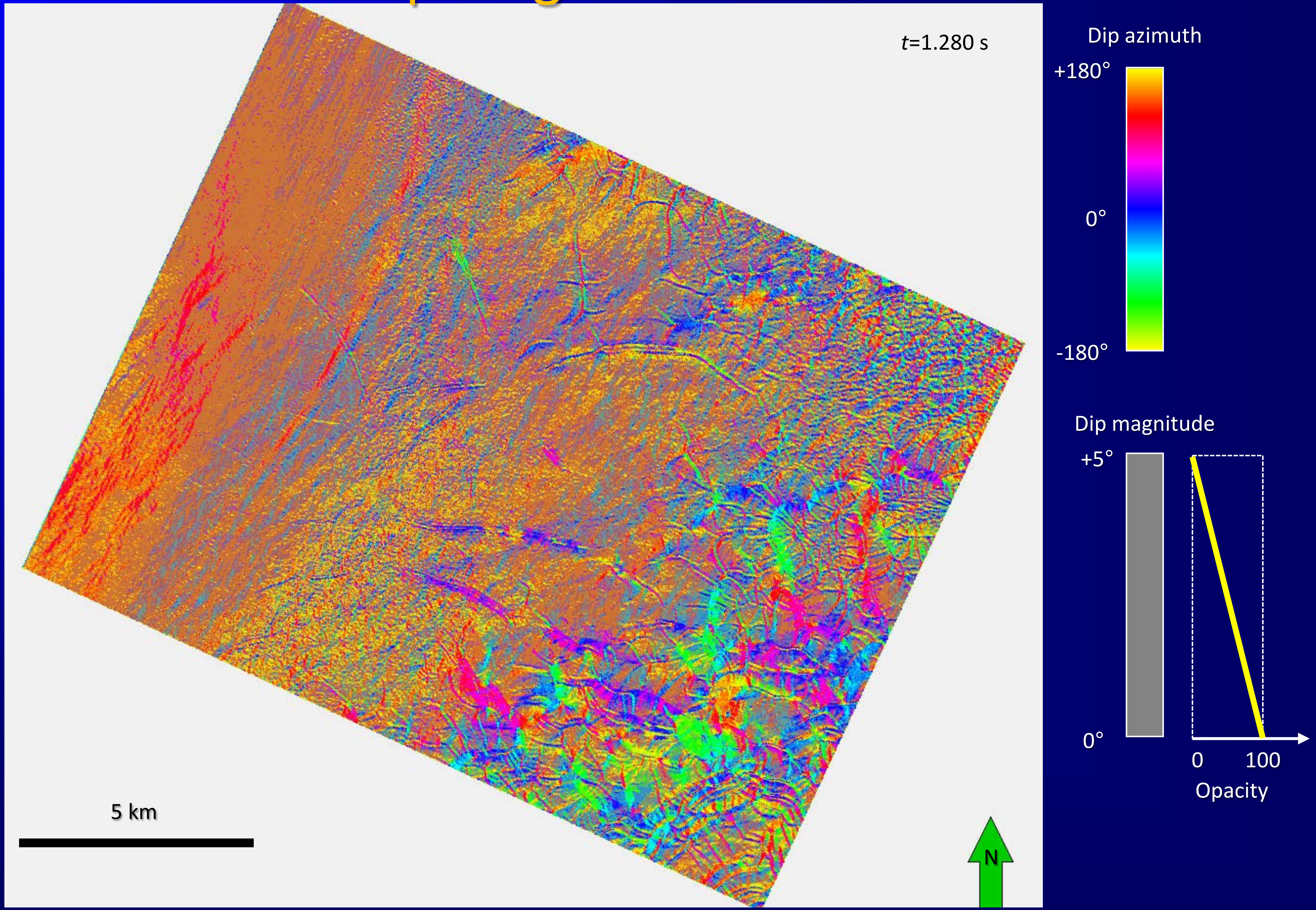
Dip magnitude



(Marfurt, 2018)

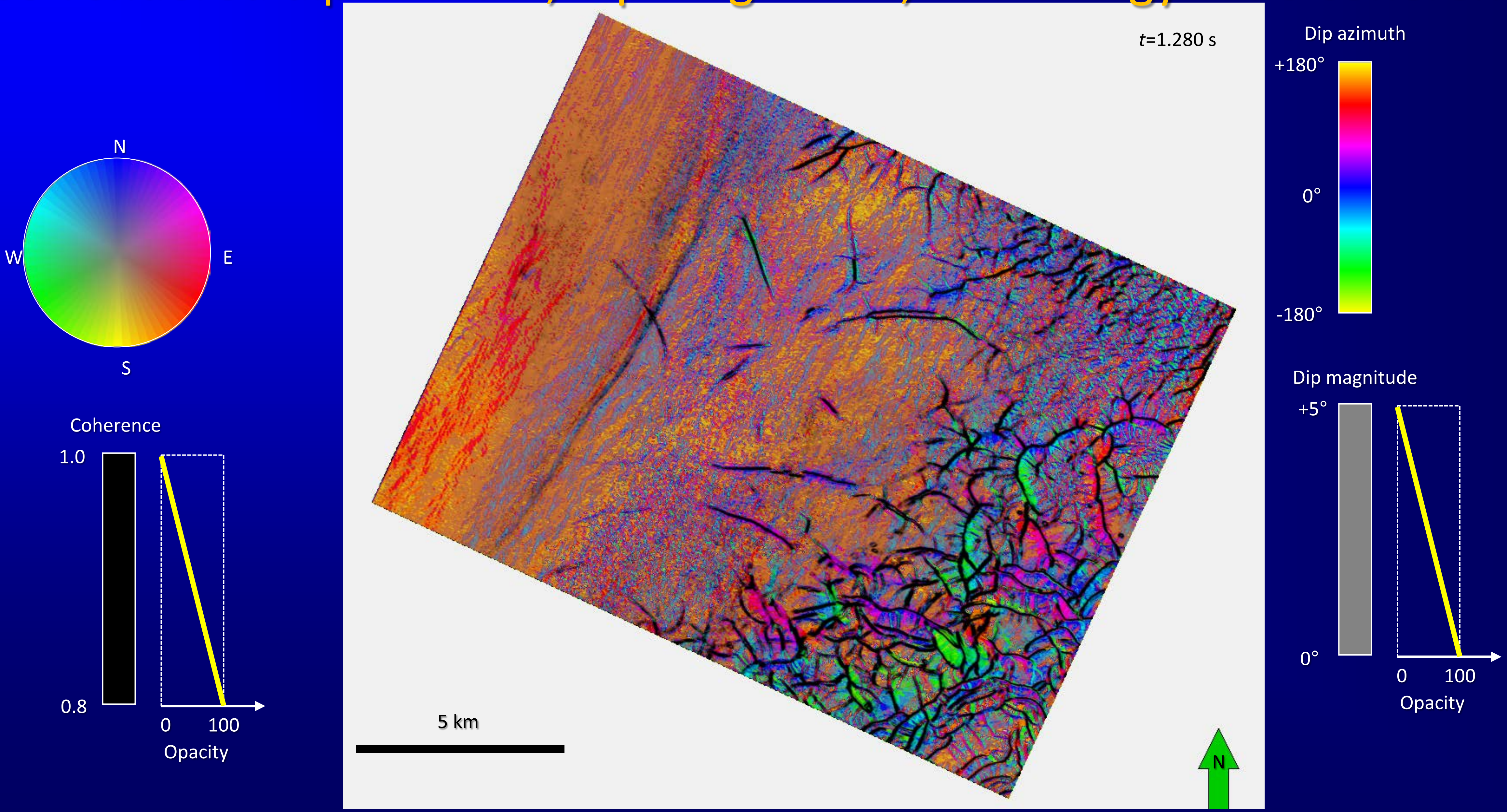
Co-rendered dip azimuth and dip magnitude





(Marfurt, 2018)

Co-rendered dip azimuth, dip magnitude, and energy-ratio coherence



(Marfurt, 2018)

Multiattribute display tools

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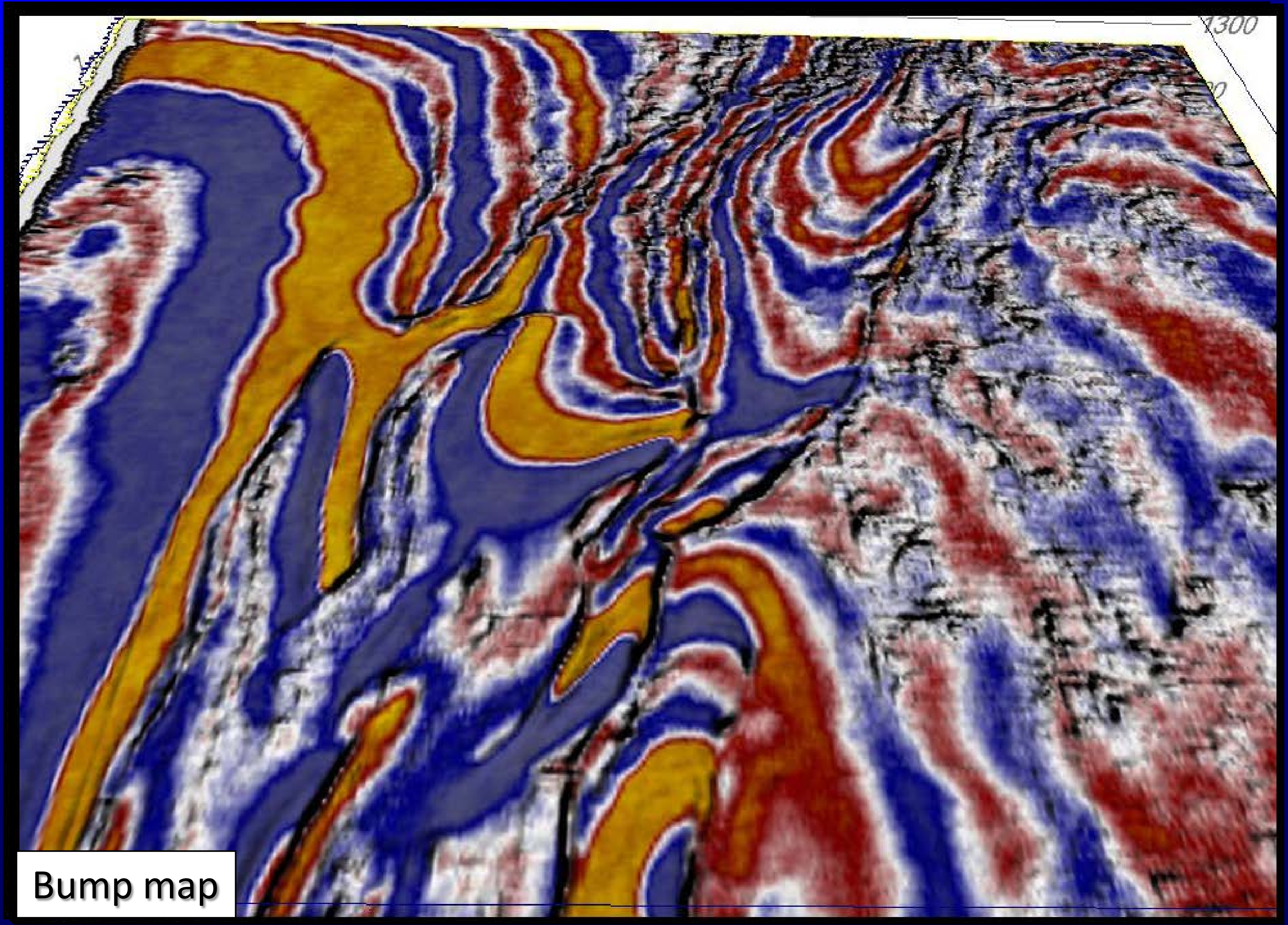
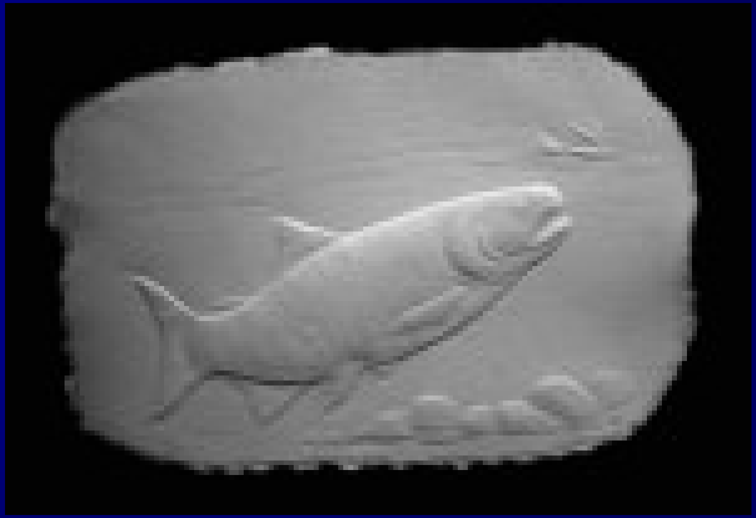
Bump maps



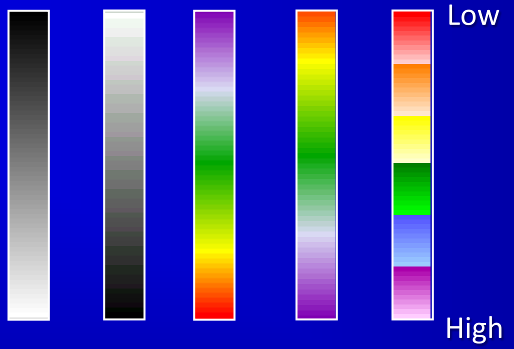
Embossing in PowerPoint



(Lynch et al., 2005)

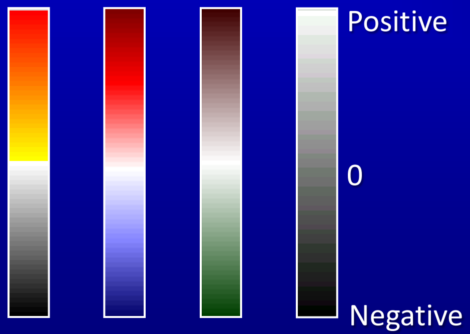
1D Color bars for effective attribute display

Color bars for single polarity attributes



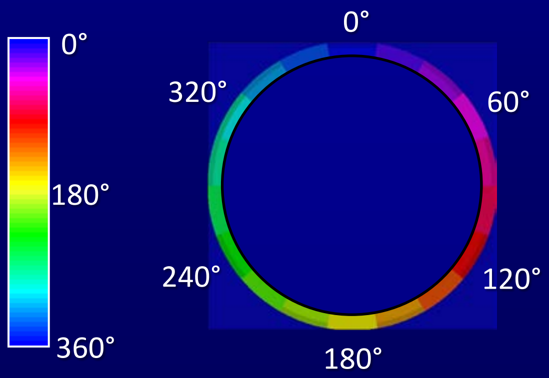
Amplitude extractions, frequency, time/structure, dip magnitude, envelope, coherence, …

Color bars for dual polarity attributes



Seismic amplitude, curvature, …

Color bars for cyclical attributes

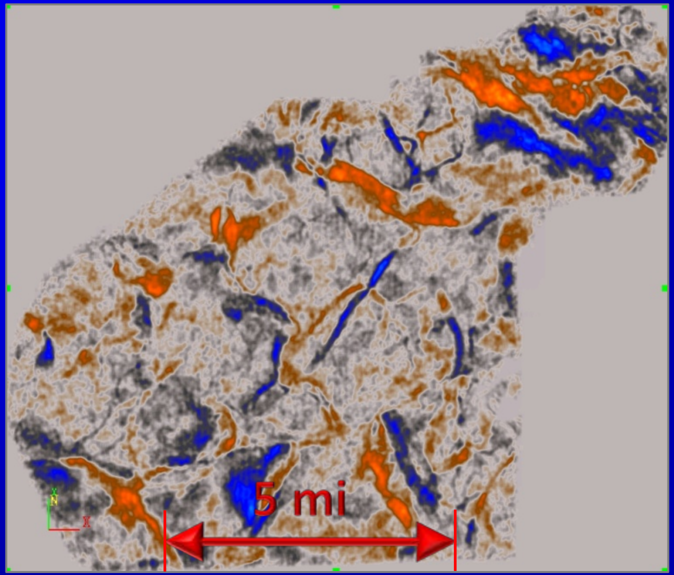


Phase, azimuth, strike,…

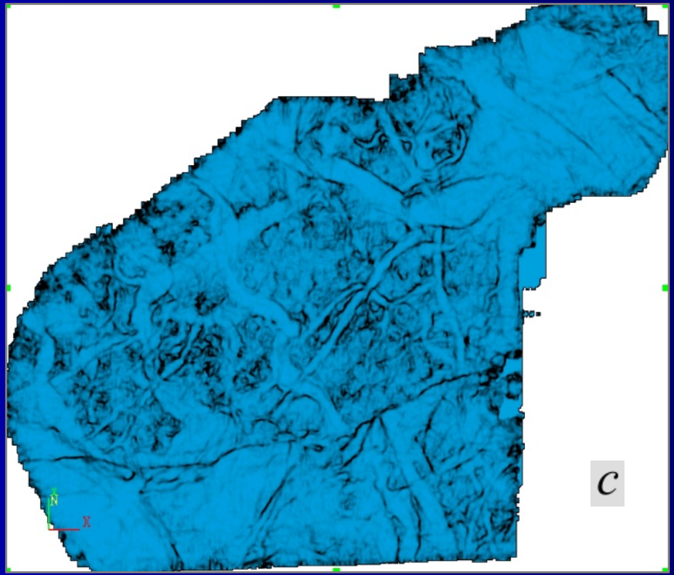
(Chopra and Marfurt, 2007)

Effective 1D colorbars

Use polychromatic colorbars for internal behavior



Amplitude

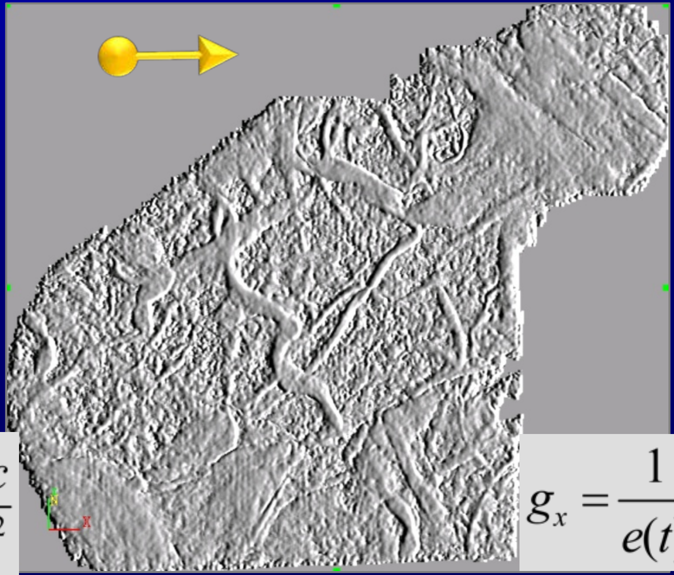


Discontinuity

Use monochromatic colorbars for edges

$$L = \frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2}$$

Laplacian filter



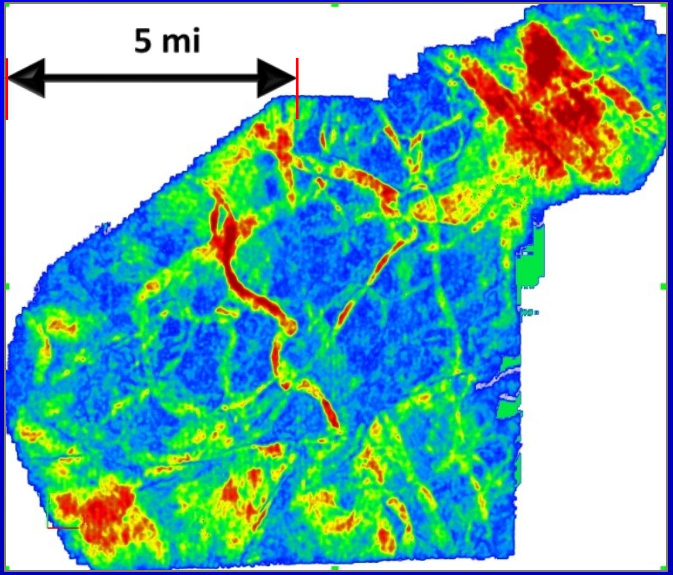
$$g_x = \frac{1}{e(t)} \frac{\partial e(t)}{\partial x}$$

EW gradient

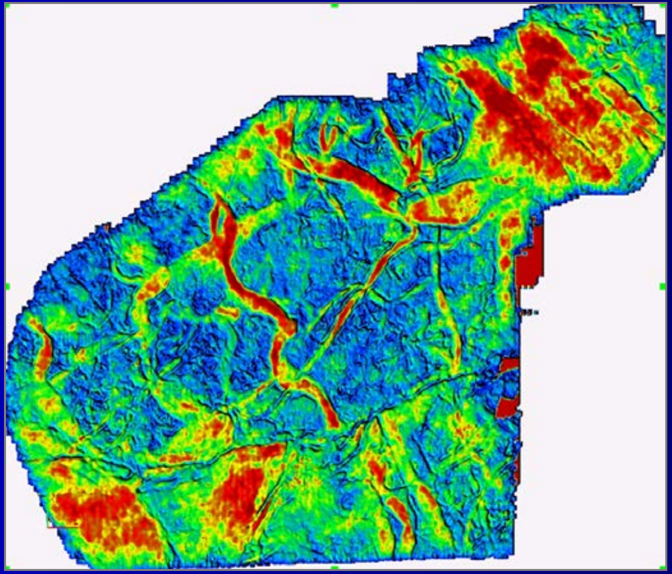
(Barnes, 2011)

Effective blended colorbars

Use polychromatic colorbars for internal behavior

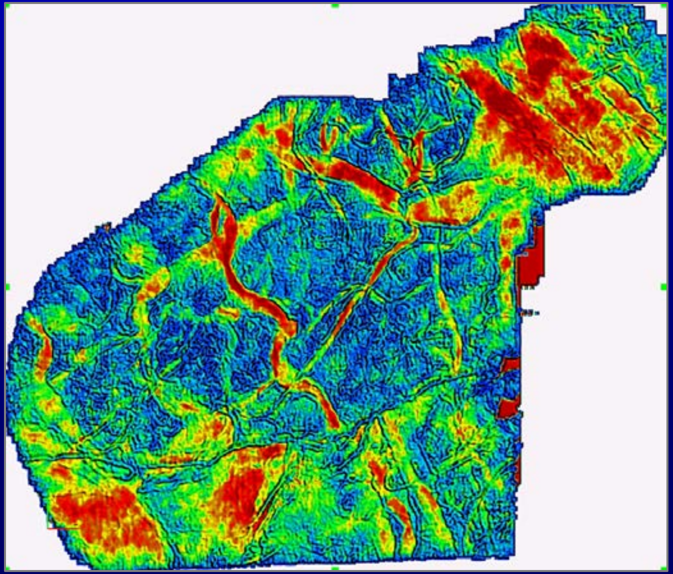


Sweetness

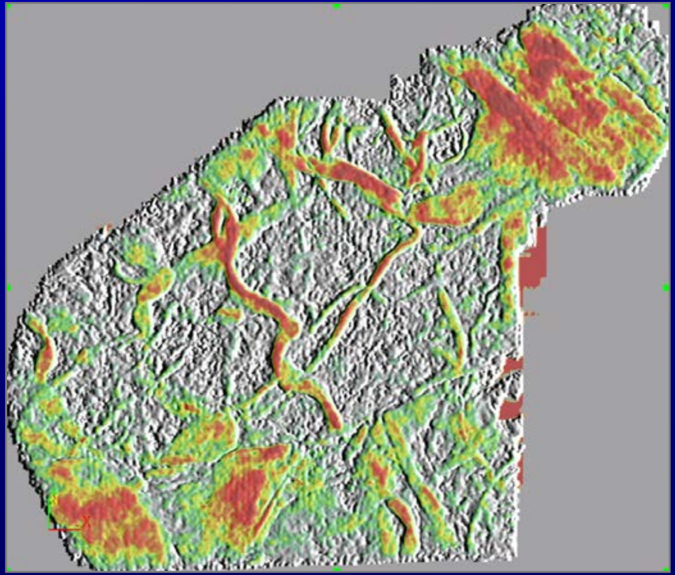


Sweetness with bump map discontinuity

Use monochromatic colorbars for edges



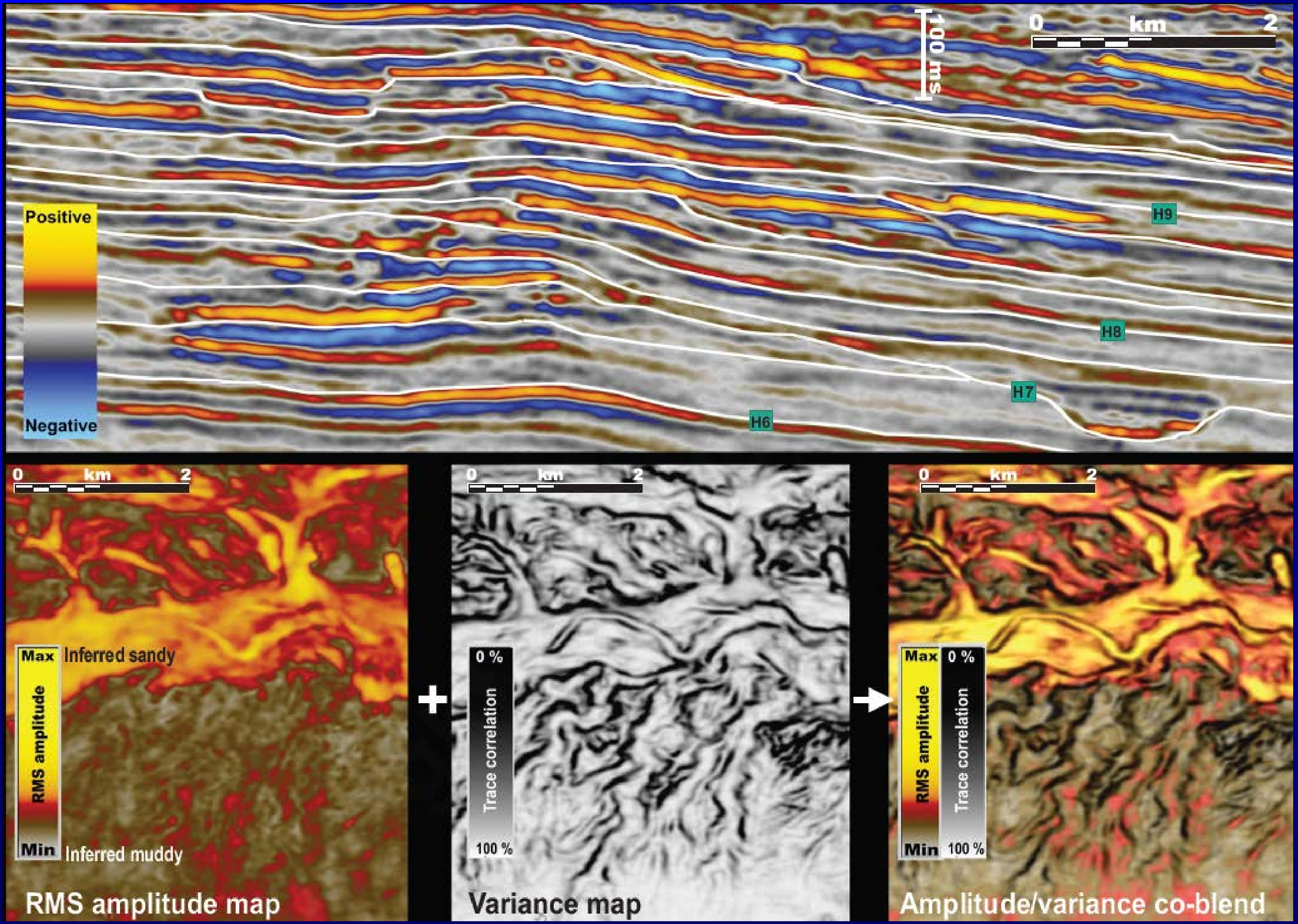
Sweetness with Laplacian filtered discontinuity



Sweetness with relative envelope gradient

(Barnes, 2011)

An effective blending scheme

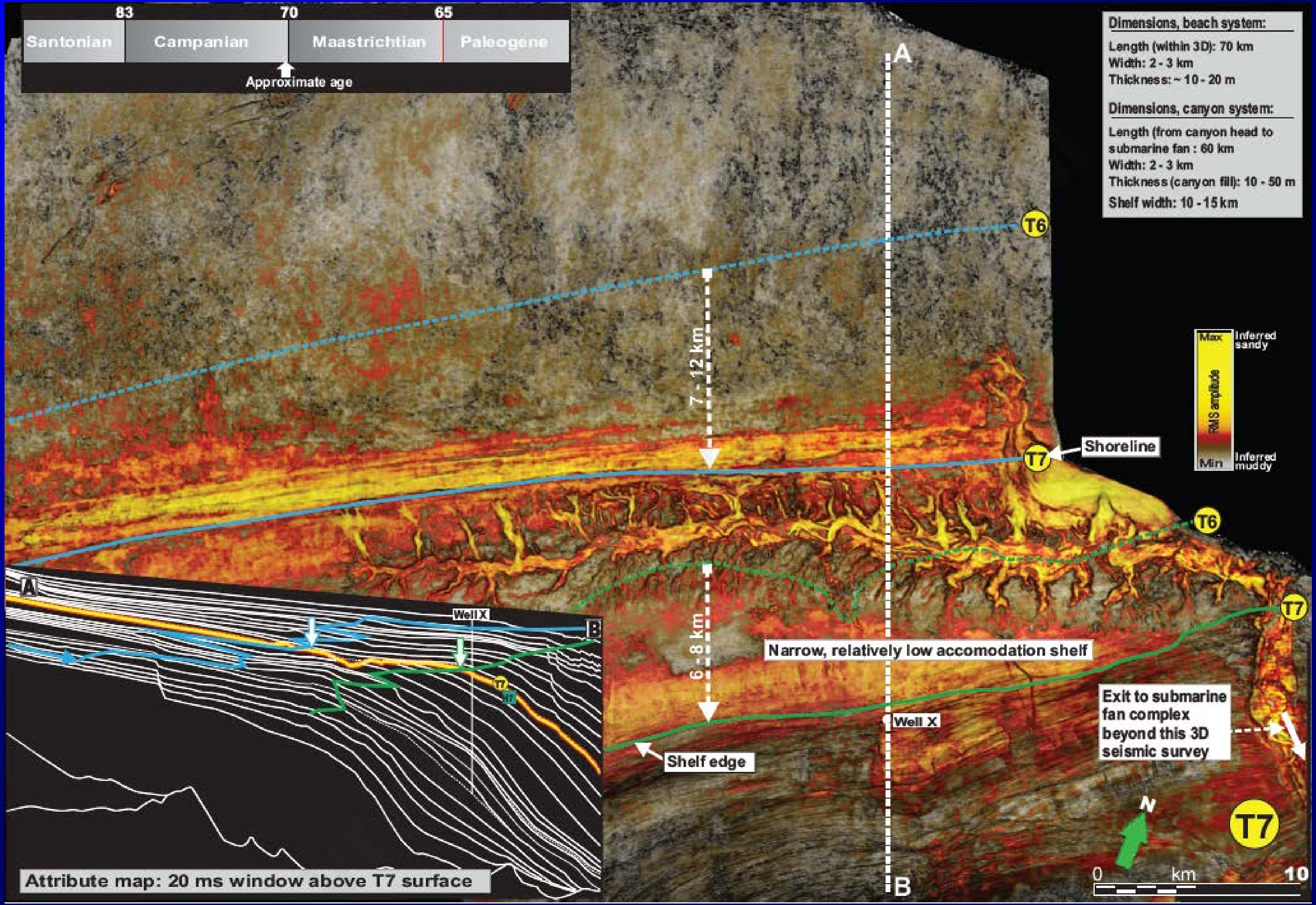


Use polychromatic color bars to represent seismic properties

Use a grayscale color bar to represent seismic edges

(Hadler-Jacobsen et al., 2010)

An effective blending scheme



(Hadler-Jacobsen et al., 2010)

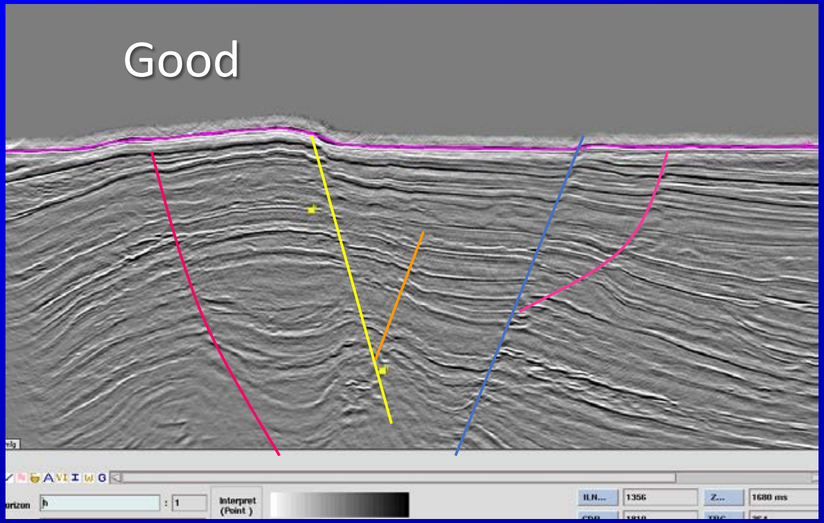
Common display pitfalls

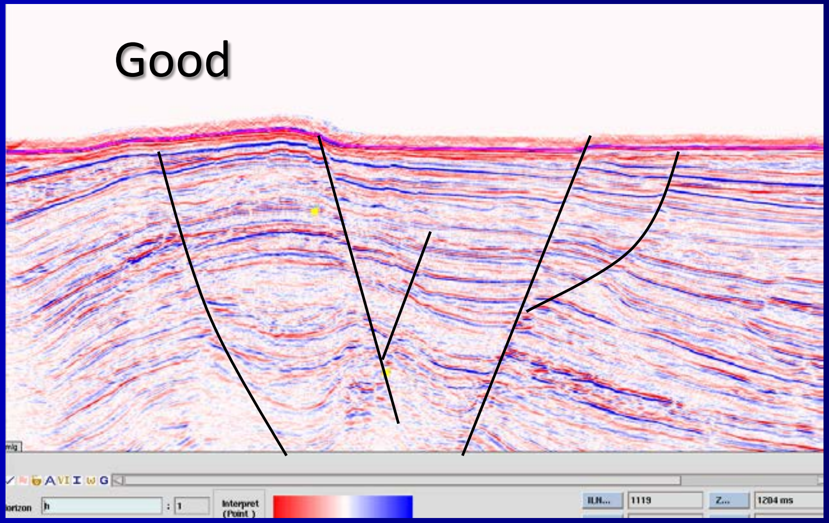
- Displaying continuous data with colors that are not adjacent in RGB or HLS space
- Using a dual gradational color bar to display single polarity data
- Not using a neutral color to display zero values
- Using a single gradational color bar to display cyclical data
- Defining display limits assuming a normal distribution histogram
- Interpolating discontinuous color bars

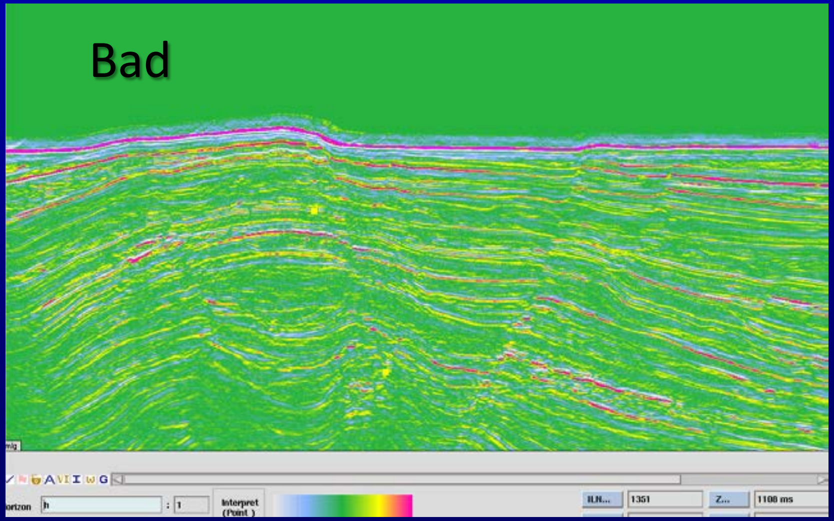
Examples of good and bad color maps

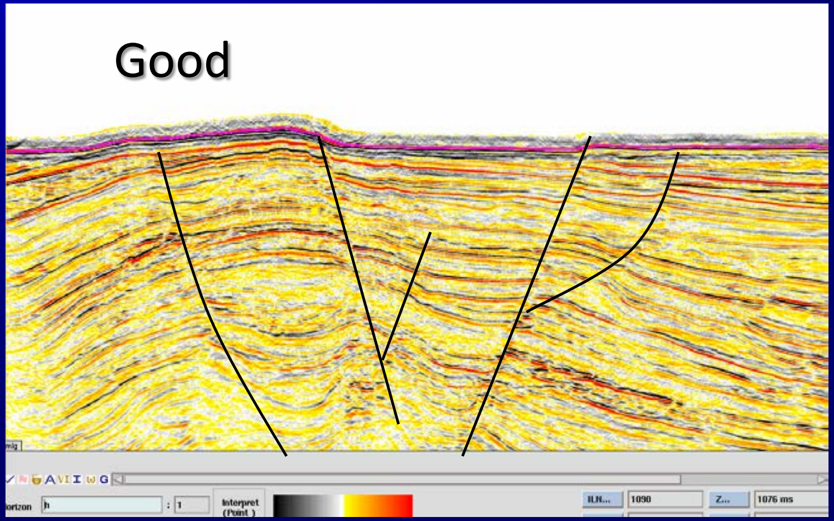
Single gradational

Double gradational









Always use a neutral background color for zero values!

(Chopra and Marfurt, 2007)

Common display pitfalls

- Displaying continuous data with colors that are not adjacent in RGB or HLS space
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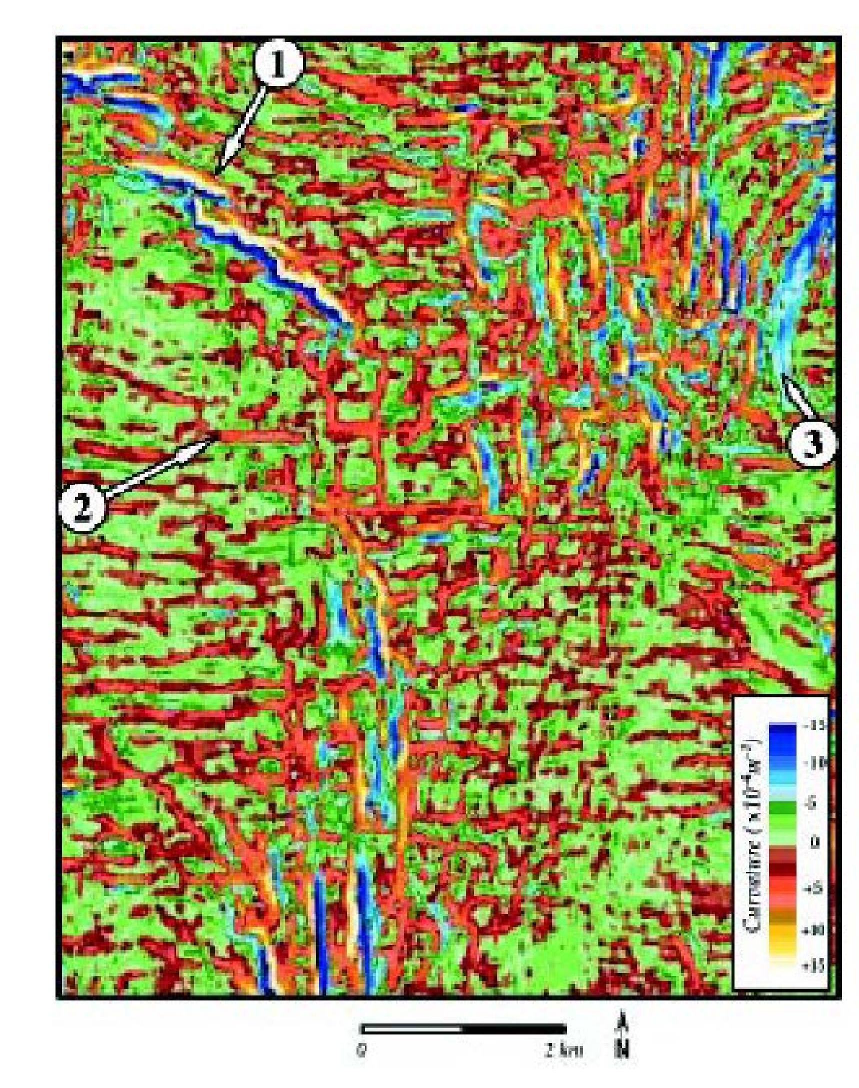
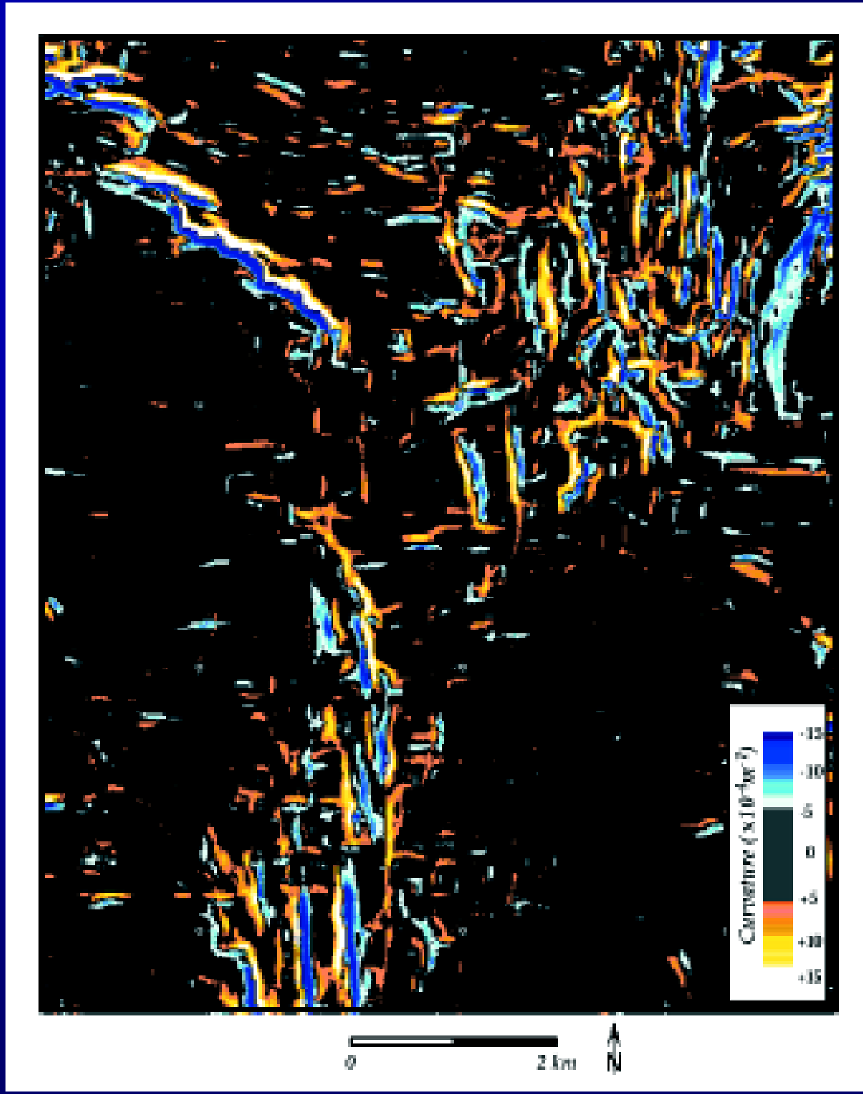
Examples of good and bad color maps



Maximum curvature, k_{max}



Maximum curvature, k_{max}
(with values near zero set to background!)

(Roberts, 2001)

Common display pitfalls

- Displaying continuous data with colors that are not adjacent in RGB or HLS space
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- Not using a neutral color to display zero values
- Using a single gradational color bar to display cyclical data
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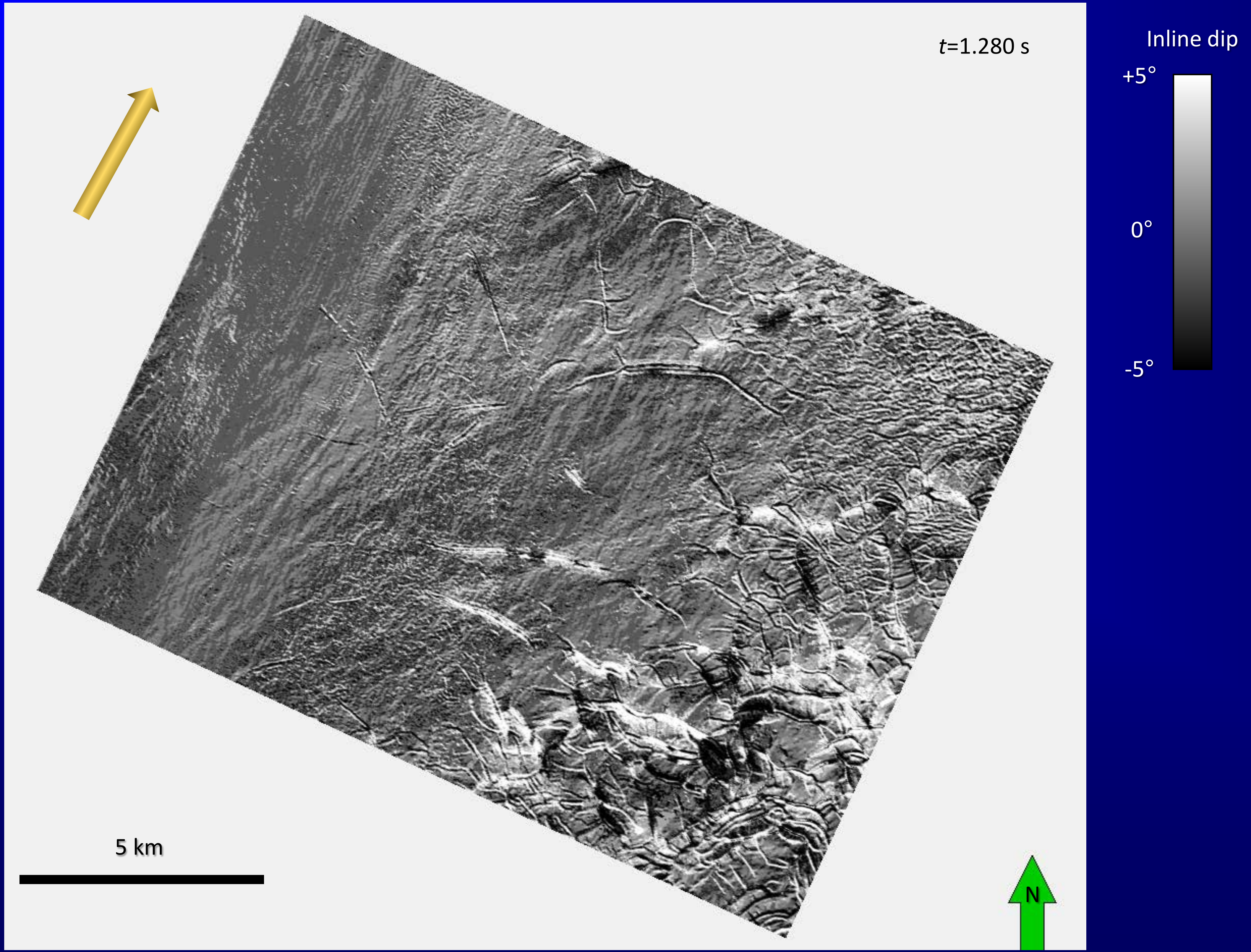
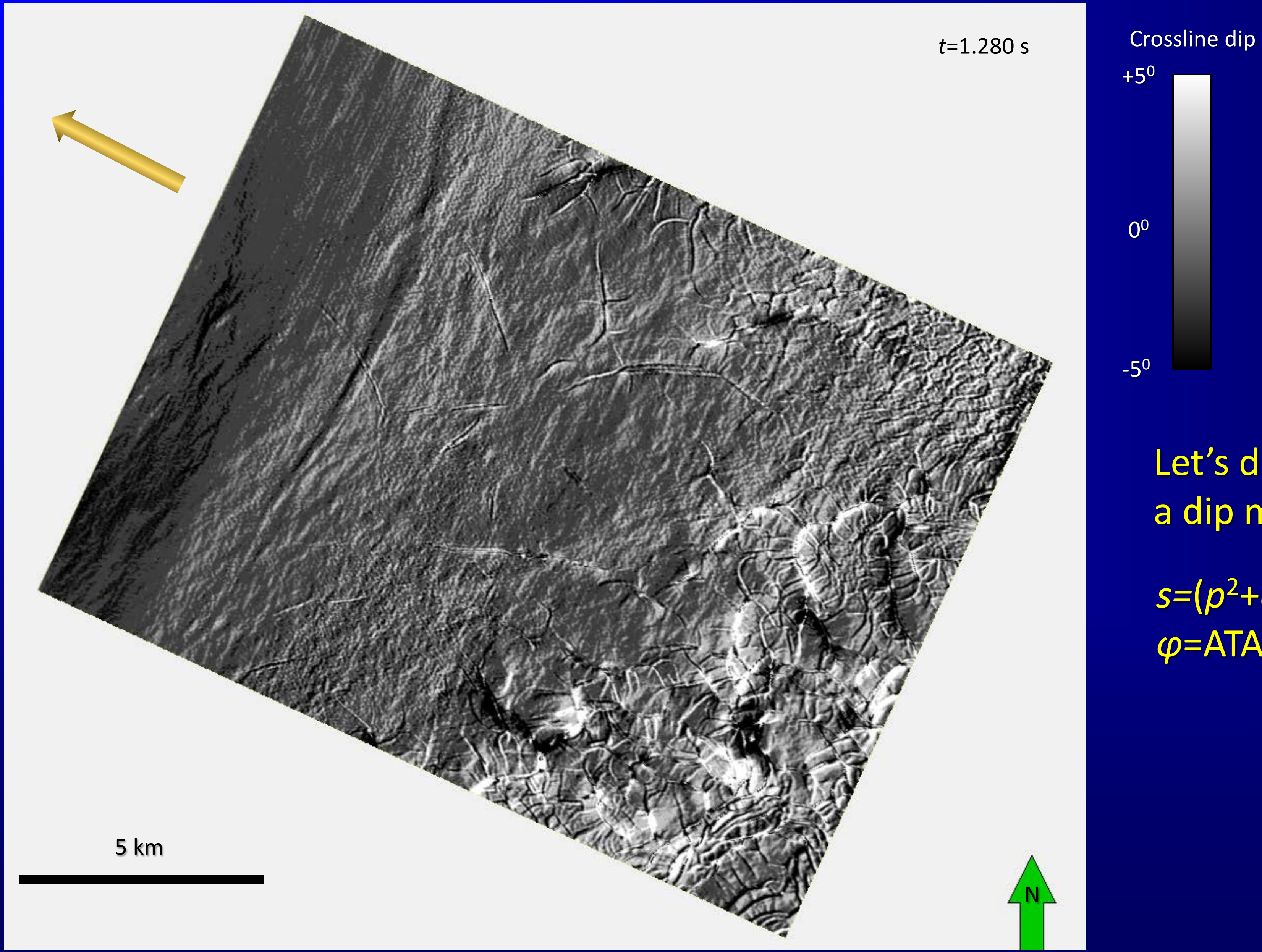
Inline dip component, *p*



(Marfurt, 2018)

Crossline dip component, q



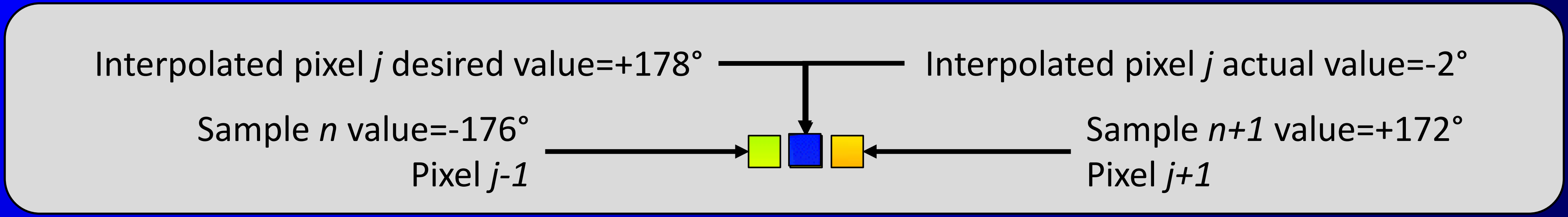
Let's display the dip components as a dip magnitude and a dip azimuth:

$s=(p^2+q^2)^{1/2}$

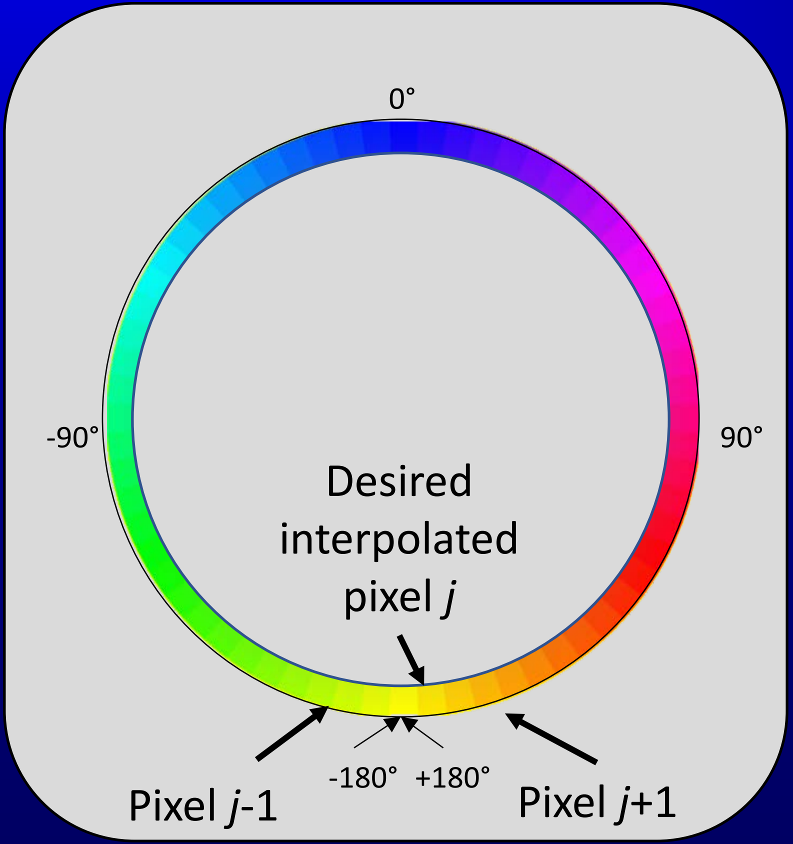
$\varphi=\mathrm{ATAN2}(q,p)$

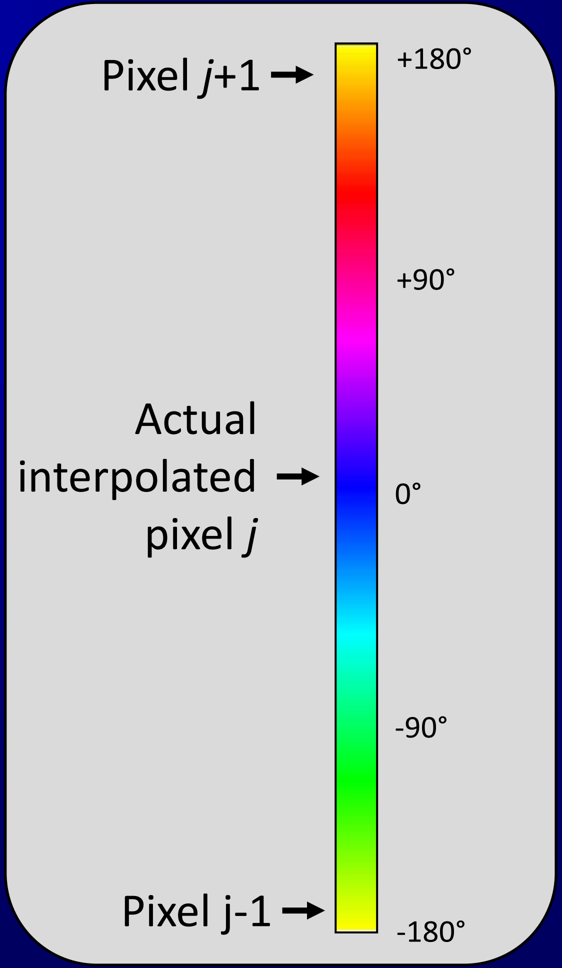
(Marfurt, 2018)

Pitfall in interpolating cyclical attributes



An interpreter's view of a cyclical colorbar

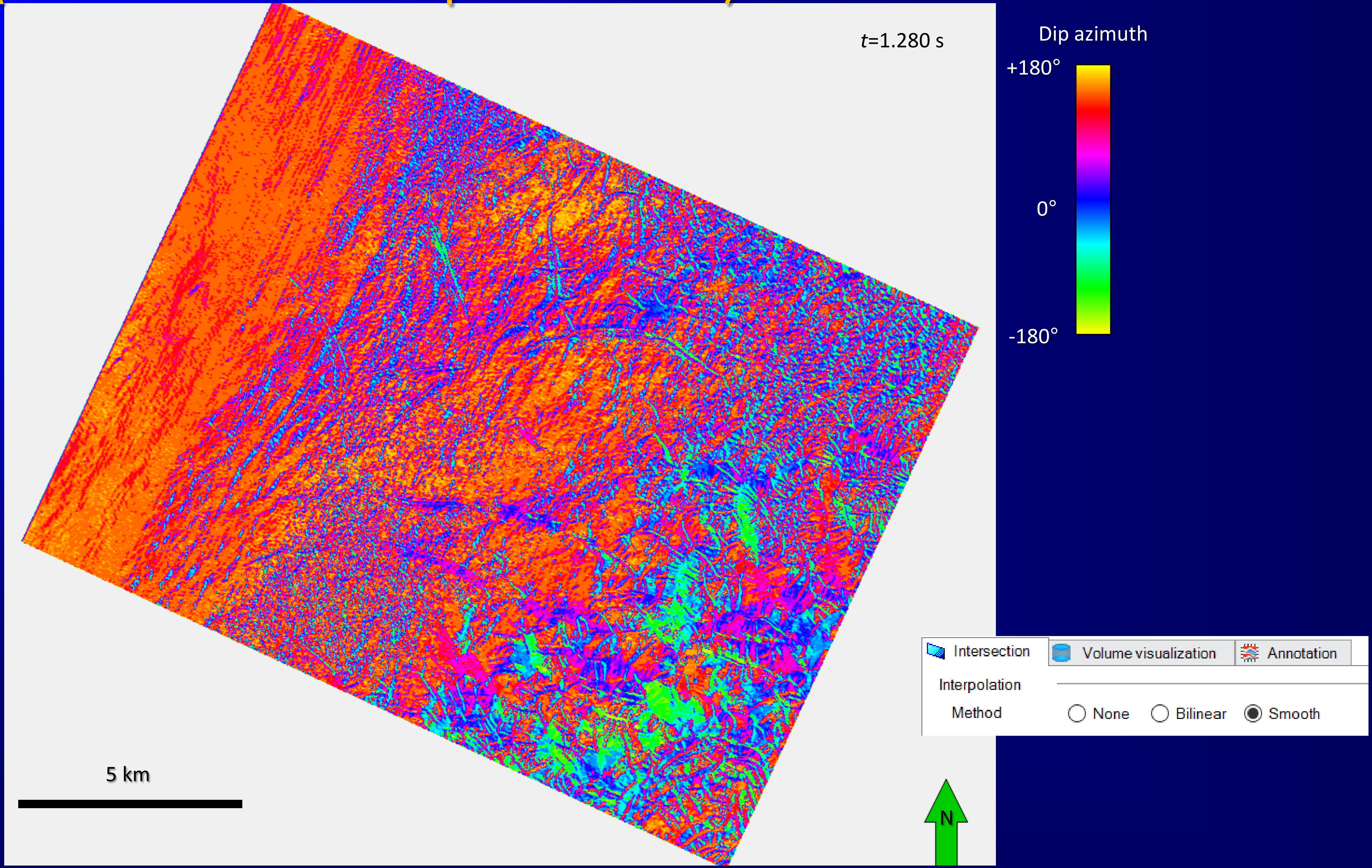




Storage of cyclical colorbars by most software

Dip azimuth, φ (with smooth interpolation on)

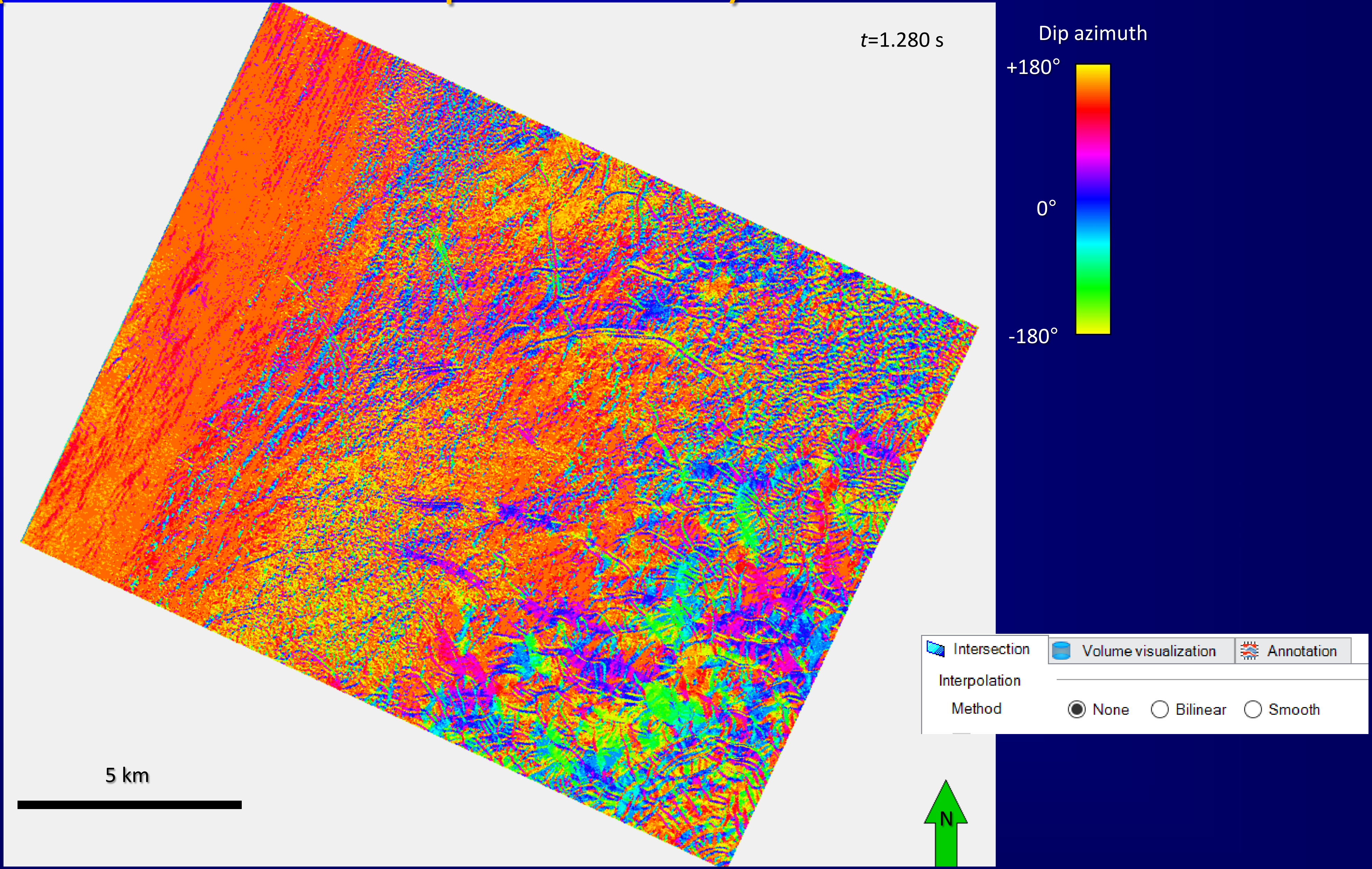
$$\varphi = \mathrm{ATAN2}(q, p)$$



(Marfurt, 2018)

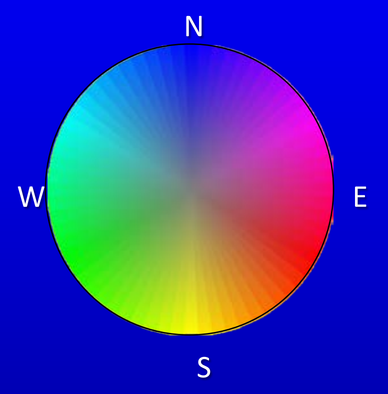
Dip azimuth, φ (with smooth interpolation off)

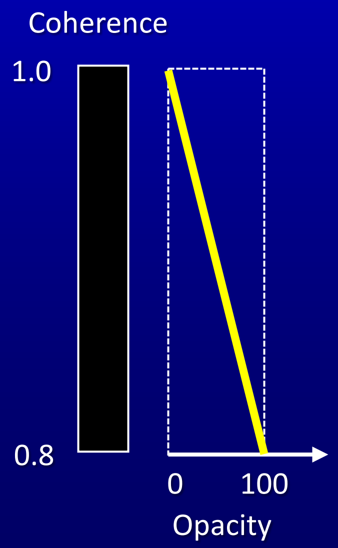
$$\varphi = \mathrm{ATAN2}(q, p)$$

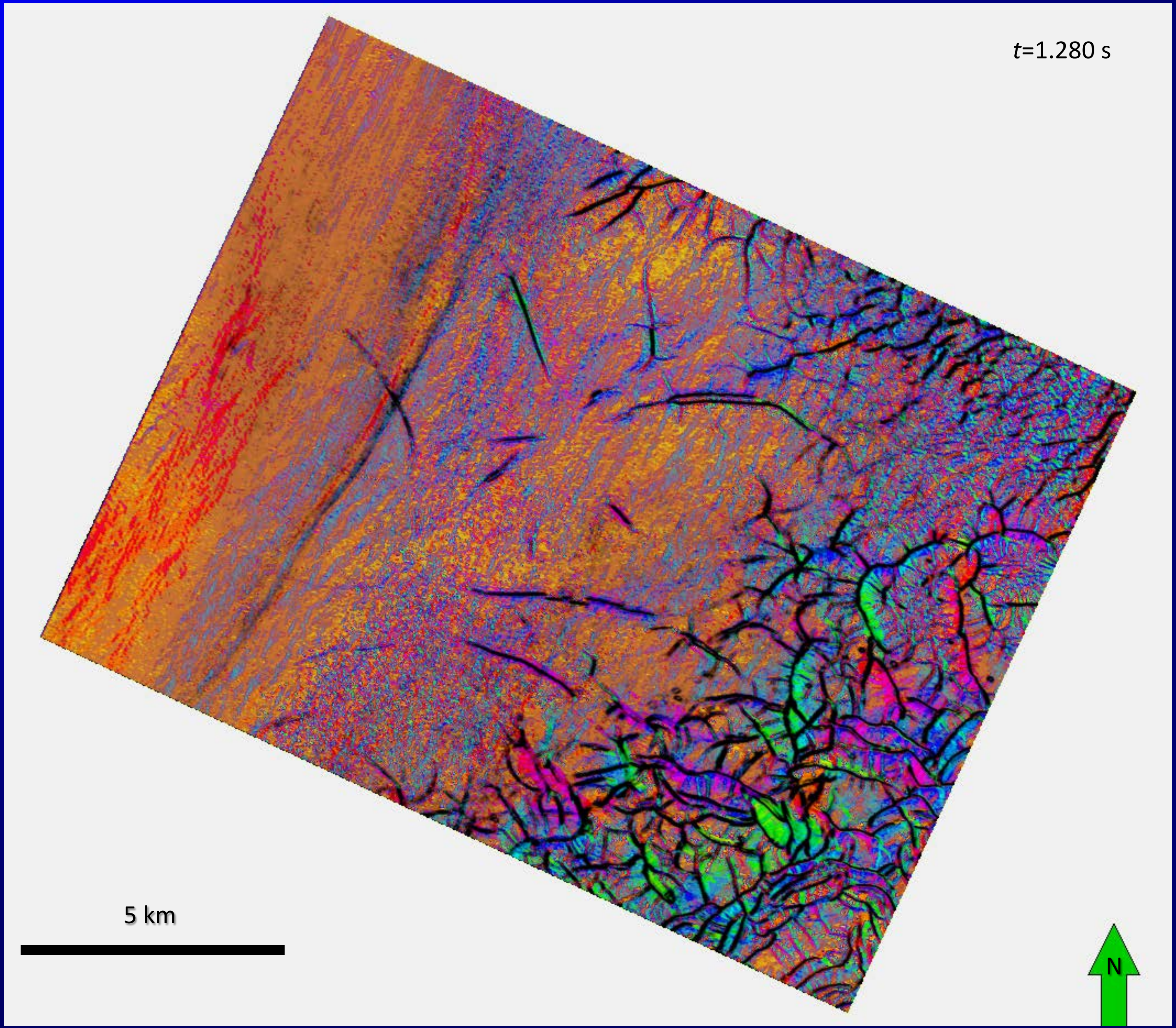


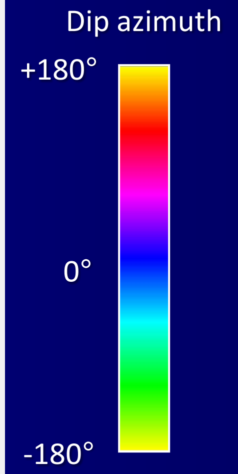
(Marfurt, 2018)

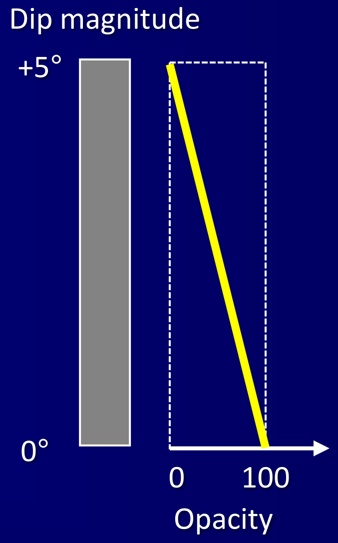
Co-rendered dip azimuth, dip magnitude, and energy-ratio coherencec





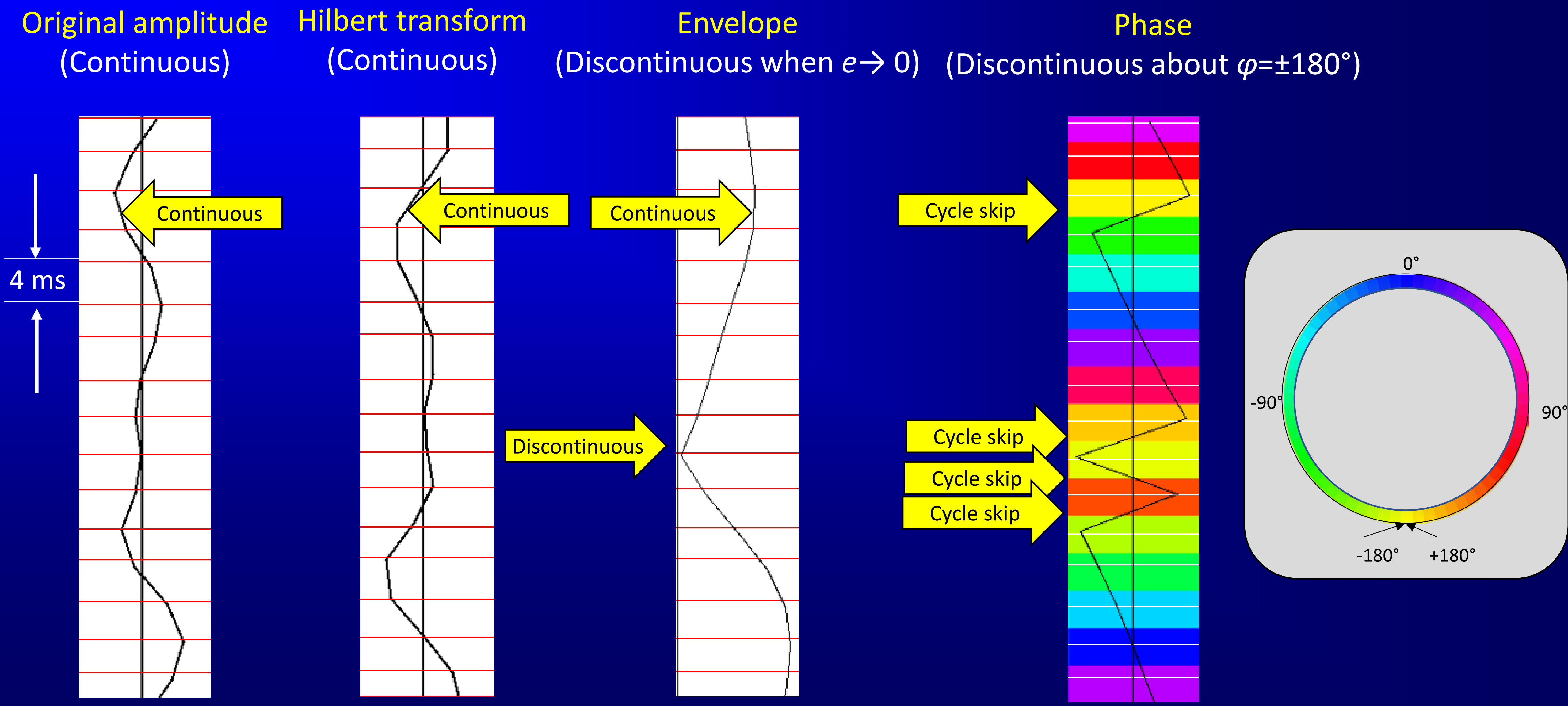






(Marfurt, 2018)

Pitfalls in interpolating envelope and phase



(Marfurt, 2021)

A better way to interpolate envelope and phase

Generate real and imaginary traces (using an attribute calculator)

$$u_{\mathrm{Re}}(t) = e(t)\cos\left[\varphi(t)\right]$$
$$u_{\mathrm{Im}}(t) = e(t)\sin\left[\varphi(t)\right]$$

Original data

Hilbert transform

Interpolate the continuous attributes (using the default parameters)

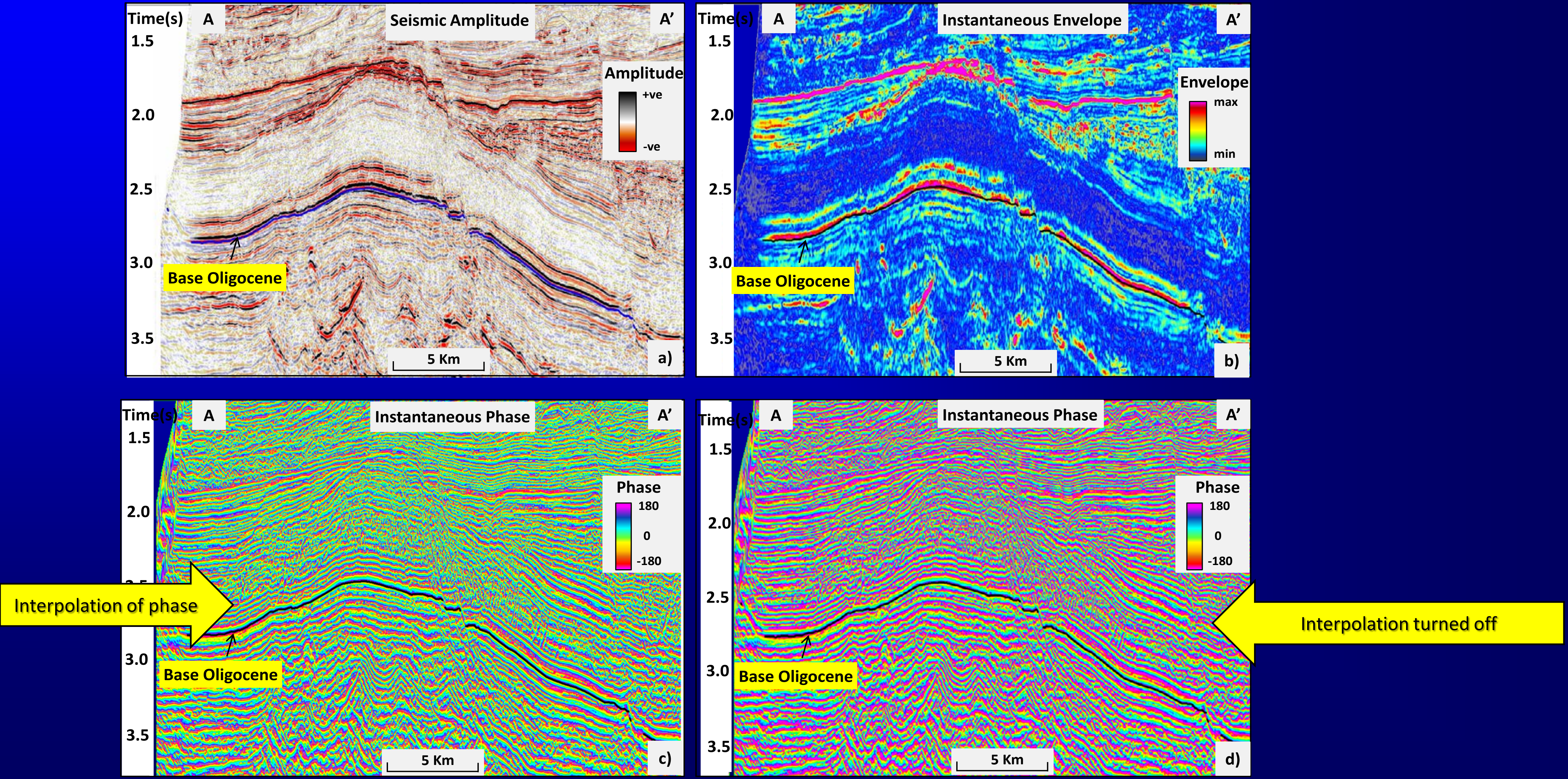
$$u_{\mathrm{Re}}(\tau)$$
$$u_{\mathrm{Im}}(\tau)$$

Recompute the envelope and phase (using an attribute calculator)

$$e(\tau) = \left[u_{\mathrm{Re}}^2(\tau) + u_{\mathrm{Im}}^2(\tau)\right]^{1/2}$$
$$\varphi(\tau) = \mathrm{ATAN2}\left[u_{\mathrm{Im}}(\tau), u_{\mathrm{Re}}(\tau)\right]$$

(Marfurt, 2021)

Pitfalls and corrections in interpolating envelope and phase

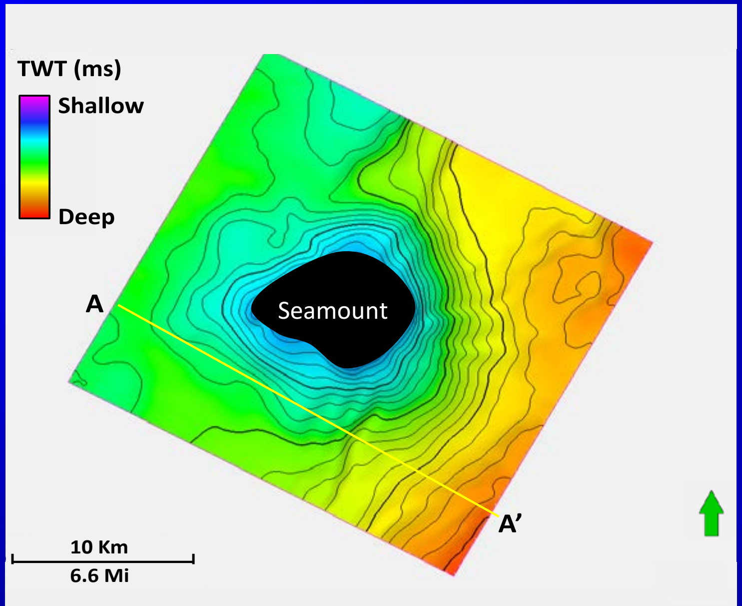


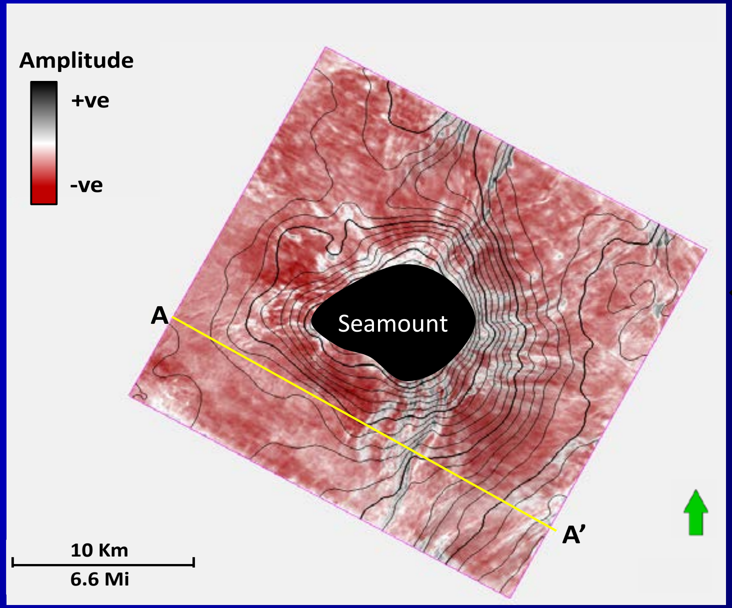
(Infante-Paez and Marfurt, 2015)

Pitfalls and corrections in interpolating envelope and phase

Base Oligocene horizon slices

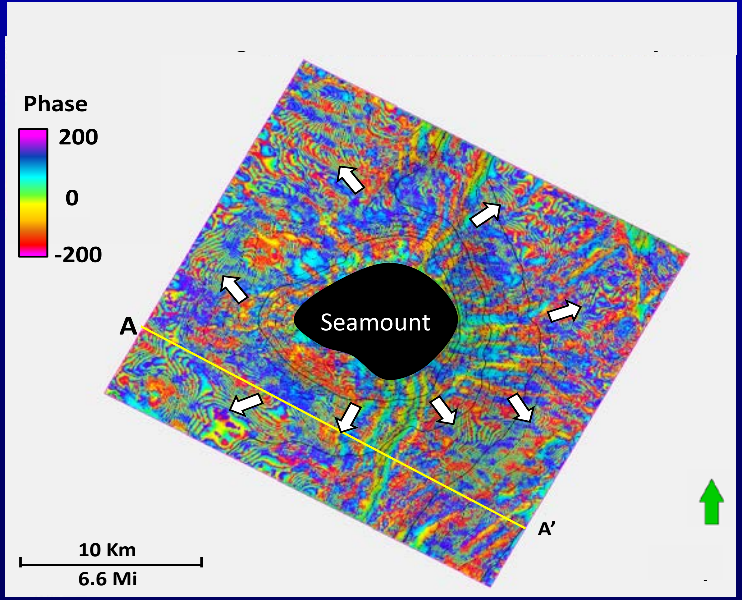
Time-structure

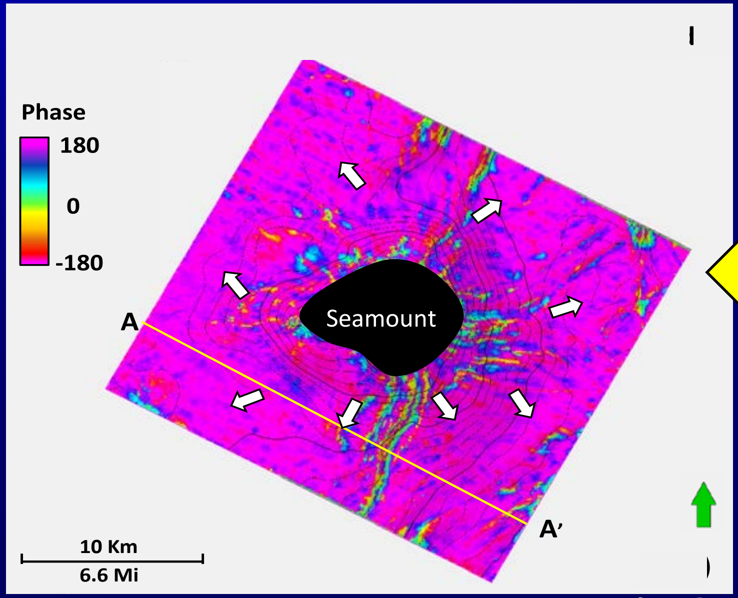




Amplitude

Interpolated phase

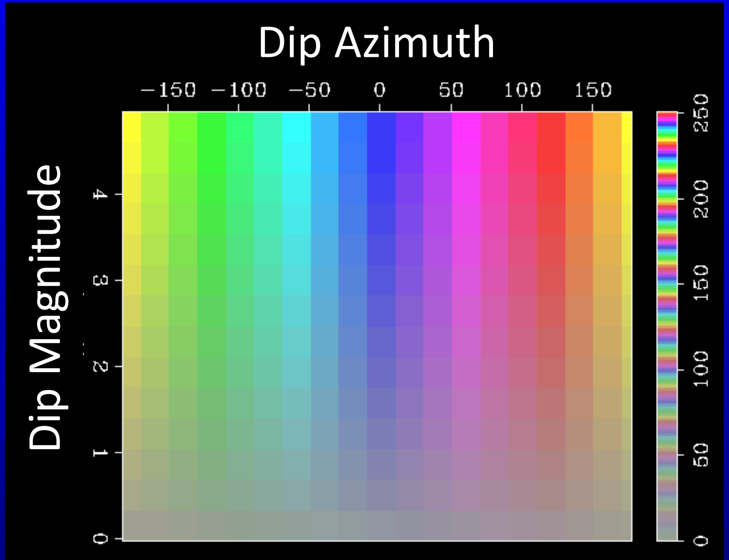




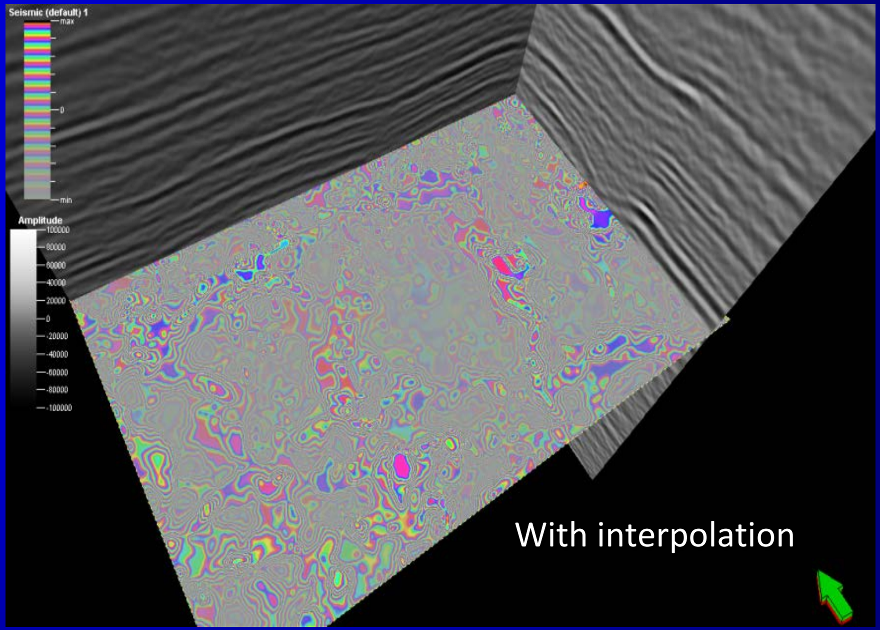
Phase computed from the interpolated amplitude and Hilbert transform volumes

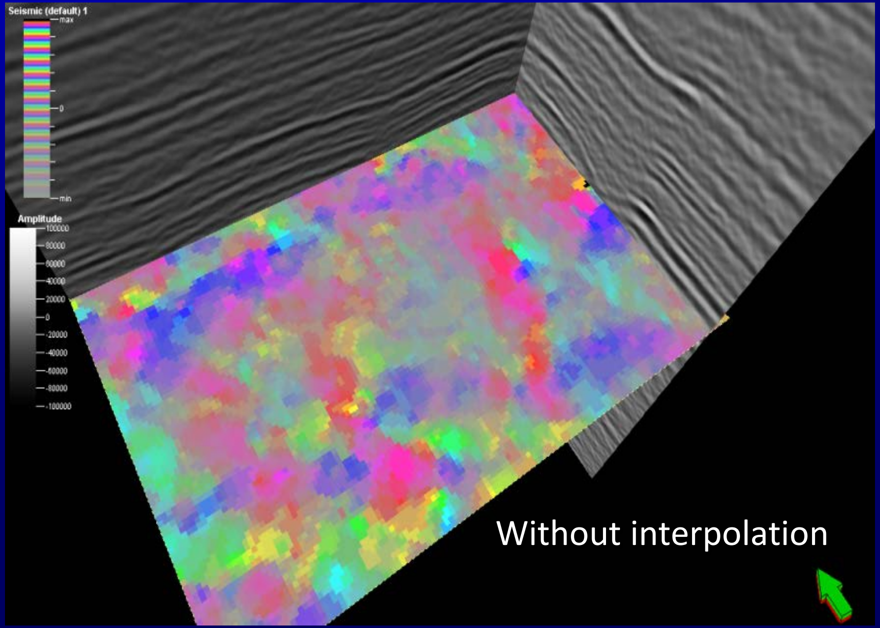
(Infante-Paez and Marfurt, 2015)

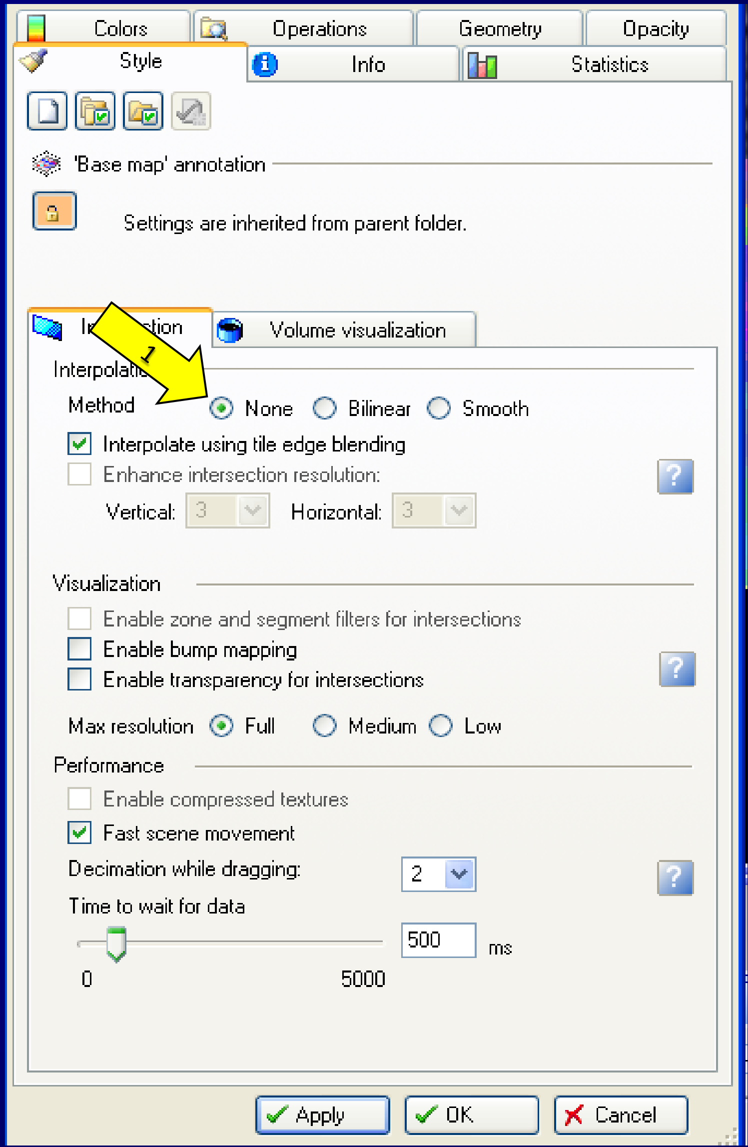
Interpolating 2D color bars loaded as a 1D color bar



16x16 2D color table (256 colors)







Single Attribute Displays

In Summary:

- The best color scales are those that have analogues to everyday human perception and/or experience (e.g. hot/cold colors, shaded relief maps, …)

- Hue is a natural choice for attributes that are cyclic (e.g. phase, azimuth, strike, …)

- Lineaments or discontinuities show up best in monochrome (gray scale, sepia,…)

- Choice of discontinuous color scales prevent the data from speaking for themselves. Rather use single or double gradational scales (Brown, 1999)

- Use a neutral background color for data having low information content! (e.g. white or black for zero curvature) (Kidd, 1999).

Multiattribute Display

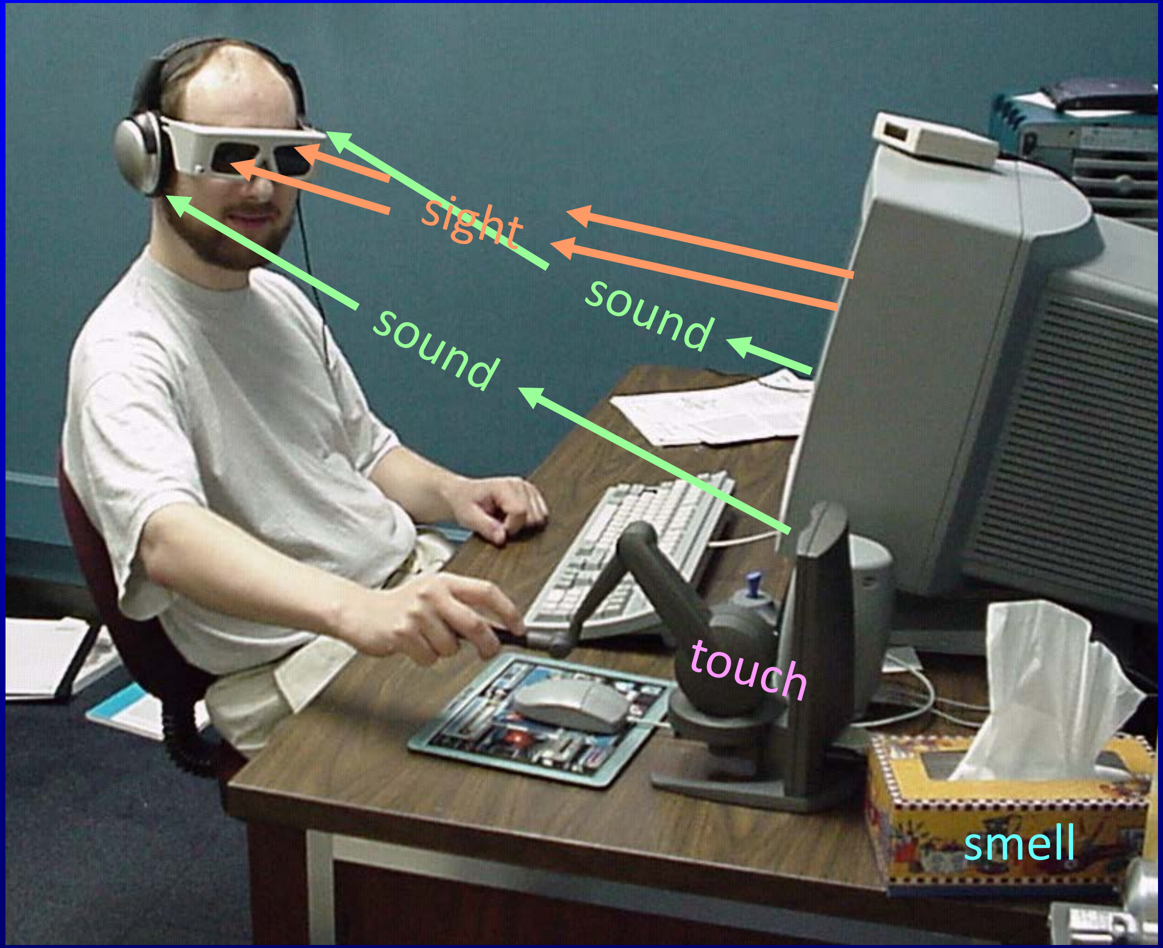
- The RGB model works best for attributes that are of the same type and have similar amplitude ranges
    - 3 spectral components
    - 3 adjacent horizon slices through amplitude
    - Coherence computed from 3 spectral components

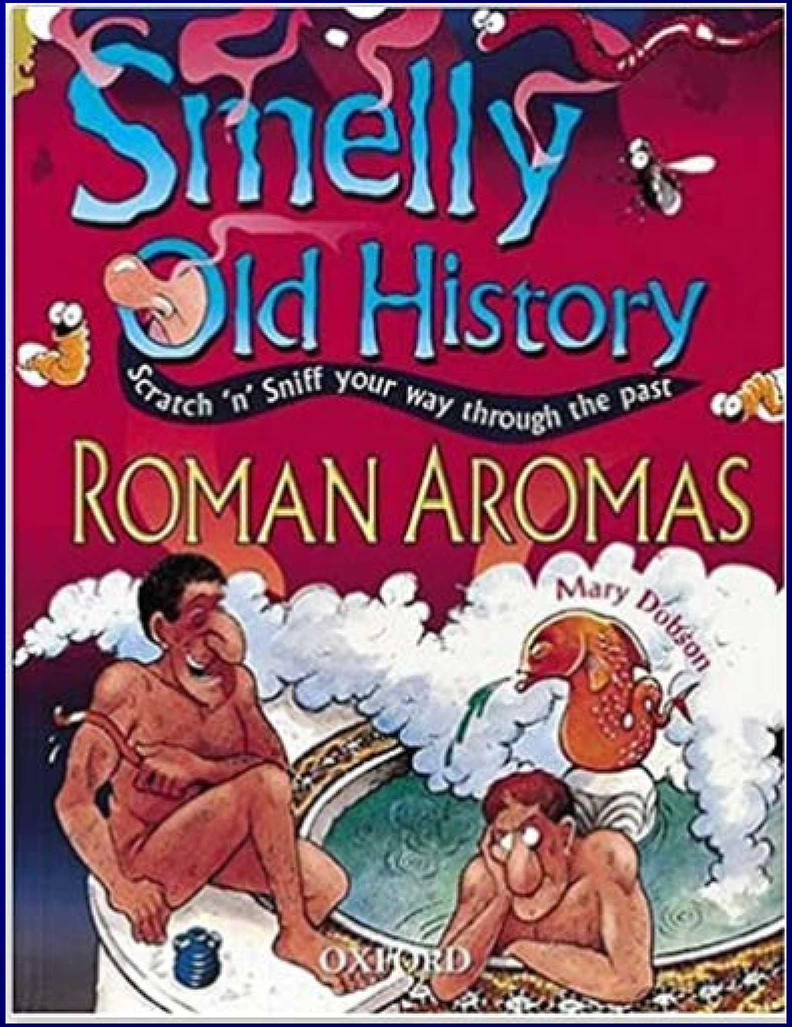
- Blending works best when one of the attributes is plotted against the black-white lightness axis, rendering easy-to-interpret pastel images

- The HLS model is the method of choice in plotting vector data
    - Dip magnitude vs. dip azimuth
    - Most positive curvature and its strike
    - Fault plane dip magnitude and azimuth
    - Degree of anisotropy and its strike

- The HLS color model provides a means of displaying ‘confidence
    - The probability that a voxel belongs in a given polychromatic facies
    - Confidence in azimuthal anisotropy estimates

Full sense interpretation





(Harding et al., 2000)

Partial list of attributes that can be plotted against HLS

Background attribute (against hue)	Modulating attribute (against saturation)	Calibration attribute (against lightness)	References
Dip Azimuth	Dip magnitude	Coherence on time slices. Amplitude on vertical slices.	Rijks and Jauffred 1991; Marfurt et al., 1998.
Strike of most-positive principal curvature	Positive value of most-positive principal curvature	Coherence on time slices. Amplitude on vertical slices.	Guo et al., 2013.
Strike of most-negative principal curvature	Positive value of most-negative principal curvature	Coherence on time slices. Amplitude on vertical slices.	Marfurt, 2010; Guo et al., 2011
Reflector shape index	Reflector curvedness	Coherence on time slices. Amplitude on vertical slices.	Marfurt, 2011; Mai et al., 2010; Marfurt, 2010.
Peak spectral frequency	Peak spectral magnitude	Coherence on time slices. Amplitude on vertical slices.	Guo et al., 2008, 2011.
Azimuth of reflector convergence	Magnitude of reflector convergence	Coherence on time slices. Amplitude on vertical slices.	Marfurt, 2010; Marfurt and Rich, 2010; Chopra and Marfurt, 2011.
Azimuth of HTI anisotropy	Magnitude of HTI anisotropy	Confidence of fit, coherence, most-positive curvature, most-negative curvature on time slices. Amplitude on vertical slices.	Guo et al., 2010, Zhang et al., 2011
Azimuth of vector correlation	Magnitude of vector correlation	Coherence on time slice. Amplitude on vertical slices.	Guo et al., 2013
Most likely facies number	none	Probability of facies	Espersen et al., 2000

(Marfurt, 2015)

Partial list of attributes that can be plotted against (x,y) then converted to (r,φ) and plotted against HLS

x axis	*y* axis	Calibration attribute (against lightness)	References
lambda-rho	mu-rho	Coherence on time slices. Amplitude on vertical slices. Microseismic events as icons.	Perez and Marfurt, 2013
Latent space axis 1	Latent space axis 2	Coherence on time slices. Amplitude on vertical slices.	Strecker and Uden, 2002; Wallet et al., 2009; Roy et al., 2011.

(Marfurt, 2015)