Seismic Attributes - from Interactive Interpretation to Machine Learning

Kurt J. Marfurt

Image Enhancement of Faults

Image enhancement of faults

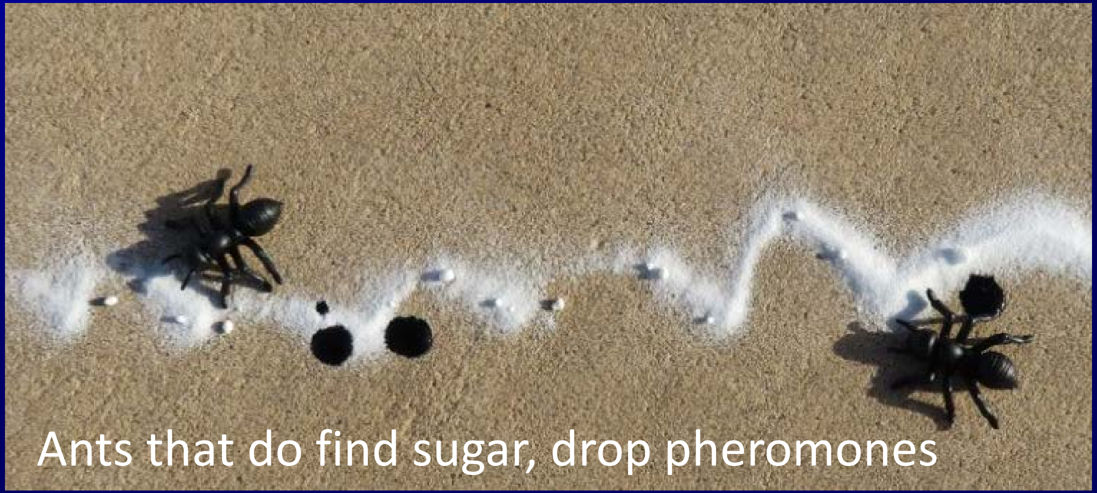
After this section you should be able to:

- Apply simple filters to coherence or other edge-sensitive attributes enhance faults and suppress stratigraphic features parallel to stratigraphy
- Estimate the orientation, and for some algorithms, the heave of individual faults

Ant-tracking

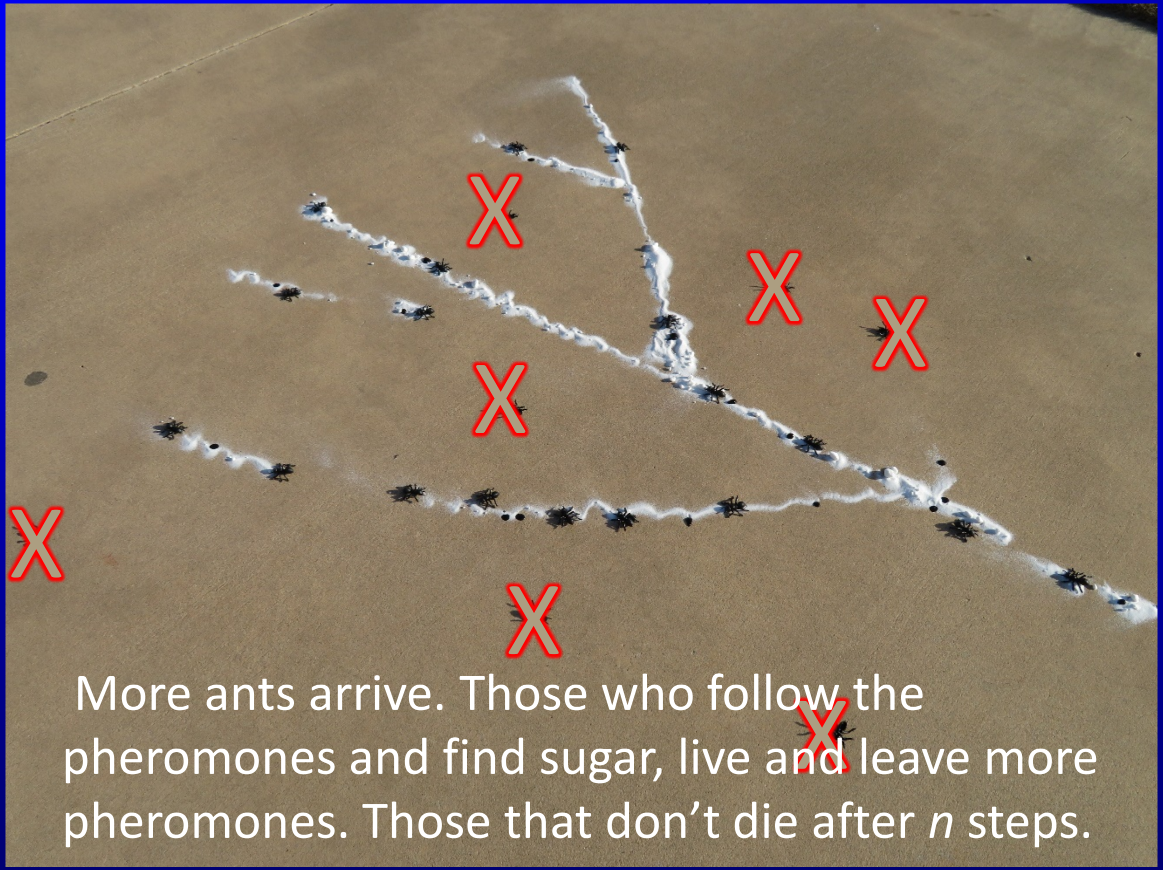
(Marfurt, 2018)

Swarm intelligence and mapping faults



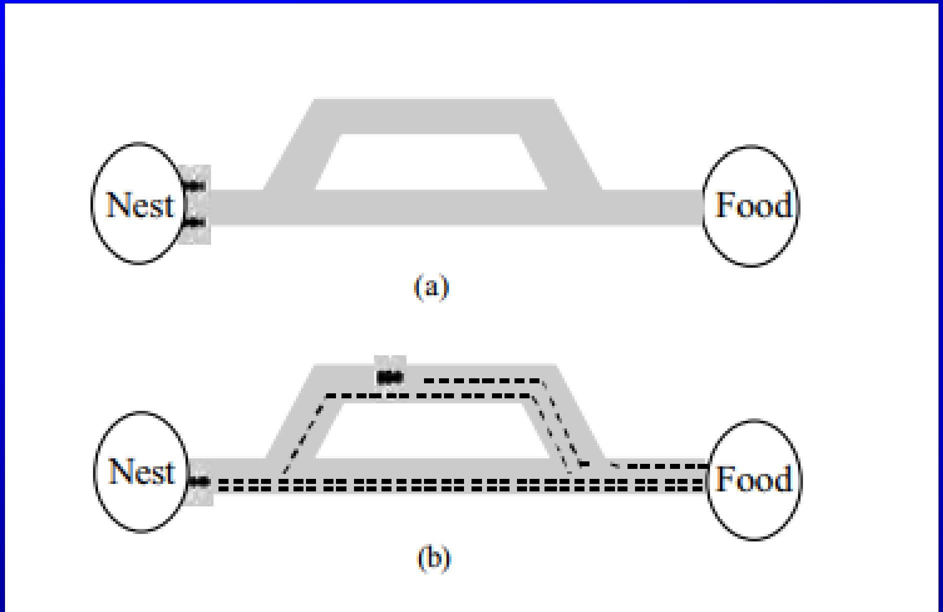
(Marfurt, 2018)

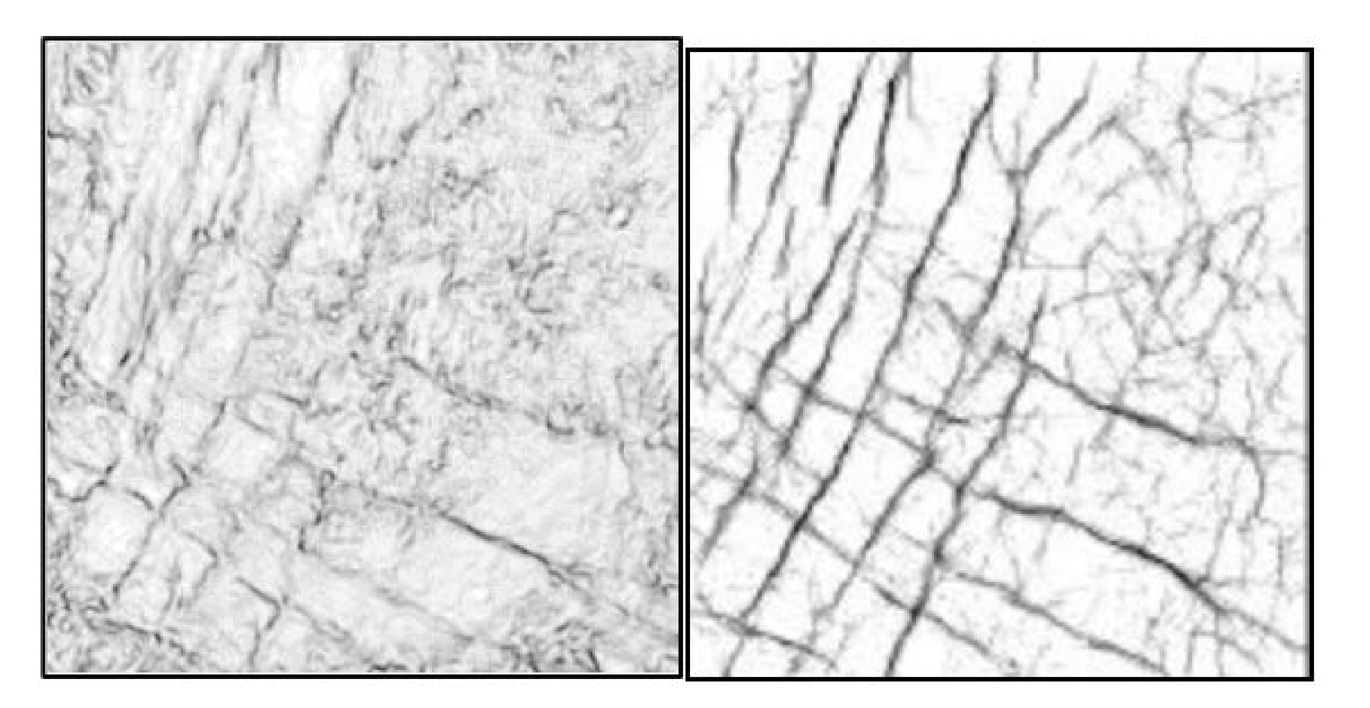
Swarm intelligence and mapping faults



(Marfurt, 2018)

Ant-tracking



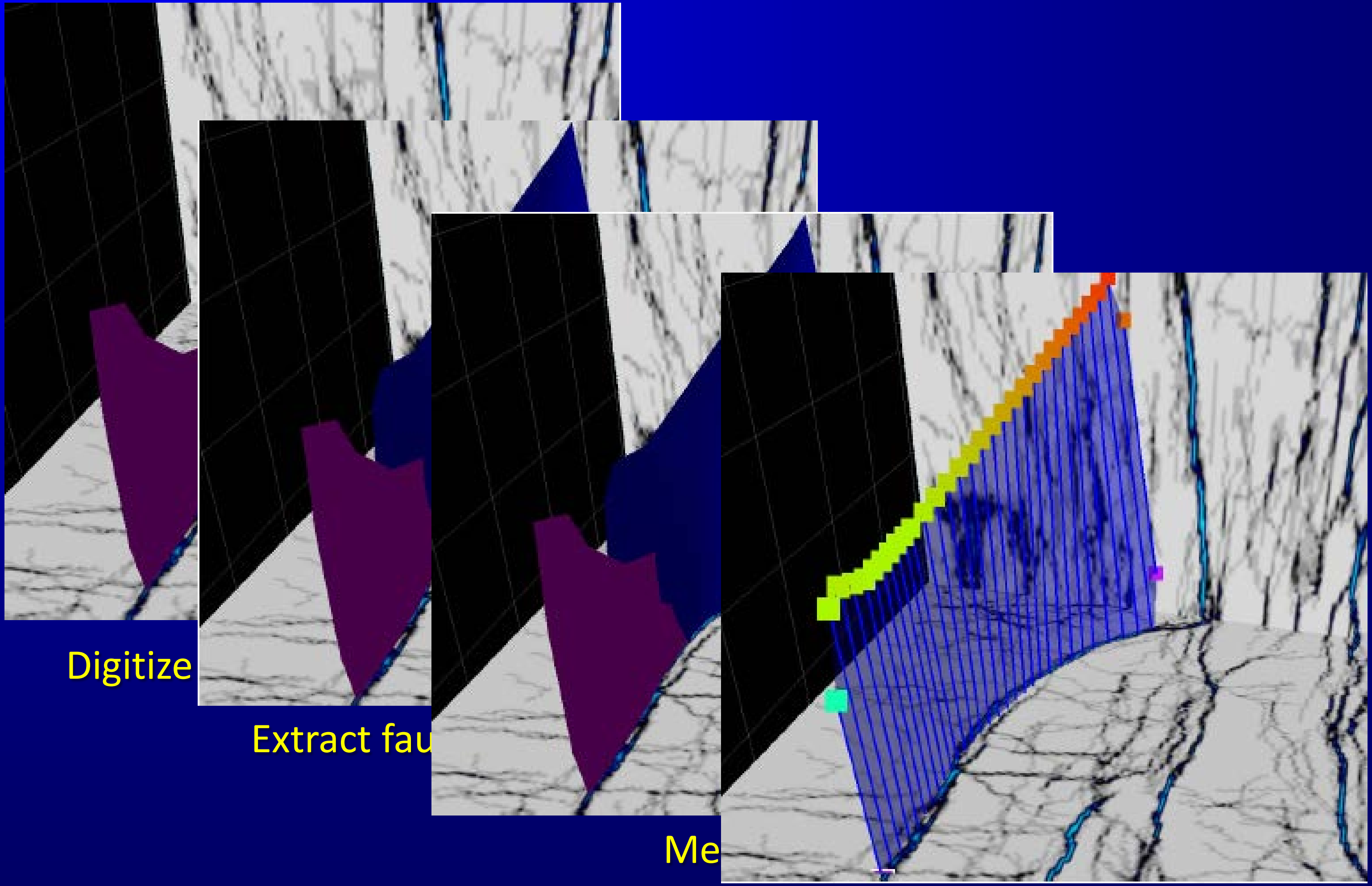


(Pedersen et al., 2002)

Fault enhancement using ant-tracking

(Silva et al., 2005)

Ant-tracking workflow



Digitize

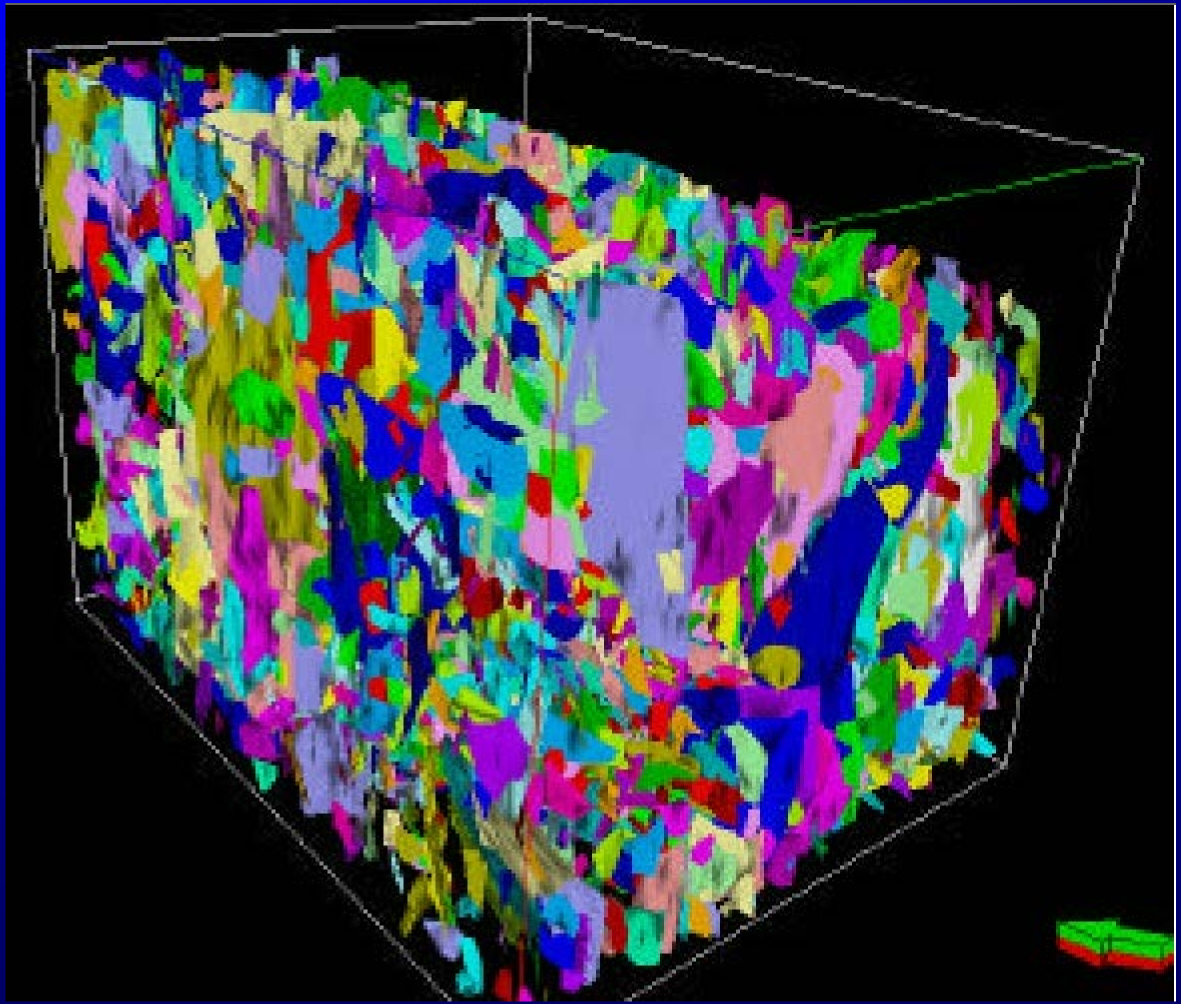
Extract fau

Me

Convert to pillars or fault segments

(Petrel documentation)

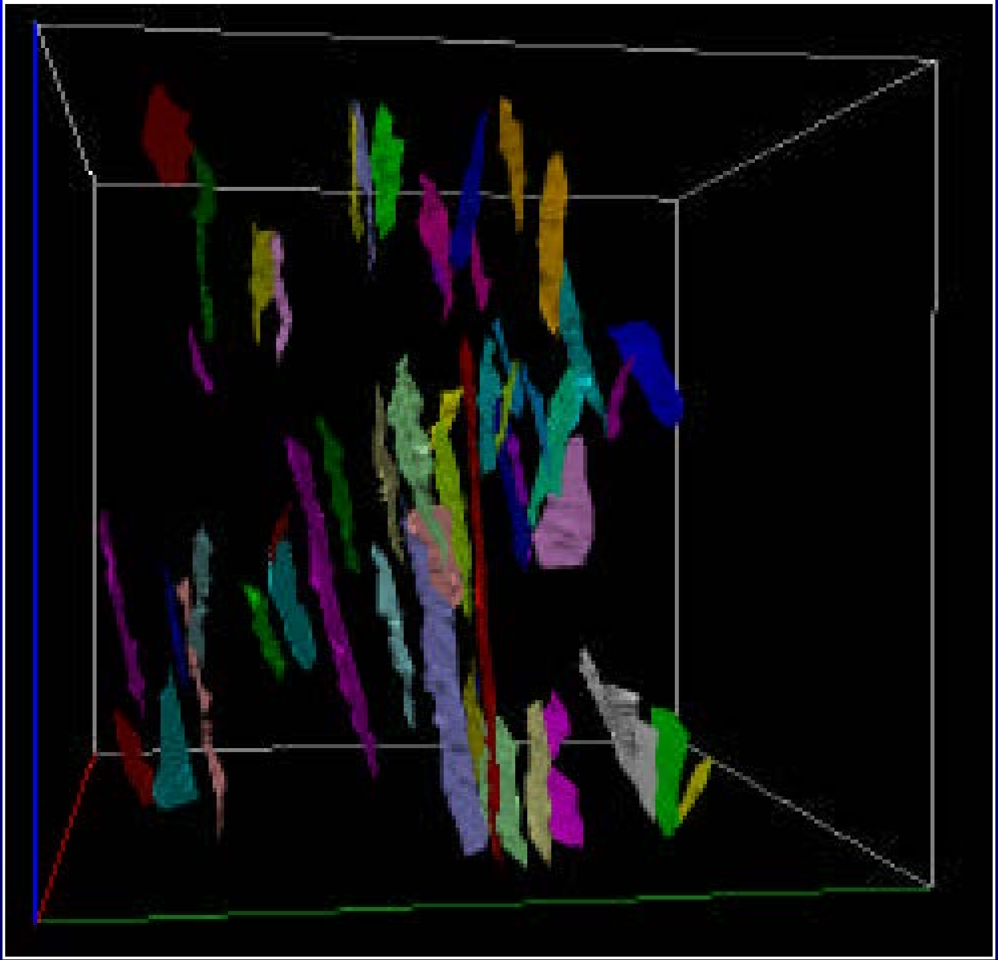
Ant-tracking workflow



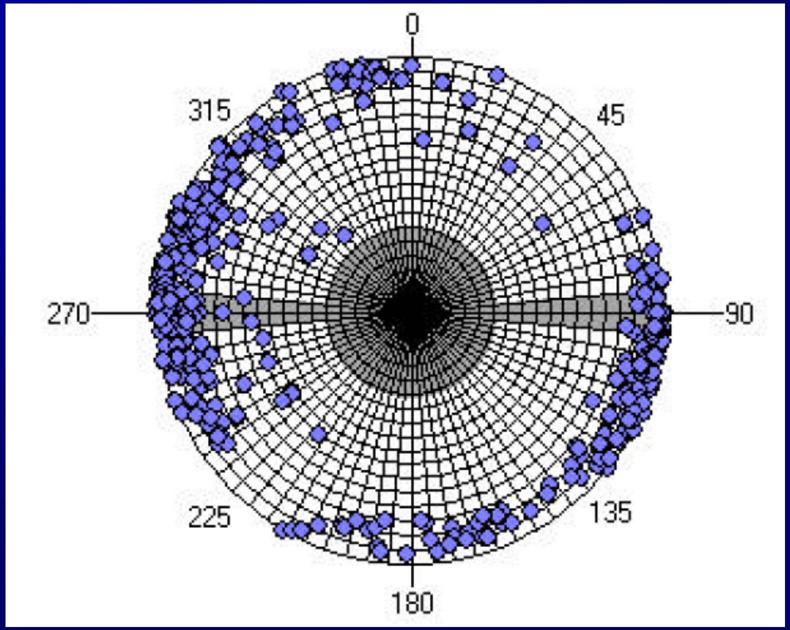
All fault patches extracted using ant-tracking

(Silva et al., 2005)

Ant-tracking workflow

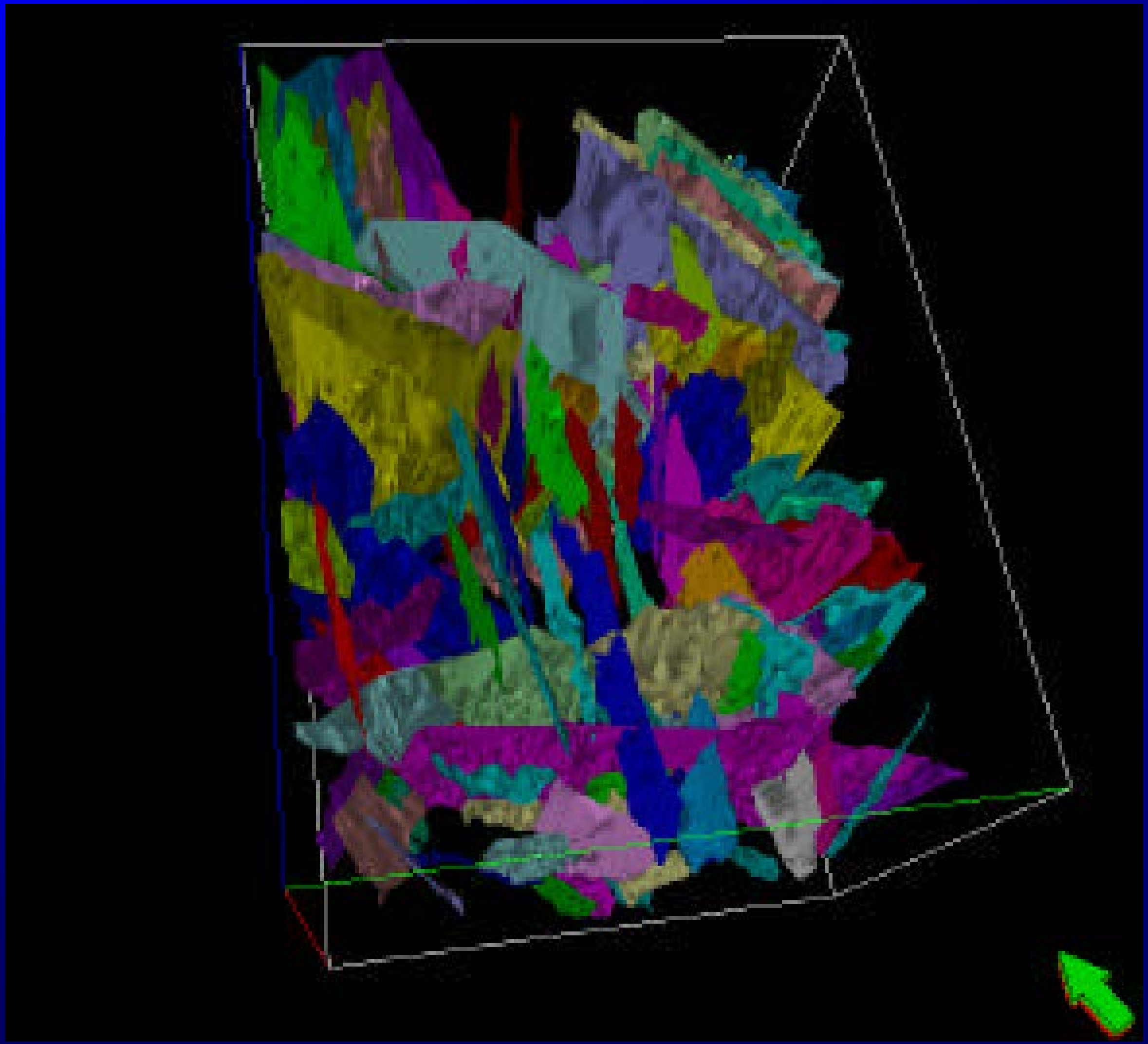


Fault patch artifacts associated with acquisition footprint



(Silva et al., 2005)

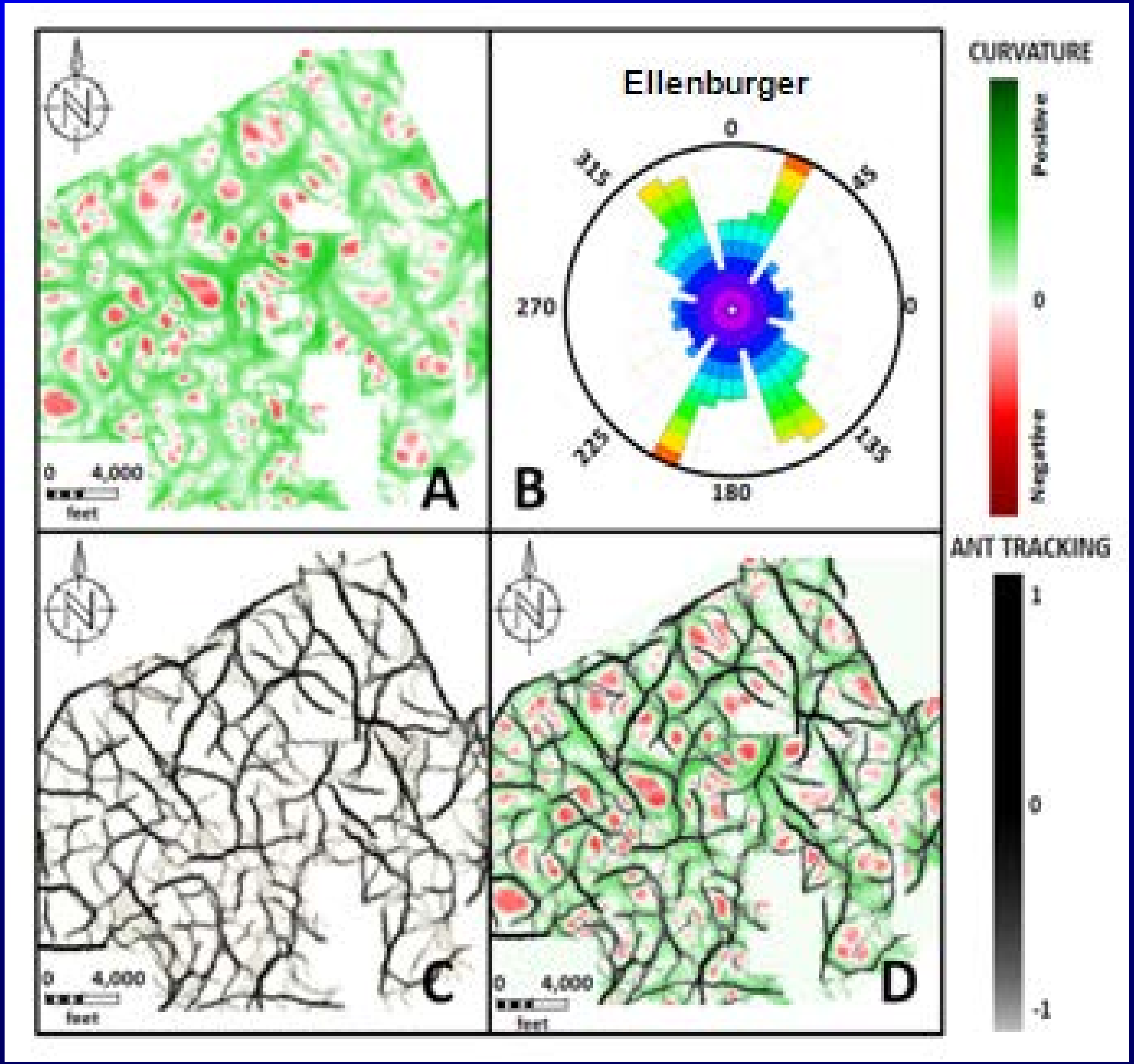
Ant-tracking workflow



The filtered fault sets

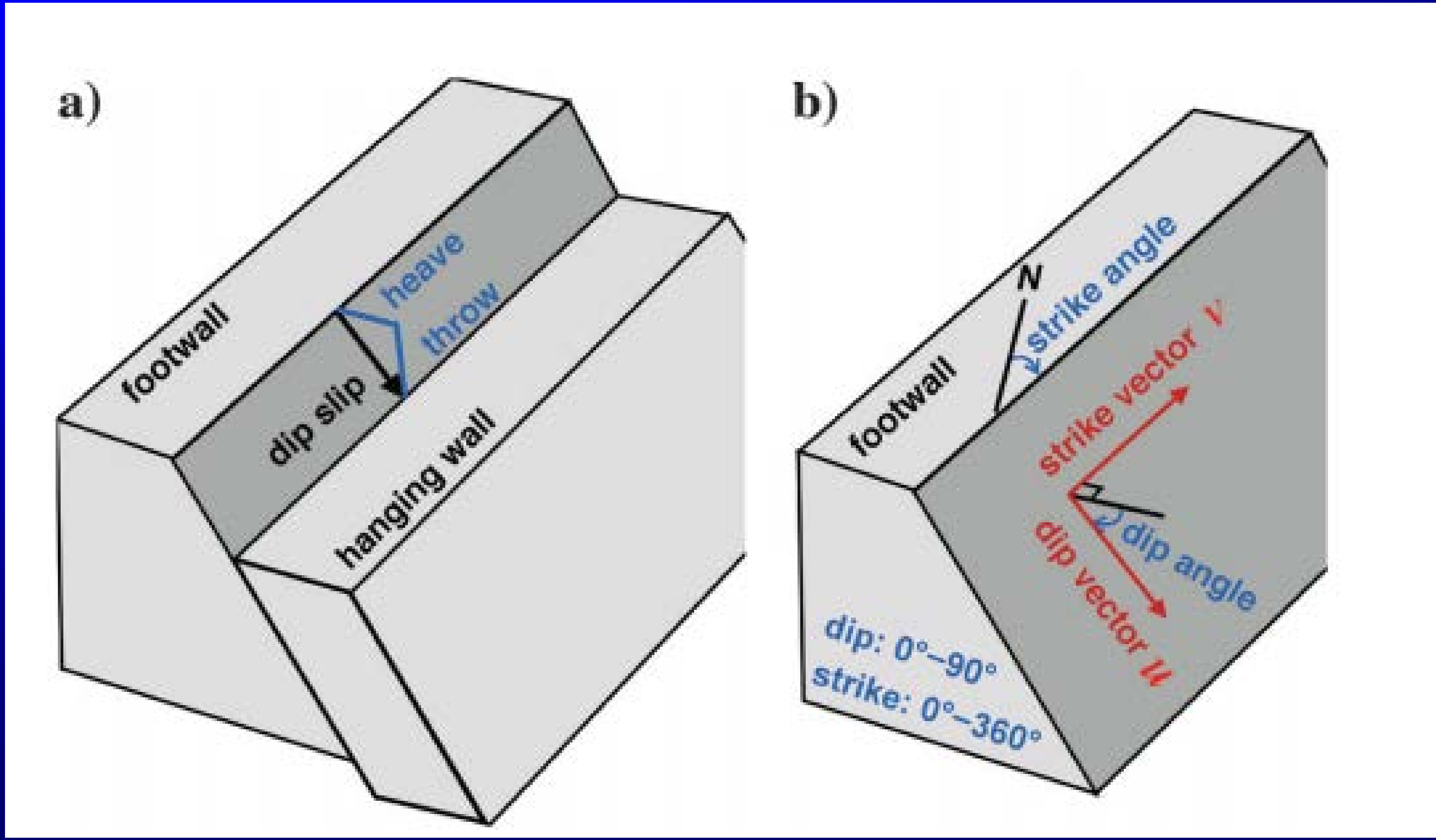
(Silva et al., 2005)

Ant-tracking applied to volumetric curvature



(Baruch et al., 2009)

Estimating fault probability, heave, and throw



(1) Computing fault images,

(2) Constructing fault samples,

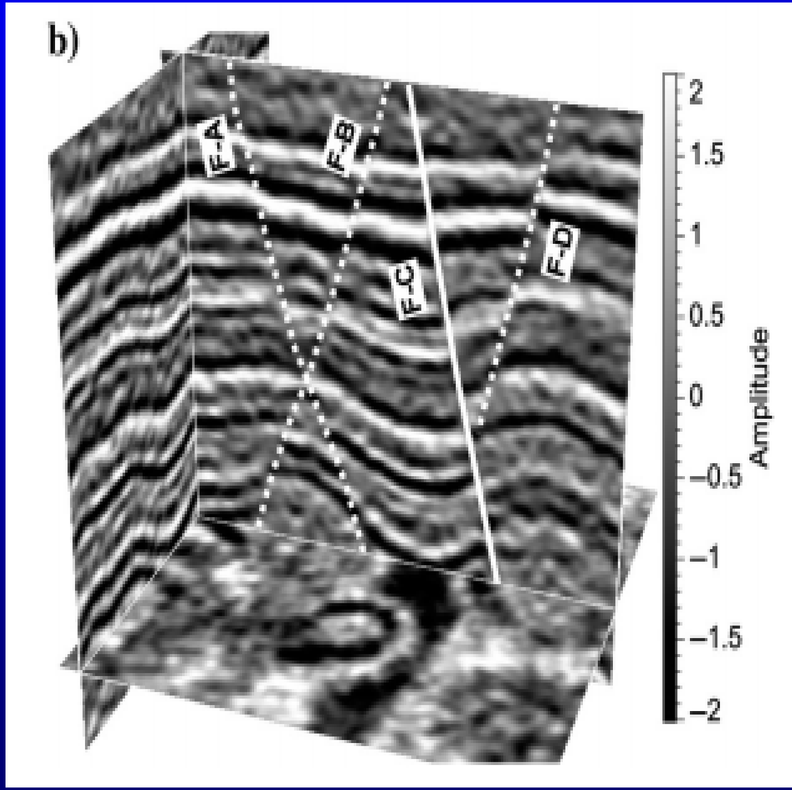
(3) Constructing fault surfaces,

(4) Estimating fault dip slips,

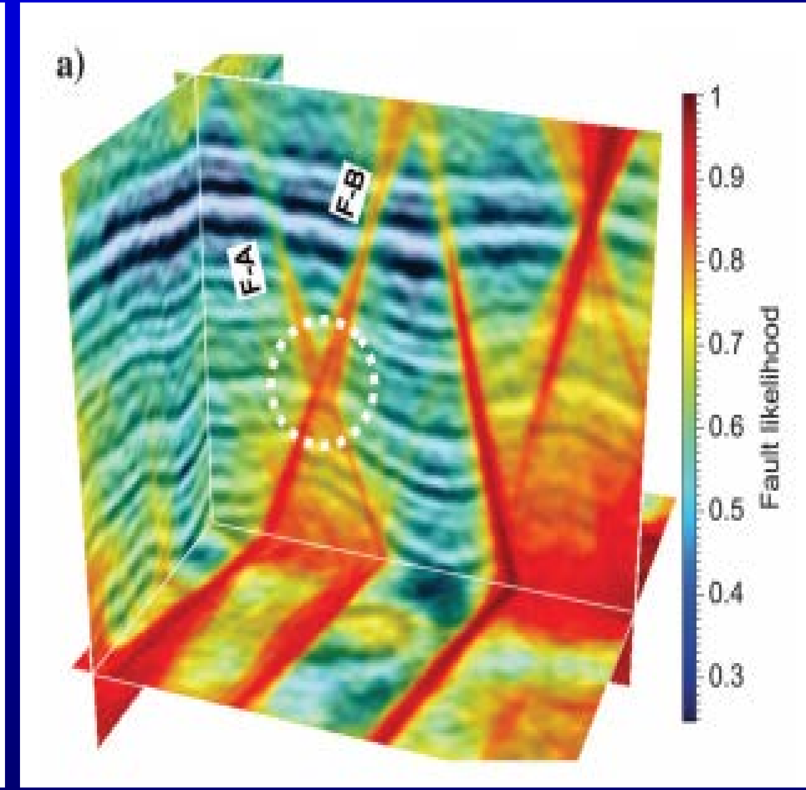
(5) Unfaulting the seismic image to assess the accuracy of those slip vectors.

(Wu and Hale, 2016)

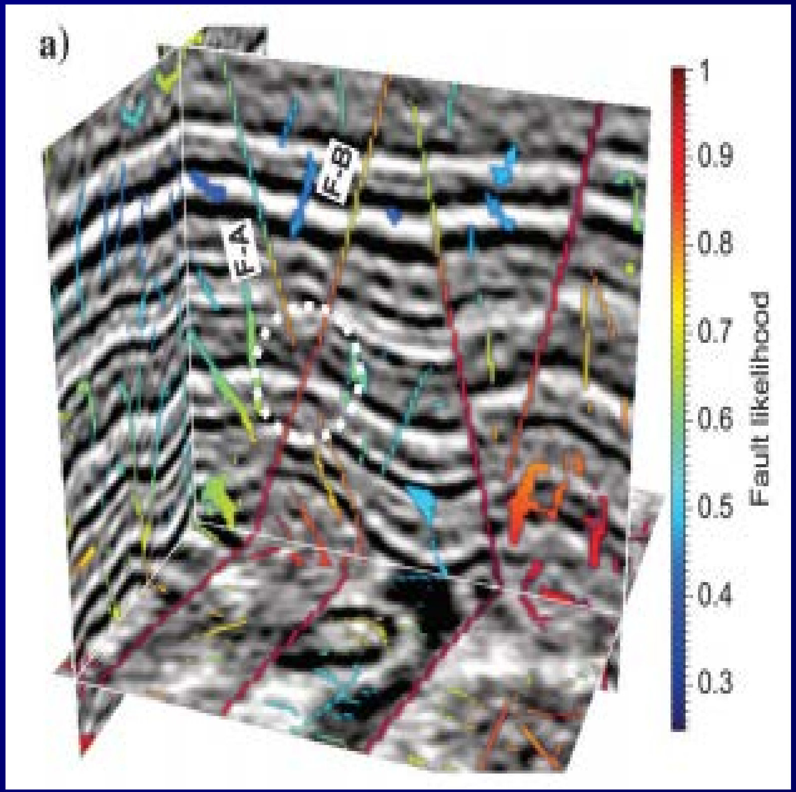
Fault likelihood using predictive error filtering



Interpreted faults



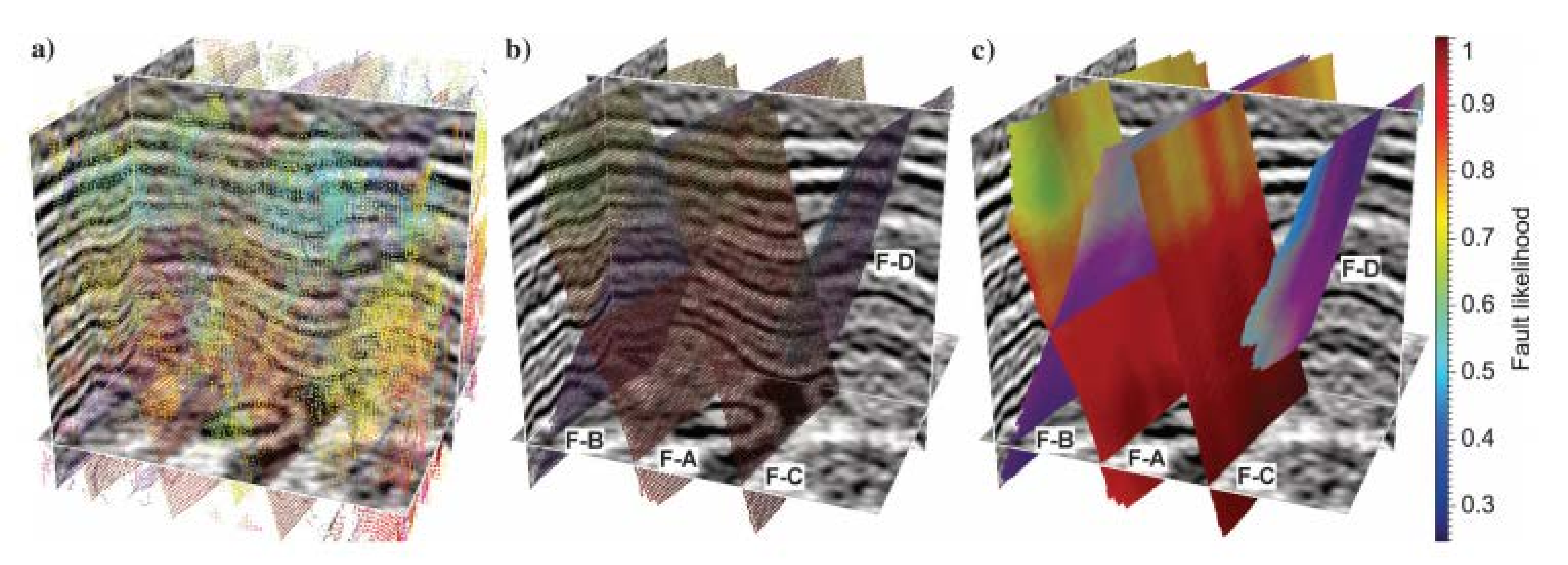
Fault likelihood



Problems with crossing faults and holes

(Wu and Hale, 2016)

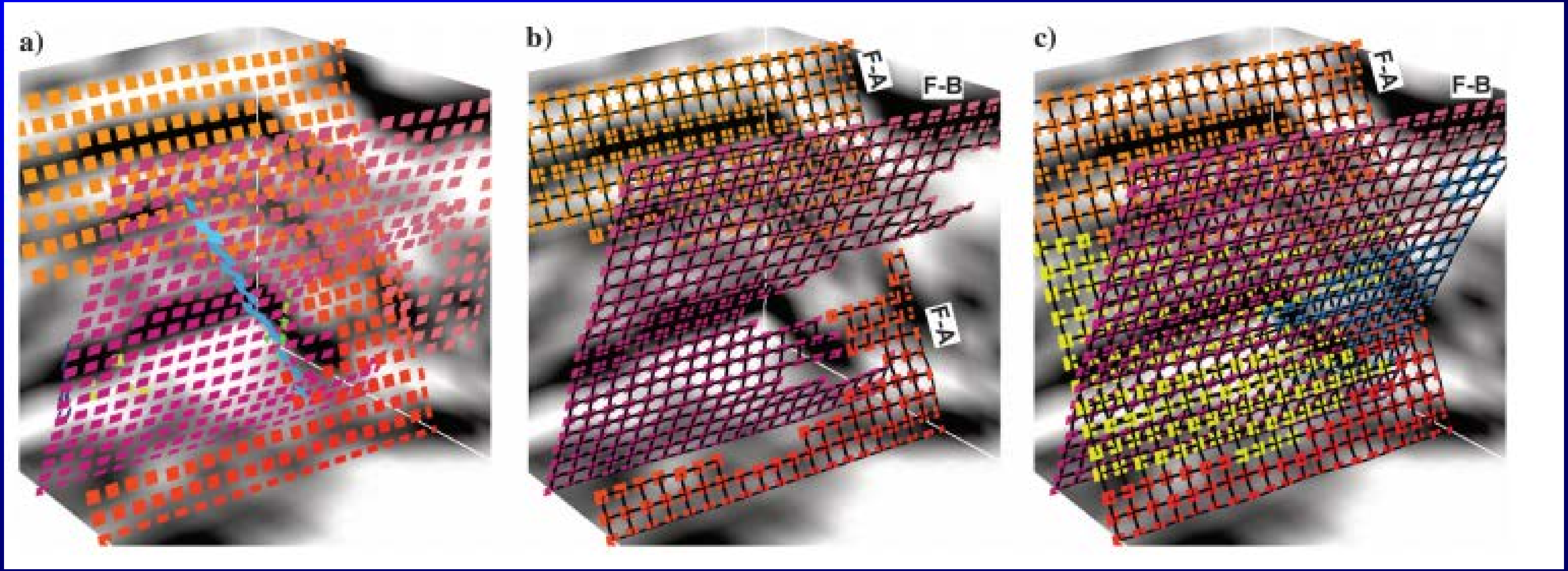
Fault likelihood using predictive error filtering



Fault squares | Linked fault squares | Filling in the holes

(Wu and Hale, 2016)

Fault likelihood using predictive error filtering



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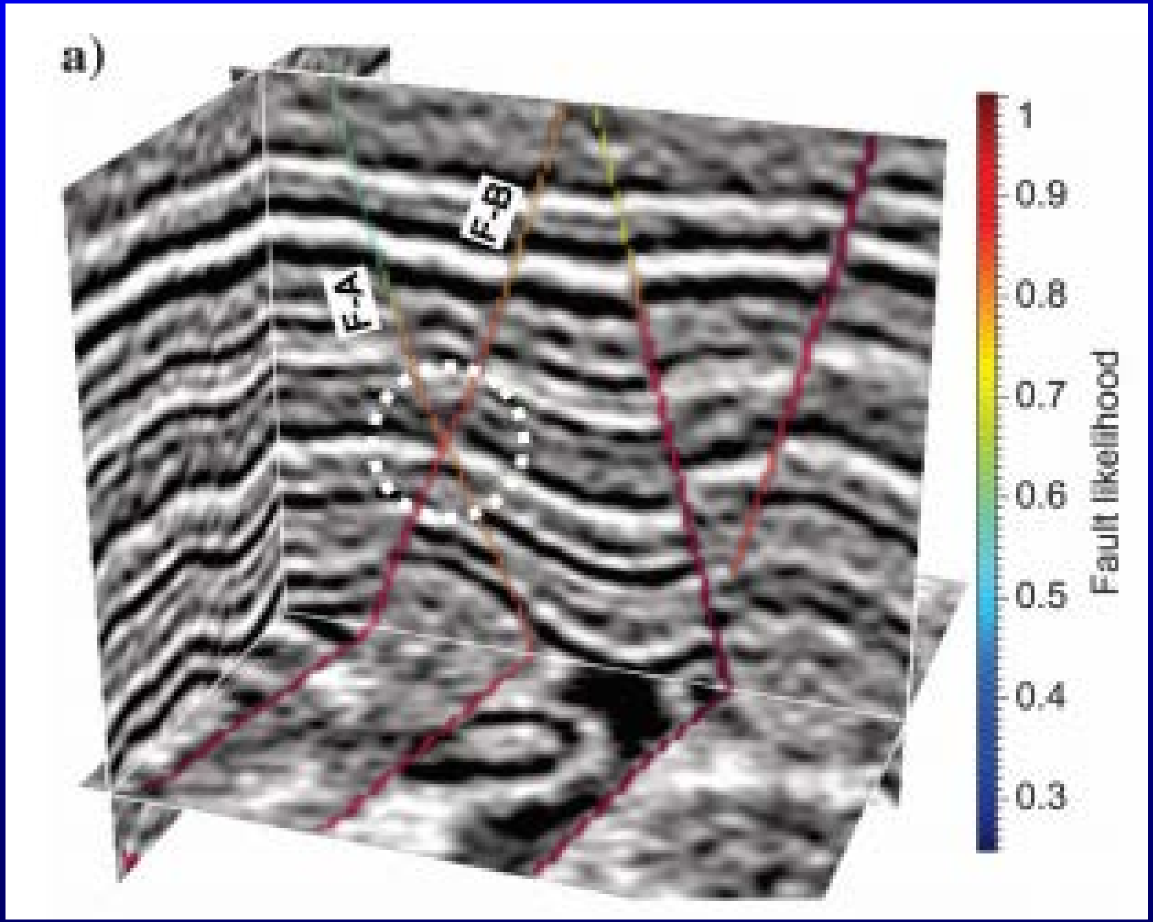
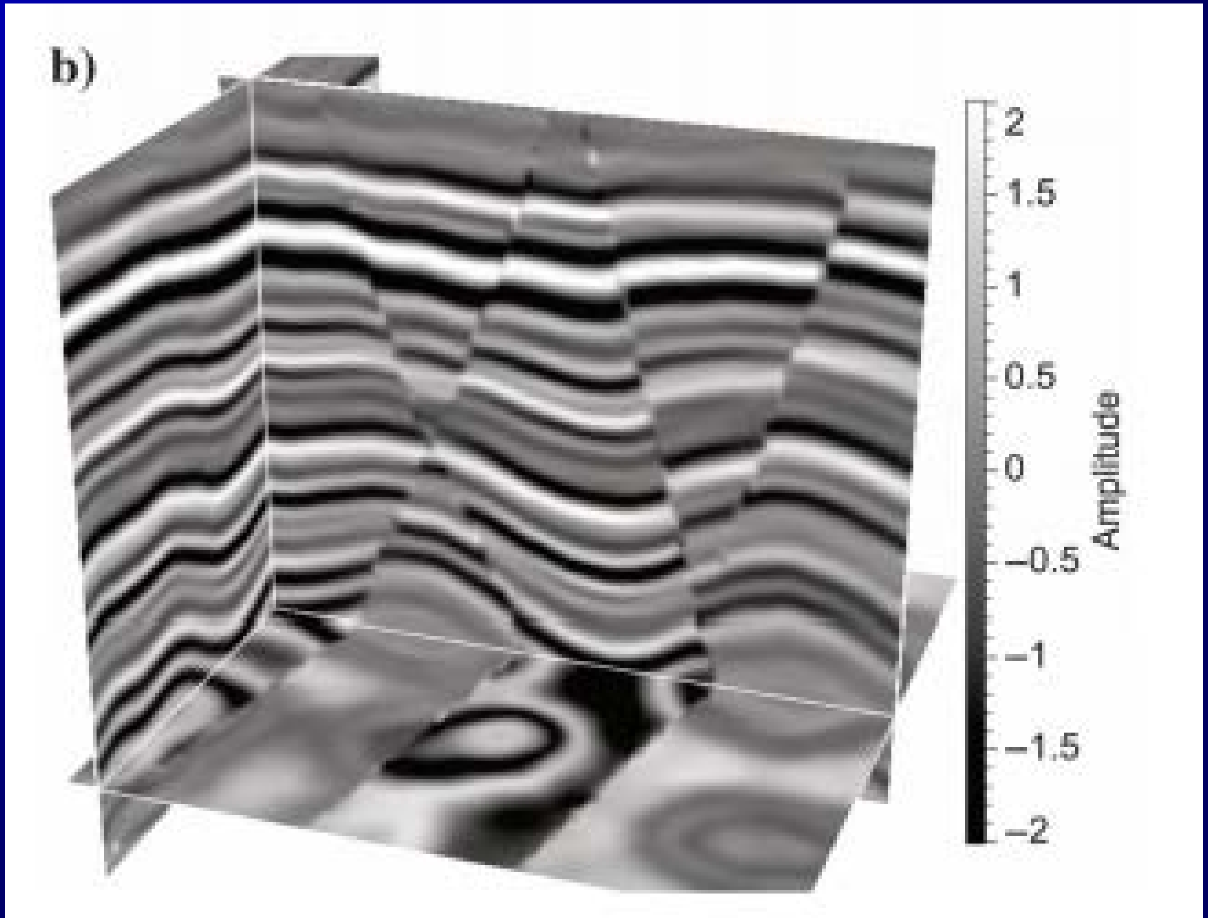


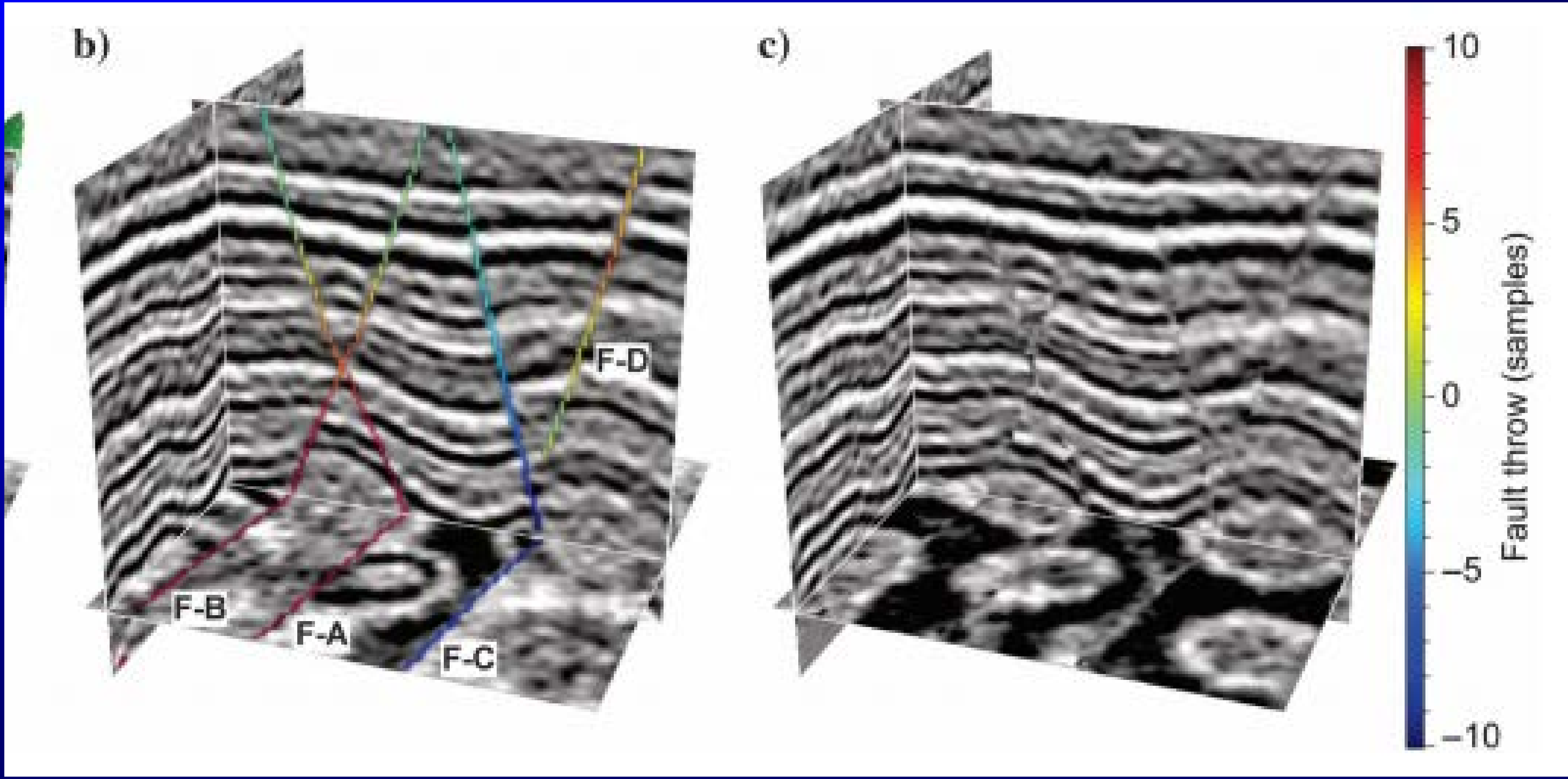
Fault likelihood



Structure-oriented filtered volume

(Wu and Hale, 2016)

Fault likelihood using predictive error filtering

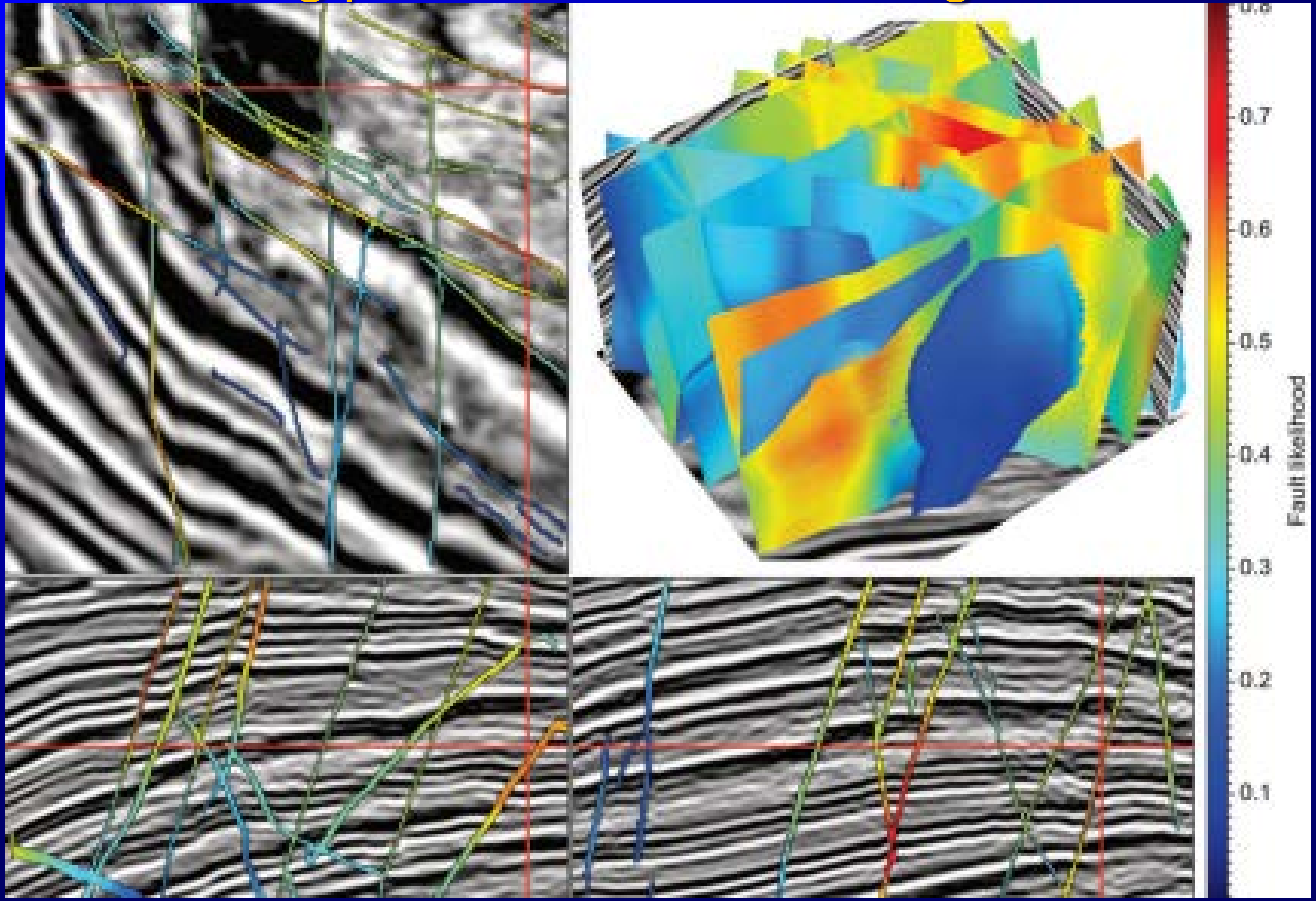


Fault likelihood

Removed fault displacement

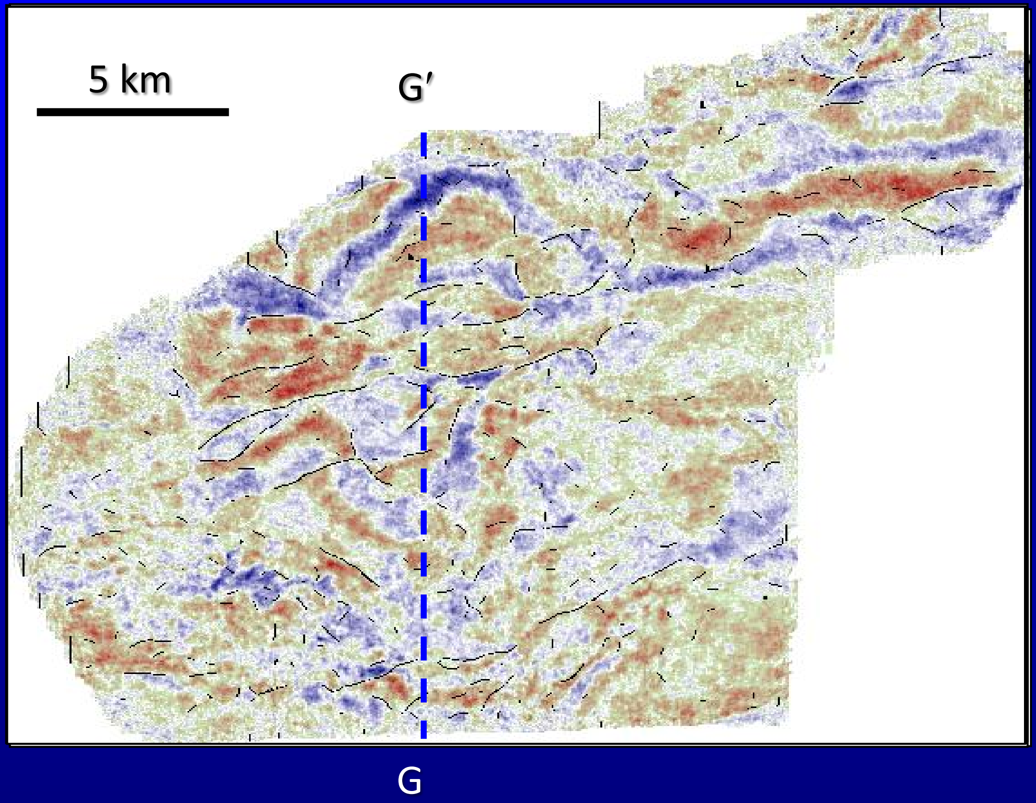
(Wu and Hale, 2016)

Fault likelihood using predictive error filtering



(Wu and Hale, 2016)

Image enhancement for fault extraction



Time slices

1. Coherence computation
2. Suppression of horizontal discontinuities
3. Image dilation
4. Image erosion.
5. Merge with seismic in workstation

(Barnes, 2006)

Fault Enhancement using a directional Laplacian of a Gaussian

- Compute a volumetric attribute sensitive to faults or axial planes
- Extract a spherical analysis window about each voxel
- Compute eigenvectors and eigenvalues of the second moment tensor
- Smooth parallel to the fault using a rotated Gaussian
- Sharpen perpendicular to the fault using a direction Laplacian of a Gaussian
- (Optionally) apply a filter to enhance or reject features parallel or perpendicular to structural dip
- Co-render sharpened planar feature with its dip magnitude and dip azimuth

Dynamics of an asteroid

Center of mass, **μ**:

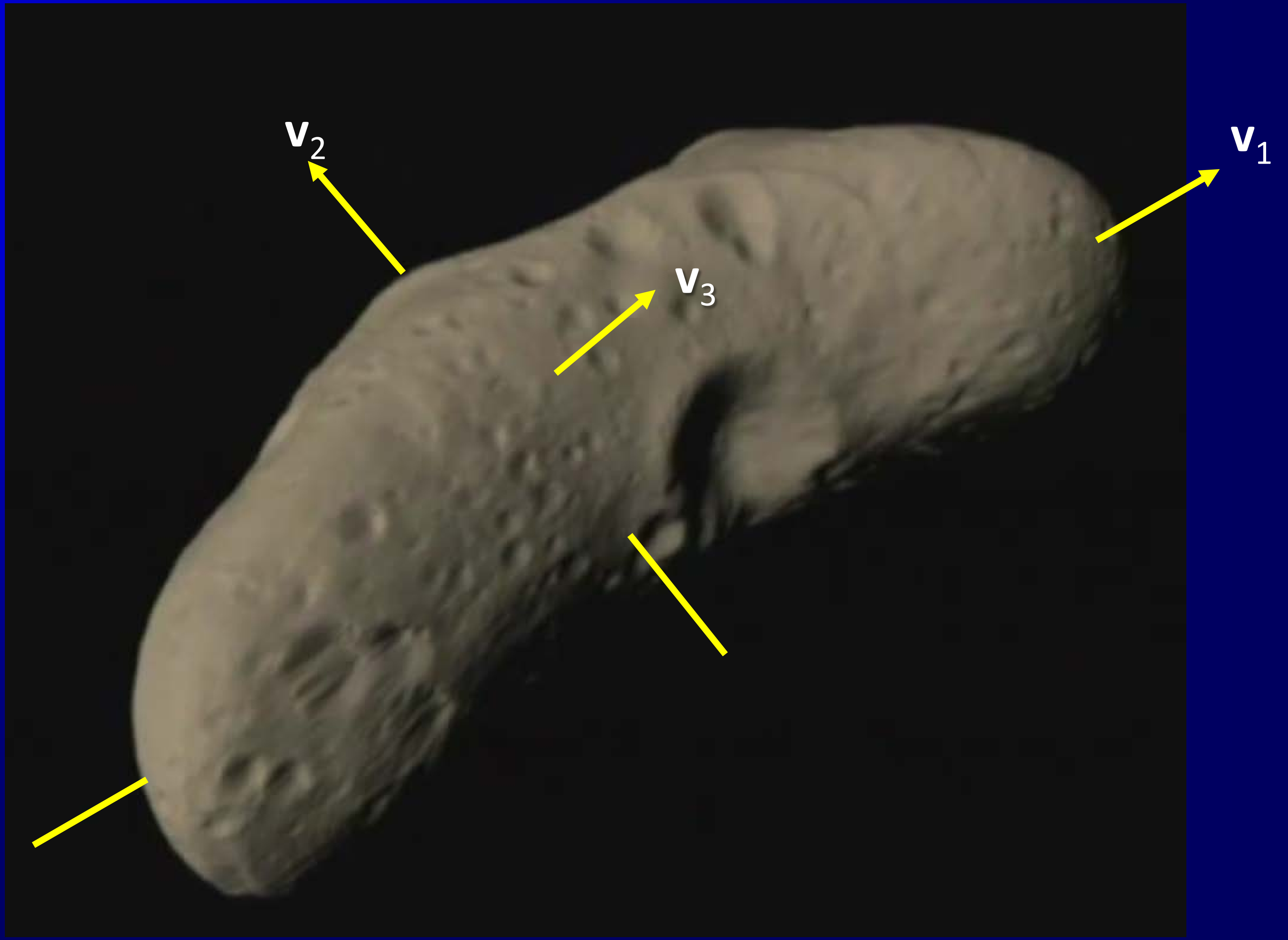
$$\mu_i = \frac{\sum_{k=1}^{K} x_{ik}\rho_k}{\sum_{k=1}^{K} \rho_k}$$

Inertia tensor, **I**:

$$I_{ij} = \frac{\sum_{k=1}^{K} (x_{ik} - \mu_i)(x_{jk} - \mu_j)\rho_k}{\sum_{k=1}^{K} \rho_k}$$

Principal axes of inertia tensor, $\mathbf{v}_n$:

$$\sum_{j=1}^{3} I_{ij} v_{jn} = \lambda_n v_{in}$$



(https://svs.gsfc.nasa.gov/2061)

Dynamics of a cloud of energy-weighted fault probability anomalies, $ep \equiv e(1-c)$

Center of mass, **μ**:

$$\mu_i = \frac{\sum_{k=1}^{K} x_{ik} e_k p_k}{\sum_{k=1}^{K} e_k p_k}$$

Inertia tensor, **I**:

$$I_{ij} = \frac{\sum_{k=1}^{K} (x_{ik} - \mu_i)(x_{jk} - \mu_j) e_k p_k}{\sum_{k=1}^{K} e_k p_k}$$

Principal axes of inertia tensor, $\mathbf{v}_n$:

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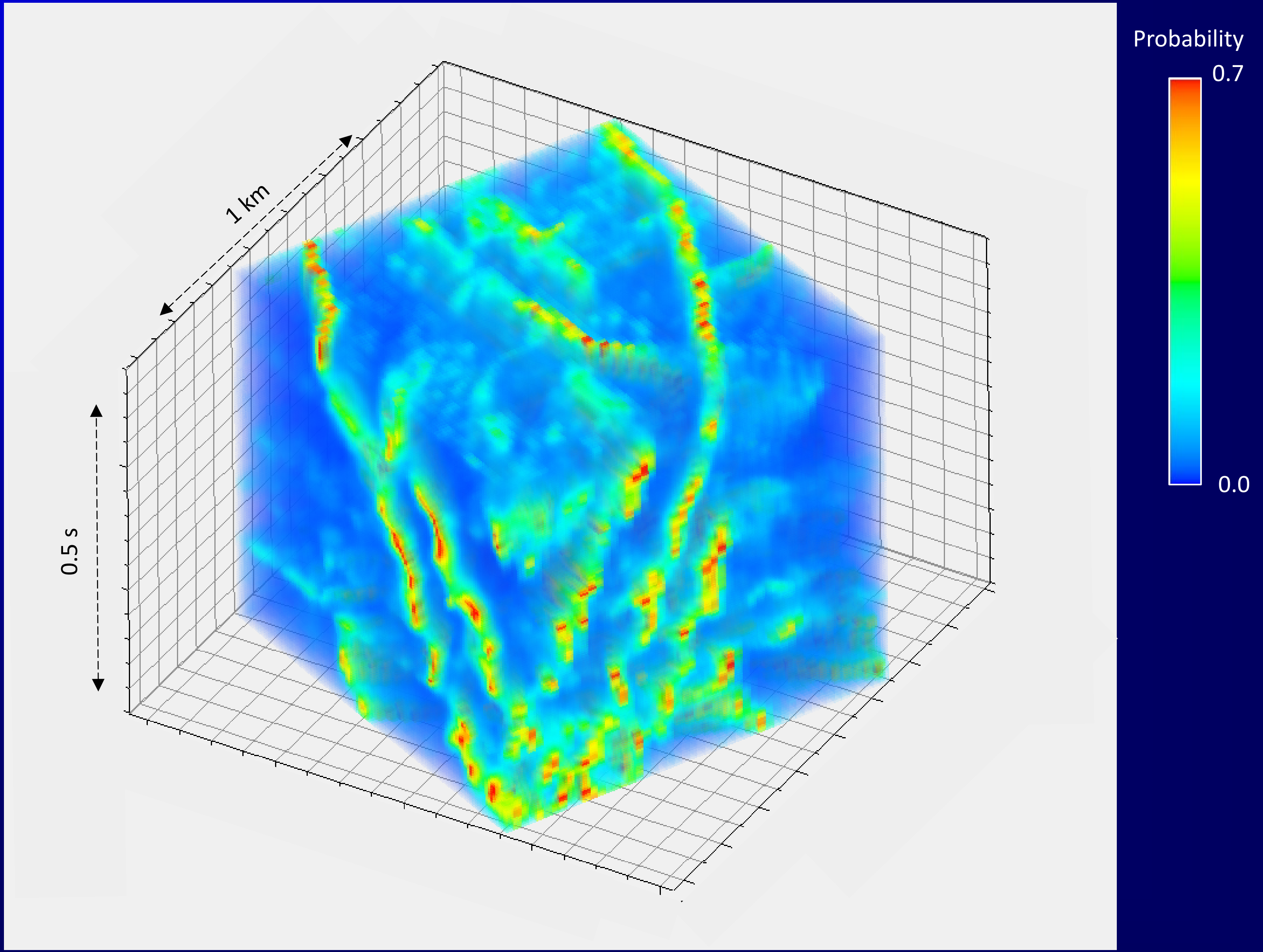
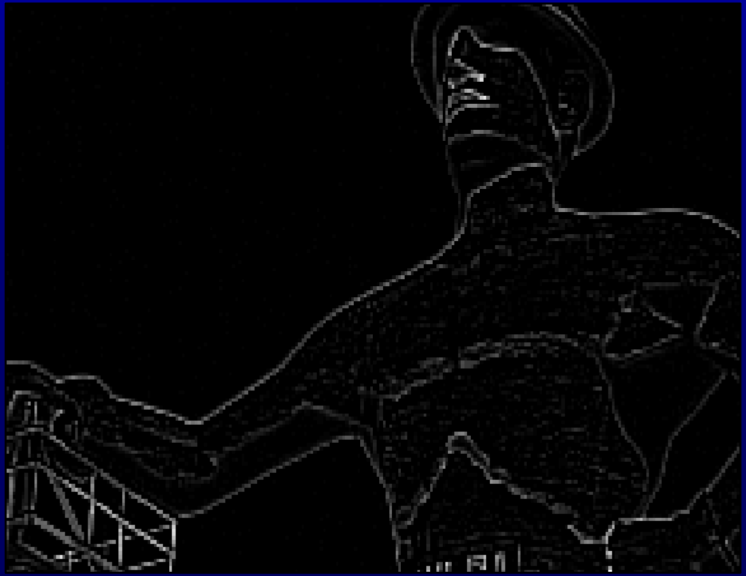


Edge enhancement filters applied to a photo

Original

Gaussian

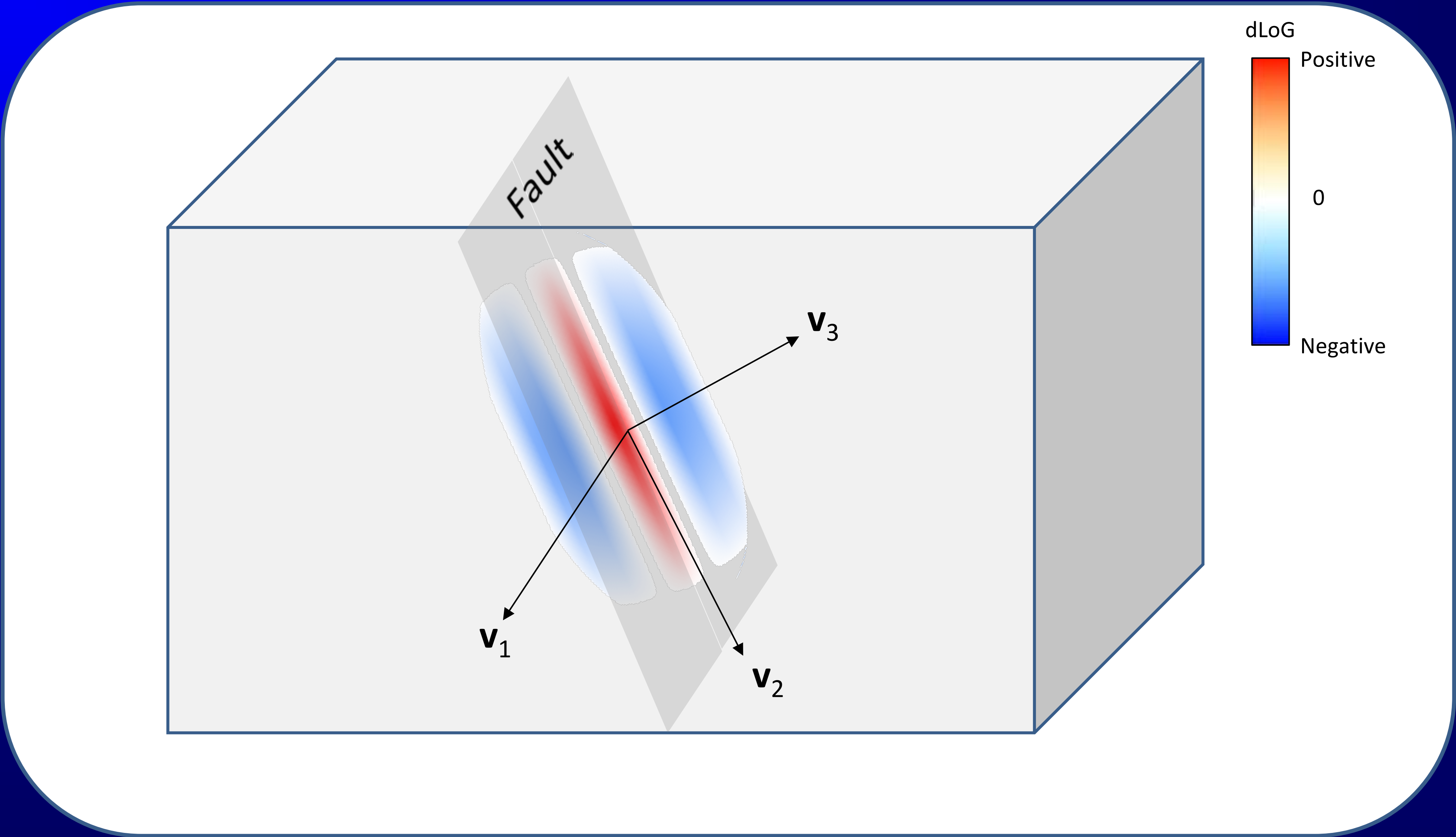
Laplacian



Laplacian of Gaussian

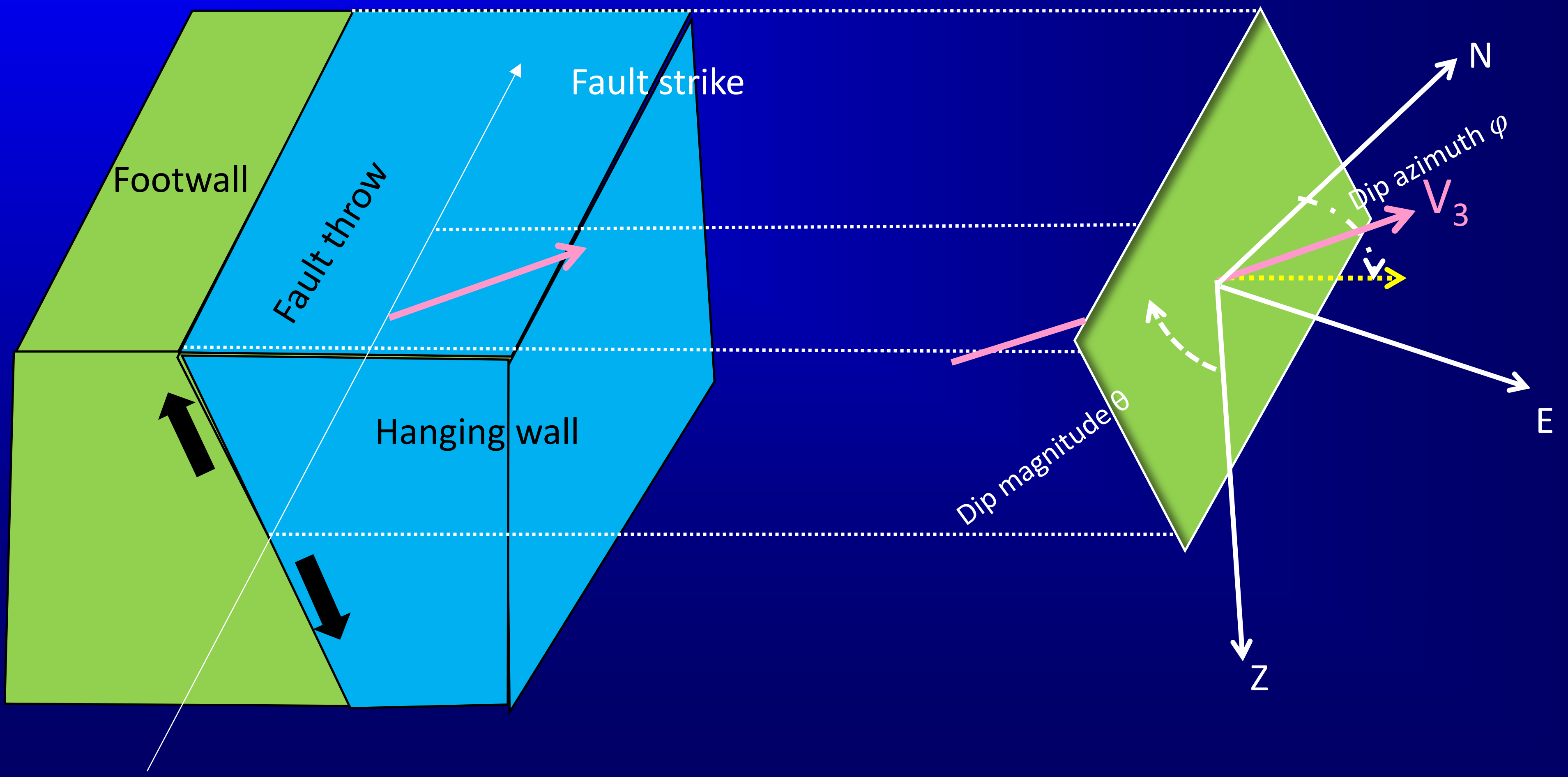
(Marfurt, 2018)

The 3D directional Laplacian of a Gaussian operator

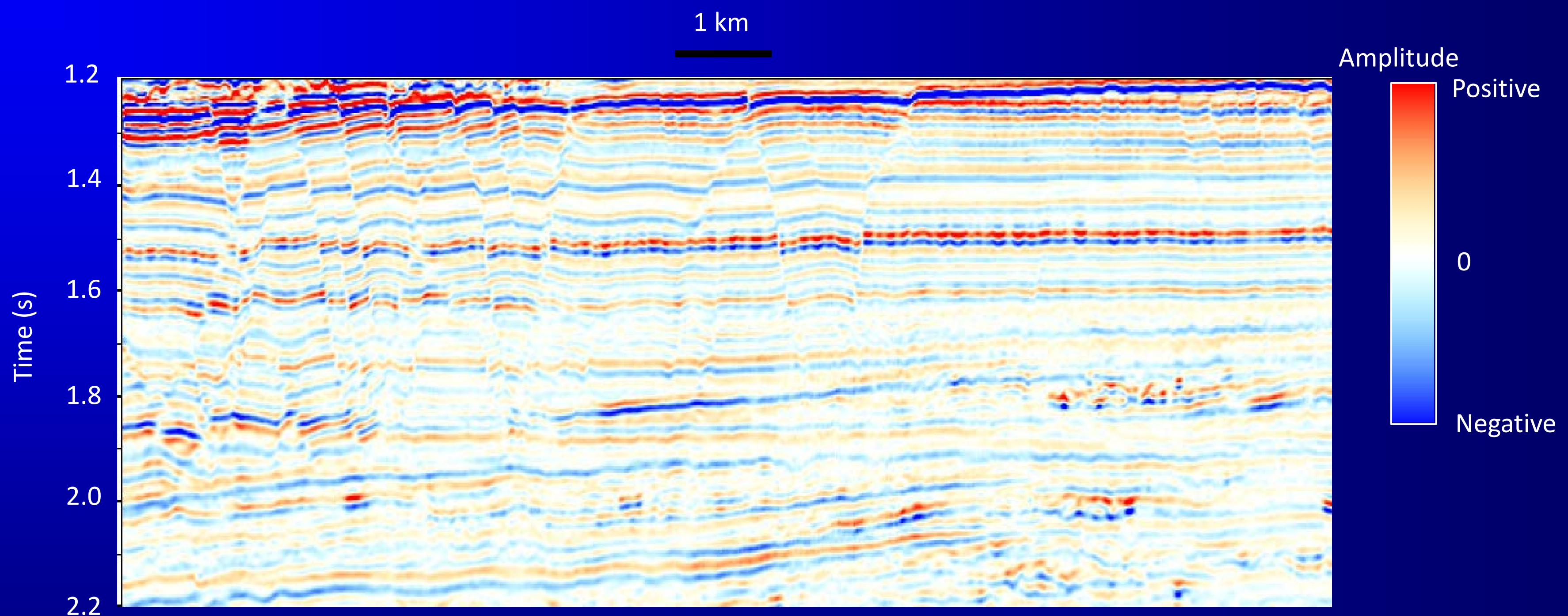


(Marfurt, 2018)

Normal fault



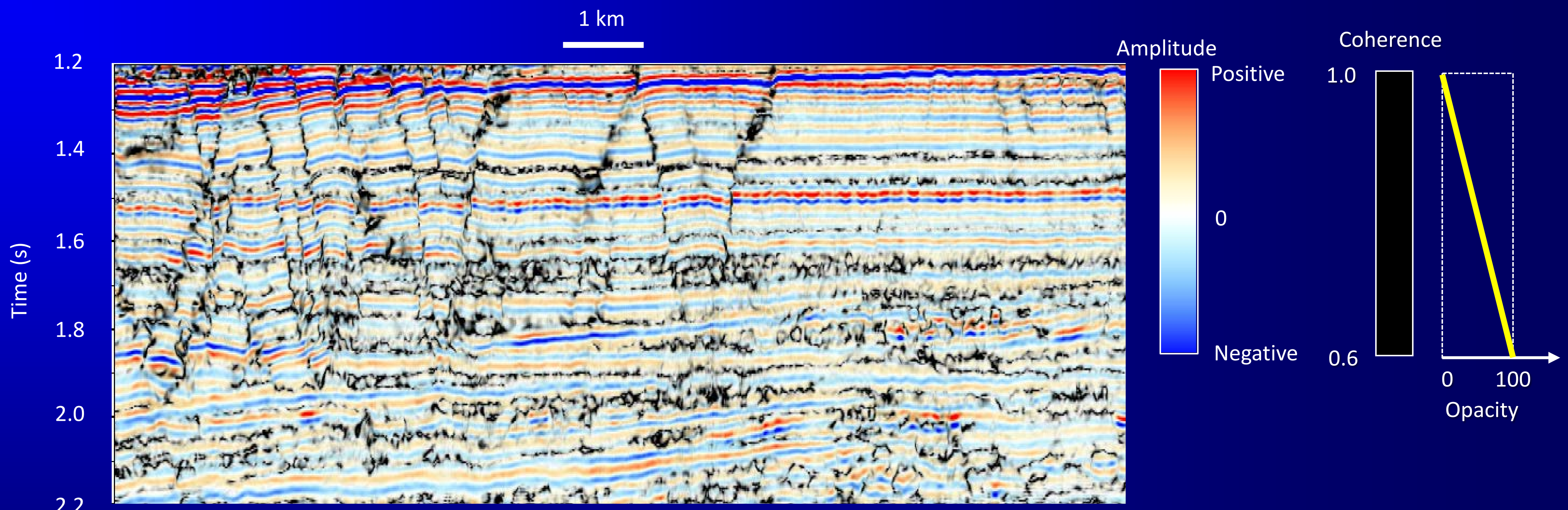
Iterative fault enhancement



Seismic amplitude

(Machado et al., 2016)

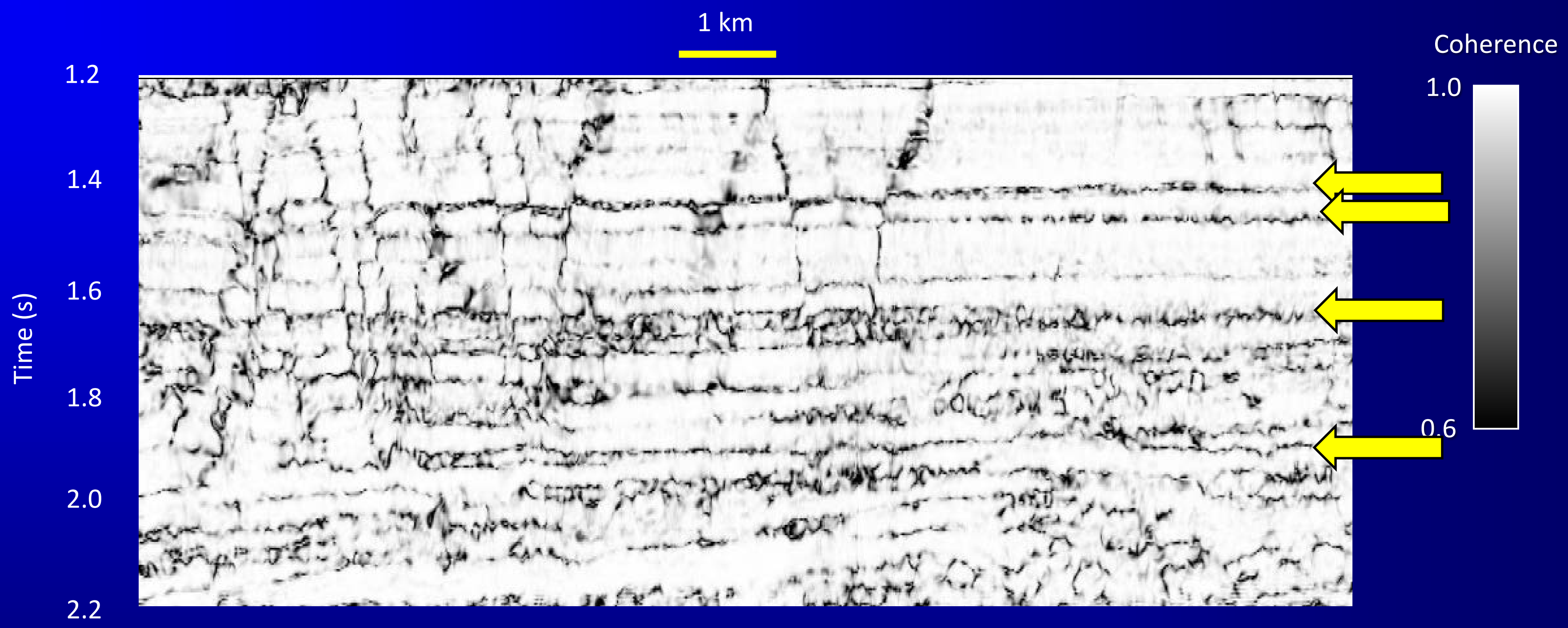
Iterative fault enhancement



Co-rendered seismic amplitude and original coherence
(5 traces, 1 complex sample)

(Machado et al., 2016)

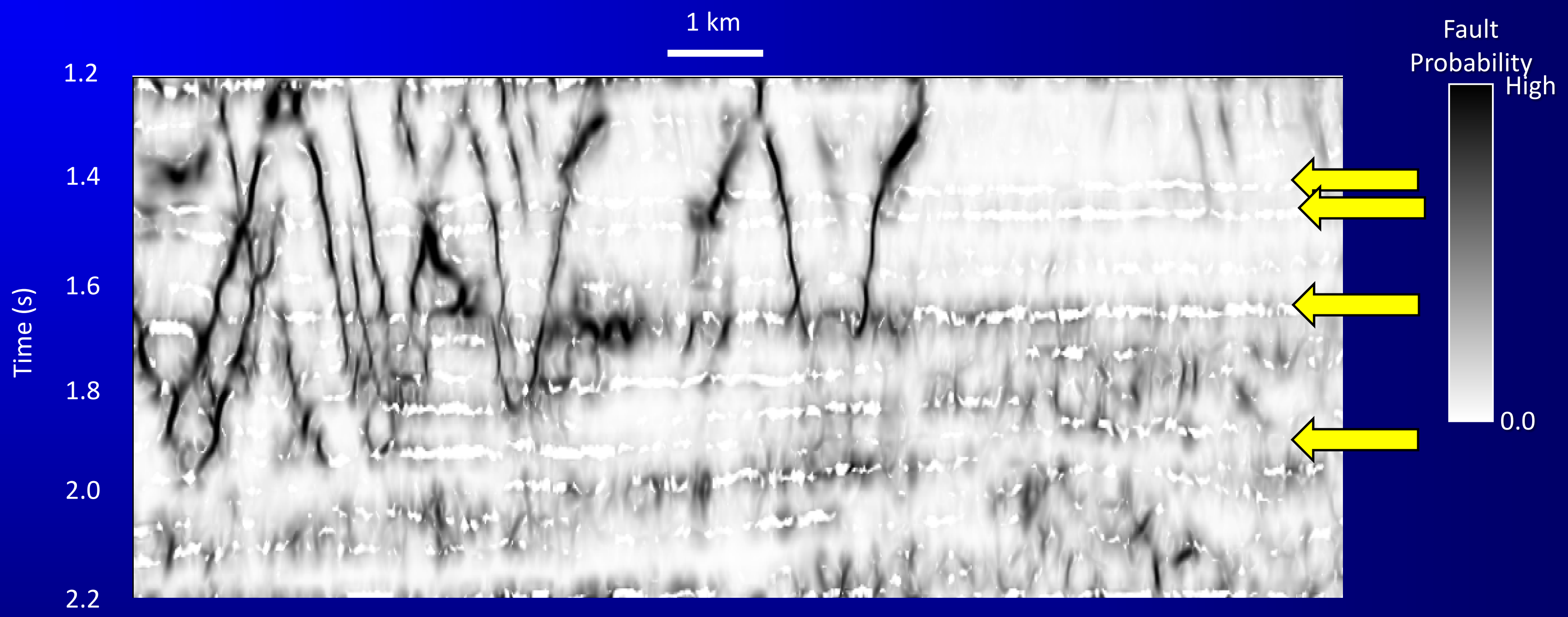
Iterative fault enhancement



Original coherence
(5 traces, 1 complex sample)

(Machado et al., 2016)

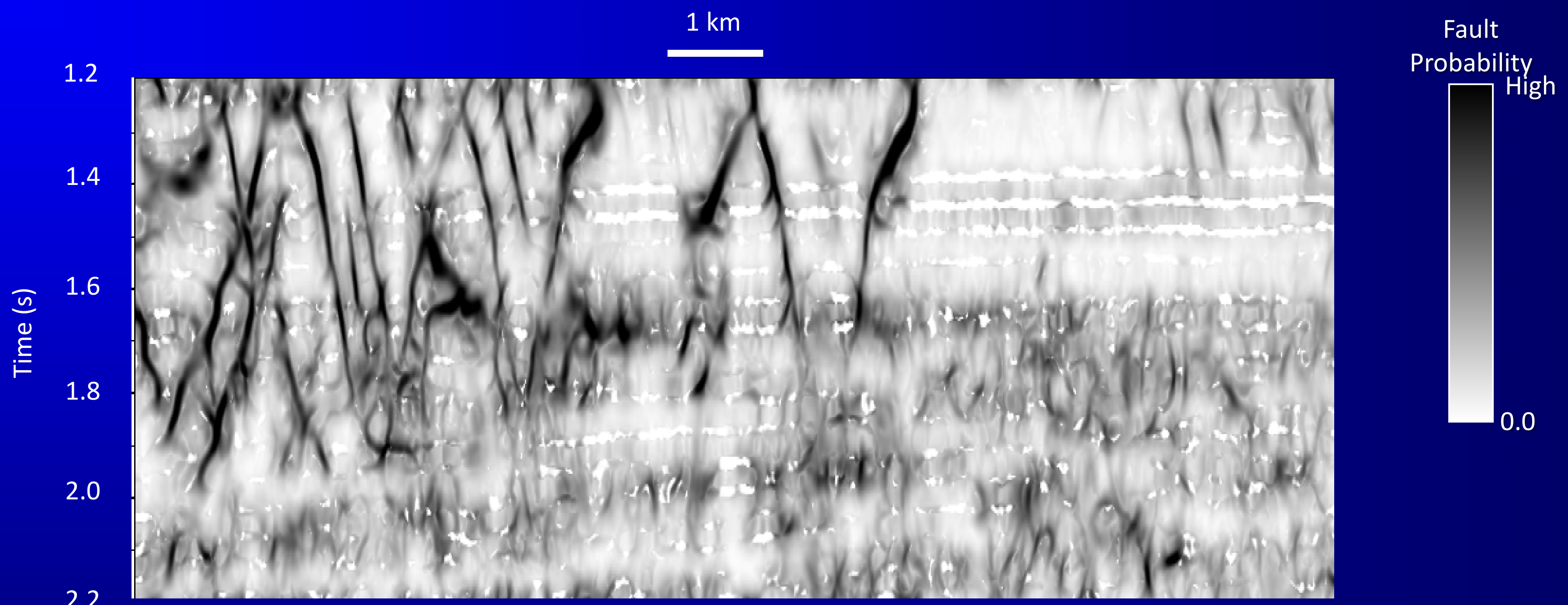
Iterative fault enhancement



Fault probability (iteration 1)

(Machado et al., 2016)

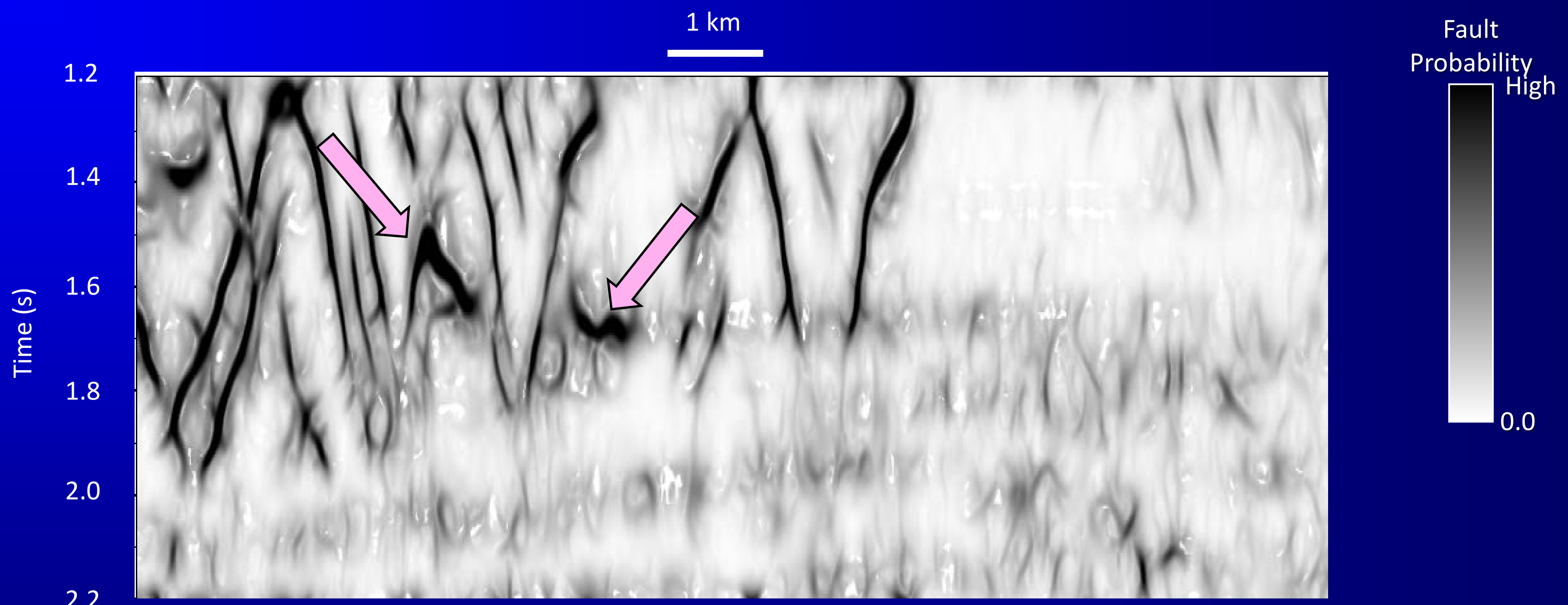
Iterative fault enhancement



Fault probability (iteration 2)

(Machado et al., 2016)

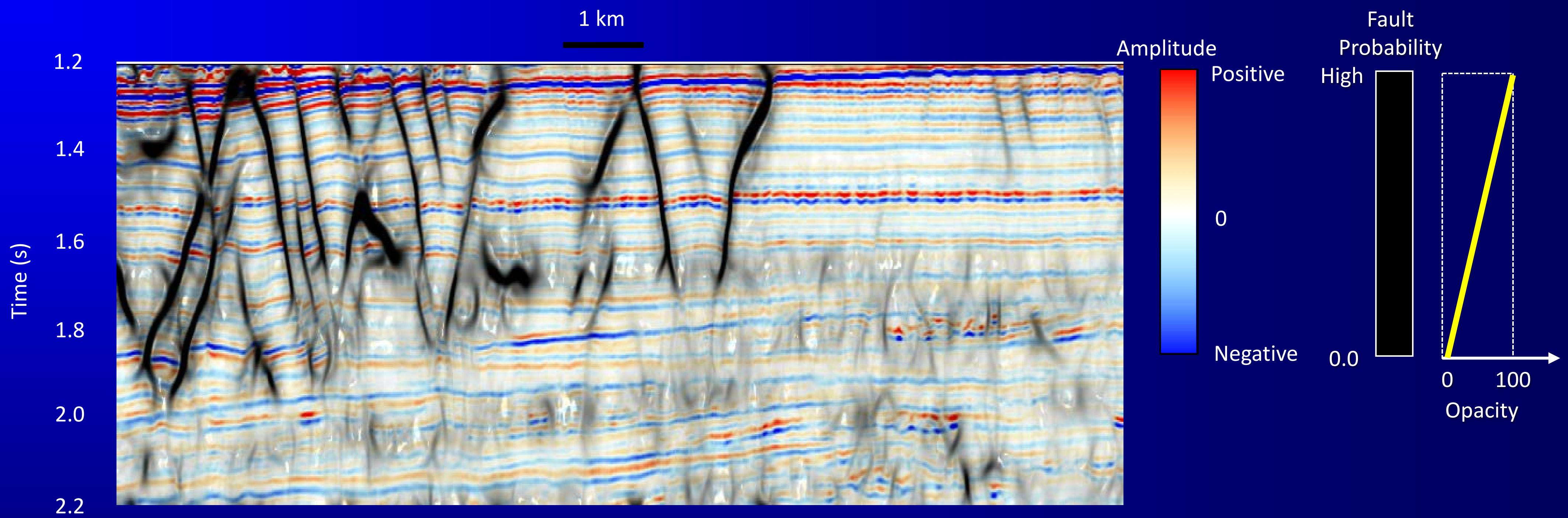
Iterative fault enhancement



Fault probability (iteration 3)

(Machado et al., 2016)

Iterative fault enhancement

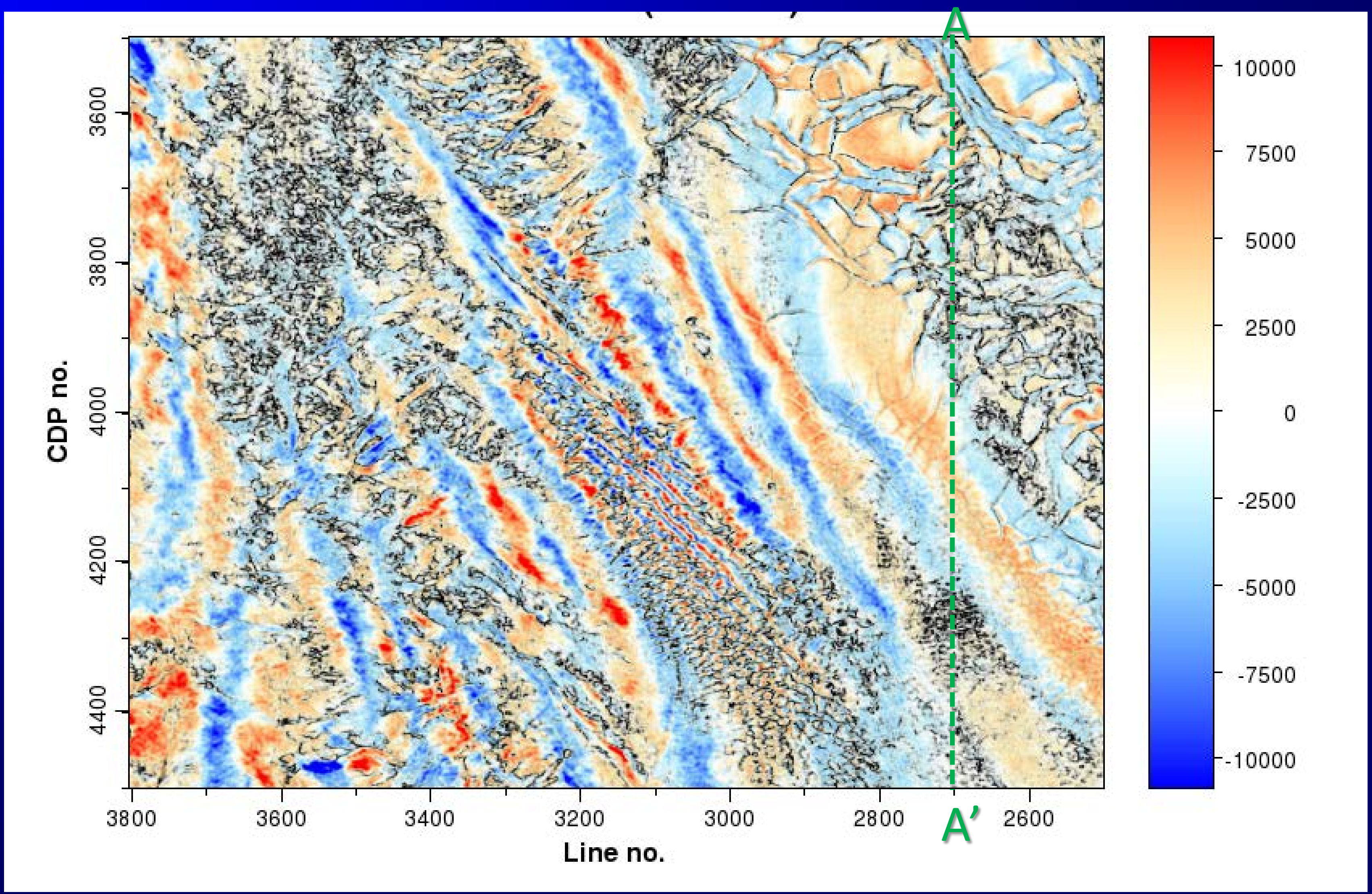


Co-rendered seismic amplitude and fault probability iteration 3

(Machado et al., 2016)

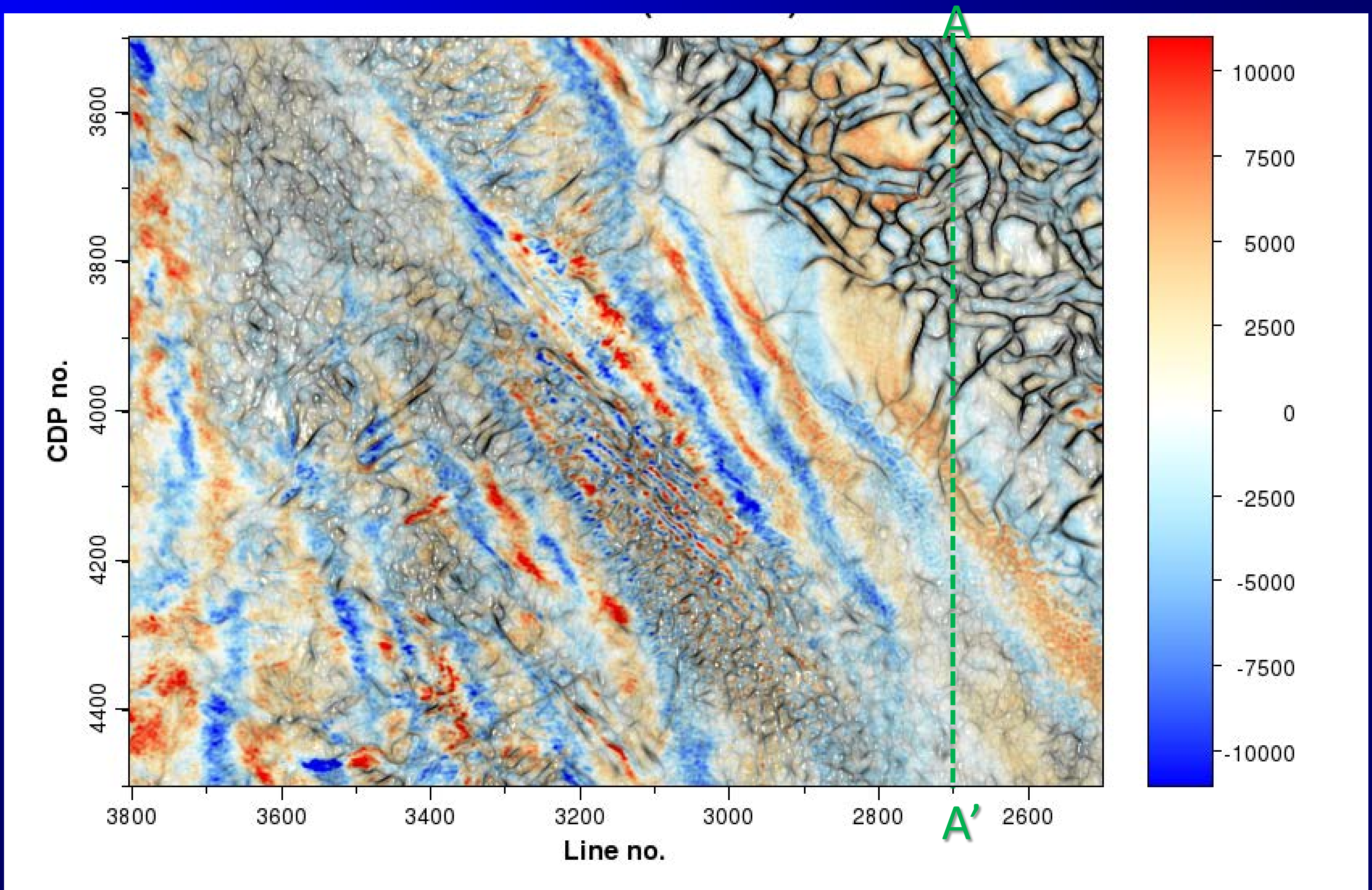
Iterative fault enhancement

Corendered seismic amplitude and original coherence (5 traces, 1 complex sample)

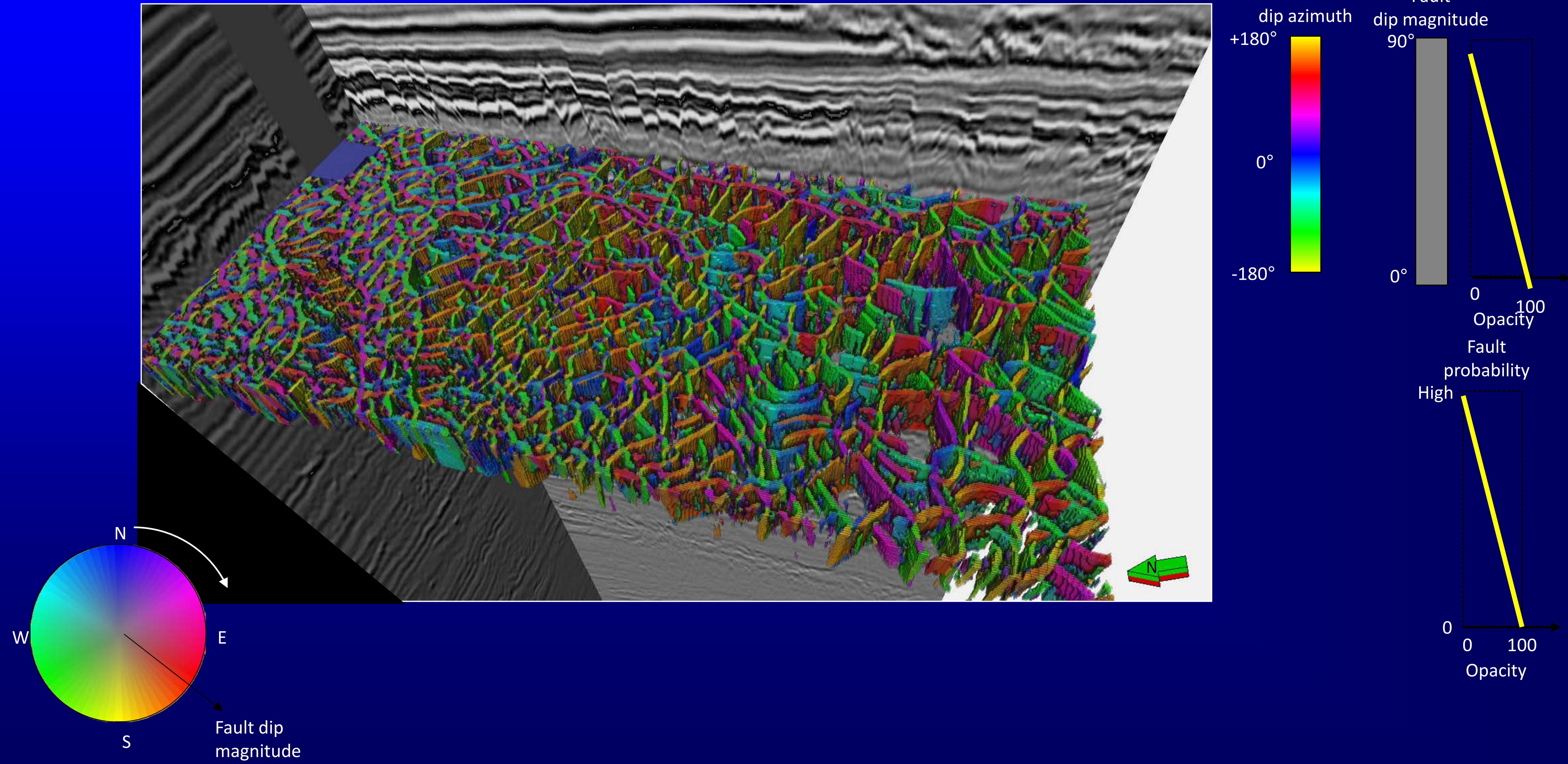


Iterative fault enhancement

Corendered seismic amplitude and fault probability iteration 3

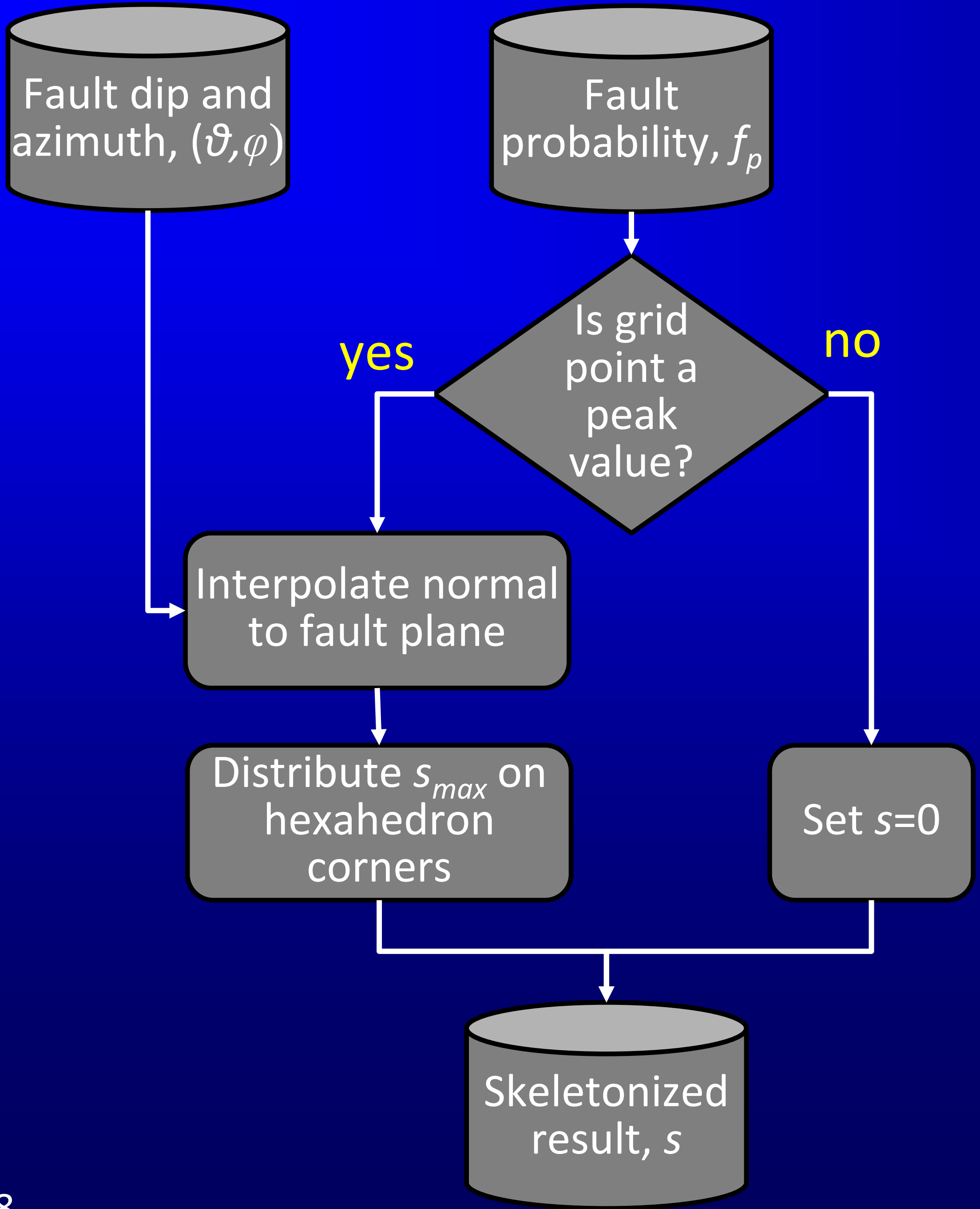


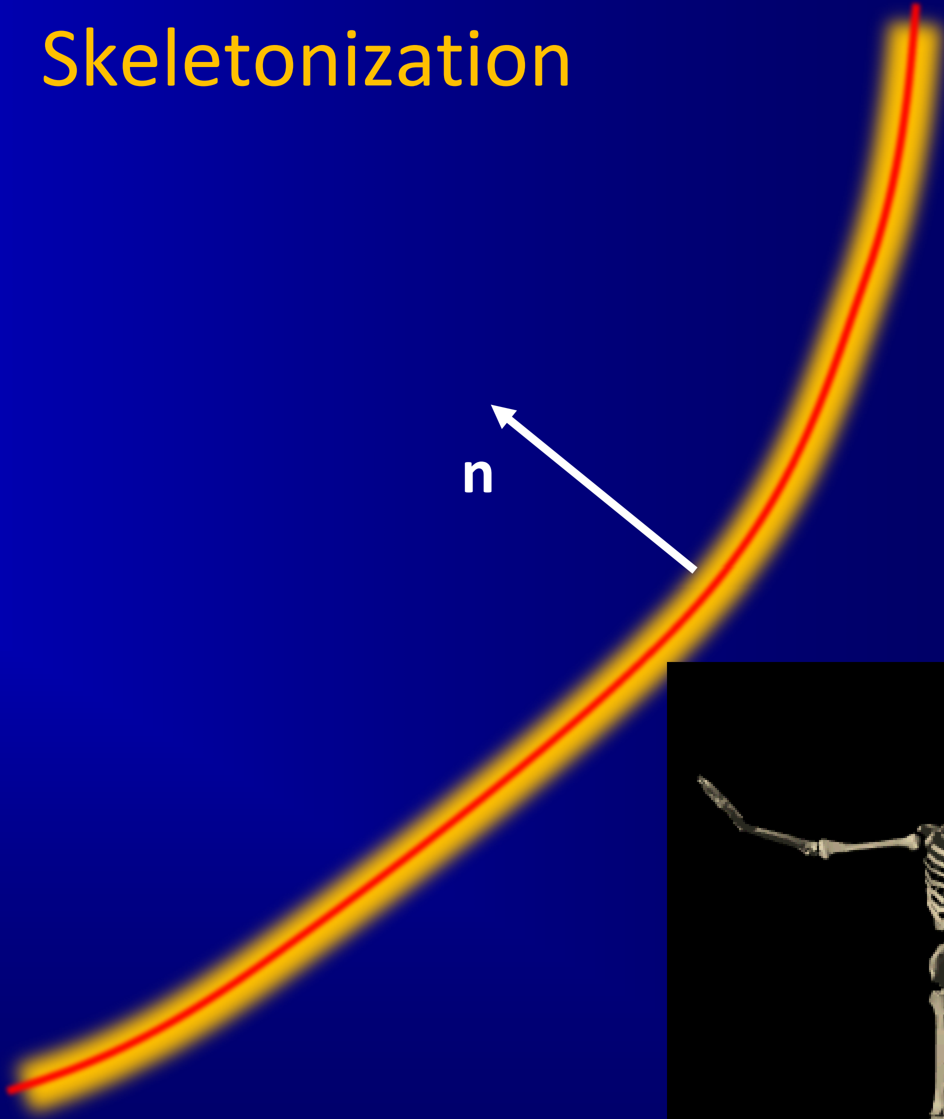
Polygonal faulting (using a box probe)



(Machado et al., 2016)

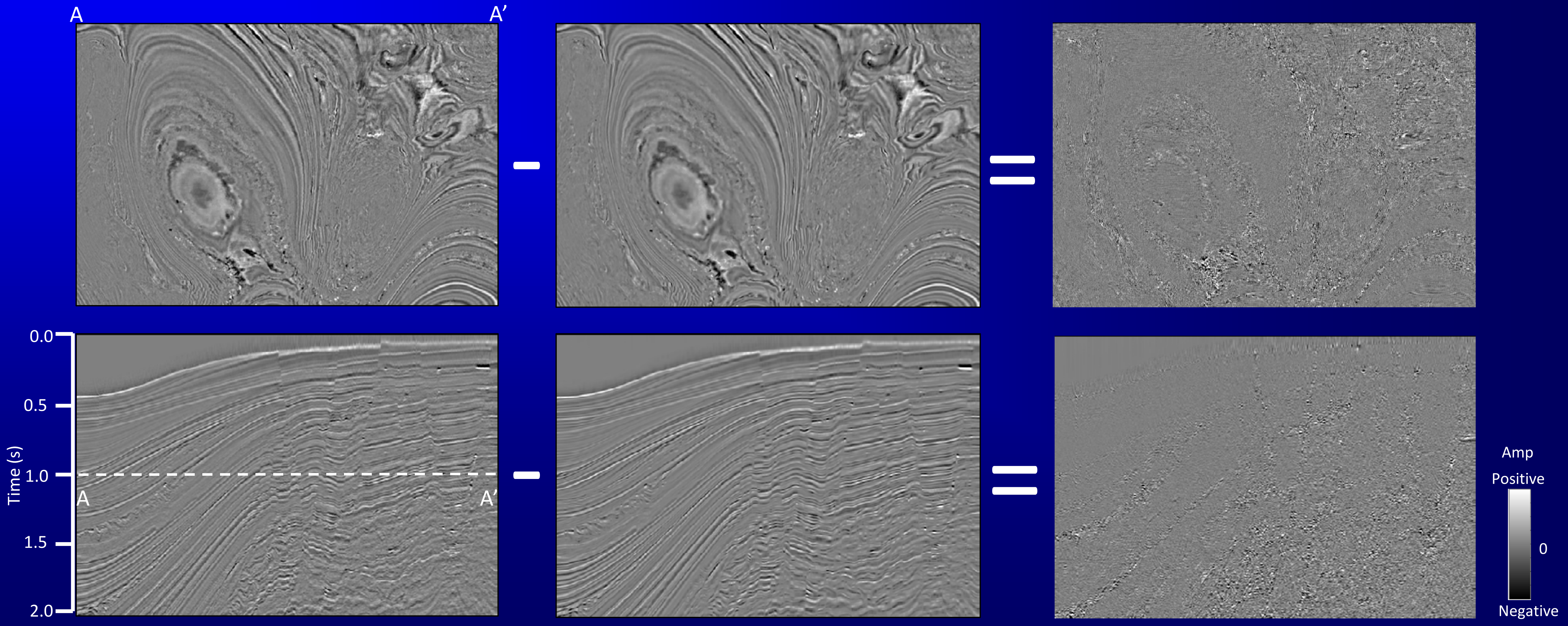
Skeletonization





(Qi et al., 2017)

Example 1: Gulf of Mexico



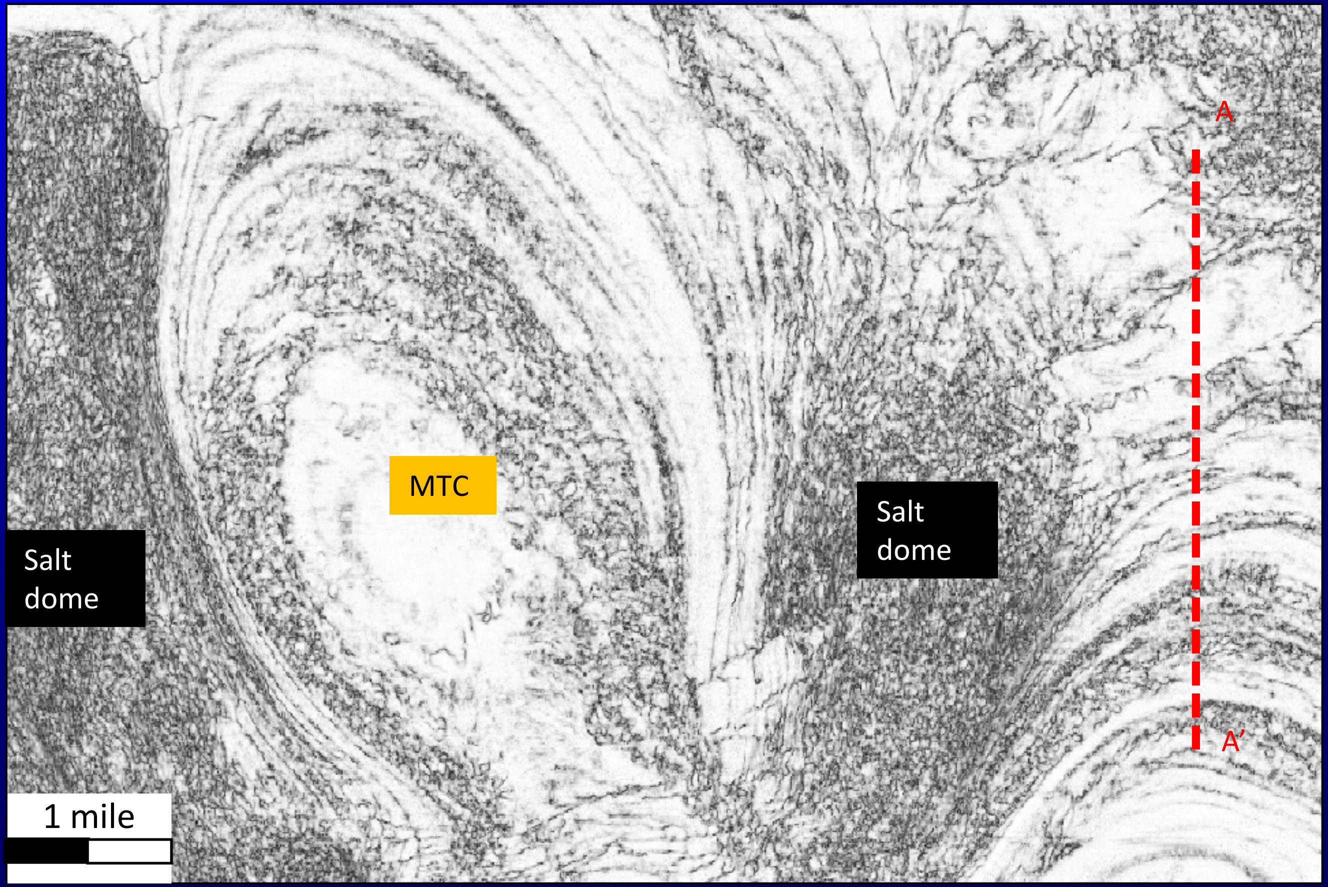
Original amplitude − SOF amplitude = Rejected noise

(Courtesy Jie Qi, OU)

Example 1: Gulf of Mexico

Coherence (original)

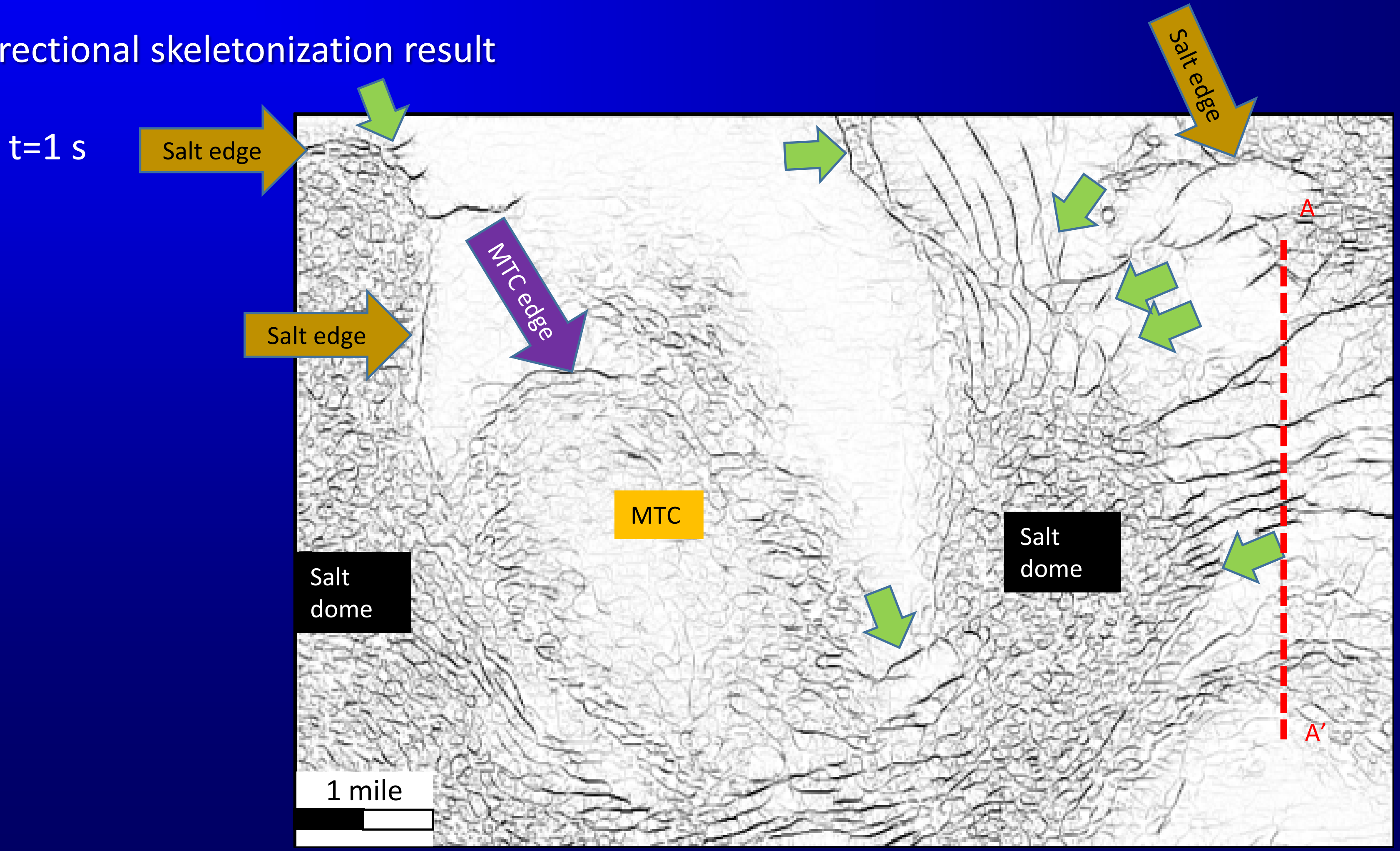
t=1 s



(Courtesy Jie Qi, OU)

Example 1: Gulf of Mexico

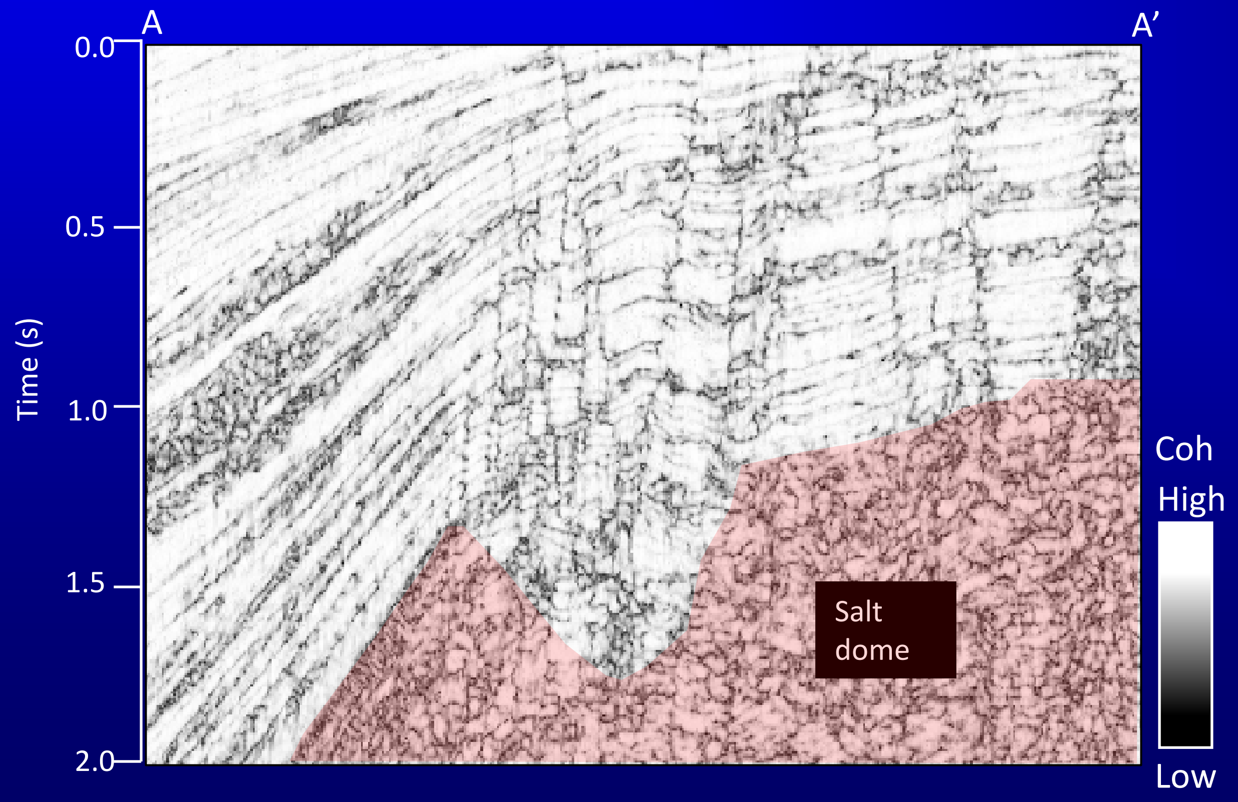
Directional skeletonization result



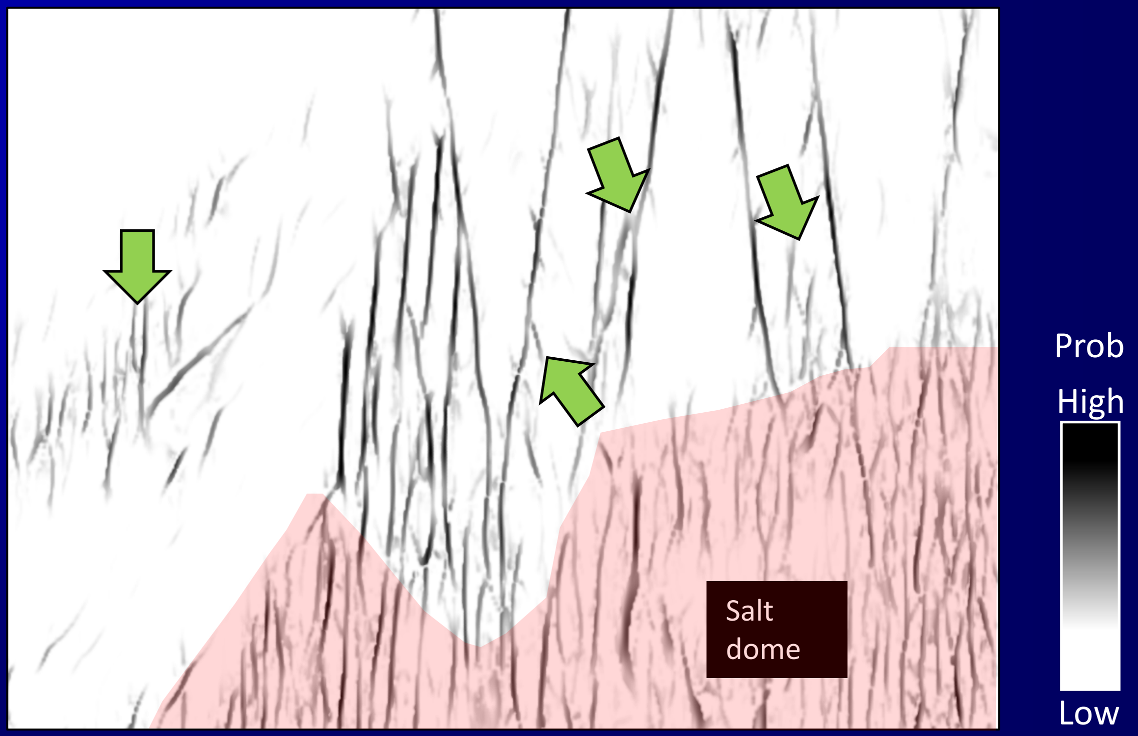
(Courtesy Jie Qi, OU)

Example 1: Gulf of Mexico

Coherence



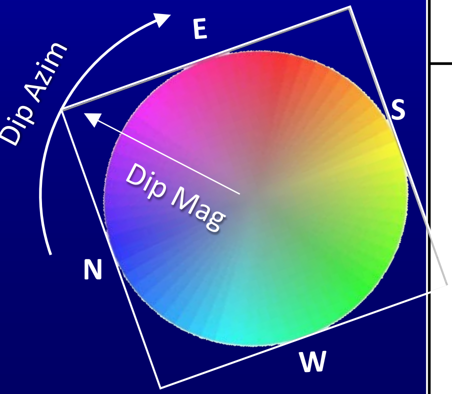
Directional LoG skeletonization result

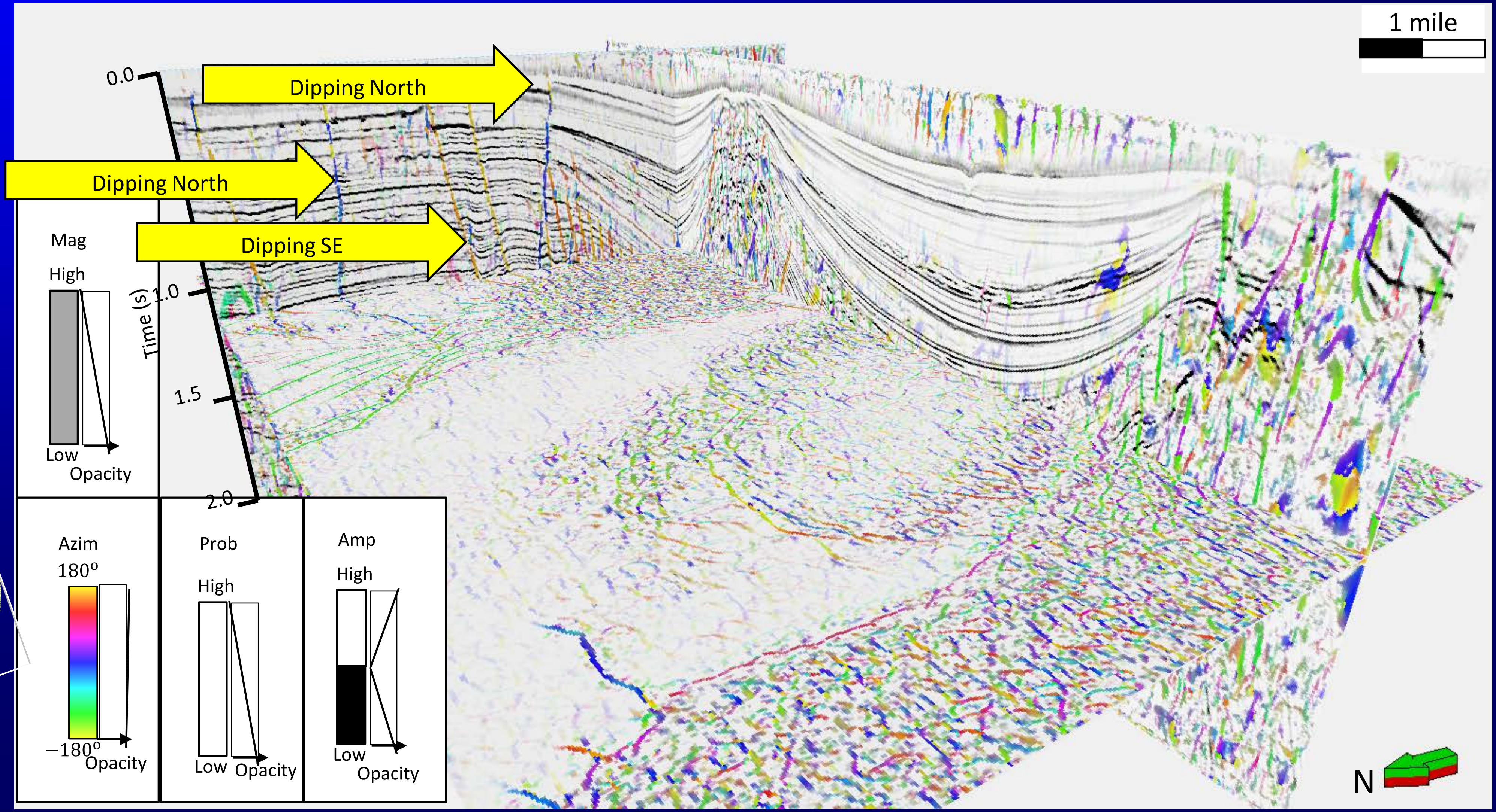


(Courtesy Jie Qi, OU)

Example 1: Gulf of Mexico

Skeletonized fault probability co-rendered with fault dip & azimuth





(Courtesy Jie Qi, OU)

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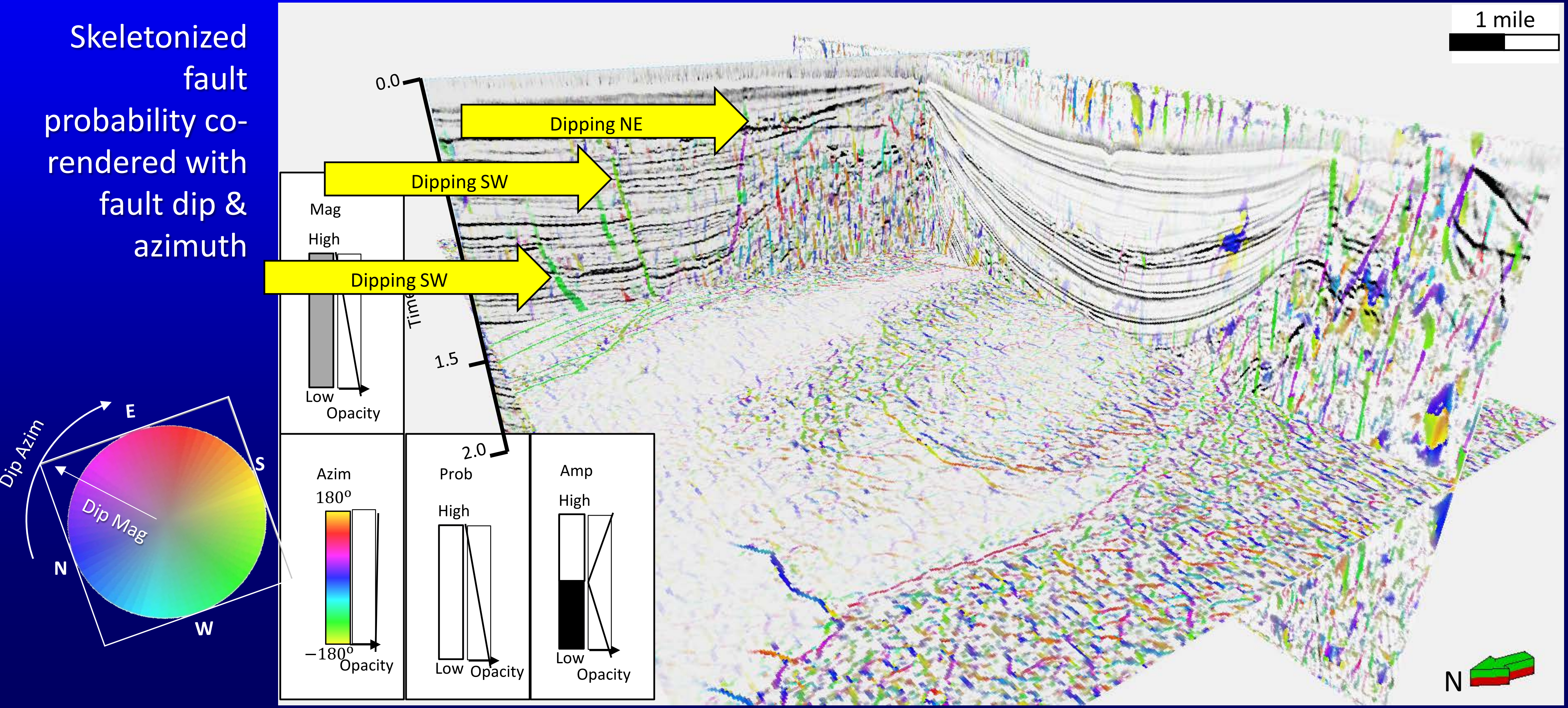
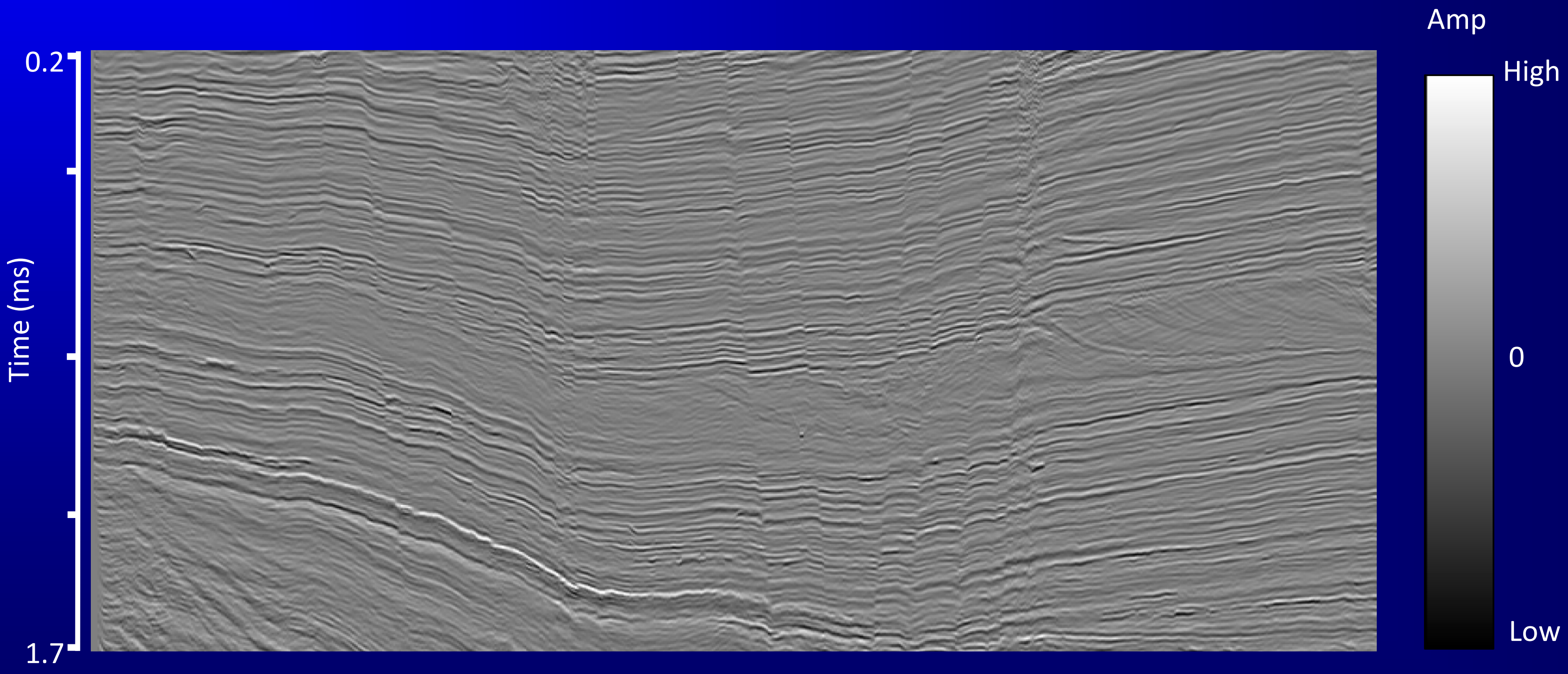


(Courtesy Jie Qi, OU)

Example 2: Taranaki Basin



(Qi, 2018)

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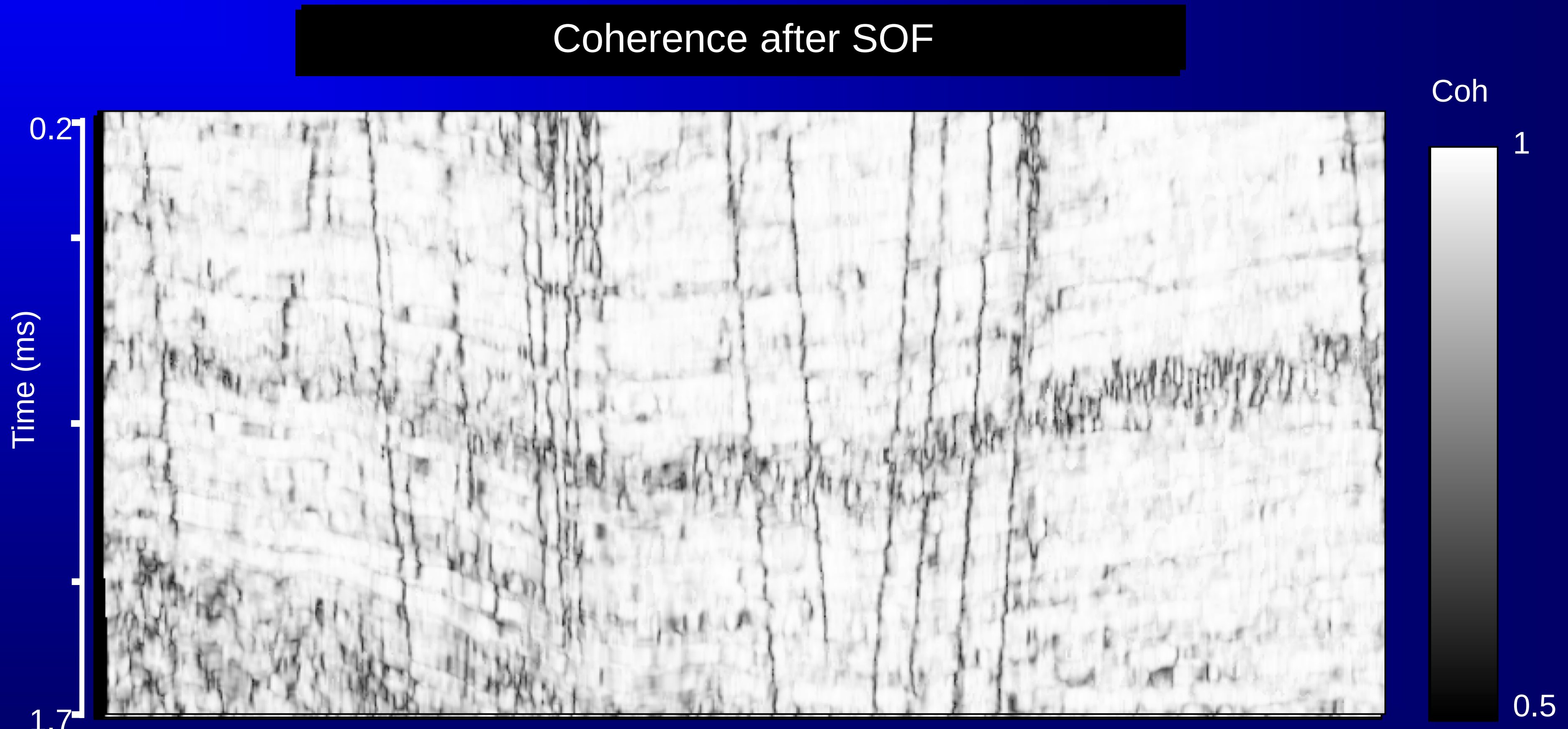

(Qi, 2018)

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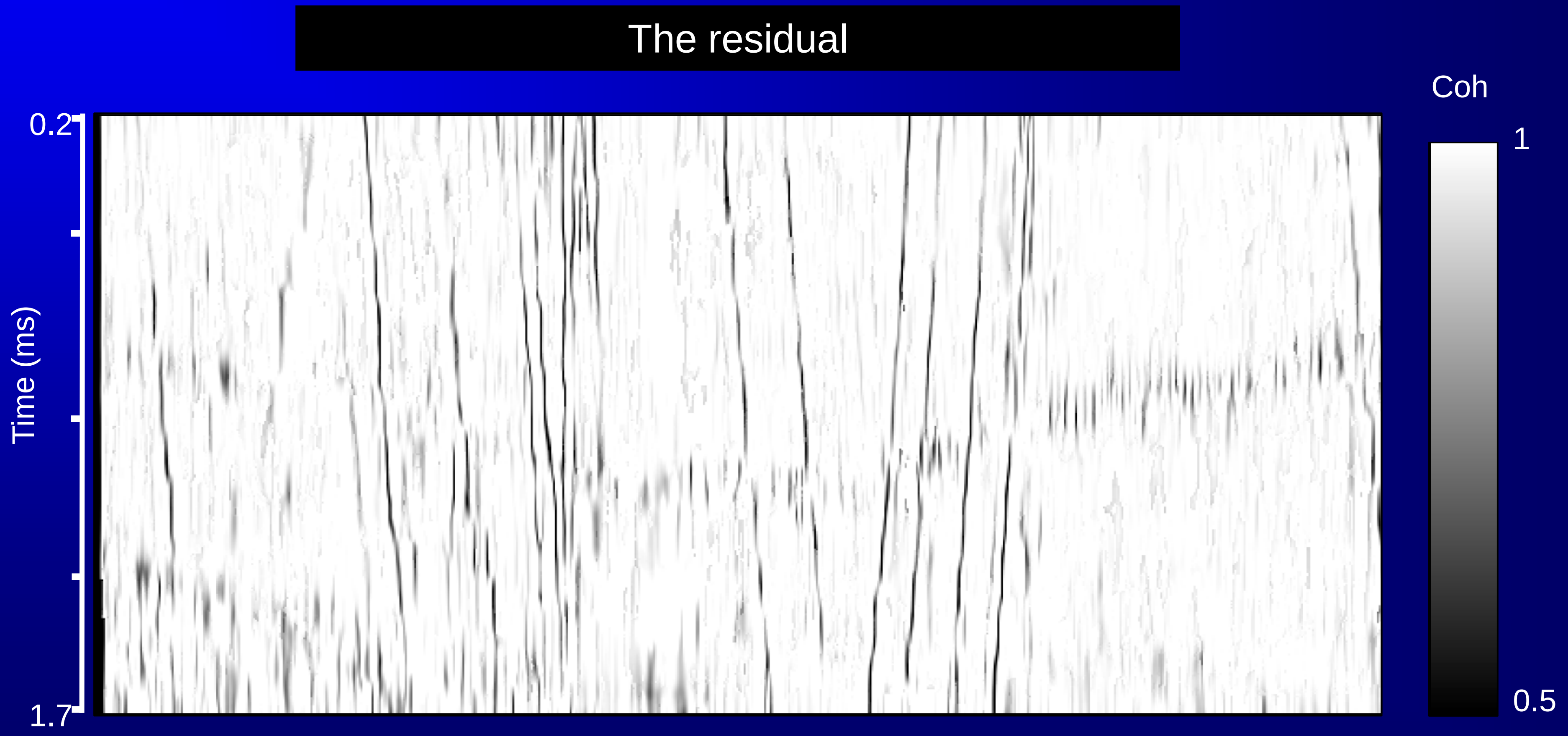

(Qi, 2018)

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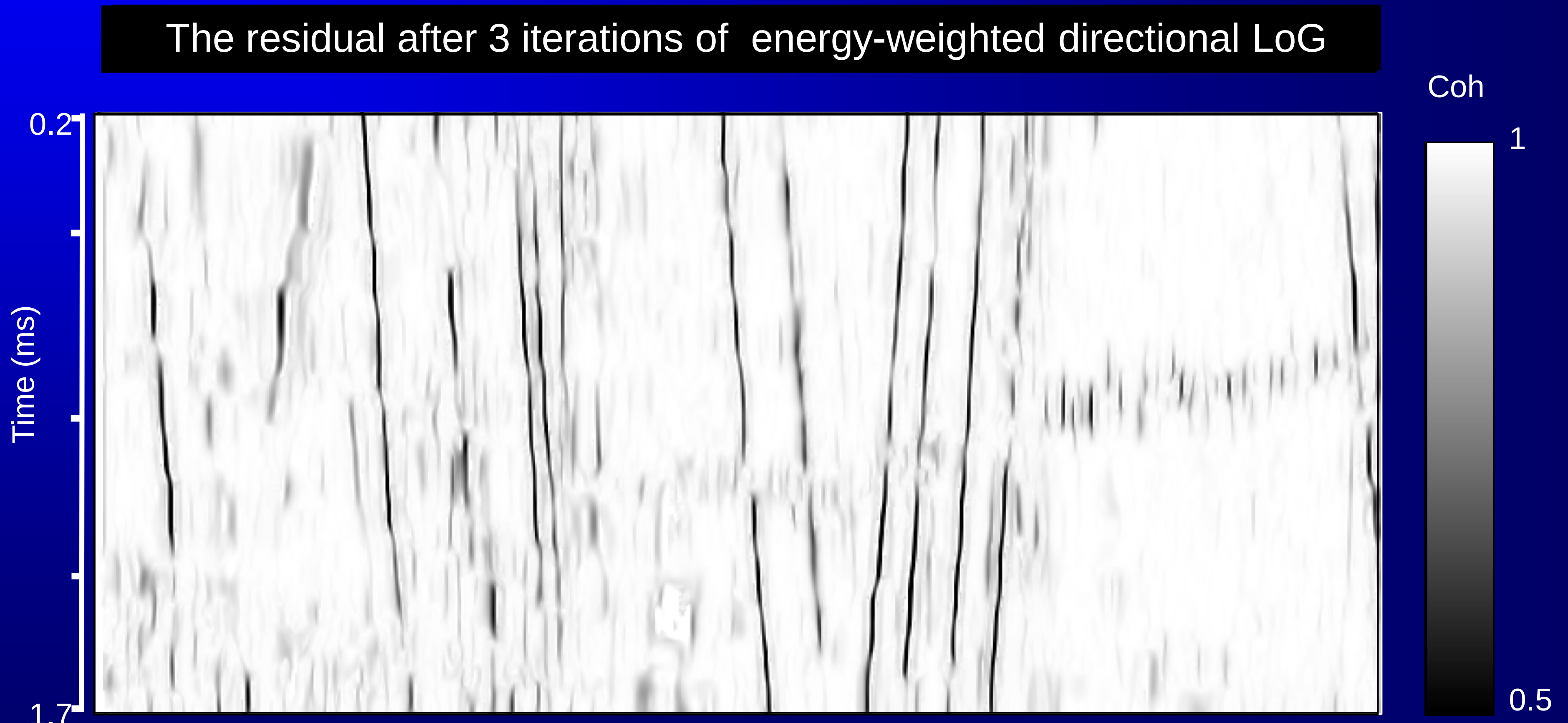
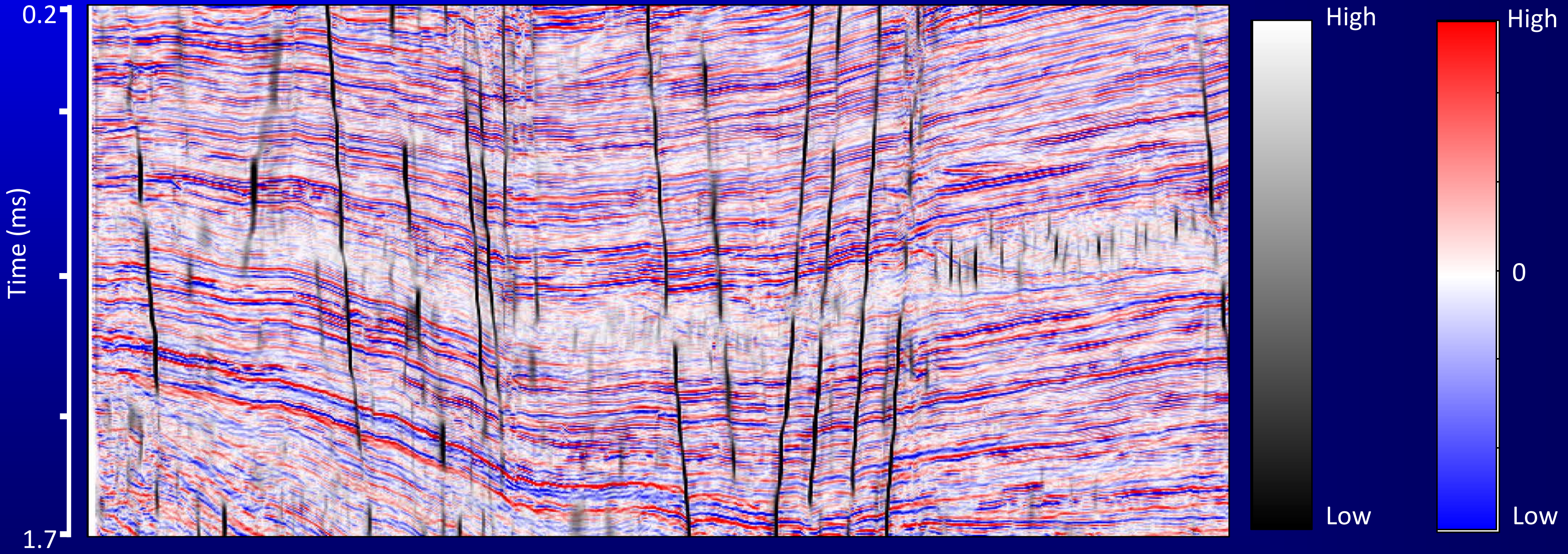


(Qi, 2018)

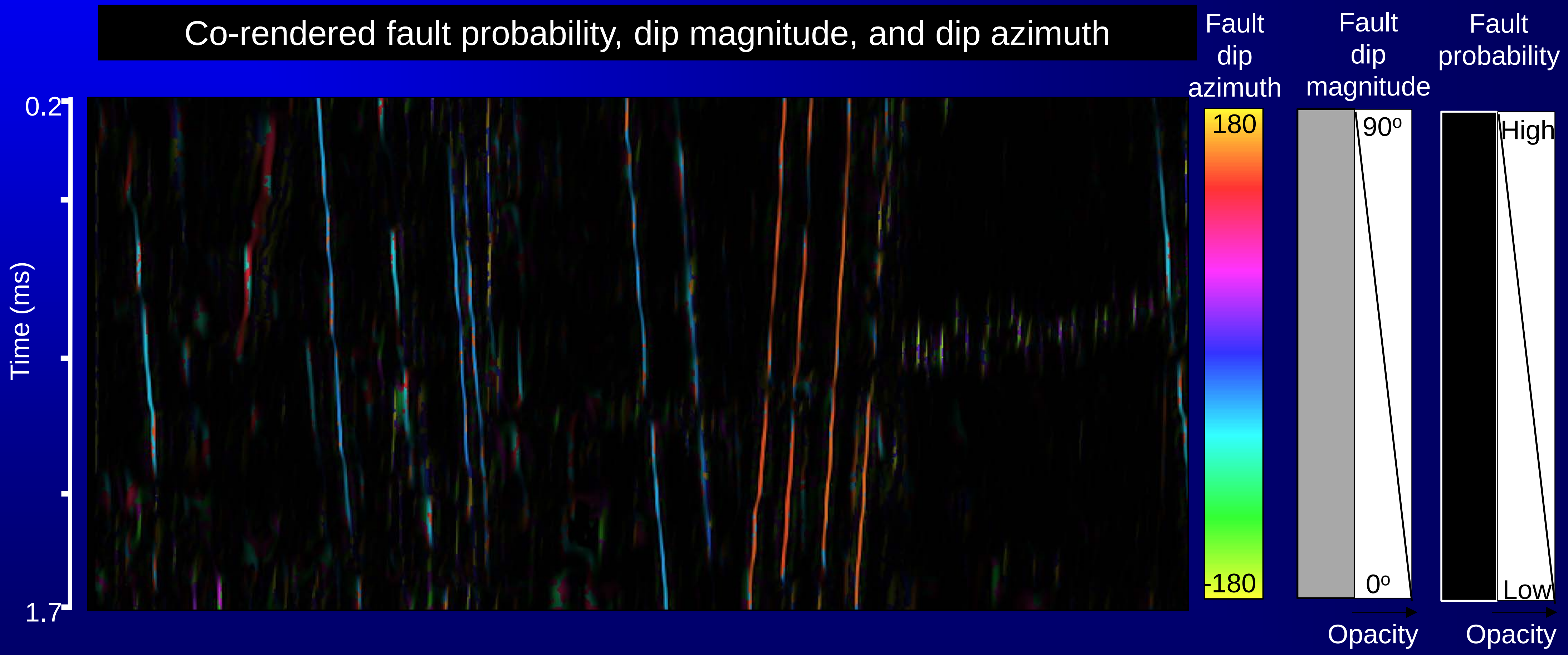
Example 2: Taranaki Basin

Seismic amplitude co-rendered with fault probability



(Qi, 2018)

Example 2: Taranaki Basin



(Qi, 2018)

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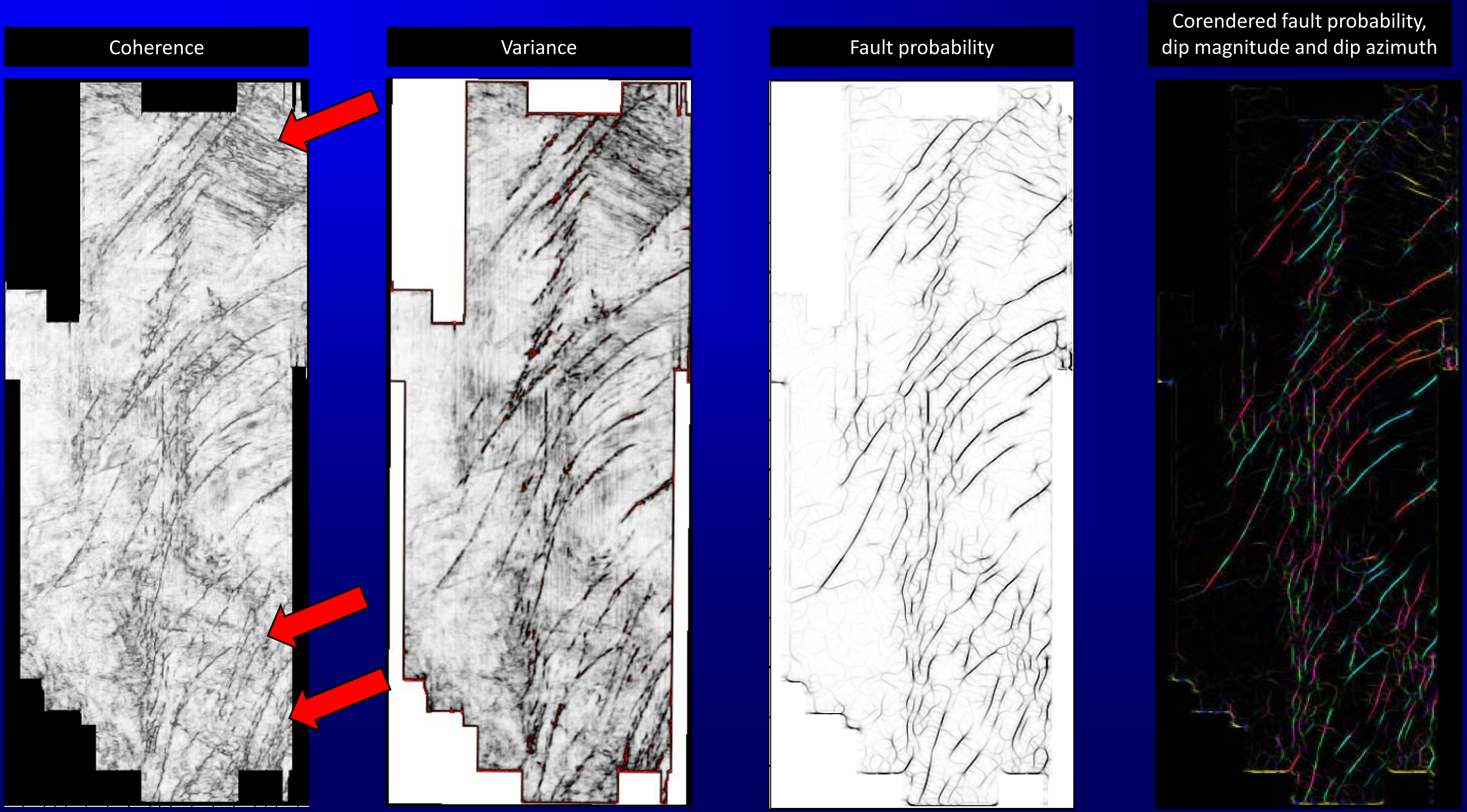
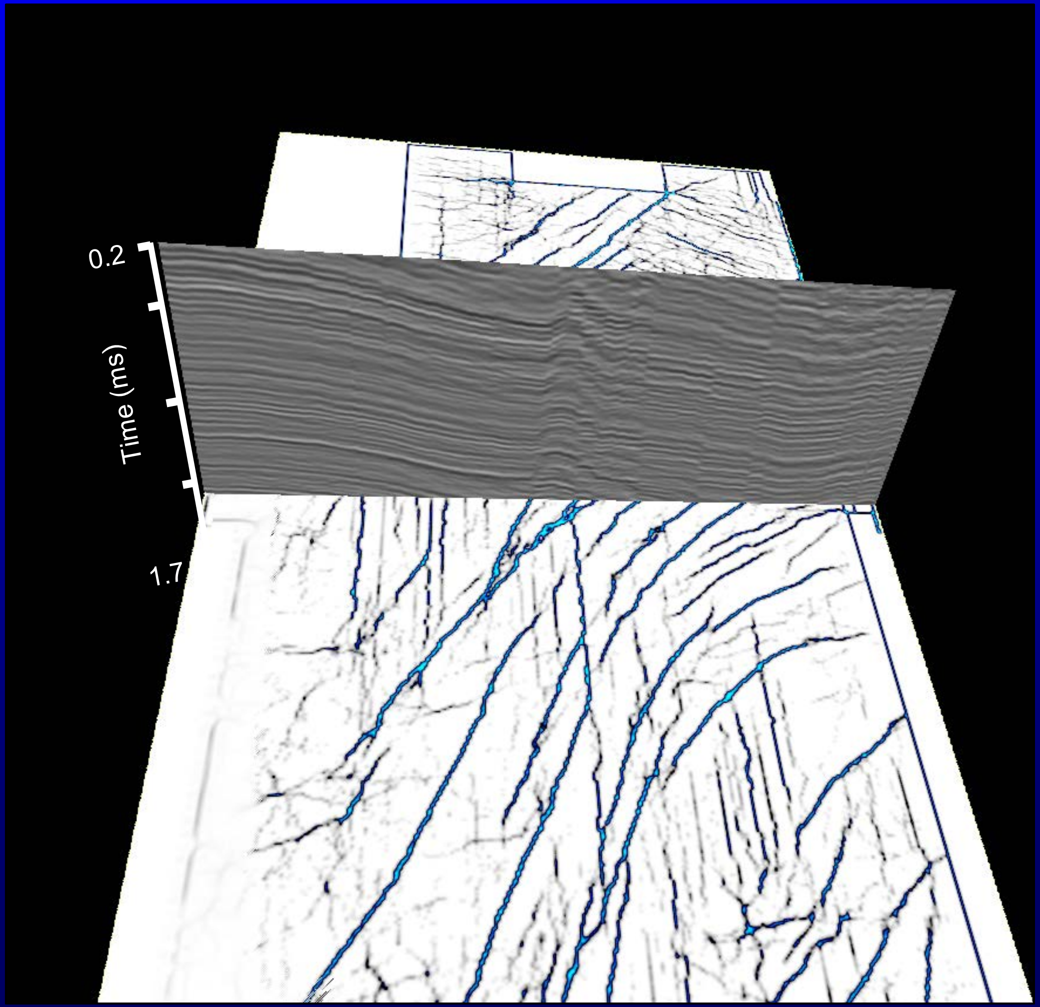


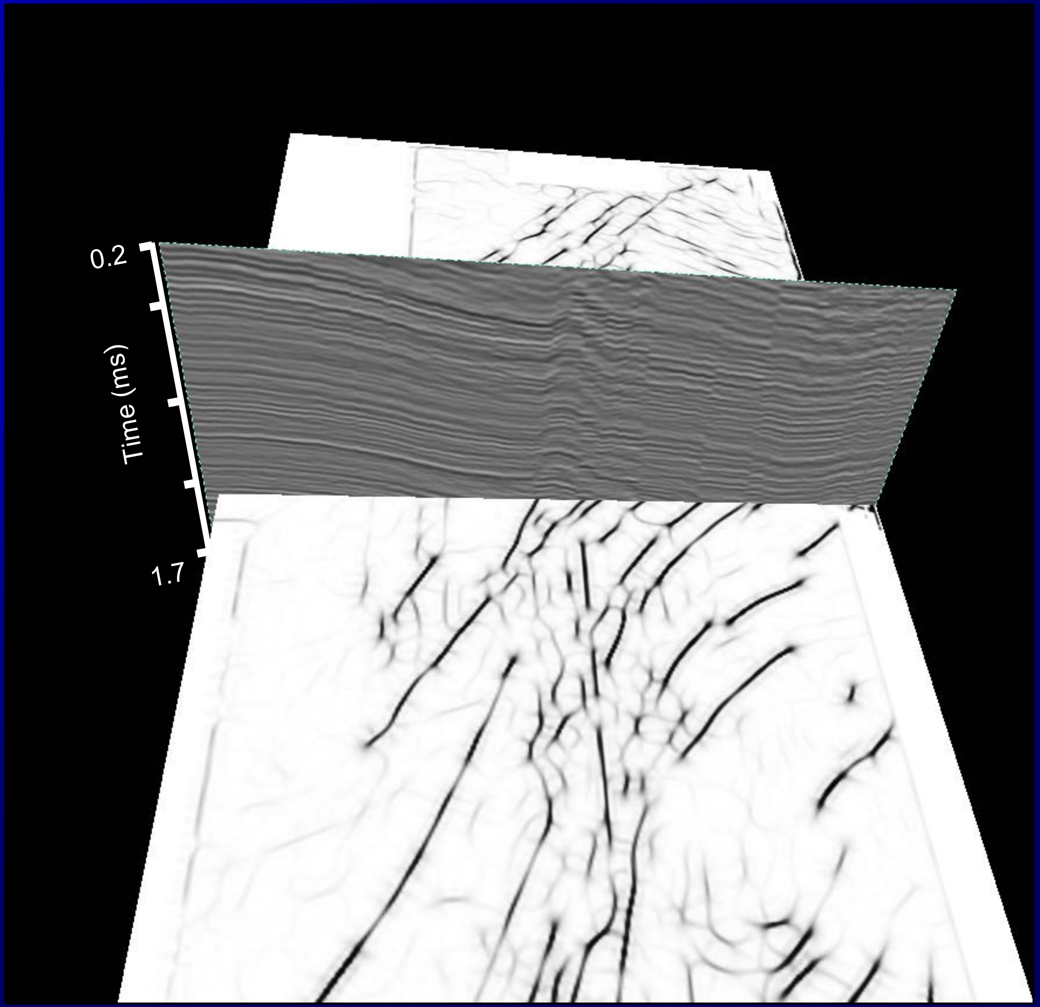
(Qi, 2018)

Example 2: Taranaki Basin

Variance followed by Ant Tracking



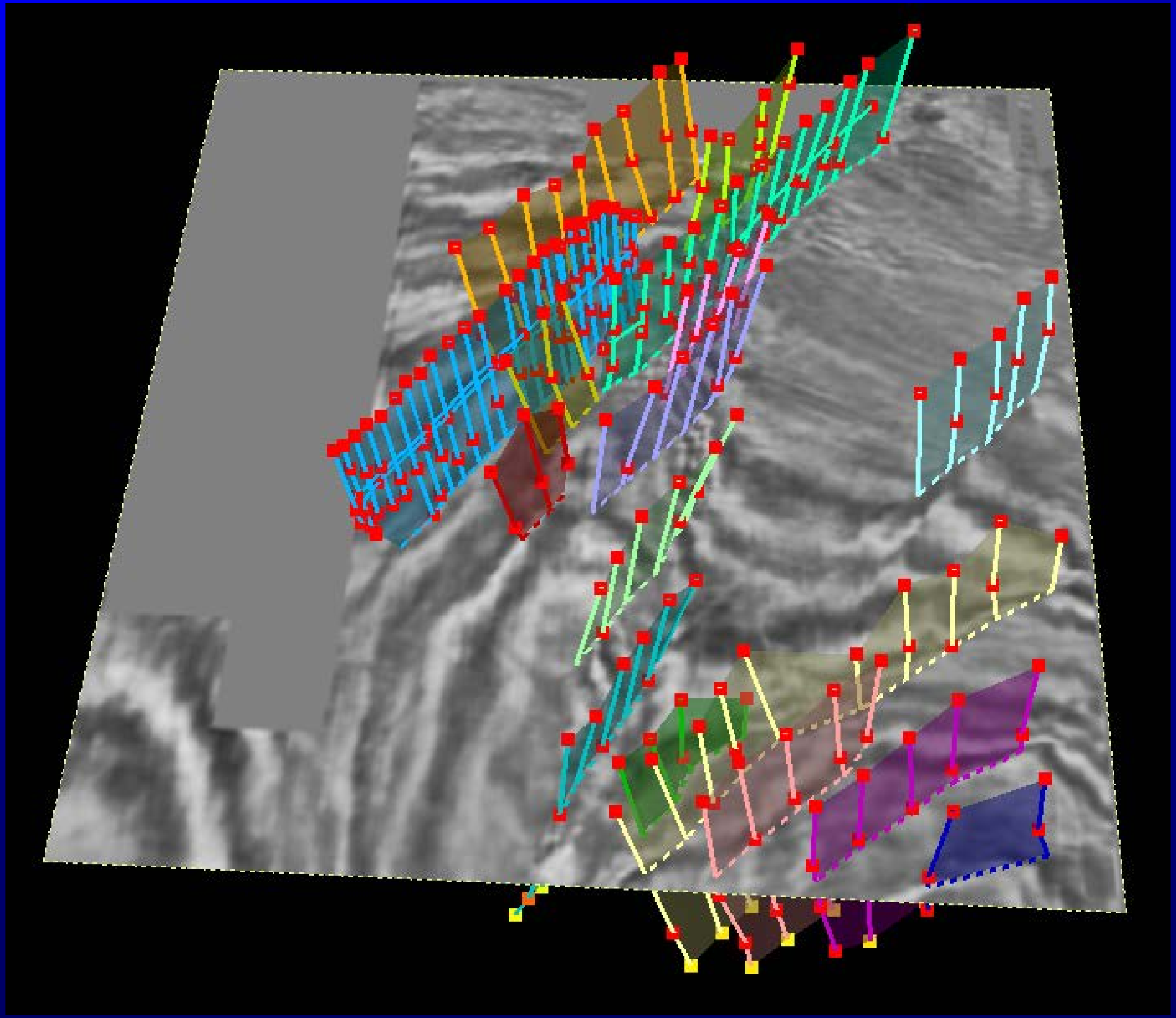
Fault probability



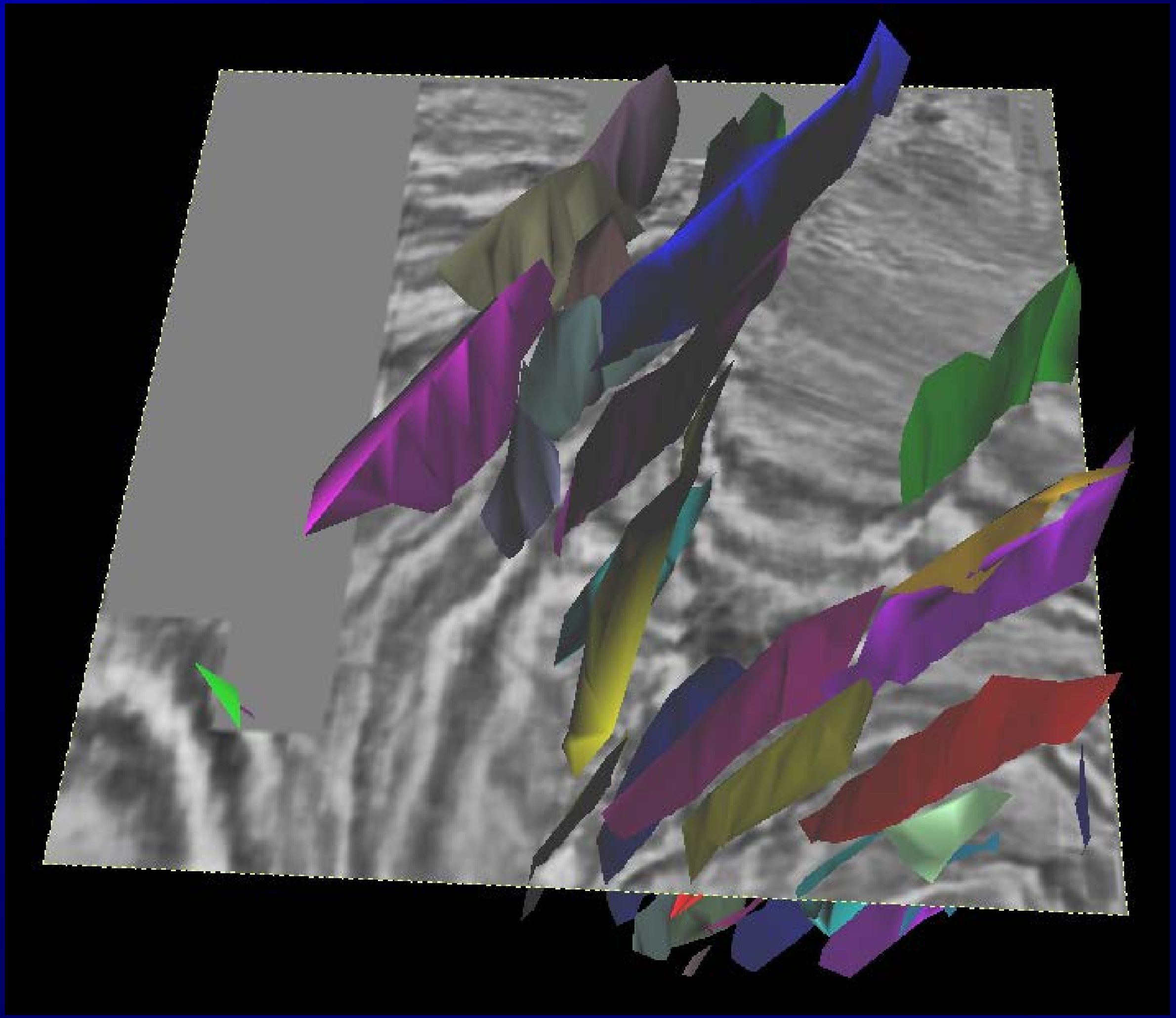
(Qi, 2018)

Example 2: Taranaki Basin

Interpreter-picked fault sticks

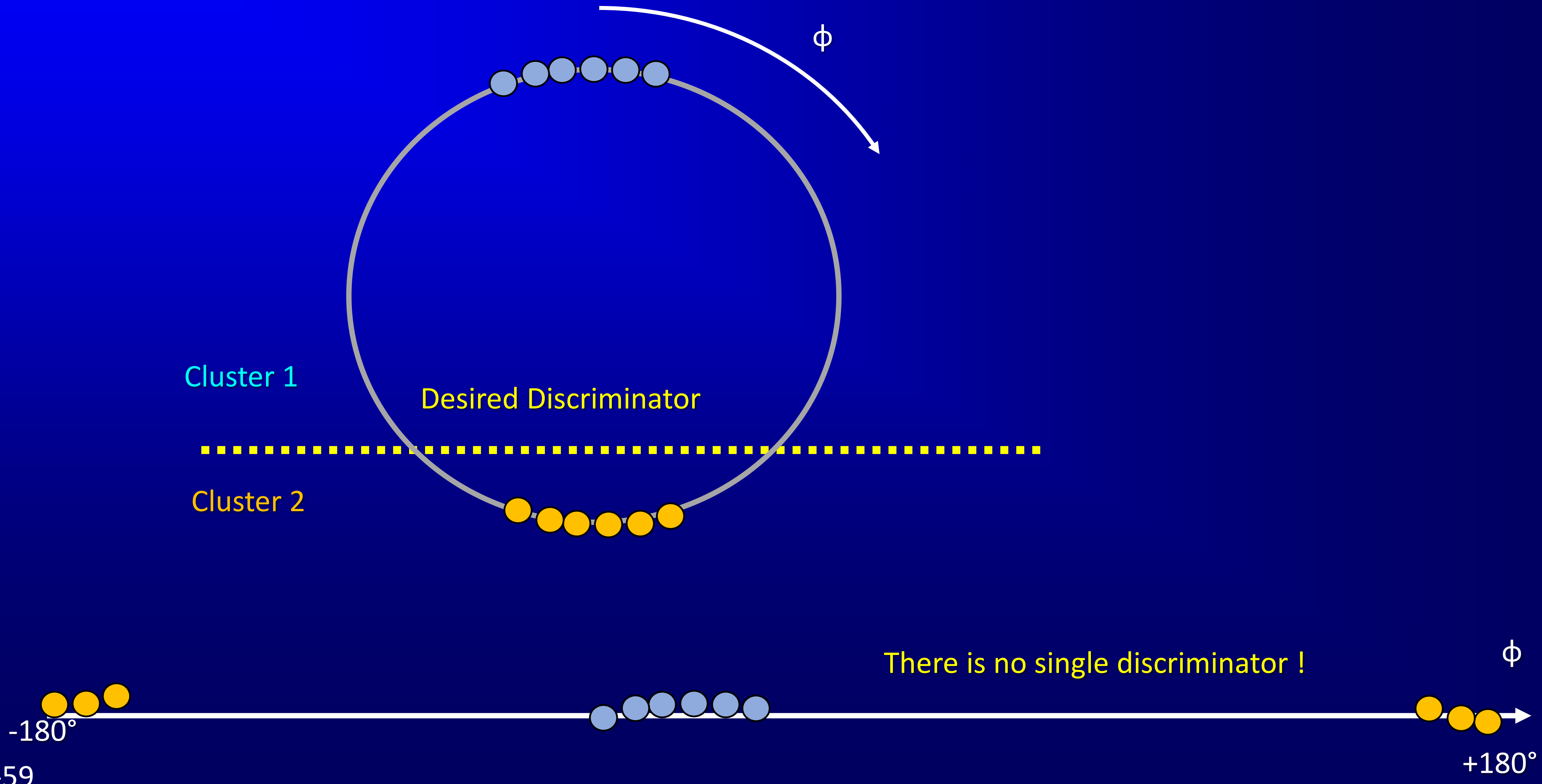


Extracted surfaces from fault probability



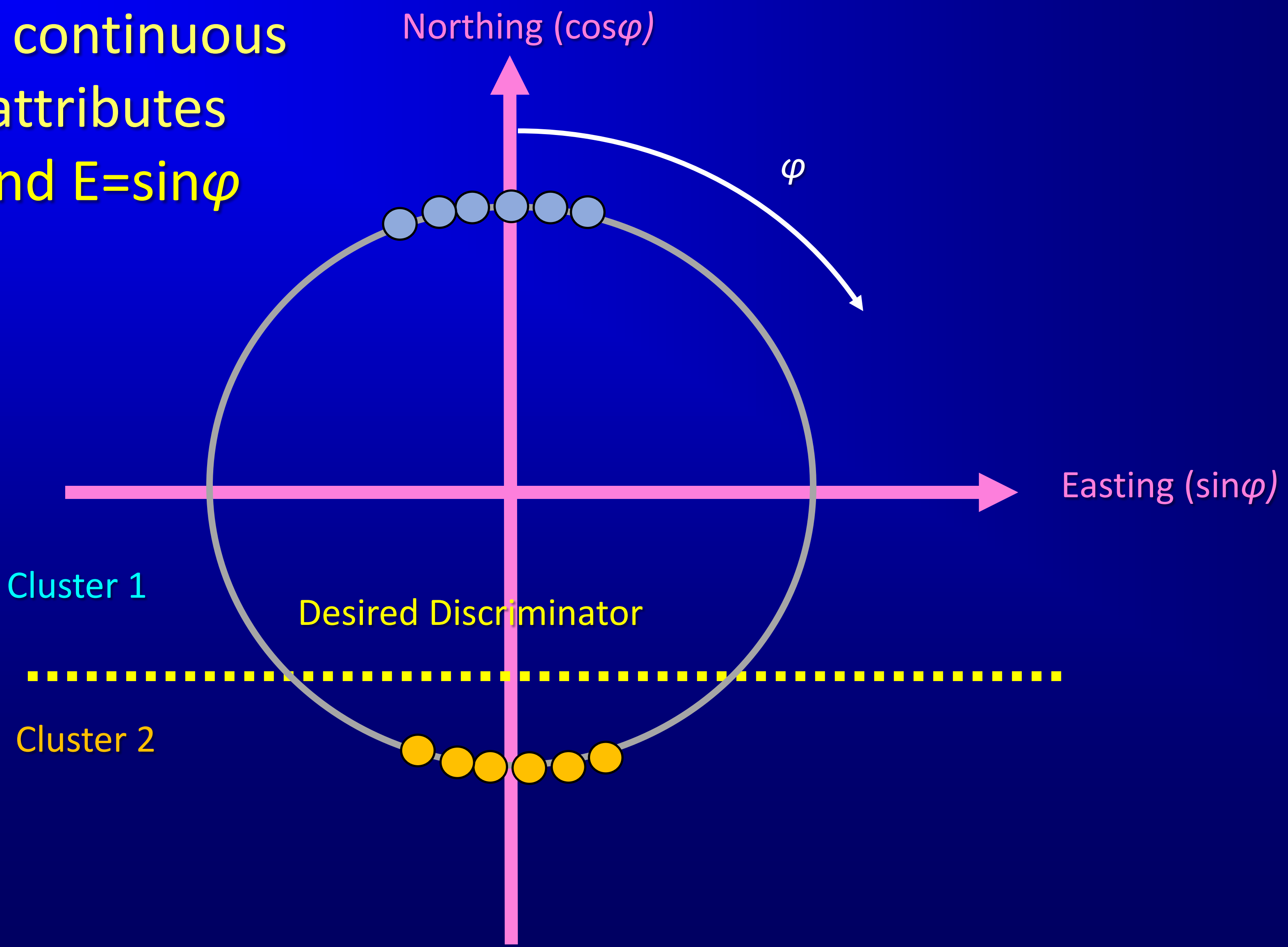
(Qi, 2018)

Pitfalls in correlating an engineering or geologic property with cyclical attributes

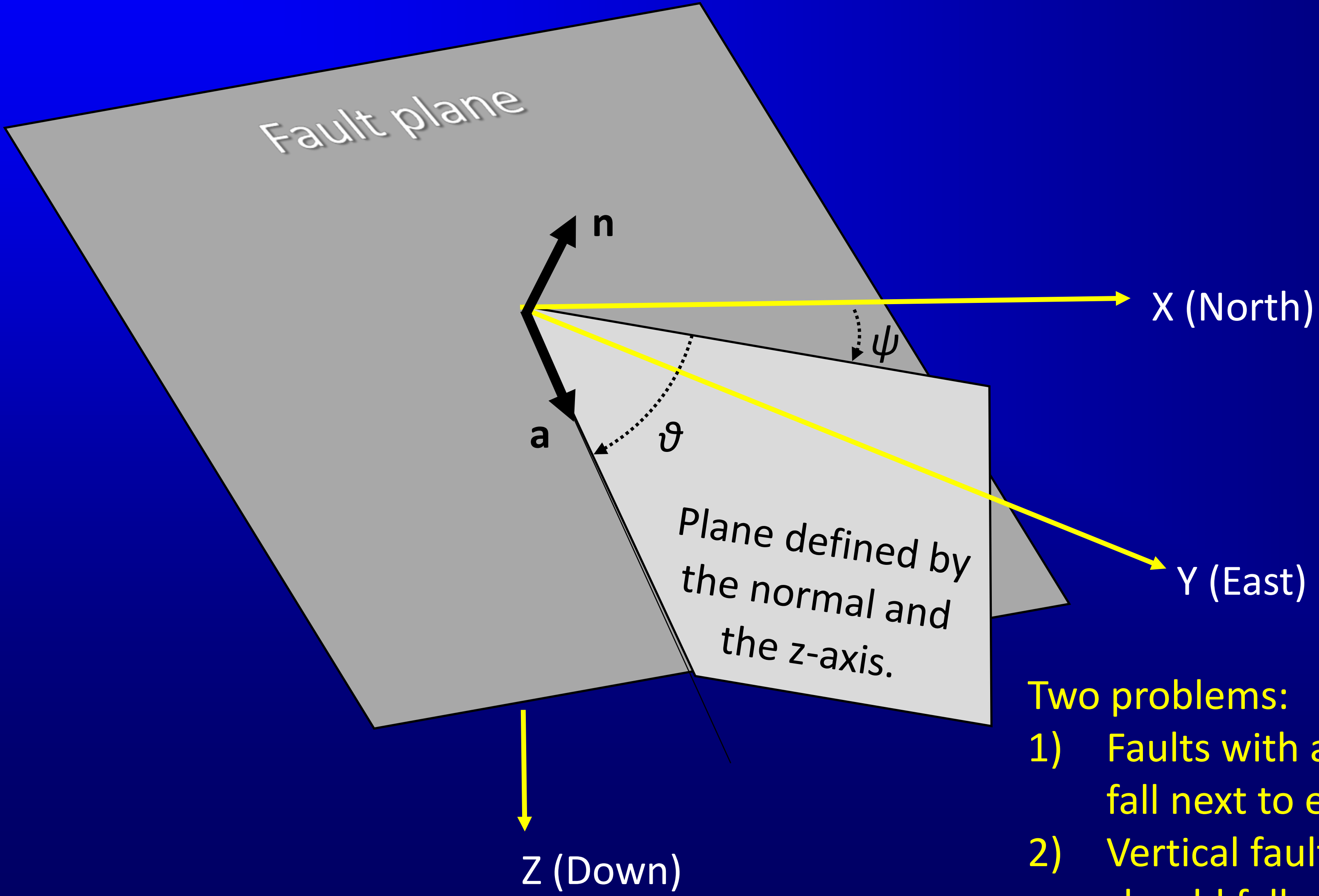


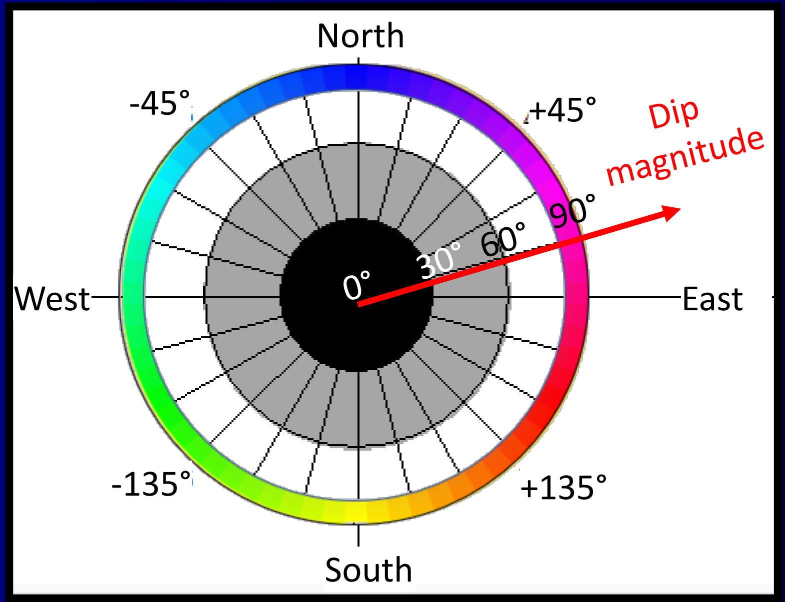
Correlating an engineering or geologic property with cyclical attributes

Construct continuous geodetic attributes $N=\cos\varphi$ and $E=\sin\varphi$



Discontinuities when defining a fault plane by its dip and azimuth



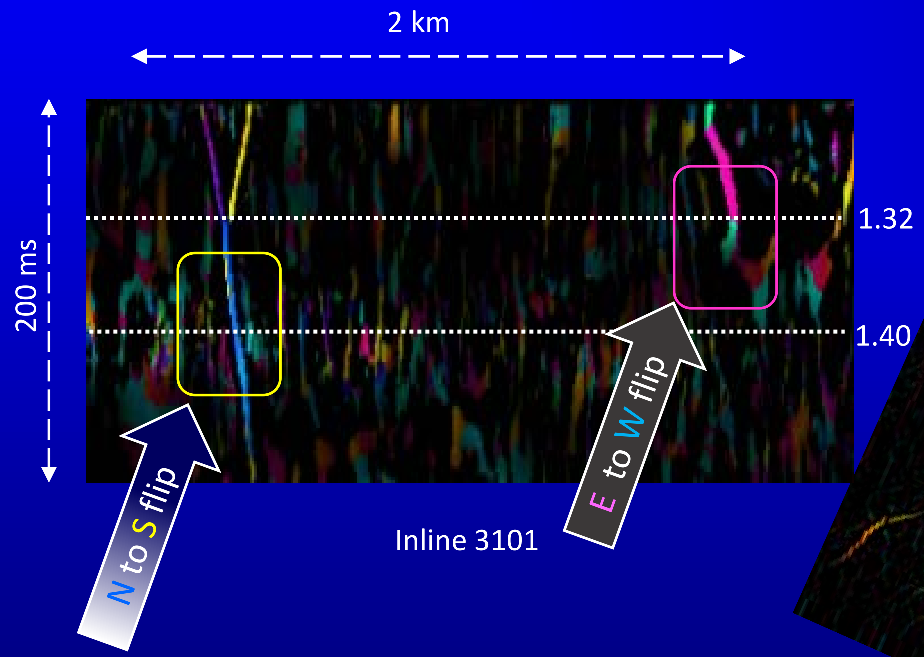


Two problems:

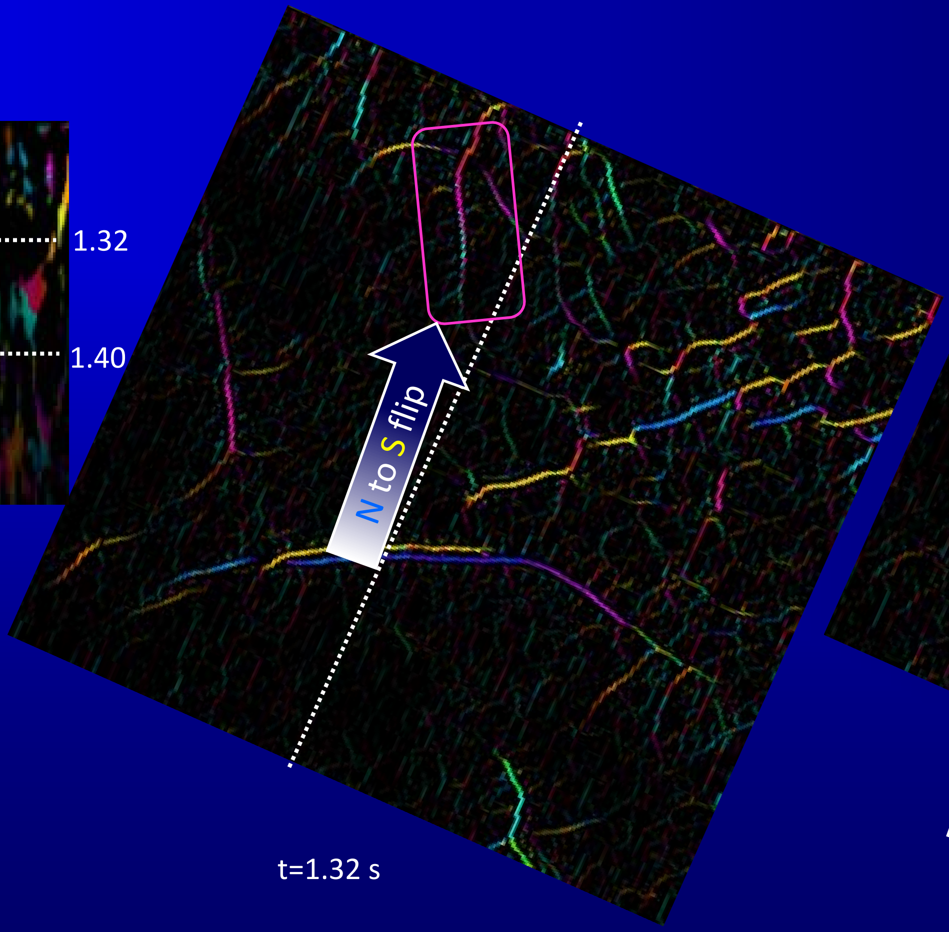
1) Faults with azimuths ≈-180° and ≈+180° should fall next to each other
2) Vertical faults with azimuths φ and φ+180° should fall next to each (and have a similar color mapping)

Pitfall: Dip azimuth values flip about vertical faults

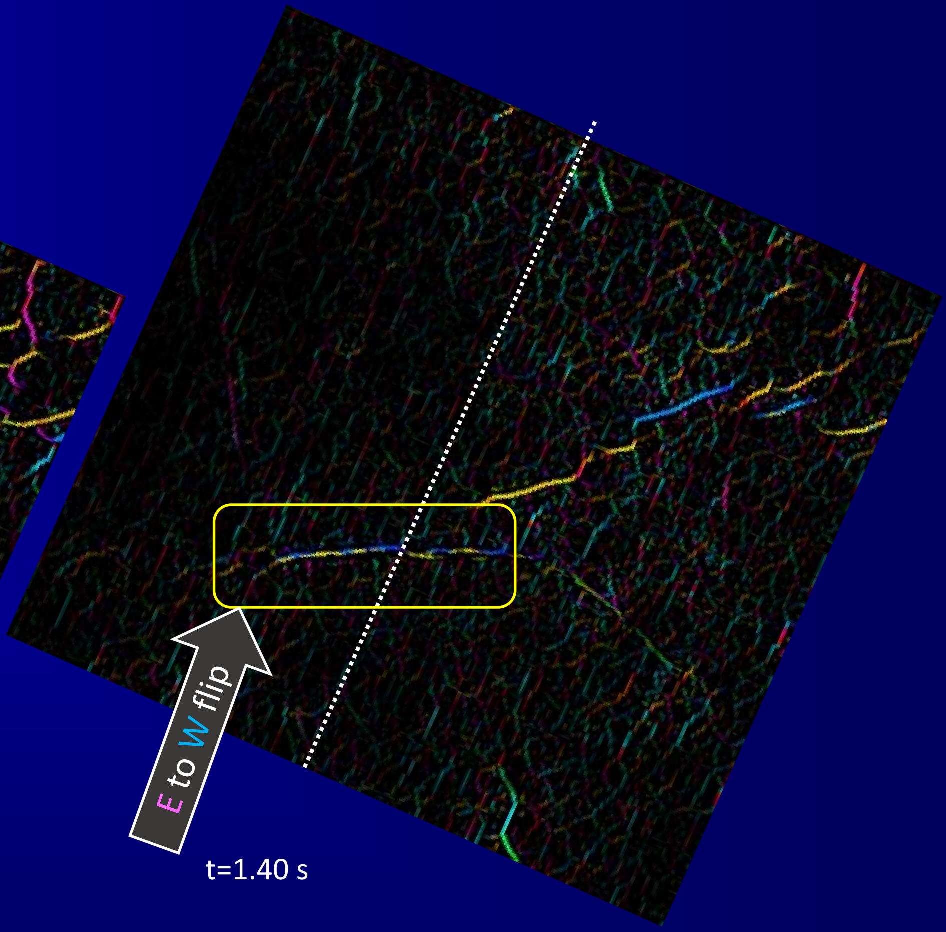
Vector display using an HSL color model resulting in polarity flips



Inline 3101



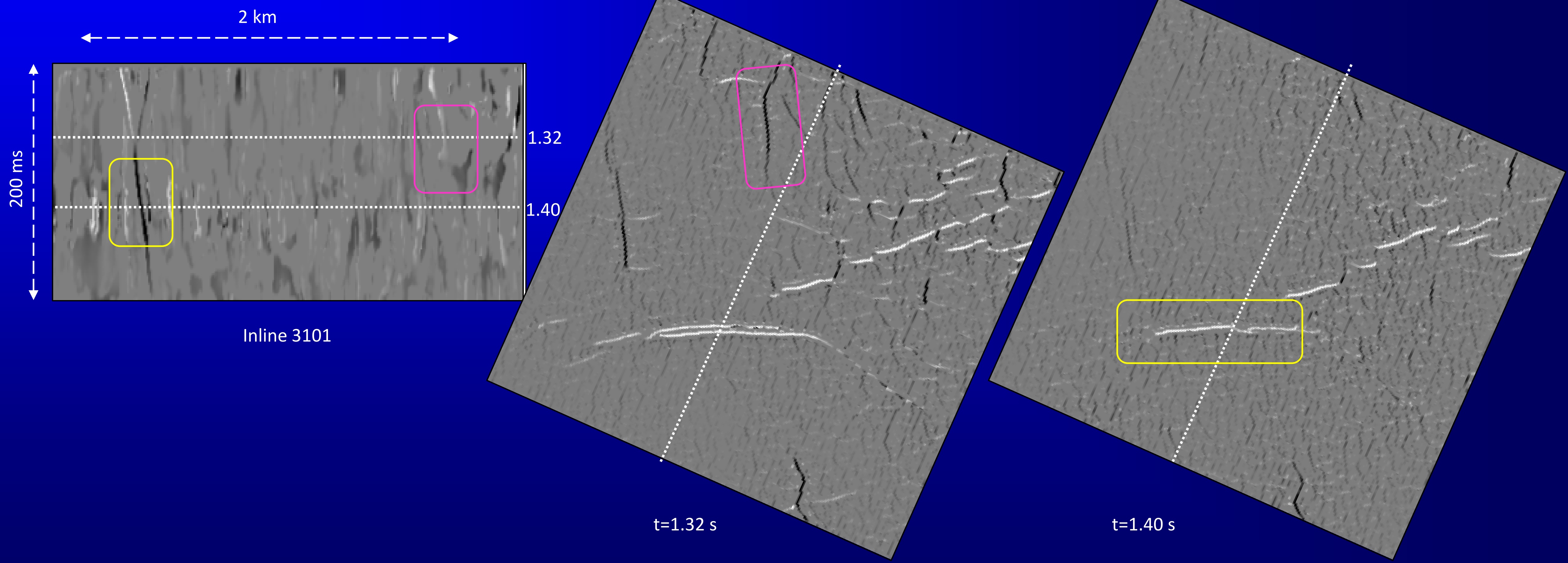
t=1.32 s



t=1.40 s

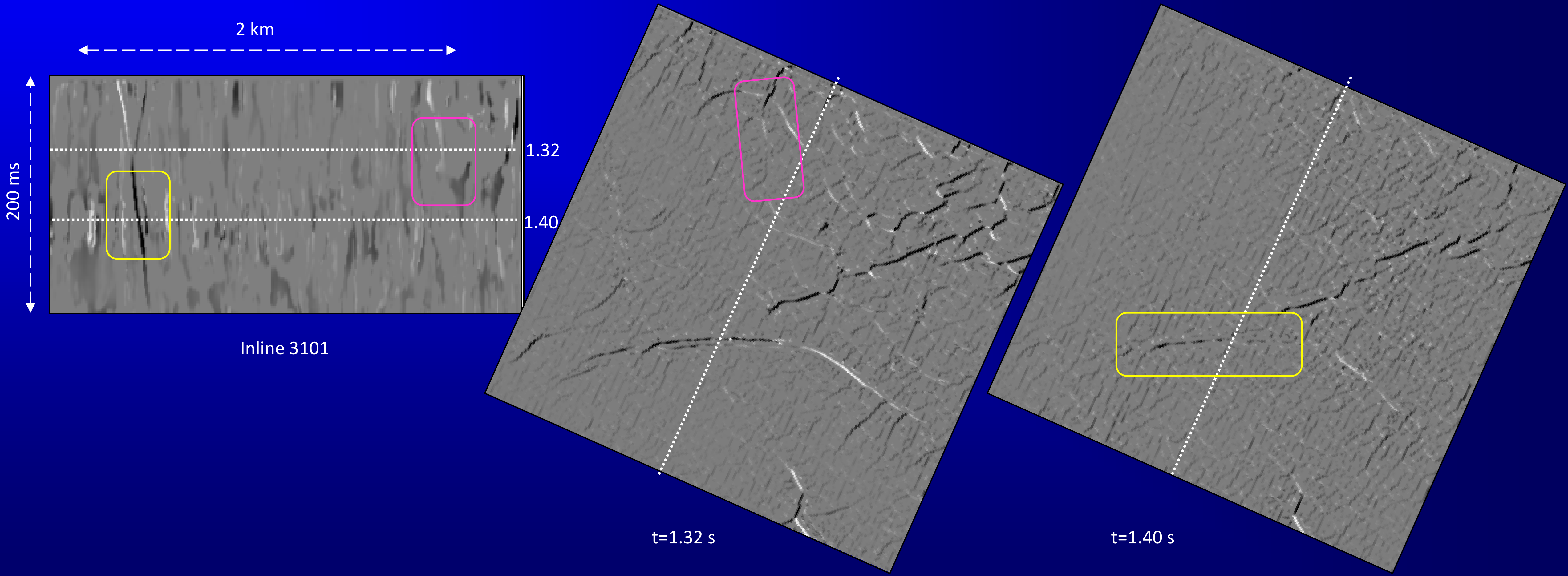
Partial solution: Generate fault orientation components

North strike component: cos(2σ); σ=ψ+90°



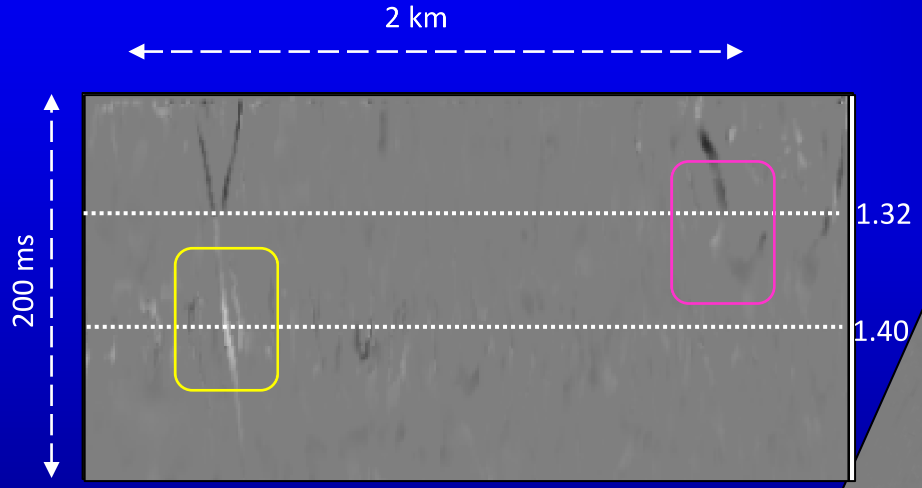
Partial solution: Generate fault orientation components

East strike component: $\sin(2\sigma)$; $\sigma=\psi+90°$

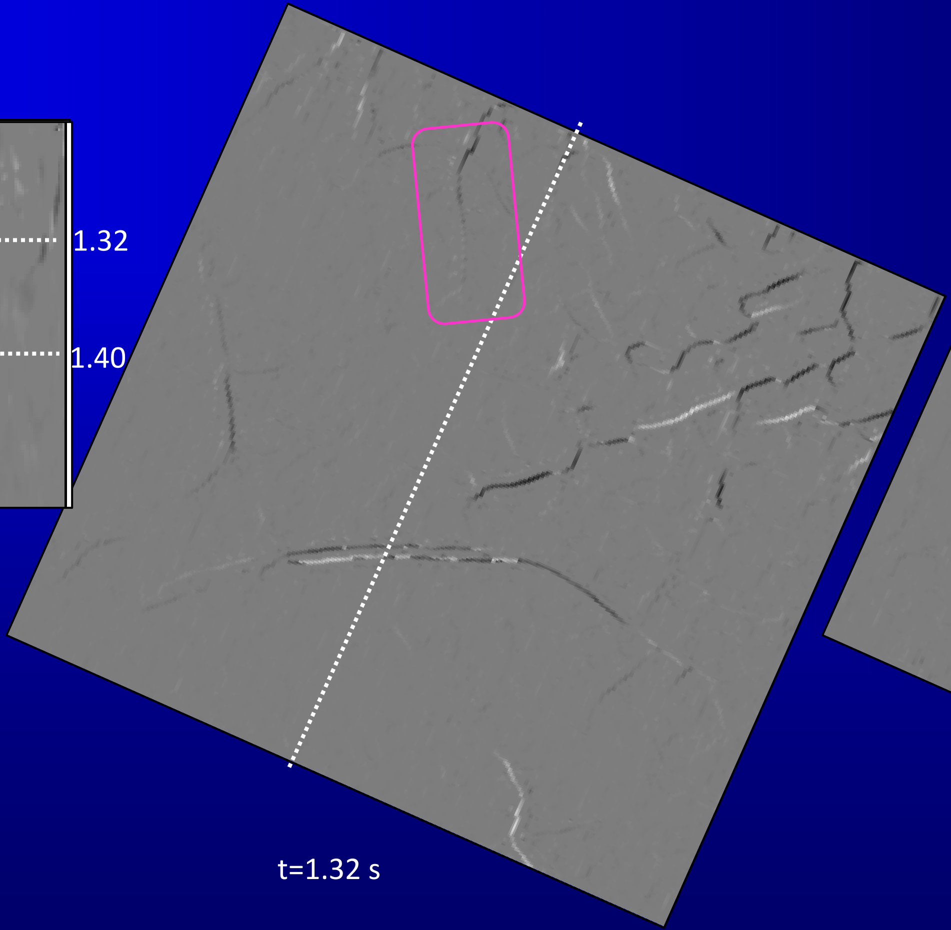


Partial solution: Generate fault orientation components

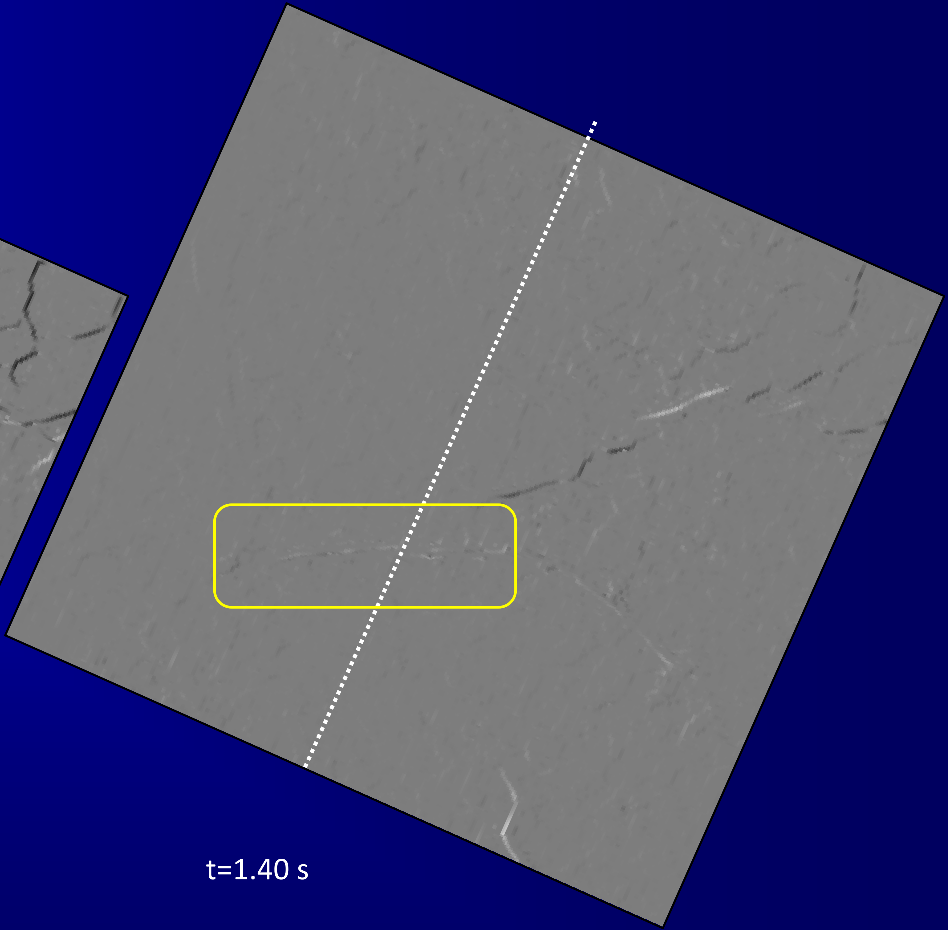
Horizontal dip component: cos(ϑ)



Inline 3101



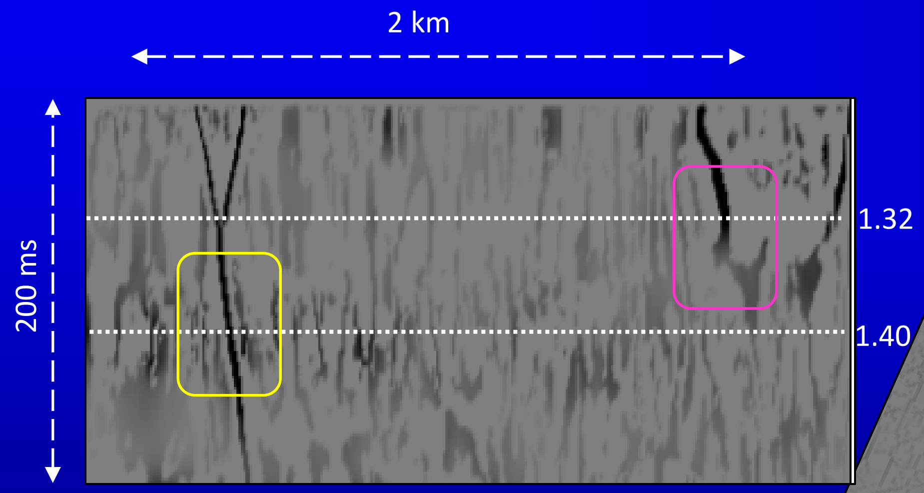
t=1.32 s



t=1.40 s

Partial solution: Generate fault orientation components

Vertical dip component: sin(ϑ)



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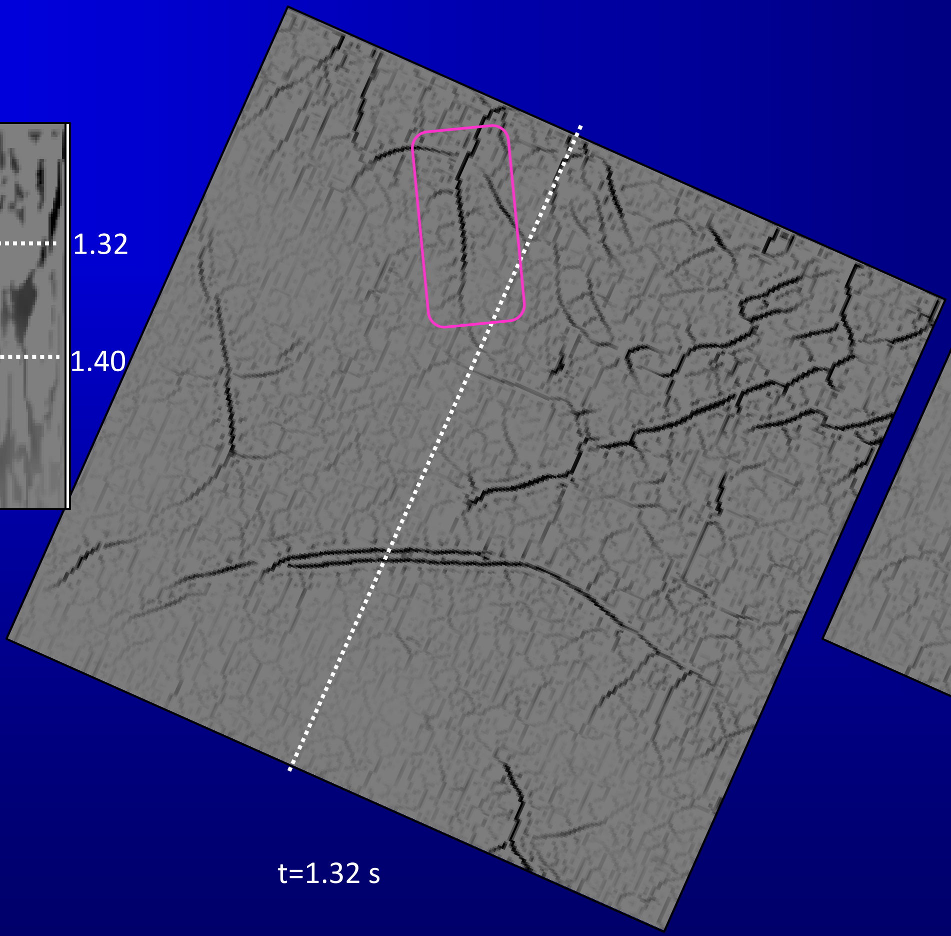
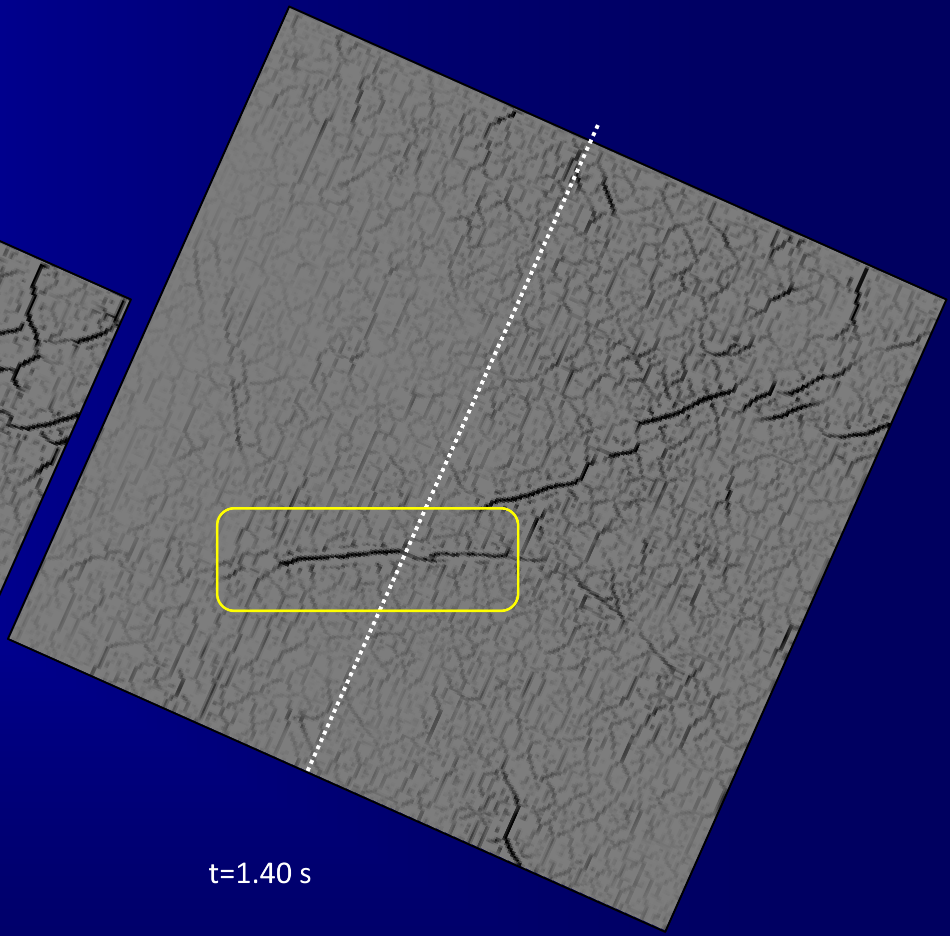


t=1.32 s



t=1.40 s

Image enhancement of faults

In Summary:

- By using iterative application of larger analysis windows, image enhancement filters can
  - fill in the holes seen in coherence images when unrelated stratigraphic reflectors correlate across a fault, and
  - minimize the stairstep artifacts associated with the seismic wavelet being imaged perpendicular to the reflector.
- Eigenvectors of the 2^{nd} moment tensor computed from coherence volumes provides
  - estimates of fault dip and azimuth, and
  - a means to directionally sharpen or smooth the fault
- Skeletonization converts diffuse fault edges into sharper surfaces
- Fault enhancement is not limited to coherence images, but can be applied to curvature volumes to better map fold axes
- Fault enhancement algorithms can also enhance footprint!