SEG 3D Advanced Seismic Modeling Project

Chevron Perspective

CSM, 12 July 2005
Houston(Hess), 8 Sept 2005
Houston(COP), 14 Oct 2005

Given

(1) the past SEG emphasis on "geometric" (container) imaging of structurally complex models with only weakly represented stratigraphy, and
(2) the growing need for better amplitude processing and seismic reservoir characterization,

we believe the SEG effort is worthwhile, and we particularly (but not exclusively) support a stratigraphically-flavored earth/seismic modeling exercise.

This will likely require elastic modeling, and certain shortcuts & compromises might be necessary, depending on model details and required accuracy.

Questions: can acoustic simulations provide enough value for stratigraphic objectives? (lose Vs effects on AVA, maintain strat scat, …). 3D vs 2.5D?

A Recipe for Realistic Stratigraphy Construction
SEG 3D Advanced Seismic Modeling Project

Joe Stefani, Chevron

CSM, 12 July 2005
Houston, 8 Sept 2005

Towards Realistic Seismic Earth Models: Evolution of Earth/Strat Models

1 Matching key property and correlation characteristics

2 Generating flat stratigraphy

3 Adding interesting reservoirs in 3D

4 Warping/Morphing by hand

4 Warping/Morphing by inverse flattening

5 Applying *mild* near-surface velocity perturbations

6 Masking-in a salt body (for structural problem)

1: Match Key Property and Correlation Characteristics

Want the model to match the Earth in these (necessary but maybe insufficient) characteristics:

spatial correlation of property variations horizontally and vertically

RMS of property fluctuations about local mean

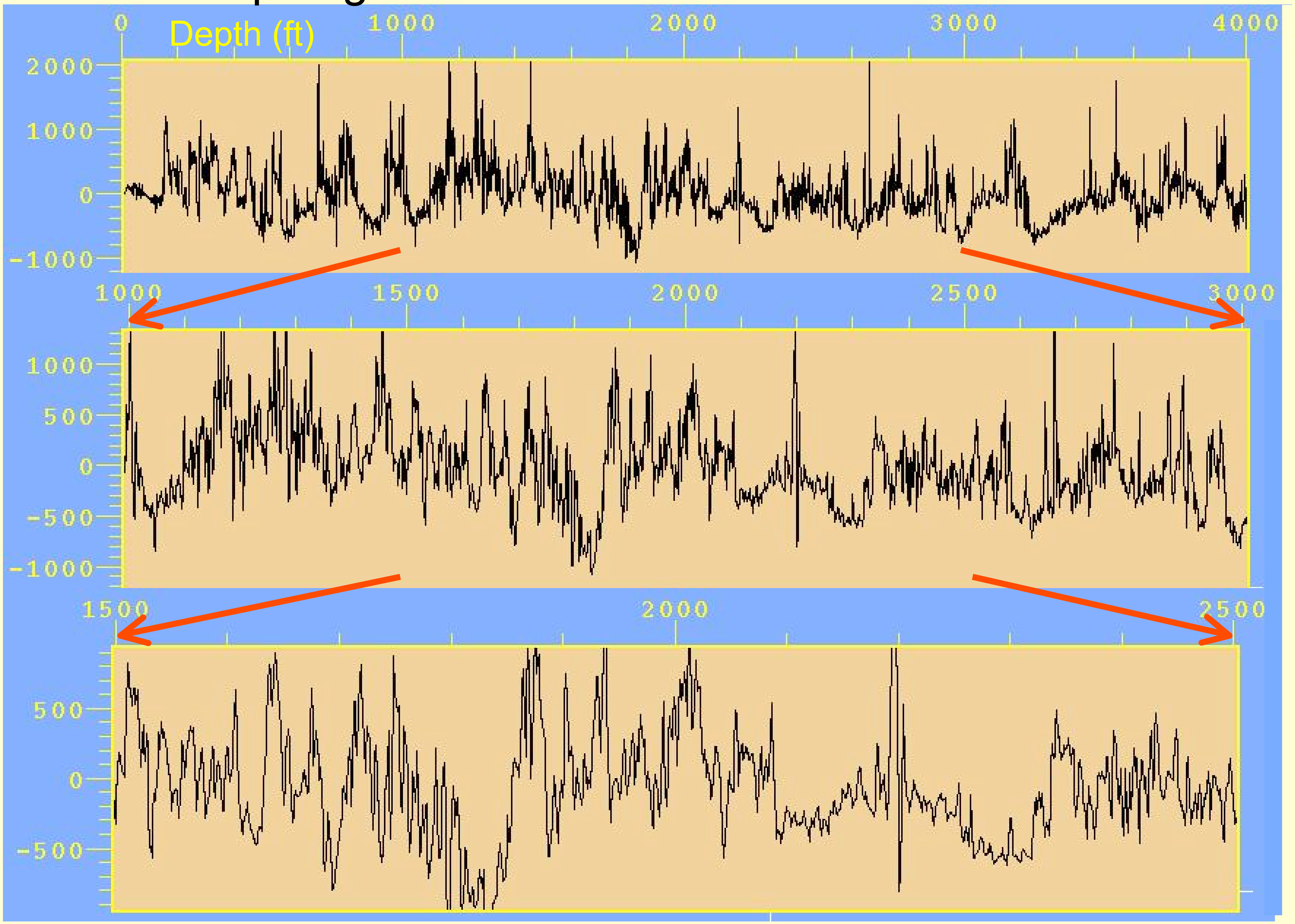
histogram of property fluctuations about local mean

correlation coefficients among Vp,Vs,Dn reflectivities

Background on Spatial Correlation of Property Variations:
Statistical Self-Similarity and Power Laws →

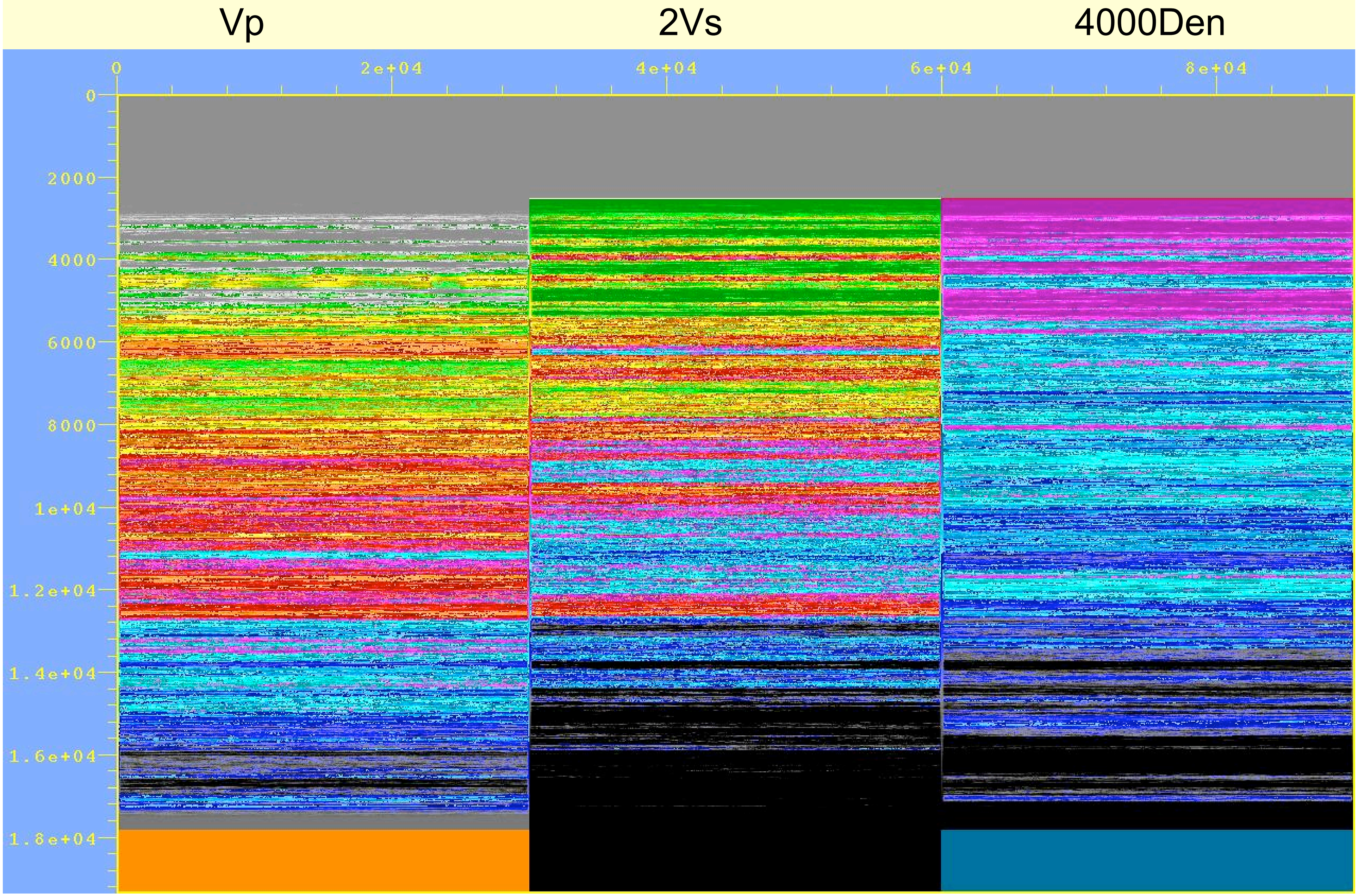
Illustration of Self-Affinity: Vertical Vp Log at 3 scales

(depth in feet, linear trend removed, power = 1.2: horzfac=2 vertfac=$2^{\beta/2}$ =1.5)

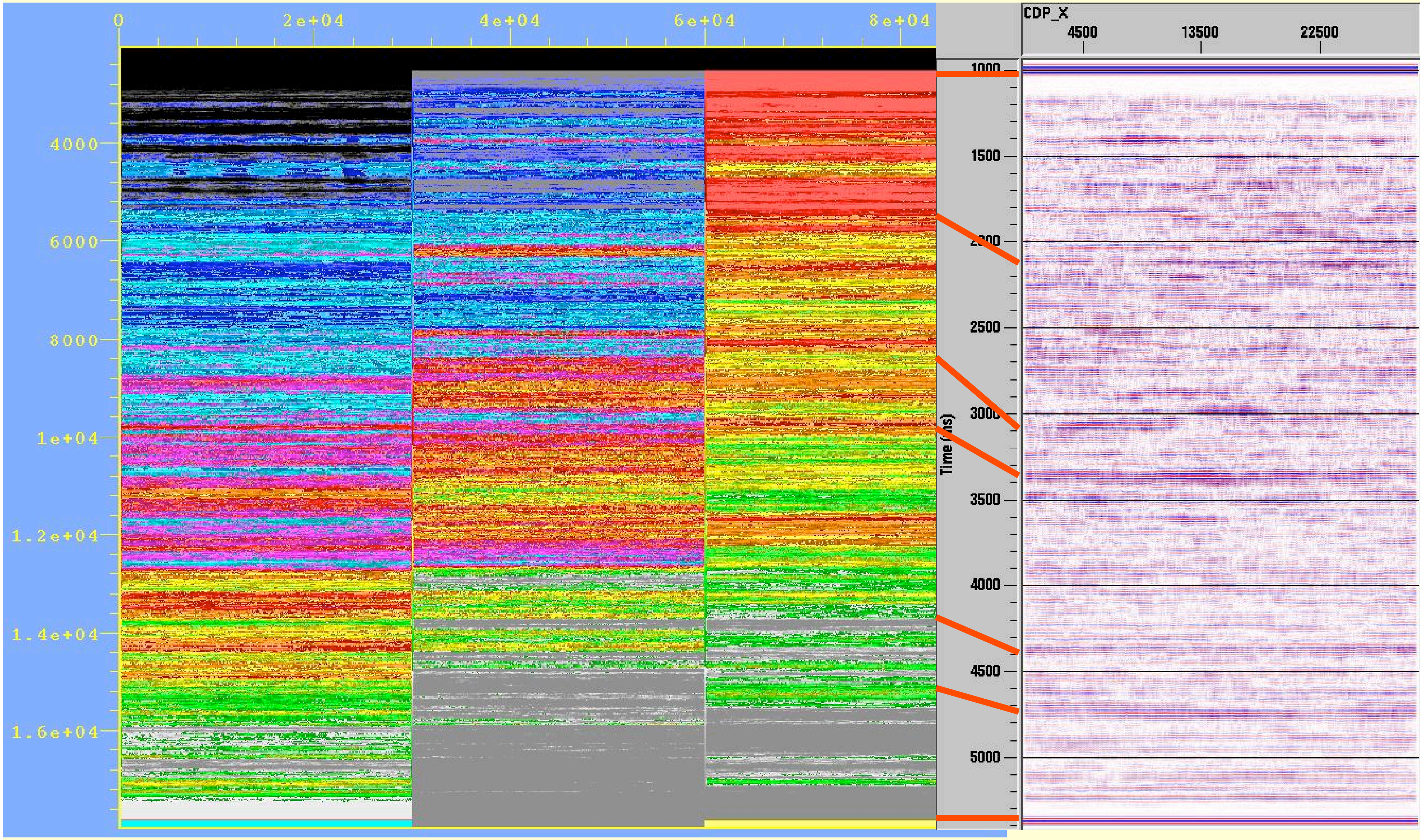


2: Generate Flat Stratigraphy

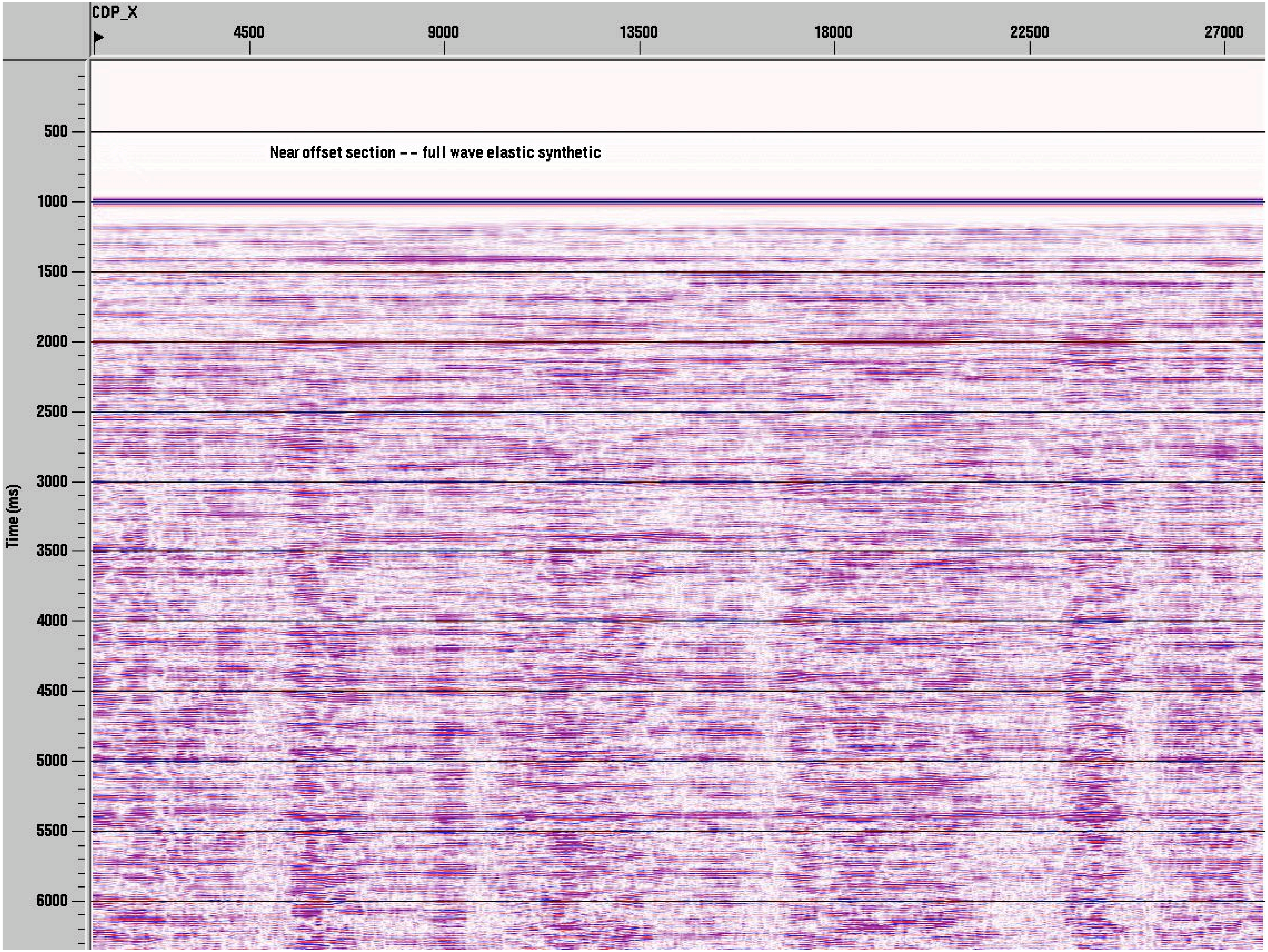
Seismic Parameters for strat5 Model (VE=3)



Vp 2Vs 4000Den Reflectivity*Wavelet



Depth Sections VE=5 Time Section

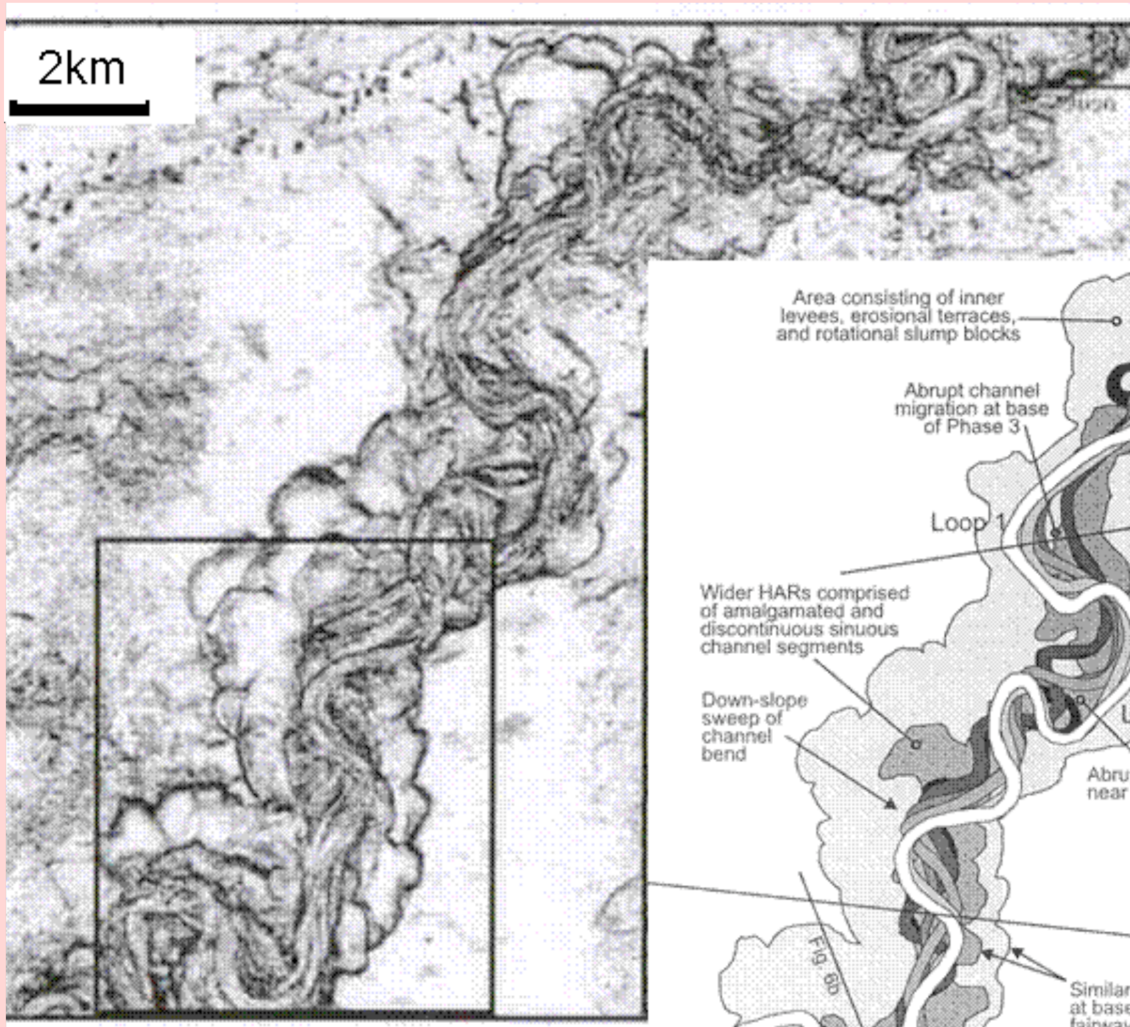


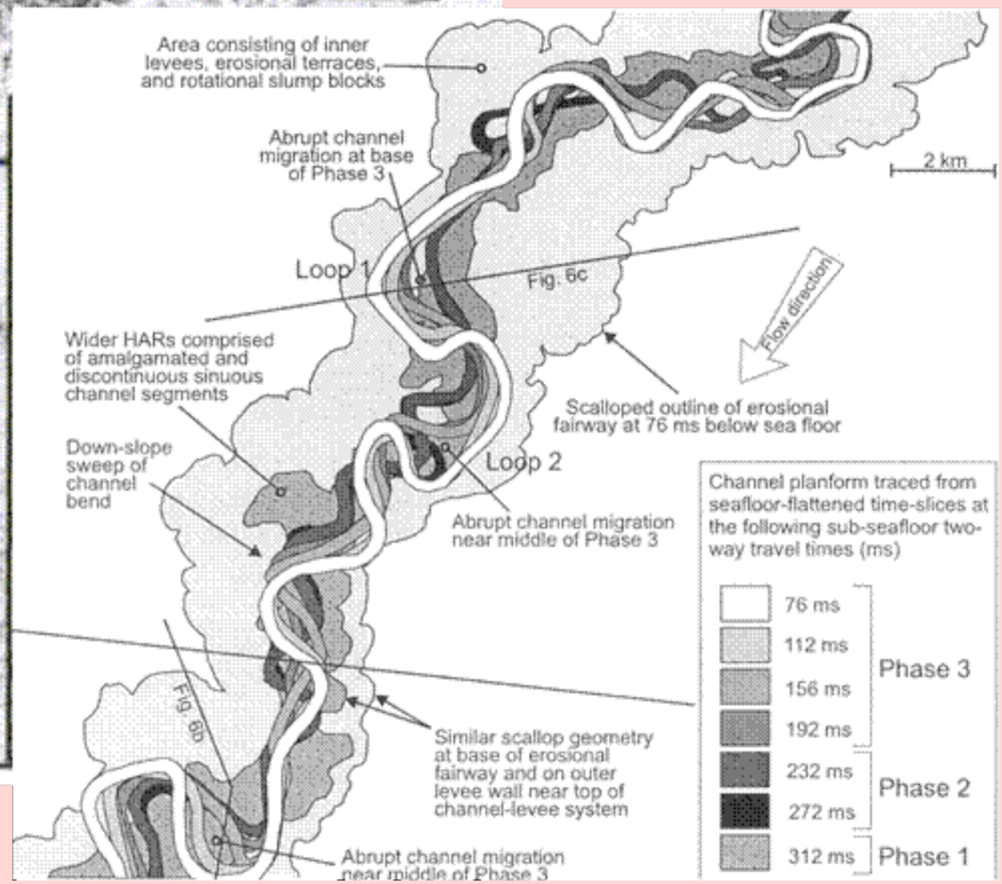
CDP_X
4500
9000
13500
18000
22500
27000
Time (ms)
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
Near offset section -- full wave elastic synthetic

3: Add Interesting Reservoirs in 3D

Alternative Slope Valley Analogue

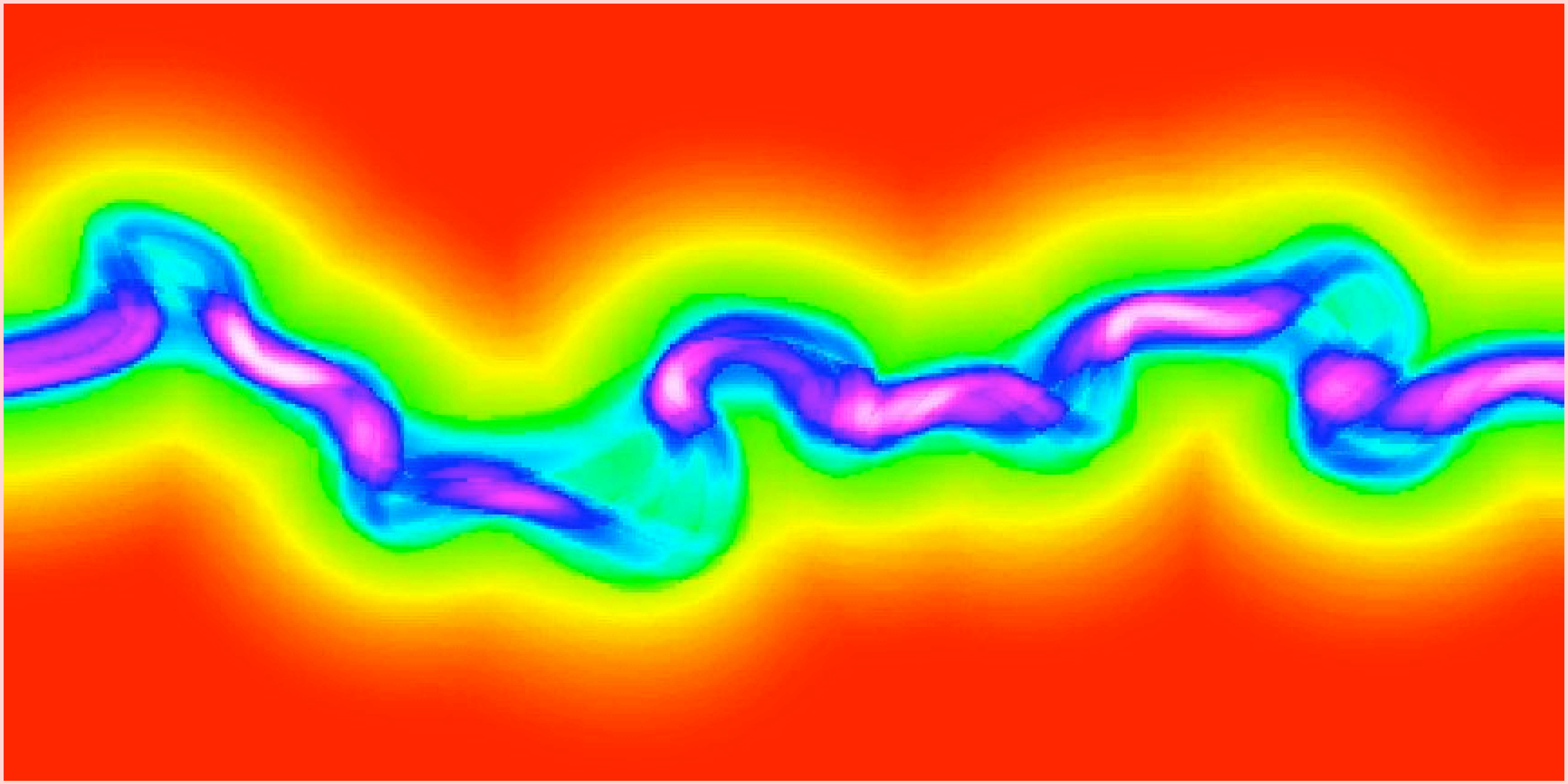
Nigeria, Deptuc et al. 2003





Channels with Levies and Downslope-Migrating Loops

Plan view of a vertical average of Vshale: (white=0, red=1)



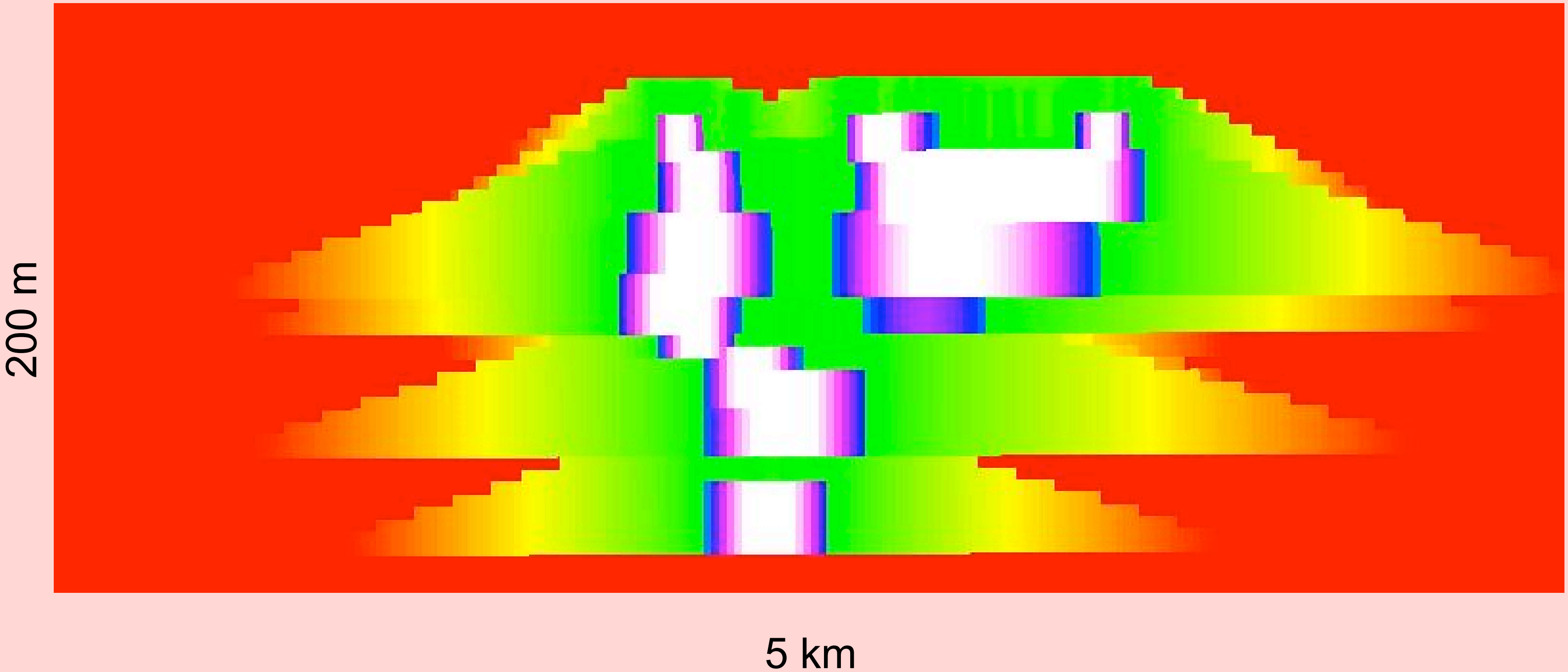
5 km

Direction of flow → 10 km

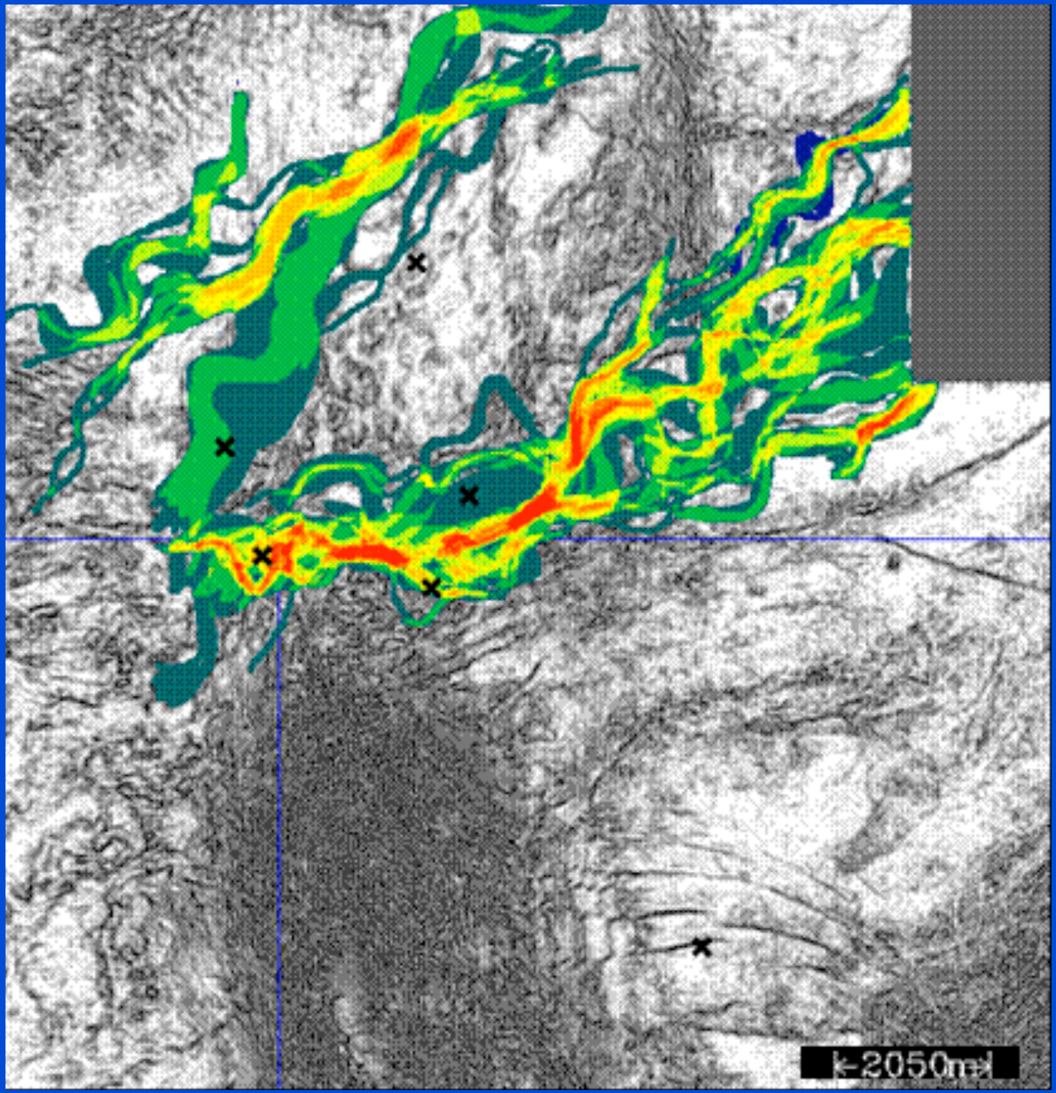
Cellular resolution: dx = dy = 25m, dz = 4m

Cross-Section of Channels with Levies Model

Vshale: (white=0, red=1)   Vert Exag = 10:1



Multi Layer Interpretation

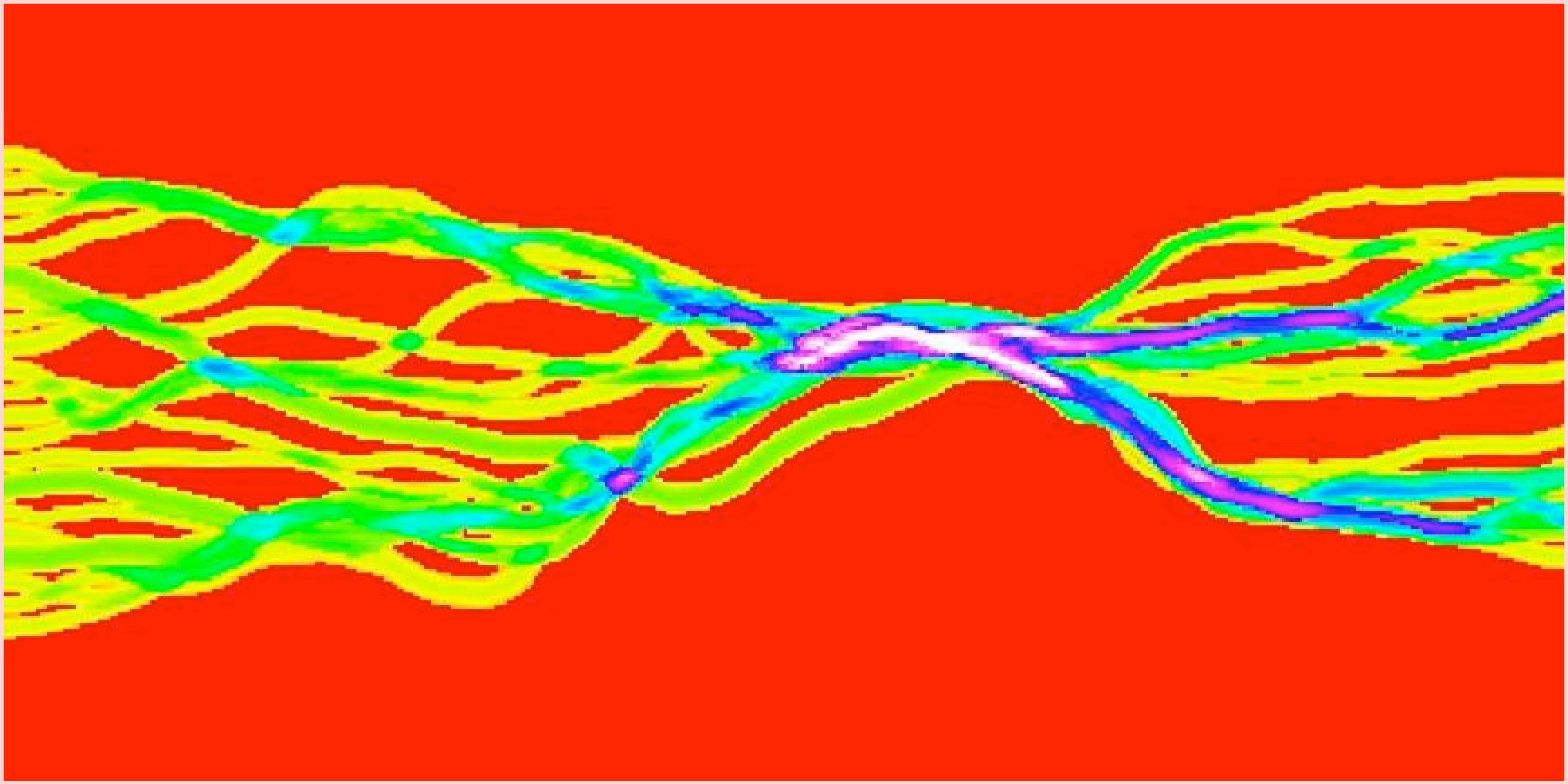


Distributary channel interpretation from 14 time slices thoughout 12.5 interval, merged to show channel stacking & switching pattern

Anastomosing & Constricted Channels without Levies

(spaghetti model)

Plan view of a vertical average of Vshale: (white=0, red=1)



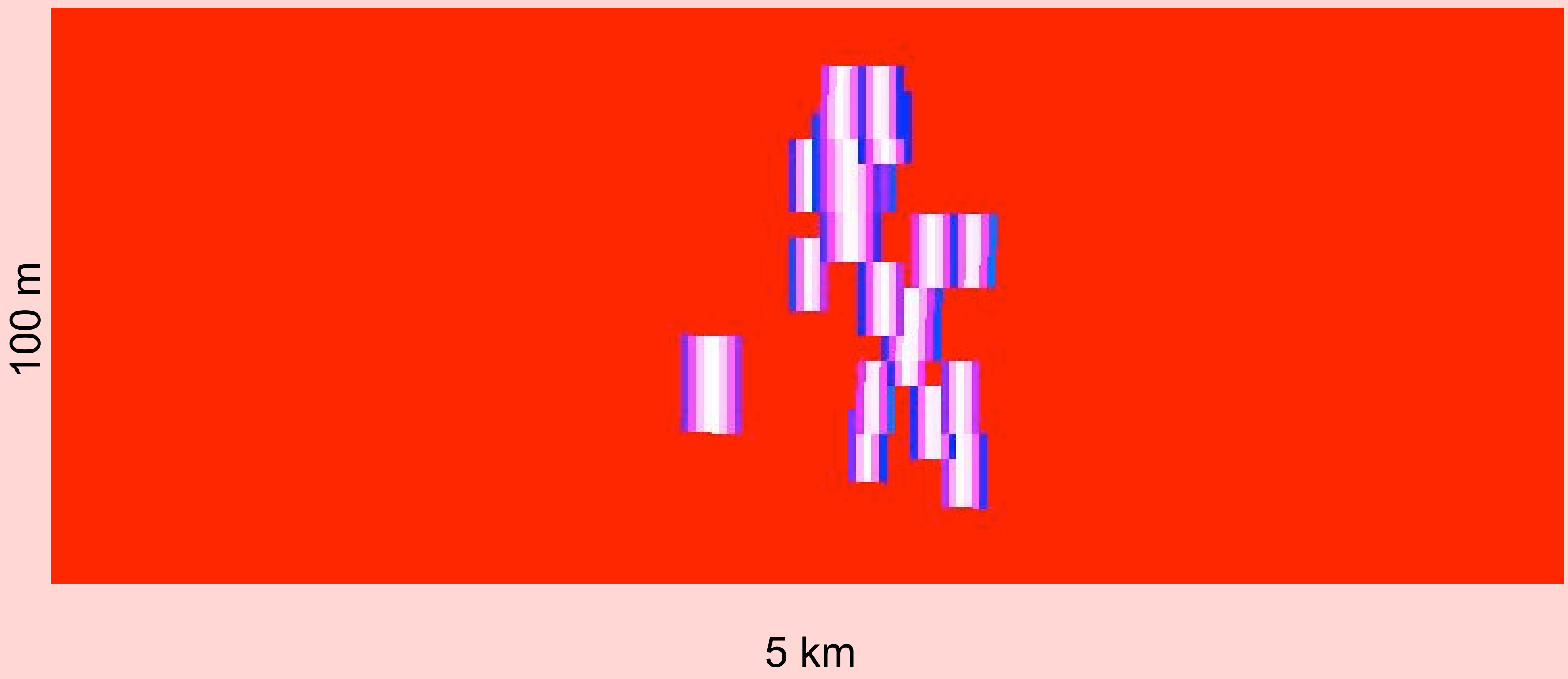
5 km

10 km

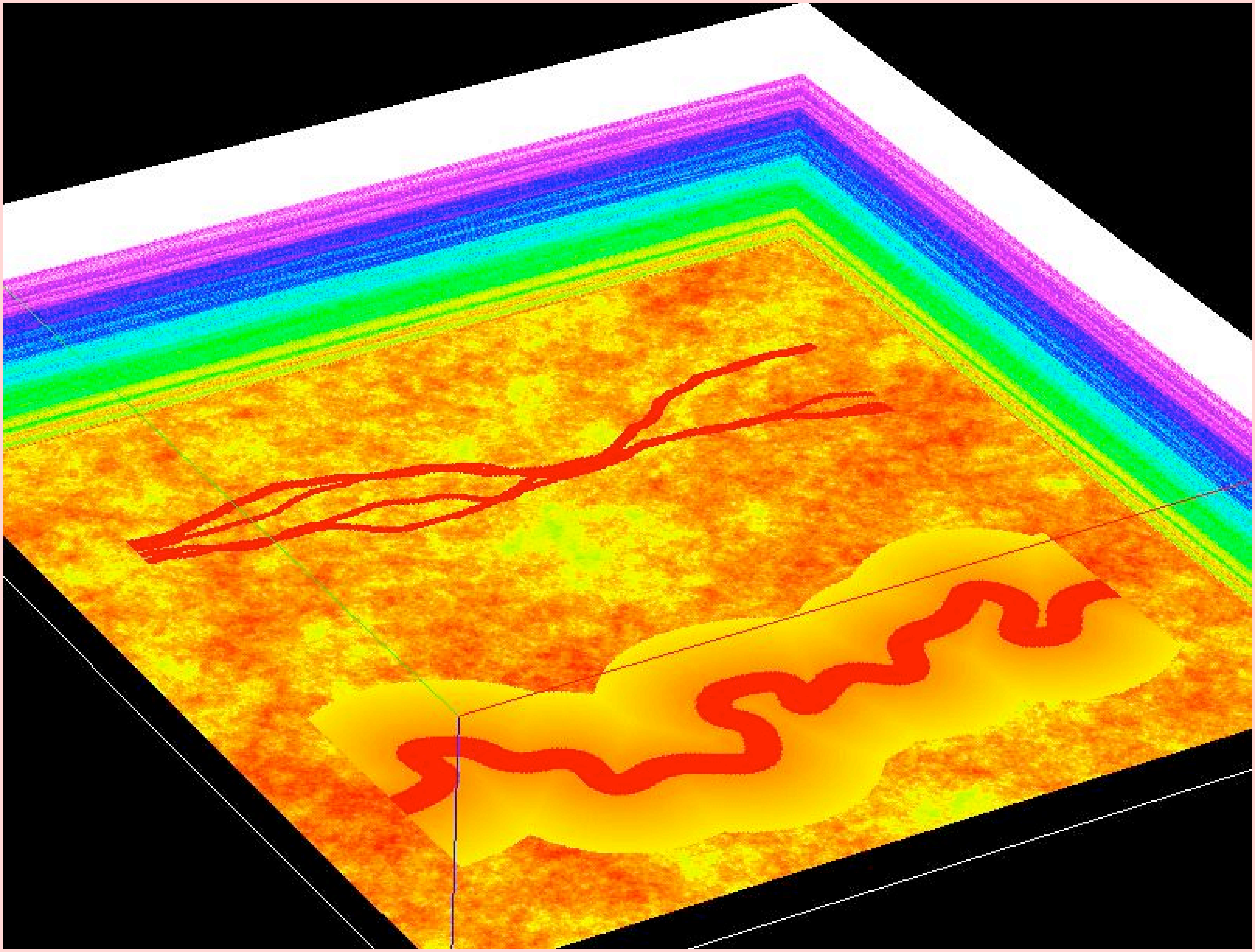
Cellular resolution: dx = dy = 25m, dz = 4m

Cross-Section (near throat) of Spaghetti Model

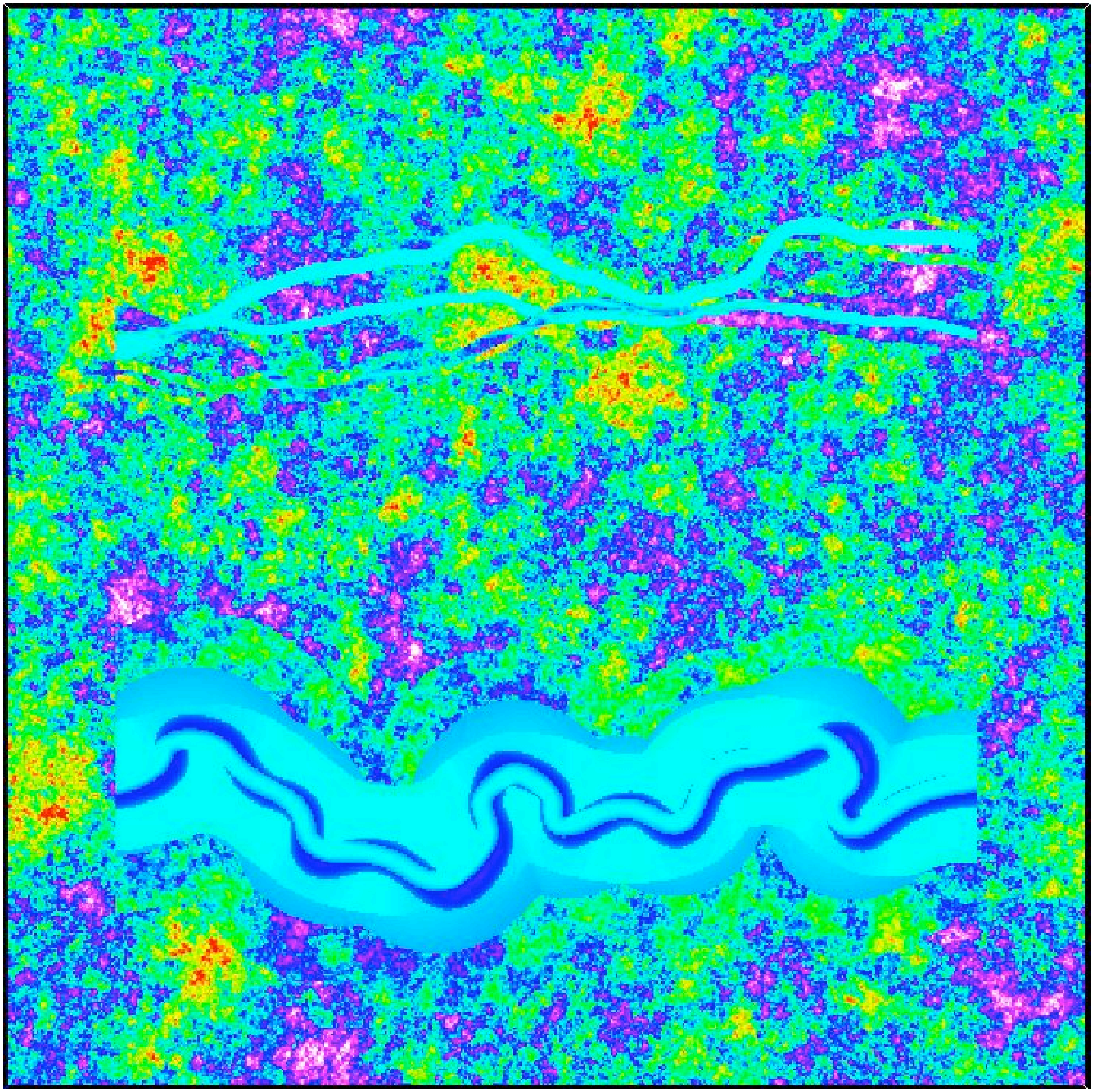
Vshale: (white=0, red=1)   Vert Exag = 20:1



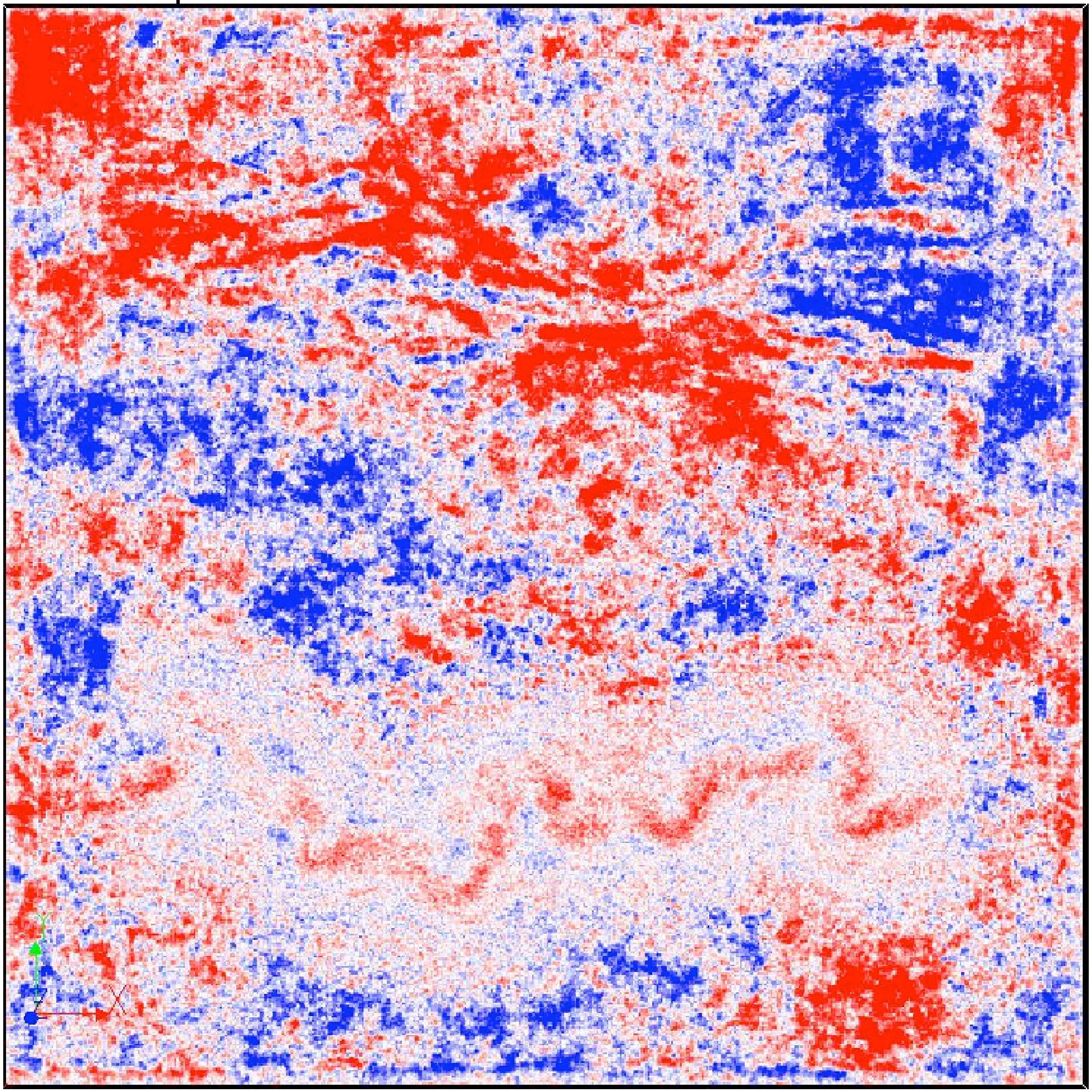
Stratigraphic Model (Vp)

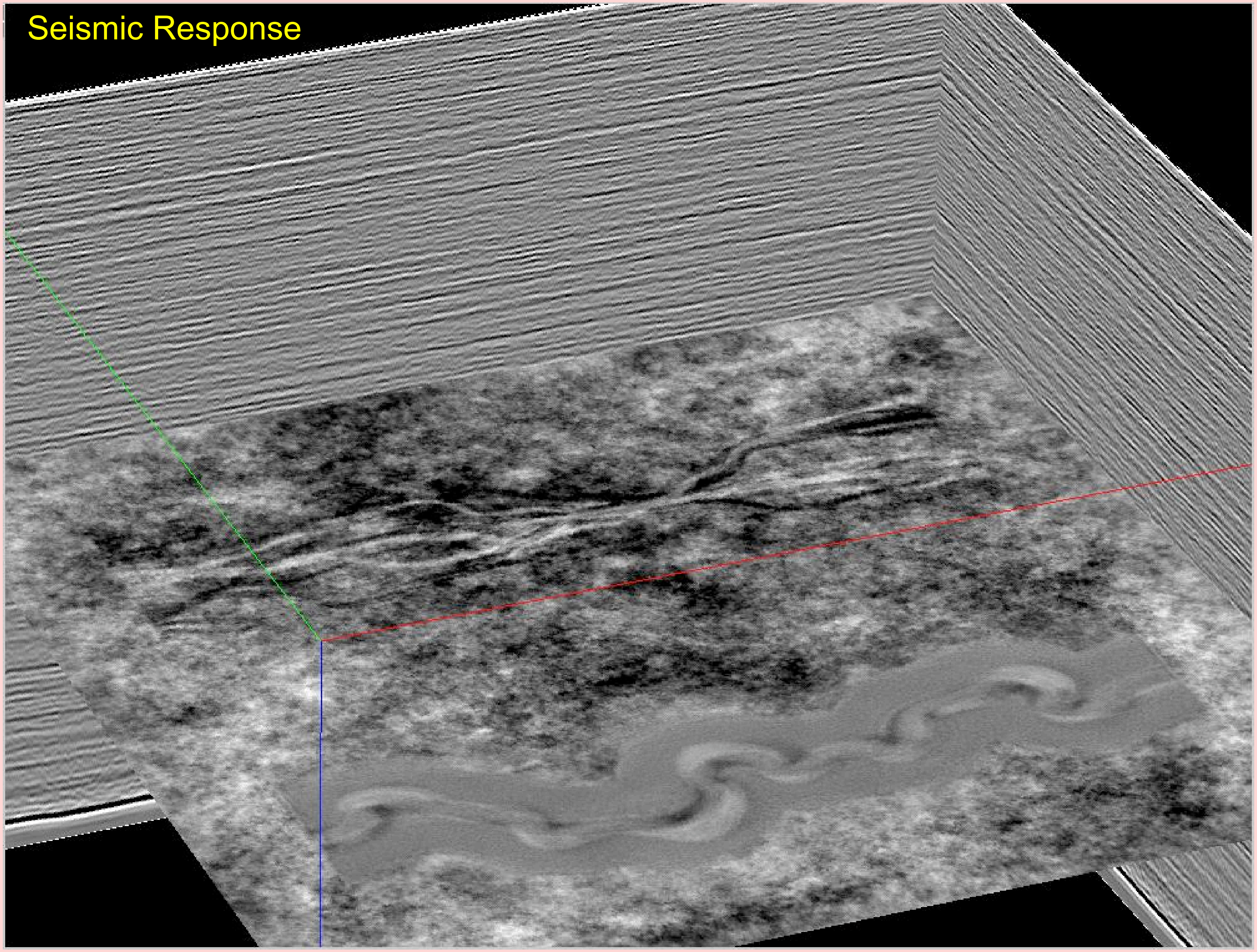


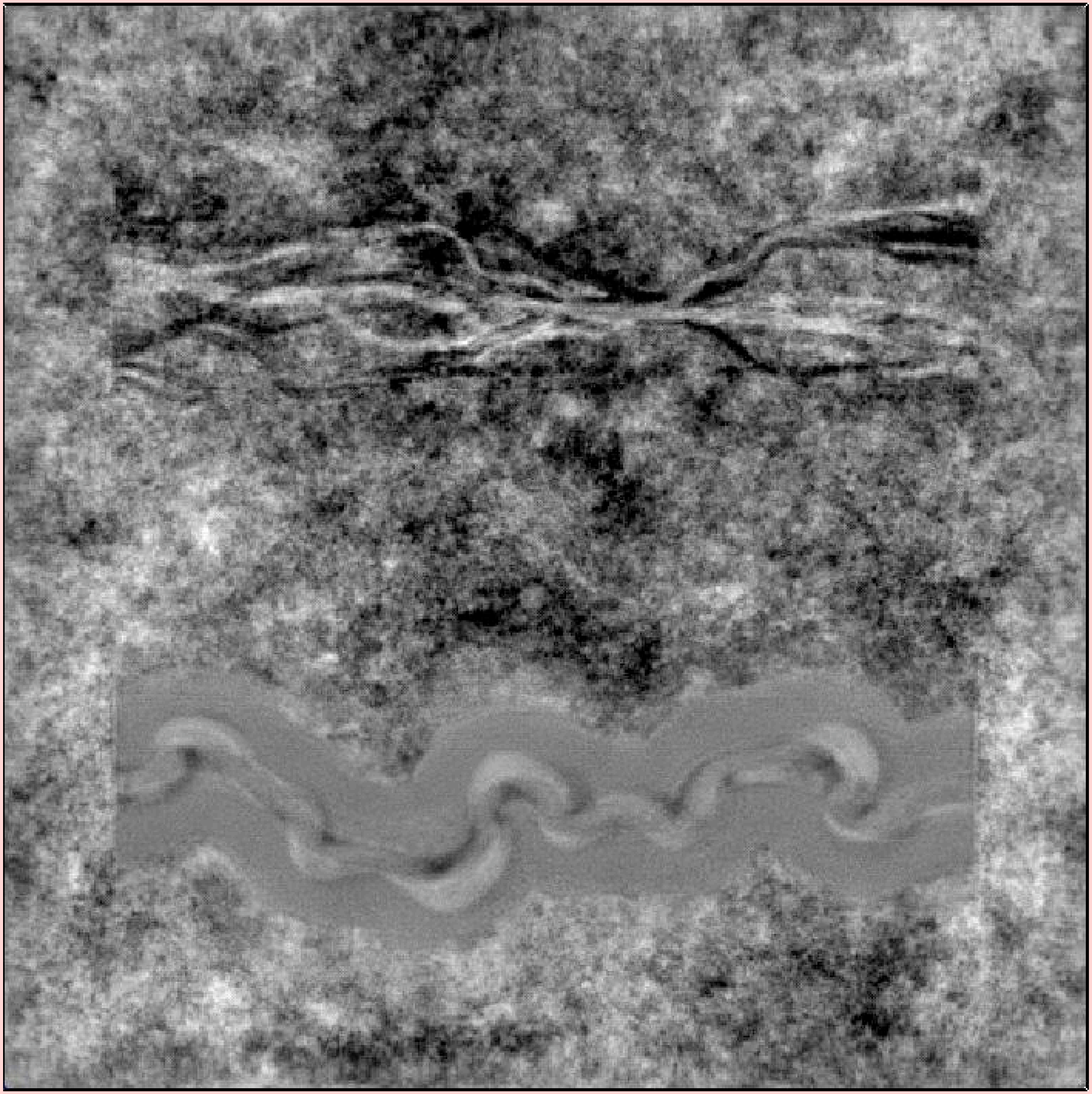
Strat example 2: Braided channels + overbank meander channel

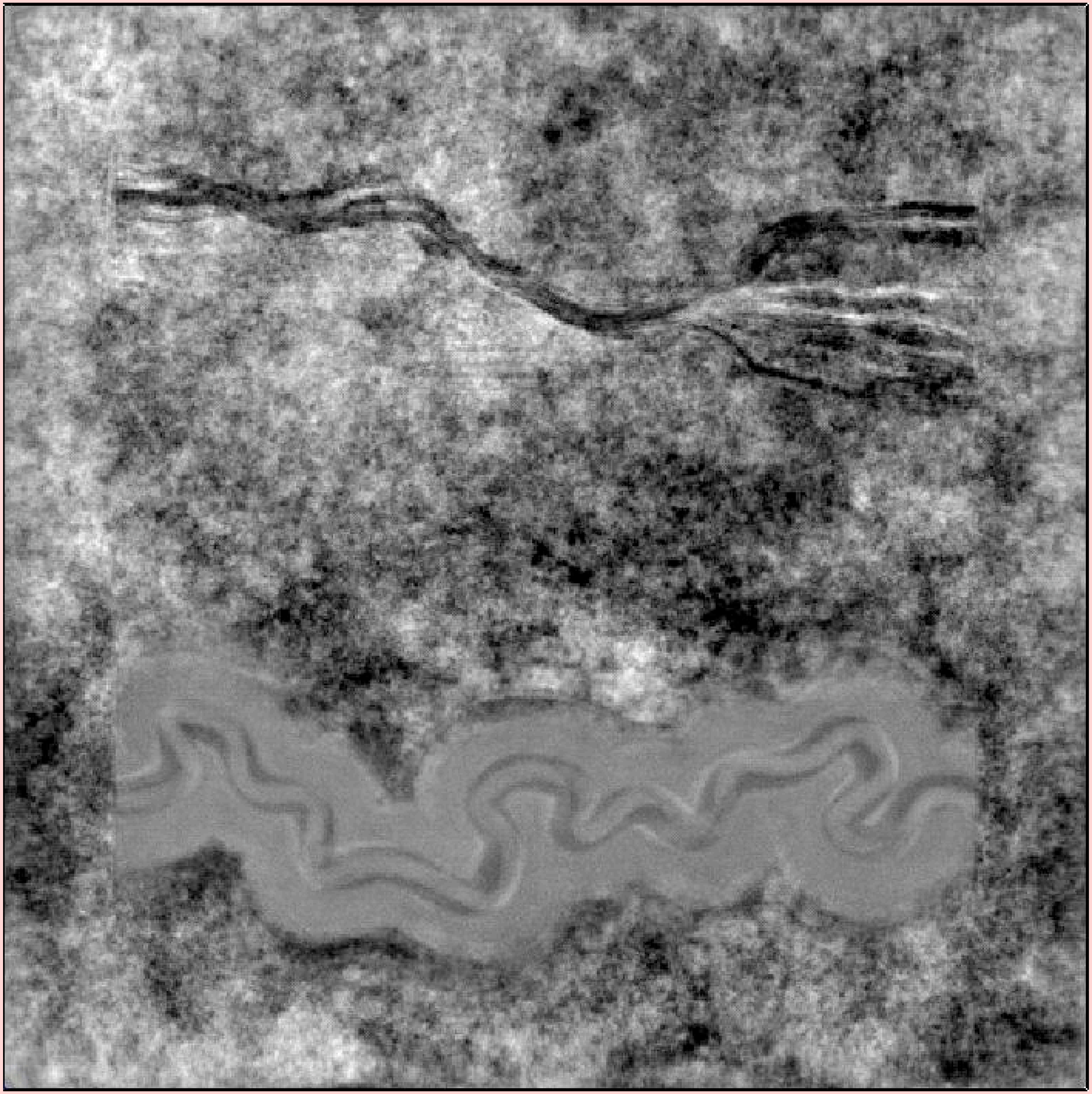


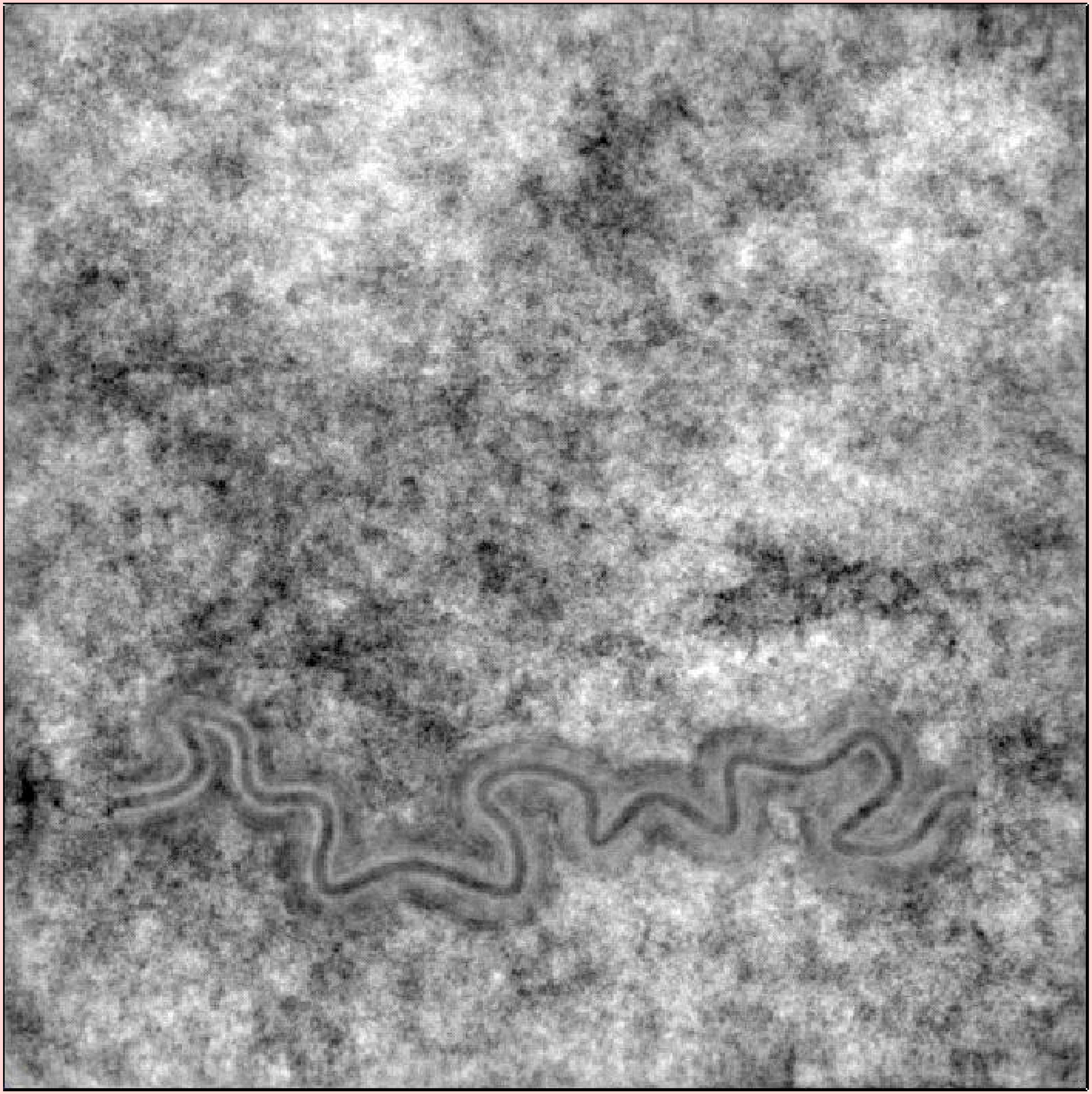
Seis example 2: Braided channels + overbank meander channel

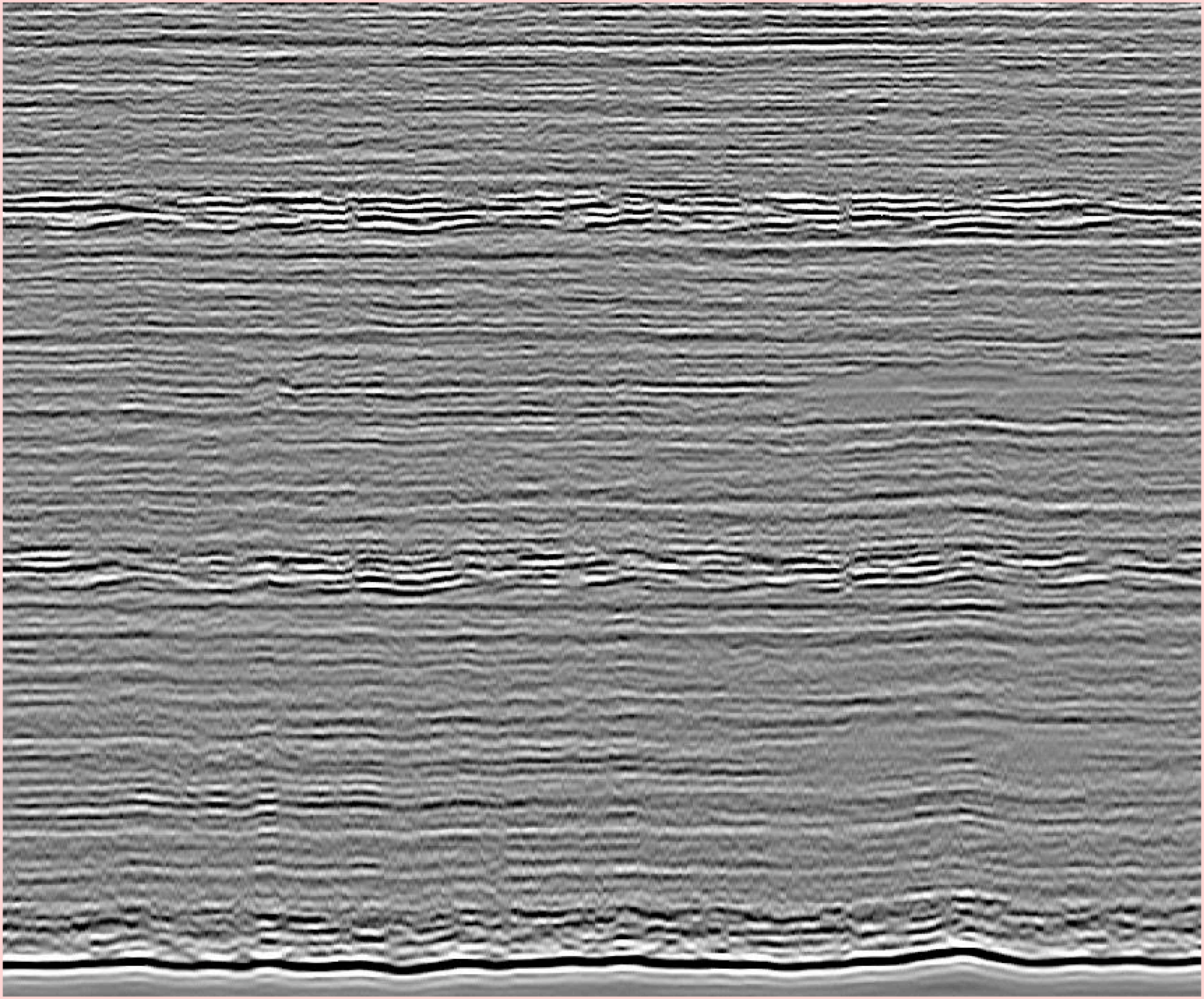



Seismic Response

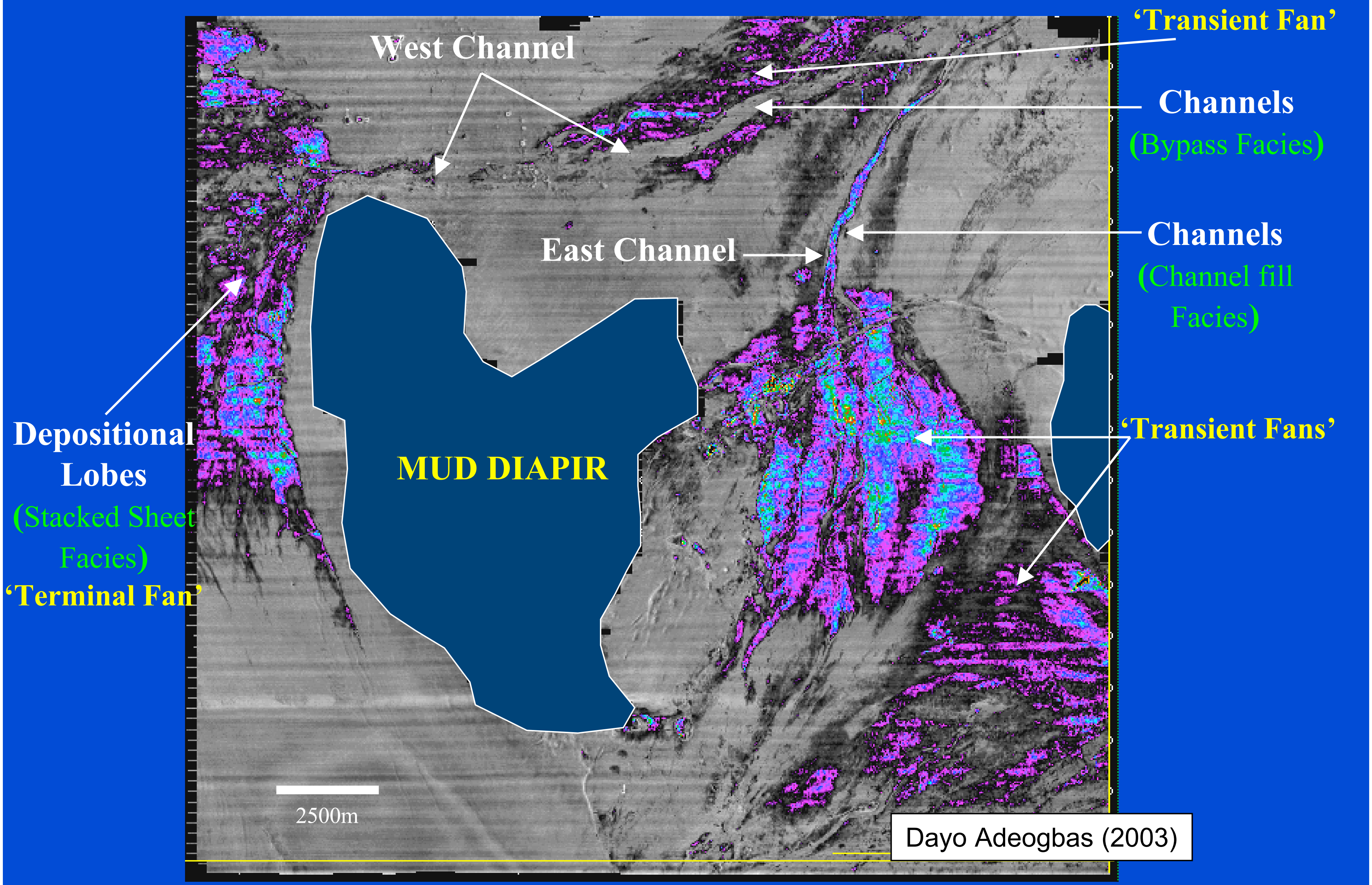


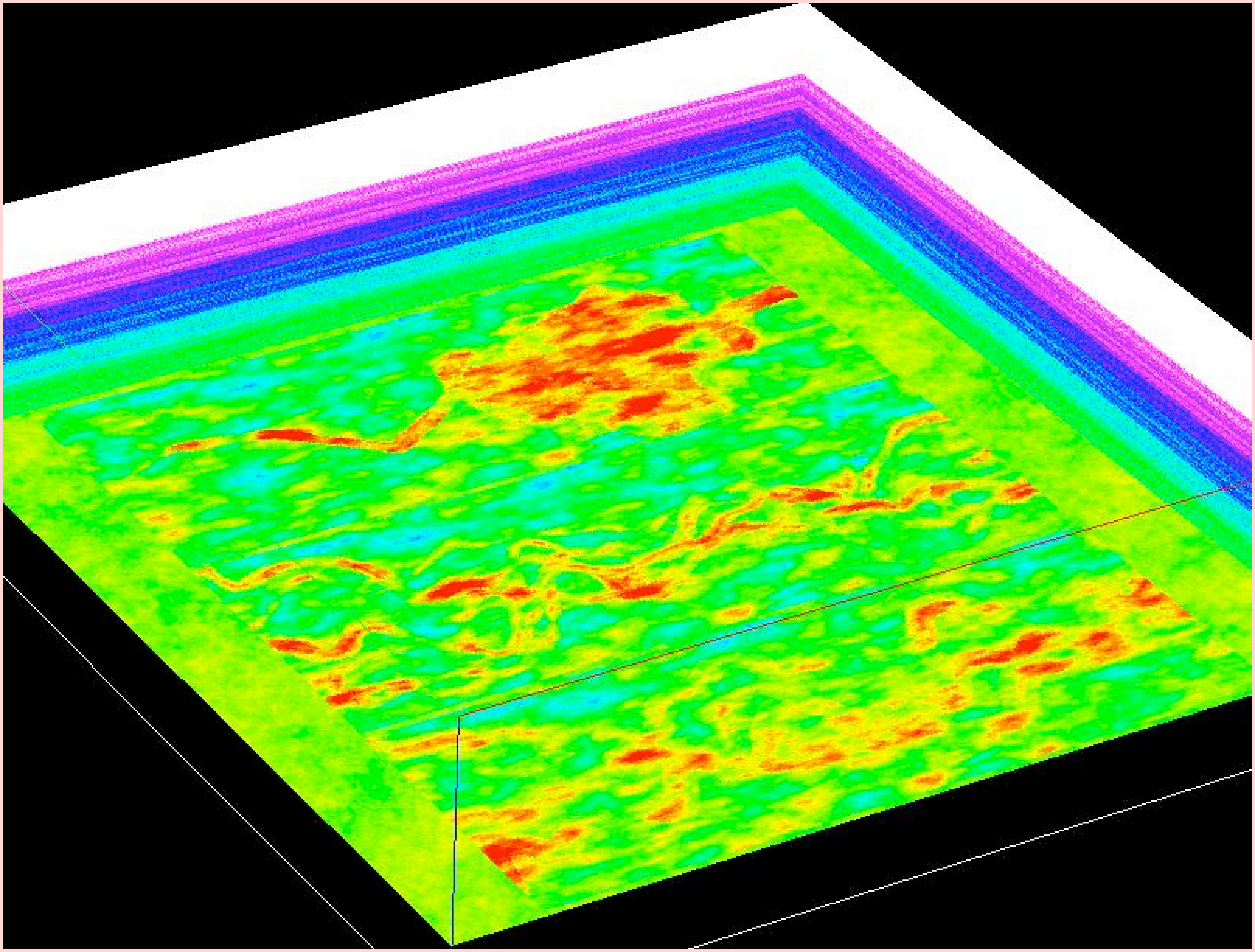




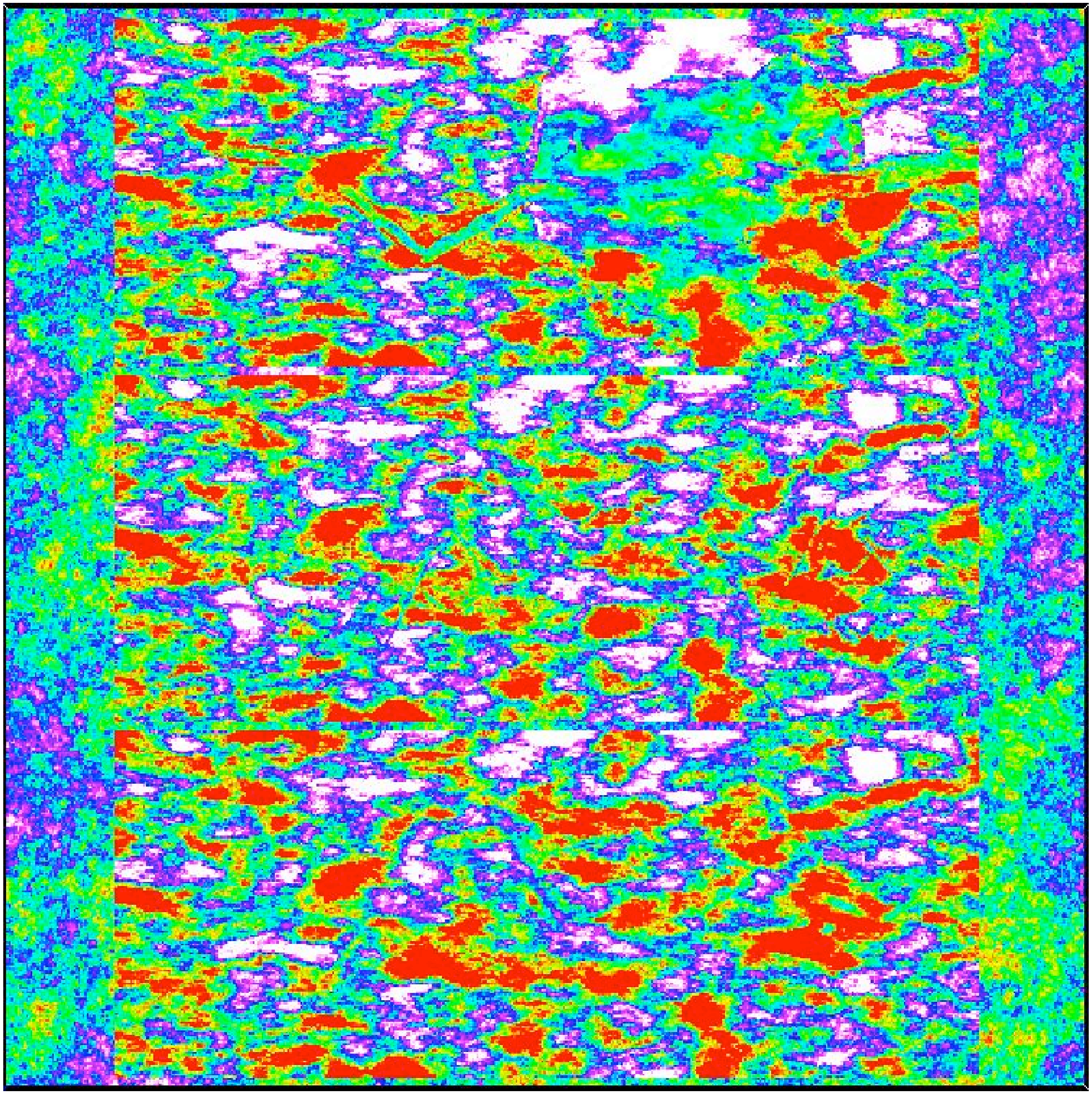


Transient Fans
Shallow Seismic Examples from Nigeria

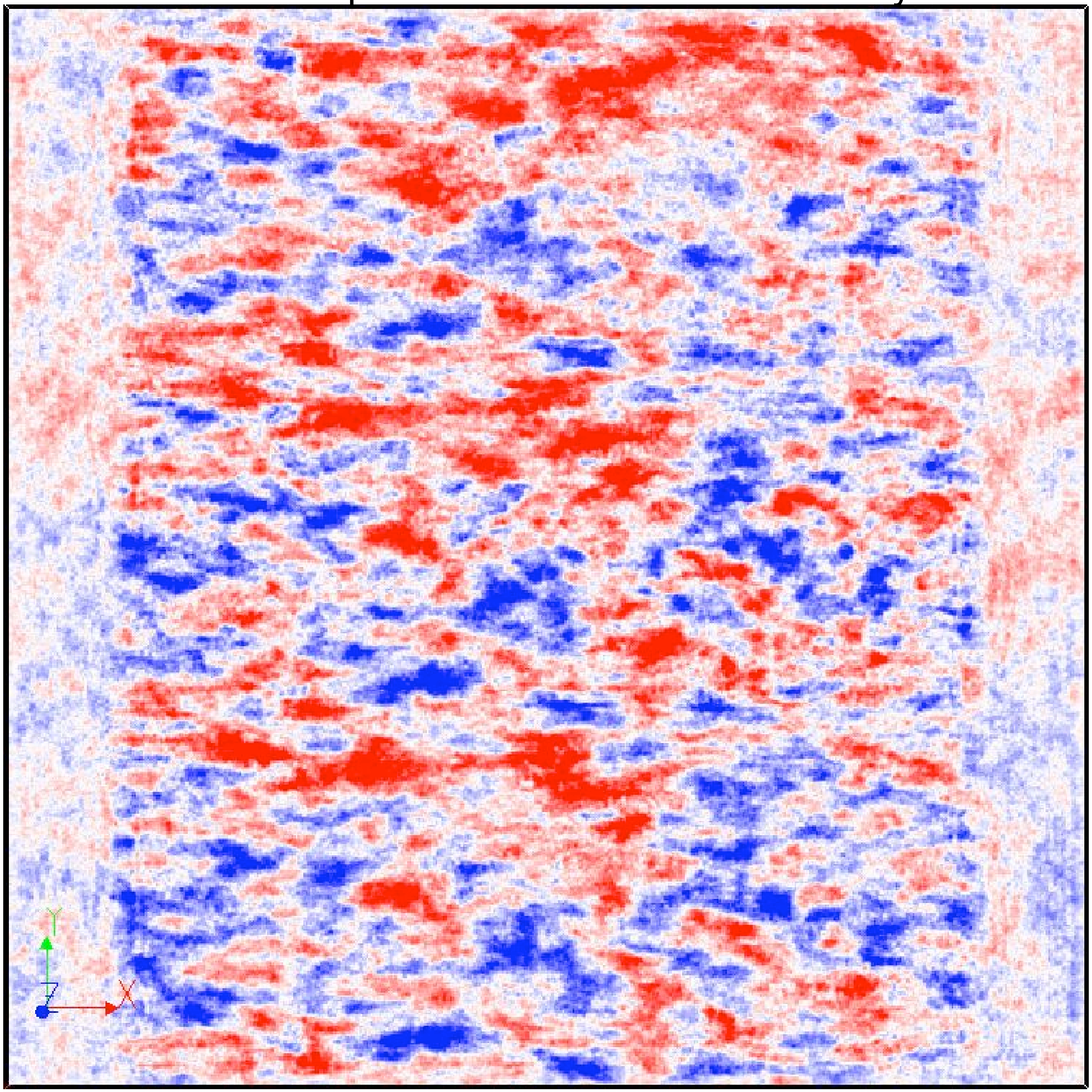




Strat example 1: Channels of low reflectivity

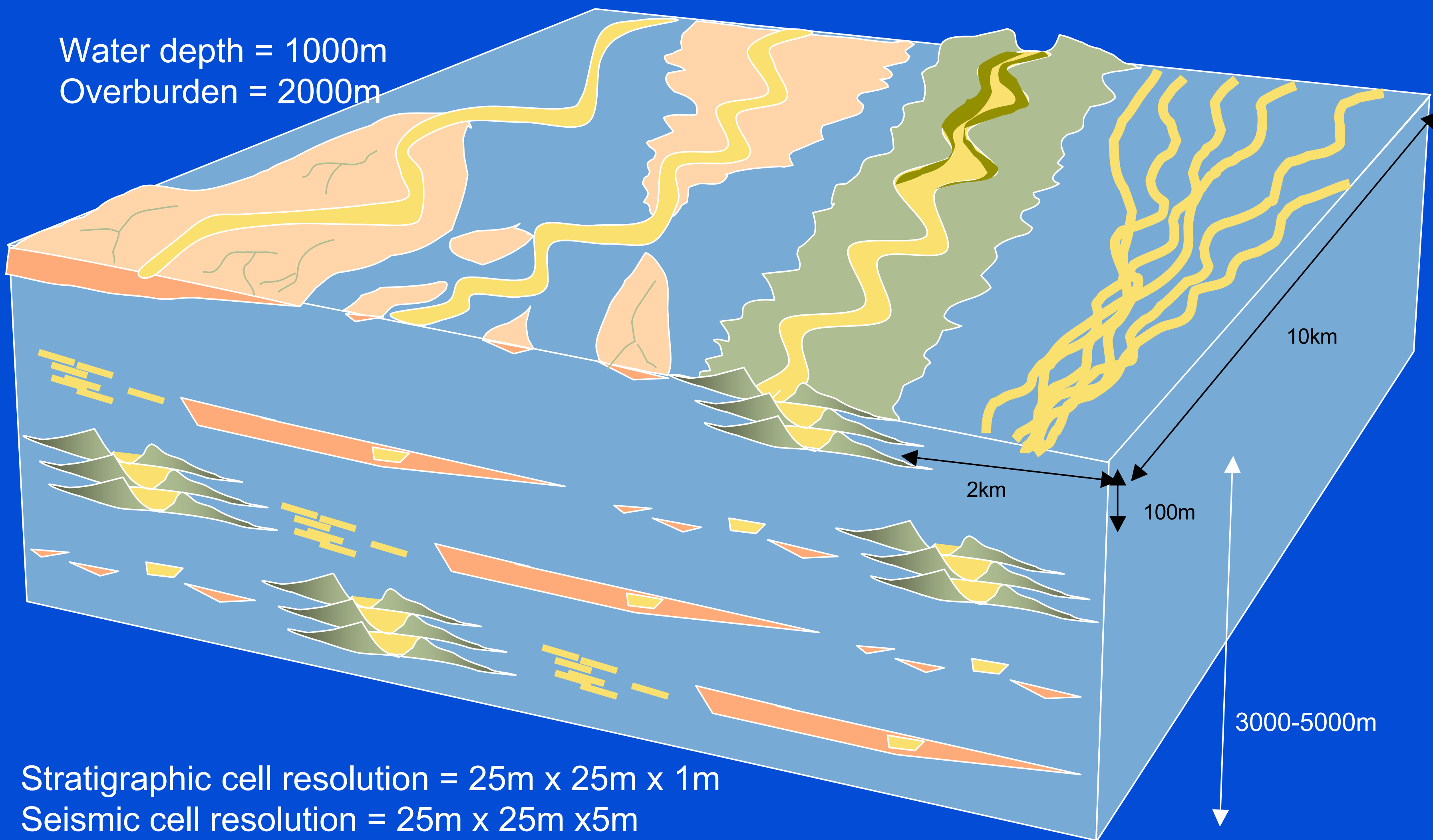


Seis example 1: Channels of low reflectivity



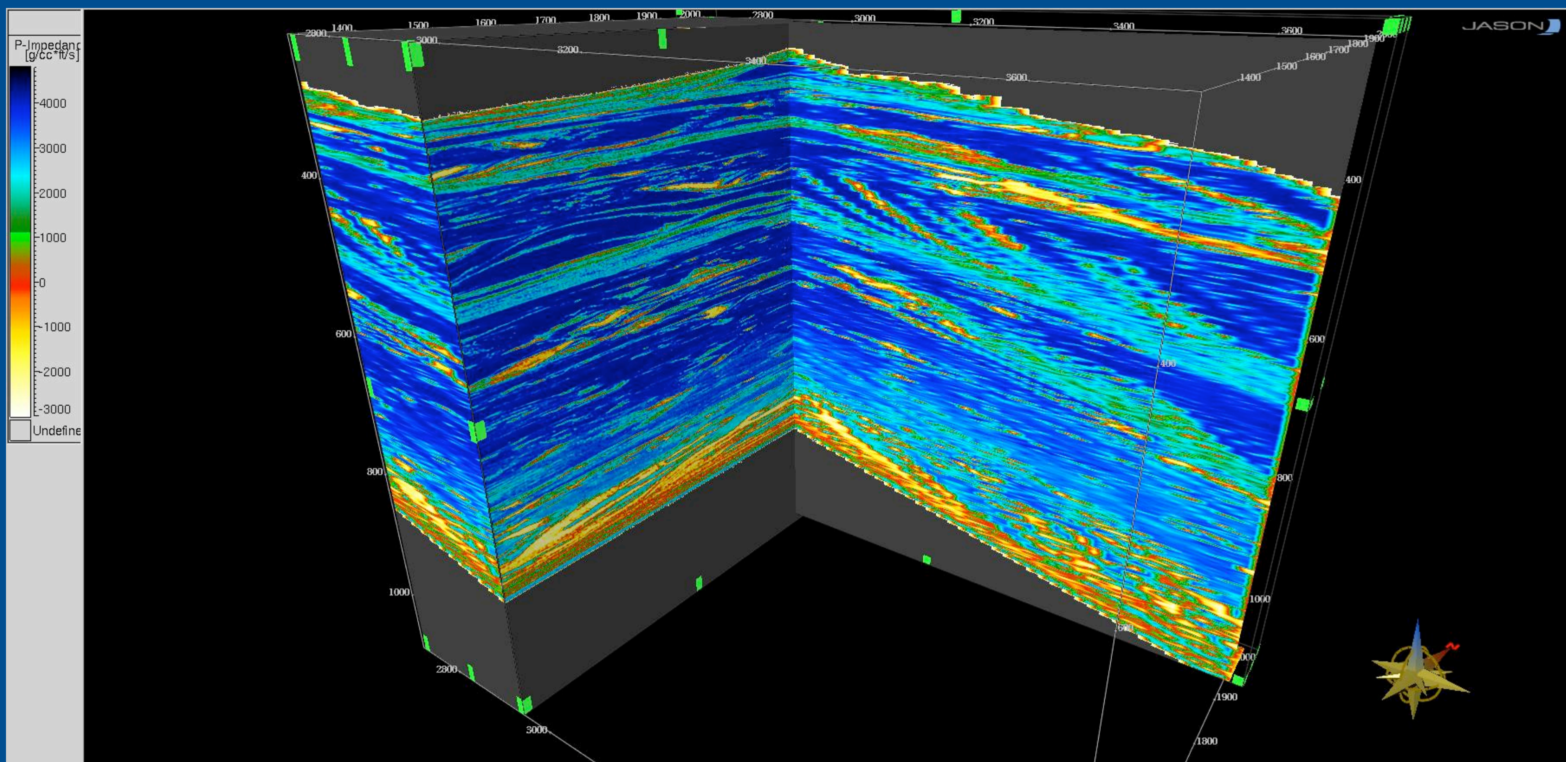
3D Conceptual Models

Water depth = 1000m
Overburden = 2000m

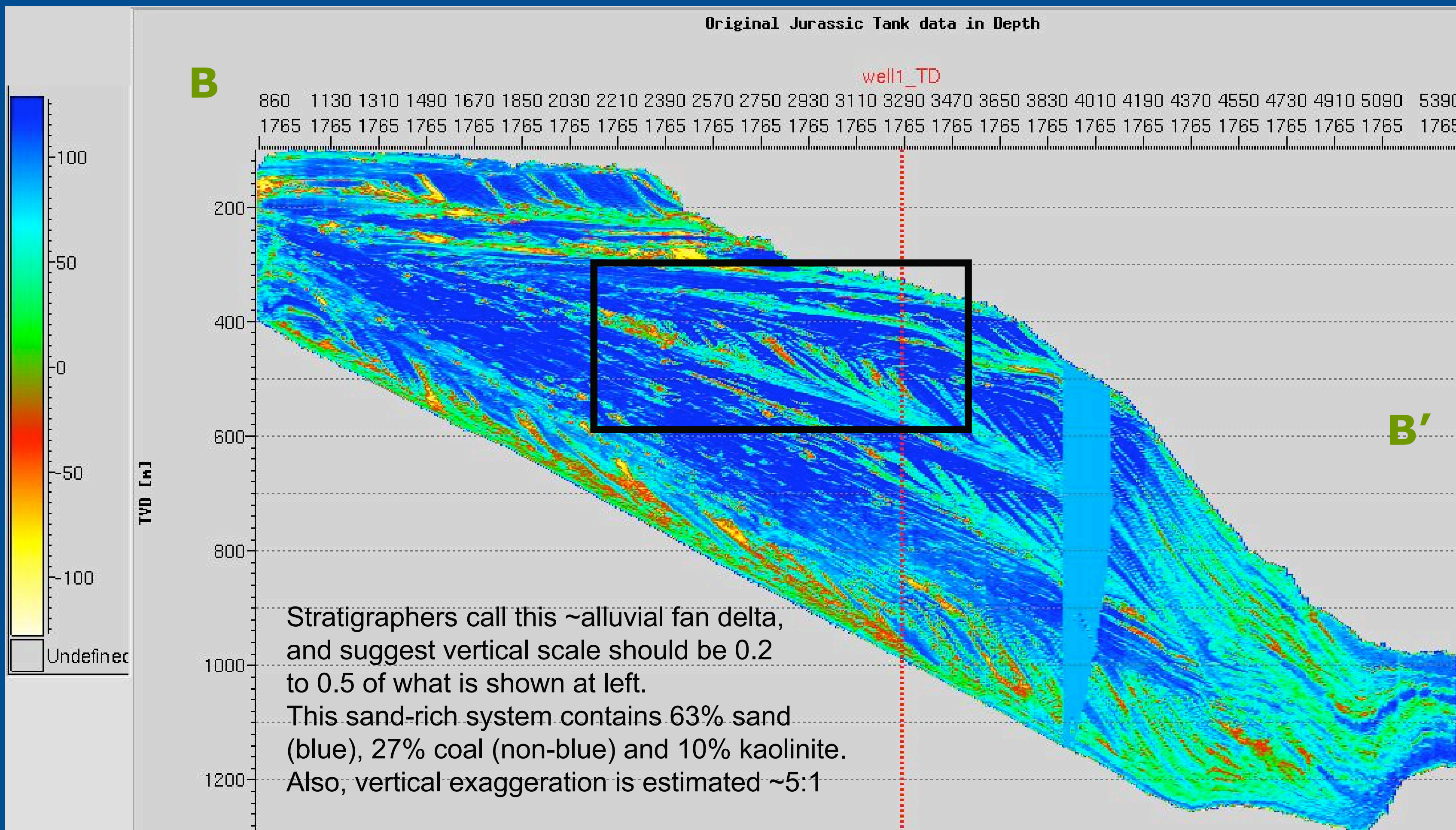


Stratigraphic cell resolution = 25m x 25m x 1m
Seismic cell resolution = 25m x 25m x5m

Jurassic Tank 3D Volume
University of Minnesota, St. Anthony Falls Laboratory
courtesy of Prof. Chris Paola

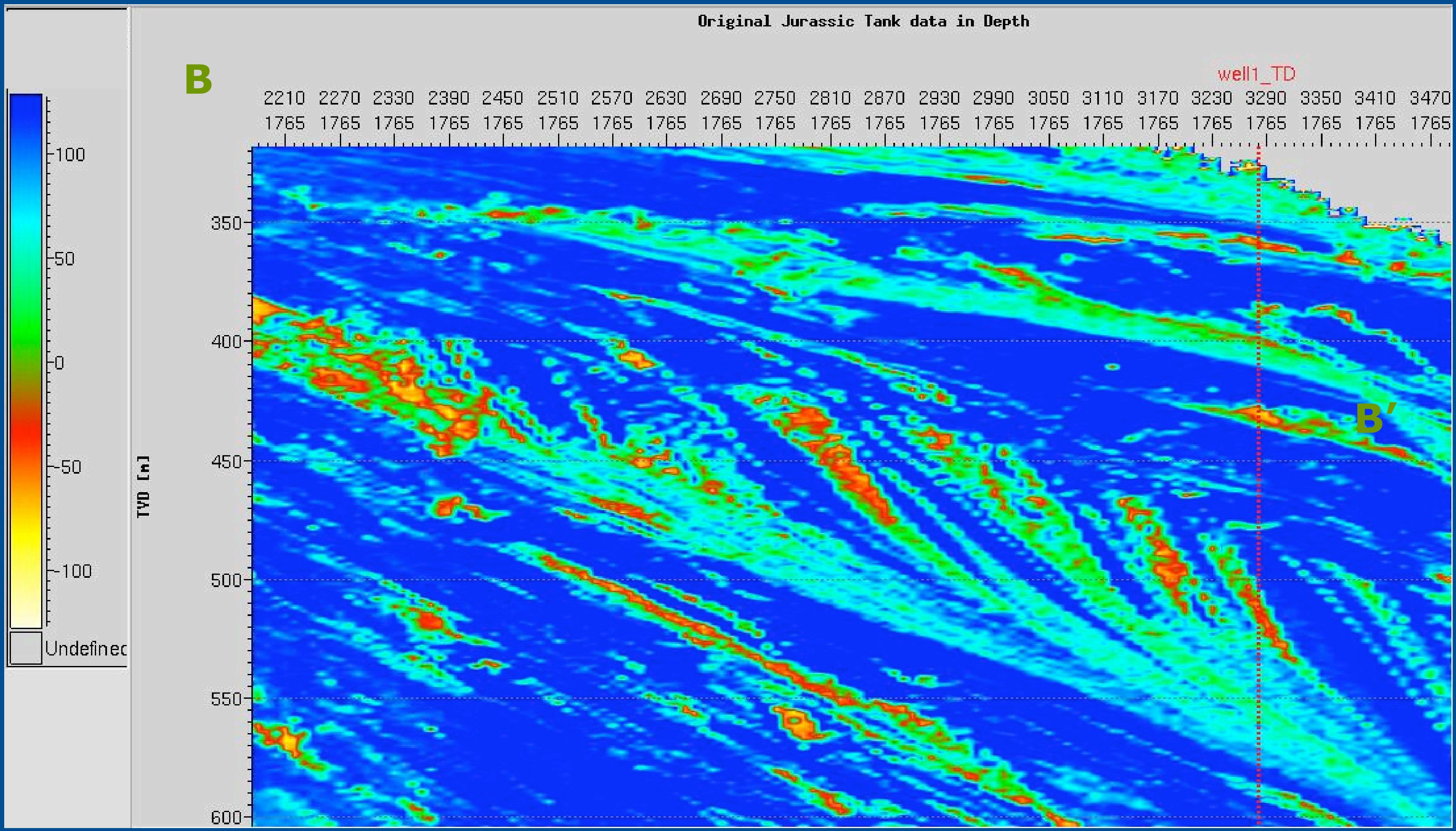


Dip Section

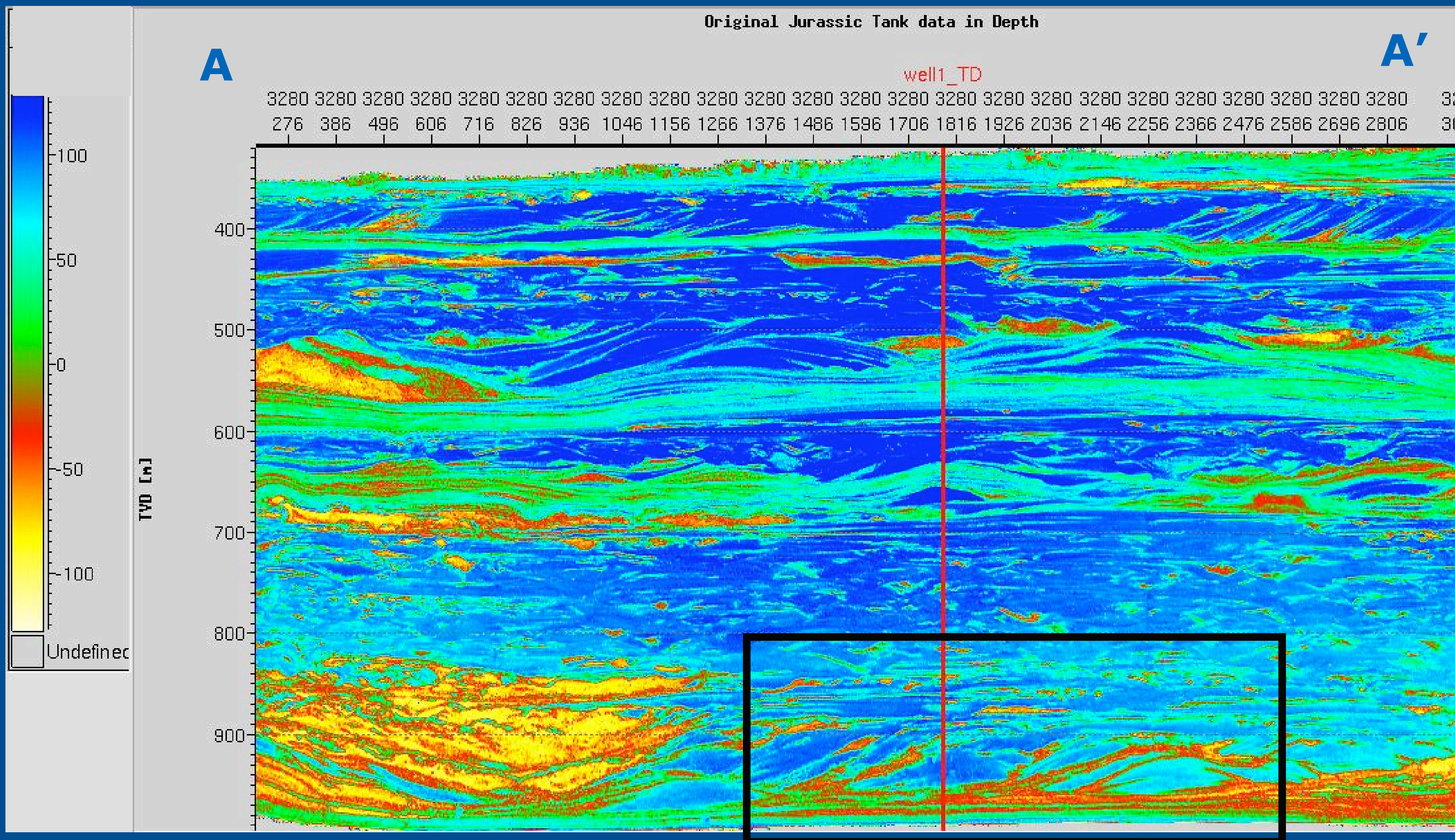


Original Jurassic Tank data in Depth
B
B'
well1_TD
860 1130 1310 1490 1670 1850 2030 2210 2390 2570 2750 2930 3110 3290 3470 3650 3830 4010 4190 4370 4550 4730 4910 5090 5390
1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765
200
400
600
800
1000
1200
TVD [m]
100
50
0
-50
-100
Undefined
Stratigraphers call this ~alluvial fan delta, and suggest vertical scale should be 0.2 to 0.5 of what is shown at left.
This sand-rich system contains 63% sand (blue), 27% coal (non-blue) and 10% kaolinite.
Also, vertical exaggeration is estimated ~5:1

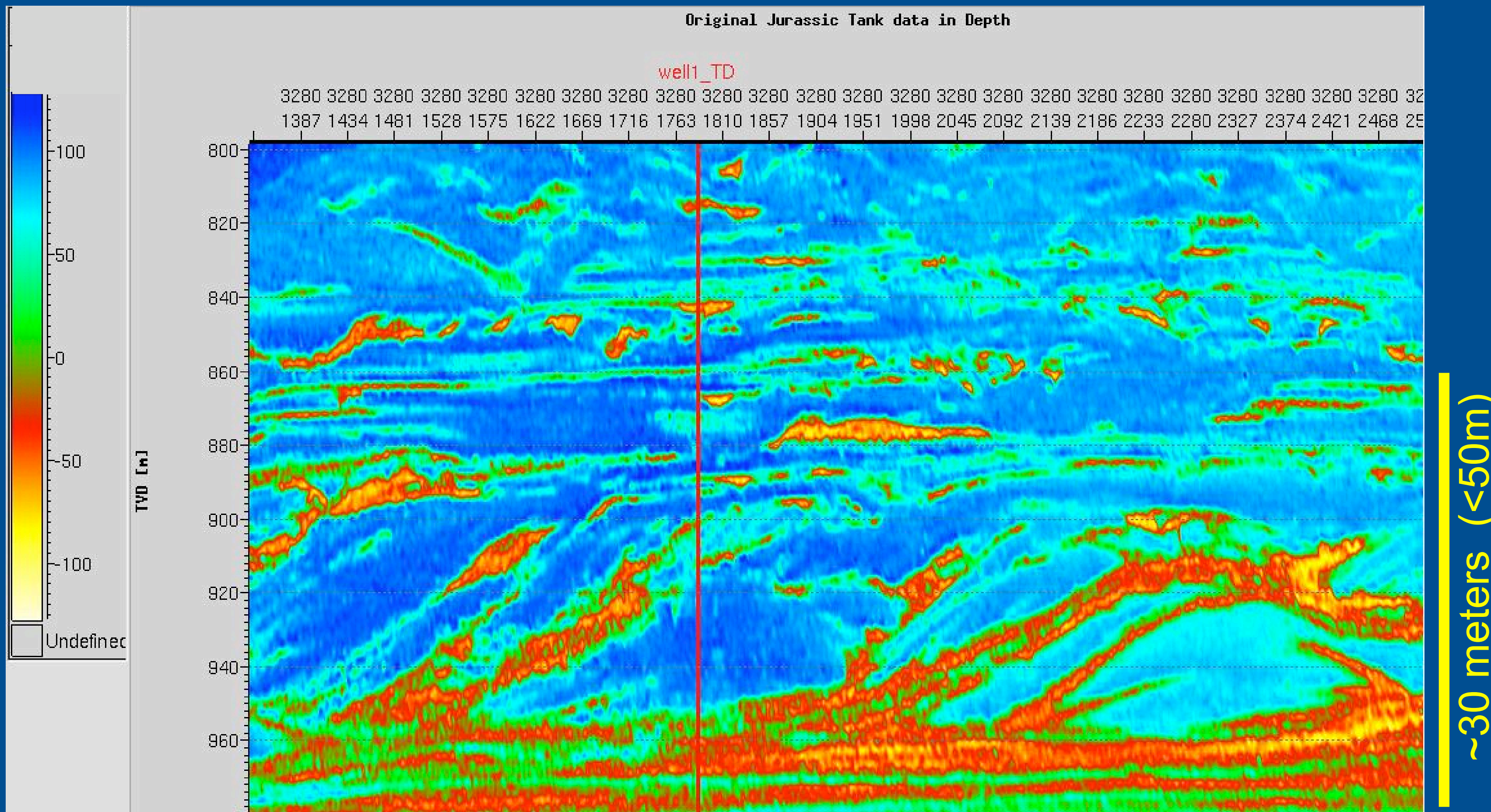
Dip Section


Original Jurassic Tank data in Depth
B
B'
well1_TD
2210 2270 2330 2390 2450 2510 2570 2630 2690 2750 2810 2870 2930 2990 3050 3110 3170 3230 3290 3350 3410 3470
1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765 1765
TVD [m]
350
400
450
500
550
600
100
50
0
-50
-100
Undefined

Strike Section



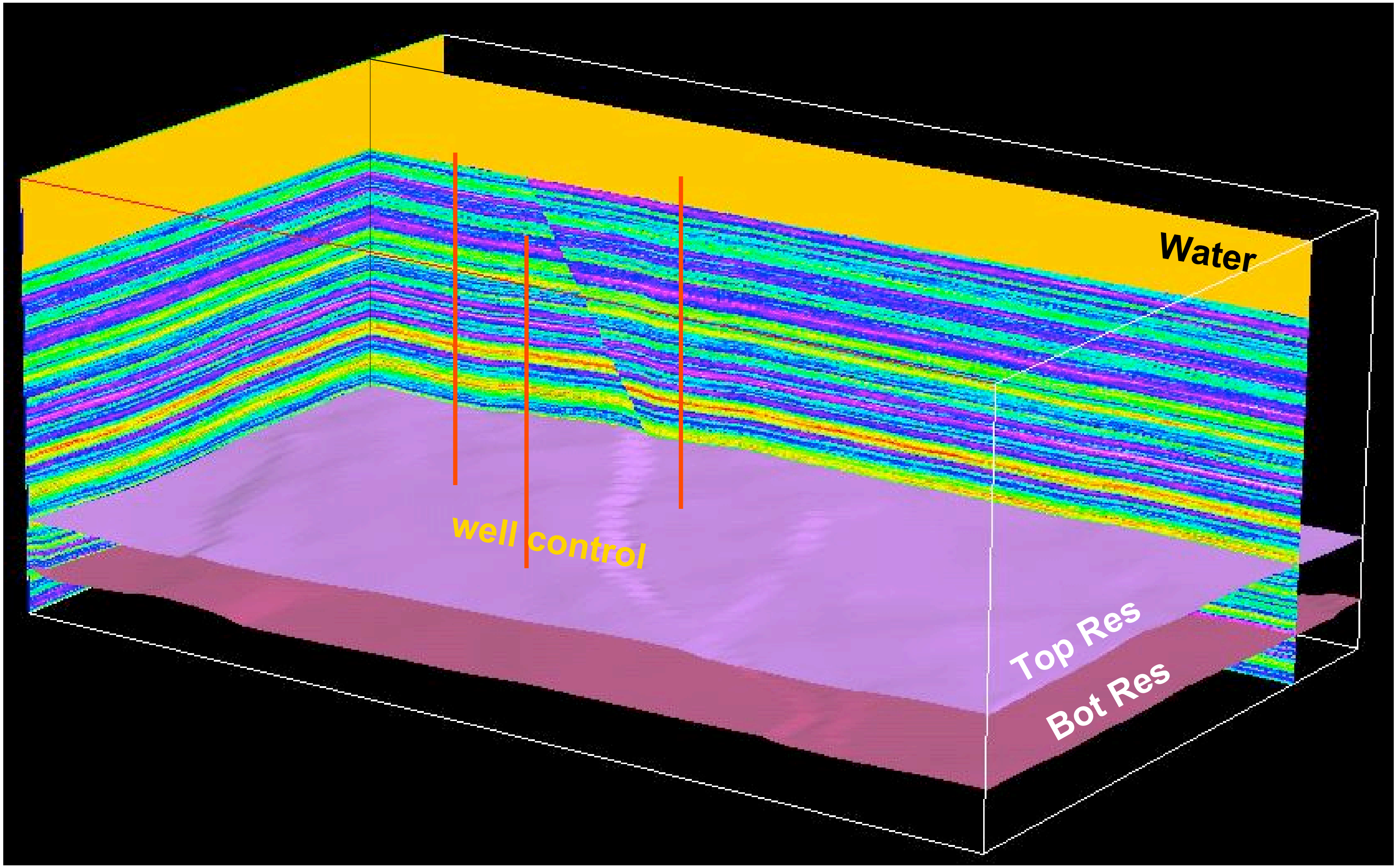
Strike Section



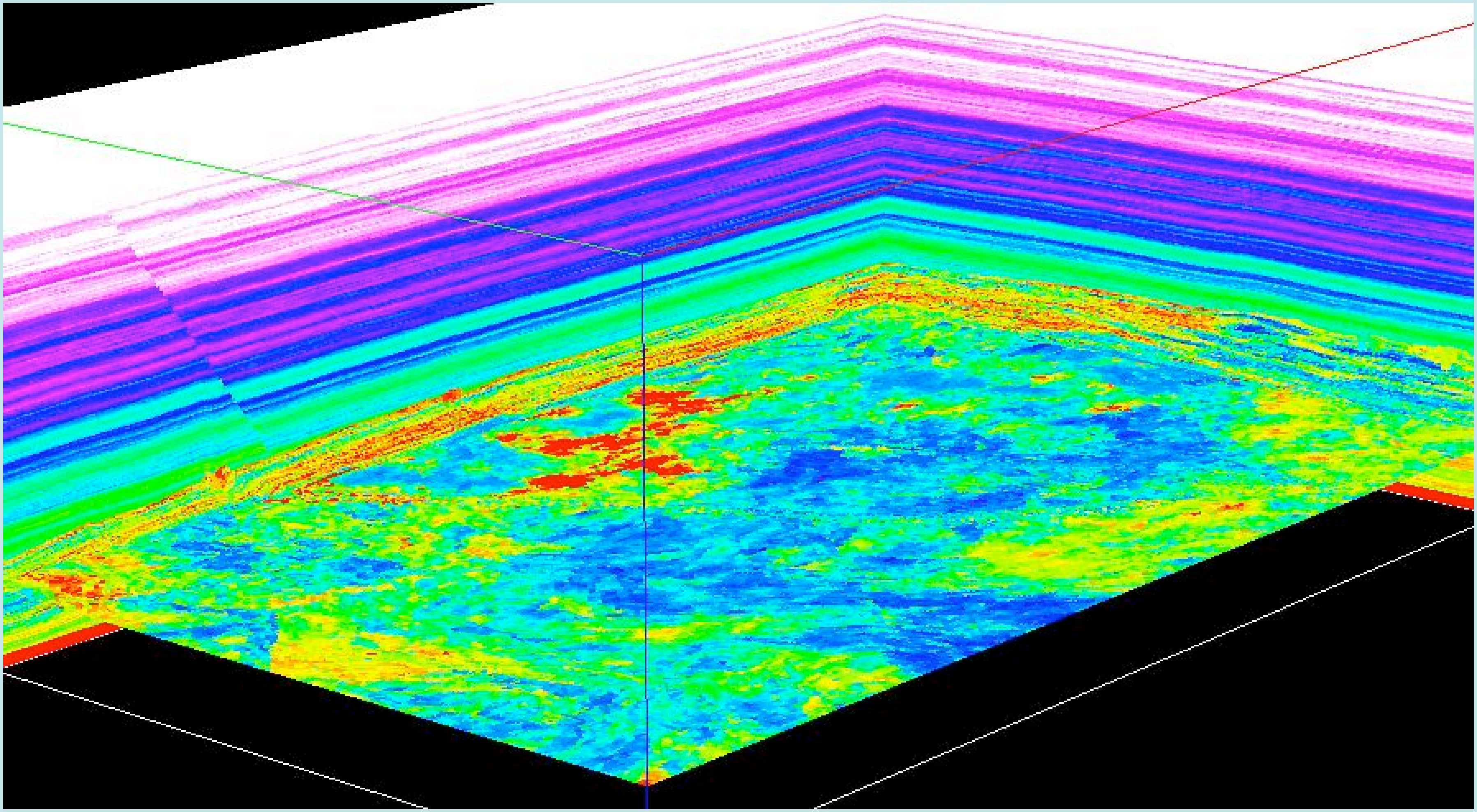
Stratigraphers would call this ~alluvial fan delta,
and would scale it vertically according to bar at right, with VE ~ 5:1

4: **Warp/Morph by Hand**

Reservoir embedded in stratigraphic container for seismic modeling

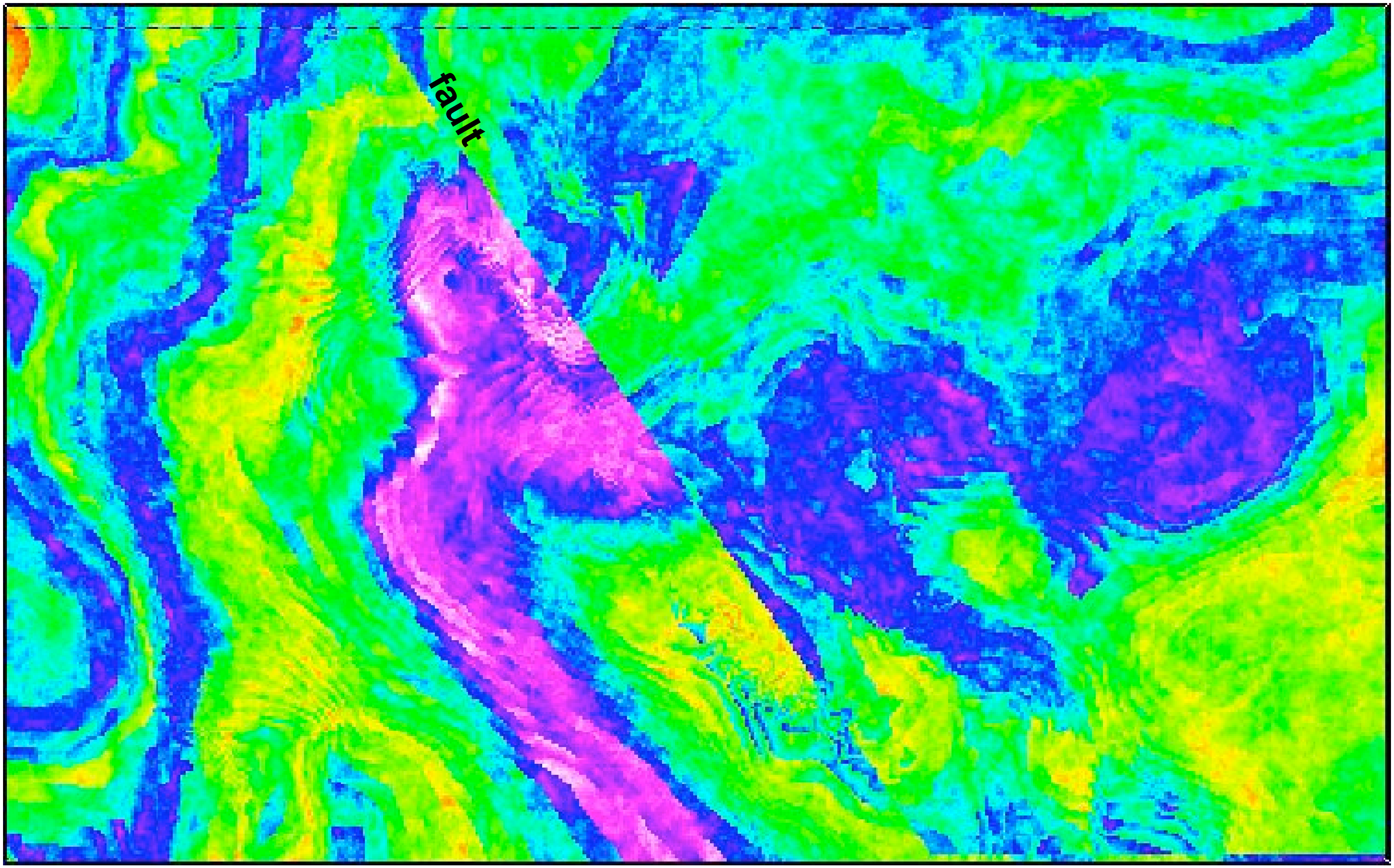


Example: Voxet sections

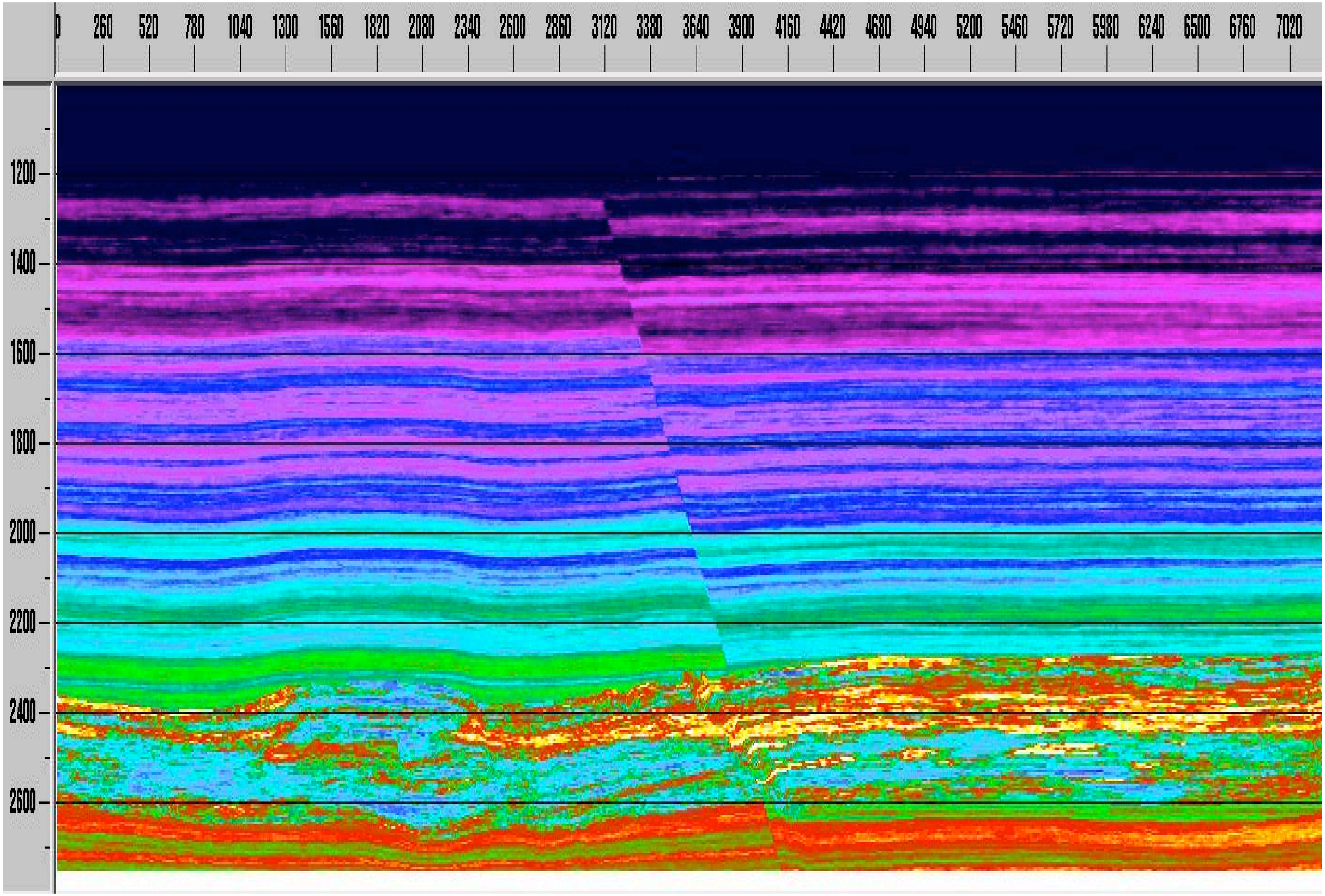


Depth slice through reservoir

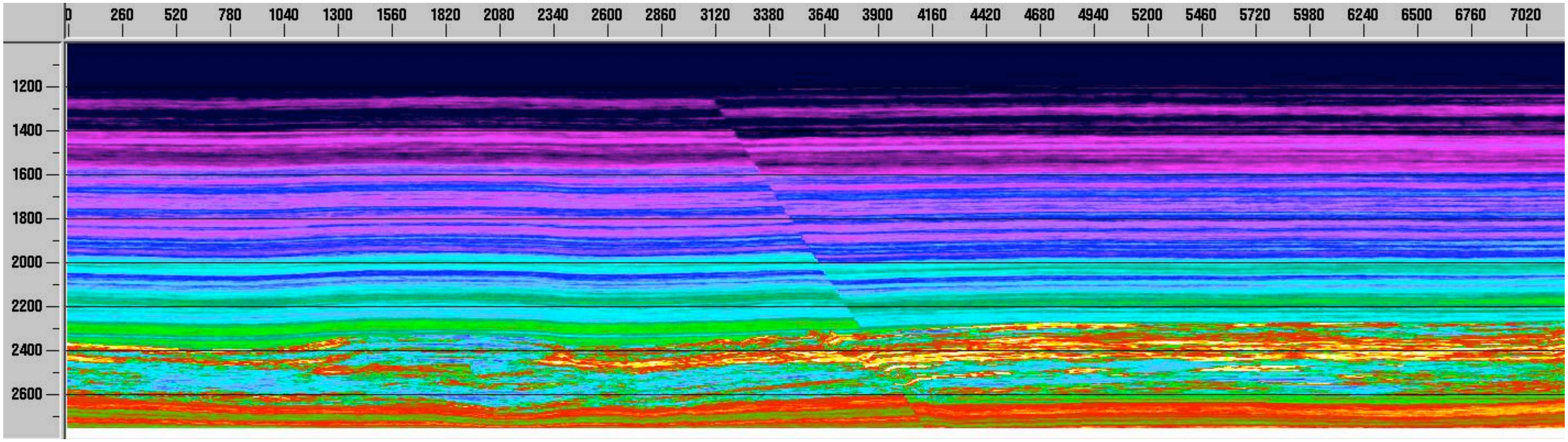
Realistic stratigraphic earth models provide a good testbed for various stochastic spatial inversion methods used in reservoir modeling and flow prediction.



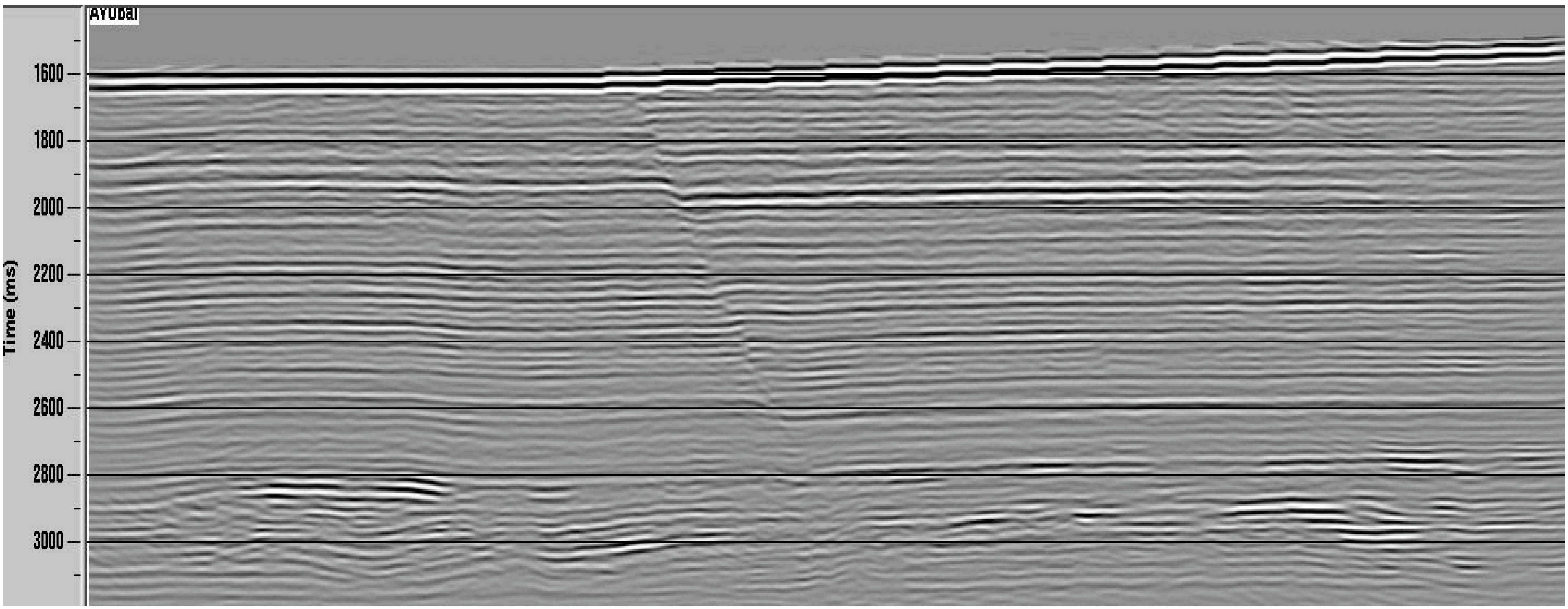
2D Slice from 3D Stratigraphic Earth Model



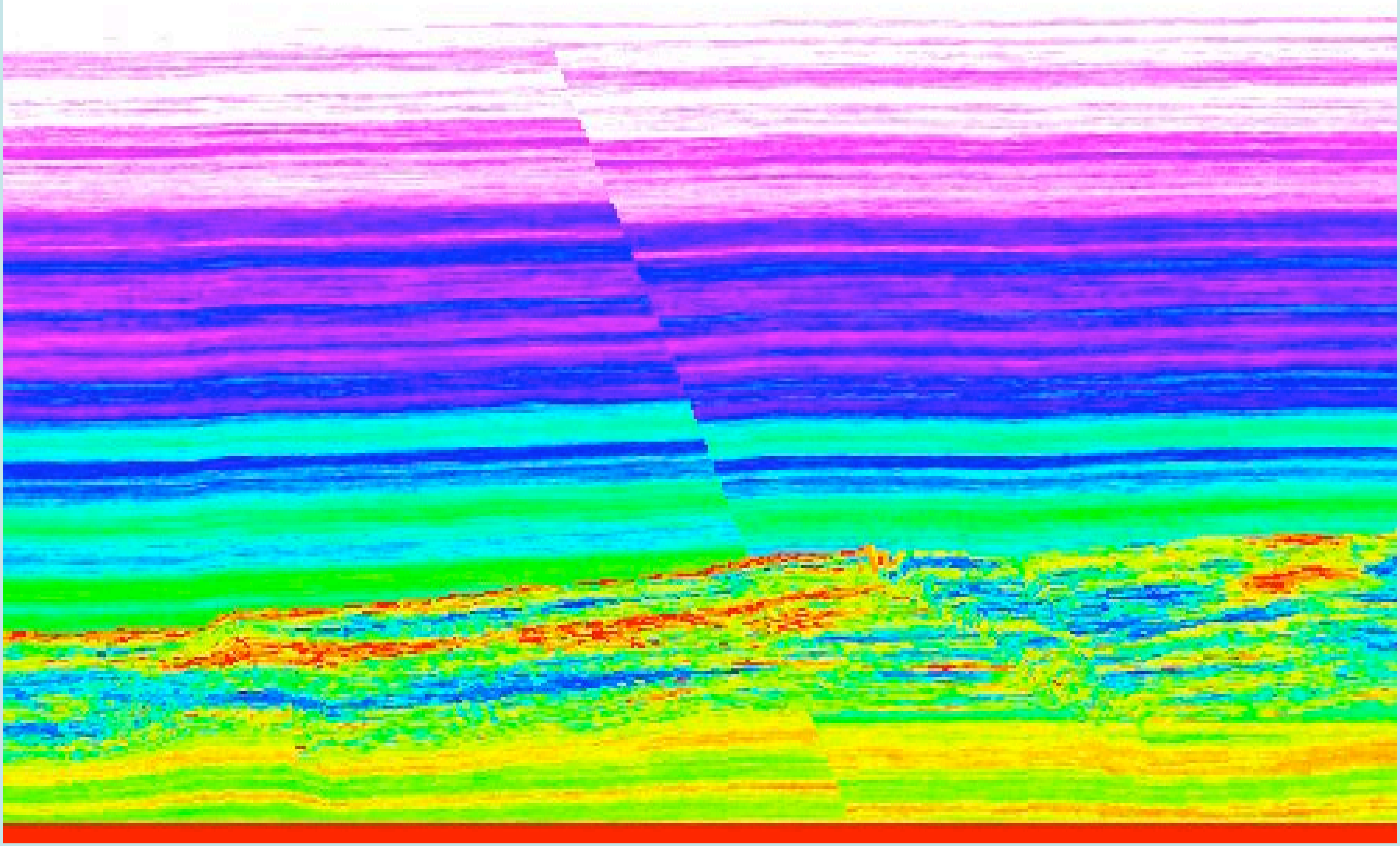
2D Stratigraphic Earth Model

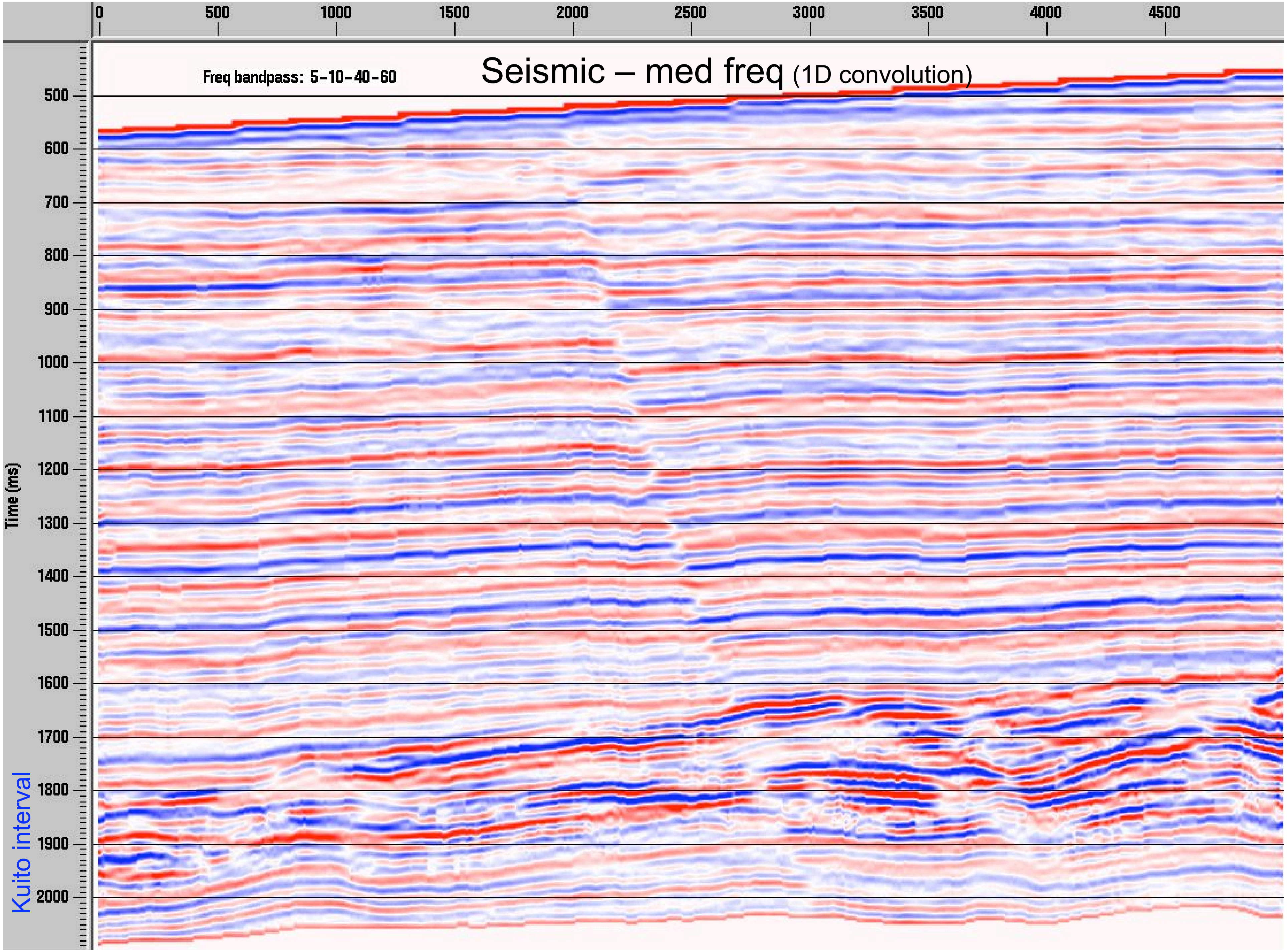


2D Elastic Finite Difference, prestack time migration, stack



Voxet slice





Seismic – med freq (1D convolution)
Freq bandpass: 5-10-40-60
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Time (ms)
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Kuito interval

4: Warp/Morph by Inverse Flattening

Flattening overview

Jesse Lomask, Antoine Guitton, Sergey Fomel, Jon Claerbout, and Alejandro Valenciano
Stanford Exploration Project

- Estimate local dip field
- Sum the dips
- Apply summed dips as time shifts

Measure 2D dip vector & Estimate 3D τ field

General idea:

wavefield $= u(x, y, \tau)$

surface of constant phase : $du = 0$

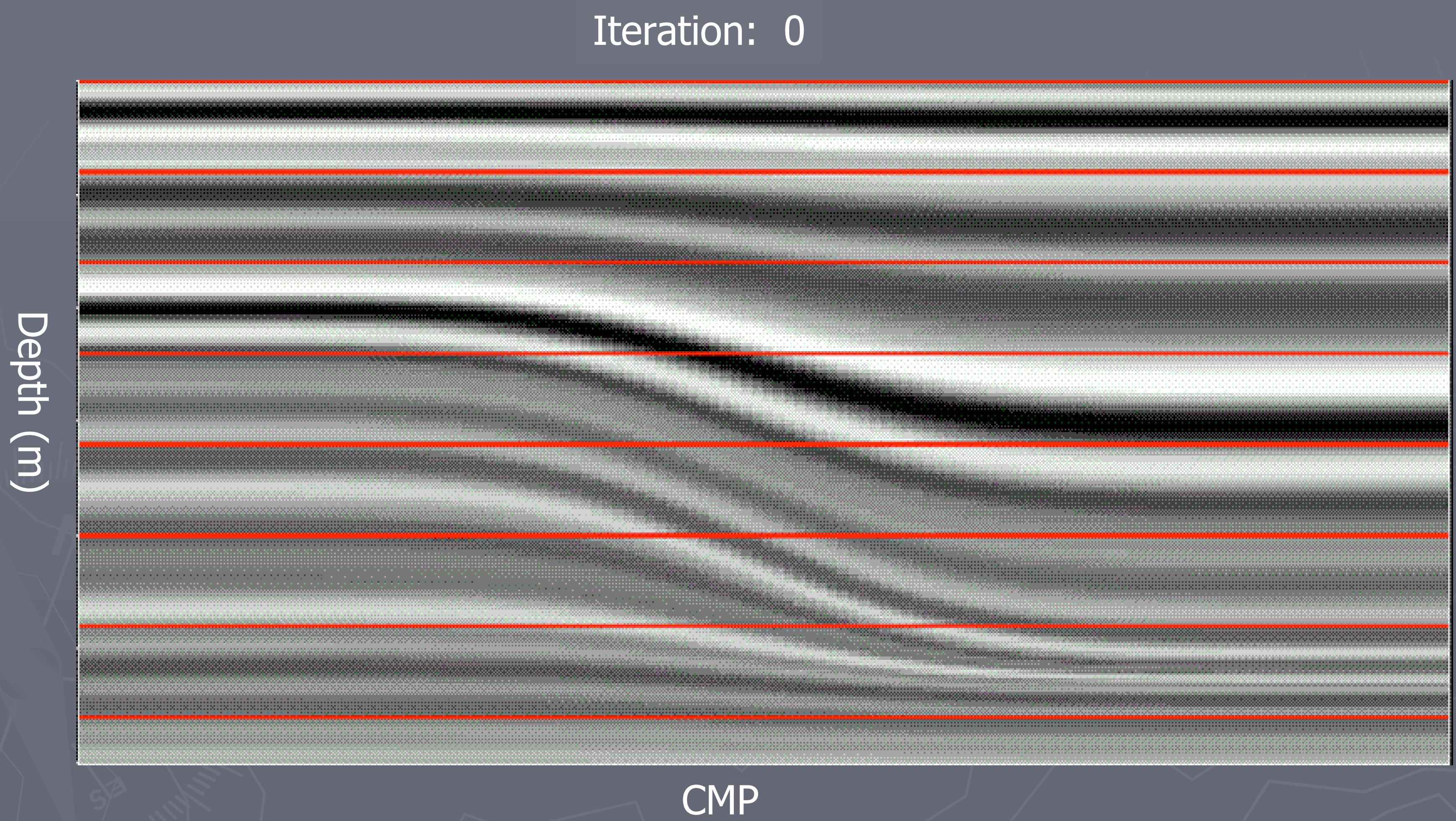
$$du = \frac{\partial u}{\partial x} dx + \frac{\partial u}{\partial y} dy + \frac{\partial u}{\partial \tau} d\tau = 0$$

for constant y, dip in x direction : $p_x \equiv \dfrac{d\tau}{dx} = -\dfrac{\partial u}{\partial x} \Big/ \dfrac{\partial u}{\partial \tau}$

for constant x, dip in y direction : $p_y \equiv \dfrac{d\tau}{dy} = -\dfrac{\partial u}{\partial y} \Big/ \dfrac{\partial u}{\partial \tau}$

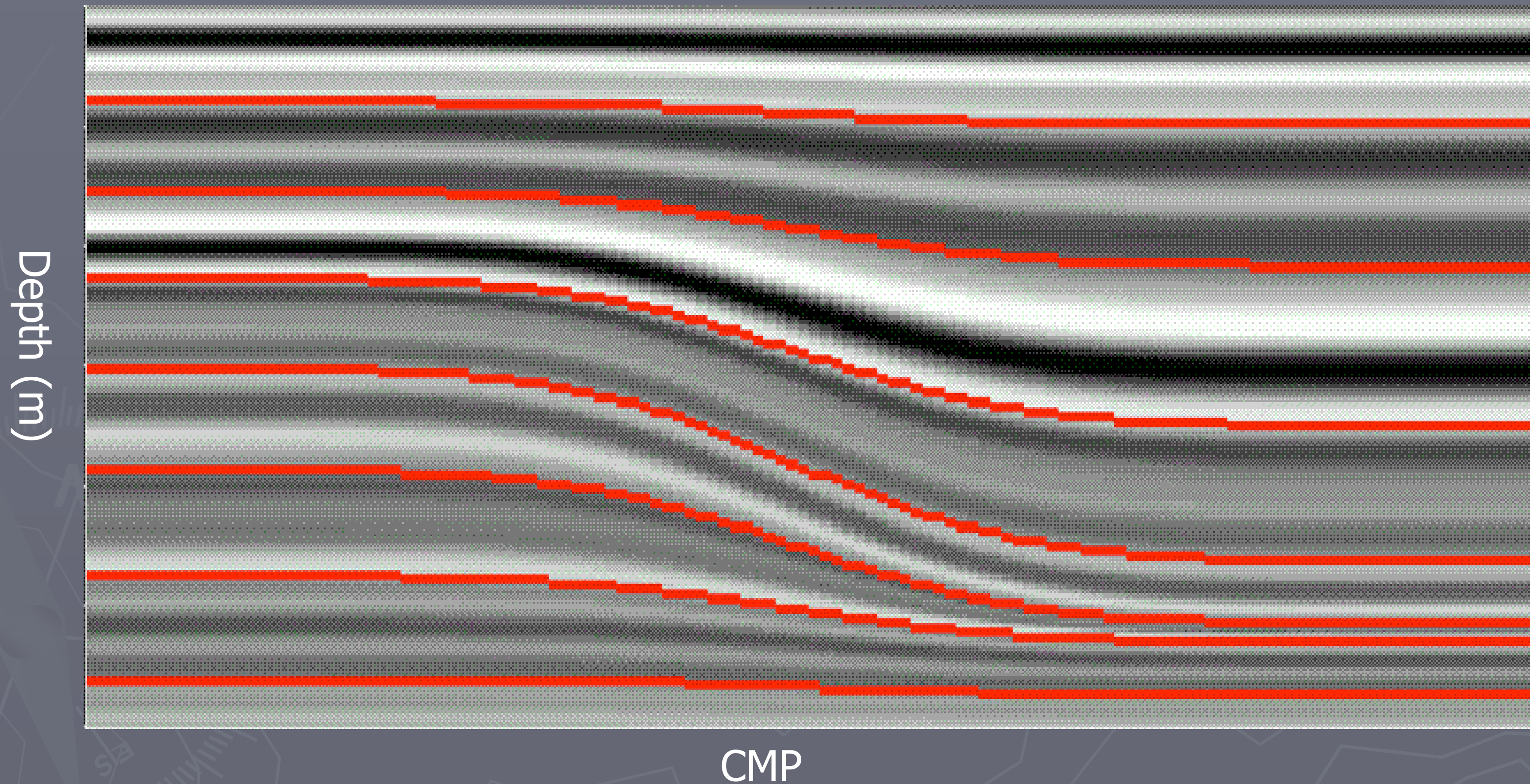
$\vec{\nabla}\tau = \vec{p}(\tau)$ least - squares soln : $\tau \approx \left(\nabla^T \nabla\right)^{-1} \nabla^T p$

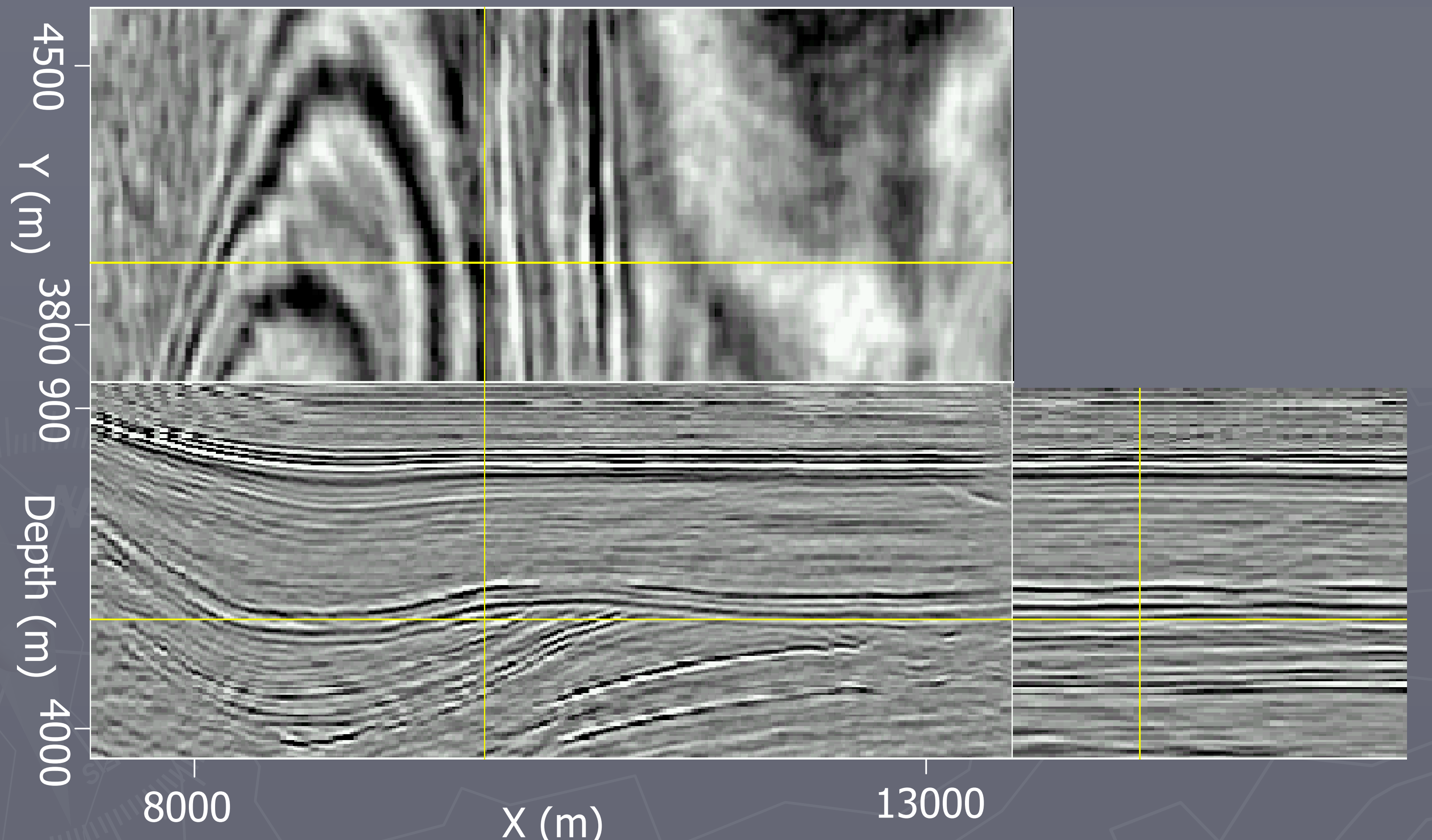
Downlap picks

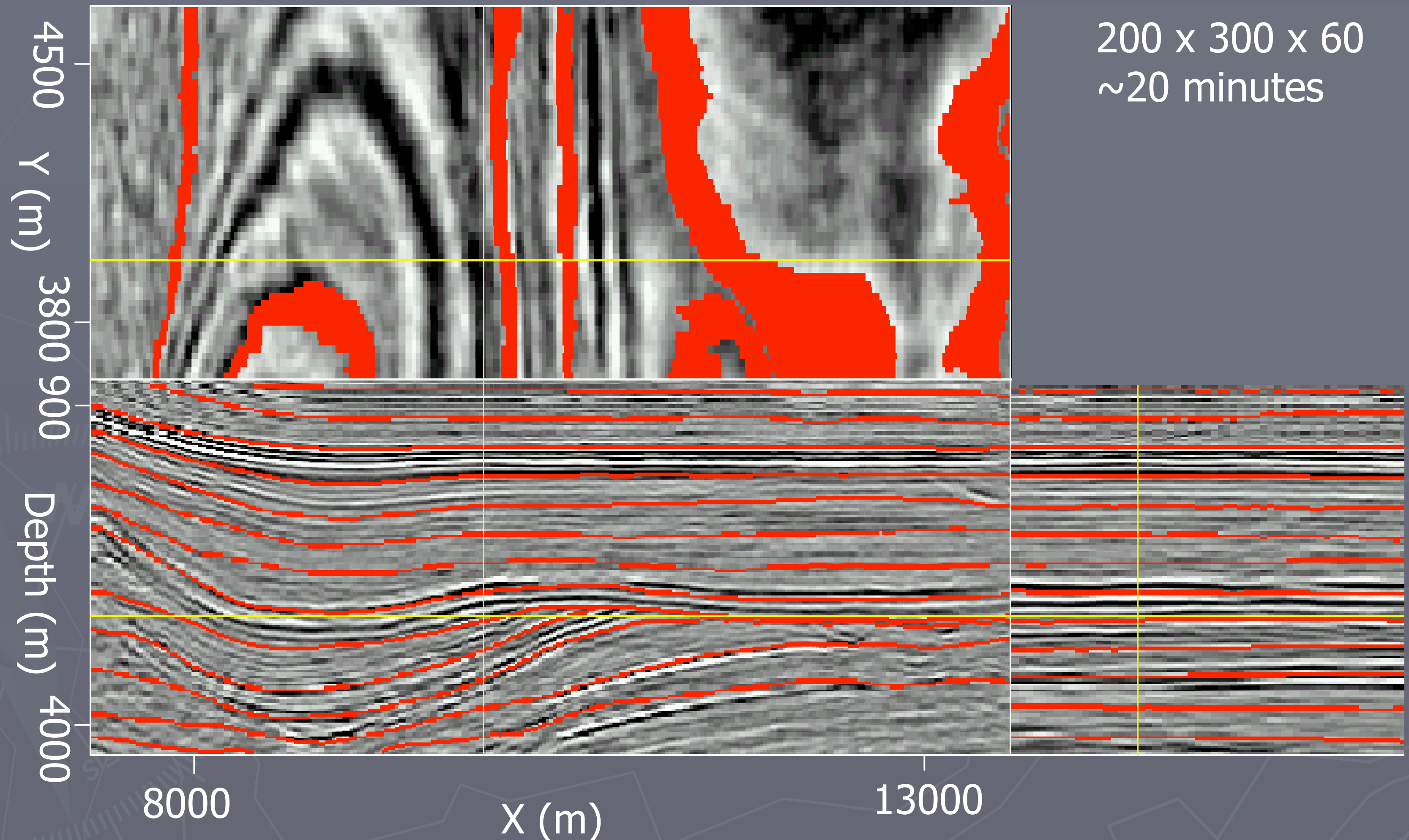


Downlap picks

Iteration: 10

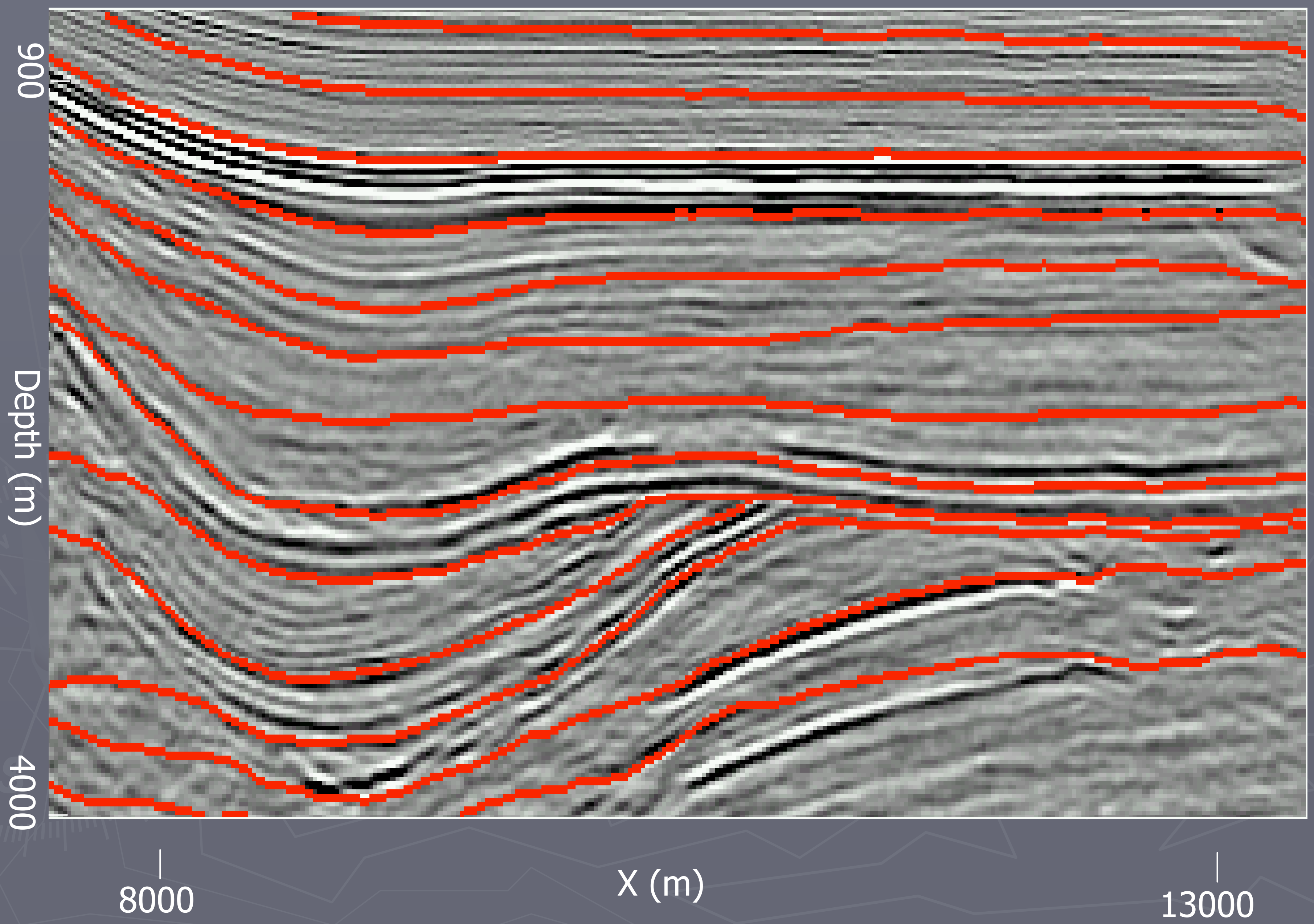



4500
Y (m)
3800
900
Depth (m)
4000
8000
X (m)
13000

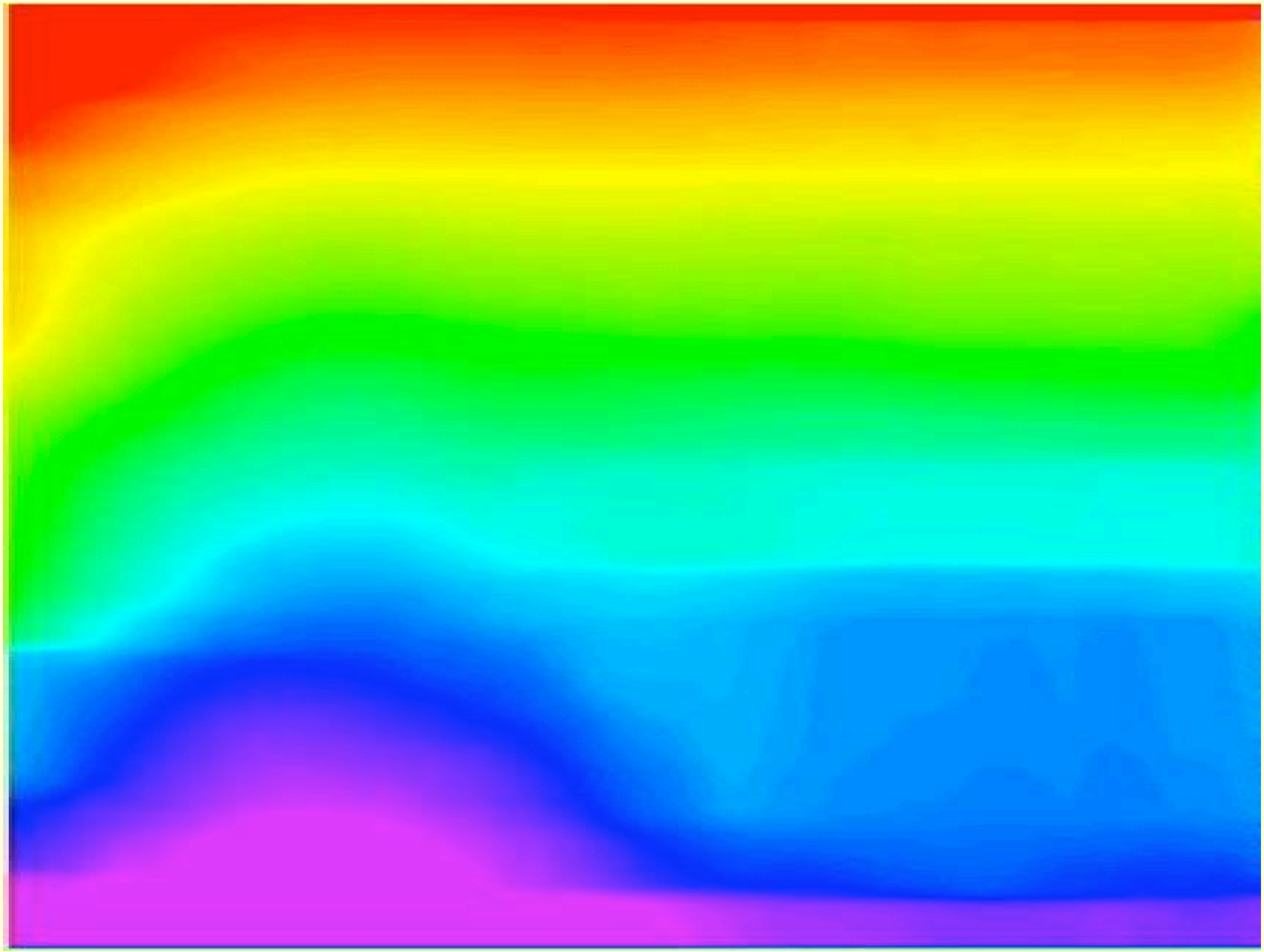


200 x 300 x 60
~20 minutes

Inverse flattening begins with flat synthetic strat and warps it according to red τ field

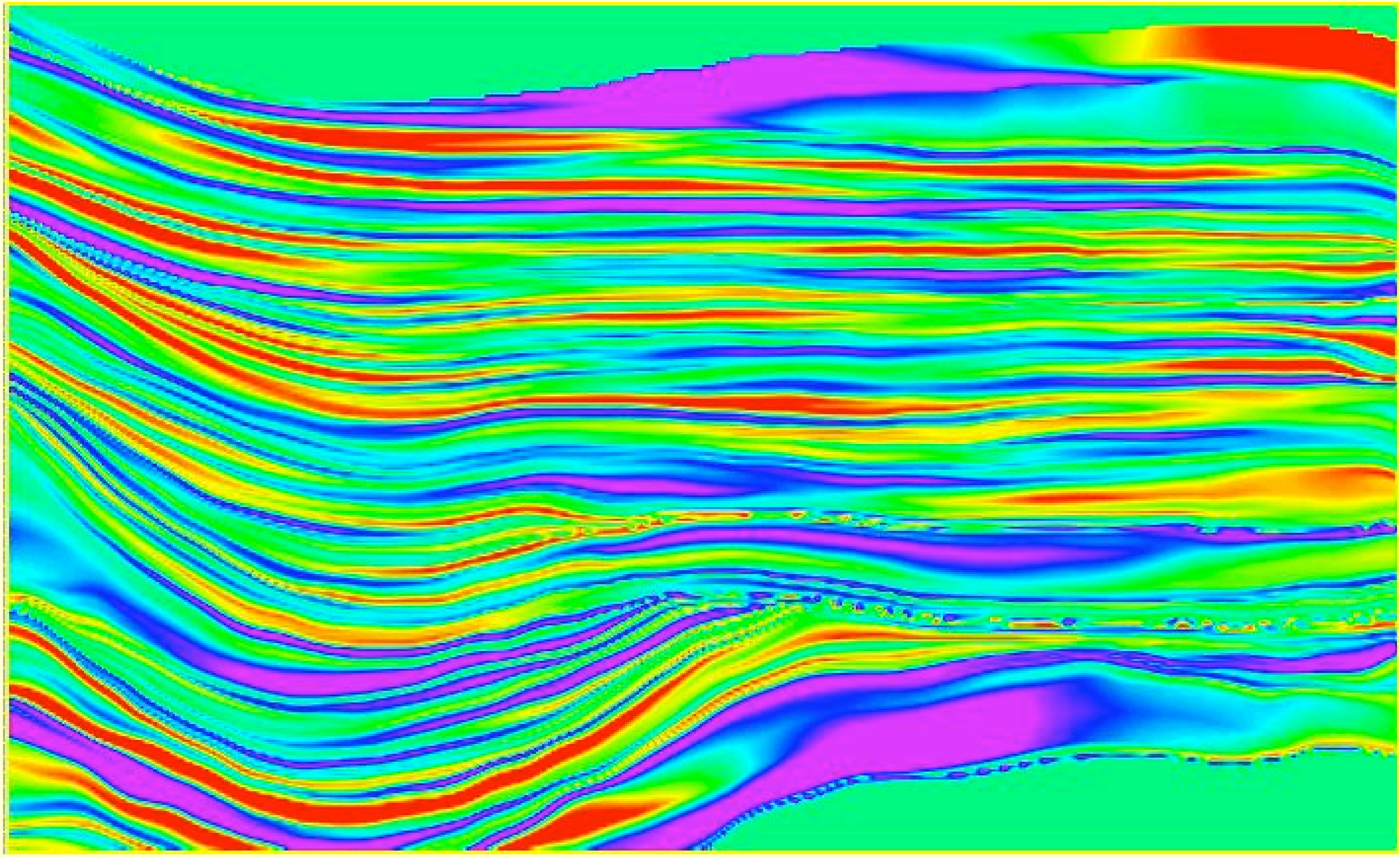


Cumulative Deformation Field (example 1)

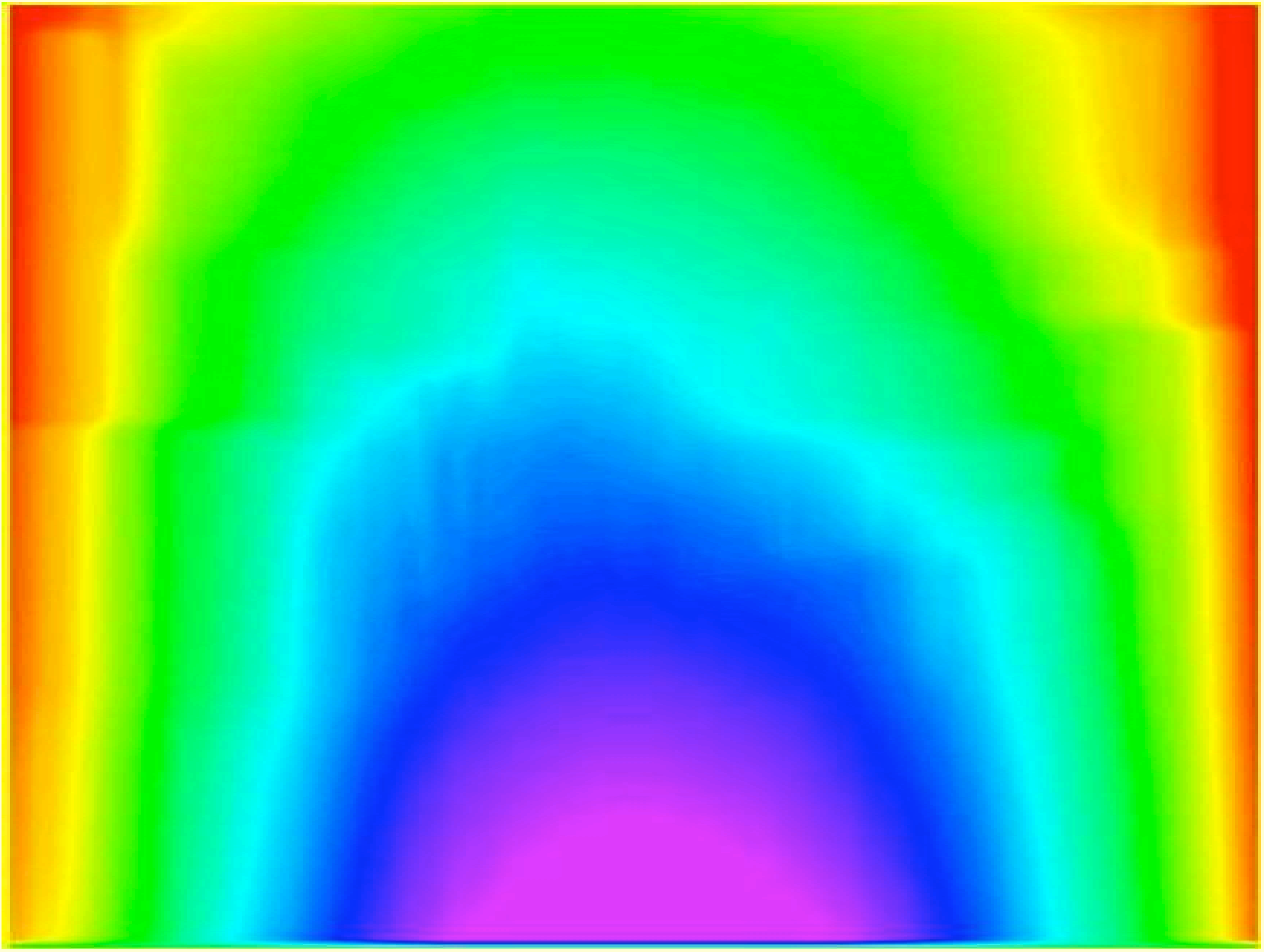


Vertically Exaggerated Flat Stochastic Stratigraphy Field (e.g. Vp, Vs or Dn)

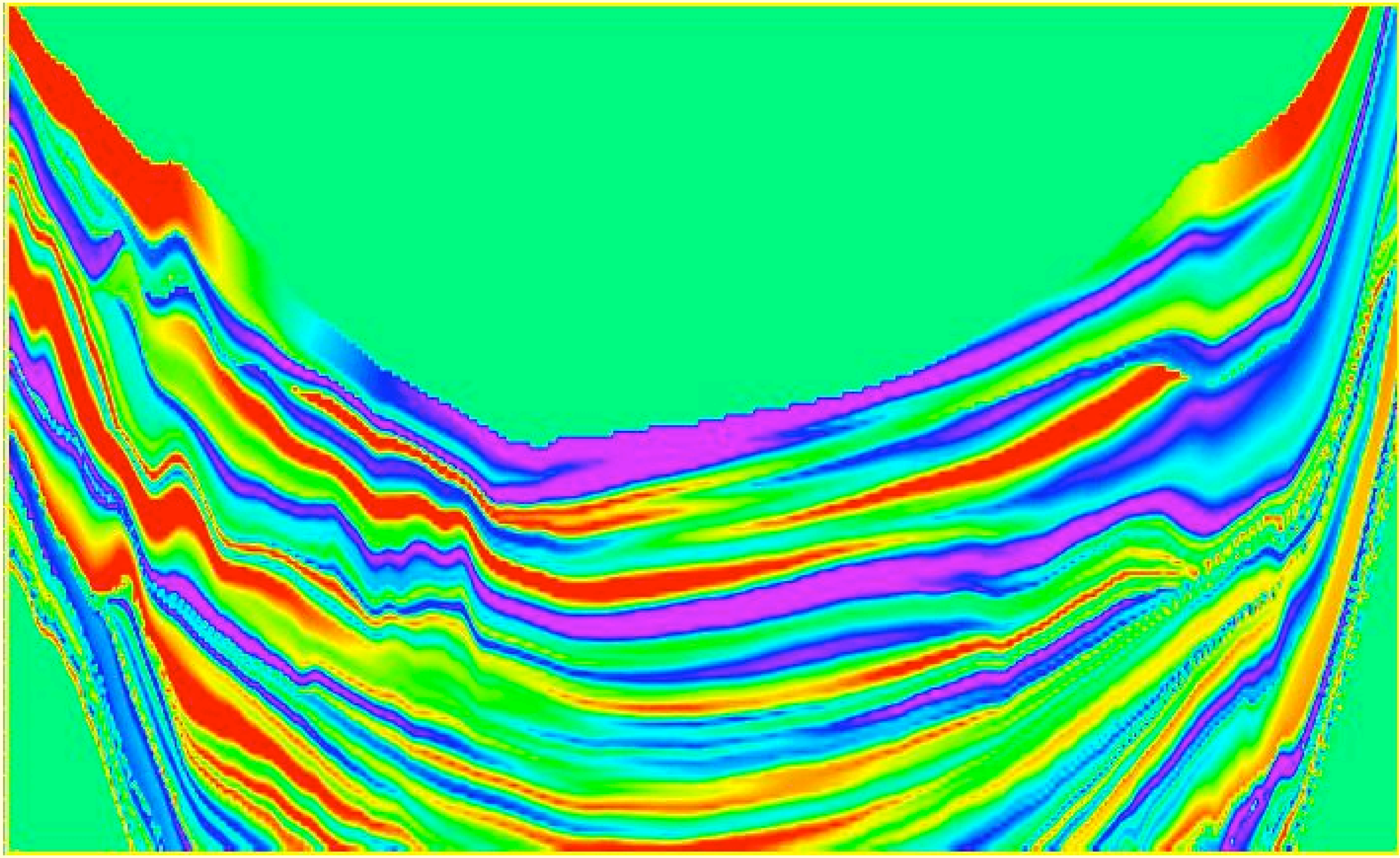
Flat Stratigraphy Warped via Inverse Flattening



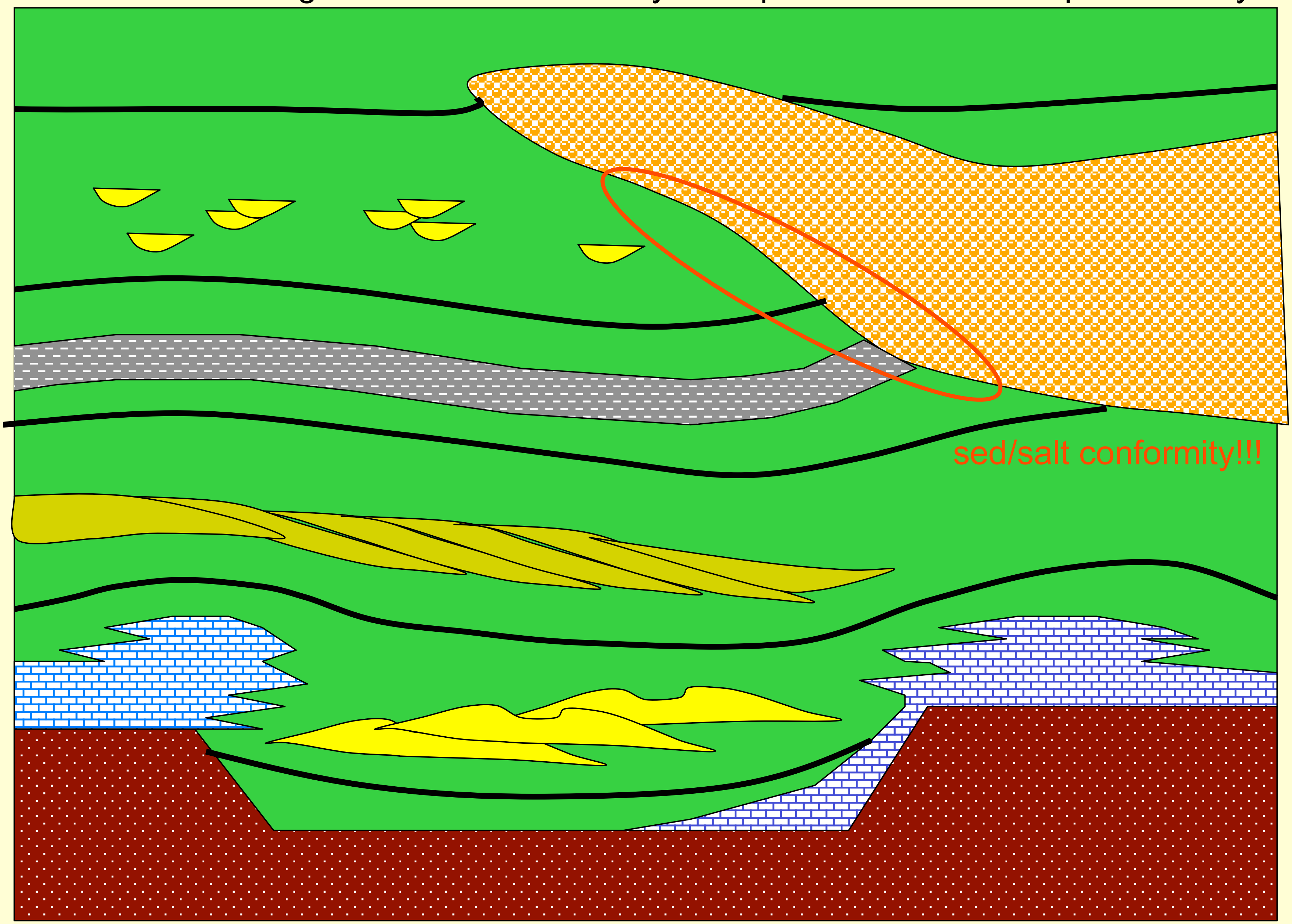
Cumulative Deformation Field (example 2)



Same Flat Stratigraphy Warped via Inverse Flattening of Example 2



Cartoon of interesting reservoirs conformably interspersed between warped refer layers



EARTH MODELING TASKS

Structure / Stratigraphy Geometric Tasks

1: Choose representative Salt body (illumination shadows, multiples, rugosity, invisible base?, variable velocity[Vp fluct ~ 500 ft/s ~ 4%??], multiple bodies)

2: Choose several interesting reservoir types and build their realizations (AVO)

3: Choose representative seismic for sediment warping template (or do by hand)

4: Decide what extra structural features the sediments should have (faults, seafloor structure, shallow anomalies, bright reference horizons, ref. point diffractors…)

5: Ensure realistic flow/structure conformity at salt/sediment interface

Vp,Vs,Dn Assignment Task

1: Build background sed model with good Vp,Vs,Dn fluctuation-correlations in X,Y,Z

2: Ensure valid correlations among the 3 elastic constants.

Small-Scale 3D Mock-Up for SEG Workshop

Inverse Flattening Issues:

To serve as a flattening template, need to choose a large enough 3D seismic volume having the characteristics of interest, such as:
regional dip, local dip, unconformities, faults.

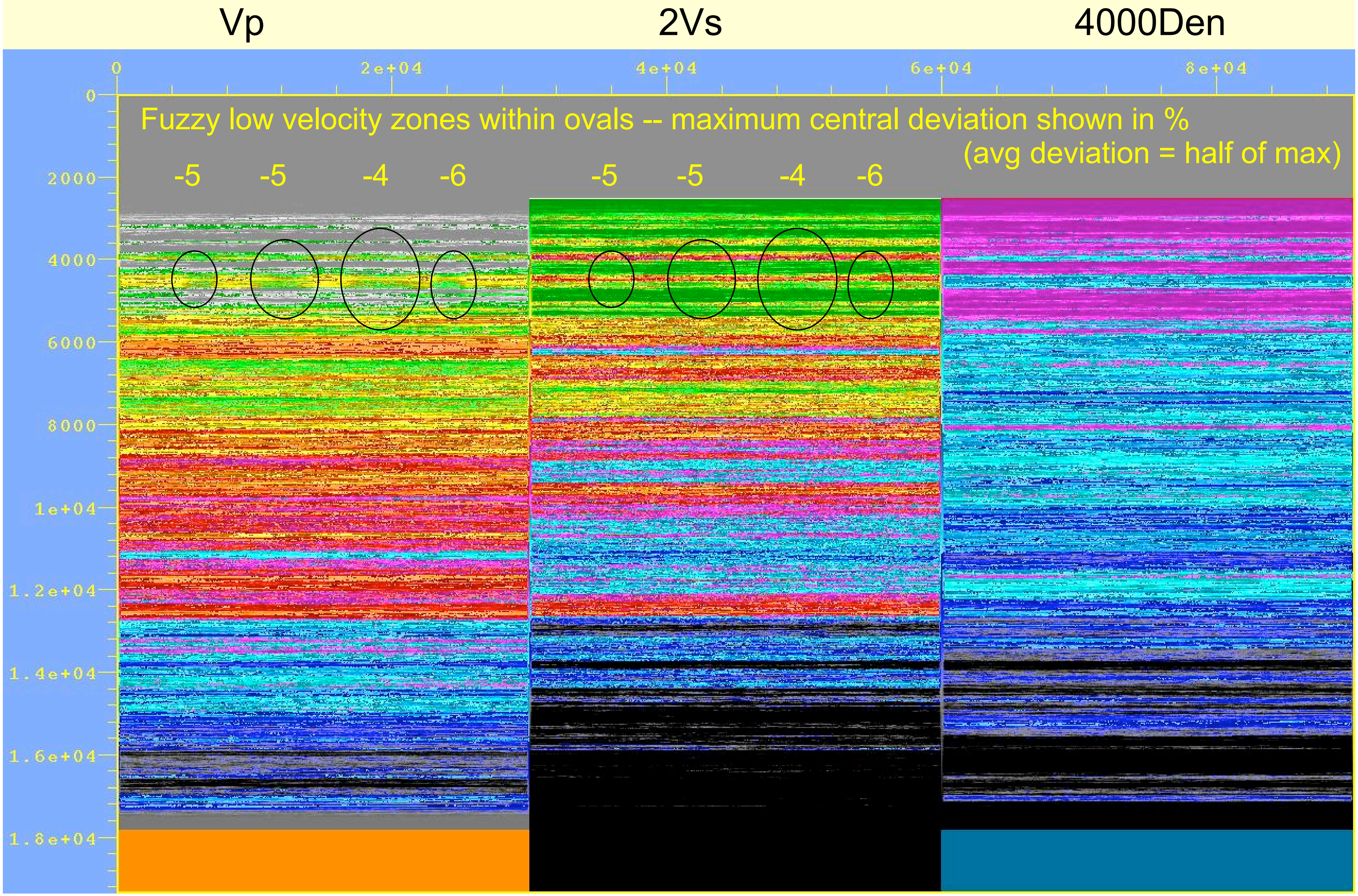
Will probably need to manually morph the resulting stratigraphy field to be in geological agreement/conformance with any allochthonous salt (step ups), or to add special faults or unconformities.

5: Apply *Mild* Near-Surface Velocity Perturbations

Why?
Observation/Motivation:

Small lateral velocity gradients (of ~1% $\delta V/V$ and below tomographic resolution) create large amplitude fluctuations/striping.

Seismic Parameters for strat5 Model (VE=3)

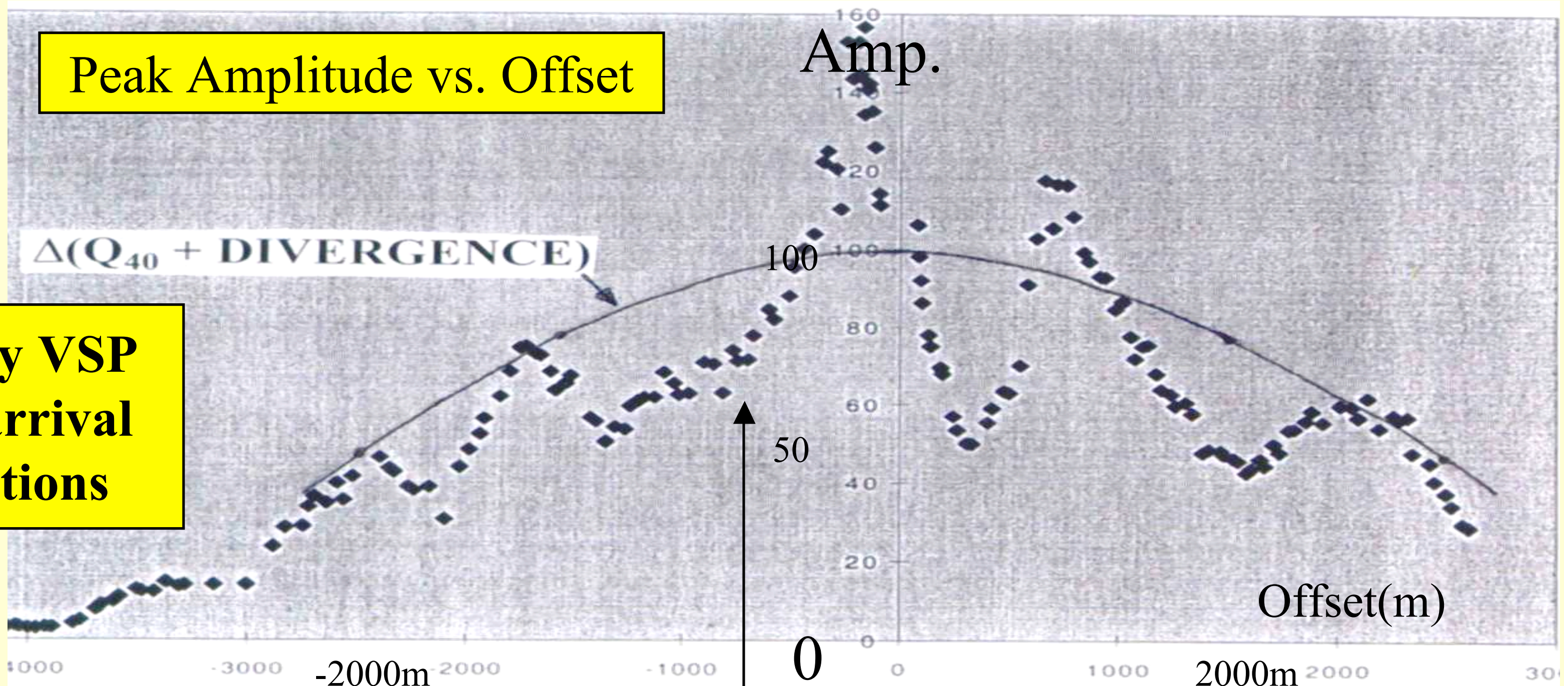


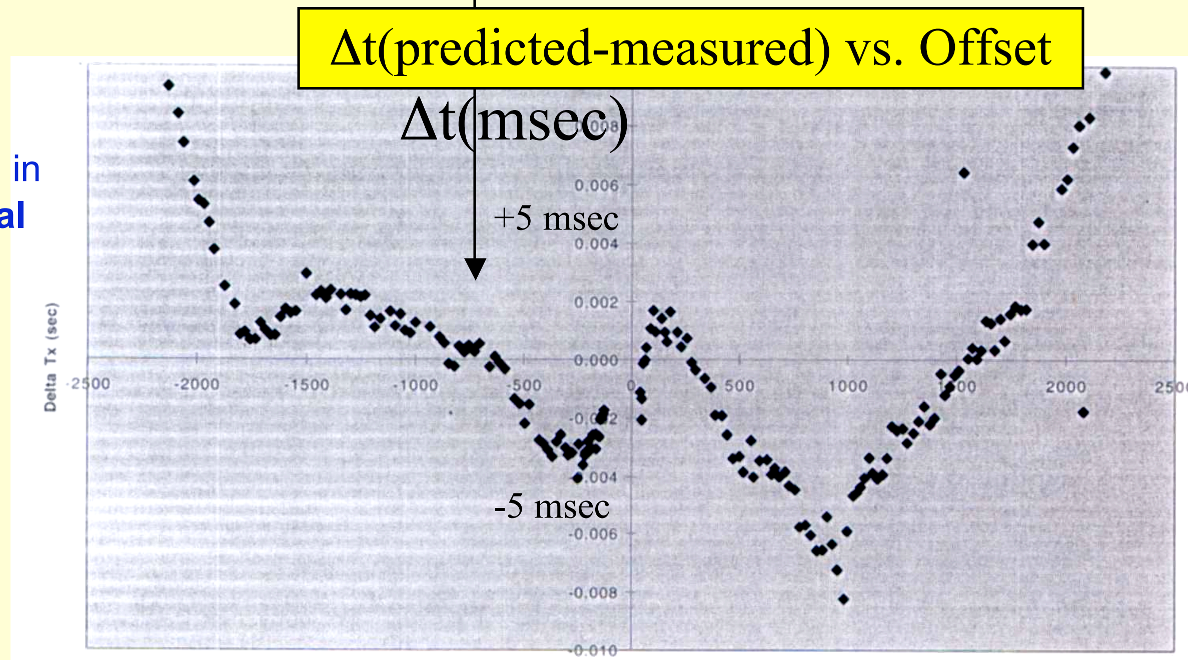
Walkaway VSP – real data

REAL DATA IMAGE REMOVED

How important is the overburden regarding amplitude behavior?

Walkaway VSP Direct P-arrival Observations





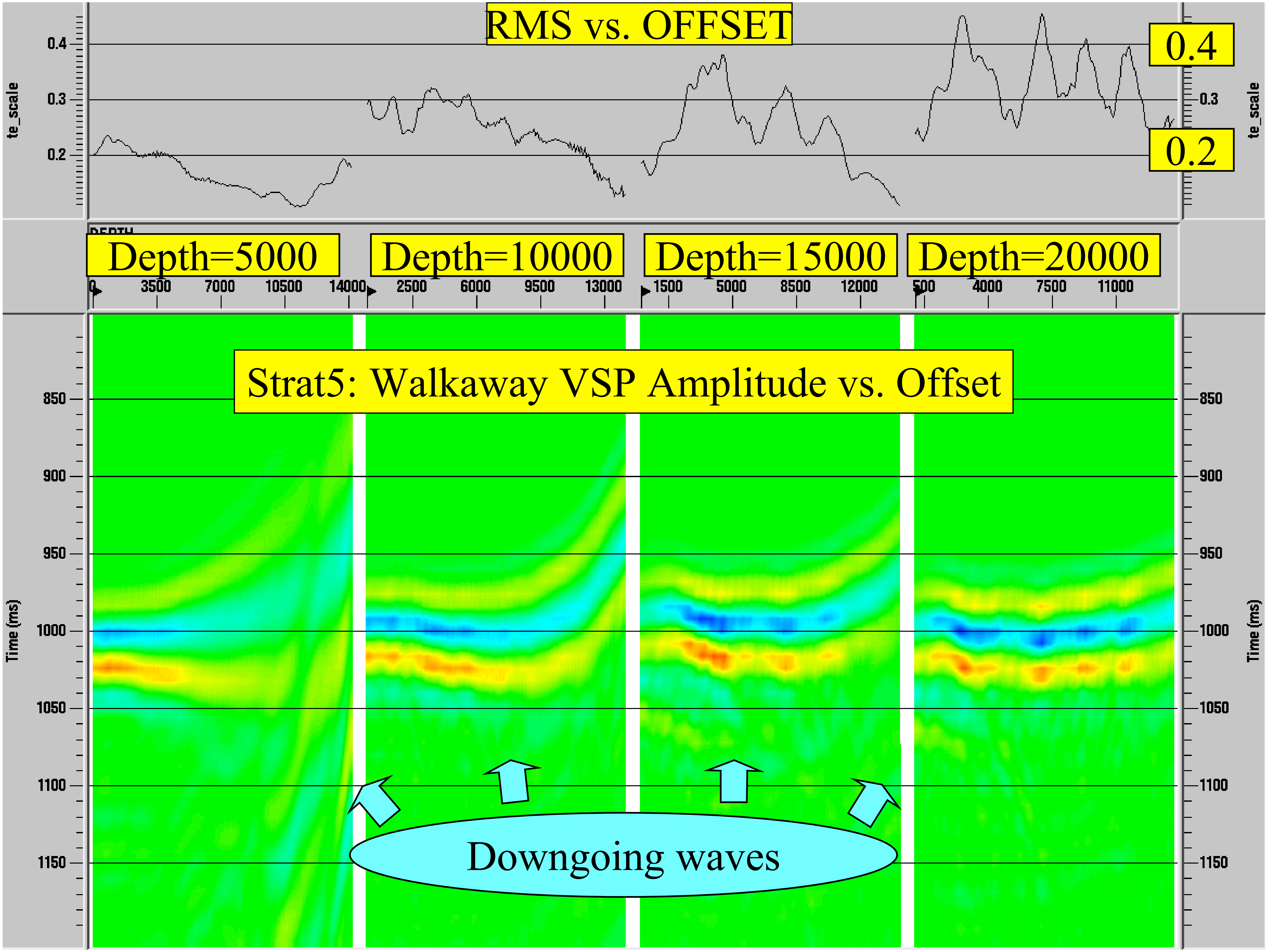
Factors of 2 to 4 in relative transmitted amplitudes over offset distances of 500m

Anomalous variations of **± 5msec**. in arrival time (implying **< 0.5% lateral velocity gradients!!)**

Correlation between anomalous amplitudes and arrival times:

- **high amplitudes correlate to time delays**
- **low amplitudes correlate to time advances**

Anomaly strength increases with path length

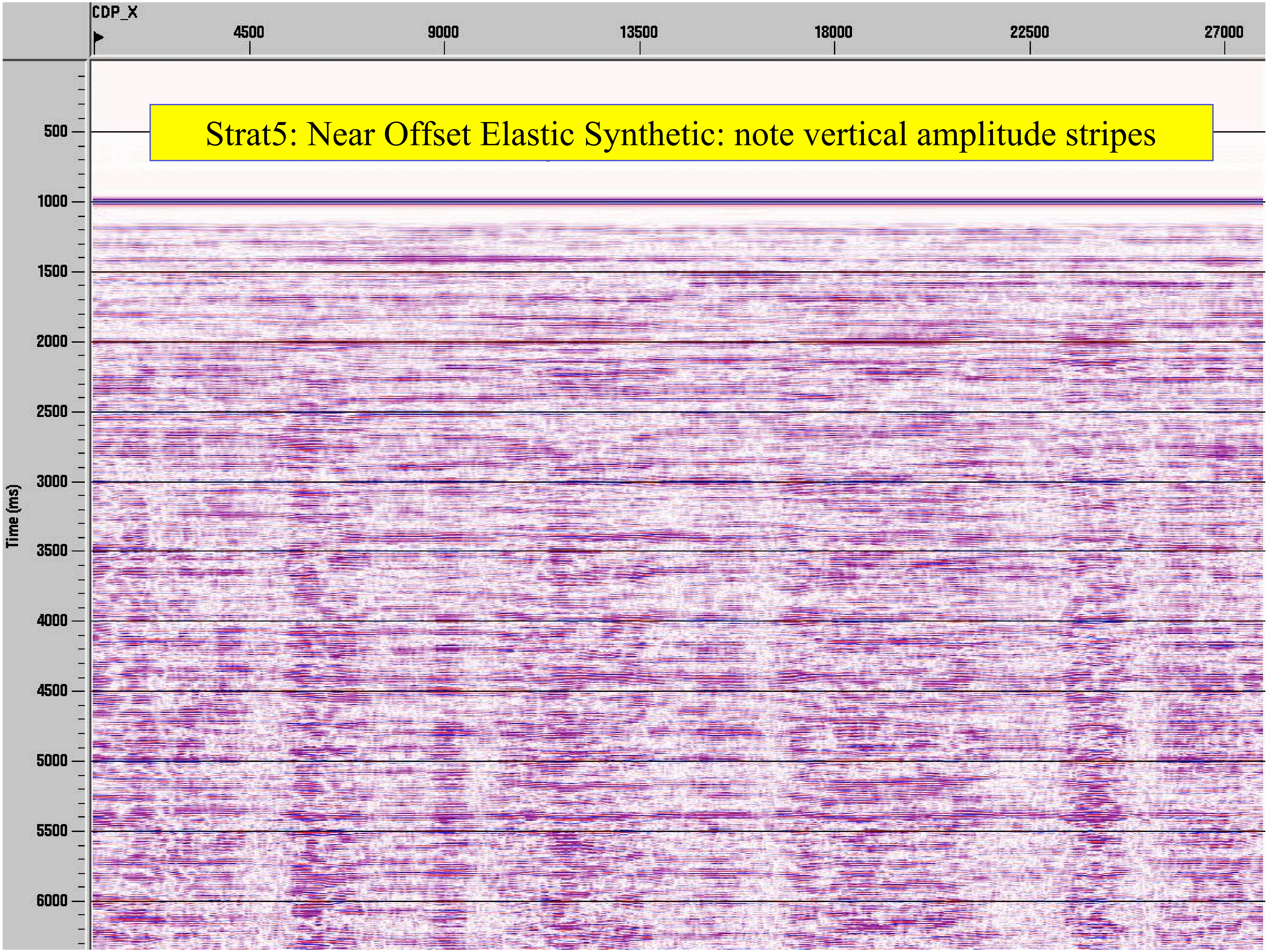


RMS vs. OFFSET
0.4
0.2
te_scale
0.4
0.3
0.2
Depth=5000
Depth=10000
Depth=15000
Depth=20000
0
3500
7000
10500
14000
2500
6000
9500
13000
1500
5000
8500
12000
500
4000
7500
11000
Strat5: Walkaway VSP Amplitude vs. Offset
Time (ms)
850
900
950
1000
1050
1100
1150
Downgoing waves

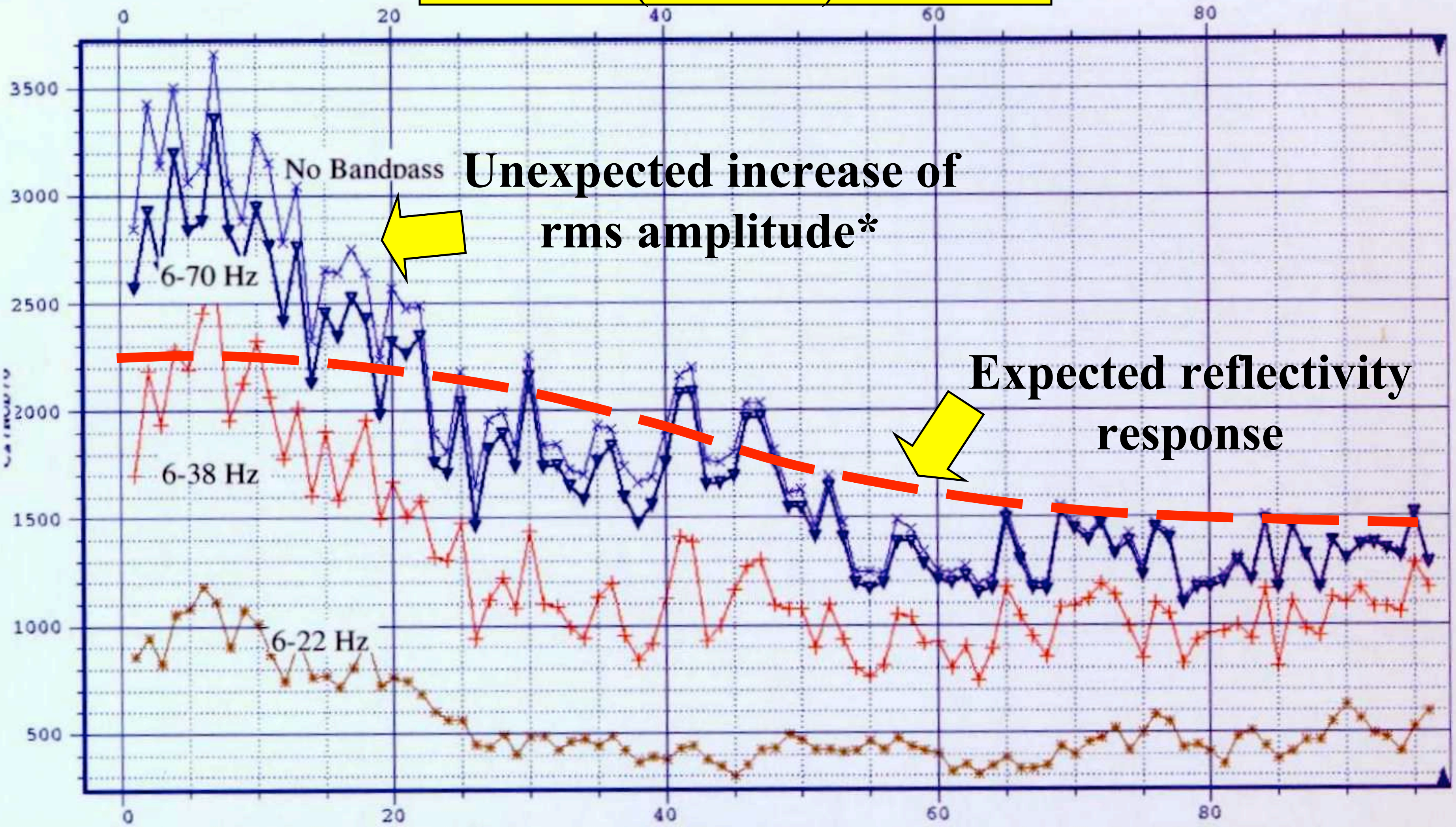
Near Offset Section (real data)

REAL DATA IMAGE REMOVED

←3 kms.→

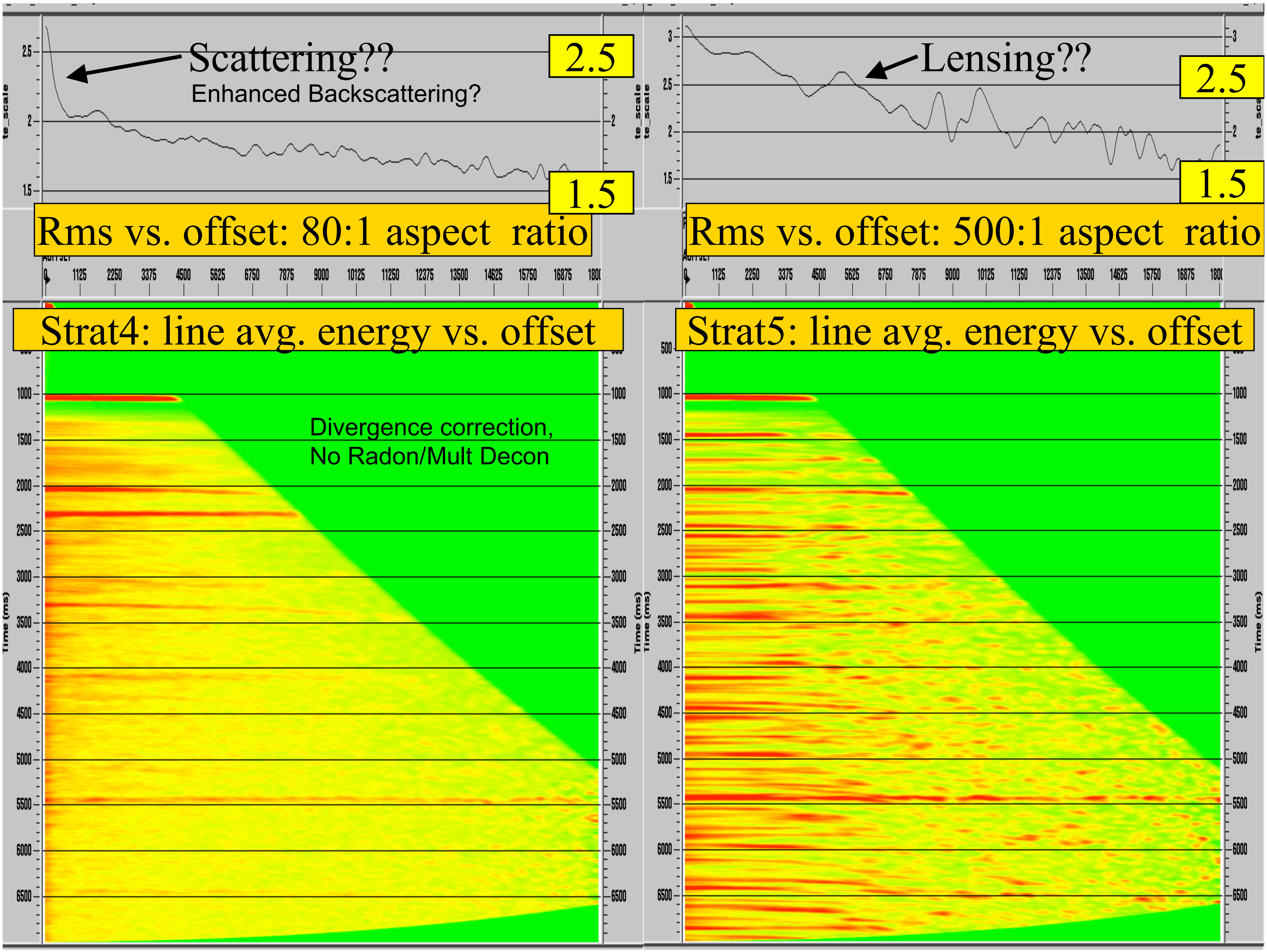

Strat5: Near Offset Elastic Synthetic: note vertical amplitude stripes
CDP_X
4500
9000
13500
18000
22500
27000
Time (ms)
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000

RMS Amplitude vs. Offset (real data)



Average RMS amplitudes for the 3700ms event, 800ms window for the data after normal spherical divergence and trace summation, no deconvolution.

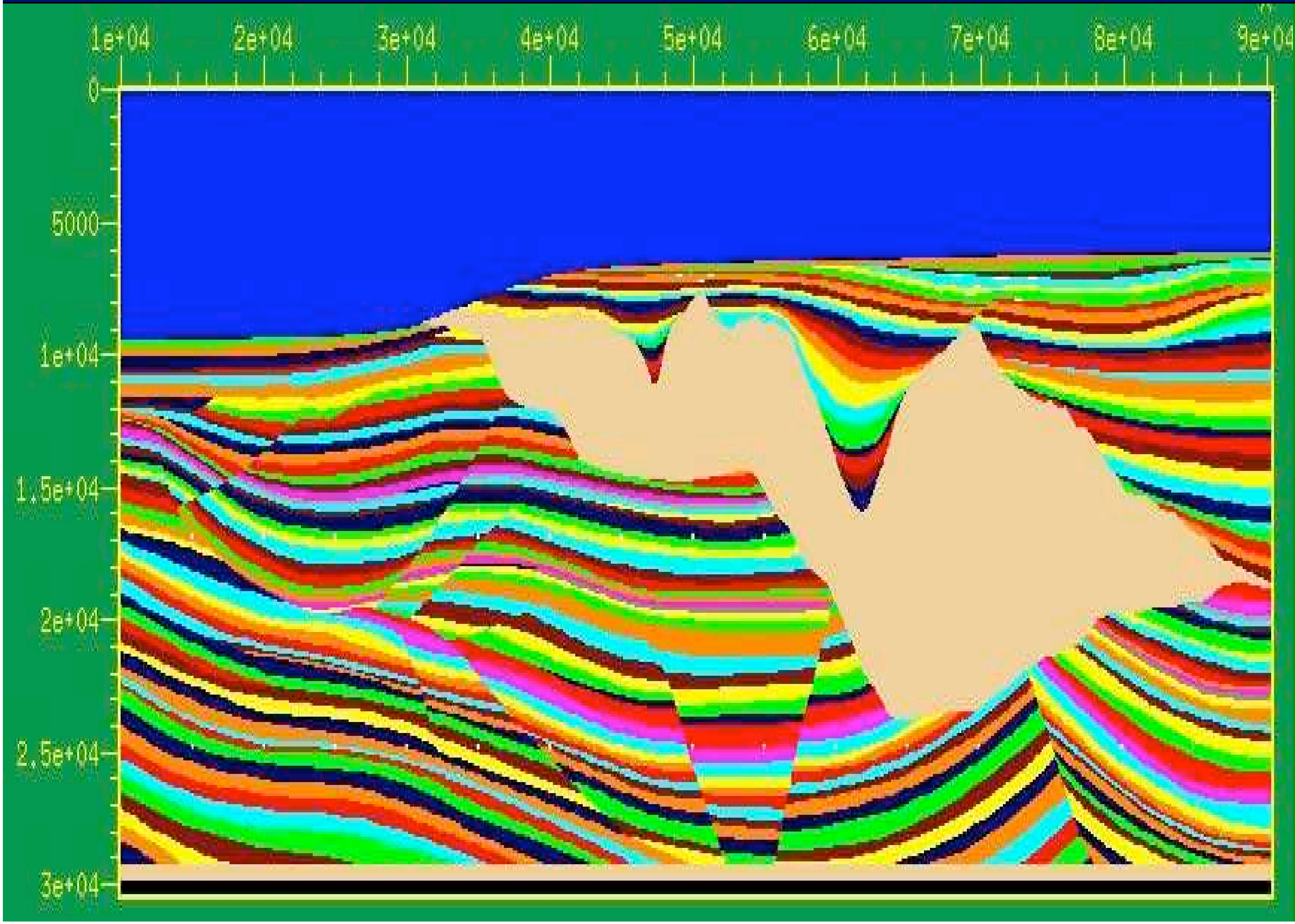
* Processing artifacts (radon filtering, decon)? Acquisition (streamer noise, directivity, etc.)?
Earth lateral heterogeneity (Lensing : Vp focus/defocus, Scattering: dVp,dVs,dDn) !!! (yes)


Scattering??
Enhanced Backscattering?
2.5
1.5
Rms vs. offset: 80:1 aspect ratio
Lensing??
2.5
1.5
Rms vs. offset: 500:1 aspect ratio
Strat4: line avg. energy vs. offset
Divergence correction,
No Radon/Mult Decon
Strat5: line avg. energy vs. offset
Time (ms)

6: Mask-in a Salt Body

Sigsbee 2 Stratigraphic Model

SMAART II



Recipe for Realistic Stratigraphic Earth Model Construction

1: Match elastic property fluctuation statistics (rms and δVp,δVs,δDn correlations) and lateral/vertical spatial correlations (power-law color, e.g. $\delta v \sim 1/k^{0.5}$).

2: Generate flat stratigraphy in a 3D container honoring the above characteristics, and containing several bright reference horizons.

3: Add interesting reservoirs in 3D parallel to the (flat) bedding.

4: Warp/Morph by hand (superseded by inverse flattening).

4: Warp/Morph by inverse flattening (uses an existing seismic image volume as a warping template; positive: little to no manual editing; negative: same).

5: Apply *mild* near-surface velocity perturbations (sub cable-length, and below the tomographic resolution threshhold). Mask in bright diffractors and basal flat layer.

6: Mask-in a salt body (for structural “add on”).

Then
Shoot seismic – flow the reservoirs “in vitro” – repeat seismic.

Notes and Opinions
On
Acoustic & Elastic
Structure & Stratigraphy
Earth Modeling & Seismic Modeling
Requirements & Tradeoffs

SEG 3D Advanced Seismic Modeling Project

Joe Stefani, Chevron

CSM, 12 July 2005

Some notes on seismic requirements

Minimum length in X, Y of fully imaged geology
Elastic Stratigraphic model: 5000 m (1 OCS block)
Acoustic Structural model: 10,000 m (want to follow events under salt)

Reasonable radial imaging aperture
Mild stratigraphic structure: 3000 m
Complex salt structure: 9000 m

Streamer length ~ 6000 m to 8000 m

Total model size in X, Y, Z
Stratigraphic model ~ 15 km X 11 km; 4 km depth
Structural model ~ 30 km X 22 km; 8 km depth

Frequency bandwidth: Strat ~ 80 Hz, Struc ~ 50 Hz

Cell size: Strat ~ 4m, Struc ~ 8 m

Nnodes ~ 4000 X 3000 X 1000 = 12 billion nodes for either model

Total runtime memory: Strat ~ 400+ Gb; Struc ~ 200 Gb (< 100 node cluster 4Gb/node)
(double all frequencies, halve all cell sizes: 1000 node cluster) **(64-bit clusters welcome!!!)**

Some opinions on earth/seismic tradeoffs

A foregone conclusion: A **3D complex-structural** earth model will be built and shot with a purely **acoustic** (Vp,Dn) **finite-difference** simulator.

The more interesting issues revolve around the **stratigraphic** earth model: In light of the economic need to allocate scarce resources for this more difficult problem, a technical discussion of geophysical trade-offs is necessary.

At the coarsest level, seismologists are concerned with **Reflection** and/or **Transmission**. E.g., imaging is mostly about transmitting waves through an overburden correctly (kinematically, perhaps dynamically); and AVO/inversion is mostly about getting the reflectivity right.

Main question: given the economics of seismic modeling, should a stratigraphic model satisfy high fidelity transmission or high fidelity reflection (assuming it cannot do both)?

Stratigraphic transmission effects: short interbed multiples & mode conversions, mild velocity heterogeneity focusing/defocusing, amplitude accuracy over a wide range of angles (0-90), shale anisotropy, …

Stratigraphic reflection effects: AVA from δ(Vp,Vs,Dn,anis), finer layering, …

What about 3D vs 2.5D? 2.5D is economical and can include all the R & T effects above, but its biggest shortcoming is the sacrifice of realistic 3D facies *shapes* (e.g. no meandering channels).

With these tradeoffs in mind →

Stratigraphic earth/seismic tradeoffs

Blue good Red bad

2-way Time extrap — Acoustic

TRANSMISSION
- Short interbed multiples
- Short mode conversions
- Vel Lens focusing/defocusing
- Wide angle amp accuracy (acoust)
- Shale anisotropy

REFLECTION
- AVA (missing Vs, missing anis)
- Fine layering (dX ~ 8m)

More kind to transmission

2-way Time extrap — Elastic

TRANSMISSION
- Short interbed multiples
- Short mode conversions
- Vel Lens focusing/defocusing
- Wide/narrow angle amp accuracy
- Shale anisotropy

REFLECTION
- AVA
- Fine layering (dX ~ 4m)

$ Unless "smaller" model OR 2.5D

?

1-way Z extrap — Acoustic

void

1-way Z extrap — Elastic

More kind to reflection

TRANSMISSION
- Short interbed multiples
- Short mode conversions
- Vel Lens focusing/defocusing
- Wide/narrow angle amp accuracy
- Shale anisotropy

REFLECTION
- AVA
- Fine layering (dX ~ 4m)

Acoustic | Elastic

More-Focused Notes and Opinions on Earth Model & *Acoustic* Seismic Algorithm Issues

SEG 3D Advanced Seismic Modeling Project

Joe Stefani, Chevron

Houston, 8 Sept 2005

Model & Algorithmic Issues

Density: Variable vs Constant in the model ?

+

Spatial Operator: X(space) vs K(spectral) ?

+

Temporal Operator: O(2) vs O(4) vs Hybrid ?

+

Dispersion Limits: % group velocity error ?

=

Floating Point Operation Count: most crucial factor, dependent on all of the above

Model & Algorithmic Issues

Density: Variable vs Constant → two 1st-order PDEs vs one 2nd-order PDE.

$$\dot{V}_i = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} \qquad \dot{P} = -K\frac{\partial V_i}{\partial x_i} \qquad \text{vs.} \qquad \ddot{P} = v^2 \nabla^2 P$$

Variable density allows richer AVO behavior compared to constant density:

$$R(\theta) = \tfrac{1}{2}\left(\frac{\Delta V_p}{V_p} + \frac{\Delta\rho}{\rho}\right) - 2\frac{\Delta\left(\rho V_s^2\right)}{\rho V_p^2}\sin^2\theta + \tfrac{1}{2}\frac{\Delta V_p}{V_p}\tan^2\theta$$

Space: Convolve in X vs spectral multiply in K → spectral has better spatial characteristics, but number of FFTs increases ~ 4X for two 1st-order PDEs vs one 2nd-order PDE.
When is spatial convolution more efficient than spectral?

Time: 2nd vs 4th order in time → 4th order has better stability & dispersion characteristics, with only a very modest increase in flops, *provided* velocity is treated as locally constant.

$$P^{t+1} - 2P^t + P^{t-1} = -(kv\Delta t)^2\left[1 - \tfrac{1}{12}(kv\Delta t)^2\right]P^t$$

$$P^{t+1} - 2P^t + P^{t-1} = -(kv\Delta t)^2 P^t$$

Dispersion = D(VarDen, SpaceOp, TimeOrder) → up to 12,000 m of 1-way propagation path,
dependencies: weak strong strong
avg wavelength ~ 120 m → 100 wavelens
want < half-wavelength dispersion error →
0.5% group velocity dispersion error

FlopCount = F(VarDen, SpaceOp, TimeOrder) ← depends on all of the above
dependencies: medium strong strong

Algorithm Implementation Issues

(spectral in space; **need to estimate flops/cell/dt for each box**)

Time Order

	O(2)	**O(4)**	**Hybrid** Const parms in 4th order term
Constant ρ $\dot{P} = v^2\nabla^2 P$	$P^{t+1} - 2P^t + P^{t-1} = (v\Delta t)^2\nabla^2 P^t$ 3 variables 2 FFTs	$P^{t+1} - 2P^t + P^{t-1} = (v\Delta t)^2\nabla^2 P^t + \frac{1}{12}\Delta t^4 v^2\nabla^2\left(v^2\nabla^2 P^t\right)$ 3 variables 4 FFTs	$P^{t+1} - 2P^t + P^{t-1} = (v\Delta t)^2\nabla^2 P^t + \frac{1}{12}(v\Delta t)^4\nabla^4 P^t$ 3 variables 3 FFTs
Variable ρ $\dot{P} = -K\frac{\partial V_i}{\partial x_i}$ $\dot{V}_i = -\frac{1}{\rho}\frac{\partial P}{\partial x_i}$	$P^{t+1} - P^t = -K\Delta t\frac{\partial V_i^{t+\frac{1}{2}}}{\partial x_i}$ $V_i^{t+\frac{1}{2}} - V_i^{t-\frac{1}{2}} = -\frac{\Delta t}{\rho}\frac{\partial P^t}{\partial x_i}$ 6 variables 8 FFTs	$P^{t+1} - P^t = -K\Delta t\frac{\partial V_i^{t+\frac{1}{2}}}{\partial x_i} - \frac{1}{24}K\Delta t^3\frac{\partial}{\partial x_i}\left[\frac{1}{\rho}\frac{\partial}{\partial x_i}\left(K\frac{\partial V_j^{t+\frac{1}{2}}}{\partial x_j}\right)\right]$ $V_i^{t+\frac{1}{2}} - V_i^{t-\frac{1}{2}} = -\frac{\Delta t}{\rho}\frac{\partial P^t}{\partial x_i} - \frac{1}{24}\frac{\Delta t^3}{\rho}\frac{\partial}{\partial x_i}\left[K\frac{\partial}{\partial x_j}\left(\frac{1}{\rho}\frac{\partial P^t}{\partial x_j}\right)\right]$ 6 variables 24 FFTs	$P^{t+1} - P^t = -K\Delta t\frac{\partial V_i^{t+\frac{1}{2}}}{\partial x_i} - \frac{1}{24}Kv^2\Delta t^3\frac{\partial^3 V_j^{t+\frac{1}{2}}}{\partial x_i\partial x_i\partial x_j}$ $V_i^{t+\frac{1}{2}} - V_i^{t-\frac{1}{2}} = -\frac{\Delta t}{\rho}\frac{\partial P^t}{\partial x_i} - \frac{1}{24}\frac{v^2\Delta t^3}{\rho}\frac{\partial^3 P^t}{\partial x_i\partial x_j\partial x_j}$ 6 variables 12 FFTs

FD Cost Spreadsheet

Bold indicates those parameters:
1) having a greater-than-linear impact on total runtime, and
2) that are probably subject to more disagreement.
For whatever method is used, the Operation count / spacetime point (ops/cell/dt) is crucial

Acoustic Finite Difference Problem Size Estimator (blue=user entry)

Earth Model Parameters		***Acquis & Proc Parameters***		***Algorithmic Parameters***		***Machine Parameters***			
Length (full model)	40000	***Max Freq***	**50**	***PseudoSpect?***	**yes**	Gflop/sec-cpu	1.50		
Width (full model)	30000	Max Offset	8000	***O(Xspace)4,6?***	6	$ per cpu-hour	0.10		
Height	10000	Desired drec	25	FDpts/minwavel	2.0				
Vmin	1500	***Nstreamers***	**10**	***O(T) 2,4,Hyb?***	Hyb				
Vmax	4500	xline/iline binsize	2	***Ops/cell/dt*** (de	**80**				
Water Depth	1000	Max Rec Time	11						
Variable Density	**yes**	***Mig-Apert Radius***	**8000**						
				Dom VKdt (~ 2/	0.192				
				2nd Order T		**4th** Order T (!! Assuming locally constant vel & den)			
				VPhase Disp% a	0.15	VPhase Disp% a	-0.0002		
				VGroup Disp%	**0.47**	**VGroup Disp%**	**-0.0010**		
Max allowed dx	15.00	Ncells (millions)	3,596	inline dShot	50	dShot unaliased	7.73		
dx (=dy=dz)	15	active nx*ny*nz*nt	7.7E+12	xline dShot	250	alias angle in cm	8		
dRec	25	**Total Model Mem (**	**53.58**			alias angle in cm	17		
nx earth model	2670	**Active Mem (Gb)**	**11.43**	Nshot iline	800				
ny earth model	2010			Nshot xline	120				
nz earth model	670			Total Nshots	96000				
nxactive	1070	Gflop/shot	5.7E+05	Total Gflop	5.5E+10				
nyactive	1070	1Shot cpu-hour	105.8	Total cpu-hour	10,160,373				
Sugg Tmax	10.04					#clstrs,6mos		Cost Sensitivities	
dT(msec)	0.0011			**x000 cpu-days**	**424**		2.3	d$/d(km)	101,600
nt	10000	**1Shot $Cost**	**10.58**	**Total $Cost**	**1,016,000**			d$/d(Hz)	121,920

Realistic Wish List?

Variable density, allowing richer AVO behavior → two 1st-order PDEs

Spectral operator in Kx Ky Kz → better spatial characteristics, but number of FFTs increases with time order and variable density. May require spatial convolution?

Hybrid temporal 4th order operator → has better stability & dispersion characteristics, with only a very modest increase in flops, *provided* velocity is treated as locally constant (local velocity gradients ignored). Conjecture(???): AVO reflectivity response only very mildly affected by this operator assumption, but large-scale waveform dispersion is minimized.

Dispersion = D(VarDen, SpectralK, Hybrid temporal) → stable with negligible dispersion

FlopCount = F(VarDen, SpectralK, Hybrid temporal) → 6X as many FFTs as compared to constant density, 2nd-order time (spatial convolution?)