Processing the KTK 3D seismic Survey for Azimuthal Information: San Joaquin Basin, California*

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Abstract

Geokinetics acquired the KTK 3D seismic survey in 2013 in conjunction with Aera Energy. The survey took place in the San Joaquin Basin in Kern, Kings, and Tulare Counties and was intended to explore the northern extent of the Monterey and Kreyenhagen formations in the Buttonwillow Depocenter which lie between 12,000 and 16,000 ft in depth (see slide 2 and slide 3).

With the recent advances in horizontal drilling and fracking in unconventional plays, the Monterey Shale has come under scrutiny as a strong candidate for similar exploitation. Chief among its attributes is not only as an excellent source rock, but an understanding of its natural fracture networks (see slide 4 and slide 5) and the local stress regime that it is subjected is important in commercial production.

The contribution of seismic data to characterizing the density and direction of fractures, as well as the direction and magnitude of the local stress fields has been well documented. Important to the success of this analysis is the acquisition of sufficient offsets in all directions (see slide 6) as well as the careful preservation of this azimuthal information in the data processing (see slide 7 and slide 8). Since land seismic acquisition is by nature irregularly sampled due to a variety of natural and man-made obstacles, sophisticated interpolation schemes and amplitude and azimuth preservative pre-stack migration must be employed to overcome the impact of these effects.

Introduction

The basic seismic properties of the shales we wish to exploit are that fractures, bedding, or stress can cause horizontal velocity anisotropy (HTI) in both P– and S-waves (see slide 9). The velocity parallel to fractures, for example, is fast (see slide 10) and the velocity perpendicular is slowest. This difference is a measure of fracture density, and by measuring the velocity at multiple azimuths it can be elliptically inverted for the fracture azimuth, fast direction, slow direction, and degree of anisotropy. Slide 11 illustrates the sinusoidal pattern of the velocities with azimuth in an example from the Marcellus from slide 10. The fast velocity direction will result in the arrival times of events being earlier in the seismic section; the slow direction later.

Similarly, the amplitudes of the measured or calculated shear impedance can be inverted from multiple azimuths to find the fast and slow directions of the fractures as well as the fracture density (see slide 12). In areas of good signal-to-noise this method is higher resolution than the velocity method.

Survey Description

(Slide 13) The KTK survey was shot with a combination of vibroseis and dynamite with the source lines orthogonal to the receiver lines. The recording system was a Sercel 428, the 4 vibes used were Unova AHV-4 62K lb with 2 sweeps of 24 seconds from 6 to 84Hz, and 7 seconds of listen time. The dynamite sources were 11 lbs at 40 ft and 16.5 lbs at 50 ft. The shot intervals were 220 ft and the source lines were 1320 ft apart. The receiver group intervals were 220 ft and the receiver lines were also 1320 ft apart. There were 3 geophones set in a triangle 10 ft on a side at each receiver station. The receiver patch was 24 lines by 144 receivers, leading to at least 15,000 ft in all azimuthal directions.

Pre-processing

A typical amplitude-preservative processing sequence was followed (see slide 14). After geometry assignment refraction statics were calculated, then spherical divergence was applied, then surface-consistent deconvolution, denoising, surface-consistent amplitude scaling, and two iterations of velocity analysis and reflection statics. After this pre-stack migration velocity analysis was performed.

Offset-Vector Tiling, 5D Interpolation, and OVT Pre-stack Time Migration

In the recent past, a typical pre-stack time migration was performed in common offsets without regard to azimuth. The migrated offsets were then analyzed for post-migration velocities and stacked, and the azimuthal information was lost. Another way of organizing the data, called Offset-Vector Tiles came into common use to address this problem. Basically the data were sorted into cubes of offset ranges and azimuth ranges, (see slide 15 and slide 16) giving rise to a “vector” description of each cube since one needed two numbers, an offset and an azimuth to describe the “tile” or cube. Thus each cube had dimensions of x, y, time, offset, and azimuth, hence giving rise to the term 5D.

If one then migrates each cube, the offset and azimuth information is preserved through the migration process, and the signal-to-noise gained from this imaging step greatly benefited the analysis of amplitudes and the timing of events as a function of azimuth. However, when subdividing the data into so many domains, a lot of holes in the data are created; thus the necessity of 5D interpolation.

The fundamental idea behind multi-dimensional interpolation is to devise a method to estimate the multi-dimensional spectrum of the data as a function of time and space. Once this is calculated then one can fill the holes in the data with traces with the appropriate amplitude and character. Several methods exist to do this; the one used here is known as the Projection Onto a Convex Set, or POSC. We show several examples of the data holes interpolated using all 5 dimensions.

Slide 17 shows Tile 1 (a near-offset tile) where several traces are missing. Slide 18 shows the interpolated traces across the gaps in 3D. Slide 19 shows the traces interpolated in 5D for Tile 1. Far better character is preserved in the 5D process. Similar comparisons for Tile 5 (slide 20 and

slide 21), Tile 10 (slide 22 and slide 23) are shown. Tile 10 in time slice before and after interpolation is shown in slide 24 and slide 25.

With the 5D interpolation completed, the OVT migration is performed and the data is now ready for analysis for anisotropy, fracture characterization, stress analysis, etc.

Conclusions and Observations

The KTK survey has been acquired and processed in such a way that a sophisticated azimuthal analysis of the Monterey and Kreyenhagen formations may be performed. The 5D interpolation is a critical step to forming complete OVTs that then may be successfully imaged and attributes such as the effect of fractures as exhibited by HTI can be quantitatively measured for direction and intensity.

Slide 26 shows a time slice from the KTK volume, and slide 27 shows the inline along the indicated traverse with the top Monterey, Kreyenhagen and Sierran Basement mapped. The Antelope Member is in light blue. It is underlain by the McDonald Shale Member (approximated by the high amplitude continuous reflector). Note the downlapping reflectors of the Lower Reef Ridge immediately above the Antelope which demonstrate the North to South advancement of the shelf and slope during the Late Miocene. These events are nicely imaged in N-S profiles as the distal downlap of broad shelf/slope clinoforms. Slide 28 is a display of the time section on the left and an OVT display on the right. In the OVT display the data is sorted in two dimensions, firstly offset and secondarily azimuth. As one proceeds left to right, offset is increasing, but there is a sinusoidal behavior from the HTI anisotropy displayed on the events as each group of azimuths for the offsets are shown. The result is a sort of “stair stepping” effect that can be used for fracture characterization. Slide 29 shows the results if these HTI effects are removed, and the events are now flat. Slide 30 displays these side by side. One can see the HTI effects on several of the events on the rhs that are then removed on the lhs. The top of the Monterey and the base of the Antelope Member are shown by the red arrows.

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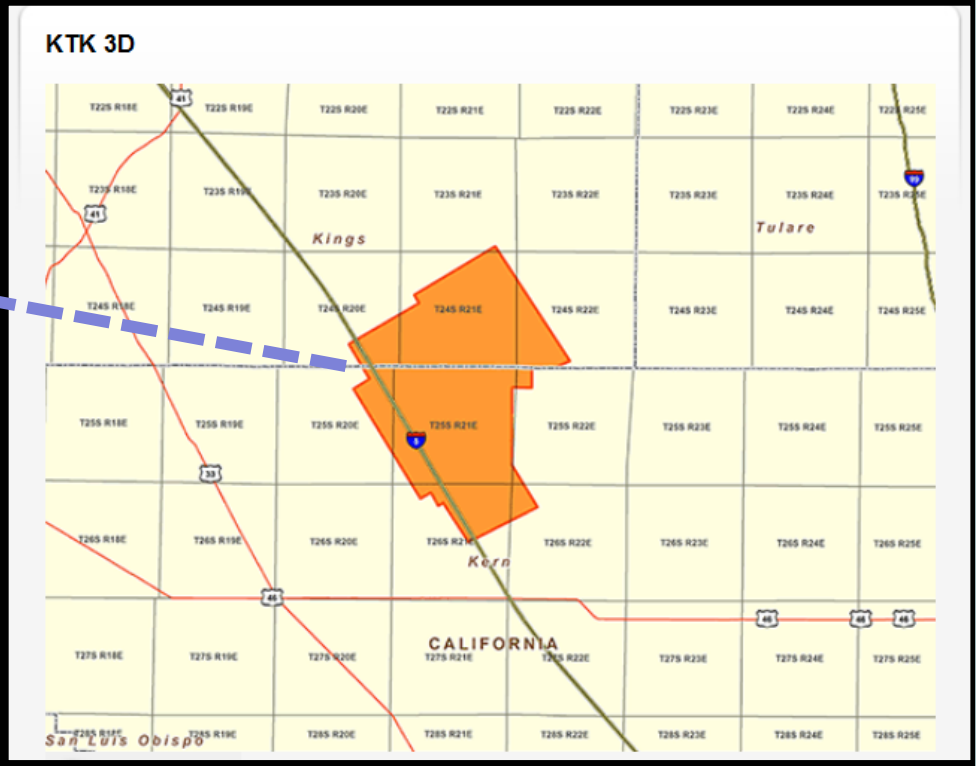
Lee Bell – Geokinetics, Inc.
and Gary Myers – Aera Energy LLC
May 4, 2015

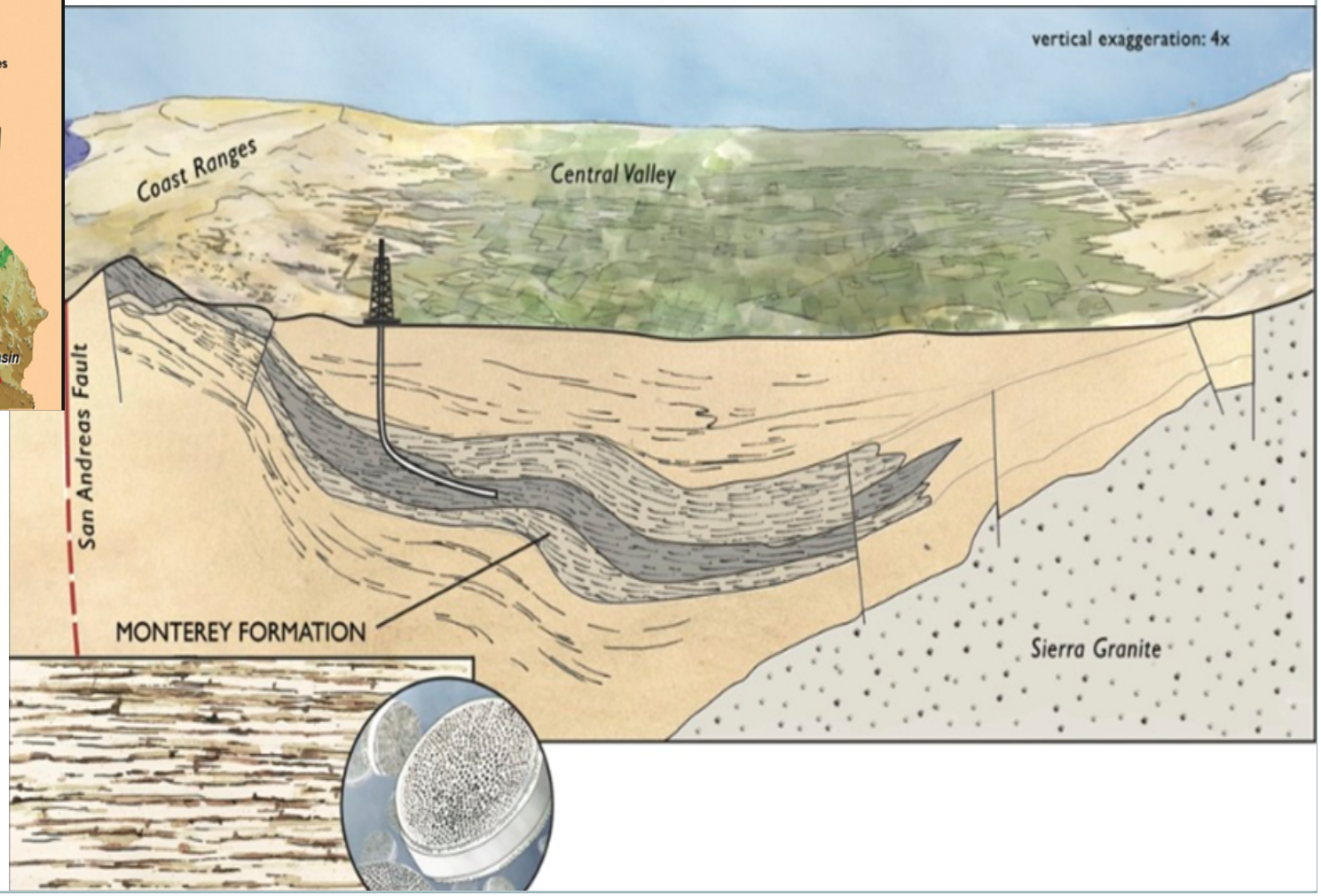
KTK 3D
Kern County, California

Geokinetics Multi-Client Data

95 sq. miles

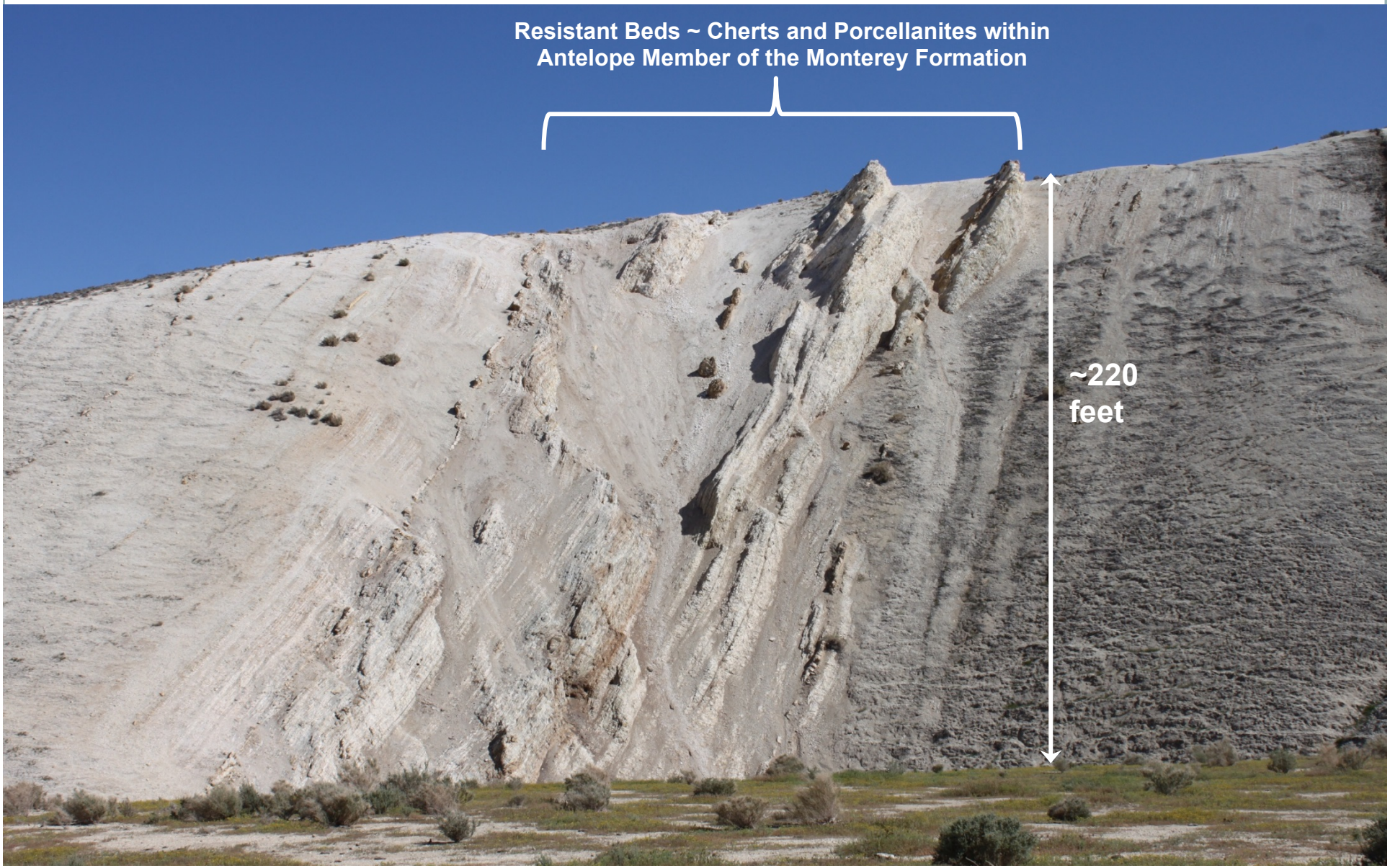


Monterey Formation



Monterey Shale
Arroyo Burro

Monterey Formation
Chico Martinez Creek – San Joaquin Basin



Acquisition Requirements

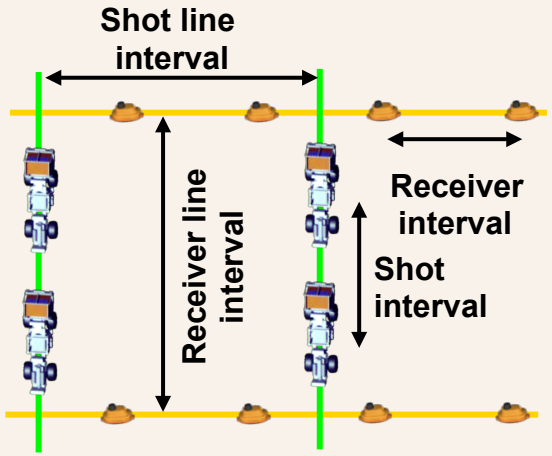
Goal: within overall economics of the play, design acquisition to achieve best possible:

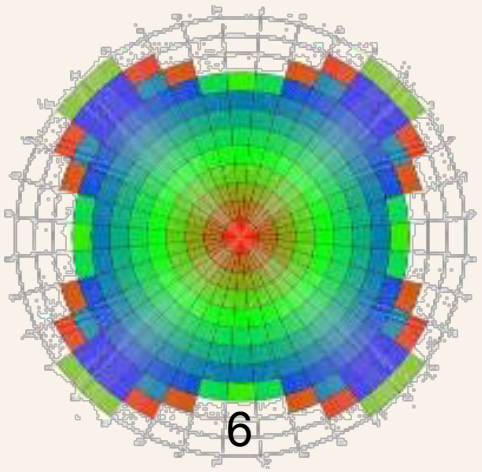
- Spatial resolution
- Structural image
- Anisotropic information
- Inversion-derived properties

Full Azimuth Acquisition encompasses the geophysical parameters that make this possible:

- Broad bandwidth
  - High fidelity phones and flexible sources
- Denser arrays
  - Smaller trace spacing and sample rate
  - Closer group spacing and line spacing
- P or PS recording
- High channel count
  - Higher fold and longer offsets
- Regular geometry and 360° recording
  - Consistent fold at all offsets
  - Consistent offsets at all azimuths
  - Uniform sampling of all azimuths

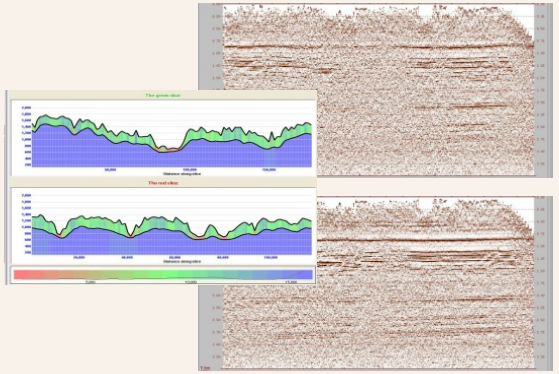
Full Azimuth Symmetric Sampling





Processing Requirements

- 3D data acquired specifically for the objectives of the play
- Near surface statics
- Noise removal and S/N optimization
- Preserve amplitude and maintain stable waveform
- Iterative velocity determination, including VTI, updating and high-res, and jointly constrained P & PS estimation



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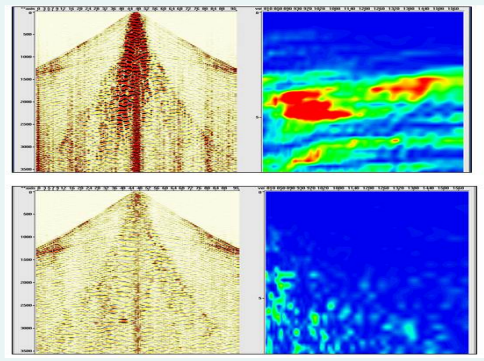
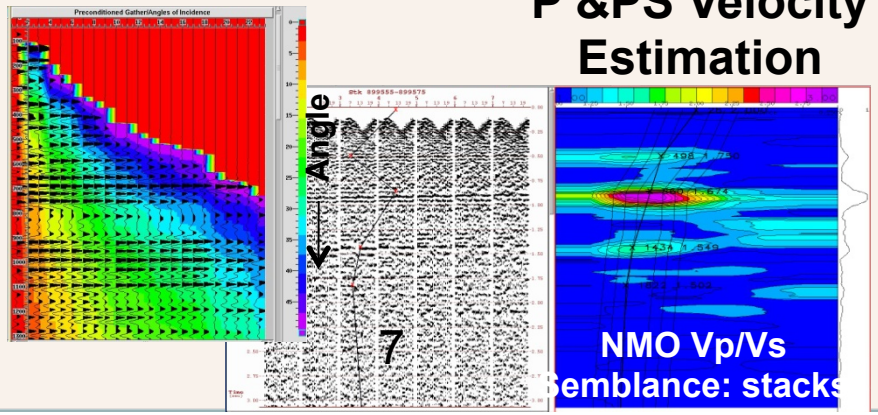


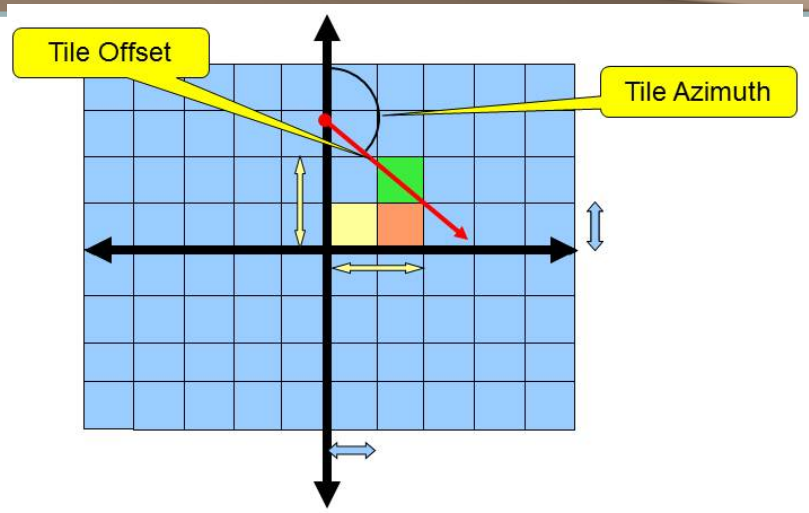
Robust Noise Attenuation

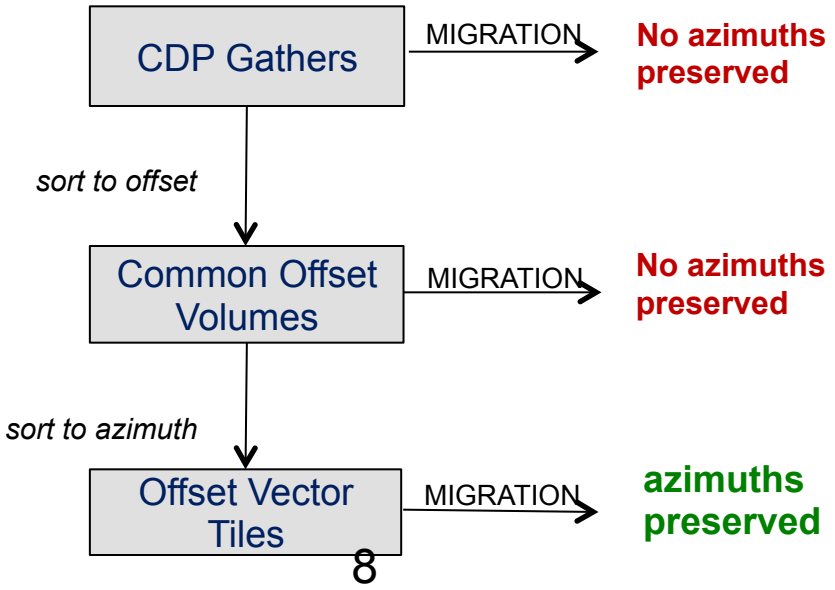
P &PS Velocity Estimation



Preserving Azimuth – Offset Vector Tiling

- To assess anisotropy in rock formations, azimuth dependent measurements are required
- Standard 3D pre-stack migrations do not preserve source-receiver azimuths after migration
- The Offset Vector Tiling (OVT) method sorts data into limited offset and azimuth sets prior to migration
- 3D pre-stack migration of the OVT sets individually preserves azimuth and allows measurements to be estimated on an azimuth-dependent basis in 3D migrated space
- The OVT method, frequently in conjunction with multi-dimensional interpolation methods is an integral part of a resource play workflow.





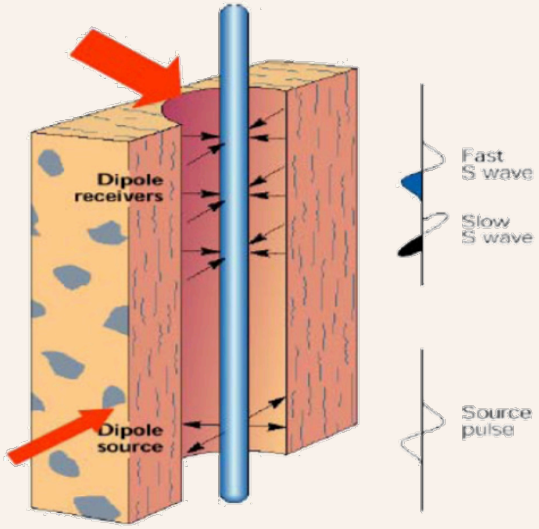
Fracture Characterization

Basis:

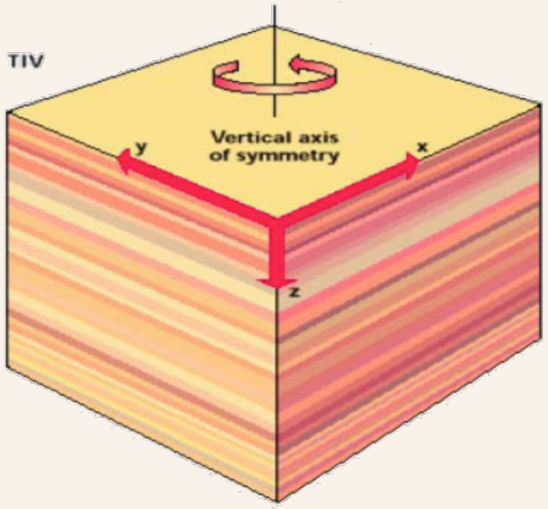
- Fractures, bedding, or stress can cause velocity anisotropy in both P- and S-waves.
- So, velocities from surface seismic data can be used to characterize fractures, bedding, or stress.

Sources of Anisotropy

Differential Stress

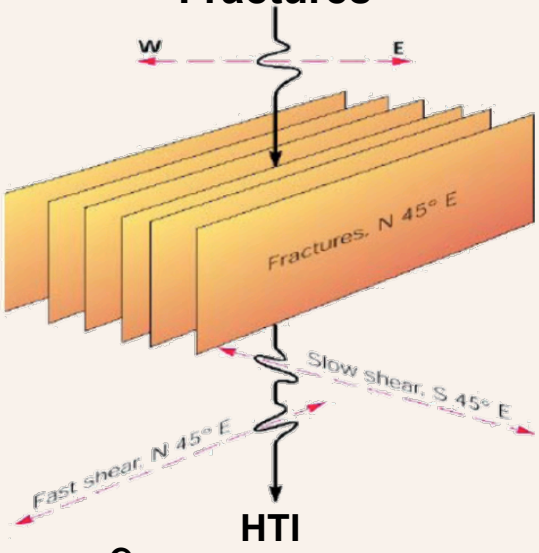


Horizontal Layering



VTI

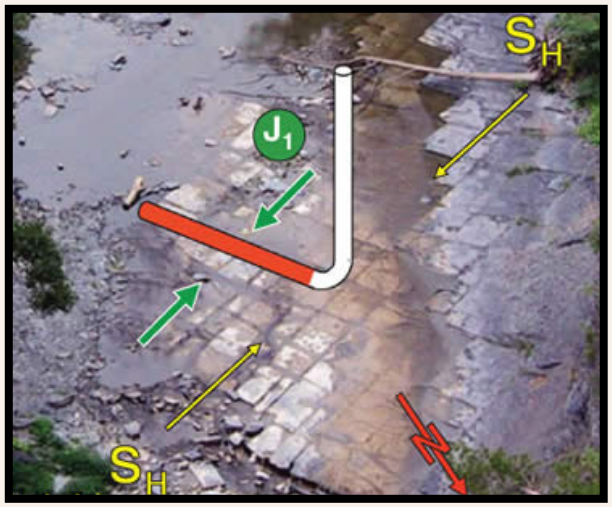
Vertically Aligned Fractures

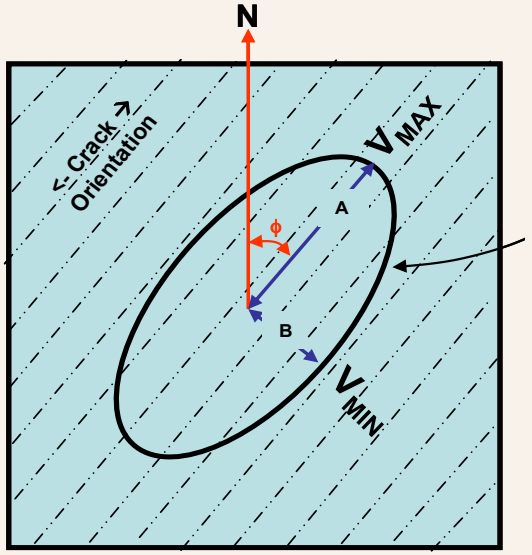


HTI

P-Wave Fracture

From P-Wave data through Elliptical Inversion:

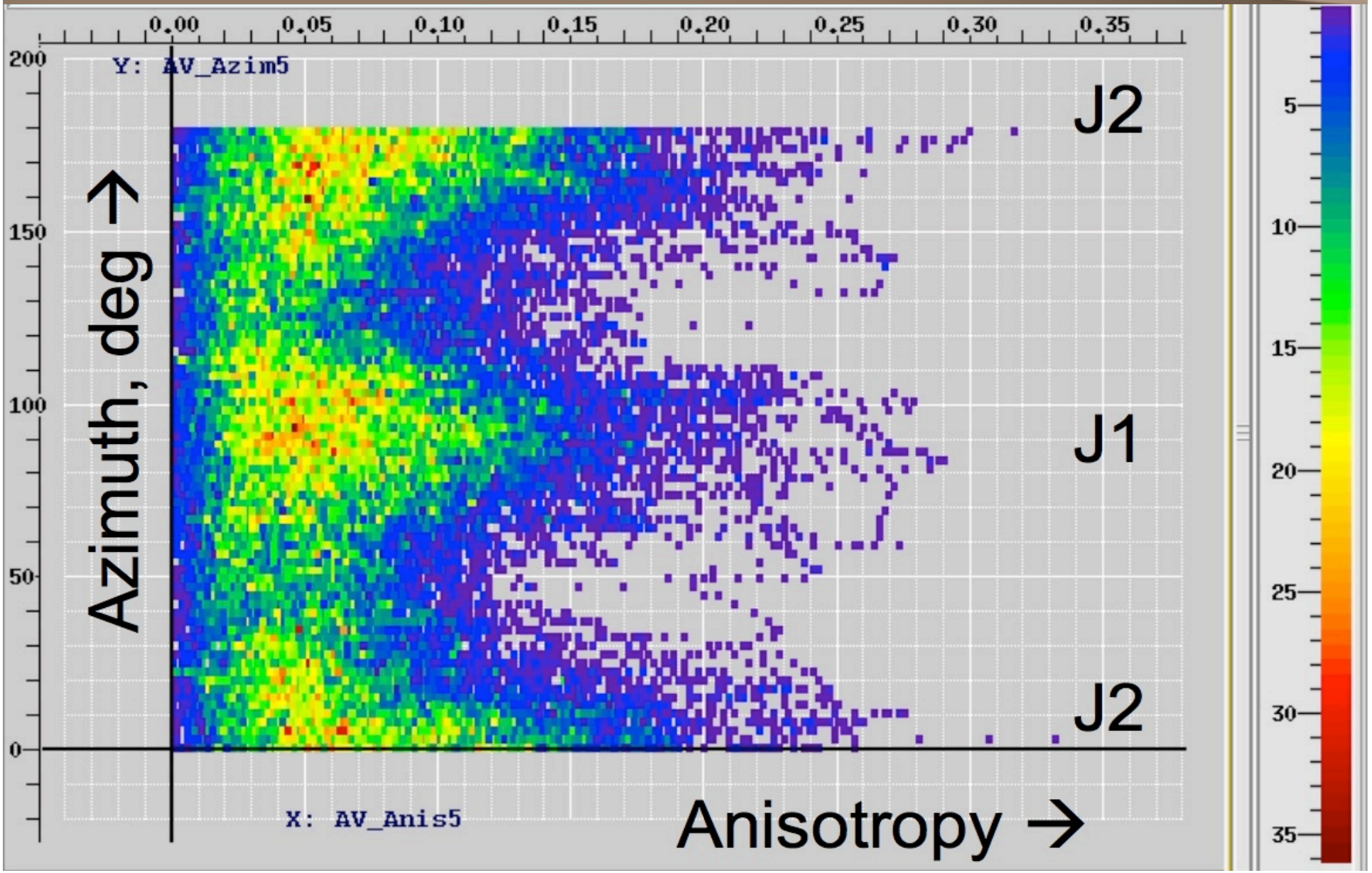




ϕ - Azimuth
V_{MAX}
V_{MIN}
$(V_{MAX}-V_{MIN})/V_{MAX}$
ε - Error

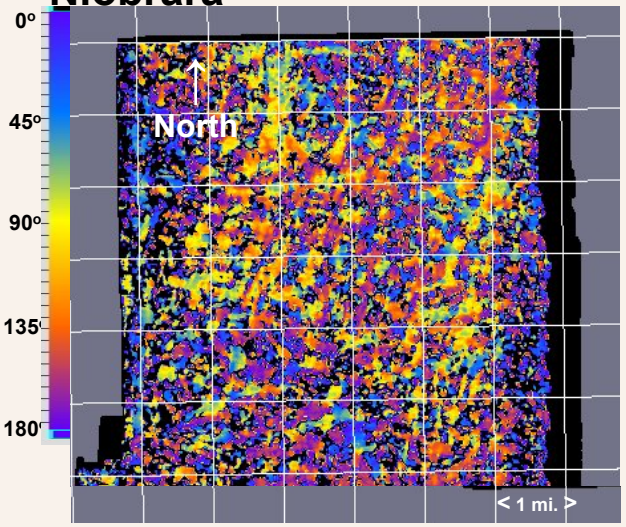
- Velocities in a fractured medium result in different wave velocities for different propagation directions (anisotropy).
- V_{MAX} is parallel to fracture direction
- Difference between fast and slow velocities (anisotropy) may be a measure of fracture density
- Elliptical attributes (azimuth, V_{MAX}, V_{MIN} and e), are obtained by fitting an ellipse to velocities derived at multiple azimuths.

P-Wave Fracture



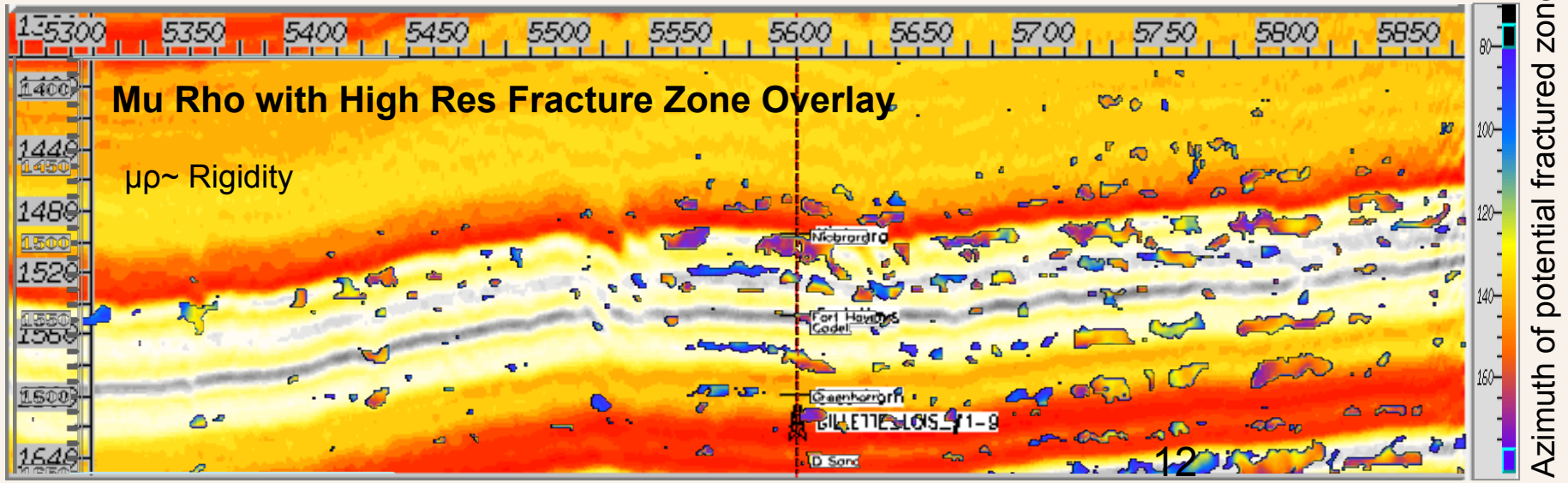
P-Wave Fracture

Azimuth at Top Niobrara



P-wave Amplitude Method:

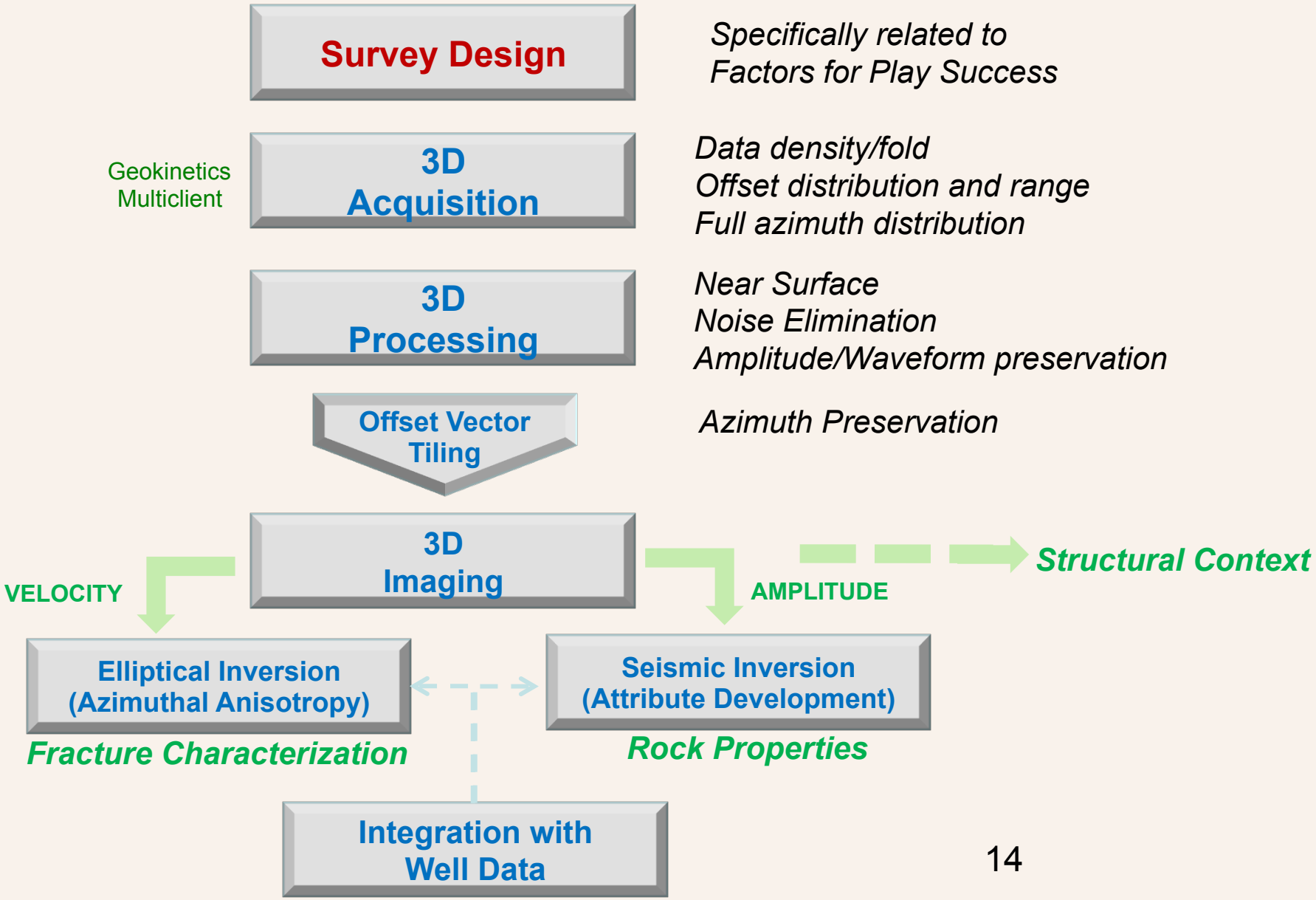
- OVT gathers sorted by Azimuth
- Shear Impedance (Is) estimated along each azimuth and elliptically inverted to find Is_{MAX} and Is_{MIN}
- Method gives higher resolution results than the interval velocity method



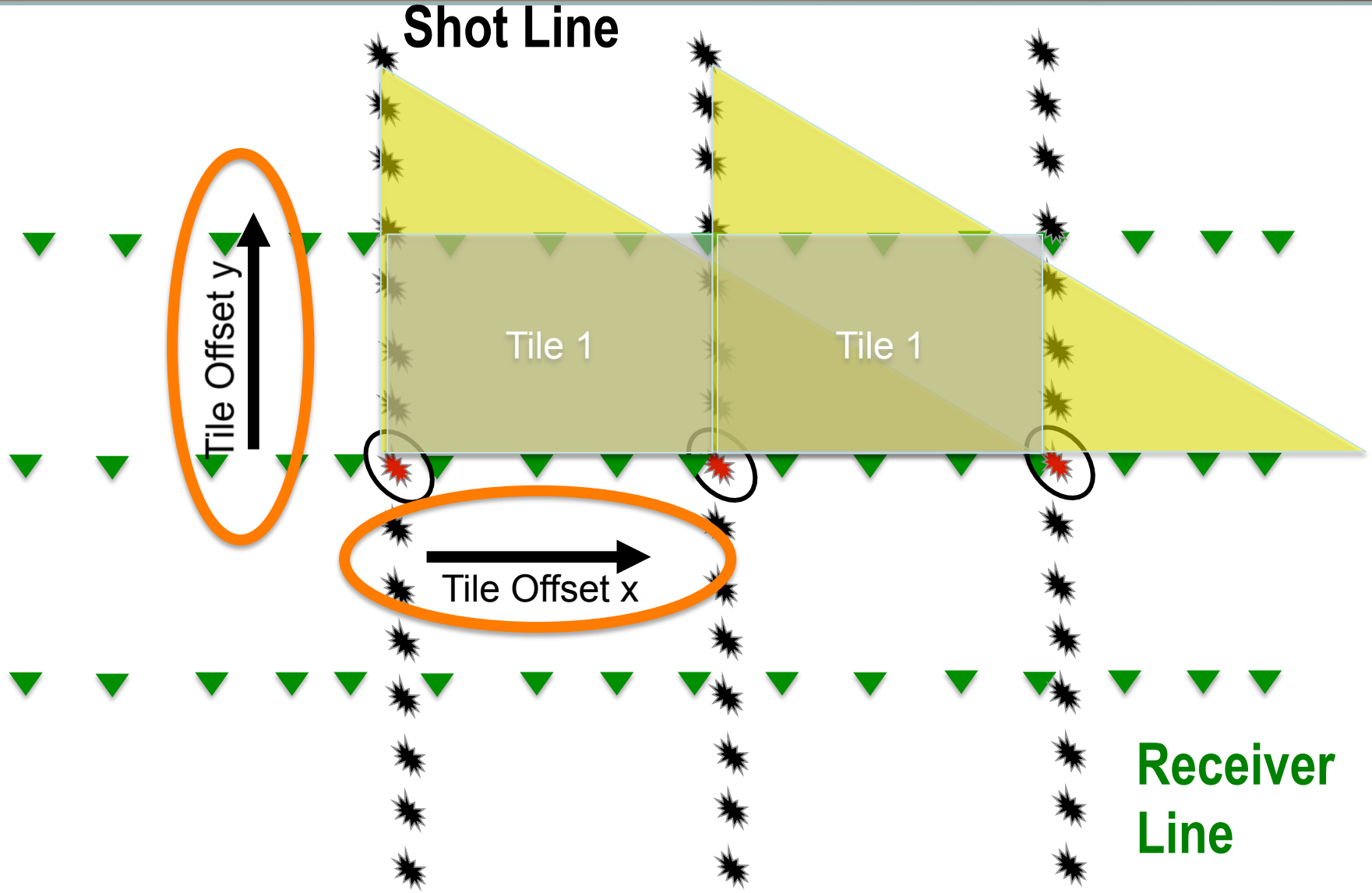
KTK 3D Survey Description

- Sources – vibroseis and dynamite
  - 4 vibes 2 sweeps 24 sec, 6-84 Hz, 7 sec recording
  - dynamite 40 ft depth, 11 lbs and 50 ft, 16.5 lbs
  - source lines 1320 ft, 220 ft shot interval
- Recording Sercel 428
  - receiver lines 1320 ft, 220 ft groups, 3 geophones/ group
  - receiver patch was 24 lines by 144 ft, with at least 15,000 ft in all azimuthal directions, 110x110 ft bins, 1 line roll

Geophysical Strategy



Offset Vector Tiles



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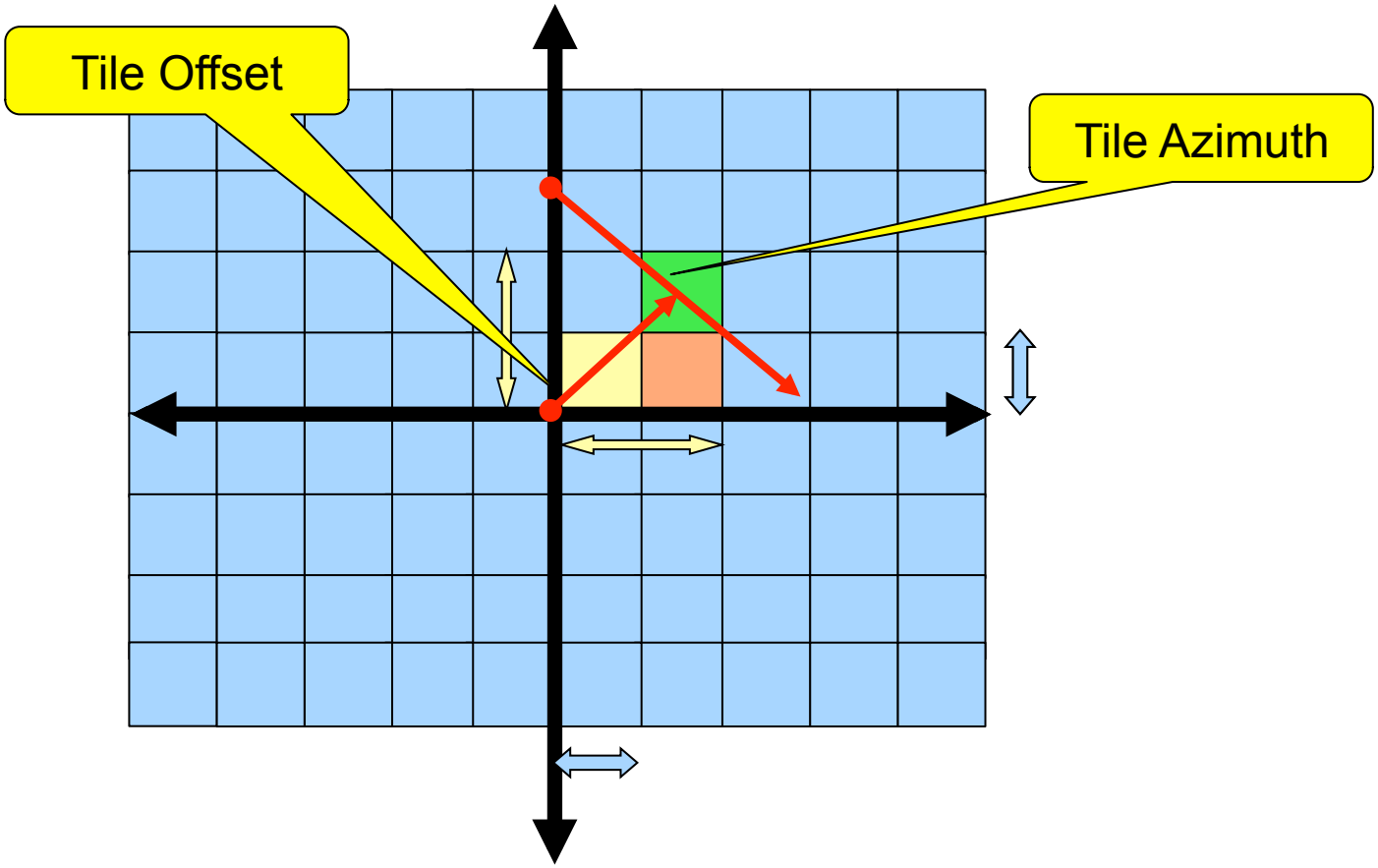

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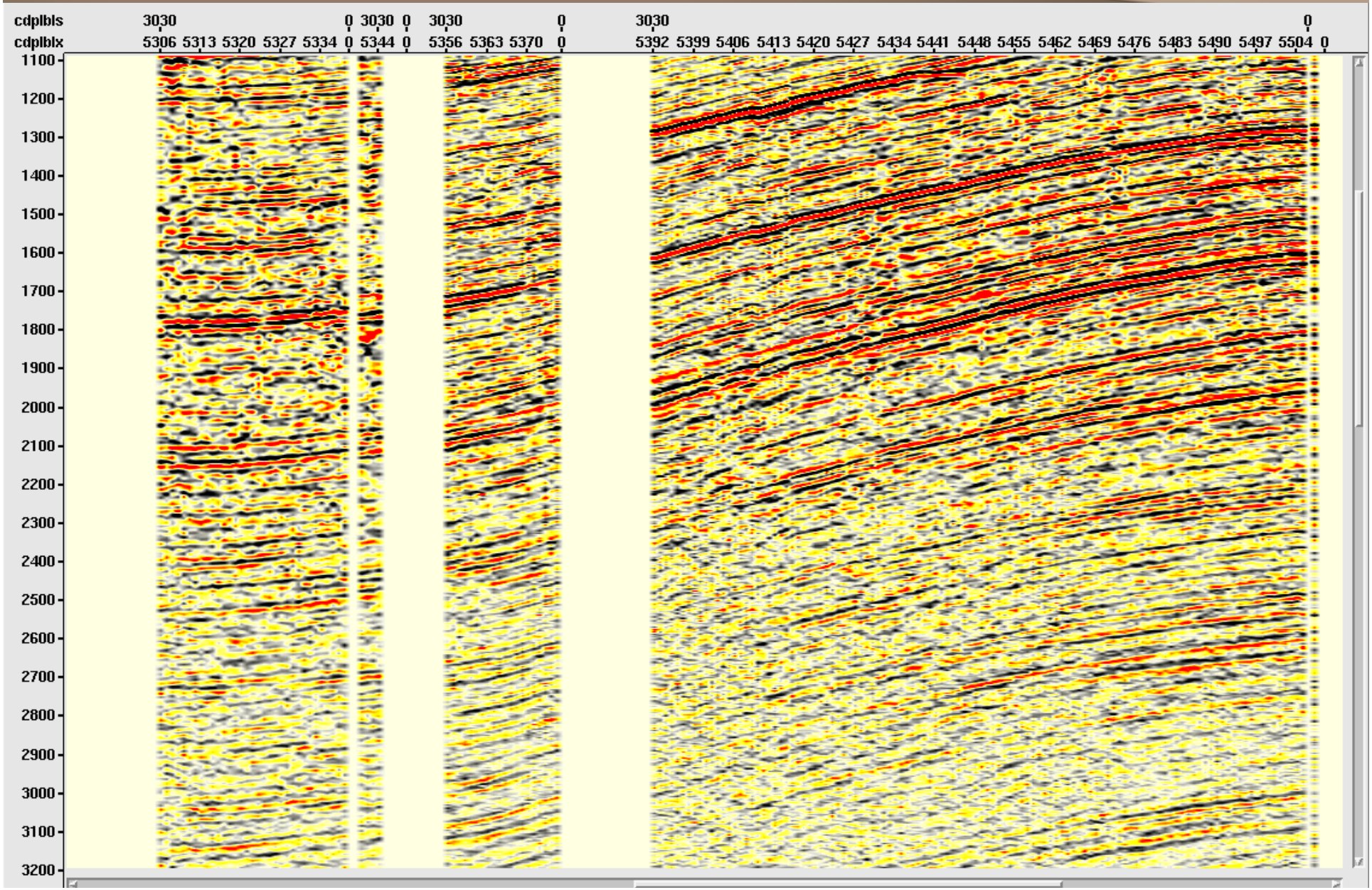
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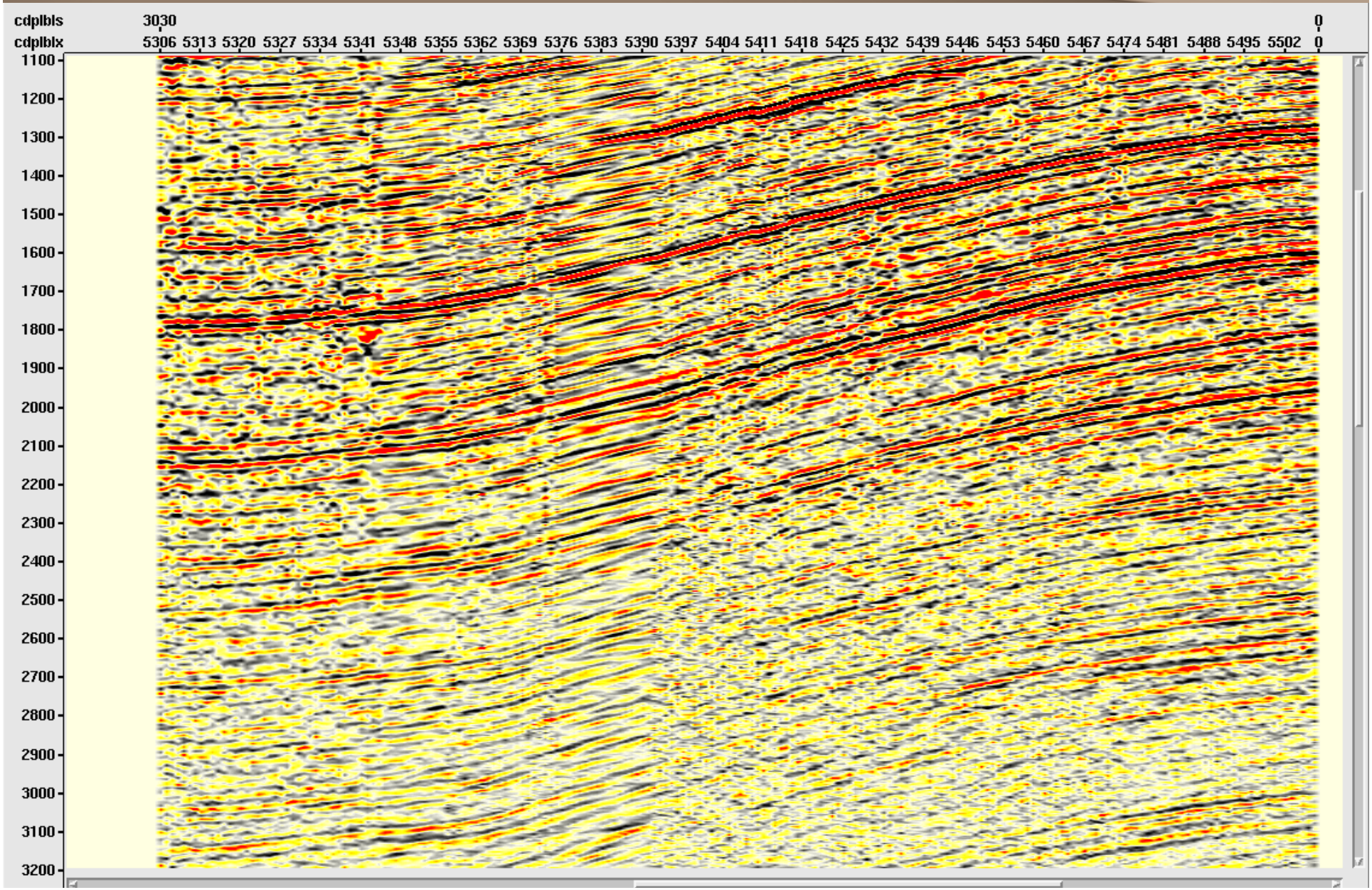
3D Tile 1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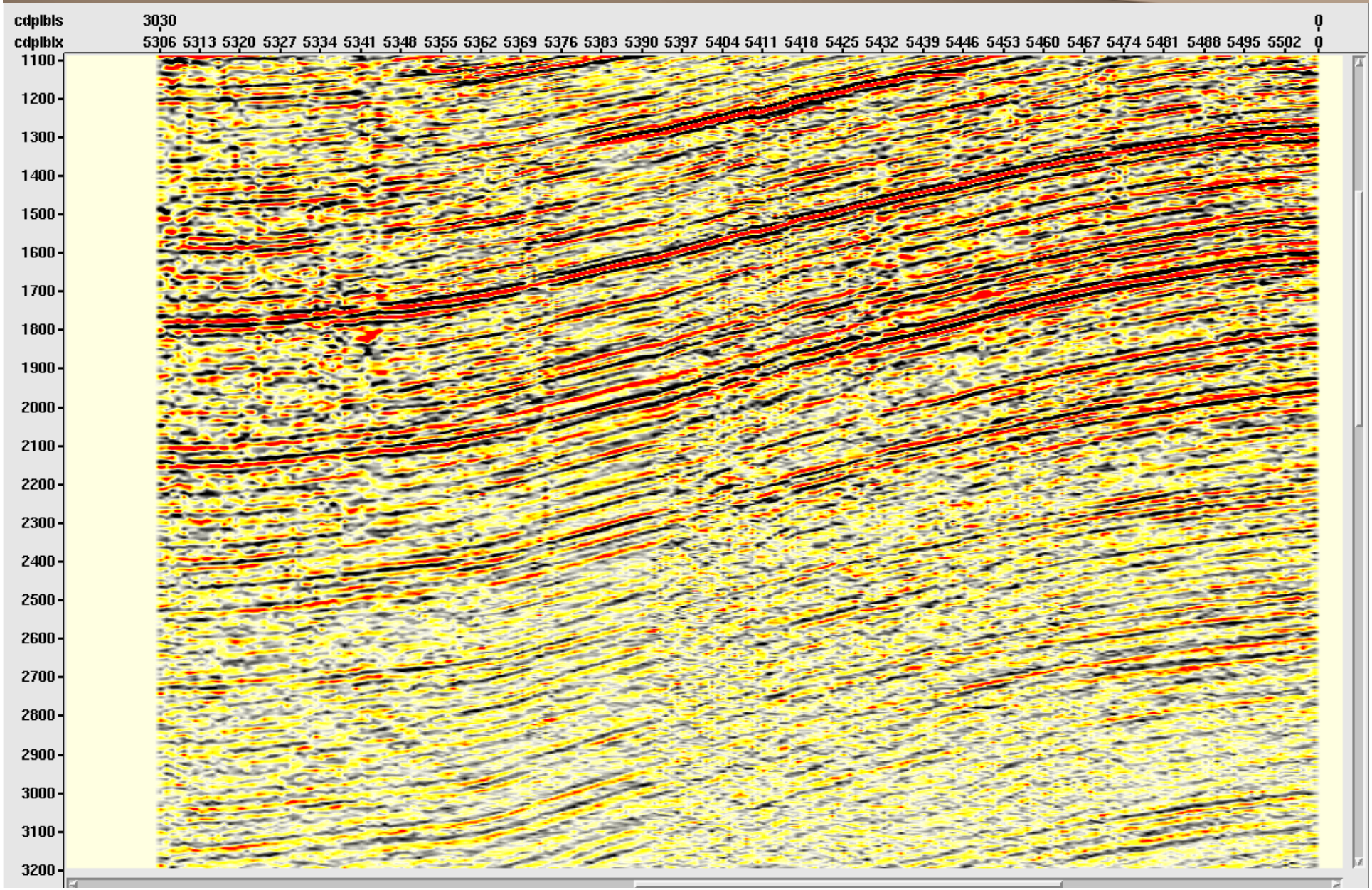
5D Tile 1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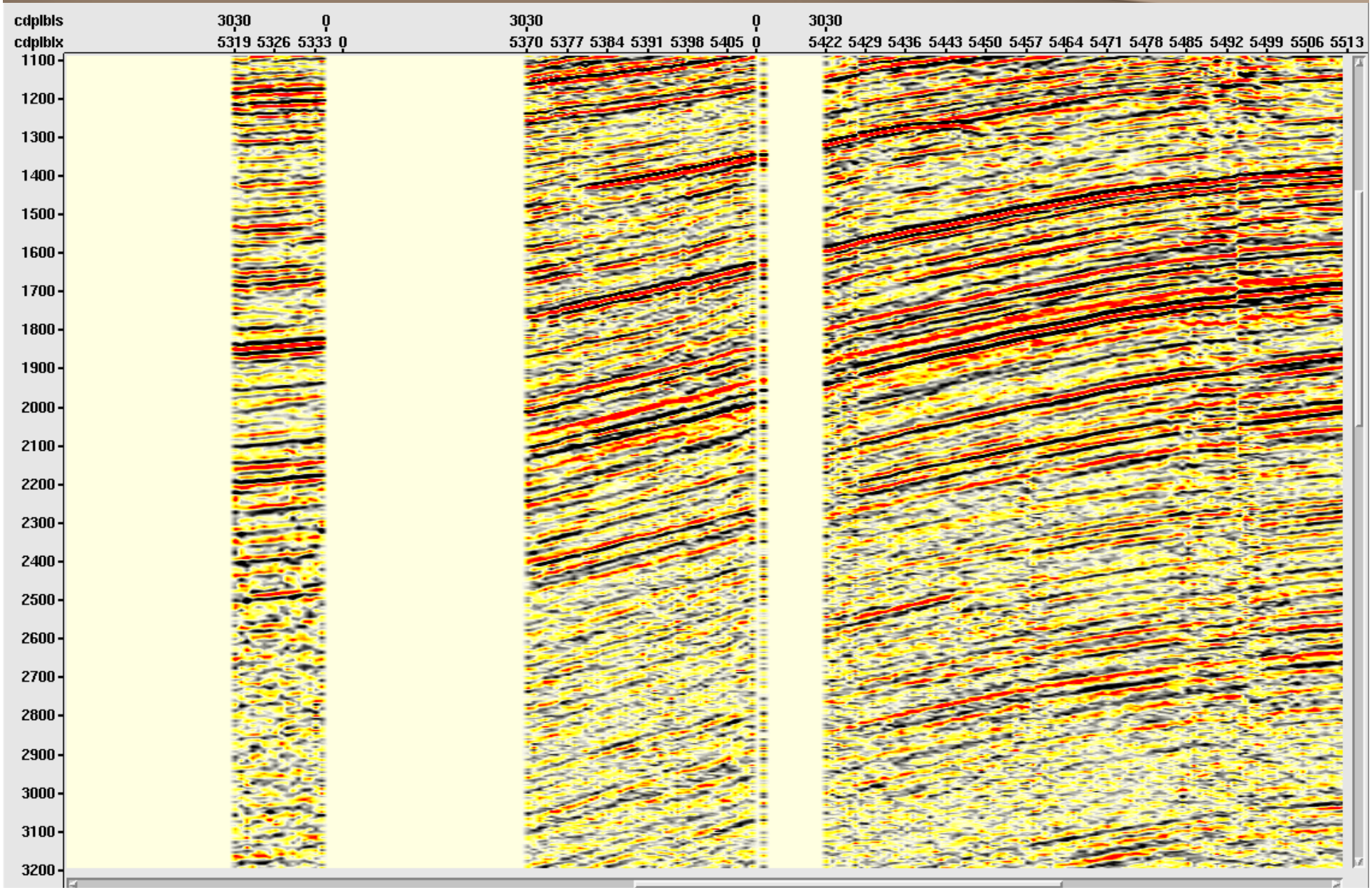
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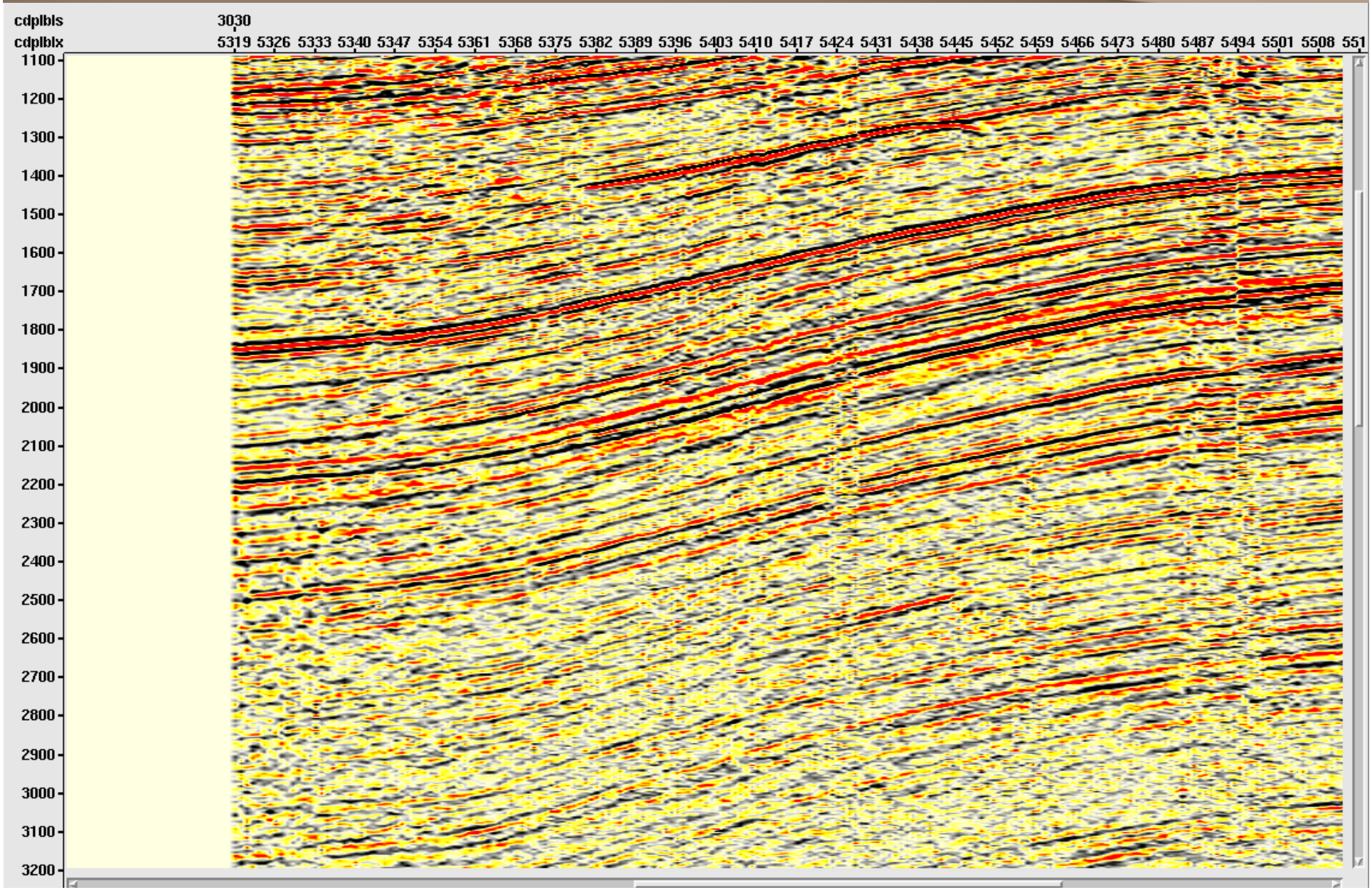
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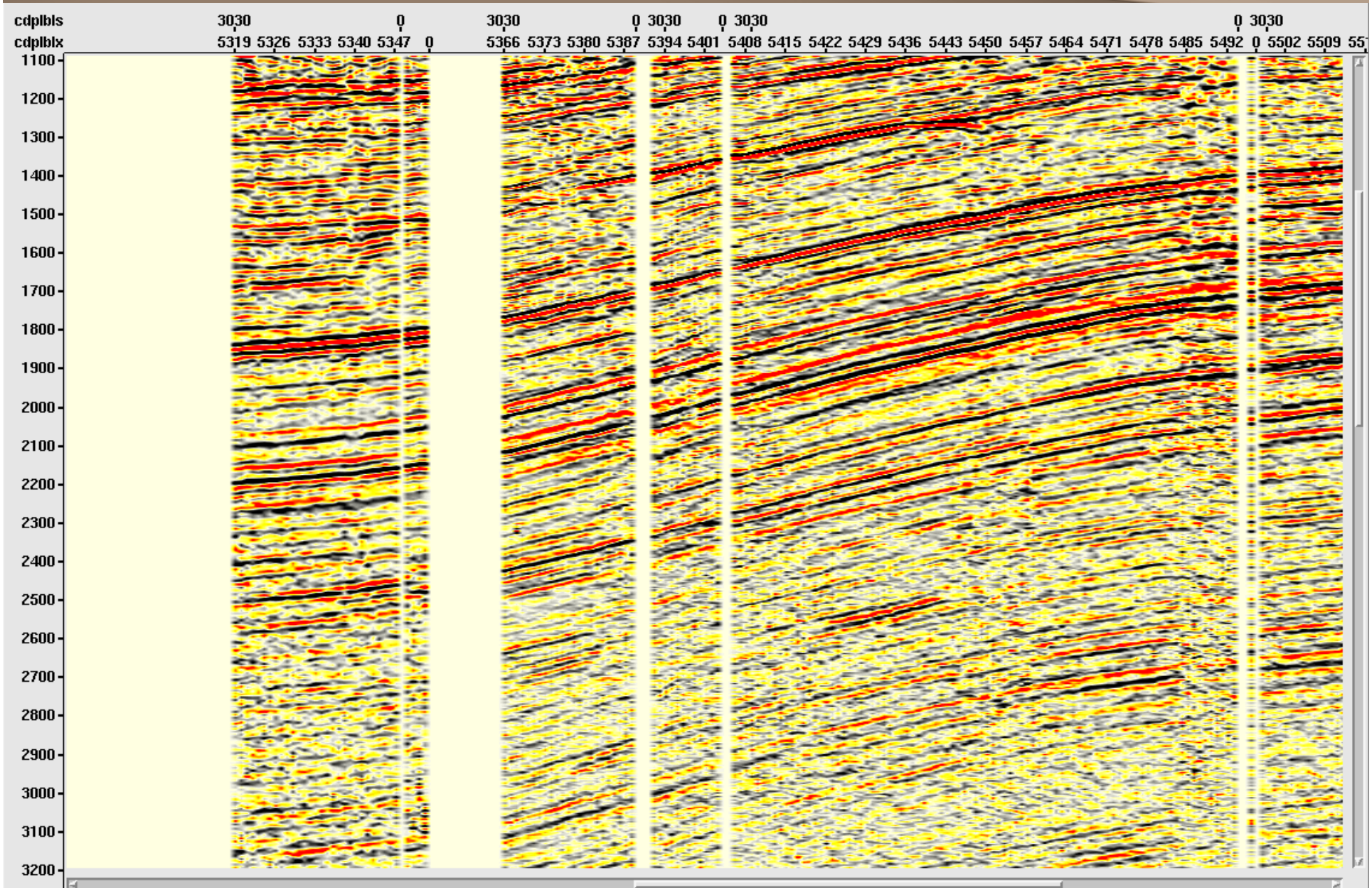
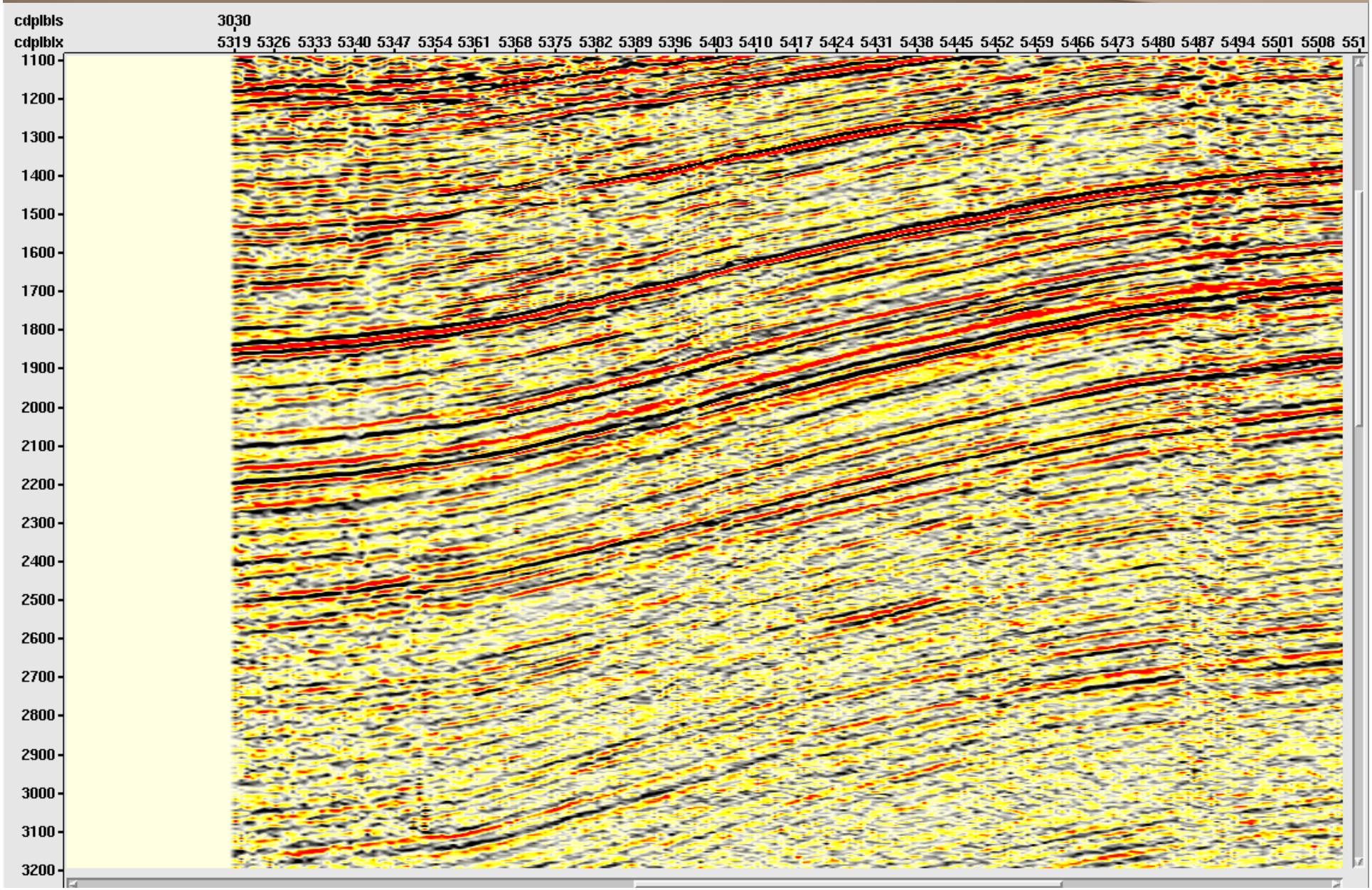


5D Tile 10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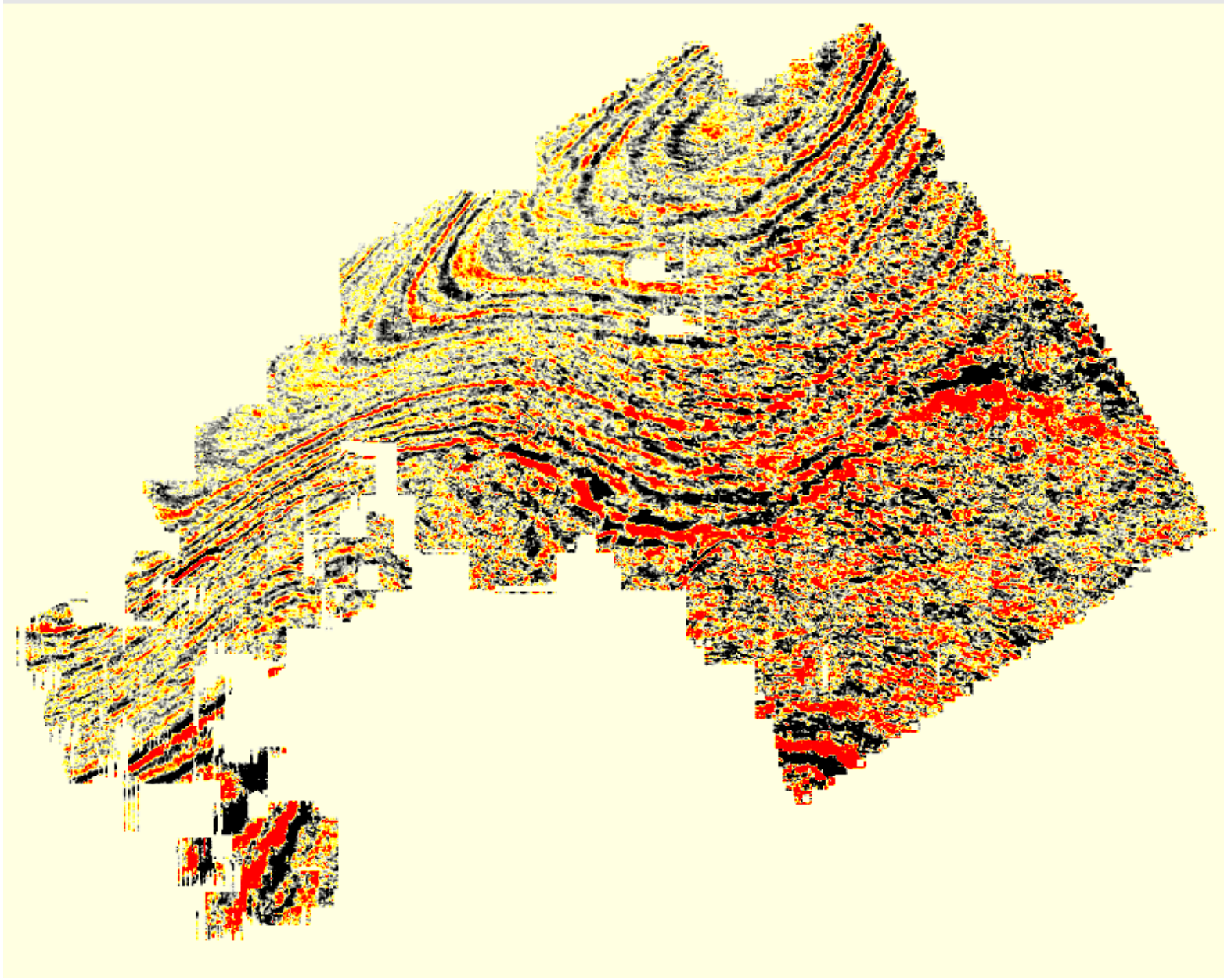
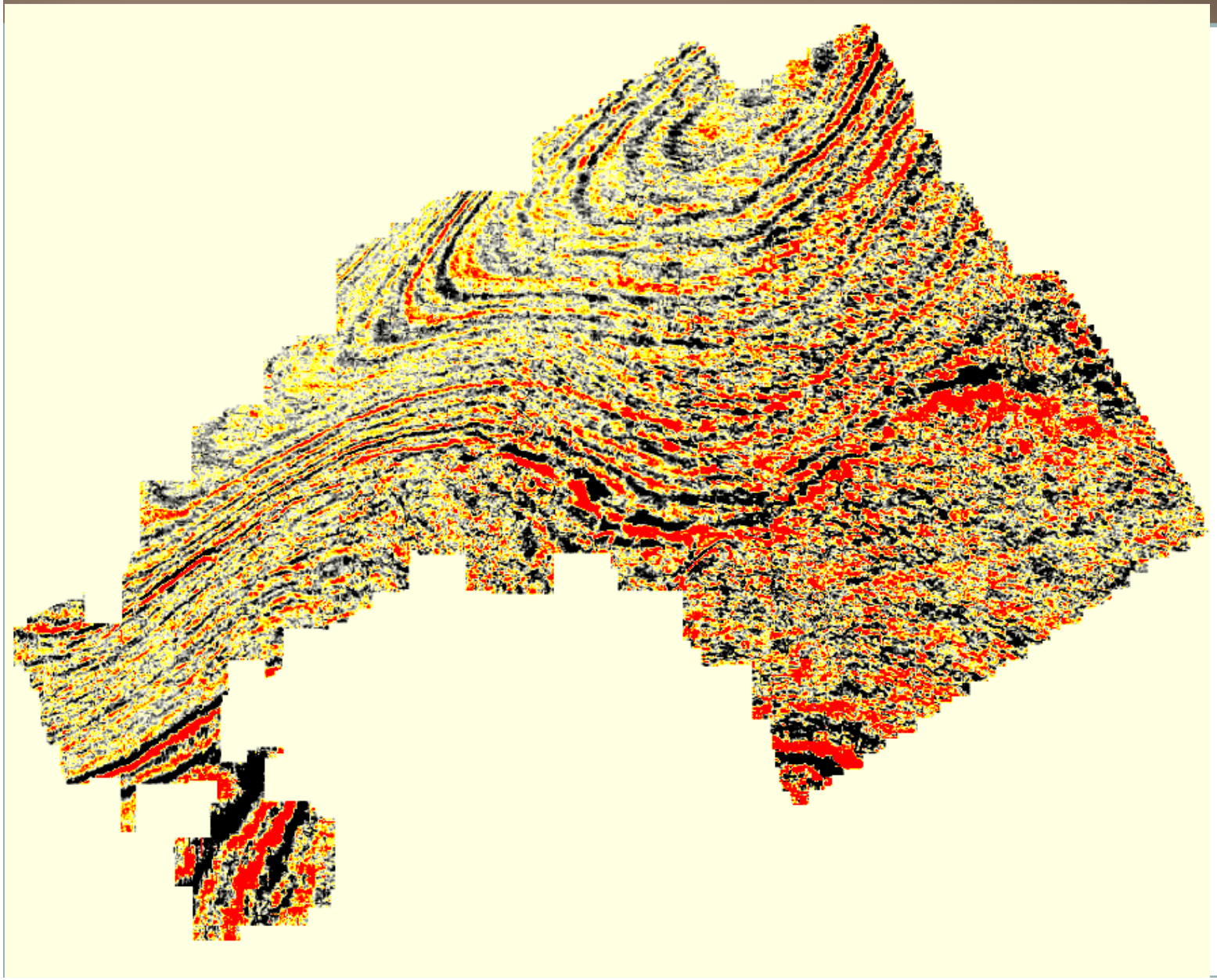
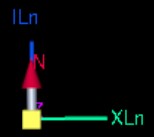


5D tile 10

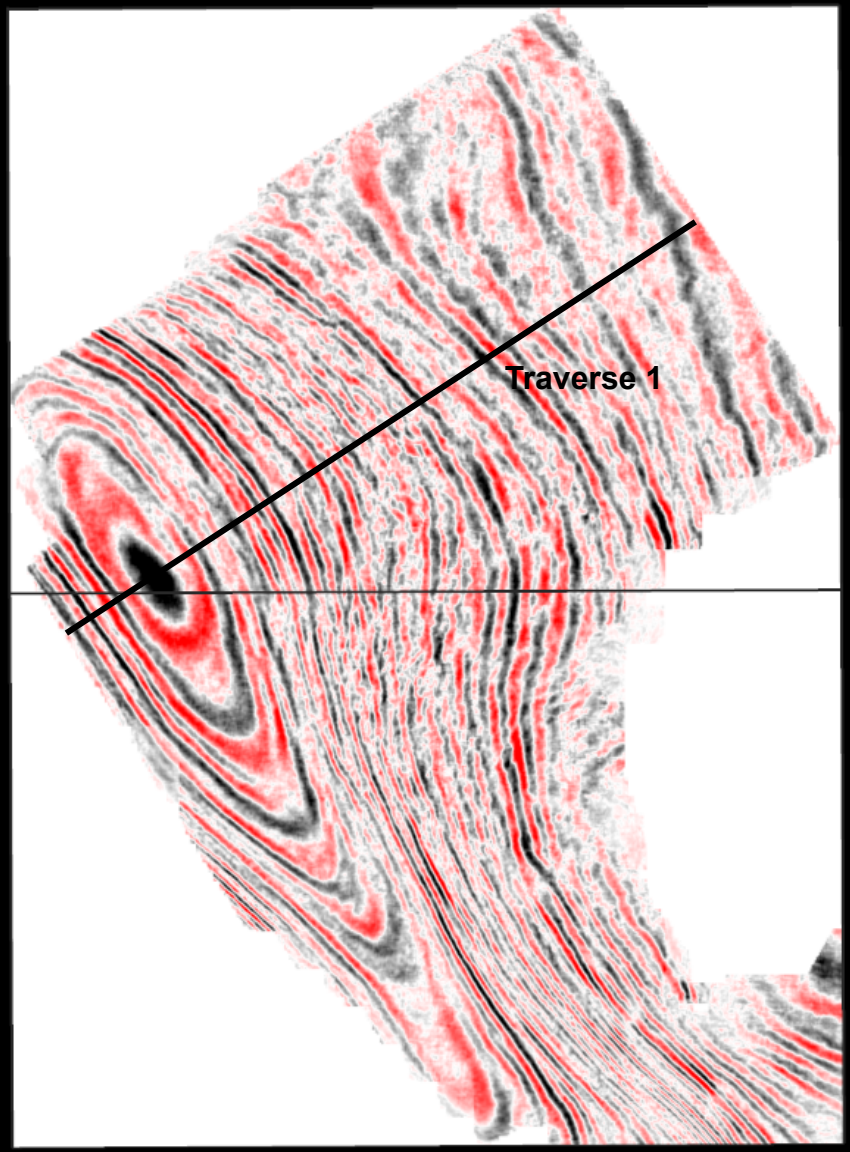


KTK 3D
Kern County, California

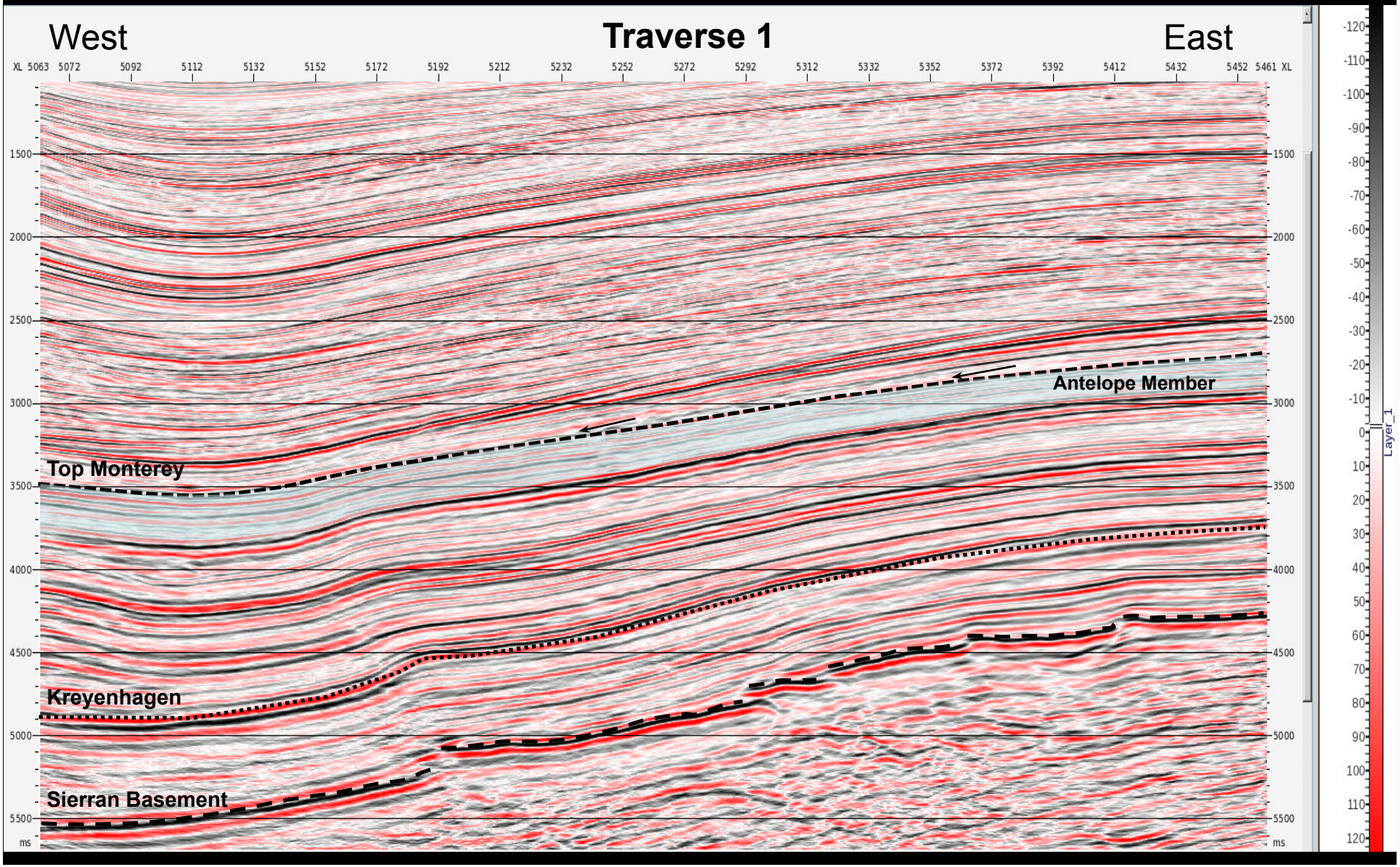
Geokinetics



Buttonwillow
Depo-center



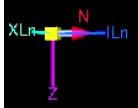
KTK 3D
Kern County, California



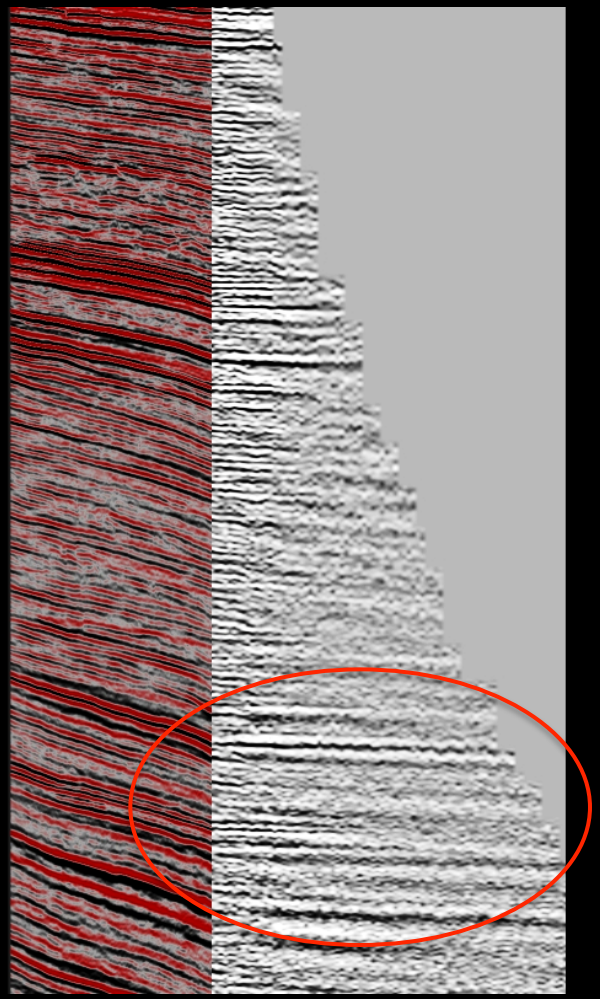
KTK 3D
Kern County, California

Geokinetics

OVT gather showing HTI



1 sec

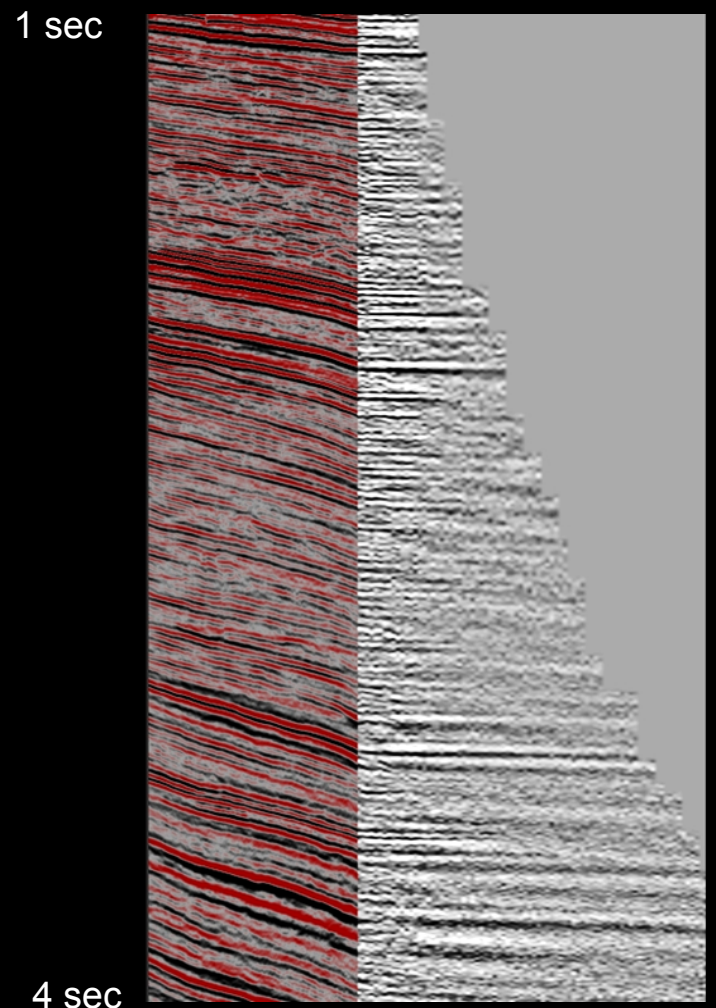


4 sec

KTK 3D
Kern County, California

Geokinetics

OVT gather with HTI removed

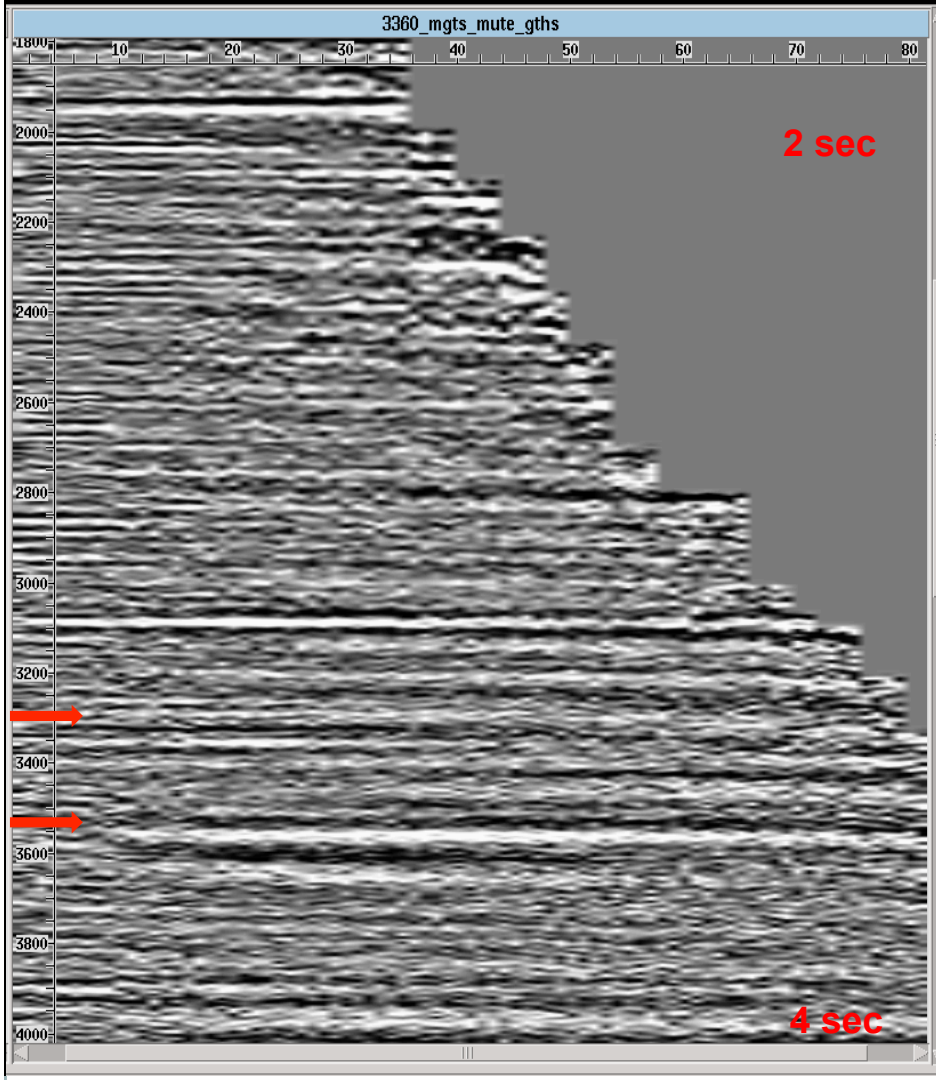
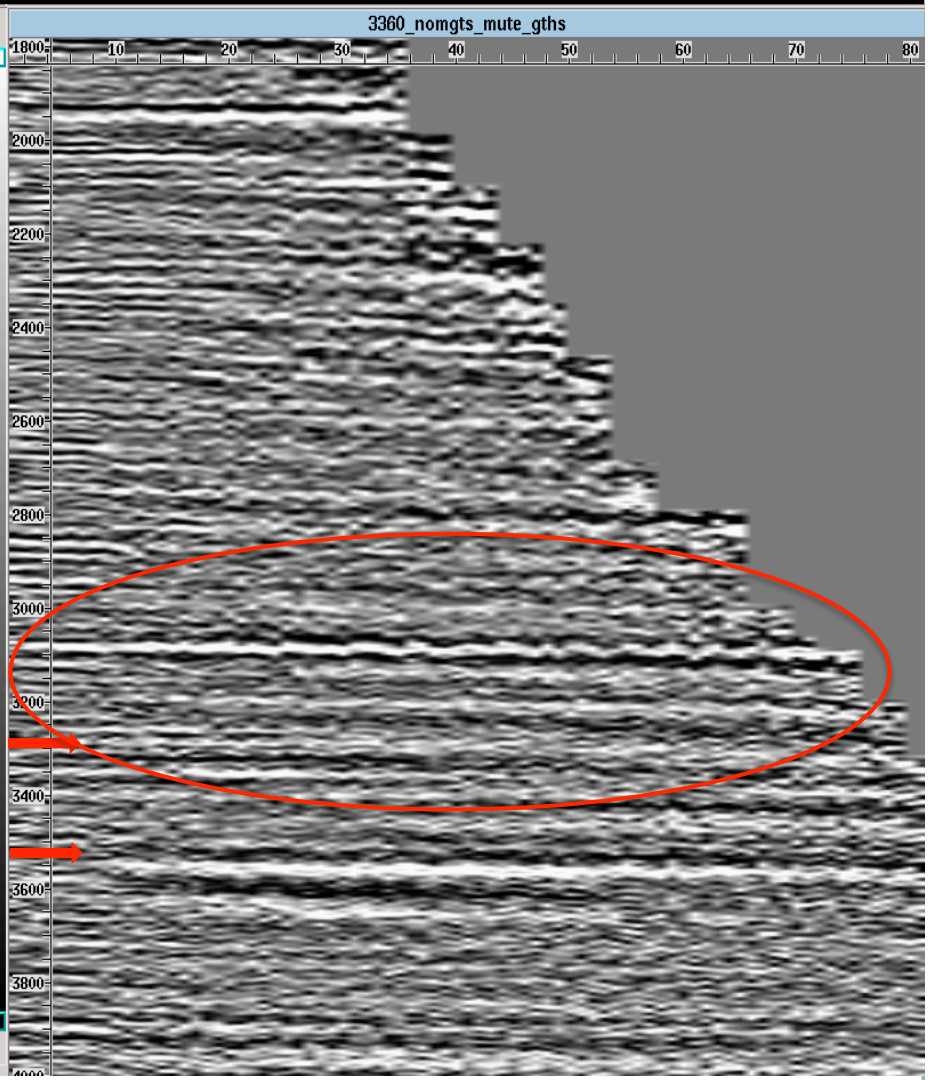


KTK 3D
Kern County, California

Geokinetics

OVT gather

HTI removed mute applied



HTI preserved – mute applied