[AV]Success Factors for Effective Subsurface Imaging of Overthrust Belt Legacy Seismic Data*

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Summary

In recent years 3-D pre-stack depth migration (PSDM) has changed industry's perspective on subsurface imaging of seismic data in areas of complex geology. By defining an *accurate* interval velocity model and 3-D pre-stack imaging in depth, the opportunity to more fully exploit the hydrocarbon potential of these difficult areas is greatly enhanced. There is an abundance of legacy seismic data sets available to industry today for re-evaluation. However, the design of many of these existing surveys does not always fully lend itself to the more rigorous re-examination demanded by depth-imaging methods. This article discusses a seismic reprocessing program intended to assess deep gas potential in a mature producing province with very complex overthrust geology using the PSDM method. The challenges presented by these vintage seismic 3-D data in a complex structural velocity regime is discussed and how leveraging external well and geologic information overcame the limited sensitivity of the available 3-D seismic data.

Introduction

The targeted area is a major gas field discovered in 1978 that has been producing large quantities of gas in the Overthrust Belt of Utah/Wyoming. The geology is characterized by significant structural distortion due to severe thrusting in the area as well as the presence of a variable thickness salt layer in the shallower section. The primary objective for this project was to aid in the economic assessment of deeper levels between 17,000 and 19,000 ft in this complexly faulted overthrust regime by clarifying uncertainties in the depth structure before committing to an expensive deep well test. Earlier phases of time and depth processing had not resolved the structure. Favorable industry gas pricing provided the motivation to revisit the deeper targets to identify additional gas reserves applying a state-of-the-art PSDM and velocity model-building solution to approximately 45 square miles of 1998 vintage seismic data based on:

- Uncertain structural extent
- Complex geology
- Variable salt layer in overburden
- Presence of rapid lateral velocity variations.

Geologic Overview

Tectonic movement in the Overthrust Belt of the Rocky Mountains of Utah/Wyoming has occurred over many miles along the Absaroka Thrust, creating major structural distortions of the Mesozoic and Paleozoic rocks below a Tertiary overburden. The area has produced around 1 TCFG with estimated ultimate recovery of 500 MMBOE (Powers, 1995) from the pre-Tertiary sedimentary section, generally below 10,000 ft from surface. The main field is a combination structural-stratigraphic trap with the primary existing reservoirs in the Mississippian Mission Canyon formation, composed of interbedded dolomite, limestone, and anhydrite running along the crest of an anticlinal closure. The rocks are typically well consolidated sandstones and limestones with a Jurassic salt layer of variable thickness present above the producing layers. There is a good distribution of wells centered along the main porosity zone structure but very limited well presence to the east.

Seismic Acquisition and Pre-processing

The 3-D data volume for this project was acquired over 45 square miles in 1998 using dynamite as source. The area is typified by rough topography and elevations ranging from 6500 ft to 8200 ft ASL. The 3-D acquisition provided a nominal 24 fold, 82.5 x 165ft data volume. Because of the acquisition geometry, the fold distribution exhibited zones of higher trace density. Offsets were available up to 17,000 ft. Inspection of the offset distributions, however, showed that there was frequently clustering of offsets and restricted offset ranges within bins, with implications for velocity sensitivity.

Effective PSDM processing requires good quality pre-processed data. Careful attention to noise reduction and removal of the variability introduced by the near-surface conditions in the area provided the basis from which a depth-imaging solution could be initiated.

Model Building Process and Issues

Once the near-surface and careful pre-processing were satisfactorily completed, an iterative tops-down PSDM workflow (Figure 1) was developed to progressively establish the upper layer velocities and horizon positions before moving deeper to define the next series of formations. This proposed workflow assumed that the initial velocity model would be high-graded using residual curvature (velocity) estimates in the model updating process at progressively increasing depth intervals for convergence on a final depth-interval velocity model. After several early iterations targeting the top 10,000 ft – 15,000 ft of the geologic section, several issues were identified that affected the stability of the imaging results.

- The interval velocity regime (Figure 2) in this highly consolidated rock environment is “fast”, typically in the 16,000 ft/sec range or greater.
- In the shallower section, because of the field acquisition geometry, only irregular sampling of the full source-receiver offset range was available to assist the velocity estimation process. Additionally, there were inconsistent distributions of offsets within and between subsurface positions resulting in varying sensitivity to velocity from position to position.
- The fast velocity regime results in low curvature across the offset range for large velocity variation (i.e., only small residual moveout error represents large velocity variation).

The net effect was that residual curvature (velocity) estimates from seismic image gathers were relatively insensitive to velocity change, compromising the ability to converge on a stable depth-interval velocity model from the available legacy data.

Following identification of this particular geology/acquisition interaction, an alternative strategy for velocity modeling and updating was pursued. This approach was highly constrained by available geologic and well data with seismically derived updating only included where it was *strongly* and *consistently* supported by the subsurface data. At each stage, a close tie to known formation tops would act as a primary criterion for velocity model accuracy. Available well data tended to be clustered in an approximately north-south trend along the crest of the major structure. For the subset of wells with both good quality check shot and formation top data available in the vicinity of the PSDM prospect area, interval velocities were derived between the major horizons of interest. With these interval velocity profiles, a “keep it simple” modeling approach was adopted with strong adherence to the well-derived interval velocity trends except where strongly and consistently contra-indicated by the seismic. This approach was especially helpful in reducing the high variability experienced in the early velocity models and providing guidance in areas of no/low well control; e.g., to the east.

With this modeling strategy, interval velocities from wells were intersected with horizons interpreted from the seismic PSDM volumes at each stage. After each iteration, data were assessed for image quality, tie to formation top information, and curvature consistency with a horizon review/update of the model before the next iteration. With this strategy in place, the PSDM process proceeded rapidly through a series of iterations to produce the final PSDM volume. An early Base Tertiary iteration was followed by iterations to Twin Creek, Base Weber, and Absaroka with a final full iteration to maximum depth.

Results

The final volume based on the geology-constrained modeling approach exhibits good image quality (e.g., Figures 3 and 4). It closely tied key formation top data within this Overthrust Belt project area and exhibited good reflector continuity in the primary zones of interest. In addition to tying available well data, confidence in the accuracy of the volume was reinforced by the stability of the deeper section (Absaroka and below) where the reflection energy in the final depth volume closely matched the known regional attitudes of these beds. The stability and geologic plausibility of the final result is evident versus the implausible reflector topography seen in the early iterations. We believe that the final velocity model used in this project contains the essential information for an accurate subsurface image in depth across the project area.

Conclusions

The velocity model-building solution developed for this project using well-derived interval velocities between the major formation boundaries as a constraint to define a narrow range of velocities allowed this greatly reduced parameter space to be explored systematically with a small number of pre-stack depth migration iterations. The method successfully overcame the dilemma of data insensitivity to velocity and provided good convergence on the best-fit model that met project objectives in this difficult subsurface imaging area. Thus, with an awareness of key success factors, effective subsurface depth imaging using legacy data sets is a very practical option. These success factors include:

- Keen awareness of the capabilities and limitations inherent in legacy data sets.
- Understanding the rocks.

- Information access and integration leverage of all available well, geologic, and associated subsurface data.
- Continuous interpreter involvement.

Acknowledgements

The authors acknowledge Chevron for permission to publish these results, and BP for the use of the data.

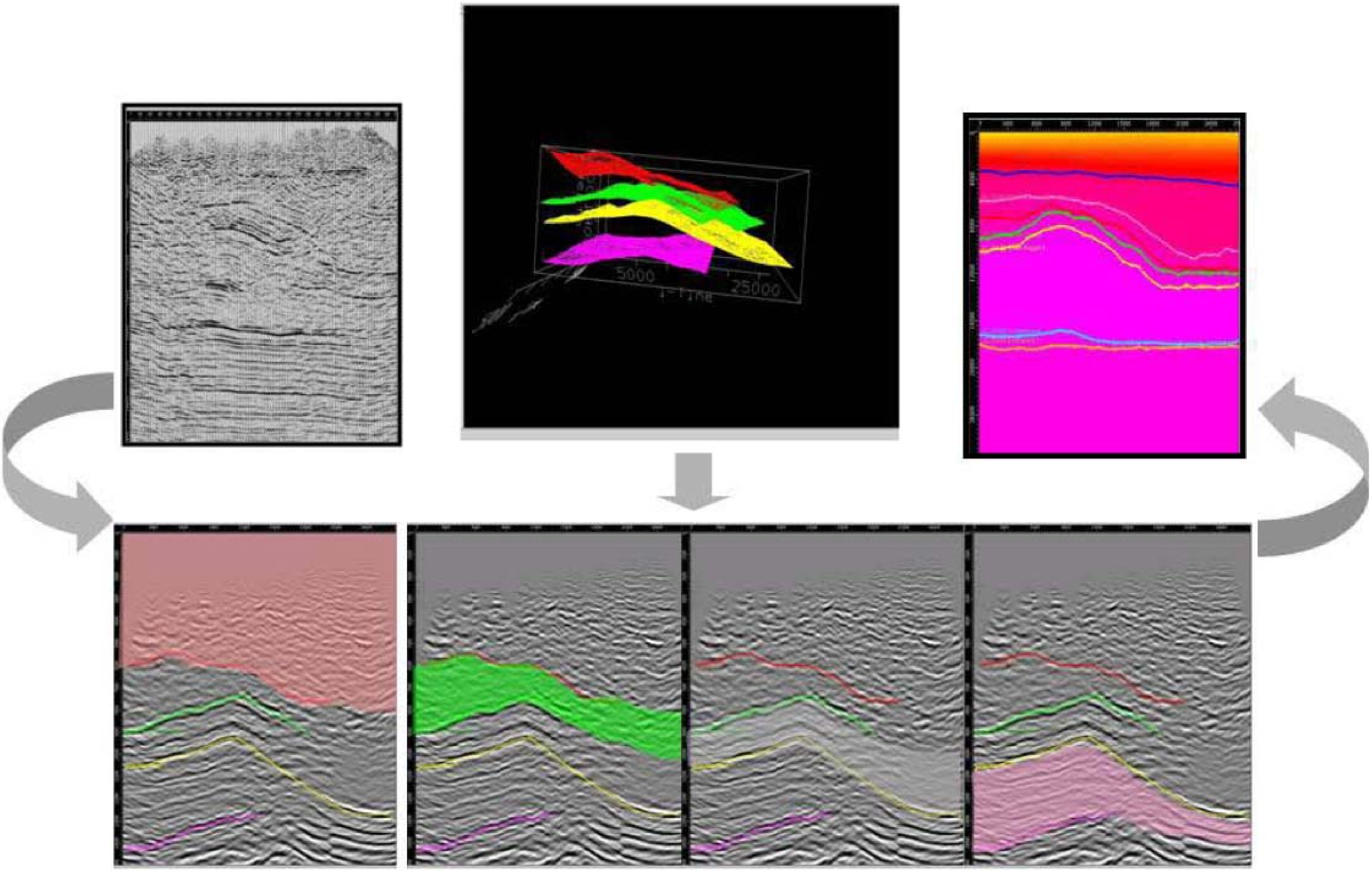


Figure 1. Proposed model-building strategy.

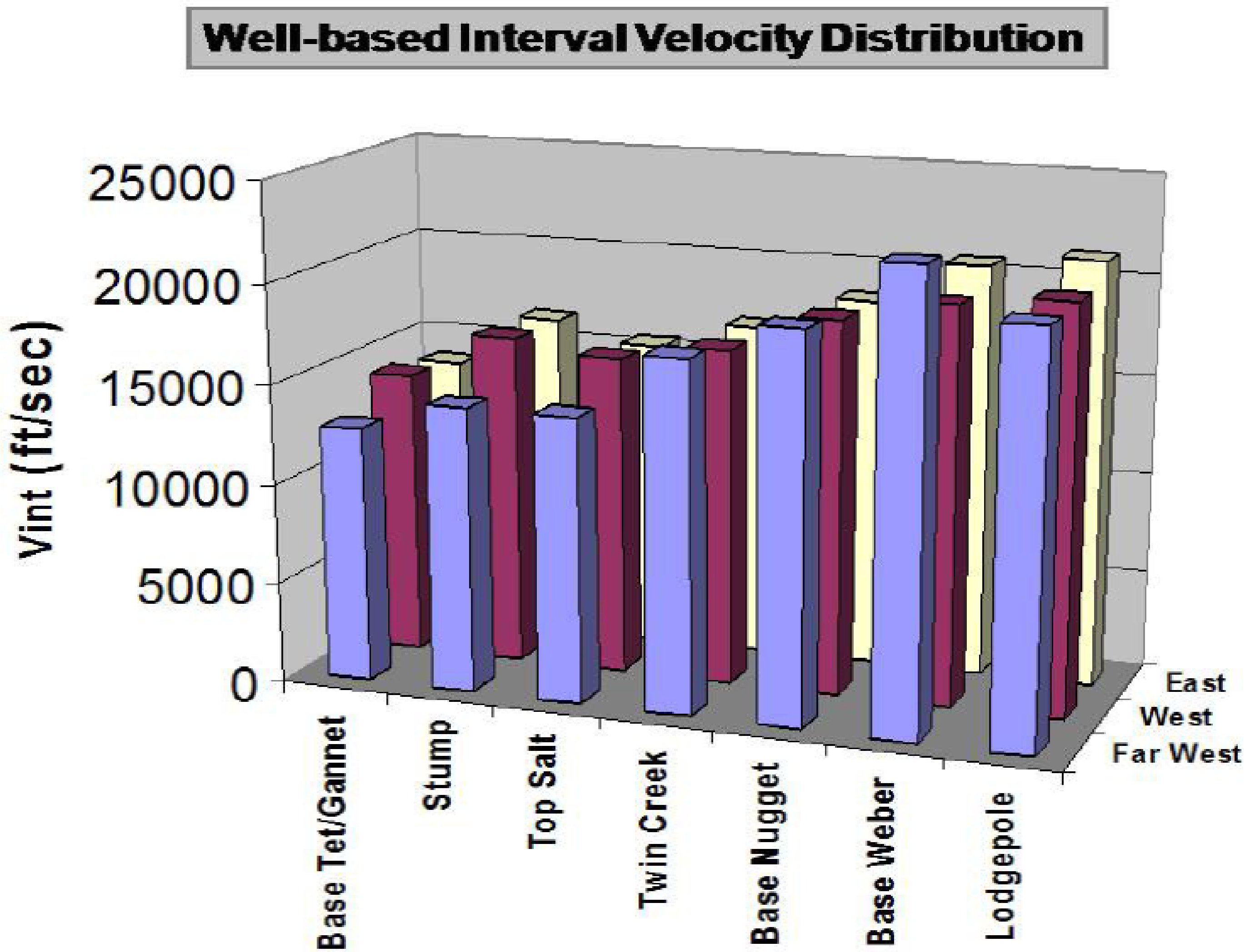


Figure 2. Interval velocity constraints.

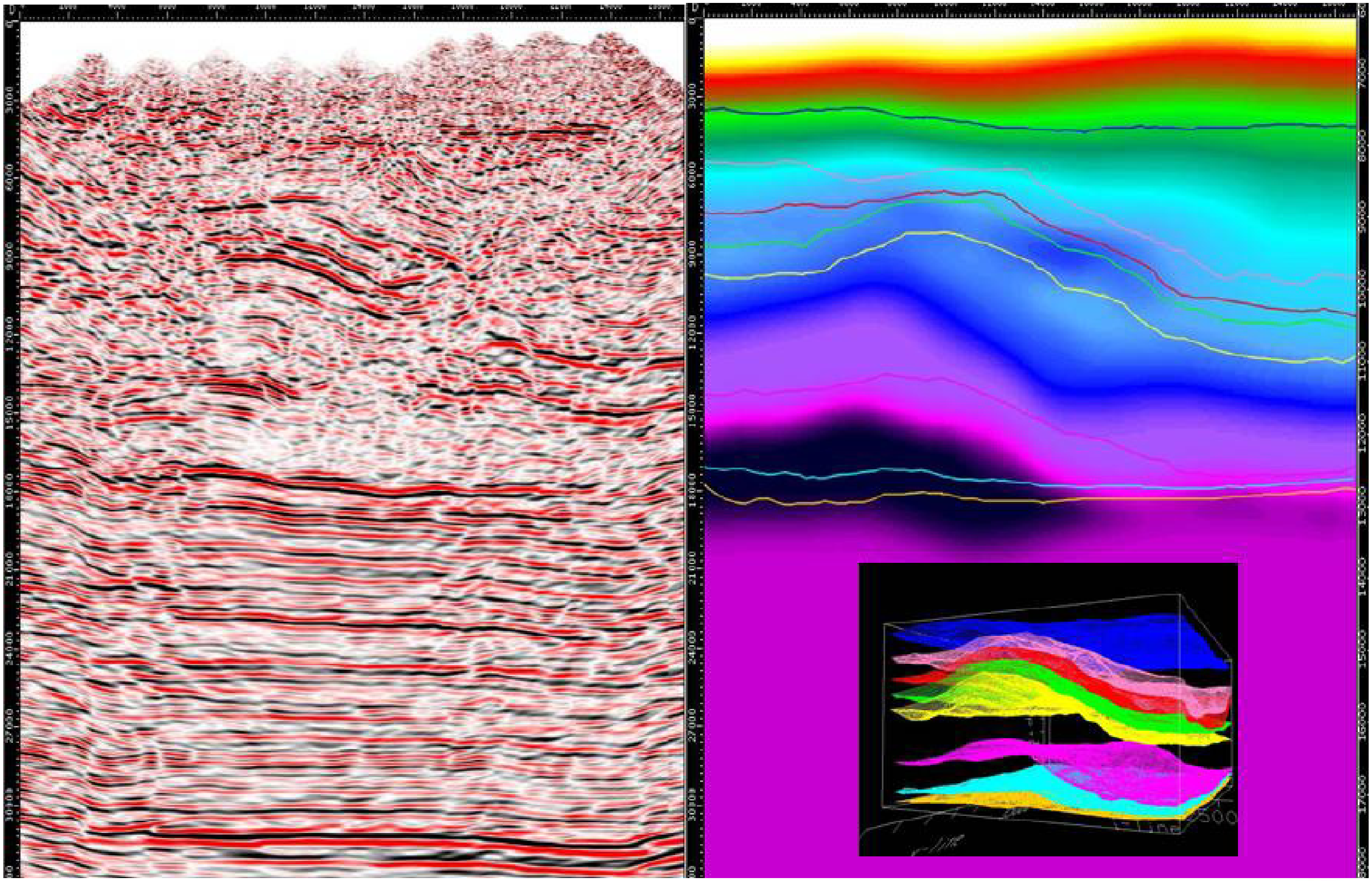
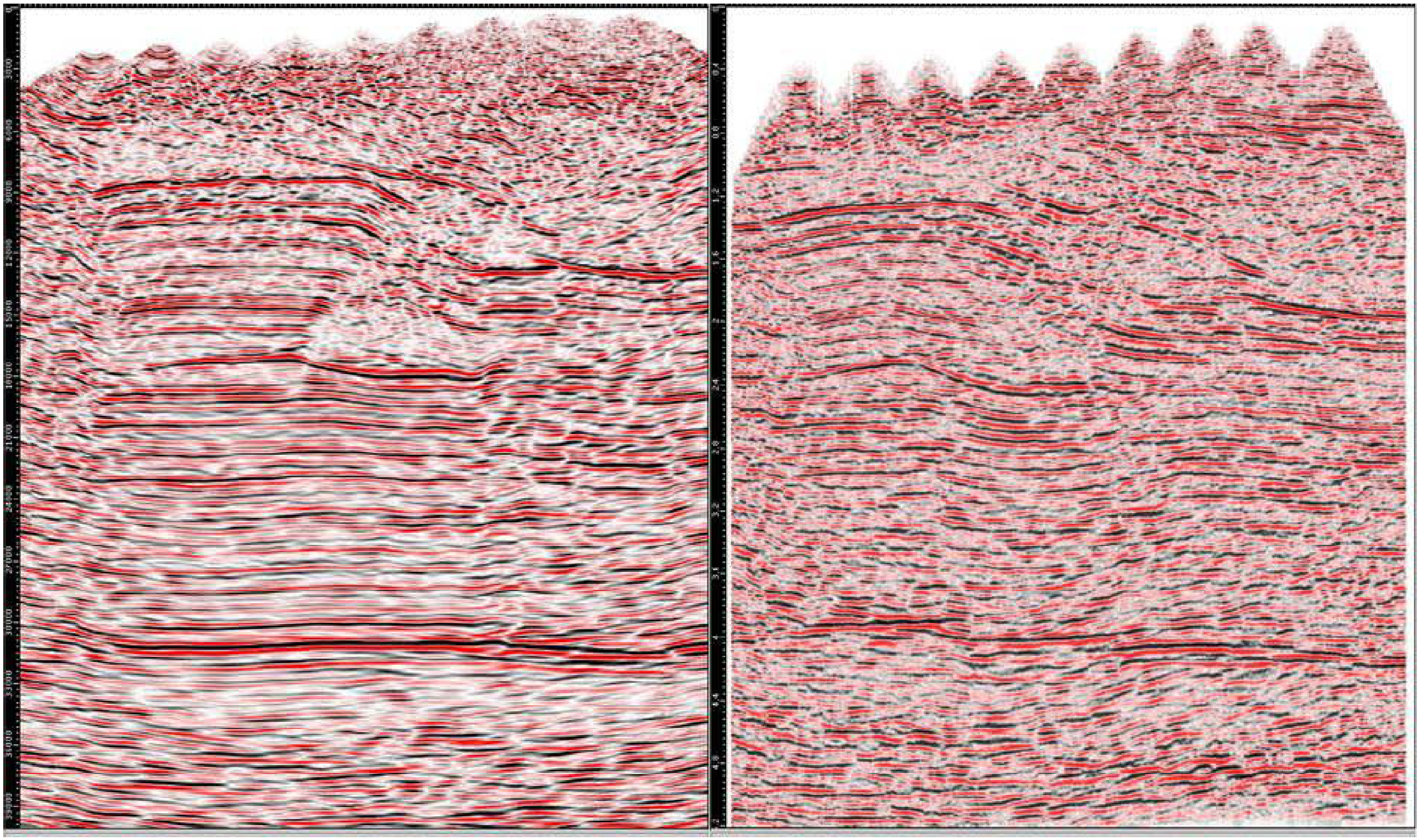


Figure 3. The model.



PSDM **PSTM**

W-E Line

Figure 4. Stable depth image versus time processing.

References

Powers, R.B., 1995, Wyoming thrust belt province: USGS 36. Web accessed 07/20/09 (http//certmapper.cr.usgs.gov/data/noga95/prov36/text/prov36.pdf)

Success Factors for Effective Subsurface Imaging of Overthrust Belt Legacy Seismic Data

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Legacy Data

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(Fast Rocks x Overthrust)

= Problem

Legacy Data

+

(Fast Rocks x Overthrust)

+

Well Information

+

Geology

= Solution

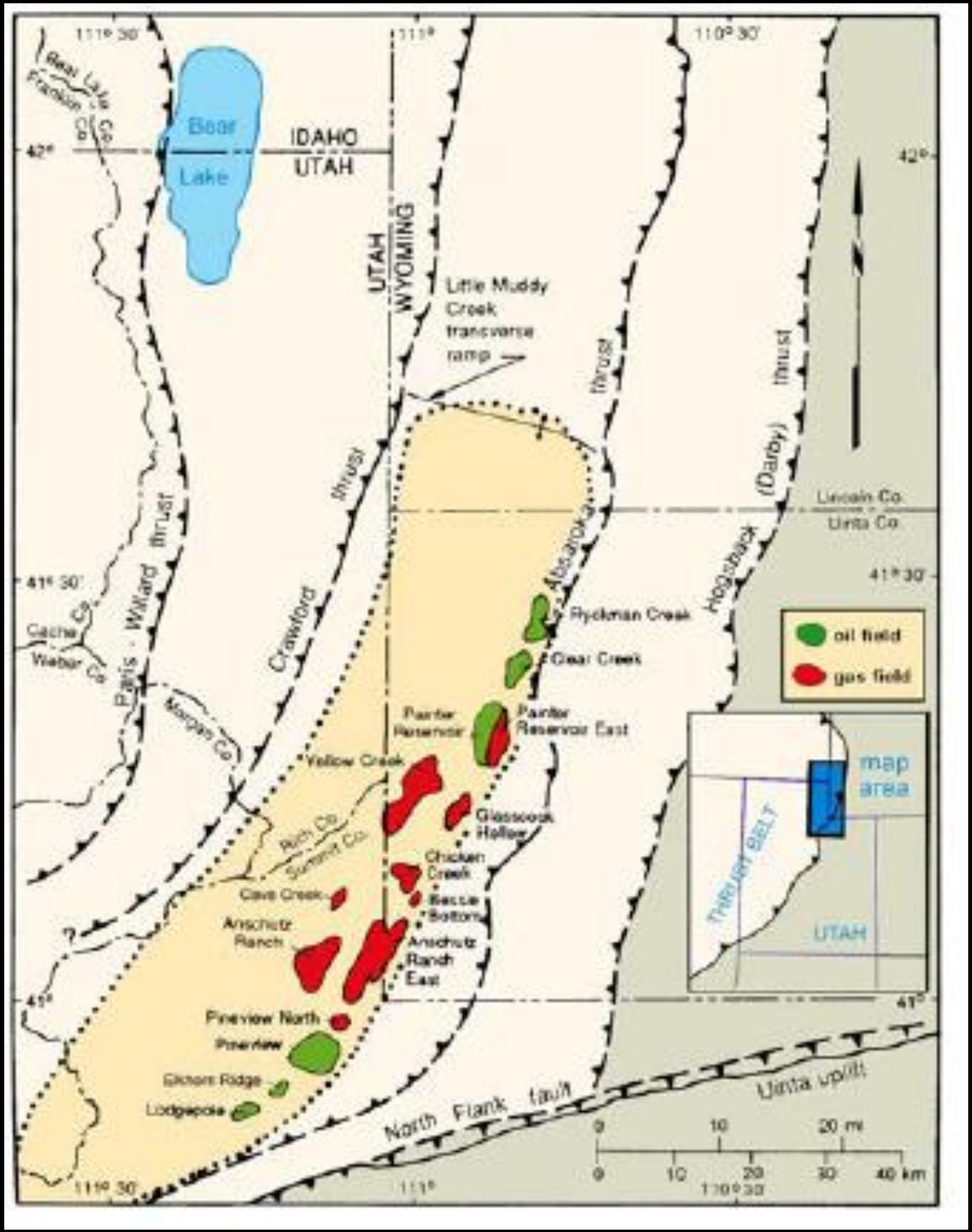
FUSION

Themes

- Know your seismic data – fit for purpose?
- Recognize the geologic regime
- Leverage all subsurface information
- "Keep it simple"
- Seismic + subsurface + interpreter = Success

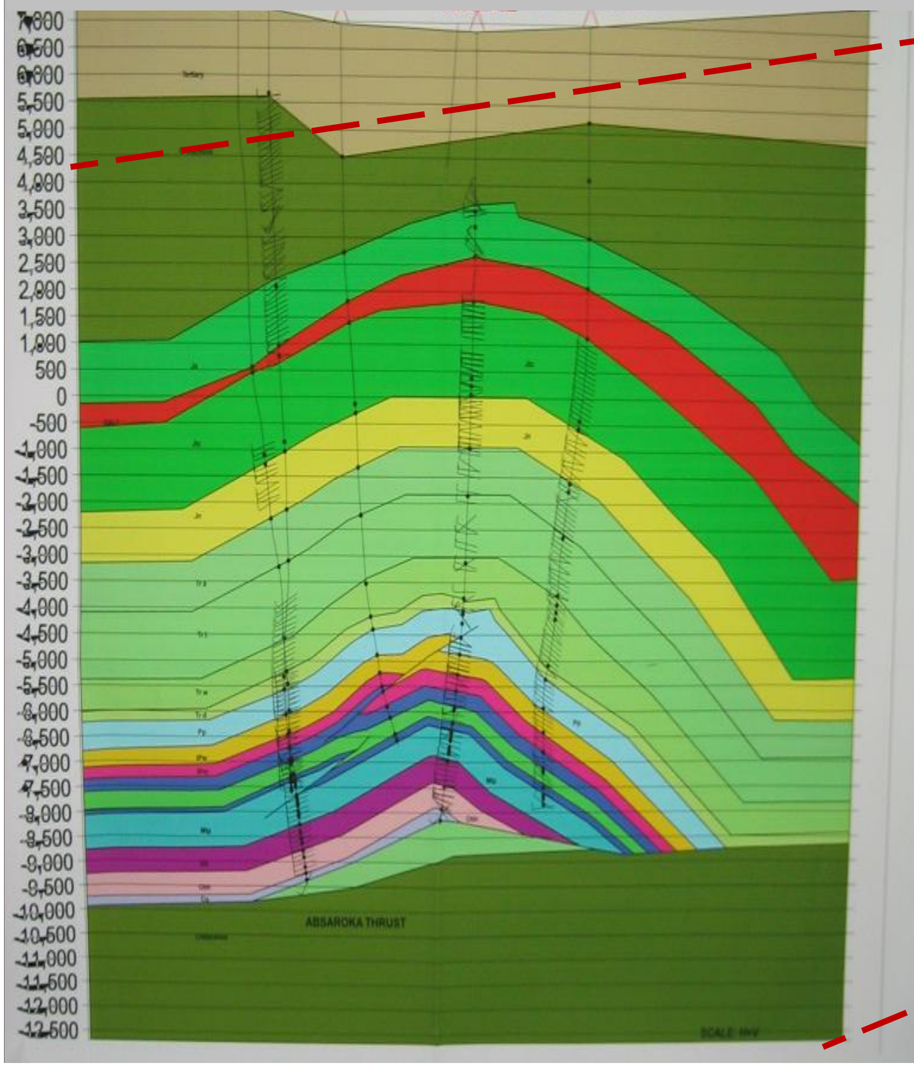
General Location

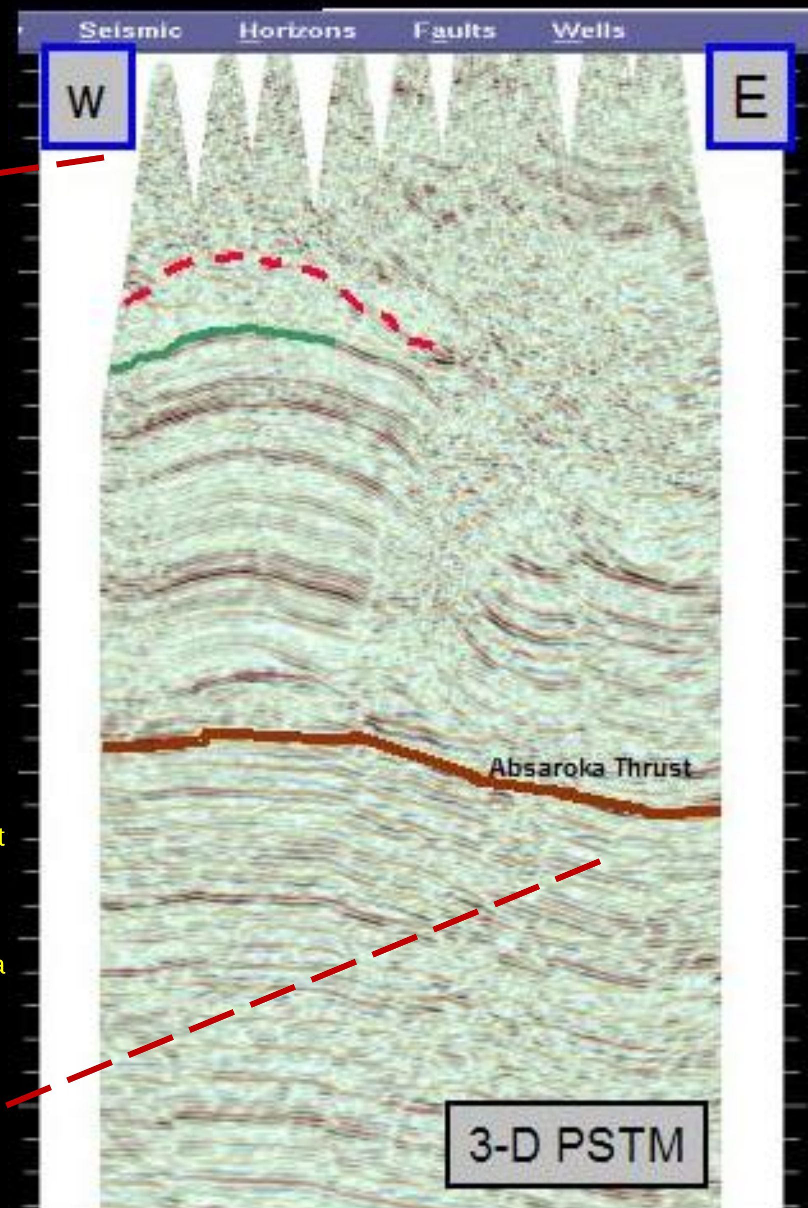
Utah/Wyoming Thrust Belt



Utah Geological Society

West-East Geologic Cross-Section





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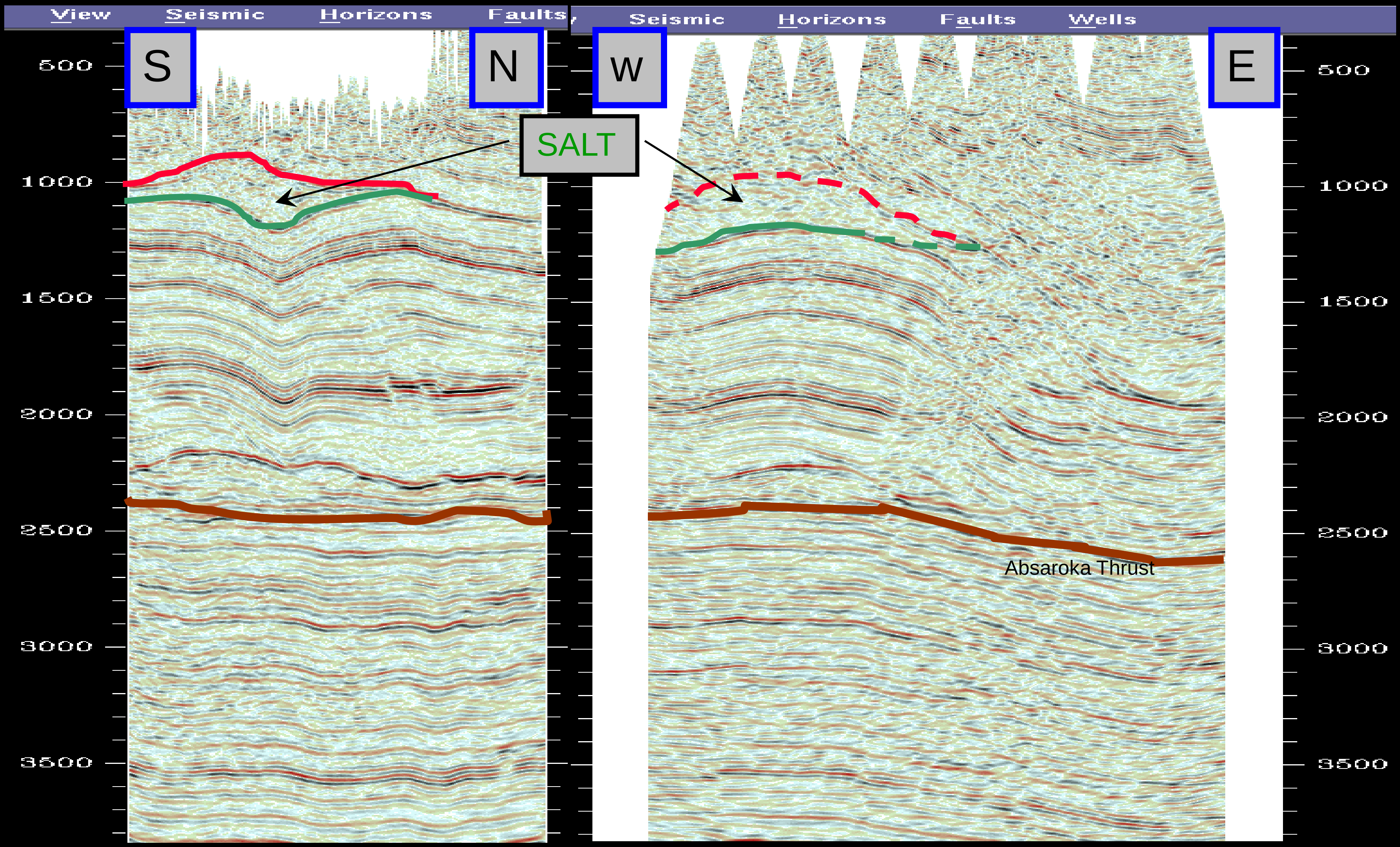
Representative X-sections - PSTM



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Project Objective

- Provide improved imaging and structural positioning in a complexly faulted overthrust regime for economic assessment of potential reservoirs below 17000ft in a major hydrocarbon-producing province

Depth Imaging Rationale

- Uncertain structural extent
- Complex geology
- Variable salt layer in overburden
- Presence of rapid lateral velocity variation

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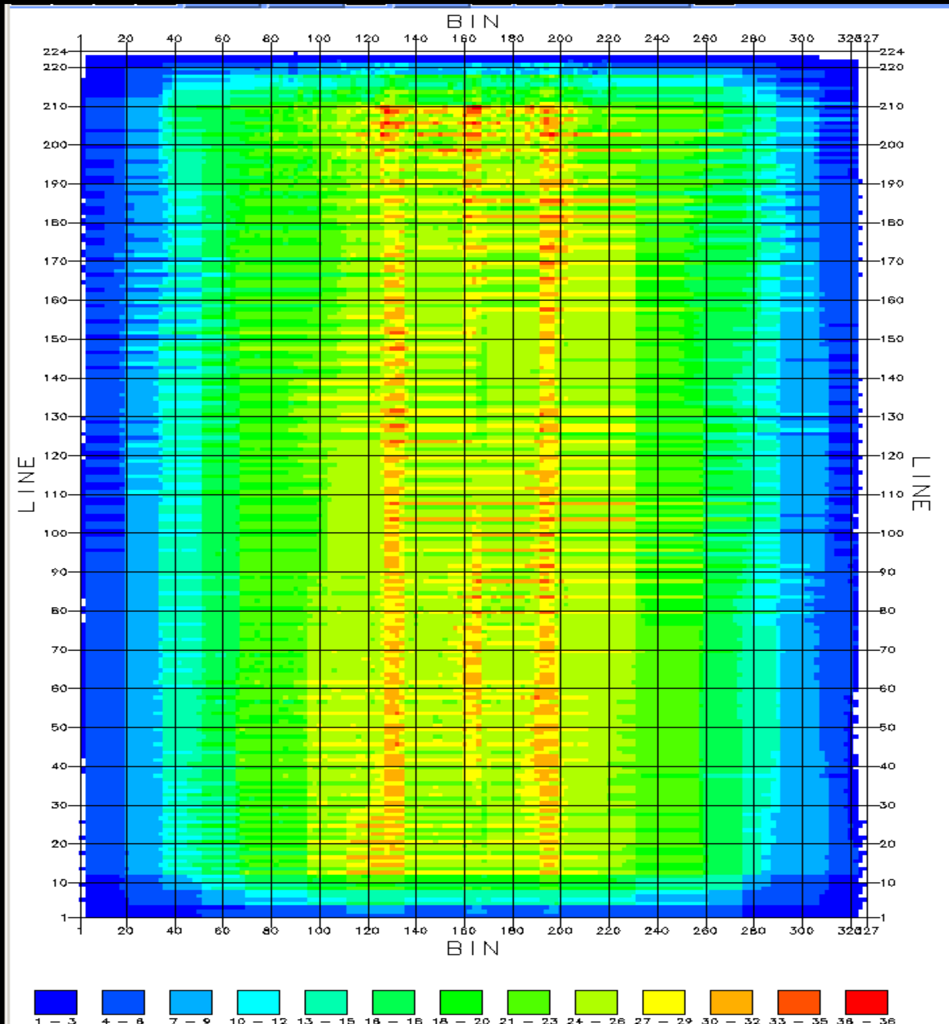


Fold

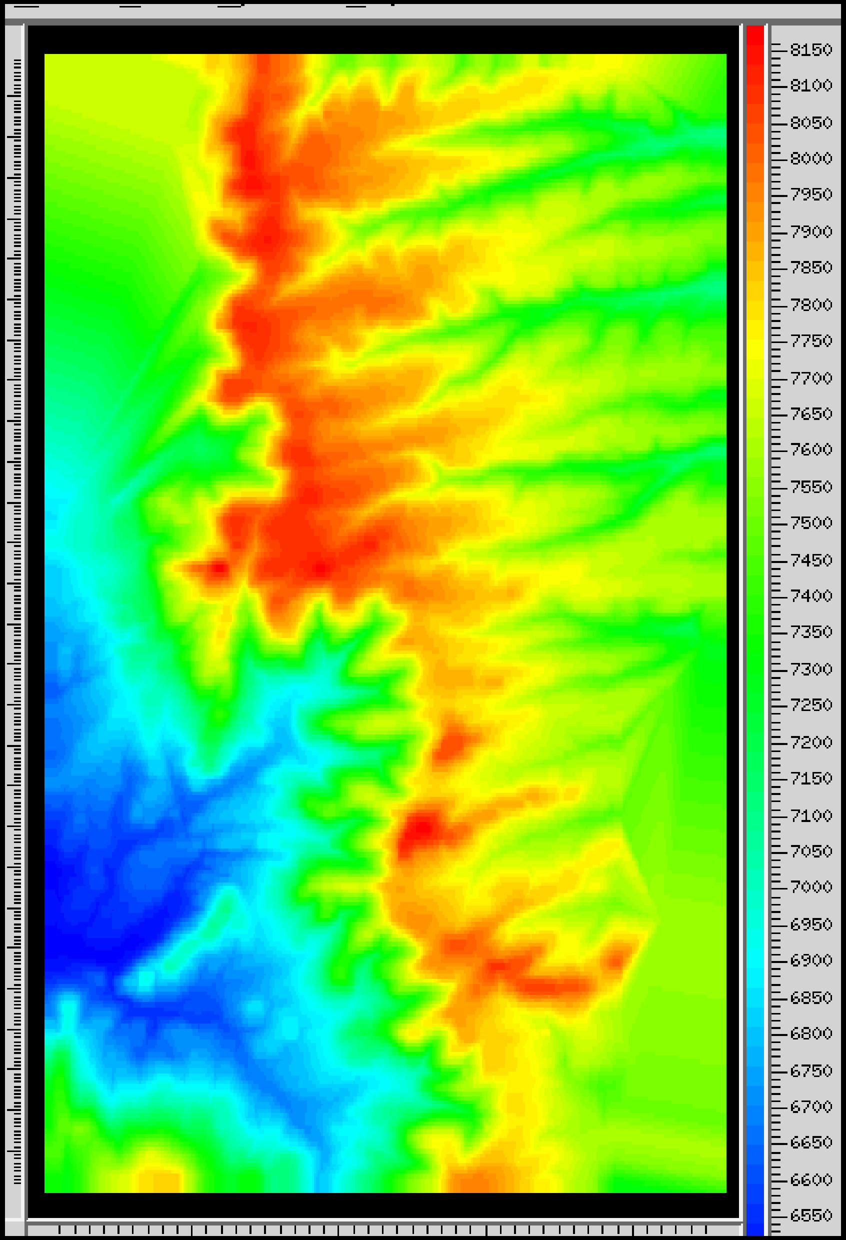
1998 3-D Acquisition

Dynamite

Max offset: 17000ft

Nominal fold: 24

Bin Size: 82.5ft x 165ft



Topography

from < 6500ft to > 8200ft)

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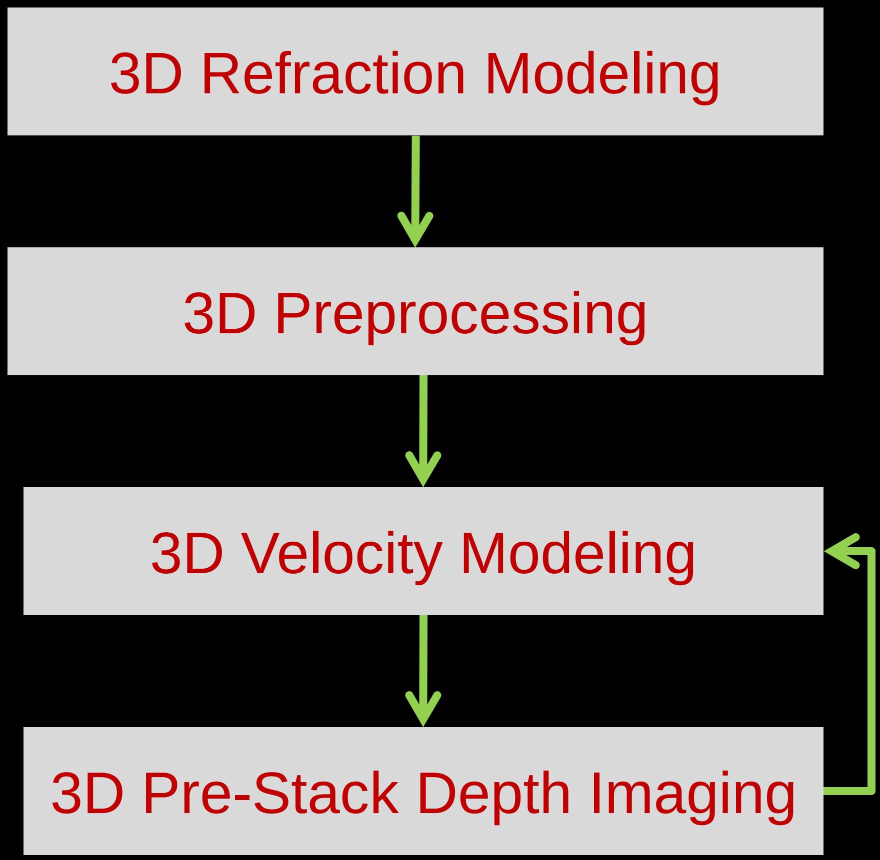
Processing Flow (simplified)



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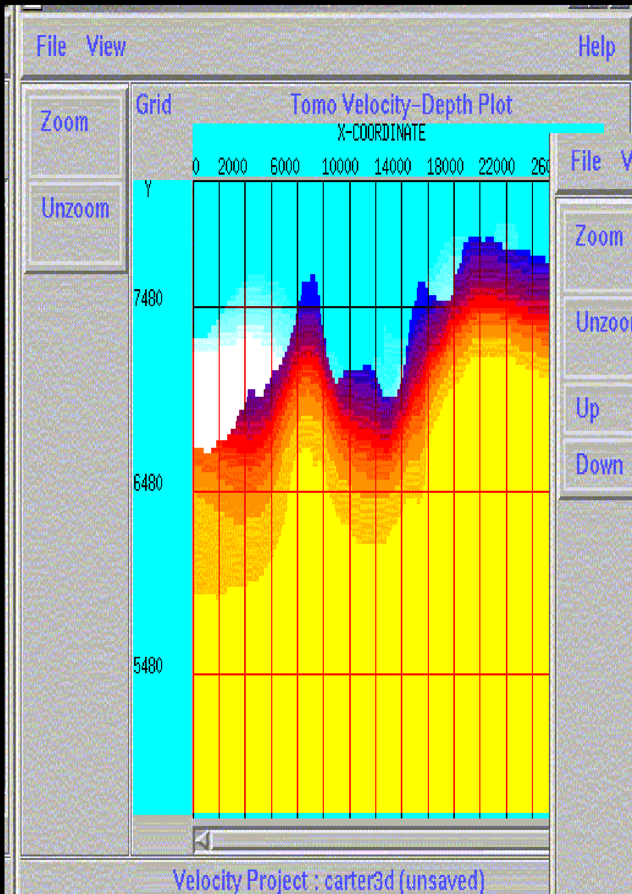
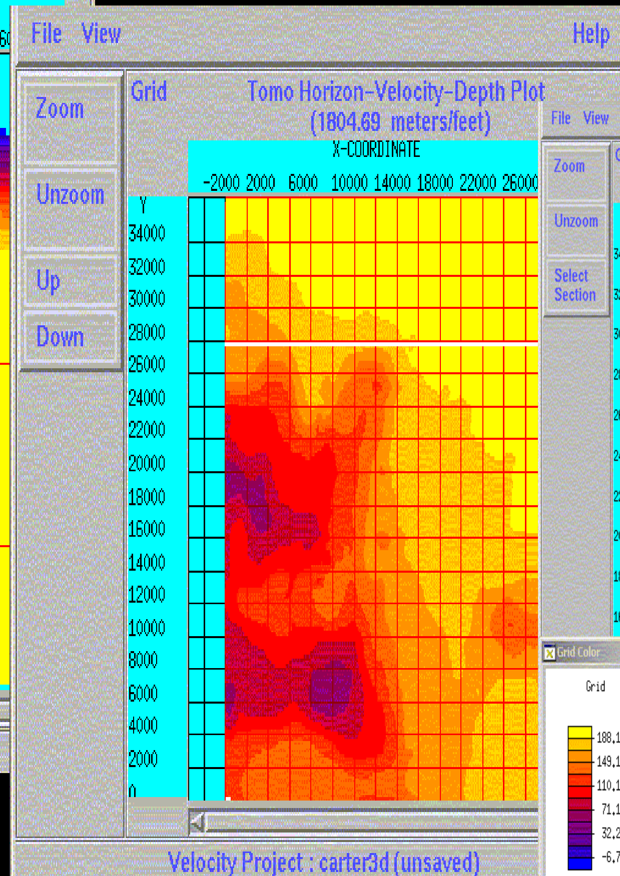
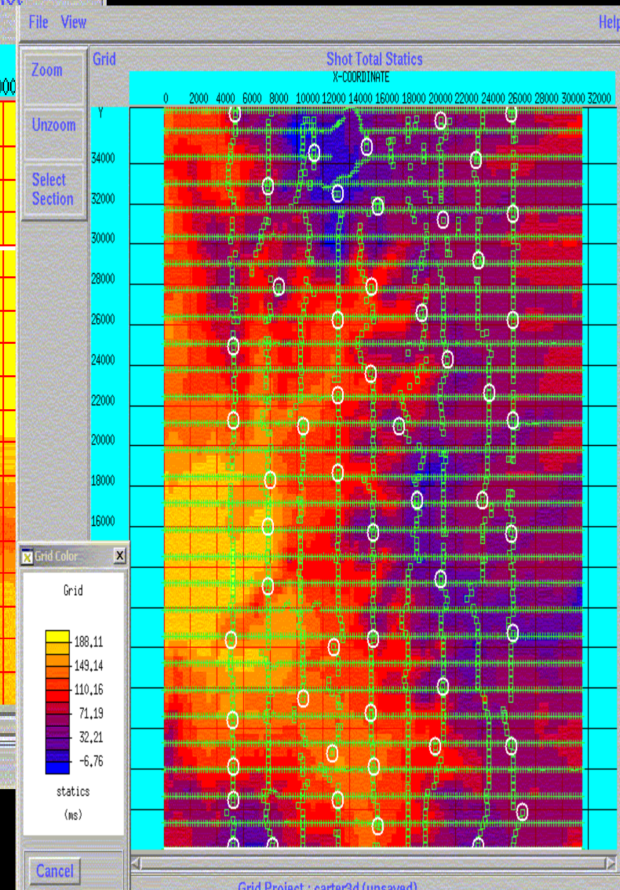


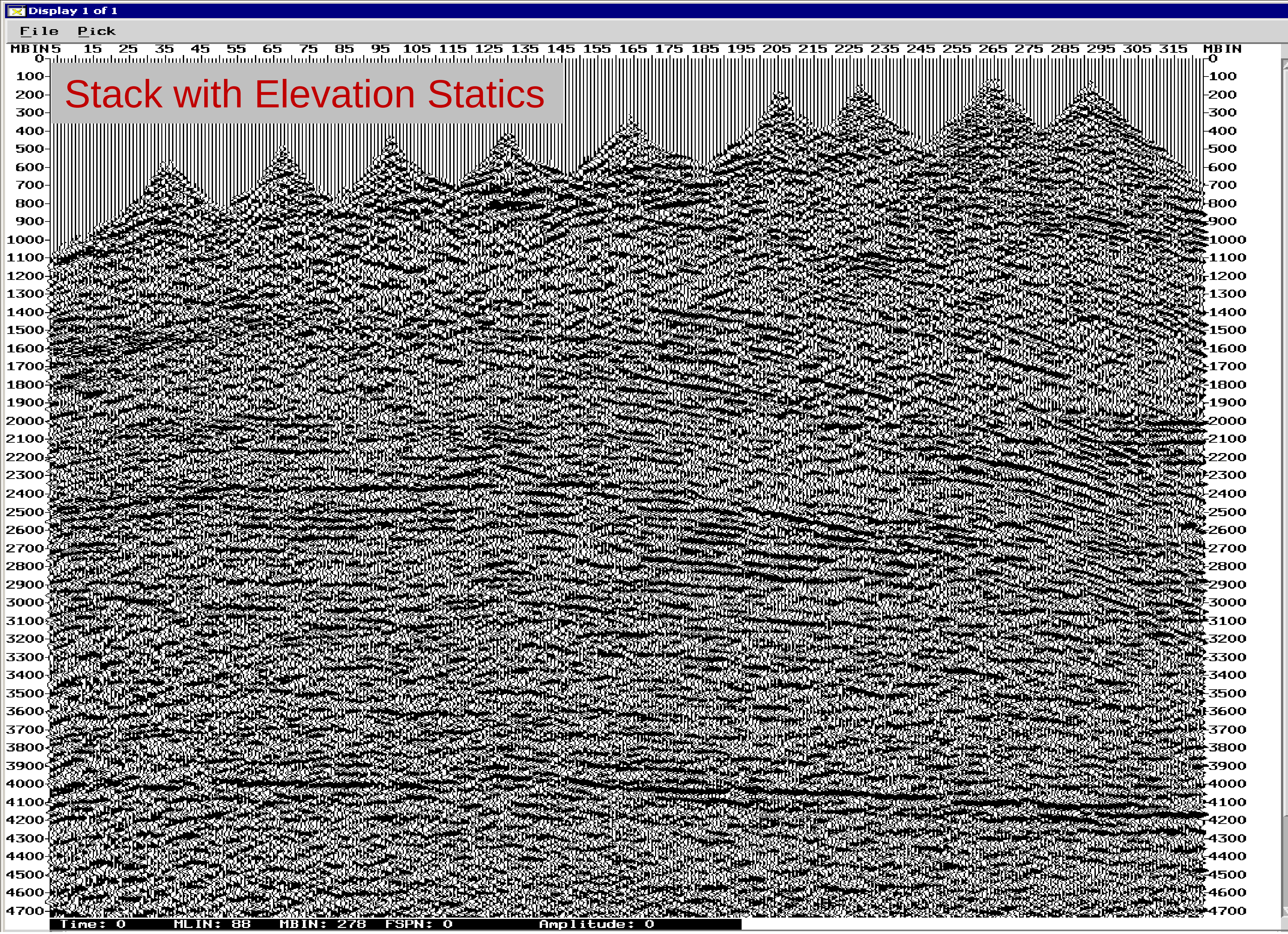
Refractor Depth Profile



Refractor Depth Map



Total Shot Statics Map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File Pick
MBIN 5 15 25 35 45 55 65 75 85 95 105 115 125 135 145 155 165 175 185 195 205 215 225 235 245 255 265 275 285 295 305 315 MBIN
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000 3100 3200 3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700
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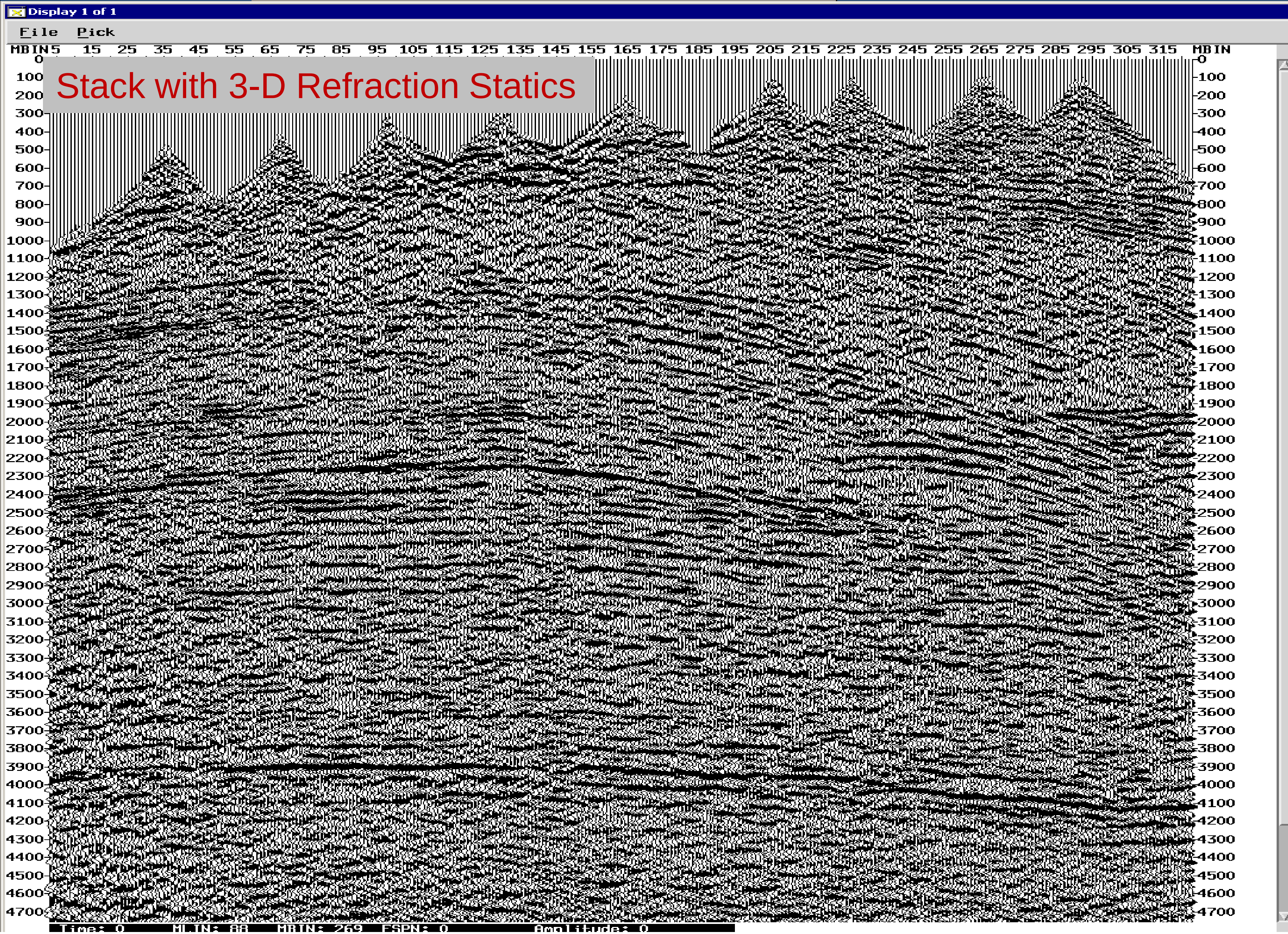
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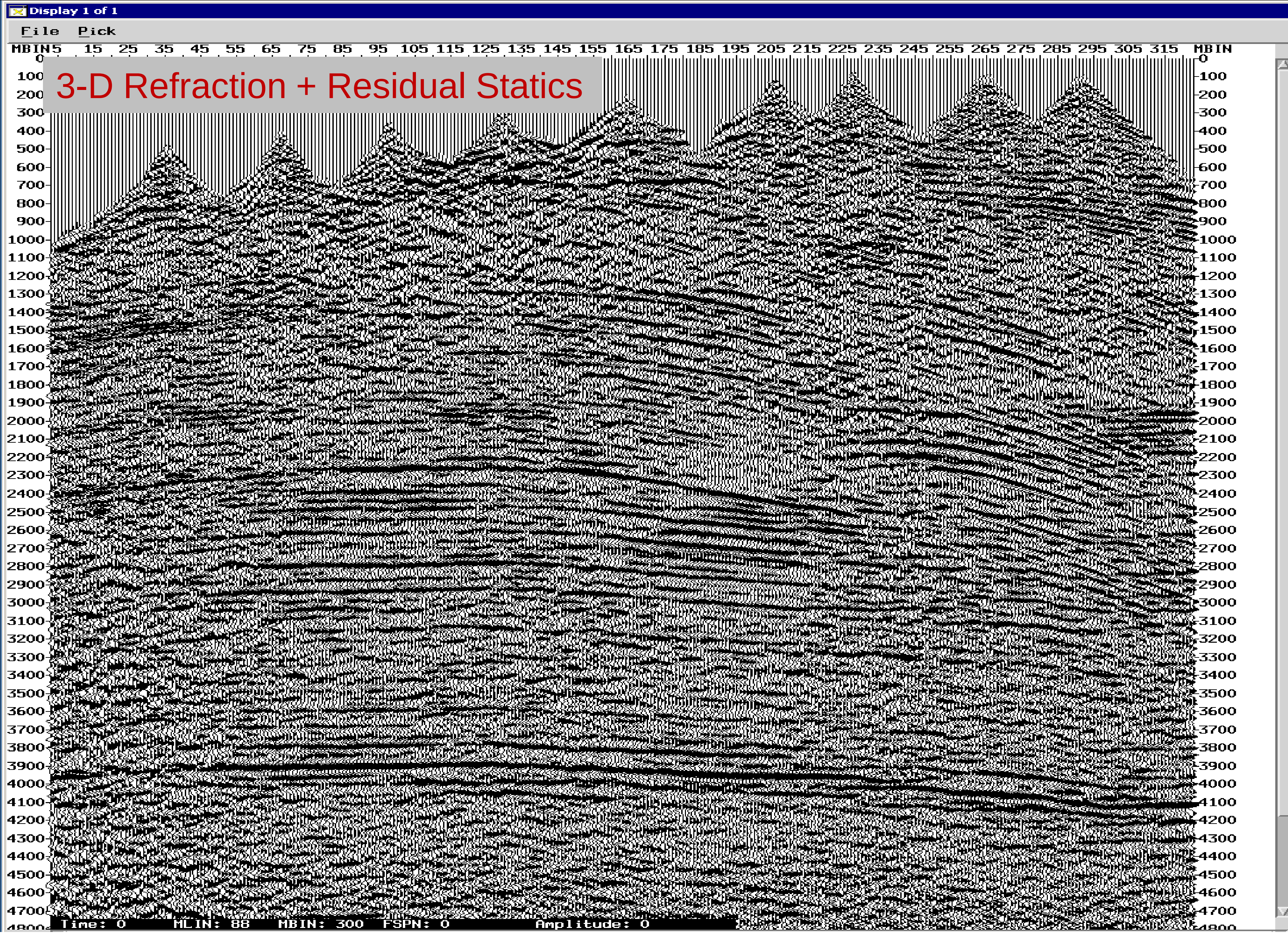
File
Pick
MBIN 5 15 25 35 45 55 65 75 85 95 105 115 125 135 145 155 165 175 185 195 205 215 225 235 245 255 265 275 285 295 305 315 MBIN
Stack with 3-D Refraction Statics
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000 3100 3200 3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700
Time: 0 MLIN: 88 MBIN: 269 FSPN: 0 Amplitude: 0


Display 1 of 1
File Pick
MBIN
3-D Refraction + Residual Statics
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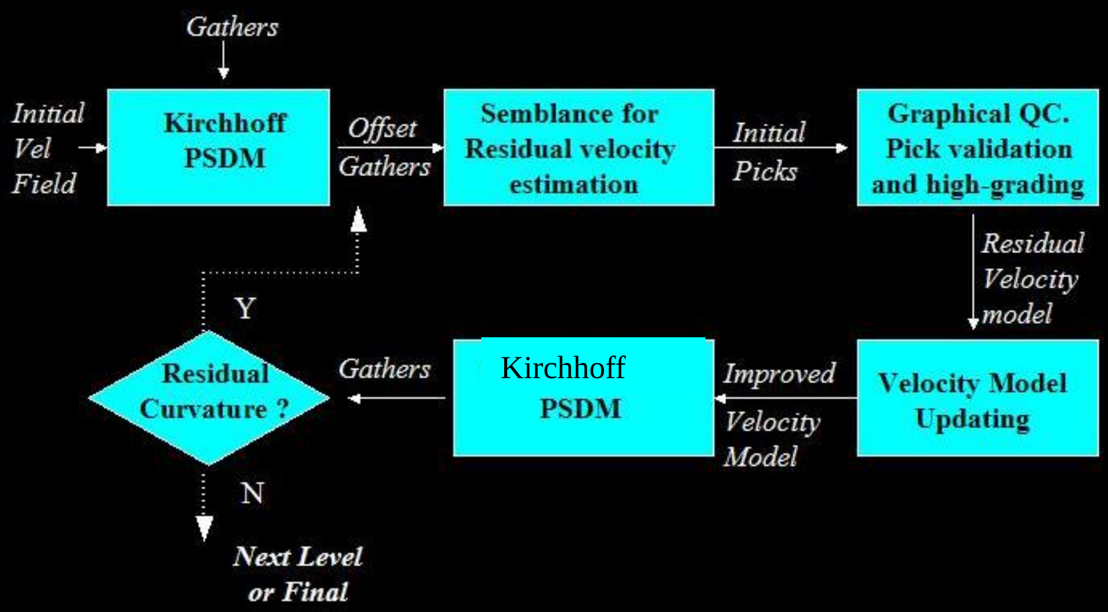
Planned PSDM Workflow



- Iterative tops-down process
- Progressively establish upper layer Vint – Z
- Initial model updated by CIG Semblance analyses
- Proceed to deeper level once satisfactory stability established
- At each level, calibrate with well data for depth fidelity

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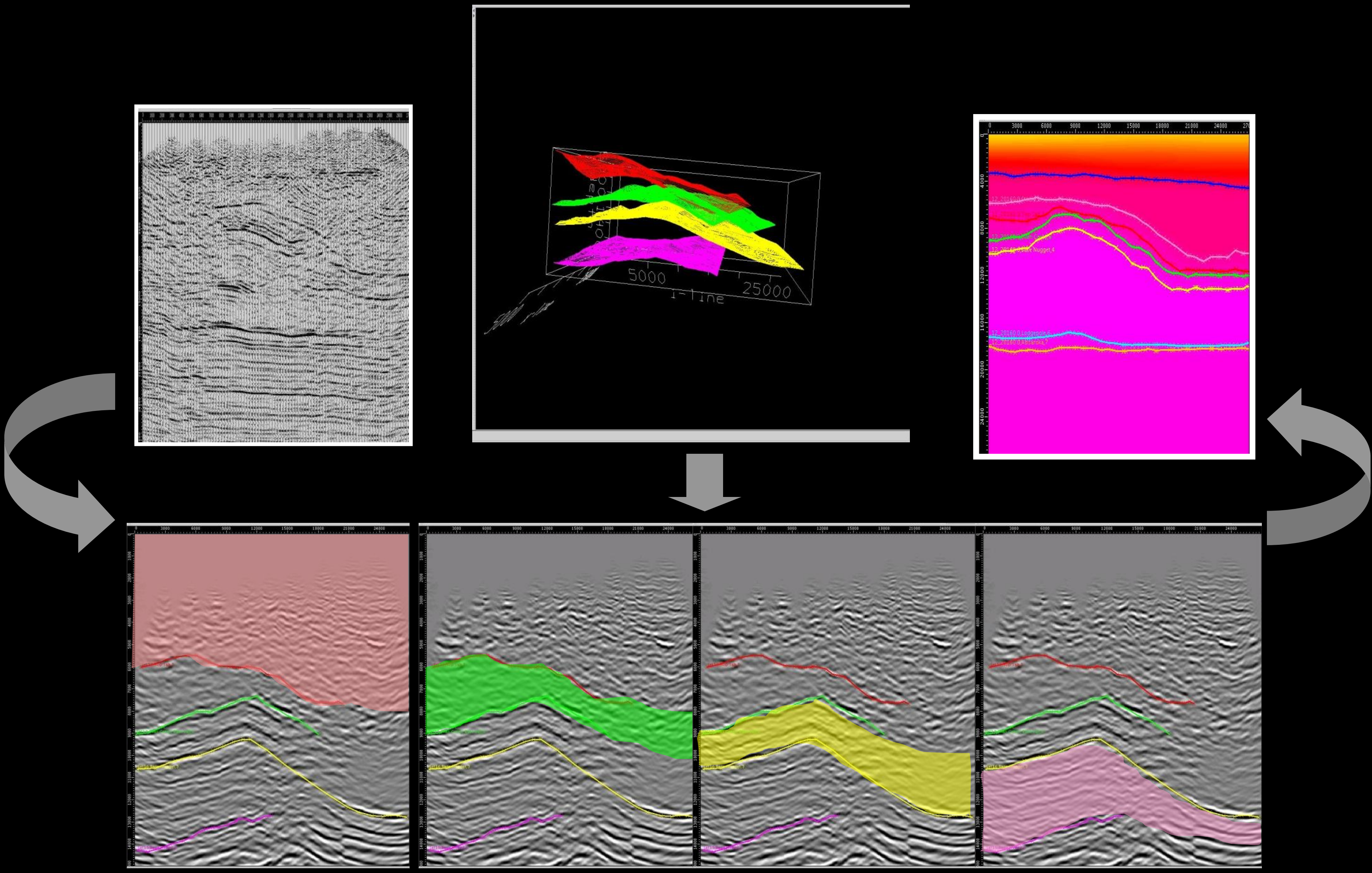

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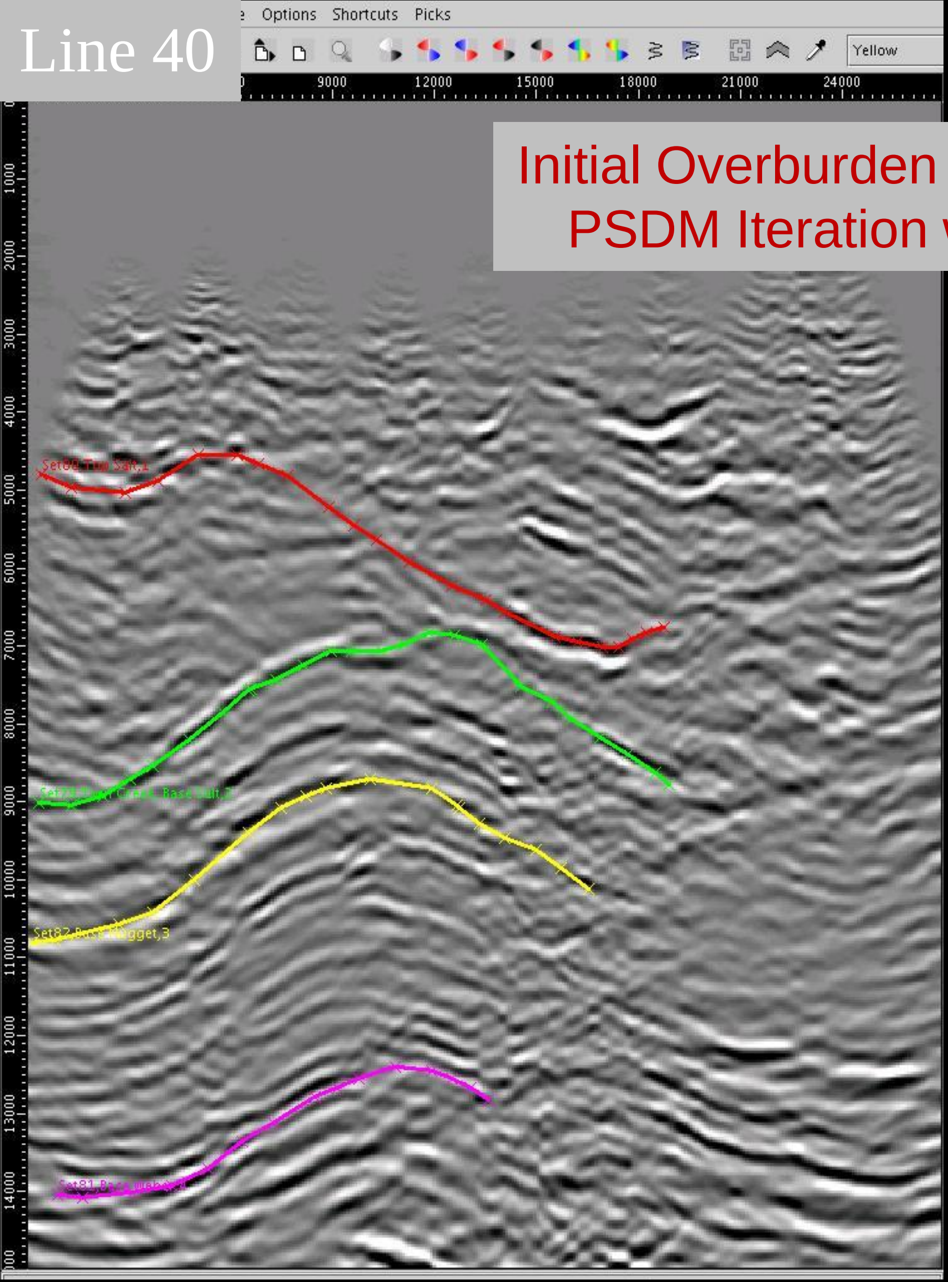
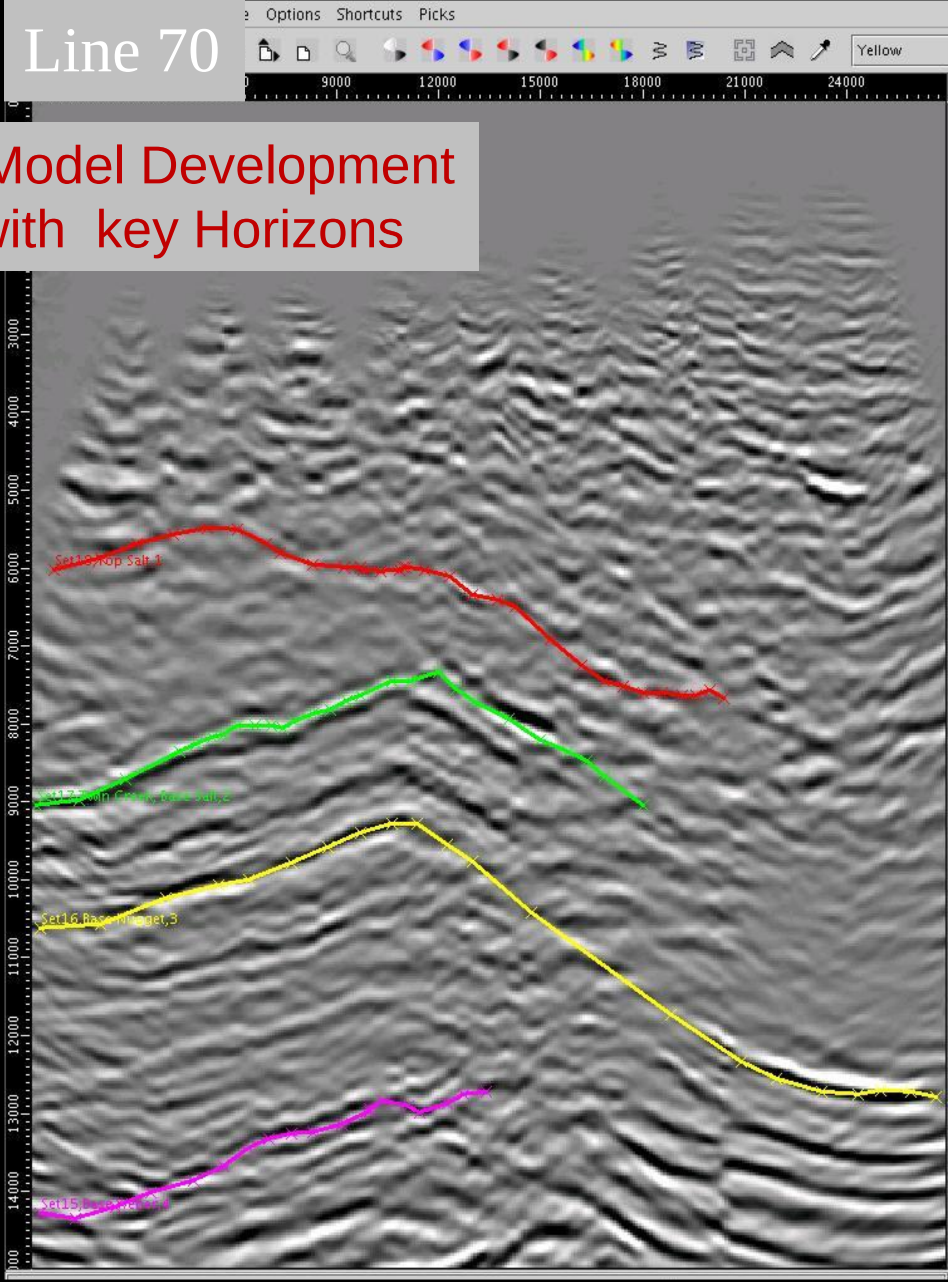
Initial Overburden Model Development
PSDM Iteration with key Horizons





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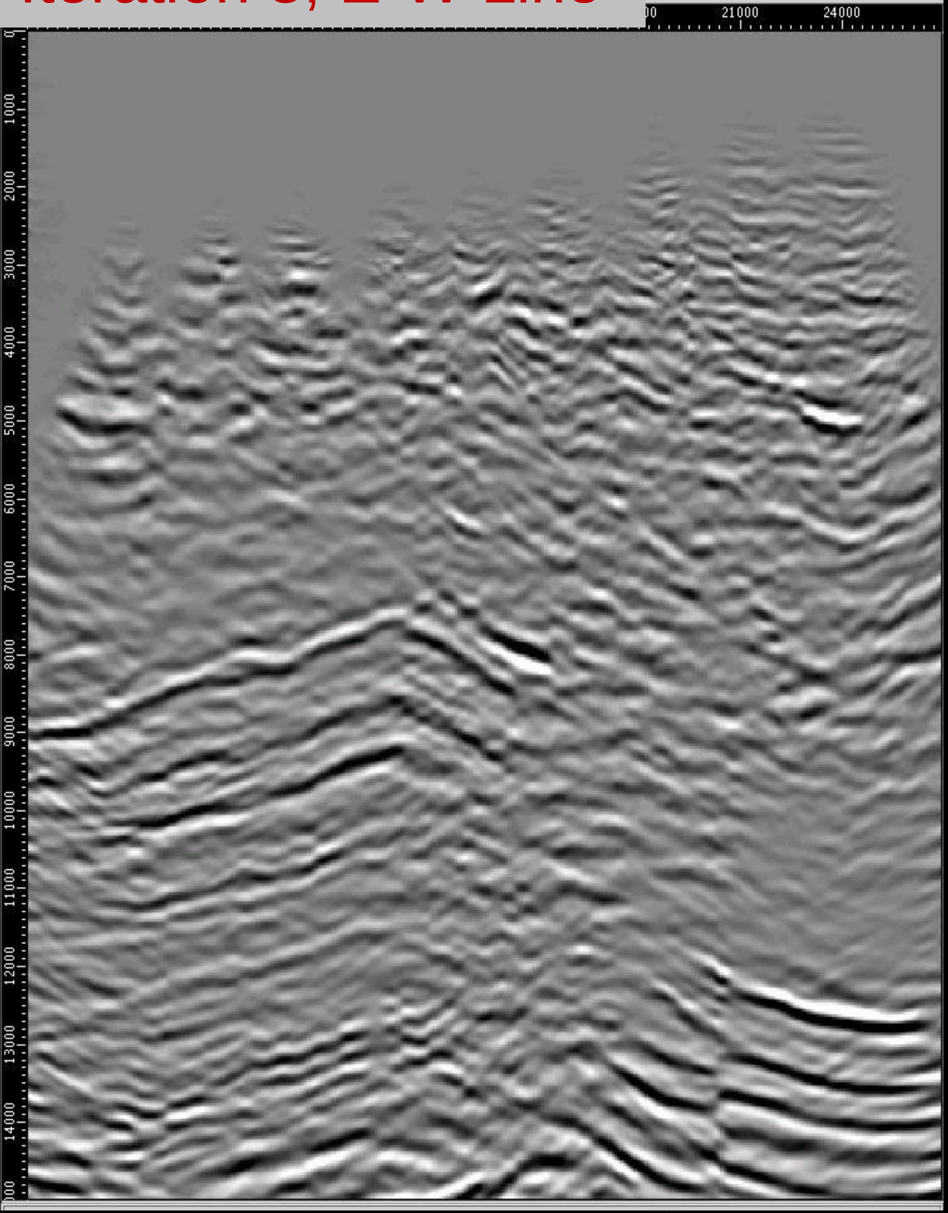
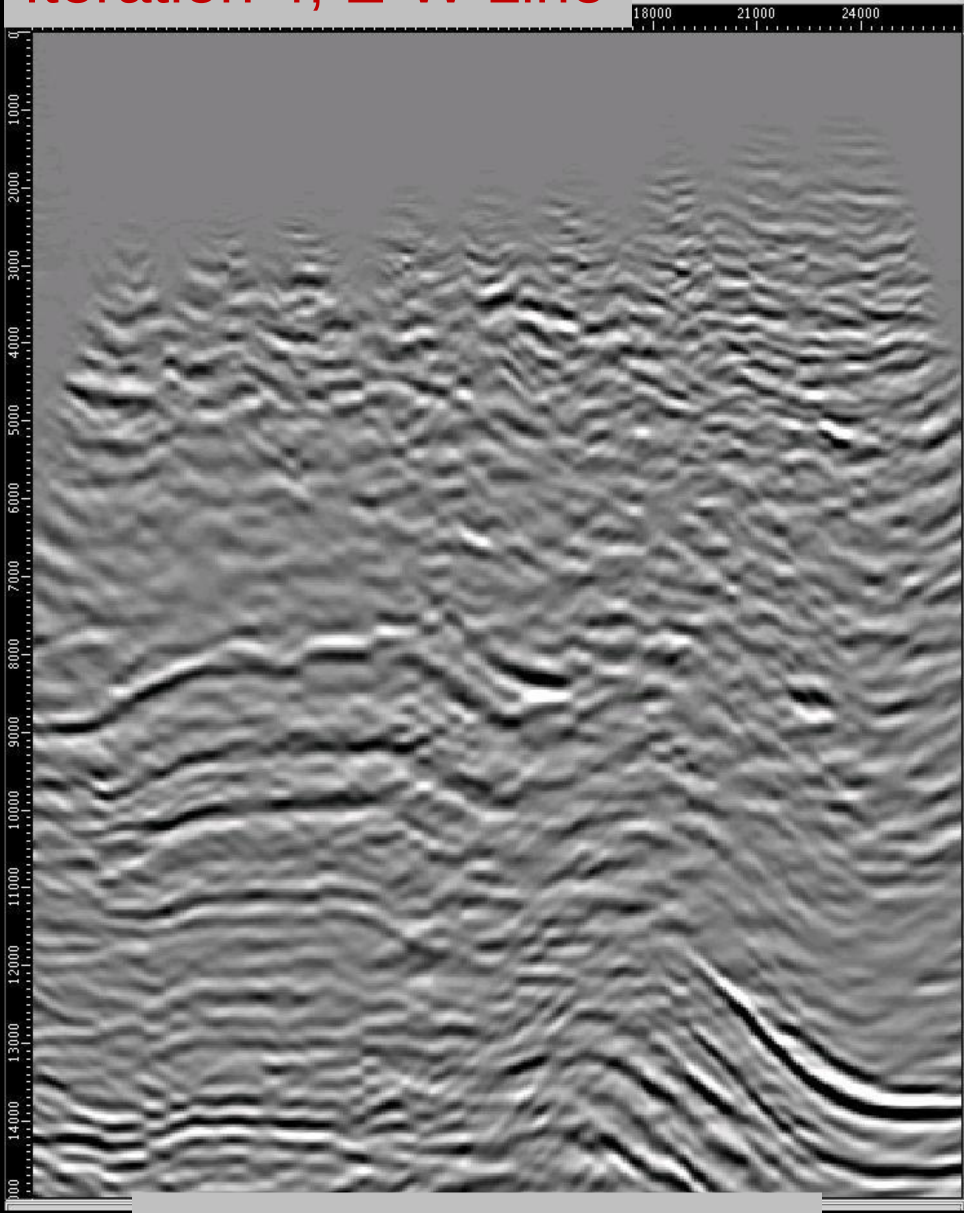
Iteration 3, E-W Line



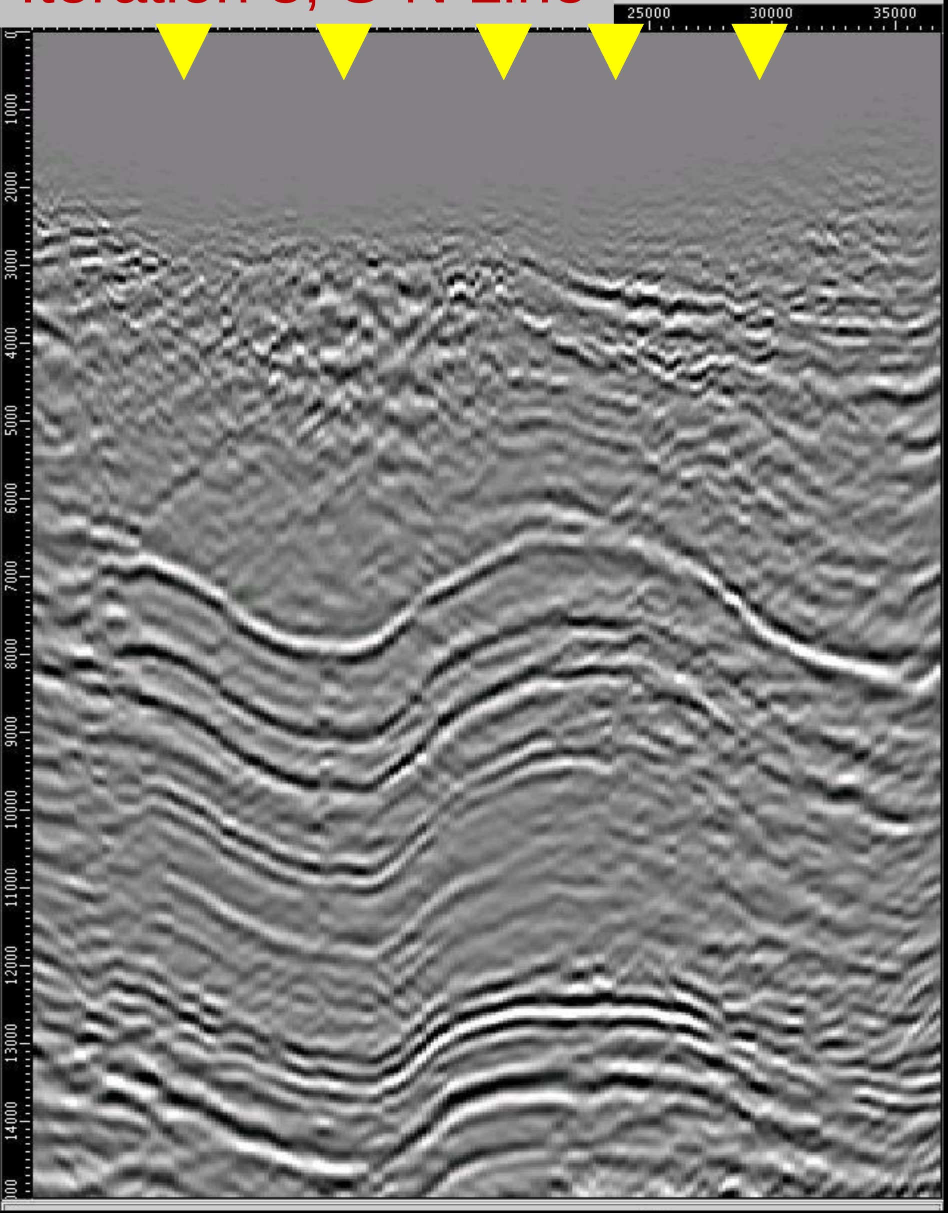
Shallow Level Iteration

Iteration 4, E-W Line



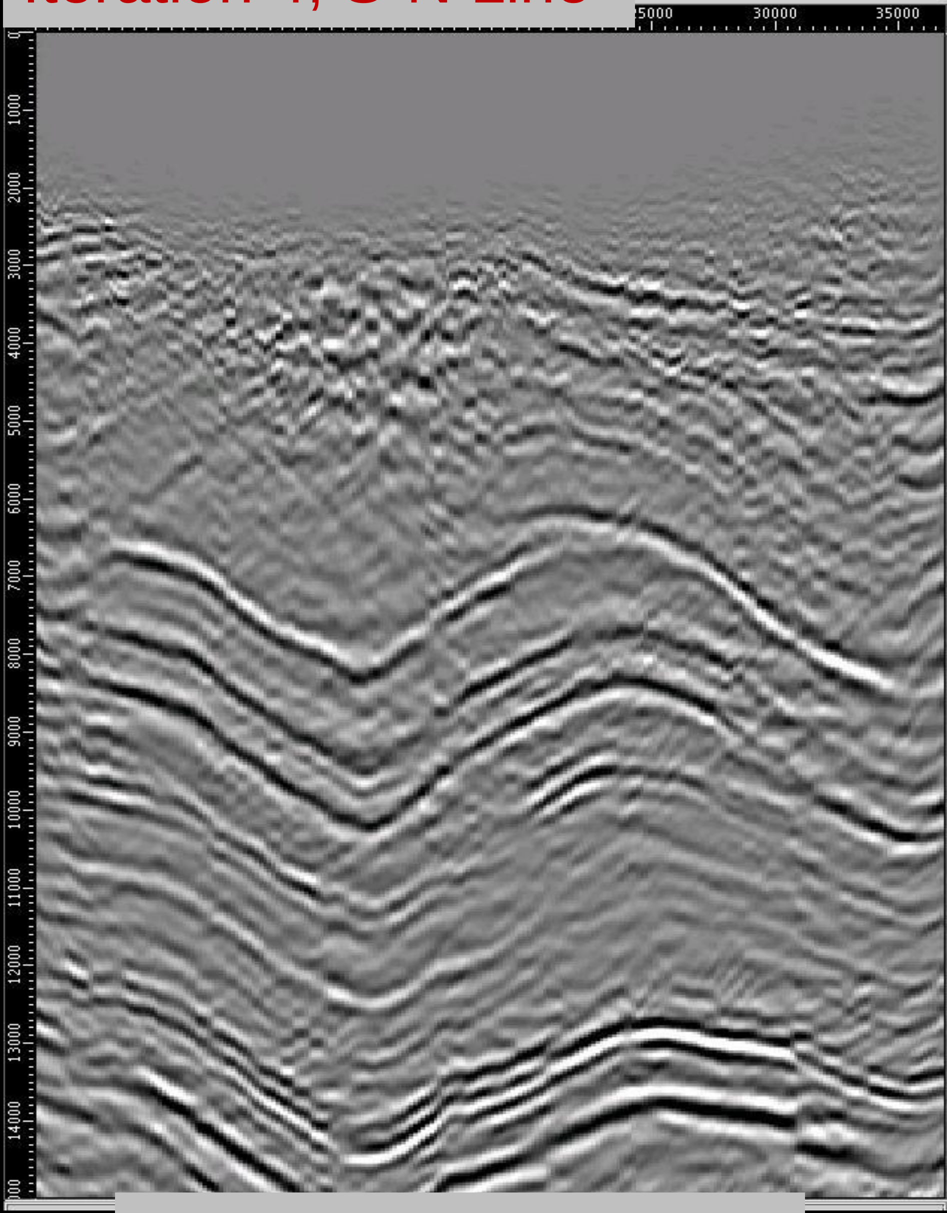
Shallow Level Iteration after Model Update

Iteration 3, S-N Line



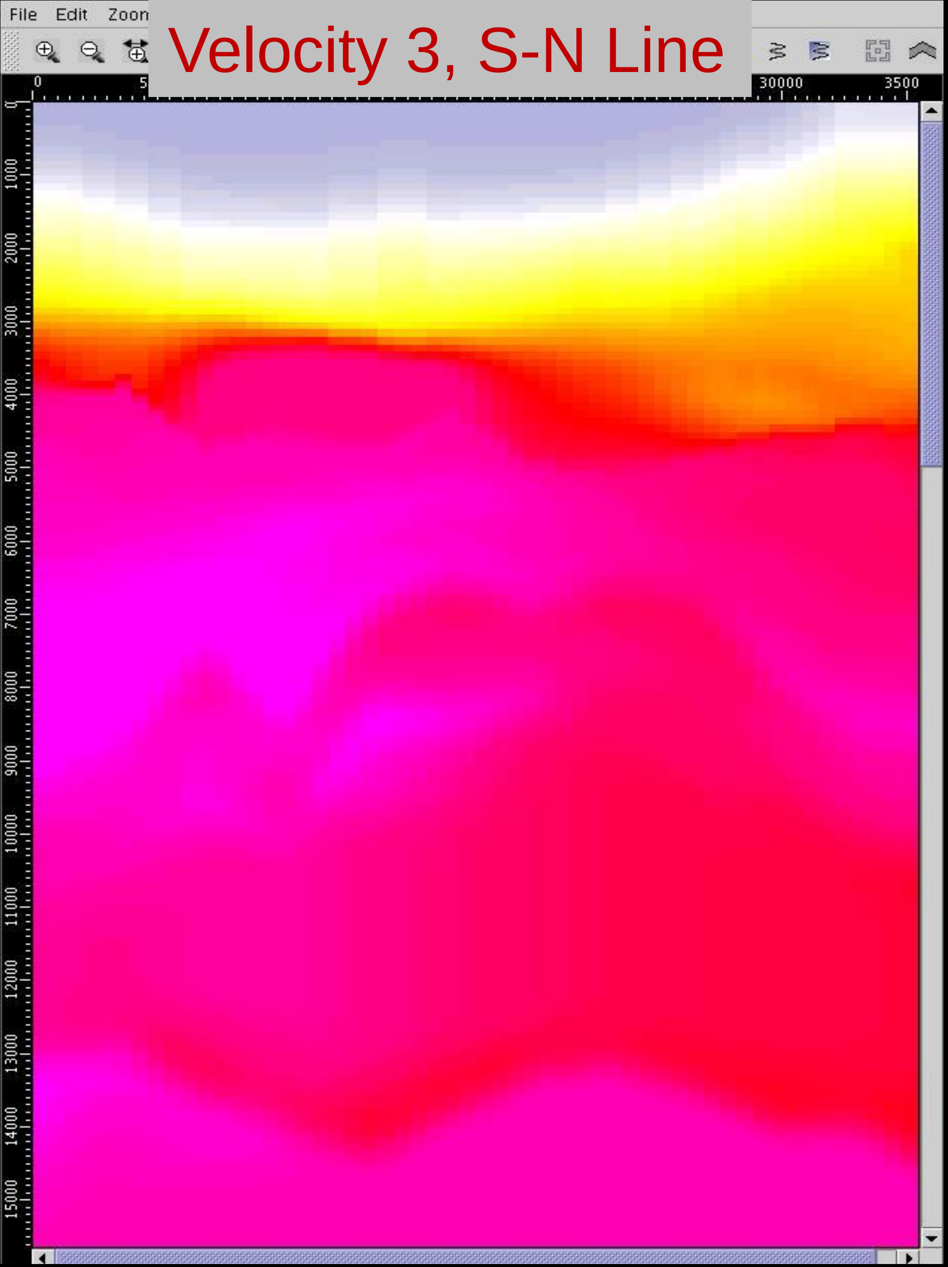
Shallow Level Iteration

Iteration 4, S-N Line

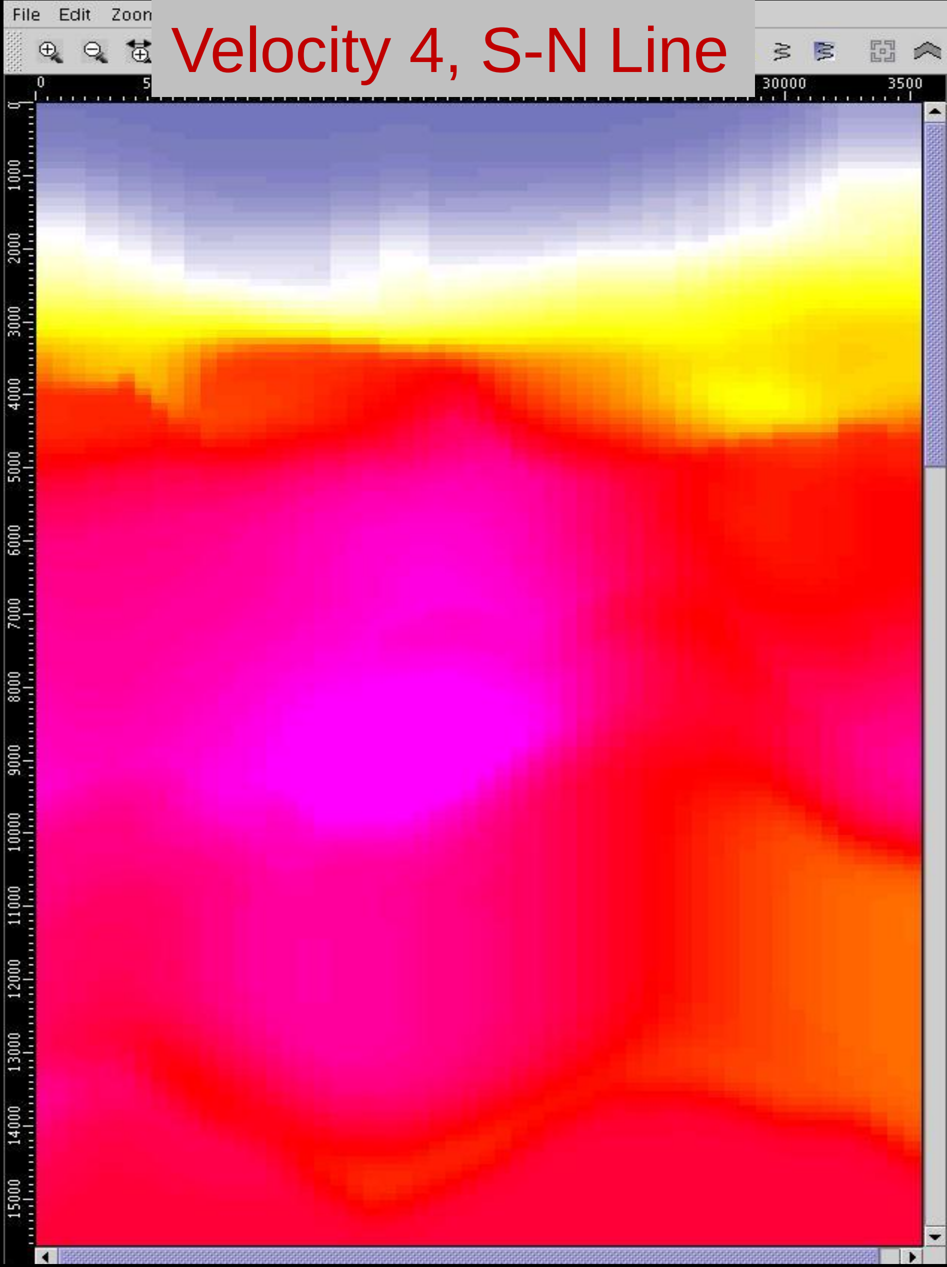


Shallow Level Iteration after Model Update

Velocity 3, S-N Line



Velocity 4, S-N Line



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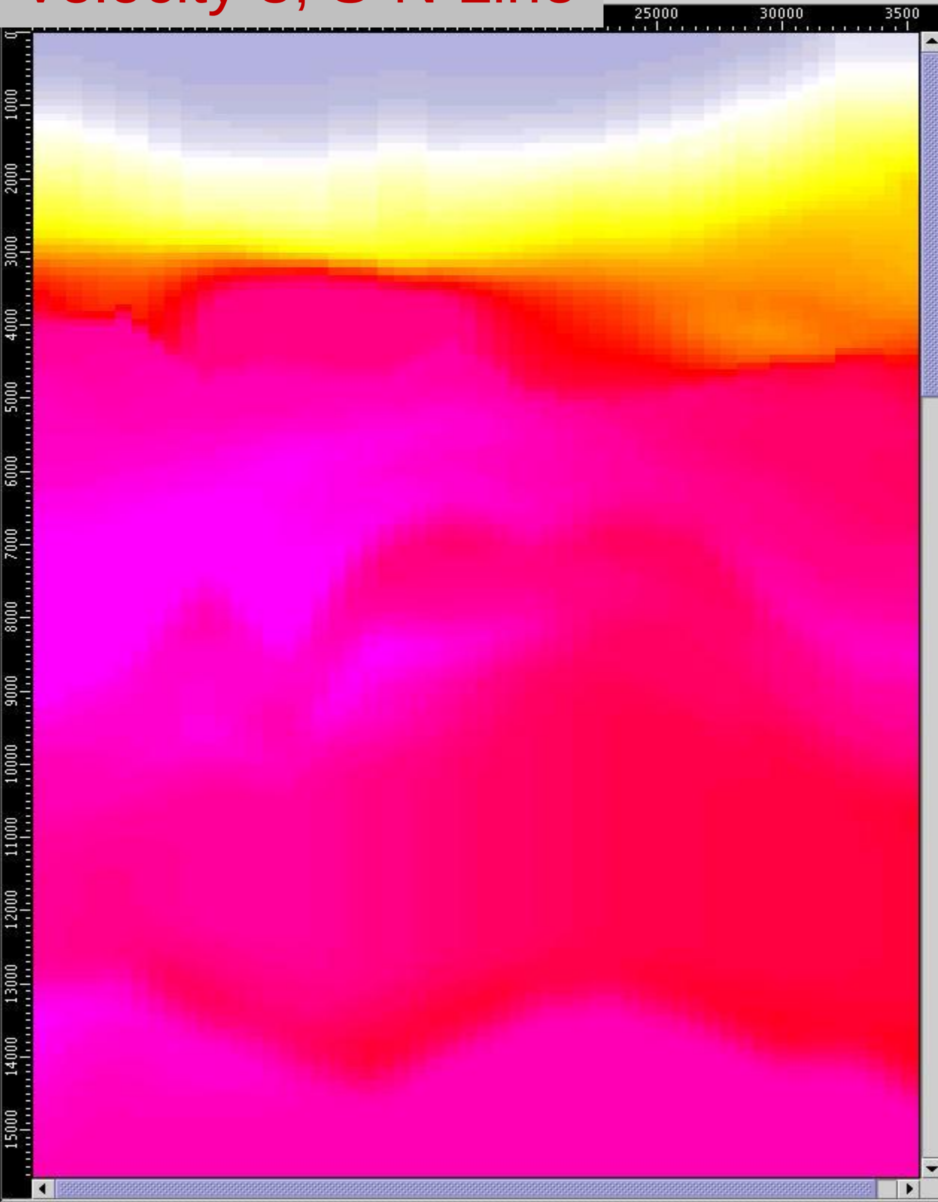
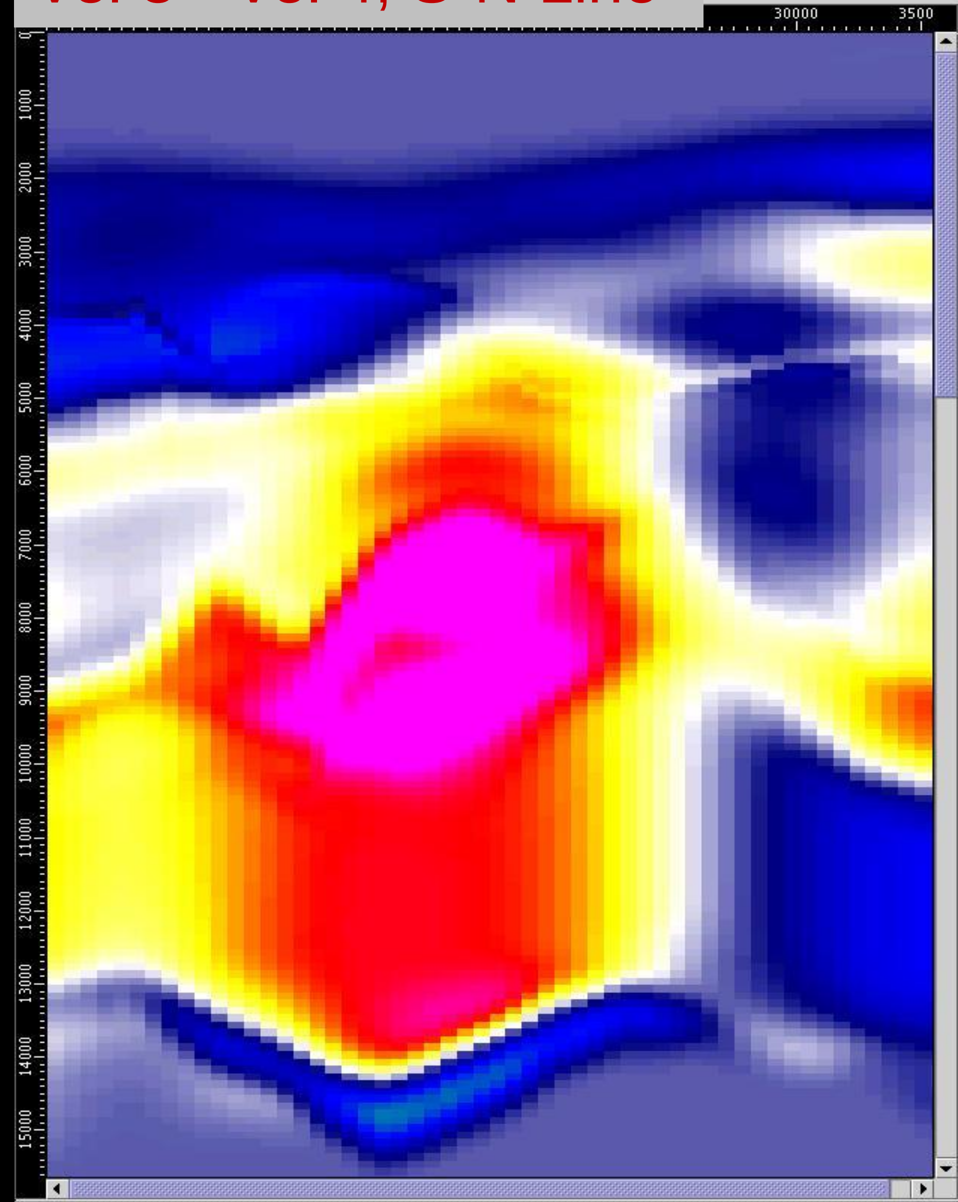
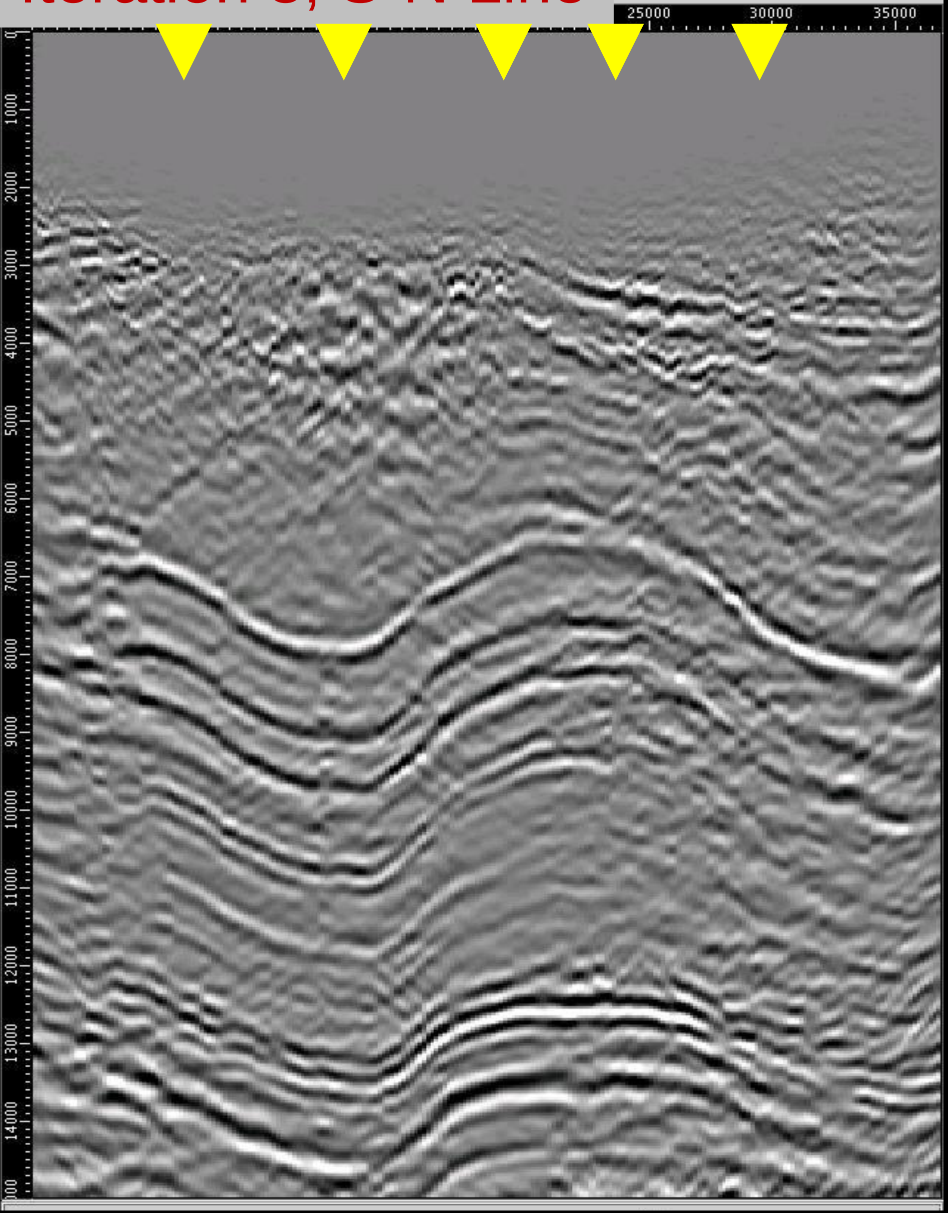
Velocity 3, S-N Line



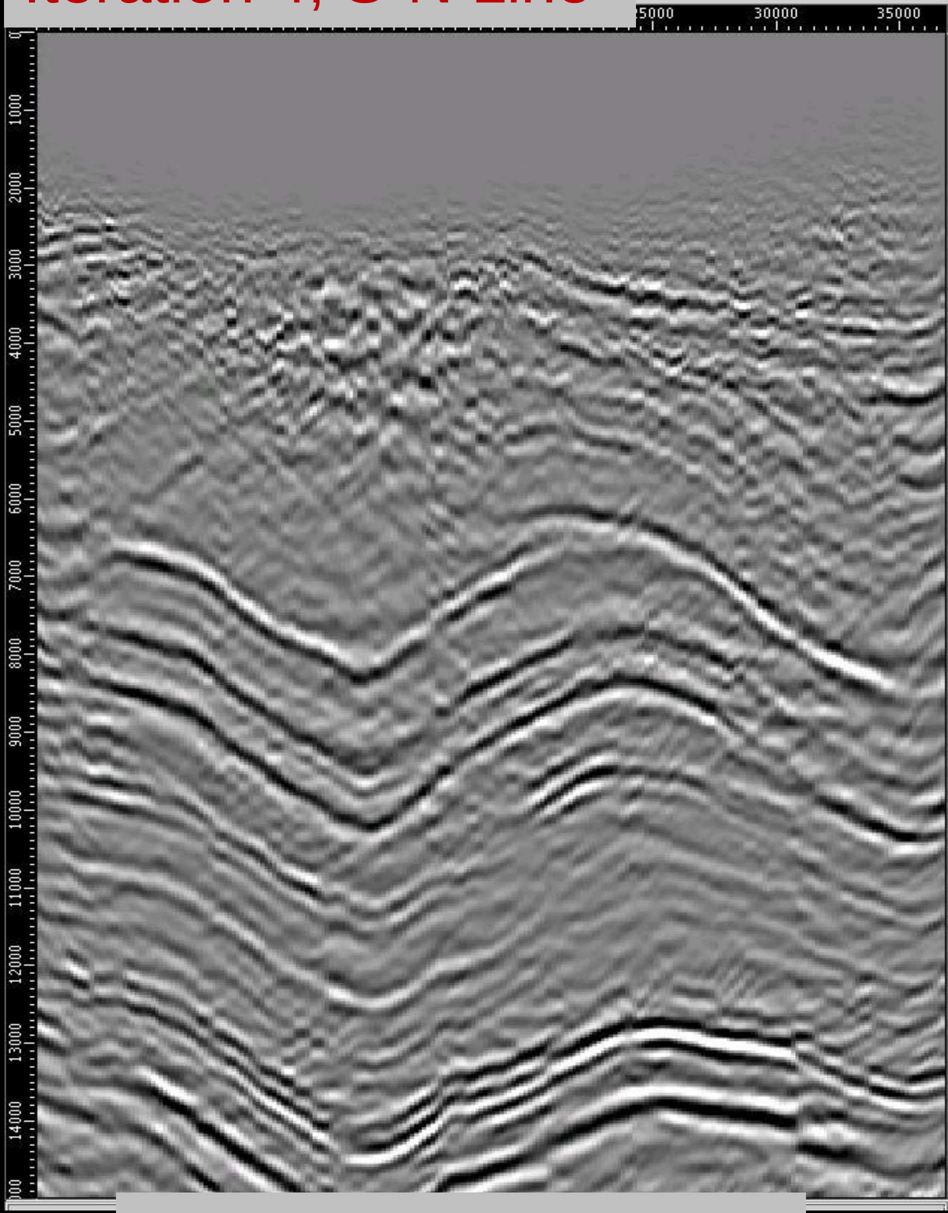
Vel 3 - Vel 4, S-N Line



Iteration 3, S-N Line



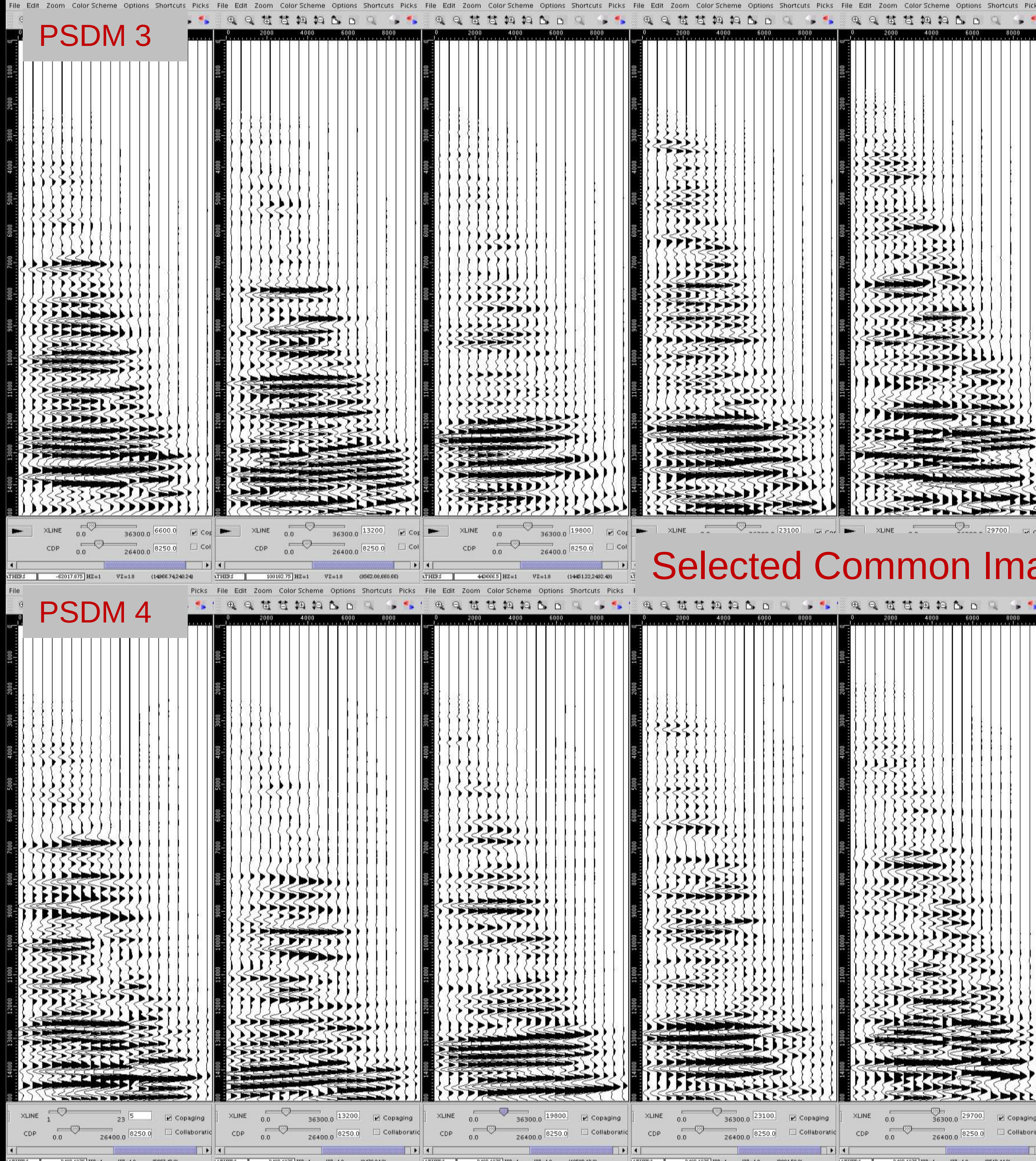
Iteration 4, S-N Line



Shallow Level Iteration

Shallow Level Iteration after Model Update

Selected Common Image Gathers



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Data and Subsurface Characteristics

- Fast rocks (>16000ft/sec) – low magnitude of reflector moveout curvature with offset – *small moveout differences, large velocity differences*
- Legacy acquisition design has variable and/or limited offset distributions within bins and with depth – *inhibits velocity resolution*
- Result: *data insensitive to velocity change and easily perturbed by "noise" in system*
- **External information required for velocity model solution**

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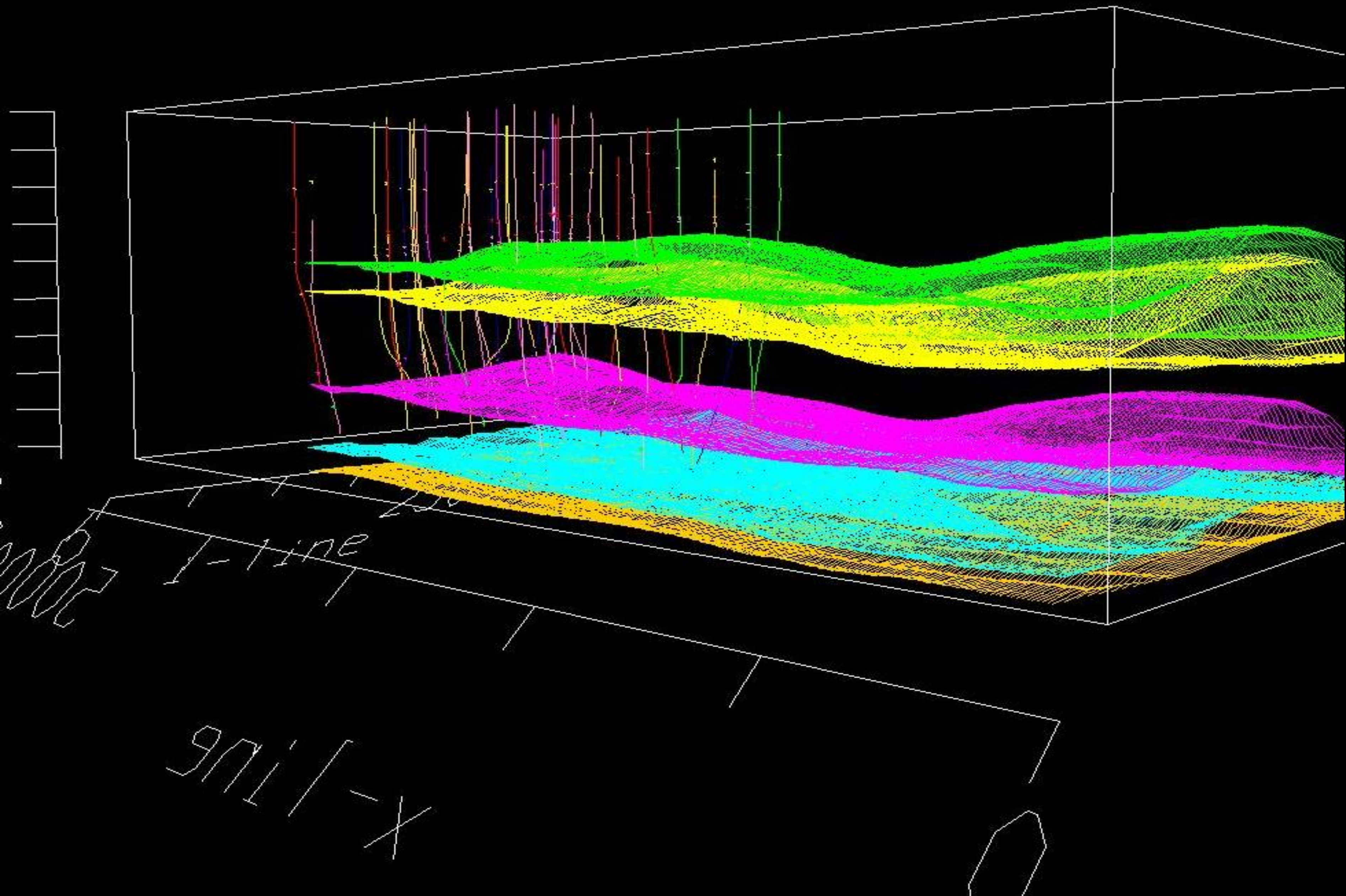

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Geology-constrained Velocity Model-building Strategy

- *Leverage geology to constrain velocity model*
- Quality controlled checkshots provide spatial interval velocity trend
- Formation top data calibrate tops-down iteration methodology
- Seismically-derived model updating only included when *strongly and consistently* supported by subsurface data
- Especially helpful in *managing the high variability* in curvature estimates and providing *trend guidance* in areas of low/no available data.
- *"Keep it Simple"*

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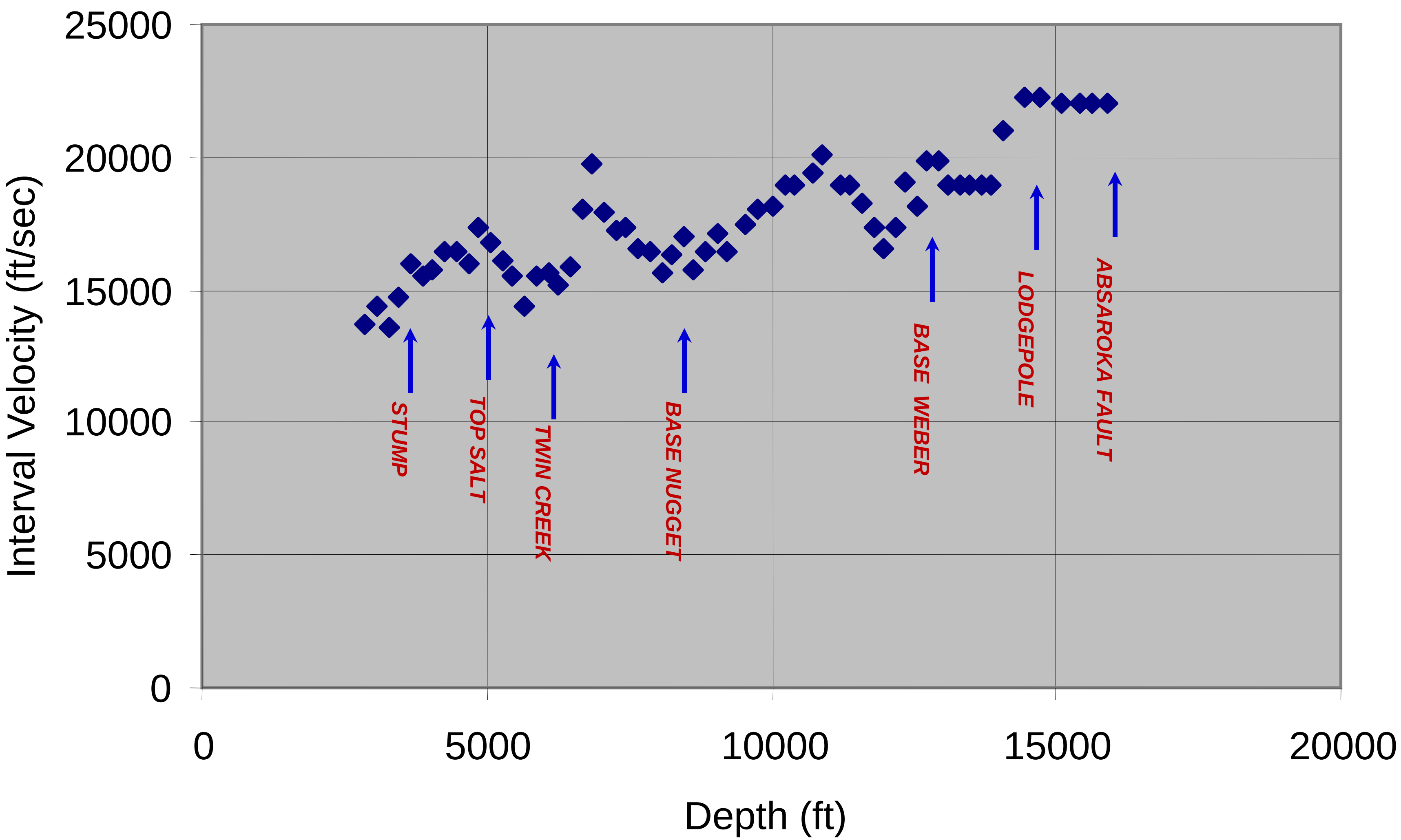
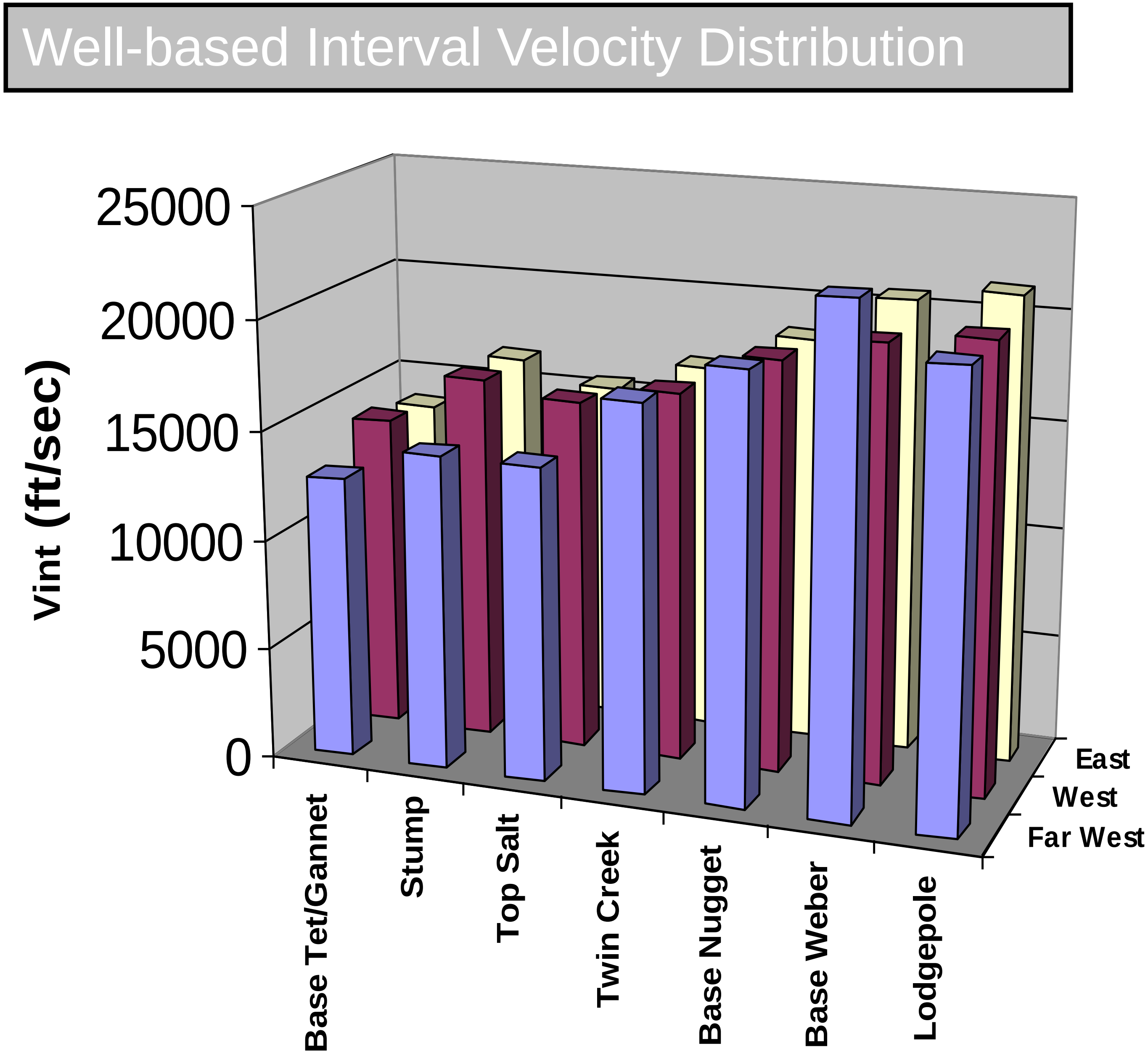
Checkshot-derived Interval Velocity Profile




Well-based Interval Velocity Distribution
Vint (ft/sec)
25000
20000
15000
10000
5000
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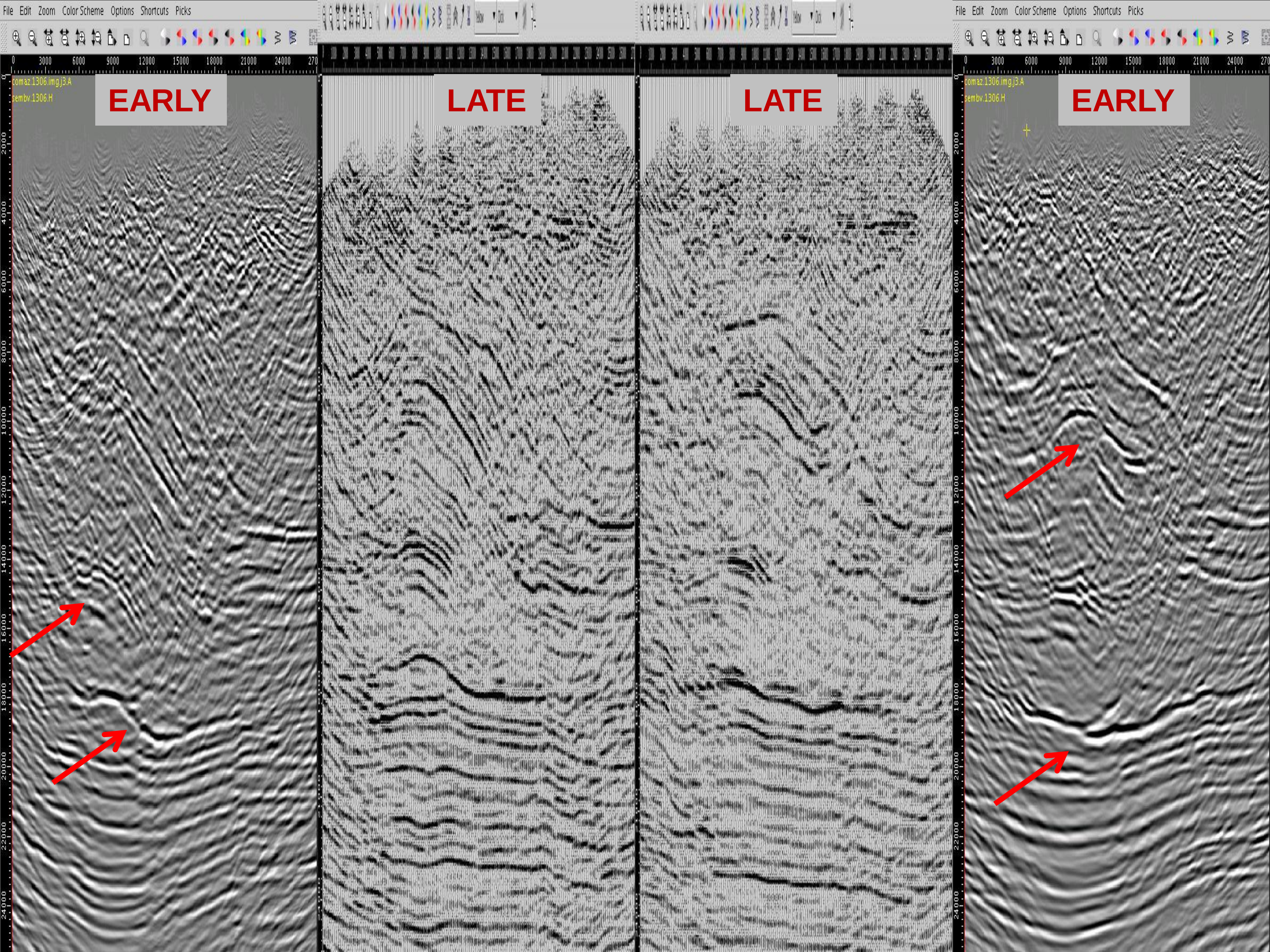
Stump
Top Salt
Twin Creek
Base Nugget
Base Weber
Lodgepole
East
West
Far West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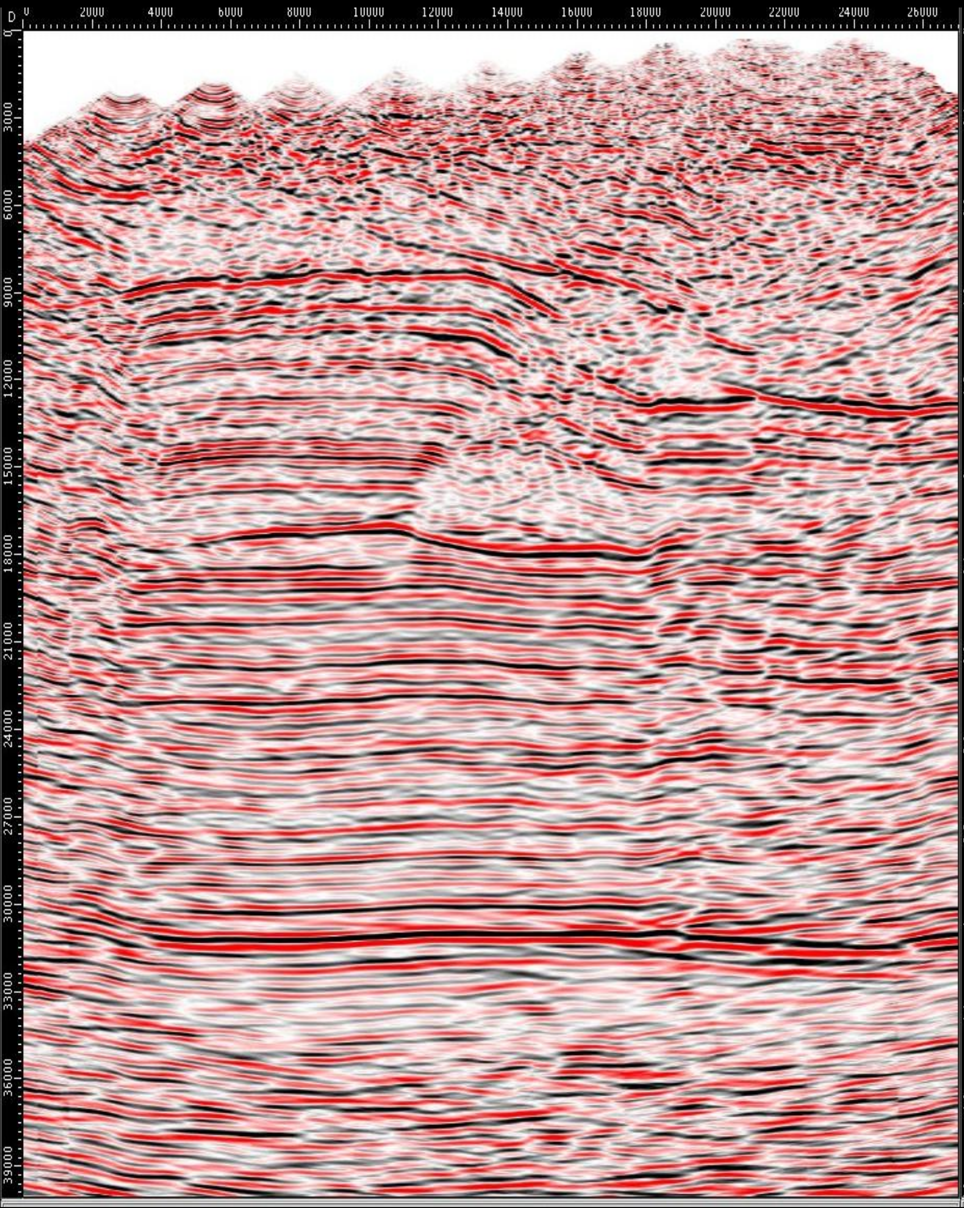

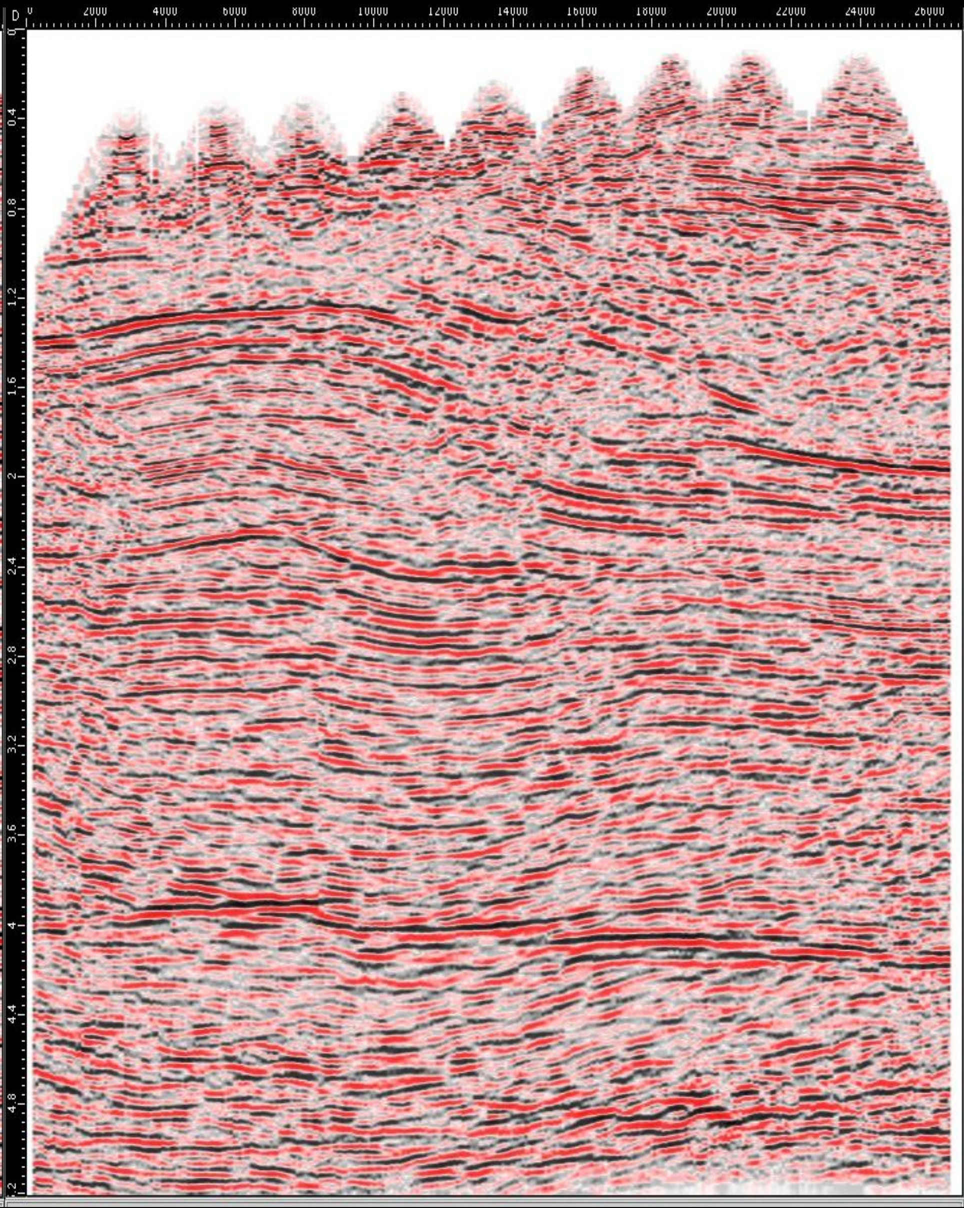

E-W PSDM

PSTM

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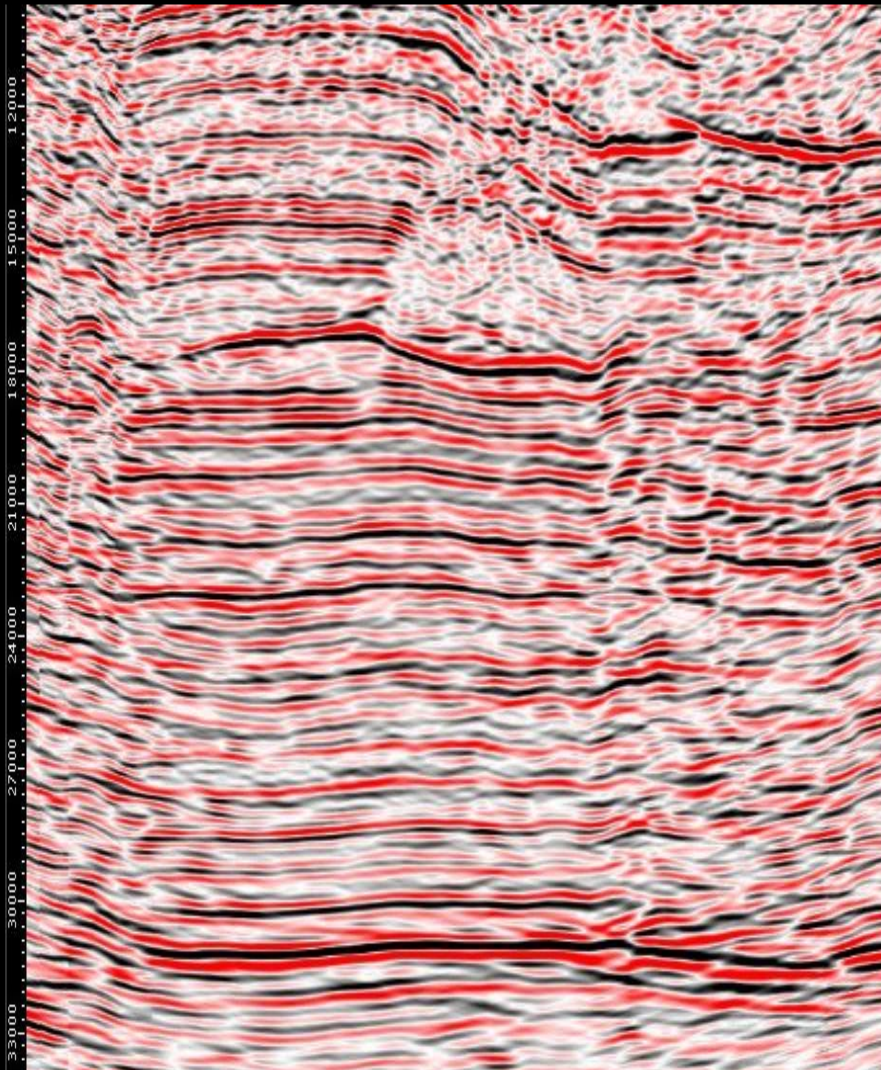
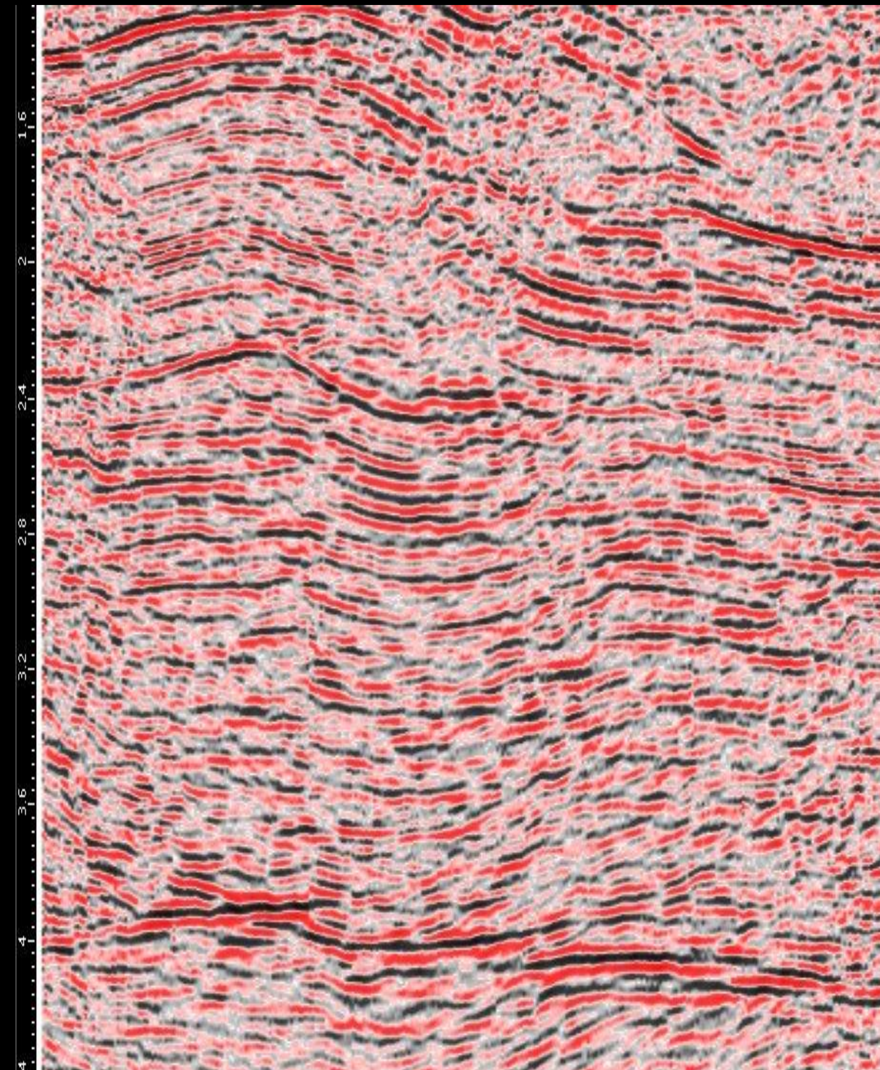


E-W PSDM Zoom



PSTM

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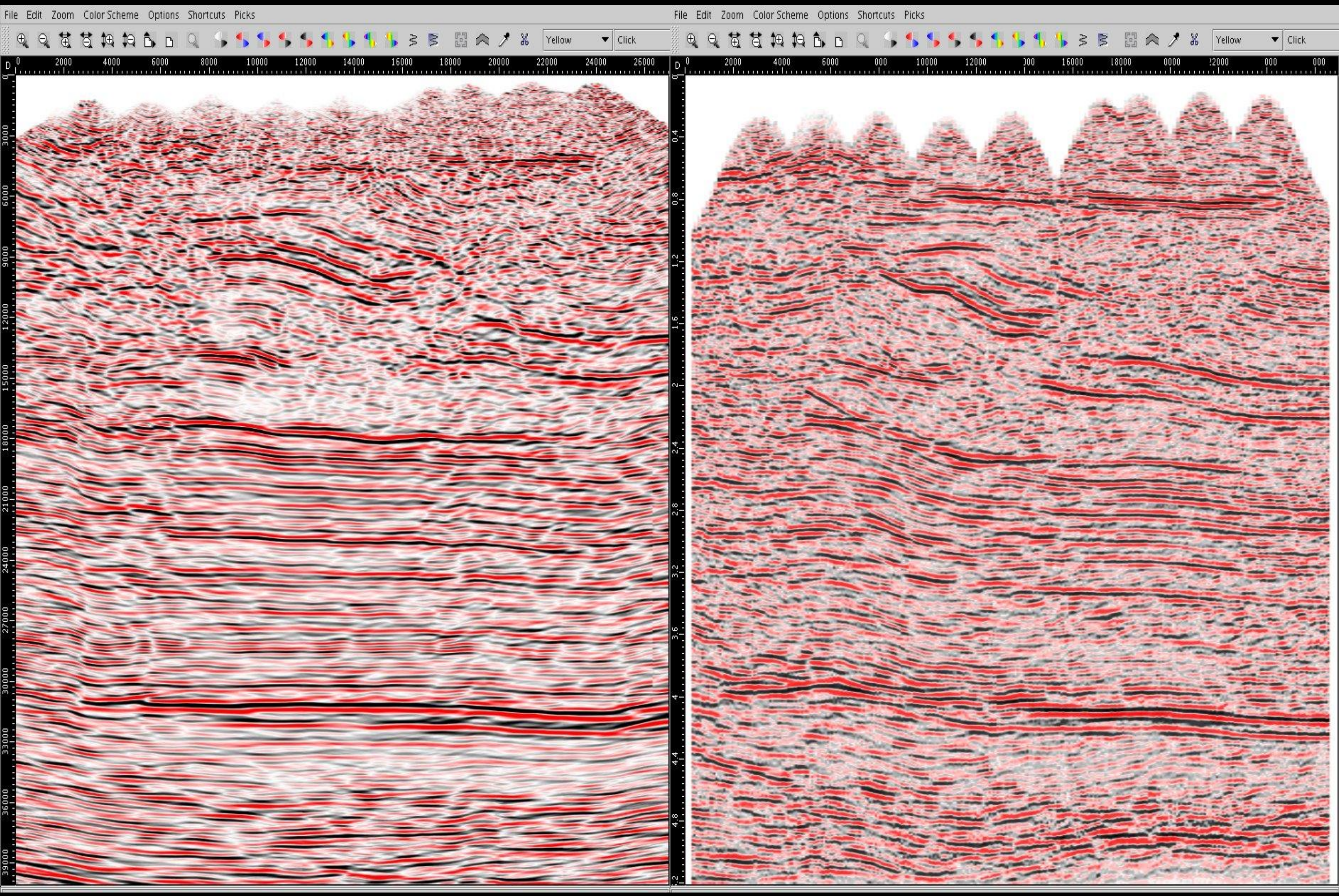
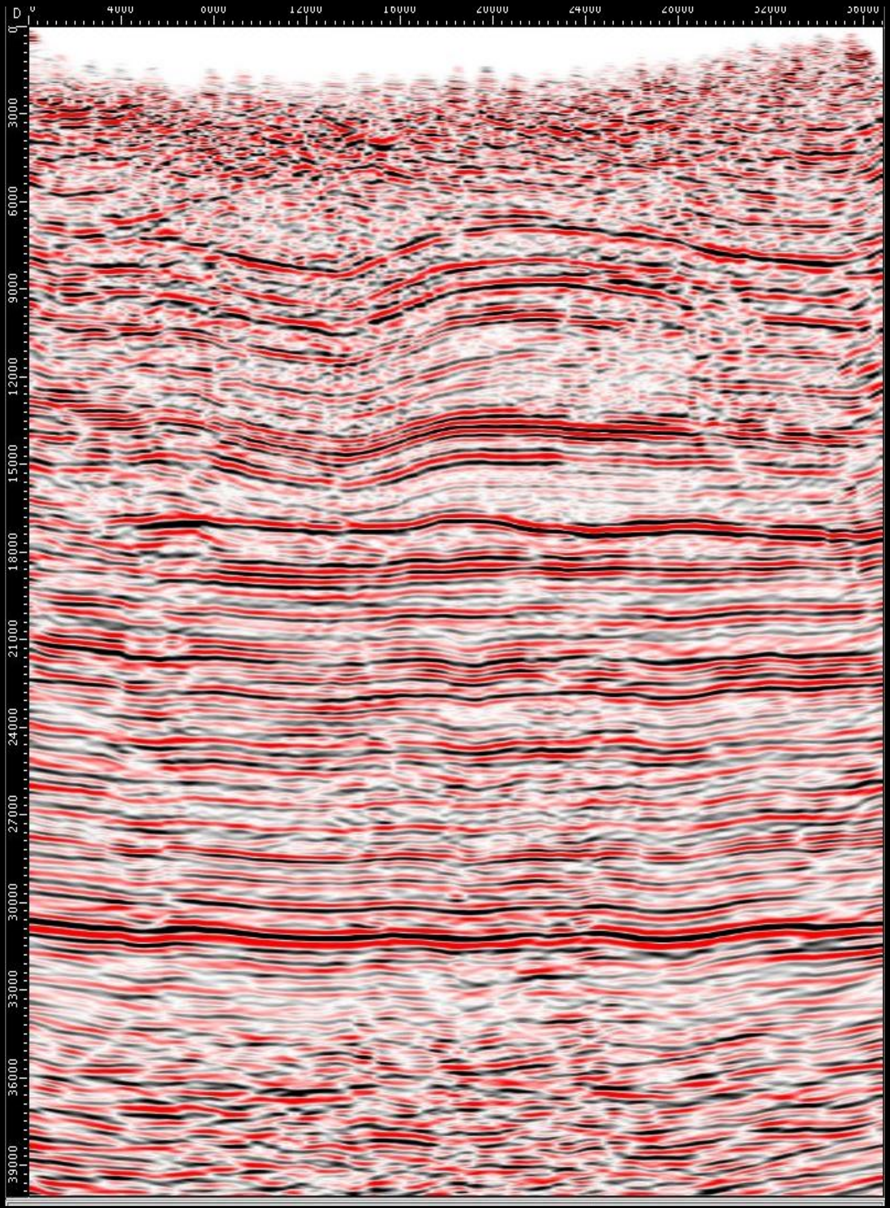
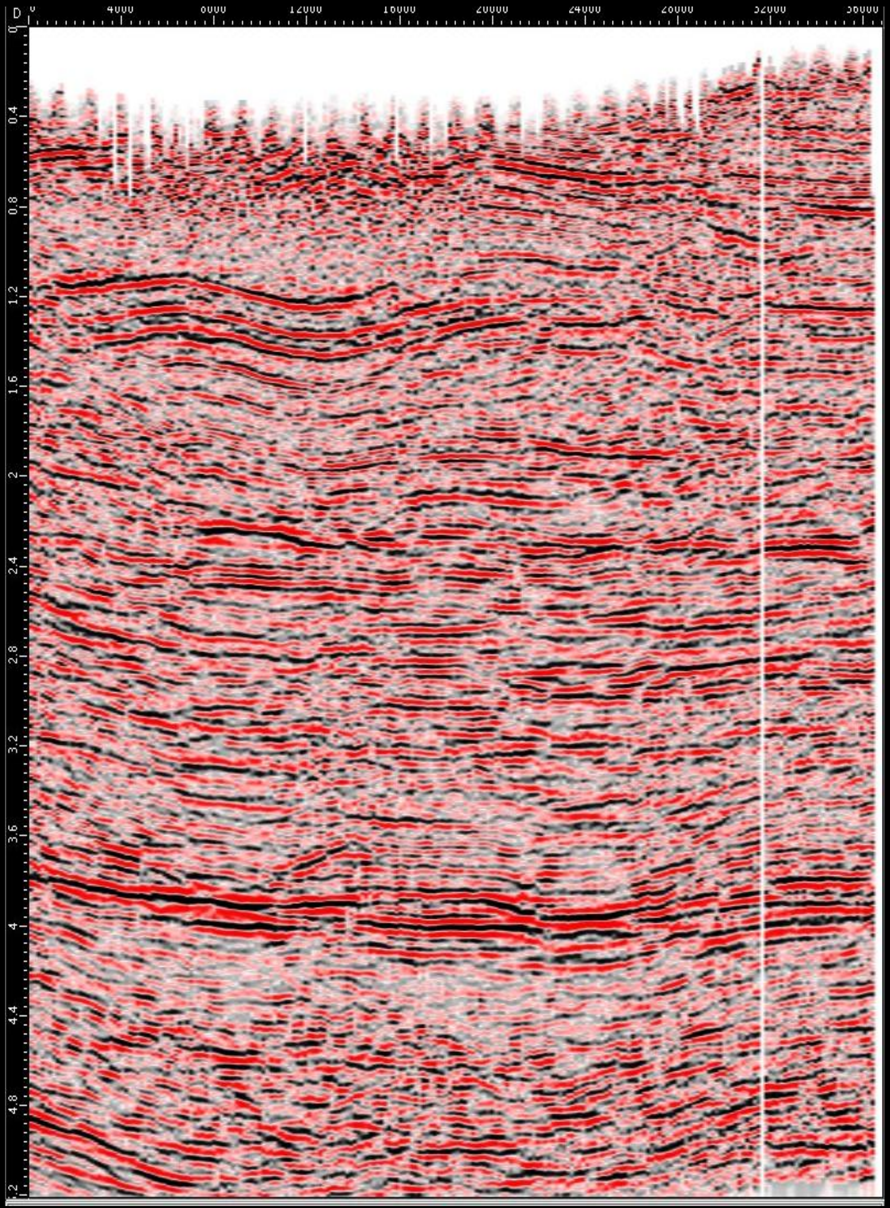


E-W PSDM

PSTM

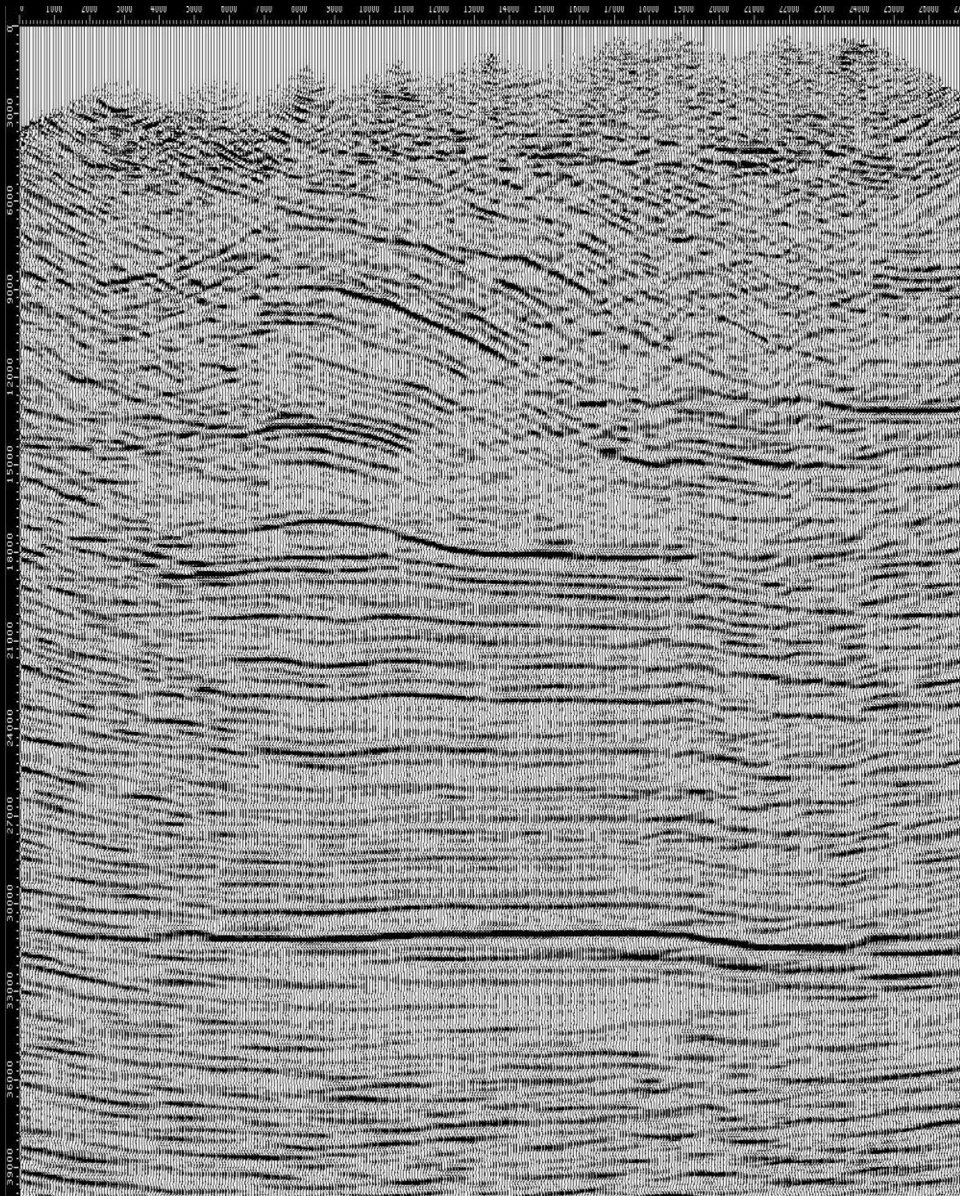
FUSION

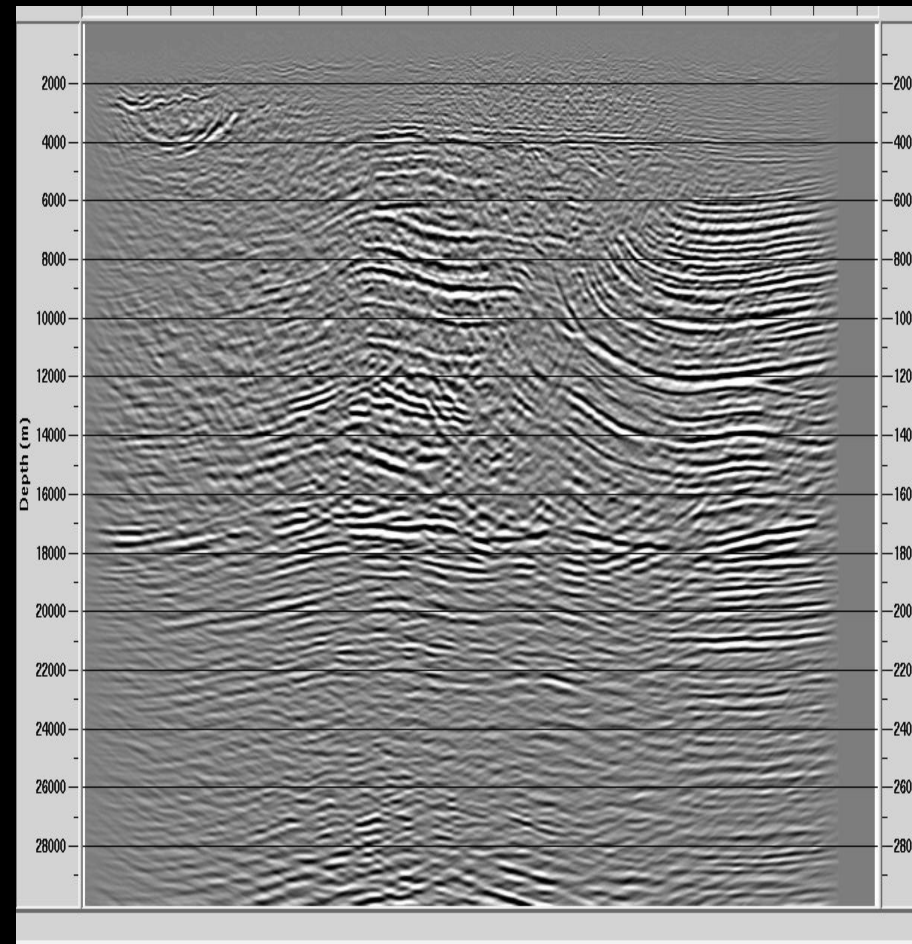




S-N PSDM

PSTM





Comparison of final SDM versus earlier unconstrained model PSDM volume

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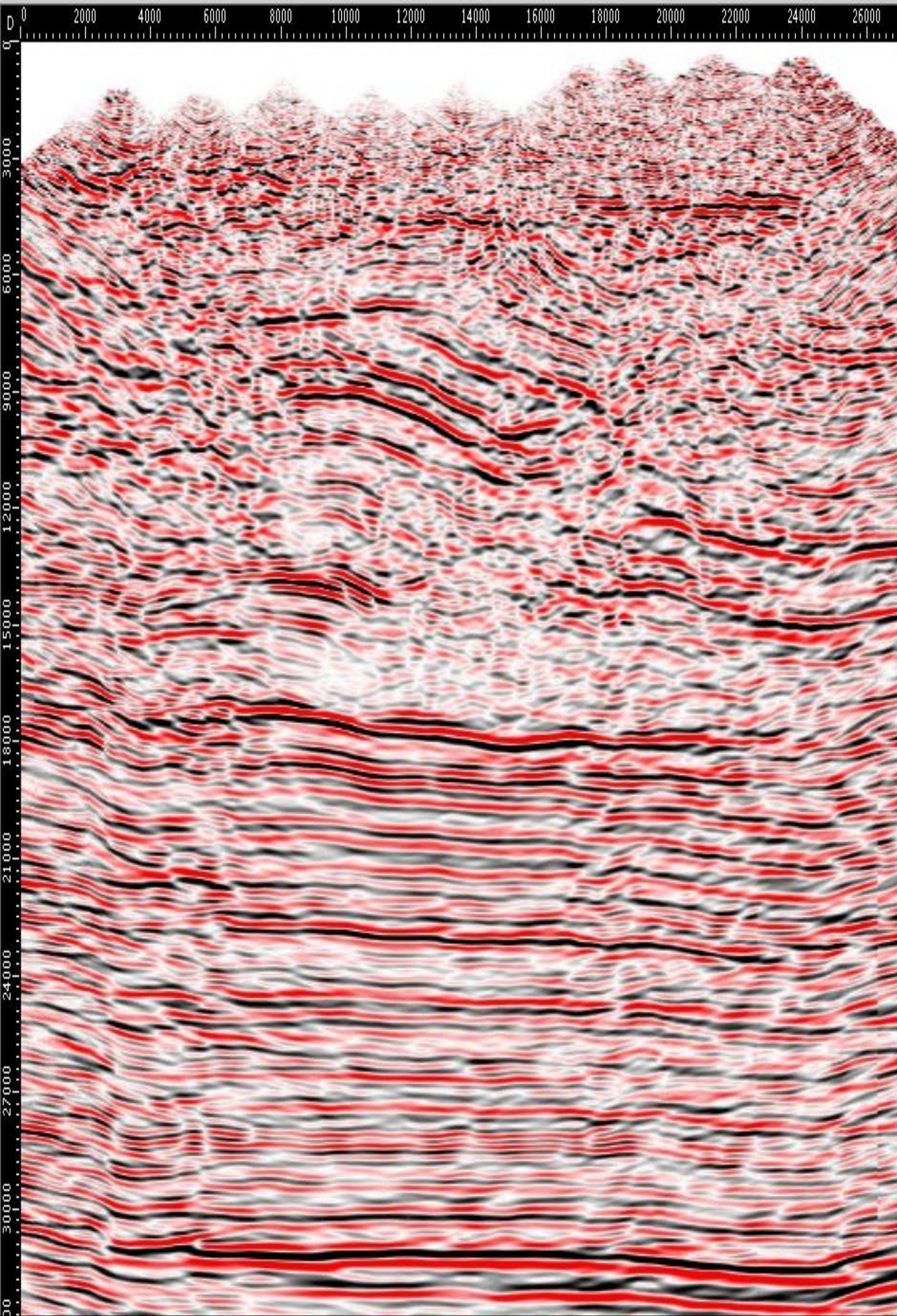
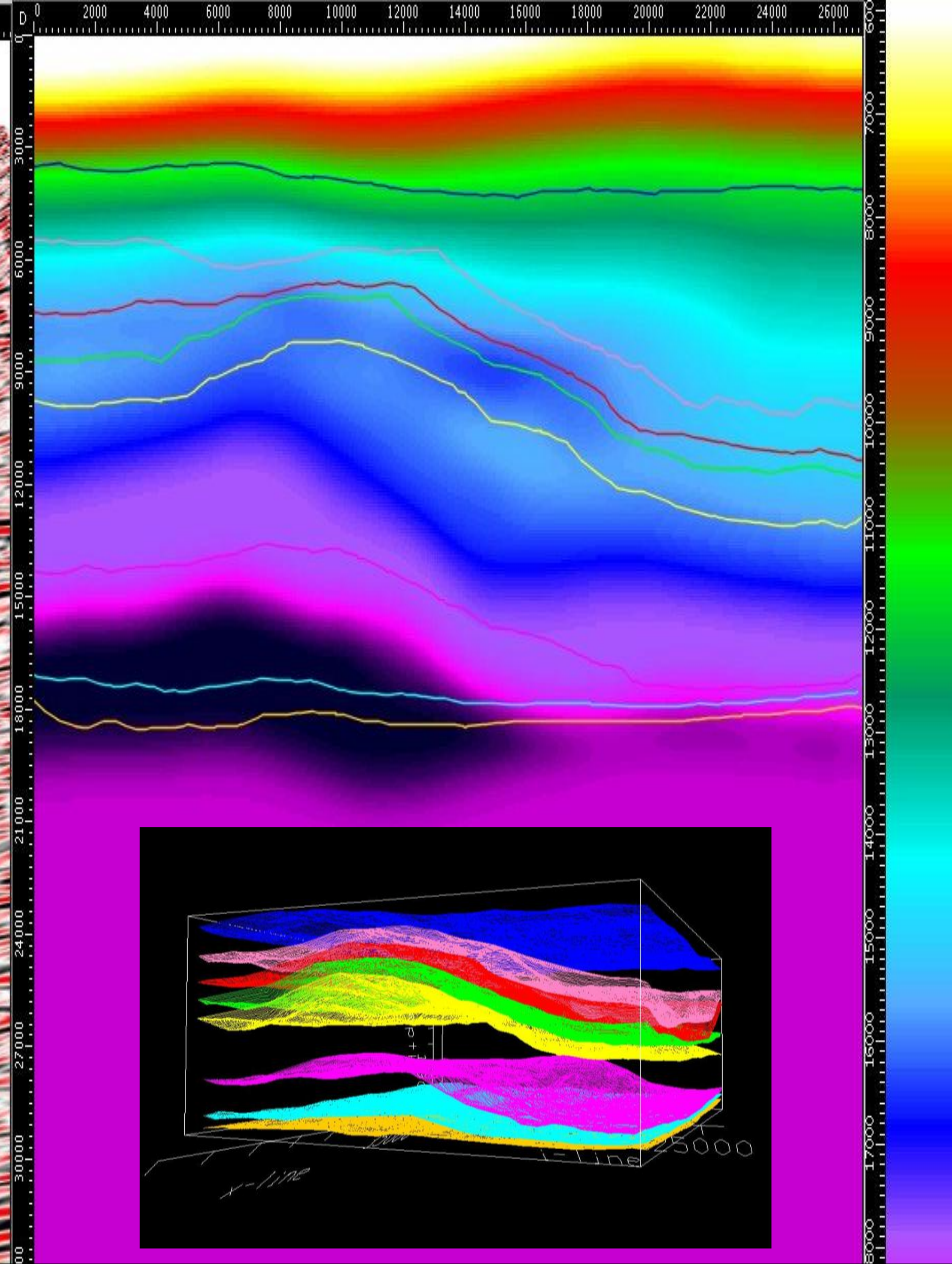


PSDM



Velocity

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Conclusions

- Geology-constrained modeling approach successfully overcame legacy data constraints to provide accurate structural context in a difficult geologic province

- Key success factors included:
  - Early awareness of the potential and the constraints inherent in the legacy data set
  - Understanding the rocks
  - Information and integration leverage from all available subsurface data
  - Critical importance of continuous interpreter involvement

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