Appendix B

RPN-1 Well Vertical Seismic Profile Modeling Study

BLUE SKY INFRASTRUCTURE

RPN-1 Well

VSP Modeling Study

Louisiana

GASSMANN FLUID-SUBSTITUTION

DISCUSSION

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Gassmann Substitution: Requirements

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- Bulk and shear moduli of solid components (minerals).
  - SOURCE: Published, commonly accepted values.
- Bulk moduli and density of pore fluids:
  - SOURCE: Algorithms based on temperature, pressure, specific gravity.
  - Specific gravity of CO_2 used to calculate fluid properties = 1.5189.
  - Brine salinity: R_W estimated from water analysis provided by Blue Sky.
- Density of solid components:
  - SOURCE: Published, commonly accepted values (e.g. quartz = 2.65 g/cc).
- Porosity and water saturation ($S_{CO_2} = 1 - S_{WT}$):
  - SOURCE: Lithology model and bulk density (modeled $S_{WT} = f$[porosity]).

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Gassmann Substitution: Pore Fluids

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- Fluid replacement occurs in effective (connected) pore space, where total and effective porosity are bounded by: $\emptyset_T \geq \emptyset_E \geq 0$.
- Gassmann is unstable at low porosity, so calculations are performed using total porosity, $\emptyset_T$, and total (modeled) brine saturation, $Sw_T \leq 1$. Only the "effective" portion of these parameters are replaced with CO_2. ($\emptyset_T$ and Sw_T include bound water associated with clay and small pores, which is not replaced in the model.)
- Effective and total water saturation are related by: $Sw_T = 1 - (Sw_E)\left(\frac{\emptyset_E}{\emptyset_T}\right)$.
- Using $\emptyset_T$, V_{CLAY} and V_{SILT} from the lithology model, $\emptyset_E$ is related to $\emptyset_T$ by: $\emptyset_E = \emptyset_T(1 - V_{CLAY} - V_{SILT})$. V_{SILT} is iterated until $\emptyset_E \approx$ free fluid derived from magnetic resonance logs (calculated by Schlumberger).
- Process assumes constant irreducible water saturation, using effective bulk volume water (BVW_E) = 0.05 (plus a small amount of Gaussian noise). From this: $Sw_E = BVW_E/\emptyset_E$ (limited 0 → 1) and $S_{CO^2} = 1 - Sw_E$.

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Gassmann's equation

$$\frac{K_{sat}}{K_o - K_{sat}} = \frac{K_{dry}}{K_o - K_{dry}} + \frac{K_{fl}}{\emptyset(K_o - K_{fl})},$$

assuming $\mu_{sat} = \mu_{dry} = \mu$ where,

- K_{dry} = bulk modulus of dry rock.
- K_{sat} = bulk modulus of rock + fluid.
- K_o = bulk modulus of solid matrix.
- K_{fl} = bulk modulus of pore fluid.
- $\emptyset$ = porosity.
- μ_{dry} = shear modulus (rigidity) of dry rock.
- μ_{sat} = shear modulus of rock + fluid.

$$V_P = \sqrt{\frac{K_{sat} + 4/3\mu}{\rho_b}}\ ;\ V_S = \sqrt{\frac{\mu}{\rho_b}}$$, ρ_b = bulk density.

Comments:

- Estimates K_{sat} of new pore fluid from K_{sat} of in-situ pore fluid with other parameters static.
- Assumptions: homogeneous/isotropic medium, connected pores (*may not work as well in shaly sediments*) **and** no relative motion (decoupling) between fluids and grains.
- "Dry rock" ≠ CO_2-saturated rock. K_{dry} is bulk modulus of rock-frame when pore pressure is held constant by allowing pore fluids to escape. Estimated as: $K_{dry} = \mu_{dry} * (K_o / \mu_o)$ where μ_o = shear modulus of solid matrix.
- Total or effective porosity can be used but, if the former, bound water in total S_W cannot be replaced.
- For curve mnemonics, μ = G (e.g. $\mu\rho$ = GRHO).

Gassmann Substitution: Workflow

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- Fluid densities and moduli are calculated as well logs from surface casing to TD from pressure, temperature, and salinity. Resulting curves are inspected for null values and corrected as necessary.
- Fluid property logs, mineral bulk moduli values, bulk density, mineral fractions and total porosity are input to Gassmann.
- Gassmann is run twice: First, using in-situ total water saturation (= 1) to estimate dry-frame bulk modulus (K_{dry}) and to check accuracy of reconstructed elastic logs (V_P, V_S), and again using modeled total water saturation (with homogeneous fluid mixing; CO_2 saturation in model is $1 - Sw_T$) in the following sands/zones:
  - 1ST UPPER MIOCENE SAND → TEX W SHALE (6109-6615.5' MD).
  - LOWER CRIS I SAND → CIB OP SHALE (7474-8155.5' MD).
  - AMPH B SAND → ROB L SAND (8446-9236' MD).
  - CAMERINA SAND → MARG A SHALE (10530-11197' MD).

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Modeled Well Logs and Crossplots

FOUR SANDS

Explanation of Tracks in Log Displays

- TRACK 1: Model of solid mineral and pseudo-mineral fractions, including pyrite, total clay, calcite, silt and sand (the last two comprising quartz). Track also shows XRD points for clay, converted from weight-percent to volume.
- TRACK 2: Volumetrics of CO_2 model with total and effective porosity from lithology model, effective bulk volume water, conventional neutron-density crossplot porosity (ANK Geosciences), with nuclear magnetic resonance total and free-fluid porosity (Schlumberger). Yellow shading is bulk volume CO_2.
- DEPTH TRACK: Modeled total and effective water saturation used in CO_2-substitution.
- TRACK 3: In-situ resistivity logs with modeled deep resistivity after CO_2-substitution. Yellow shading spans in-situ deep resistivity to modeled deep resistivity.
- TRACK 4: In-situ (lightly edited) density and neutron logs with CO_2-substituted versions. Yellow shading spans CO_2-substituted logs.
- TRACK 5: In-situ (lightly edited) P- and S-sonic logs with CO_2-substituted versions. Yellow shading spans CO_2-substituted P-sonic to in-situ P-sonic.
- TRACK 6: In-situ and CO_2-substituted V_P/V_S, with shading.
- Arrows denote depth range of display interval, relative to entire well.

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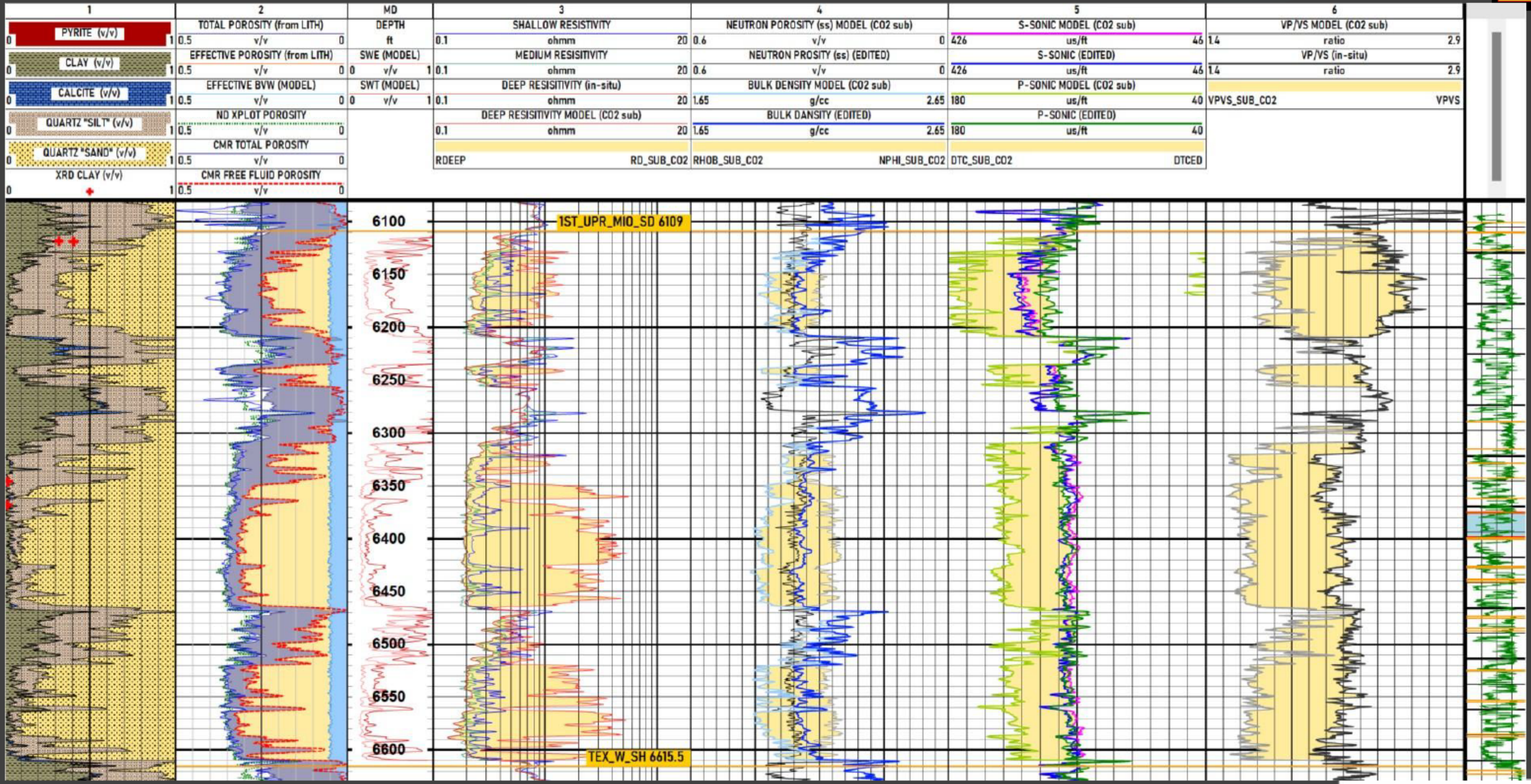
Explanation of Crossplot Displays

- Crossplots show P-impedance (x-axis) versus V_P/V_S (y-axis).
- Crossplots are shown as pairs: in-situ followed by CO_2-substitution
- Color axis represents a lithology index:
  - End members shale, sand, silt and limestone (LS) have ≥ 60% of either clay, sand, silt or calcite by volume.
  - All other lithology types represent mixtures in which two components dominate (e.g. SD+SLT = sand and silt fractions comprise bulk of composition). Marl is calcite + clay.
  - Sand and silt fractions are split from quartz.
  - All lithology types can contain “sand”, even if in small quantities.
  - Only the sand fraction participates in CO_2-substitution.

MODEL: 1ST Upper Miocene Sand



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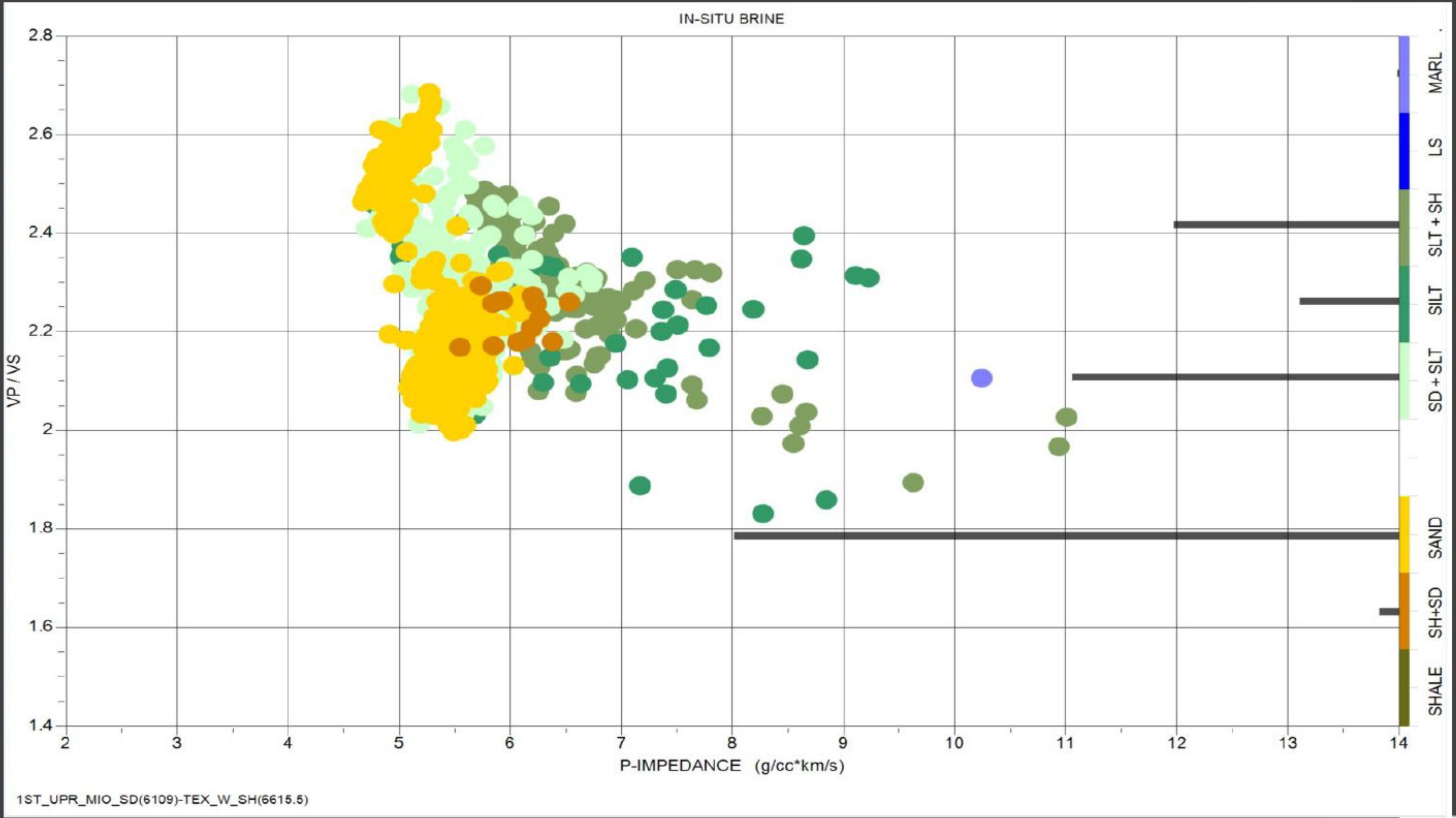
1st Upper Miocene Sand (in-situ brine)



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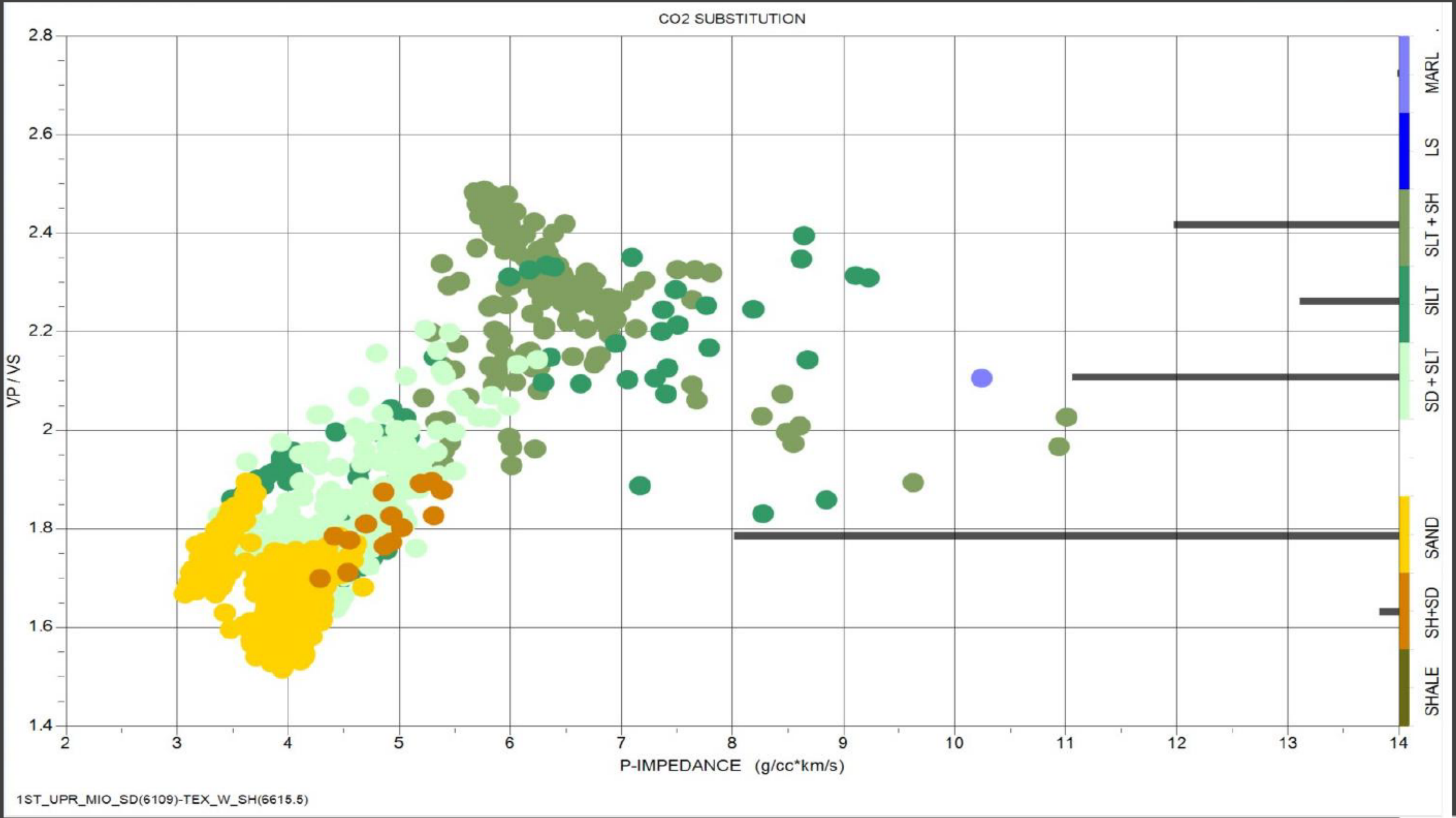
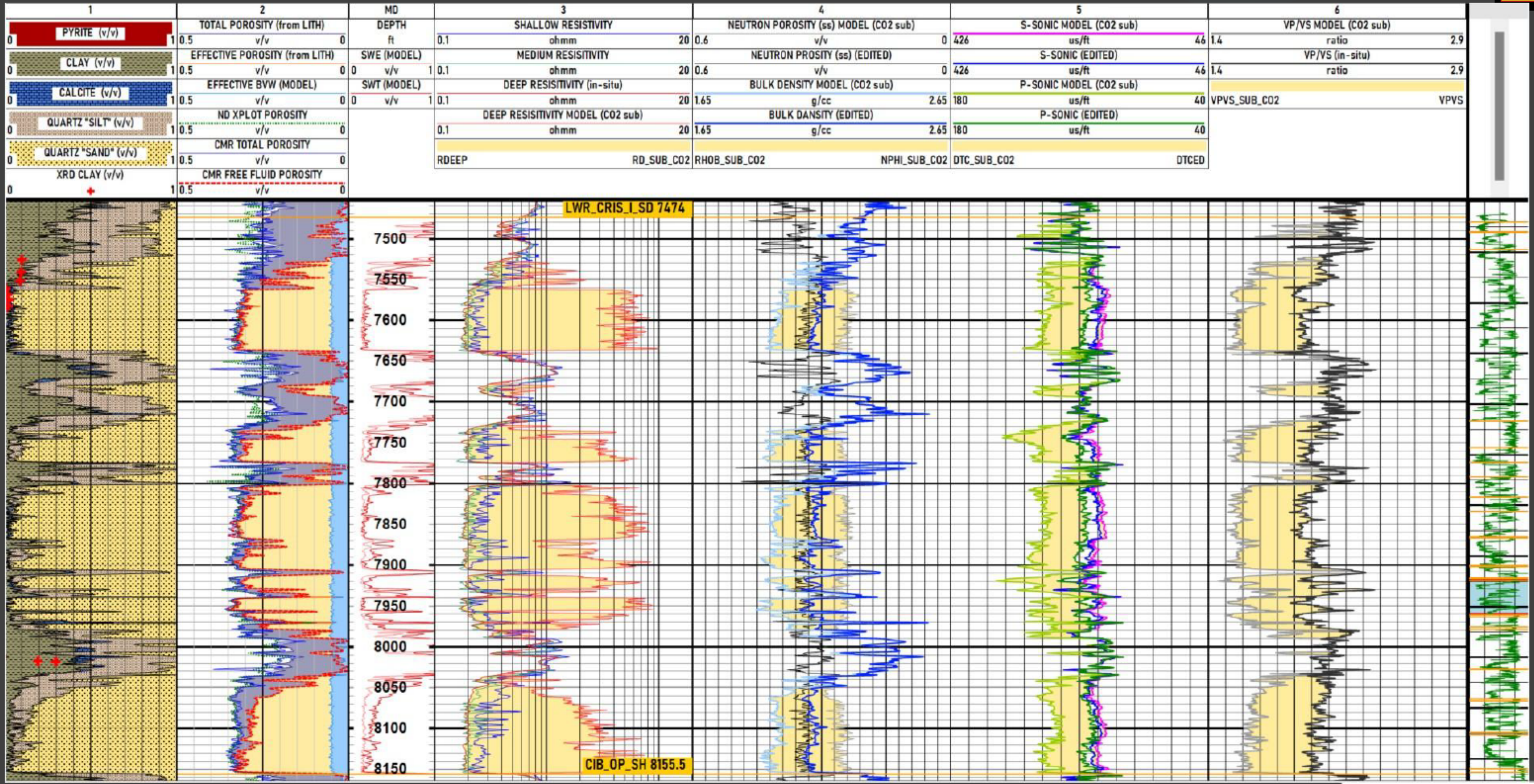
1st Upper Miocene Sand (CO_2 model)



MODEL: Lower Cris I Sand



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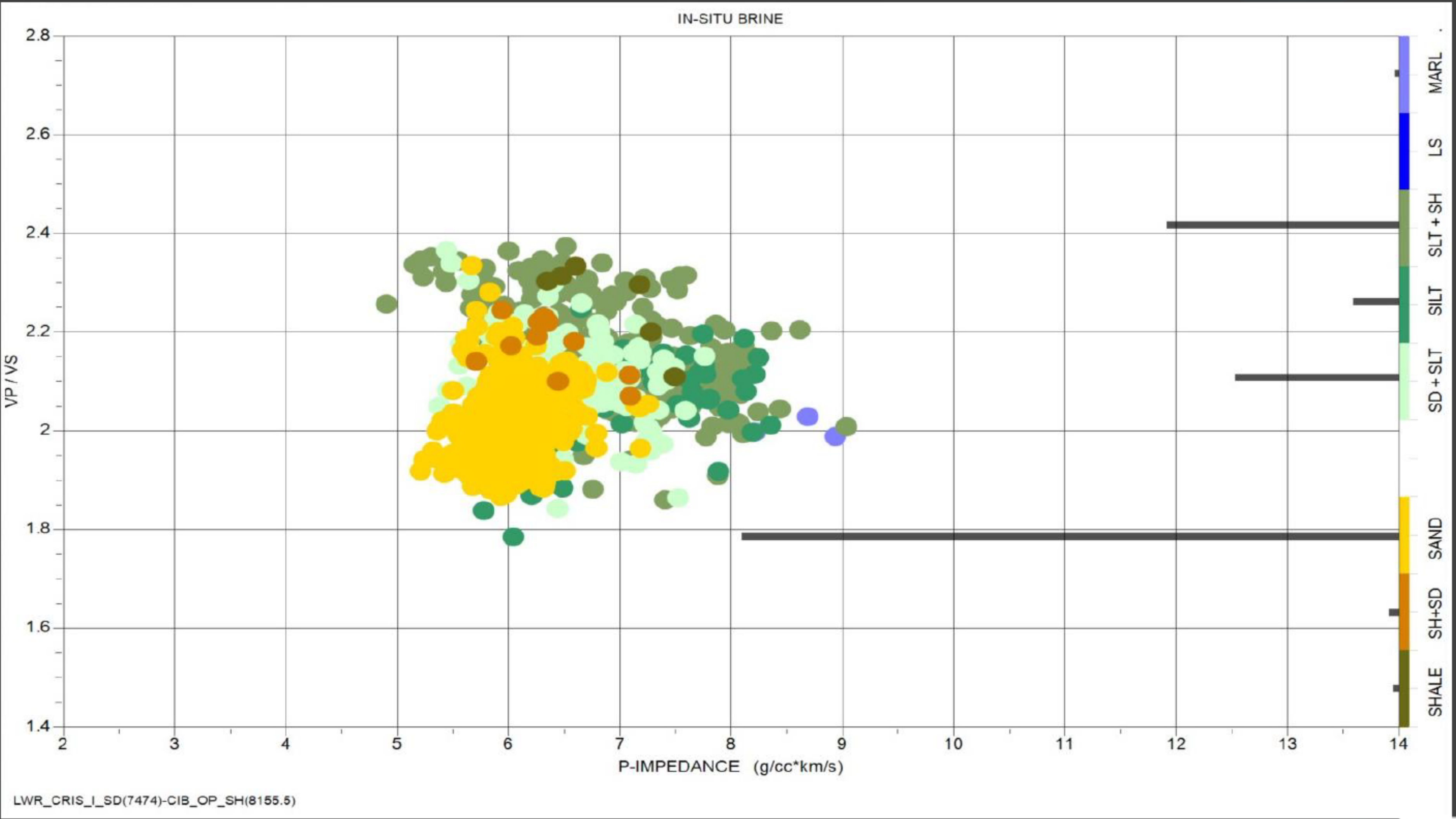
Lower Cris I Sand (in-situ brine)



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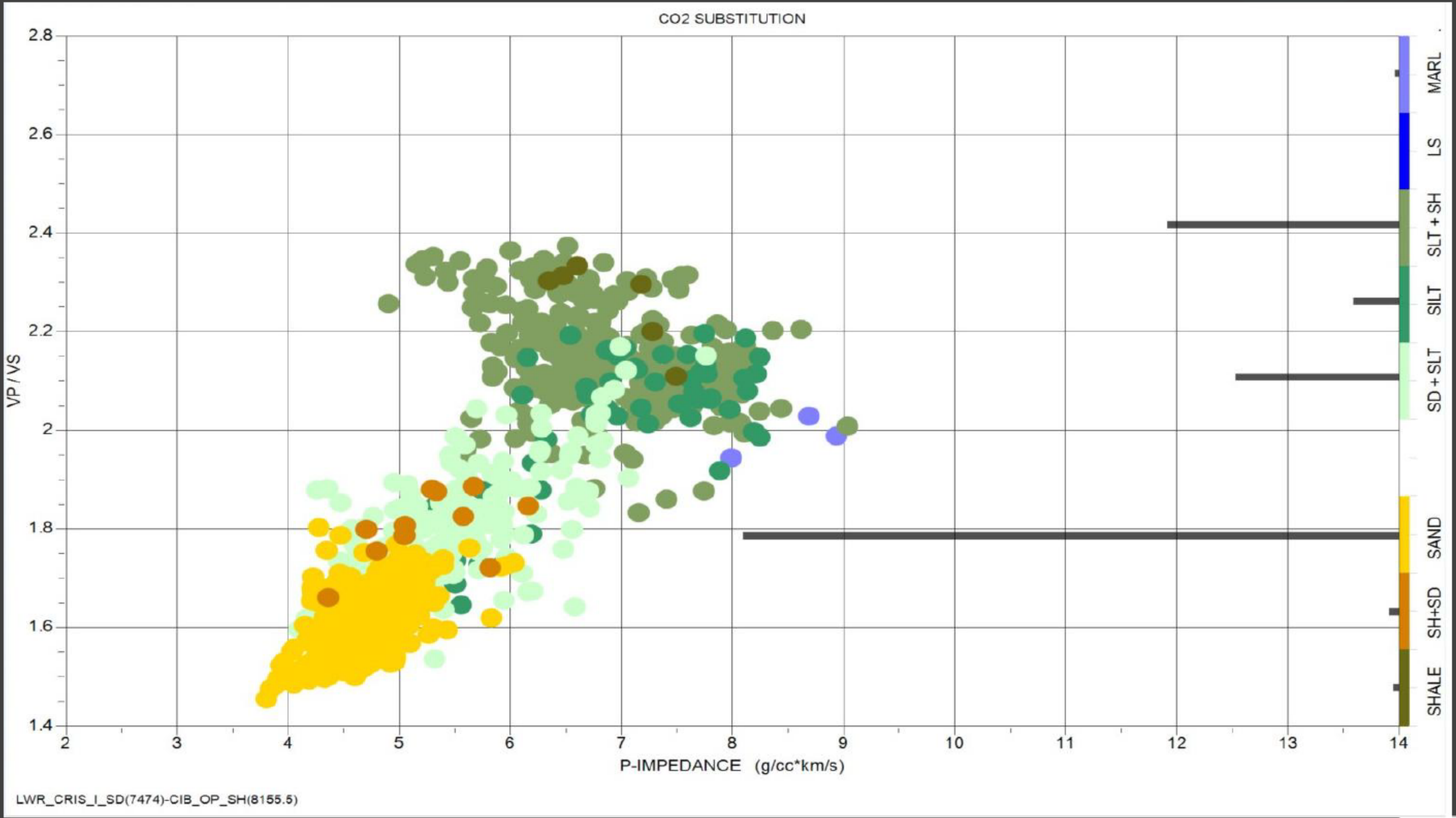
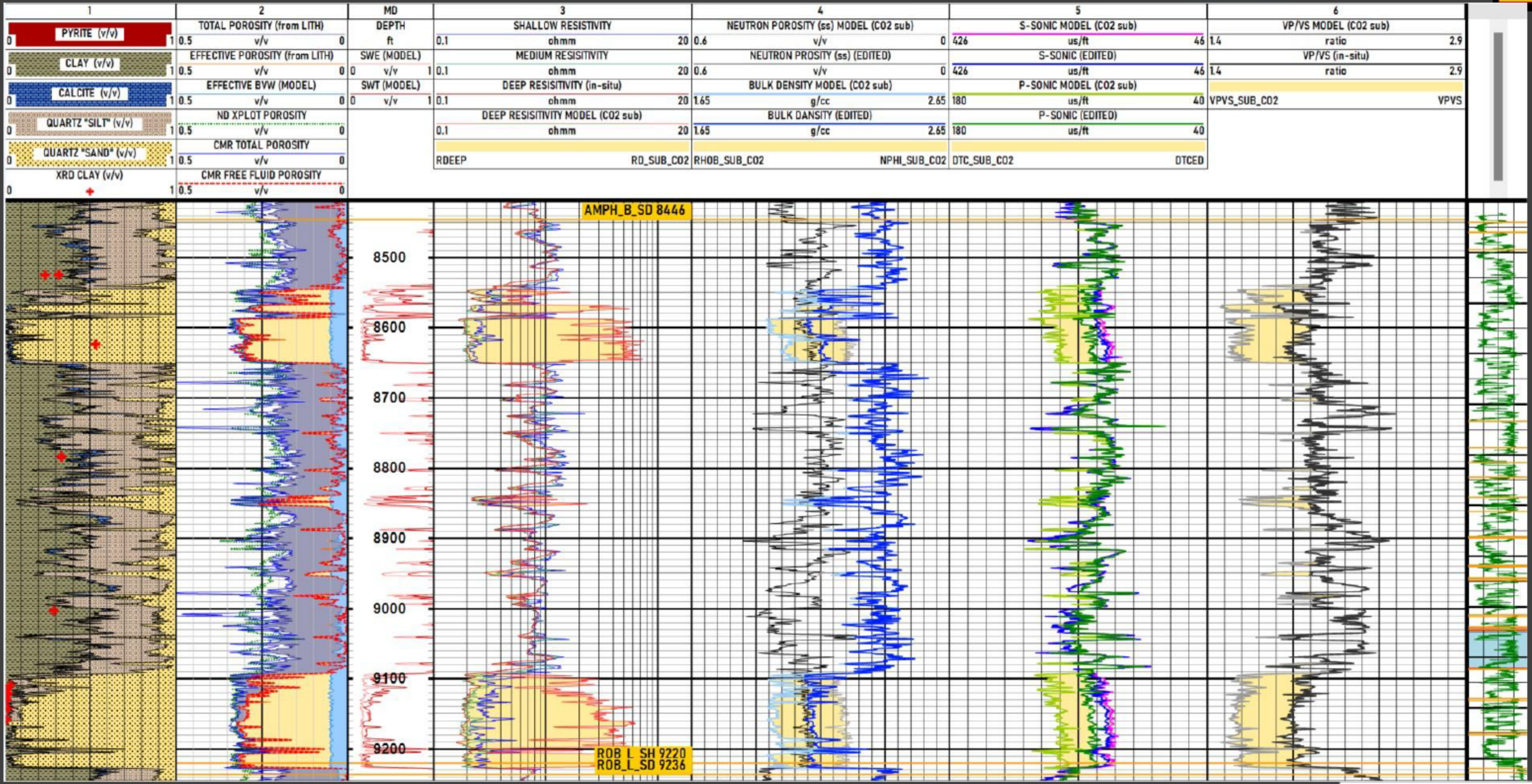
Lower Cris I Sand (CO_2 model)



ANK Geosciences

MODEL: Amph B Sand



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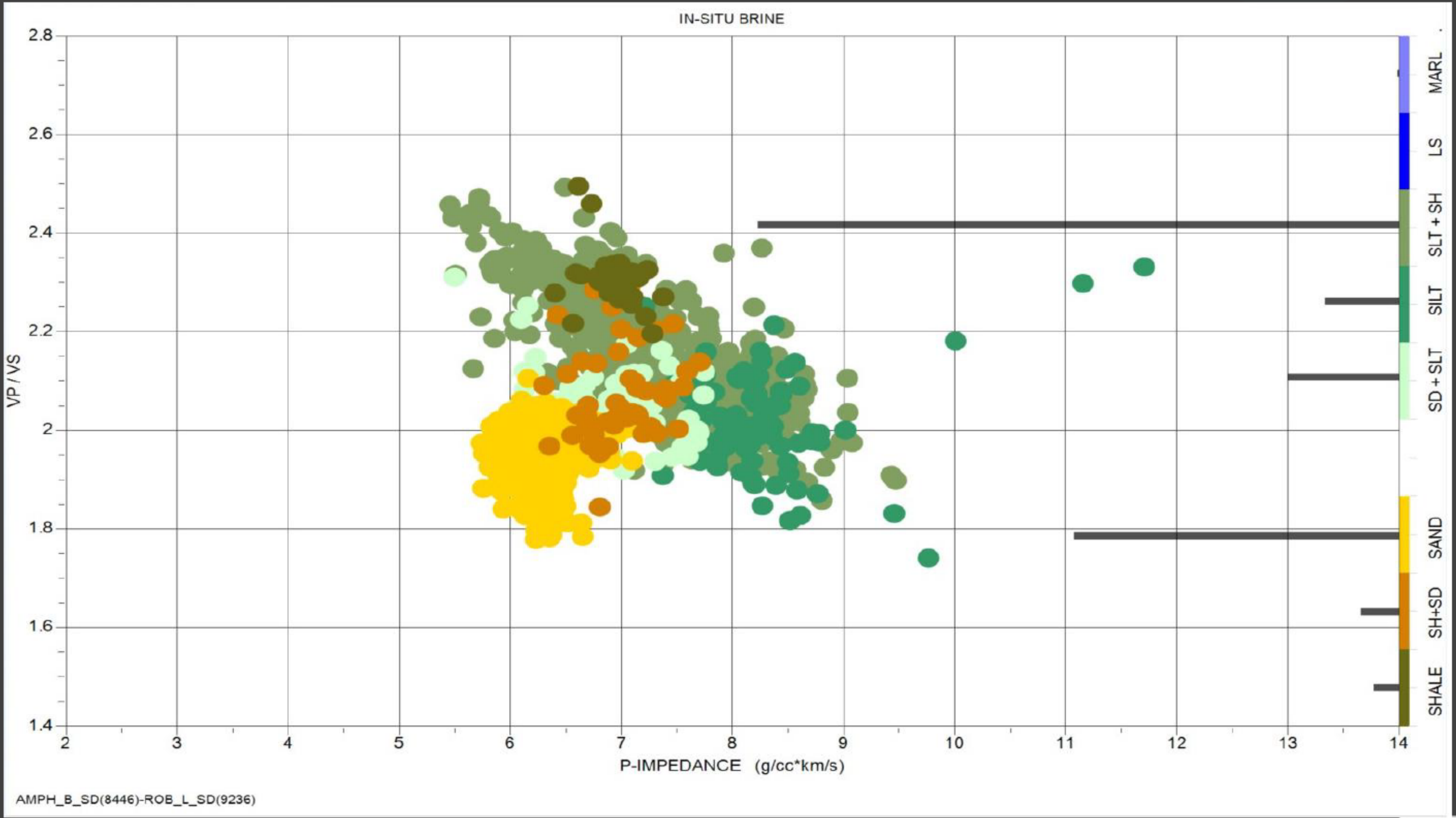
MODEL: Amph B Sand (in-situ brine)



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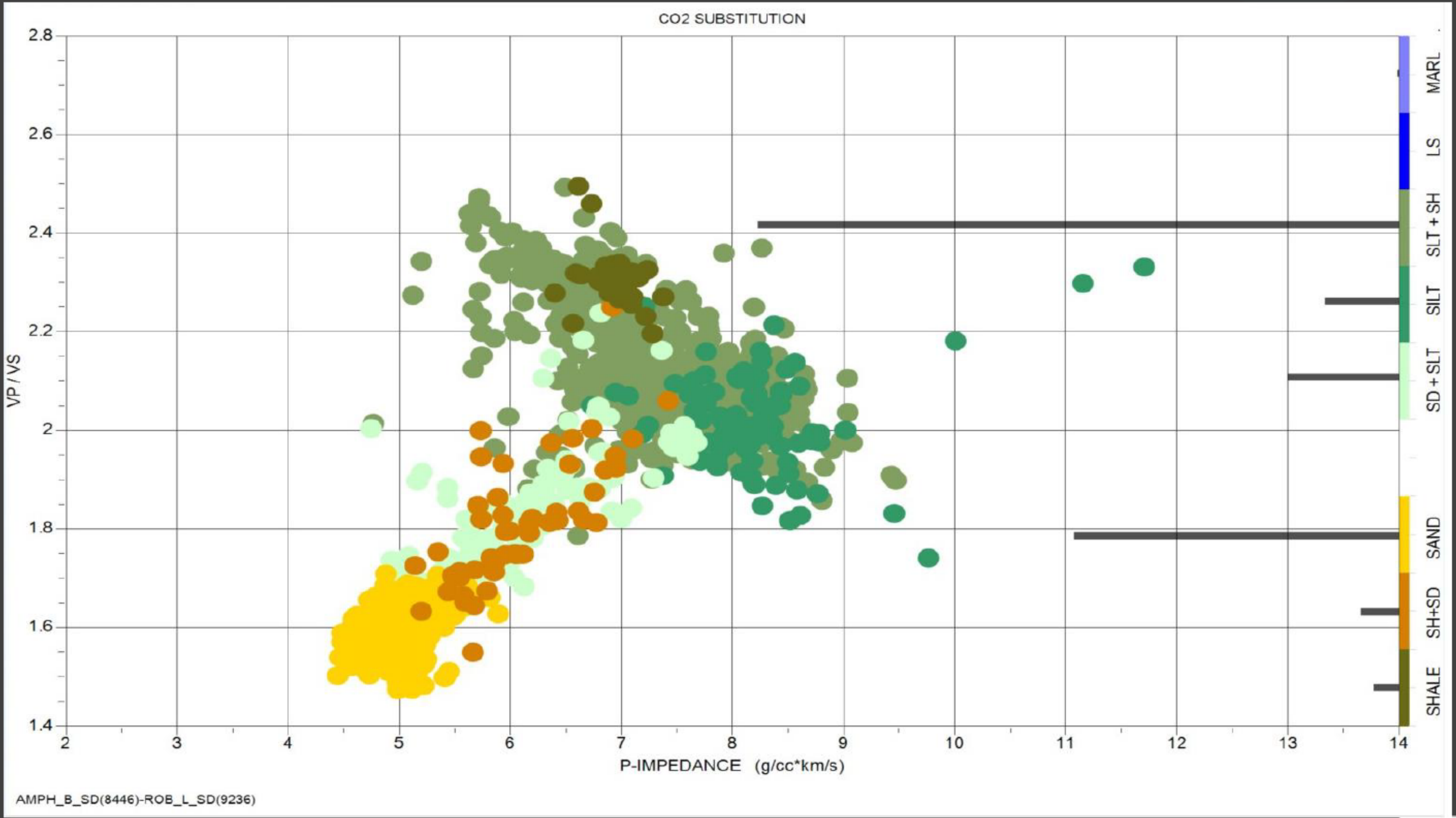
MODEL: Amph B Sand (CO_2 model)



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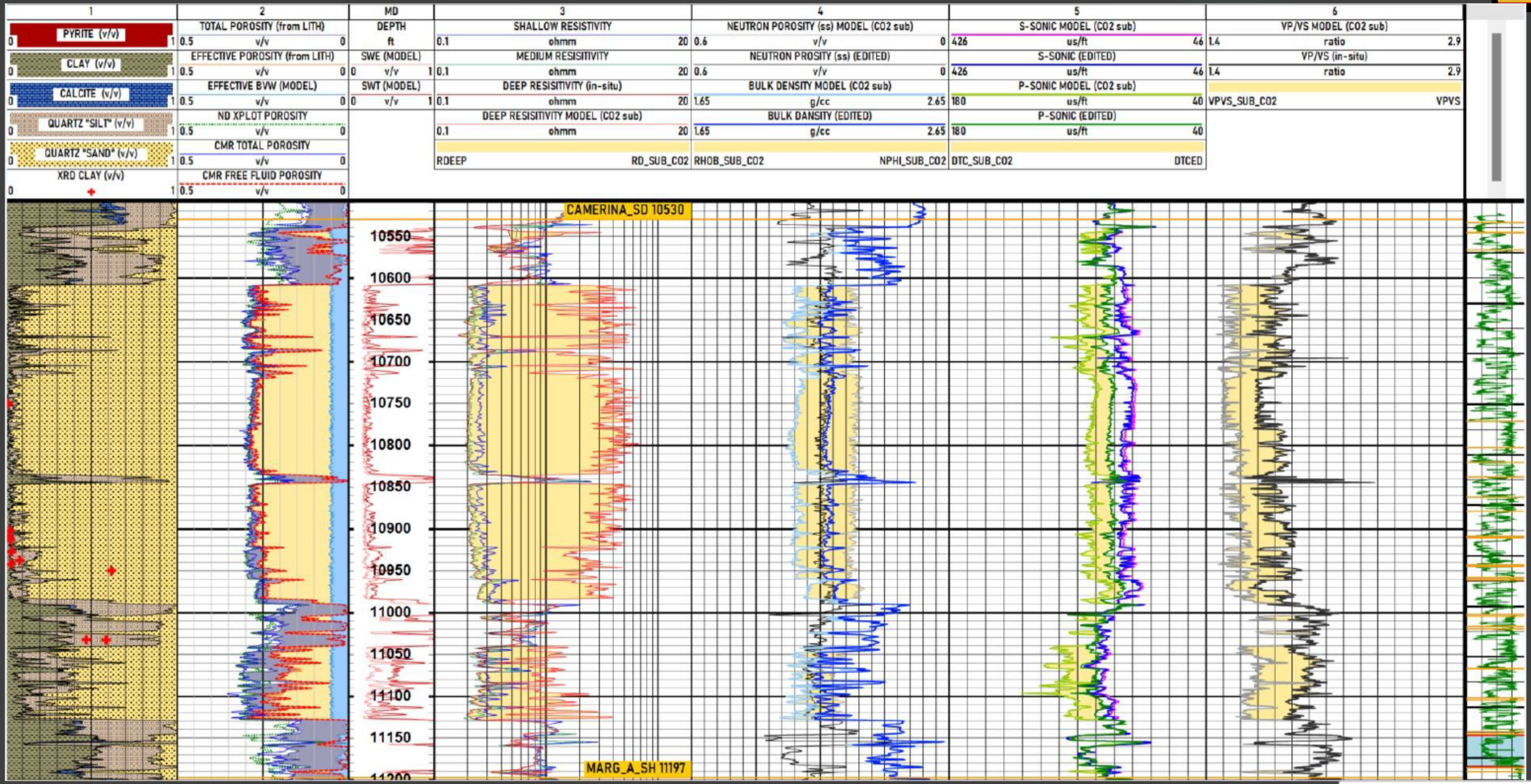
MODEL: Camerina Sand



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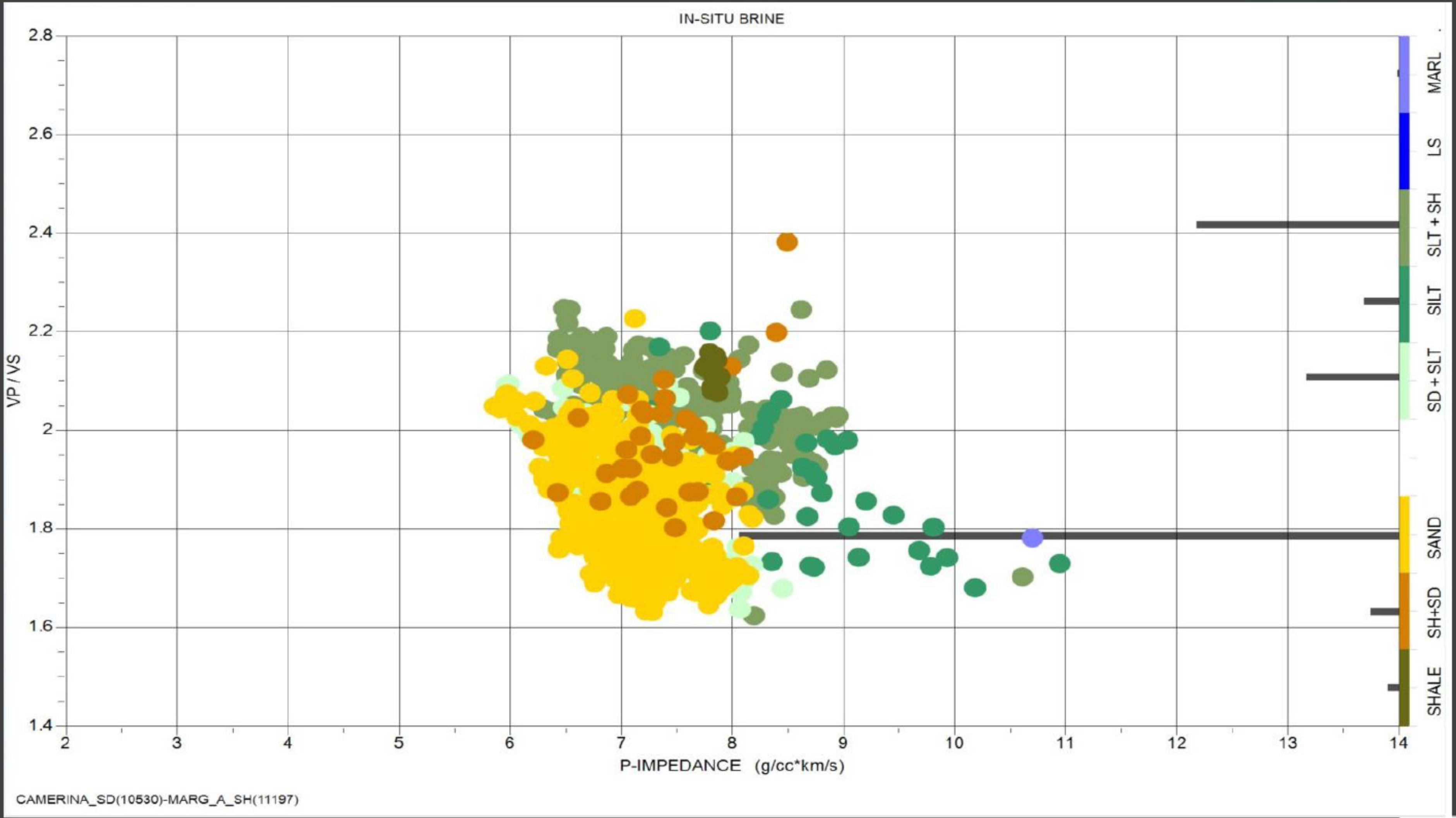
MODEL: Camerina Sand (in-situ brine)



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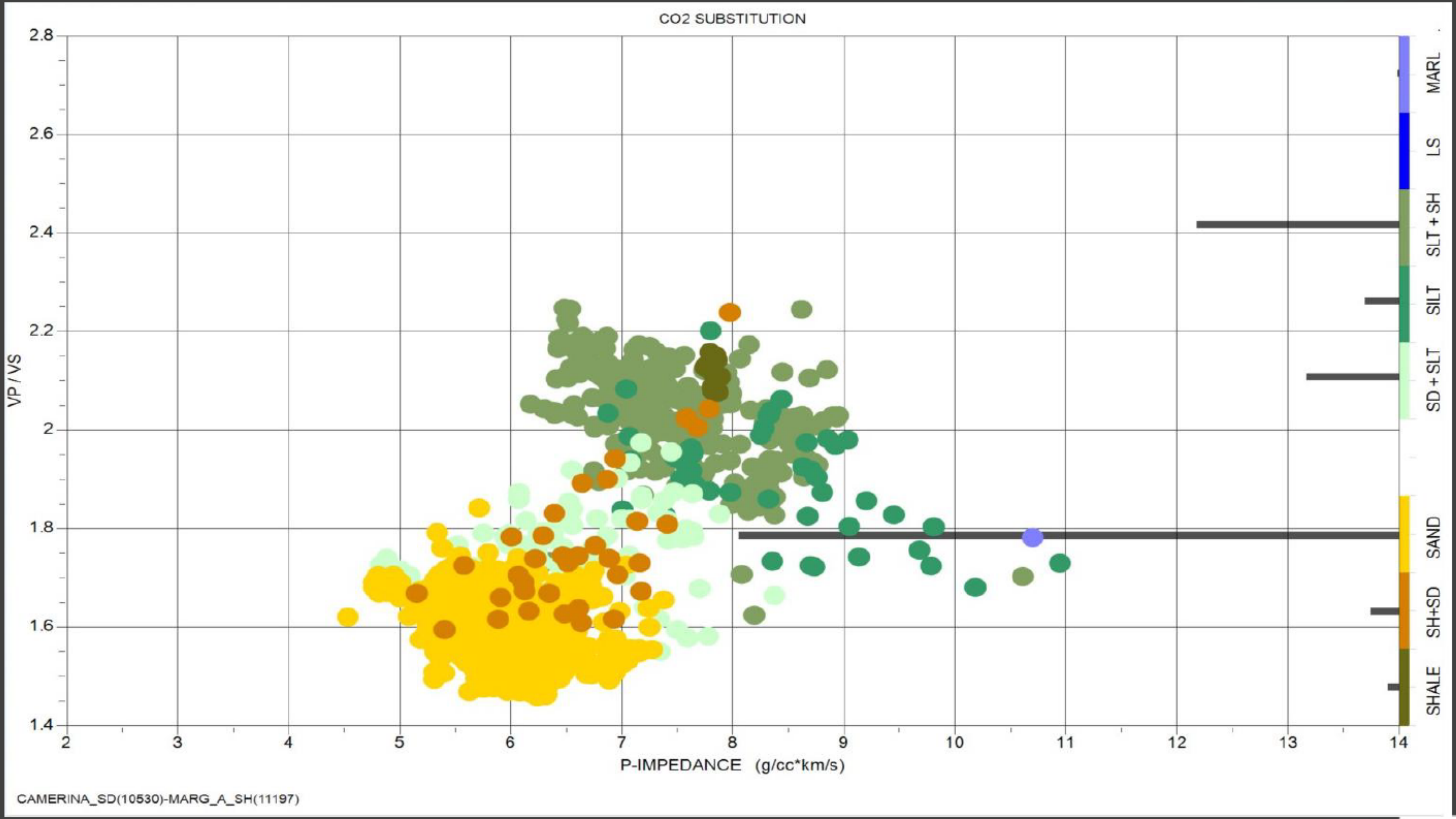
MODEL: Camerina Sand (CO_2 model)



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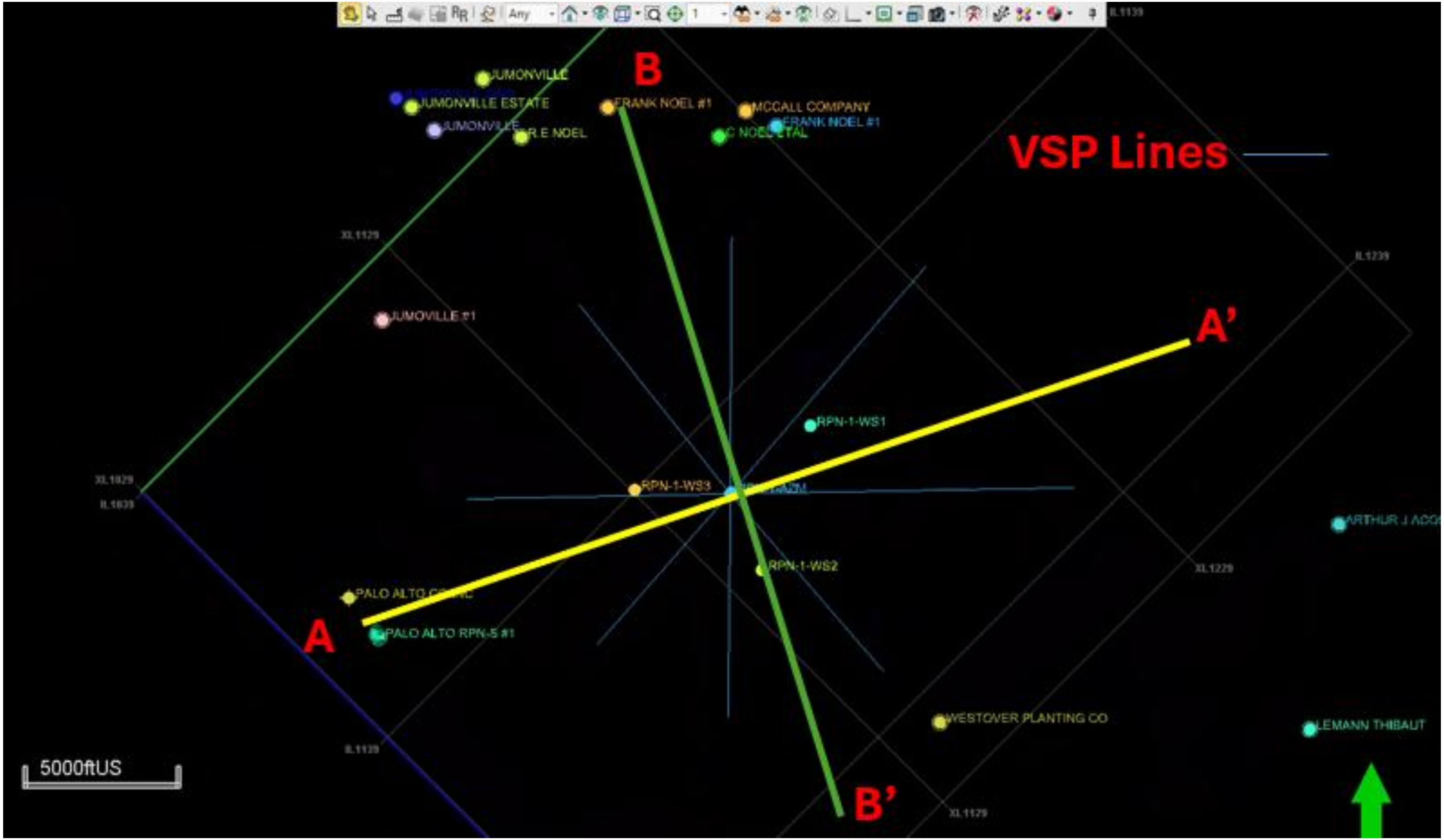
Preliminary VSP Ray Tracing and Finite Difference Modeling

Nominal 2D Walkaway/Offset VSP Lines



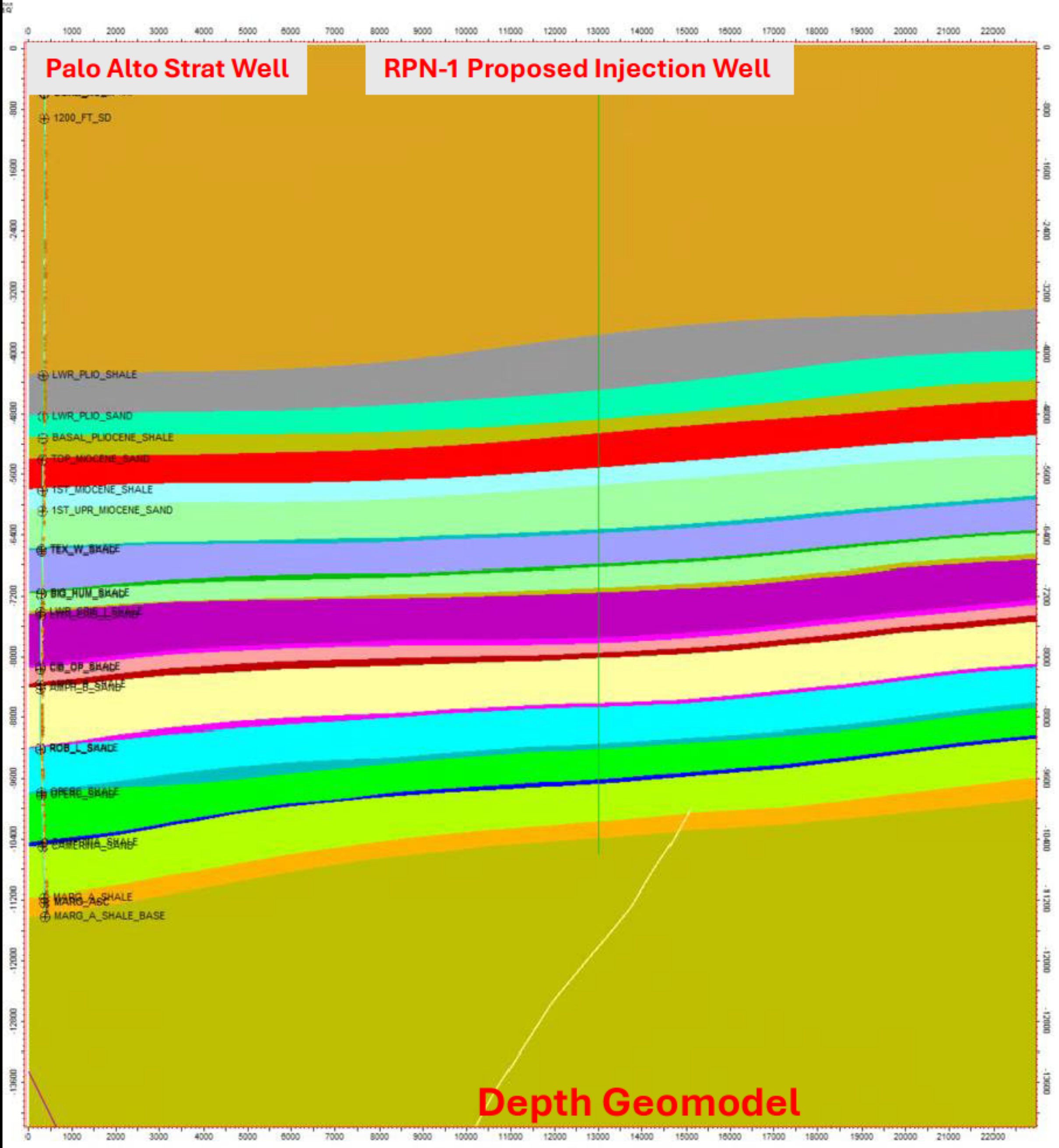
Line AA' Cross Section

A A'

Claimed as PBI

[redacted]

A A'

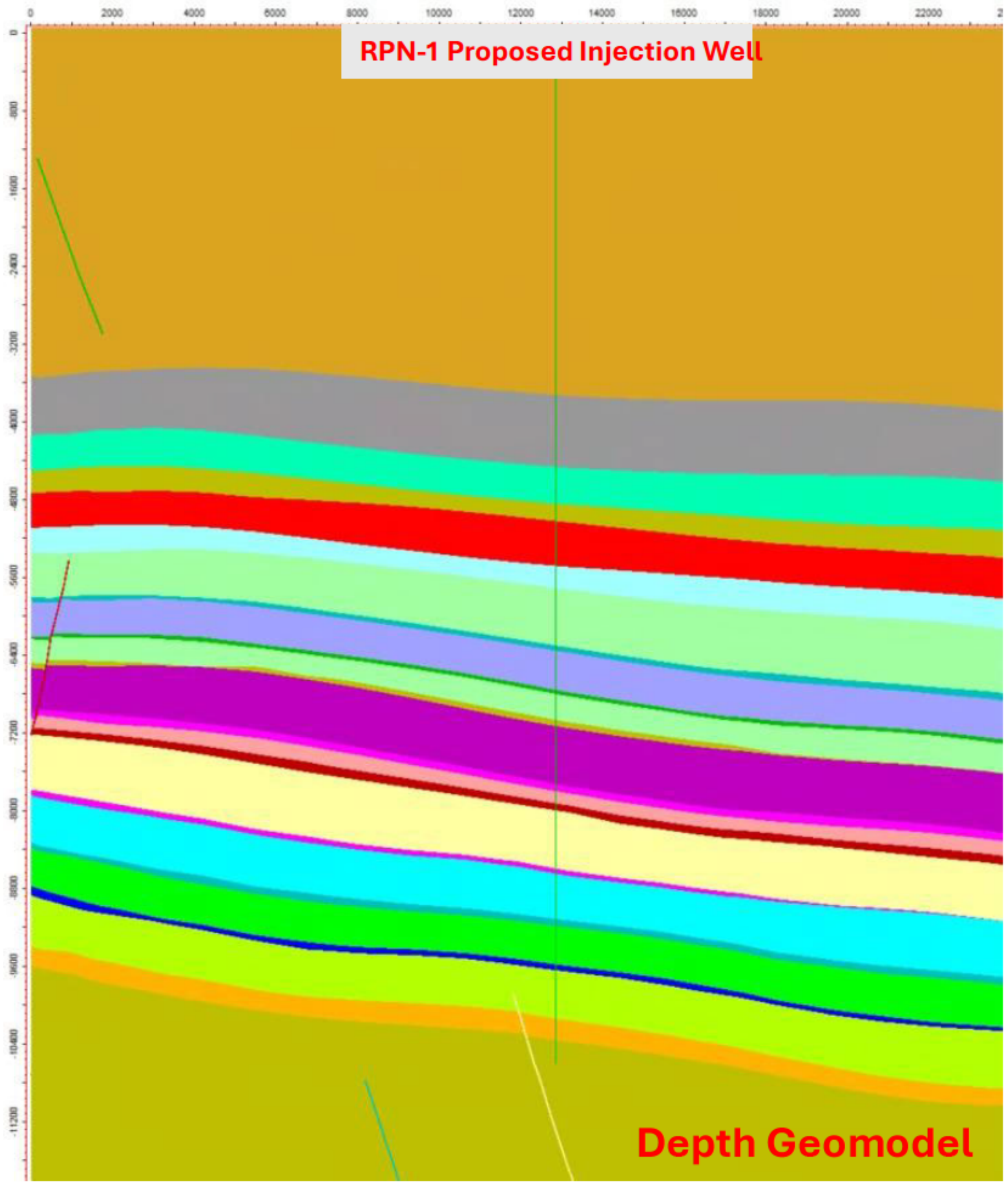


Line BB' Cross Section

B B'

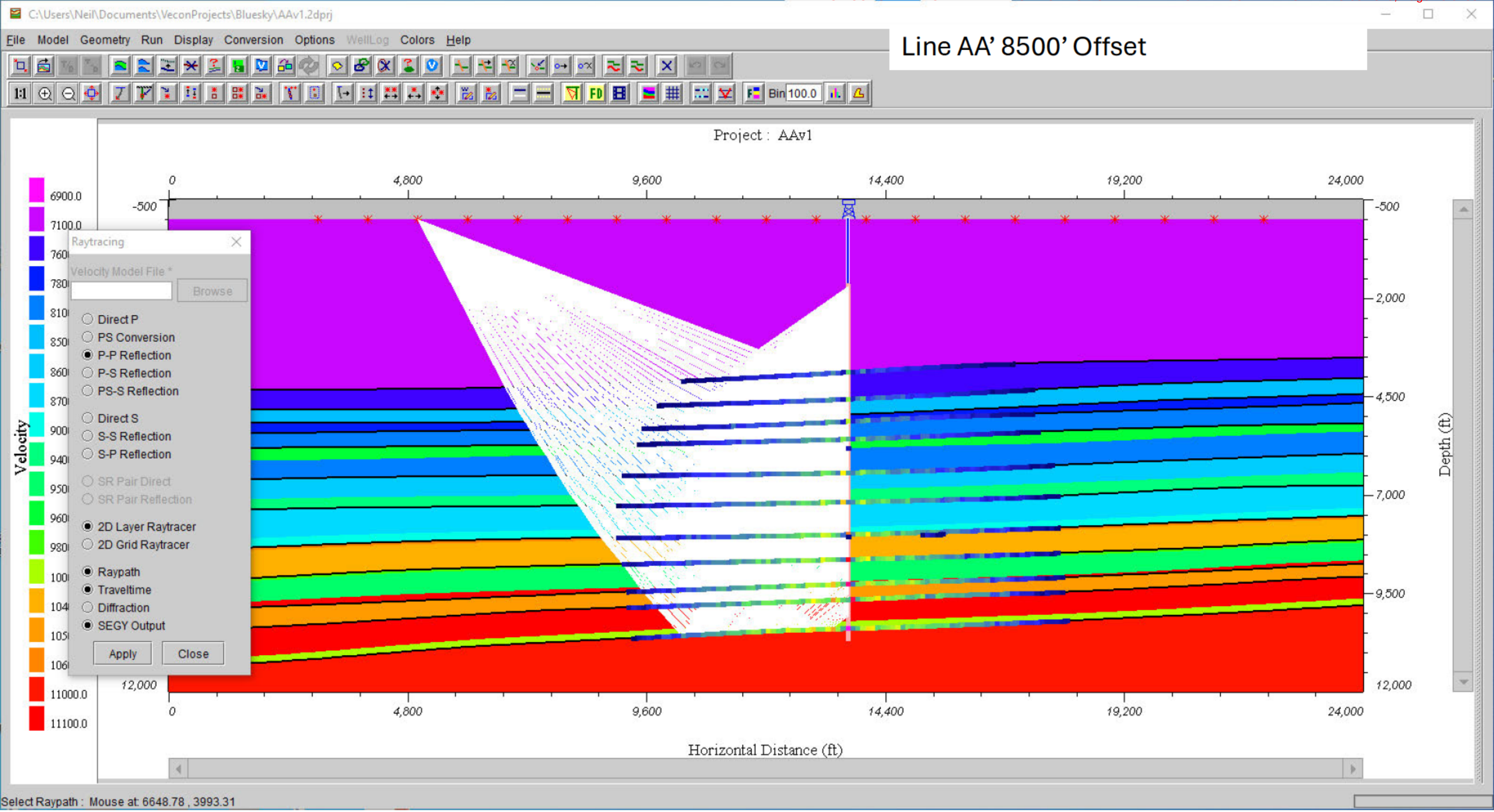
Claimed as PBI

[redacted]



Line AA’

- Sources set at 1000’ intervals along the surface
- DAS fiber set at TD to 1650’ in the well @ 25’ intervals
- Representative layers picked for reflections at all main formations.
- Seismic displays are ray traced reflectivities convolved with 35 Hz Ricker to show event continuity and travel times. Used to evaluate distortion in the first arrival and reflection times to assess maximum useful offset range.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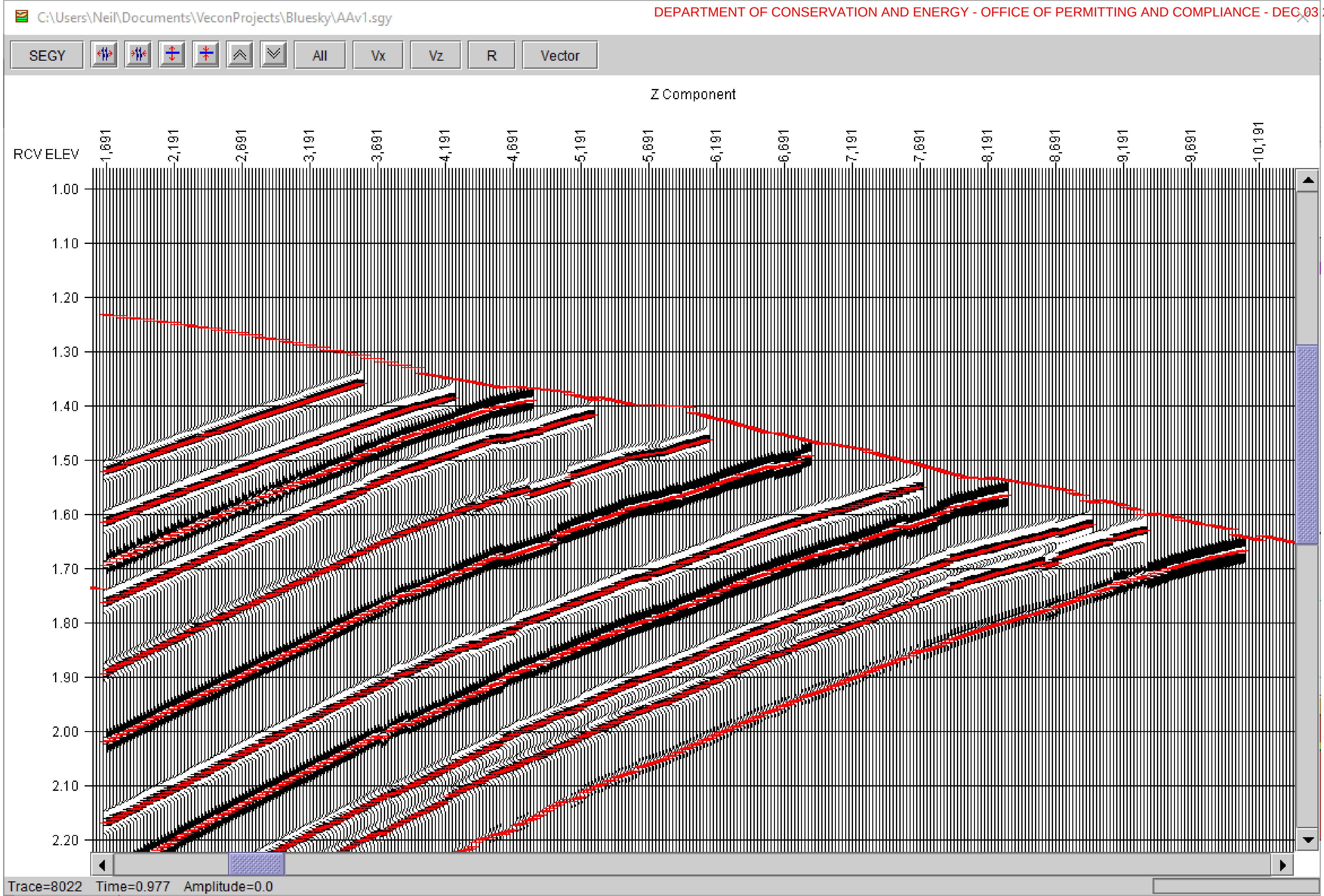
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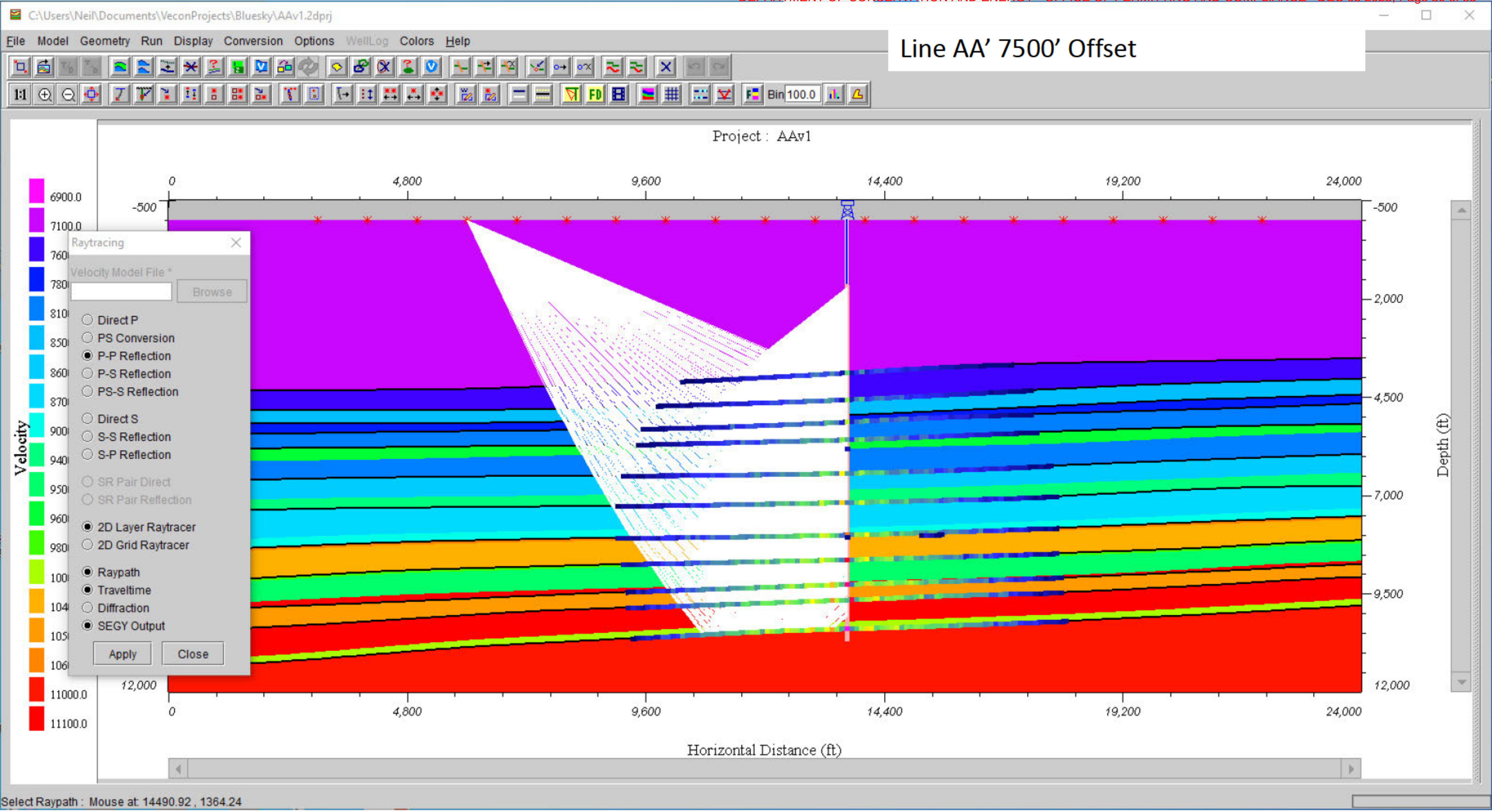

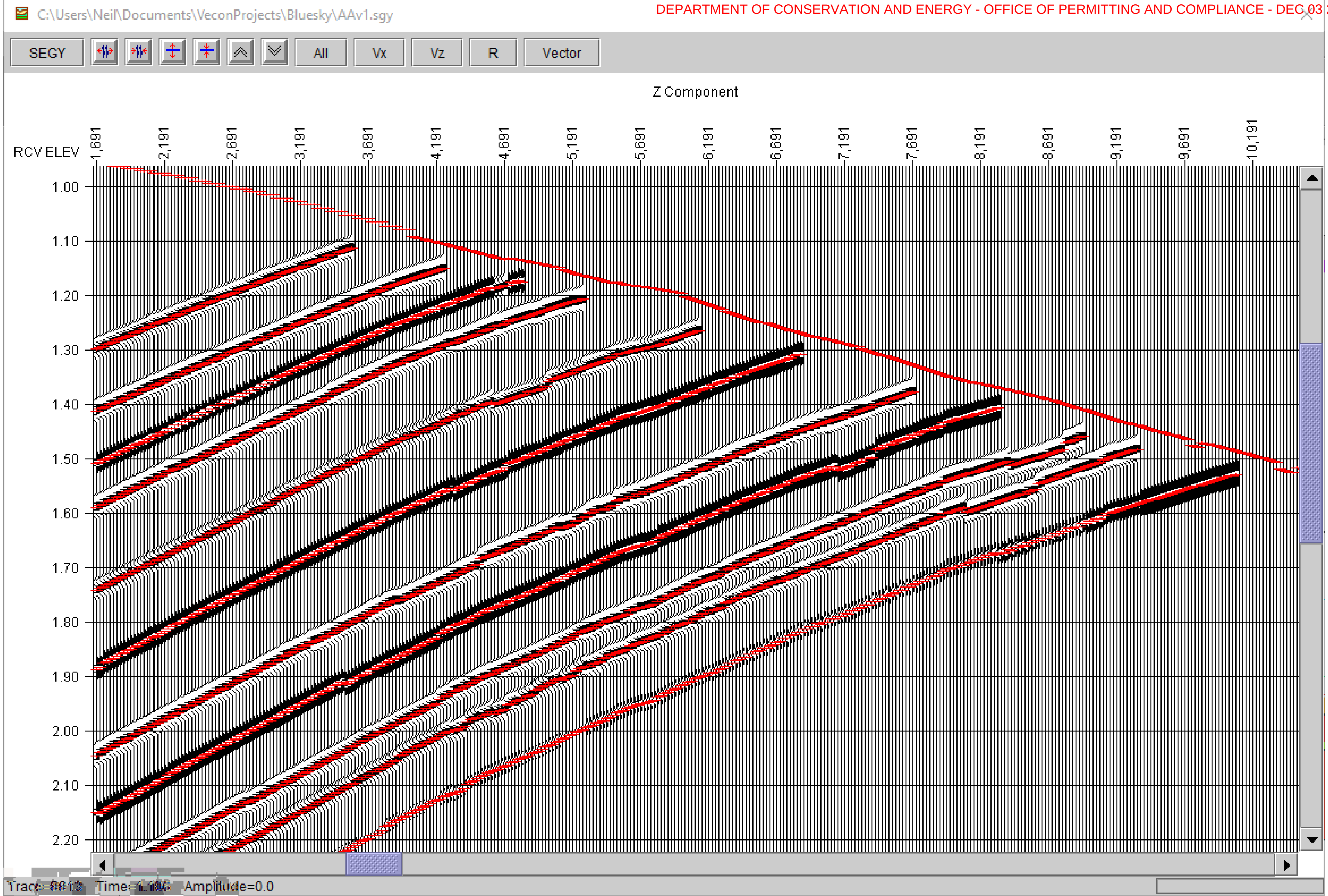
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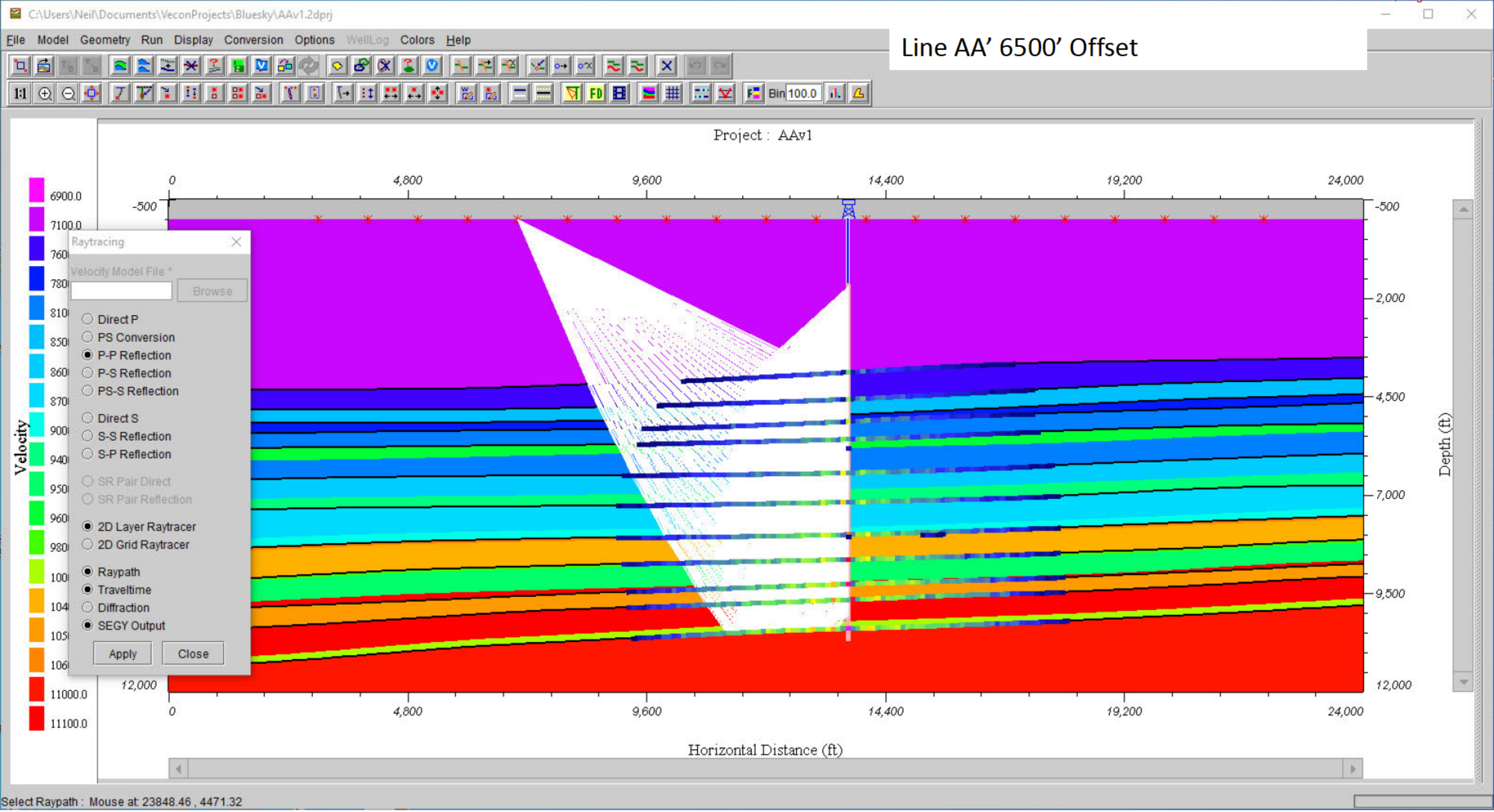
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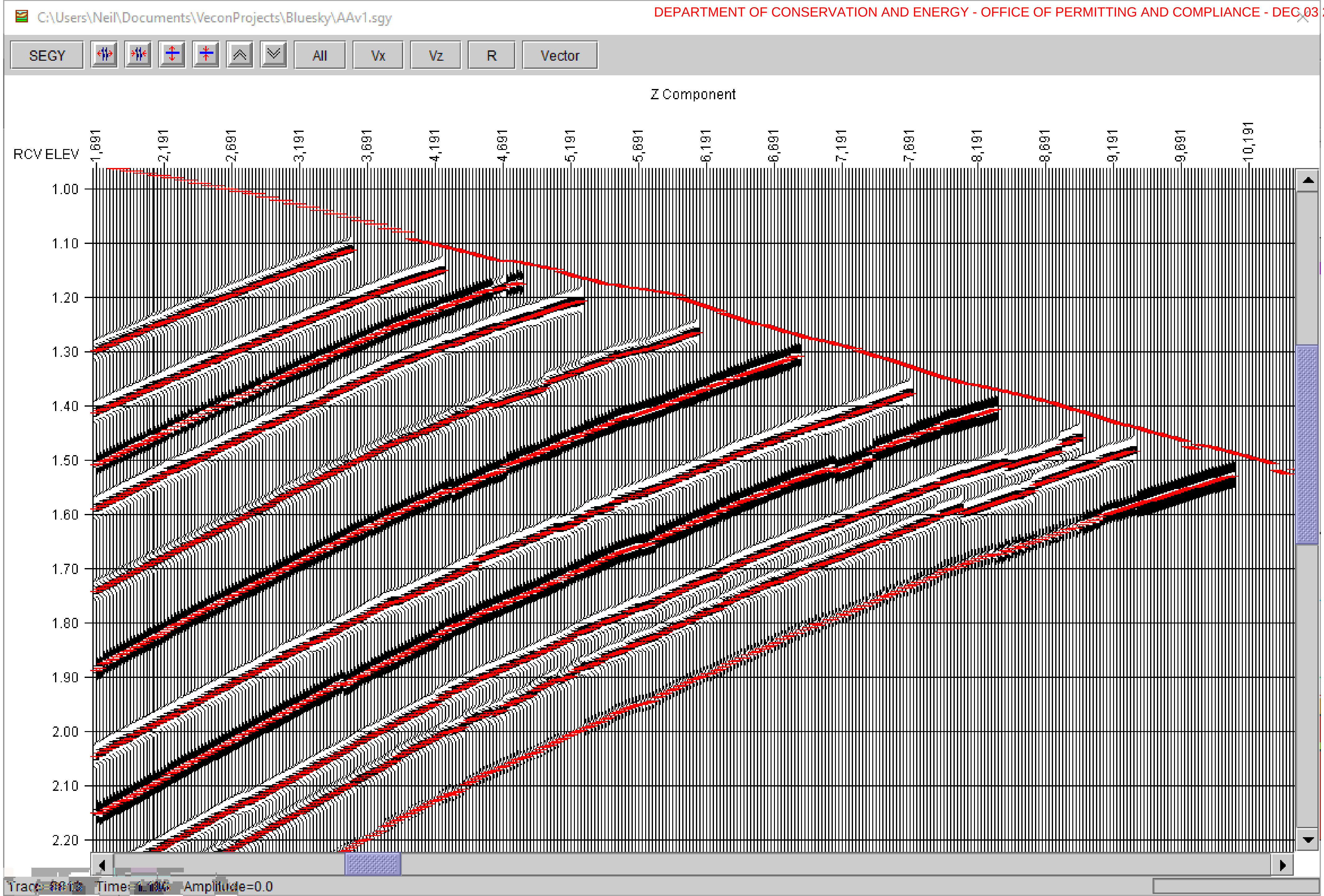
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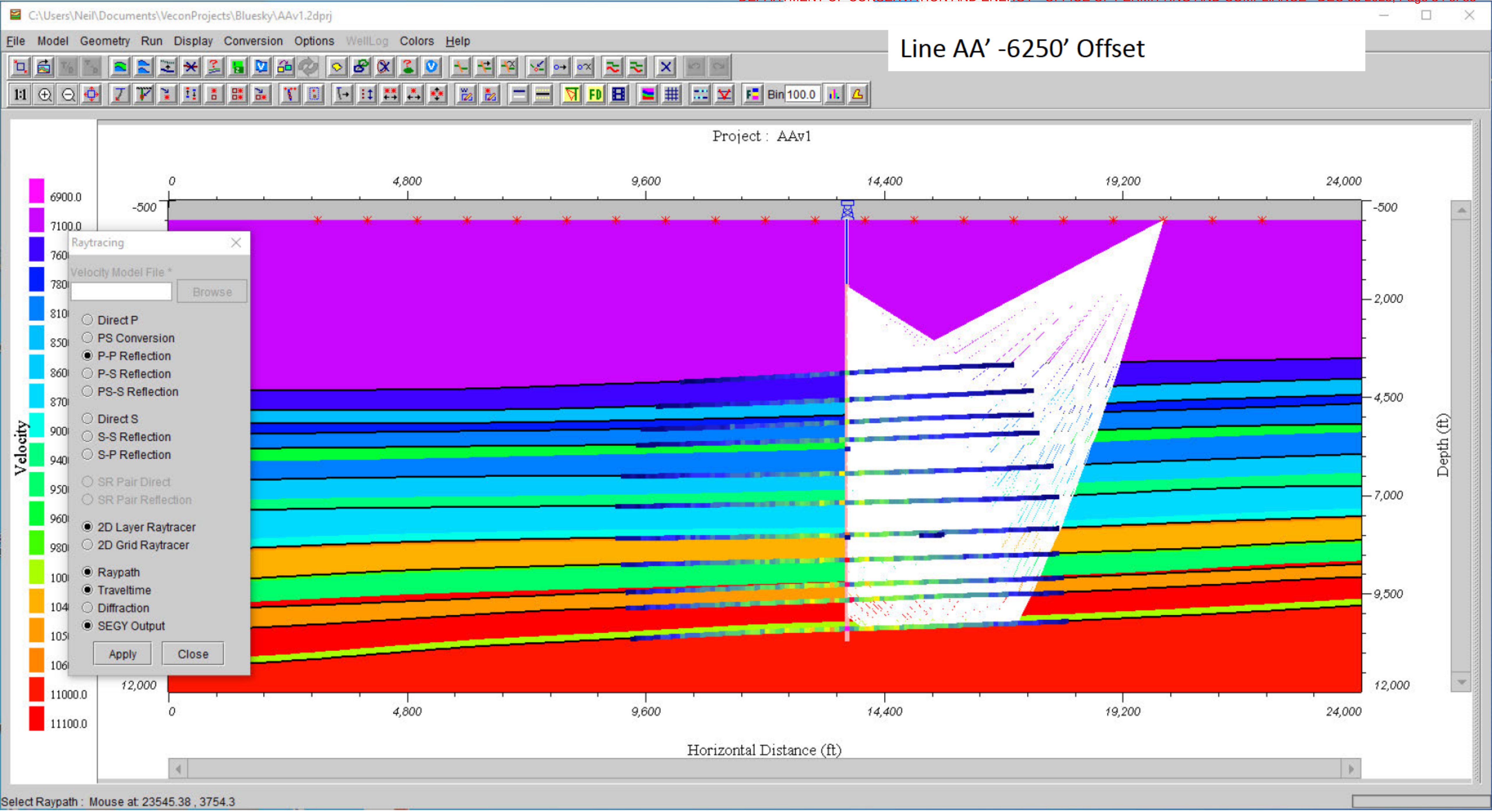

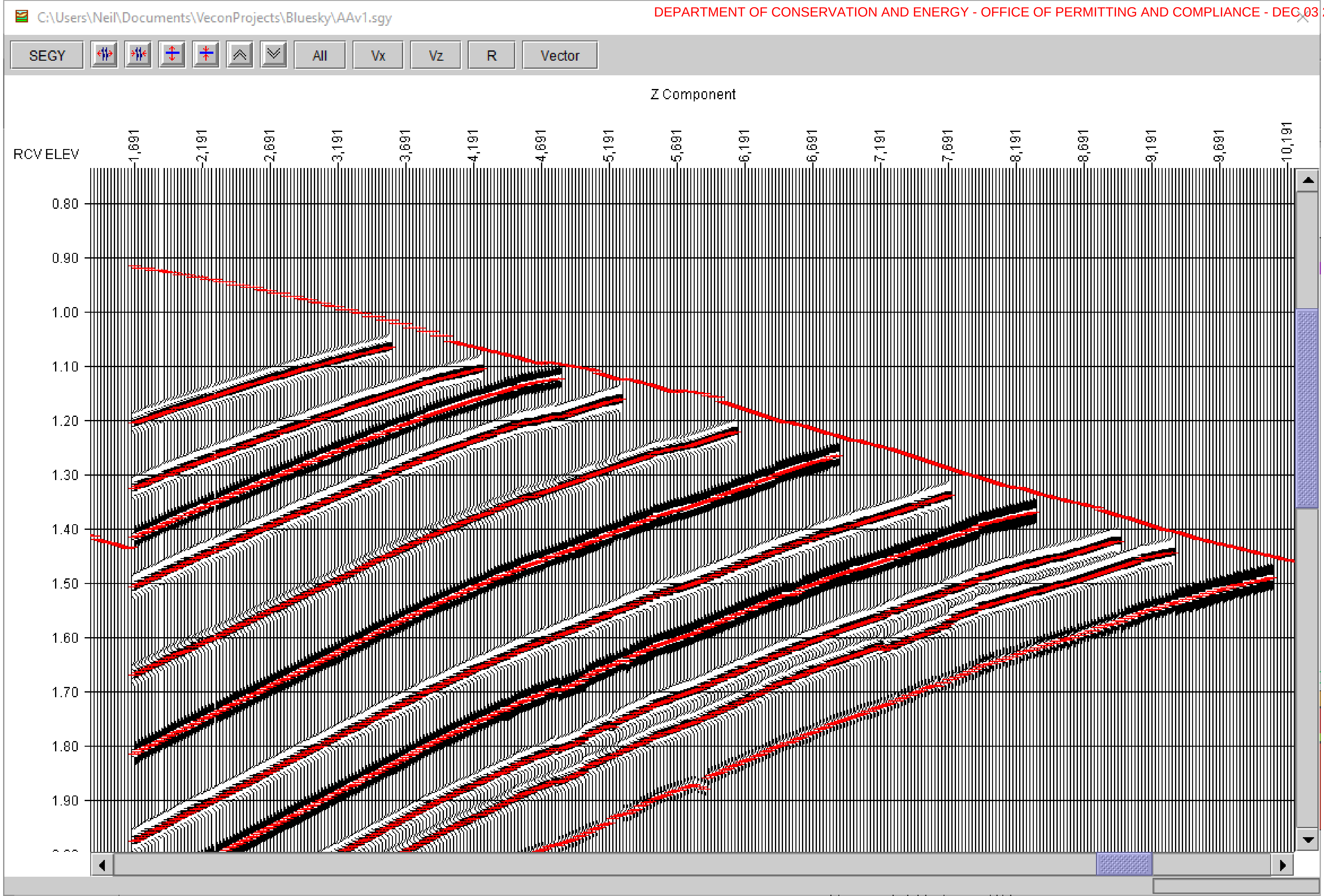
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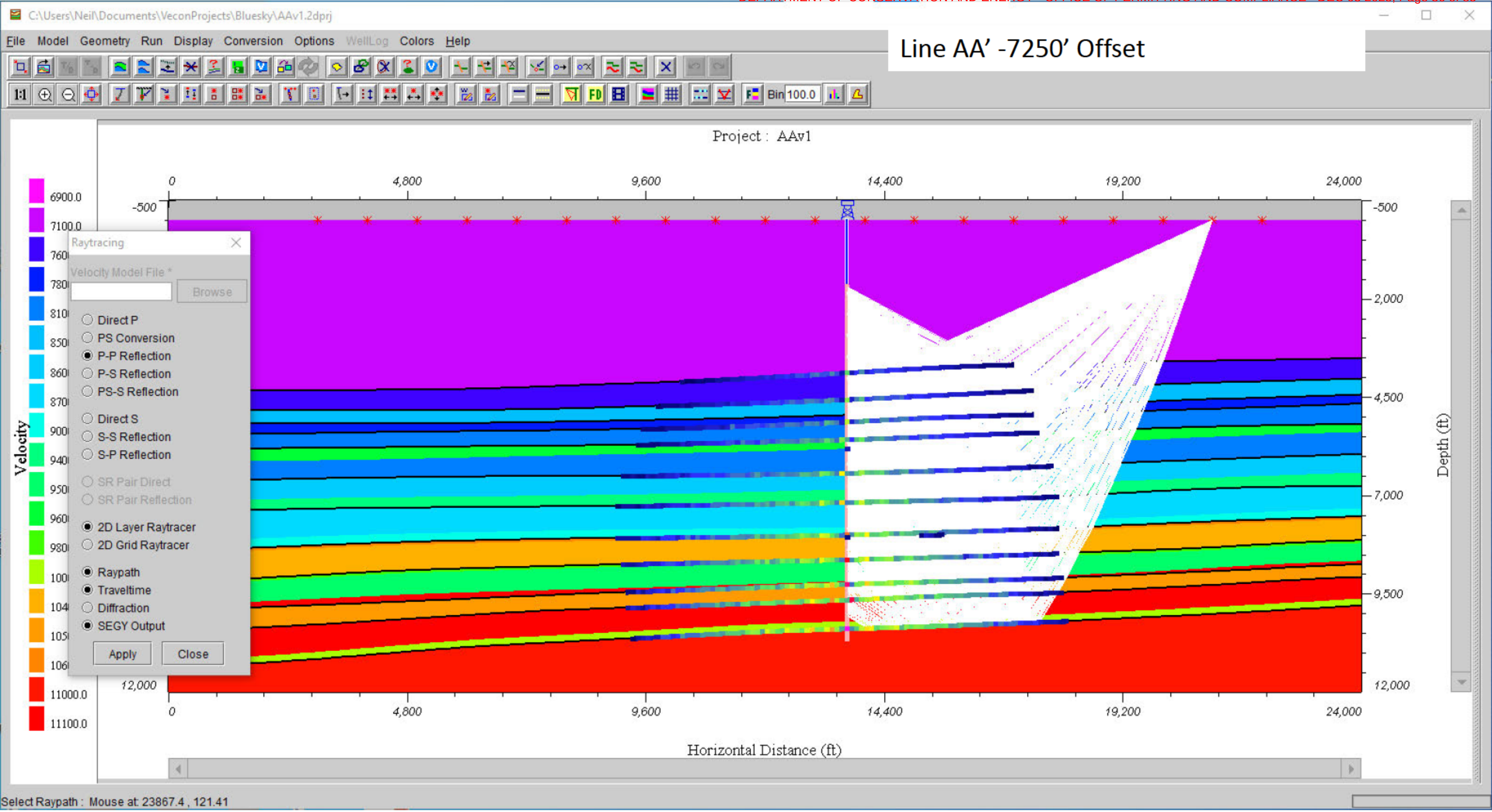
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Horizontal Distance (ft)
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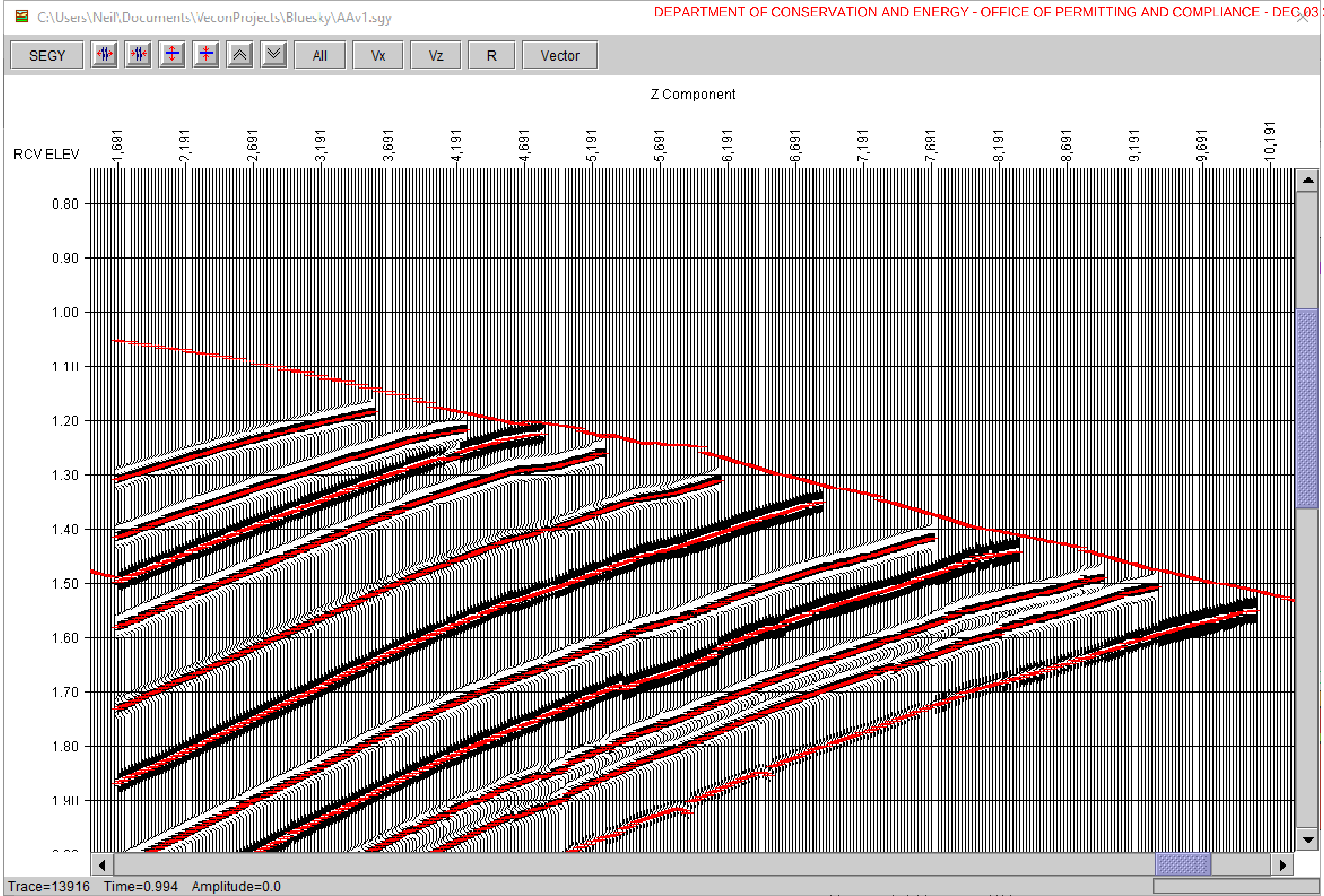

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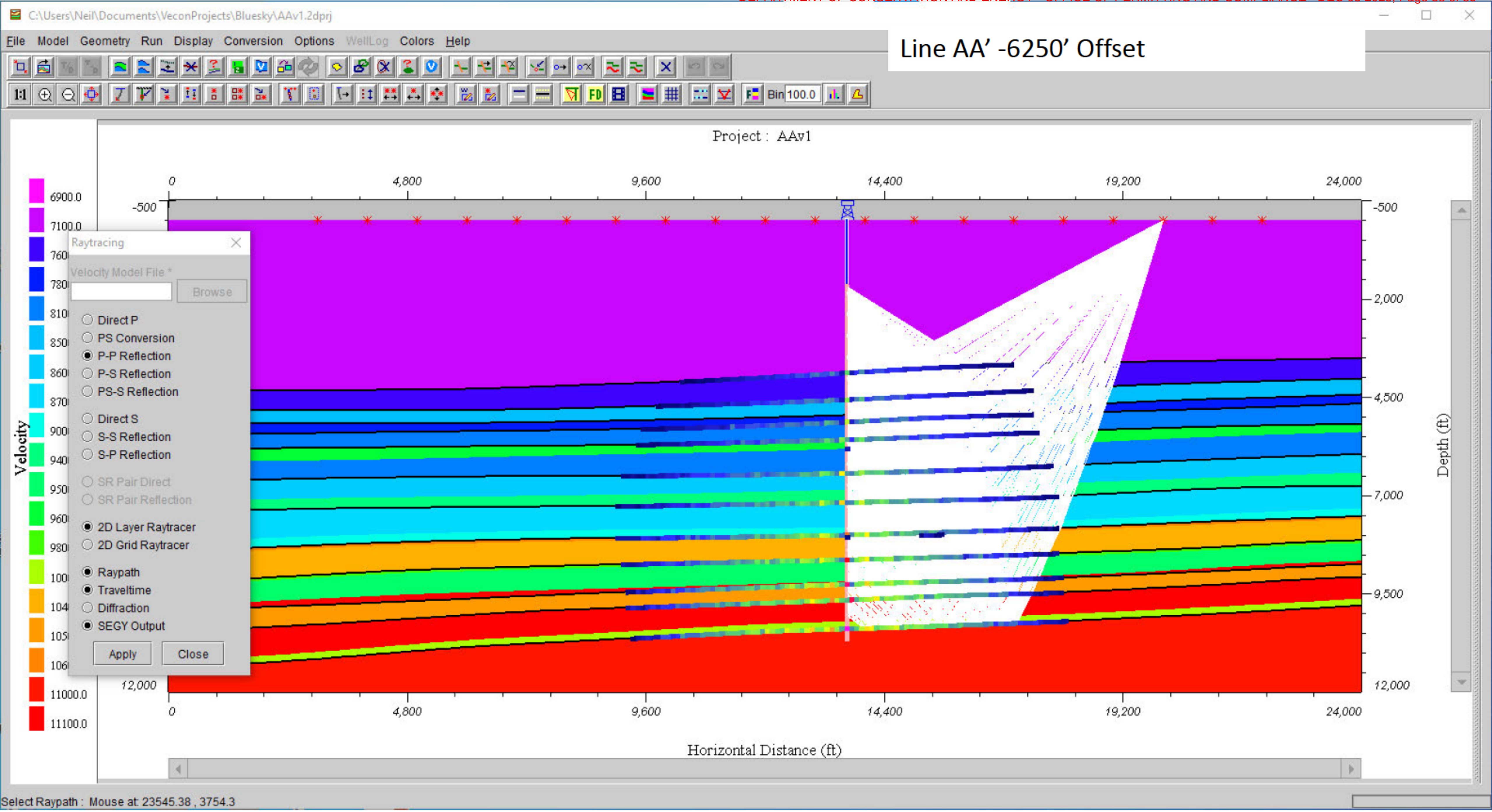

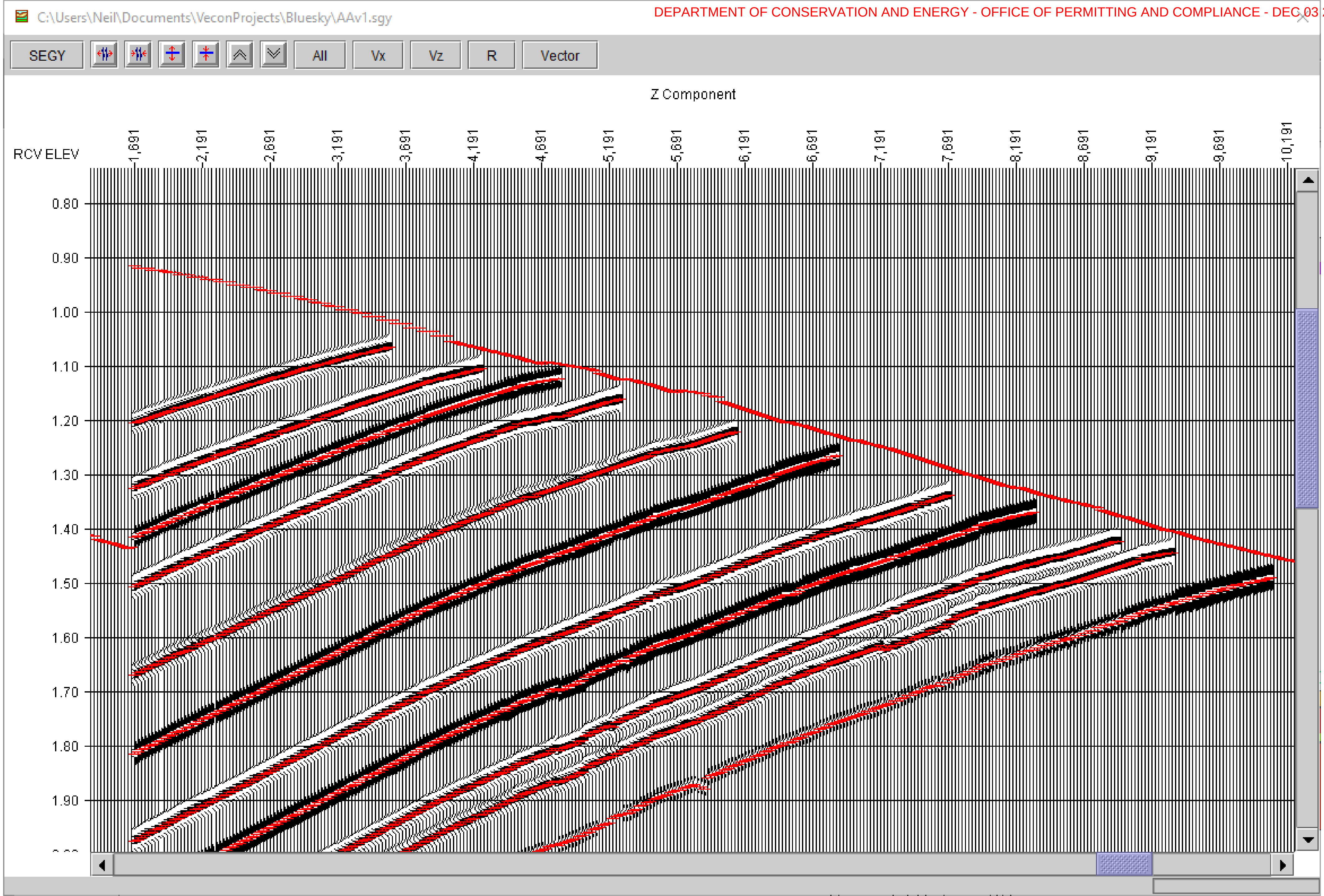
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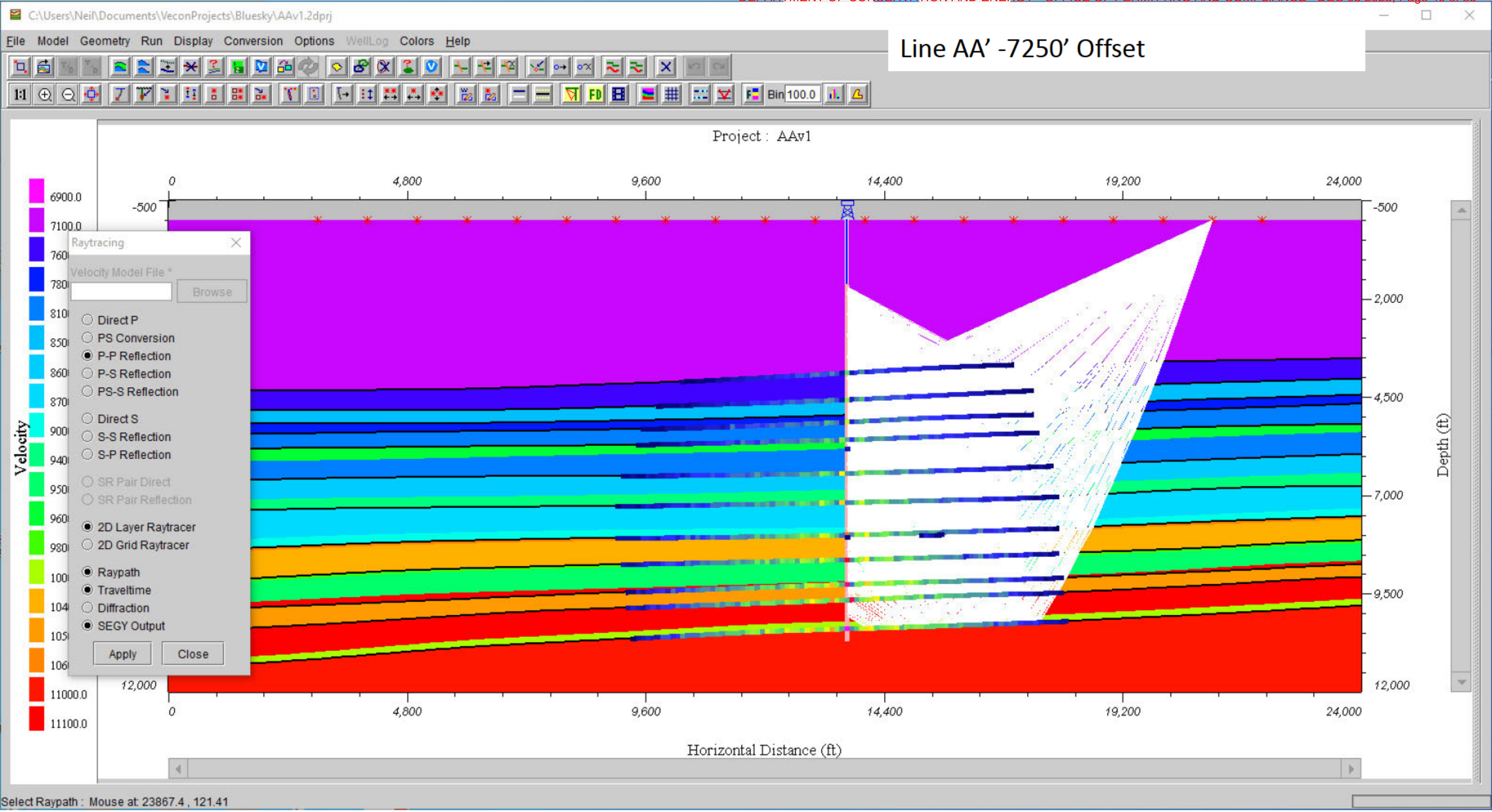

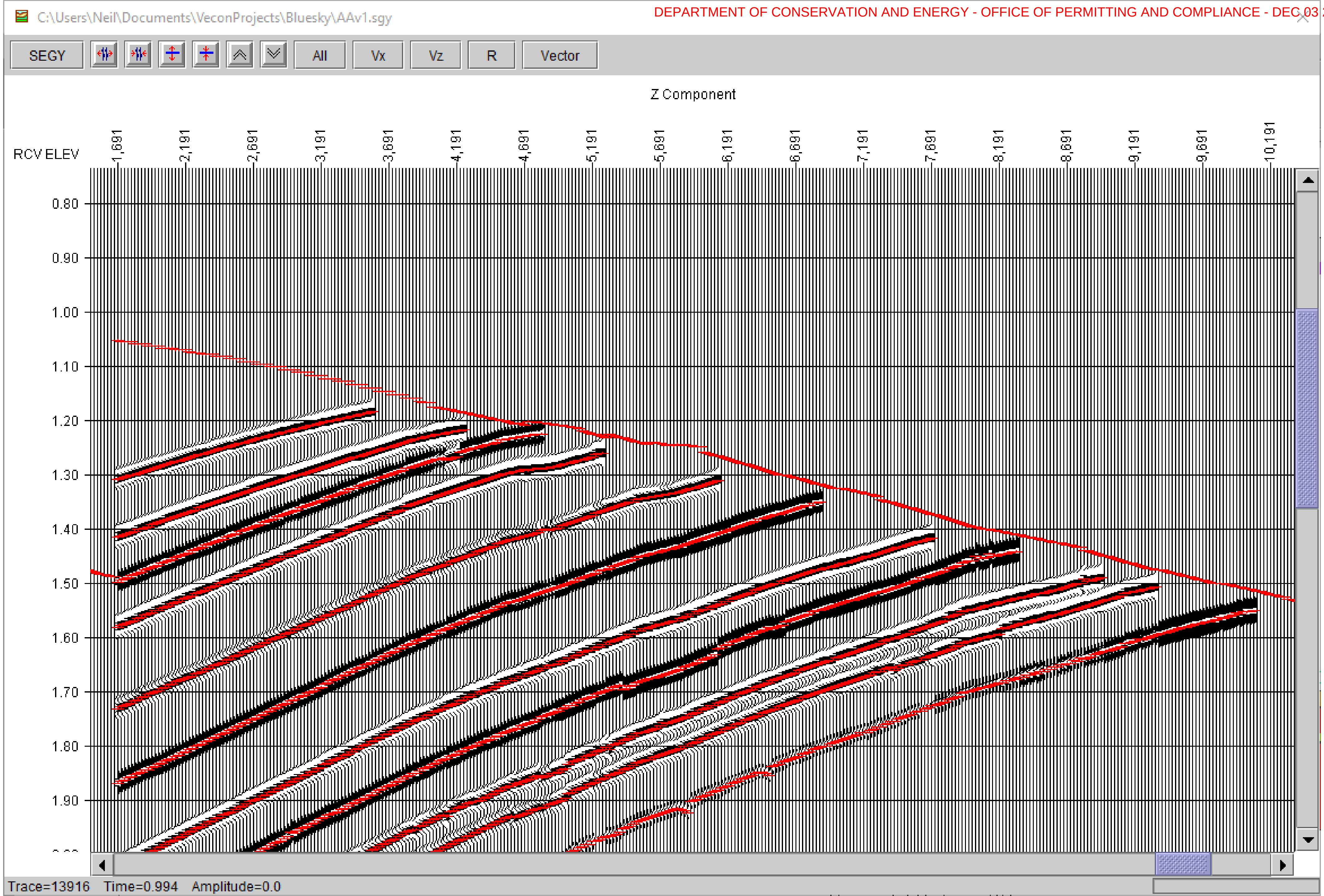
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Vector
Z Component
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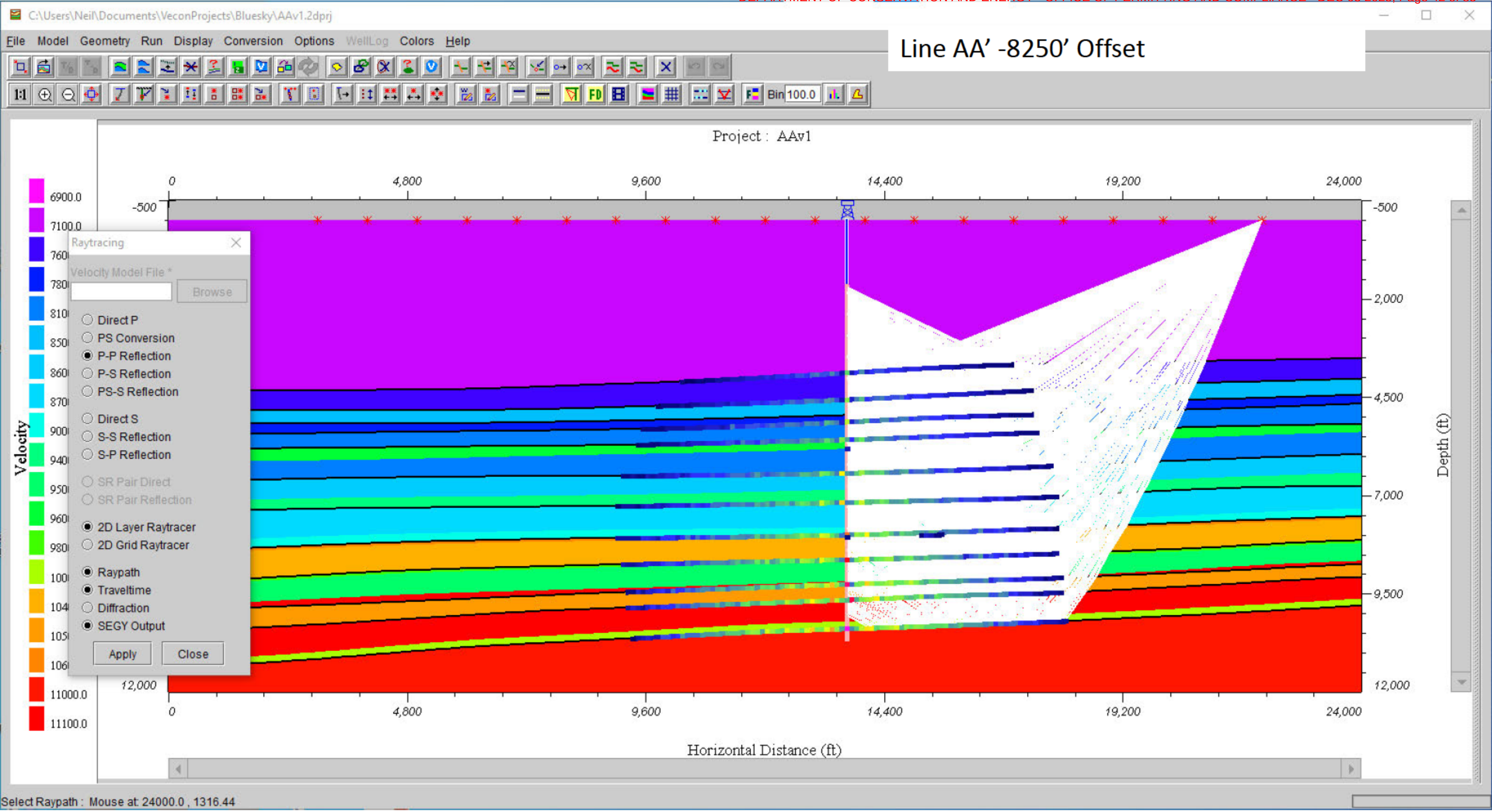

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Raytracing
Velocity Model File *
Browse
Direct P
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P-P Reflection
P-S Reflection
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S-P Reflection
SR Pair Direct
SR Pair Reflection
2D Layer Raytracer
2D Grid Raytracer
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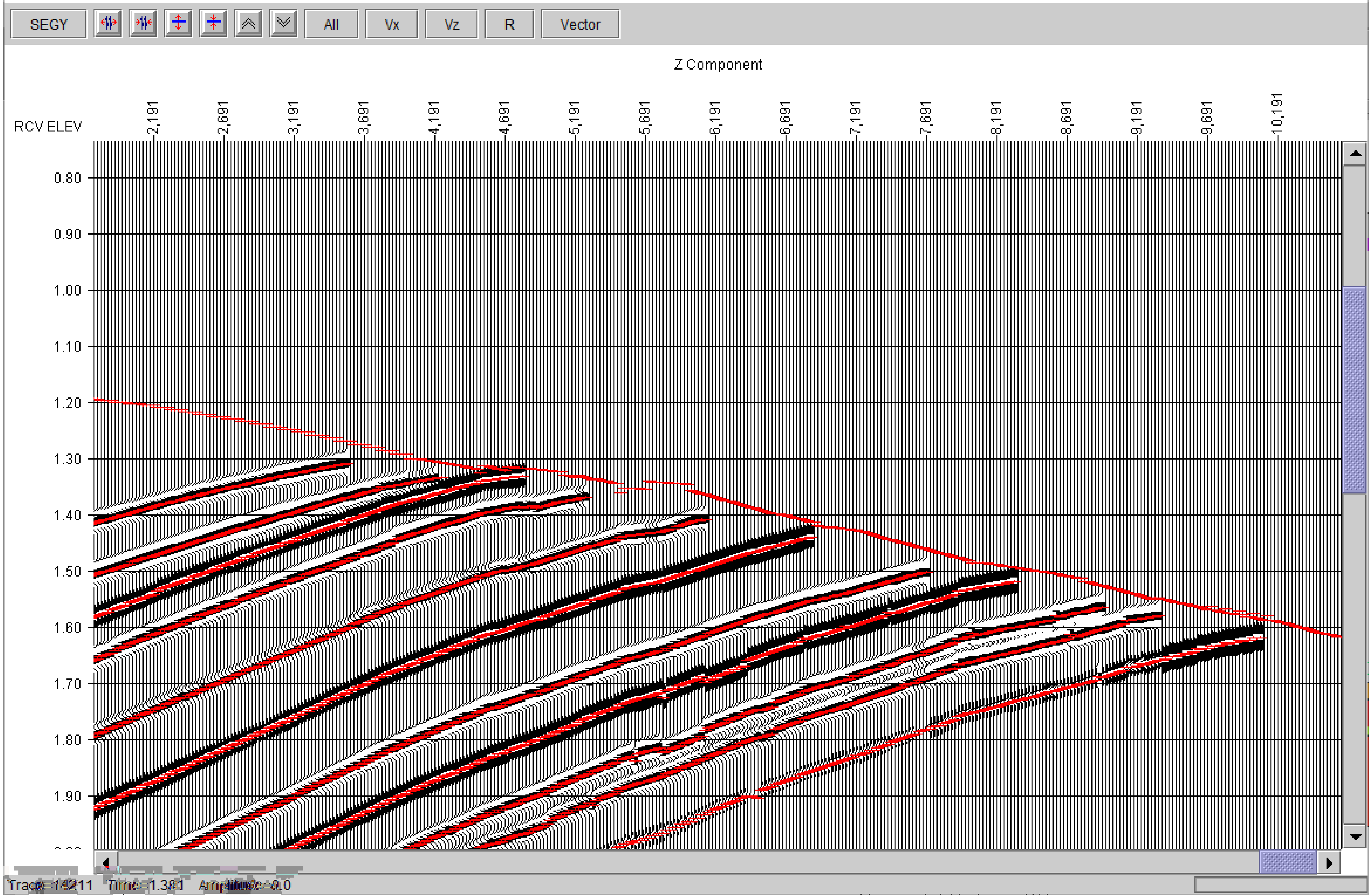
4,800
9,600
14,400
19,200
24,000
-500
2,000
4,500
7,000
9,500
12,000
Depth (ft)
Horizontal Distance (ft)
Select Raypath : Mouse at: 24000.0 , 1316.44

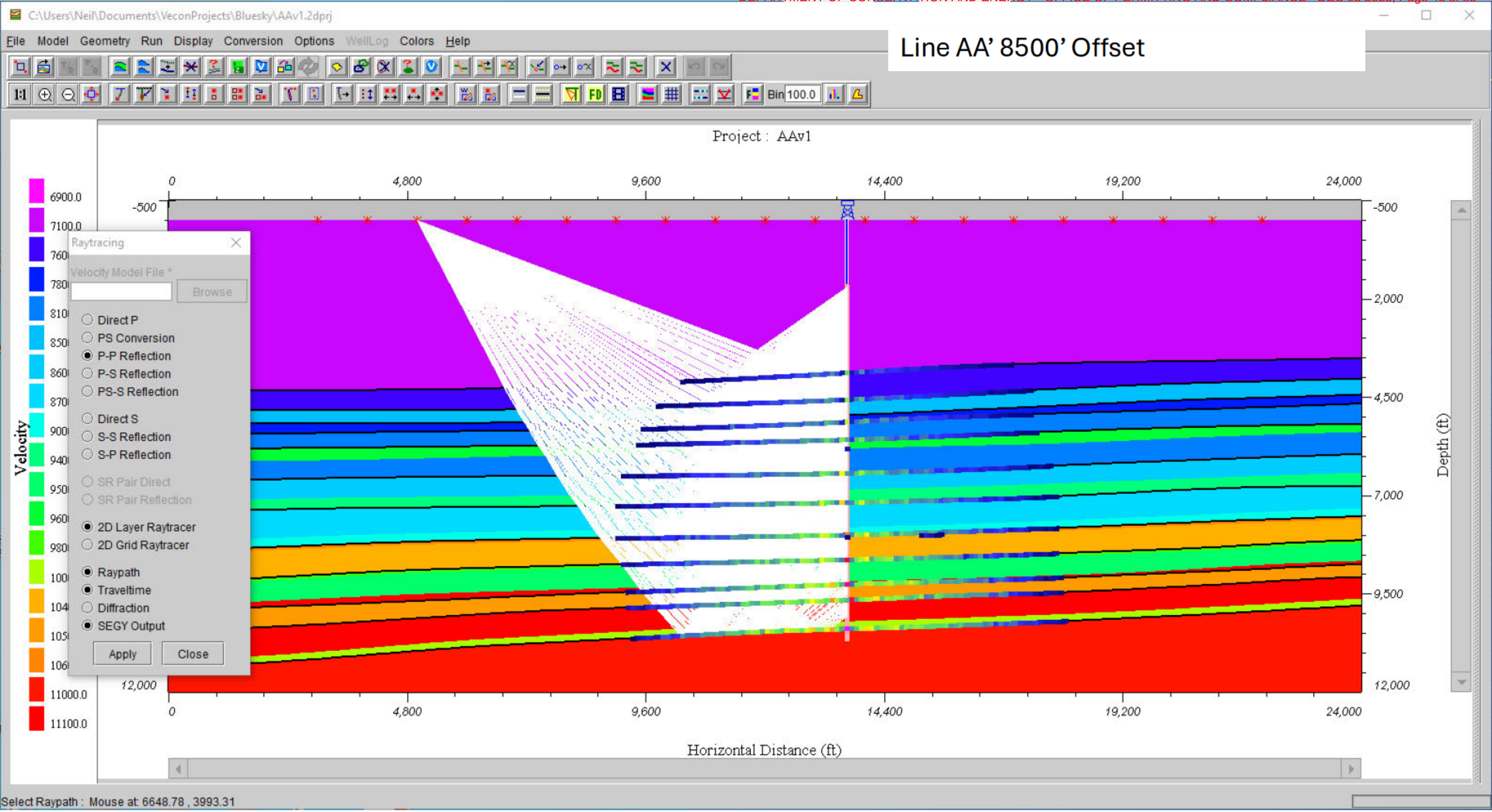
C:\Users\Neil\Documents\VeconProjects\Bluesky\AAv1.sgy

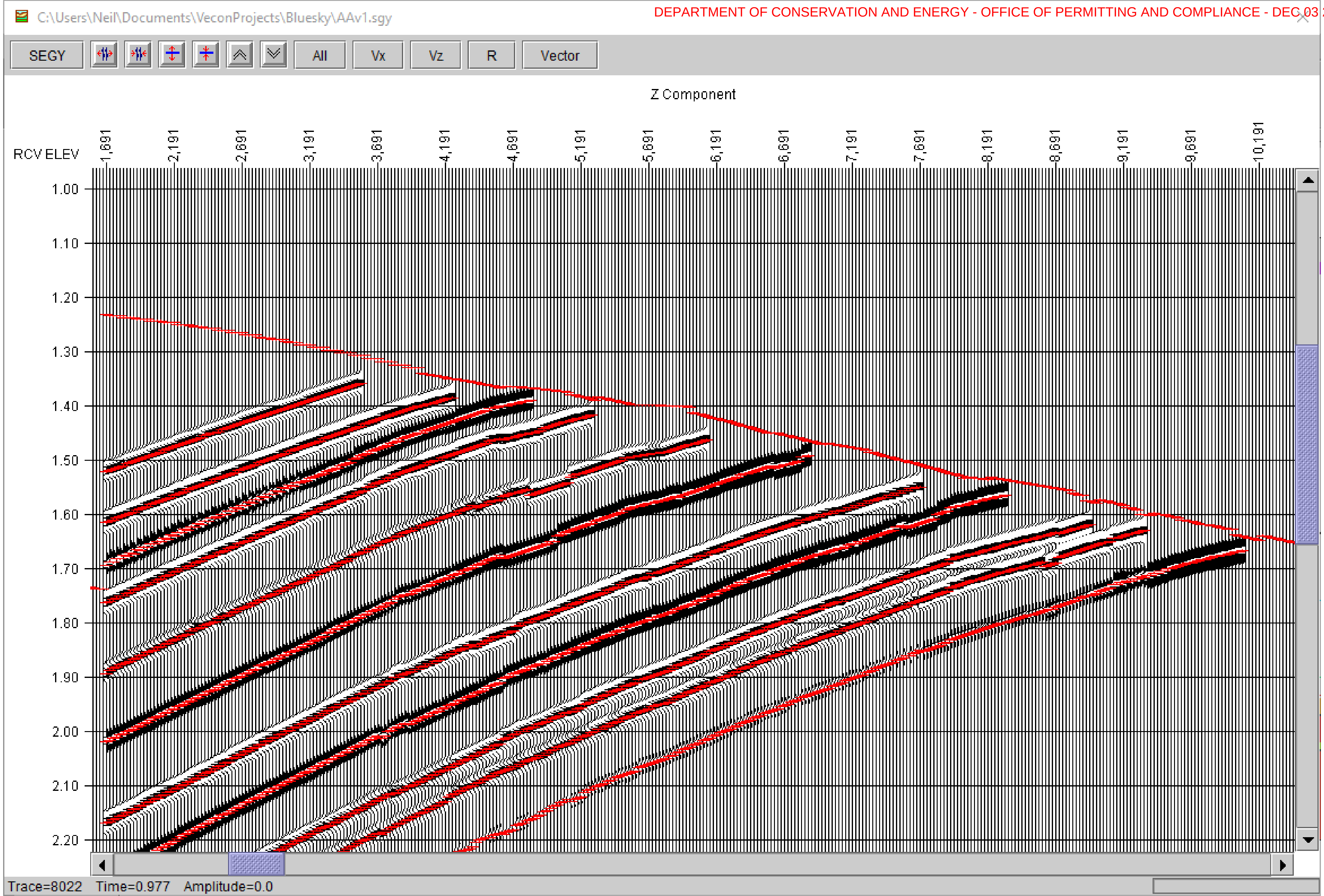


Line BB’

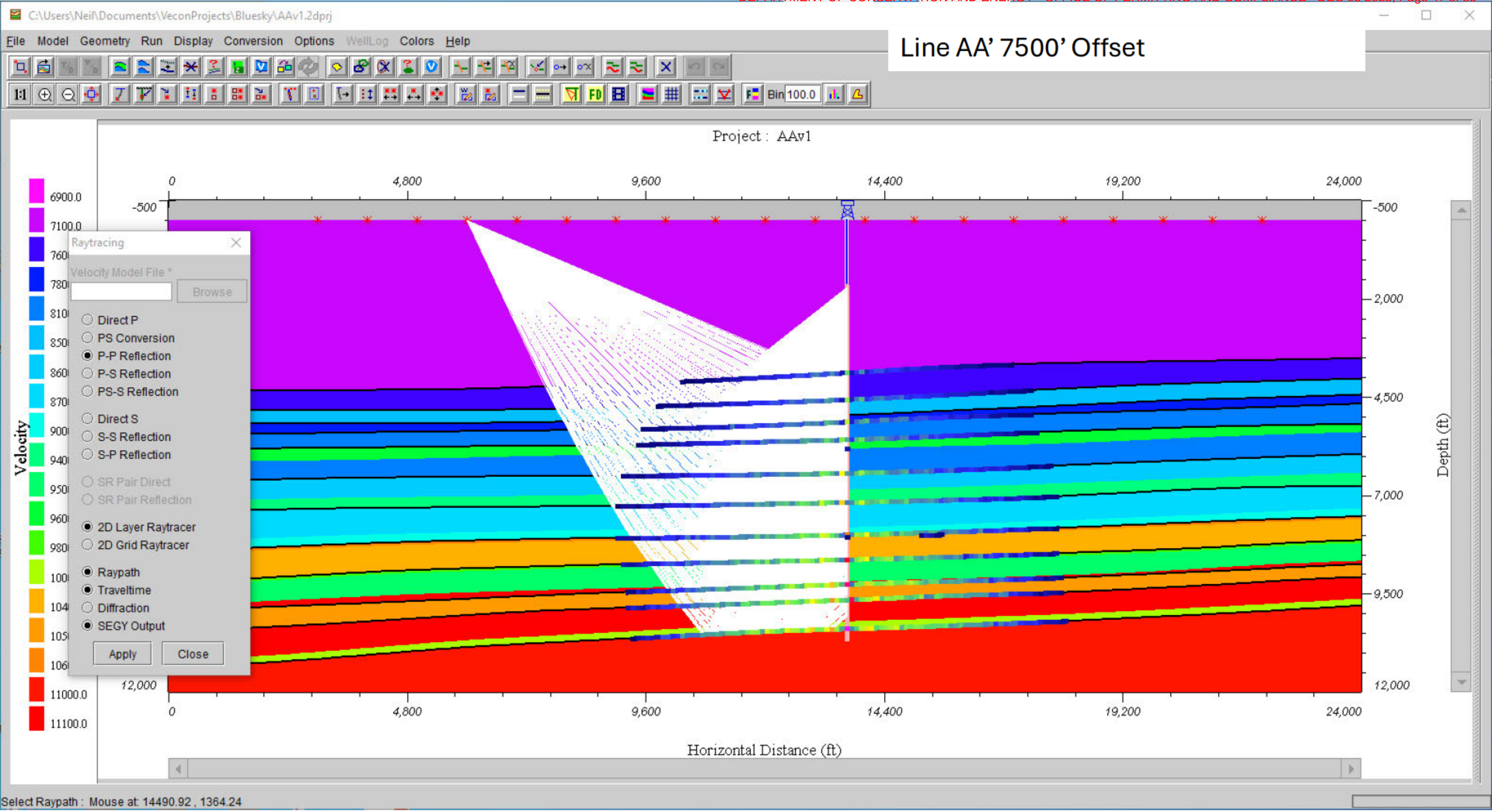
- Sources set at 1000’ intervals along the surface
- DAS fiber set at TD to 1650’ in the well @ 25’ intervals
- Representative layers picked for reflections at all main formations.
- Seismic displays are ray traced reflectivities convolved with 35 Hz Ricker to show event continuity and travel times. Used to evaluate distortion in the first arrival and reflection times to assess maximum useful offset range.

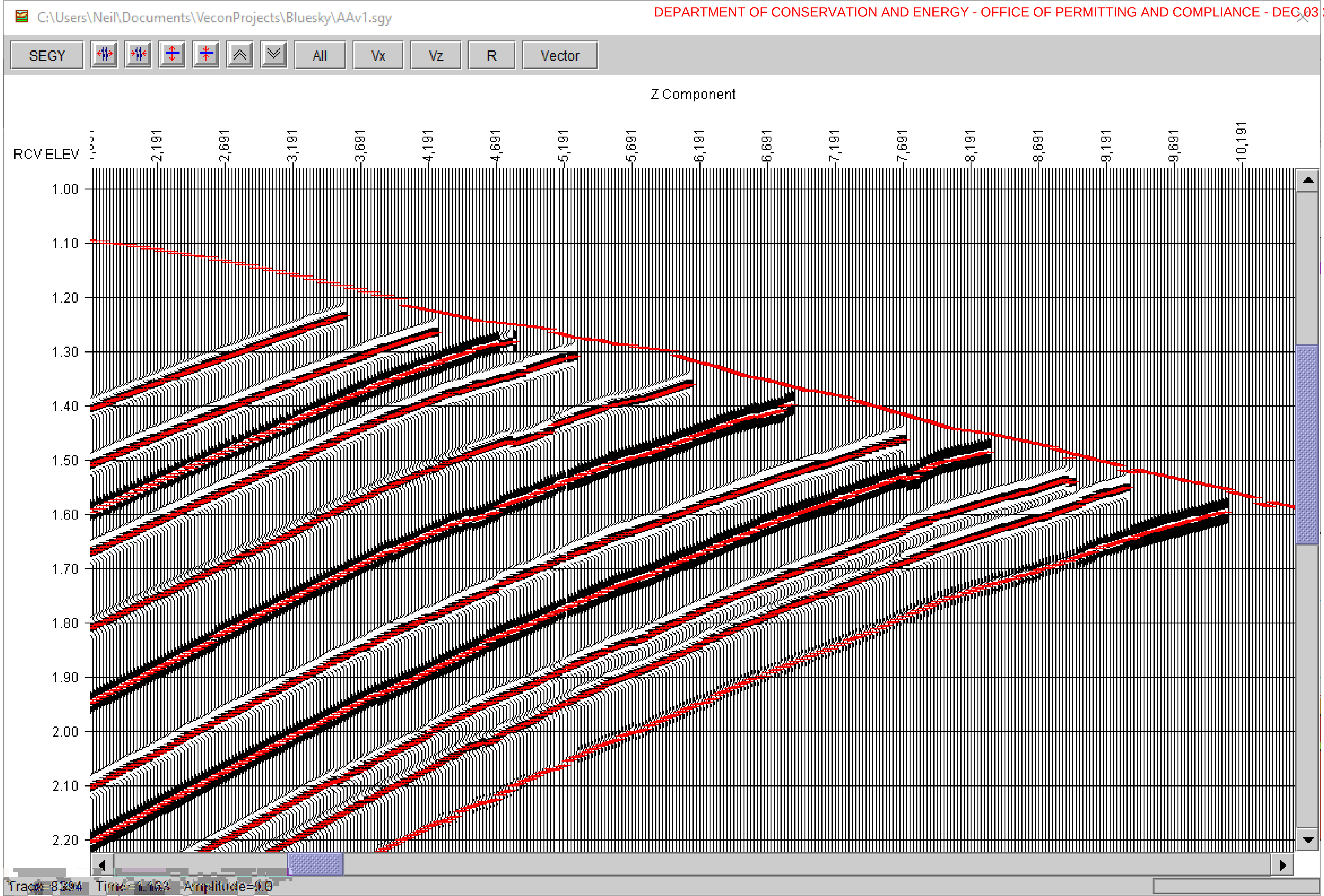
Line AA' 8500' Offset



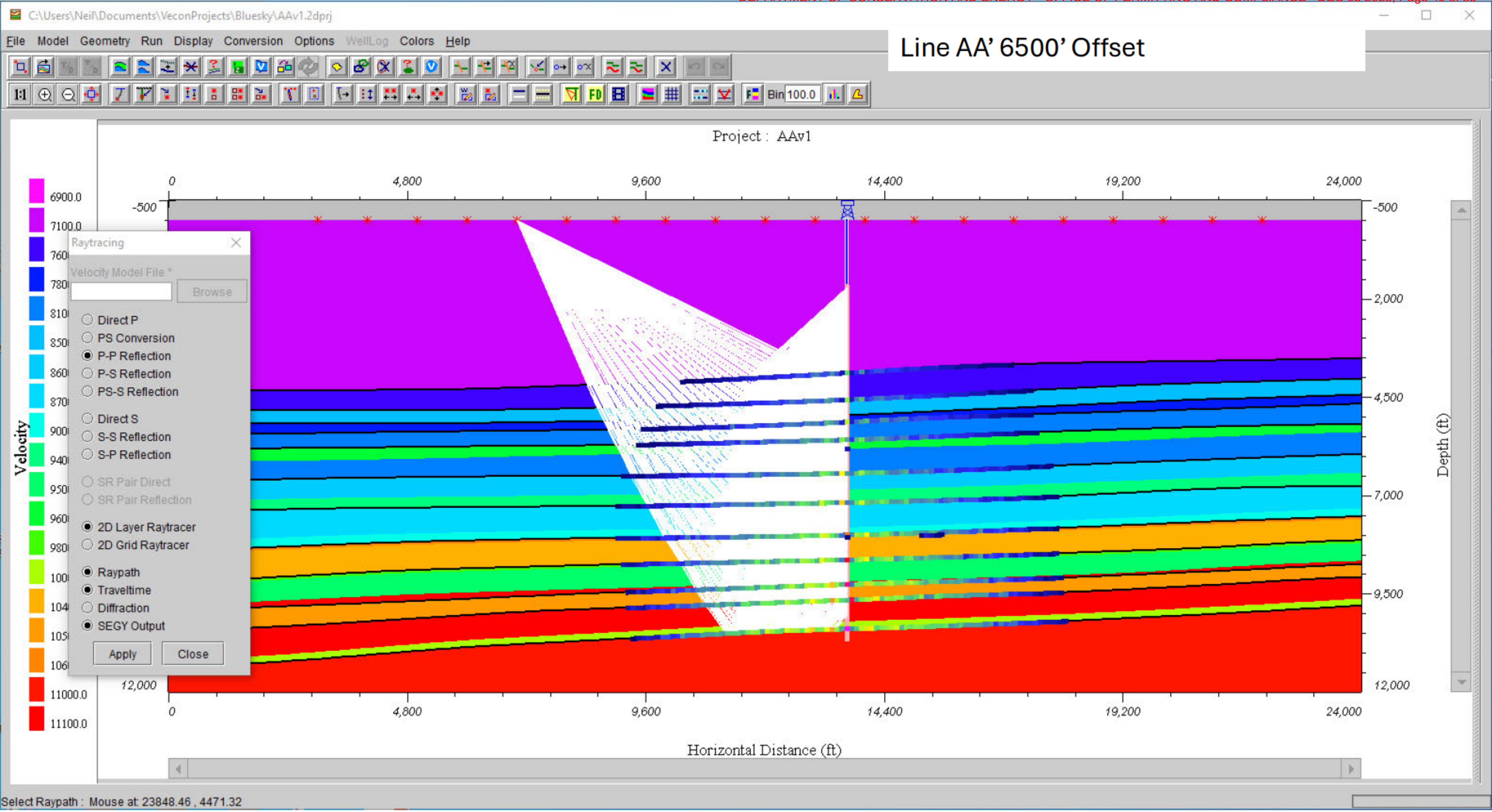

C:\Users\Neil\Documents\VeconProjects\Bluesky\AAv1.sgy
SEGY
All
Vx
Vz
R
Vector
Z Component
RCV ELEV
1,691
2,191
2,691
3,191
3,691
4,191
4,691
5,191
5,691
6,191
6,691
7,191
7,691
8,191
8,691
9,191
9,691
10,191
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
Trace=8022
Time=0.977
Amplitude=0.0

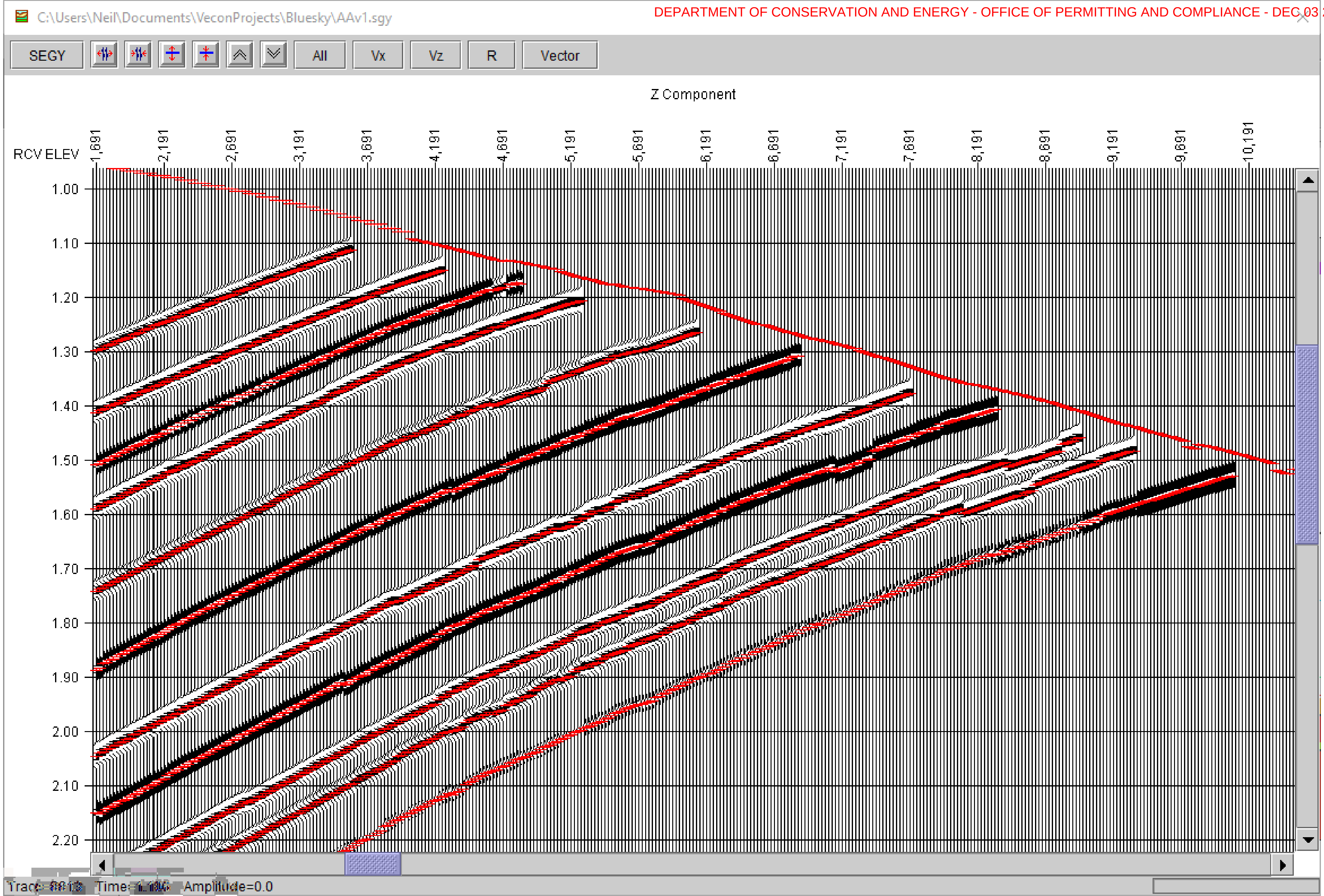
Line AA' 7500' Offset




C:\Users\Neil\Documents\VeconProjects\Bluesky\AAv1.sgy
SEGY
All
Vx
Vz
R
Vector
Z Component
RCV ELEV
2,191
2,691
3,191
3,691
4,191
4,691
5,191
5,691
6,191
6,691
7,191
7,691
8,191
8,691
9,191
9,691
10,191
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20

Line AA' 6500' Offset



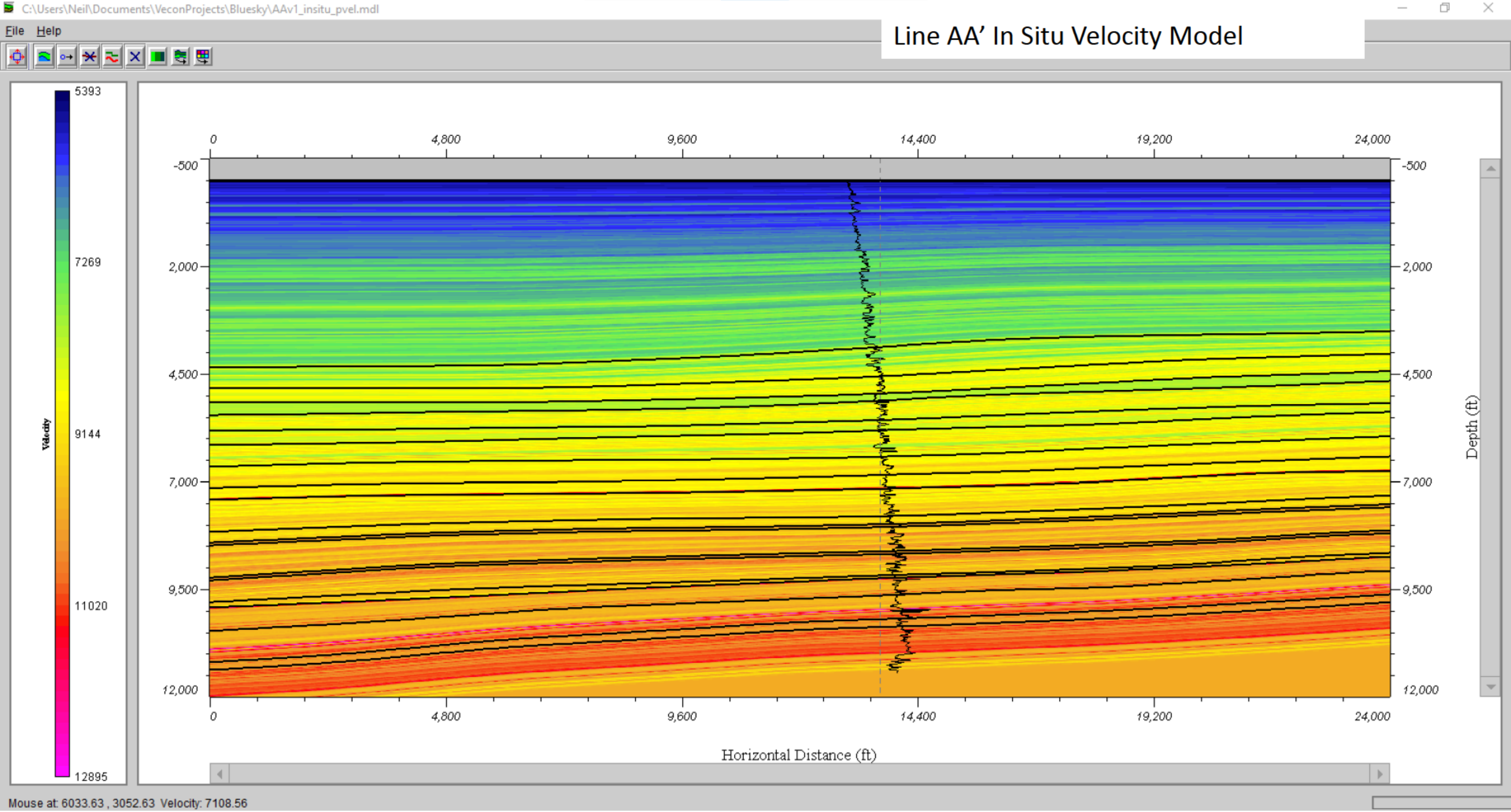


C:\Users\Neil\Documents\VeconProjects\Bluesky\AAv1.sgy
SEGY
All
Vx
Vz
R
Vector
Z Component
RCV ELEV
1,691
2,191
2,691
3,191
3,691
4,191
4,691
5,191
5,691
6,191
6,691
7,191
7,691
8,191
8,691
9,191
9,691
10,191
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
Amplitude=0.0

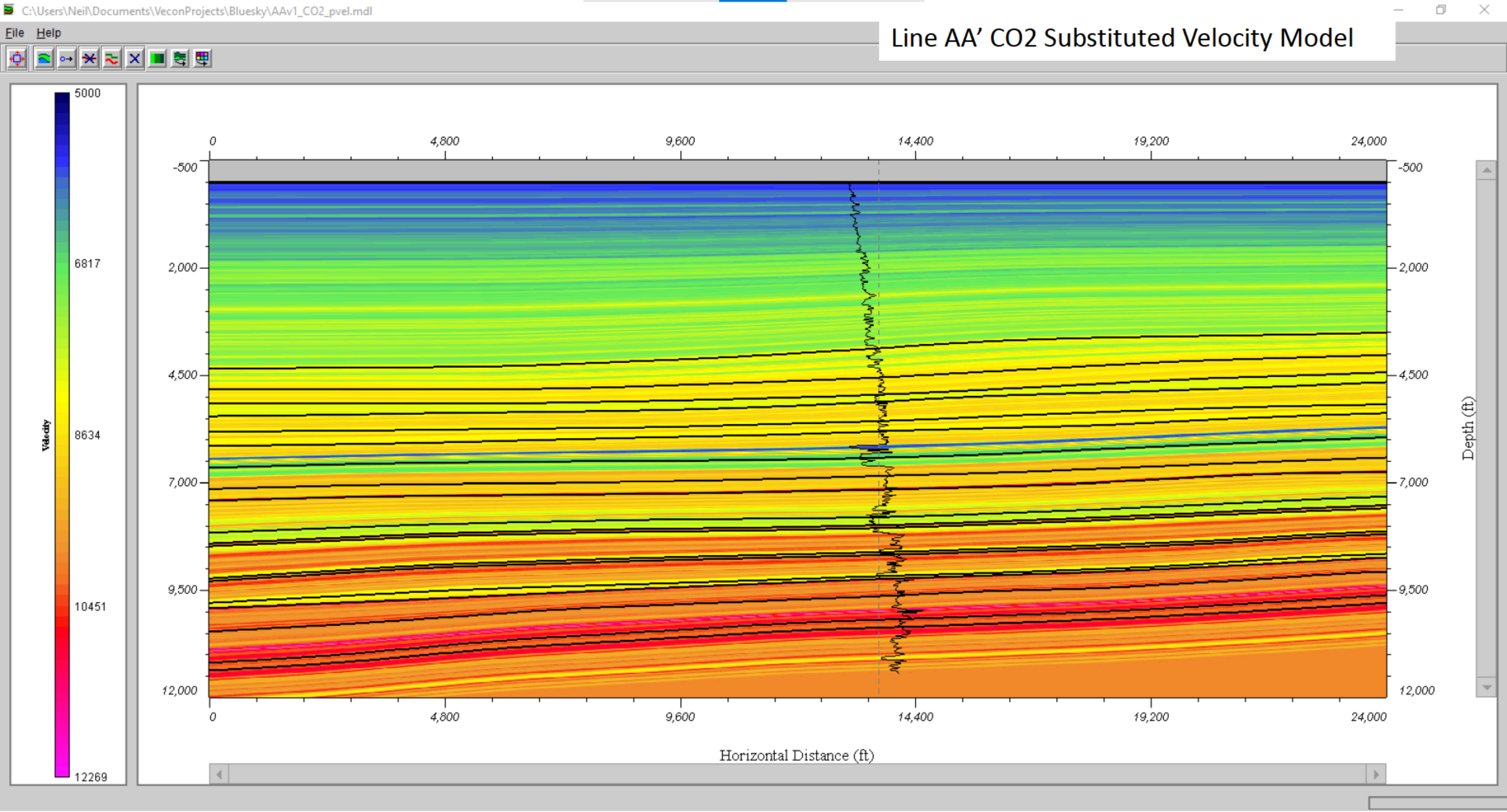
4D Effects

- Grid models for both velocity and density based on the well logs and structural horizons are built for both the in-situ case and for the CO_2 substitution case using the logs produced through the rock physics phase of the project.
- Finite difference modeling is used to provide a synthetic seismic simulation using the finely gridded models.
- These are then processed through VSP processing techniques to isolate a final reflected wavefield, then the insitu and CO_2 substituted cases are differenced to evaluate any 4D signal due to the presence of CO_2 in the system

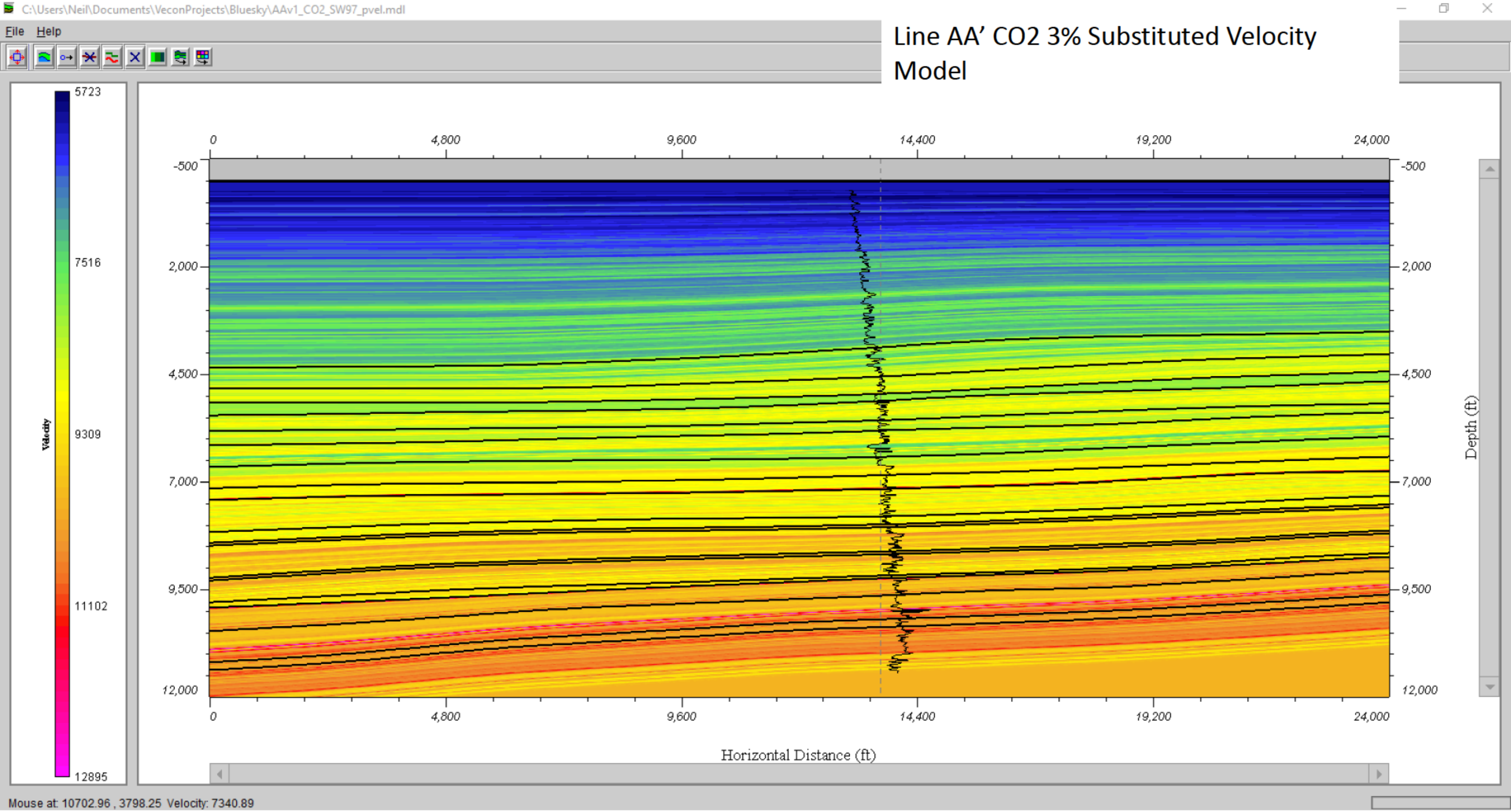
Line AA' In Situ Velocity Model



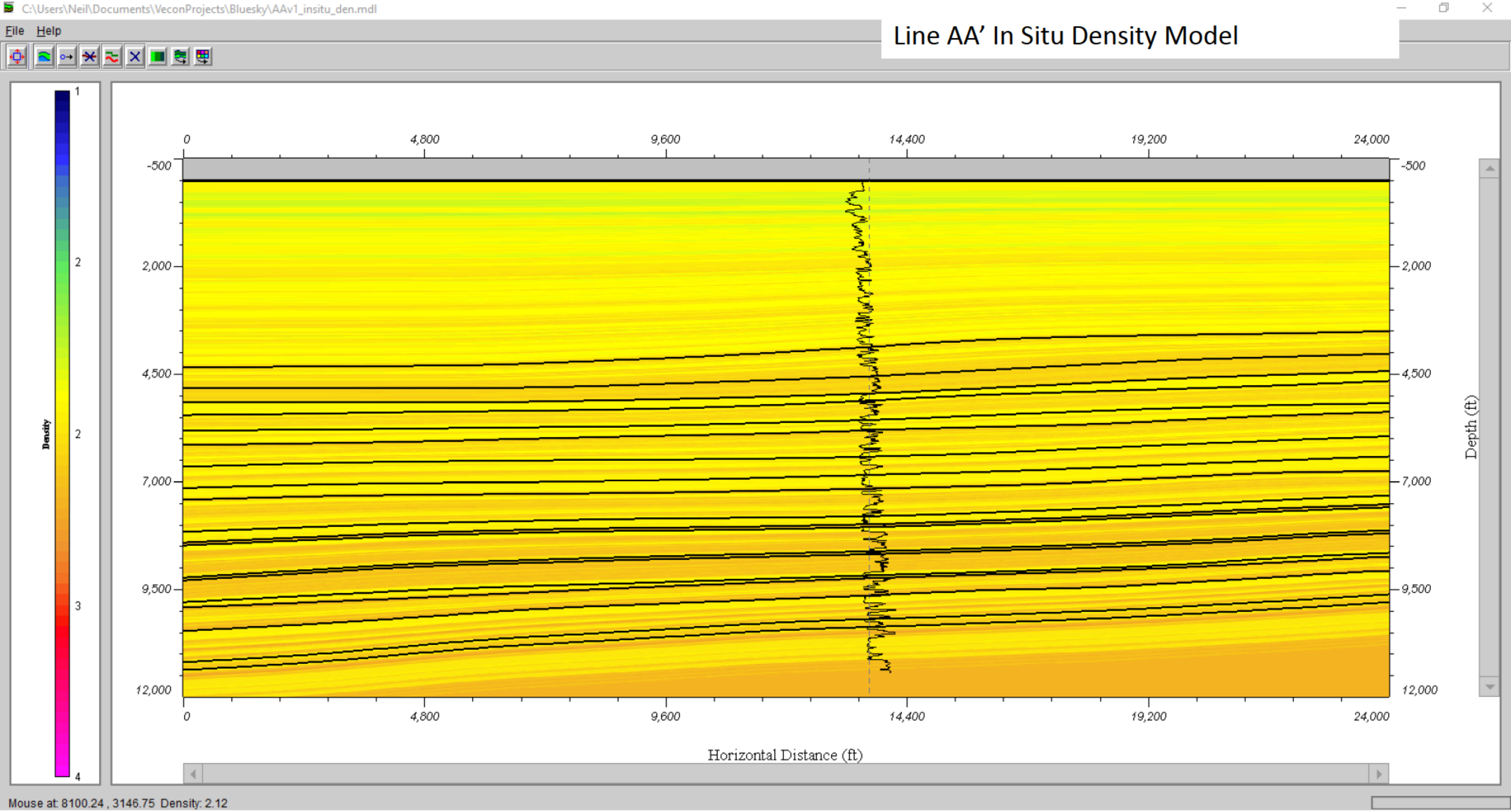
Line AA' CO2 Substituted Velocity Model



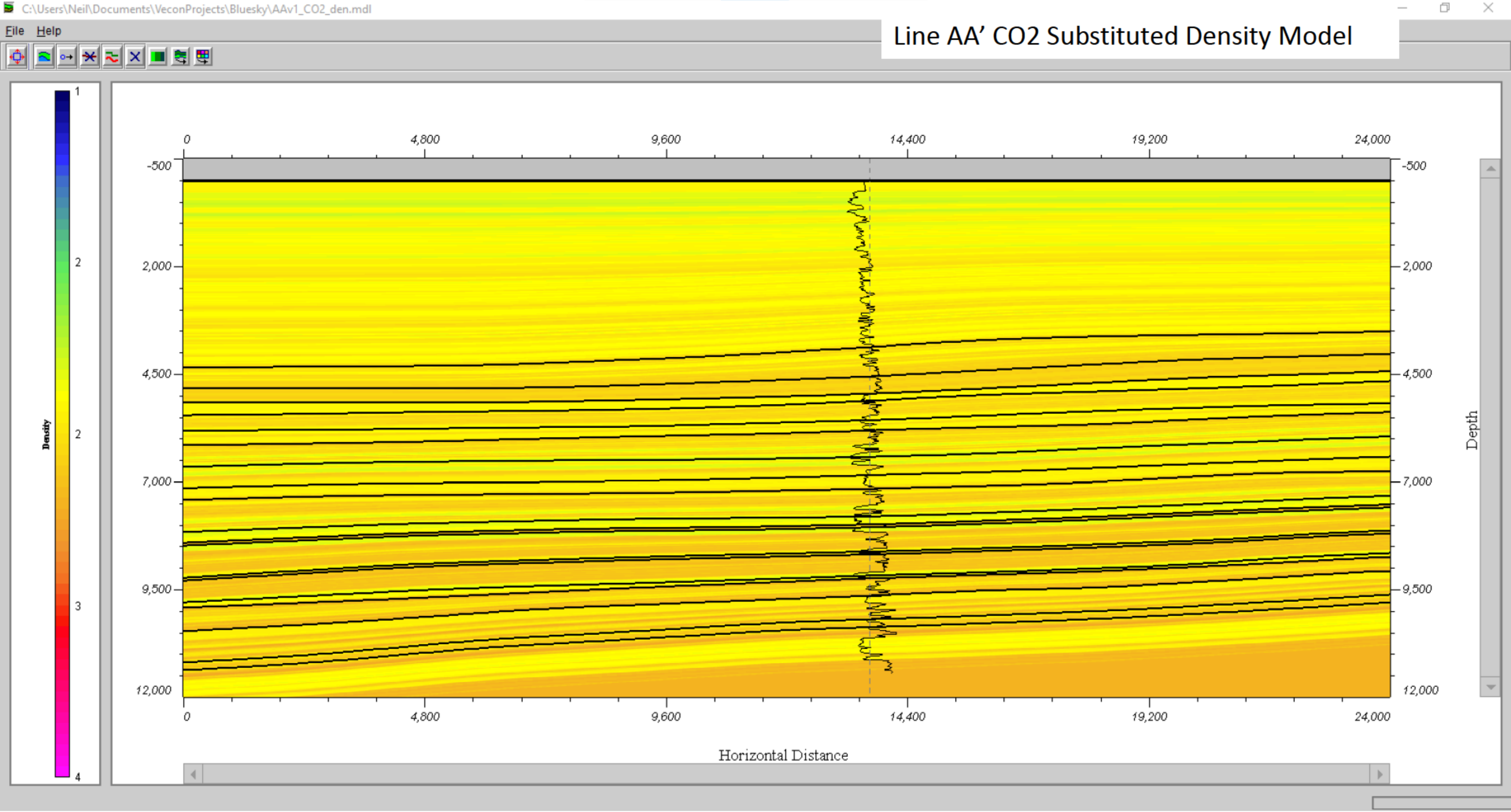
Line AA' CO2 3% Substituted Velocity Model



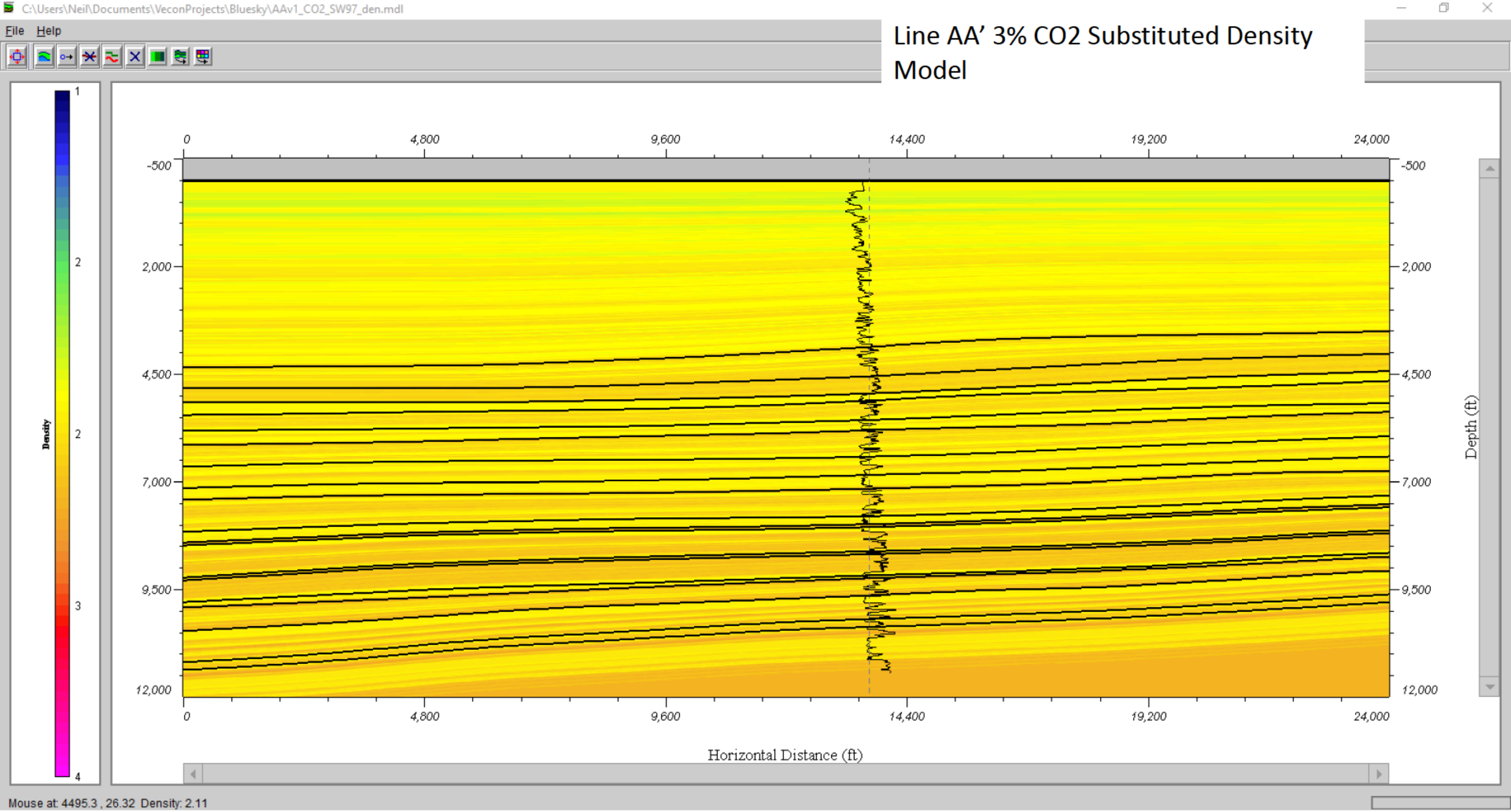
Line AA' In Situ Density Model



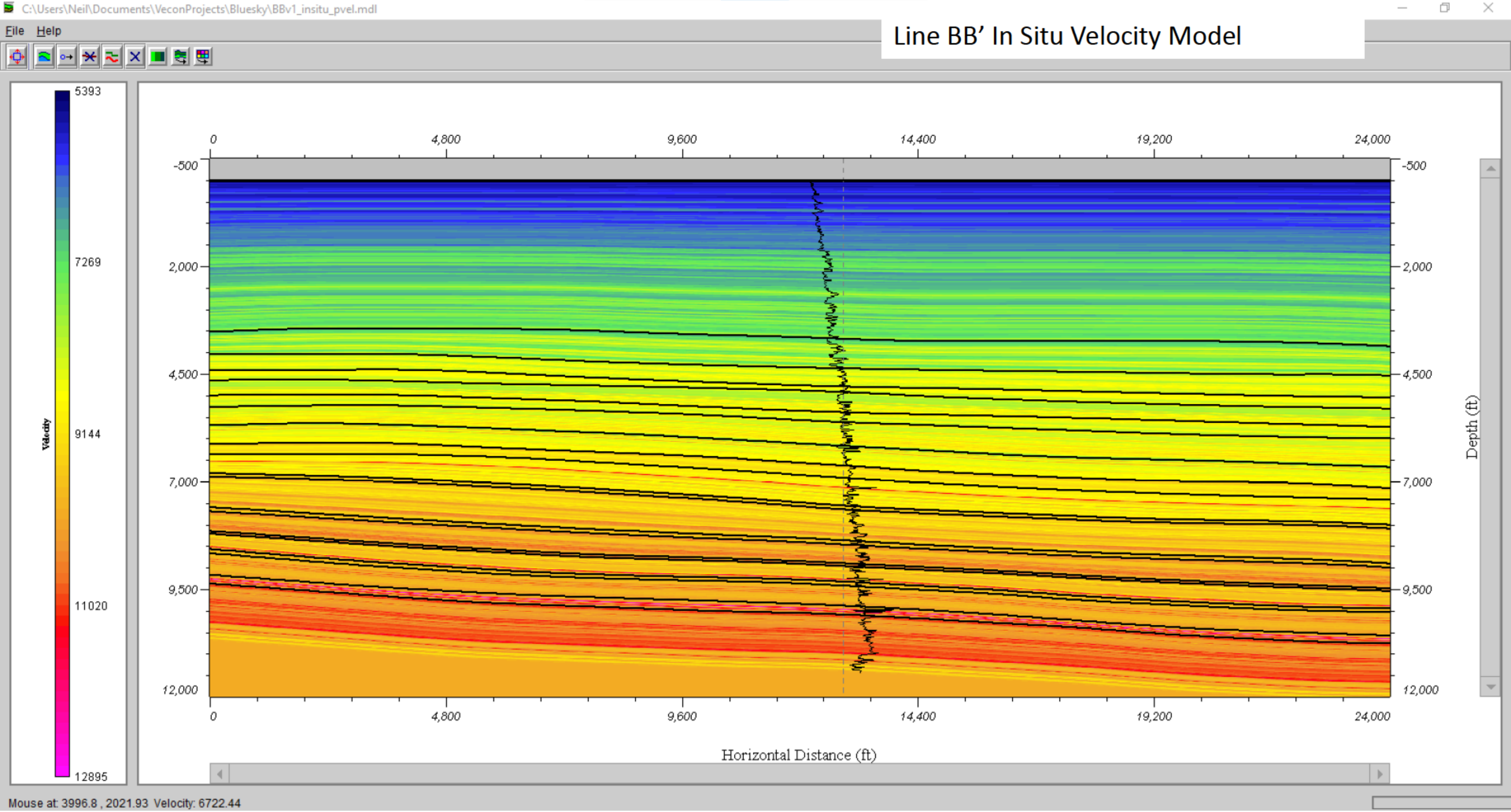
Line AA' CO2 Substituted Density Model



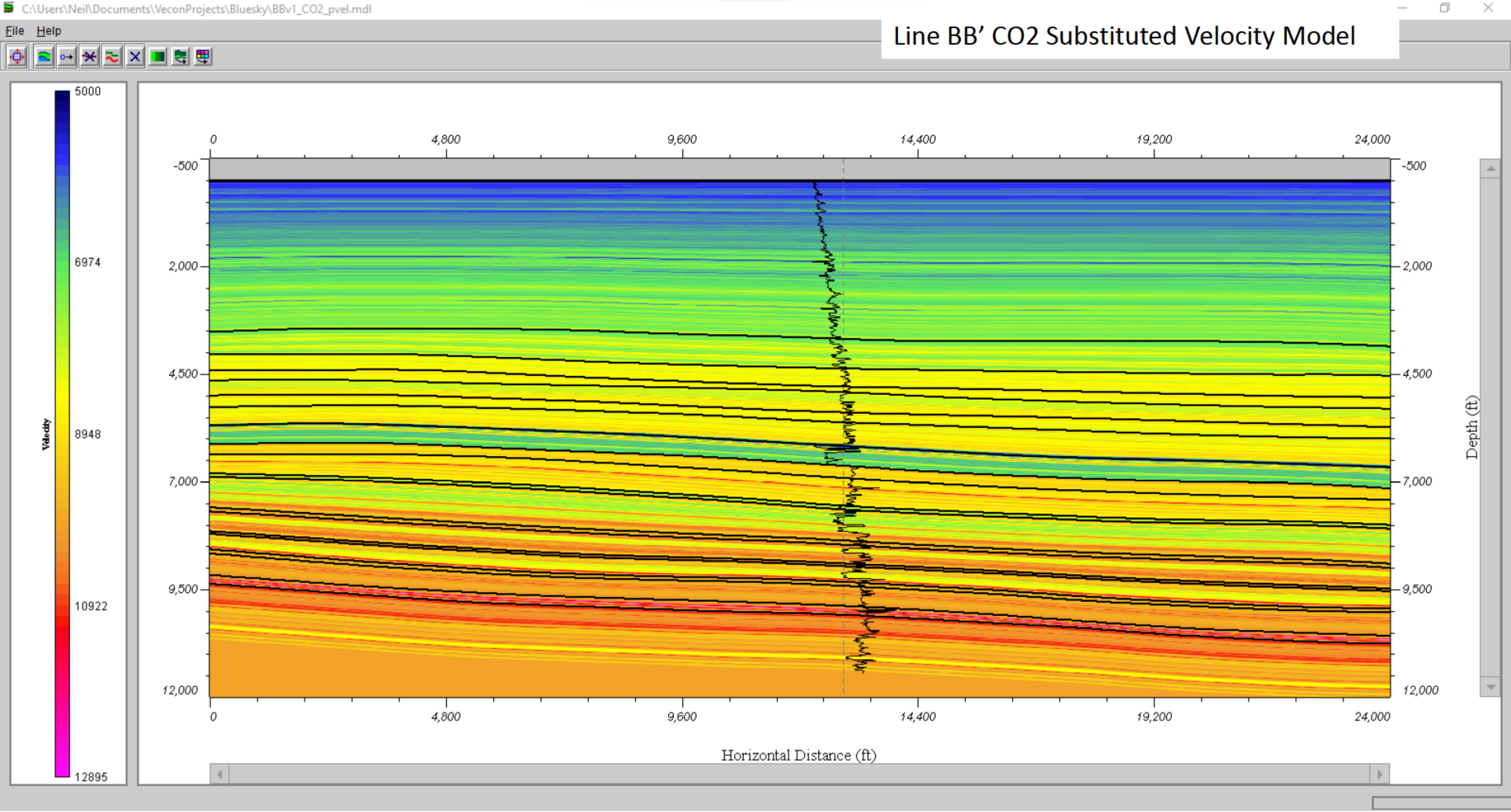
Line AA' 3% CO_2 Substituted Density Model



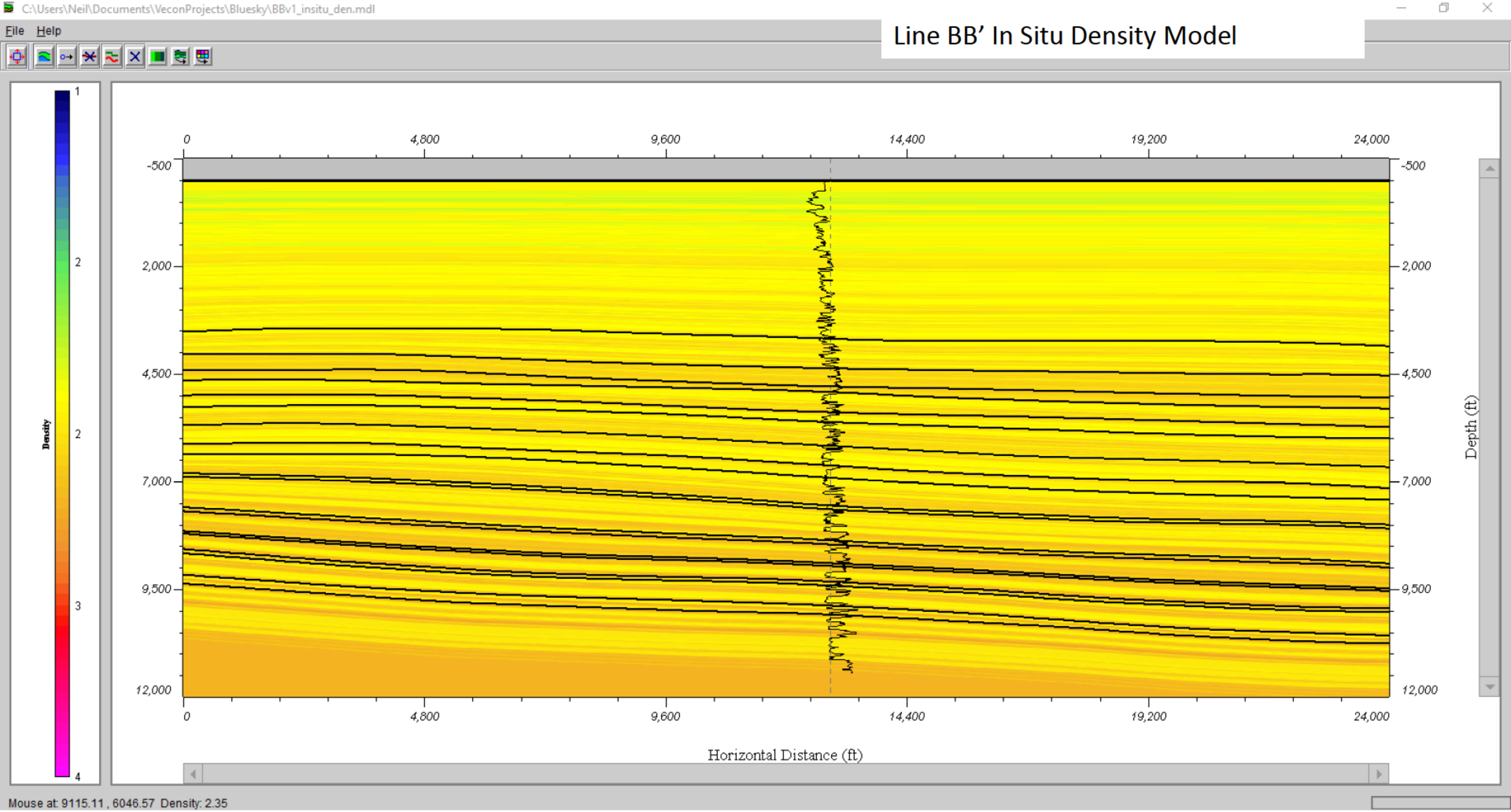
Line BB' In Situ Velocity Model



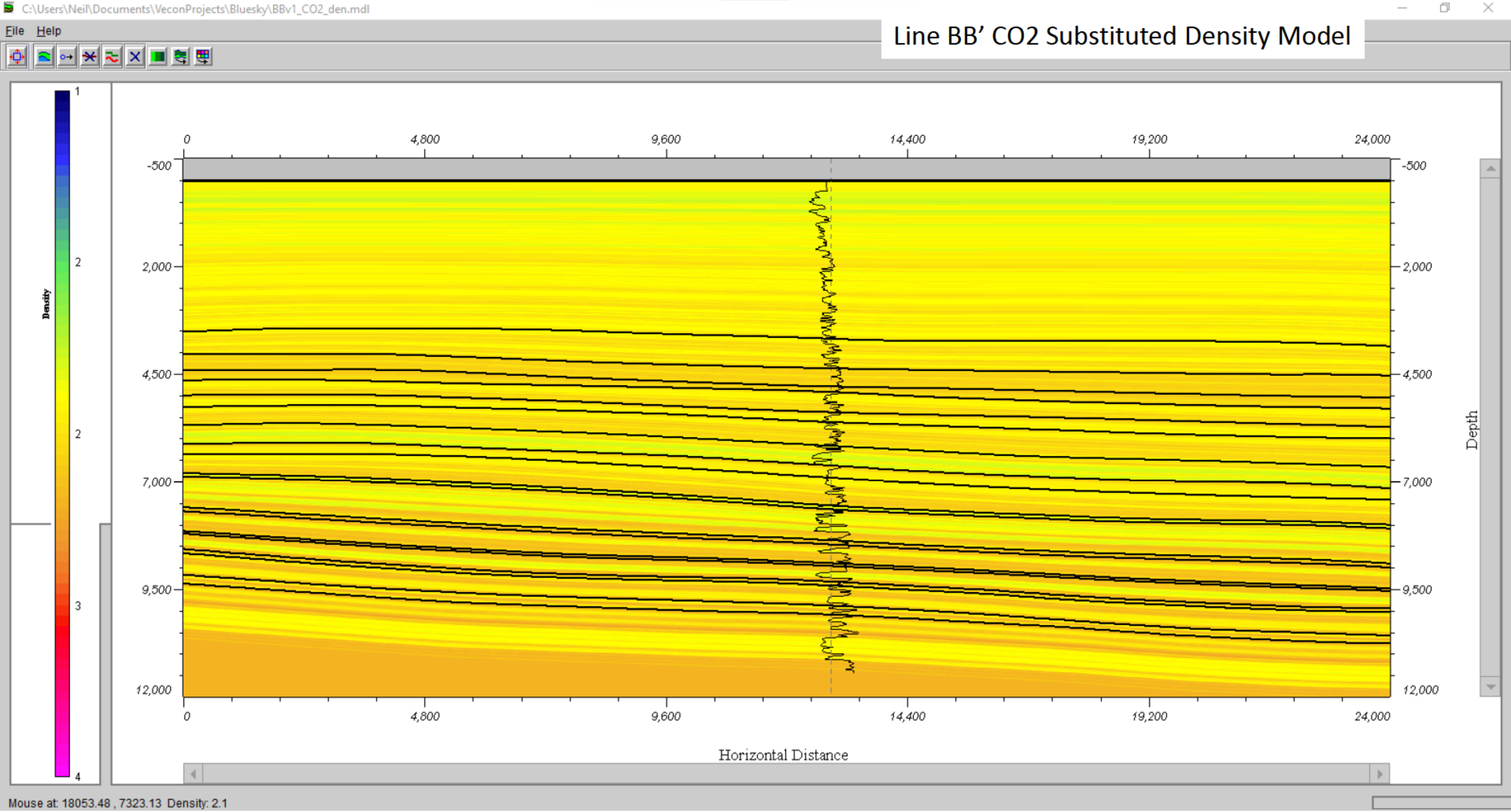
Line BB' CO2 Substituted Velocity Model



Line BB' In Situ Density Model



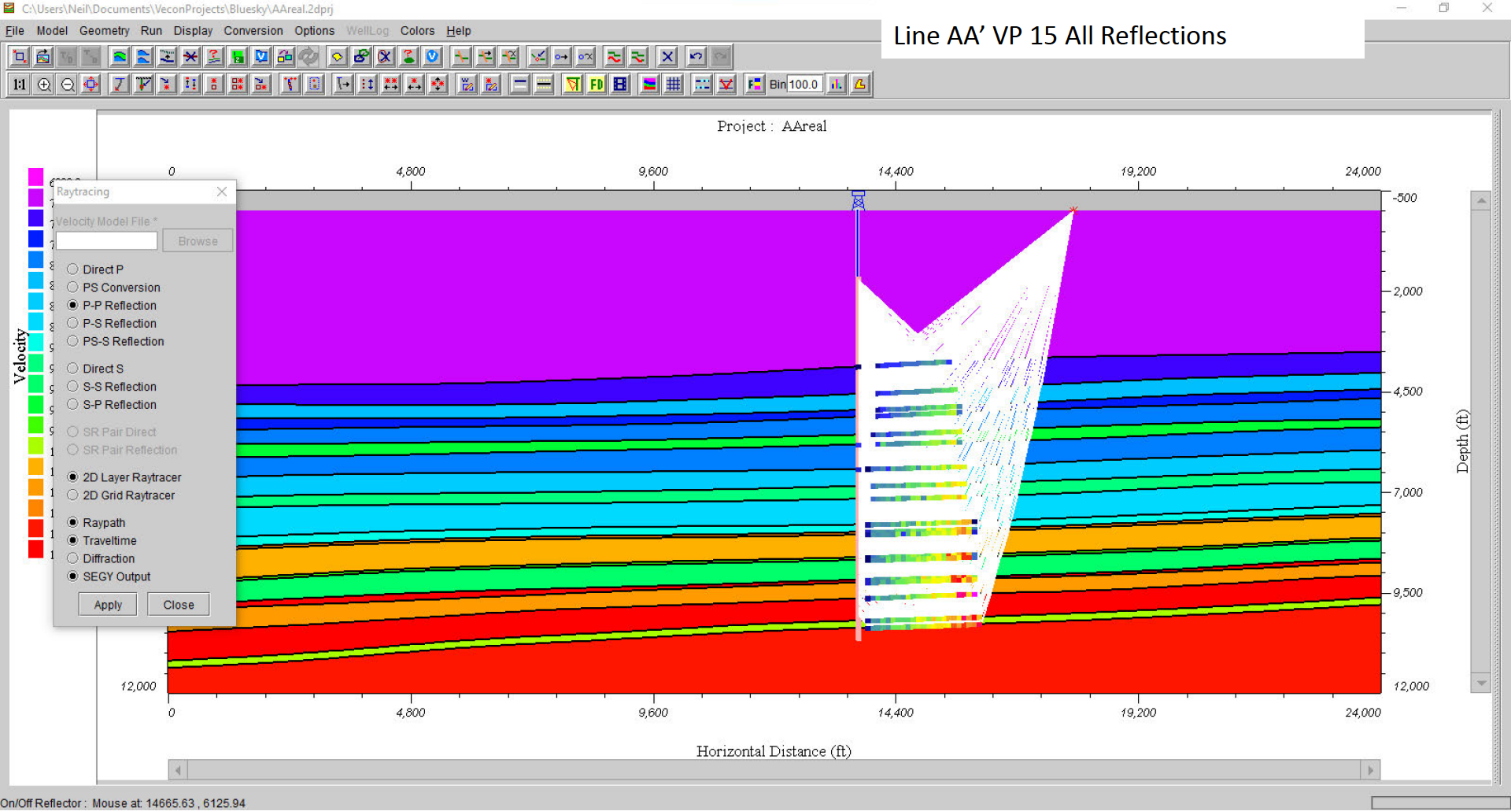
Line BB' CO2 Substituted Density Model



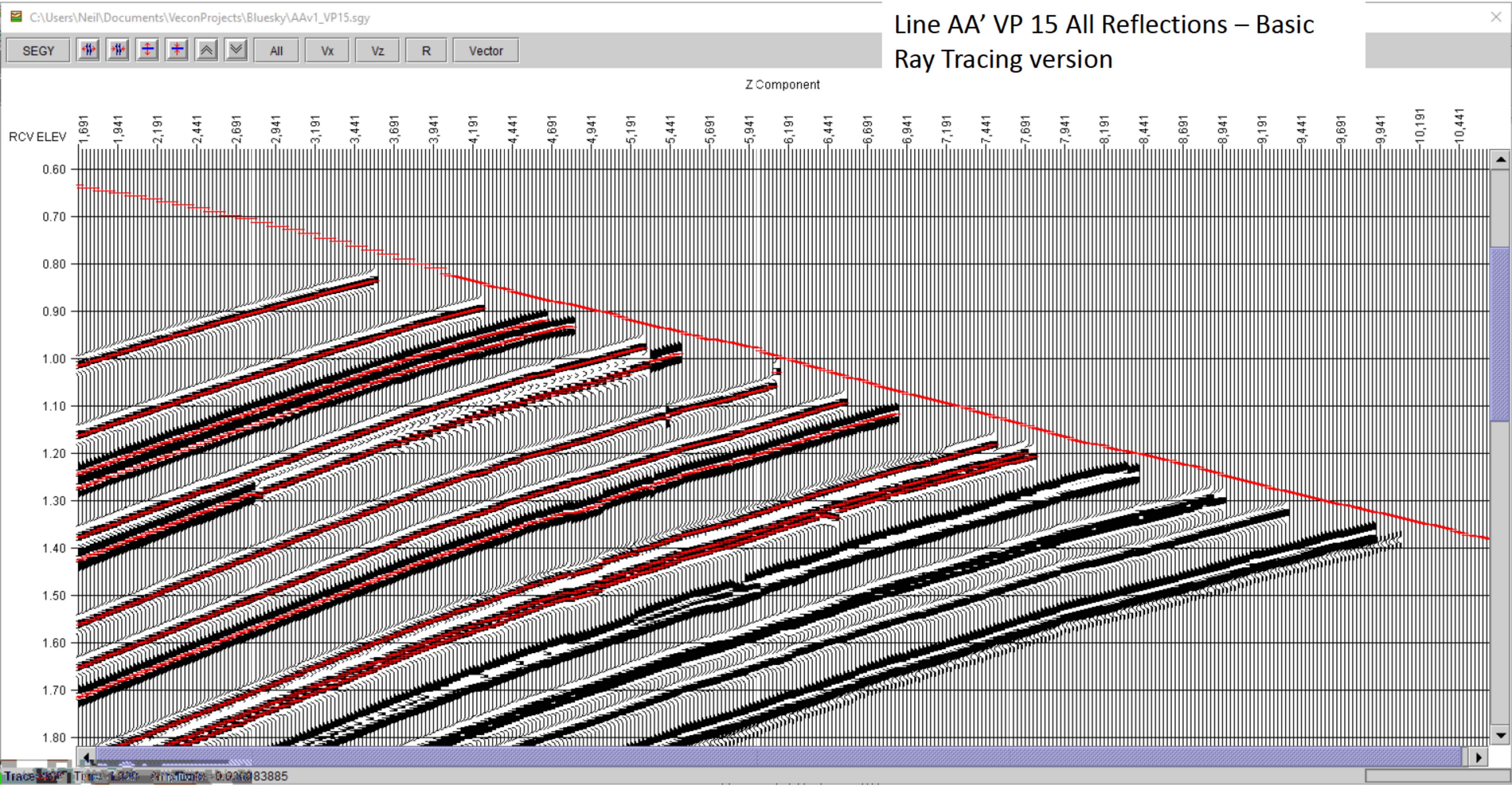
4D Effects

- VP 15 on Line AA' was chosen as a good representative for 4D modeling. This represents a medium offset VSP which should have good imaging.
- 4D effects largely depend on the velocity and density models derived from the log data, and as such are not expected to change much with offset until we get to much longer offset ranges.
- Finite difference modeling is used to provide a synthetic seismic simulation using the finely gridded models. Grid cell size 10'
- These are then processed through VSP processing techniques to isolate a final reflected wavefield, then the insitu and CO_2 substituted cases are differenced to evaluate any 4D signal due to the presence of CO_2 in the system
- An additional case representing 3% CO_2 saturation (SW 97%) is also modeled.

Line AA' VP 15 All Reflections



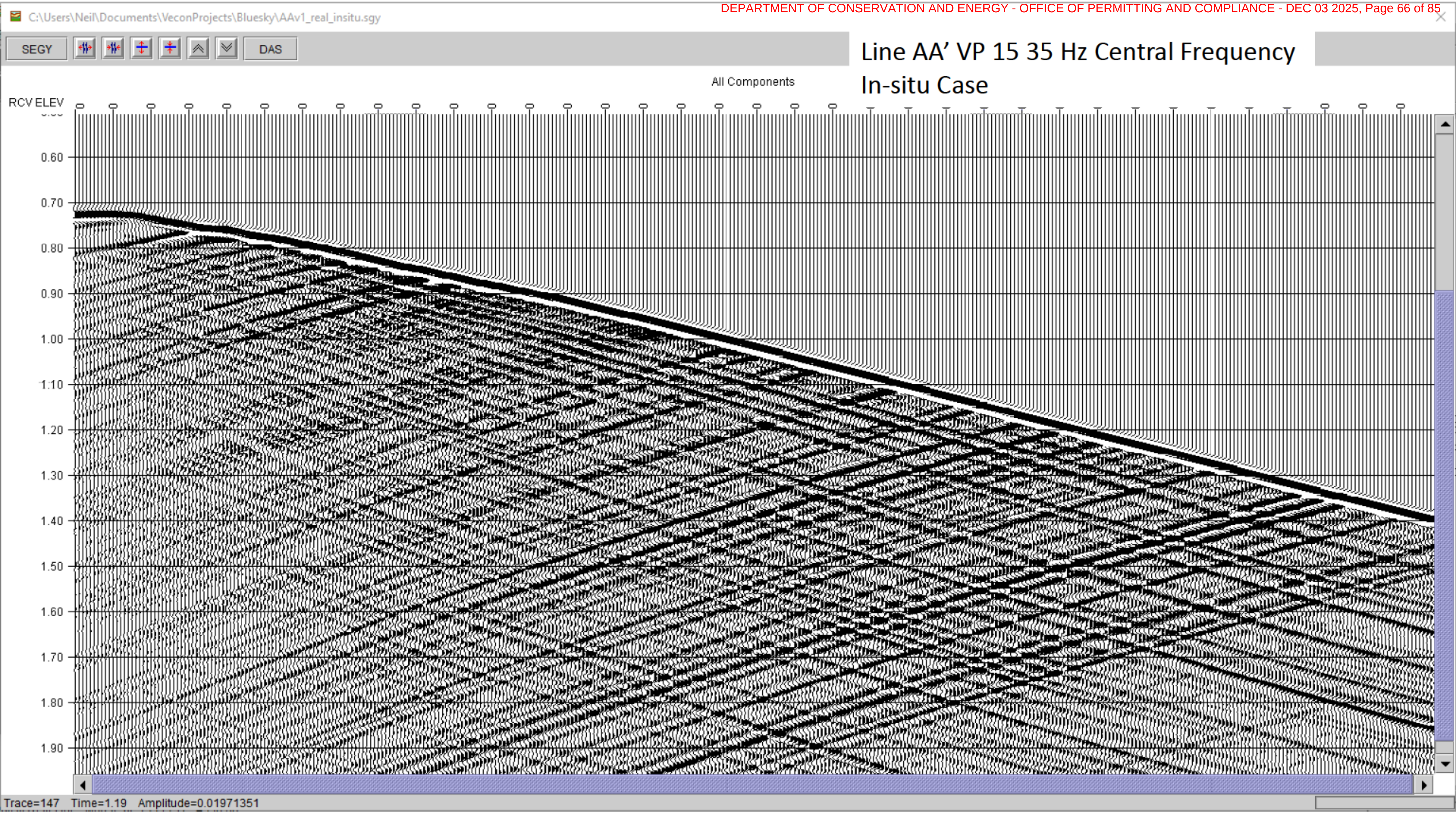
Line AA' VP 15 All Reflections – Basic Ray Tracing version



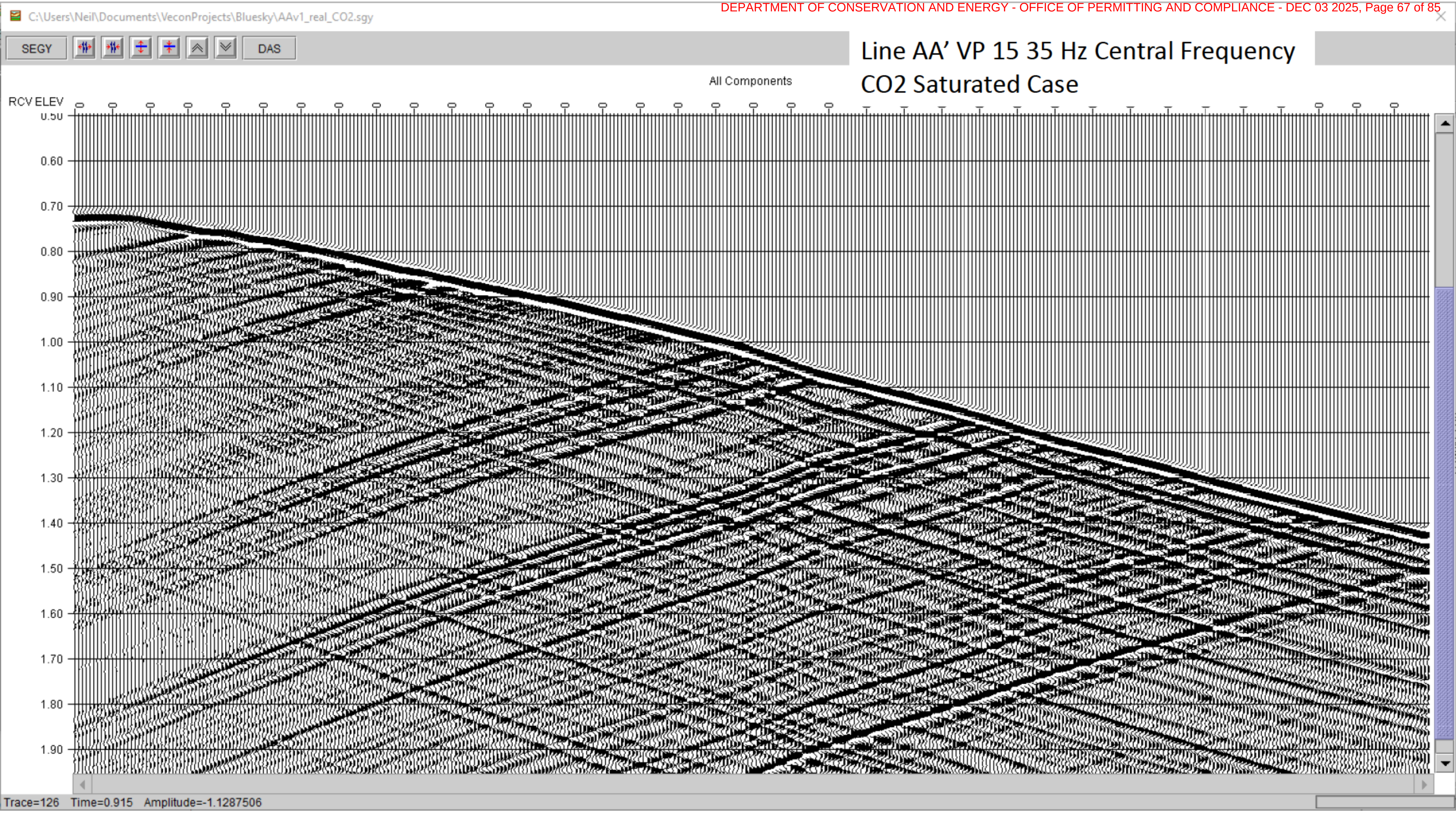
Finite Difference Modeling

- The first pass of FD modeling is performed based on a 35 Hz Ricker wavelet. This simulates a VSP with good signal to noise. The receiver is simulated as DAS fiber.
- The FD is performed using Acoustic Finite Difference. Elastic FD is not required for this level of modeling and would be used if shear energy was deemed important.
- VSP is simulated with downgoing and upgoing arrivals
- VSP data is separated into downgoing and upgoing wavefields.
- The upgoing wavefields are differenced to observe any 4D signal
- Deconvolution is not applied so multiples remain in the data.

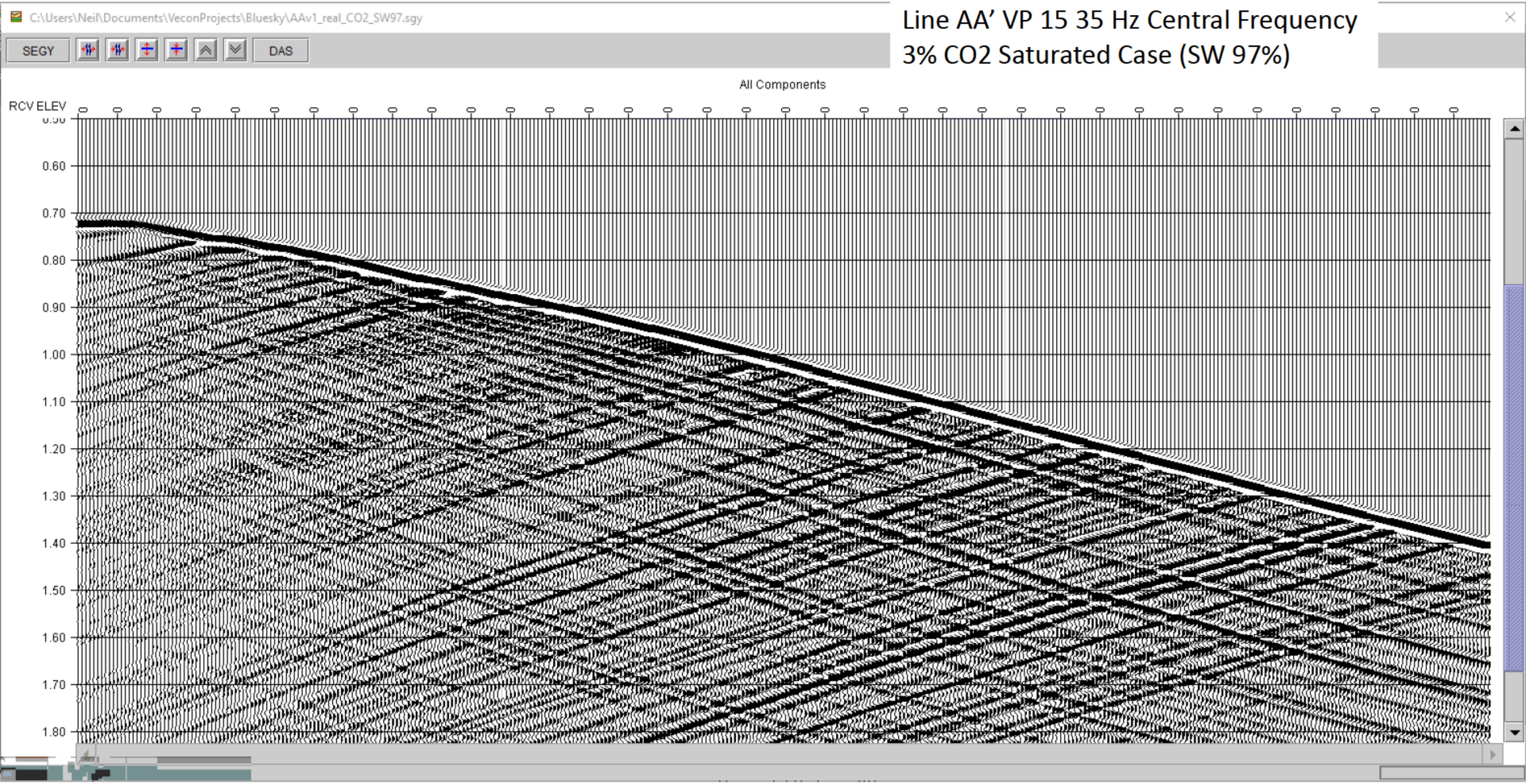
Line AA’ VP 15 35 Hz Central Frequency In-situ Case



Line AA' VP 15 35 Hz Central Frequency
CO2 Saturated Case



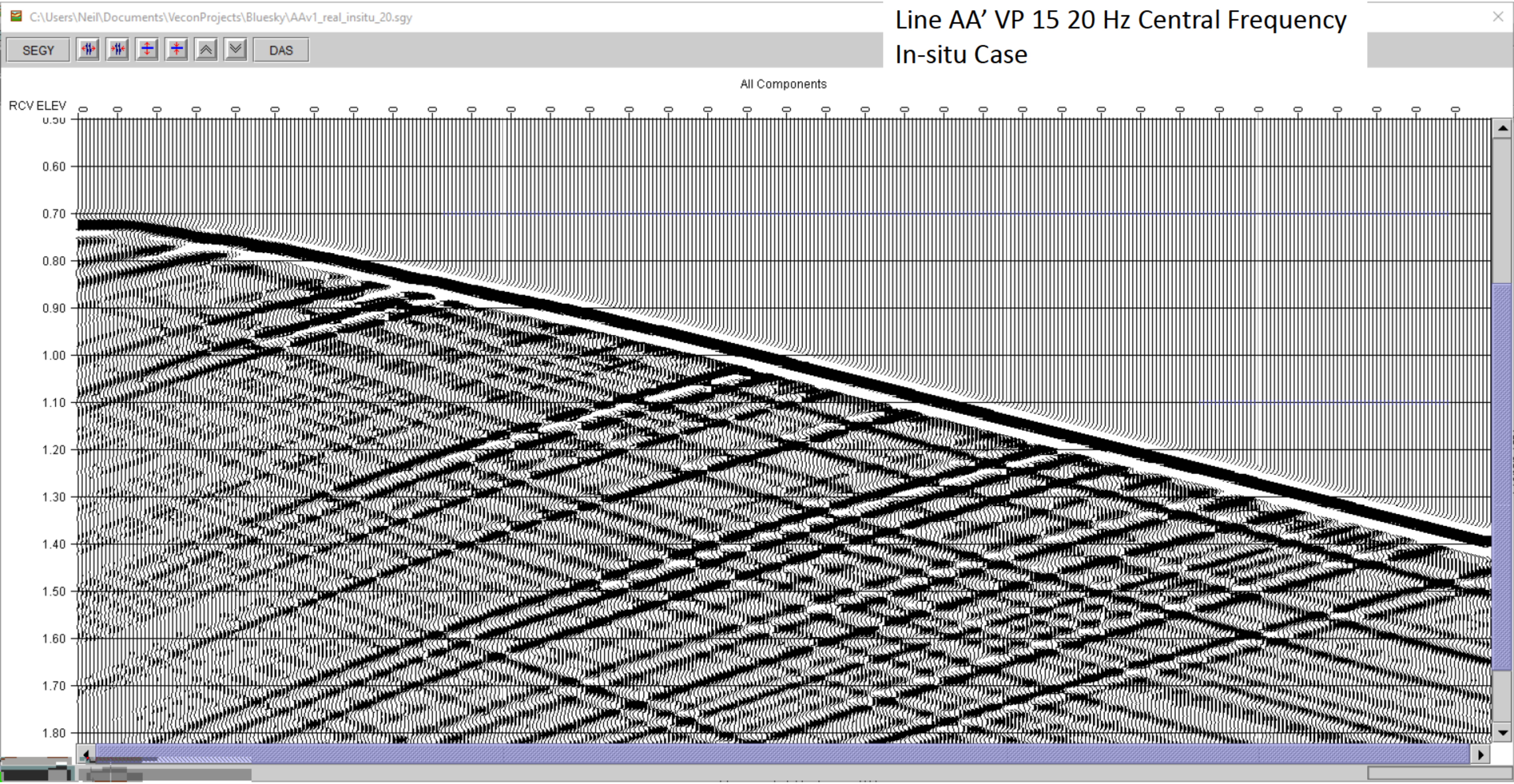
Line AA' VP 15 35 Hz Central Frequency 3% CO2 Saturated Case (SW 97%)



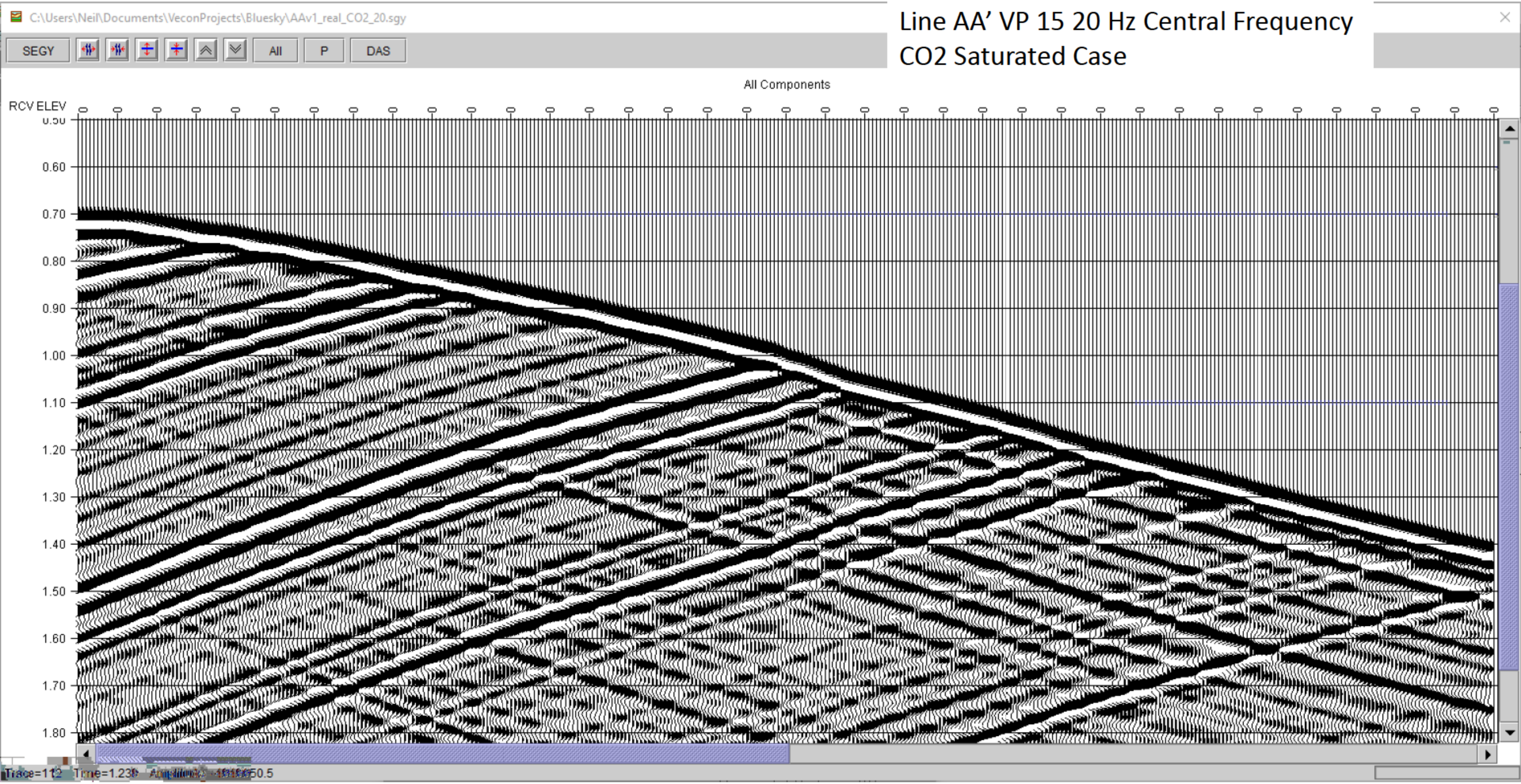
Finite Difference Modeling

- The second pass of FD modeling is performed based on a 20 Hz Ricker wavelet. This simulates a VSP with poor signal to noise or could be used to represent a surface seismic based geometry The receiver is simulated as DAS fiber.

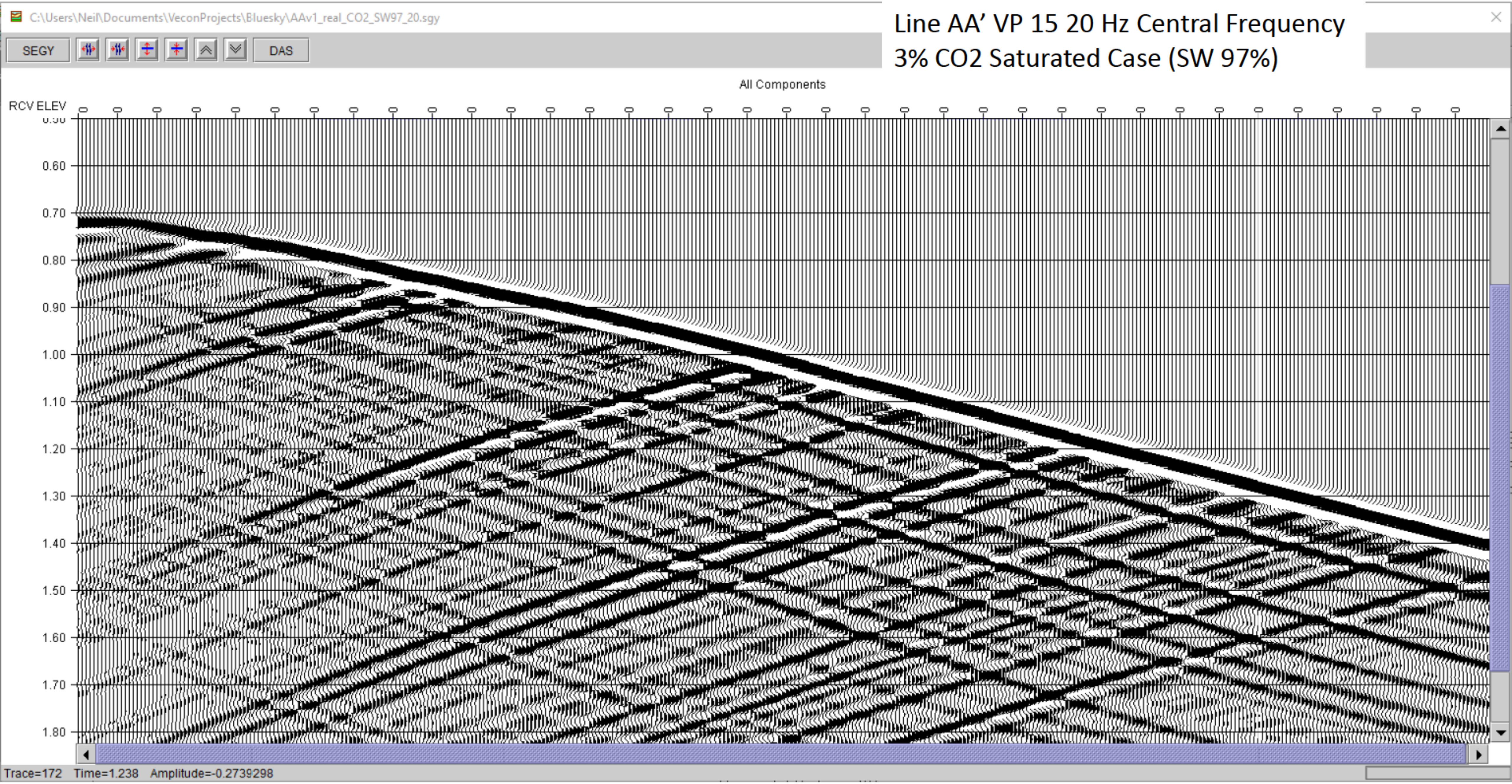
Line AA' VP 15 20 Hz Central Frequency In-situ Case



Line AA' VP 15 20 Hz Central Frequency CO2 Saturated Case



Line AA' VP 15 20 Hz Central Frequency
3% CO2 Saturated Case (SW 97%)

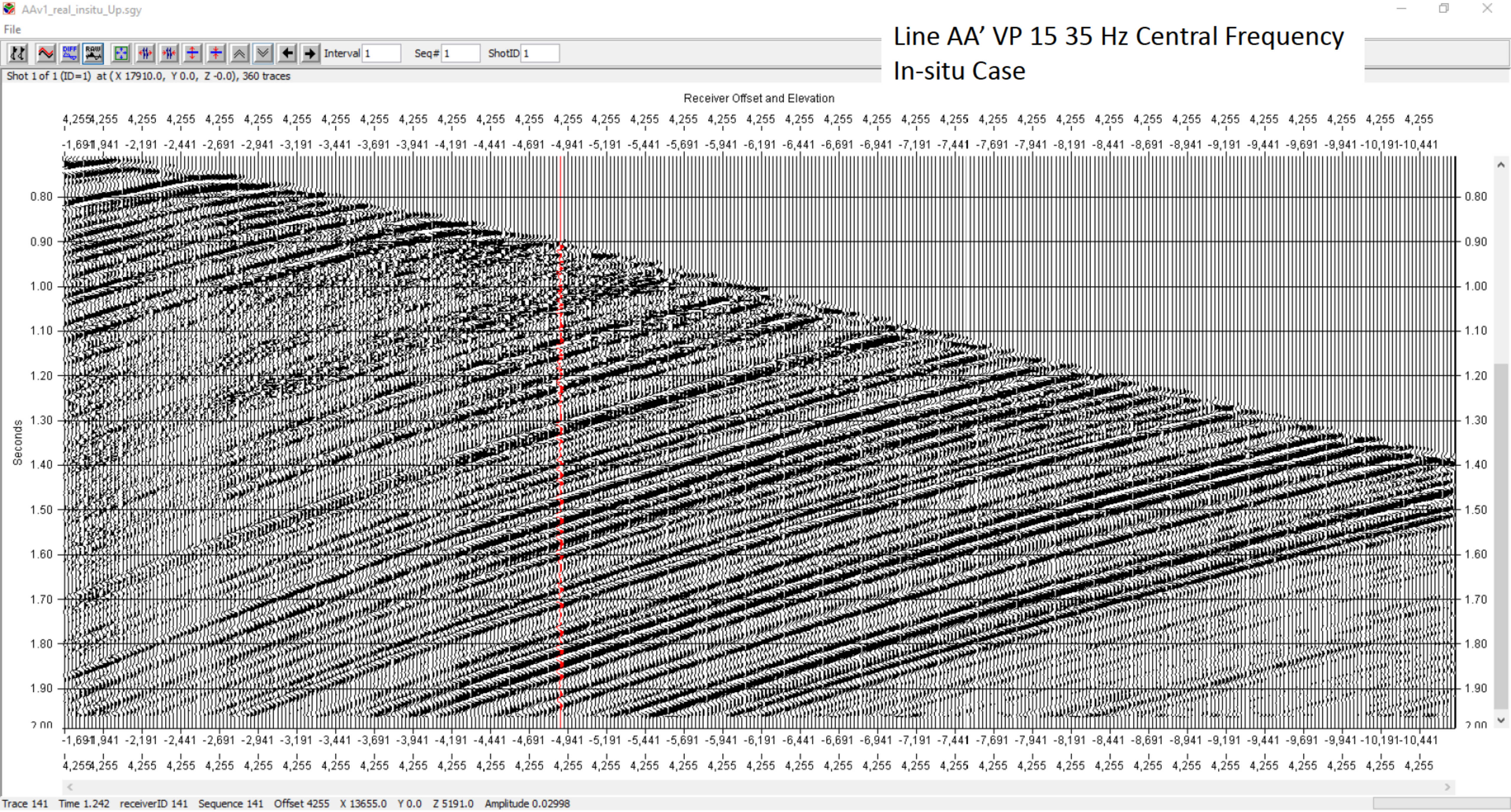


4D Signal

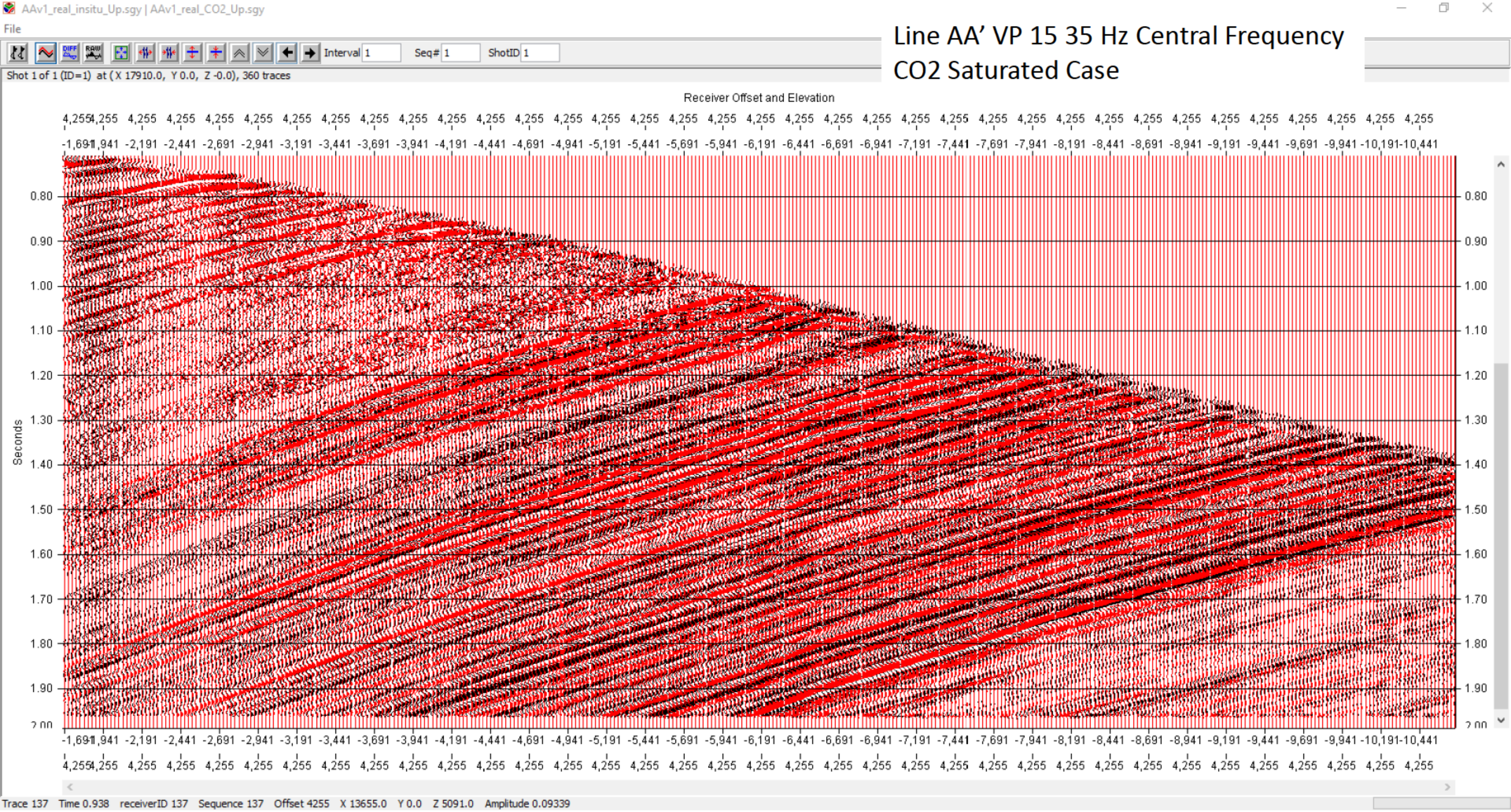
- Black display indicates In-situ Case
- Red display shows CO_2 Saturated/3% Saturated Cases
- Blue display shows the difference

- Trace scaling is based on fixed levels and so the amplitudes should represent real variations between datasets.

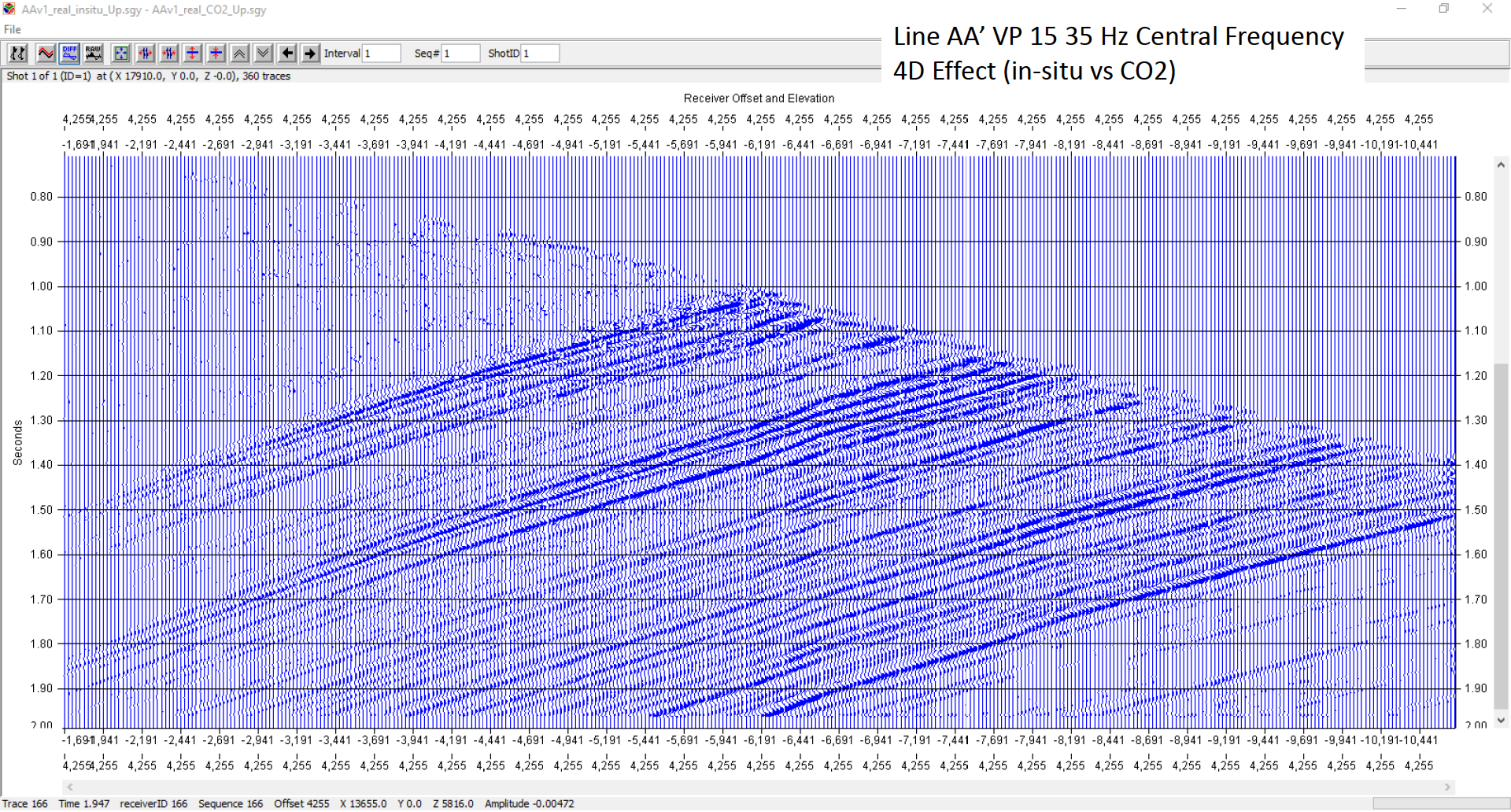
Line AA' VP 15 35 Hz Central Frequency In-situ Case



Line AA' VP 15 35 Hz Central Frequency CO2 Saturated Case



Line AA' VP 15 35 Hz Central Frequency 4D Effect (in-situ vs CO_2)

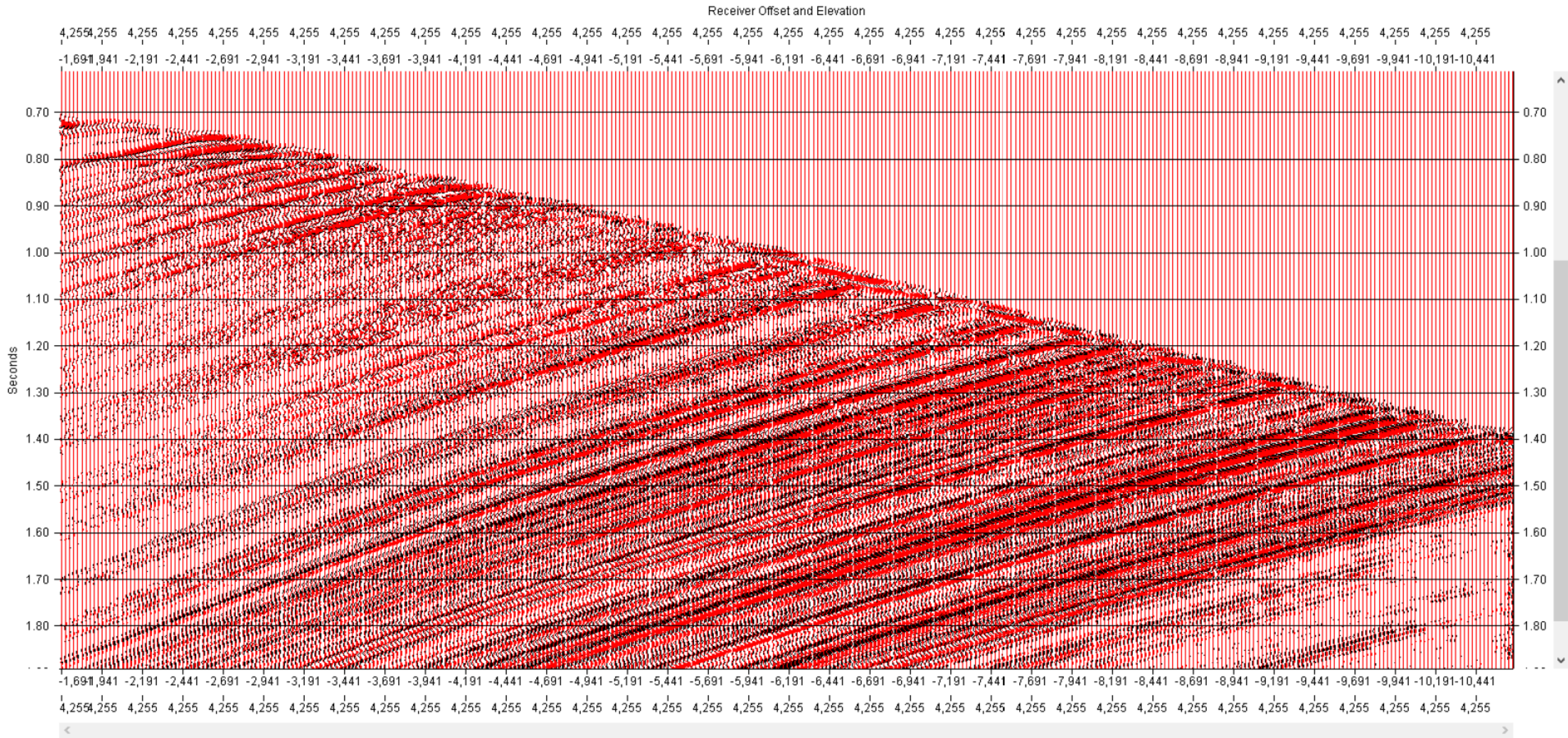


AAv1_real_insitu_Up.sgy | AAv1_real_CO2_SW97_Up.sgy

Line AA' VP 15 35 Hz Central Frequency
3% CO_2 Saturated Case (97% SW)

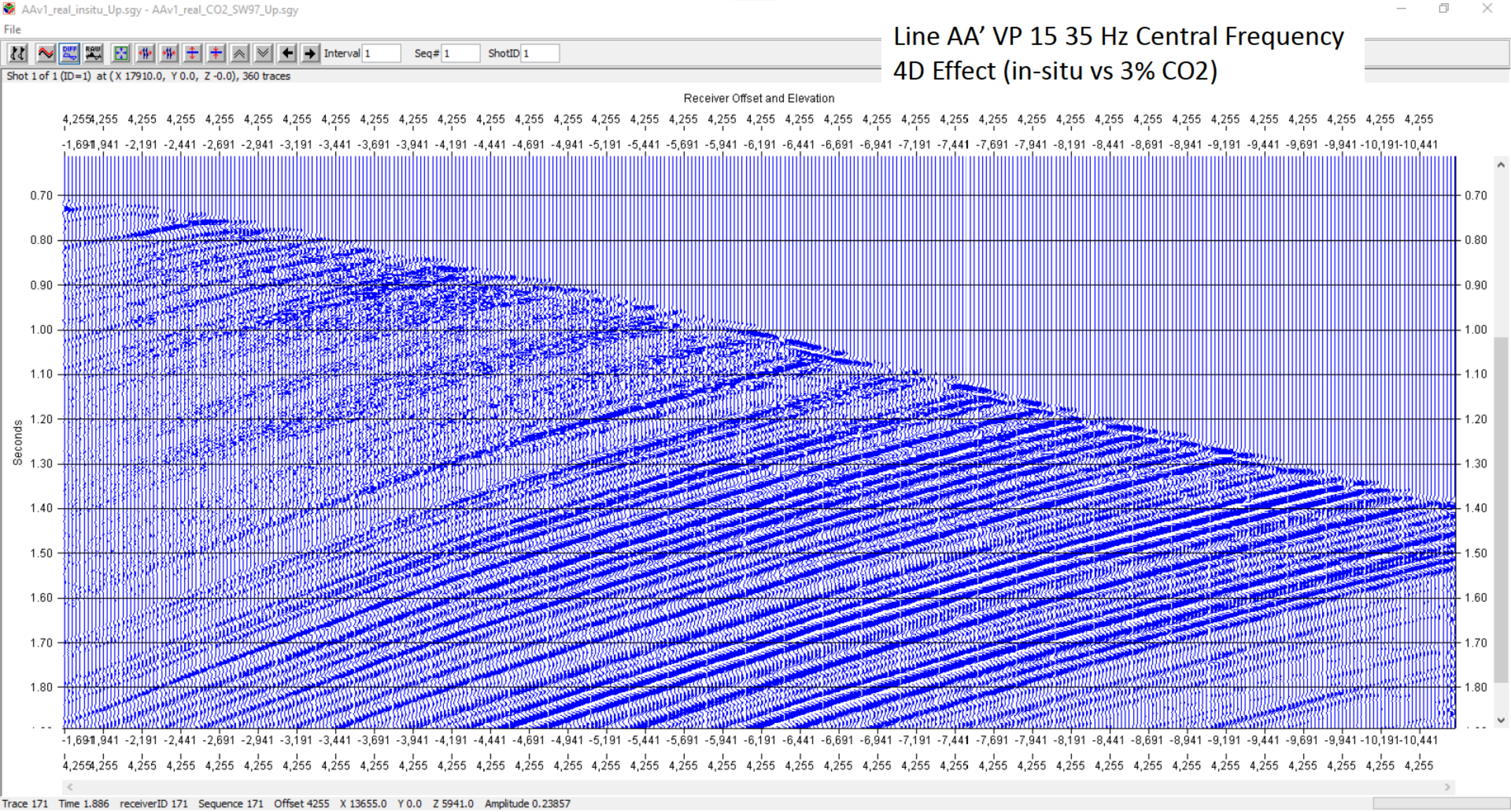
Interval 1 Seq# 1 ShotID 1

Shot 1 of 1 (ID=1) at (X 17910.0, Y 0.0, Z -0.0), 360 traces

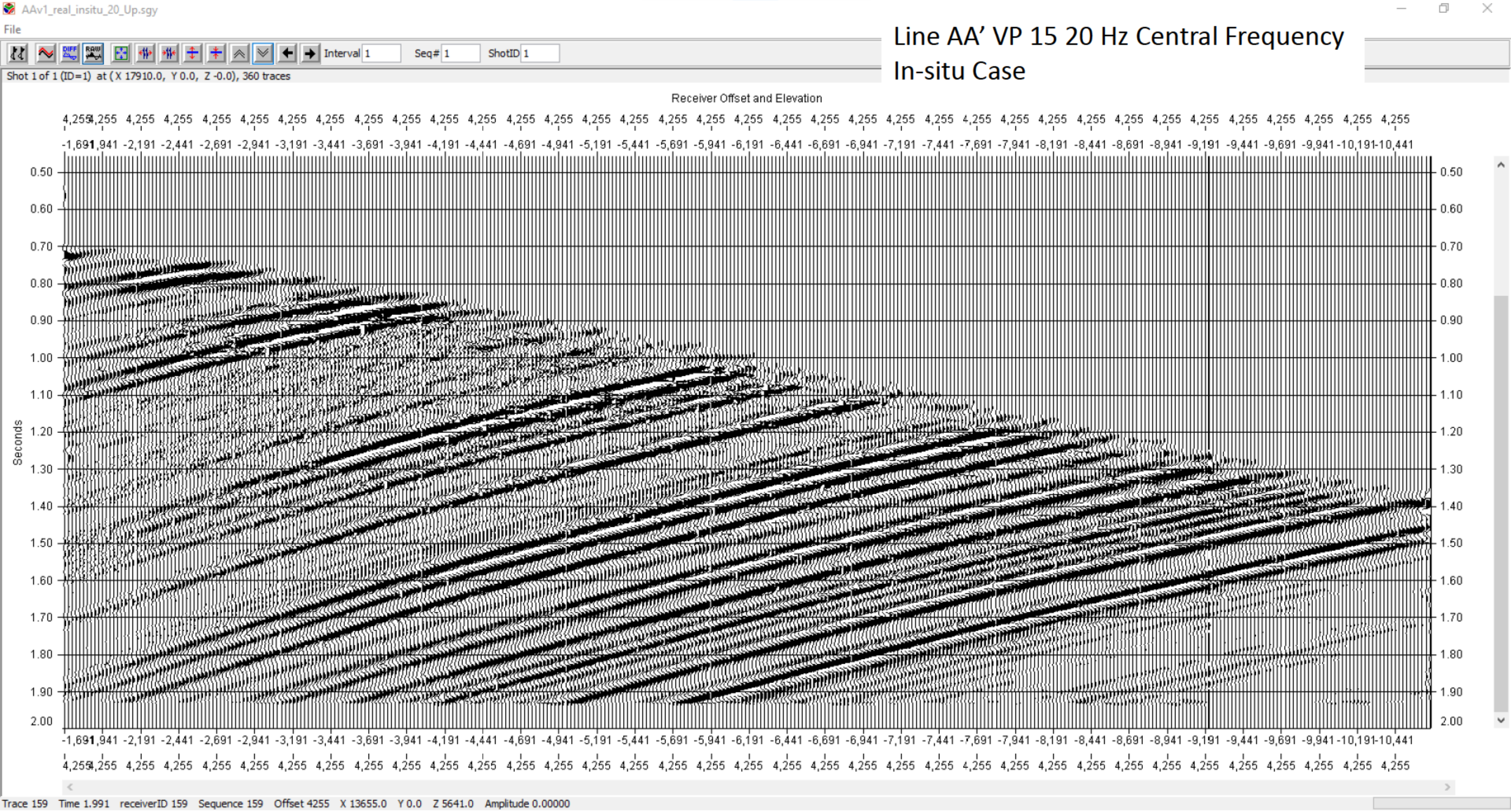


Trace 166 Time 1.888 receiverID 166 Sequence 166 Offset 4255 X 13655.0 Y 0.0 Z 5816.0 Amplitude -0.18358

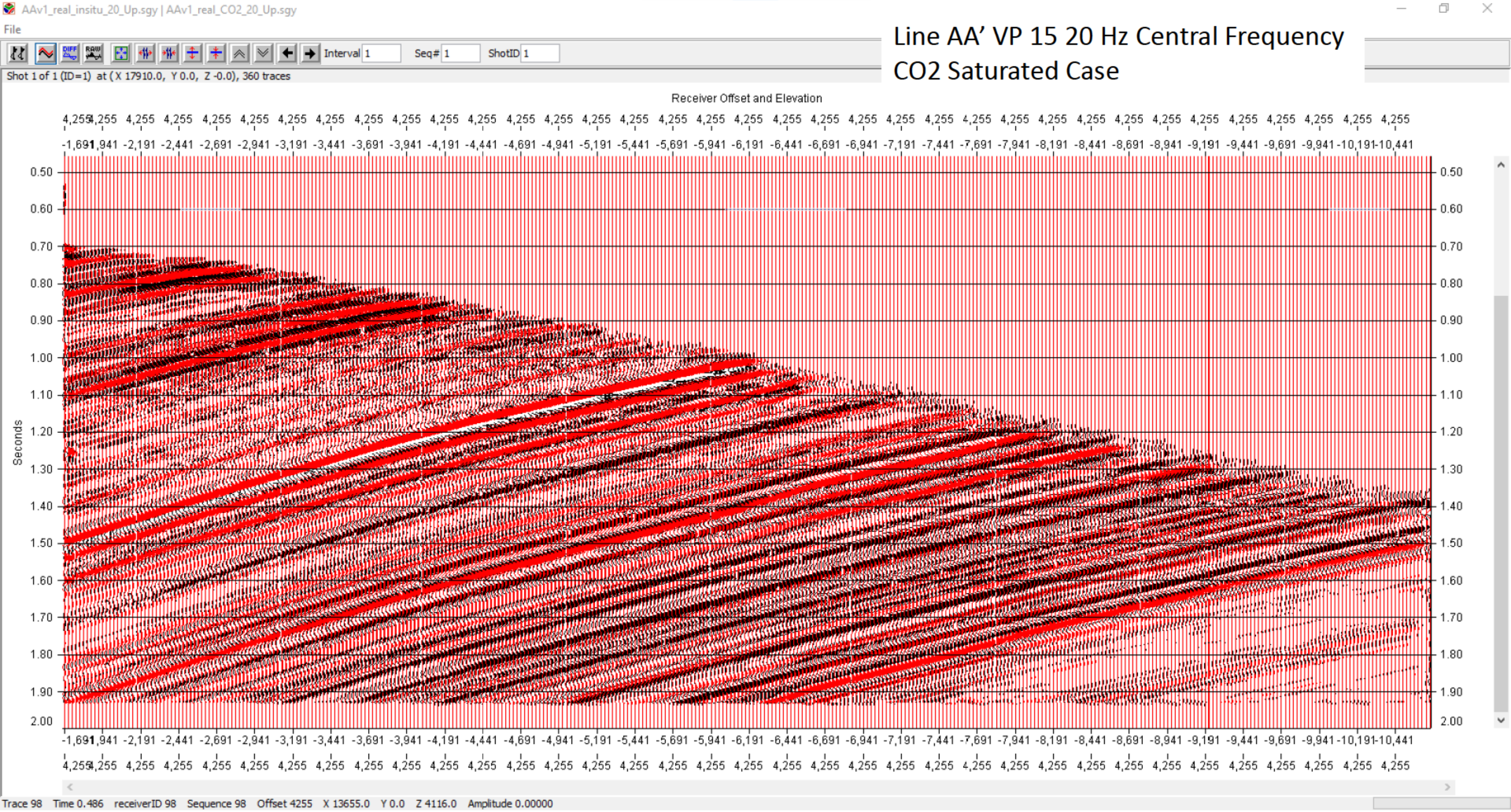
Line AA’ VP 15 35 Hz Central Frequency 4D Effect (in-situ vs 3% CO2)



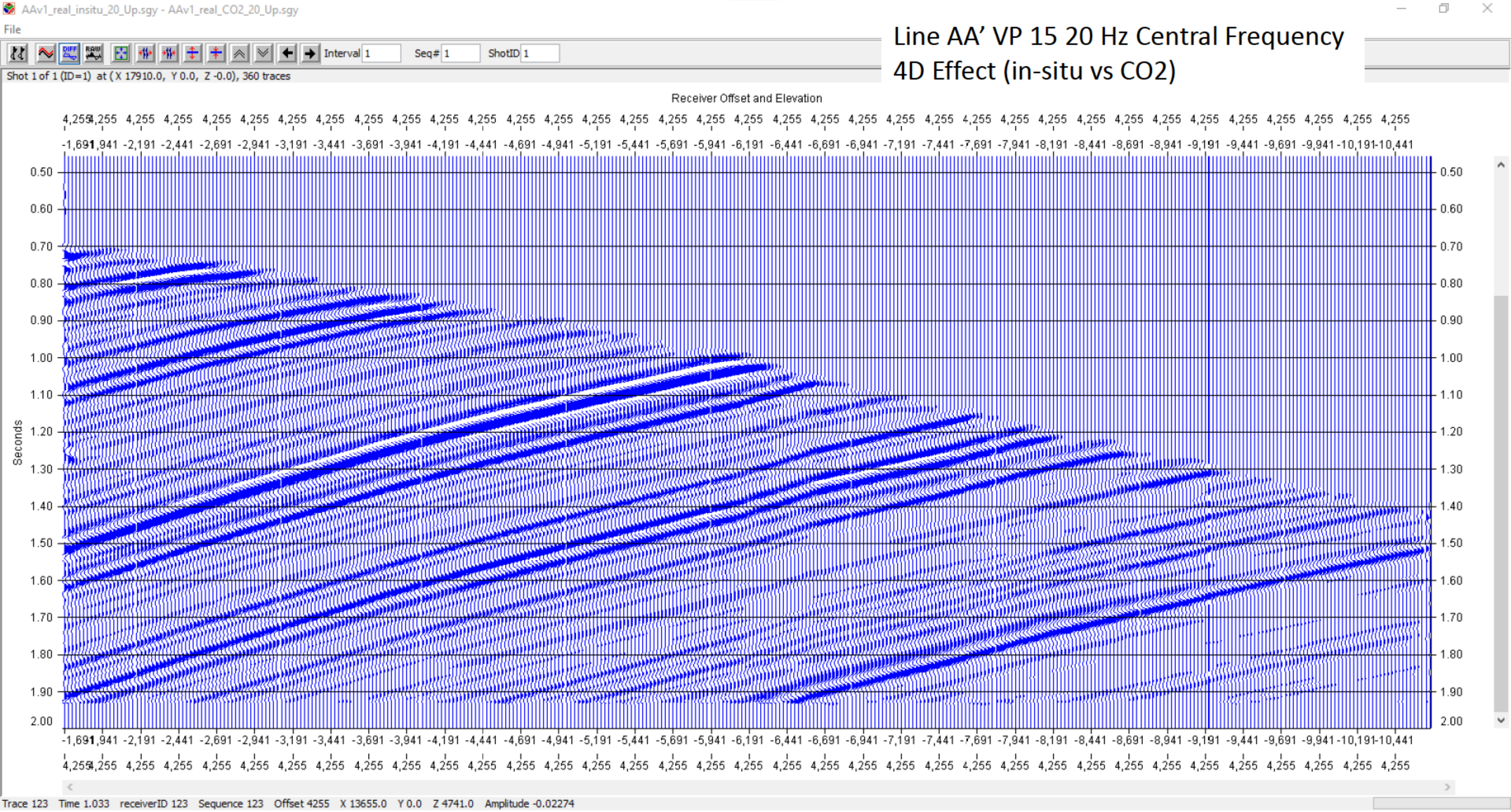
Line AA' VP 15 20 Hz Central Frequency In-situ Case



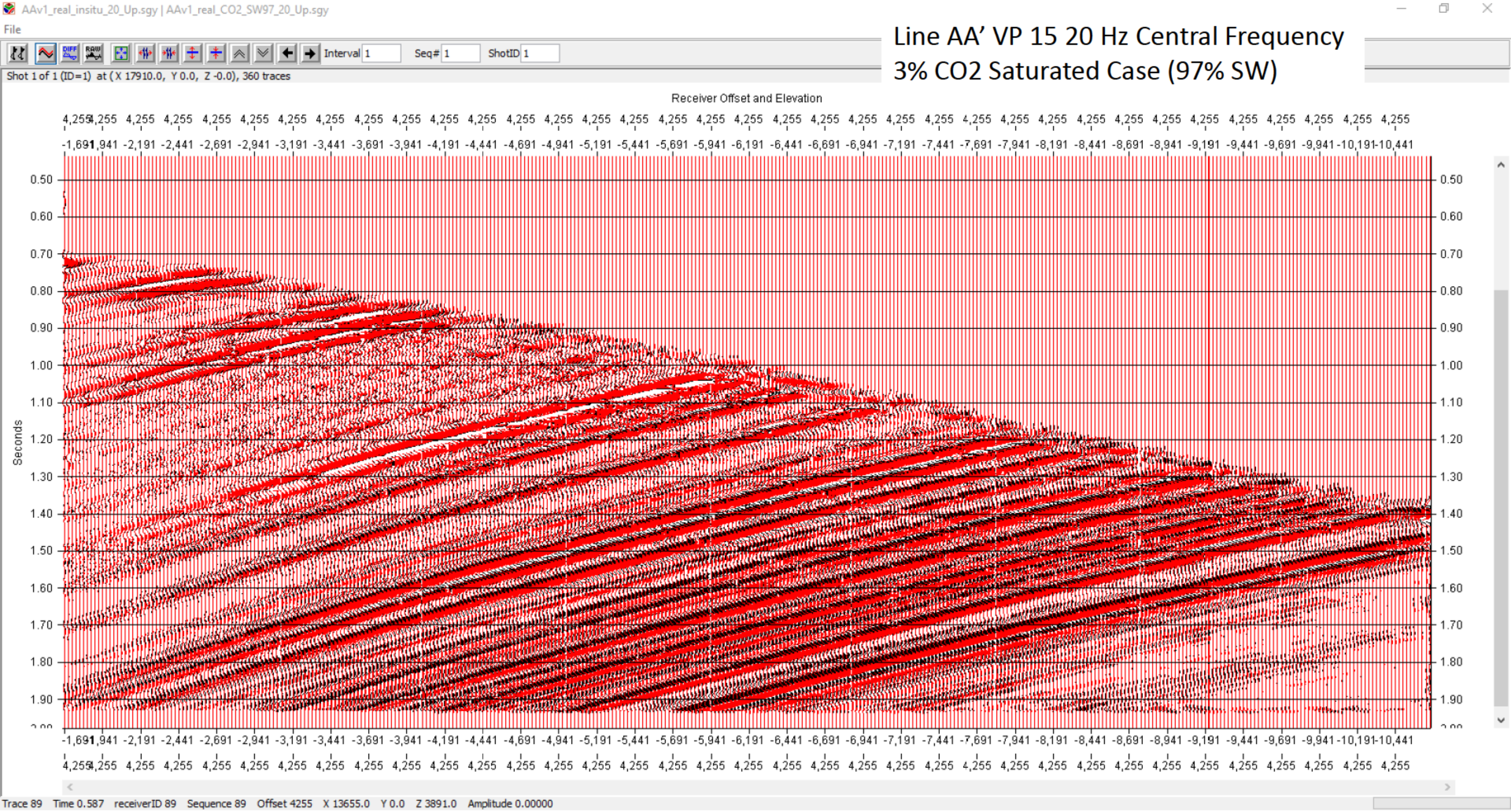
Line AA' VP 15 20 Hz Central Frequency CO2 Saturated Case



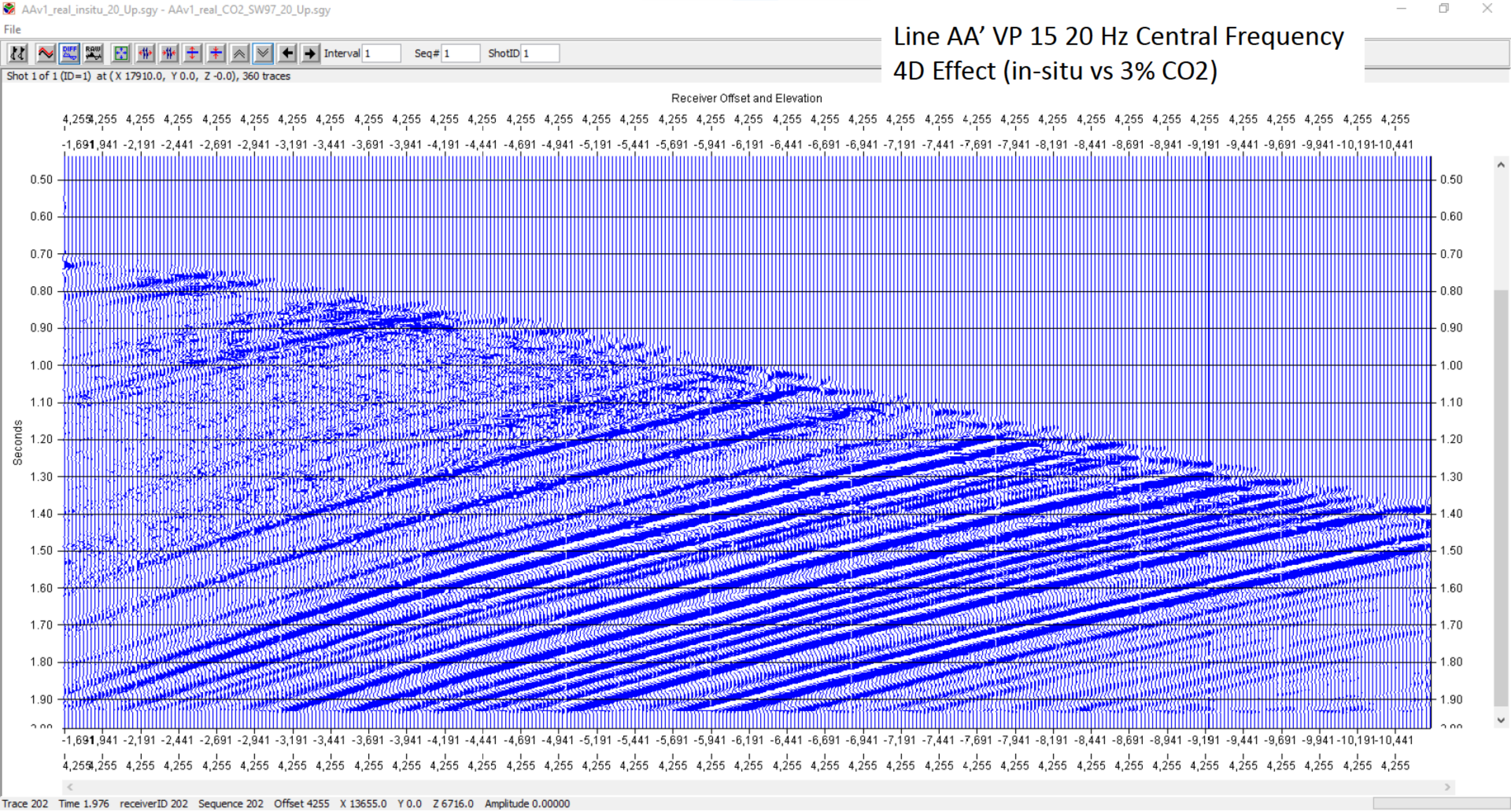
Line AA' VP 15 20 Hz Central Frequency 4D Effect (in-situ vs CO_2)



Line AA’ VP 15 20 Hz Central Frequency
3% CO2 Saturated Case (97% SW)



Line AA' VP 15 20 Hz Central Frequency 4D Effect (in-situ vs 3% CO2)



4D Signal

- The slides above show that there is a good 4D signal due to the presence of CO2 in the system at all depths fluid substitution was performed.
- This appears to be true both for the fully saturated and 3% saturated cases, indicating that CO2 injection will have a strong influence on seismic character and as such should be identifiable from a seismic survey (VSP or surface).

Conclusions

- The slides above show that there is a reasonable 4D signal due to the presence of CO2 in the system at all depths fluid substitution was performed.
- This appears to be true both for the fully saturated and 3% saturated cases, indicating that CO2 injection will have an influence on seismic character and as such will likely be identifiable from a seismic survey (VSP or surface).