QUARTERLY PROGRESS REPORT

To
DOE-NETL
Brian Dressel, Program Manager
Award Number: DE-FE0006821

SMALL SCALE FIELD TEST DEMONSTRATING CO_2 SEQUESTRATION IN ARBUCKLE SALINE AQUIFER AND BY CO_2-EOR AT WELLINGTON FIELD, SUMNER COUNTY, KANSAS

Project Director/Principal Investigator:
W. Lynn Watney
Senior Scientific Fellow
Kansas Geological Survey
Ph: 785-864-2184, Fax: 785-864-5317
lwatney@kgs.ku.edu

Joint Principal Investigator:
Jason Rush

Prepared by Lynn Watney, Eugene Holubnyak, John Victorine, Jennifer Raney, Alex Nolte, Brent Campbell, George Tsoflias, Tiraz Birdie, Jason Rush, Mina Fazelalavi, Brandon Graham, John Doveton, Jason Bruns,
Brett Blazer, Dana Wreath, Christa Jackson, Katie Graham, Brock Norwood

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Recipient: University of Kansas Center for Research &
Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66047

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Twentieth Quarterly Report
Period Covered by the Report: August 1, 2016 through October 31, 2016

Signature of Submitting Official:

Jason Rush
Jason Rush

EXECUTIVE SUMMARY

PROJECT OBJECTIVES

The objectives of this project are to understand the processes that occur when a maximum of 70,000 metric tonnes of CO2 are injected into two different formations to evaluate the response in different lithofacies and depositional environments. The evaluation will be accomplished through the use of both in situ and indirect MVA (monitoring, verification, and accounting) technologies. The project will optimize for carbon storage accounting for 99% of the CO2 using lab and field testing and comprehensive characterization and modeling techniques.

CO2 will be injected under supercritical conditions to demonstrate state-of-the-art MVA tools and techniques to monitor and visualize the injected CO2 plume and to refine geomodels developed using nearly continuous core, exhaustive wireline logs, and well tests and a multi- component 3D seismic survey. Reservoir simulation studies will map the injected CO2 plume and estimate tonnage of CO2 stored in solution, as residual gas, and by mineralization and integrate MVA results and reservoir models shall be used to evaluate CO2 leakage. A rapid- response mitigation plan will be developed to minimize CO2 leakage and provide comprehensive risk management strategy. A documentation of best practice methodologies for MVA and application for closure of the carbon storage test will complete the project. The CO2 shall be supplied from a reliable facility and have an adequate delivery and quality of CO2.

SCOPE OF WORK

Budget Period 1 includes updating reservoirs models at Wellington Field and filing Class II and Class VI injection permit application. Static 3D geocellular models of the Mississippian and Arbuckle shall integrate petrophysical information from core, wireline logs, and well tests with spatial and attribute information from their respective 3D seismic volumes. Dynamic models (composition simulations) of these reservoirs shall incorporate this information with laboratory data obtained from rock and fluid analyses to predict the properties of the CO2 plume through time. The results will be used as the basis to establish the MVA and as a basis to compare with actual CO2 injection. The small scale field test shall evaluate the accuracy of the models as a means to refine them in order to improve the predictions of the behavior and fate of CO2 and optimizing carbon storage.

Budget Period 2 includes completing a Class II underground injection control permit; drilling and equipping a new borehole into the Mississippian reservoir for use in the first phase of CO2 injection; establishing MVA infrastructure and acquiring baseline data; establishing source of CO2 and transportation to the injection site; building injection facilities in the oil field; and injecting CO2 into the Mississippian-age spiculitic cherty dolomitic open marine carbonate reservoir as part of the small scale carbon storage project.

In Budget Period 3, contingent on securing a Class VI injection permit, the drilling and completion of an observation well will be done to monitor injection of CO2 under supercritical conditions into the Lower Ordovician Arbuckle shallow (peritidal) marine dolomitic reservoir.

Monitoring during pre-injection, during injection, and post injection will be accomplished with MVA tools and techniques to visualize CO_2 plume movement and will be used to reconcile simulation results. Necessary documentation will be submitted for closure of the small scale carbon storage project.

PROJECT GOALS

The proposed small scale injection will advance the science and practice of carbon sequestration in the Midcontinent by refining characterization and modeling, evaluating best practices for MVA tailored to the geologic setting, optimize methods for remediation and risk management, and provide technical information and training to enable additional projects and facilitate discussions on issues of liability and risk management for operators, regulators, and policy makers.

The data gathered as part of this research effort and pilot study will be shared with the Southwest Sequestration Partnership (SWP) and integrated into the National Carbon Sequestration Database and Geographic Information System (NATCARB) and the 6th Edition of the Carbon Sequestration Atlas of the United States and Canada.

Project Deliverables by Task

1.5 Well Drilling and Installation Plan (Can be Appendix to PMP or Quarterly Report)
1.6 MVA Plan (Can be Appendix to PMP or Quarterly Report)
1.7 Public Outreach Plan (Can be Appendix to PMP)
1.8 Arbuckle Injection Permit Application Review go/no go Memo
1.9 Mississippian Injection Permit Application Review go/no go Memo
1.10 Site Development, Operations, and Closure Plan (Can be Appendix to PMP)
2.0 Suitable geology for Injection Arbuckle go/no go Memo
3.0 Suitable geology for Injection Mississippian go/no go Memo
11.2 Capture and Compression Design and Cost Evaluation go/no go Memo
19 Updated Site Characterization/Conceptual Models (Can be Appendix to Quarterly)
21 Commercialization Plan (Can be Appendix to Quarterly Report).
30 Best Practices Plan (Can be Appendix to Quarterly or Final Report)

CO_2-EOR Accomplishments

1. Day-to-day field operations similar to that reported last quarter (Q19) and are a continuation of Tasks 12–15
2. Continued monitoring of CO2 injection
    a. Recorded volumes of CO2 produced, oil, and brine recovered
    b. Reduced well-based monitoring to seven wells after CO2 ended and continuous water injection began. Past geochemical analyses indicate the plume has largely stabilized. As such, only the seven innermost wells are currently being sample for on-site (performed by KGS) and lab-based geochemical analyses (performed by Baker Chemicals). CO2 gas quality measurements are being performed by Berexco staff.
3. Since mid-April 2016, continuous (1-sec) baseline pressure measurements have been acquired in the perforated lower Arbuckle zone in the shut-in Class VI injector (See Appendix 1). Because of this monitoring, the well has not been retrofitted for installation of MVA tools (BP2 Milestone).
4. The primary CO2 plume has been managed by pressure maintenance including use of two nearby injection wells and targeted fluid withdrawal in eight surrounding wells. The CO2 injection conforms largely to the stratigraphic architecture recorded in the geocellular model. Key work for the remainder of the CO2-EOR phase is to continue measuring all inputs and outputs to obtain accurate measurement of CO2 sequestered in the reservoir and the incremental oil produced from a single injection cycle.
5. On September 30, 2016 the daily CO2 amount recorded was 190 MCFD down from 450 MCFD on July 25th. As of September 30, 2016, the cumulative produced CO2 accounts for 16% of the injected volume (up from 11% in July).
6. The new 2D seismic survey was acquired, processed, and delivered. For consistency, all 2-D seismic lines were processed or reprocessed using the most-recent technologies offered by Fairfield-Nodal (see Appendix 2).

Geosequestration and Class VI Permit Accomplishments

1. The 2D seismic survey was successfully acquired and will have sufficient offset to evaluate optimized AVO (Amplitude vs. Offset) for detecting the CO2 plume during geosequestration operations.
2. Model-based simulations for 10,000 tonnes of CO2 injected into Arbuckle saline aquifer were performed to forecast plume dimensions.
3. AVO modeling of plume dimensions indicates that a 10,000 tonne plume will be seismically resolvable.
4. Prepared and submitted written response dated August 17, 2016 for U.S. EPA RFI#12 pertaining to differences in porosity distributions and simulation results.
5. Financial assurance documents related to insurance were submitted to the U.S. EPA by Berexco this quarter.
6. A meeting is planned for early December with Berexco, KGS, and U.S. EPA to review results of Class VI permit.

Monitoring Activity	Pre-Injection	Injection	Post-Injection
CO_2 Fluid Chemical Analysis	x	x	-
CO_2 Injection Rate and Volume[1]	-	x	-
CO_2 Injection Pressure at Wellhead[1]	-	x	-
CO_2 Injection Pressure at Well Bottom[1]	x	x	x
Internal MIT (Anulus Pressure Test)	x	-	-
External MIT (Temperature Log)	x	x	x
Continuous Annular Pressure	-	x	-
Corrosion	-	x	x
Pressure Fall Off Test	x	-	-
Pressure in Arbuckle Monitoring Well (Direct Arbuckle Monitoring)	x	x	x
INSAR (Indirect Arbuckle Pressure Monitoring)	x	x	x
USDW Geochemistry	x	x	x
Mississippian Geochemistry	x	x	x
U-Tube (Direct Arbuckle Geochemistry Monitoring)	x	x	x
CASSM (Indirect Arbuckle Plume-Front Monitoring)	x	x	x[2]
Crosswell Seismic (Indirect Arbuckle Plume-Front Monitoring)	x	x	-
3D Seismic Survey (Indirect Arbuckle Plume-Front Monitoring)	x	-	x

[1] Monitored continuously
[2] If CO_2 plume is detected at KGS 2-28 during the injection phase, then CASSM will not be conducted during the post-injection phase.

Table 1. MVA activities submitted to the U.S. EPA permit

Q20 Tasks

Site Characterization of Mississippian Reservoir for CO2-EOR – Wellington Field

The CO2 injection was completed in 165 days or approximately 5 months with an average of 120 tonnes per day of CO2 injected (Figures 1 and 2). Oil rates have declined to about 22–25 BOPD. On September 30, 2016 the daily CO2 amount recorded was 190 MCFD down from 450 MCFD on July 25th. As of September 30, 2016, the cumulative produced CO2 accounts for 16% of the injected volume (up from 11% in July). Geochemical analyses from June 2016 indicate the plume has largely stabilized. As such, only the seven innermost wells are currently being sample for on-site (performed by KGS) and lab-based geochemical analyses (performed by Baker Chemicals). The relatively low amounts of recovered CO2 (Figures 1 and 2) and evidence of diffusion in brine data maps (Figure 3) indicate the flood is conformable and is not bypassing through conductive fractures. Key observations this quarter: 1) incremental oil production is 2X greater than before injection (Figure 2; 2) the pH in well 69 continues to drop (from 5.81 to 5.41); 3) the temperature in Well 47 dropped 9°C, 4) the wellhead pressure in well 61 has dropped from approximately 300 to 80 psi, and; 5) the amount of CO2 vented stabilized to between 60 and 80 MCFD during October (Figures 3 and 4). These observations are consistent with the cessation of CO2 injection and the flood-front sweeping laterally away from the injector. In addition, efforts were made in the field to control CO2-related corrosion within the pilot area.

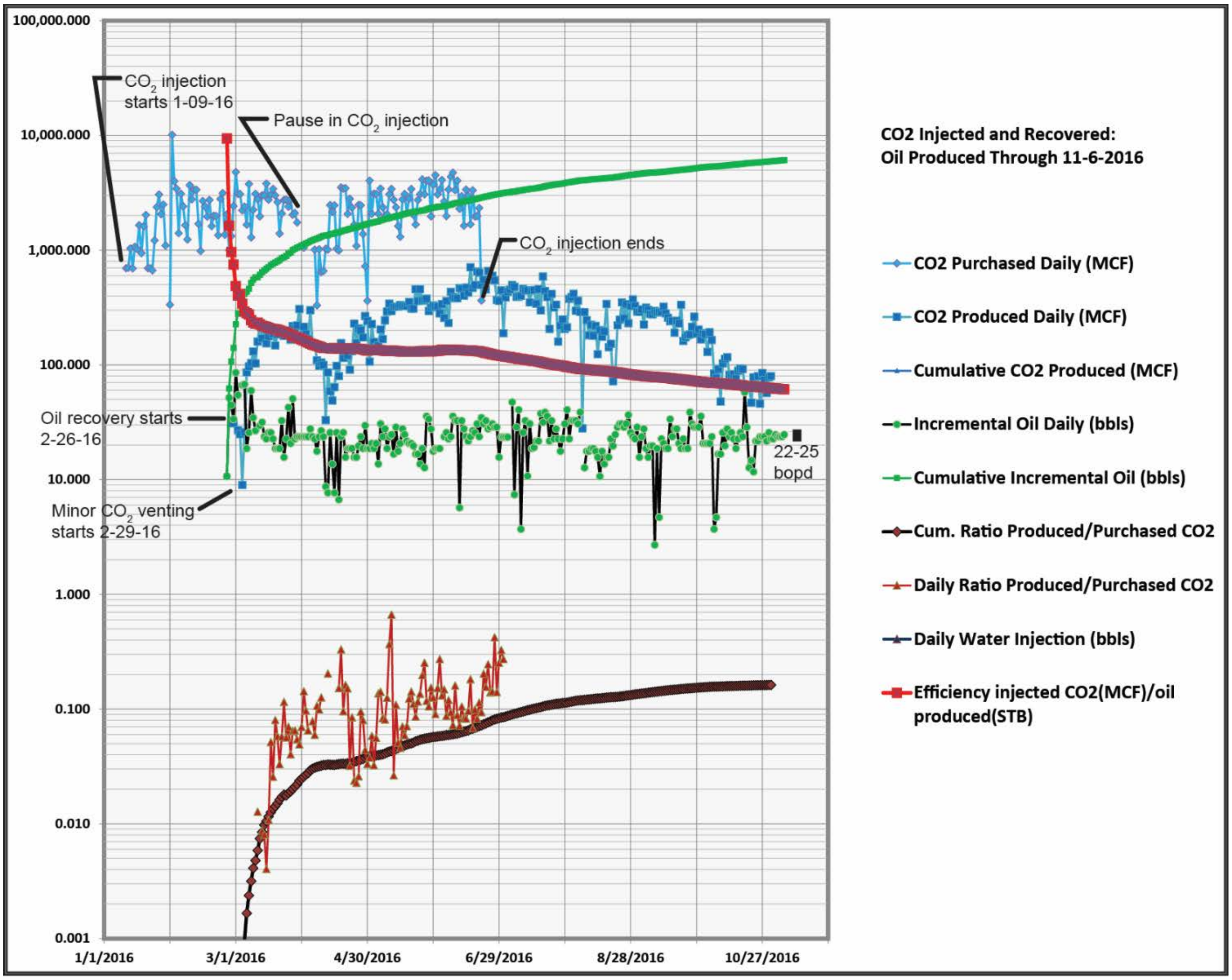


Figure 1. CO2 injected and CO2 and oil recovered in pilot scale injection in the Mississippian oil reservoir in Wellington Field.

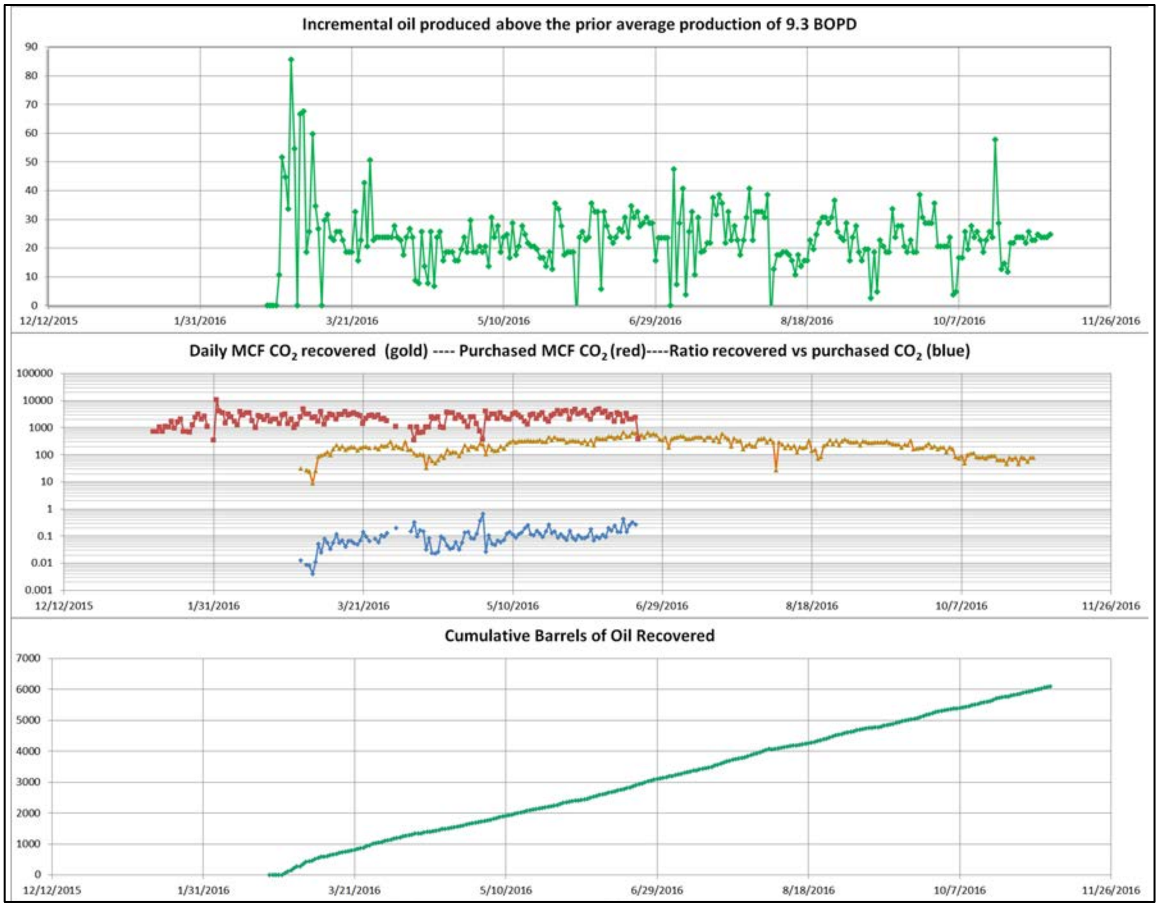


Figure 2. Incremental and cumulative barrels of oil recovered, comparison of CO2 recovered vs. purchased. CO2 recovered has remained at comparatively low levels compared to the amount of CO2 that has been injected. Incremental oil has actually increased slightly since water injection began indicating that the CO2 is being pushed away rather uniformly away from the injection well, #2-32. The response closely resembles what has been forecast from the simulations.

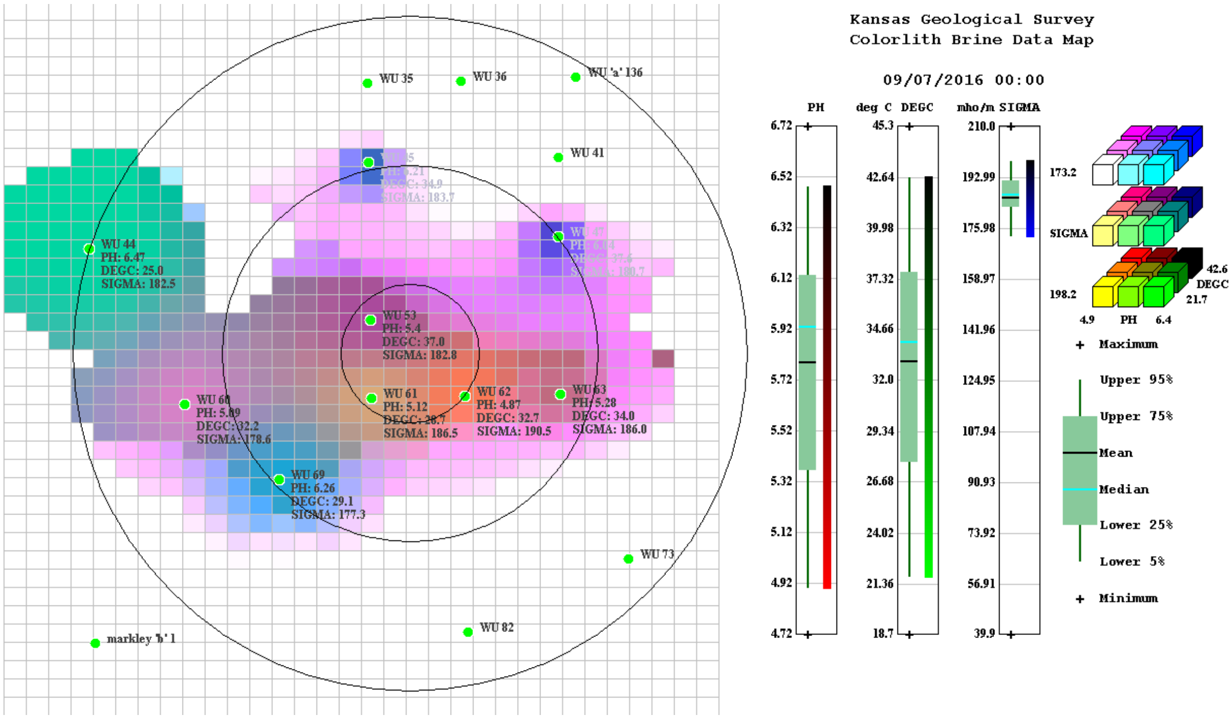


Figure 3. Map showing results of brine analyses for September 2016.

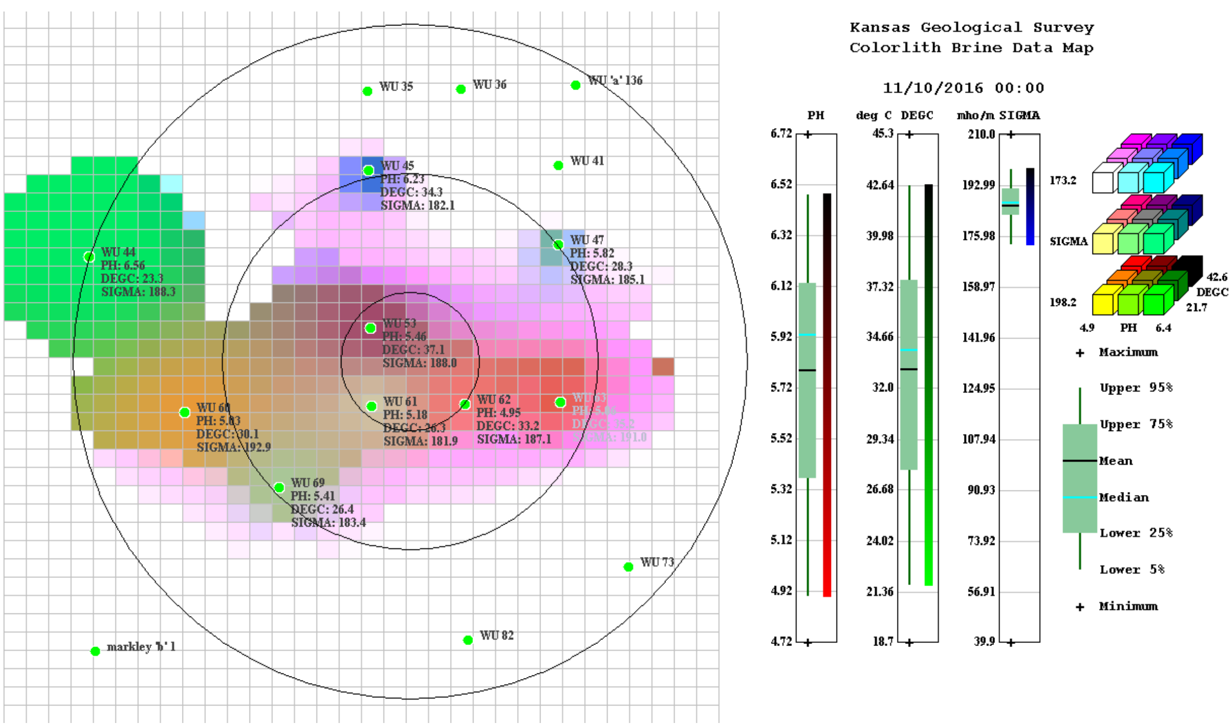


Figure 4. Map showing results of brine analyses for November 2016.

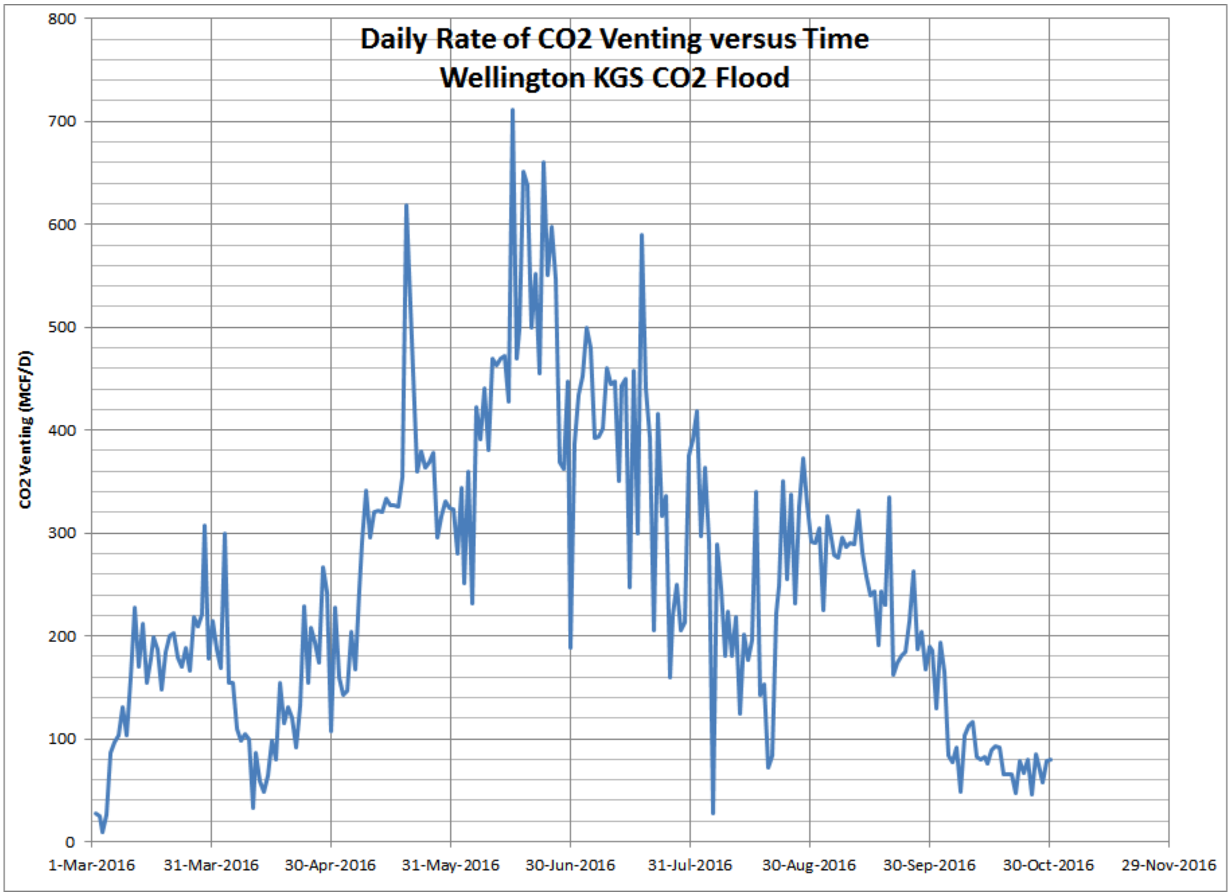


Figure 5. Total CO_2 vented in MCFD. The amount vented has stabilized at 60–80 MCFD.

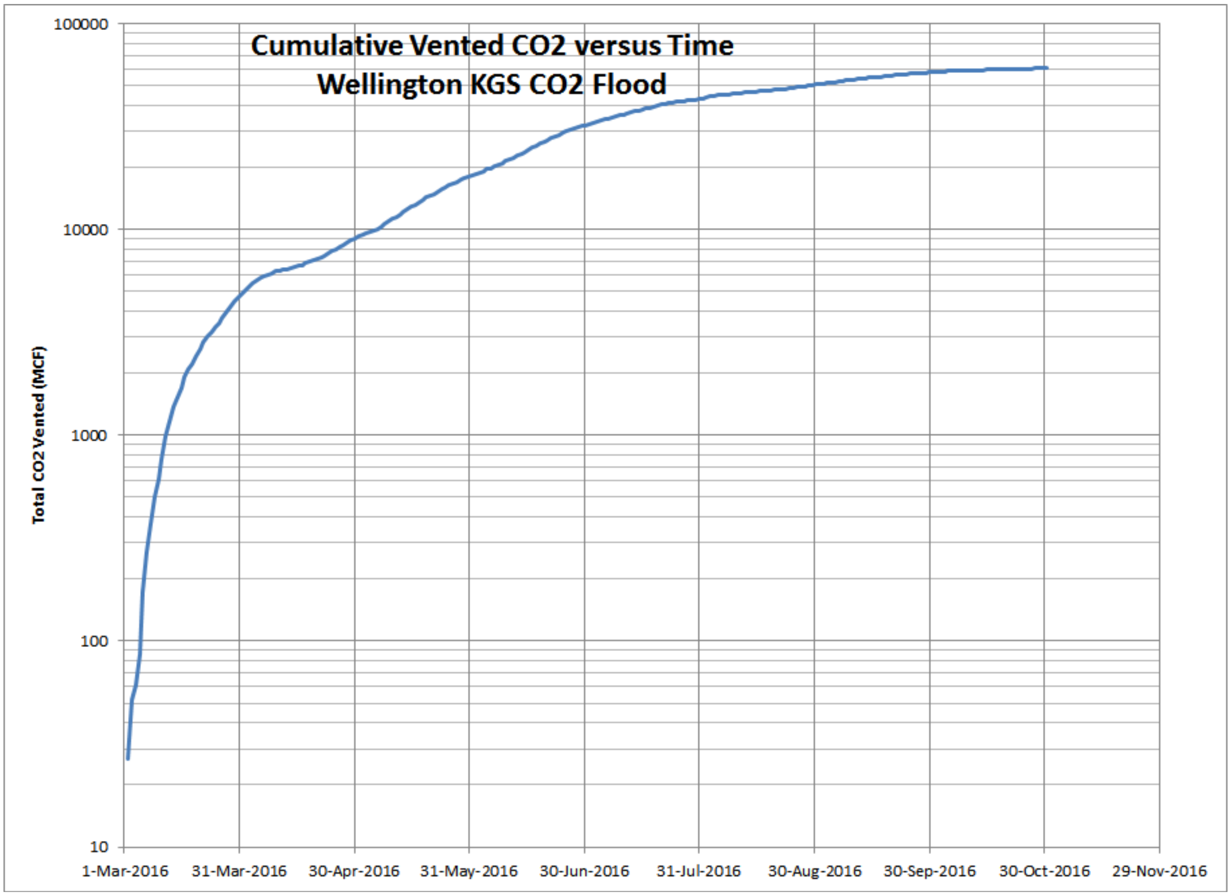


Figure 6. Cumulative CO_2 production, MCF. Trend is similar to that seen in Figure 5 indicating that a large volume ~84% of the CO_2 is still trapped within the reservoir.

Geosequestration Arbuckle

10,000 tonne CO_2 Plume (Simulation and AVO-based Forward Modeling)

Simulation

A simulation case was run for the Wellington Field site (Arbuckle reservoir) where: 1) water is injected at 1,600 bbls/day for 3 months; 2) CO_2 is injected at 112 tones/day for 3 months, and; 3) water is injected at 1,600 bbls/day for 5 months. CO_2 changes its properties due to temperature and pressure (phase transition), whereas water is largely unaffected.

Simulations were run using the following parameters calculated using the water density calculator. At reservoir conditions, water is not compressible. The density of water is affected by salinity (i.e., TDS) and temperature. At surface conditions, Arbuckle brine TDS is ~160 g/l and at T=70F, density of this brine is 1124 kg/m3. At reservoir conditions, (TDS is the same, T=140F), density = 1103.7 kg/m3.

At surface conditions, CO_2 is at ~300 psi and -20F, and this means liquid phase with density of 1073.1 kg/m3. At reservoir conditions (P=~2100 psi, T=~140 F), density of CO_2 is 571.2 kg/m3. The density of CO_2 under reservoir conditions is about half the density of water (571/1104 = ~0.52 kg/m3). 40,000 tons of Arbuckle brine (1104 kg/m3) = 227,892 bbls (9,571,451 gal). Therefore, the volume of CO_2 at reservoir conditions (571 kg/m3) is going to be ~twice (/0.52) the volume of water or ~ 438,254 bbls. Daily rate is therefore ~1623 bbls/day.

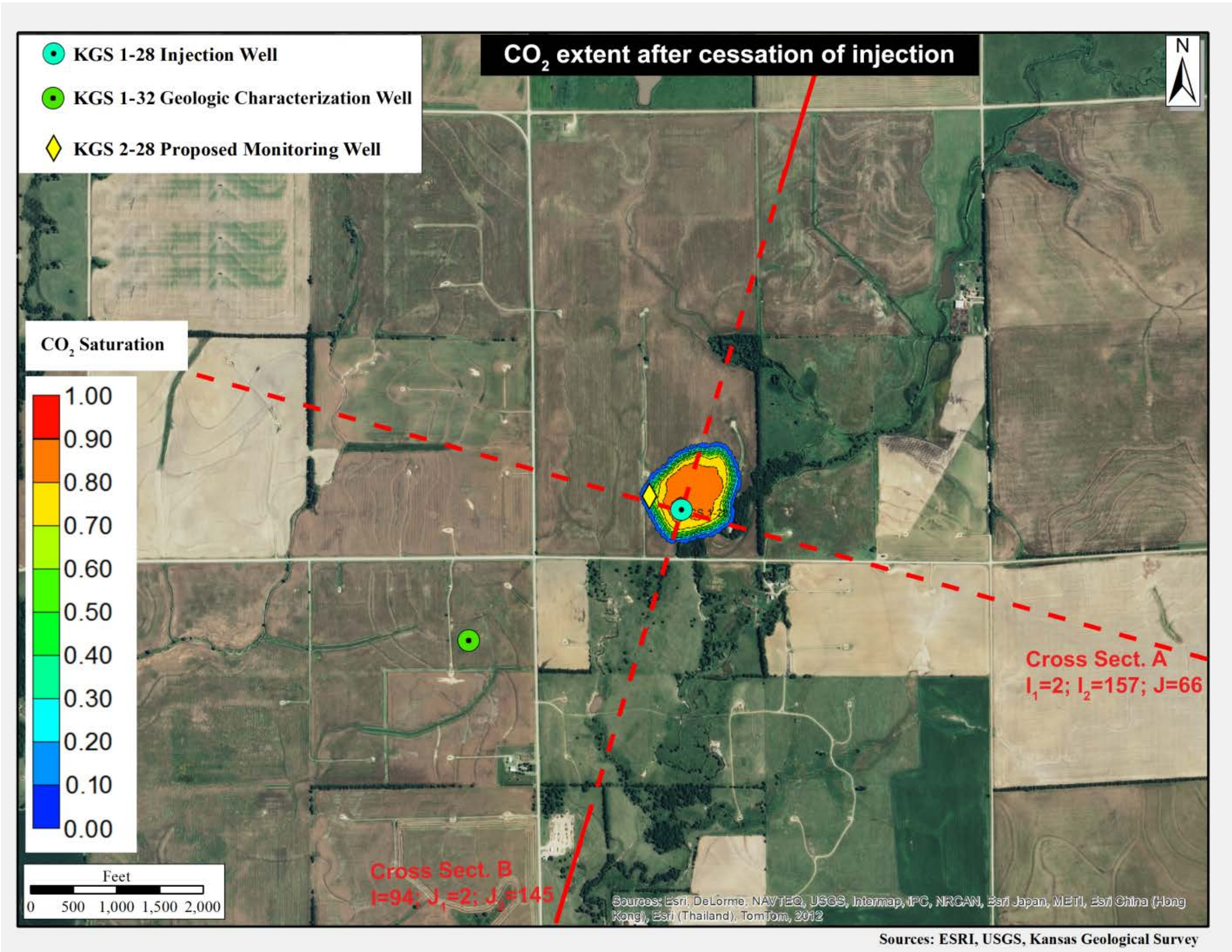


Figure 7. Map showing the aerial extent of CO_2 (in saturation) at end of injection (10K tonnes CO_2). Note plume asymmetry reflecting facies and structural control on distribution.

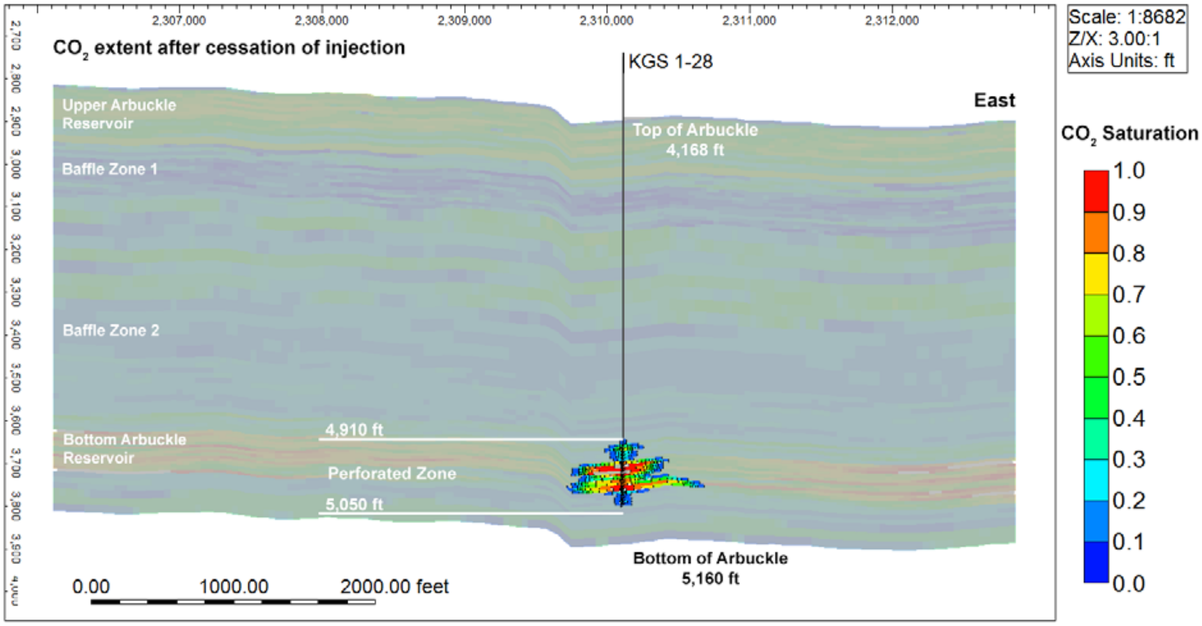


Figure 8. Cross-section A shown in Figure 1. Extent of plume at end of injection (10K tonnes CO2).

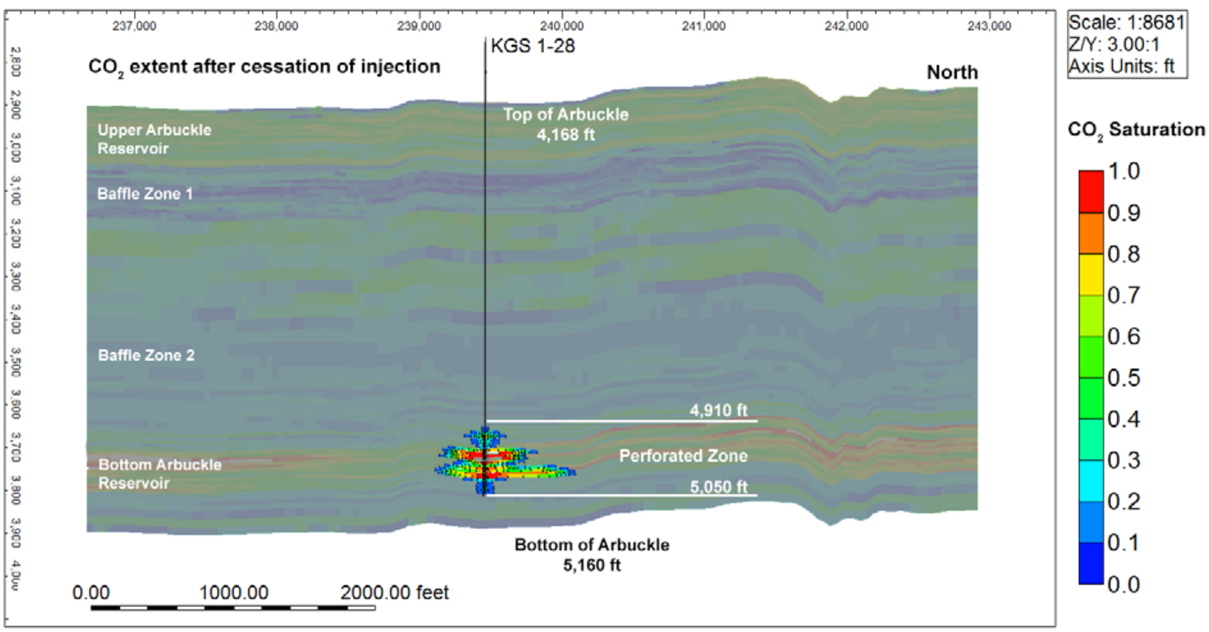


Figure 9. Cross-section B shown in Figure 1. Extent of plume at end of injection (10K tonnes CO2).

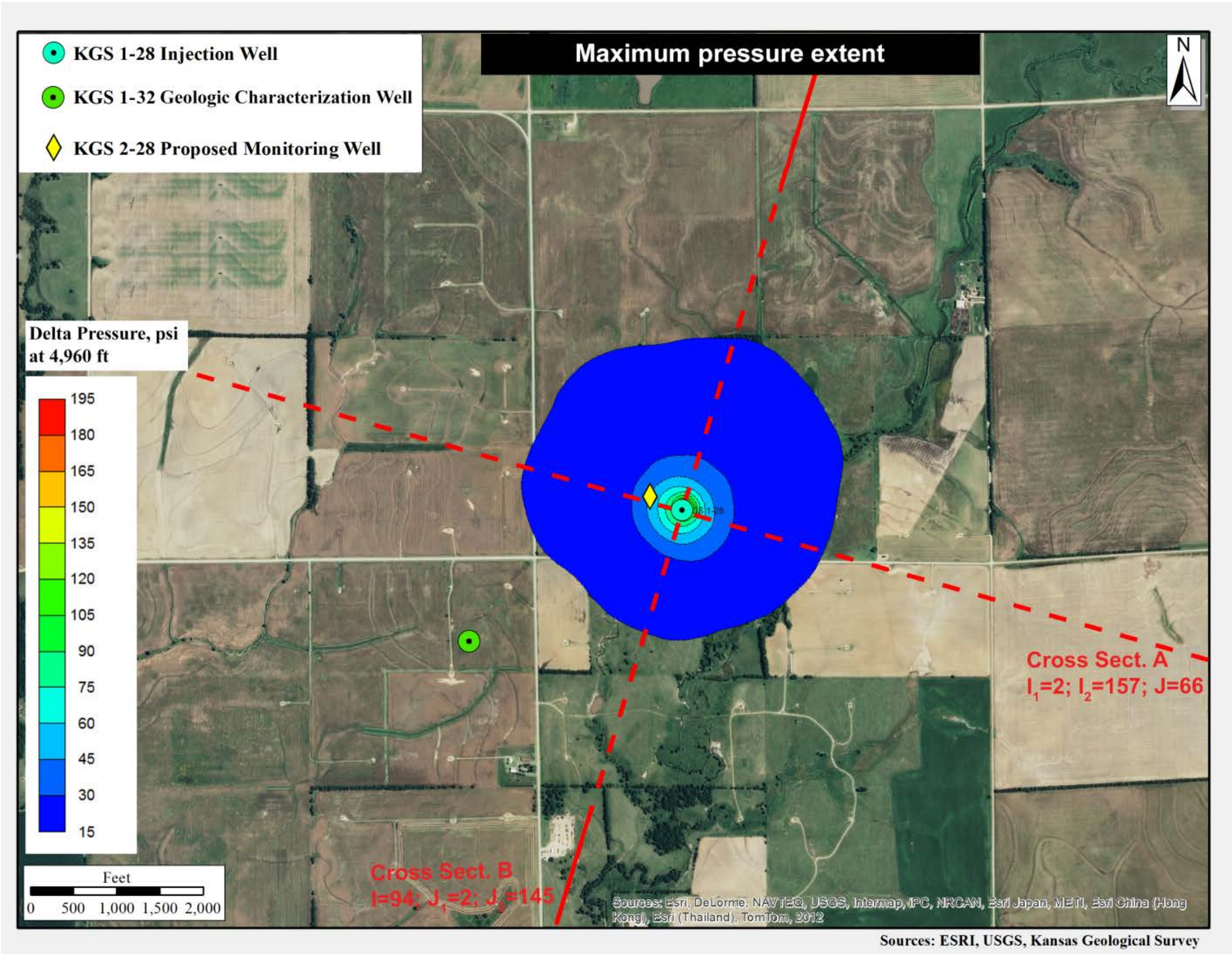


Figure 10. Map showing the simulated increase in pressure 1-year after the start of injection.

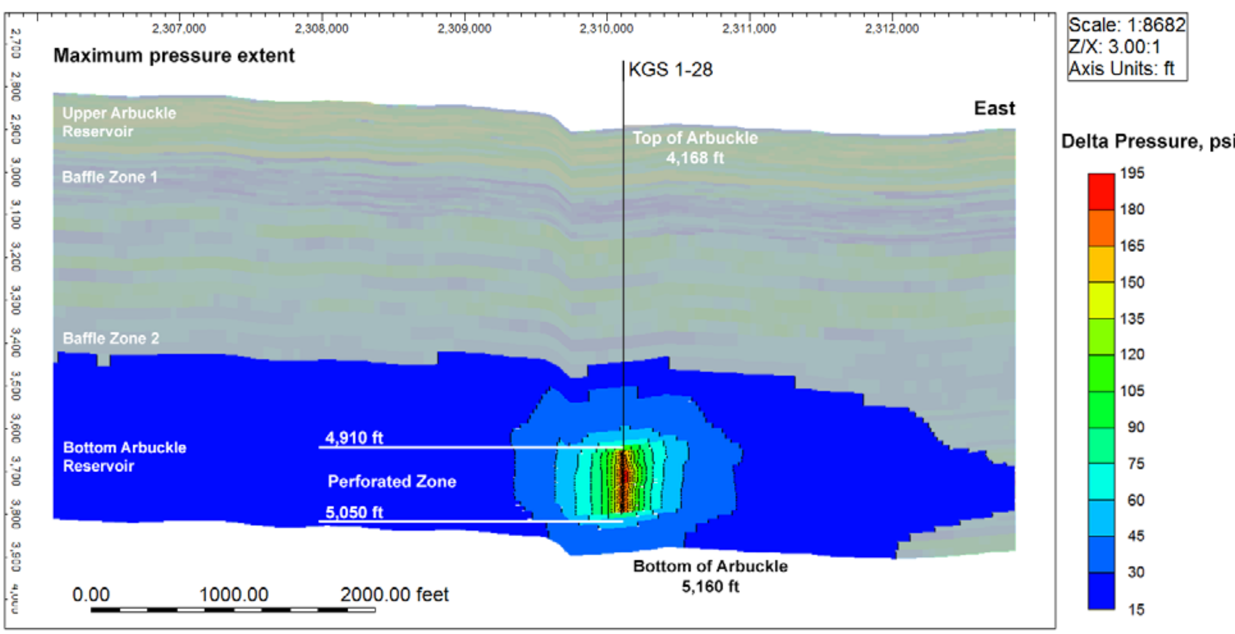


Figure 11. Cross-section A in Figure 4 showing the extent of the pressure front.

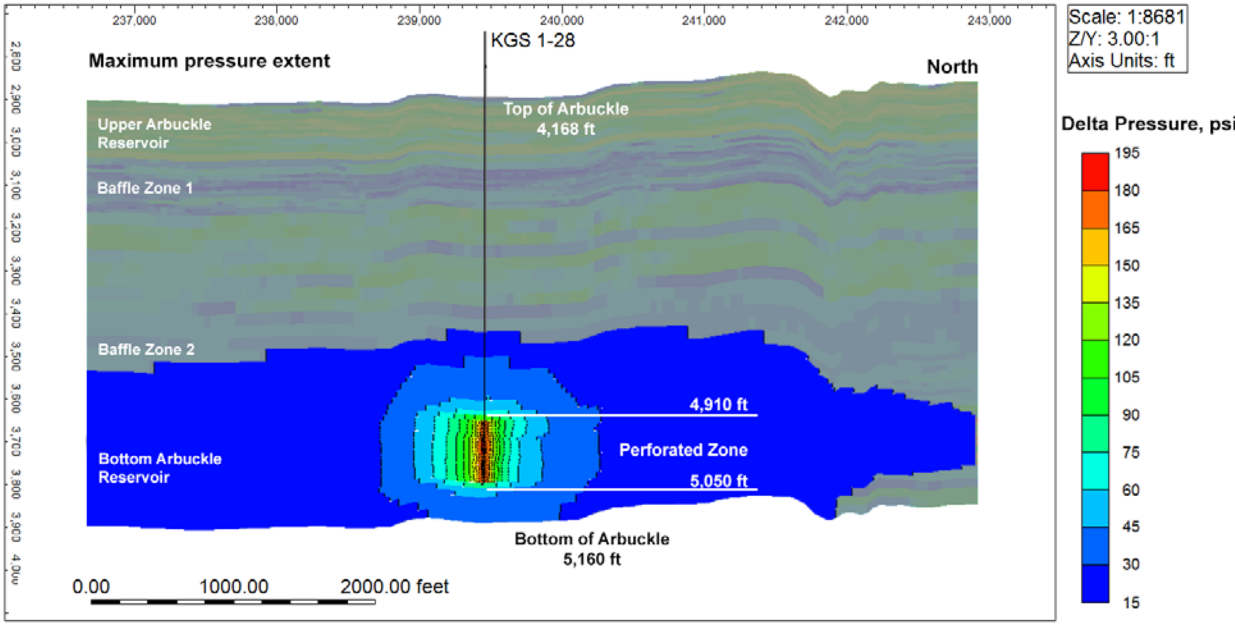


Figure 12. Cross-section B in Figure 4 showing the extent of the pressure front.

AVO-based forward modeling

To ascertain whether a 10K tonne plume of carbon dioxide (CO_2) is seismically resolvable in the Arbuckle, seismic fluid substitution modeling was performed at Well API 12-191-22590 (KGS 1-28). Simulation results were obtained using Hampson Russell Suite [Systematic Changes]. This program utilizes the well logs to create synthetic pre-stack seismic traces of a defined interval, and then alters the properties to calculate the effect at that location. The 80-ft thick, high permeability interval within the perforated zone was used during fluid substitution modeling (Figure 8–9). Synthetic seismic results were picked for the amplitude horizons at the zone of injection and then the amplitude was plotted to compare:

- The percent change from 0% CO_2 saturation (100% background brine solution) in post stack reflection amplitude to 100% CO_2 saturation for the top reflection and bottom reflection (Figure 13)
- The change in the pre-stack domain for Amplitude Variation with Offset (AVO) with change in CO_2 saturation from 0% (100% background bine solution) to 100% CO_2 saturation for the top reflection and bottom reflection (Figures 14, 15, and 17, respectively)

Post-stack amplitude analysis provides a percent change in the reflection amplitude. Calculation of the percent change from 0% CO_2 saturation to increased saturation is shown in Figure 13. For both the top and bottom reflector, the stacked amplitude will increase by up to 80% for the top reflector and 75% for the bottom reflector. This is equivalent to 2.5 dB increase in reflection strength. If the signal is sufficiently above the noise, this increase in reflection amplitude should be evident in the seismic data. The Arbuckle injection zone is characterized by small lithologic impedance contrasts (as opposed to the Arbuckle–Simpson interface), which should promote detection of CO_2-induced impedance anomalies.

Pre-stack AVO analysis is an important and useful tool for determining variations in fluid properties.

The effect of the CO_2 on the AVO response changes both the amplitude and slope reflection. This effect is observed in the 3D plots in Figures 14–17. Figures 14 and 15 are of the same plot with a rotated view in order to show the far offset angles at increased CO_2 saturation. Figure 16 is a 2D representation of select saturations to illustrate the importance of the far offsets (>30°) for improved determination of CO_2 saturation. As the saturation increases, the reflection amplitude becomes more negative. At far offsets (30°-45°), the reflection amplitude has a greater change than at near offsets, allowing for improved fitting to the Ruger equations. For offsets greater than 30°, a third term, curvature, can be added to the AVO analysis, and allows for estimation of density from the seismic volume. The bottom reflector from the CO_2 plume shows a greater AVO response at higher saturations than in the top reflector. The increased response however is significantly more prominent in the far offsets (>30°). As observed in the pre-stack synthetic data, collecting high quality, wide offset seismic data will be important in accurately and quantitatively determining CO_2 in the reservoir from the injection.

Results and Uncertainties

Modeling results indicate that a 10K CO_2 plume will be seismically resolvable. However, as the lateral dimension of the plume decreases, the uncertainty increases as the plume will overlap with fewer traces. The current 3-D seismic bin size is 85 ft. Depending on the orientation of a 1000-ft wide plume, it would coincide with 10–12 seismic traces.

Repeat 2-D Seismic Line

In late October, FairfieldNodal reprocessed all the 2-D lines using the same workflow and their latest technology. Differences among the 2-D seismic lines was related to spiking ensemble deconvolution and spectral whitening versus different noise attenuation and surface consistent deconvolution with no spectral whitening. Preliminary results from this latest processing is shown in Appendix 2. The next step is to compare data in 4-D to determine if the CO_2 plume is resolvable in the Mississippian.

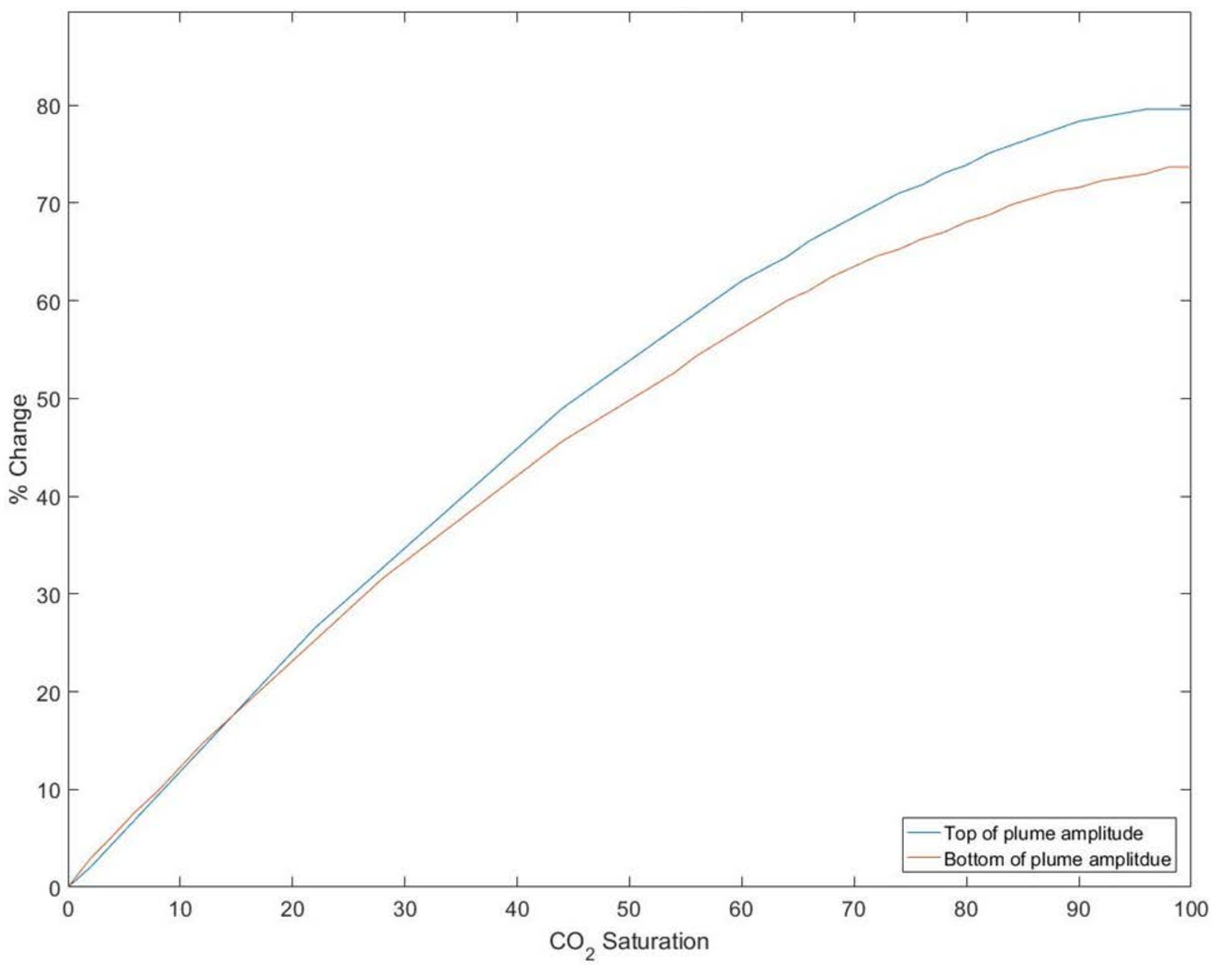


Figure 13. Arbuckle zero-offset showing percent change in reflection amplitude with increasing CO2 saturation.

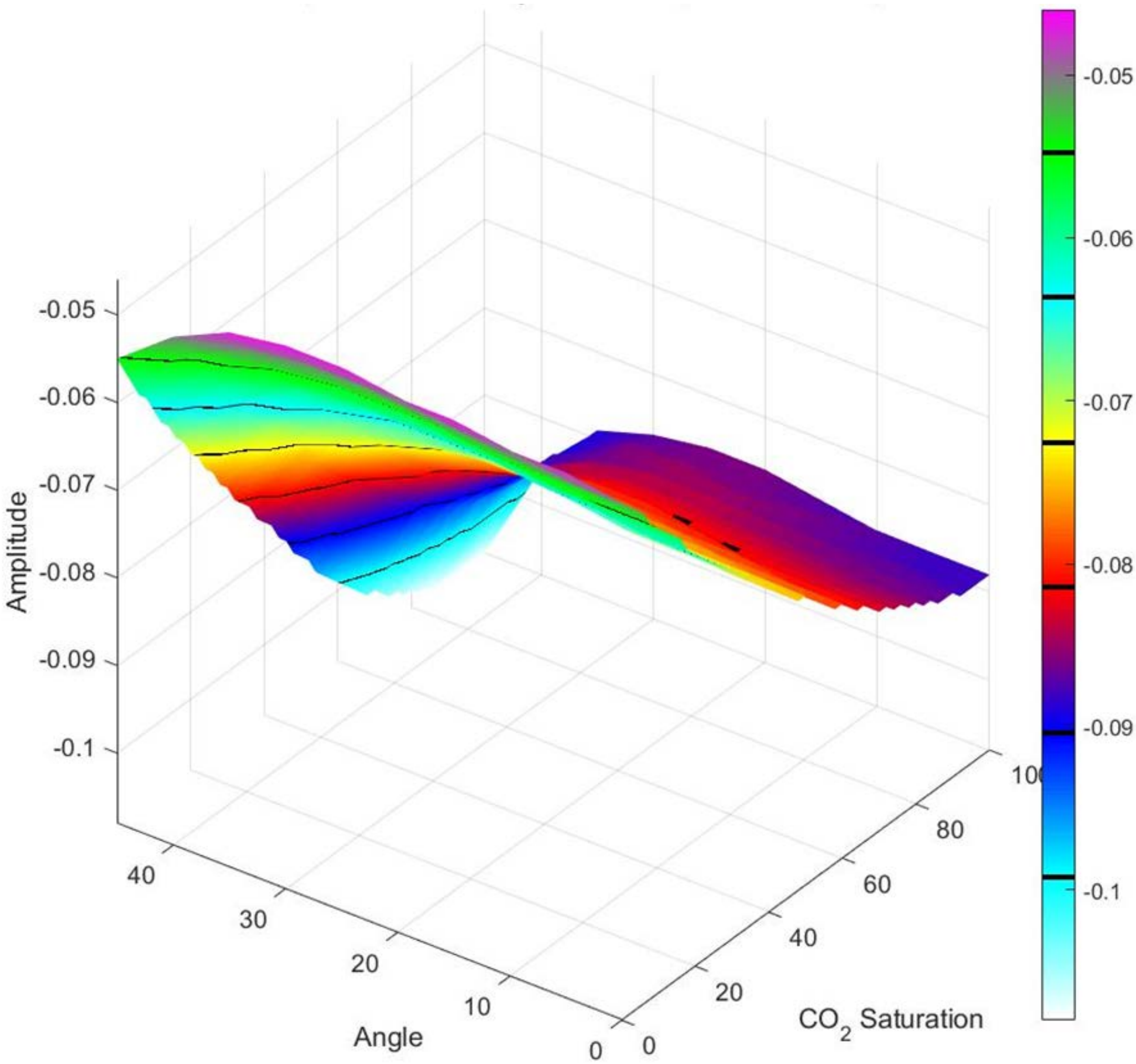


Figure 14. Top of Arbuckle injection zone, pre-stack amplitude.

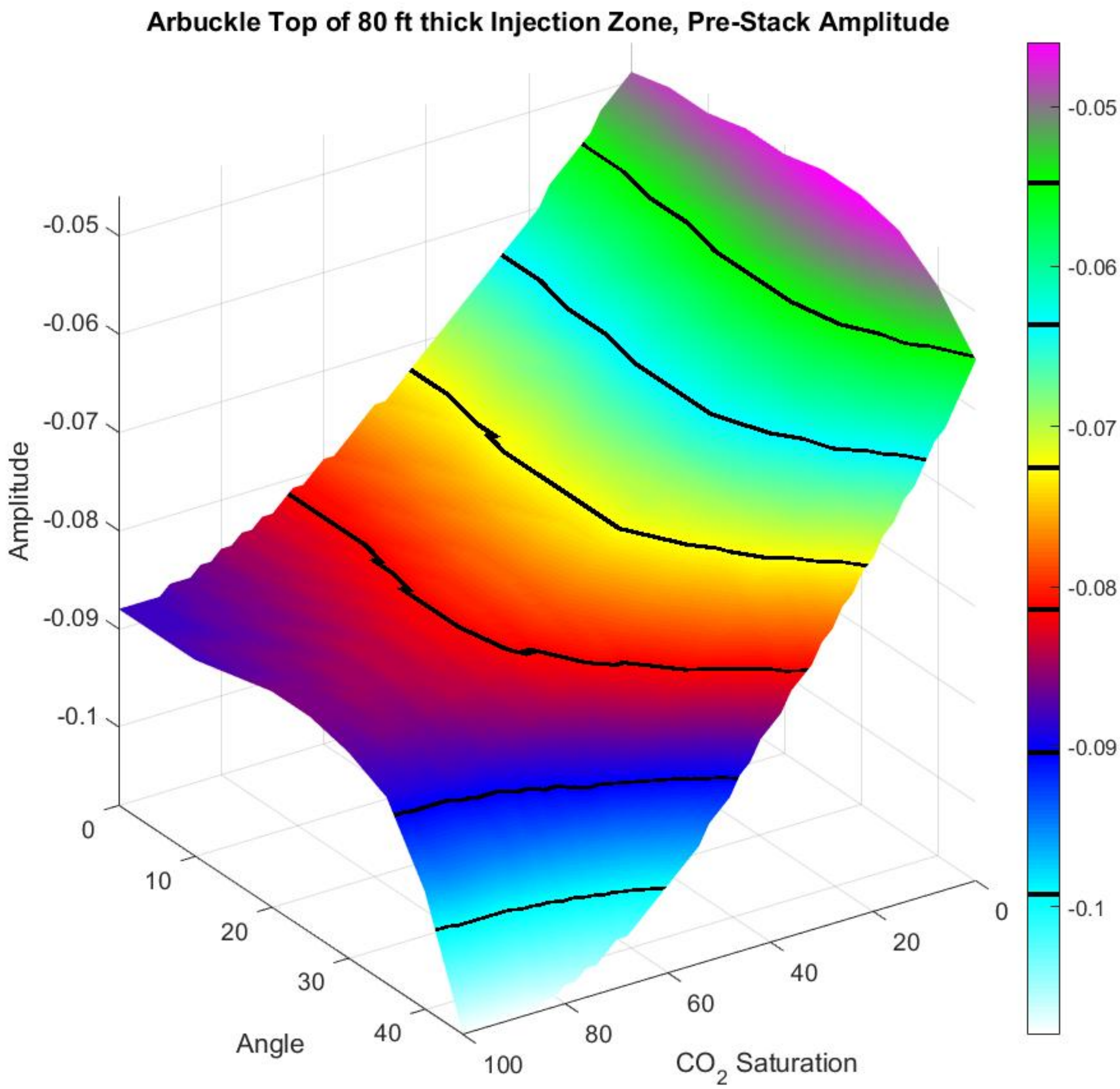


Figure 15. Top of Arbuckle injection zone, pre-stack amplitude. Same data as in Figure 8. Plot has been rotated (details in text).

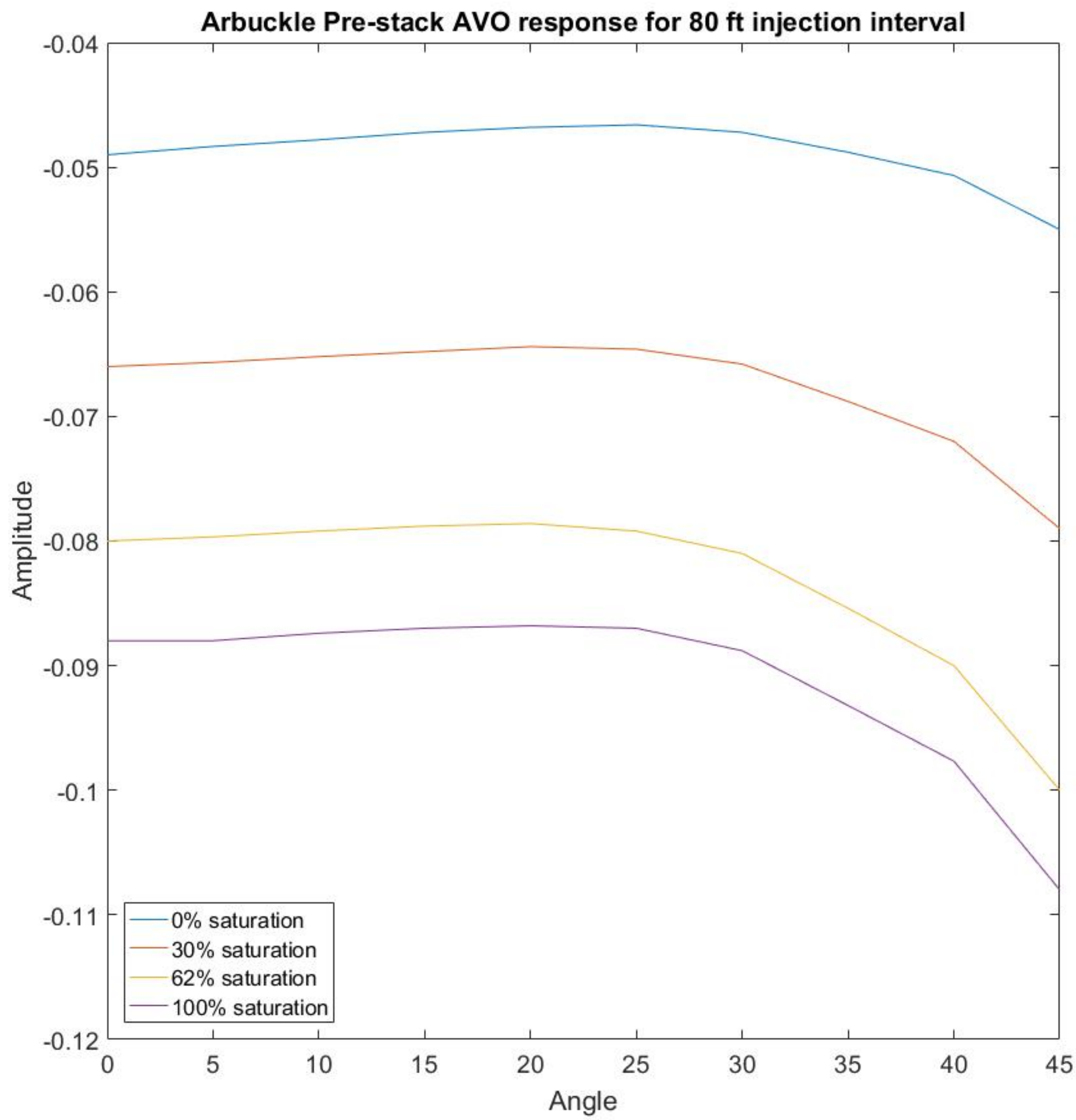


Figure 16. Arbuckle pre-stack AVO response for 80-ft thick injection interval.

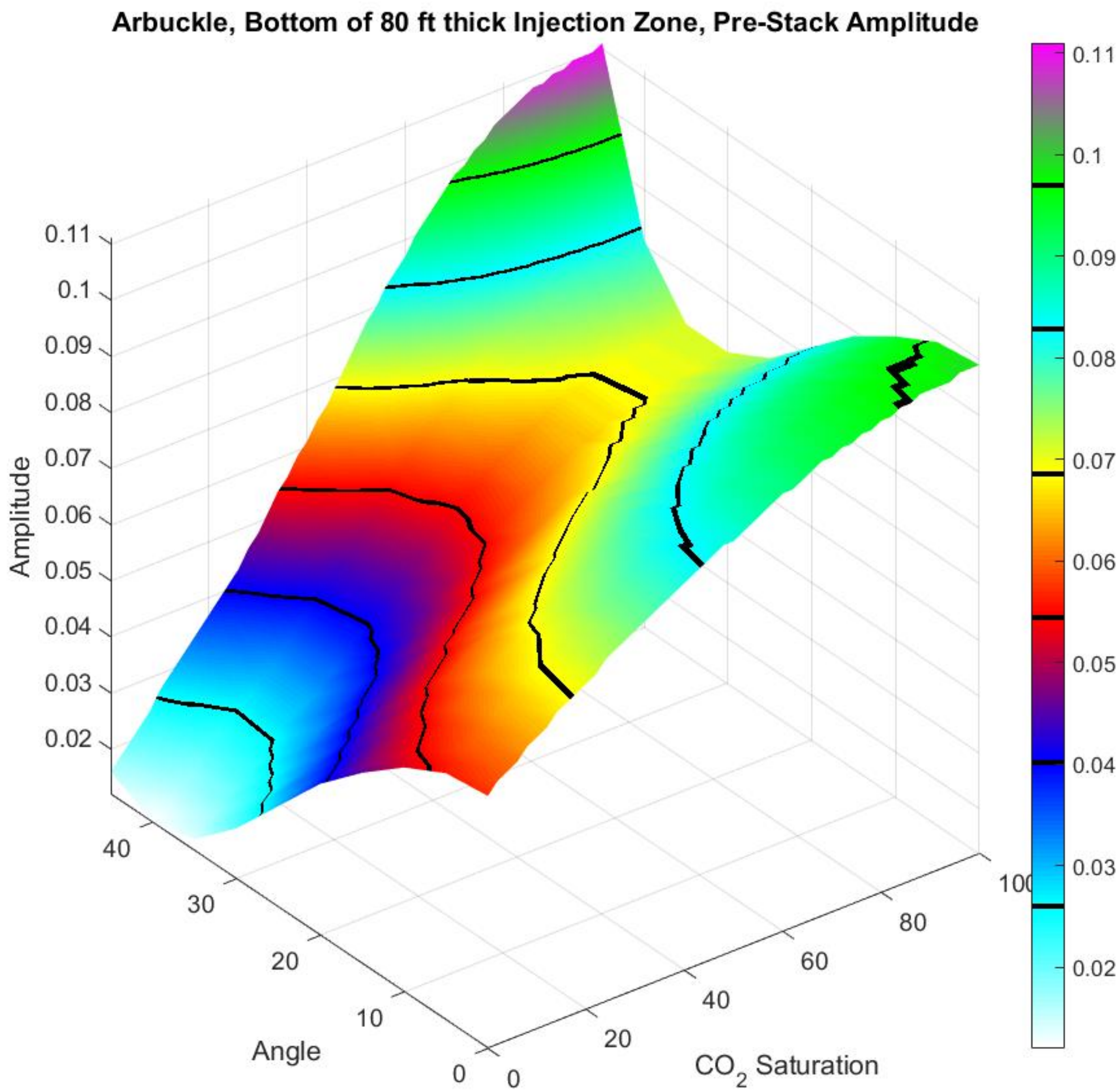


Figure 17. Arbuckle pre-stack amplitude showing bottom of 80-ft thick injection zone.

Summary

1. Produced (i.e., vented) CO2 accounts for 16% of the CO2 injected
2. CO2 has not broken through at any location including along the small fault bordering the east side of the CO2 injection well.
3. CO2 has been detected in all offsetting wells indicating the sweep is quite uniform and dominated largely by matrix properties.
4. The CO2 plume (i.e., sweep) largely conforms to the distribution of matrix properties demonstrating the viability of this reservoir for both CO2-EOR and carbon storage.
5. The Wellington seismometer array provides a dependable earthquake catalog and is updated on a weekly basis.

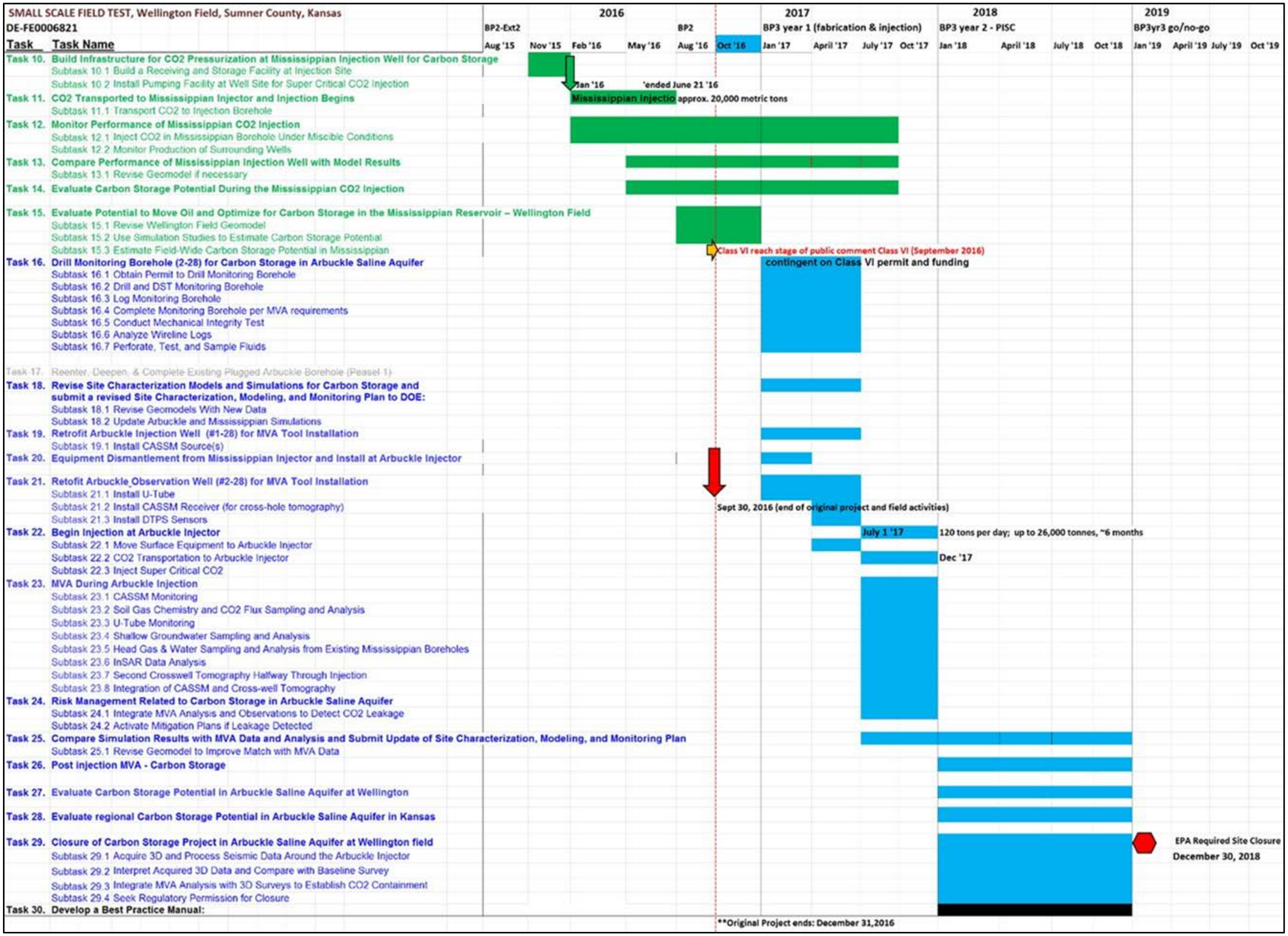
6. Introduction of continuous downhole pressure monitoring in the Arbuckle in the idle well #1-28 shows considerable promise to establish that static pressure in the lower Arbuckle has risen since the well was last tested in August 2011. We are also investigating the potential for the pressure transducer to record short term pressure perturbations that correspond to disposal wells or earthquakes. The well information will be compared with updates to the regional brine simulations and is currently being compared in time with events from the Wellington earthquake catalog. Importantly, no pressure pulses were recorded during the recent earthquake activity from July–October 2016.
7. The repeat, 2-D seismic line was successfully acquired and re-processed using same routines as the two 2-D lines acquired before injection.
8. Simulations were run for a 10K tonne CO2 injection case in the Arbuckle
9. AVO-based forward modeling indicates a 10K plume would be seismically resolvable
10. EPA meeting scheduled for early December to discuss results of EPA Class VI permit.

PROJECT SCHEDULE

Schedule and costs for Arbuckle CO2 injection

Wellington project currently is scheduled to end on September 30, 2016. The information for the Determinations and Findings (D&F) was submitted on August 7, 2016 requesting an extension of 1 year for fabrication and Arbuckle CO2 injection beginning as BP3 year 1 on January 1, 2017 followed by BP3 year 2 starting January 1, 2018 for post injection site care (PISC) to comply with anticipated determination from EPA as a requirement before the Class VI permitted well can be closed (Figure 1). Based on a go no-go decision, Berexco requests that an additional two years of monitoring be included if EPA requests additional monitoring.

The completion date anticipated for the Arbuckle CO2 injection is anticipated to be the end of July 2017. The one year post injection site care as proposed to EPA would begin in August 2017 and continue through August 2018.



SMALL SCALE FIELD TEST, Wellington Field, Sumner County, Kansas
DE-FE0006821
2016
2017
2018
2019
BP2-Ext2
BP2
BP3 year 1 (fabrication & injection)
BP3 year 2 - PISC
BP3yr3 go/no-go
Aug '15
Nov '15
Feb '16
May '16
Aug '16
Oct '16
Jan '17
April '17
July '17
Oct '17
Jan '18
April '18
July '18
Oct '18
Jan '19
April '19
July '19
Oct '19
Task
Task Name
Task 10. Build Infrastructure for CO2 Pressurization at Mississippian Injection Well for Carbon Storage
Subtask 10.1 Build a Receiving and Storage Facility at Injection Site
Subtask 10.2 Install Pumping Facility at Well Site for Super Critical CO2 Injection
Task 11. CO2 Transported to Mississippian Injector and Injection Begins
Subtask 11.1 Transport CO2 to Injection Borehole
Task 12. Monitor Performance of Mississippian CO2 Injection
Subtask 12.1 Inject CO2 in Mississippian Borehole Under Miscible Conditions
Subtask 12.2 Monitor Production of Surrounding Wells
Task 13. Compare Performance of Mississippian Injection Well with Model Results
Subtask 13.1 Revise Geomodel if necessary
Task 14. Evaluate Carbon Storage Potential During the Mississippian CO2 Injection
Task 15. Evaluate Potential to Move Oil and Optimize for Carbon Storage in the Mississippian Reservoir – Wellington Field
Subtask 15.1 Revise Wellington Field Geomodel
Subtask 15.2 Use Simulation Studies to Estimate Carbon Storage Potential
Subtask 15.3 Estimate Field-Wide Carbon Storage Potential in Mississippian
Task 16. Drill Monitoring Borehole (2-28) for Carbon Storage in Arbuckle Saline Aquifer
Subtask 16.1 Obtain Permit to Drill Monitoring Borehole
Subtask 16.2 Drill and DST Monitoring Borehole
Subtask 16.3 Log Monitoring Borehole
Subtask 16.4 Complete Monitoring Borehole per MVA requirements
Subtask 16.5 Conduct Mechanical Integrity Test
Subtask 16.6 Analyze Wireline Logs
Subtask 16.7 Perforate, Test, and Sample Fluids
Task 17. Reenter, Deepen, & Complete Existing Plugged Arbuckle Borehole (Peasel 1)
Task 18. Revise Site Characterization Models and Simulations for Carbon Storage and submit a revised Site Characterization, Modeling, and Monitoring Plan to DOE:
Subtask 18.1 Revise Geomodels With New Data
Subtask 18.2 Update Arbuckle and Mississippian Simulations
Task 19. Retrofit Arbuckle Injection Well (#1-28) for MVA Tool Installation
Subtask 19.1 Install CASSM Source(s)
Task 20. Equipment Dismantlement from Mississippian Injector and Install at Arbuckle Injector
Task 21. Retofit Arbuckle Observation Well (#2-28) for MVA Tool Installation
Subtask 21.1 Install U-Tube
Subtask 21.2 Install CASSM Receiver (for cross-hole tomography)
Subtask 21.3 Install DTPS Sensors
Task 22. Begin Injection at Arbuckle Injector
Subtask 22.1 Move Surface Equipment to Arbuckle Injector
Subtask 22.2 CO2 Transportation to Arbuckle Injector
Subtask 22.3 Inject Super Critical CO2
Task 23. MVA During Arbuckle Injection
Subtask 23.1 CASSM Monitoring
Subtask 23.2 Soil Gas Chemistry and CO2 Flux Sampling and Analysis
Subtask 23.3 U-Tube Monitoring
Subtask 23.4 Shallow Groundwater Sampling and Analysis
Subtask 23.5 Head Gas & Water Sampling and Analysis from Existing Mississippian Boreholes
Subtask 23.6 InSAR Data Analysis
Subtask 23.7 Second Crosswell Tomography Halfway Through Injection
Subtask 23.8 Integration of CASSM and Cross-well Tomography
Task 24. Risk Management Related to Carbon Storage in Arbuckle Saline Aquifer
Subtask 24.1 Integrate MVA Analysis and Observations to Detect CO2 Leakage
Subtask 24.2 Activate Mitigation Plans if Leakage Detected
Task 25. Compare Simulation Results with MVA Data and Analysis and Submit Update of Site Characterization, Modeling, and Monitoring Plan
Subtask 25.1 Revise Geomodel to Improve Match with MVA Data
Task 26. Post injection MVA - Carbon Storage
Task 27. Evaluate Carbon Storage Potential in Arbuckle Saline Aquifer at Wellington
Task 28. Evaluate regional Carbon Storage Potential in Arbuckle Saline Aquifer in Kansas
Task 29. Closure of Carbon Storage Project in Arbuckle Saline Aquifer at Wellington field
Subtask 29.1 Acquire 3D and Process Seismic Data Around the Arbuckle Injector
Subtask 29.2 Interpret Acquired 3D Data and Compare with Baseline Survey
Subtask 29.3 Integrate MVA Analysis with 3D Surveys to Establish CO2 Containment
Subtask 29.4 Seek Regulatory Permission for Closure
Task 30. Develop a Best Practice Manual:
Jan '16
'ended June 21 '16
Mississippian injectio approx. 20,000 metric tons
Class VI reach stage of public comment Class VI (September 2016)
contingent on Class VI permit and funding
Sept 30, 2016 (end of original project and field activities)
July 1 '17
120 tons per day; up to 26,000 tonnes, ~6 months
Dec '17
EPA Required Site Closure
December 30, 2018
**Original Project ends: December 31,2016

Figure 18. Previous page. Updated Gantt Chart of Wellington Project with revised schedule for proposed BP3 Arbuckle injection.

MILESTONE STATUS REPORT

Task	Budget Period	Number	Milestone Description	Status
Task 2.	1	1	Site Characterization of Arbuckle Saline Aquifer System - Wellington Field	Completed
Task 3.	1	2	Site characterization of Mississippian Reservoir for CO2 EOR - Wellington Field	Completed
Task 10.	2	3	Pre-injection MVA - establish background (baseline) readings	Completed
Task 13.	2	4	Retrofit Arbuckle Injection Well (#1-28) for MVA Tool Installation	Completed
Task 18.	3-yr1	5	Compare Simulation Results with MVA Data and Analysis and Submit Update of Site Characterization, Modeling, and Monitoring Plan	Completed
Task 22.	3-yr1	6	Recondition Mississippian Boreholes Around Mississippian CO2-EOR injector	Completed
Task 27.	3-yr2	7	Evaluate CO2 Sequestration Potential of CO2-EOR Pilot	Completed
Task 28.	3-yr2	8	Evaluate Potential of Incremental Oil Recovery and CO2 Sequestration by CO2-EOR - Wellington Field	In Progress

FUTURE PLANS

1. Continue post-injection monitoring on a monthly basis for wells that are responding to flood.
2. Continue weekly sampling of wells to monitor production including CO2, oil, and brine recovered
3. Perform on-site and lab geochemical analysis for select wells with the exception of alkalinity that is limited only to measurements at the well
4. Continue operation of the Wellington seismometer array
5. Continue baseline pressure measurements in the perforated lower Arbuckle zone of the shut-in Class VI injection well
6. Continue to acquire SAR satellite images and recording cGPS for analysis of ground motion
7. Contrast 2-D seismic (pre-and post-CO2 injection in the Mississippian) to determine plume’s extent
8. Passive seismic monitoring will continue as a very important component for DOE and EPA.
9. BP3 tasks and budget have been updated for the Arbuckle injection pending Class VI permit and extending the project beyond September 30th
10. Submit a BP3 contingency plan if Class VI permit is not approved.

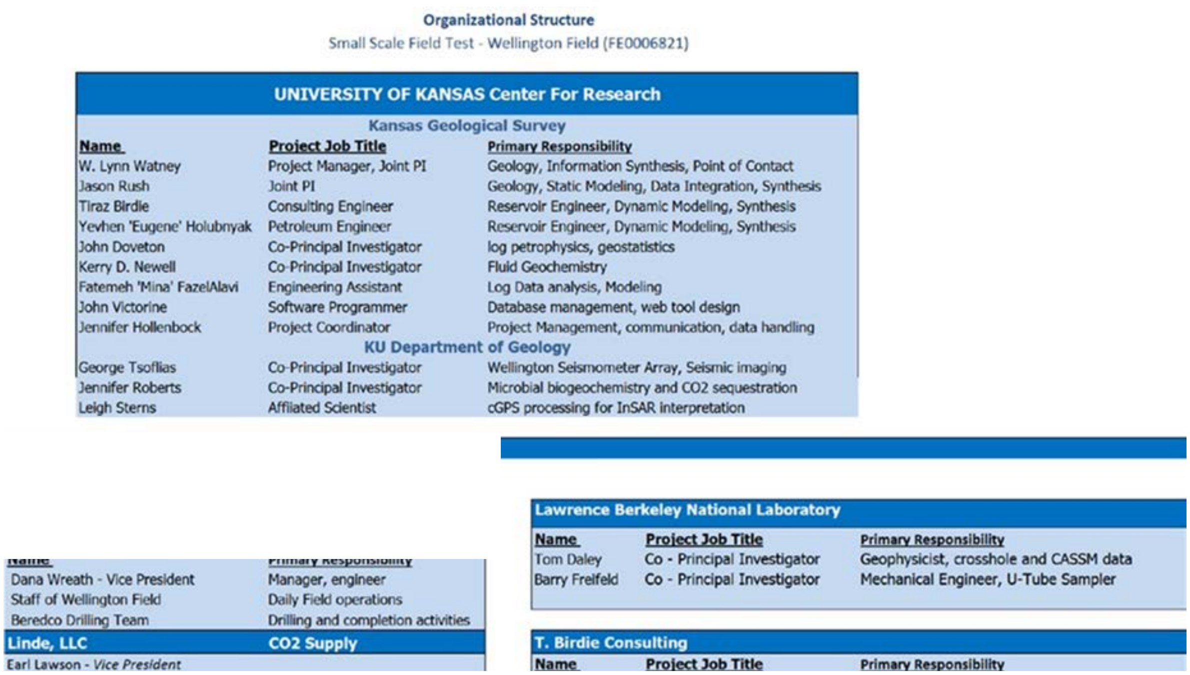
PRODUCTS

Publications, conference papers, and presentations

Gupta, M., K. Spikes, and B. Hardage, 2017, Characterization of naturally fractured Arbuckle Group in the Wellington Field, Kansas, using S-wave amplitude variation with offset: Interpretation, T49–T63.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

A project organization chart follows (Figure 49). The work authorized in this budget period includes office tasks related to preparation of reports and application for a Class VI permit to inject CO2 into the Arbuckle saline aquifer.



Organizational Structure
Small Scale Field Test - Wellington Field (FE0006821)

UNIVERSITY OF KANSAS Center For Research		
Kansas Geological Survey		
Name	**Project Job Title**	**Primary Responsibility**
W. Lynn Watney	Project Manager, Joint PI	Geology, Information Synthesis, Point of Contact
Jason Rush	Joint PI	Geology, Static Modeling, Data Integration, Synthesis
Tiraz Birdie	Consulting Engineer	Reservoir Engineer, Dynamic Modeling, Synthesis
Yevhen 'Eugene' Holubnyak	Petroleum Engineer	Reservoir Engineer, Dynamic Modeling, Synthesis
John Doveton	Co-Principal Investigator	log petrophysics, geostatistics
Kerry D. Newell	Co-Principal Investigator	Fluid Geochemistry
Fatemeh 'Mina' FazelAlavi	Engineering Assistant	Log Data analysis, Modeling
John Victorine	Software Programmer	Database management, web tool design
Jennifer Hollenbock	Project Coordinator	Project Management, communication, data handling
KU Department of Geology		
George Tsoflias	Co-Principal Investigator	Wellington Seismometer Array, Seismic imaging
Jennifer Roberts	Co-Principal Investigator	Microbial biogeochemistry and CO2 sequestration
Leigh Sterns	Affiliated Scientist	cGPS processing for InSAR interpretation

Name	Primary Responsibility
Dana Wreath - Vice President	Manager, engineer
Staff of Wellington Field	Daily Field operations
Beredco Drilling Team	Drilling and completion activities
Linde, LLC	**CO2 Supply**
Earl Lawson - *Vice President*	

Lawrence Berkeley National Laboratory		
Name	**Project Job Title**	**Primary Responsibility**
Tom Daley	Co - Principal Investigator	Geophysicist, crosshole and CASSM data
Barry Freifeld	Co - Principal Investigator	Mechanical Engineer, U-Tube Sampler

T. Birdie Consulting		
Name	**Project Job Title**	**Primary Responsibility**

Figure 19. Updated Organizational Chart.

IMPACT

The response of the CO2-EOR has been successful. Downhole pressure monitoring is important in validating hypotheses to explain the effects of large scale injection. All of information requested EPA by has been submitted for the application of a Class VI injection permit.

CHANGES/PROBLEMS

P.I. Lynn Watney has been away since November 1, 2016 due to an illness. He is expected to return to the office in early December 2016. During this period of time Jason Rush (Joint PI) will fulfill the obligations of the project P.I. Lynn Watney has forwarded all files relevant to the project to the joint P.I., which includes draft reports, memos, and proposals related to the project. Funds are very tight due to the no cost time extensions necessary to permit review and response to for the Class VI permit.

BUDGETARY INFORMATION

Cost Status Report

Baseline Reporting Quarter	10/1/15 - 12/31/15 Q17	1/1/16 - 3/31/16 Q18	4/1/16 - 6/30/16 Q19	7/1/16 - 9/30/16 Q20	10/1/16 - 12/31/16 Q21	1/1/17 - 3/31/17 Q22
Baseline Cost Plan (from SF-424A)						
Federal Share	$325,087.75	$325,087.75	$325,087.75	$325,087.75	$0.00	$0.00
Non-Federal Share	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Total Planned (Federal and Non-Federal)	$325,087.75	$325,087.75	$325,087.75	$325,087.75	$0.00	$0.00
Cumulative Baseline Cost	$13,008,472.53	$13,333,560.28	$13,658,648.03	$13,983,735.78	$13,983,735.78	$13,983,735.78
Actual Incurred Costs						
Federal Share	$329,868.02	$271,440.25	$1,743,607.98	$1,191,333.63	$0.00	$0.00
Non-Federal Share	$0.00	$0.00	$69,879.00	$1,322.91	$0.00	$0.00
Total Incurred Costs-Quarterly (Federal and Non-Federal)	$329,868.02	$271,440.25	$1,813,486.98	$1,192,656.54	$0.00	$0.00
Cumulative Incurred Costs	$3,278,018.21	$3,549,458.46	$5,362,945.44	$6,555,601.98	$6,555,601.98	$6,555,601.98
Variance						
Federal Share	-$4,780.27	$53,647.50	-$1,418,520.23	-$866,245.88	$0.00	$0.00
Non-Federal Share	$0.00	$0.00	-$69,879.00	-$1,322.91	$0.00	$0.00
Total Variance-Quarterly Federal and Non-Federal)	-$4,780.27	$53,647.50	-$1,488,399.23	-$867,568.79	$0.00	$0.00
Cumulative Variance	**$9,730,454.32**	**$9,784,101.82**	**$8,295,702.59**	**$7,428,133.80**	**$7,428,133.80**	**$7,428,133.80**

APPENDIX 1

Pressure Monitoring
The continuous pressure monitoring in the lower Arbuckle was set up because a large rate and high volume brine disposal in the area is believed to be responsible for the induced seismicity. "The assumption in the case of the testing in the Arbuckle is that the observed pressure is being transmitted at depth in the basement where faults are critically stressed, requiring a small force to move. To date the vast majority of earthquakes have occurred in the shallow basement." Quarterly Report-19, 2016. Trilobite Testing of Hays Kansas installed the pressure gauge in the Wellington KGS 1-28 at about 5020 feet depth from surface. The instrument is programmed to sample every second with an accuracy of 0.1 psi. About a week of pressure data is sent to KGS as a Comma Separated Values (CSV) file.

A Java computer program was developed to analyze the pressure data from the Wellington KGS 1-28 to understand the pressure changes, to remove solar & lunar Tidal pressures along with barometric pressure changes. The idea is that if you can remove or explain the natural every day influences you are left with the geological influences and maybe you might be able to identify fluid movement due to brine injection, micro quake swarms, etc. Figure 1 is an illustration of the raw pressure measurement in psig units over a 4 day period, 30 July to 2 August 2016.

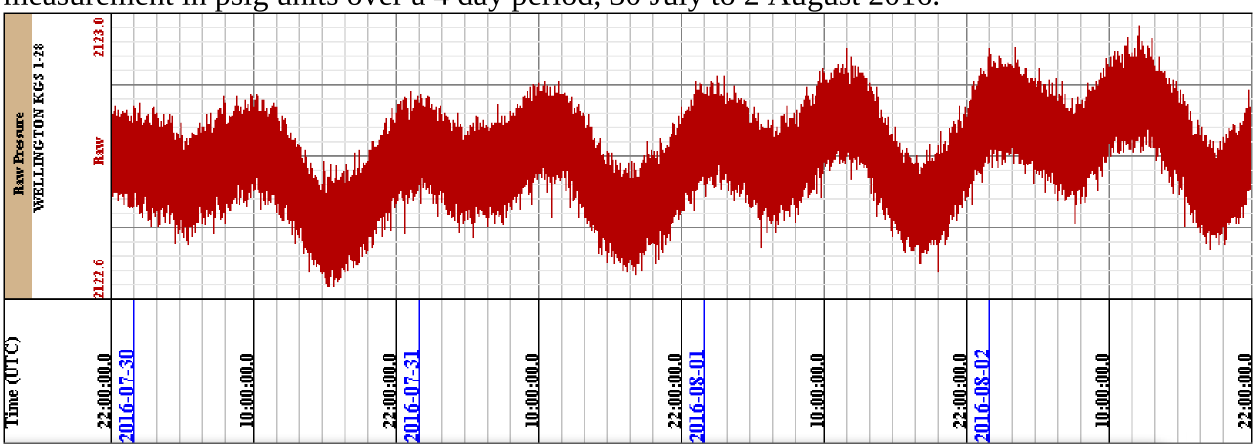


Figure 5: Raw Pressure Data Measurements in the Wellington KGS 1-28 between 30 July to 2 August 2016.

The computer program will filter the noise from the raw pressure data, compute the lunar & solar tidal pressures along with the barometric pressures influence, and then subtract that from the raw pressure data. In an ideal situation if these are the only pressures influencing the pressure measurements then the pressure data should result in a straight line. The first step was to filter out as much of the measurement noise in the Raw Pressure data. Playing with a simple square pulse filter of varying width gives varying improvements to the Pressure data, see figure 2. The best result was the 1000 points (1000 seconds) square pulse applied to the raw data. This method removed most of the noise, without removing signals that may be of interest down the line. You can see the lunar and solar cycle in the pressure wave as well as "noise" on top of that signal or is it barometric pressure or something else.

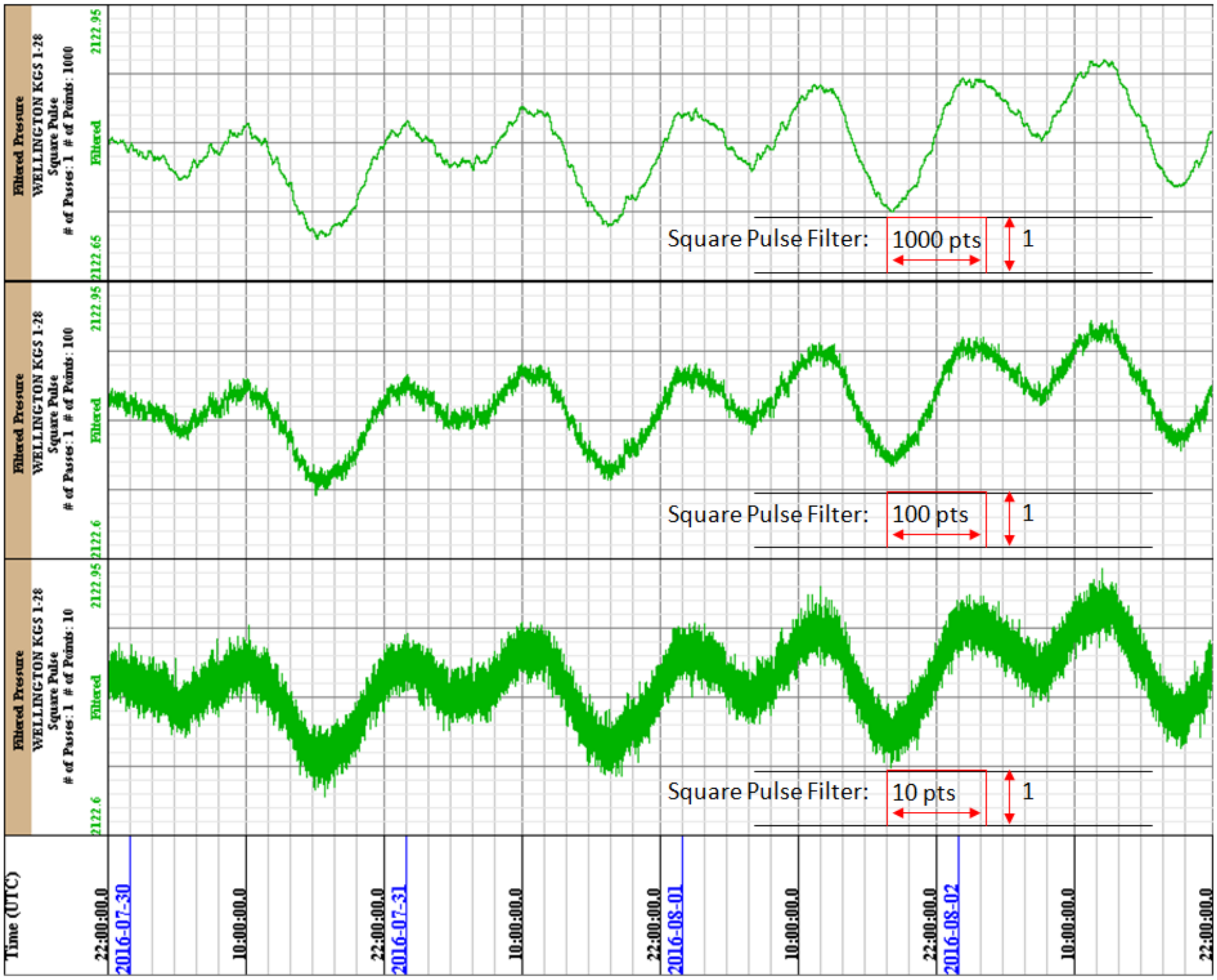


Figure 6: Varying widths of Square Pulse filter on Raw Pressure Data.

[2]It is well known that the sinusoidal water level variations observed in open wells are directly related to lunar & solar tidal influence. It is also believed that the tidal effects are related to the characteristics of the formation and to the fluid contained in the formation. The lunar & solar attraction of the earth generates a state of stress on the earth's surface which induces a radial deformation of the earth. As the gravitational force of attraction between two masses is inversely proportional to the square of the distance between these two masses, the potential derived from this force will be inversely proportional to the distance between the two masses. In Bredehoeft[1] he attributes to Love[3] (pg 52) that the tide generating potential W may be approximated with sufficient accuracy as a spherical harmonic of second degree.

$$W = 0.5 * (GM_b/D_b) \ (a/D_b)^2 \ (3 \cos^2 \theta_b - 1) \qquad (1)$$

where G is the Gravitational Constant = 6.67408×10^{-11} [m3]/{[kg][sec2]}

M_b - Mass of the body

D_b - Distance between earth and body

a - Earth Radius = 6.371×10^{6} [m]

θ_b - angle between earth and body

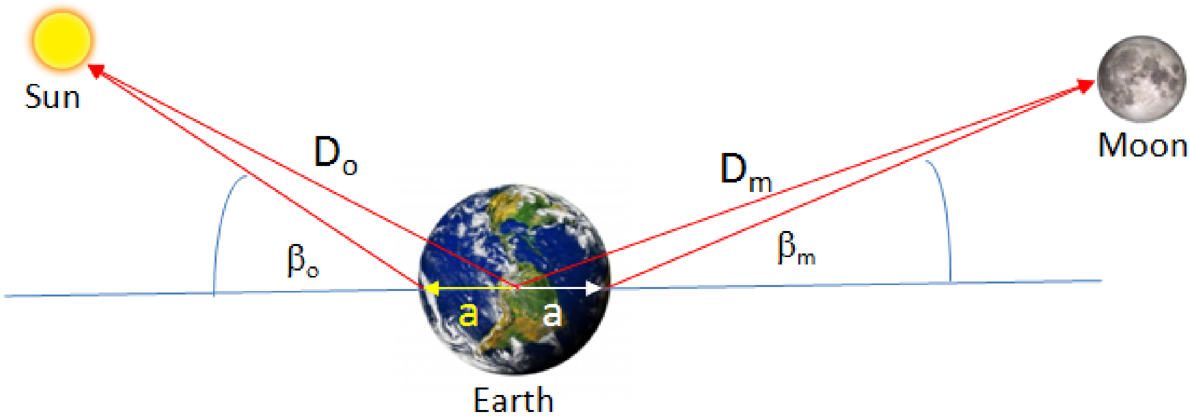


Figure 7: Geometry of the Sun and Moon with respect to Earth.

Expanding cos(□b□□with respect to earths latitude and long

cos(□□b□b□= sin(□e) sin(□b) + cos(□e) cos(□b) cos(□t (2)

where □- angle between earth and body

□- frequency of the Earth's rotation = 1.1600804 X 10-5 [Hz]

□e– latitude of the Wellington KGS 1-28 = 37.3194833 degrees

□b– latitude of the body, which is "moving" up and down with respect to earth with time

□b– longitude of the body, which is "moving" around earth with time

Lunar tidal influence is about twice as strong as the solar tidal influence, but not insignificant as some authors imply. Using the tide generating potential constant (GMb/Db) (a/Db)2 for both the moon and the sun,

Mm - Mass of the moon = 7.34767309 X 1022 [kg]

Dm - Average distance between earth and moon = 3.84402 X 108 [m]

Mo - Mass of the sun = 1.989 X 1030 [kg]

Do - Average distance between earth and sun = 1.495979 X 1011 [m]

	Moon	Sun
(GMb/Db) (a/Db)2	3.504275 [m/sec]2	1.69404 [m/sec]2

Bredehoeft1 states that the dilatation in an aquifer will depend not only on the tidal strain but also on the effect of change in internal fluid pressure produced by the tidal dilation. The aquifer will be subjected to tidal strains latitudinal and longitudinal directions that are almost entirely determined by the elastic properties of the earth as a whole. Love3 (pg53) showed that the dilation can be related to the disturbing potential by introducing a fourth Love number, F(r), where

□ = F(r) * (W / g)

Takeuchi 4 evaluated F(r) by numerical calculations indicating that near the earth's surface the dilatation is given by

□ = (0.49 / a) * (W / g) (3)

where a is the earth's radius, g is the acceleration due to gravity (9.8 m/sec2) and W is the lunar & solar tide generating potential. Bredehoeft continues to derive the effects of the dilation as change in pressure of the earth tide in an aquifer system and shows that the earth tide P is,

P = □gh = □/ (Cw □) (4)

where □ is the density of the flu[...] and h is the height of the fluid above the aquifer, □ is the poro[...] the surface of the earth, Cw is the compressibility of the water. The compressibility of the rock itself was neglected because Bredehoeft assumed that the change in rock matrix volume was small compared to that of the water volume.

The lunar & solar tide generating potential, Wb, equation used in the Java Web App is as follows,
Wb = 0.75 * [GMb/Db] * [a/Db]2 * {
(3*cos(2* □b) -1) * (3*cos(2* □e) -1)/12.0 Long term cycle
+ sin(□b) * sin(□e) * cos(□ (□b - □w) + □corr) Diurnal ~1 day cycle
+ cos2 (□b) * cos2(□e) * cos[2*(□ (□b - □w) + □corr)]} Semidiurnal ~1/2 day cycle

where G is the Gravitational Constant = 6.67408 X 10-11 [m3]/{[kg][sec2]}
Mb - Mass of the body
Db - Distance between earth and body varying with time
a - Earth Radius = 6.371 X 106 [m]
□ - Frequency of the Earth's rotation = 1.1600804 X 10-5 [Hz]
□e - Latitude of the Wellington KGS 1-28 = 37.3194833 degrees
□b - Latitude of the body, which is varying with time, and computed from the degrees above the horizon assuming that 90o is straight above the location of the Wellington KGS 1-28 latitude, i.e. □b = □e * Height [...]
□b - Longitude of the body, which is varying with time, computed from right ascension.
□w - Longitude of the Wellington KGS 1-28 = -97.433378 degrees
□corr - Correction angle due to the "starting time" of pressure data file.

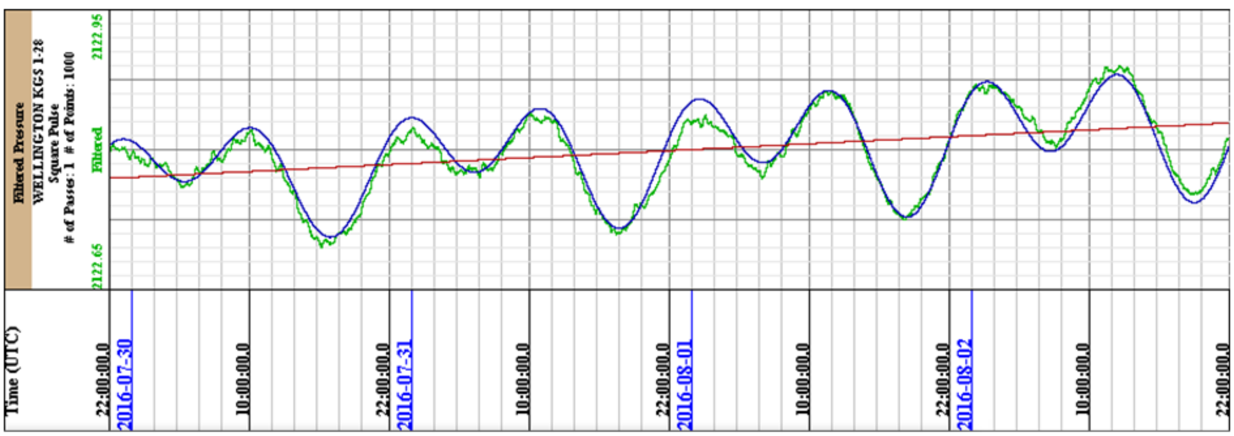
The total generating potential W is the sum of lunar (Wm) and solar (Wo) potentials, i.e. W = Wm + Wo. Substituting the total generating potential W into equation (3) and then into equation (4) gives the pressure due to earth tide as follows,

P = (0.49 / a) * (W / g) / (Cw □)
where in Wellington KGS 1-28 at 5020 feet below the surface in the Arbuckle formation the water temperature is 133.01 oF from the Temperature Log, log date 3 March 2011 by Halliburton, gives a water compressibility (Cw) of 0.4437 [1/GPa] and the Porosity of the aquifer (□) is about 0.[...]
The apparent latitude and apparent longitude of the Moon and Sun is computed from tables5,6 using linear interpolation between dates supplied, i.e. for the example shown 30 July to 2 August 2016 as follows,

	Sun			Moon		
	Apparent	° above	Distance	Apparent	° above	Distance
UTC (0.0)	R.A.	Horizon	A.U.	R.A.	Horizon	km
7/28/2016,	08 30 50.59,	71.4,	1.015442,	03 12 08.50,	67.0,	369726.0
7/29/2016,	08 34 45.53,	71.2,	1.015337,	04 09 30.01,	69.4,	370288.0
7/30/2016,	08 38 39.89,	70.9,	1.015228,	05 08 00.82,	70.7,	371462.0
7/31/2016,	08 42 33.67,	70.7,	1.015113,	06 07 01.28,	70.8,	373309.0
8/01/2016,	08 46 26.84,	70.4,	1.014992,	07 05 35.56,	69.6,	375854.0
8/02/2016,	08 50 19.42,	70.2,	1.014866,	08 02 46.93,	67.4,	379066.0
8/03/2016,	08 54 11.39,	69.9,	1.014733,	08 57 53.10,	64.4,	382835.0
8/04/2016,	08 58 02.75,	69.6,	1.014596,	09 50 34.78,	60.7,	386978.0
8/05/2016,	09 01 53.50,	69.4,	1.014453,	10 40 55.42,	56.8,	391243.0
8/06/2016,	09 05 43.65,	69.1,	1.014304,	11 29 15.74,	52.8,	395339.0
8/07/2016,	09 09 33.18,	68.8,	1.014150,	12 16 06.99,	48.8,	398957.0

1.496×10^{11} [m] = 1 Astronomical Unit [AU]

The slope is computed by taking the first 1000 points (1000 seconds) and computing the average and then taking the last 1000 points (1000 seconds) and computing the average, then visually modifying the starting pressure and ending pressure with respect to the filtered pressure curve after the lunar & solar pressure is subtracted to represent the slope of the filtered pressure data.



Slope of the Filtered Pressure Wave – Start of file = 2122.77 psi; End of file = 2122.88 psi
Slope of the Filtered Pressure Wave plus Tidal Pressure Wave. { ϕ = 0.09 [PU]; C_w = 0.4437 1/[Gpa]; ϕ_{corr} = -88 [deg] }
Filtered Pressure Data

Figure 8: Filtered pressure data with the computed lunar & solar pressure wave.

The last step in the program is to subtract the lunar & solar tidal pressure wave from the filtered pressure wave, which should show the data to be linear. The data is not totally linear, which suggest there is something else pulling and pushing the pressure curve. The project does not have a barometric pressure meter on the Wellington KGS 1-28 so barometric pressure measured at Strother Field Airport, Hackney, Kansas is used, which is 24.2335 miles to the Southeast of the well. If there were major pressure fronts or large storms then the barometric pressure from Strother Field Airport should suggest the changes in the deviation of the filtered pressure wave after the lunar & solar wave is subtracted. The pressure change from the surface pressure and the pressure measured at the pressure sensor is just the weight of the water column above the sensor, i.e., Psensor = Patmosphere + □gh.

where is the dens
and h is the height of the fluid above the pressure sensor.

We do not have the exact height of the water column above the pressure sensor, so the only way to incorporate the barometric pressure influence at the pressure sensor is to estimate what the measured pressure data should be at the sensor. The atmospheric pressure at Wellington KGS 1-28 is about 14.11 psi from the calculation of ideal altitude versus pressure curve. Ideally if the lunar & solar pressure curve is subtracted from the measured data then the measured data should be a straight line. It is basically a straight line in the image below (Figure 5) but there are deviations.

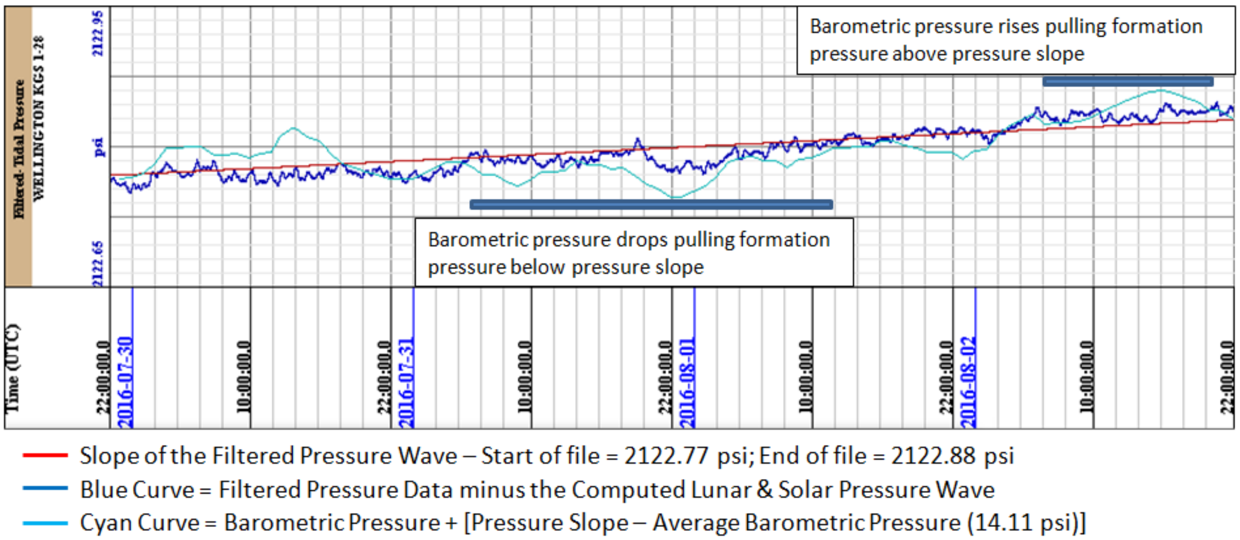


Figure 9: Lunar & Solar Pressure Wave removed from measured pressure data.
A pressure curve is constructed by adding the barometric pressure measured at Strother Field Airport with the difference of the Pressure Slope and 14.11 psi the average ideal barometric pressure at this elevation and overlaying that on the measured data. It can be seen that there is some comparison with the measured data. Ideally if the barometric pressure is measured at Wellington KGS 1-28 then the computed barometric pressure should line up exactly with the linear pressure curve and any deviations from that would be other geological effects, i.e. fluid movement, etc.

References:

Response of Well Aquifer Systems to Earth Tides by John D. Bredehoeft, Journal of Geophysical Research, Vol 72, No 12 June 15, 1967.
2) The Earth Tide Effects on Petroleum Reservoirs, Thesis submitted to the Department of Petroleum Engineering of Stanford University by Patricia C. Arditty, May 1978
3) Love, A. E. H., Some Problems o] Geodynamics, 180 pp., Cambridge University Press, Cambridge, 1911, https://archive.org/details/cu31924060184367
4) Takeuchi, H., On the earth tide of compressible earth of variable density and elasticity, Trans. Am. Geophys. Union, 31, 651-689, 1950.
5) Planetary Ephemeris Data for the Sun and Moon
http://astropixels.com/ephemeris/ephemeris.html

6) Sun or Moon Altitude/Aximuth Table, Form B – Location Worldwide
http://aa.usno.navy.mil/data/docs/AltAz.php

All of the pressure analyses shown above will located on the KGS website and will be publically accessible (Figure 17).

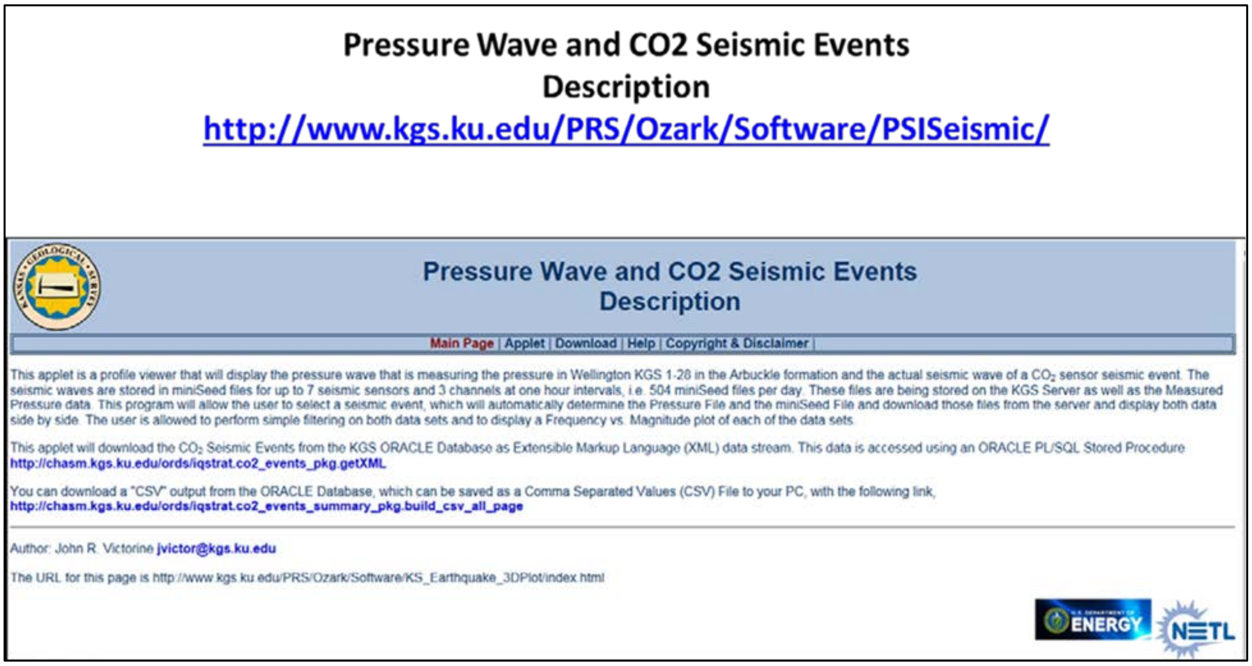
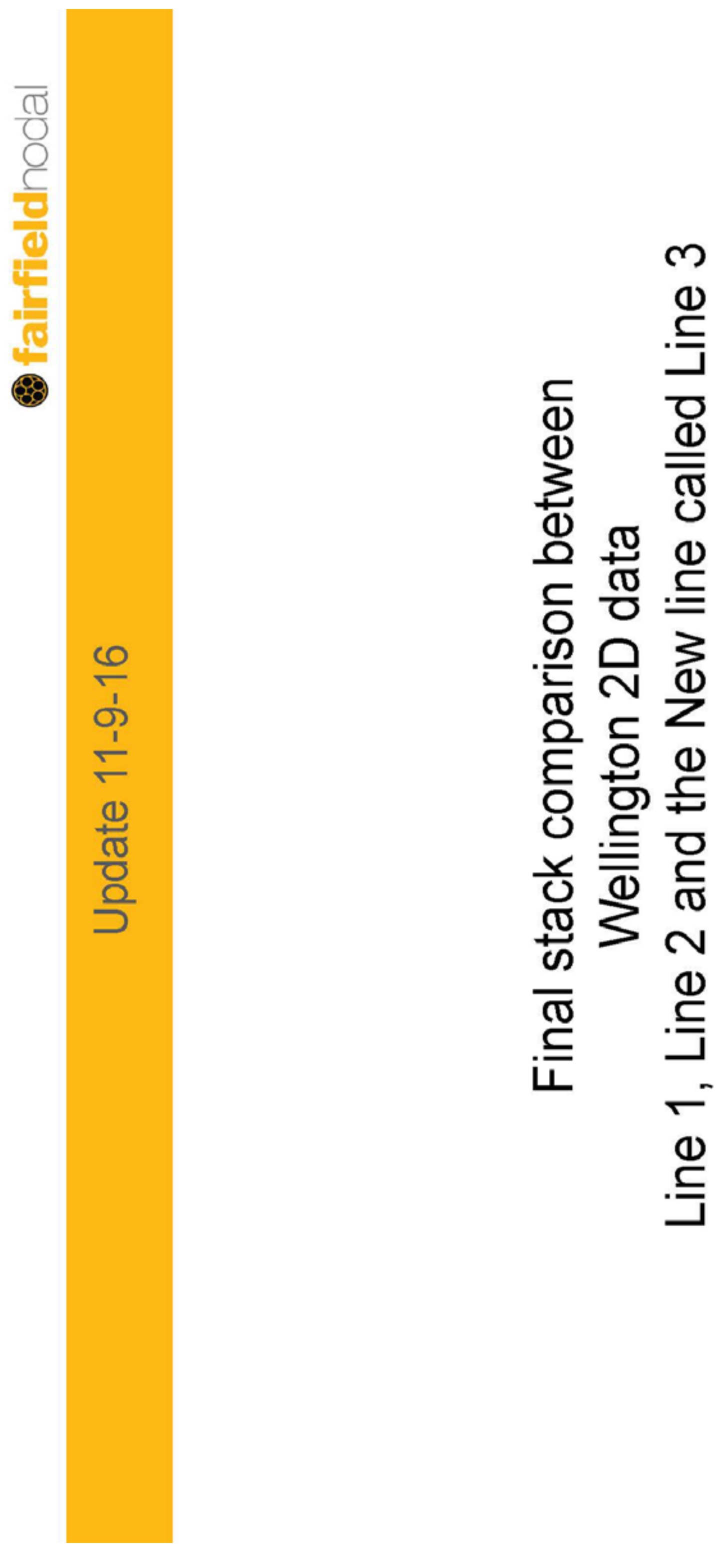


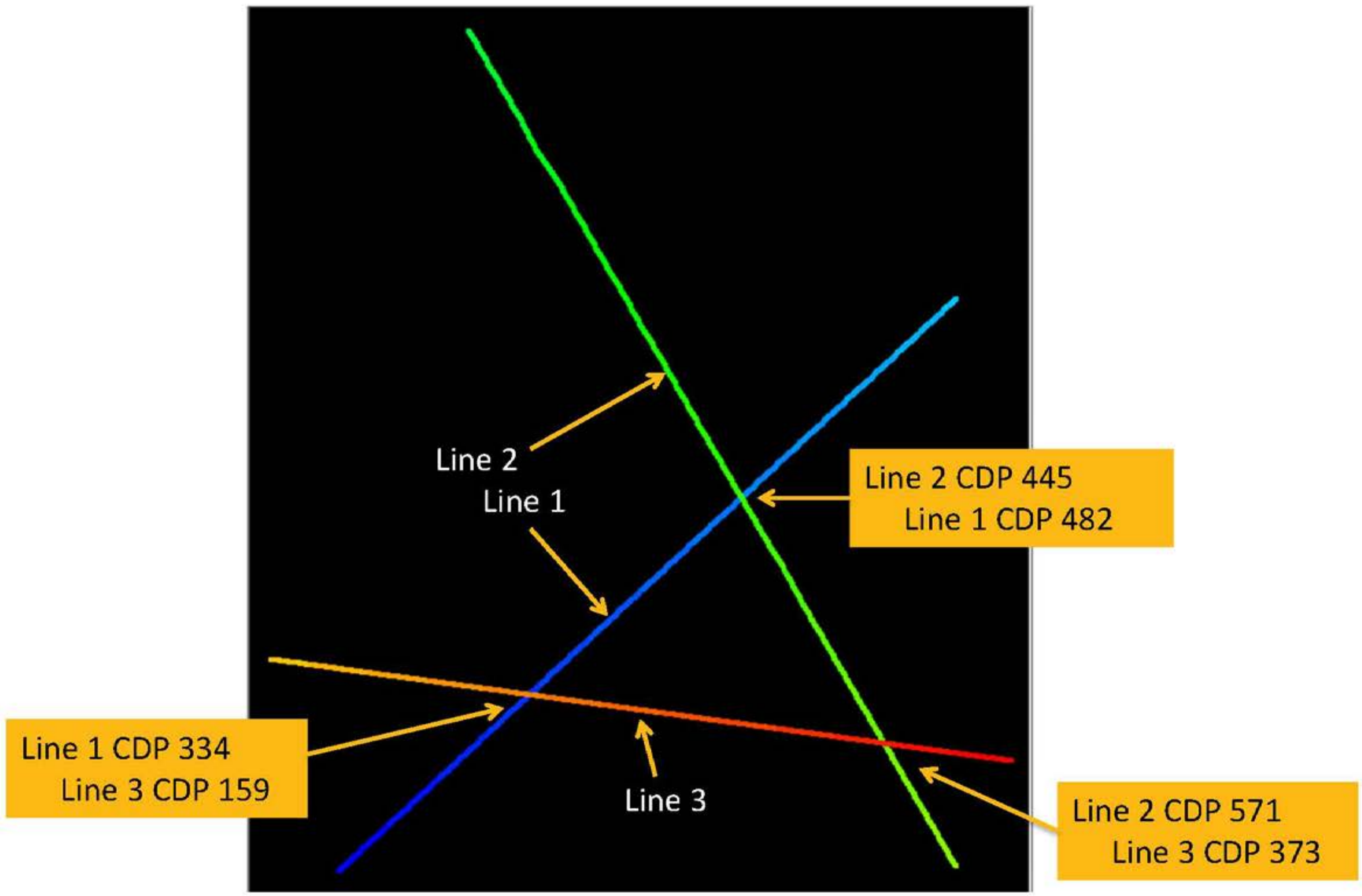
Figure 17. Access to Java web applications developed under DOE support available from the KGS website.

The solid earth tidal effects were computed solutions are shown illustrated in Figures 18 and 19.

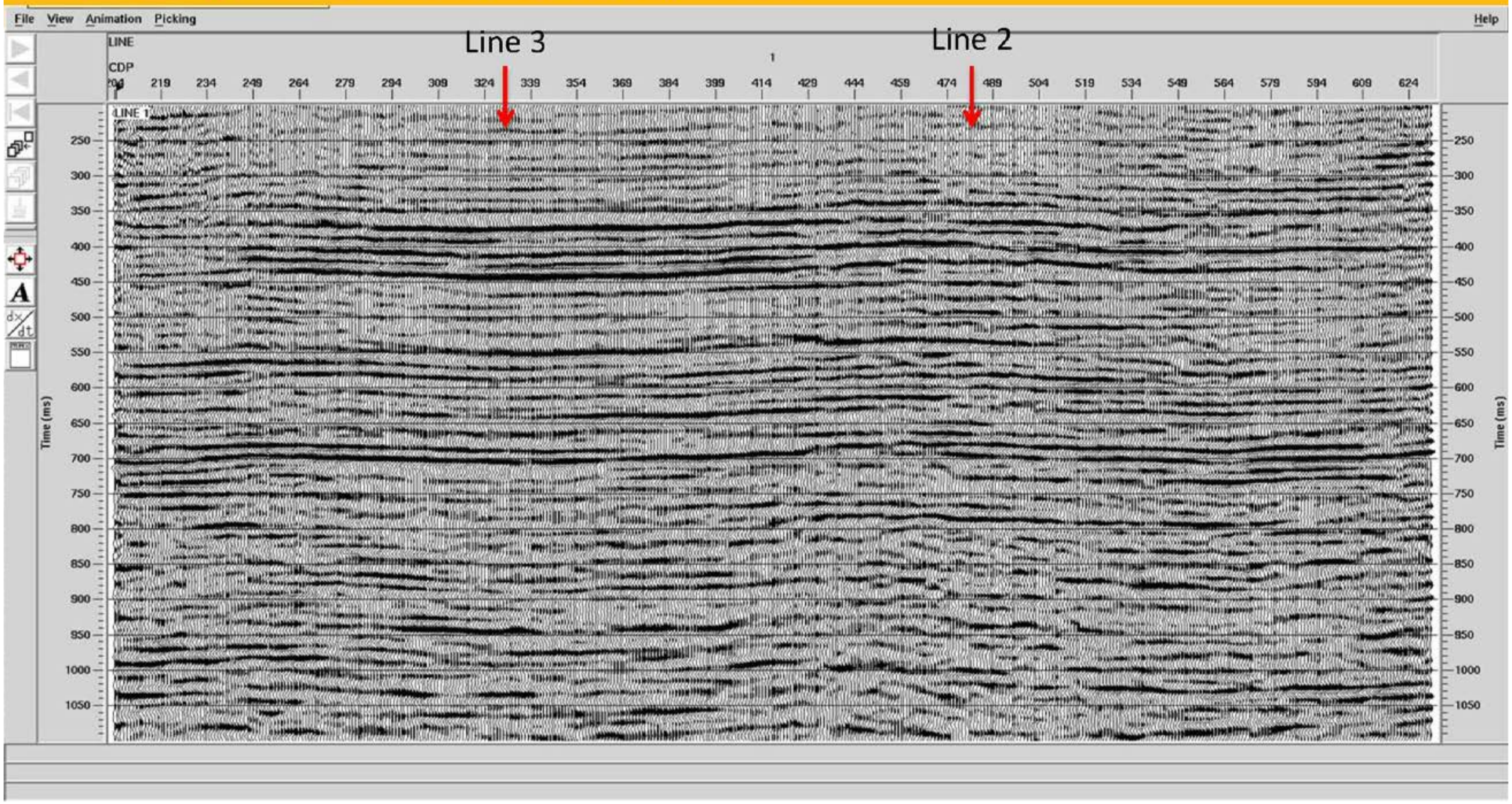
APPENDIX 2


fairfieldnodal
Update 11-9-16
Final stack comparison between
Wellington 2D data
Line 1, Line 2 and the New line called Line 3

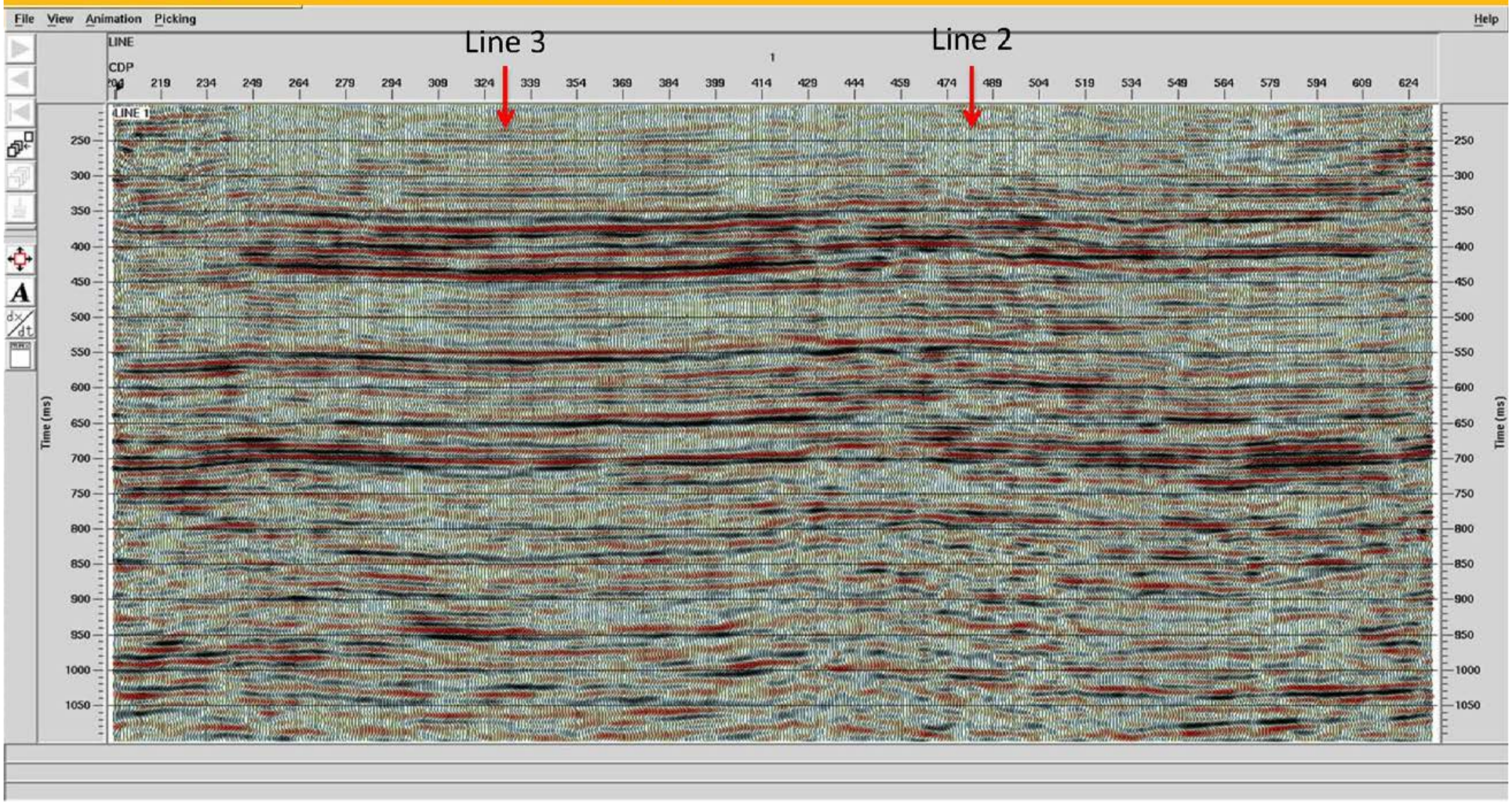
2D lines orientation



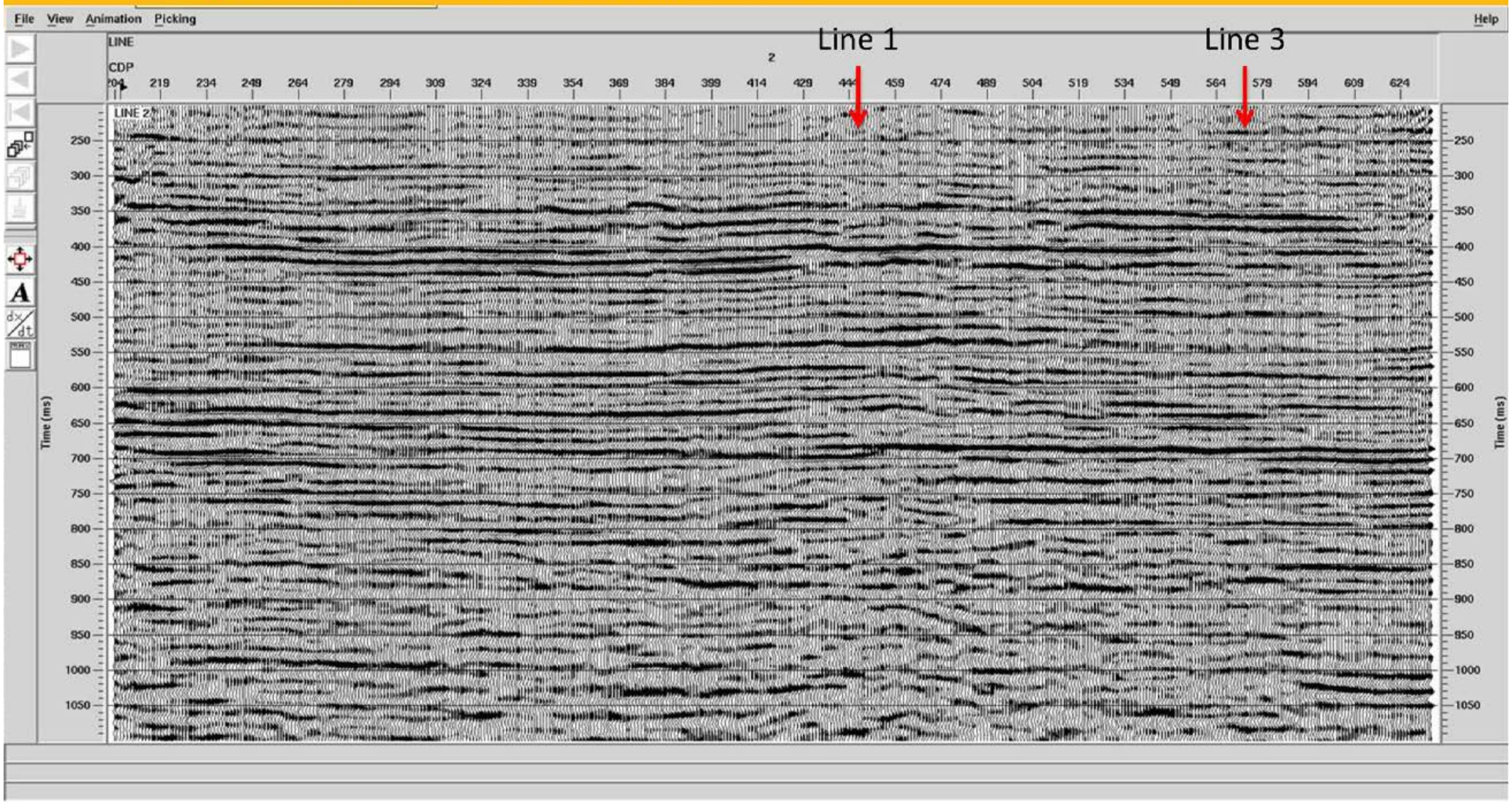
Reprocessing of Line 1, 4D Parameters select, Final Stack

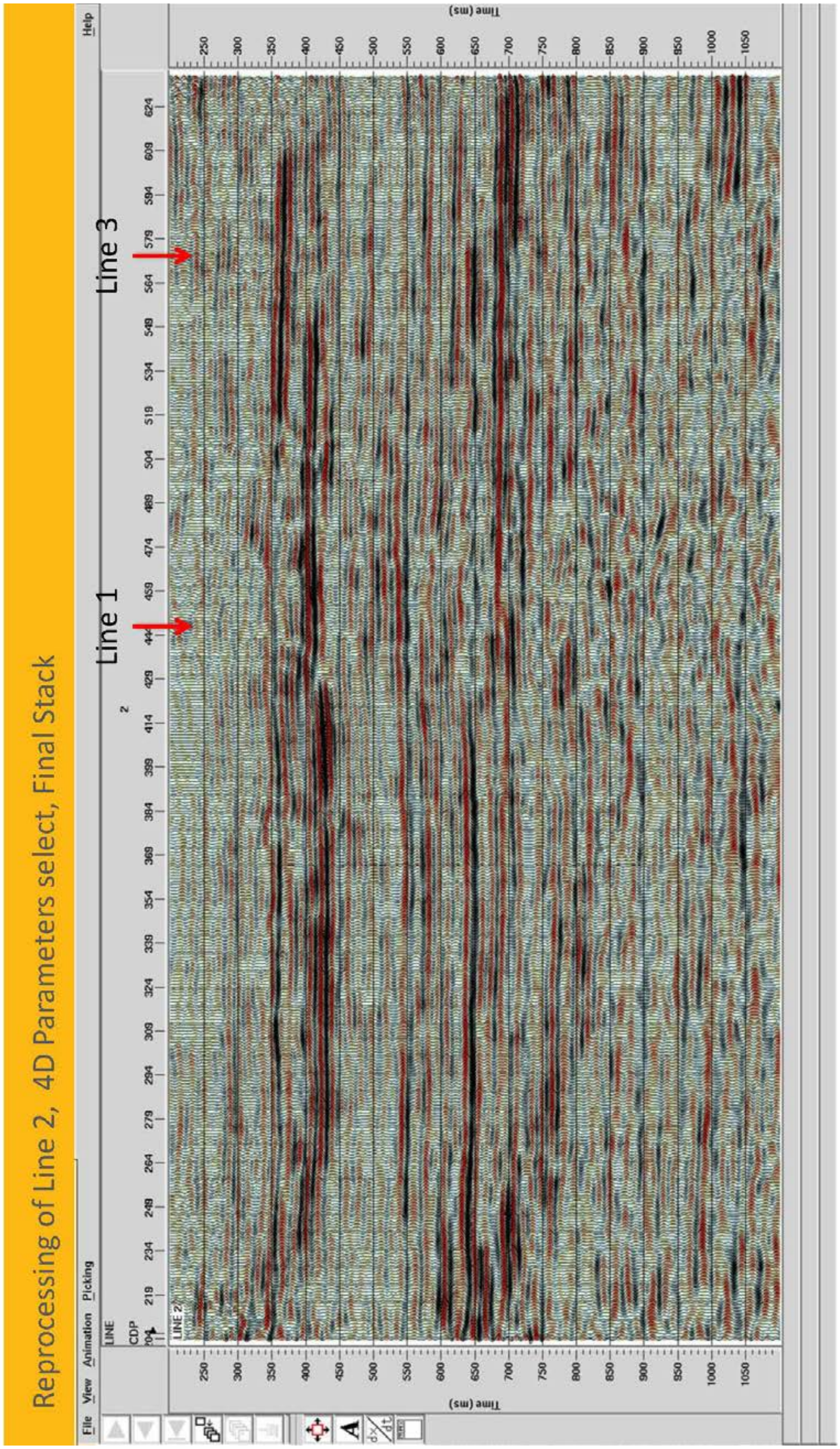


Reprocessing of Line 1, 4D Parameters select, Final Stack



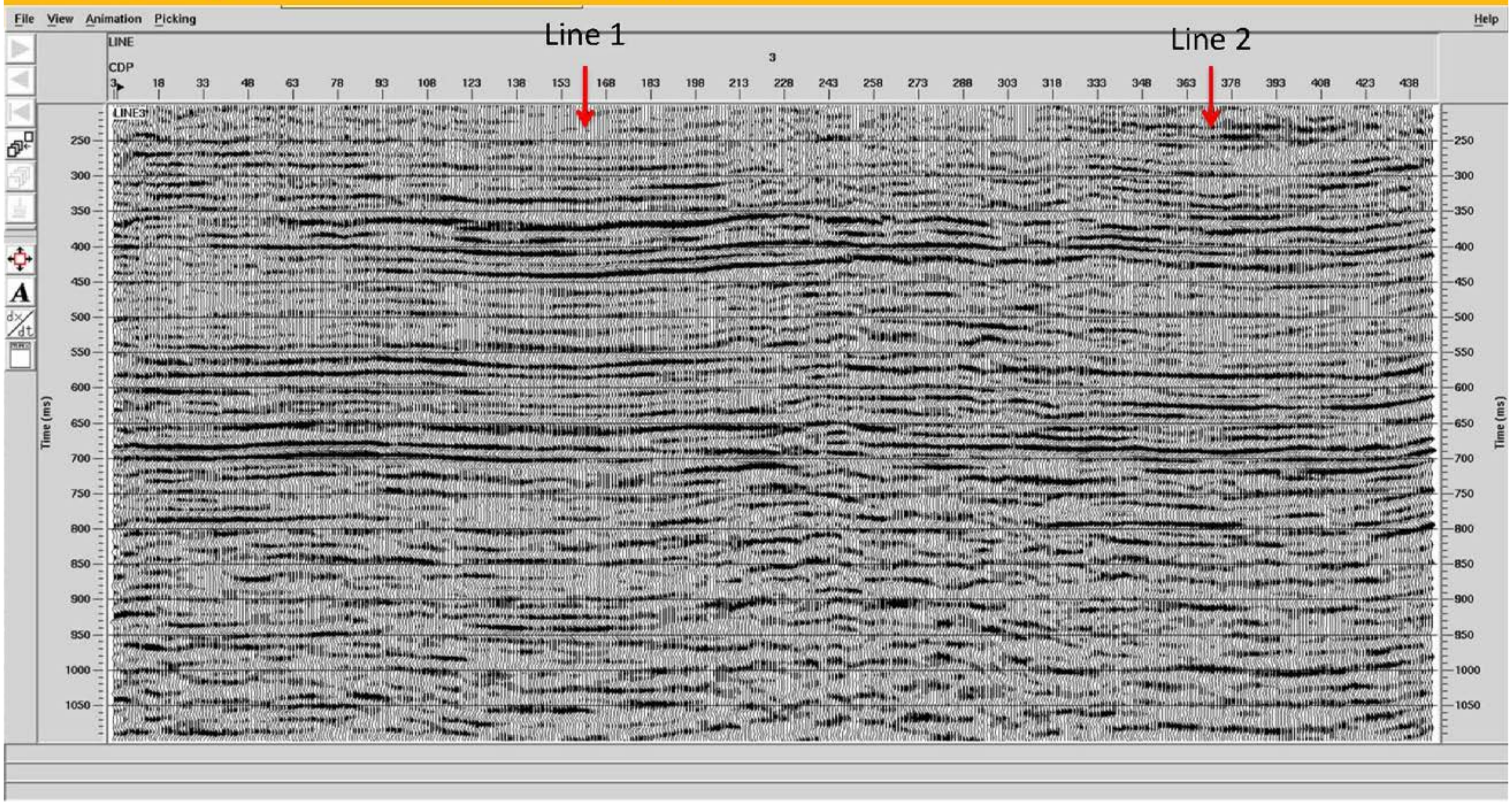
Reprocessing of Line 2, 4D Parameters select, Final Stack



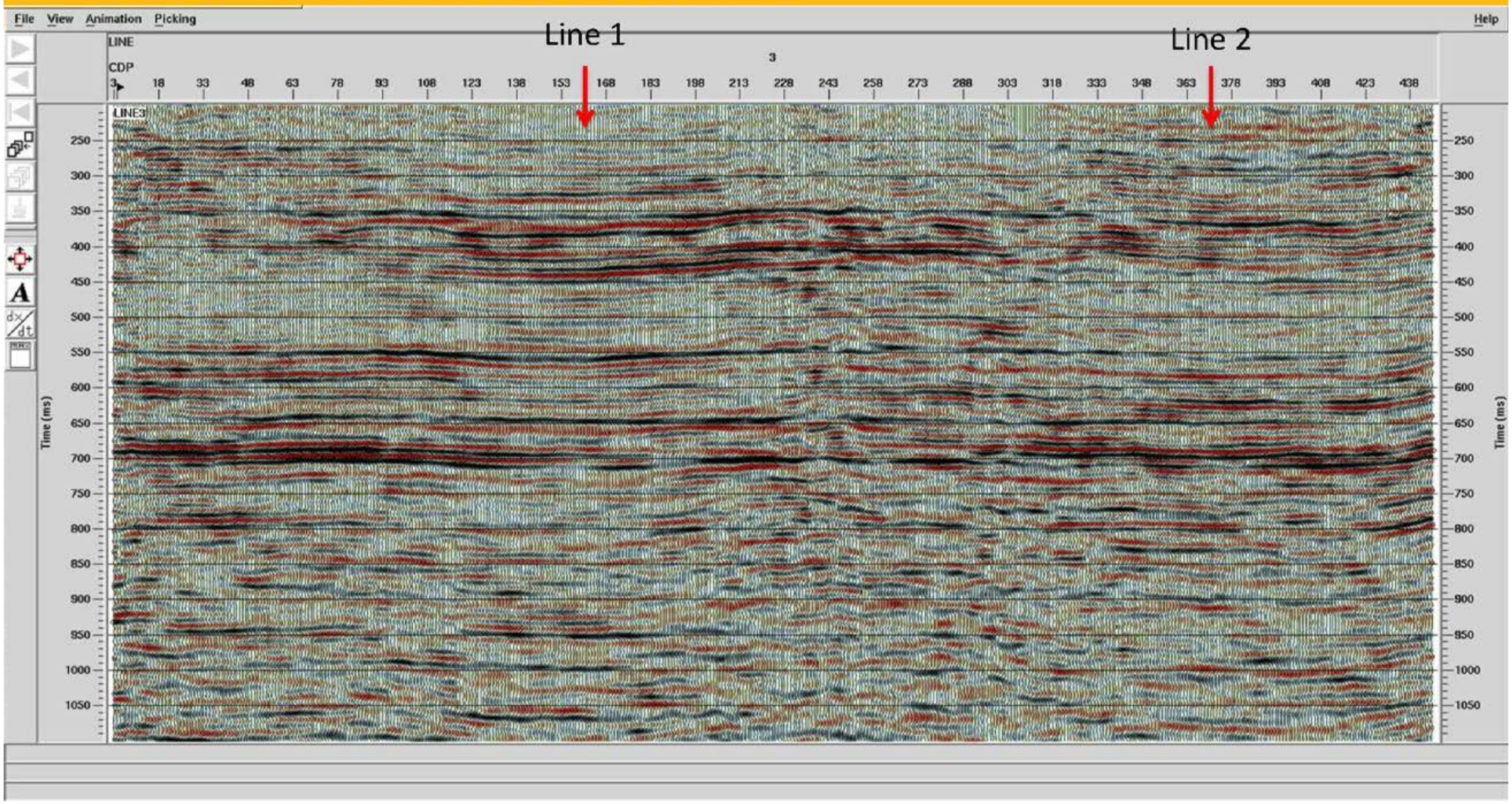

Reprocessing of Line 2, 4D Parameters select, Final Stack
fairfieldnodal
File View Animation Picking Help
LINE
CDP
2
Line 1
Line 3
Time (ms)
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

fairfieldnodal

Reproccessing of Line 3, 4D Parameters select, Final Stack

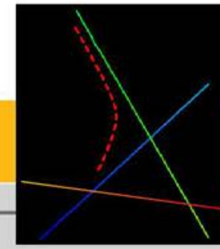


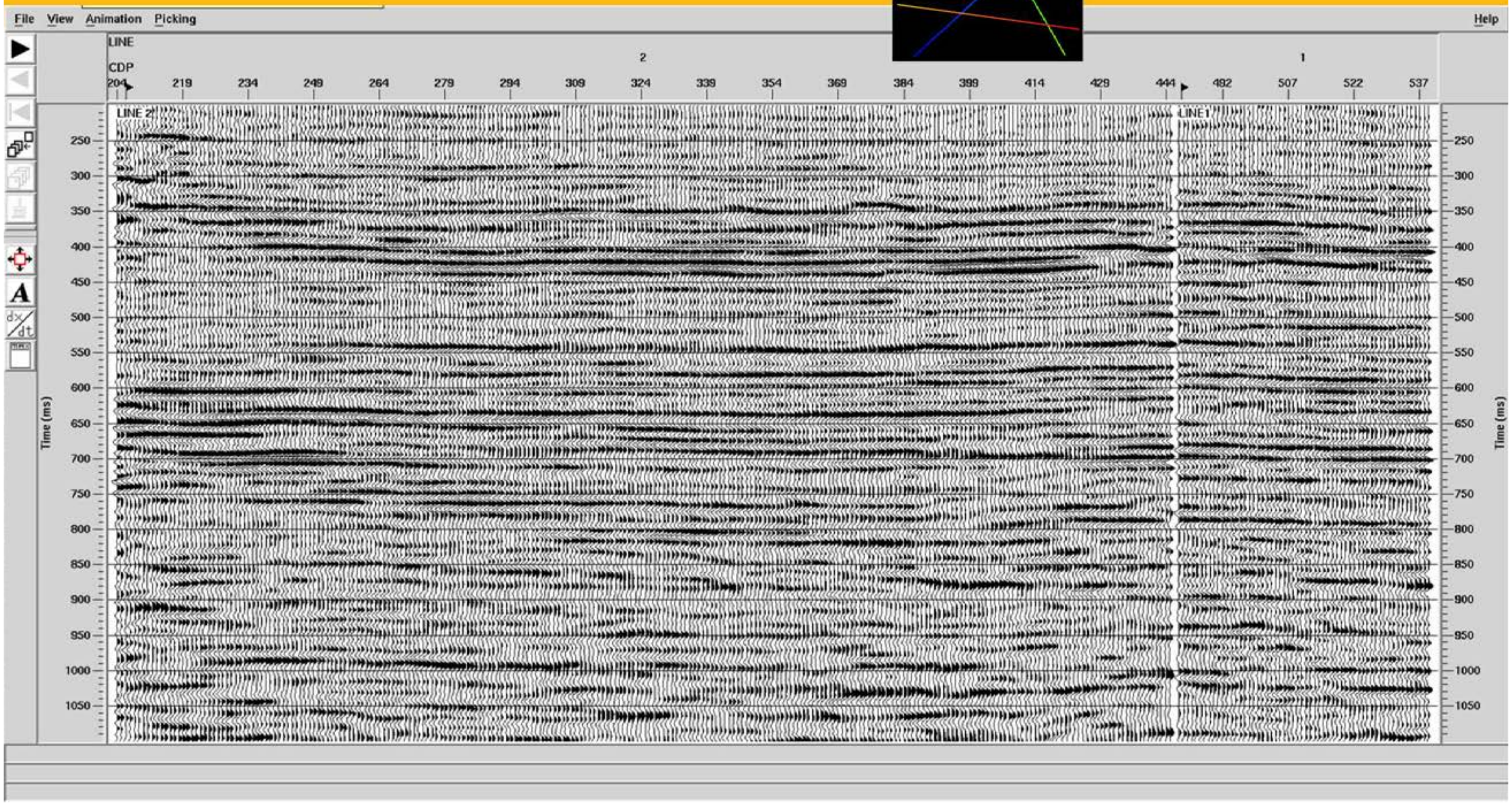
Reprocessing of Line 3, 4D Parameters select, Final Stack

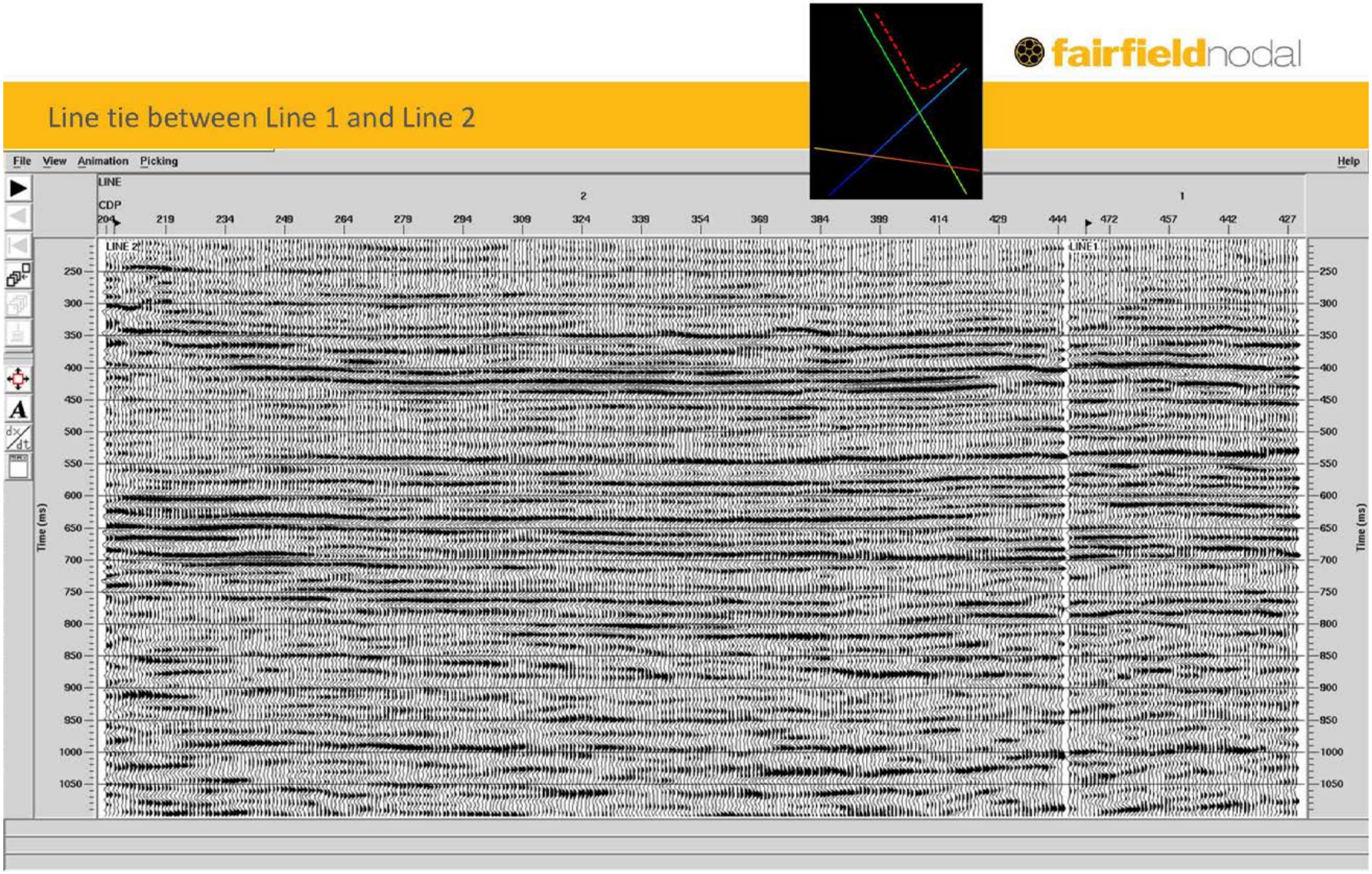


Line tie comparison between Line 1 and Line 2

Line tie between Line 1 and Line 2

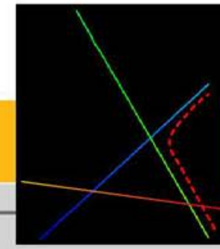


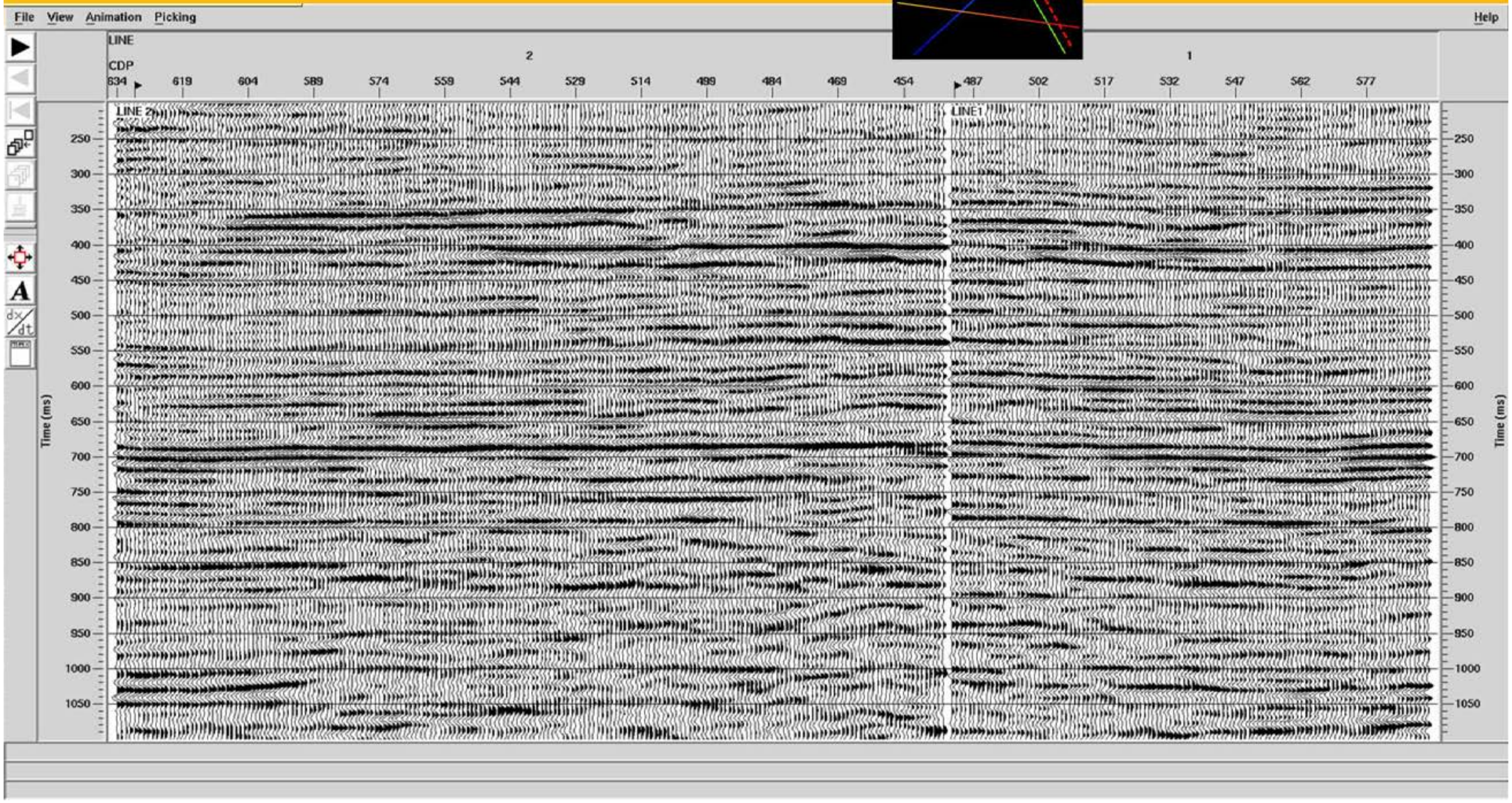



fairfieldnodal
Line tie between Line 1 and Line 2
File View Animation Picking
Help
LINE
CDP
2
1
204 219 234 249 264 279 294 309 324 339 354 369 384 399 414 429 444 472 457 442 427
LINE 2
LINE 1
250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050
Time (ms)

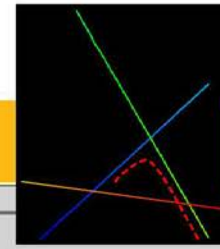
fairfieldnodal

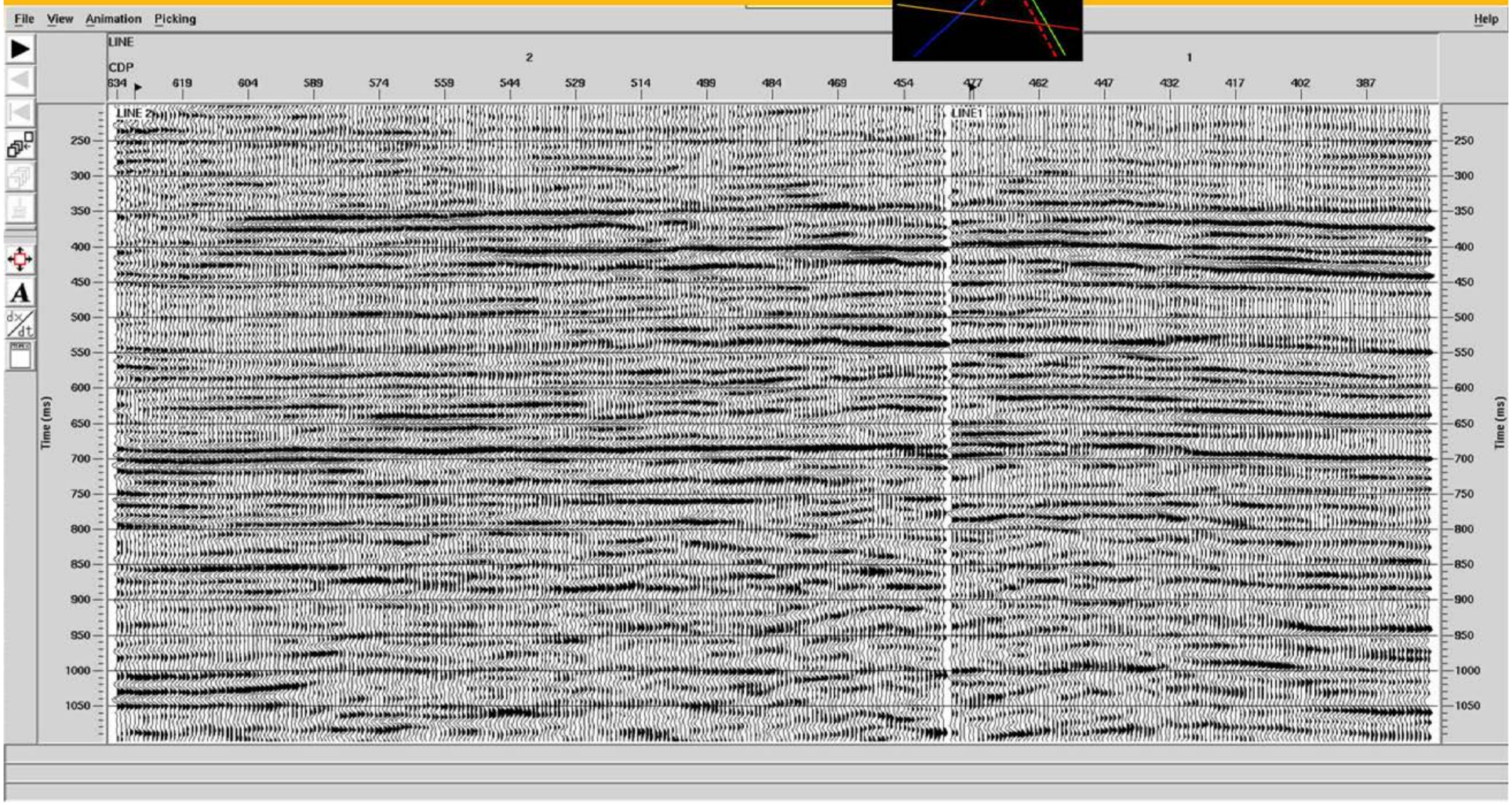
Line tie between Line 1 and Line 2





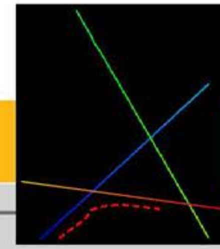
Line tie between Line 1 and Line 2

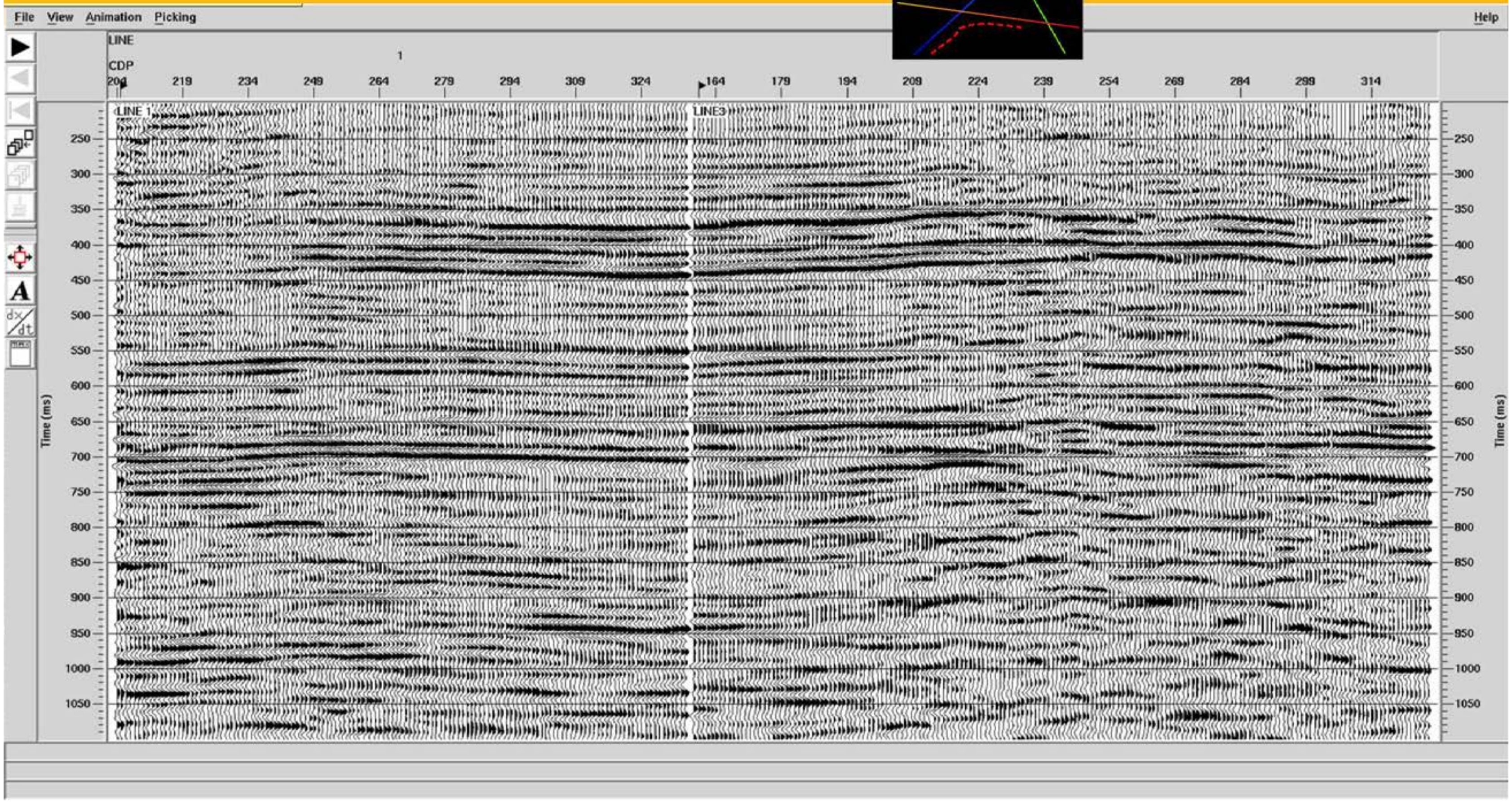




Line tie comparison between Line 1 and New Line 3

Line tie between Line 1 and the new Line 3





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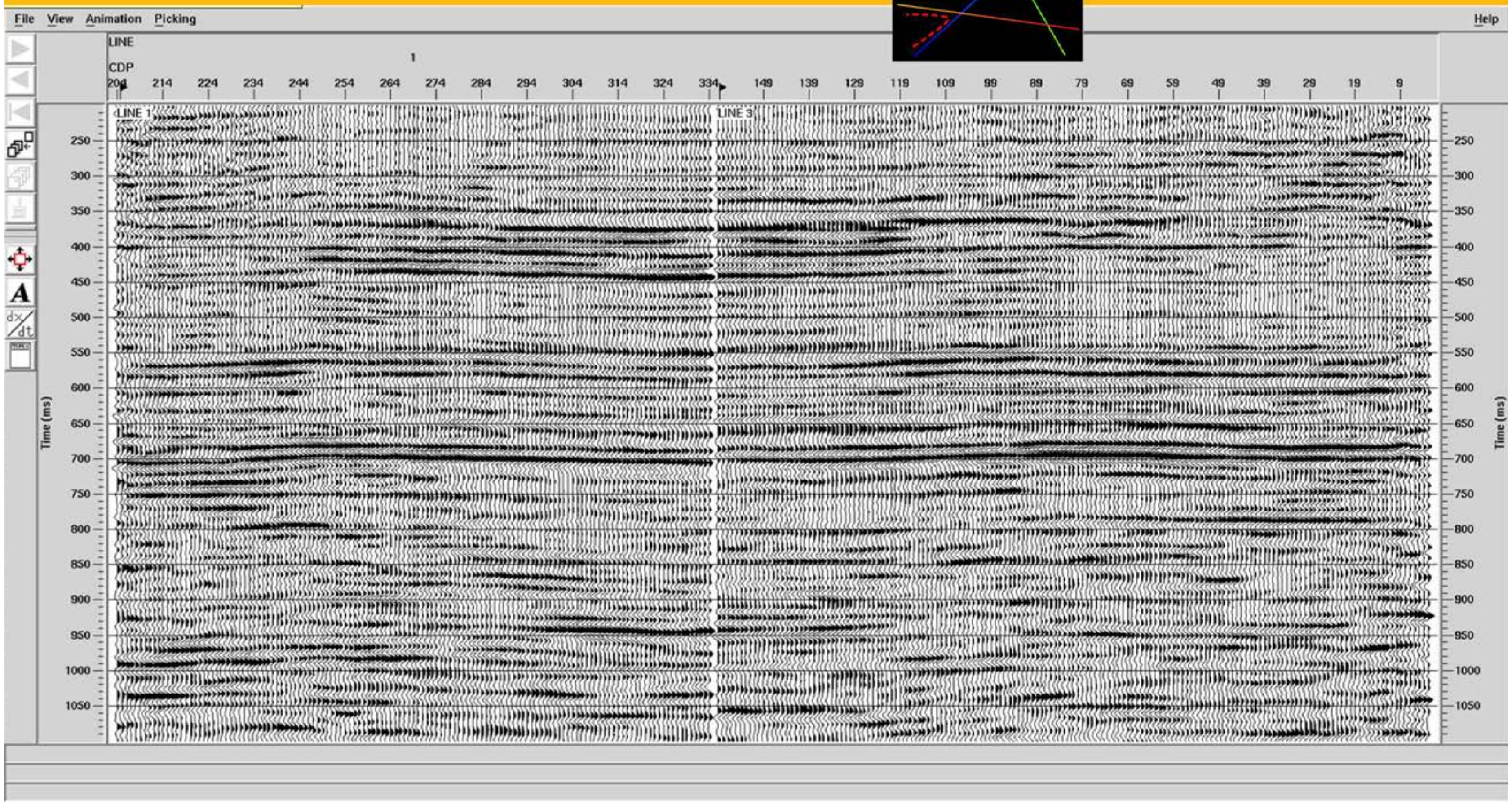
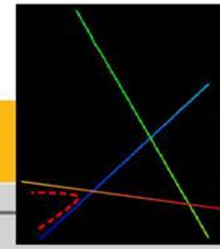
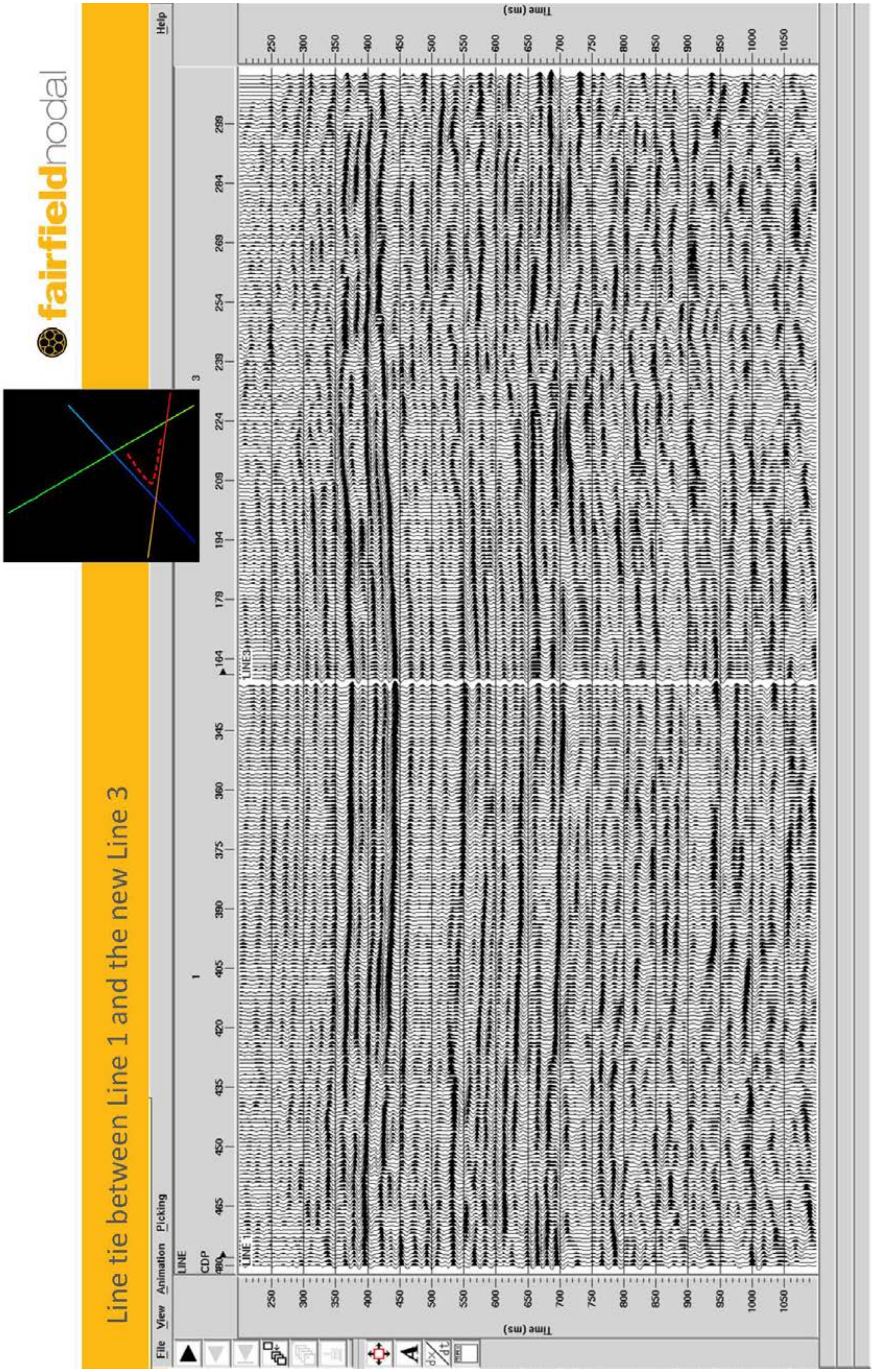
Line tie between Line 1 and the new Line 3

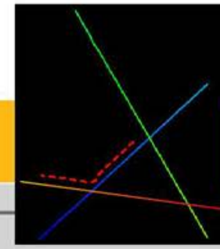


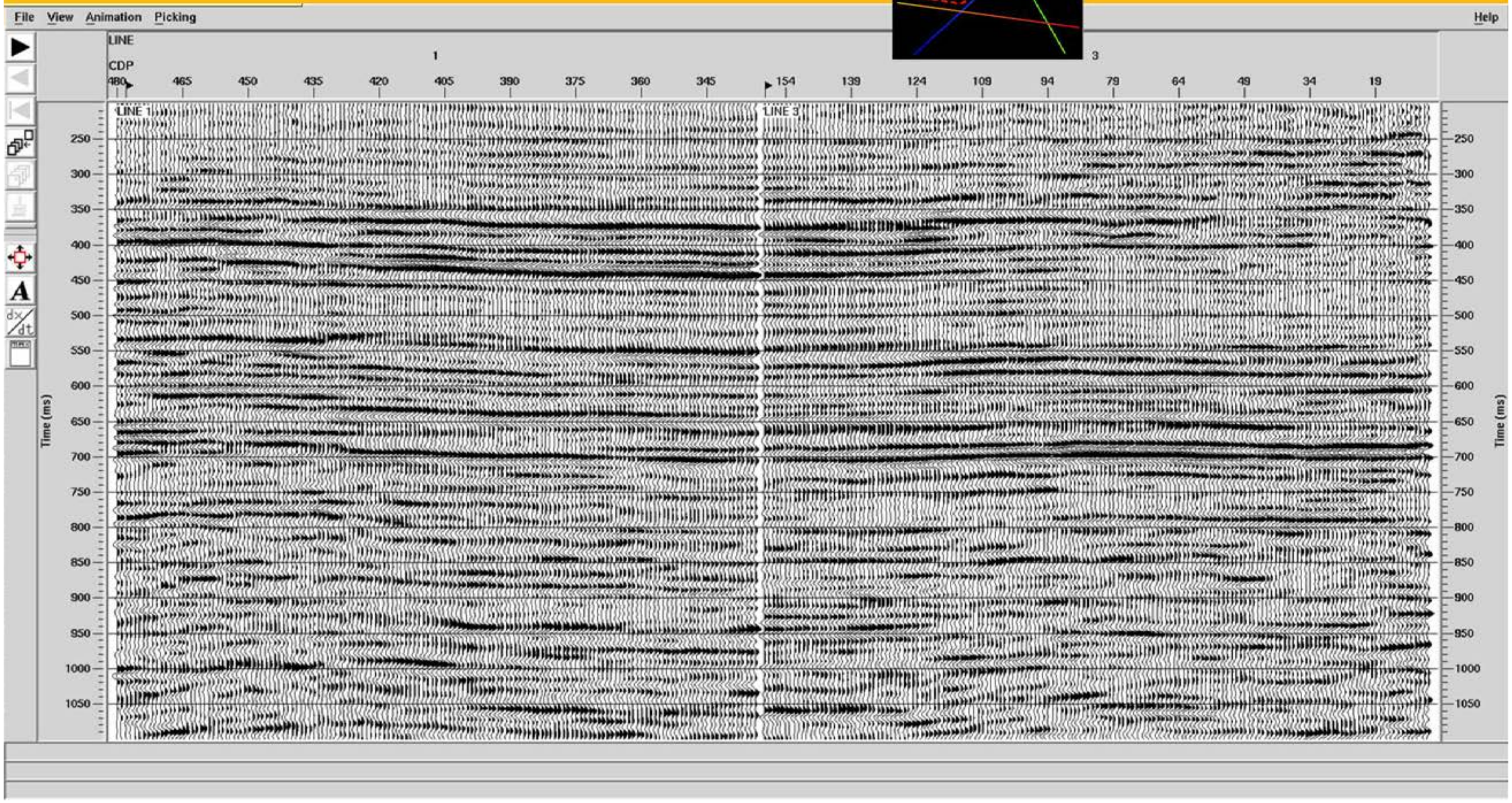




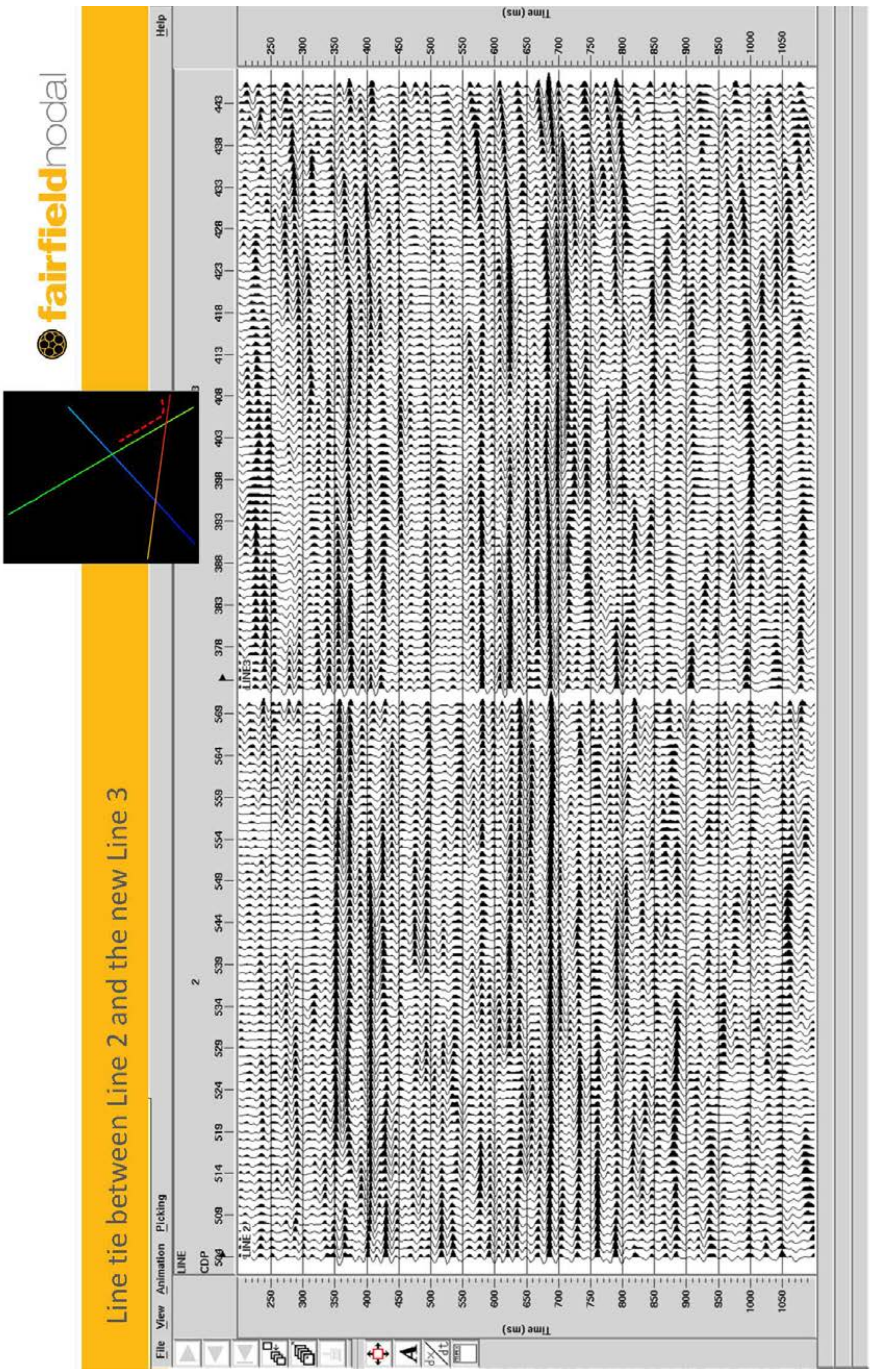
Line tie between Line 1 and the new Line 3
fairfieldnodal
File View Animation Picking Help
LINE
CDP
1
3
LINE 1
LINE 3
480 465 450 435 420 405 390 375 360 345
164 179 194 209 224 239 254 269 284 299
250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050
Time (ms)

Line tie between Line 1 and the new Line 3



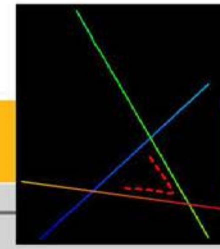


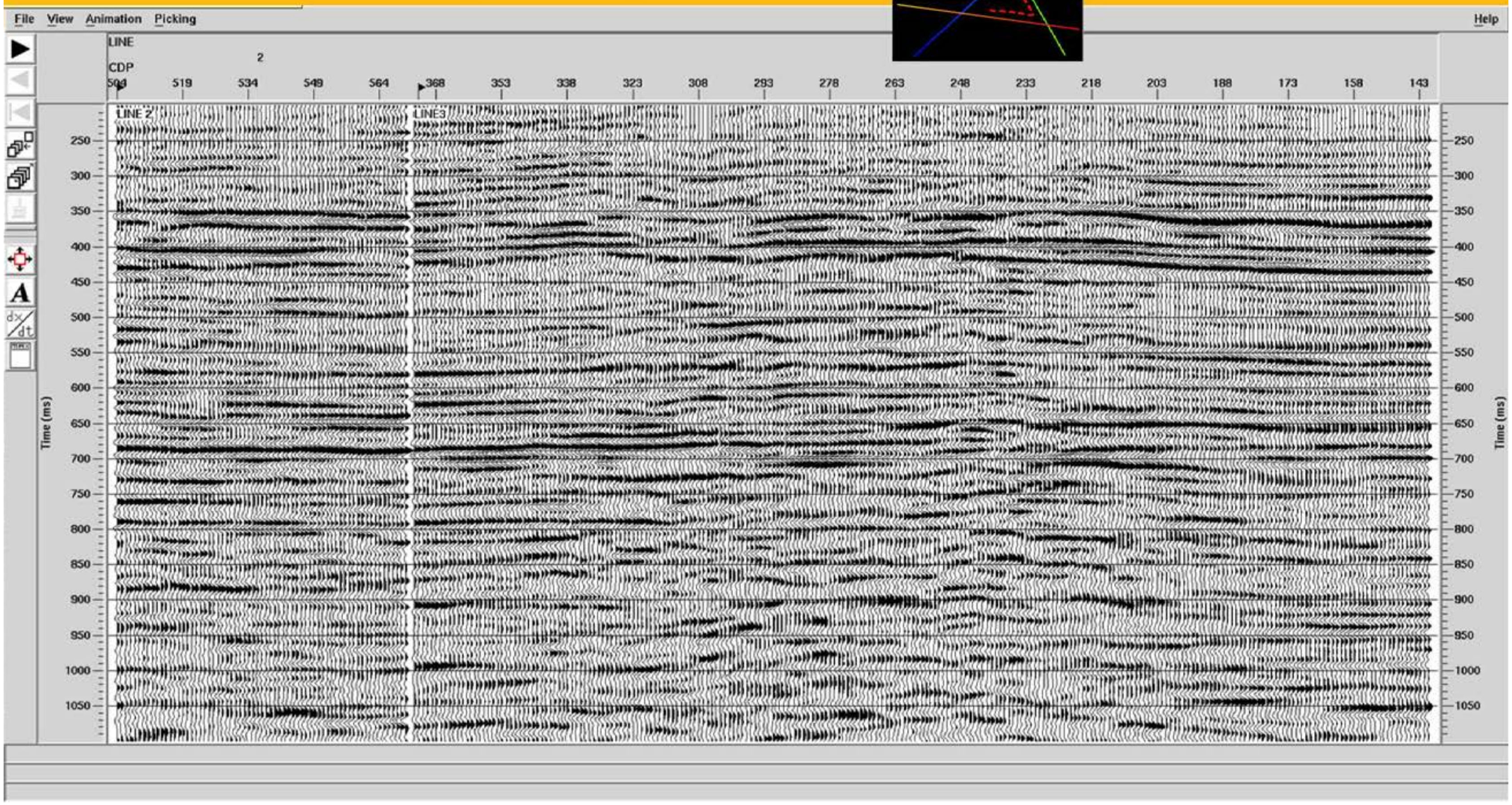
Line tie comparison between Line 2 and New Line 3

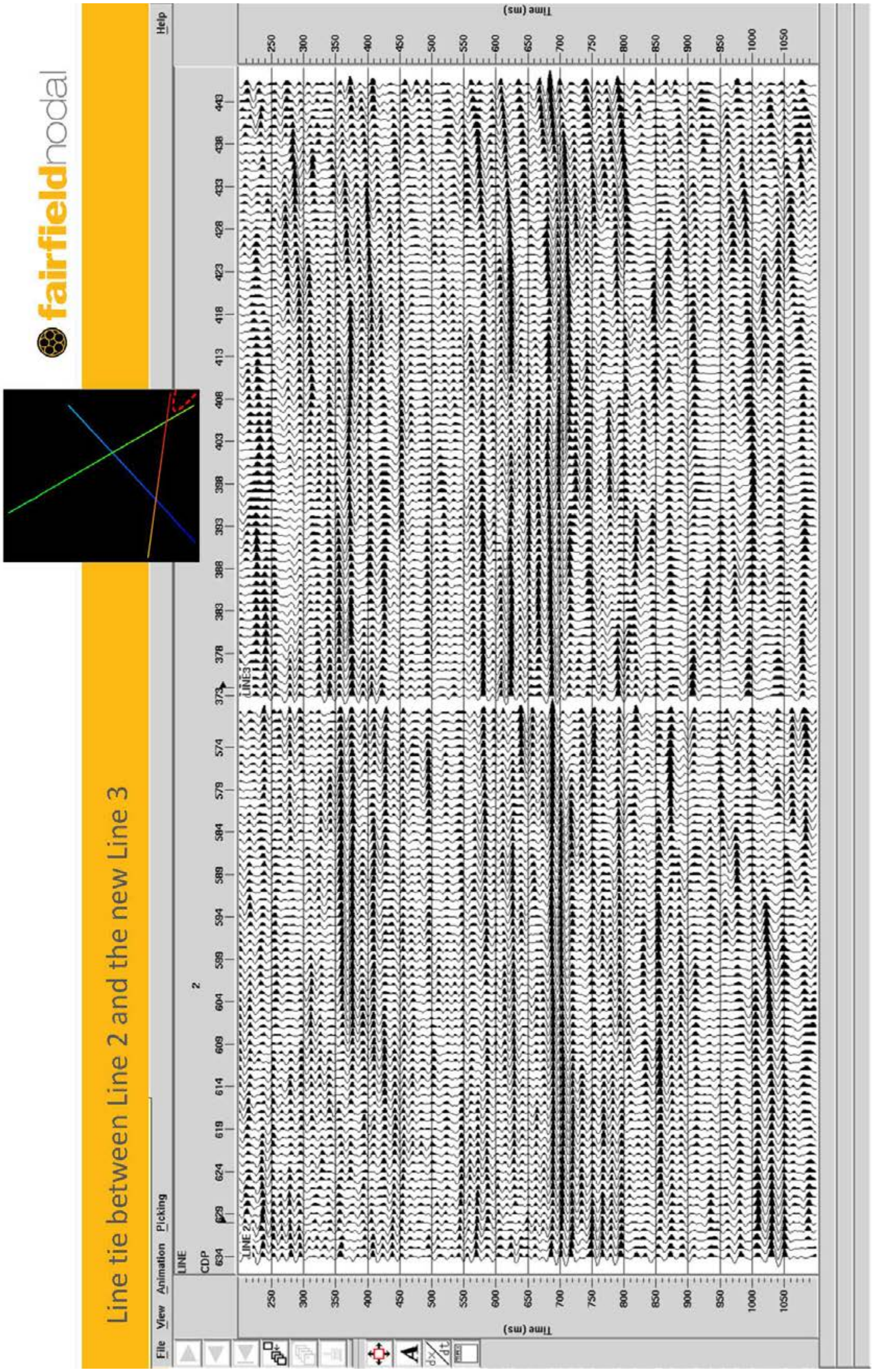

Line tie between Line 2 and the new Line 3
File View Animation Picking Help
LINE 2
LINE 3
Time (ms)

fairfieldnodal

Line tie between Line 2 and the new Line 3






Line tie between Line 2 and the new Line 3
fairfieldnodal
File View Animation Picking Help
LINE
CDP
2
LINE 2
LINE 3
Time (ms)

fairfieldnodal

Line tie between Line 2 and the new Line 3