Critical Challenges. Practical Solutions.

Energy & Environmental Research Center (EERC)

JOINT INVERSION OF TIME-LAPSE SEISMIC DATA

DE-FOA0001725

U.S. Department of Energy National Energy Technology Laboratory
Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting
August 26–30, 2019

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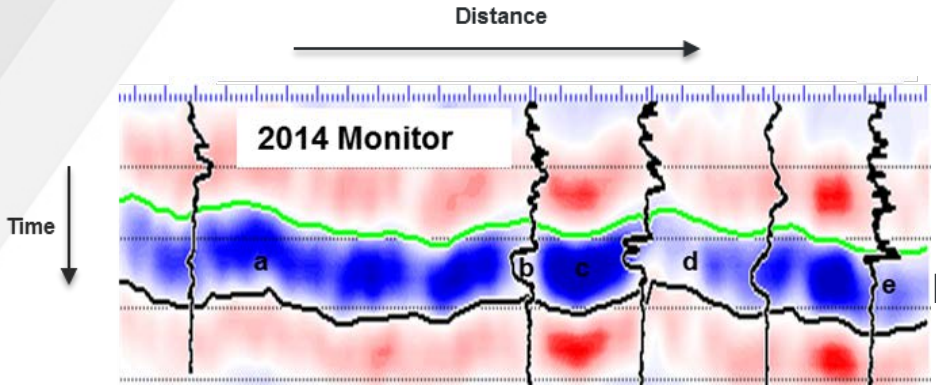
Senior Geophysicist

PRESENTATION OUTLINE

- Time-Lapse Seismic Data
- Seismic Joint Inversion to Improve the Certainty of CO_2 Plume Position
- Accomplishments
- Lessons Learned
- Synergy Opportunities
- Summary

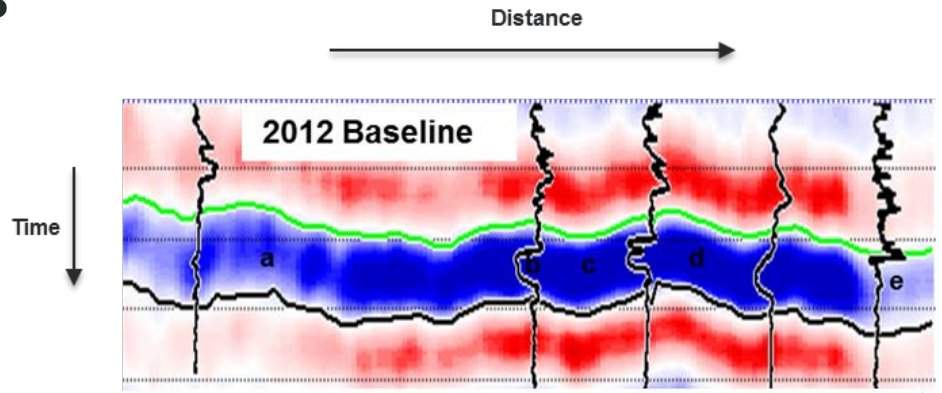
TIME-LAPSE SEISMIC DATA

Amplitudes



Reservoir

After CO_2 Injection



Reservoir

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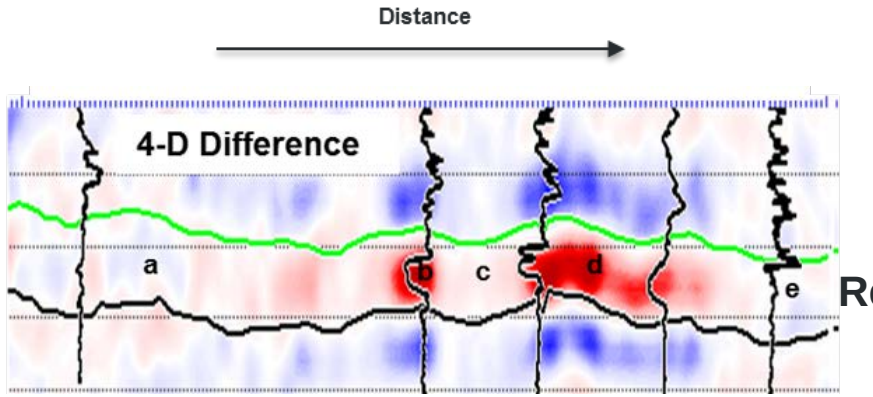
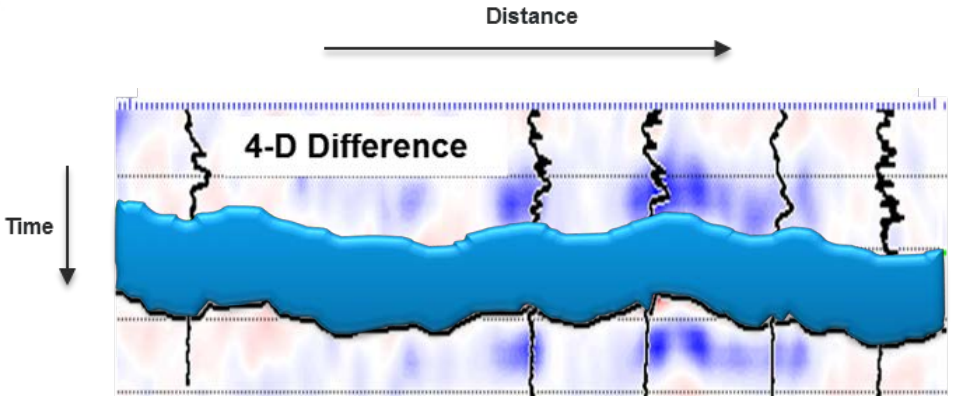


Reservoir

JOINT INVERSION

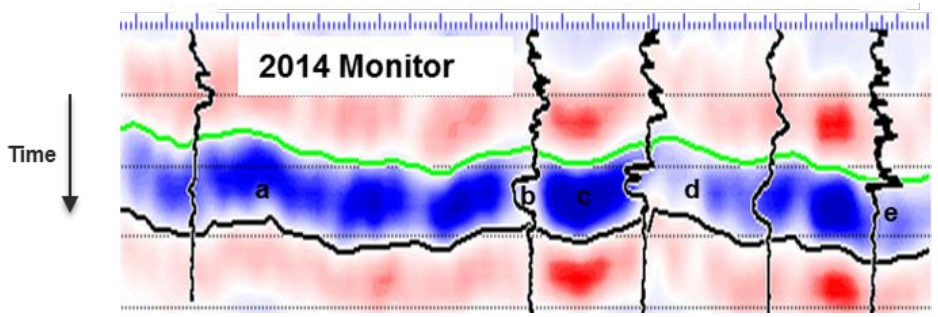
Inverse Problem

Reservoir Properties Estimation

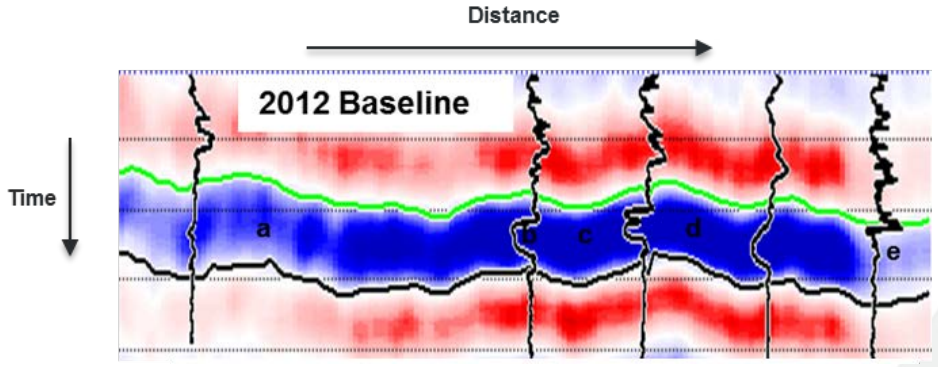


Reservoir — **Pressure**, **Saturation**

Amplitudes



After CO_2 Injection



Before CO_2 Injection

- Reduce the uncertainty of detecting and assessing the location of CO_2 plume boundaries

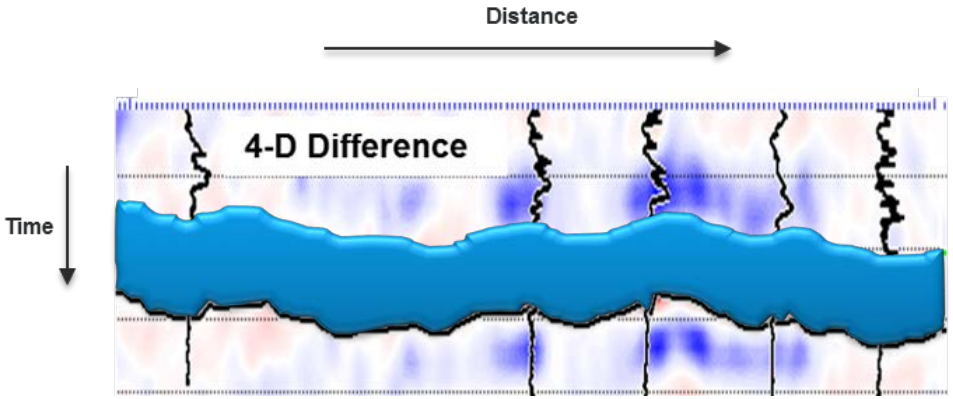
JOINT INVERSION

Wave-Equation-Based Amplitude-Variation-with-Offset

Joint Impedance and Facies Inversion

Reservoir Properties Estimation

Amplitudes



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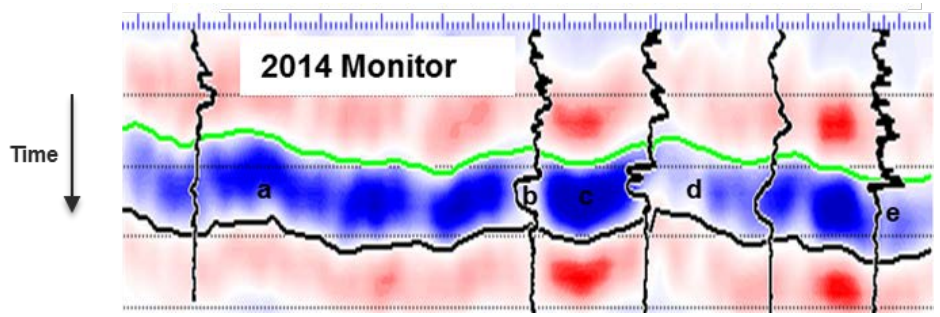

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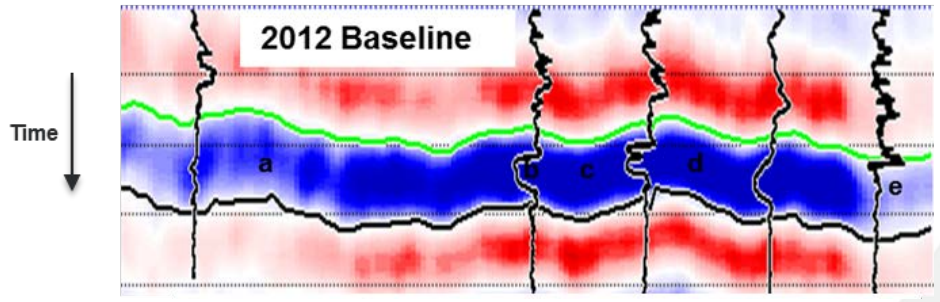


Before CO_2 Injection

- Reduce the uncertainty of detecting and assessing the location of CO_2 plume boundaries

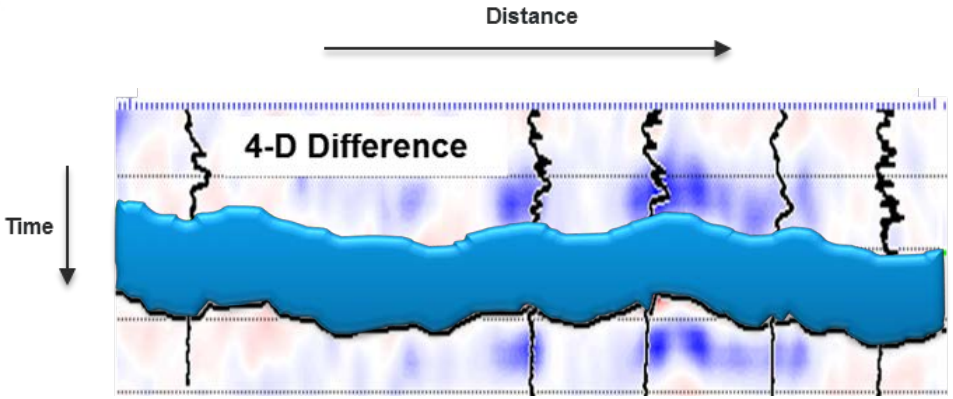
JOINT INVERSION

Delft Inversion

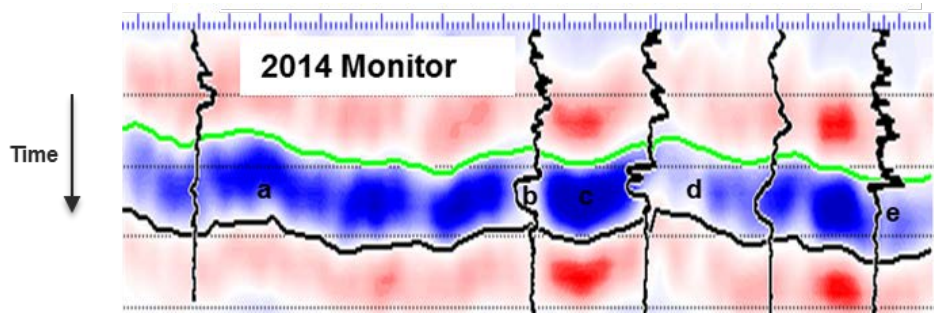
Ikon Science

Reservoir Properties Estimation

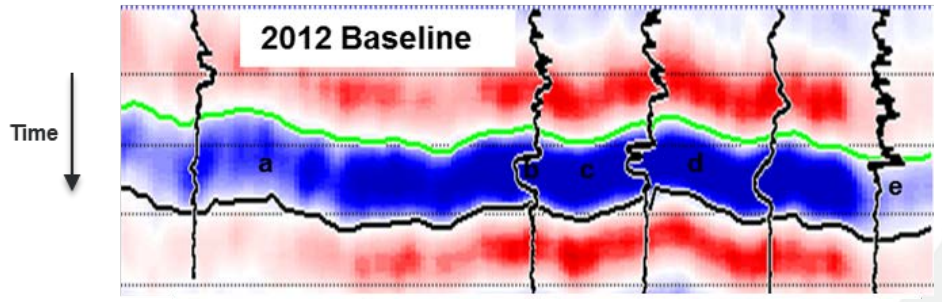
Amplitudes



Reservoir — **Pressure**, **Saturation**



After CO_2 Injection

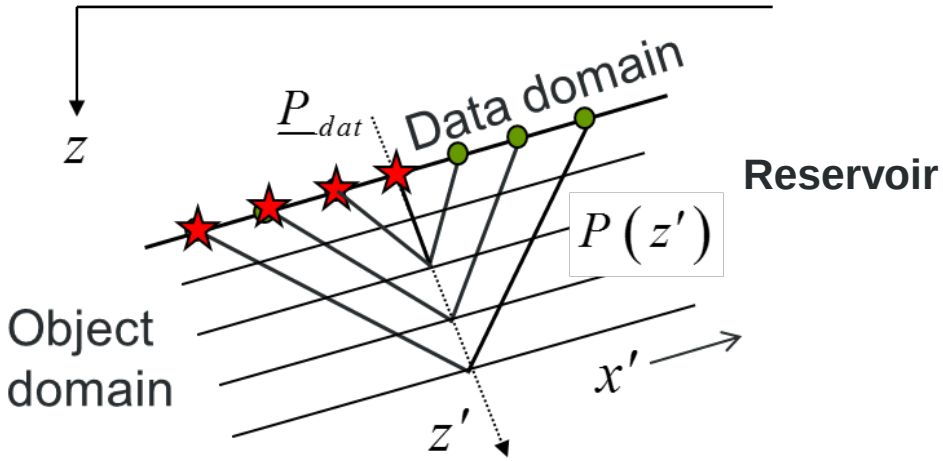


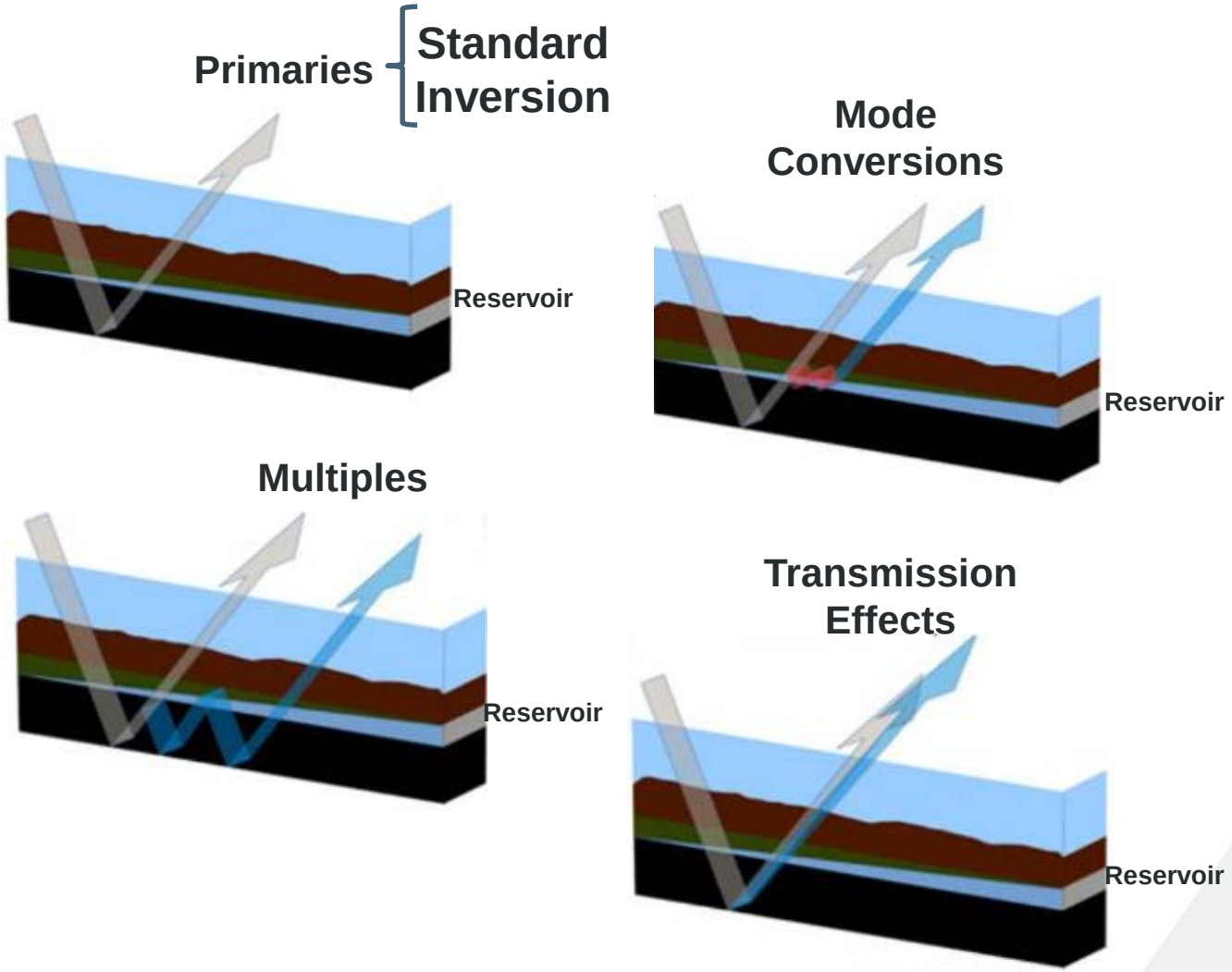
Before CO_2 Injection

- Reduce the uncertainty of detecting and assessing the location of CO_2 plume boundaries

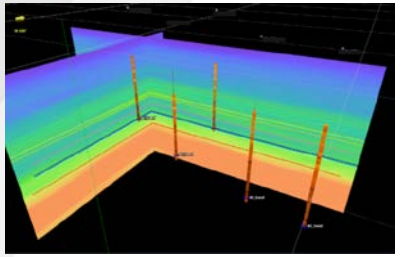
WAVE-EQUATION-BASED AMPLITUDE-VARIATION-WITH-OFFSET (WEB-AVO)

- Target-oriented full-waveform elastic inversion of seismic data.
- Directly inverts for compressibility (κ) (1/bulk modulus) and shear compliance (M) (1/shear modulus).
- Simultaneous joint inversion of baseline and monitor surveys.

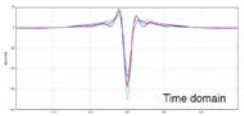




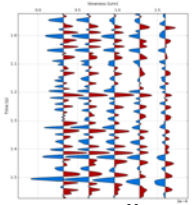
WEB-AVO



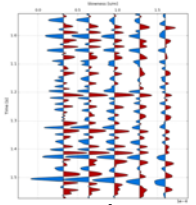
Well Logs, Horizons and Seismic Velocities



Wavelet



Baseline



Monitor

Incident field (in background)

Migrated seismic gather

AVO inversion

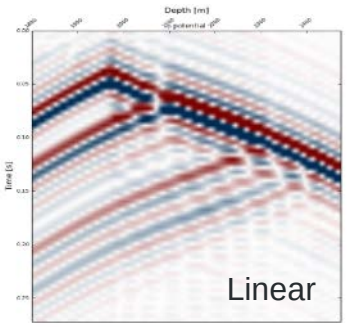
Simultaneous

Elastic reservoir properties

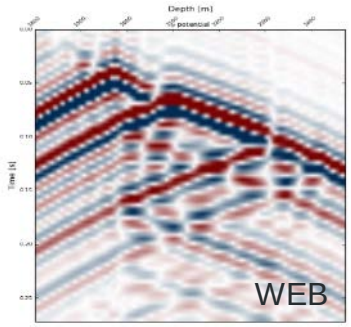
κ, M, ρ

Use wave-equation to add higher order of scattering

Updated total field

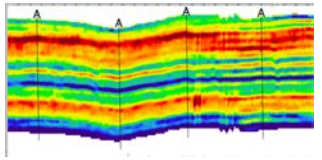


Linear

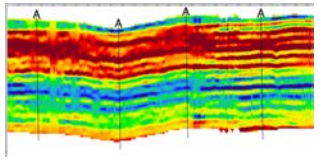


WEB

Baseline

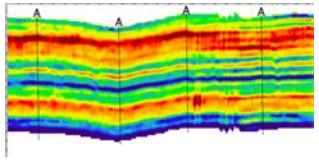


κ

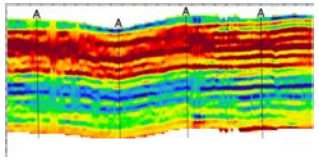


M

Monitor

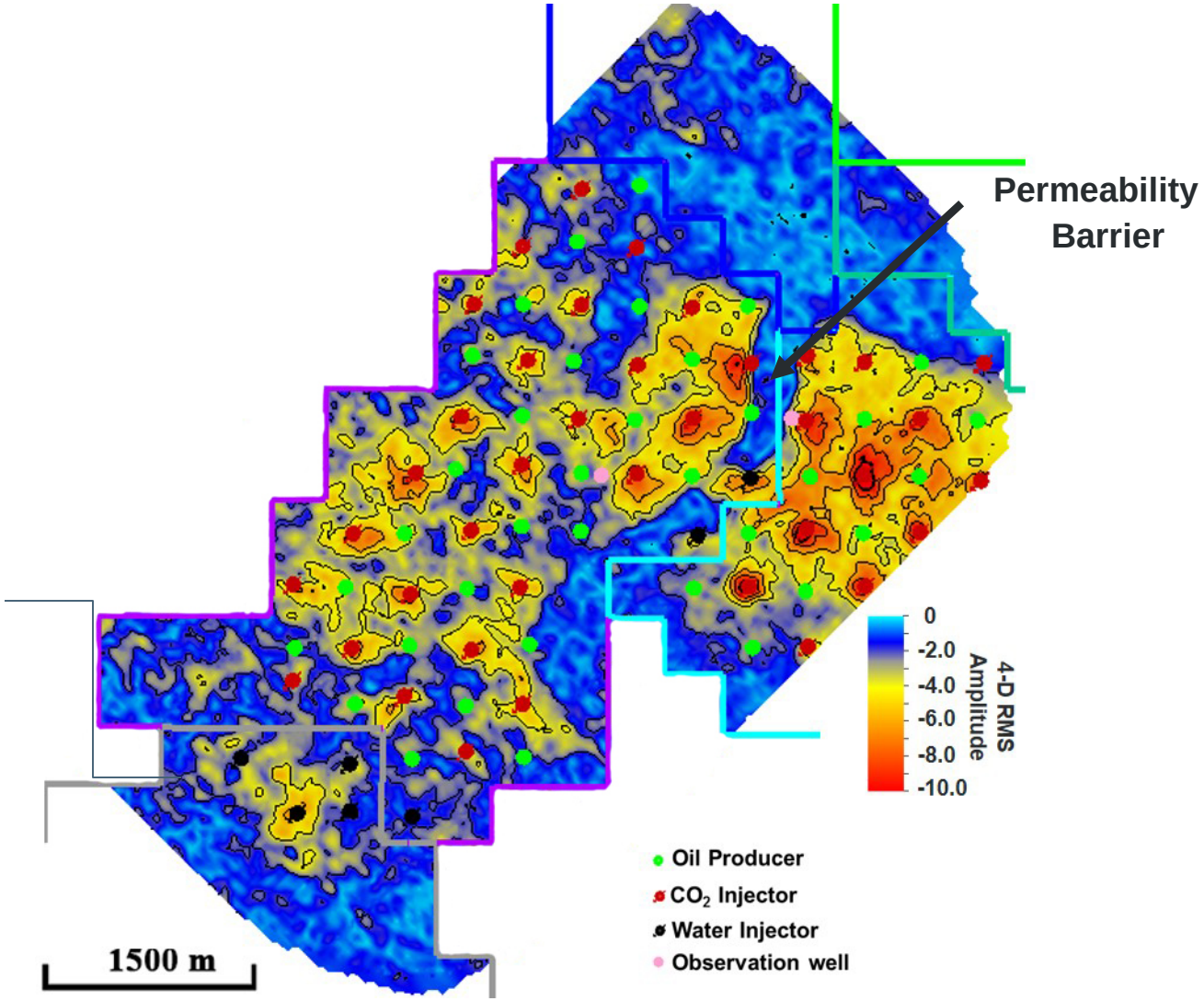


κ



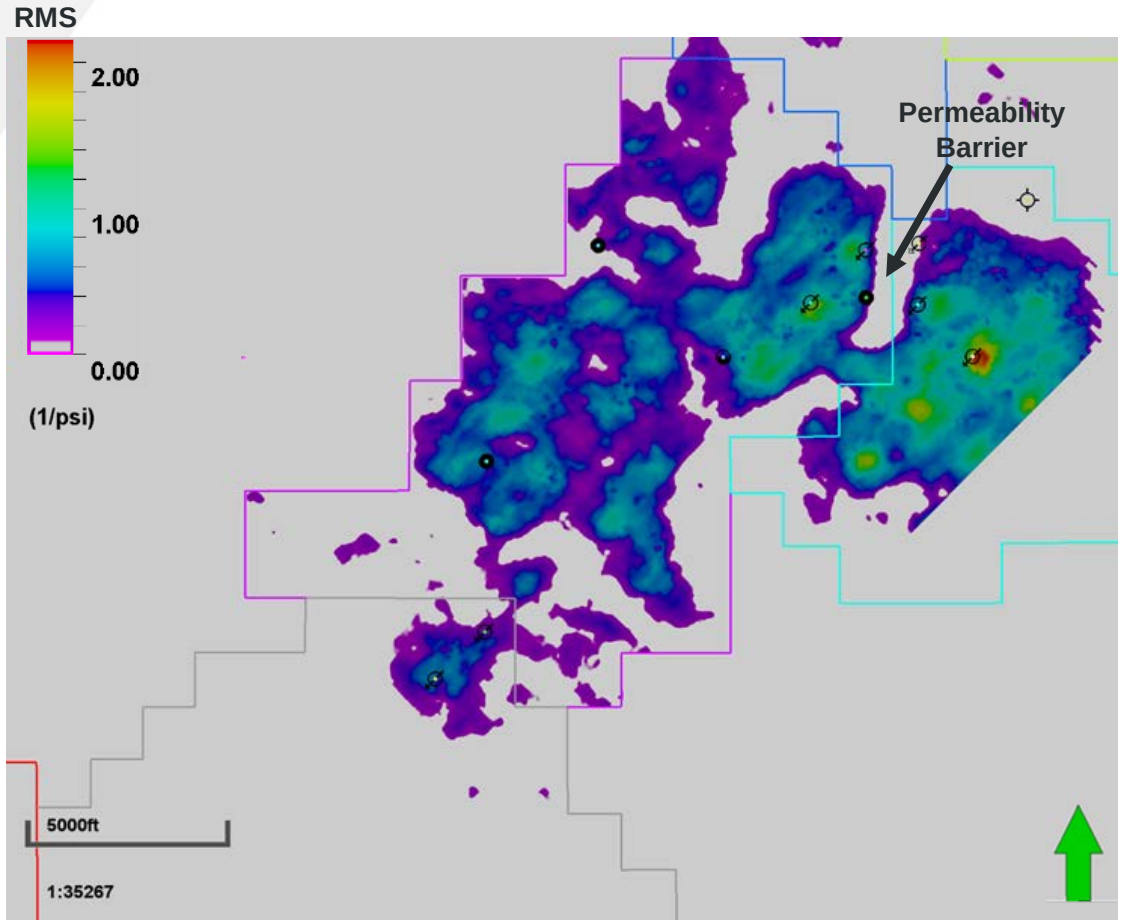
M

TIME-LAPSE AMPLITUDE DIFFERENCE

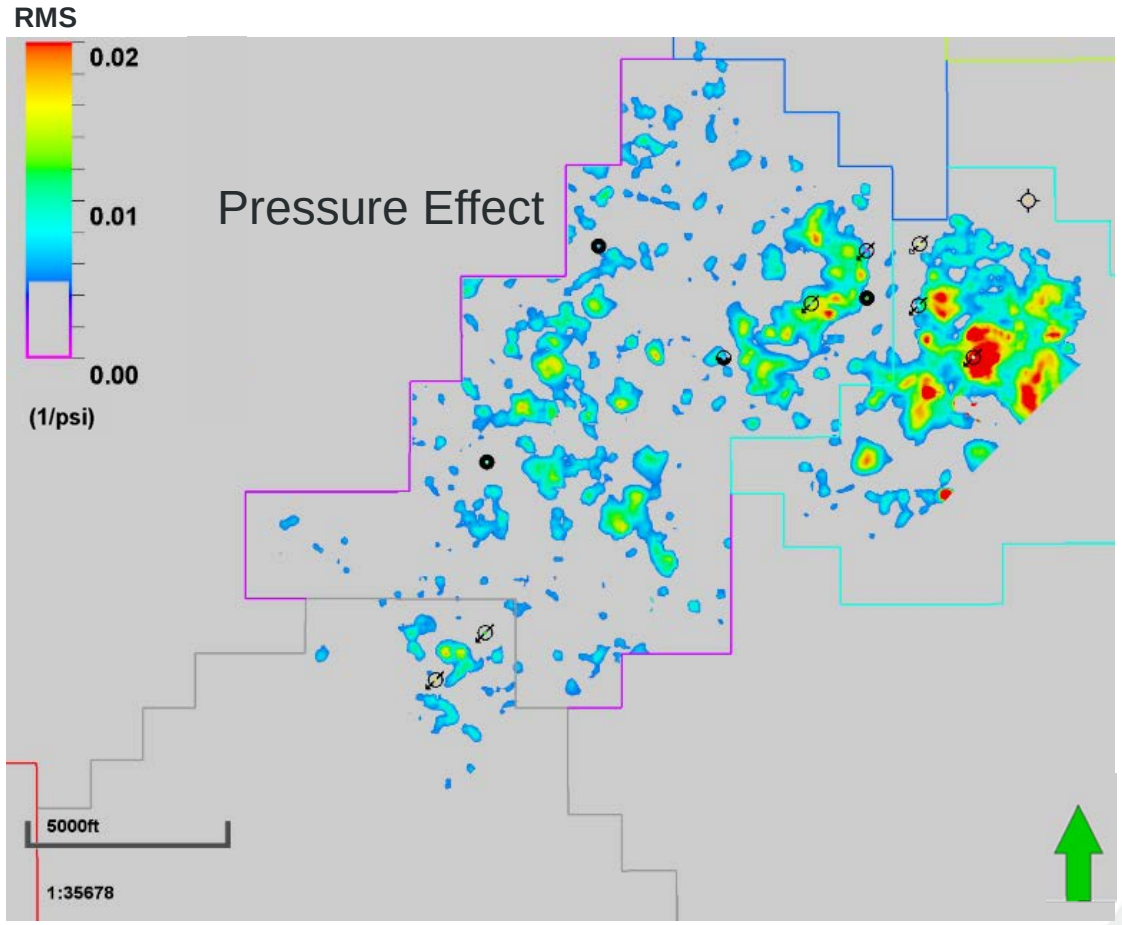


TIME-LAPSE WEB-AVO PARAMETERS

Simultaneous Joint Inversion of 2012–2014 Time-Lapse Data Set



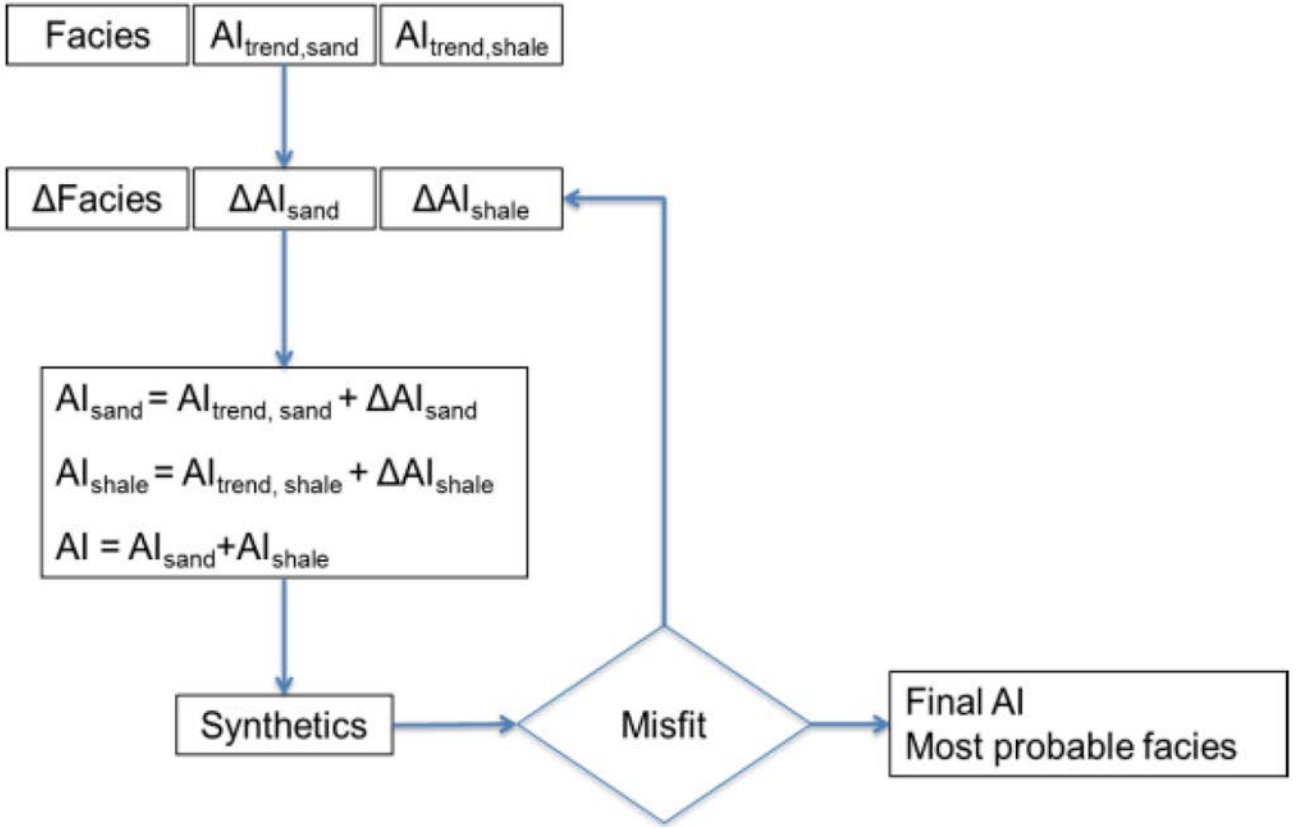
Compressibility (κ)



Shear Compliance (M)

JOINT IMPEDANCE AND FACIES INVERSION (Ji-Fi)

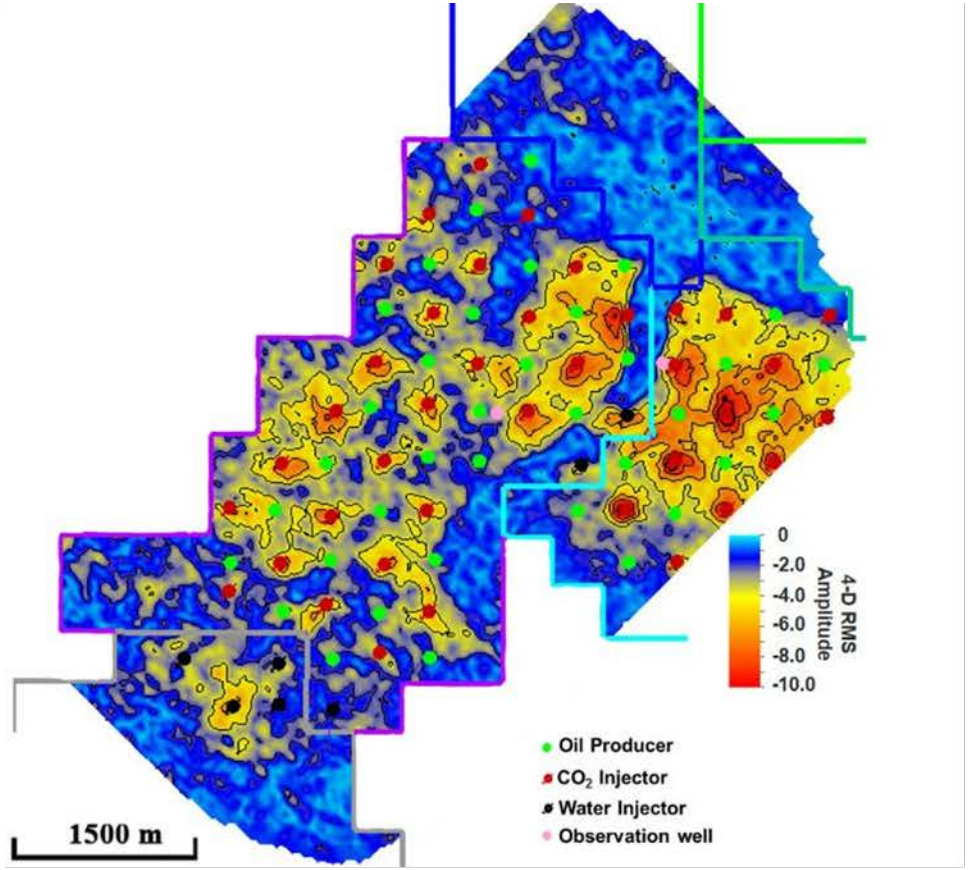
- Facies included directly within the inversion algorithm
- Different low-frequency models for each defined facies
  - Bayesian analysis within the inversion to choose low frequency model
  - Not interpolated between wells
- Rock physics constrained by geologic facies
- Time-lapse difference from single or multirealization inversions



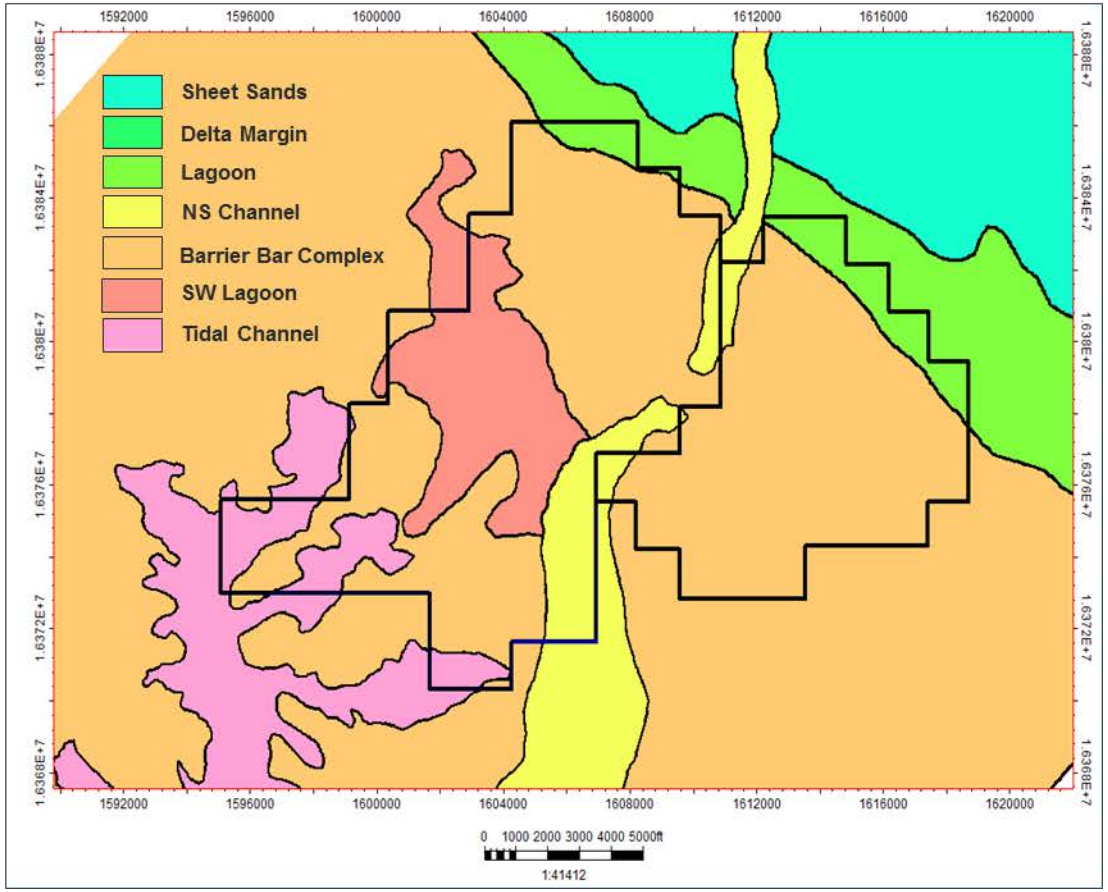
(Waters et al., 2016)

Ji-Fi

Time-Lapse Amplitude Difference

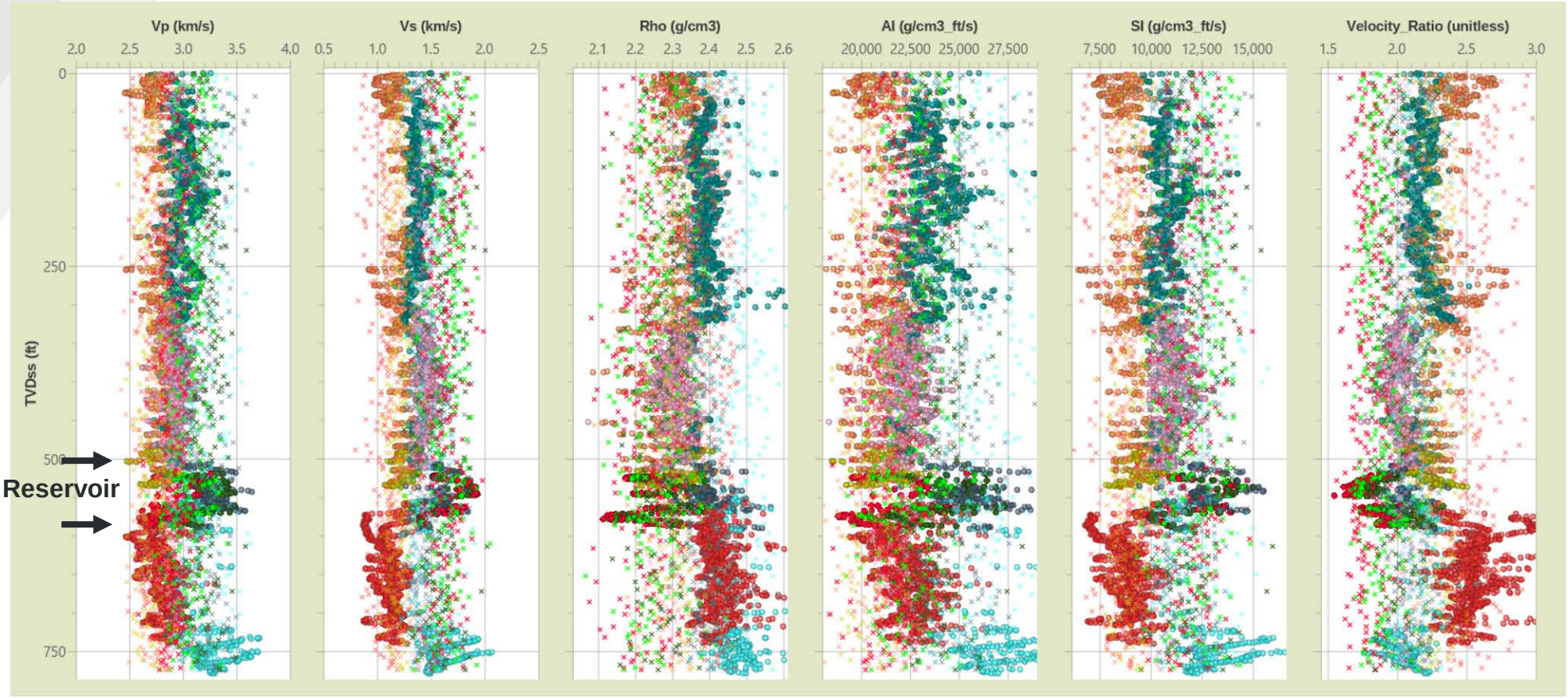


Geologic Facies



Ji-Fi

Depth Trend Analysis

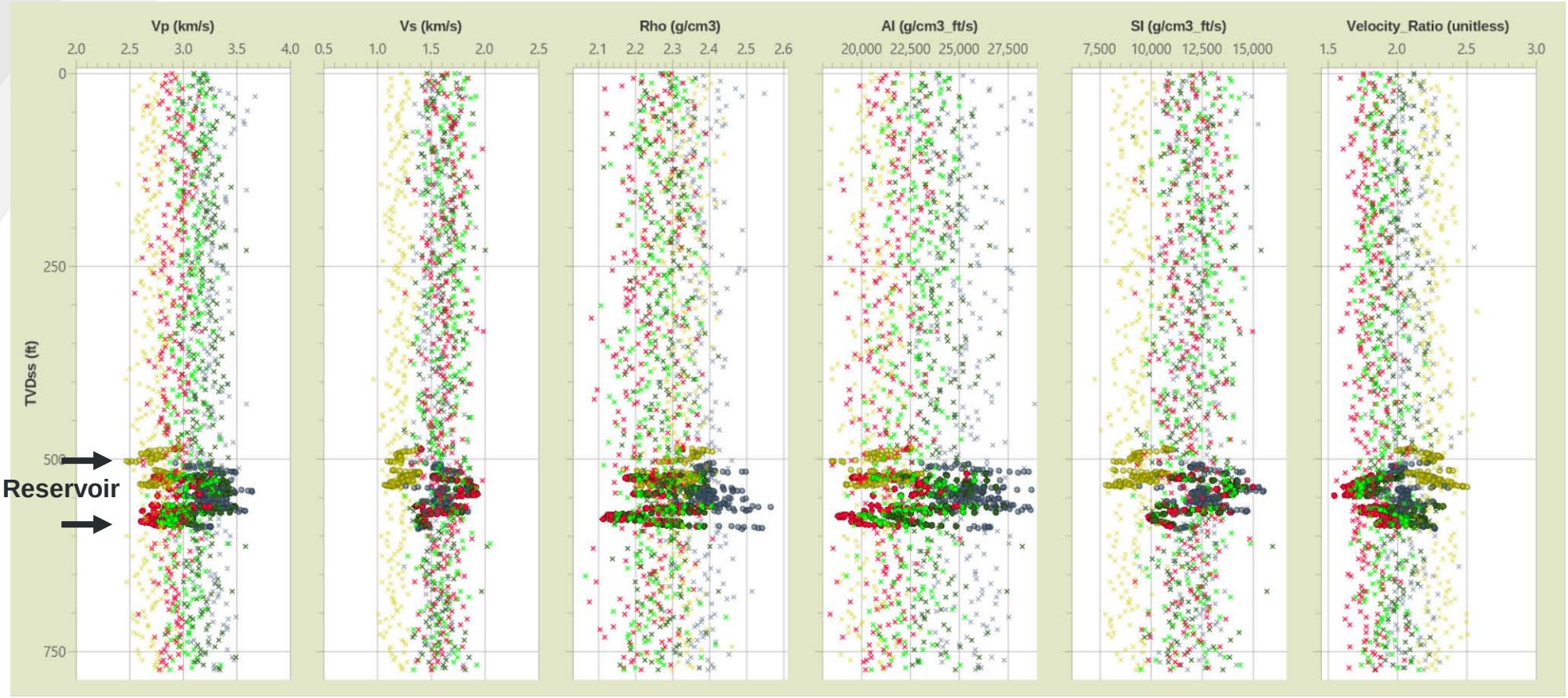


Closed Circles: Well data
Crosses: Prior data

Color	Facies
	Shallow Marine 1
	Marine 1
	Marine 2
	Shell Creek
	Barrier Bar
	Shallow Marine Intrareservoir
	Extra Shale
	Shallow Marine 2
	Marine 3
	Barrier Bar – Dead Oil & Water
	Barrier Bar – Oil
	Barrier Bar – CO_2
	Barrier Bar – Water

Ji-Fi

Depth Trend Analysis



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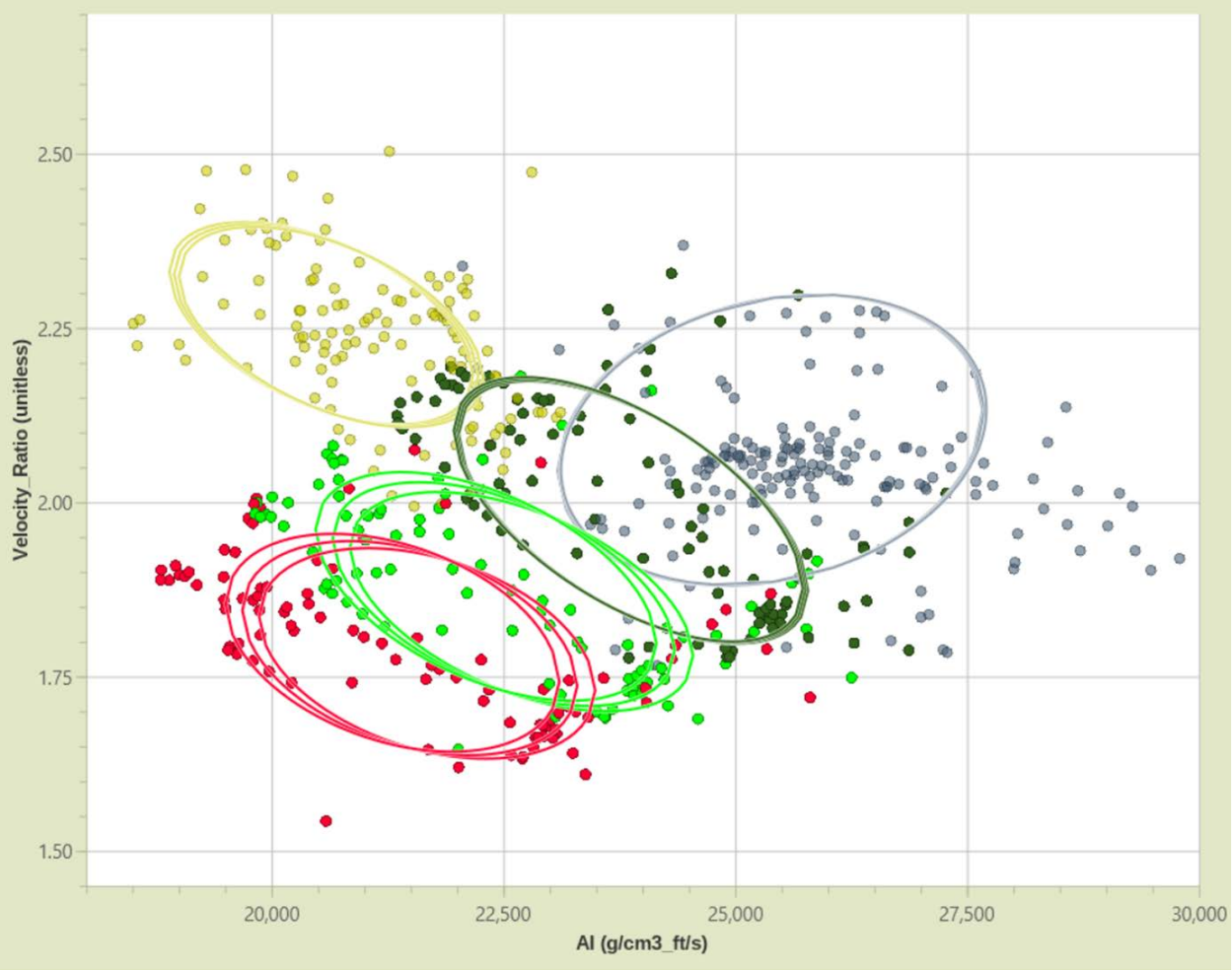
Ji-Fi



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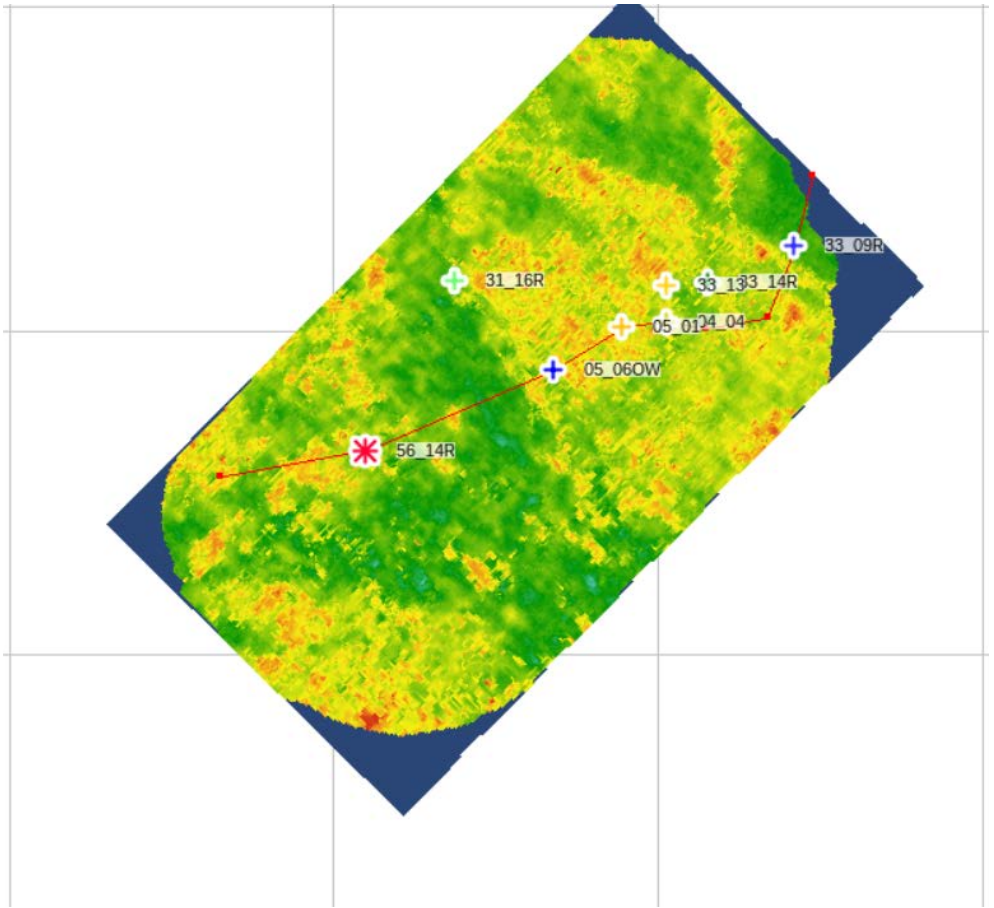
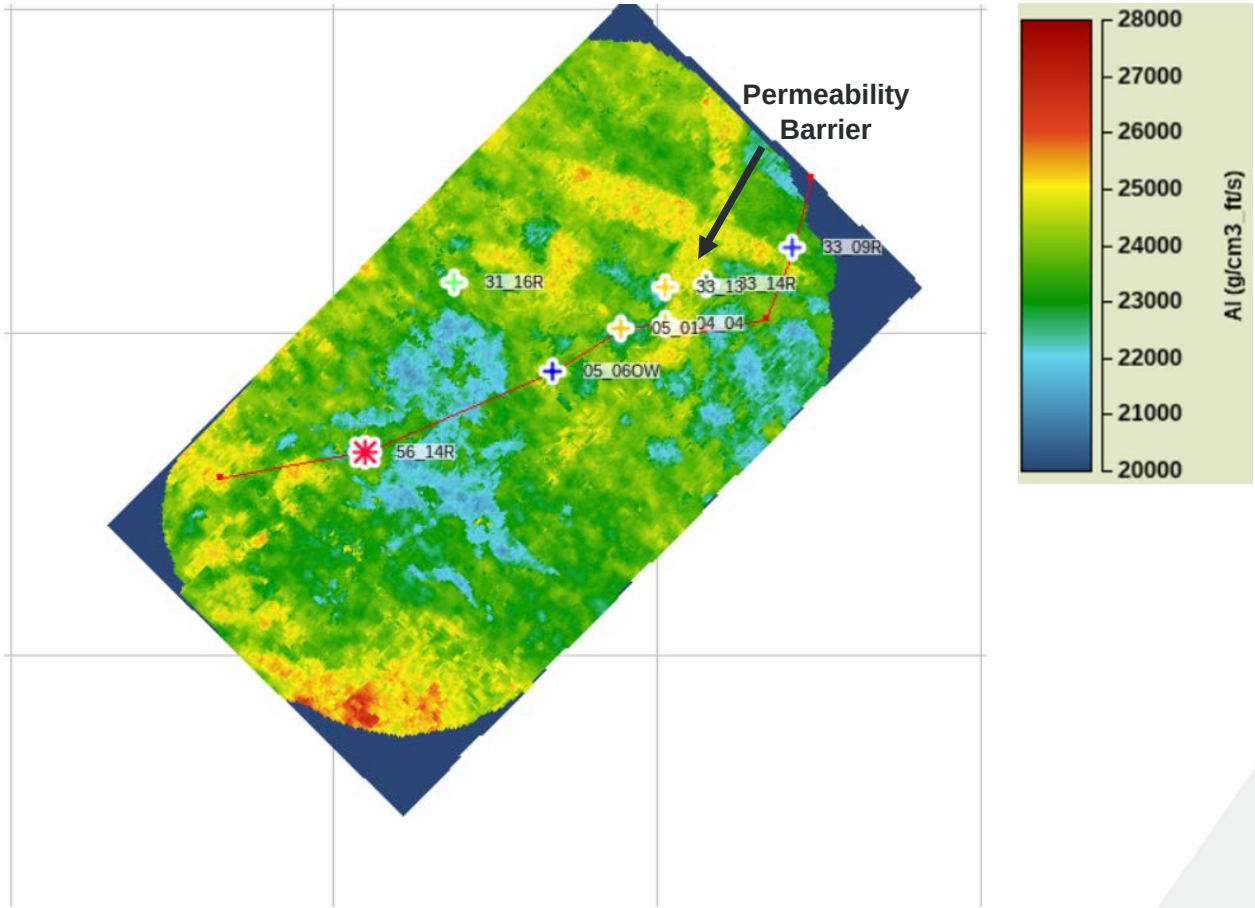
Closed Circles: Well data
Ellipses: Prior data

Ji-Fi: ACOUSTIC IMPEDANCE

Before CO_2 Injection

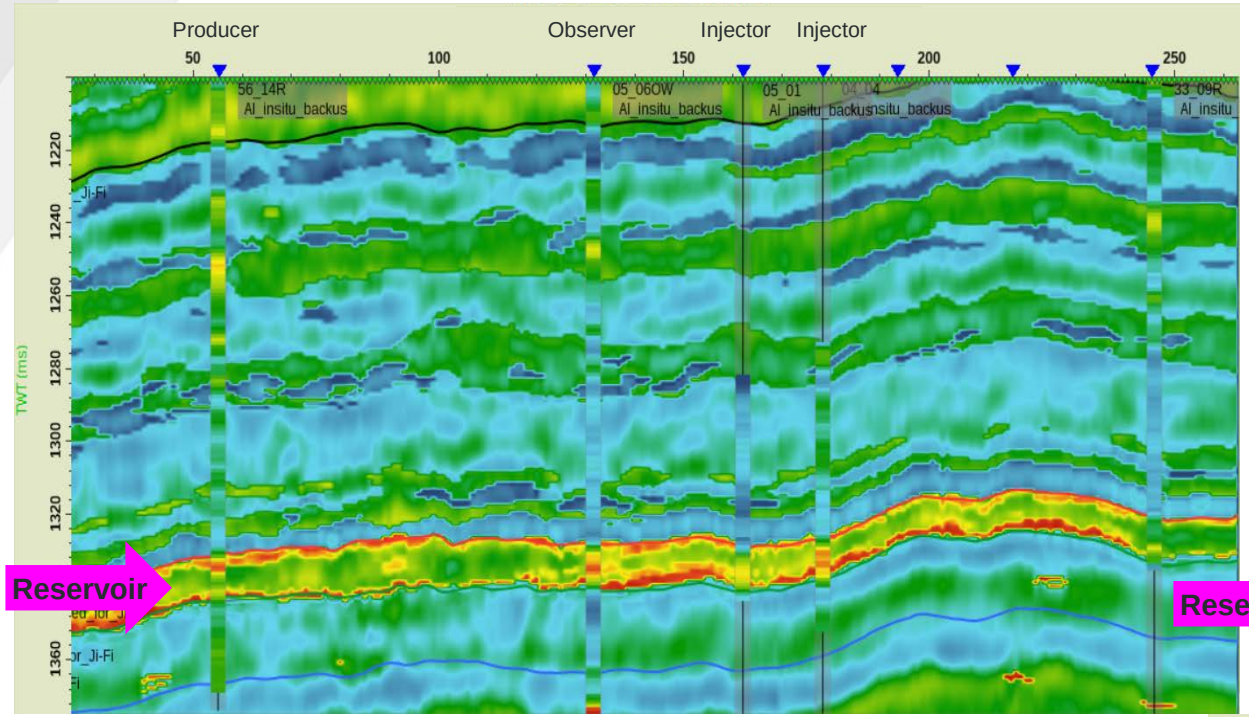


After CO_2 Injection

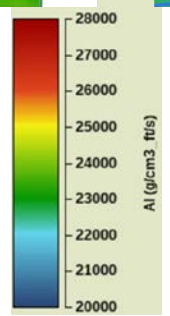


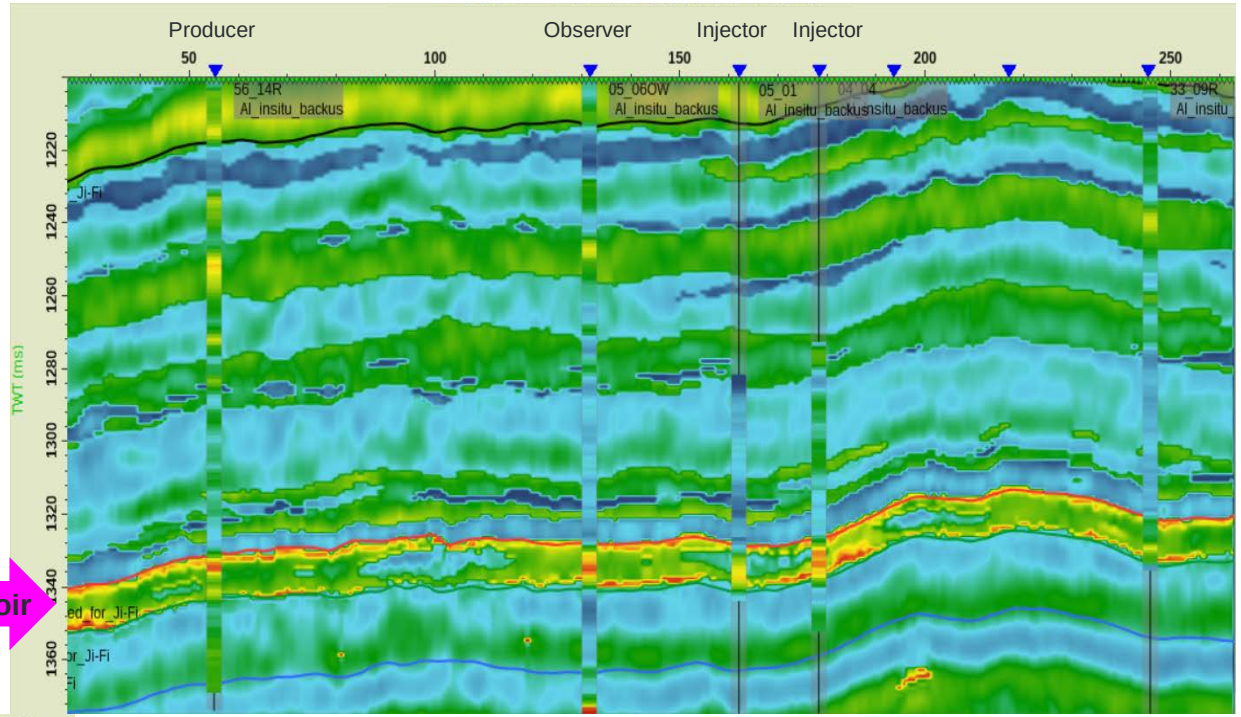
Ji-Fi: ACOUSTIC IMPEDANCE

Arbitrary Line



Before CO_2 Injection



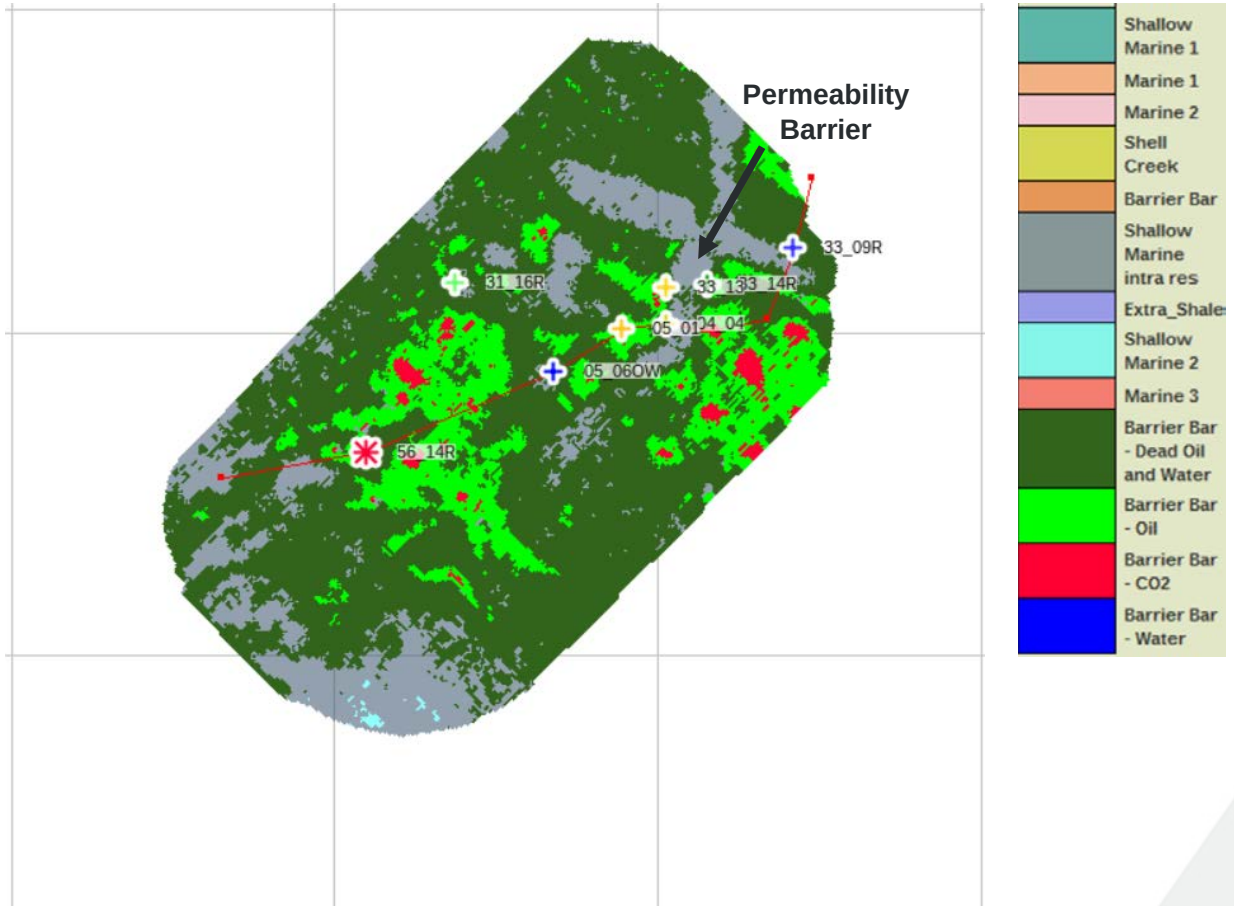


After CO_2 Injection

Ji-Fi: FACIES

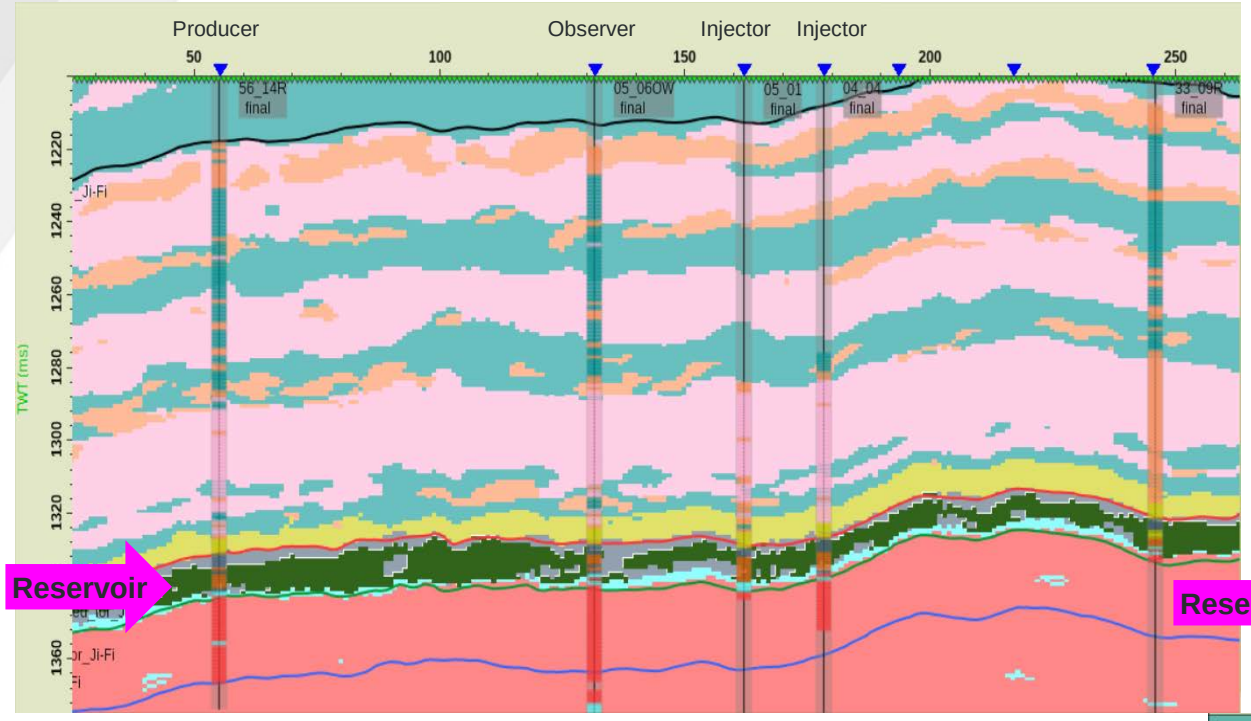
Before CO_2 Injection

After CO_2 Injection



Ji-Fi: FACIES

Arbitrary Line



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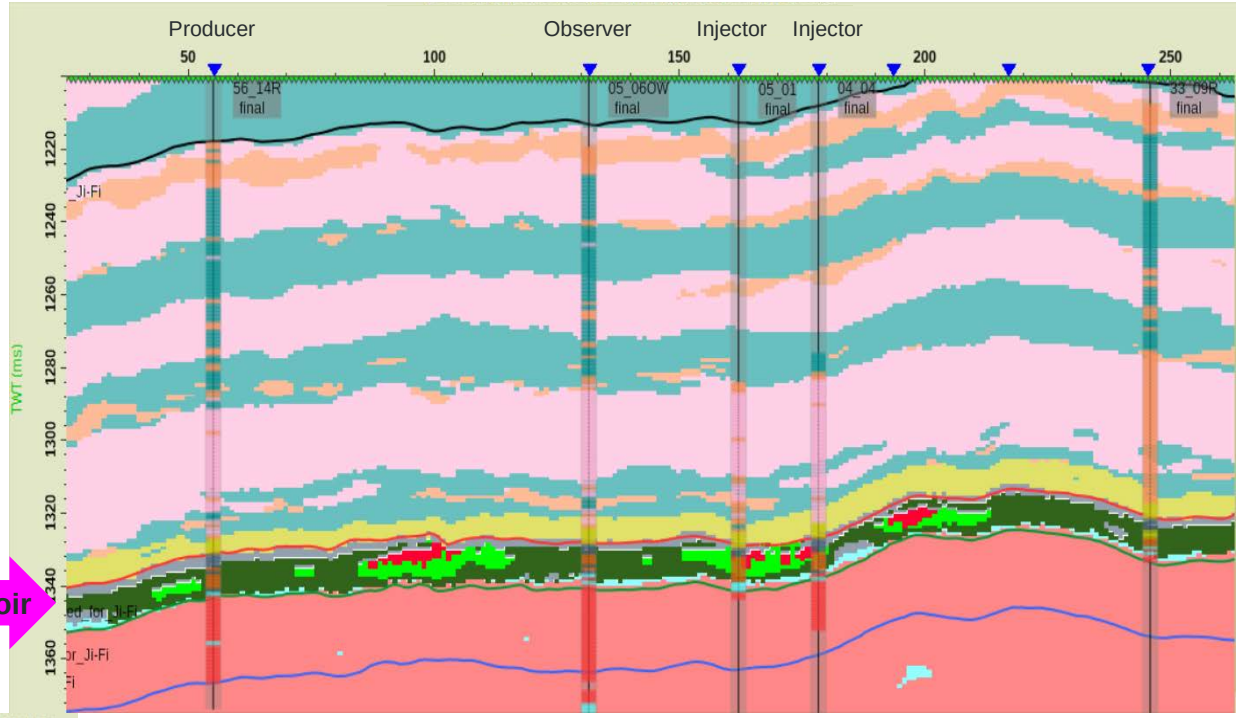
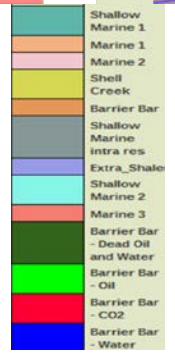
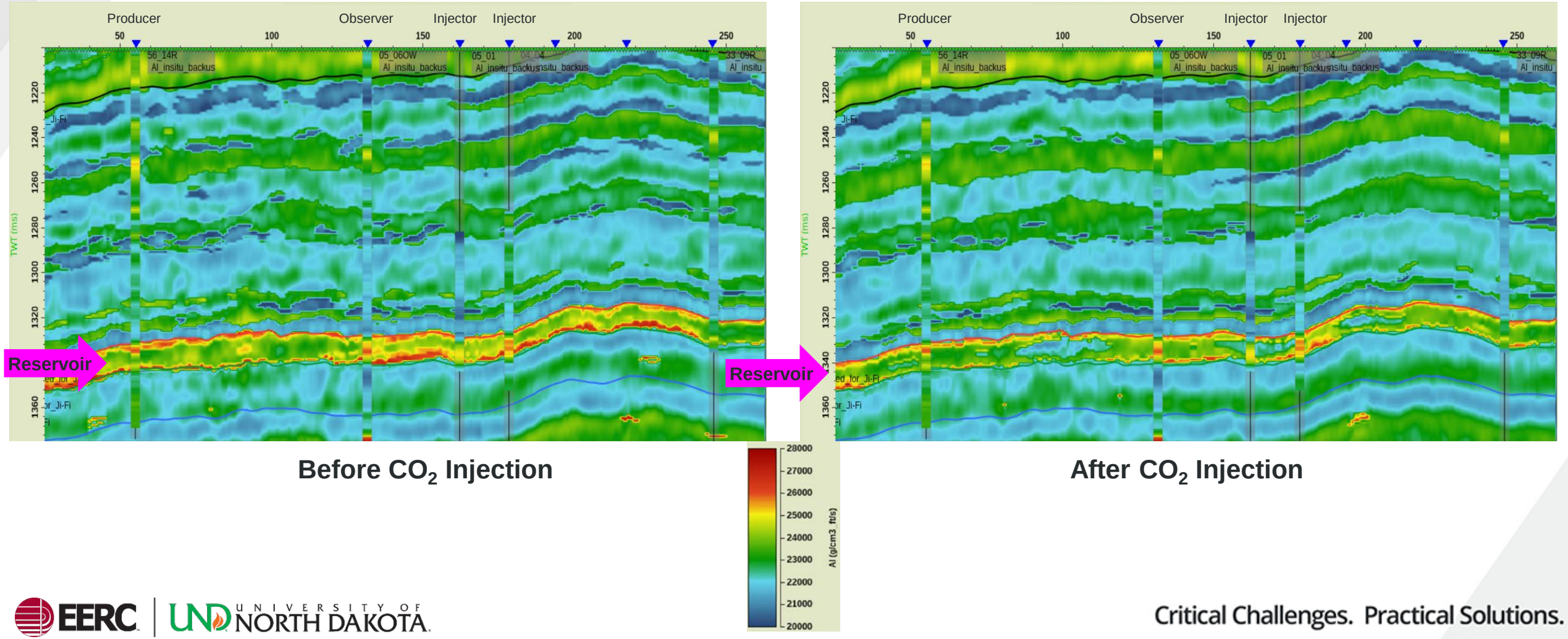


After CO_2 Injection



Ji-Fi: ACOUSTIC IMPEDANCE

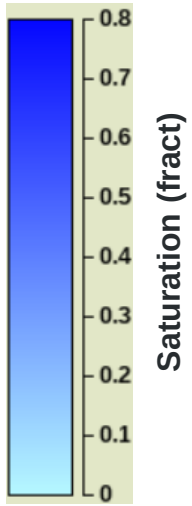
Arbitrary Line



Before CO_2 Injection

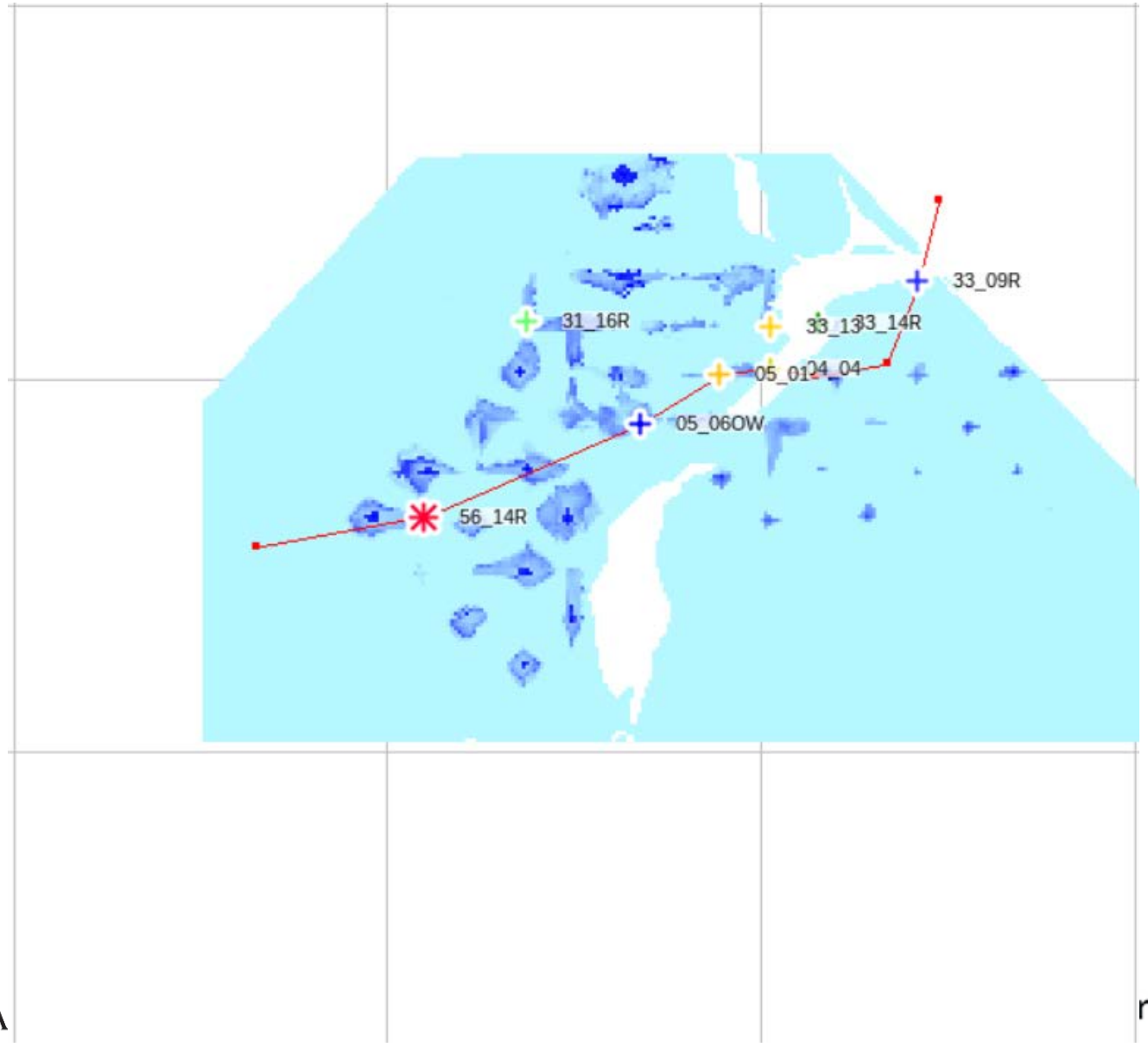
After CO_2 Injection

GAS SATURATION (RESERVOIR SIMULATION)



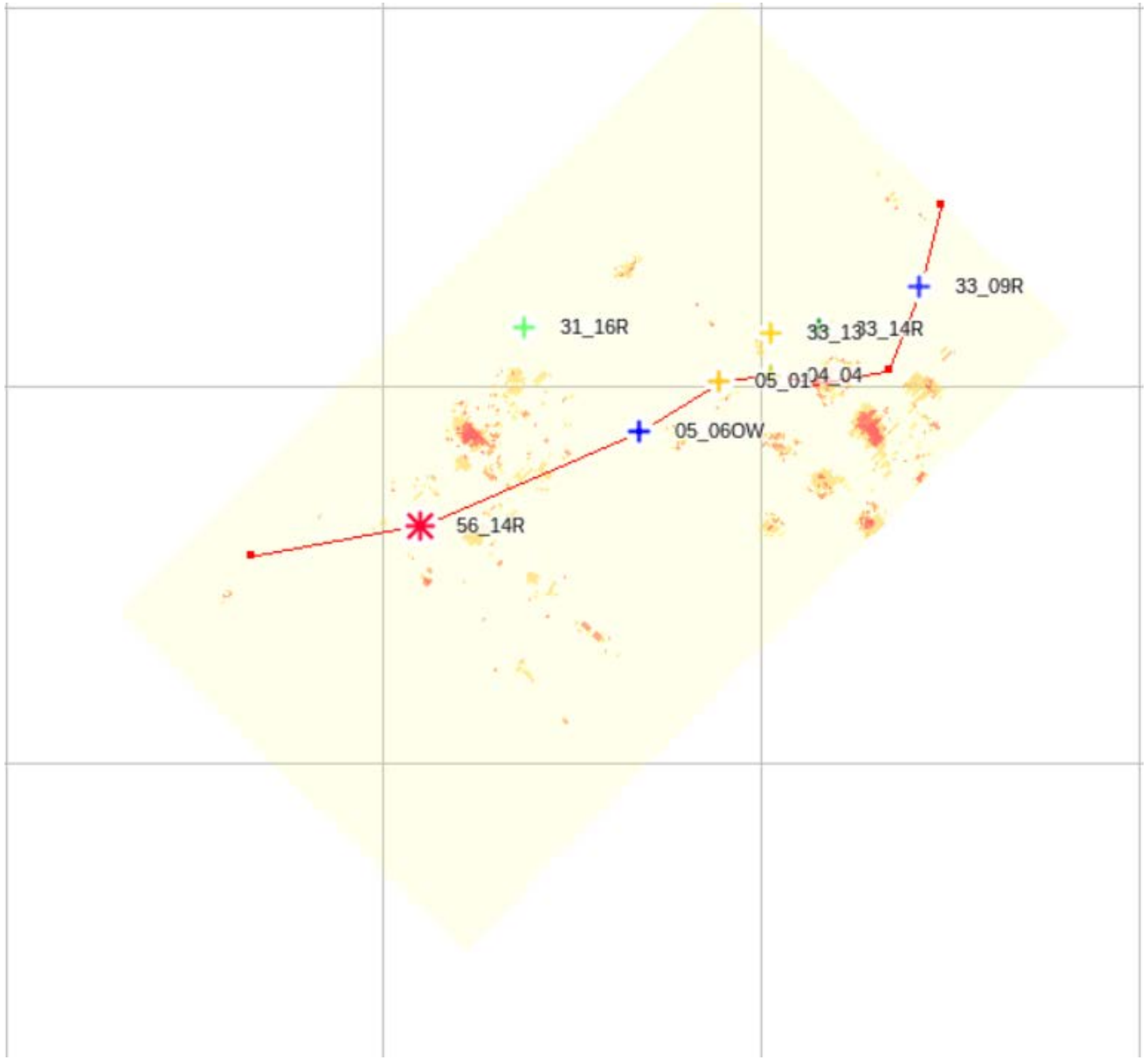
Reservoir Simulation

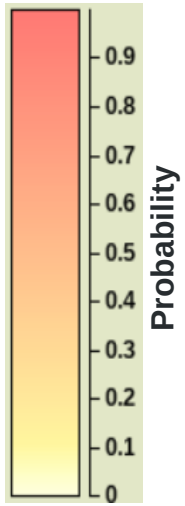
October 2014



Ji-Fi

Probabilities of Free CO_2 Distribution

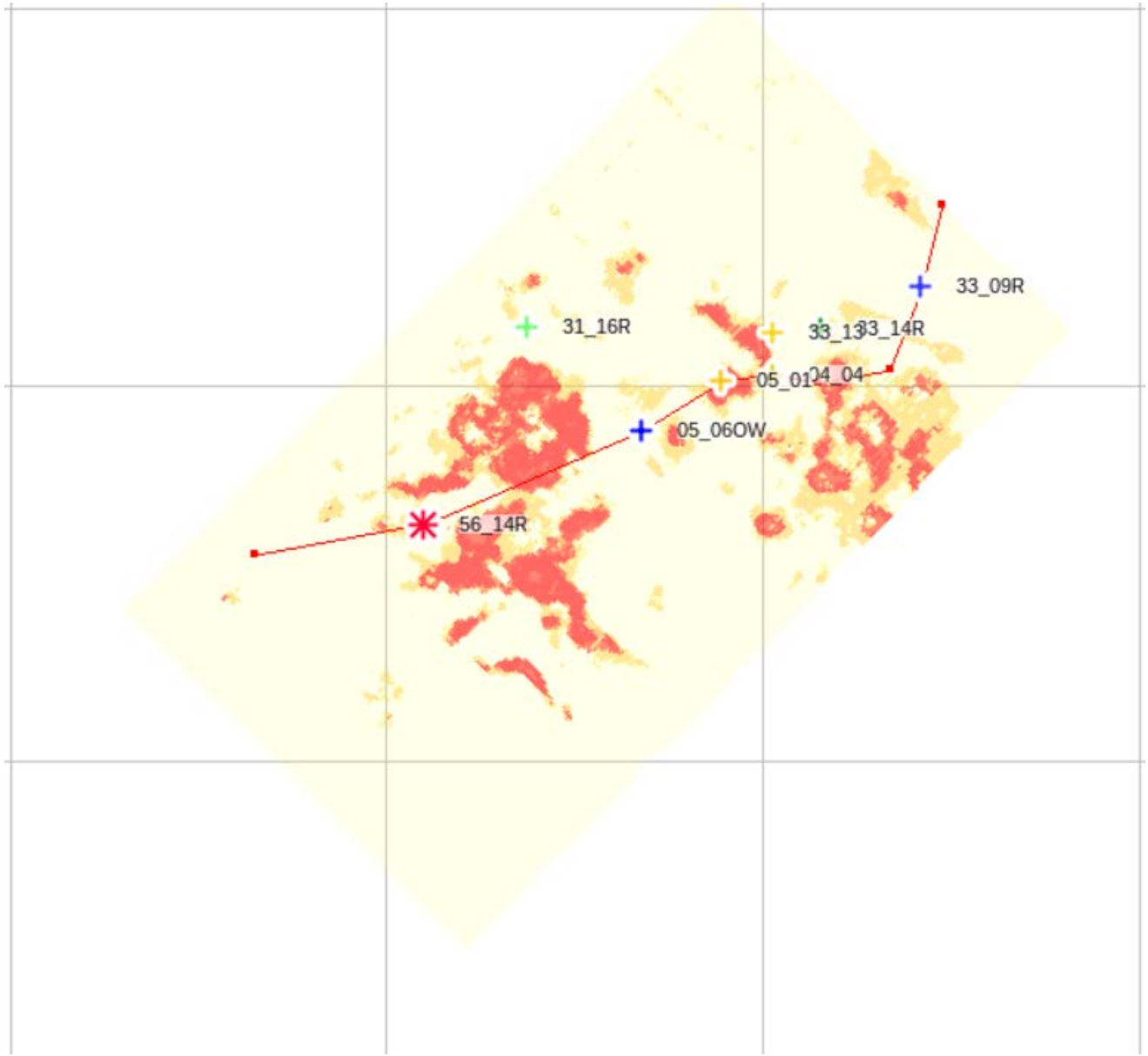


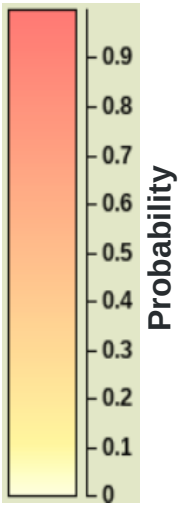


Ji-Fi

Ji-Fi

Probabilities of Oil Saturated with CO_2 Distribution

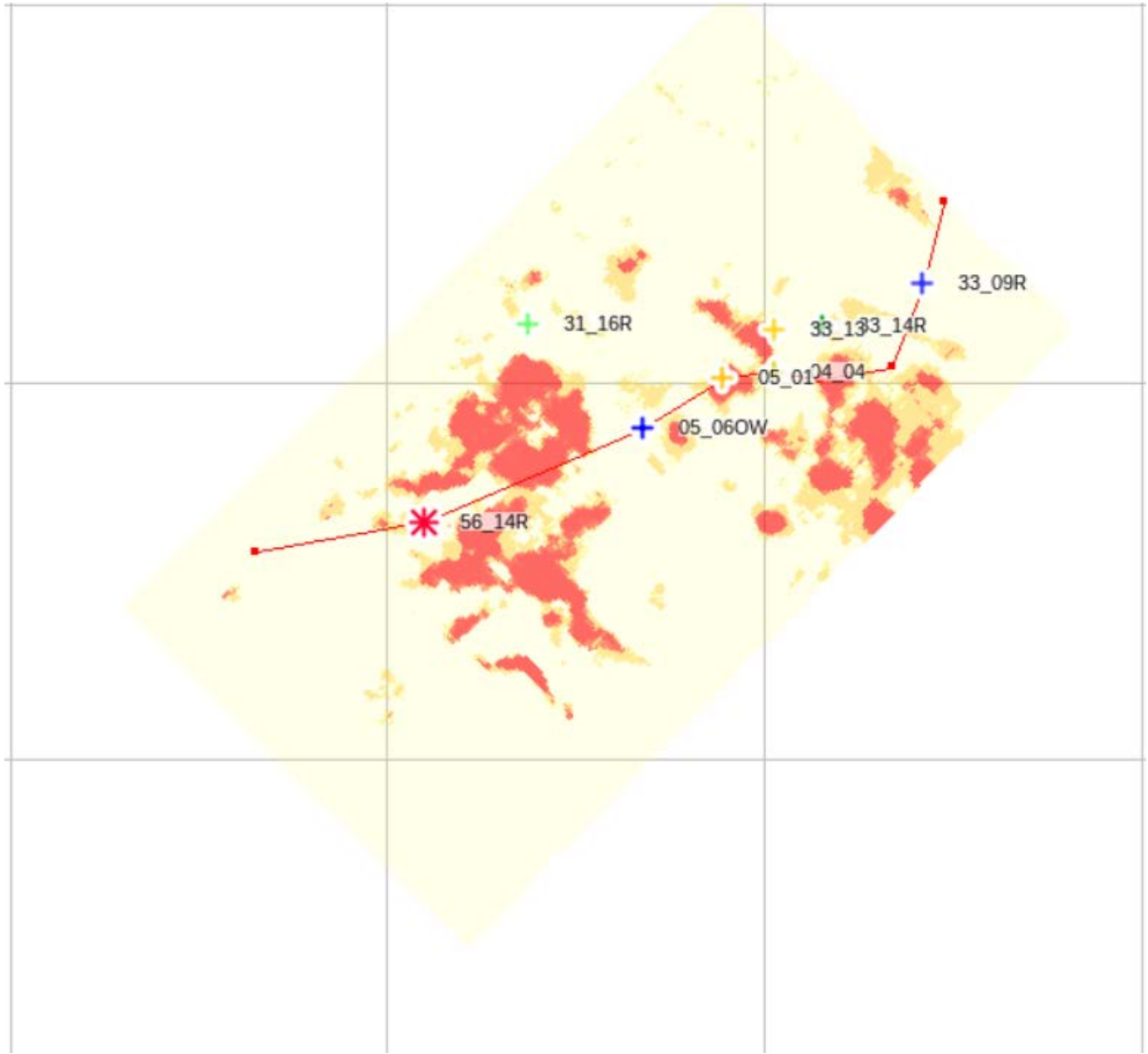


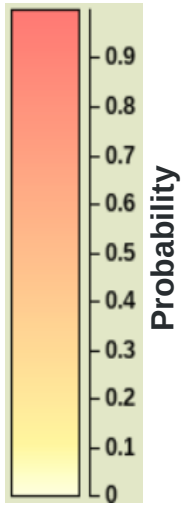


Ji-Fi

Ji-Fi

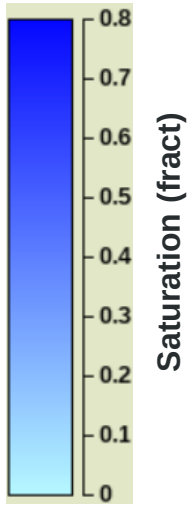
Probabilities of Free CO_2 and Oil Saturated with CO_2 Distribution





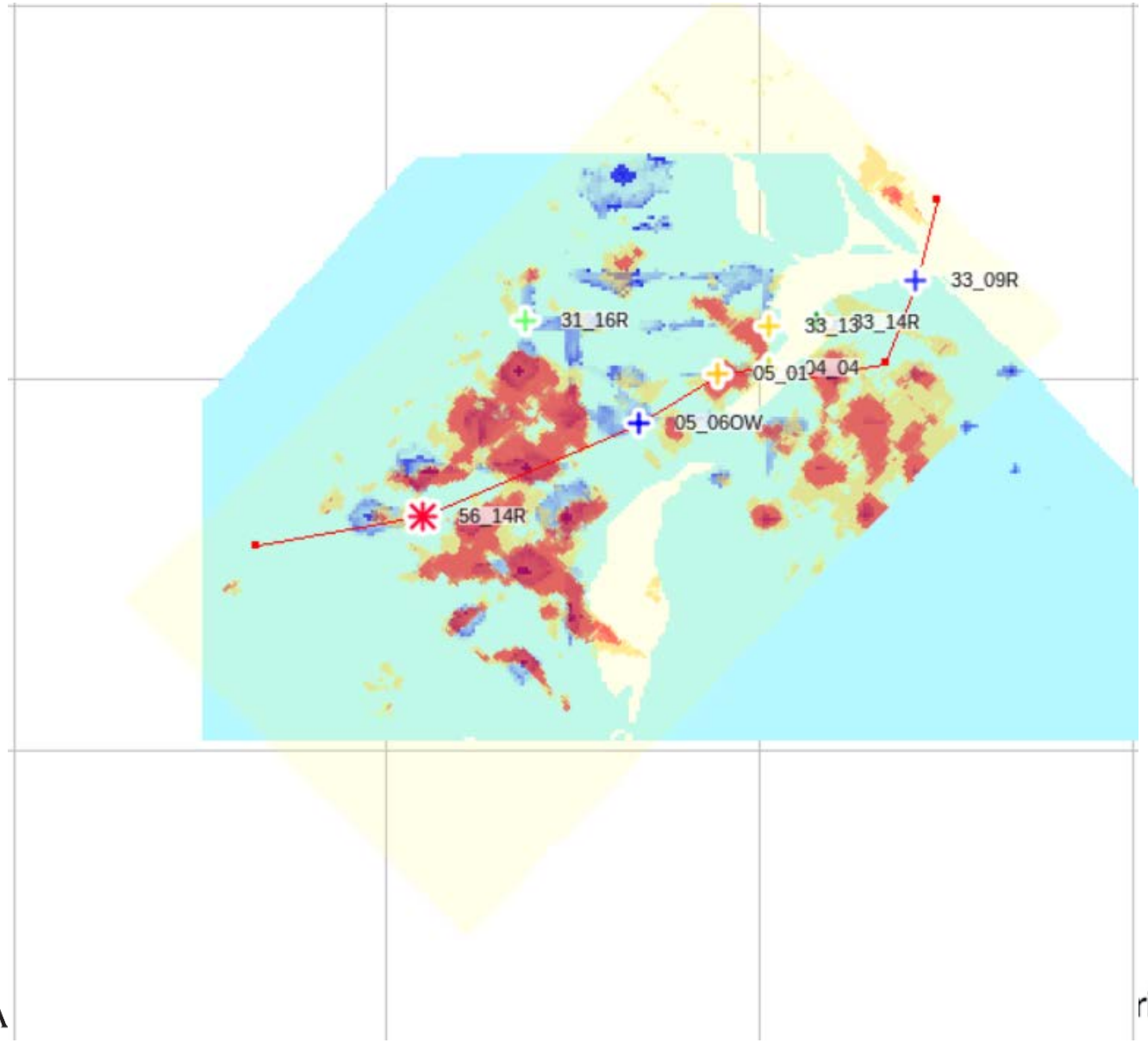
Ji-Fi

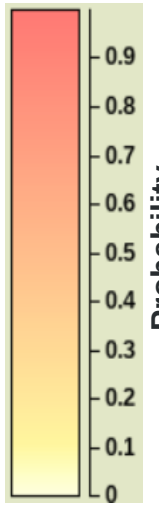
RESERVOIR SIMULATION vs. Ji-Fi



Reservoir Simulation

October 2014





Ji-Fi

ACCOMPLISHMENTS TO DATE

- Two workflows have been developed to estimate reservoir properties from time-lapse seismic inverted parameters that improve the certainty about the position of the CO_2 plume over time.
  - WEB-AVO
    - A new simultaneous time-lapse joint inversion algorithm was developed for this project and successfully applied to our data set.
  - Ji-Fi
    - Highly heterogeneous reservoir has been satisfactorily mapped to lithological and litho-fluid facies.
    - Capability to quantify uncertainty detecting CO_2 distributions.

ACCOMPLISHMENTS TO DATE

- First validations of shear compliance as indicator of pressure effect and saturation distributions based on reservoir simulations.
- Extended abstract (Society of Exploration Geophysicists)
  - Simultaneous time-lapse WEB-AVO inversion for seismic reservoir monitoring: Application to CO_2 enhanced oil recovery at the Bell Creek oil field.

LESSONS LEARNED

- Land seismic data present more challenges than marine data.
- A multidisciplinary approach is required from the beginning of the project.
- WEB-AVO
  - Several test iterations are required to optimize the performance of a new algorithm.
  - Intensive data analysis is necessary when changing dimensionality (2-D to 3-D) of the problem.
- Ji-Fi
  - More details of the geological heterogeneity of the studied reservoir.

SYNERGY OPPORTUNITIES

- Any CO_2 storage project with conventional time-lapse seismic data
- Any project that requires reservoir characterization
- Joint inversion projects with conventional surface seismic and controlled source electromagnetic data

PROJECT SUMMARY

- **Key findings**
  - Workflows based on different inversion schemes (WEB-AVO and Ji-Fi) can complement each other or be used individually to improve the certainty about the position of CO_2 distribution in a reservoir.
  - High sensitivity to compressibility and good quality of data to estimate a parameter sensitive to pressure (WEB-AVO-*M*).
  - A Bayesian inversion approach that implicitly includes seismic facies can be used to reduce the uncertainty in forecasting CO_2 saturation changes within the reservoir.
  - Seamless integration of inversion results to reservoir simulation to update static and dynamic reservoir models.

PROJECT SUMMARY

- **Next steps**
  - Finalize analysis and validation of inversion results.
  - Complete update of the static geologic model and dynamic simulation model.
  - Publish results of the project.
  - Final report.

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THANK YOU

Critical Challenges. Practical Solutions.

APPENDIX

BENEFITS TO THE PROGRAM

Program Goals Addressed

1. Develop methods that improve the certainty about the position of the CO_2 plume over time, within various geologic formations and depositional environments.
2. Detect stored CO_2 and assess the CO_2 plume boundaries over time.
3. Quantify the limits of detection and thresholds of uncertainty.
4. Account for the qualities of the fluids and types of storage reservoirs (formations, depositional environments, depths) during and after injection.
5. Associate the monitoring technique with plume extent and location.
6. Apply data from multiple monitoring sources. The approach employs both Bayesian techniques and joint inversion.
7. Validation is required. This will be done by using existing software historical monitoring data (a time-lapse seismic data set from 2012 and 2014).
8. Continue development of technologies that have been validated at the proof-of-concept level, or TRL3.
9. Technologies should progress through TRL4 such that components are integrated and tested in a laboratory environment to ensure that performance is consistent with updated performance attributes and requirements.
10. Supports goals 1, 2, and 4 of DOE's Carbon Storage Program goals.

Benefits Statement

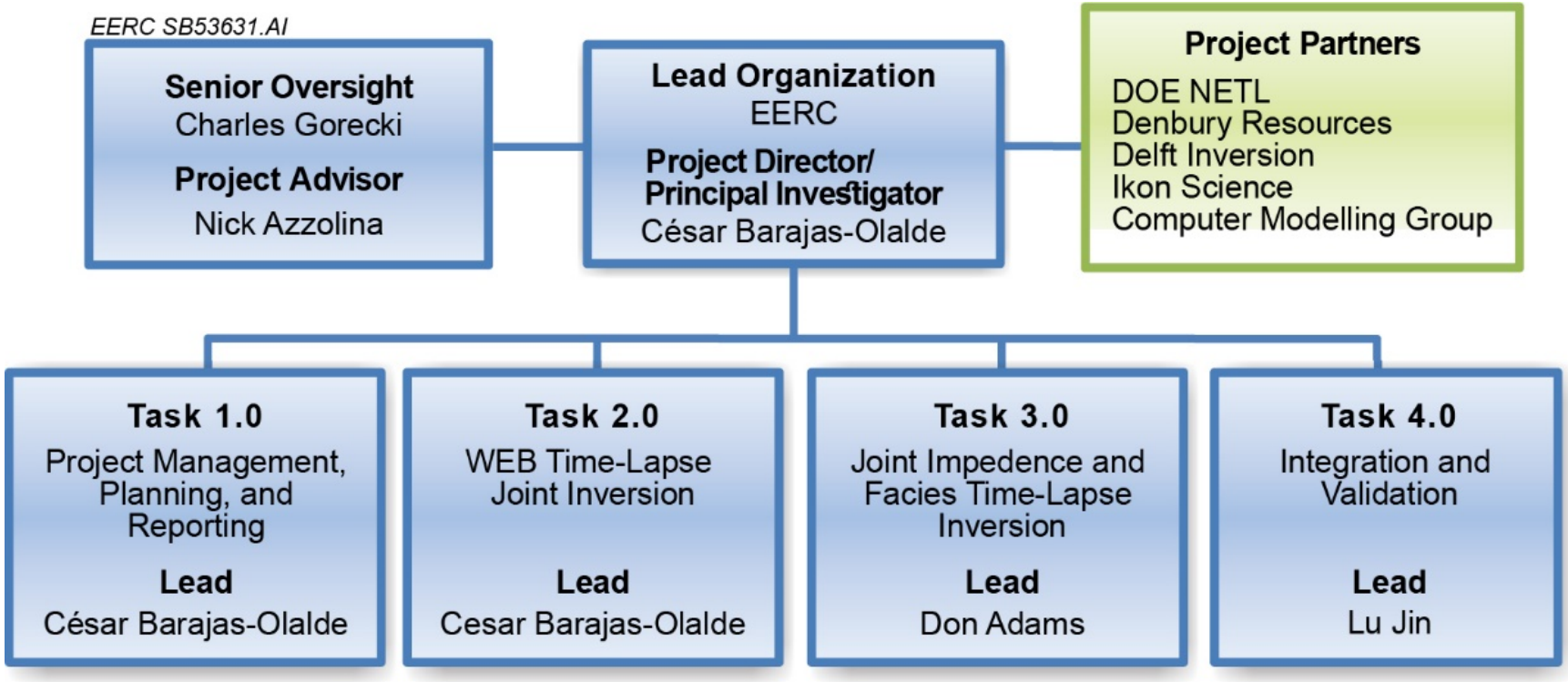
The proposed project will develop and apply new modeling and monitoring tools in the form of two promising joint inversion techniques. The tools will be applied to a time-lapse 4-D seismic data set to address and resolve shortcomings of current inversion technology and time-lapse amplitude difference interpretation. WEB time-lapse joint inversion offers the ability to separate the effects of CO_2 saturation from pressure by inverting directly for compressibility and by outputting a CO_2 saturation model in depth, which will better define the extent and position of the CO_2 saturation plume and provide an independent means of determining the mass of stored CO_2. Joint impedance and facies inversion are expected to improve the resolution of facies and their effect on the distribution of CO_2. Incorporating the inversion results into predictive simulations could lead to better understanding of the subsurface behavior, position, and boundaries of the CO_2 plume over time. The proposed research supports the DOE Carbon Storage Program's goals to 1) develop and validate technologies to ensure 99% storage permanence and 2) develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness. 3) Information produced will be useful for inclusion in DOE's Carbon Storage best practices manuals for monitoring, verification, and accounting.

PROJECT OVERVIEW – GOALS AND OBJECTIVES

- Develop a workflow to quantitatively estimate reservoir properties and the amount of CO_2 stored in the reservoir from time-lapse seismic inverted parameters, calibrated and validated with a rock physics model and geologic information.
- Reduce the uncertainty in detecting and assessing the location of the CO_2 plume boundaries using Bayesian techniques in the joint inversion of seismic parameters and sedimentary facies.
- Validate by comparing the results to conventional inversion and previous qualitative reservoir characterization.
- Use the results from (1) and (2) to update the static geologic model and dynamic simulation model.

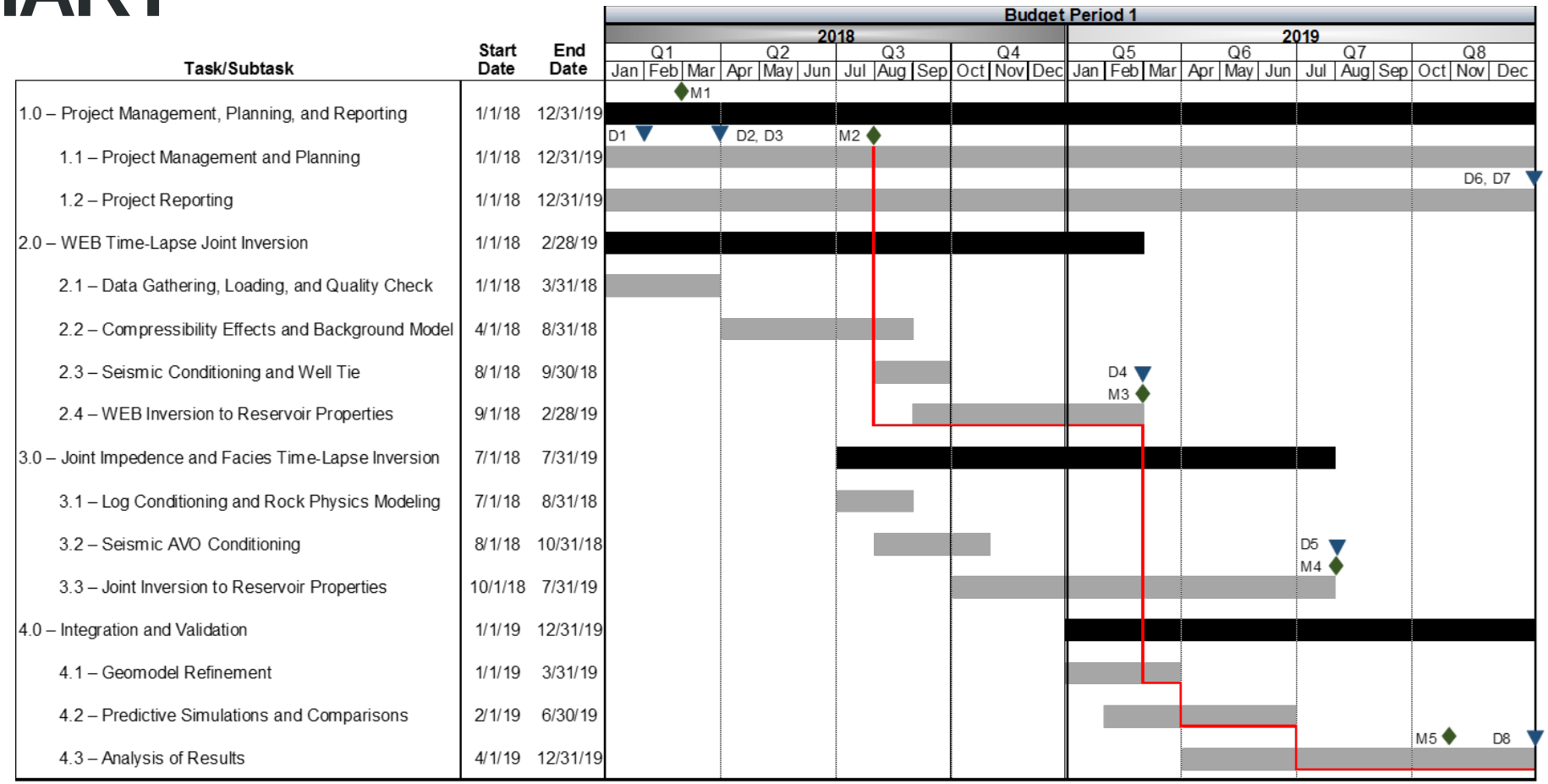
- Anticipated Outcome: Advancement of state-of-the-art CO_2 monitoring methods from the current TRL3 to TRL4.

ORGANIZATION CHART



GANTT CHART

2-year Project
One Budget Period



BIBLIOGRAPHY

- Peer-reviewed publications generated from the project:

  - Barajas-Olalde, C., Haffinger, P., Gisolf, D., Zhang, M., Droujinina, A., Doulgeris, P., Khatibi, S., Jin, L., Burnison, S.A., Hamling, J.A., and Gorecki, C.D., 2019, Simultaneous time-lapse WEB-AVO inversion for seismic reservoir monitoring: Application to CO_2 enhanced oil recovery at the Bell Creek oil field. SEG Annual International Meeting, Expanded Abstracts, p. 564–568.

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