
EERC
UNIVERSITY OF NORTH DAKOTA
Critical Challenges. Practical Solutions.

Energy & Environmental Research Center (EERC)

JOINT INVERSION OF TIME-LAPSE SEISMIC DATA

DE-FOA0001725

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National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

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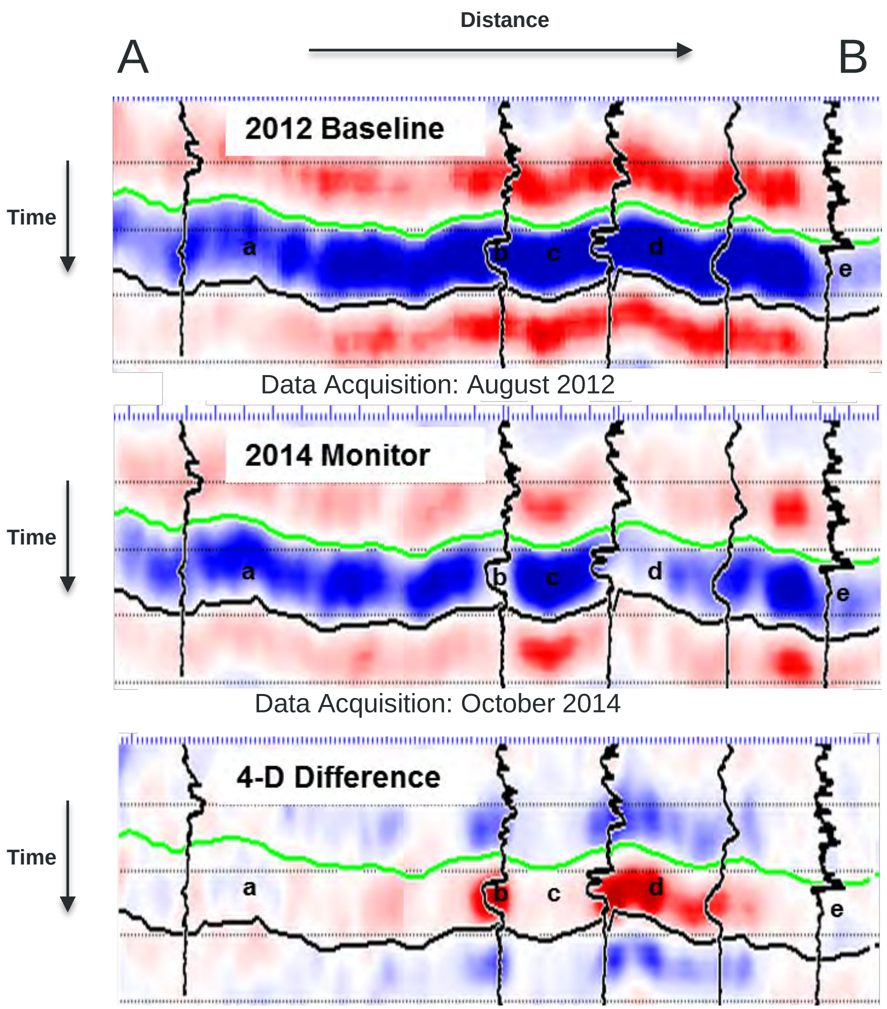
Critical Challenges. Practical Solutions.

PRESENTATION OUTLINE

- Interpretation of Time-Lapse Seismic Data
- Towards Improving the Certainty of CO_2 Plume Position with Seismic Joint Inversion
  a) Wave-Equation-Based (WEB) Amplitude-Variation-with-Offset (AVO)
     ♦ Preliminary Results: Single vs. Joint Inversion
  b) Joint Impedance and Facies Inversion
- Accomplishments
- Lessons Learned
- Synergy Opportunities
- Summary

TIME-LAPSE DIFFERENCE: SEISMIC DATA (2012–2014)

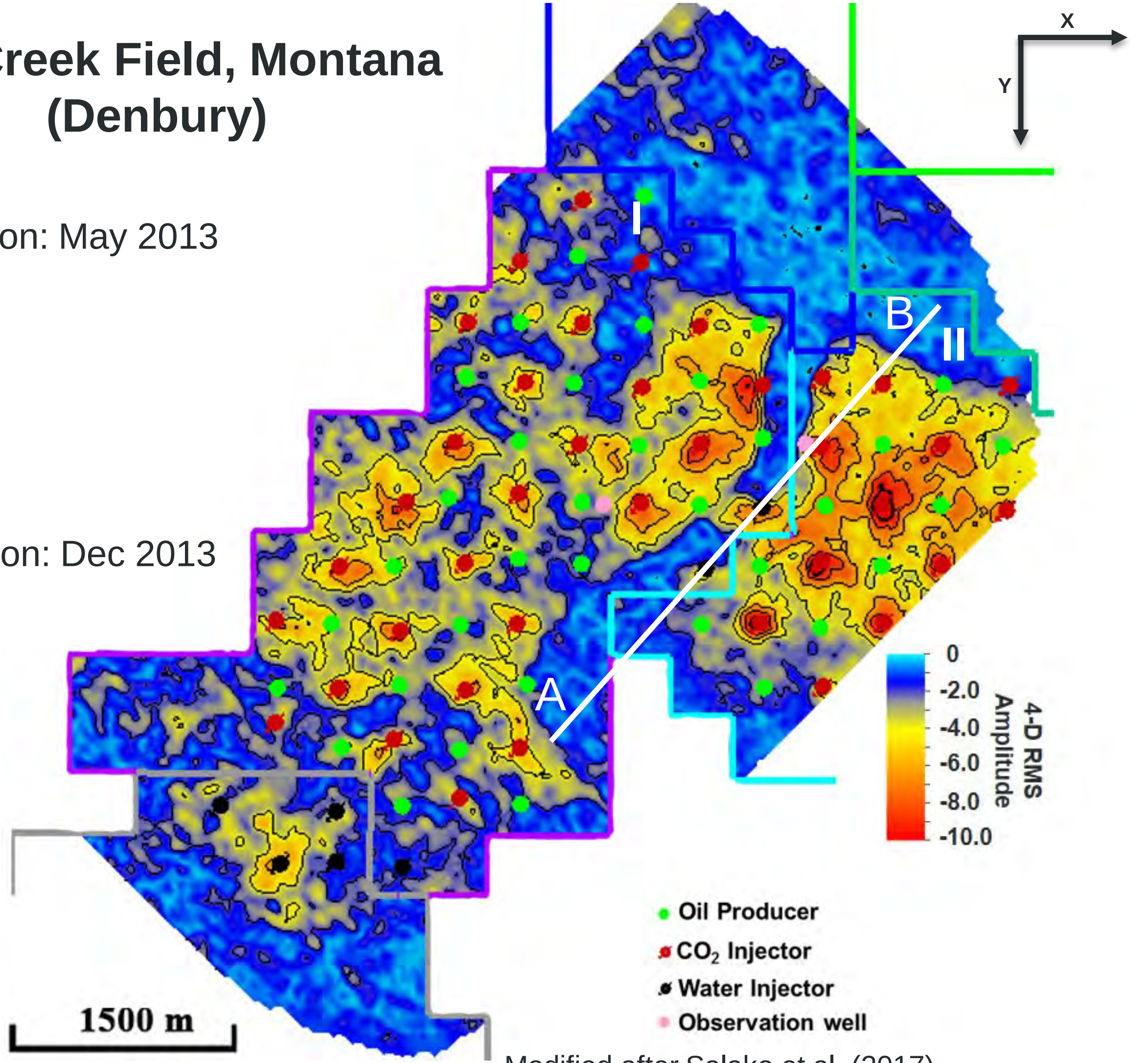


Modified after Salako et al. (2018)

Bell Creek Field, Montana (Denbury)

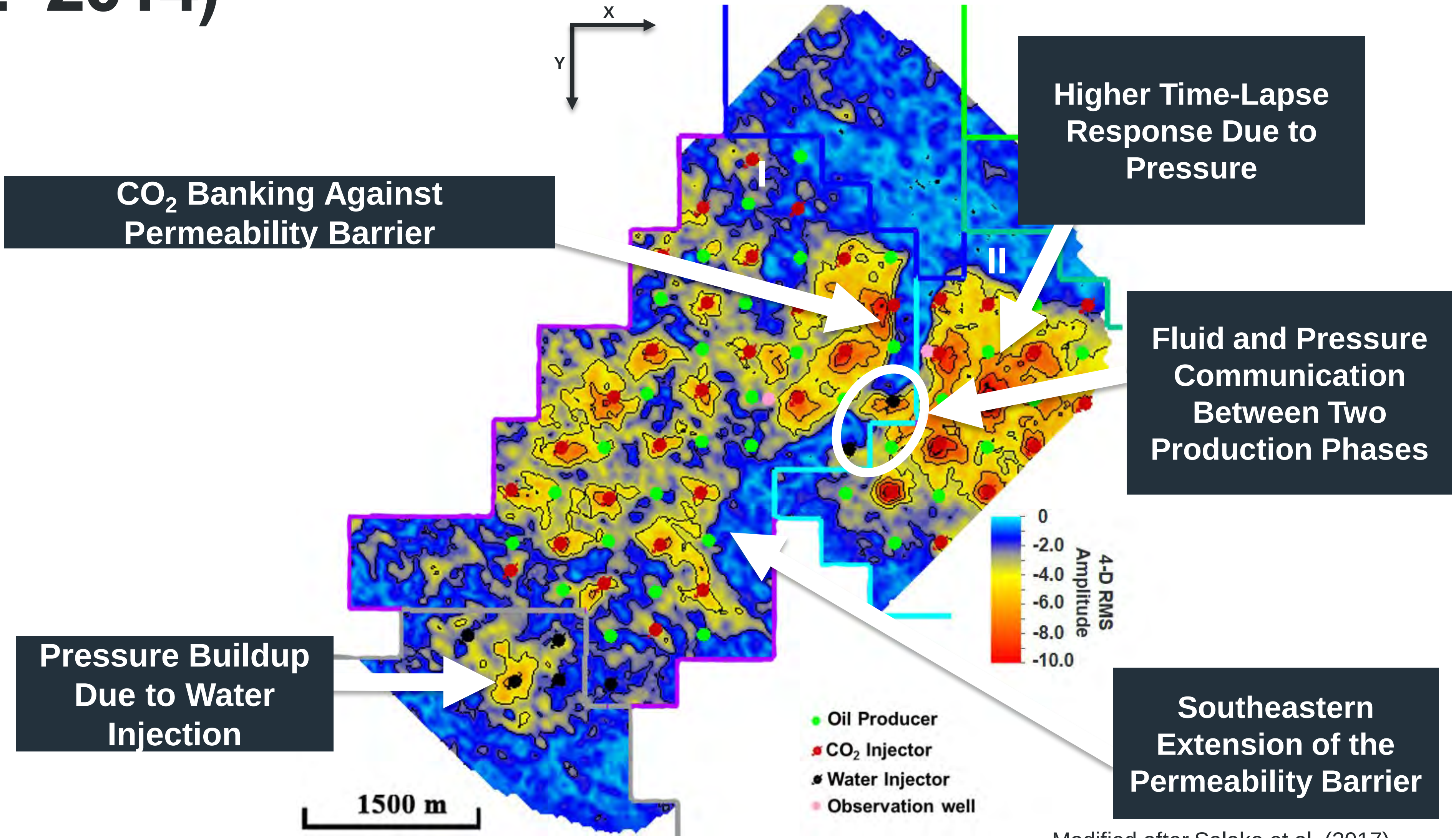
CO_2 injection: May 2013

CO_2 injection: Dec 2013



Modified after Salako et al. (2017)

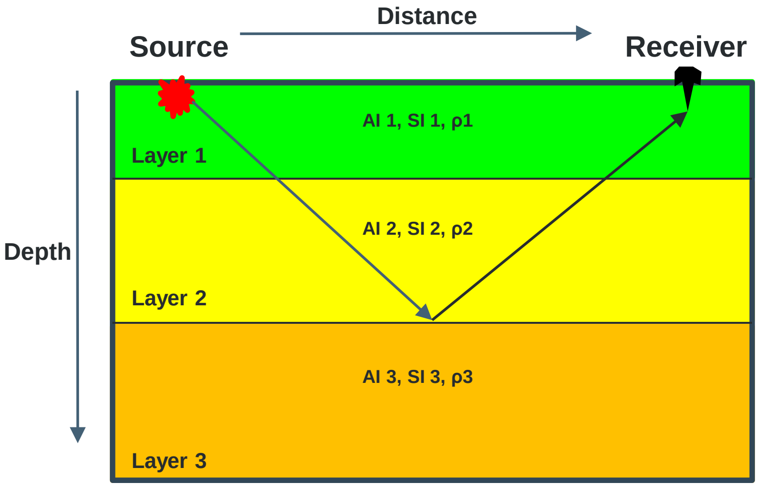
INTERPRETATION OF TIME-LAPSE SEISMIC DATA (2012–2014)



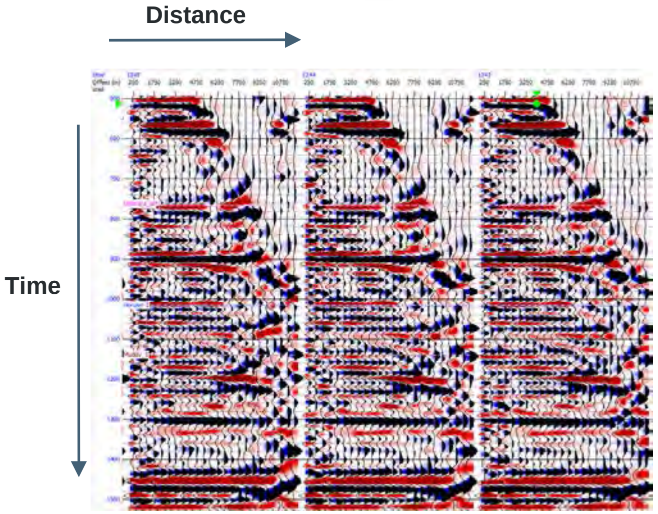
Modified after Salako et al. (2017)

SEISMIC INVERSION

Inverse Problem



ELASTIC PROPERTIES

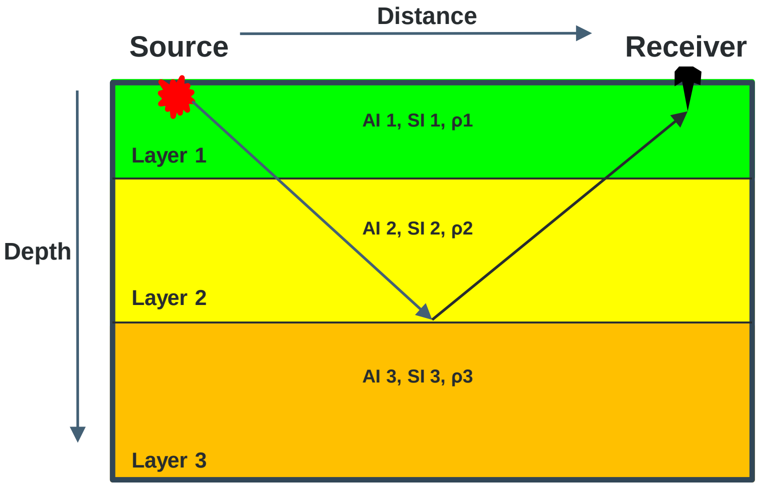


SEISMIC DATA
+ WELL LOGS + GEOLOGIC INFORMATION

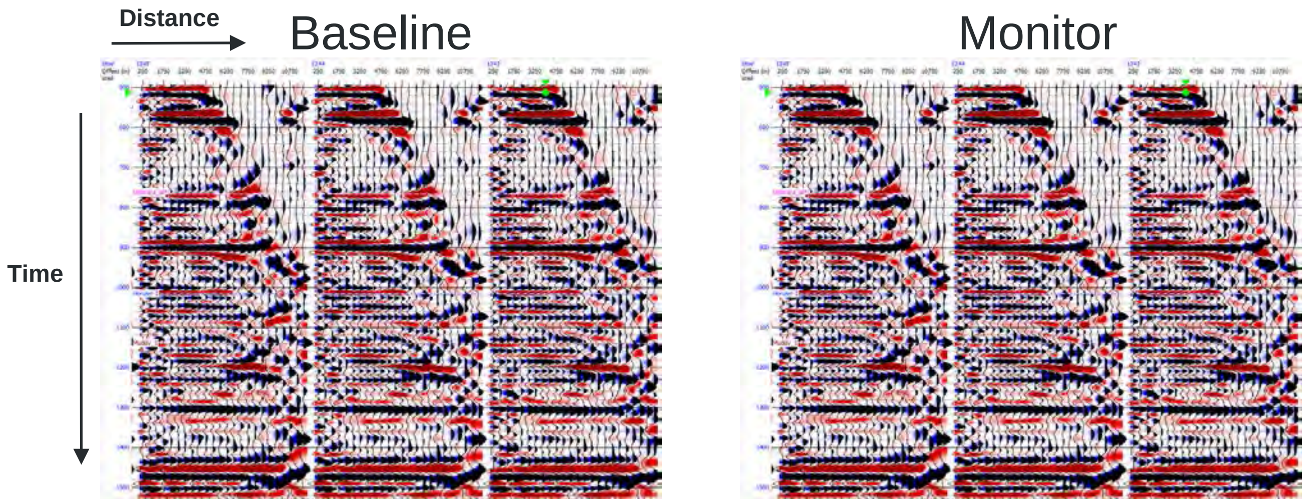
Forward Problem

JOINT INVERSION

Inverse Problem



ELASTIC
PROPERTIES

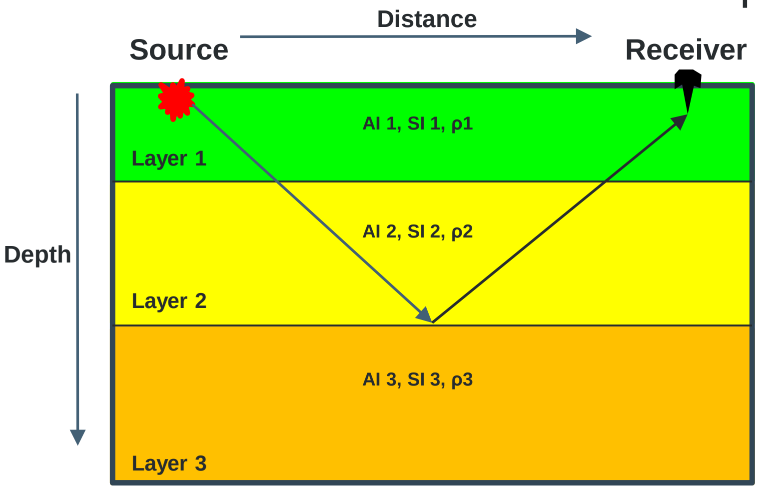


TIME-LAPSE SEISMIC DATA
+ WELL LOGS + GEOLOGIC
INFORMATION

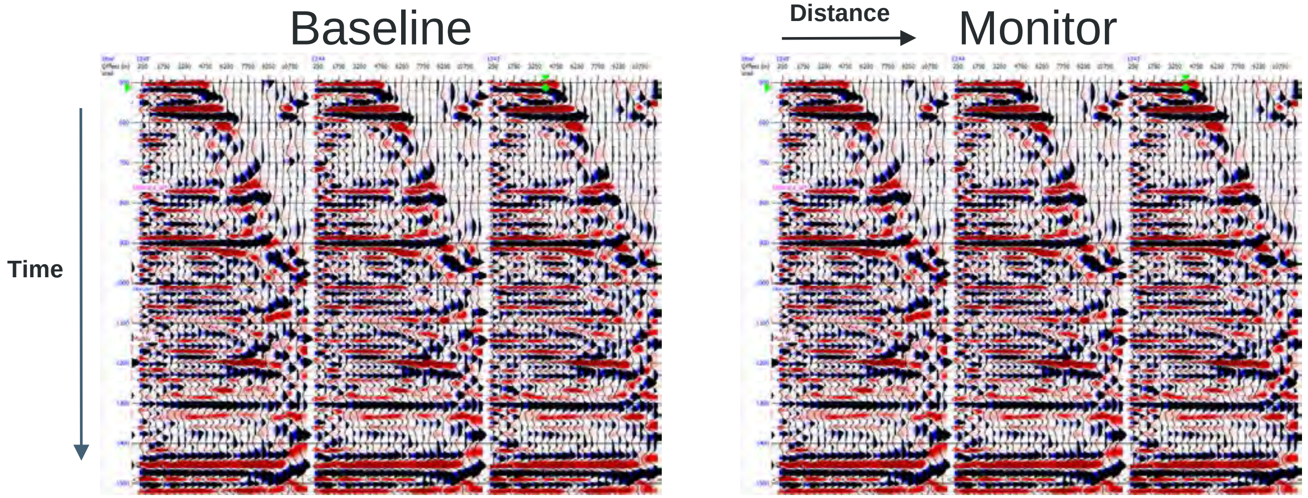
Wave-Equation-Based Amplitude-Variation-with-Offset (Delft Inversion)

Inverse Problem

Joint Impedance and Facies Inversion (Ikon Science)



ELASTIC PROPERTIES



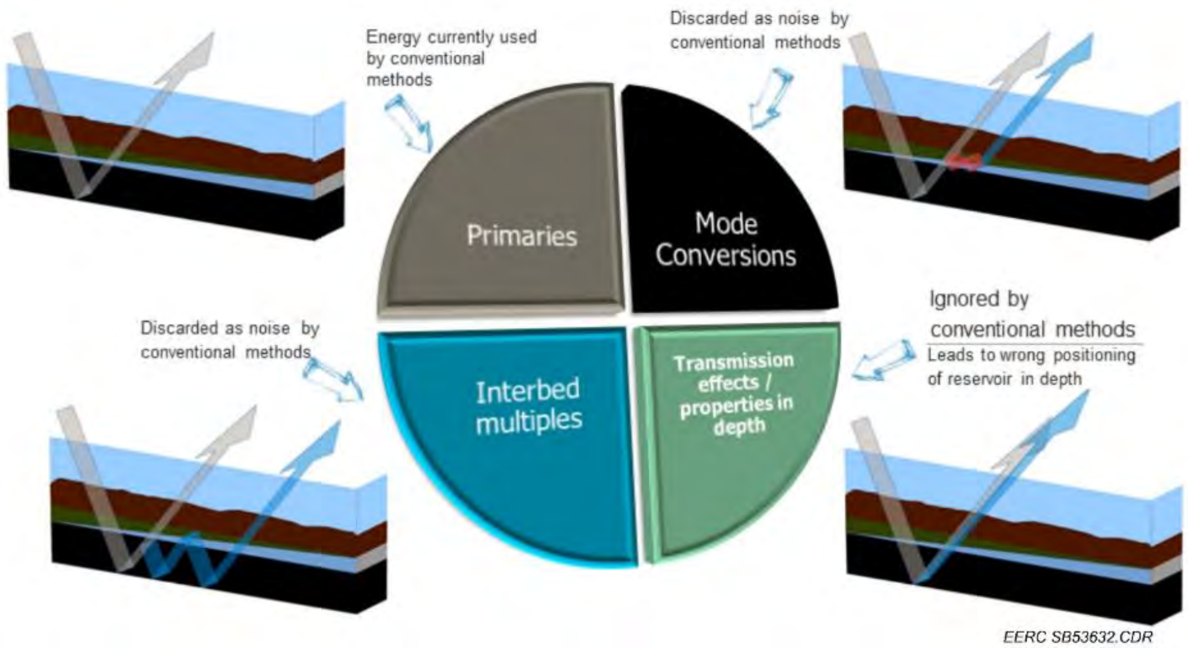
TIME-LAPSE SEISMIC DATA + WELL LOGS + GEOLOGIC INFORMATION

Rock Physics

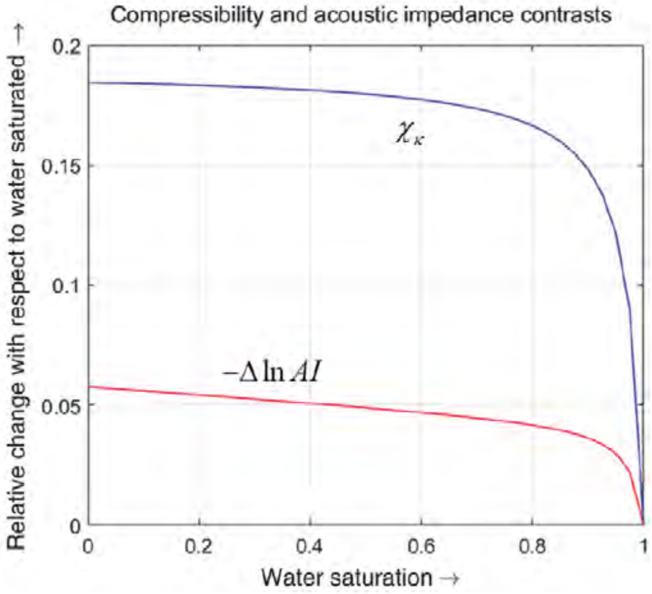
CO_2 SATURATION MODELS & AMOUNT OF STORED CO_2

WEB-AVO

- Target-oriented full-waveform elastic inversion of seismic data.
  - Wider bandwidth and less noise
- Directly inverts for compressibility (1/bulk modulus) and shear compliance (1/shear modulus).
  - More sensitivity to changes in pore fill => highly suitable for time-lapse monitoring
- Inversion of migrated data in time and output in depth.
  - Avoid prone-error postinversion depth conversions



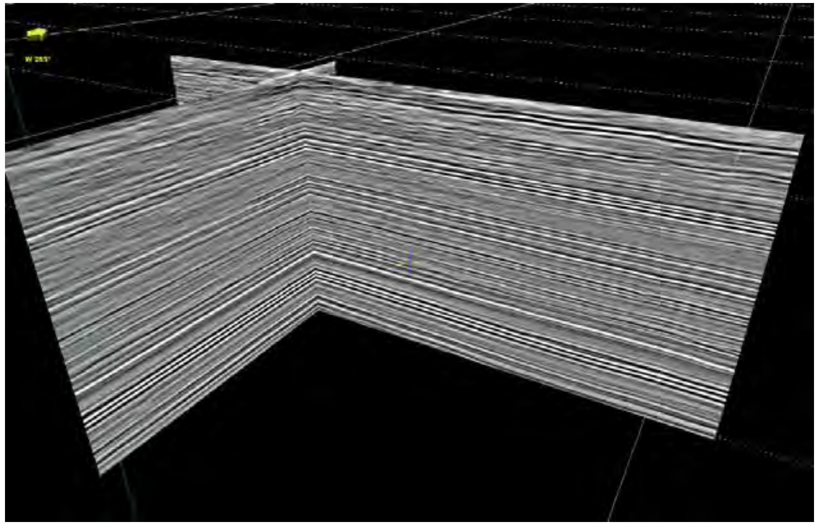
Doulgeris (2017)

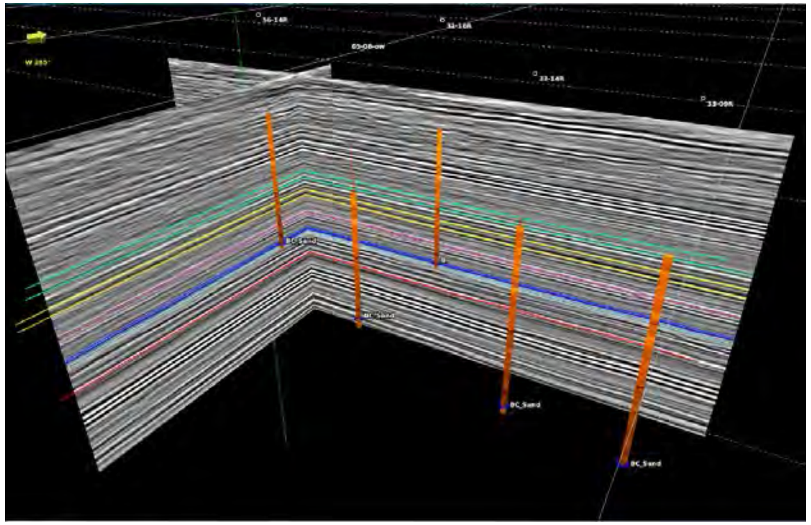


Gisolf et al. (2017)

INPUT DATA

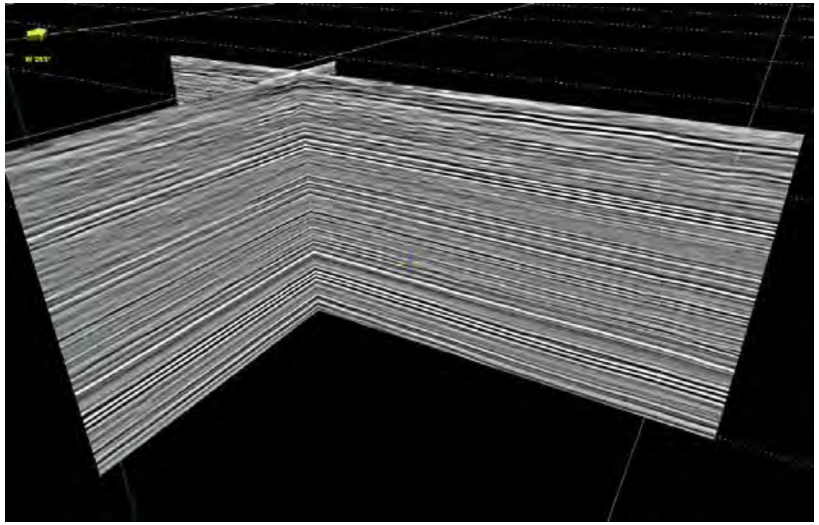
3-D
Seismic Data
Baseline
(2012)

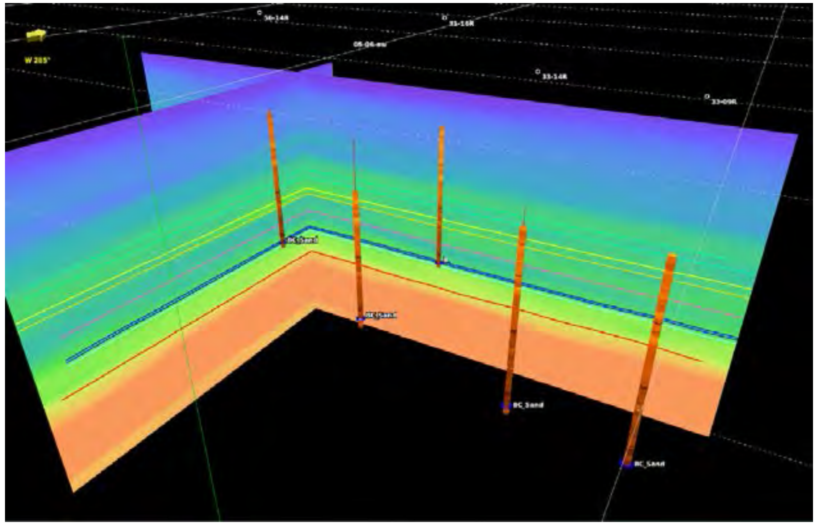




Well Logs and
Horizons

3-D
Seismic Data
Monitor
(2014)

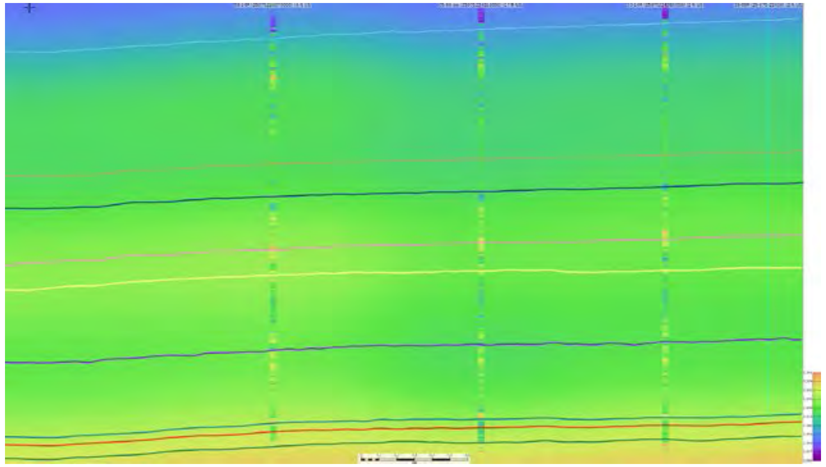




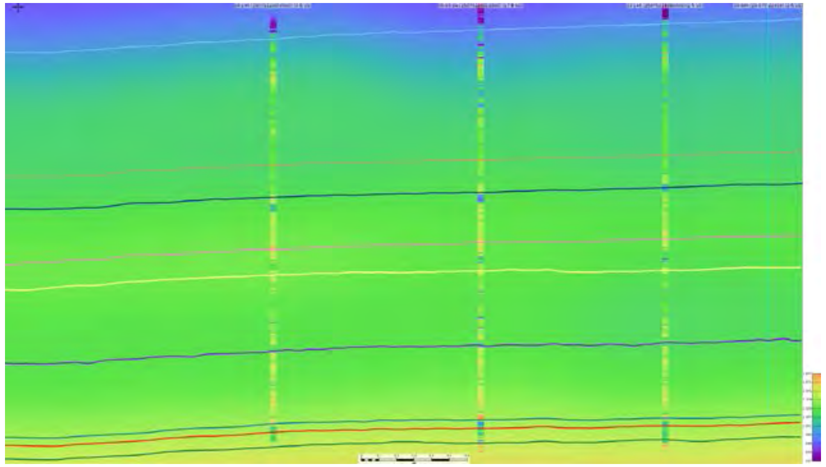
Seismic
Velocities

BACKGROUND MODEL

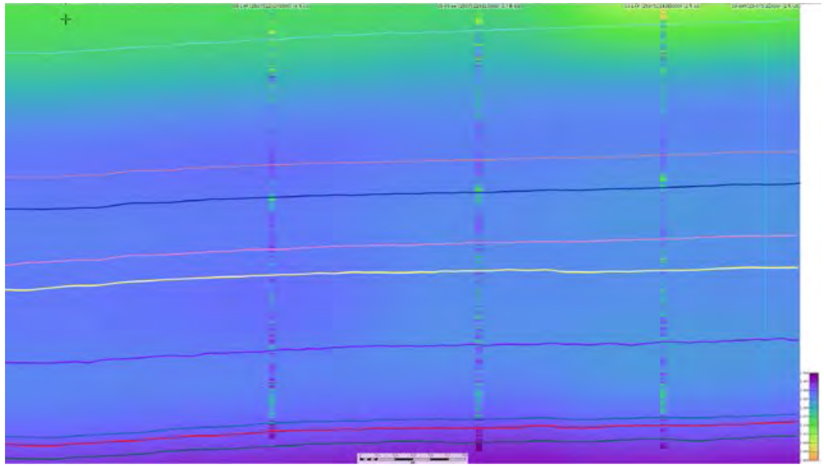
P Velocity



S Velocity

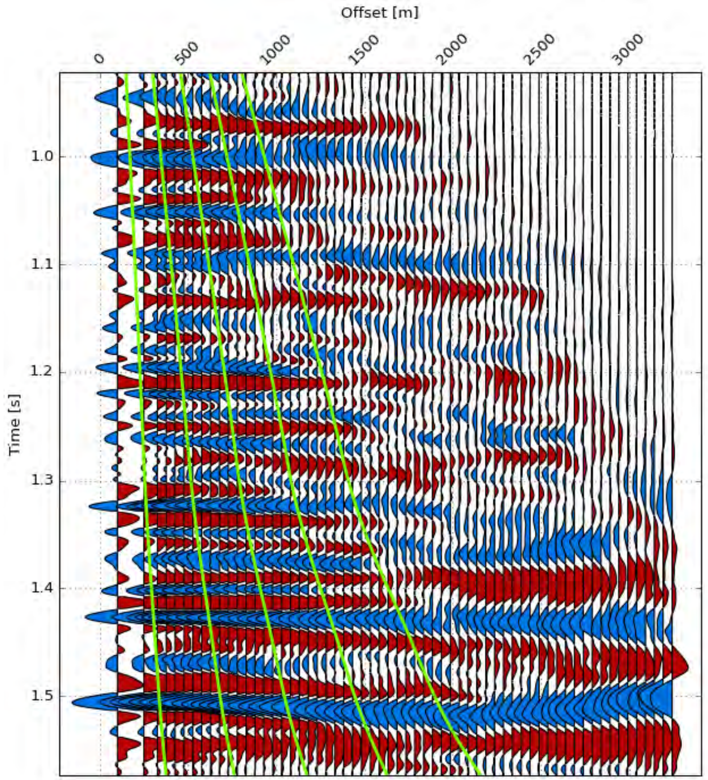


Density

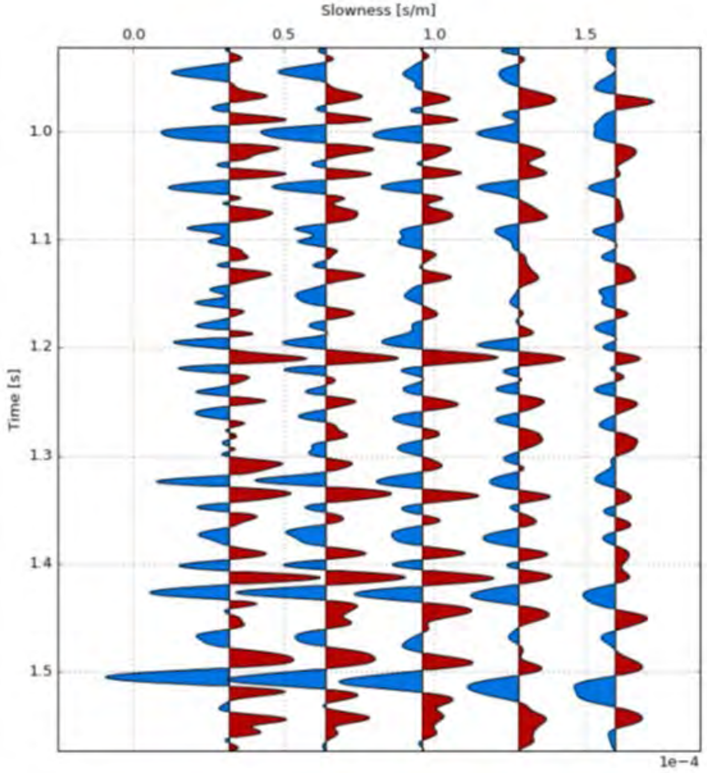


DATA PRECONDITIONING I

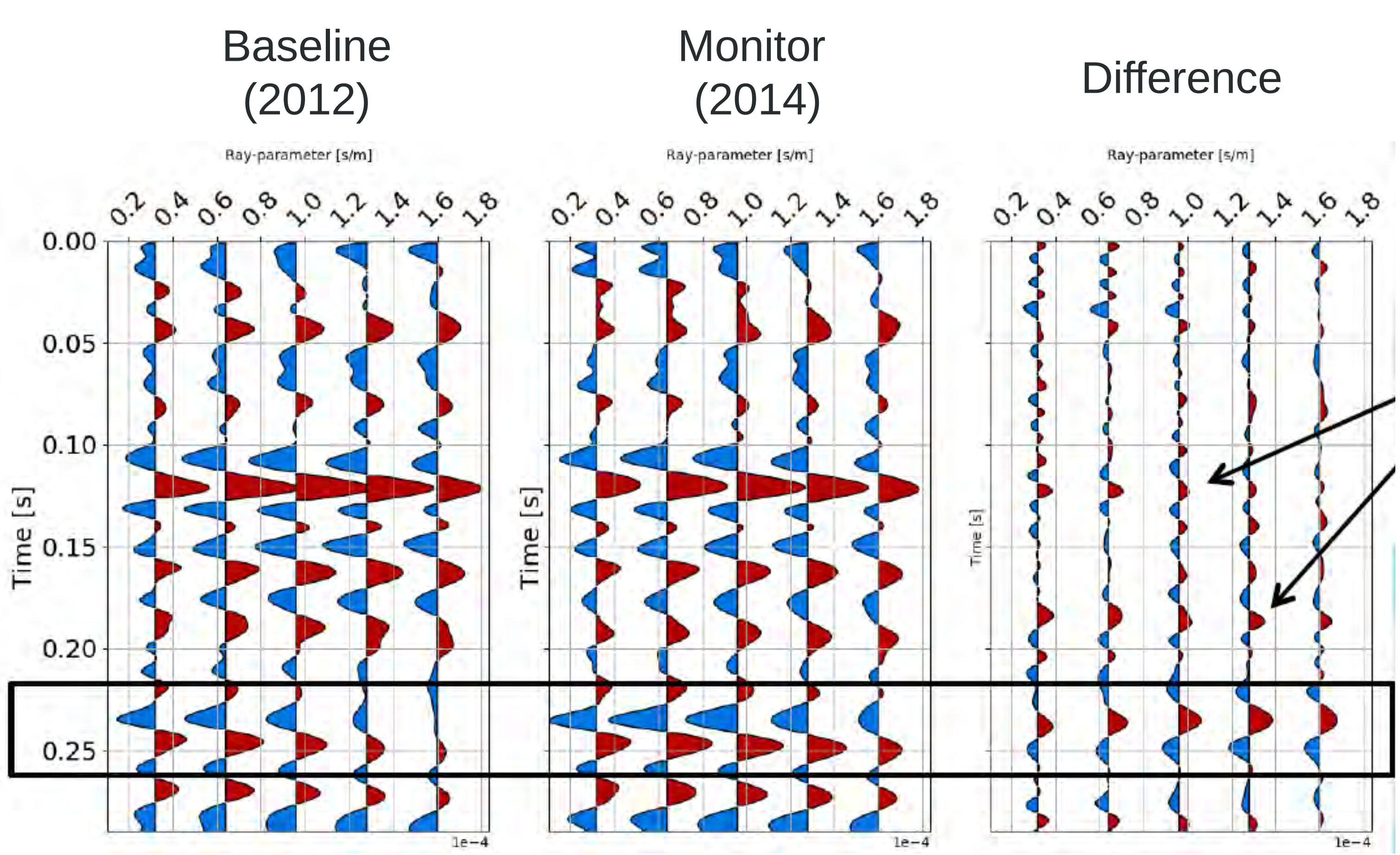
Common Offset Gather



Ray Parameter Gather



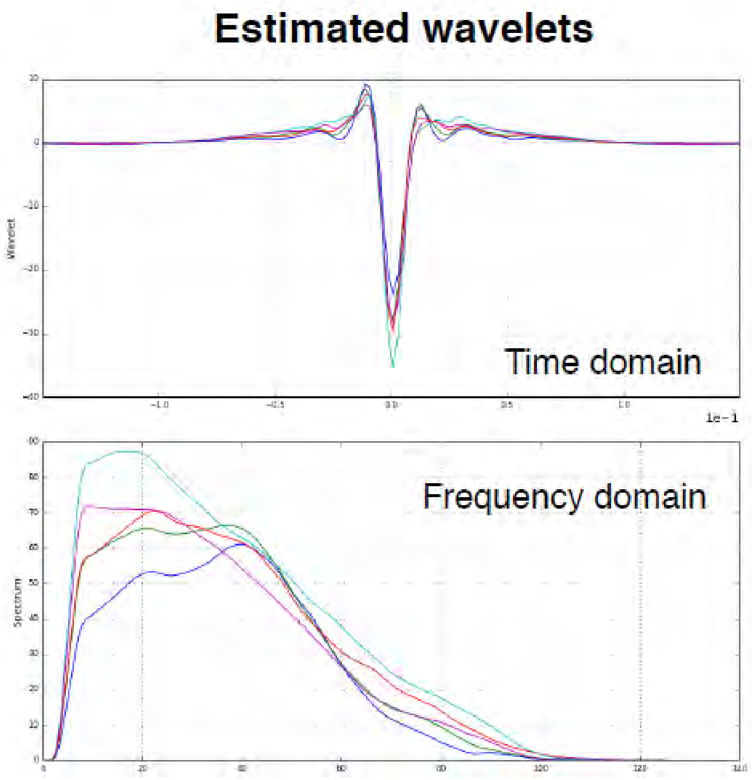
DATA PRECONDITIONING II

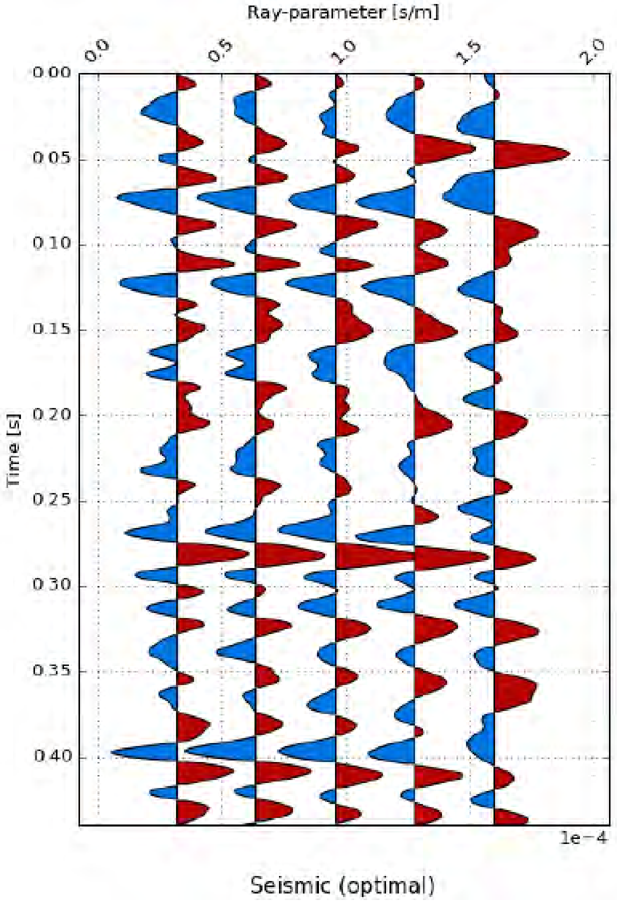


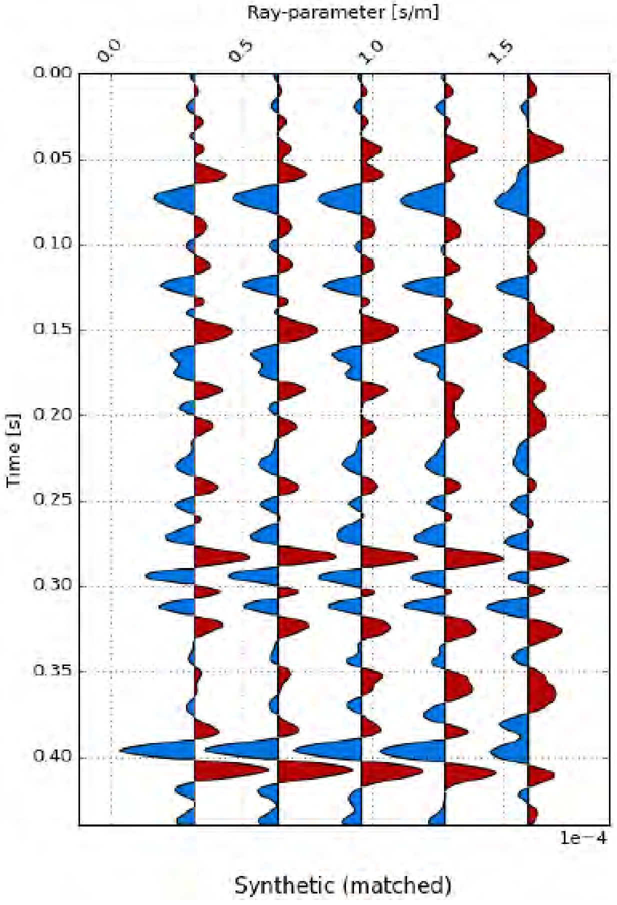
After Preconditioning

- Dip Filtering
- Offset Amplitude Balancing

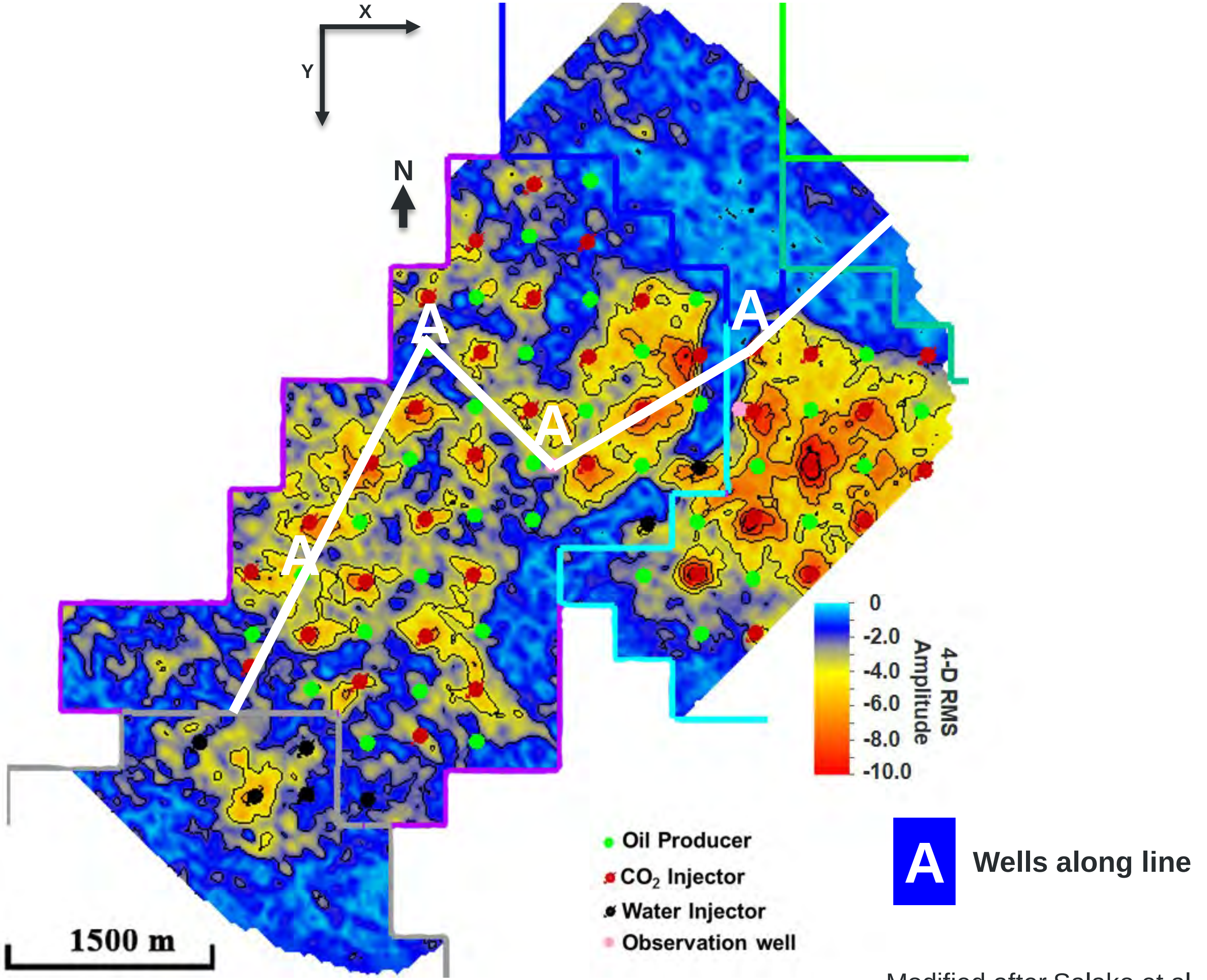
WAVELET ESTIMATION FROM SEISMIC-TO-WELL TIE – EXAMPLE





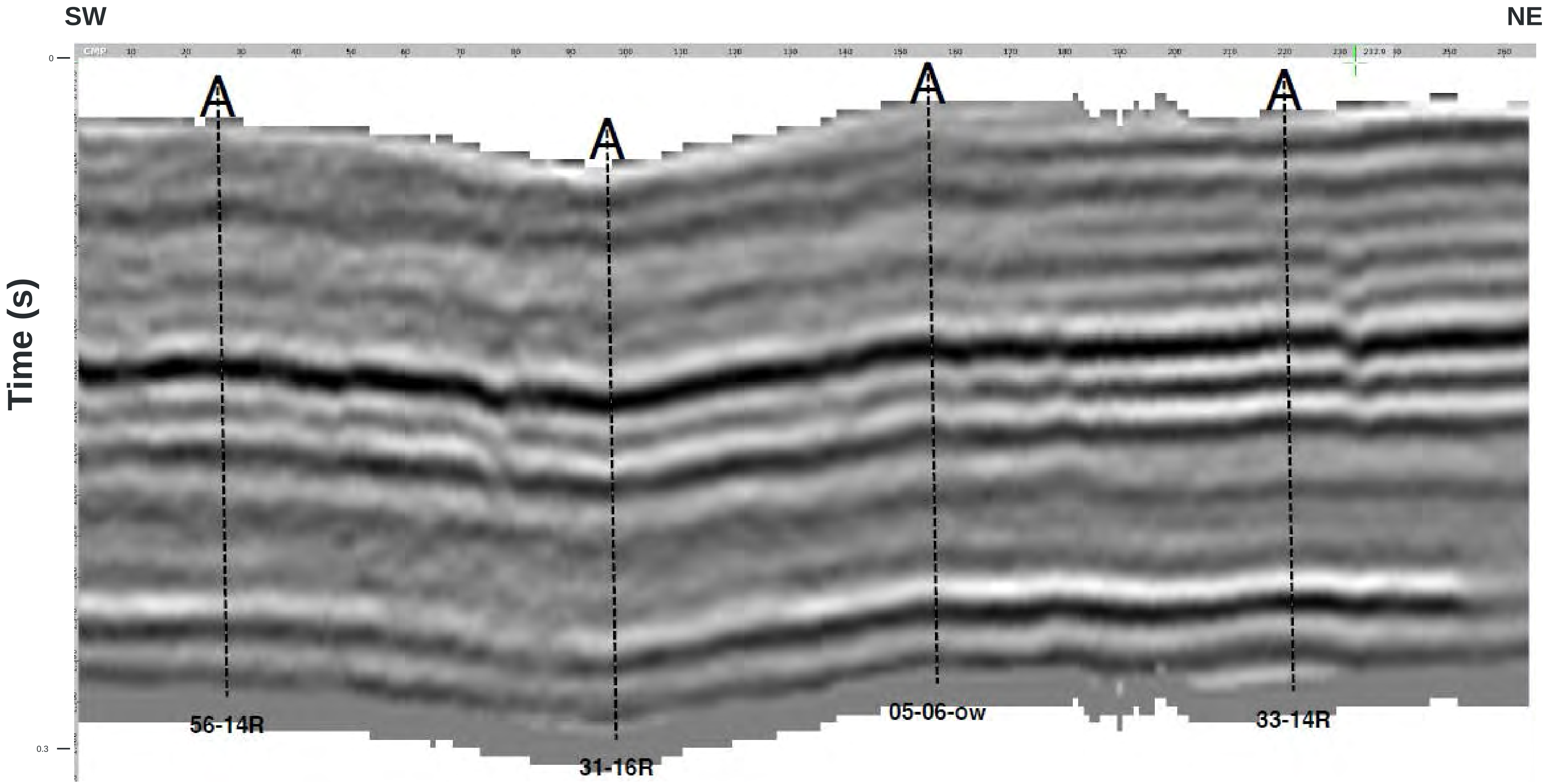


INVERSION ALONG AN ARBITRARY LINE

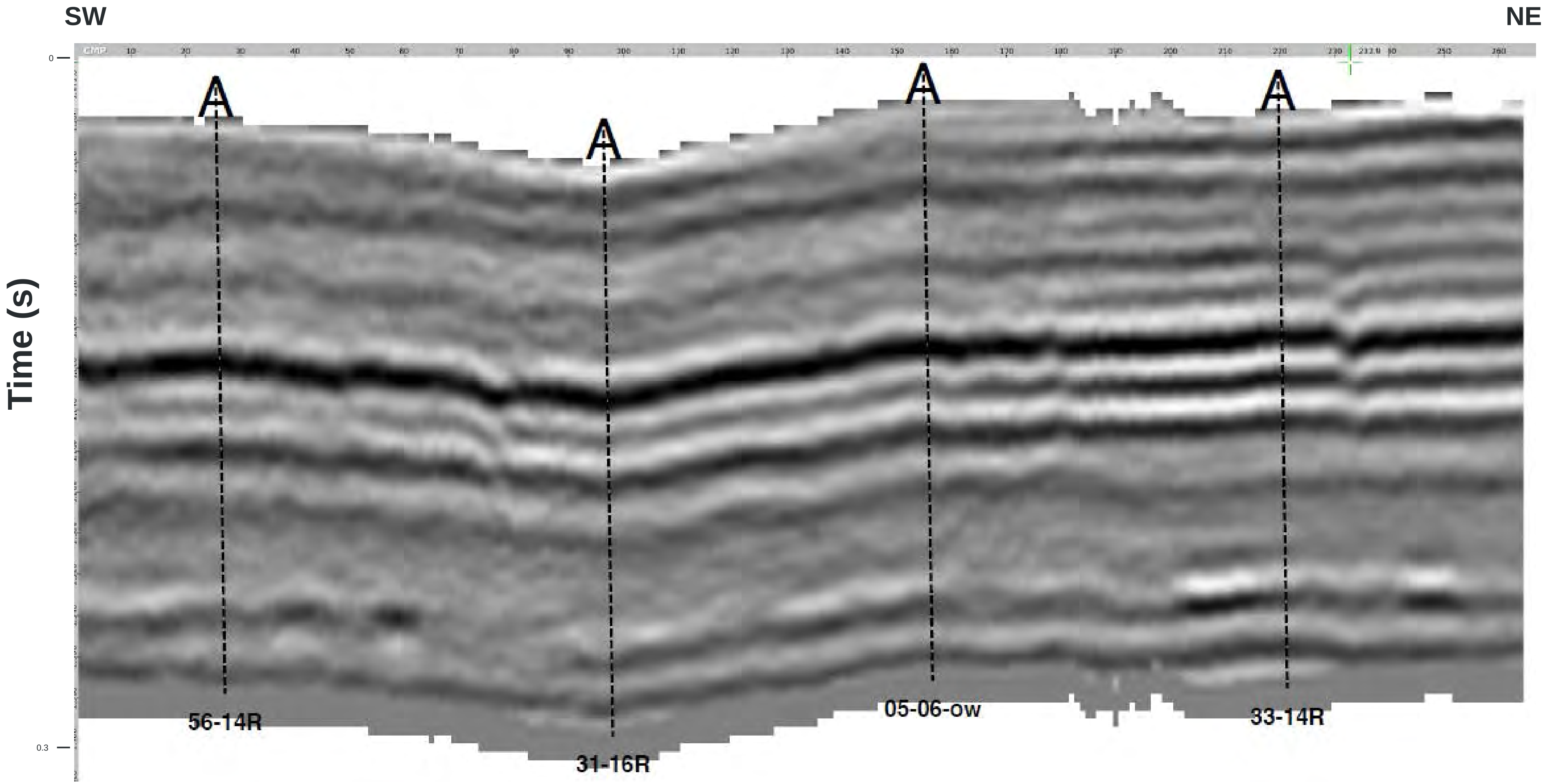


Modified after Salako et al. (2017)

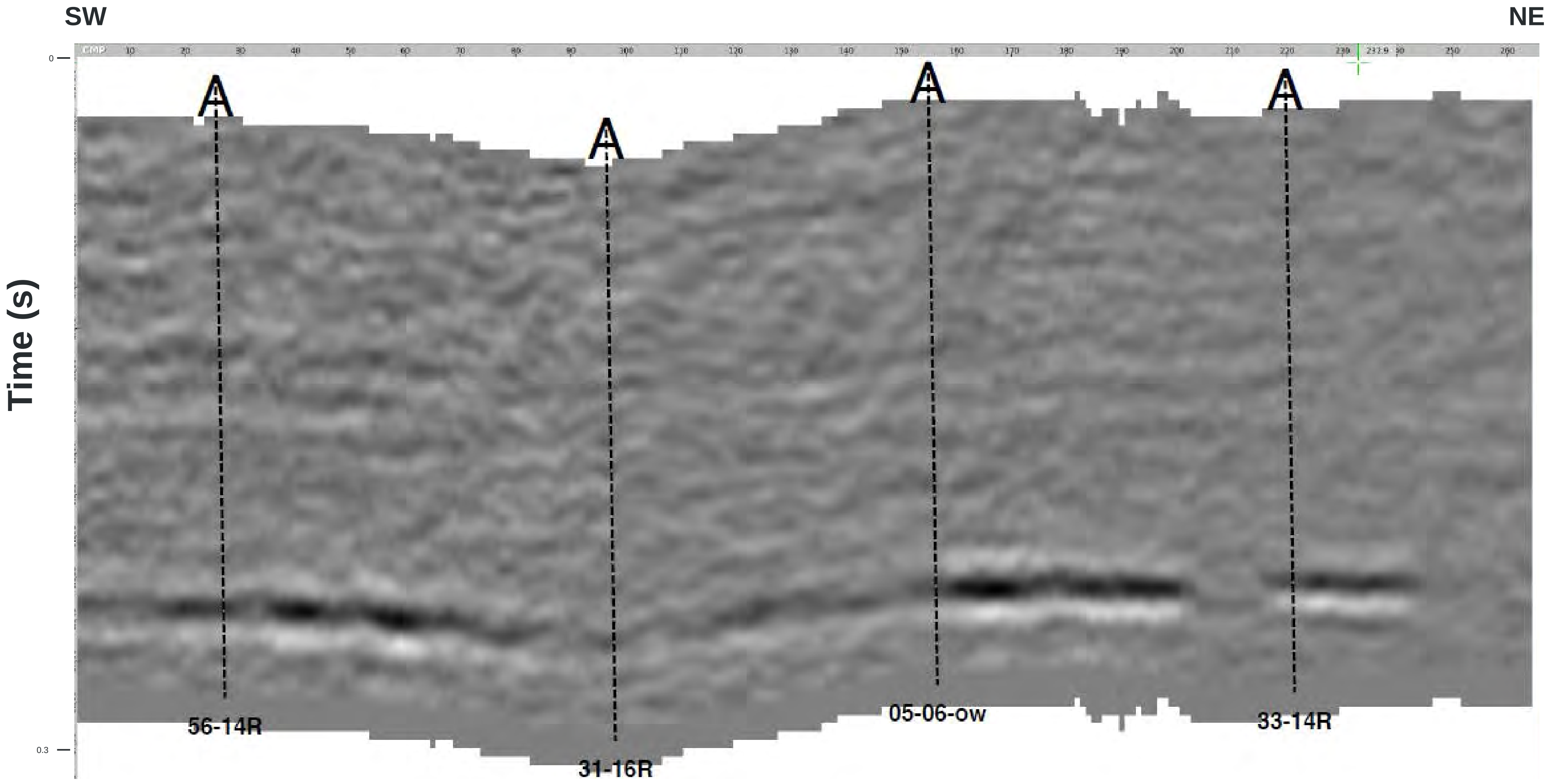
SEISMIC DATA – BASELINE (2012)



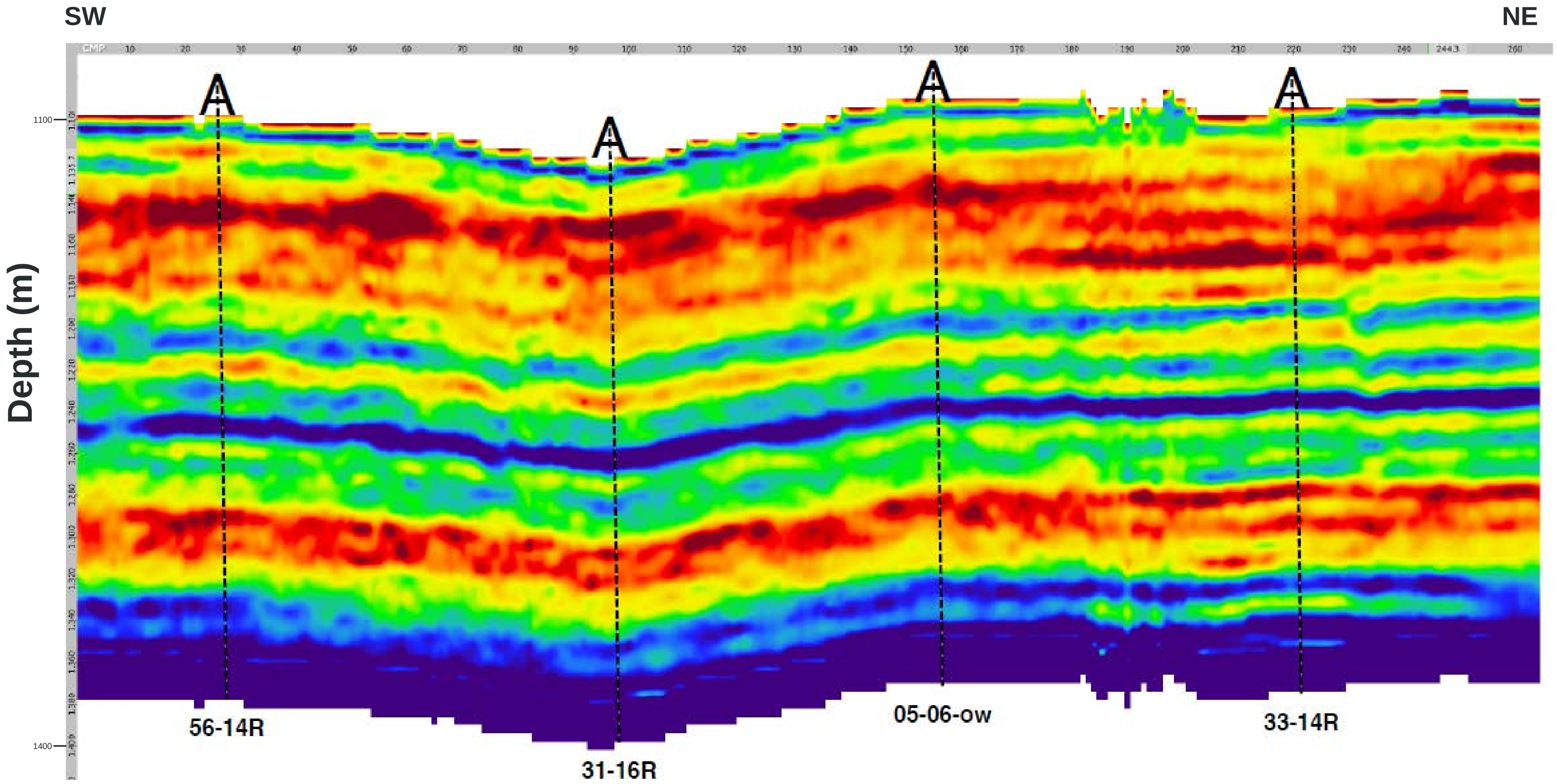
SEISMIC DATA – MONITOR (2014)



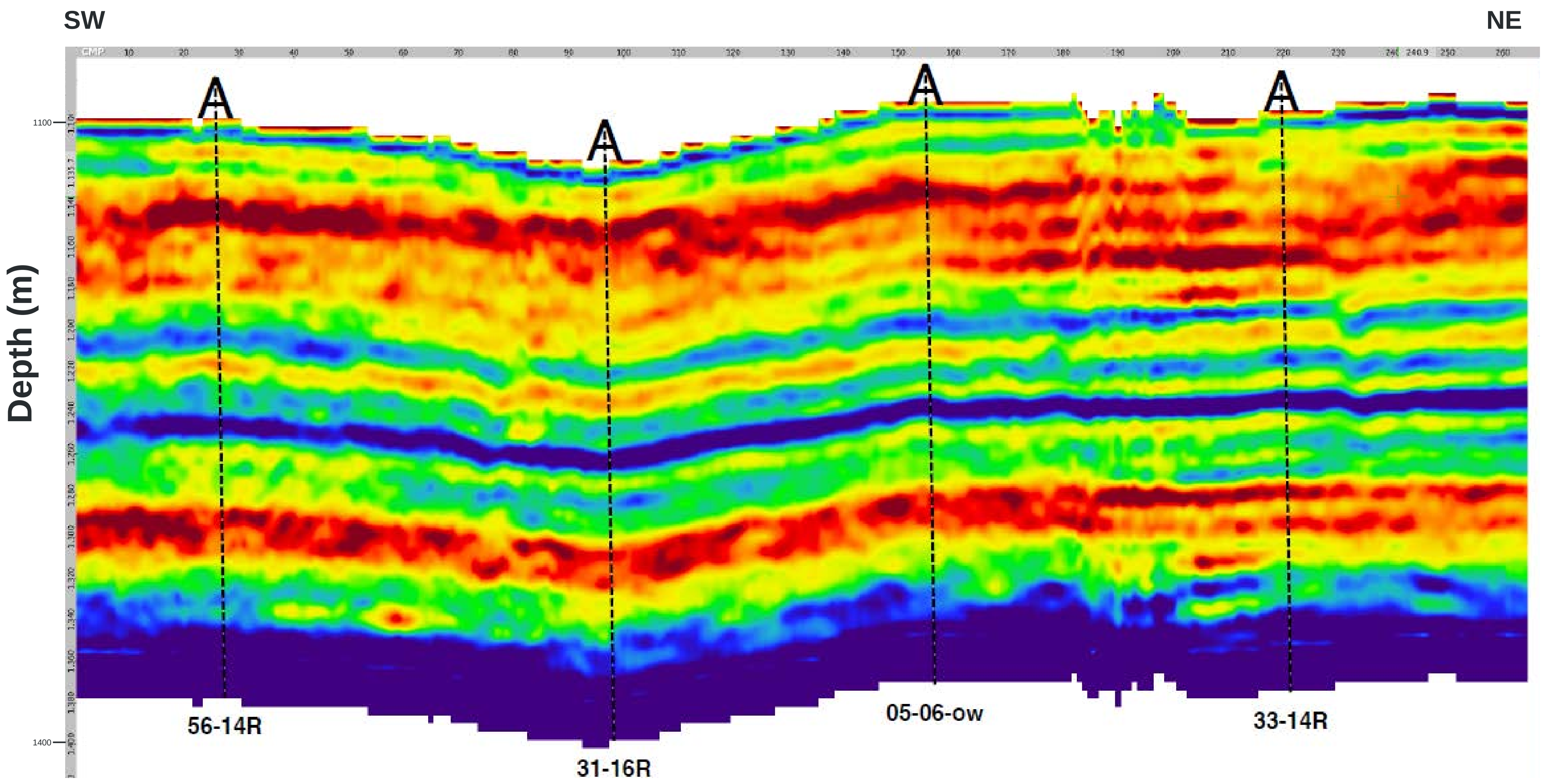
TIME-LAPSE DIFFERENCE (MONITOR – BASELINE)



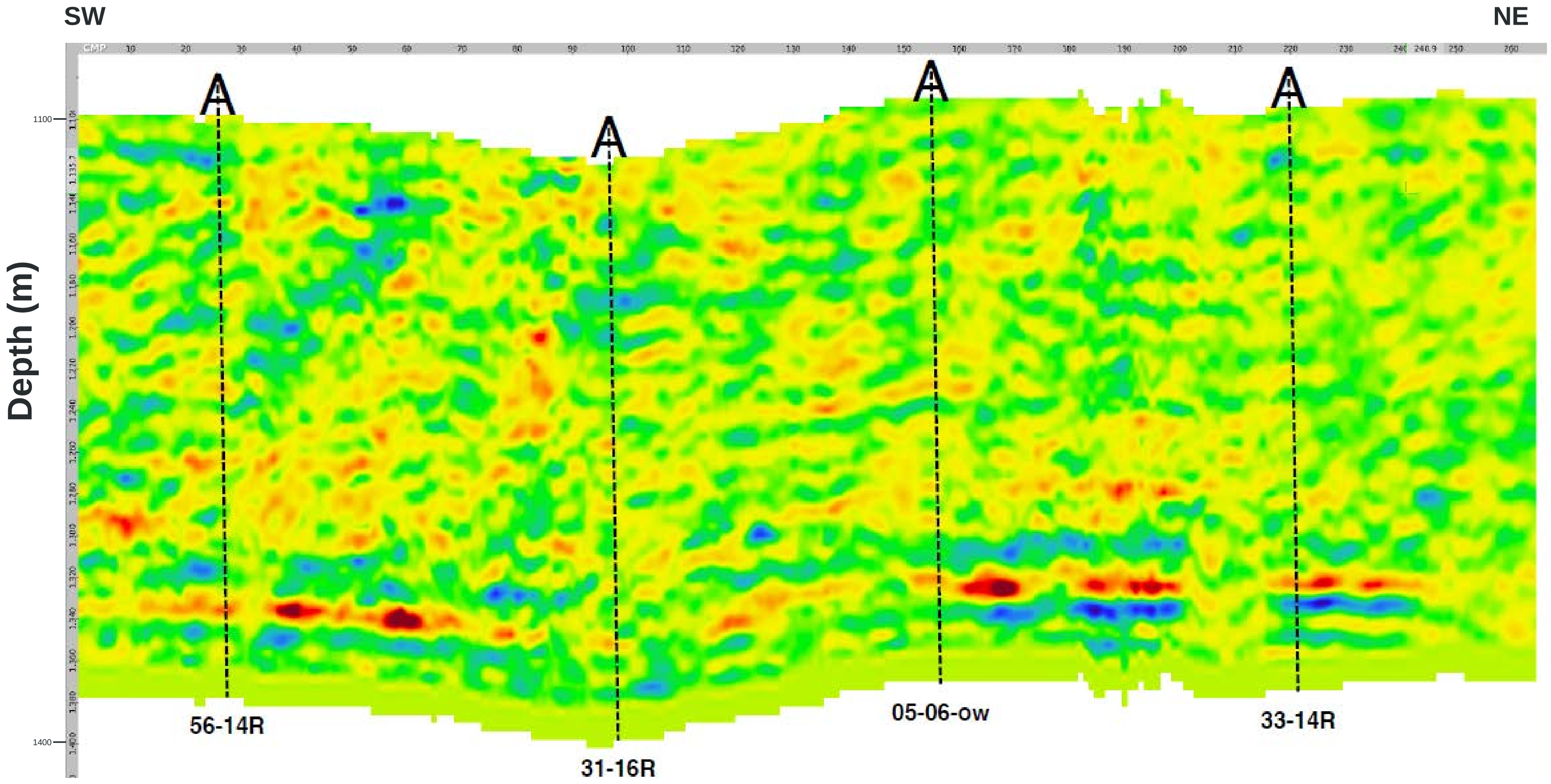
SINGLE INVERSION: COMPRESSIBILITY BASELINE



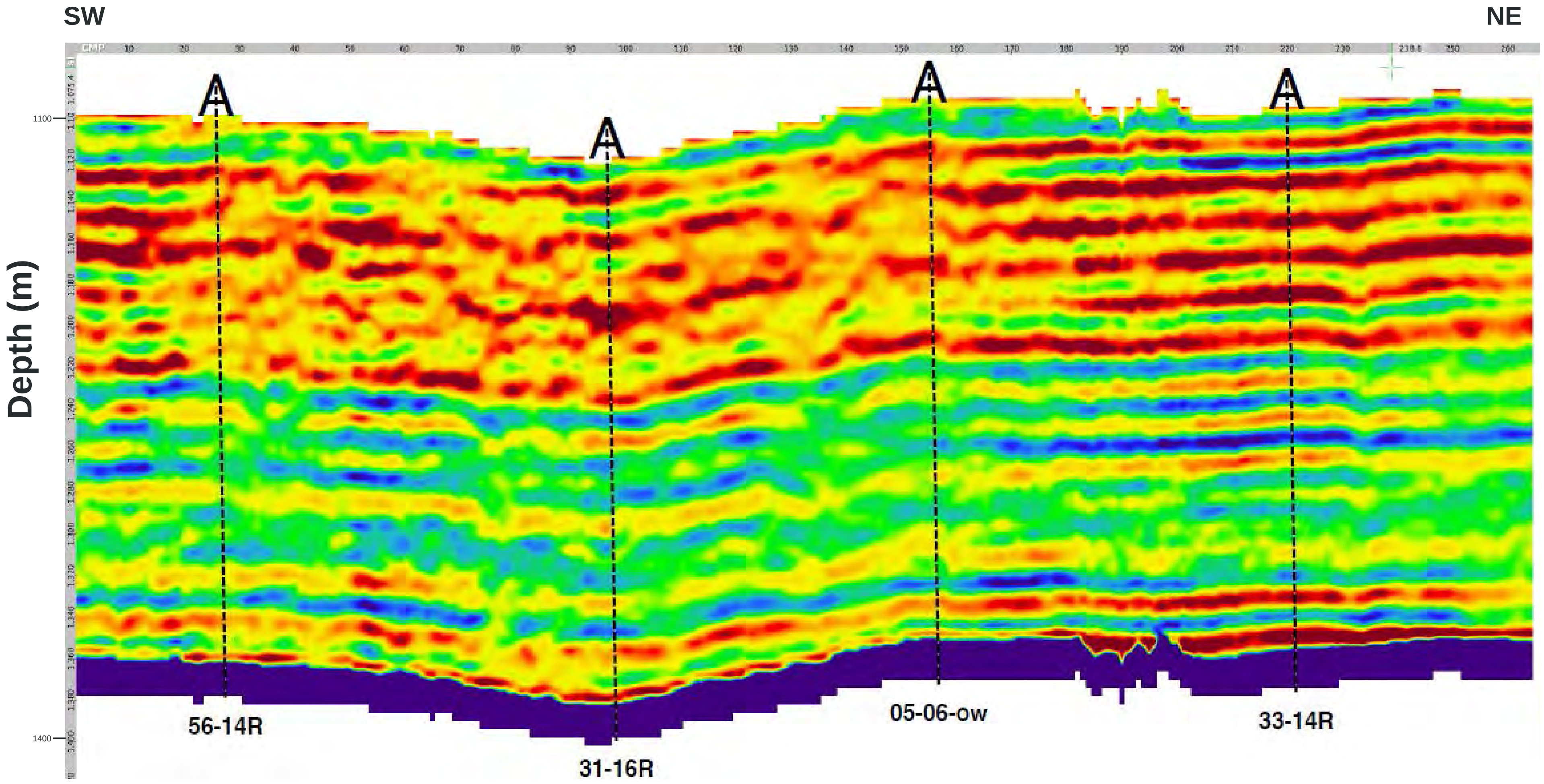
SINGLE INVERSION: COMPRESSIBILITY MONITOR



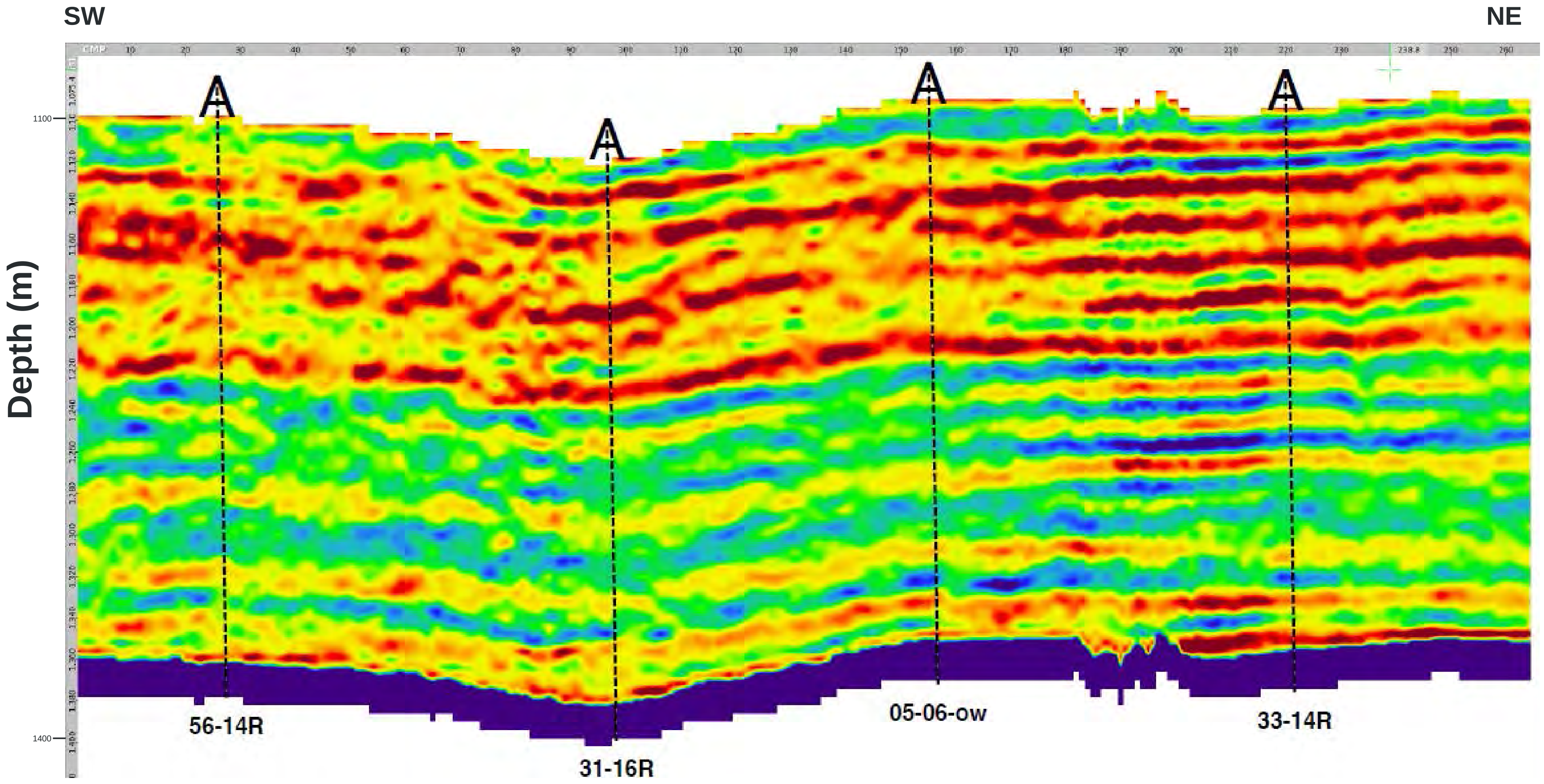
SINGLE INVERSION: TIME-LAPSE DIFFERENCE OF COMPRESSIBILITY



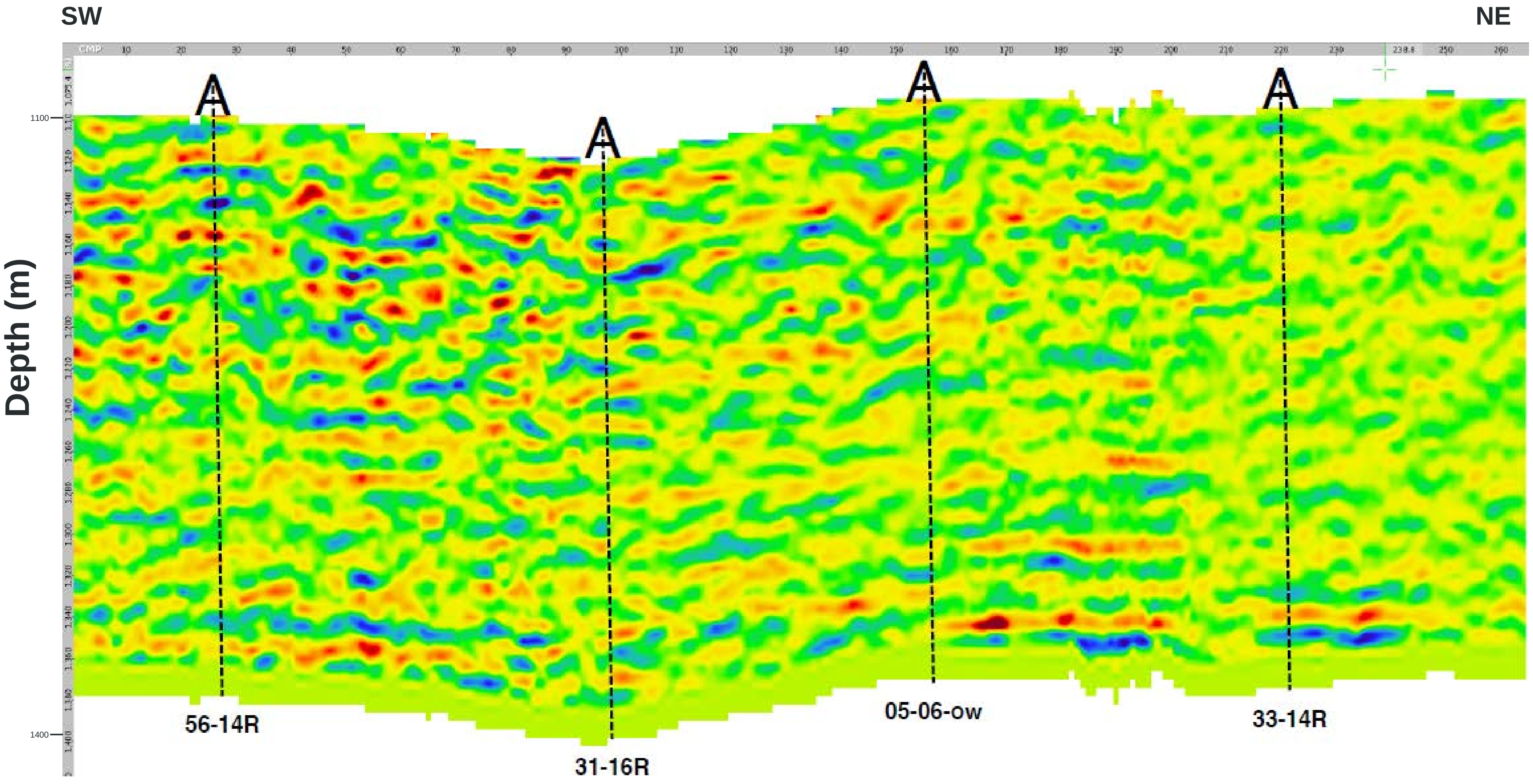
SINGLE INVERSION: SHEAR COMPLIANCE BASELINE



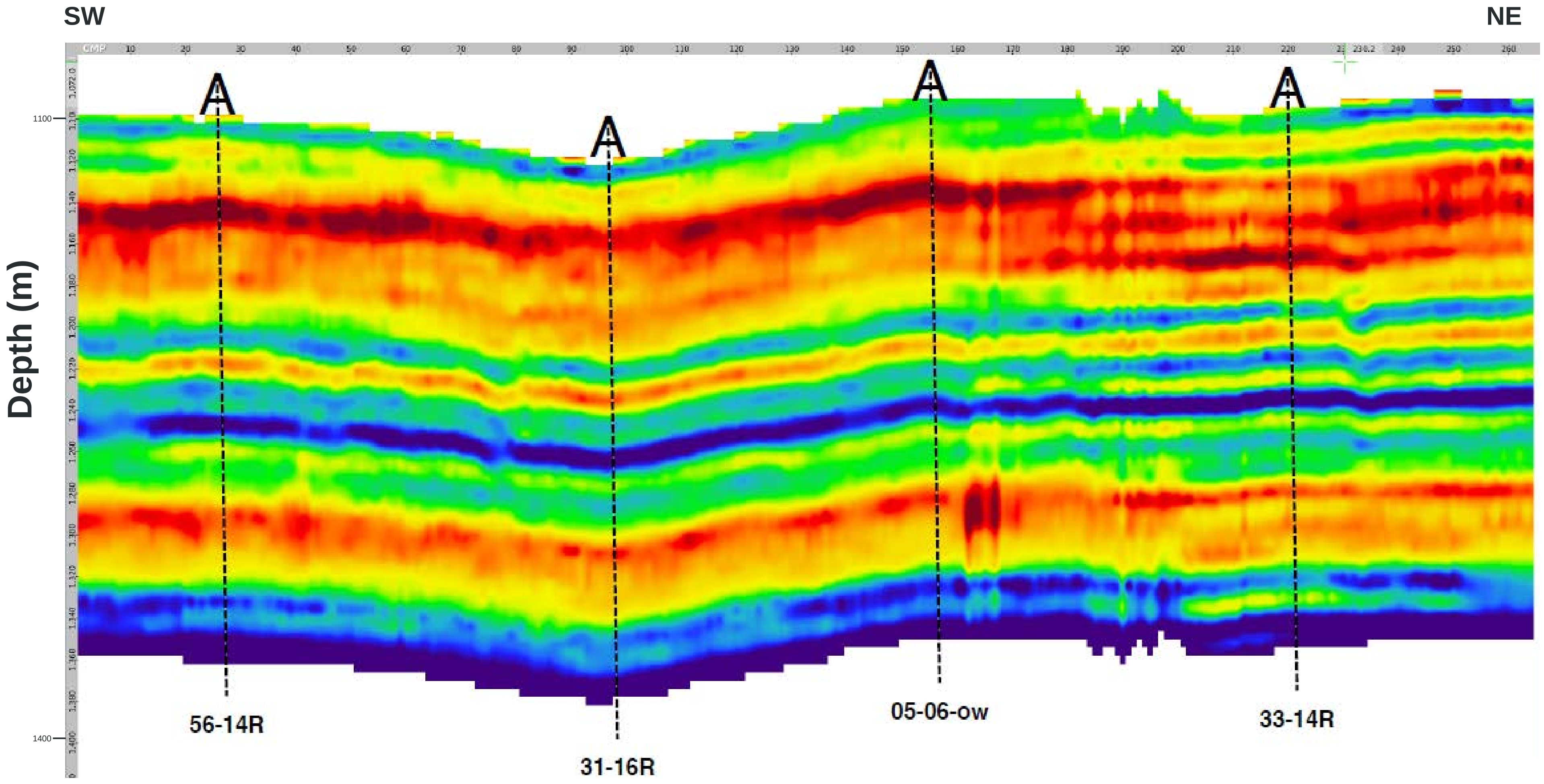
SINGLE INVERSION: SHEAR COMPLIANCE MONITOR



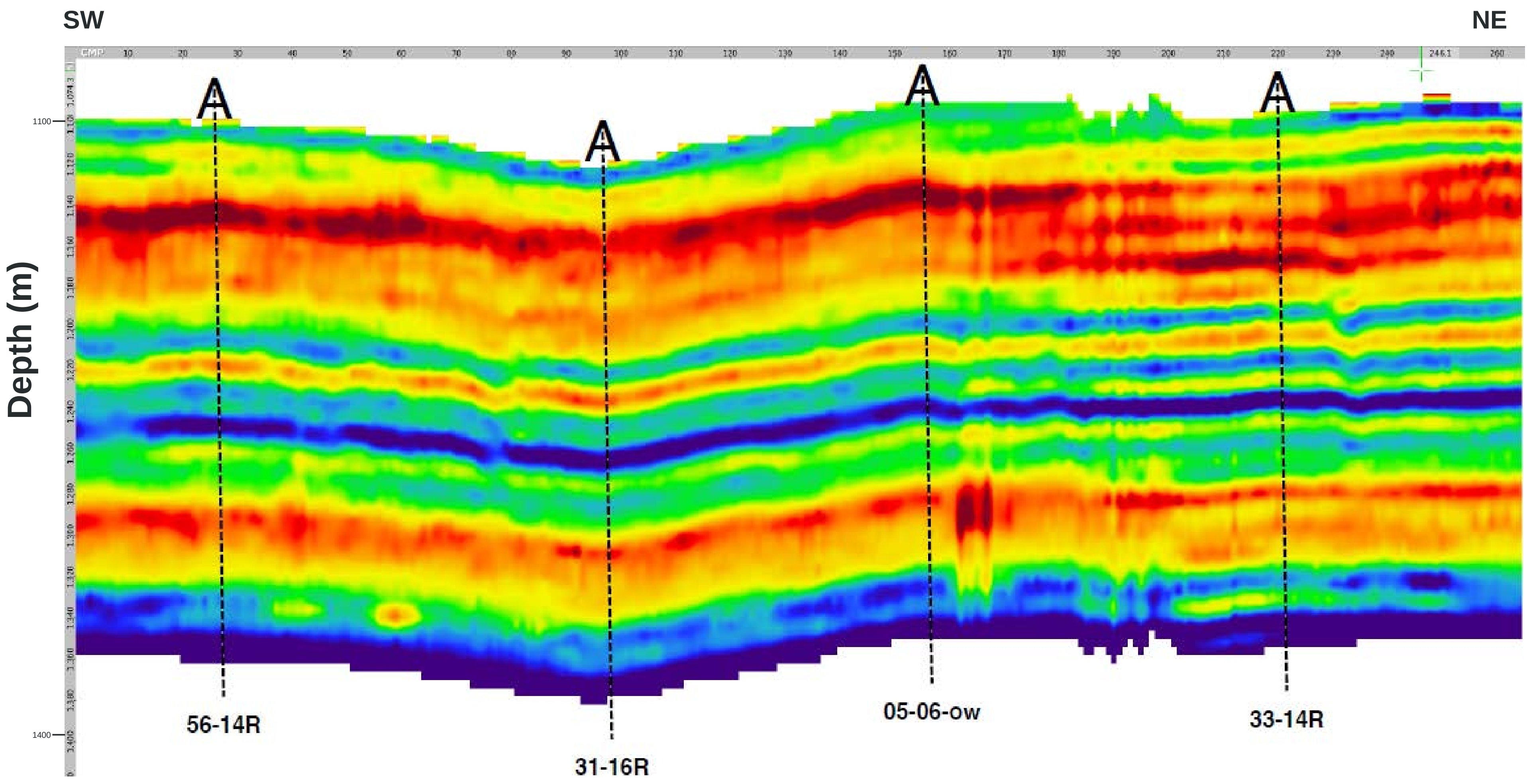
SINGLE INVERSION: TIME-LAPSE DIFFERENCE OF SHEAR COMPLIANCE



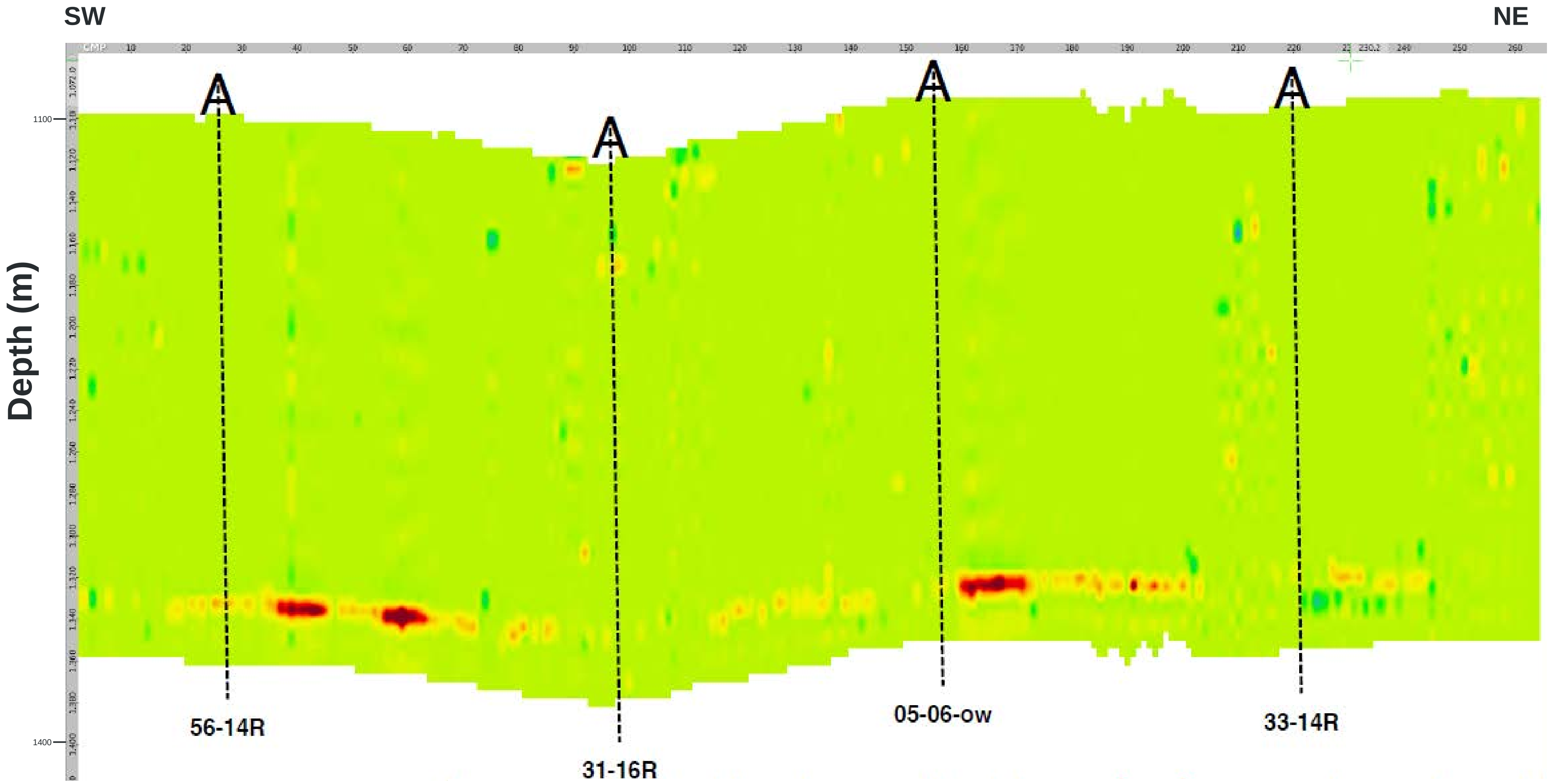
JOINT INVERSION: COMPRESSIBILITY BASELINE



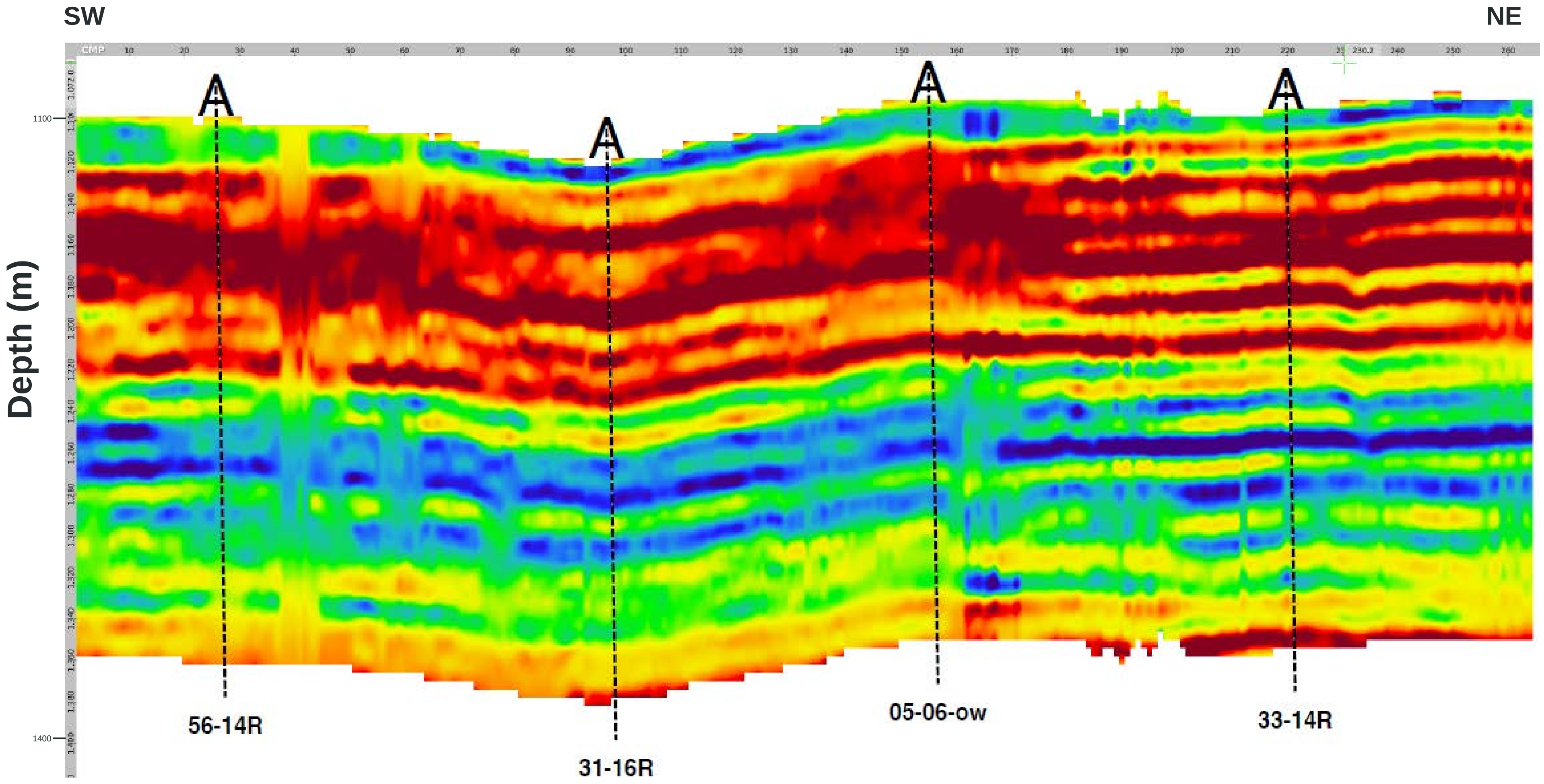
JOINT INVERSION: COMPRESSIBILITY MONITOR



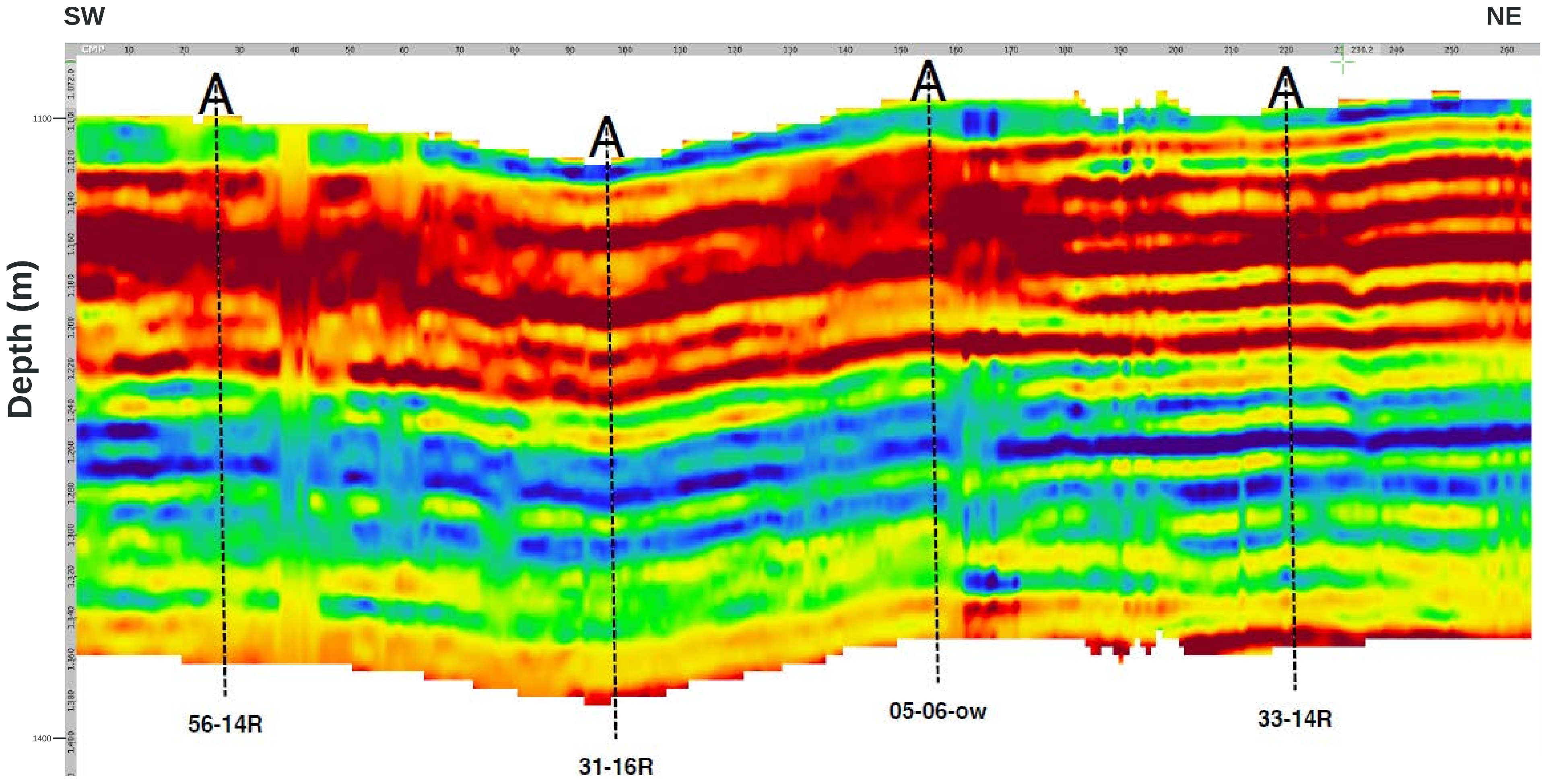
JOINT INVERSION: TIME-LAPSE DIFFERENCE OF COMPRESSIBILITY



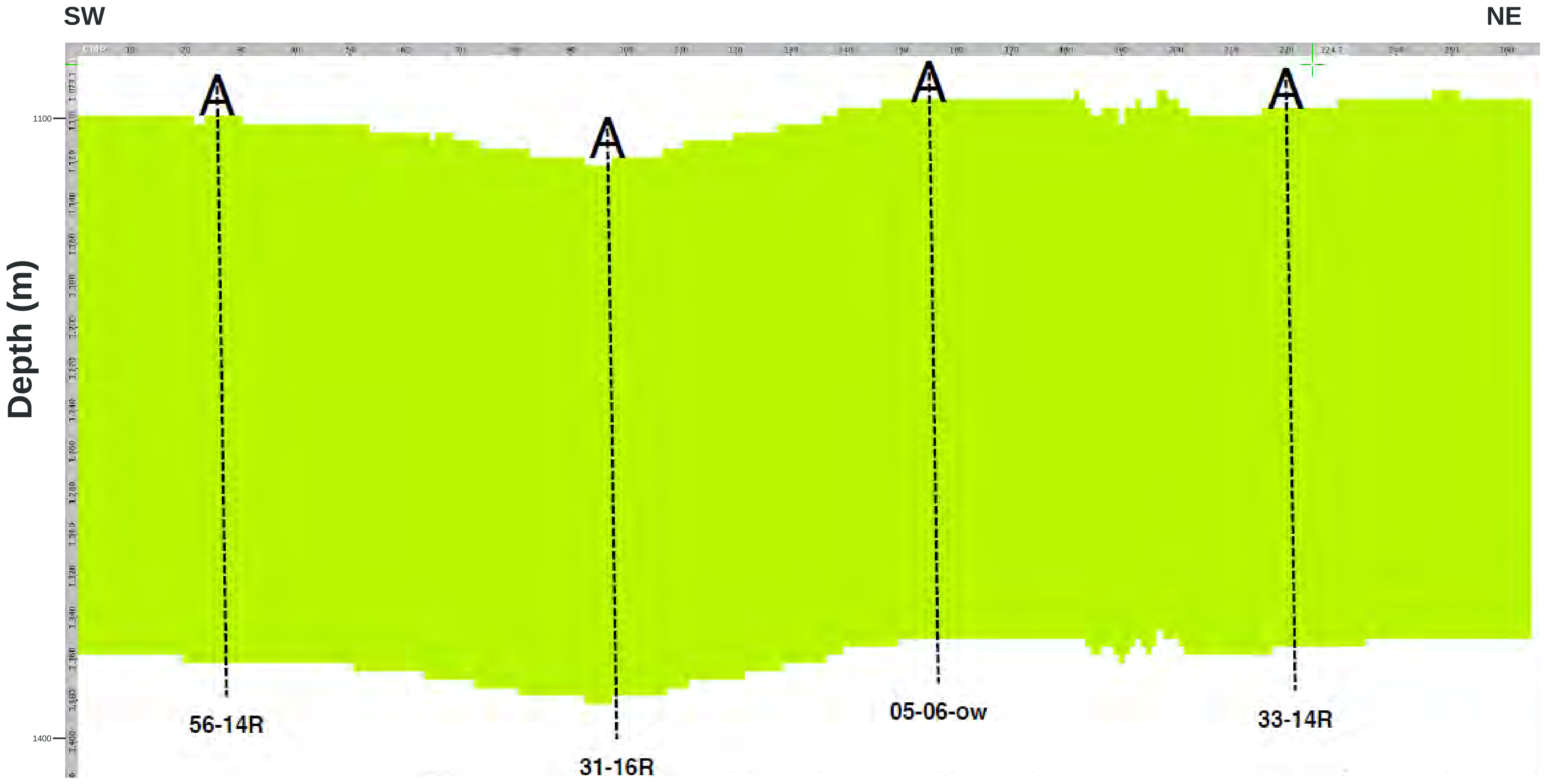
JOINT INVERSION: SHEAR COMPLIANCE BASELINE



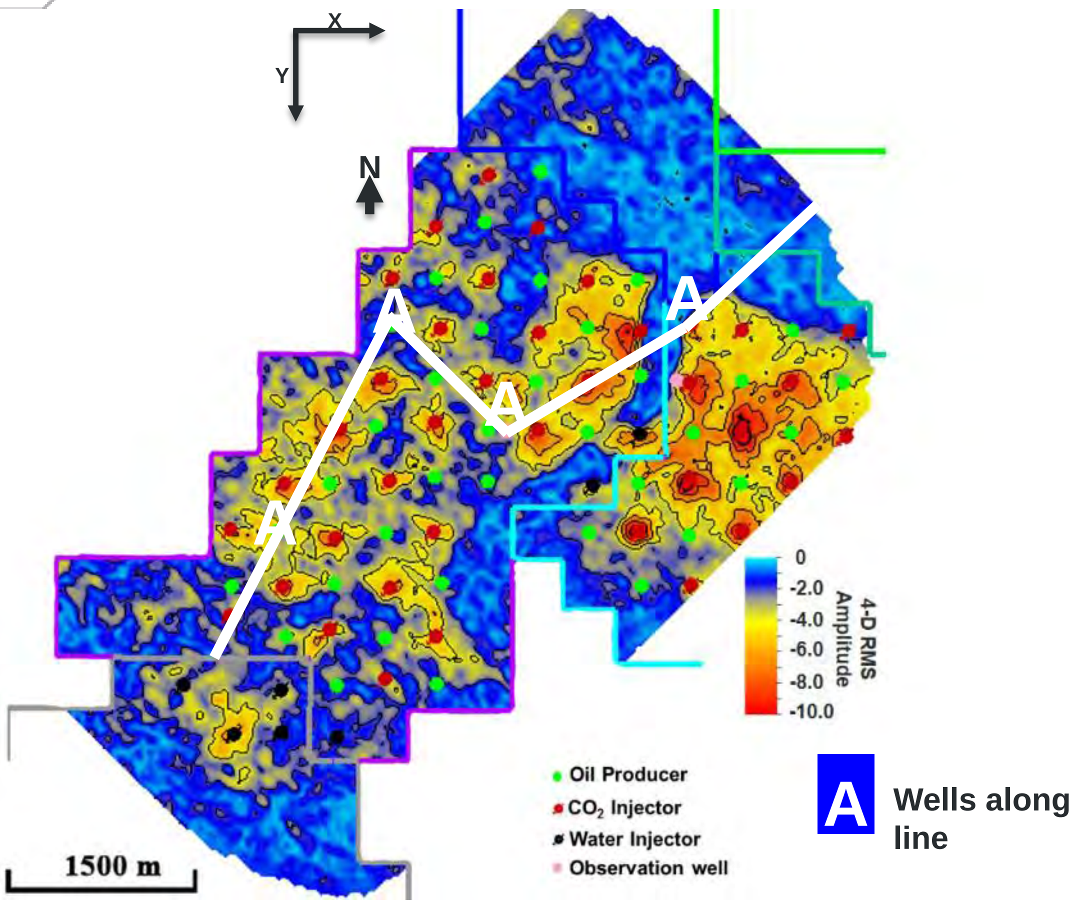
JOINT INVERSION: SHEAR COMPLIANCE MONITOR

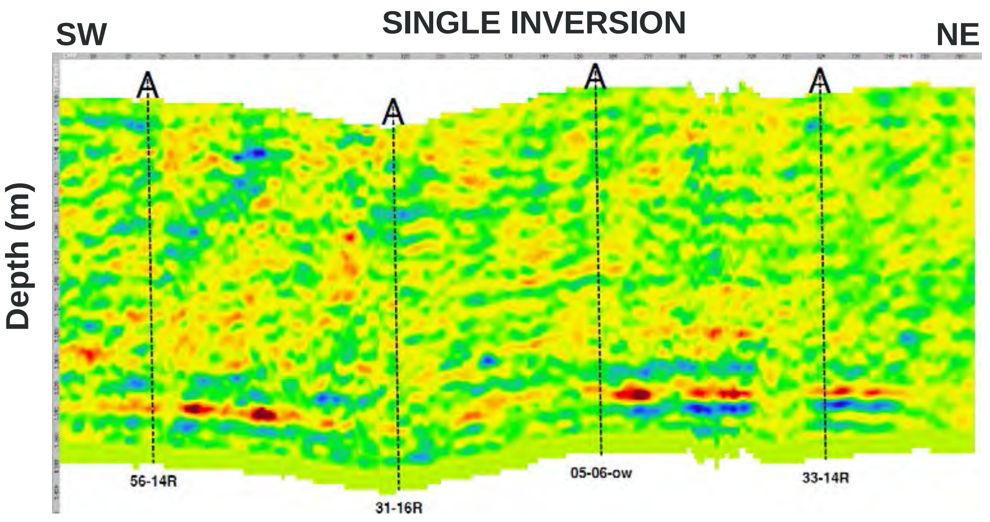


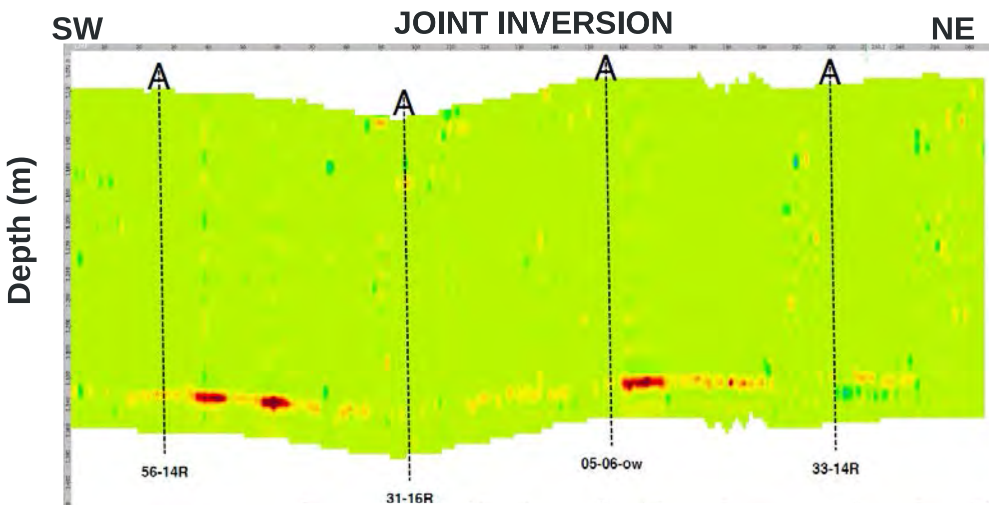
JOINT INVERSION: TIME-LAPSE DIFFERENCE OF SHEAR COMPLIANCE



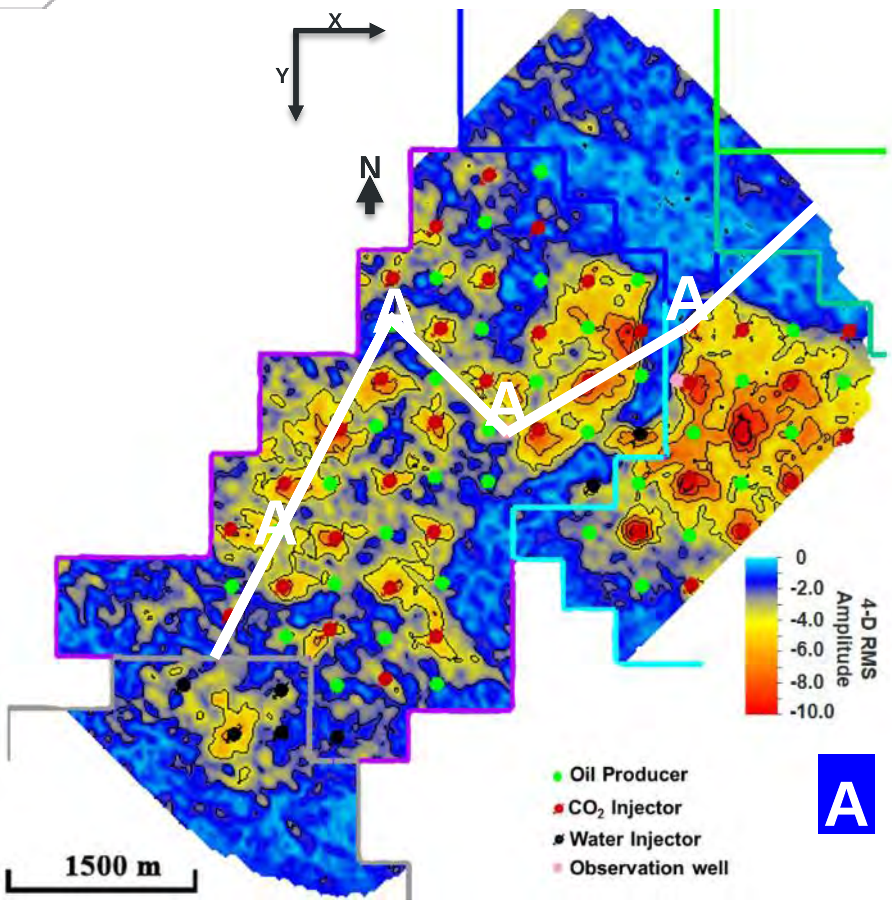
TIME-LAPSE DIFFERENCE OF COMPRESSIBILITY



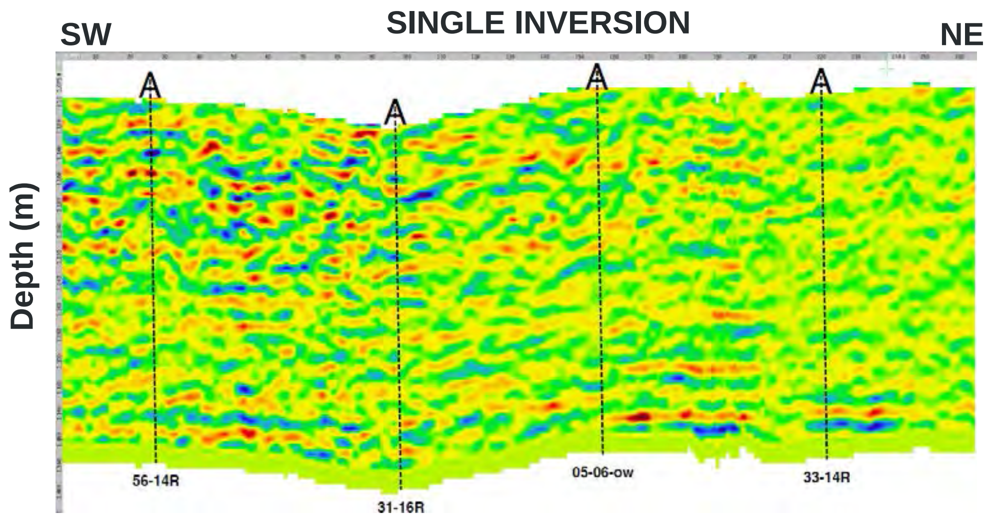


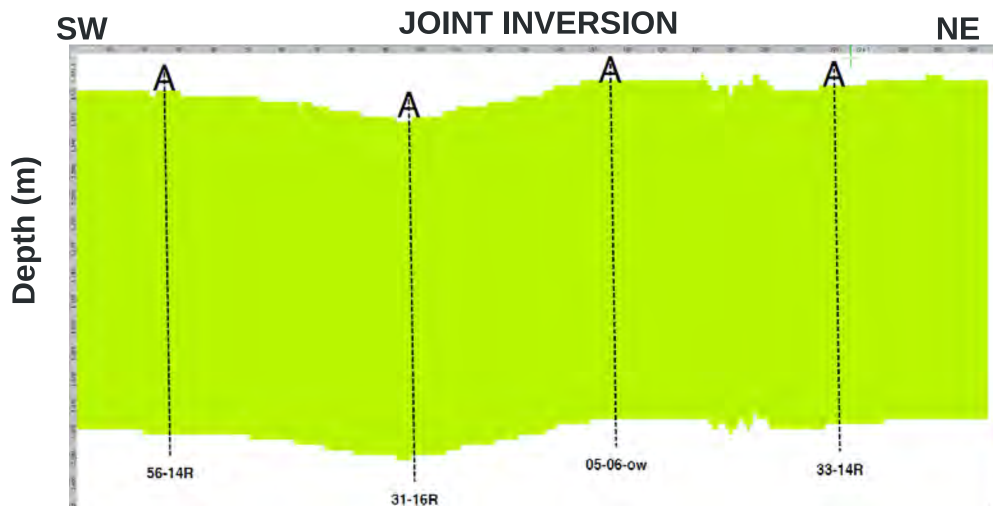


TIME-LAPSE DIFFERENCE OF SHEAR COMPLIANCE



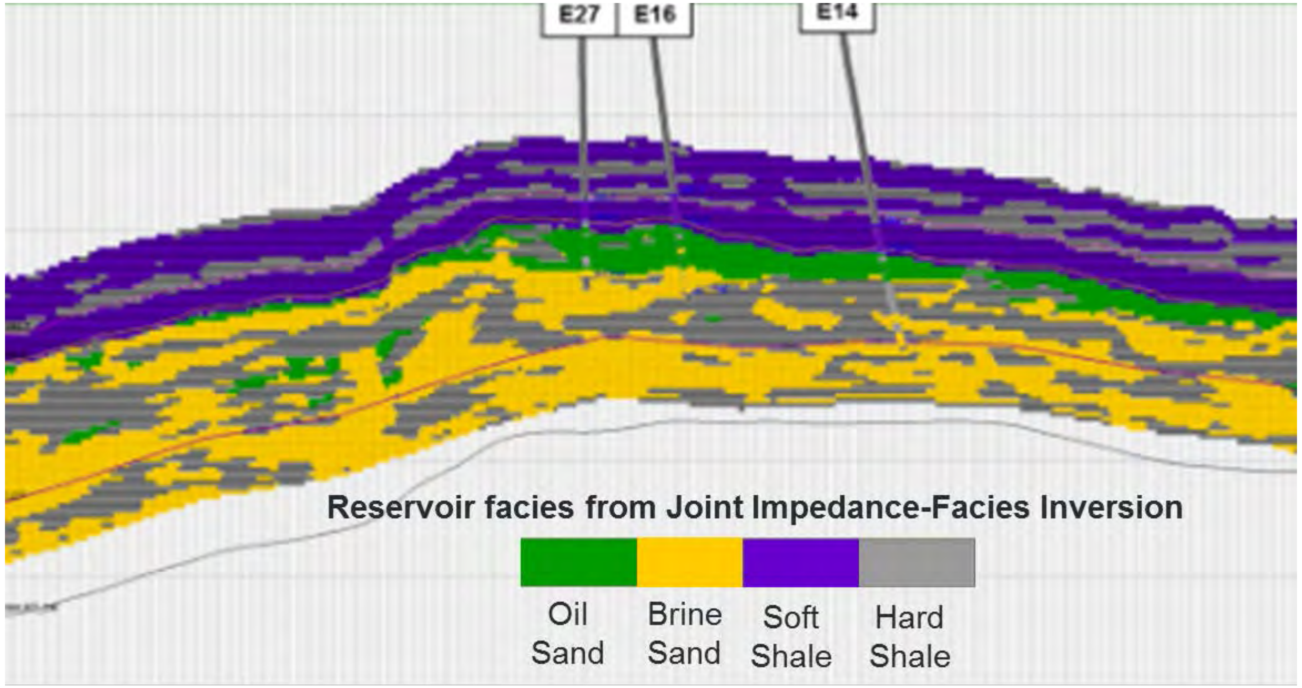
A Wells along line





JOINT IMPEDANCE AND FACIES INVERSION

- Different low-frequency models for each defined facies.
  - Bayesian analysis within the inversion to choose low-frequency model.
  - Multiple facies-based low-frequency models => Better quality of inverted elastic parameters than conventional inversions.
- Rock physics constrained by geologic facies => representative of subsurface geology.
- Time-lapse difference from single or joint inversion => high-quality images of the dynamic changes in reservoir.



(www.ikonscience.com/software/ji-fi-introduction)

ACCOMPLISHMENTS TO DATE

Wave-Equation-Based (WEB) Amplitude-Variation-with-Offset (AVO)

- Data gathered, loaded, quality-checked.
- Created initial background model.
- First seismic data-conditioning tests completed.
- Finished well tie and estimated wavelet activities.
- Defined tests of single vs. joint inversion.
  - Line of arbitrary geometry.
  - First joint inversion with WEB-AVO accomplished.

Joint Impedance and Facies Inversion

- Defined hardware to be used in the project.
- Arranged software training.

LESSONS LEARNED

- Input data require detailed analysis before using in inversion.
- A multidisciplinary approach is required from the beginning of the project.
- Results of the joint inversion should be validated with detailed analysis of engineering data.
- Land seismic data present more challenges than marine data.
- Seismic data conditioning may require several iterations for WEB-AVO single inversion.
- Arbitrary lines can be used to conduct rapid tests before three-dimensional tests.

SYNERGY OPPORTUNITIES

- Any CO_2 storage project with conventional time-lapse seismic data.
- Joint inversion projects with conventional surface seismic and controlled source electromagnetic data.

PROJECT SUMMARY

- Key findings
  - Encouraging results of WEB-AVO joint inversion.
- Next steps
  - Wave-Equation-Based Amplitude-Variation-with-Offset
    - ♦ More tests using an arbitrary line that consider geophysical, geological, and reservoir engineering information.
    - ♦ Define new seismic data-conditioning tests.
    - ♦ Thorough validation of joint inversion option.

  - Joint Impedance and Facies Inversion
    - ♦ Complete software training, and start rock physics tests.

CONTACT INFORMATION

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THANK YOU!

APPENDIX

BENEFIT 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

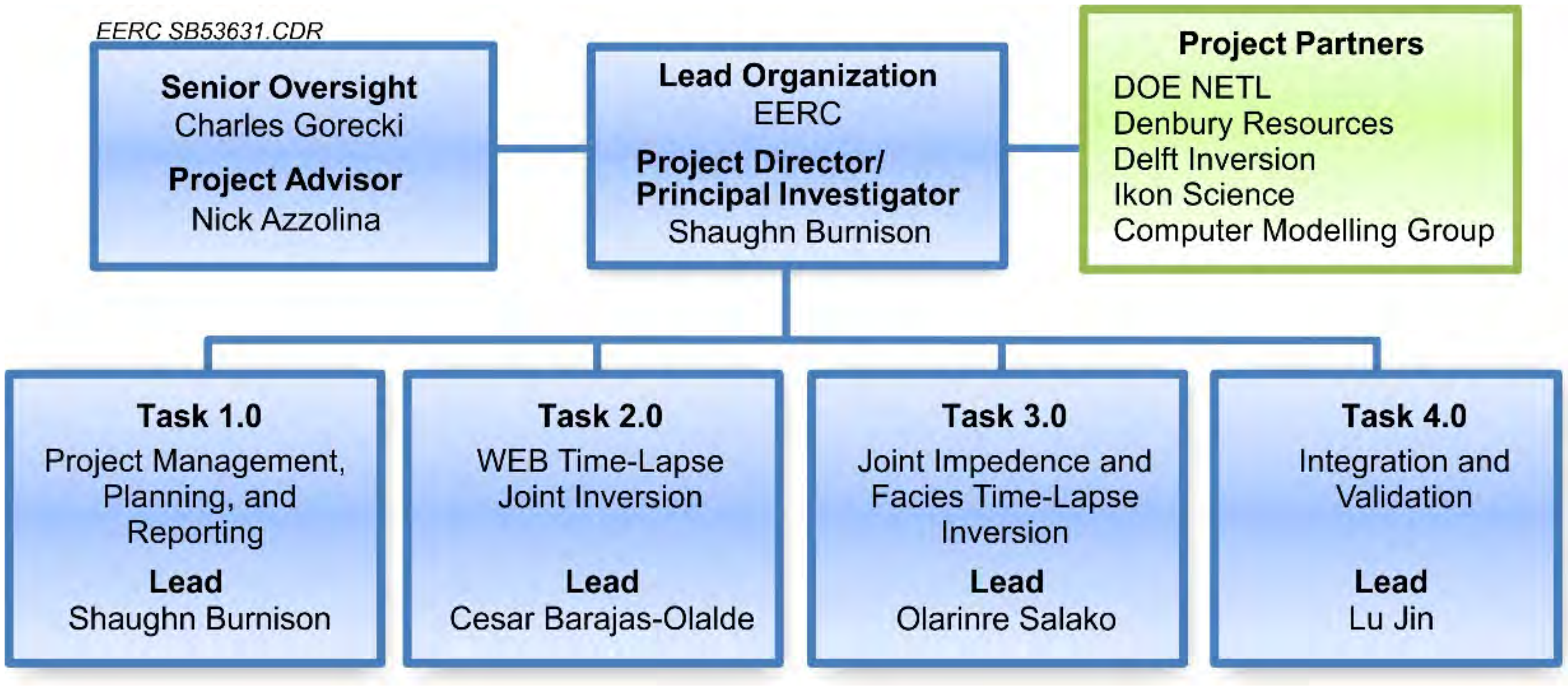
1. Develop a workflow (tool) to quantitatively estimate reservoir properties and the amount of CO_2 stored in the reservoir from time-lapse seismic inverted parameters, calibrated and validated with a rock physics model and geologic information.
2. Reduce the uncertainty in detecting and assessing the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

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

PROJECT MILESTONES

Task/Subtask	Milestone Title	Planned Completion Date	Verification Method
1.0 – Project Management, Planning, and Reporting	M1 – Hold DOE NETL Kickoff Meeting	2/28/18	Presentation file submitted to DOE
1.0 – Project Management, Planning, and Reporting	M2 – Finalize Contracts with Project Partners	7/31/18	Reported in subsequent quarterly report
2.4 – WEB Inversion to Reservoir Properties	M3 – Complete WEB Time-Lapse Joint Inversion	2/28/19	Reported in subsequent quarterly report
3.3 – Joint Inversion to Reservoir Properties	M4 – Complete Joint Impedence and Facies Inversion	7/31/19	Reported in subsequent quarterly report
4.3 – Analysis of Results	M5 – Complete Predictive Simulations and Comparisons	10/31/19	Reported in subsequent quarterly report

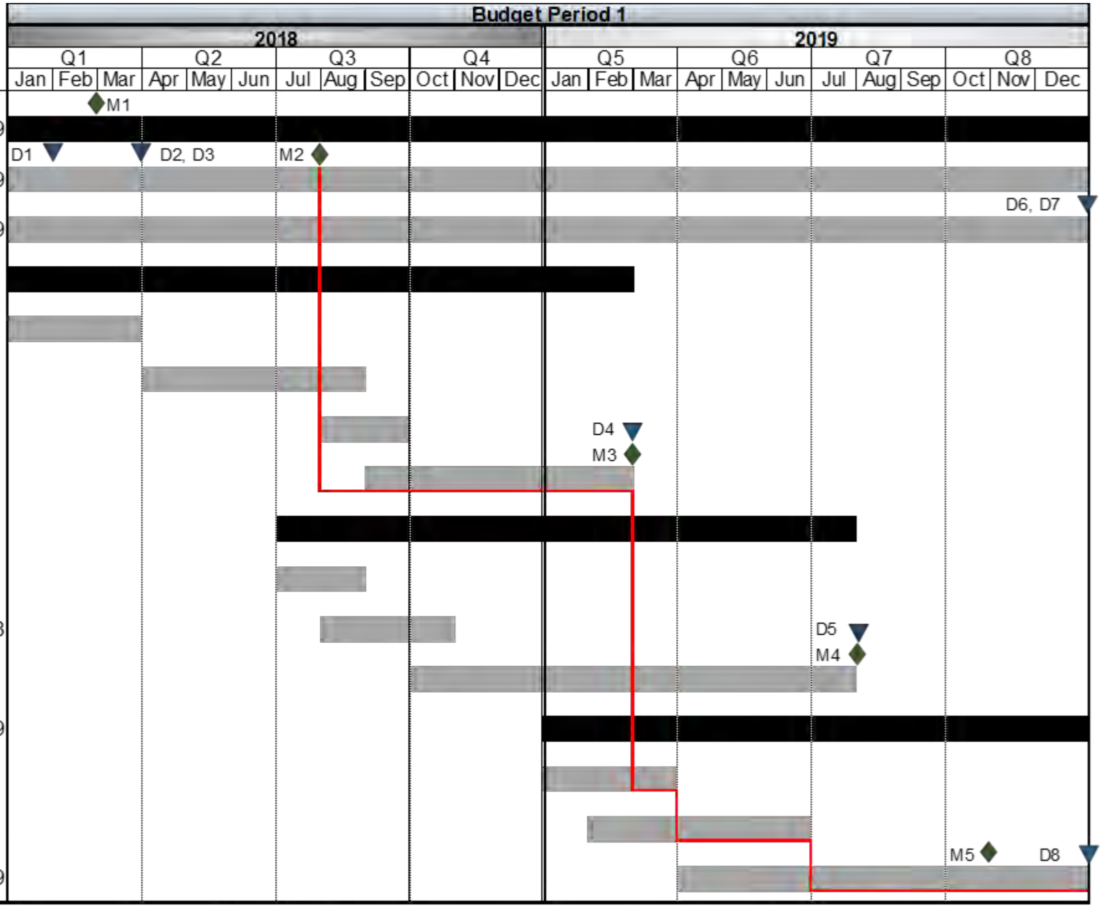
ORGANIZATION CHART



PROPOSED SCHEDULE

- 2-year project
- One budget period

Task/Subtask	Start Date	End Date
1.0 – Project Management, Planning, and Reporting	1/1/18	12/31/19
1.1 – Project Management and Planning	1/1/18	12/31/19
1.2 – Project Reporting	1/1/18	12/31/19
2.0 – WEB Time-Lapse Joint Inversion	1/1/18	2/28/19
2.1 – Data Gathering, Loading, and Quality Check	1/1/18	3/31/18
2.2 – Compressibility Effects and Background Model	4/1/18	8/31/18
2.3 – Seismic Conditioning and Well Tie	8/1/18	9/30/18
2.4 – WEB Inversion to Reservoir Properties	9/1/18	2/28/19
3.0 – Joint Impedence and Facies Time-Lapse Inversion	7/1/18	7/31/19
3.1 – Log Conditioning and Rock Physics Modeling	7/1/18	8/31/18
3.2 – Seismic AVO Conditioning	8/1/18	10/31/18
3.3 – Joint Inversion to Reservoir Properties	10/1/18	7/31/19
4.0 – Integration and Validation	1/1/19	12/31/19
4.1 – Geomodel Refinement	1/1/19	3/31/19
4.2 – Predictive Simulations and Comparisons	2/1/19	6/30/19
4.3 – Analysis of Results	4/1/19	12/31/19



Milestones

M1 – Hold DOE NETL Kickoff Meeting
M2 – Finalize Contracts with Project Partners
M3 – Complete WEB Time-Lapse Joint Inversion
M4 – Complete Joint Impedence and Facies Inversion
M5 – Complete Predictive Simulations and Comparisons

Deliverables

D1 – Project Management Plan (updated)
D2 – Technology Maturation Plan (updated)
D3 – Data Management Plan (updated)
D4 – Interim Report on Web Time-Lapse Joint Inversion
D5 – Interim Report on Joint Impedence and Facies Inversion
D6 – Final Technical Report
D7 – Data Submitted to NETL EDX
D8 – Journal Article or Technical Paper Draft

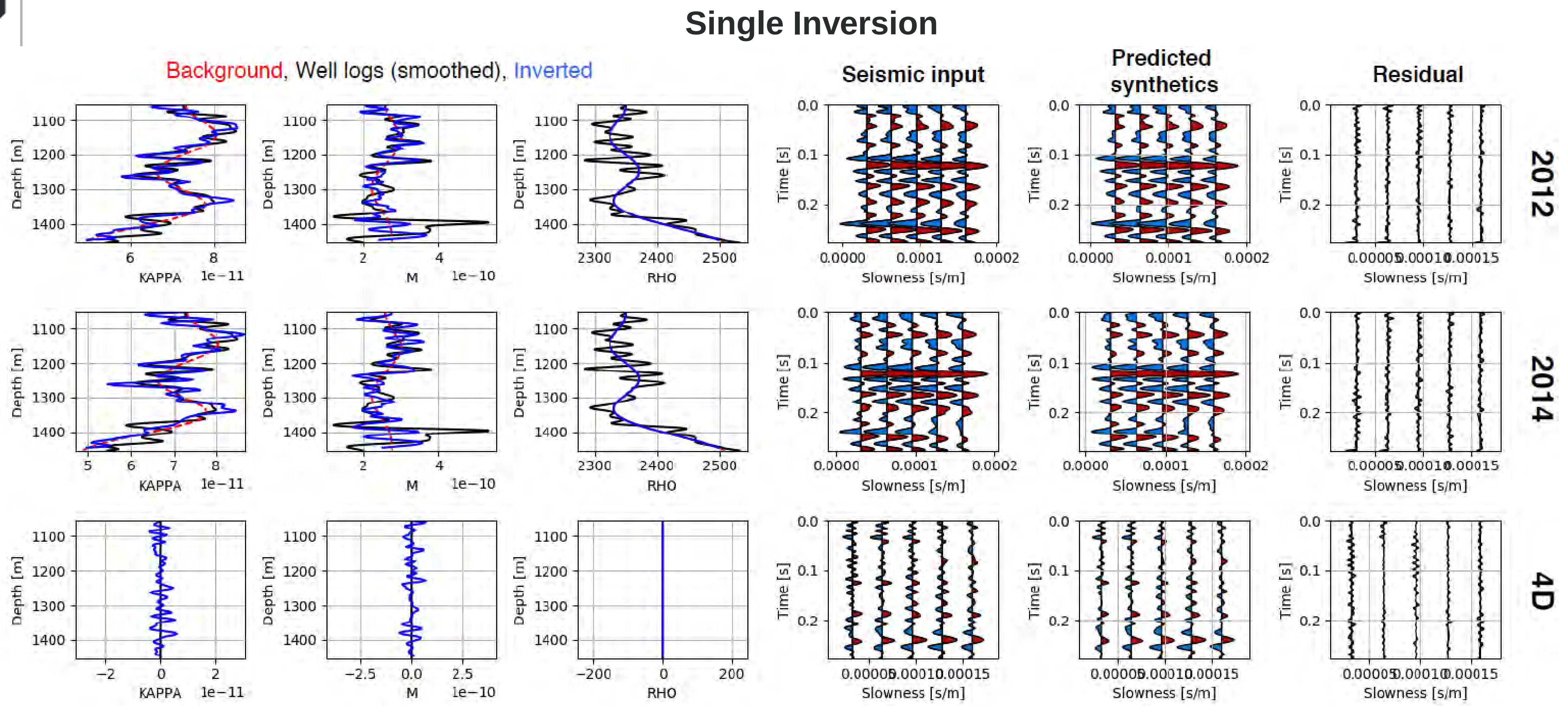
12.8.17 hmv

BIBLIOGRAPHY

The following publications were referenced in the presentation:

- Doulgeris, P., 2017, Personal communication.
- Gisolf, D., Haffinger, P.R., and Doulgeris, P., 2017, Reservoir-oriented wave-equation seismic amplitude variation with offset inversion: Interpretation, v. 5, no. 3, p. SL43–SL56.
- Salako, O., Jin, L., Burnison, S.A., Hamling, J.A., Gorecki, C.D., Reed, S., and Richards, T., 2017, The value of 4-D seismic monitoring at Bell Creek – a mature oil field undergoing CO_2 enhanced oil recovery: 79th EAGE Conference & Exhibition, We B1 06.
- Salako O., Burnison S.A., Bosshart N.W., Jin L., Kalenze N.S., Hamling J.A., and Gorecki C.D. 2018, 4-D seismic amplitude interpretation improves understanding of reservoir heterogeneity at a mature oil field undergoing CO_2 enhanced oil recovery and associated storage: International Journal of Greenhouse Gas Control [in review].

SINGLE INVERSION AT ONE OF THE WELLS



JOINT INVERSION AT ONE OF THE WELLS

Simultaneous Joint Inversion (baseline and monitor)