Rock physics and time-lapse seismic analysis of thermal heavy oil production

Evan Mutual, David Cho and Kristopher Innanen

Outline

- Introduction and objectives
- Study area and overview
- Rock physics modeling
- Seismic pre-conditioning
- Low-frequency modeling
- Results
- Conclusion
- Acknowledgements

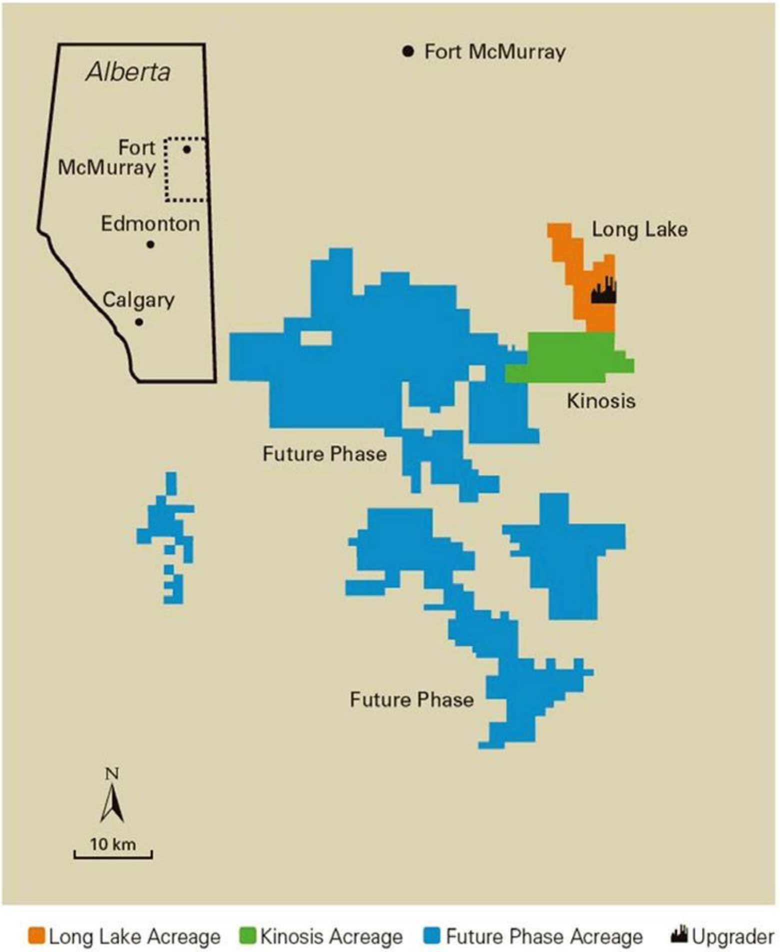
Introduction

- What is 4D AVO Inversion?
  - Estimation of ***changes*** in elastic properties from surface seismic
    - Acoustic impedance, shear impedance, Vp/Vs and density
  - ***Quantitative*** measurement of reservoir changes in terms of elastic and reservoir properties
- Why is it Important?
  - Enhanced decision making based on quantitative results
  - Changes in *actual* reservoir parameters corresponding to changes in fluids, pressures and temperatures

Study Area and Overview

- Steam assisted gravity drainage (SAGD) operations in McMurray formation
- Permanent buried geophones installed designed to allow year-round monitoring of operations.
  - Baseline survey acquired in 2006 prior to permanent geophone installation.
  - Monitor survey acquired in 2015 after approximately 6 months of steam injection. Little-no production had taken place.

- Survey info
  - ~1.54 km2
  - 10m x 10m bin size
  - 1ms sample rate
  - 3 vertical wells over survey area with elastic and petro-physical logs.



Workflow

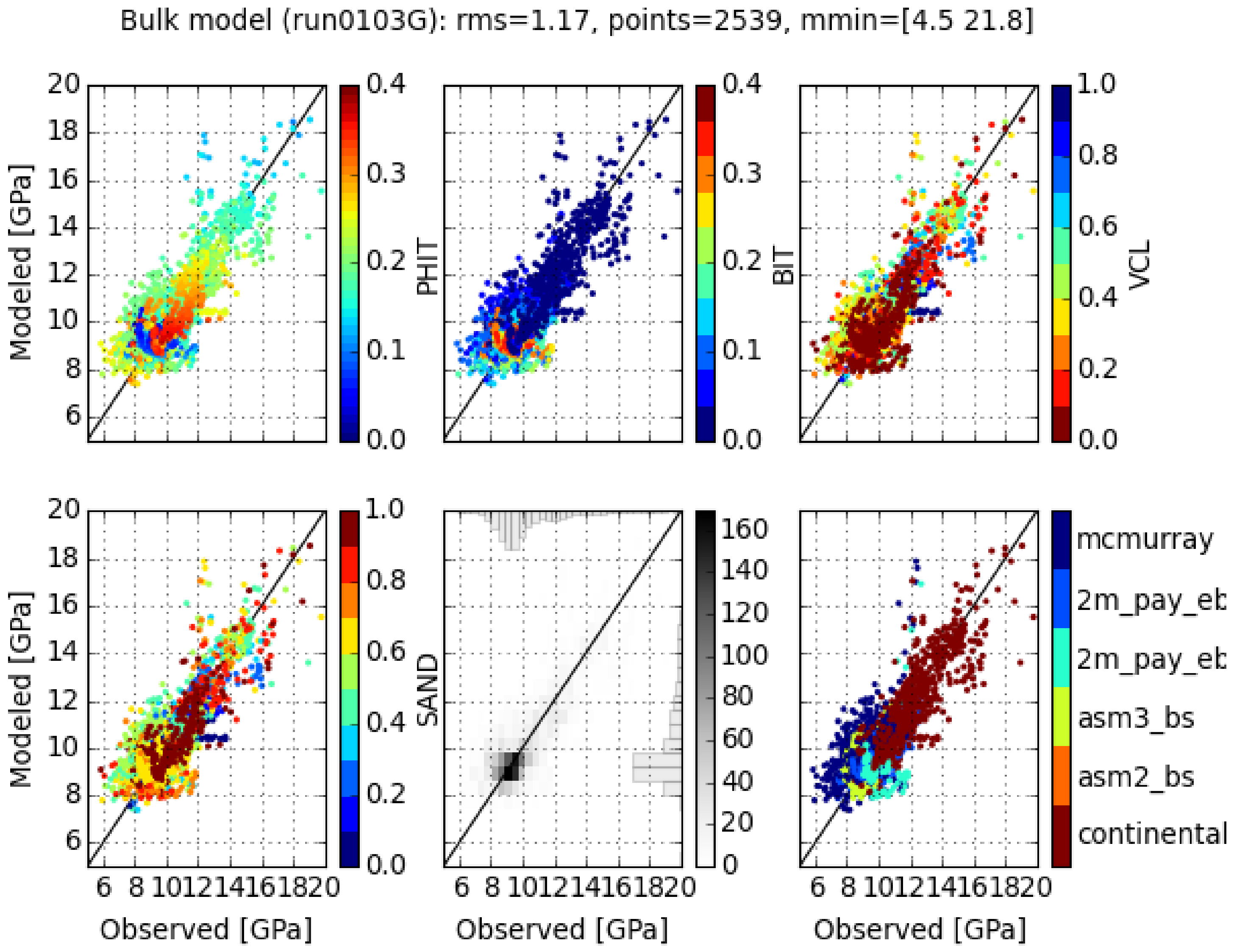
- Create 4D rock physics model
  - Use as basis for interpretation of 4D AVO inversion results.
- Pre-condition seismic data
  - Reduce noise and match data between vintages while preserving the 4D changes due to steam injection and production.
- 4D Low-frequency modeling
  - Investigate effect of band-limited nature of seismic signal on 4D inversion results.
  - Use time-shifts and rock physics analysis to create 4D low-frequency models.
- 4D AVO Inversion
  - Perform simultaneous pre-stack AVO inversion of baseline and monitor surveys to map changes in elastic properties due to thermal heavy oil production

Rock physics modeling

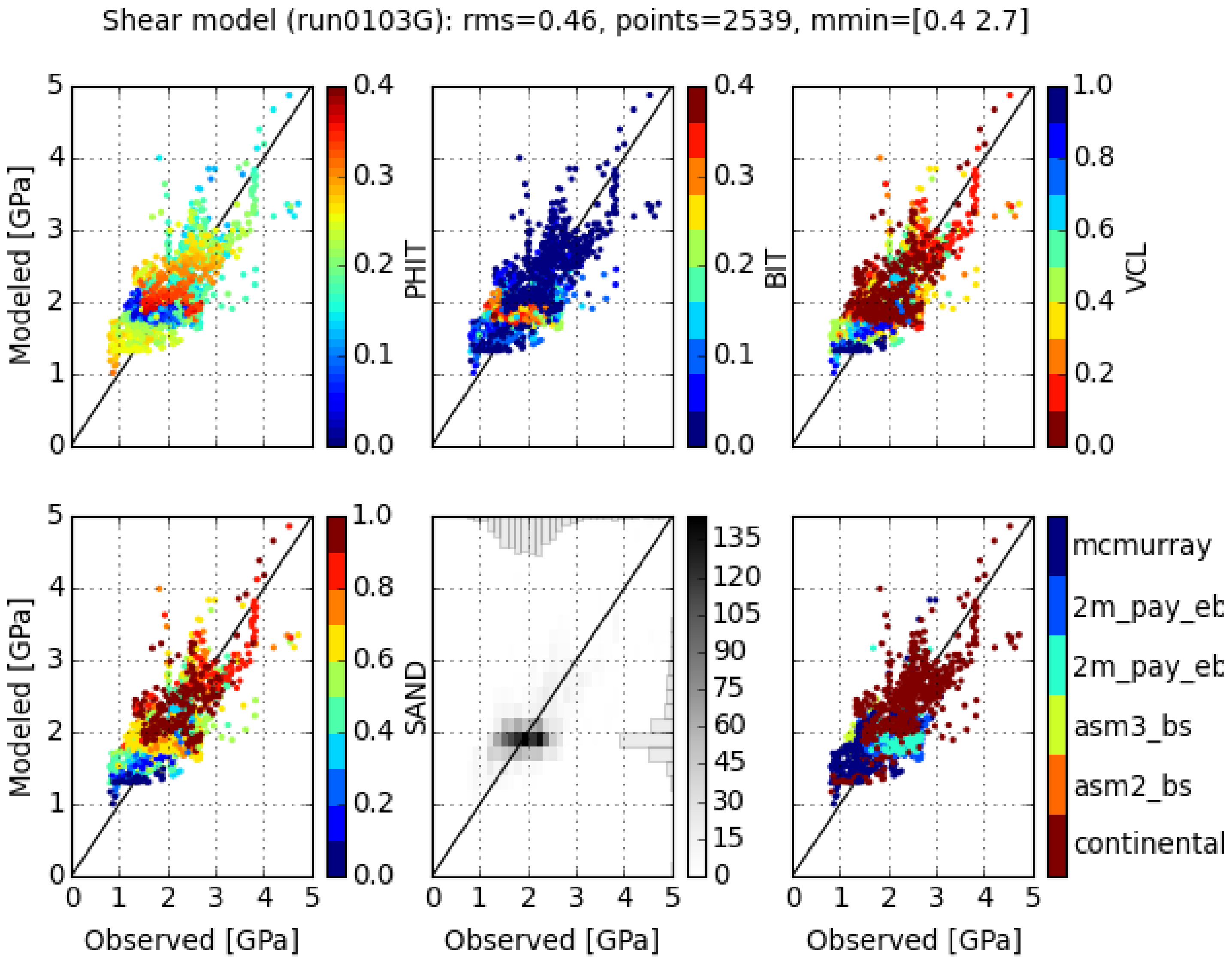
- Conventional rock physics models are not appropriate for oil sands
  - Bitumen has a finite shear modulus
- Strategy
  - Consider bitumen as a third solid mineral in addition to quartz and clay
    - Renormalize petrophysical logs
      - Matrix composed of quartz, clay and bitumen
      - 100 % water saturated porosity
  - Estimate mineral end member properties for in-situ case
  - Replace bitumen with fluids at operating pressures and temperatures
- Non-linear regression-based model that obeys physical bound theory and honours single and multi-mineral fluid substitution theory injection.
  - Connects the elastic moduli of the rock with porosity, mineral fractions, mineral moduli and effective fluid moduli
- Investigate production related changes in elastic properties caused by steam injection
  - Replacement of bitumen with heated oil phase
  - Presence of steam

$$\frac{1}{M+M_0} = \sum(1-\varphi)\frac{v_i}{M_i+M_0} + \frac{\varphi}{M_{fluid}+M_0}$$

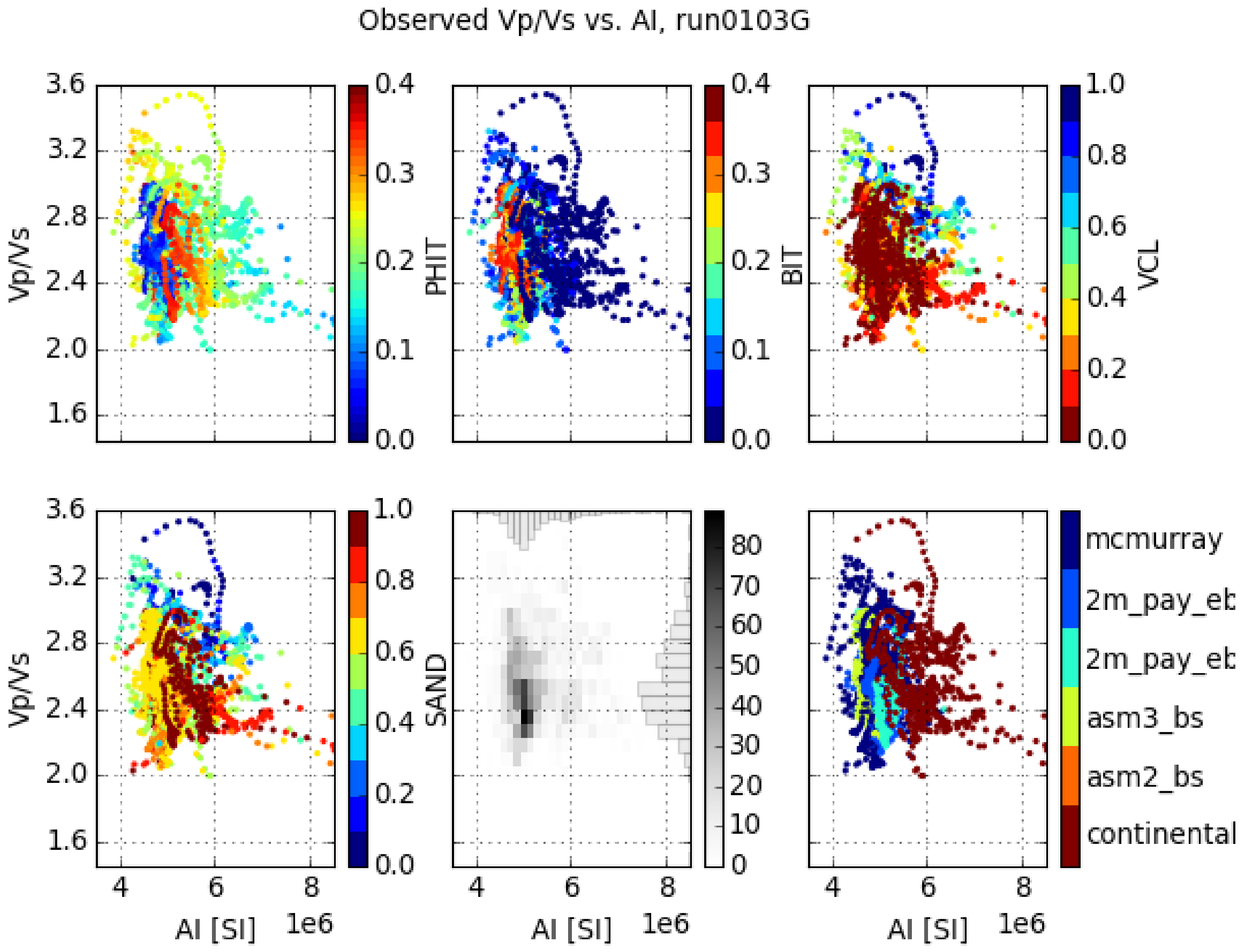
Rock physics modeling: Bulk Modulus



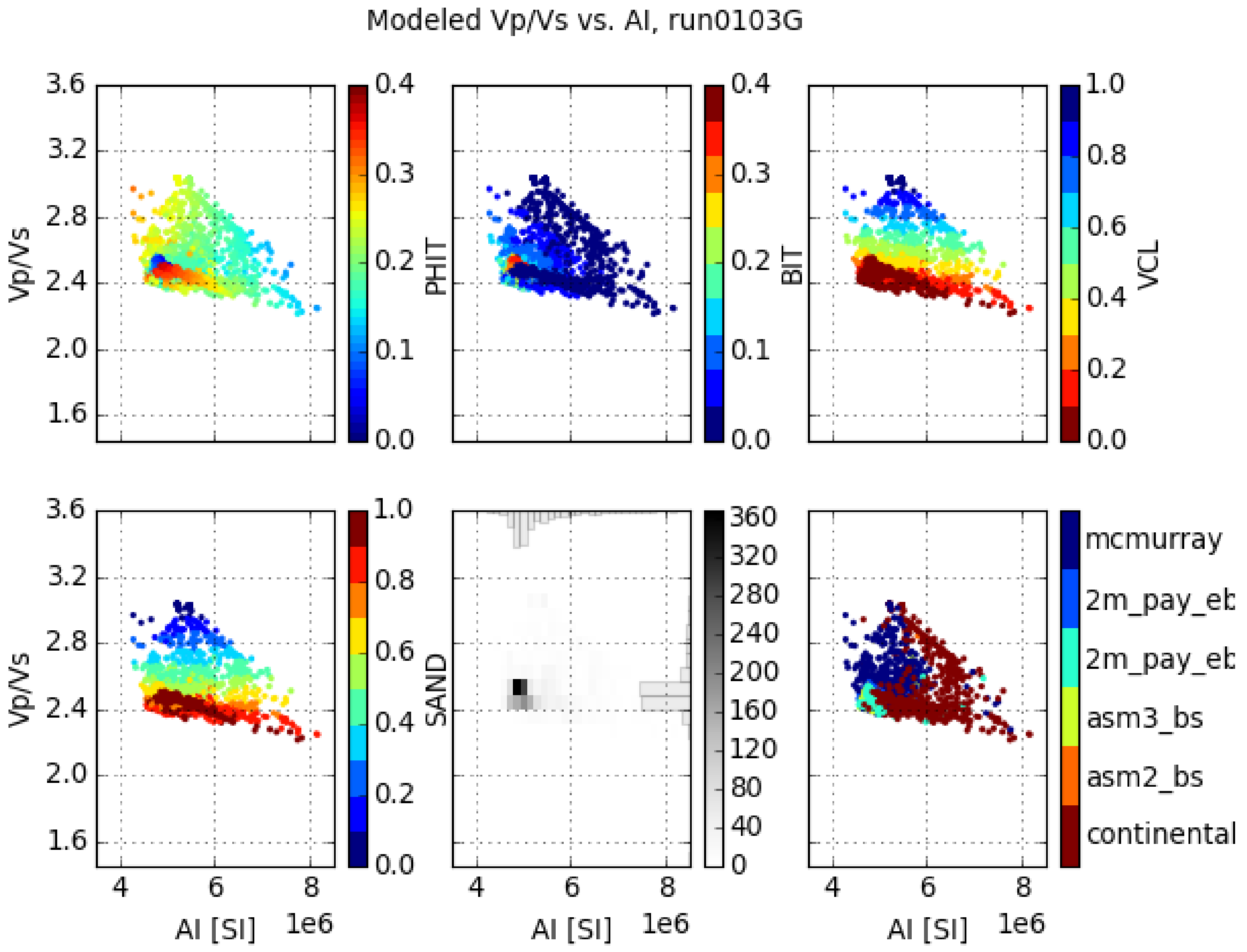
Rock physics modeling: Shear Modulus



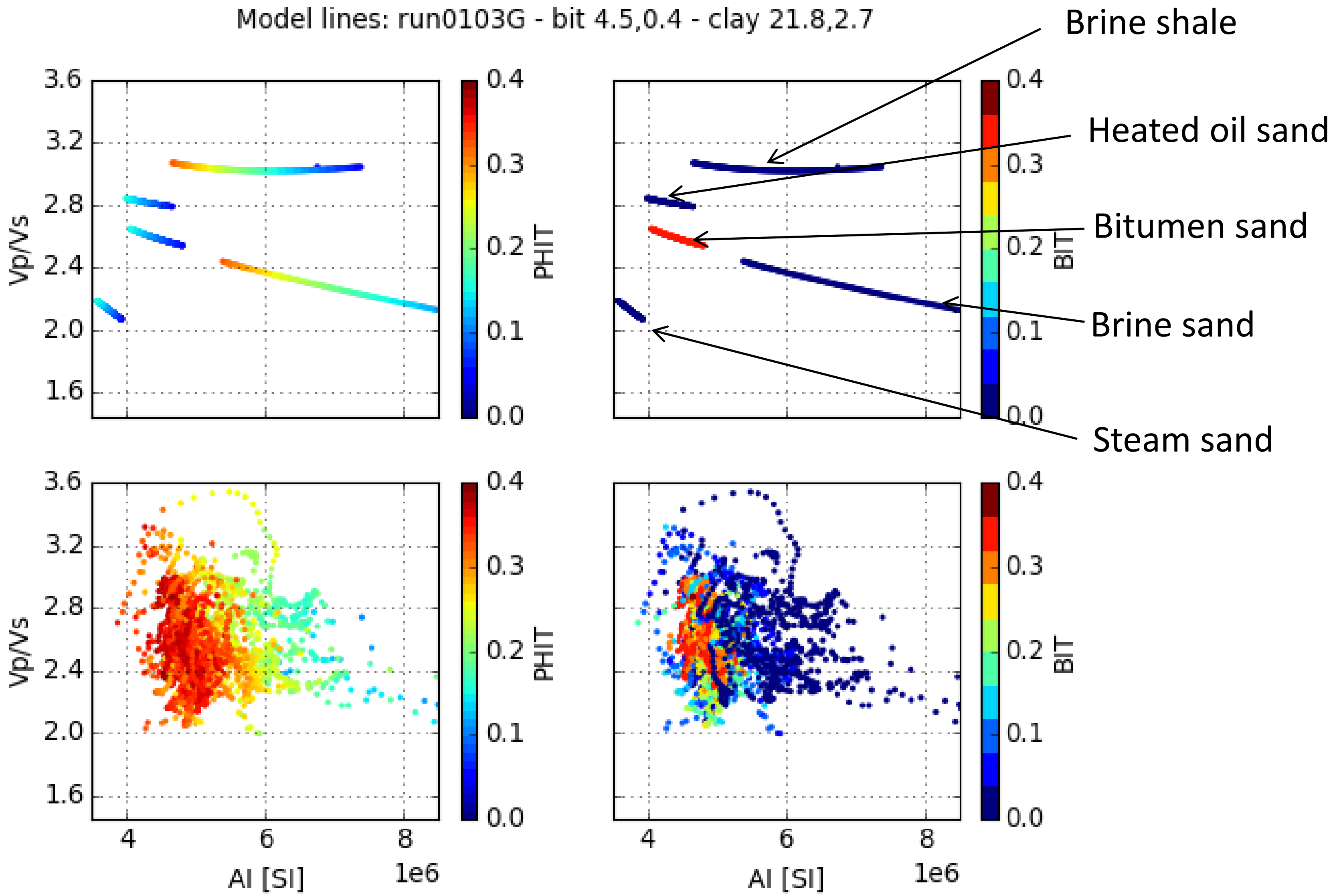
Rock physics modeling: Observed Data



Rock physics modeling: Modeled Data



4D Rock physics model



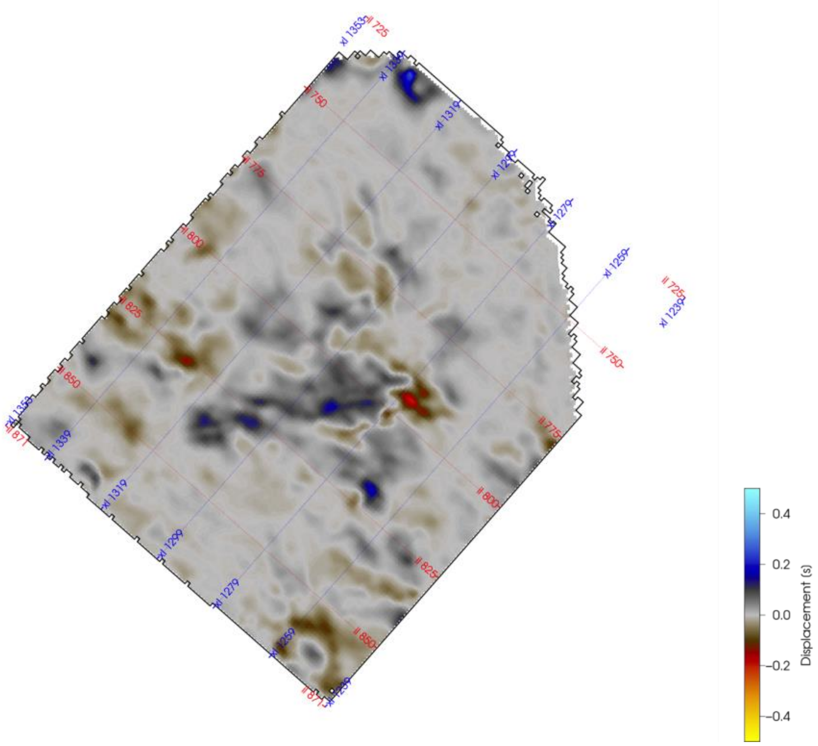
Seismic pre-conditioning

- Tailored pre-conditioning workflow reduces noise while preserving change related to steam injection and production.
  - Without pre-conditioning, 4D anomalies due to differences in acquisition, processing and travel times are incorrectly identified as physical changes in the subsurface.

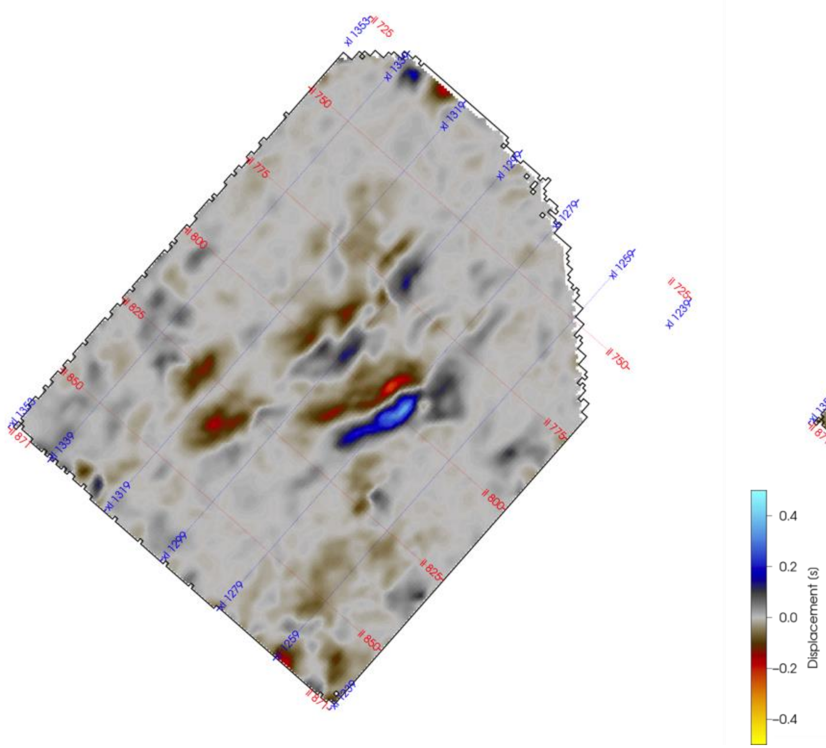
- Workflow includes the following steps:
  - Exponential gain correction
    - Correct for time related differences in amplitude levels.
  - Spectral matching
    - Stabilize spectra between vintages
  - **Seismic warping/alignment**
    - Correct intra-vintage residual move-out and inter-vintage travel time and/or imaging differences.

Seismic pre-conditioning: Warping displacement

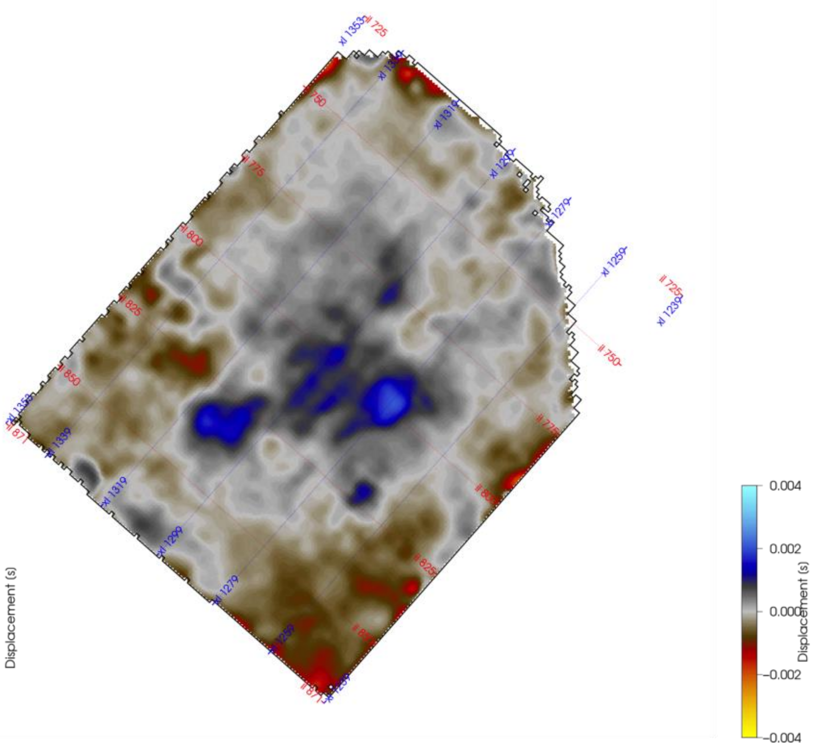
Inline



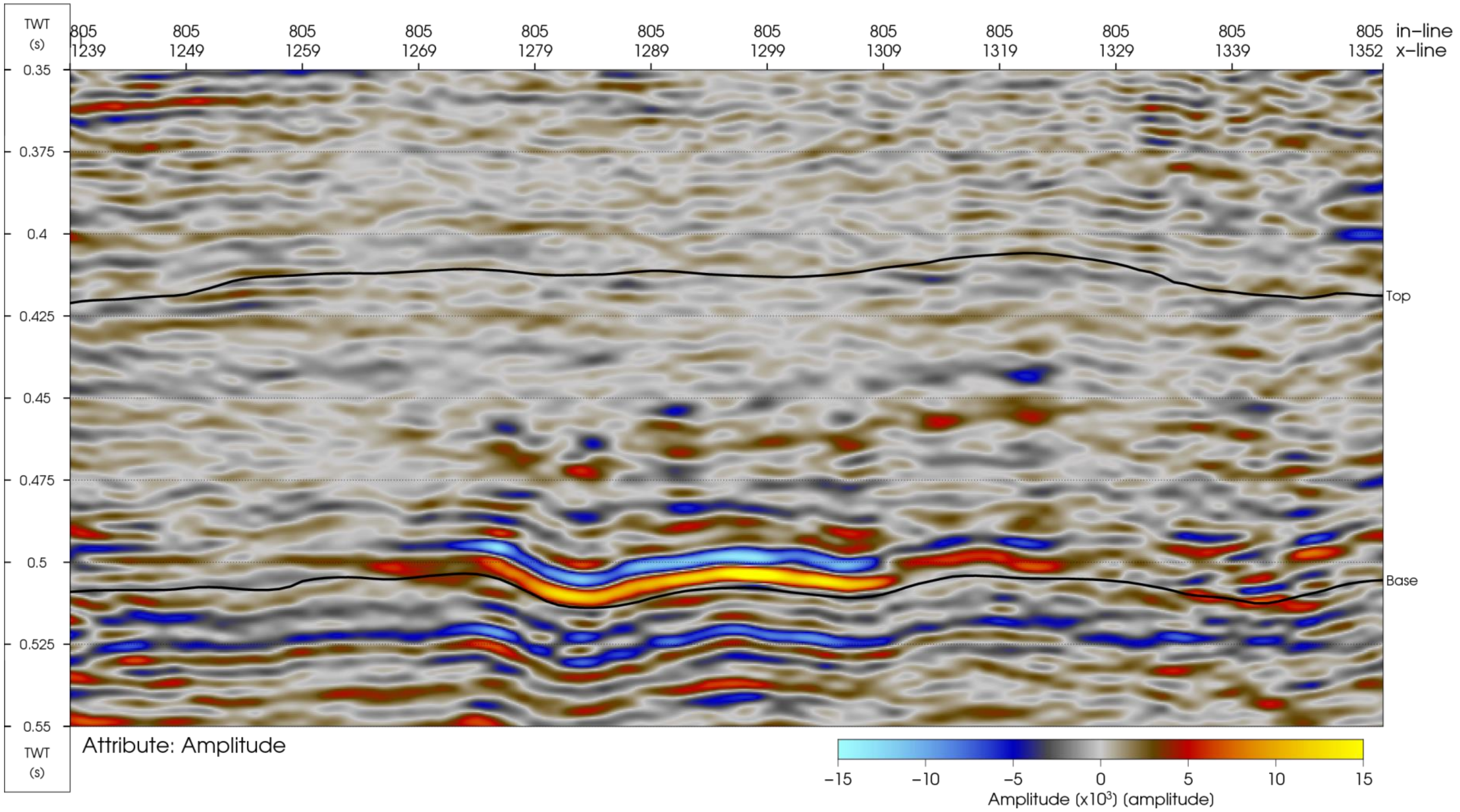
Cross-line



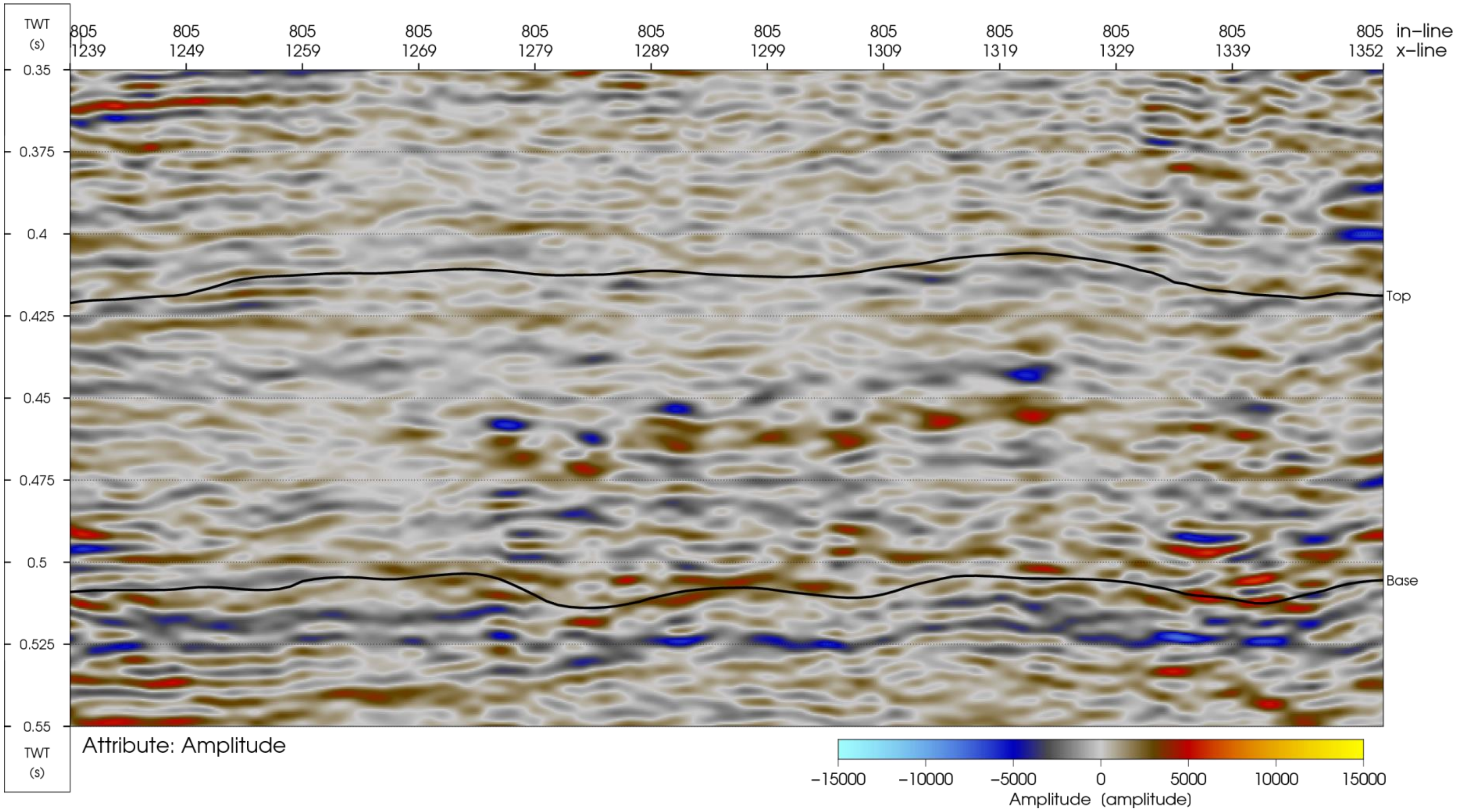
Time



Seismic pre-conditioning: Before pre-conditioning

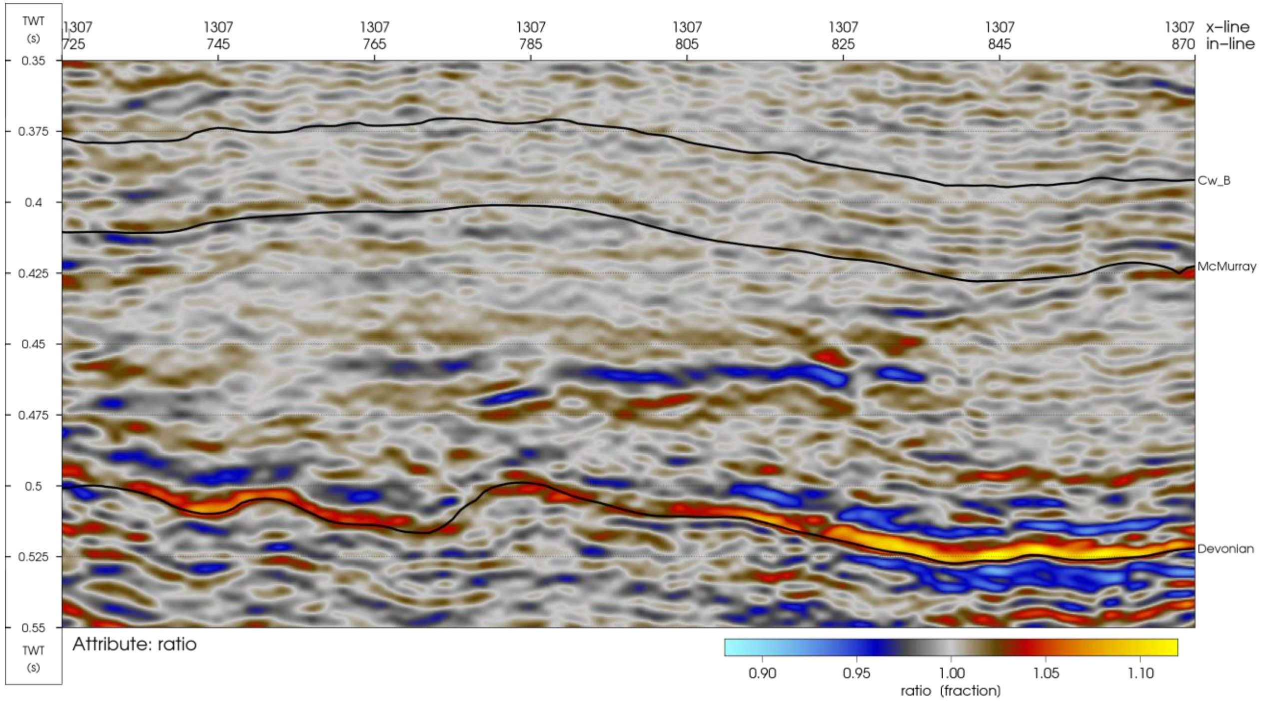


Seismic pre-conditioning: After pre-conditioning

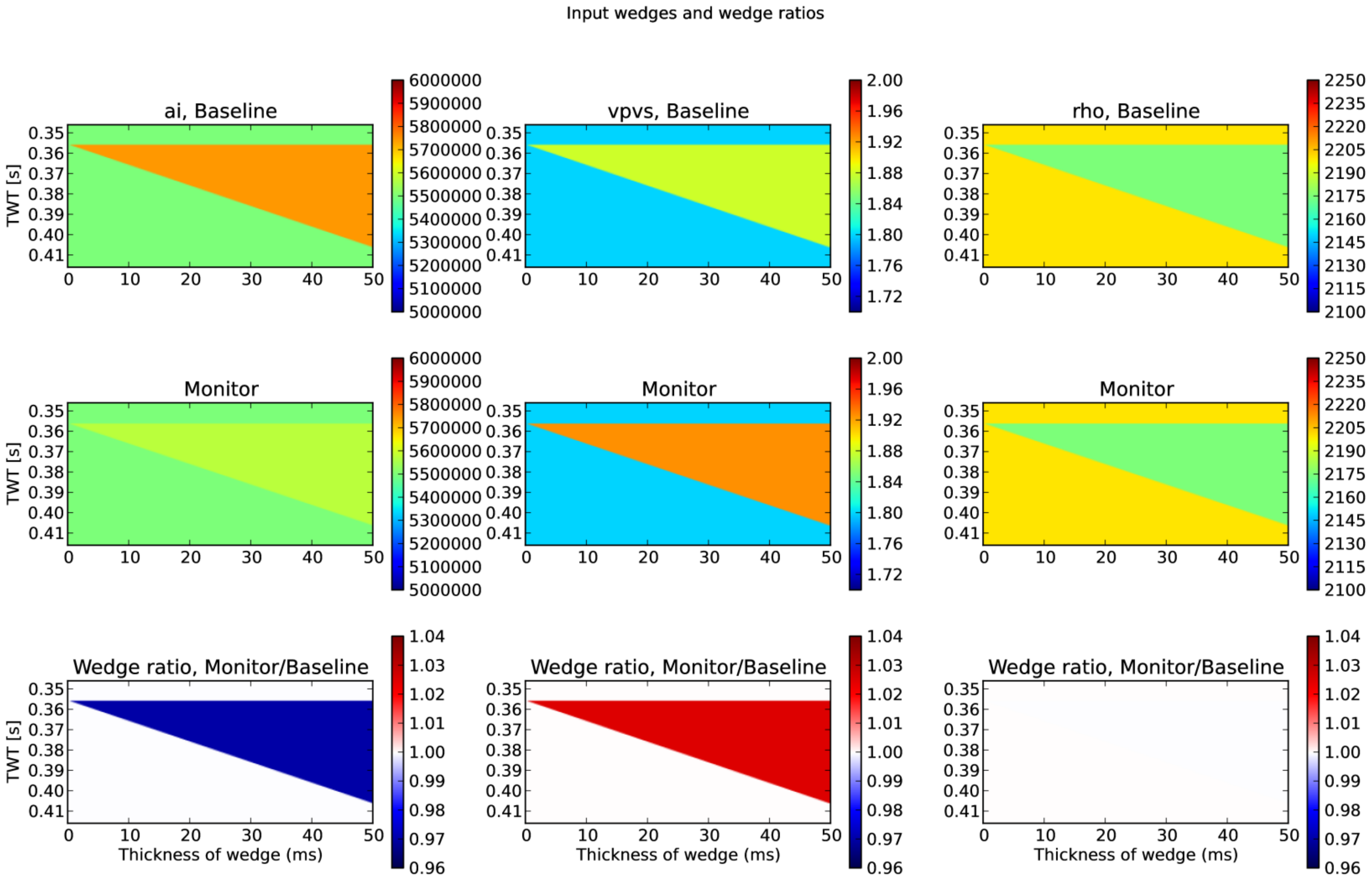


Low-frequency modeling

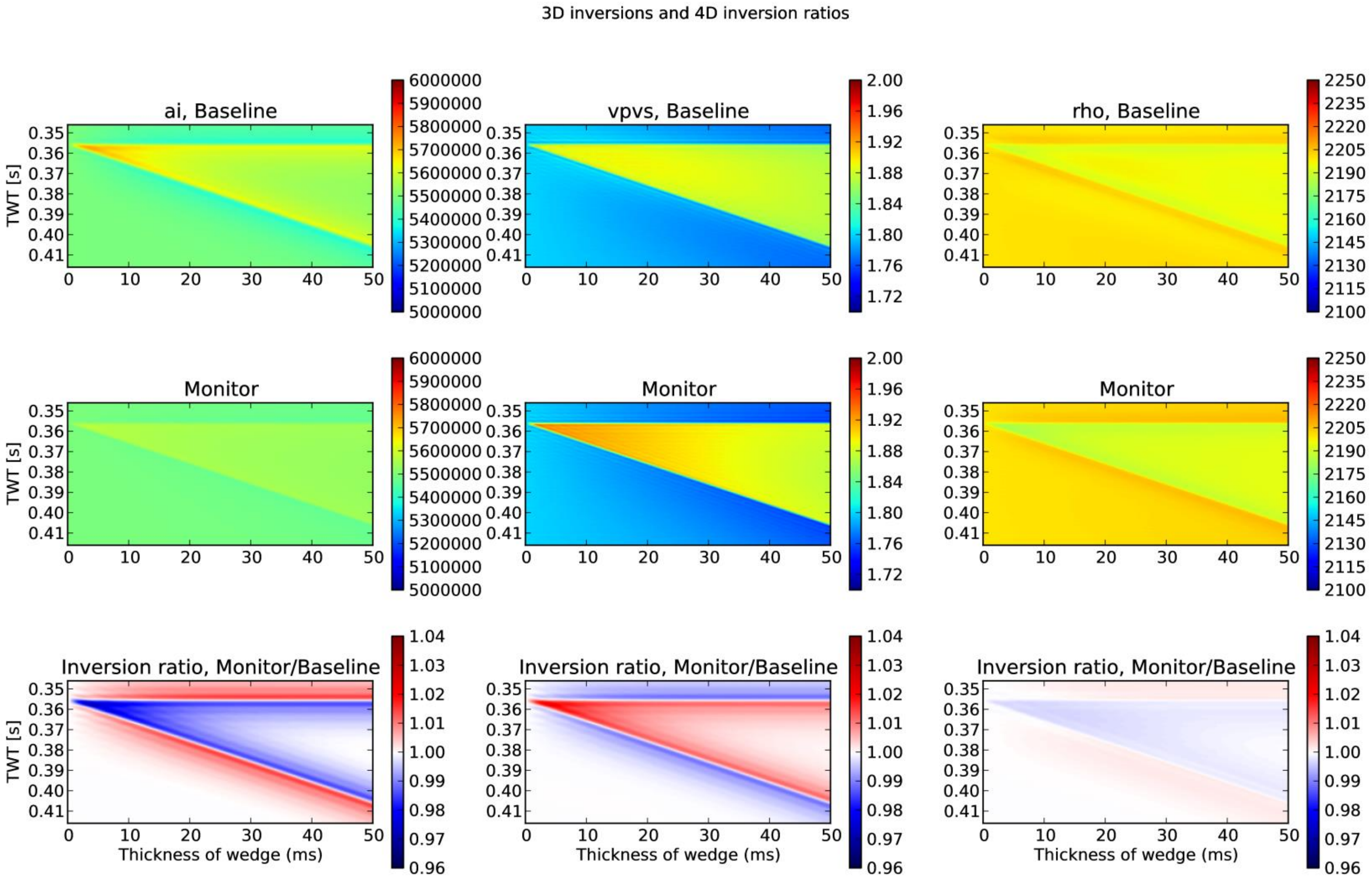
- Relative 4D inversion results are difficult to interpret.
  - Apparent “bounding” of decreases in AI, Vp/Vs by increases above and below.
- Investigate effect of band-limited nature of seismic data on 4D inversion results using wedge modeling.



Low-frequency modeling: Wedge modeling-full bandwidth



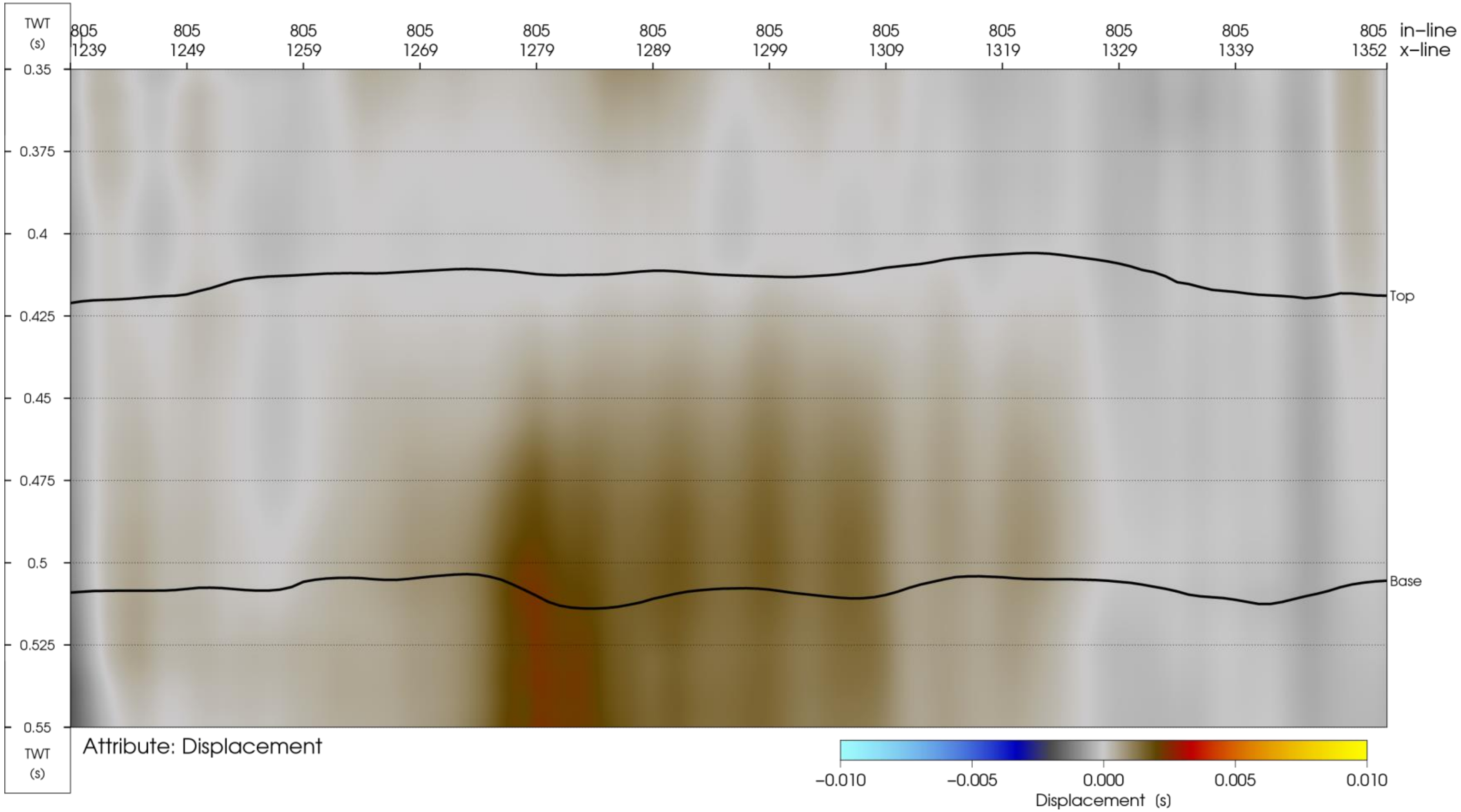
Low-frequency modeling: Wedge modeling-band-limited



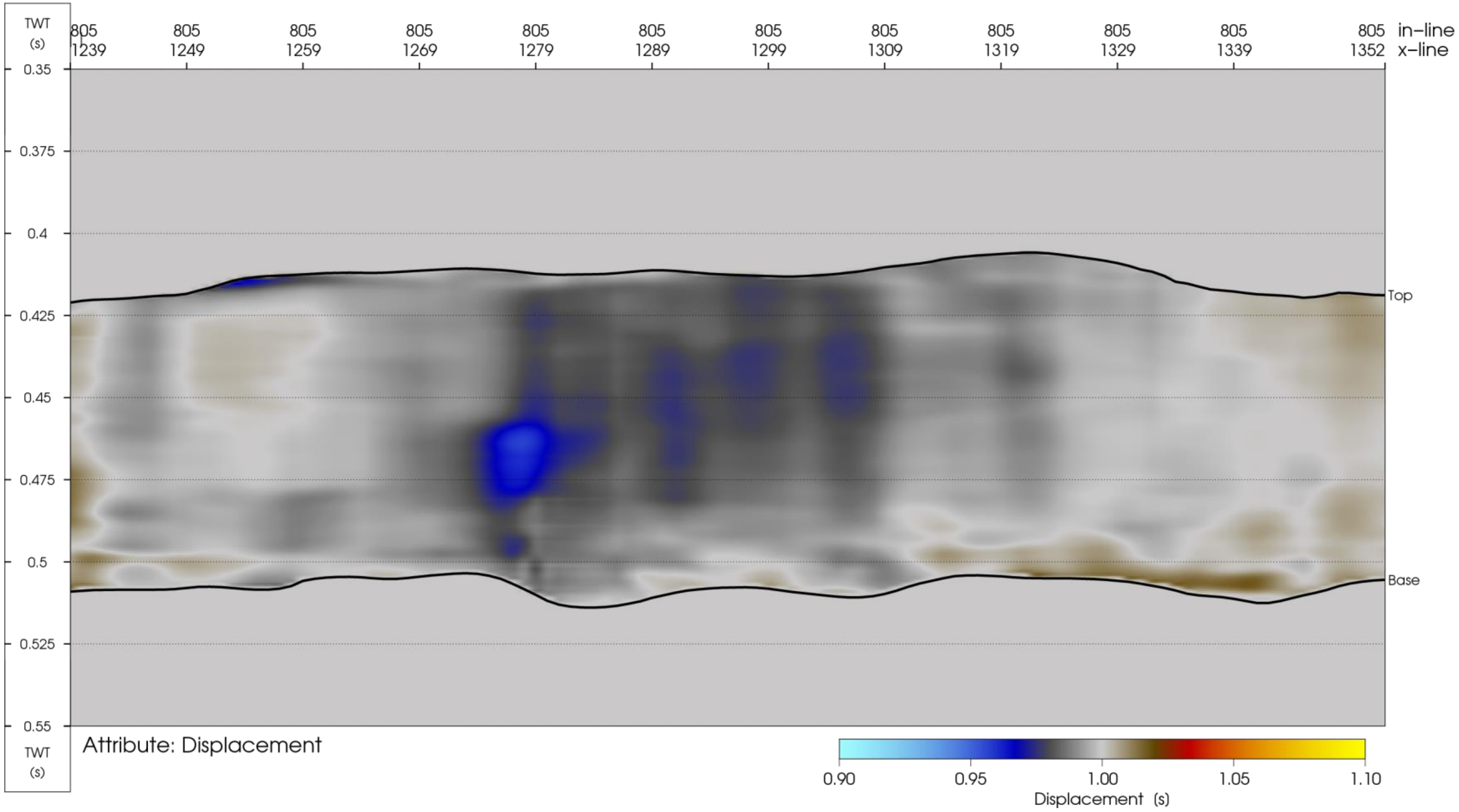
Low-frequency modeling

- To optimize inversion results, missing low-frequencies must be derived from mean other than seismic.
  - Typical 3D low-frequency modeling methods such as extrapolating low-pass filtered well log trends not available in 4D sense.
- Under assumption of non-compacting reservoir, 4D time shifts can be differentiated to produce a dVp field that can be used as an input for AI.
- 4D Vp/Vs model can be approximated using probabilistic facies classification of relative inversion results informed by rock physics modelling (similar to Nassar et al. (2016)).
  - In dAI, dSI space, classify increases in AI and SI as lobe energy, and discriminate between steam response and heated oil response by comparing relative change of AI and SI.
  - If 3C data were available, a more robust, optimum 4D Vp/Vs model can be created using time shifts of both PP and PS data (Gray et al. (2016)).

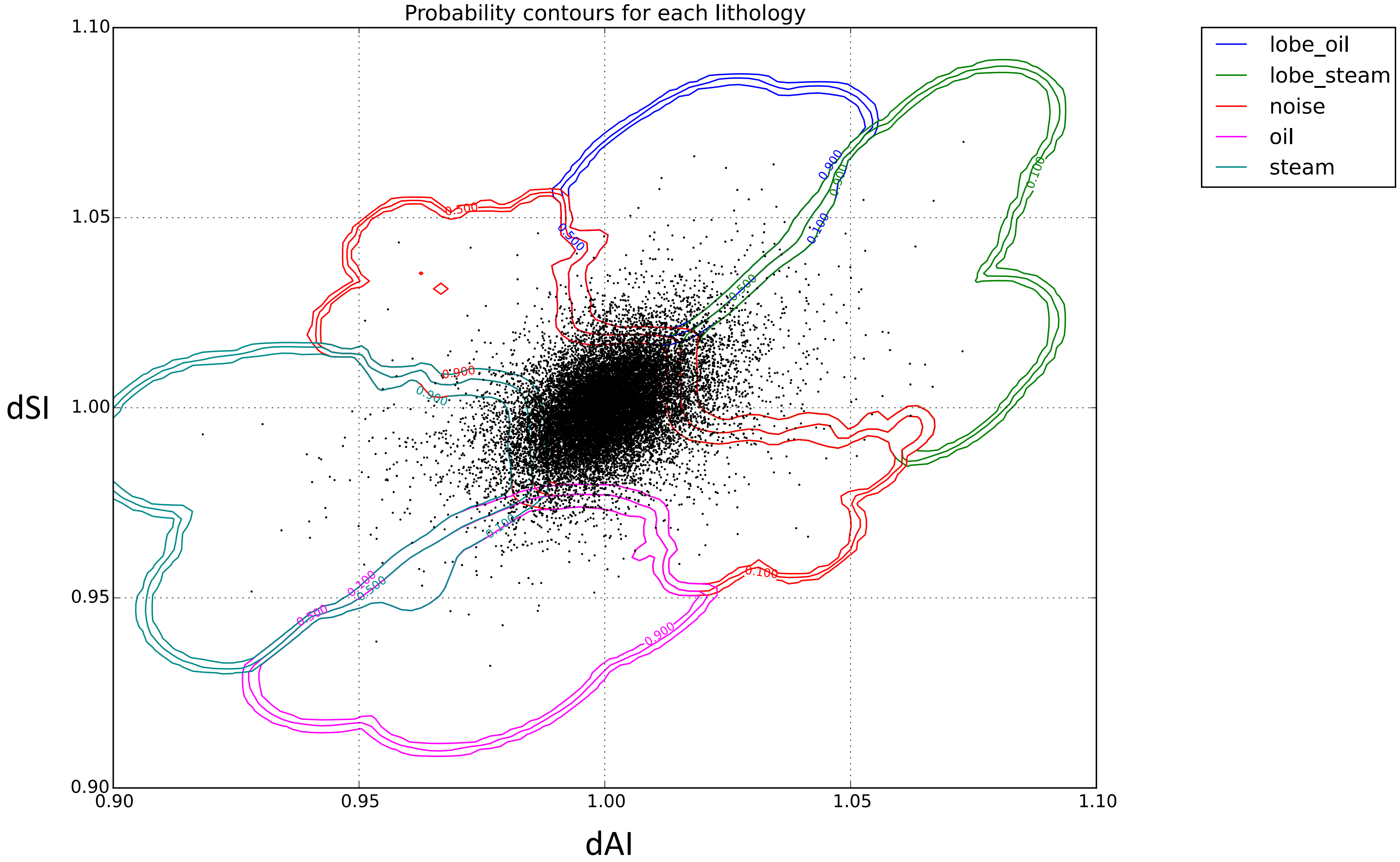
Low-frequency modeling: 4D time-shifts



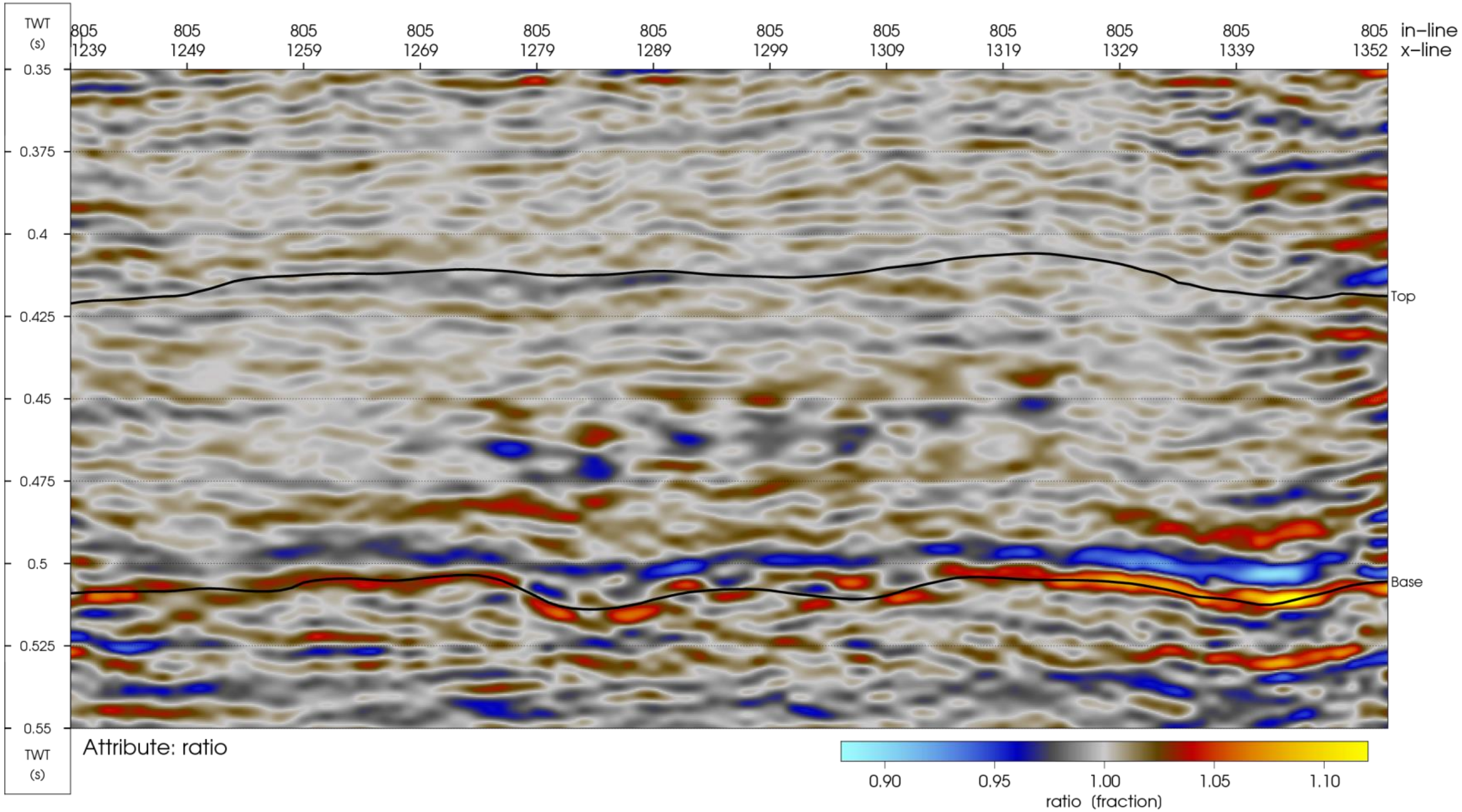
Low-frequency modeling: 4D AI low-frequency model



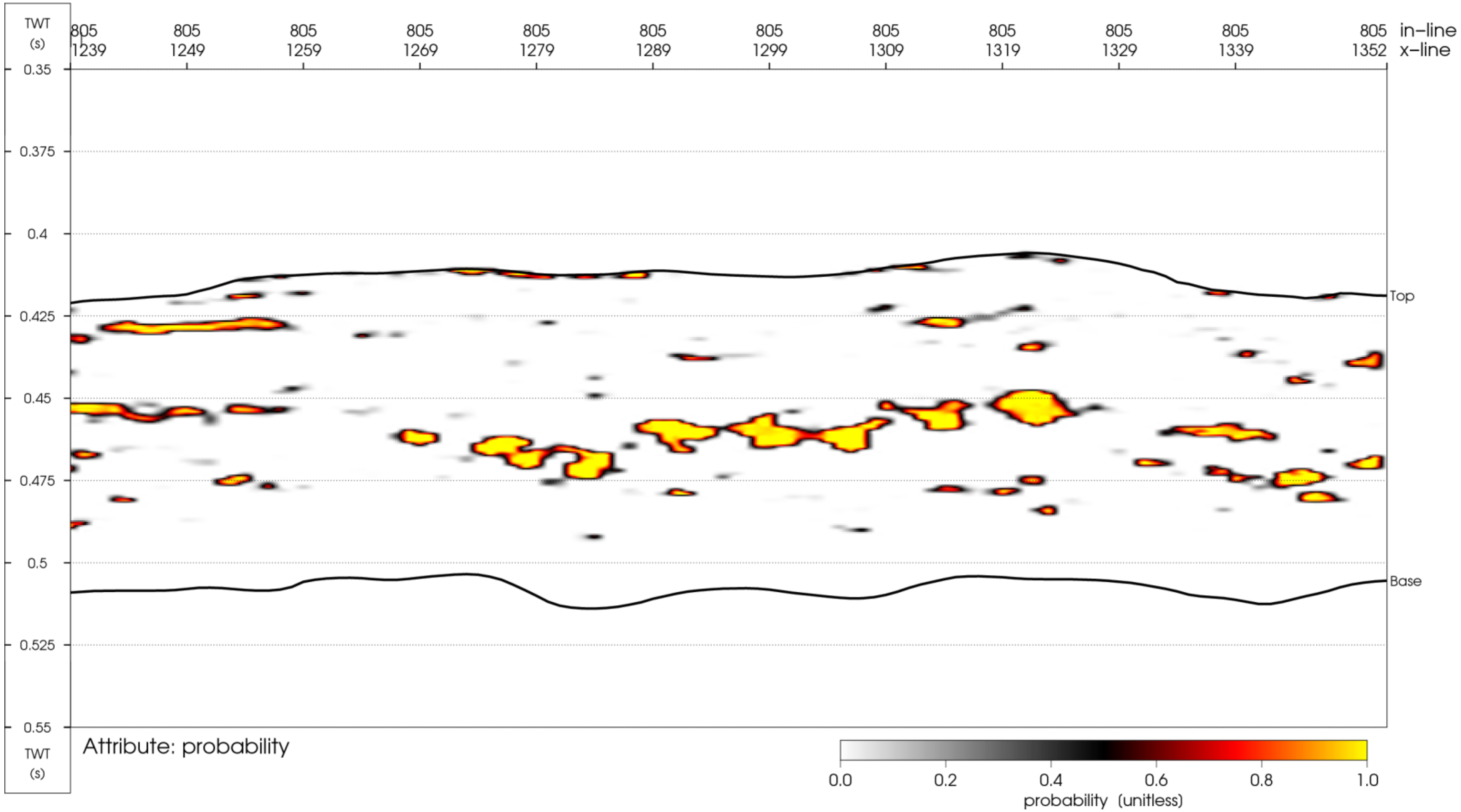
Low-frequency modeling: Probabilistic classification



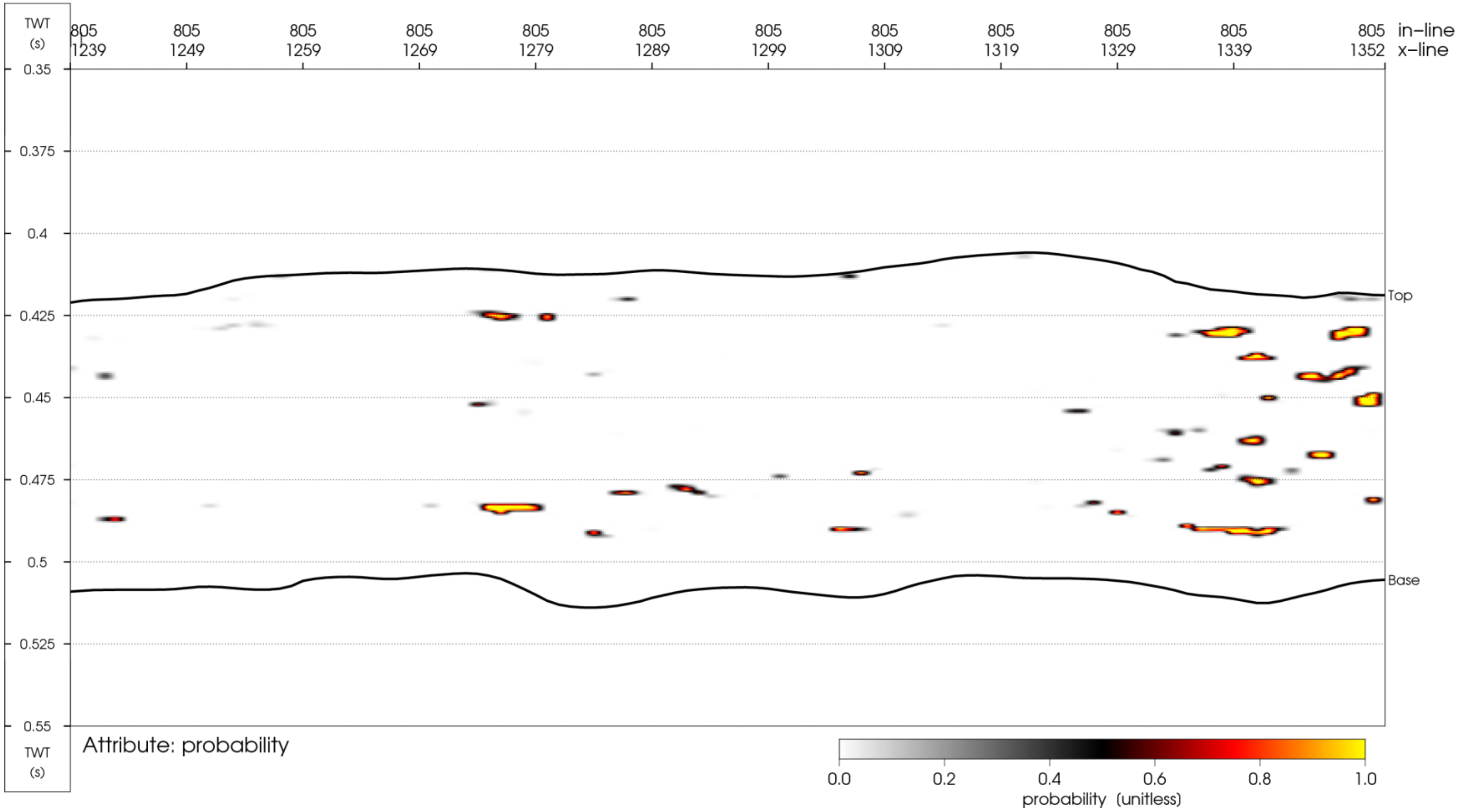
Low-frequency modeling: Relative Vp/Vs inversion results



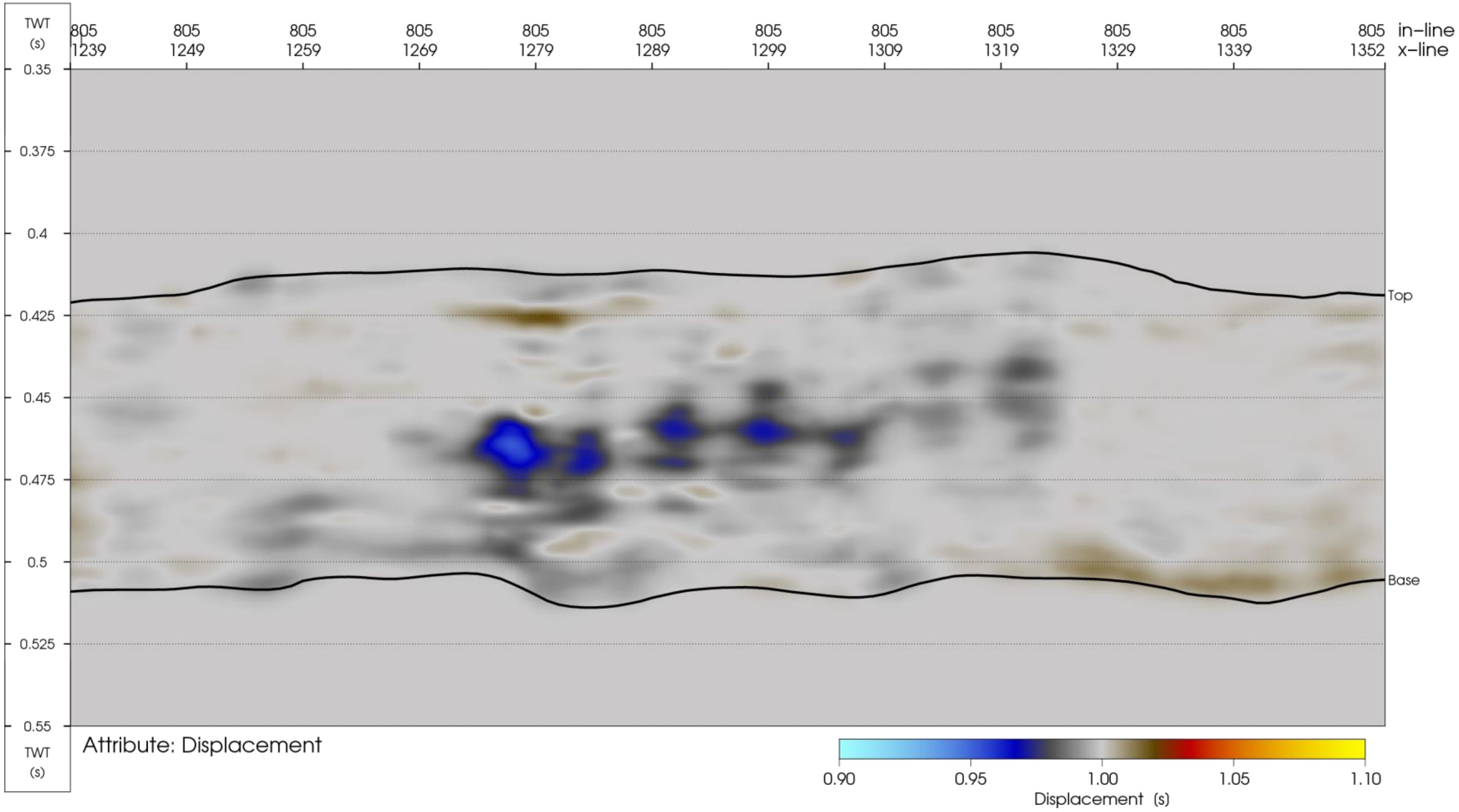
Low-frequency modeling: Probabilistic classification-steam



Low-frequency modeling: Probabilistic classification-oil



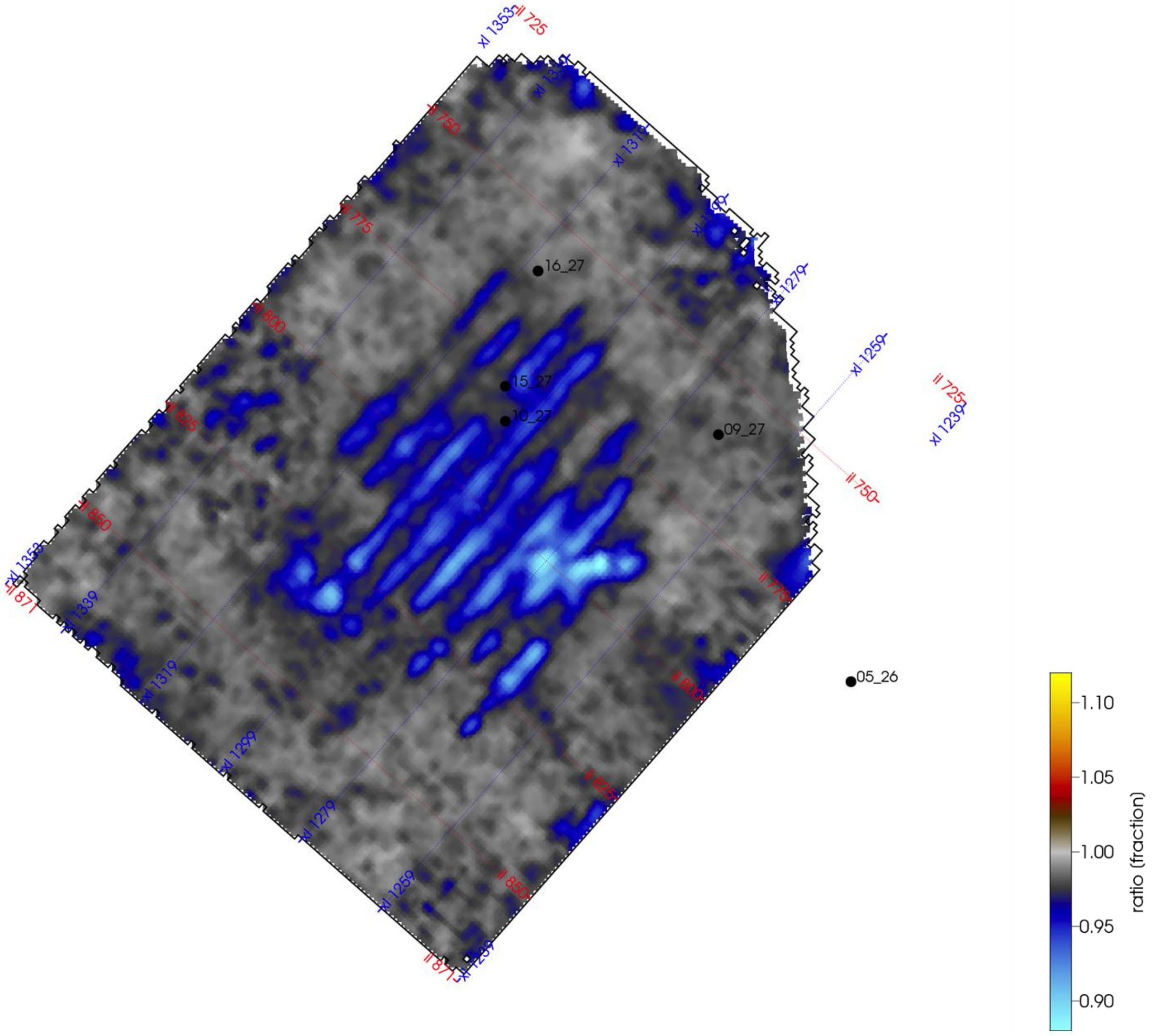
Low-frequency modeling: 4D Vp/Vs low-frequency model



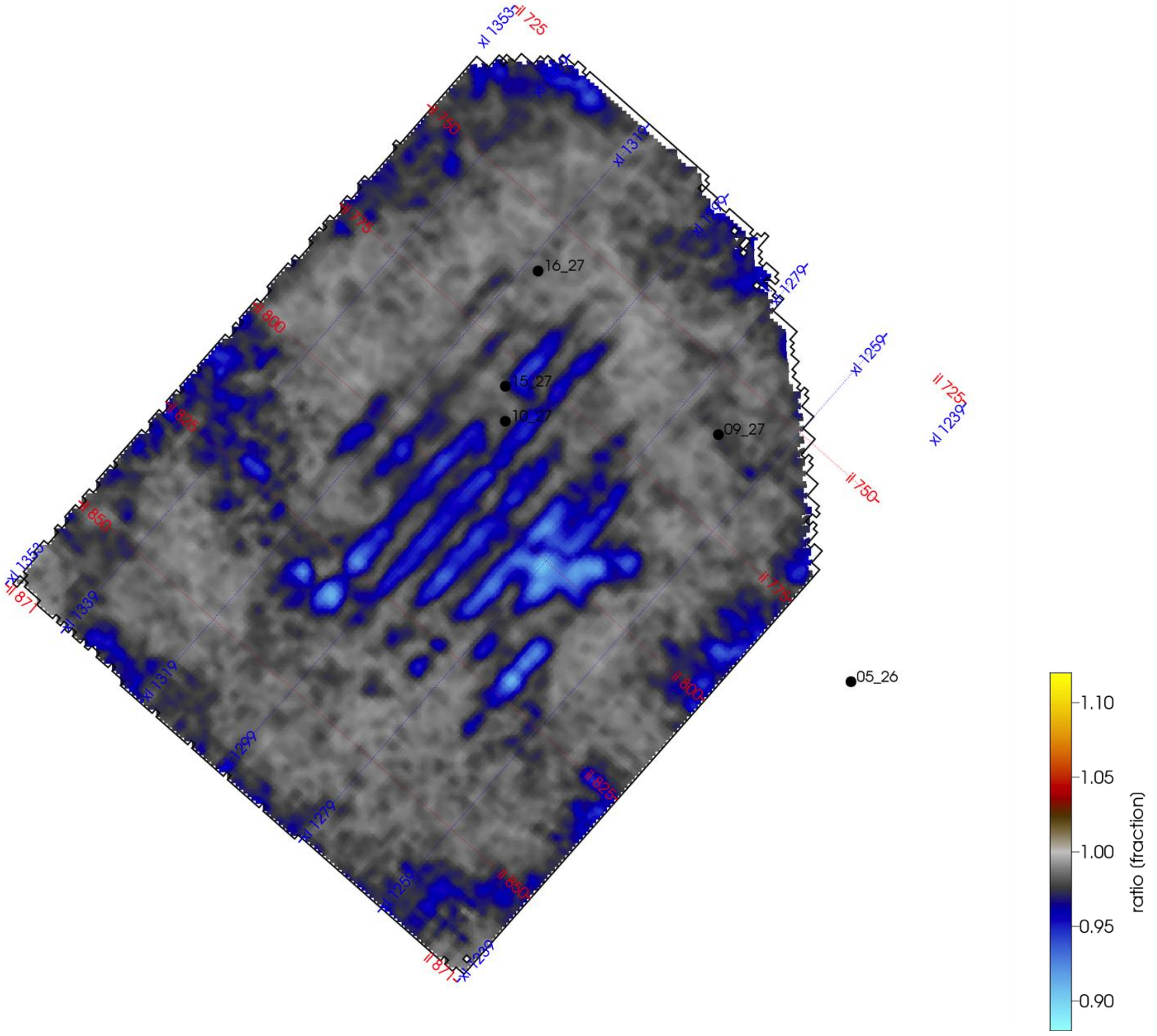
Results

- 4D AVO inversion using the 4D AI and 4D Vp/Vs models as input to the inversion.
  - Simultaneous pre-stack inversion of both vintages. Six angle-stacks per vintage.
  - Inclusion of low-frequency models reduces the observed side-lobes and improve interpretability of results.
- Steam response is observed along all well-bores in spite of the monitor survey being acquired after only approximately 6 months of steaming.
- Possible heated oil response is observed in some areas as evidenced by an increase in Vp/Vs and a decrease in AI.

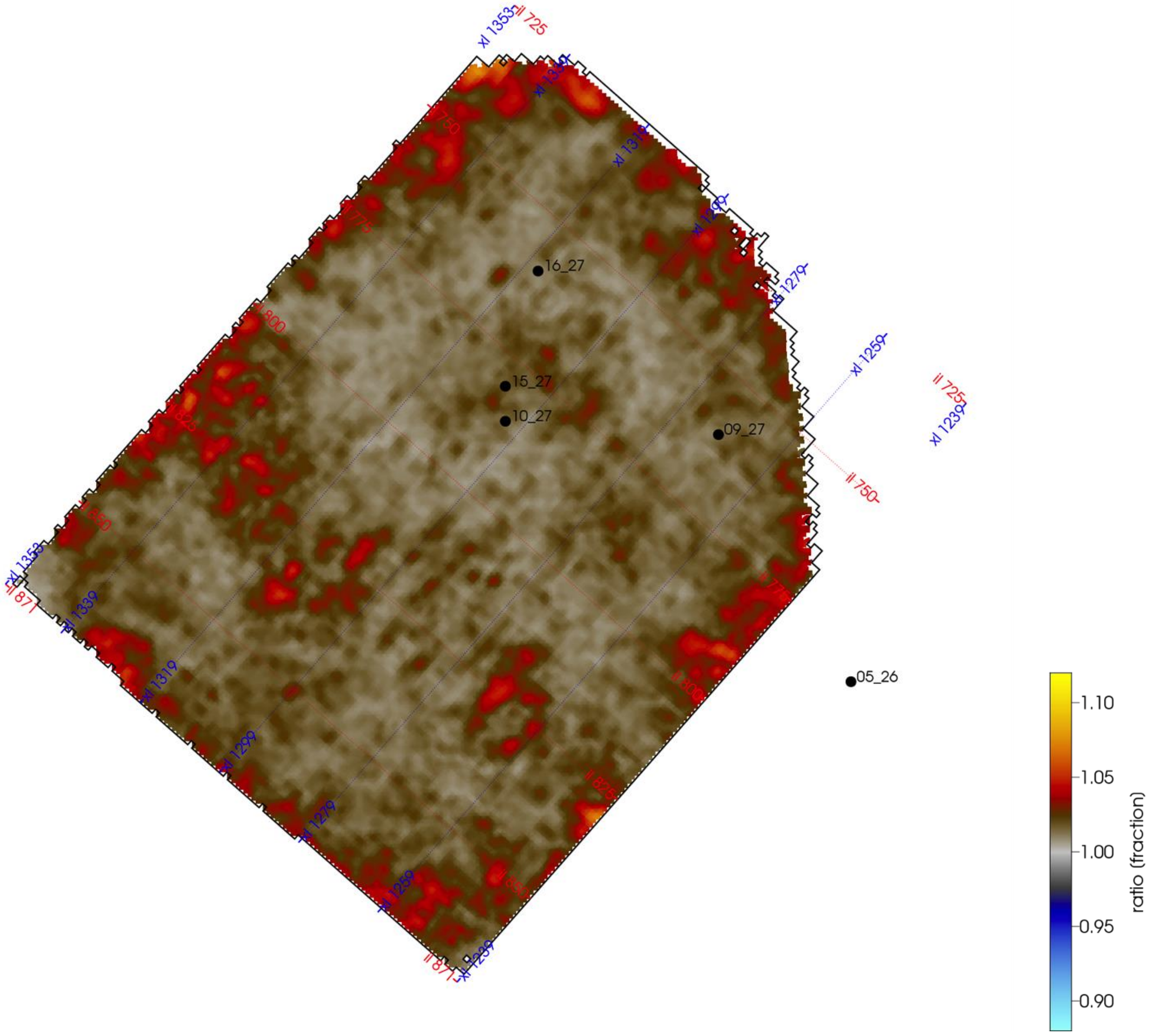
Results: AI decrease extracted through reservoir interval



Results: Vp/Vs decrease extracted through reservoir interval



Results: Vp/Vs increase extracted through reservoir interval



Conclusions

- 4D AVO inversion workflow allows us to estimate changes in elastic properties due to thermal heavy oil production.
- Quantifying elastic property changes removes the ambiguity of 4D anomalies associated with amplitude differences.
    - 4D rock physics modeling is essential to inform the interpretation of inverted properties. Allows discrimination between steam and heated oil response.
- Goal is to use 4D elastic changes to perform 4D rock physics inversion that quantifies changes in fluid, pressure, temperature.
    - De-coupling of fluid, temperature and pressure effects is continued source of uncertainty in interpretation of elastic results.
    - Properly calibrated 4D rock physics model requires actual measurements of elastic changes during steaming/production.
    - To limit bias of inversion results, 4D calibration points in the form of observation well data or production data should be used.

Acknowledgements

- CREWES sponsors, staff and students
- NSERC through grant CRDPJ 379744-08
- Mitacs Accelerate
- Qeye Labs
- Nexen CNOOC Ltd.
- Dr. David Cho, Dr. Kris Innanen, Byron Kelly and David Gray
- Key Seismic for processing the data