Imaging and Full Waveform Inversion of seismic data from the CO_2 gas cloud at Sleipner

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Background

- The applications of full waveform inversion (FWI) on synthetic and field data the last decade have proved that FWI is a promising method for parameter model estimation
- The increase in computational power leads to an increase in possible problem sizes and type of wave phenomena included in the modeling and inversion
- Limited number of 3D applications in the literature

Objectives

- Apply three dimensional elastic isotropic FWI on field time-lapse data from the Sleipner area
- Use the inverted elastic models to obtain depth migration seismic images of the area before and after ten years of injection of CO_2.
- Investigate the migration path for the injected CO_2 gas.

Outline

- Theory
  - Full waveform inversion
  - Imaging work flow
- Results
  - Baseline inversion
  - Monitor inversion
  - Seismic images
- Conclusions

A quick overview of full waveform inversion

Overall goal

Find a parameter model from which it is possible to create synthetic data that is close to some measured data

Define $S(\mathbf{m})$ as the measure between synthetic and measured data. The FWI is then the problem

$$\arg\min_{\mathbf{m}} S(\mathbf{m})$$

A quick overview of full waveform inversion

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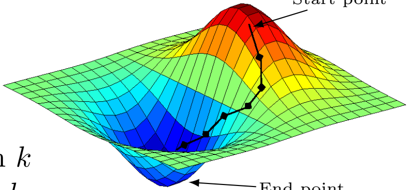
$$\arg\min_{\mathbf{m}} S(\mathbf{m})$$

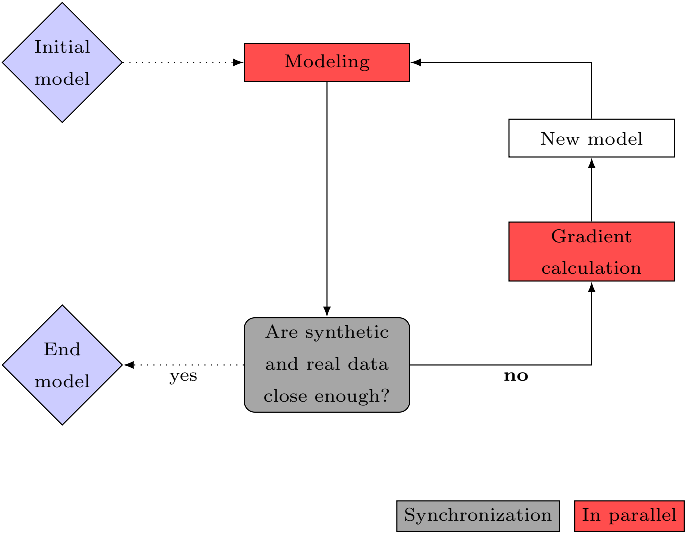
Solved using an iterative method

$$\mathbf{m}_{k+1} = \mathbf{m}_k - \alpha_k \mathbf{H}_k^{-1} \mathbf{g}_k,$$



$\mathbf{m}_k$	model at iteration k
$\mathbf{g}_k$	gradient of $S(\mathbf{m})$ at iteration k
$\mathbf{H}_k$	Hessian of $S(\mathbf{m})$ at iteration k
α_k	step length at iteration k

Schematic view of FWI



Time-lapse full waveform inversion

Goal

Use full waveform inversion to quantify changes in time for parameters affecting wave propagation.

May be used

- as monitoring tool during the life-time of a reservoir
- to monitor injection of CO_2 in CCS experiments
- quantify amount of injected CO_2

Time-lapse full waveform inversion

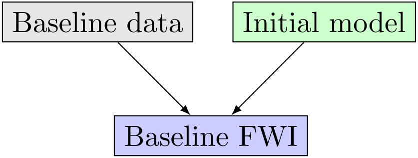
Goal

Use full waveform inversion to quantify changes in time for parameters affecting wave propagation.

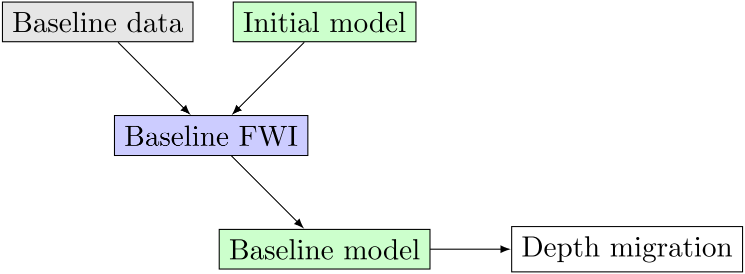
Challenges

- Need to perform at least two inversions
- The method may introduce artifacts in the time-lapse images due to for instance
  - non-linearity
  - ill-posedness
  - data differences
  - bad repeatability in the time-lapse data

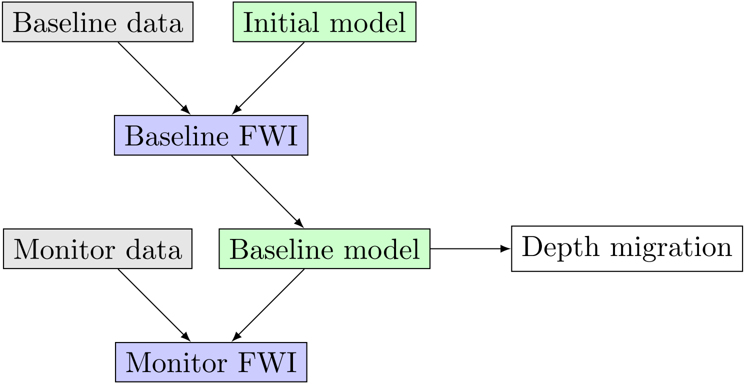
Seismic imaging work flow



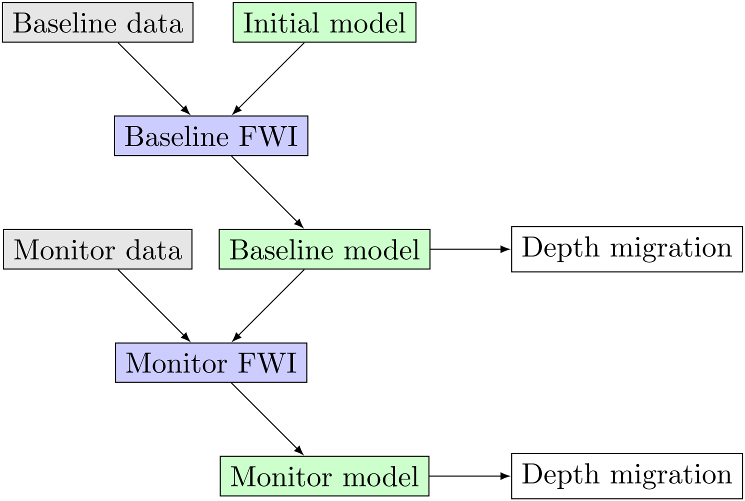
Seismic imaging work flow



Seismic imaging work flow

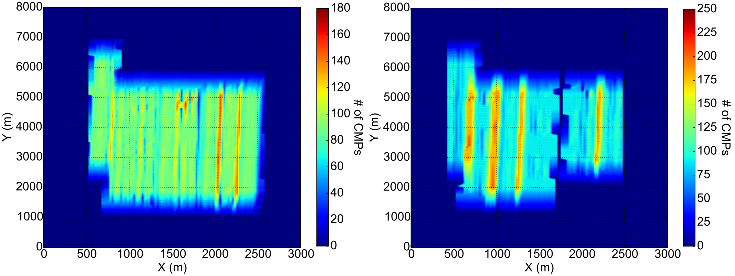


Seismic imaging work flow



Results: Sleipner data details

- Baseline dataset: 1994 survey
  - 852 shots, 570840 data traces
  - 1700 m offset
- Monitor dataset: 2006 survey
  - 1180 shots, 1274400 data traces
  - 1700 m offset

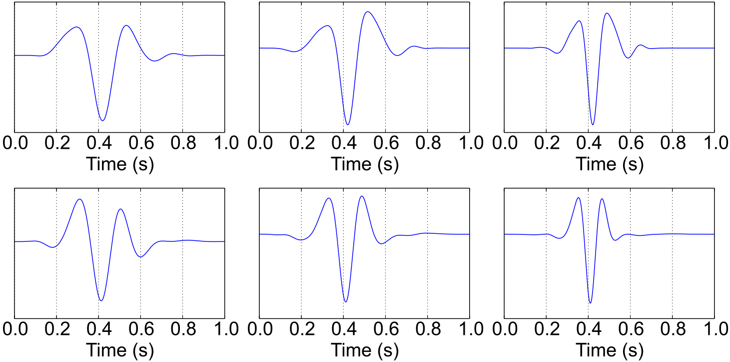


Fold maps: left: baseline, right: monitor.

Inversion strategy

- Invert for v_p, and couple v_s and ρ using empirical relationships
- Invert sequentially using the frequency bands: 6–8Hz, 6–11Hz, 6–15Hz.
- Source signatures are estimated using FWI
- First, invert for baseline data to obtain a baseline elastic model
- Second, use target-oriented FWI when inverting for the monitor data

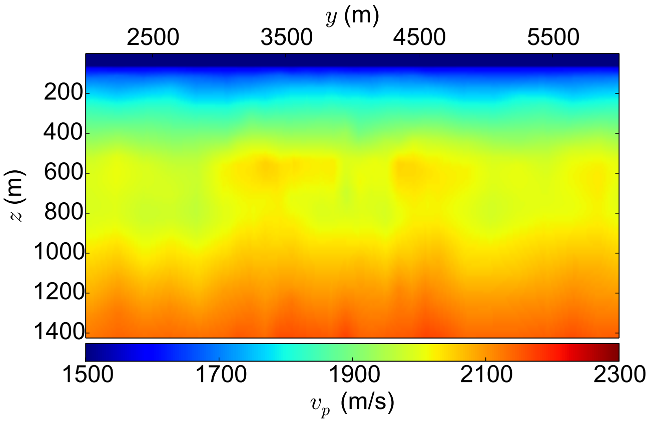
Estimated source signatures



Source signatures: top: baseline dataset, bottom: monitor dataset.

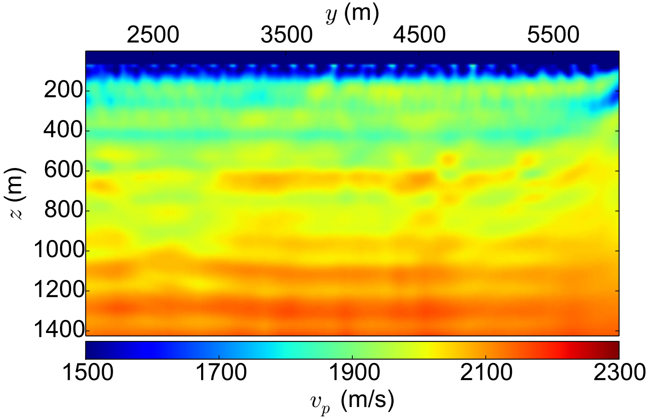
Left: 6–8 Hz, middle 6–11 Hz, right: 6–15 Hz.

Baseline FWI: Vertical slice



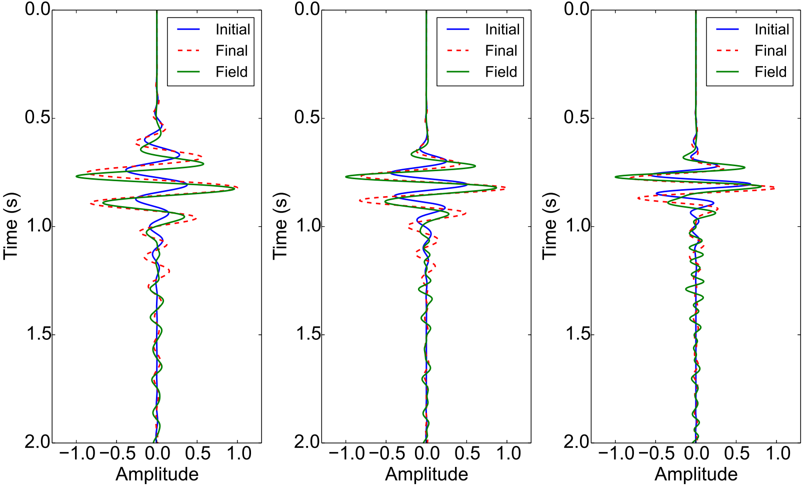
Initial model

Baseline FWI: Vertical slice



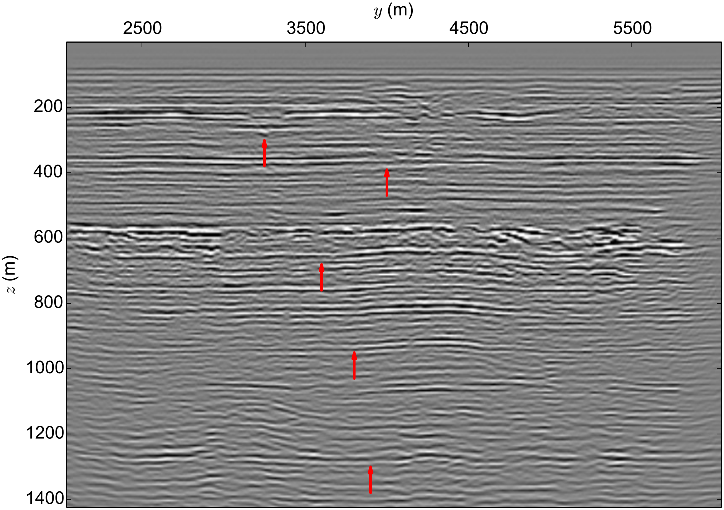
Final model

Baseline FWI: Data



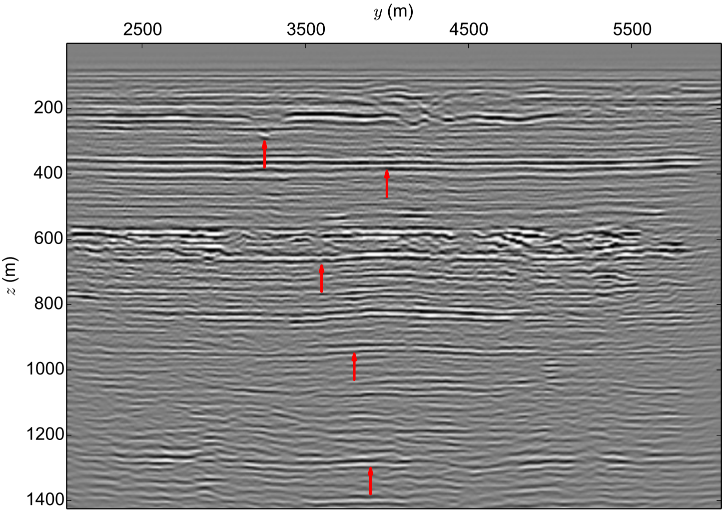
Comparison: left: 6–8 Hz, middle: 6–11 Hz, right: 6–15 Hz.

Baseline migration: Vertical slice



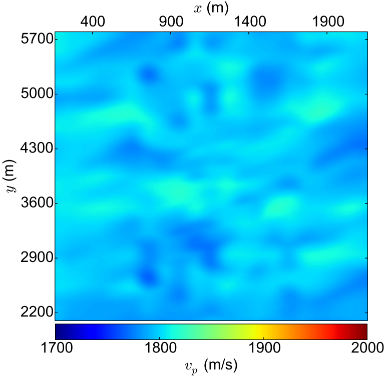
Initial model

Baseline migration: Vertical slice



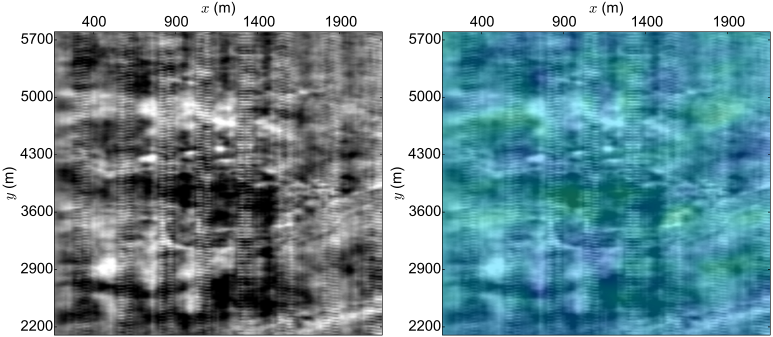
Final inverted model

Baseline FWI: Horizontal slice



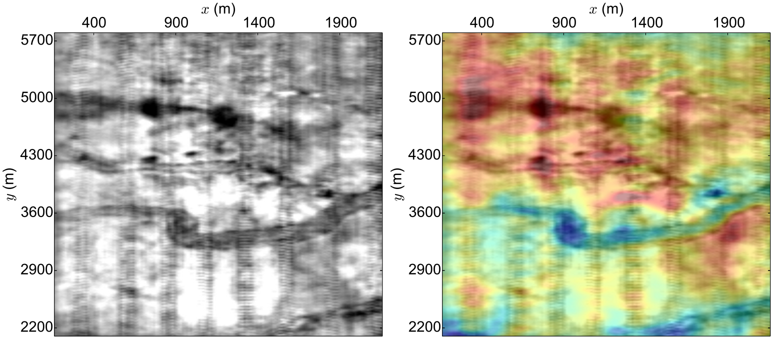
v_p: left: initial, right: final.

Baseline FWI: Horizontal slice



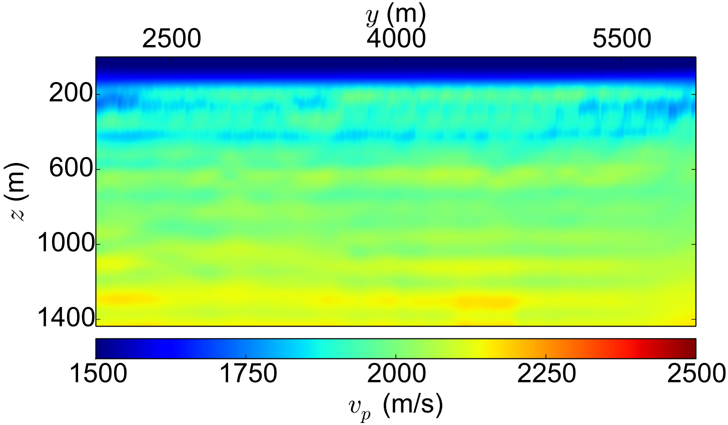
Initial: left: seismic image, right: overlay.

Baseline FWI: Horizontal slice



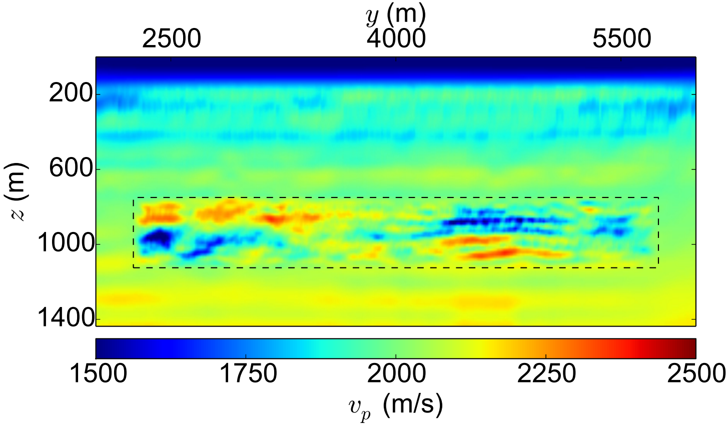
Final: left: seismic image, right: overlay.

Monitor FWI: Vertical slice



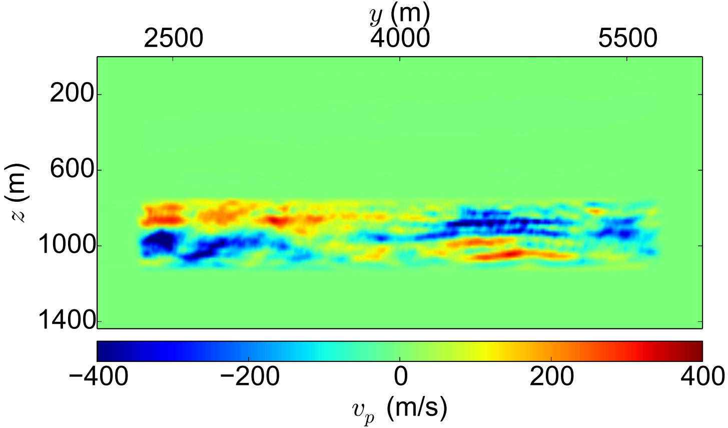
Baseline

Monitor FWI: Vertical slice



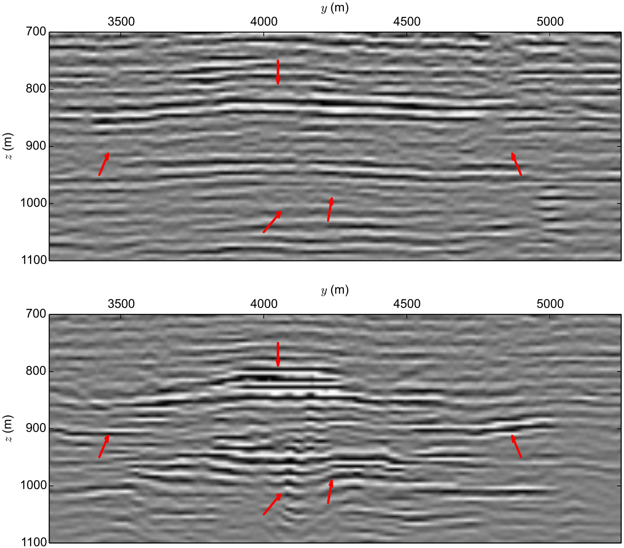
Monitor

Monitor FWI: Vertical slice



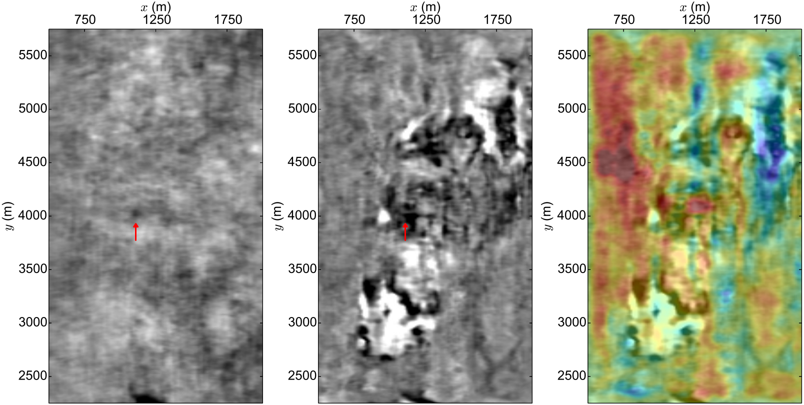
Time-lapse

Migration: Vertical slice



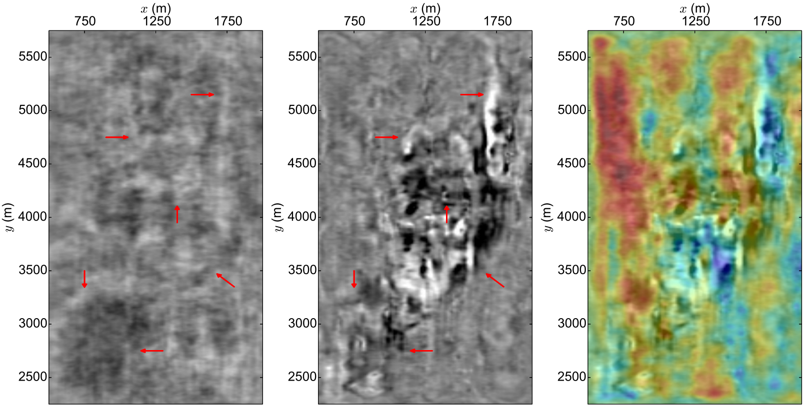
Close-up of gas cloud: top: baseline, bottom: monitor.

Migration: Horizontal slice



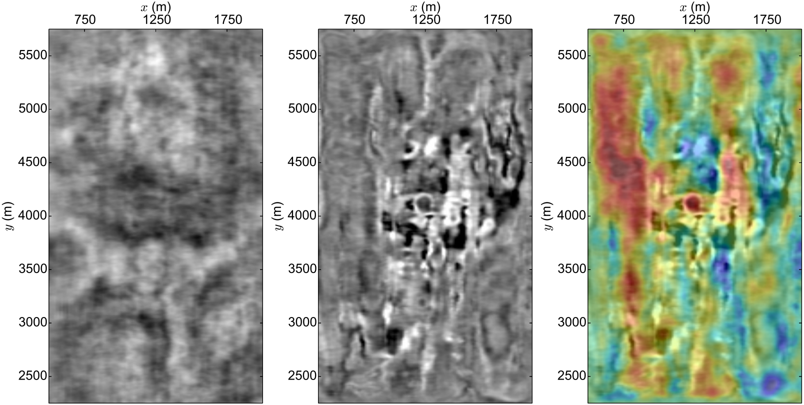
Slice at $z = 881.25m$**:** left: baseline, middle: monitor, right: overlay

Migration: Horizontal slice



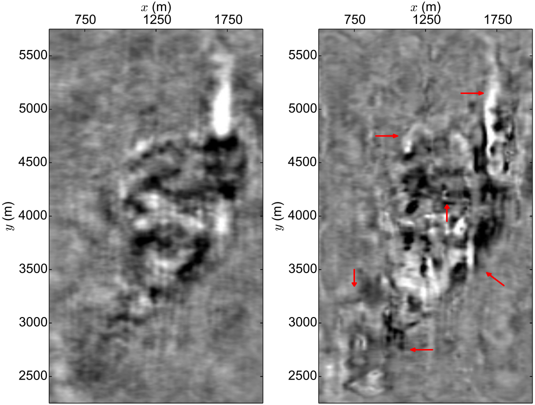
Slice at $z = 918.75m$: left: baseline, middle: monitor, right: overlay

Migration: Horizontal slice



Slice at $z = 943.75m$**:** left: baseline, middle: monitor, right: overlay

Migration: Different migration models



Slice at $z = 918.75m$: left: baseline FWI model, right: monitor FWI model

Conclusions

- FWI improves the elastic models and matches the field data
- FWI produces models that can improve the resolution and focusing of seismic images
- Injected gas at Sleipner has migrated into structures that are visible on the baseline images
- The gas has migrated upwards through a fault

Acknowledgements

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