Elastic Time-lapse Full Waveform Inversion

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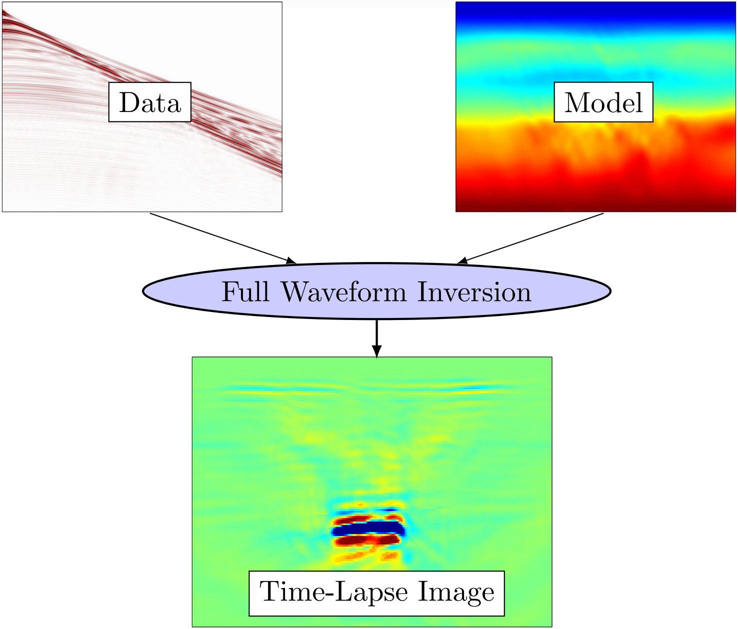

Data
Model
Full Waveform Inversion
Time-Lapse Image

Outline

A Quick Overview of Full Waveform Inversion

Overall Goal

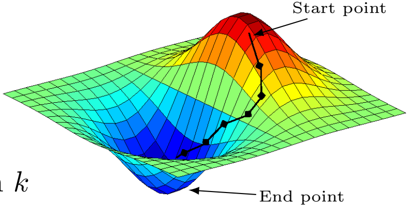
Find an Earth model from which it is possible to create synthetic data that is close to some measured data

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

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

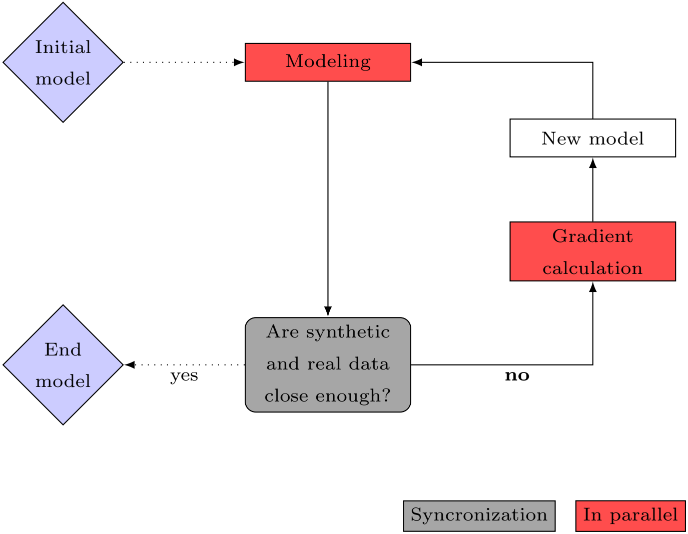
Solved using an iterative method

$$m_{k+1} = m_k - \alpha_k g_k,$$

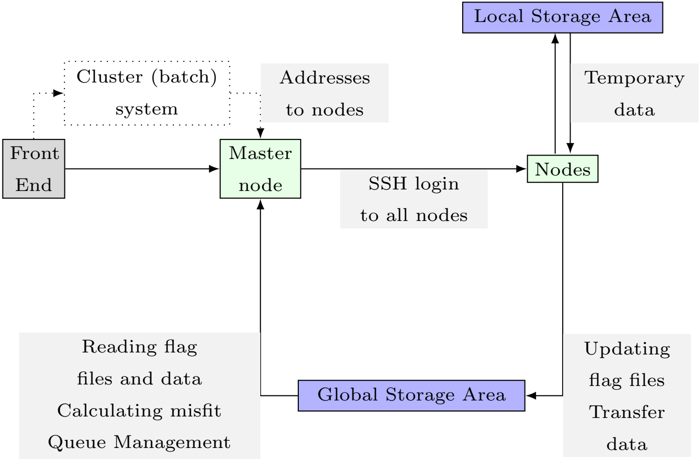


m_k	model at iteration k
g_k	gradient of $S(\mathbf{m})$ at iteration k
α_k	step length at iteration k

Schematic View of FWI



Schematic View of Implementation



Time-lapse FWI

Goal

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

Different ways of doing this:

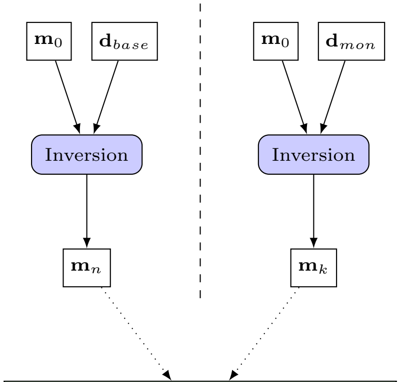
Approach 1: Two independent inversions og base and monitor

Approach 2: Invert first for base, and use the end model as input for monitor

Approach 3: Invert first for base, and use the end model in combination with a data modification as input for monitor

The time-lapse image is found by comparing the two end models.

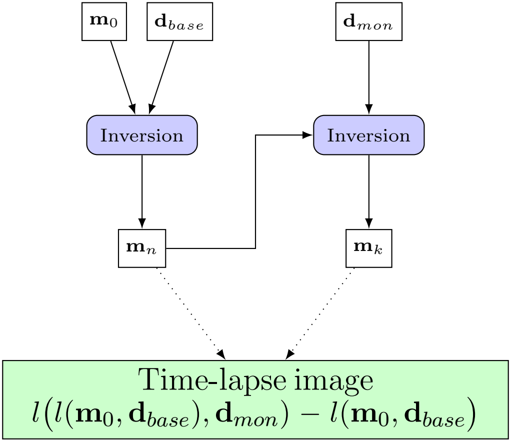
Approach 1



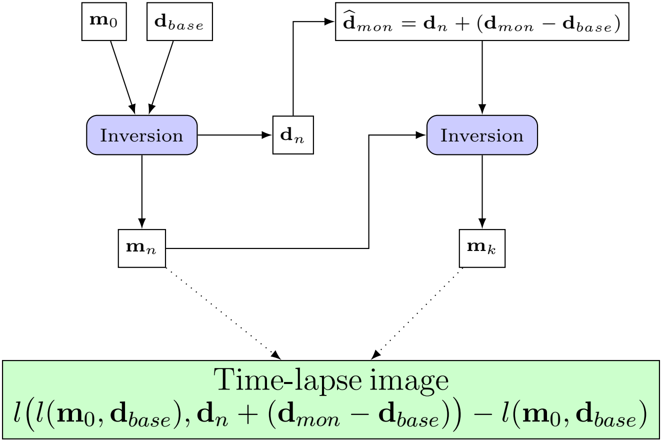
Definition: $l(\mathbf{m}, \mathbf{d})$ is the inverted model using $\mathbf{m}$ as initial model and $\mathbf{d}$ as observed data.

Time-lapse image
$l(\mathbf{m}_0, \mathbf{d}_{mon}) - l(\mathbf{m}_0, \mathbf{d}_{base})$

Approach 2


$\mathbf{m}_0$
$\mathbf{d}_{base}$
$\mathbf{d}_{mon}$
Inversion
Inversion
$\mathbf{m}_n$
$\mathbf{m}_k$
Time-lapse image
$l\big(l(\mathbf{m}_0, \mathbf{d}_{base}), \mathbf{d}_{mon}\big) - l(\mathbf{m}_0, \mathbf{d}_{base})$

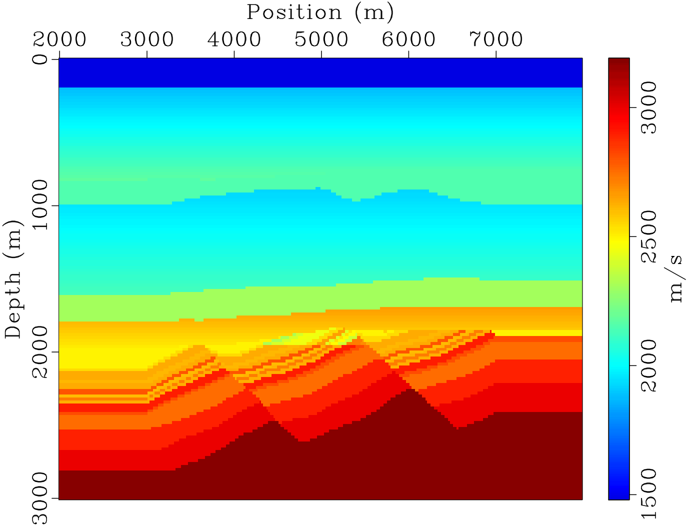
Approach 3


$\mathbf{m}_0$
$\mathbf{d}_{base}$
$\widehat{\mathbf{d}}_{mon} = \mathbf{d}_n + (\mathbf{d}_{mon} - \mathbf{d}_{base})$
Inversion
$\mathbf{d}_n$
Inversion
$\mathbf{m}_n$
$\mathbf{m}_k$
Time-lapse image
$l\big(l(\mathbf{m}_0, \mathbf{d}_{base}), \mathbf{d}_n + (\mathbf{d}_{mon} - \mathbf{d}_{base})\big) - l(\mathbf{m}_0, \mathbf{d}_{base})$

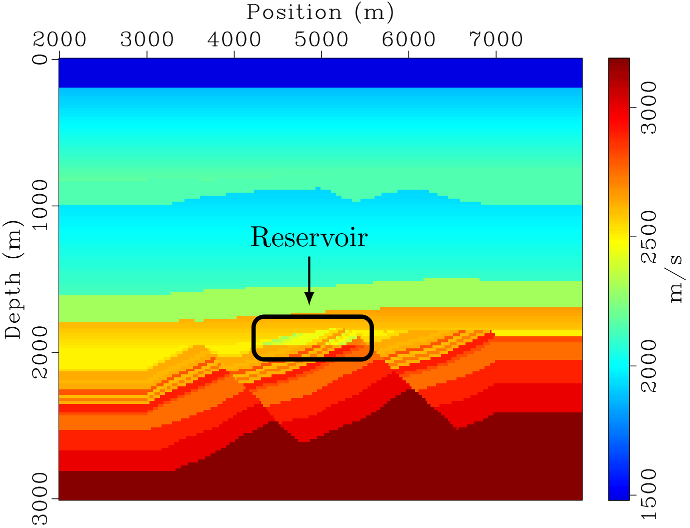
Synthetic Example

- The test model is an elastic model of the Gullfaks field.
- Base model: Reservoir filled with oil
- Monitor model: Reservoir filled with water
- P-wave velocity change locally within reservoir: $0 - 153$ m/s
- Marine streamer survey with 370 shots and 6 km streamer length
- The streamer has 300 receivers which are separated by 20 m
- The shot interval is 20 m

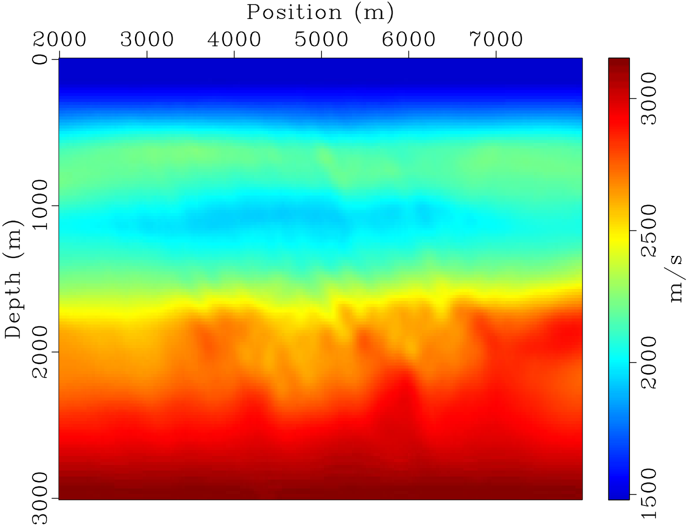
True Model


Position (m)
2000
3000
4000
5000
6000
7000
Depth (m)
0
1000
2000
3000
m/s
1500
2000
2500
3000

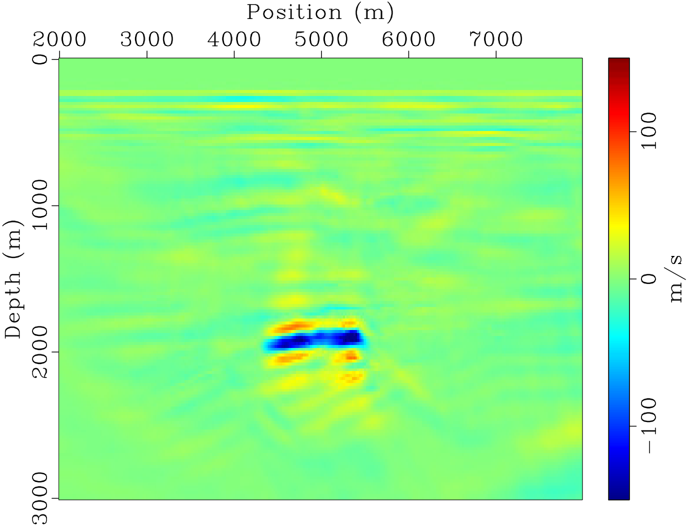
True Model


Position (m)
2000 3000 4000 5000 6000 7000
Depth (m)
0 1000 2000 3000
Reservoir
m/s
1500 2000 2500 3000

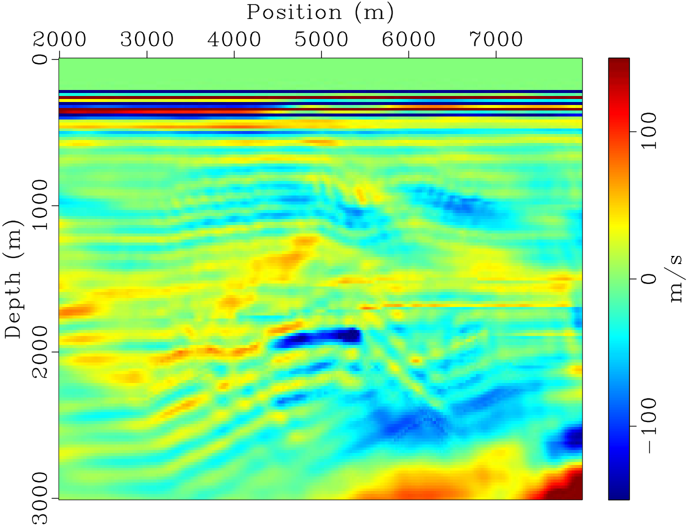
Initial Model



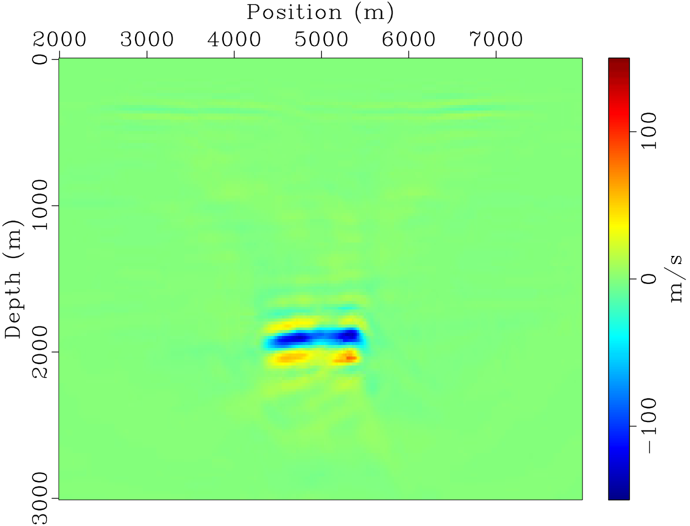
Time-Lapse Image Approach 1



Time-Lapse Image Approach 2



Time-Lapse Image Approach 3



Real Example

- Time-lapse data from the Norwegian North Sea
- Base dataset aqcuired in 1988 and monitor dataset in 1990
- Between the dataset the field was exposed to a subsurface gas leakage in one of the producing wells
- Marine streamer survey with 230 shots and 1253 m streamer length
- The streamer had 95 receivers separated by 12.5 m
- Shot intervall 12.5 m

From Acoustic to Elastic FWI

We are inverting for P-wave velocities, leaving density and S-wave velocity constant during the inversion.

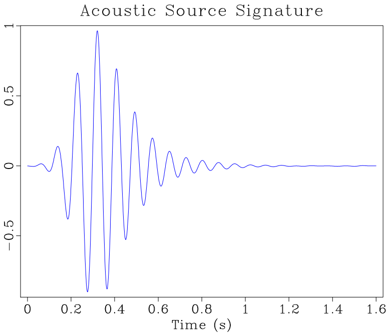
The initial model is obtained using wave equation migration analysis (WEMVA).

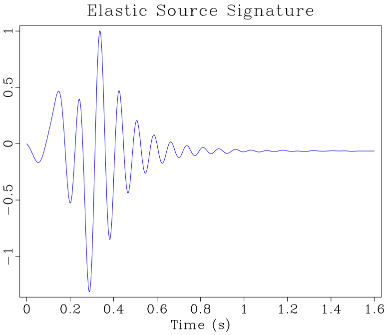
To obtain the S-wave velocity we use the following empirical V_p/V_s relation [Mavko et al., 2009]

$$V_s = 0.862V_p - 1.172.$$

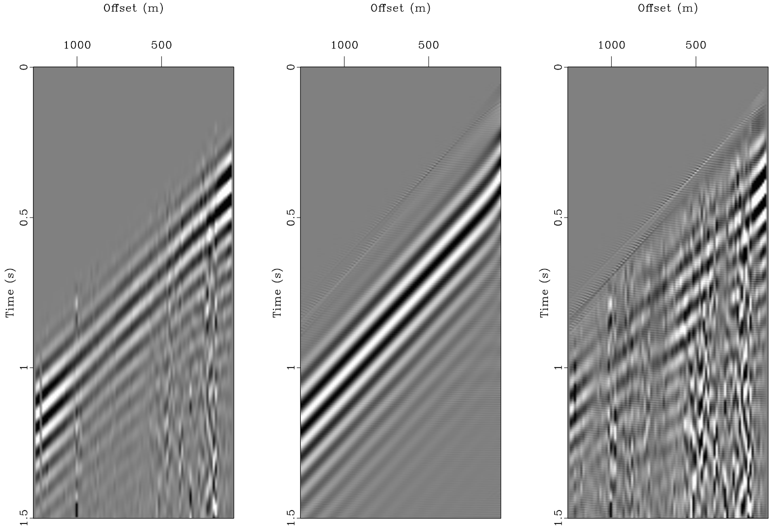
Source Estimation

The source is estimated using the FWI method, and the same source is used in all shots.



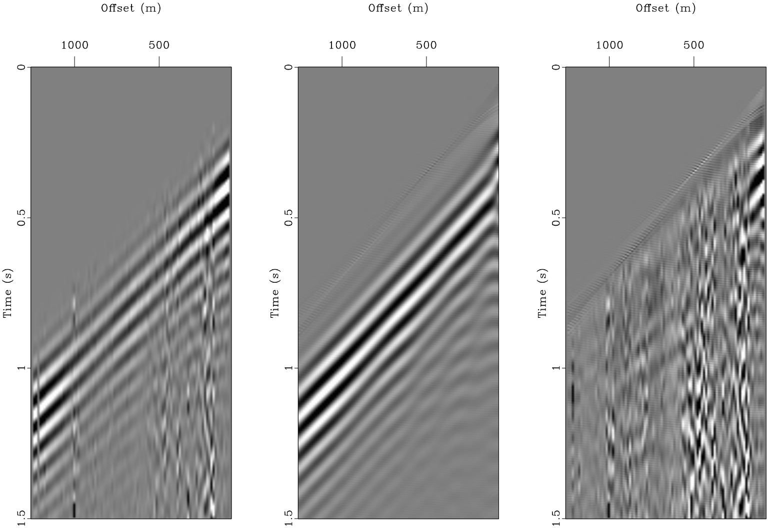


QC: Elastic Inversion - First iteration



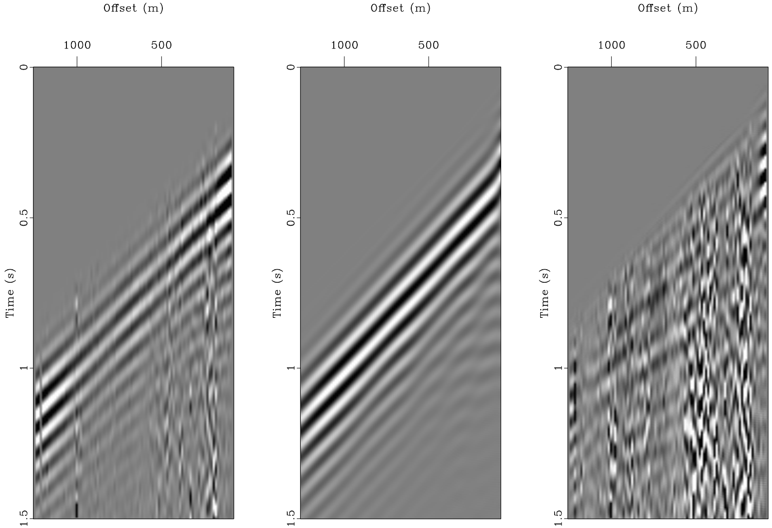
Real data Synthetic data Residual

QC: Elastic Inversion - Last iteration



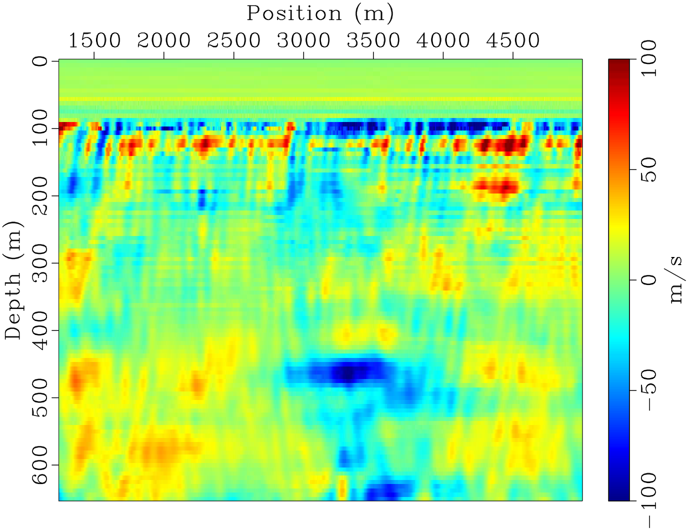
Real data Synthetic data Residual

QC: Acoustic Inversion - Last iteration

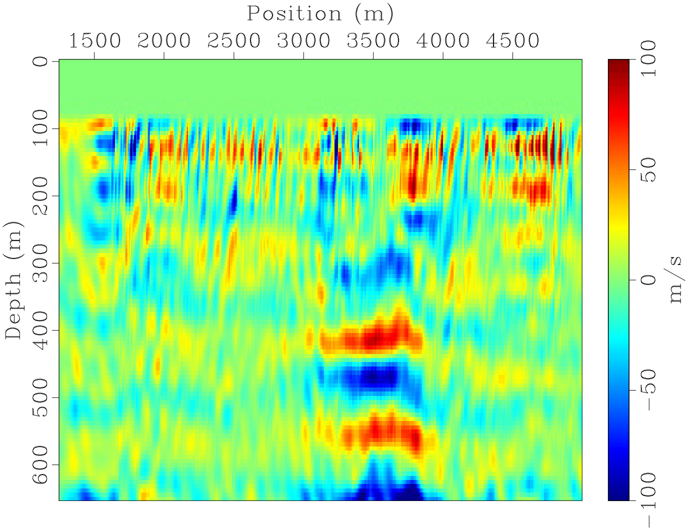


Real data Synthetic data Residual

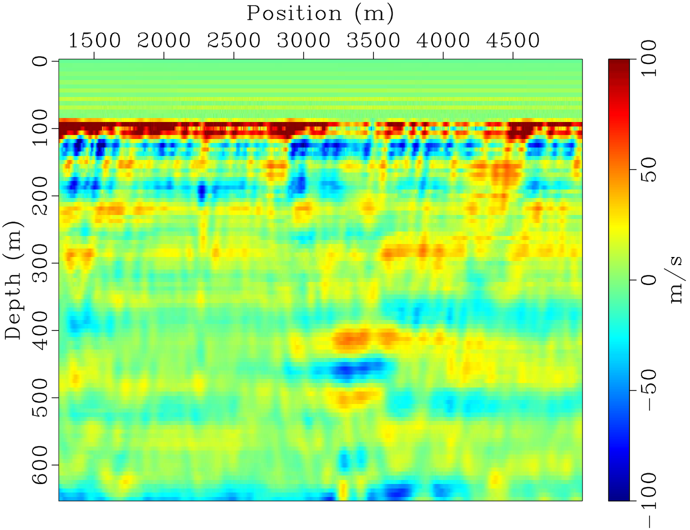
Acoustic Time-Lapse Image: Approach 1



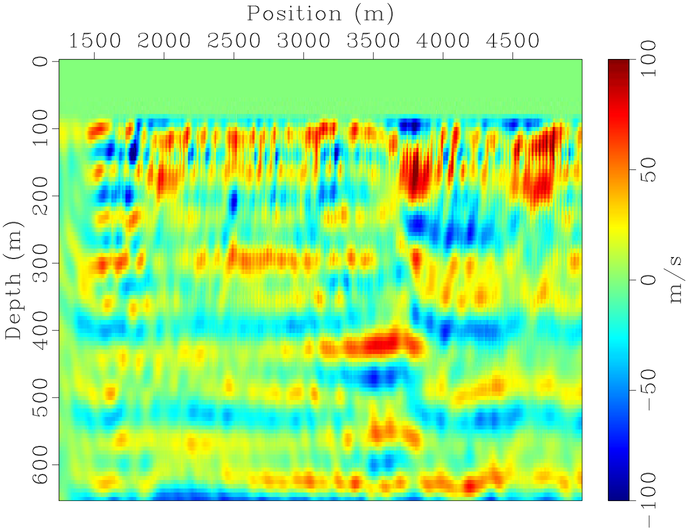
Elastic Time-Lapse Image: Approach 1



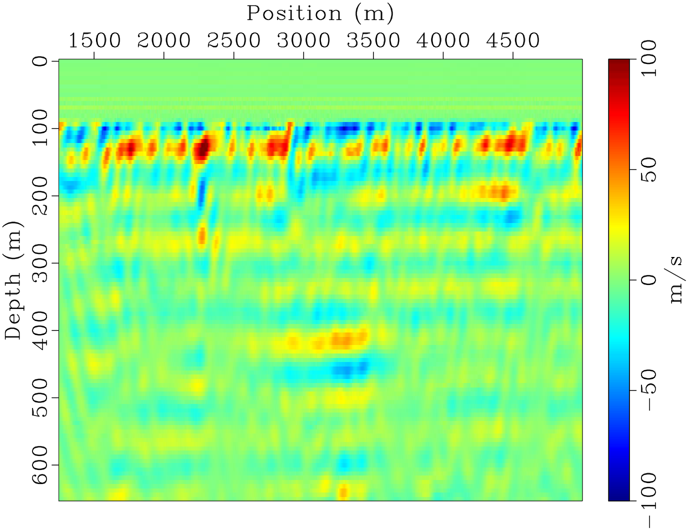
Acoustic Time-Lapse Image: Approach 2



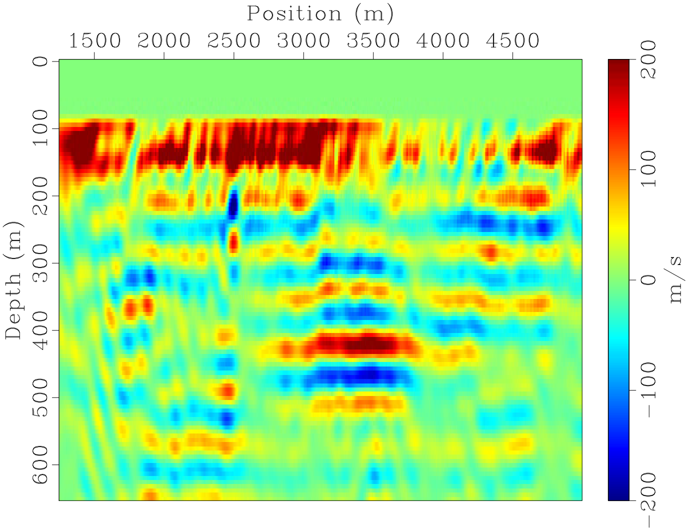
Elastic Time-Lapse Image: Approach 2



Acoustic Time-Lapse Image: Approach 3



Elastic Time-Lapse Image: Approach 3



Conclusions

- Full waveform inversion can be used to quantify time-lapse changes in the subsurface
- Elastic inversion is favourable over acoustic inversion
- Source estimation results in different source signatures for acoustic and elastic inversion
- Several artifacts appear in the time-lapse images that must be studied further. Add regularization?
- Good repeatability in the data is important for time-lapse full waveform inversion
- Modeling in 2D while data is 3D: No geometrical spreading. May improve results by inverting in 3D.

Acknowledgements

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