Time-lapse full waveform inversion: Synthetic and real data examples

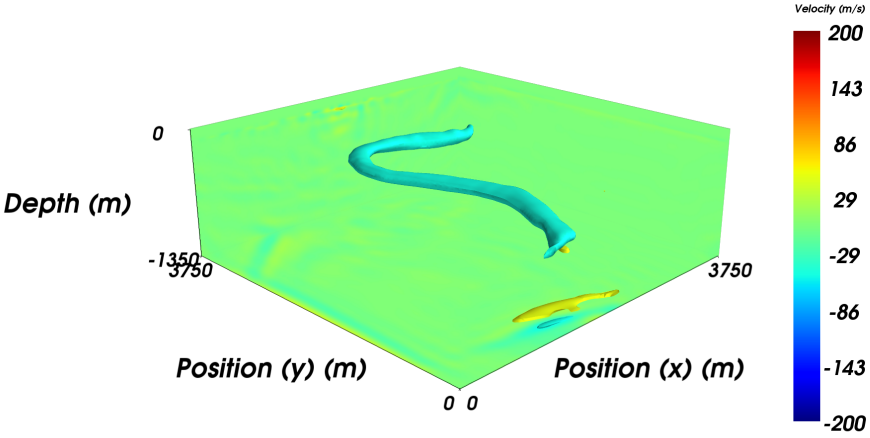
Espen Birger Raknes*, Wiktor Weibull, and Børge Arntsen

Norwegian University of Science and Technology (NTNU)
Department of Petroleum Engineering & Applied Geophysics
E-mail: espen.raknes@ntnu.no

SEG Annual Meeting 2013
September 24th 2013

NTNU – Trondheim
Norwegian University of Science and Technology

Time-lapse Image



Background

- During the last decade full waveform inversion has proven to be a promising method for parameter model estimation
- Increase in computational power leads to an increase in problem size
- We are now able to do inversion using elastic theory
- In a time-lapse setting, full waveform inversion yields results in the model domain, compared to conventional methods that yield results in the time domain
- Different approaches for performing time-lapse FWI exist in the literature

Objectives

- Apply elastic full waveform inversion on time-lapse data
- Investigate behavior of full waveform inversion in a time-lapse setting using different streamer geometries
- Investigate different time-lapse approaches using full waveform inversion
- Apply the approaches on both synthetic and real datasets

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

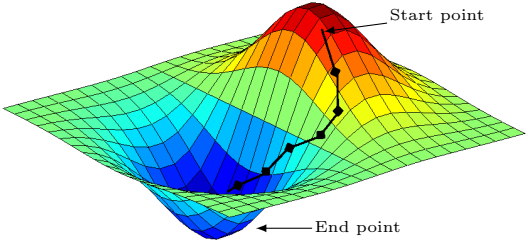
Define $S(\mathbf{m})$ as the measure between synthetic and measured data. FWI is then the problem

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

Solved using an iterative method

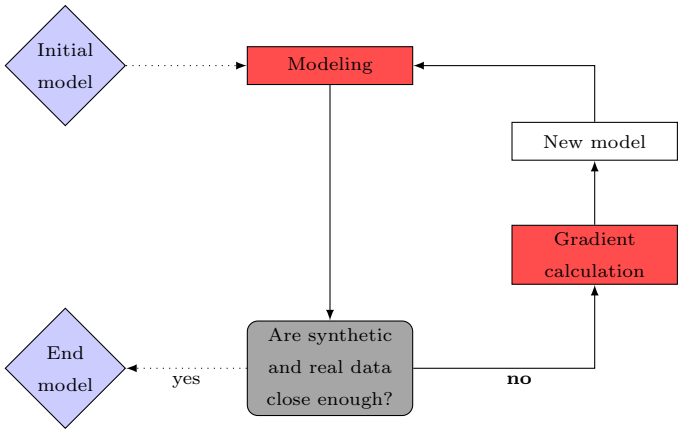
$$\mathbf{m}_{k+1} = \mathbf{m}_k - \alpha_k \mathbf{g}_k,$$

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

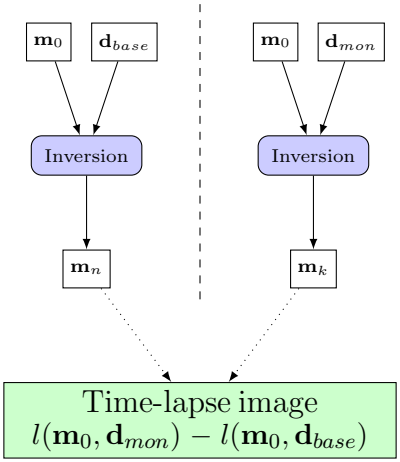


Schematic View of FWI

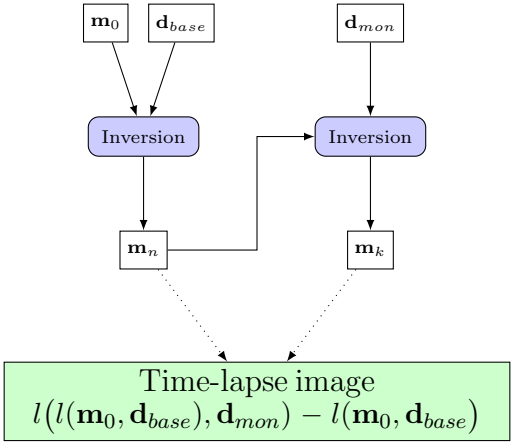
- Modeling using a staggered grid finite difference method
- Parallelized on a shot-by-shot basis
- Minimization algorithm is L-BFGS



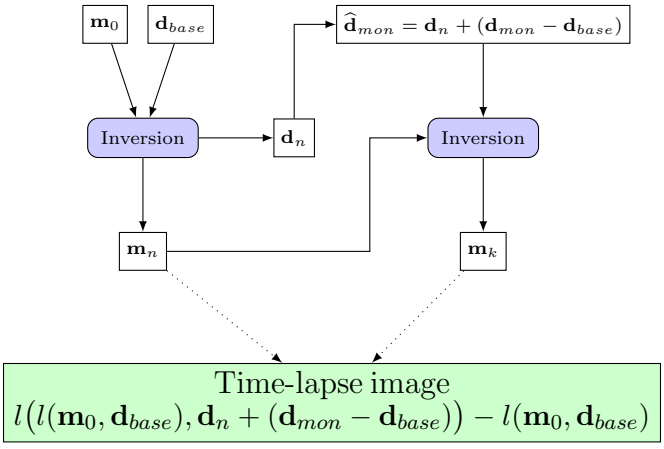
Time-lapse FWI: Approach 1



Time-lapse FWI: Approach 2



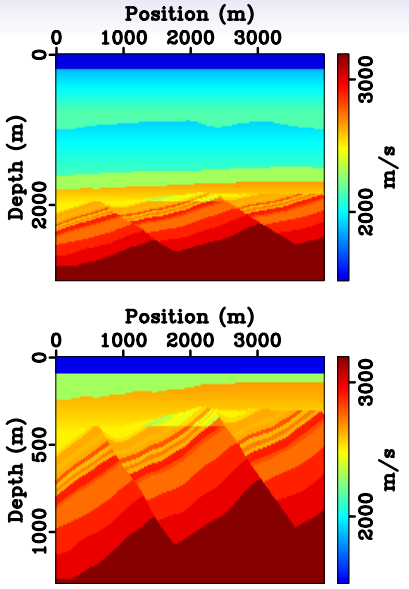
Time-lapse FWI: Approach 3



Ref: [Zheng et al., 2011]

Synthetic examples

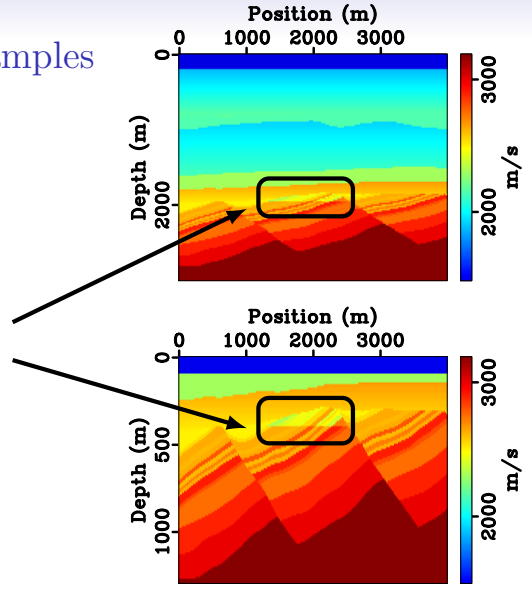
- Two test cases:
  - Deep model with 6 km streamer length
  - Shallow model with 1.2 km streamer length
- Reservoir acts as time-lapse anomaly
- Identical surveys acquired for baseline and monitor models



Synthetic examples

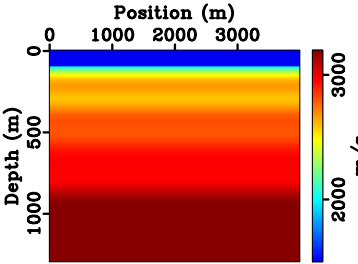
Reservoir:

- 1000 m wide, 100 m deep
- Baseline: oil filled
- Monitor: water filled
- P-wave changes: -153 – 0 m/s

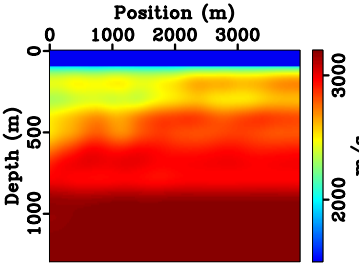


Workflow for synthetic examples

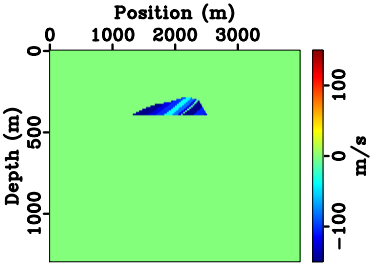
- Using WEMVA for creating initial models for FWI [Weibull et al., 2012]
- Elastic modeling and inversion
- Inverting for P-wave velocities, no updates for S-wave velocities and density



Initial model for WEMVA

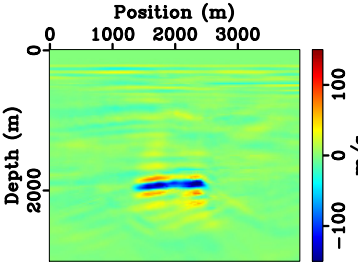


Initial model for FWI

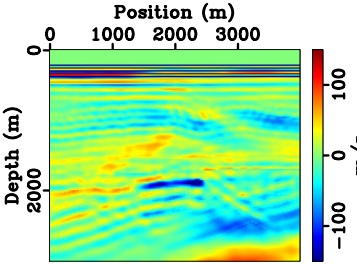


True time-lapse effect (shallow model)

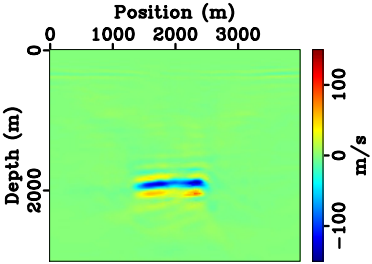
Time-lapse images: long streamer



Approach 1

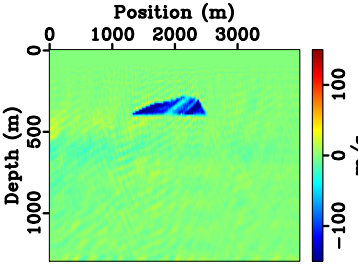


Approach 2

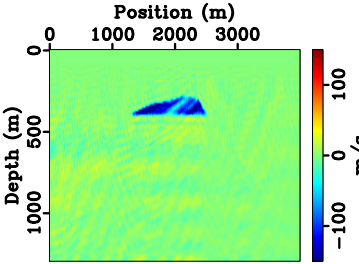


Approach 3

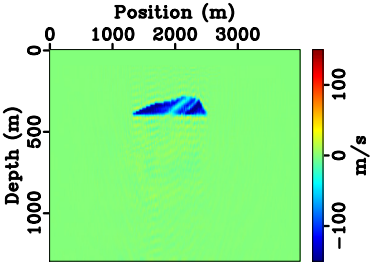
Time-lapse images: short streamer



Approach 1



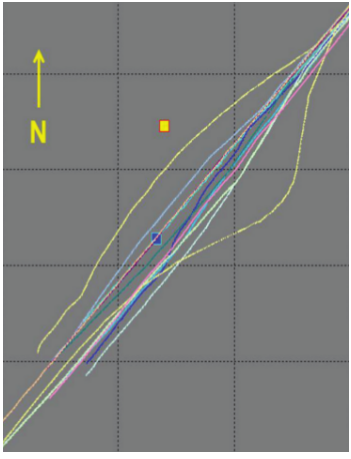
Approach 2



Approach 3

Real example

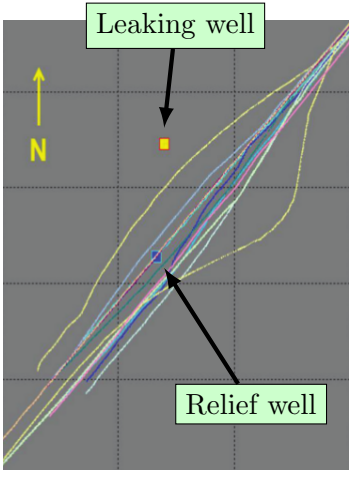
- Time-lapse data from the Norwegian North Sea
- Base dataset acquired in 1988 and monitor dataset in 1990
- Between the dataset the field was exposed to a subsurface gas leakage in one of the producing wells
- Marine streamer survey: 230 shots and 1253 m streamer length
- Streamer: 95 receivers separated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



Ref: [Landrø,2011]

Real example

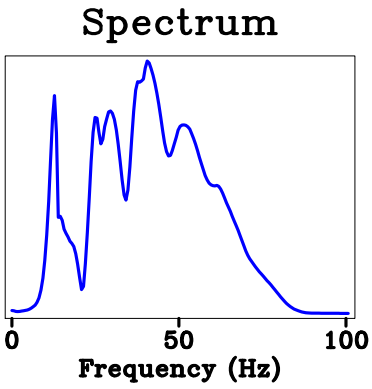
- Time-lapse data from the Norwegian North Sea
- Base dataset acquired in 1988 and monitor dataset in 1990
- Between the dataset the field was exposed to a subsurface gas leakage in one of the producing wells
- Marine streamer survey: 230 shots and 1253 m streamer length
- Streamer: 95 receivers separated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



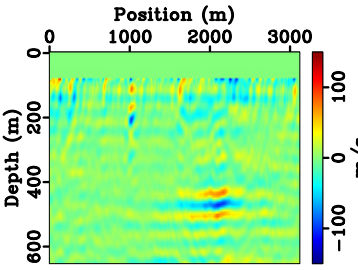
Ref: [Landrø,2011]

Workflow for real example

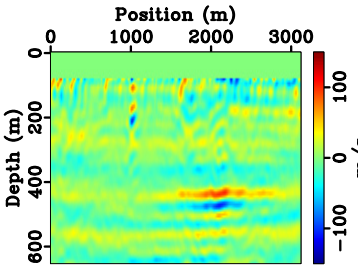
- Data is regularized into a identical grid using linear interpolation
- Bandpass filter (2-20 Hz) is applied
- Grid cells with grid spacing 6.25 m is used
- Initial model estimated using WEMVA
- Source is estimated using FWI keeping parameter models constant
- Inverting for P-wave velocities, linking S-wave velocities and densities using empirical relations



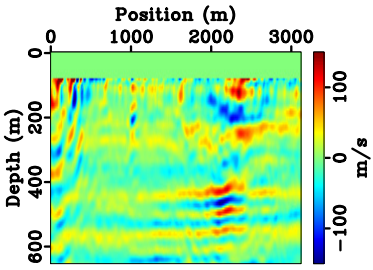
Time-lapse images: Real example



Approach 1

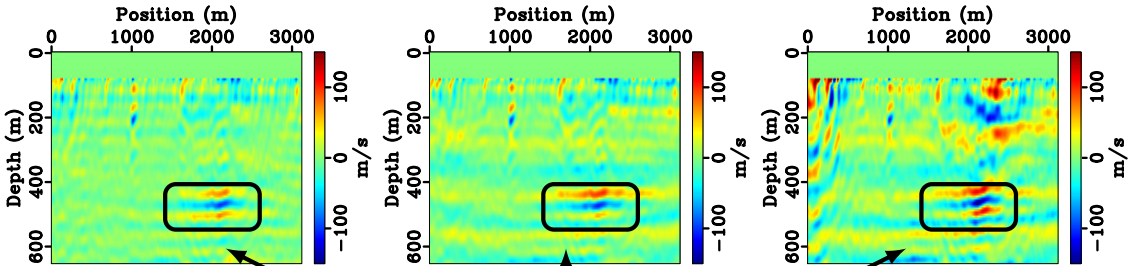


Approach 2



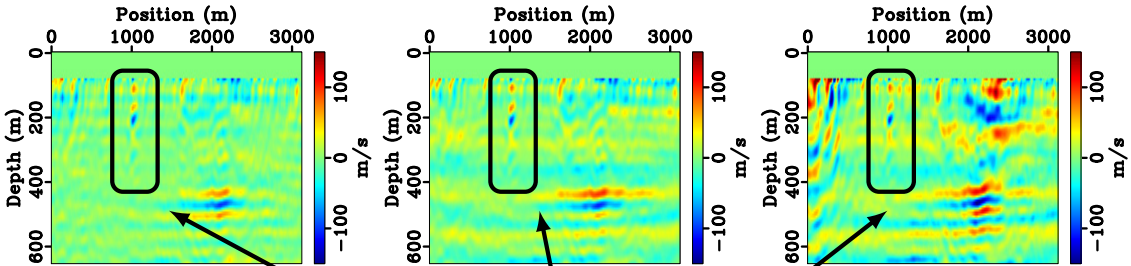
Approach 3

Time-lapse images: Real example



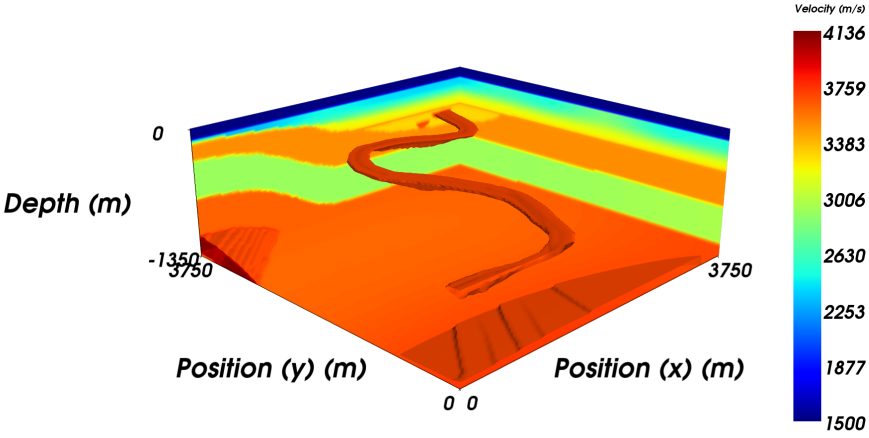
Well-known time-lapse effect:
Gas leaked into a sand layer at this depth

Time-lapse images: Real example



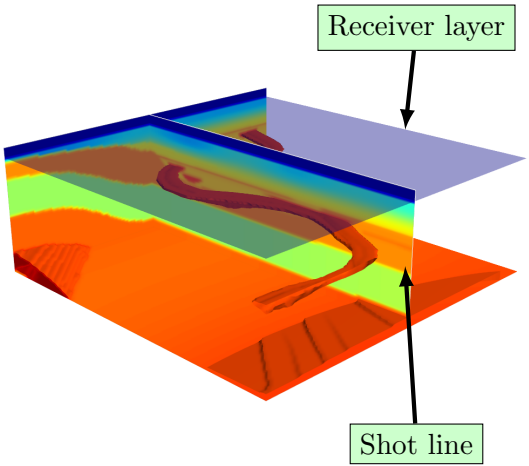
The relief well was drilled at this position:
Is the well visible?

3D synthetic example

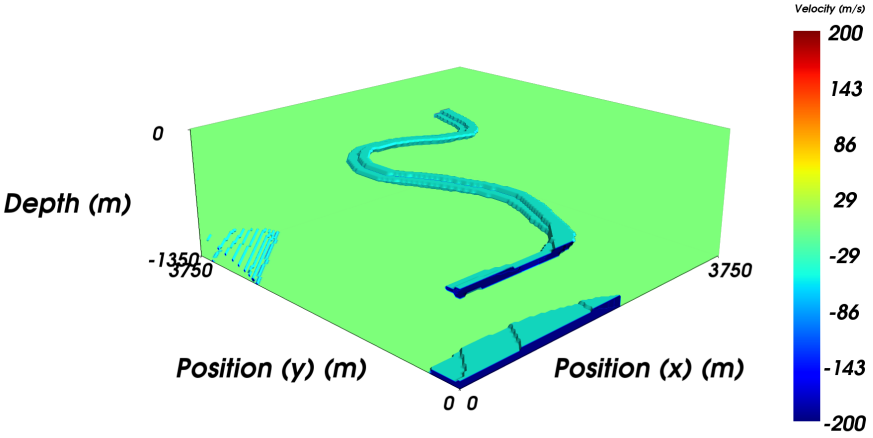


FWI setup

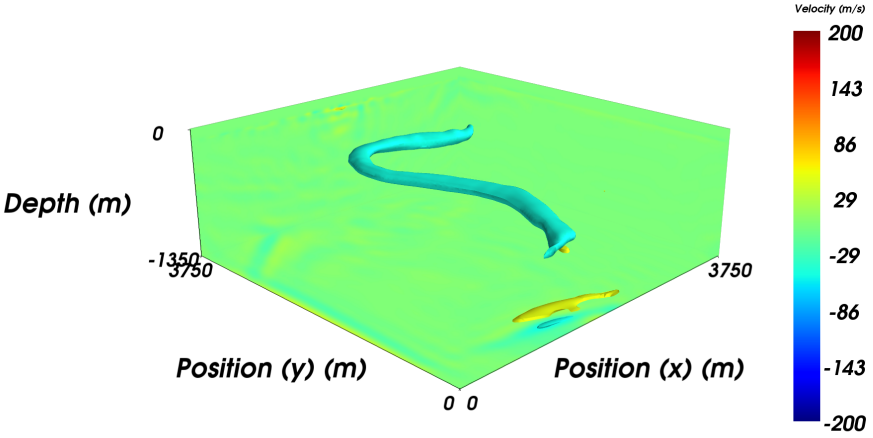
- Grid spacing: 25 m
- Receivers in every grid point in a layer in water column
- 72 shots along a line on y-axis in the middle of the model
- Ricker wavelet with center frequency 5.0 Hz



True 3D time-lapse effect



Inverted 3D time-lapse effect



Conclusions

- Full waveform inversion are able to reveal time-lapse effects
- Time-lapse artifacts are dependent on receiver and source geometries, and depth
- Difficult to make a conclusion on which of the approaches that is the best
- We are able to detect already known time-lapse effects on the real dataset
- Promising synthetic time-lapse result in three dimensions

Acknowledgments

This publication has been produced with support from the BIGCCS Centre, performed under the Norwegian research program Centres for Environment-friendly Energy Research (FME). The authors acknowledge the following partners for their contributions: ConocoPhillips, Gassco, Shell, Statoil, TOTAL, GDF SUEZ and the Research Council of Norway (193816/S60).

- Biondi, B., C. Deutsch, R. Gundesø, D. Lumley, G. Mavko, T. Mukerji, J. Rickett, and M. Thiele, 1996, Reservoir monitoring: A multi-disciplinary feasibility study: SEG Technical Program Expanded Abstracts 1996, 1775–1778.
- Johnston, D., R. McKenny, J. Verbeek, and J. Almond, 1998, Time-lapse seismic analysis of fulmar field: The Leading Edge, **17**, 1420–1428.
- Landrø, M.,2011 Seismic Monitoring of an old underground blowout - 20 years later: First Break, **29**,39-48.
- Liu, F., L. Guasch, S. A. Morton, M. Warner, A. Umpleby, Z. Meng, S. Fairhead, and S. Checkles, 2012, 3-d time-domain full waveform inversion of a valhall obc dataset: SEG Technical Program Expanded Abstracts 2012, 1–5.
- Lumley, D., 2010, 4d seismic monitoring of co2 sequestration: The Leading Edge, **29**, 150–155.

- Lumley, D., D. C. Adams, M. Meadows, S. Cole, and R. Wright, 2003, 4d seismic data processing issues and examples: SEG Technical Program Expanded Abstracts 2003, 1394–1397.
- Nocedal, J., and S. J. Wright, 2006, Numerical optimization, second ed.: Springer Science+ Business Media, LLC.
- Routh, P., G. Palacharla, I. Chikichev, and S. Lazaratos, 2012, Full wavefield inversion of time-lapse data for improved imaging and reservoir characterization: SEG Technical Program Expanded Abstracts 2012, 1–6.
- Routh, P. S., and P. D. Anno, 2008, Time-lapse noise characterization by inversion: SEG Technical Program Expanded Abstracts 2008, 3143–3147.
- Tarantola, A., 1984, Inversion of seismic reflection data in the acoustic approximation: Geophysics, **49**, 1259–1266.

Virieux, J., and S. Operto, 2009, An overview of full-waveform inversion in exploration geophysics: Geophysics, **74**.

Weibull, W., B. Arntsen, and E. Nilsen, 2012, Initial velocity models for full waveform inversion: SEG Technical Program Expanded Abstracts 2012, 1–4.

Zheng, Y., P. Barton, and S. Singh, 2011, Strategies for elastic full waveform inversion of time-lapse ocean bottom cable (obc) seismic data: SEG Technical Program Expanded Abstracts 2011, 4195–4200.