FULL-WAVEFORM INVERSION FOR CO2 QUANTIFICATION – APPLICATION TO REAL DATA AT SLEIPNER

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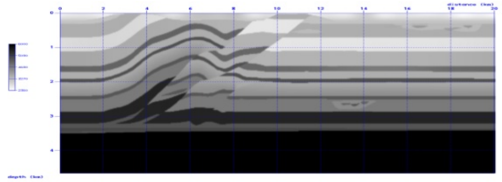
Outline

- Principle of Full-waveform inversion (FWI)
- Full-waveform inversion for CO_2 imaging
- Synthetic example at the Sleipner field
- Results using Sleipner real data (2006 and 2008 datasets)
  - Pre-processing
  - Initial velocity model
  - Results
- Conclusions

Principle of Full-Waveform Inversion

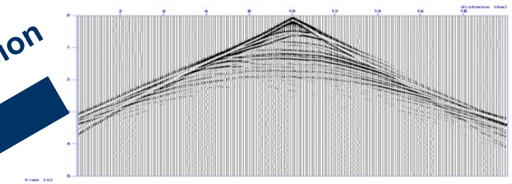
- Introduced in the 1980s (A. Tarantola, 1984)
- Exploits the complete information in the waveforms of seismograms
- Finds the “best” model that minimises the misfit between the observed and the computed seismic data (amplitude and phase)
- Formulation in
  - Time Domain *(Tarantola, 84)*
  - Frequency Domain *(Pratt et al., 90)*
  - Laplace domain *(Shin , 2008)*

Principle of Full-Waveform Inversion



Seismic acquisition

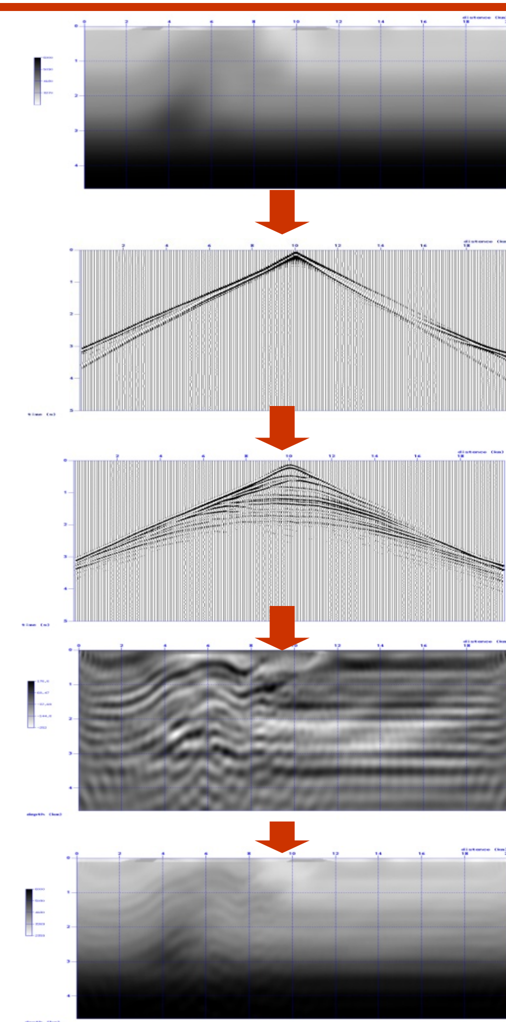
Input for full-waveform inversion



Full-seismic wavefield recorded

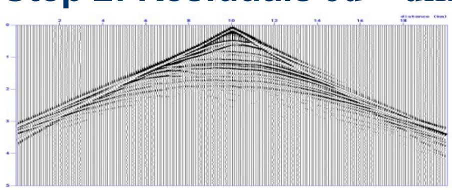
Full-waveform iteration loop

Initial velocity model m0



Step 1: Full-waveform modelling by Finite difference in the initial model

Step 2: Residuals δd = difference between observed and computed data



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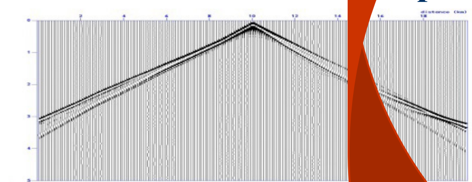

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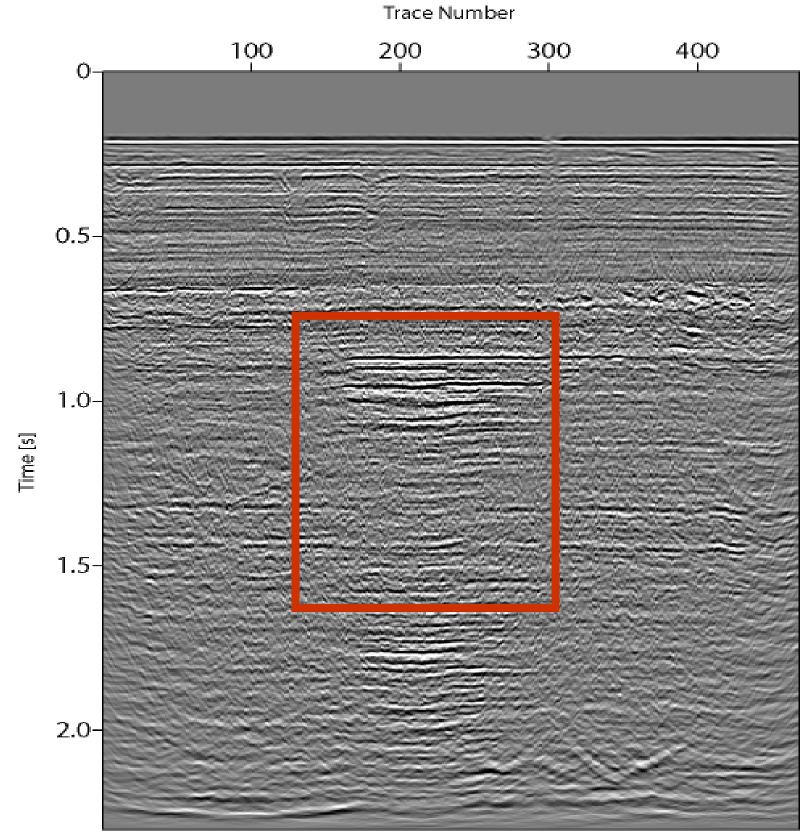
Step 3: Perturbation model that minimizes δd

Step 4: Compute step α and new model $m = m0 + \delta m$

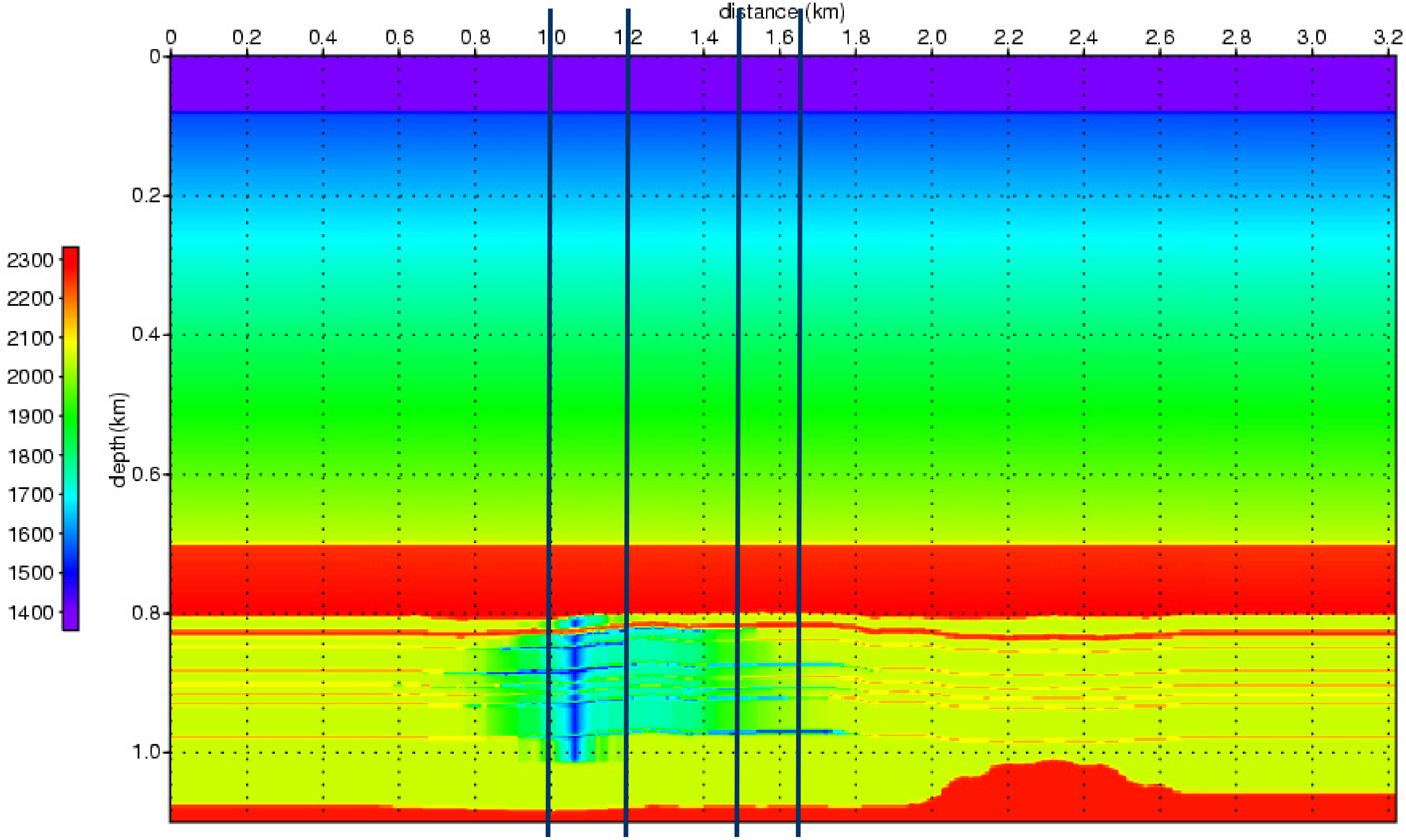
Application to the Sleipner field

- CO_2 monitoring at Sleipner
  - CO_2 injection in a saline reservoir at Sleipner (North Sea) since 1996
  - 3D seismic monitoring to follow the CO_2 plume migration
  - CO_2 appears as clear reflectors on post-injection seismic
  - CO_2 accumulations under intra shales layers within the Utsira sand
- Challenges:
  - CO_2 accumulations within extremely thin layers (~10 meters)
  - Low velocity inversions (1300 m/s)
  - Inter-bed and surface multiples
  - Limited range of offsets
- Apply FWI to better characterise thickness and Vp velocity at Sleipner
  - Synthetic test
  - 2006 real dataset
  - 2008 real dataset



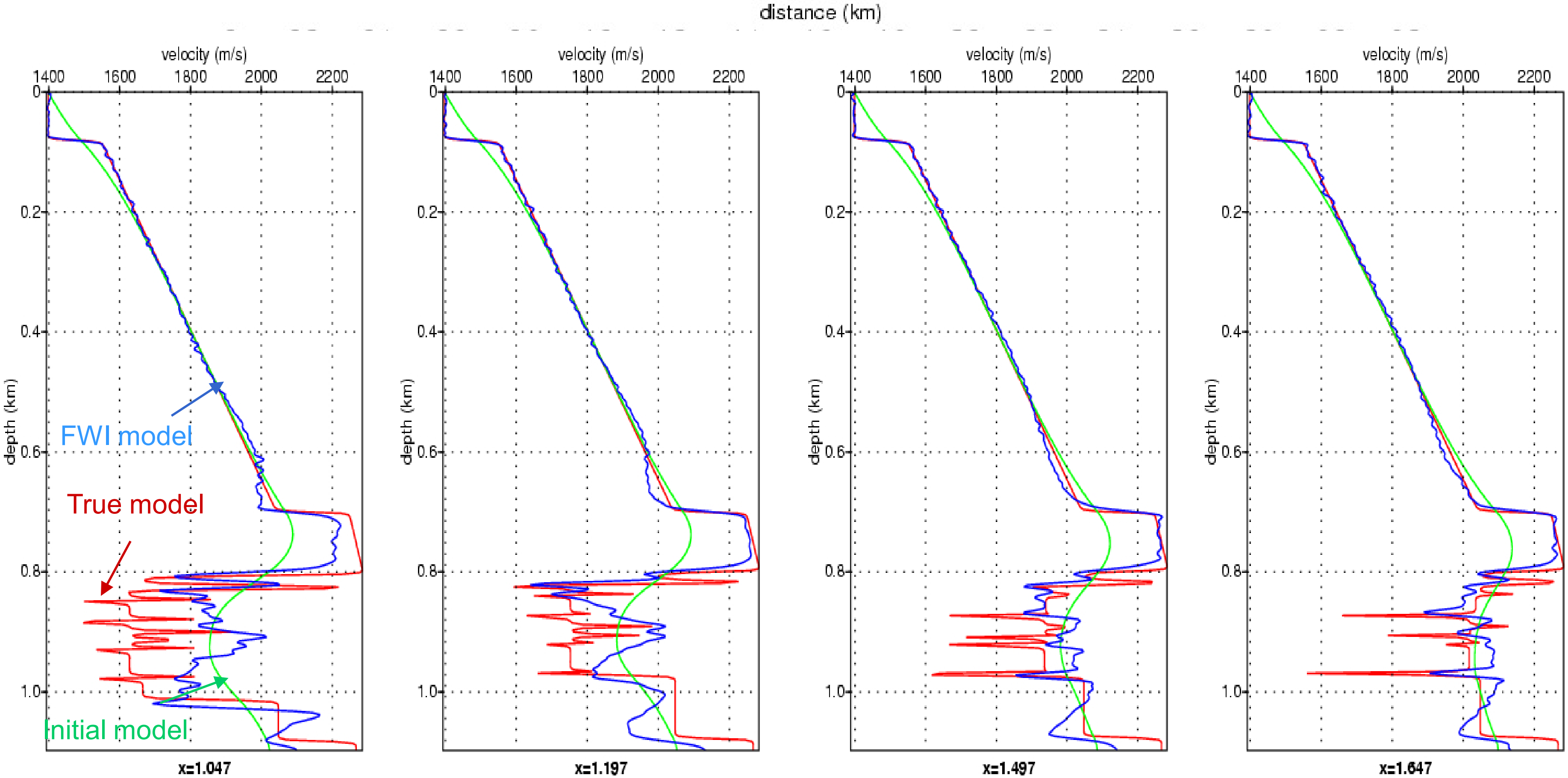
Synthetic example on the Sleipner field

- Synthetic 2D velocity model from TNO
- Model 3.3 km x 1.2 km
- Regular square grid of 3 m
- CO_2 layers of 10-20 m thick
- CO_2 layers with velocities of 1500 m/s



Synthetic example on the Sleipner field

- Ocean Bottom acquisition
- 3.2 km acquisition
- Smoothed initial model
- 10 Hz initial frequency
- 15 frequencies every 5 Hz component
- Maximum frequency of 80 Hz

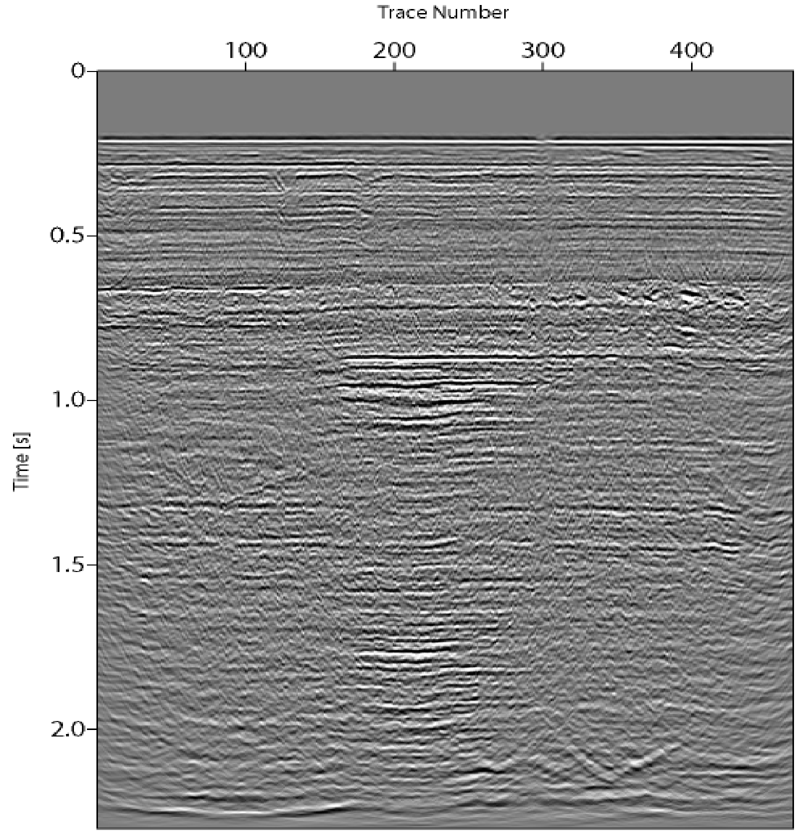


Conclusions form the synthetic tests

- Well constrained Vp velocity model
- Reconstructed low velocity layers (16 to 20 m thickness)
- Good estimation of the velocity in the CO_2 accumulations down to 0.9 km depth
- Layers with thickness about 9 meters requires sources with a high frequency content
- Application to real data should give interesting results if they are not too noisy

Application to real data

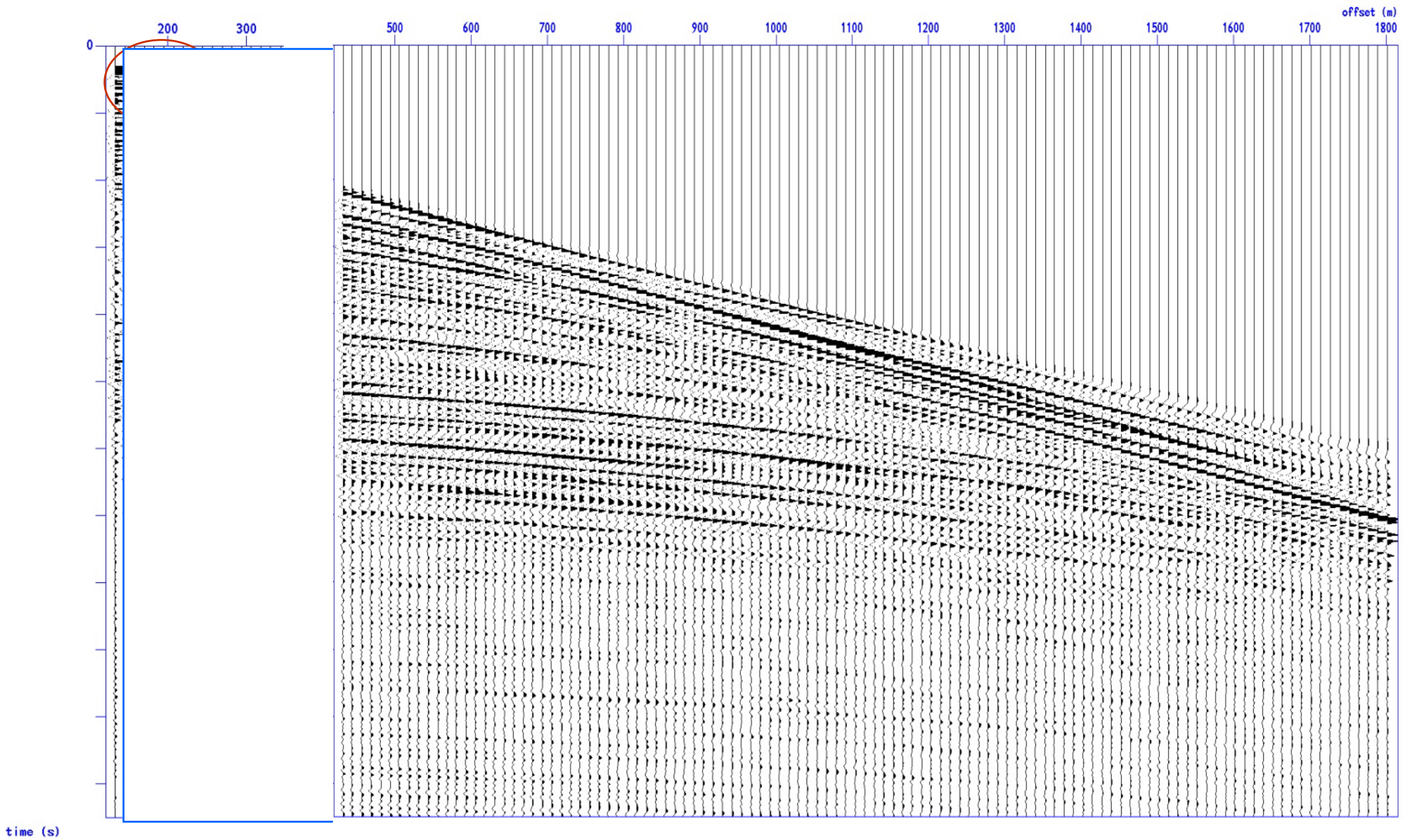
- 2006 and 2008 datasets
- Extracted a 2D line from both 3D datasets
- Post-swell processed data
- Maximum offset of 1.8 km
- Frequency content of the data is from 6 Hz to 80 Hz
- CO_2 accumulations are visible on the near offset section



Specific pre-processing

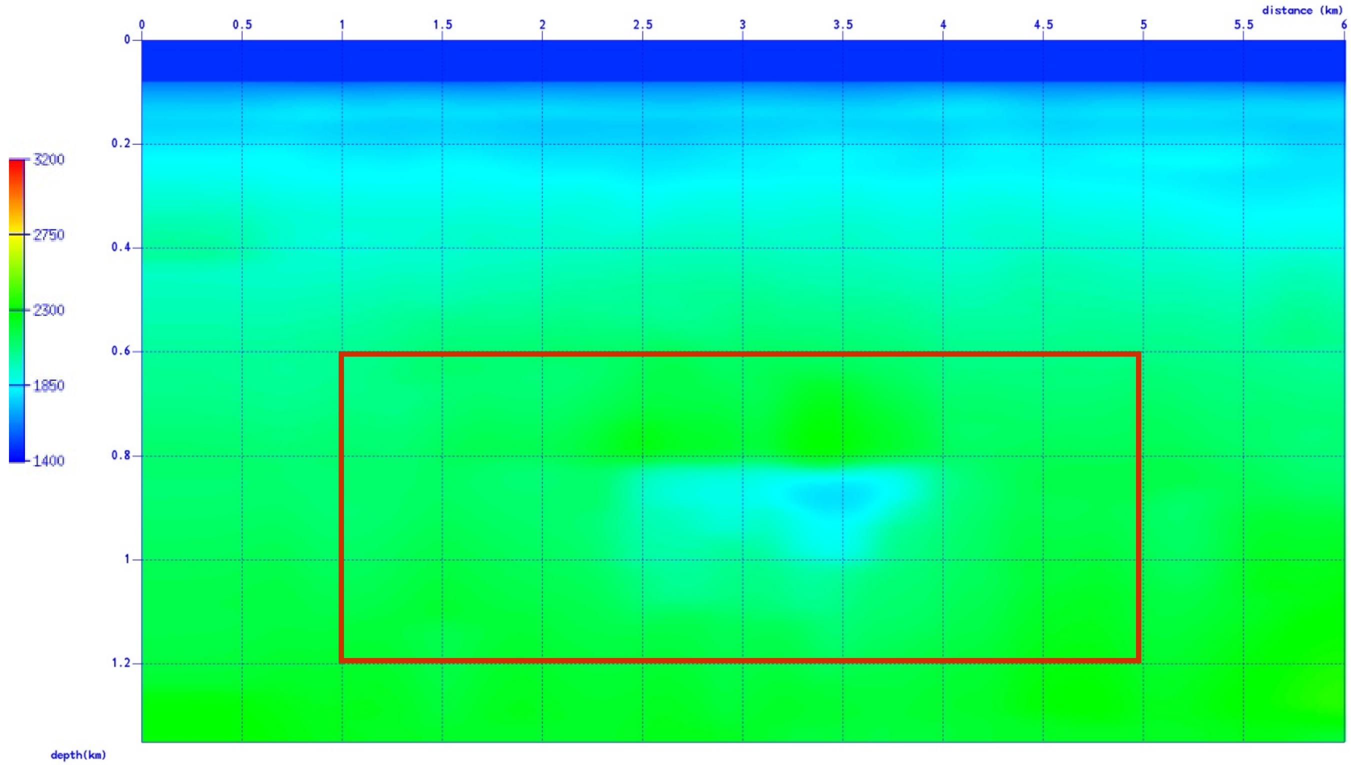
- Removed t^2 gain
- Mute before first-arrivals
- data with offset larger than 420 m
- Time shift to get causal signal
- 3D to 2D conversion
- Multiples still in the data

→ Same pre-processing for 2006 and 2008 datasets



Initial velocity model

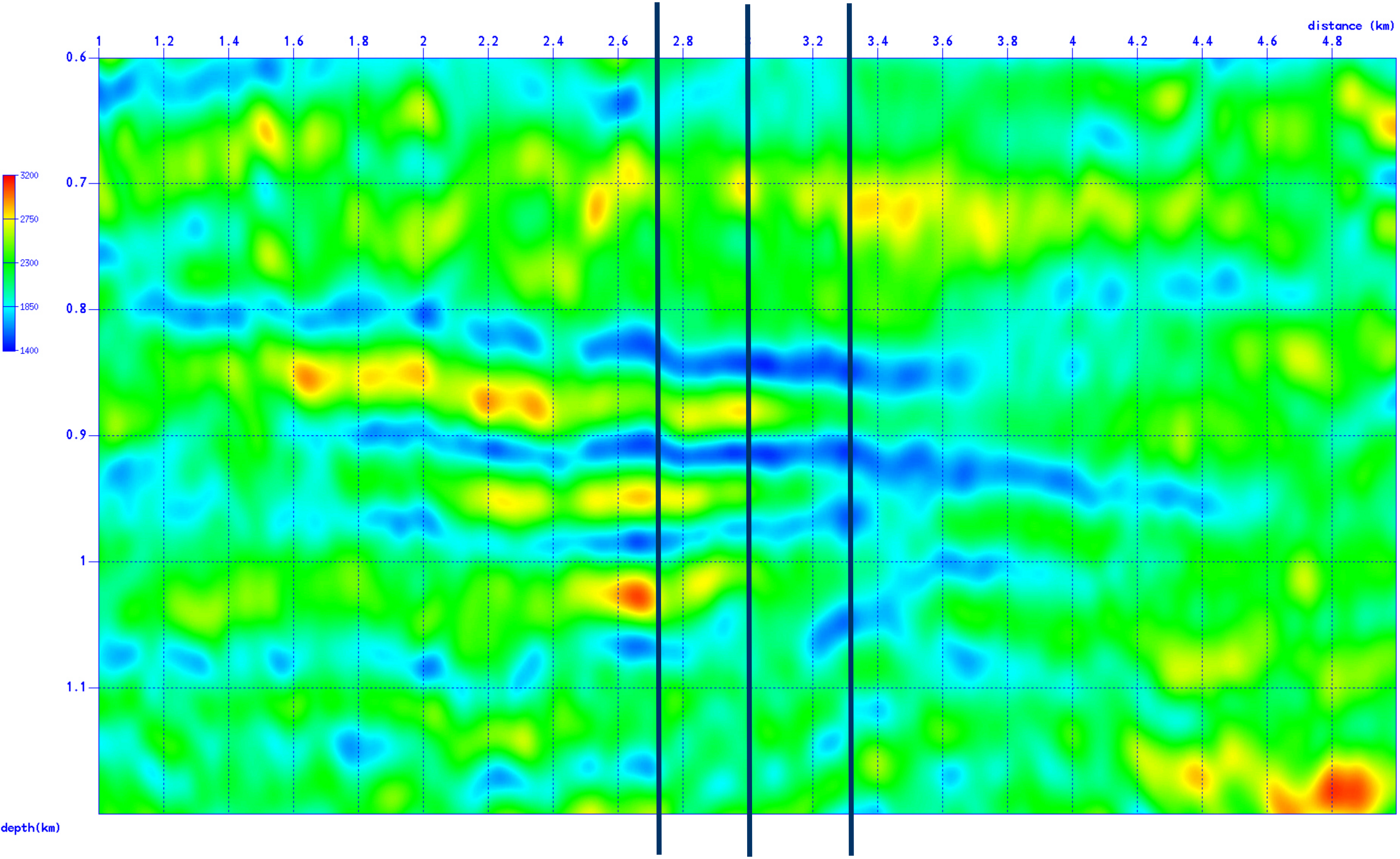
- Stacking velocities converted into interval velocities in depth
- Velocity model is 6 km long
- Model defined on a regular 3m squared grid
- Validity checked by finite difference modelling



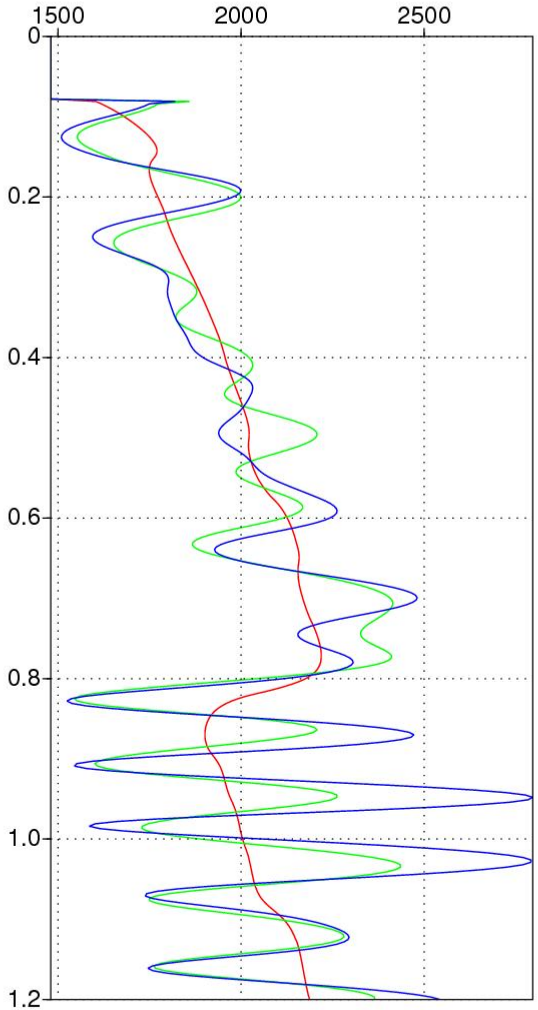
Full-waveform inversion of the real Sleipner data

- Invert for 6 frequencies between 10 and 20 Hz
- Inversion is performed frequency by frequency: from low to high frequencies to reduce the non-linearity of the inverse problem
- 10 iterations per frequency
- Invert for the source wavelet
- Released the smoothing constraints during inversion

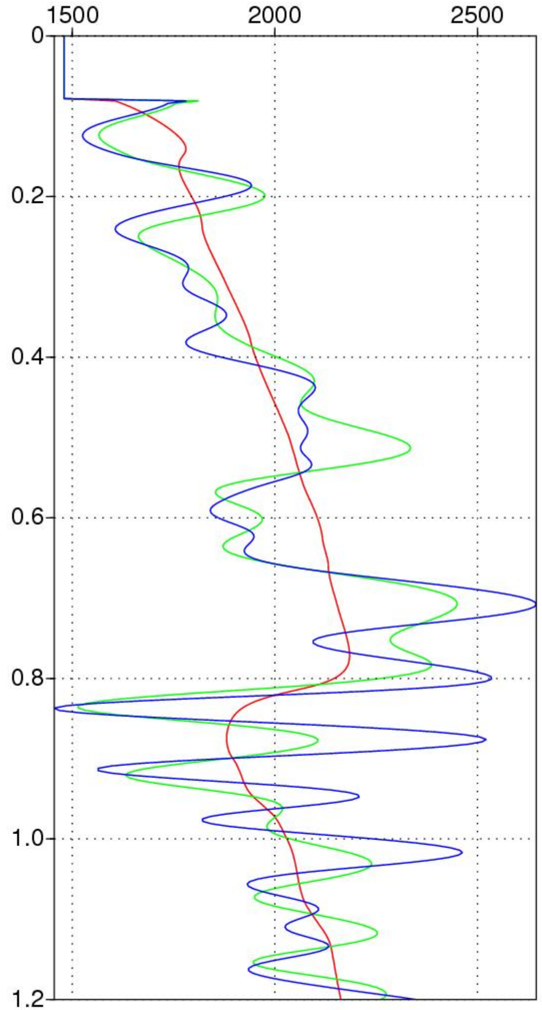
Velocity models derived from FWI (2006 dataset)



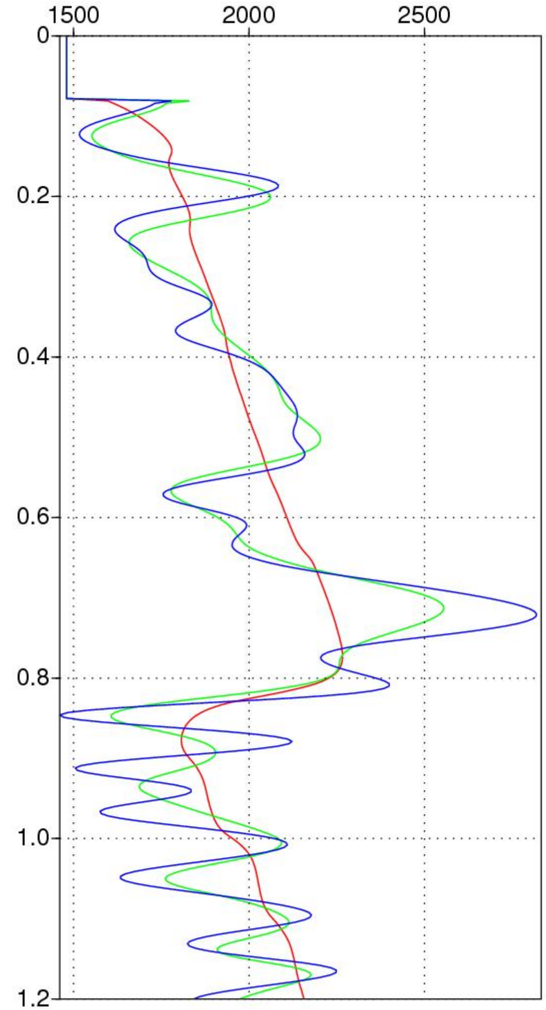
Extraction of 1D velocity profiles (2006 dataset)



2.7 km

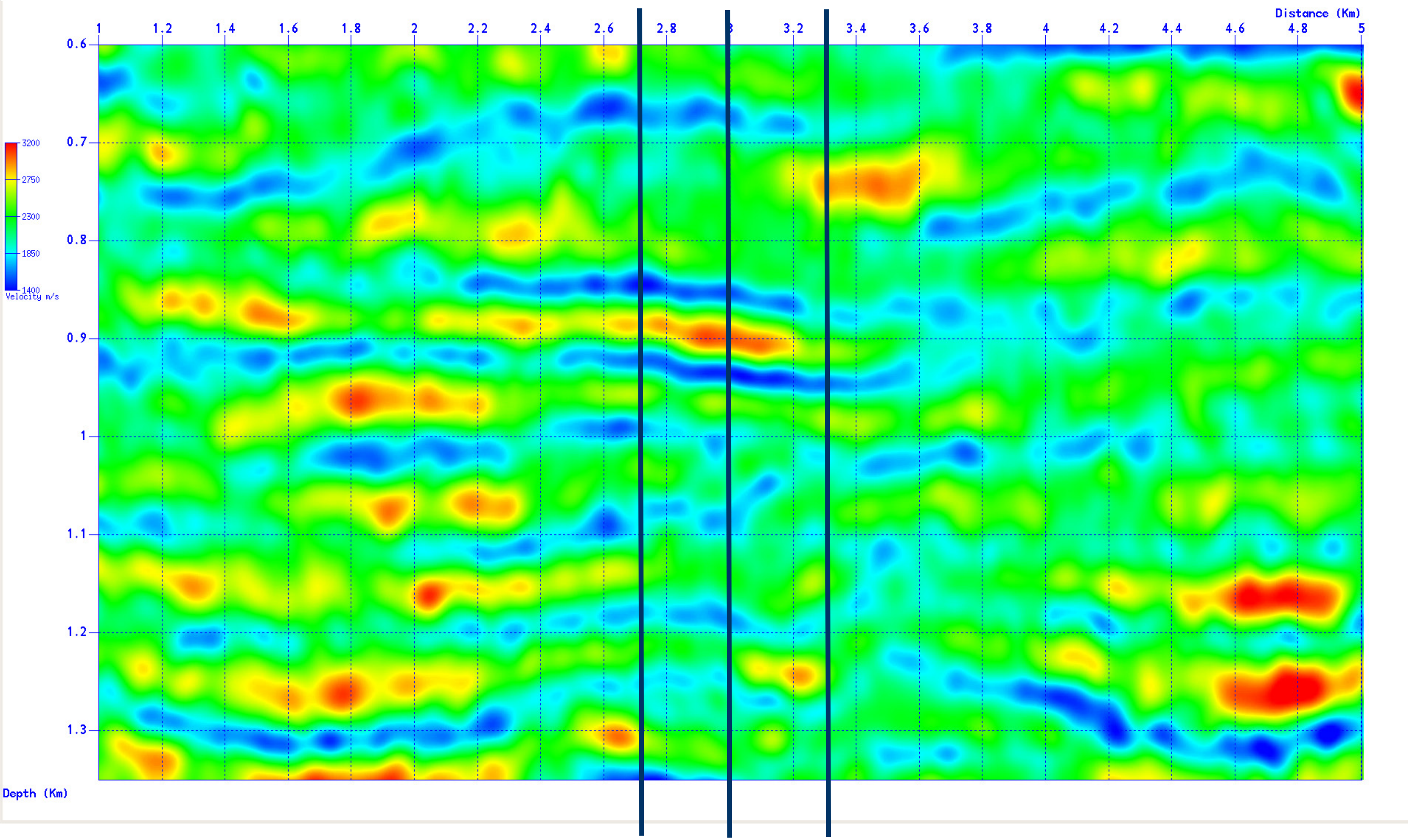


3.0 km

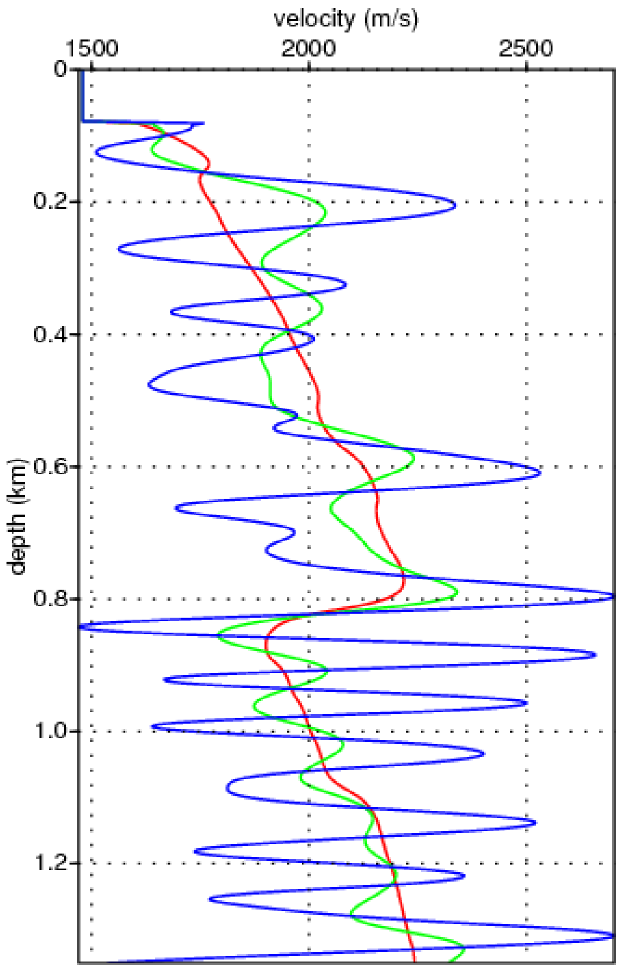


3.3 km

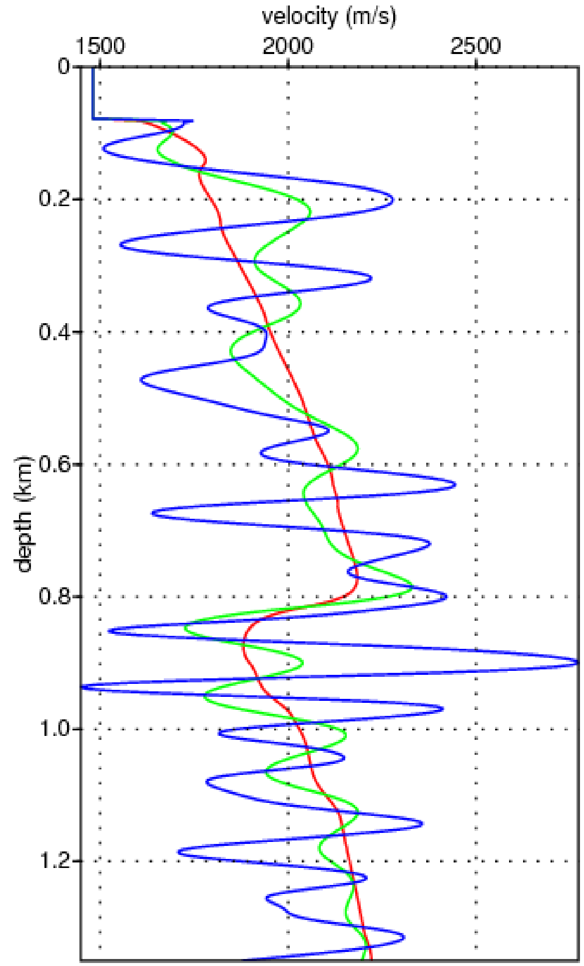
Velocity models derived from FWI (2008 dataset)



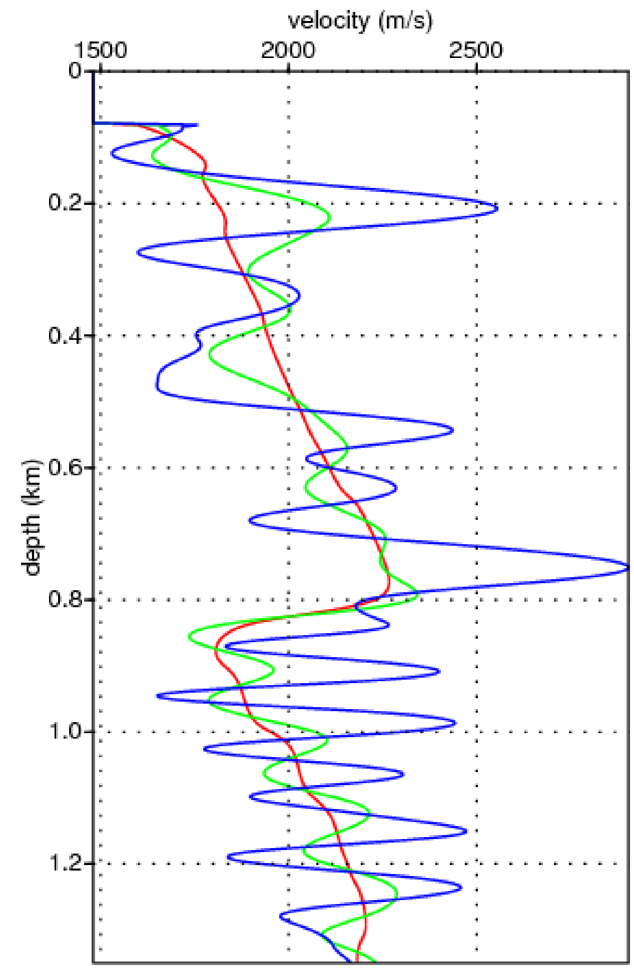
Extraction of 1D velocity profiles (2008 dataset)



2.7 km

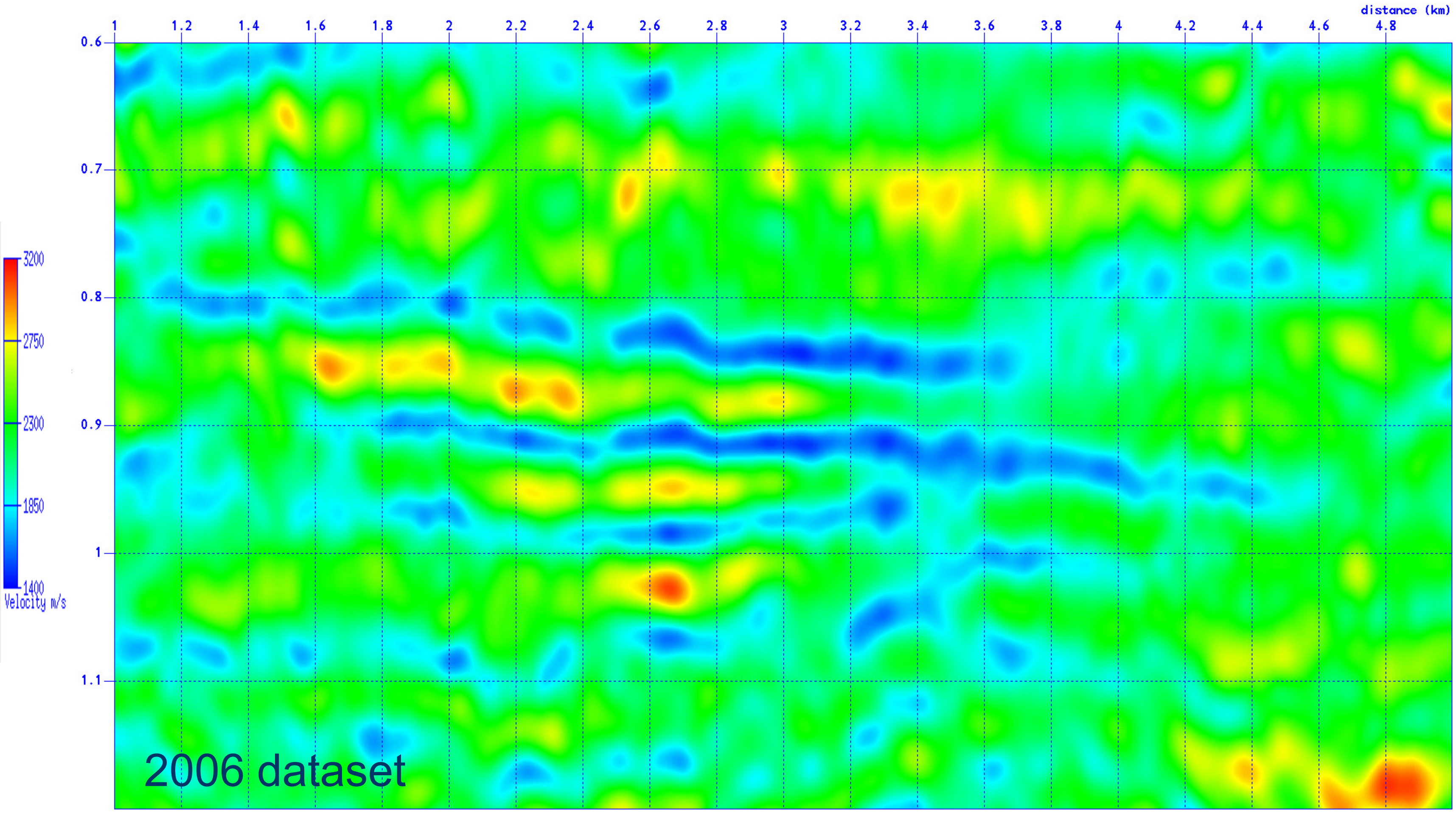


3.0 km



3.3 km

Velocity models derived from FWI



Results of FWI

- Improved image of the velocity in the CO_2 plume
- 2-3 layers with velocities of about 1480 m/s and thickness of about 40-60 m
- Better data explanation (frequency and time)
- Same pre-processing for 2006 and 2008 datasets
- Inversion is converging toward possible solutions in both cases

Conclusions

- FWI is a promising method to better characterise thickness and Vp velocity at Sleipner

- Synthetic case:
  - Capability of the method
  - Imaging of thin CO2 layers can be performed using
    - Reasonable initial frequency (10Hz)
    - Good initial model
    - Classic acquisition geometry

- Results on real data (2006 and 2008 datasets):
  - Improved low frequency velocity image within CO_2 plume
  - Consistent models with 2006 and 2008 datasets
  - Velocity changes of CO2 layers
- Future work:
  - Higher frequency inversion (> 20 Hz)
  - Initial velocity model
  - Pre-processing of the data
  - Effects on the migrated image (using RTM)
  - 3D inversion

Acknowledgments

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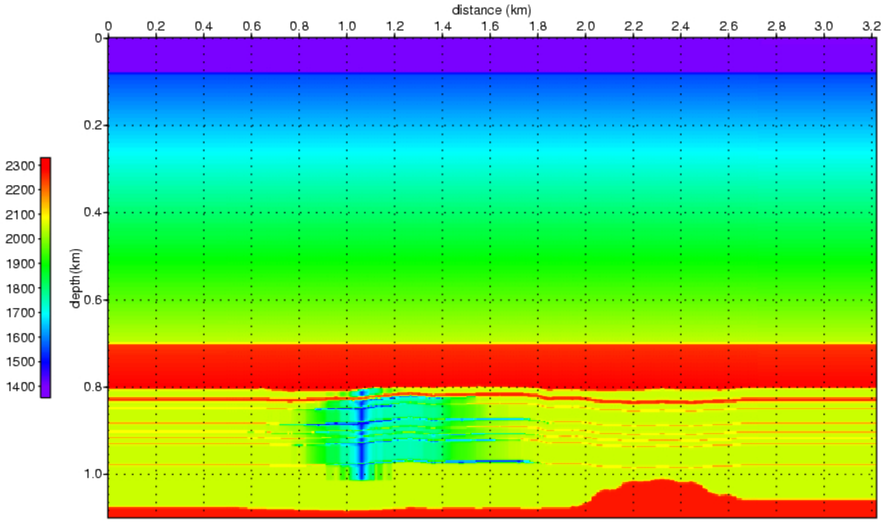
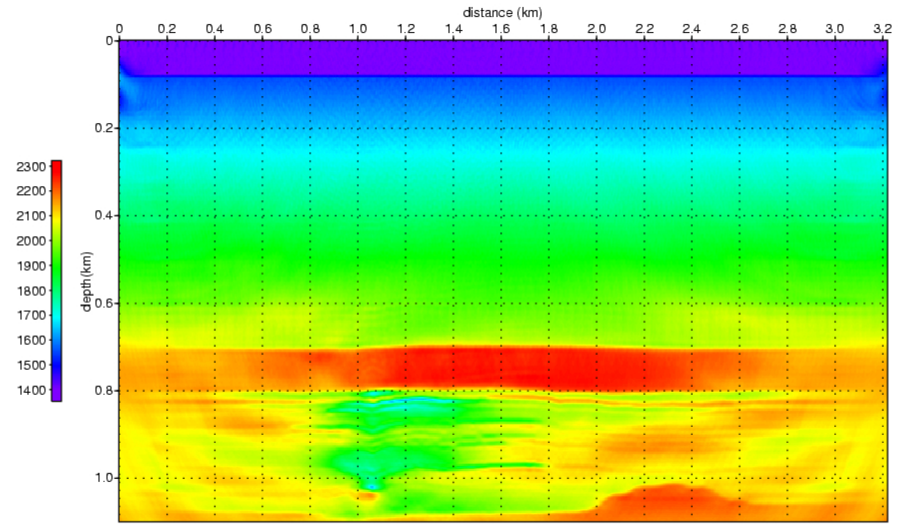
- We also want to thank Statoil for providing the Sleipner data and TNO for providing the synthetic Sleipner model

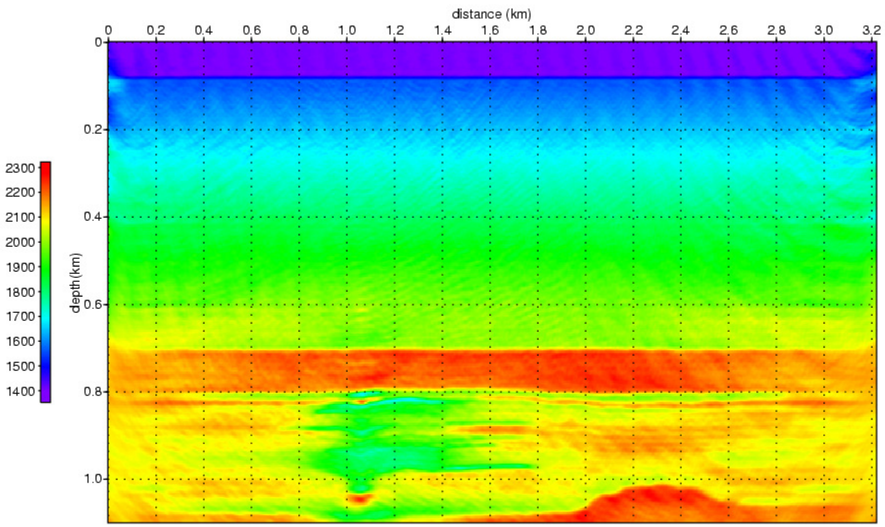
Synthetic example on the Sleipner field



True TNO model



Velocity model with 3.2 km offset

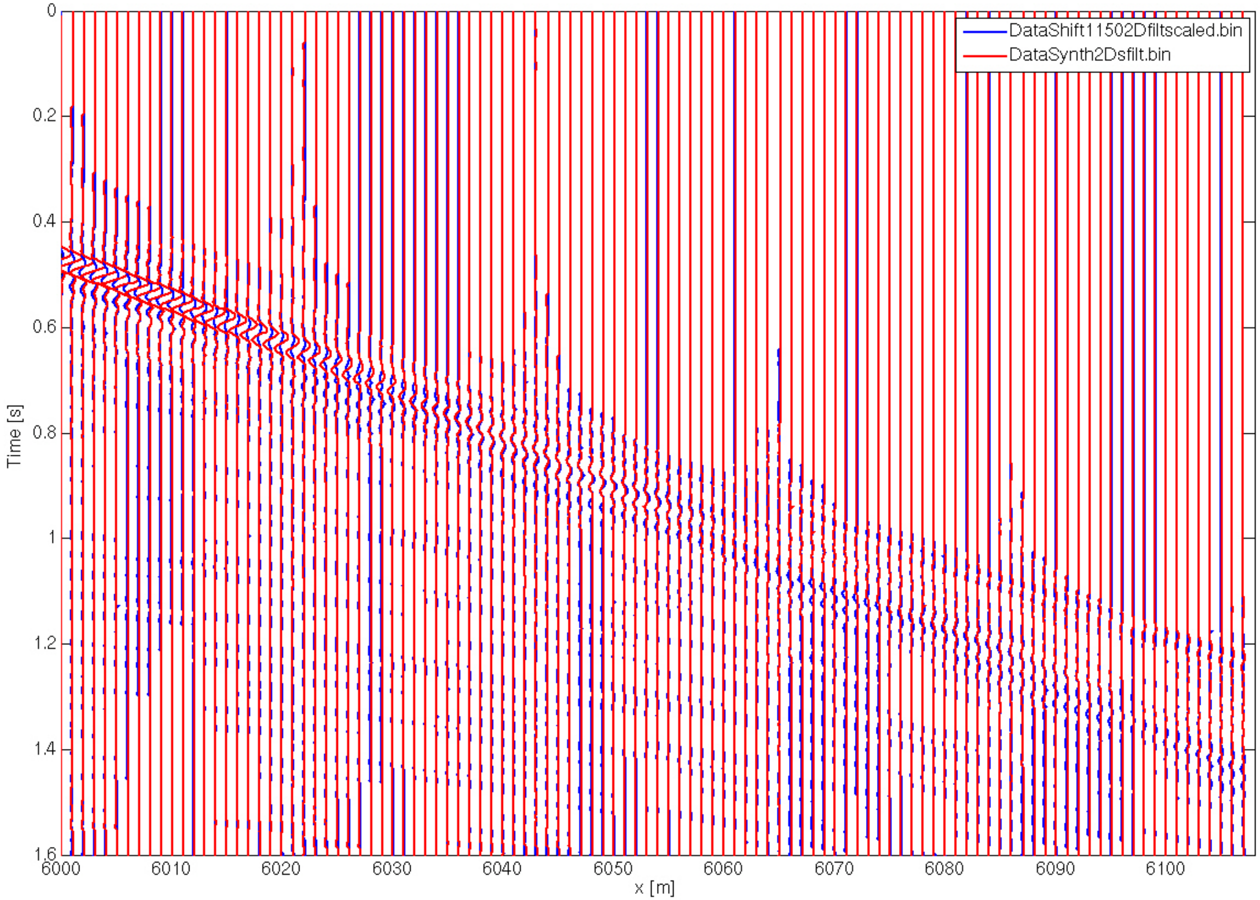


Velocity model with 1.8km offset

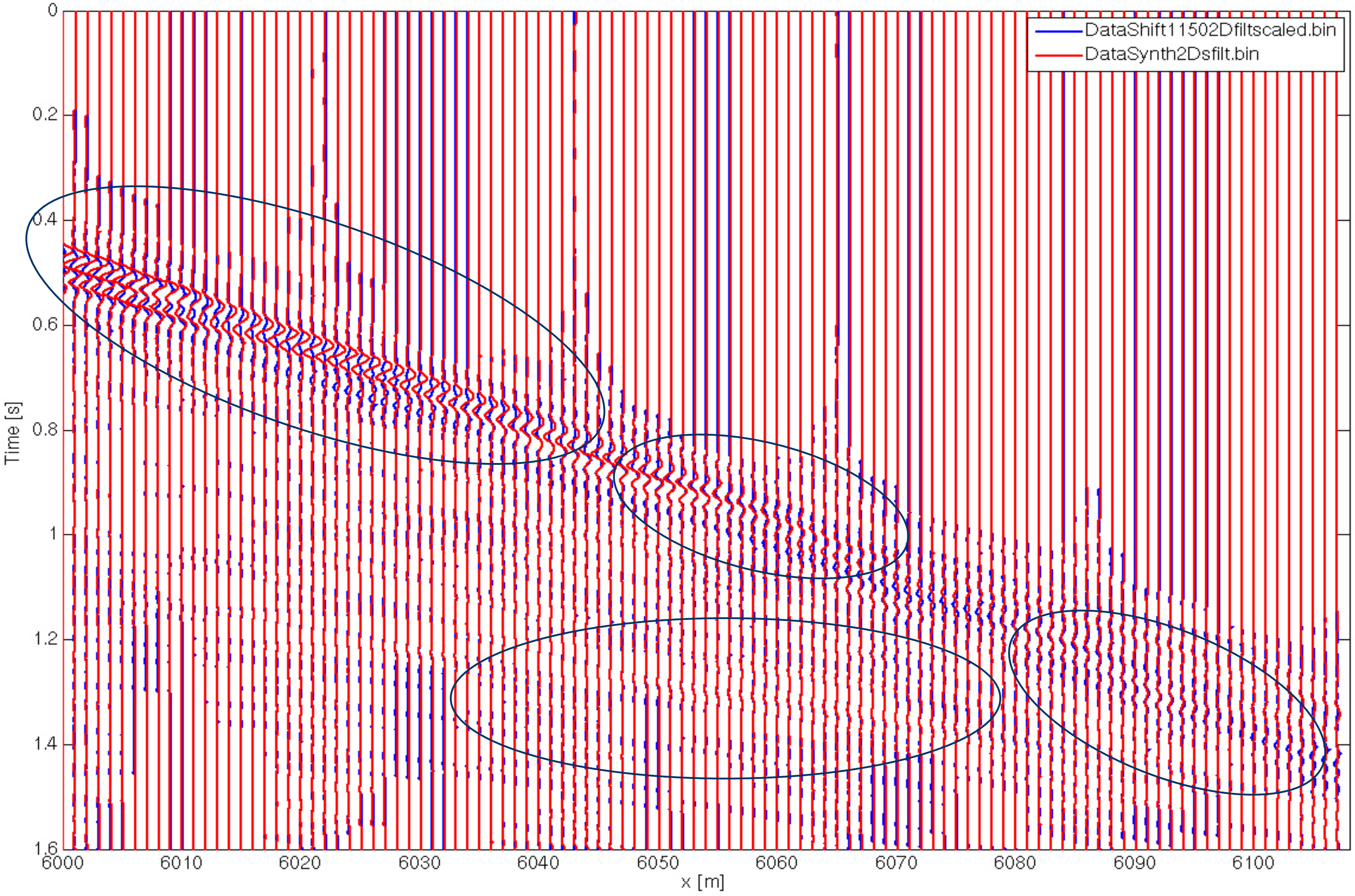
- Better results with 3.2 km offset
- Model derived with 1.8 km offset is still well constrained
- With less offset range more frequency components need to be inverted

Data fit in the initial velocity model

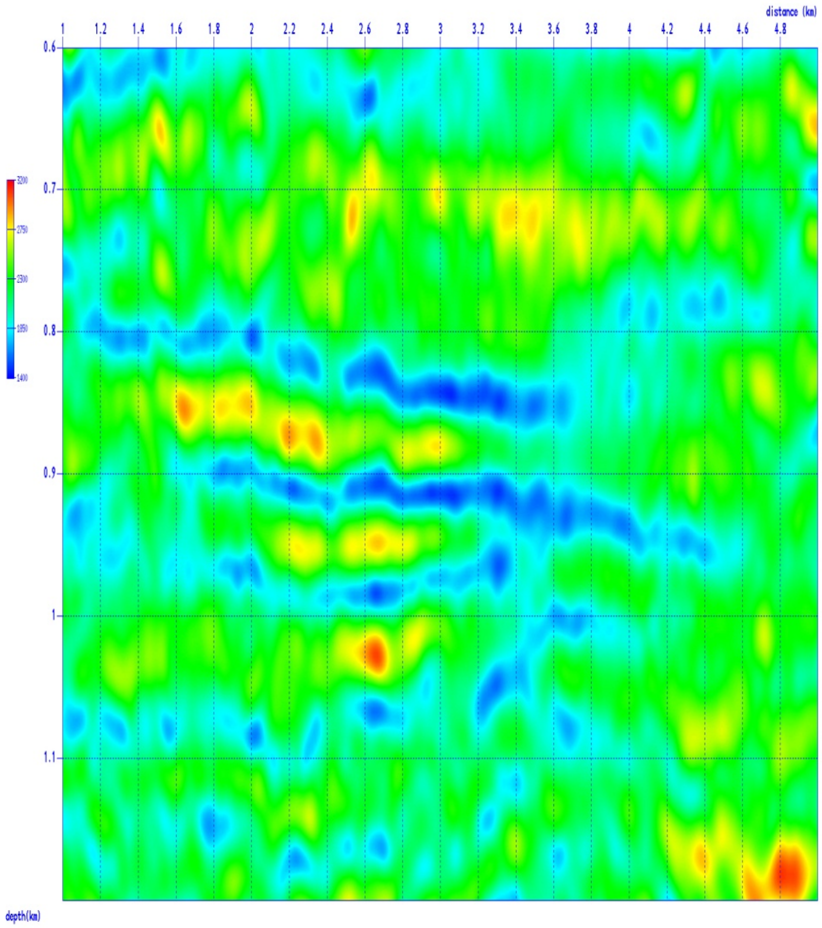
- First-arrivals for the first offset in phase but not amplitude
- First-arrivals at larger offsets
- Does not explain reflections associated with CO_2 plume
- Model is correct but probably not optimal

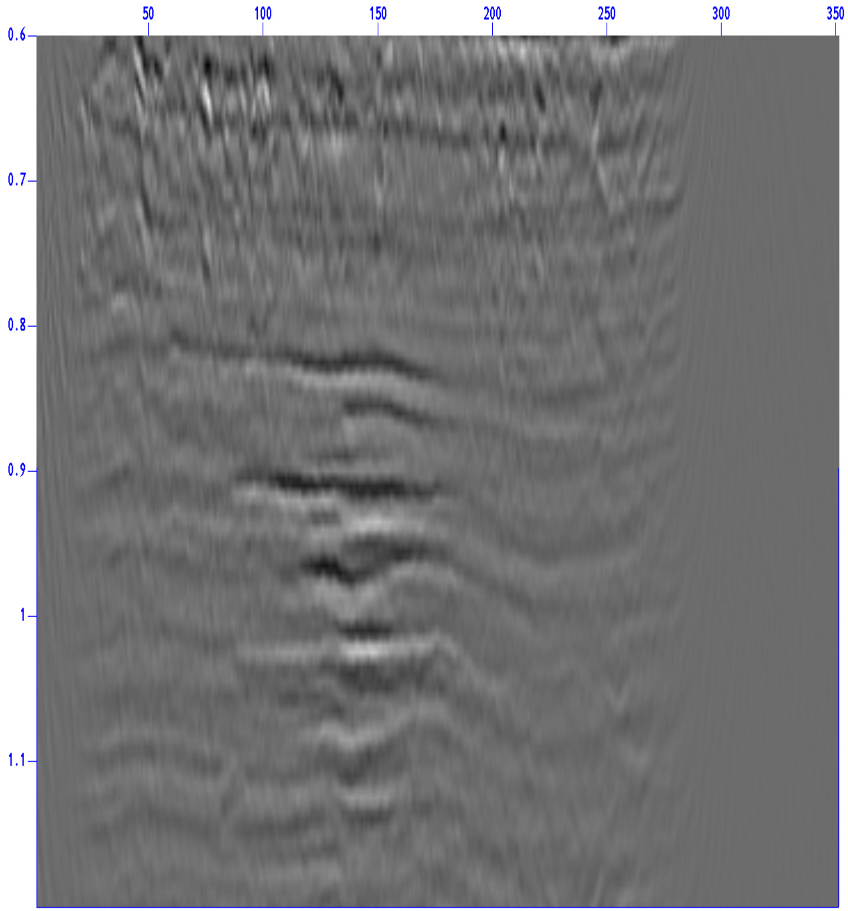


Data fit in the time domain

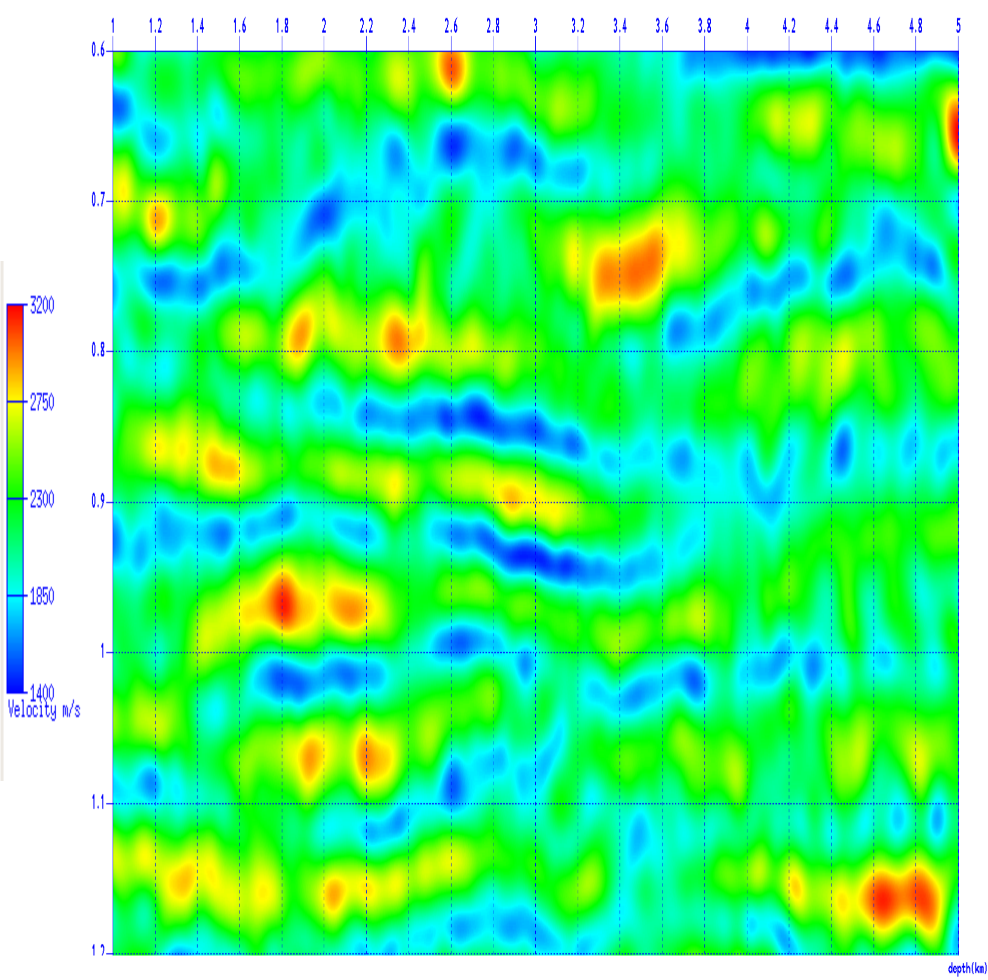


Comparison with migrated image in initial model

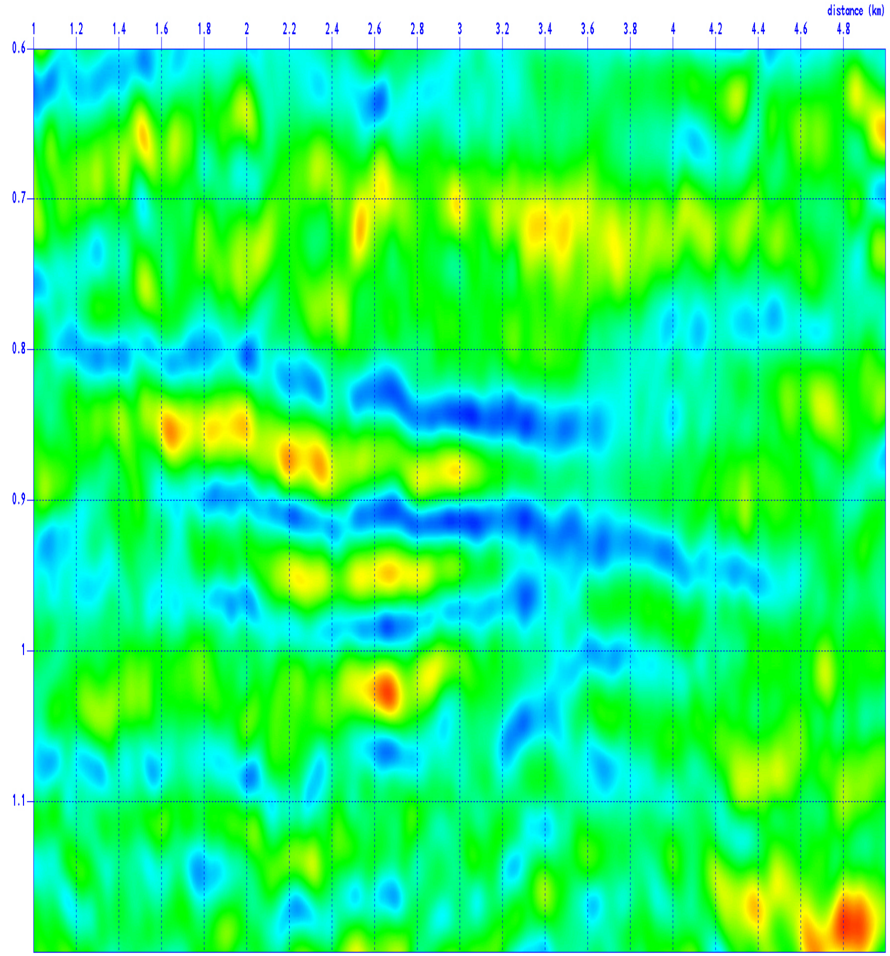




Velocity models derived from FWI



2008 dataset



2006 dataset