# ROSE Meeting 2015

# 3-D Wave Equation Migration Velocity Analysis of seismic data from Sleipner

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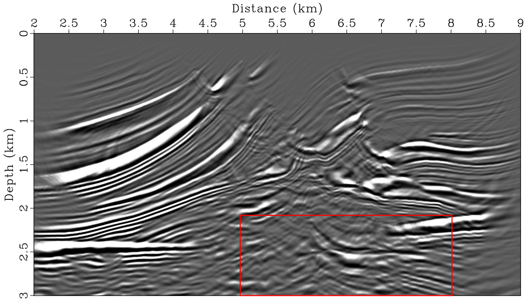
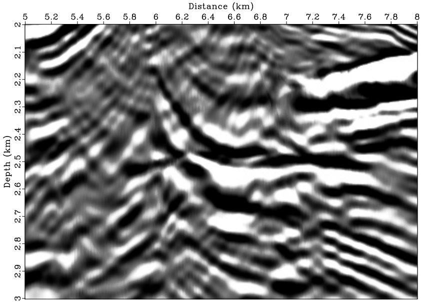
# Ray based Kirchhoff migration

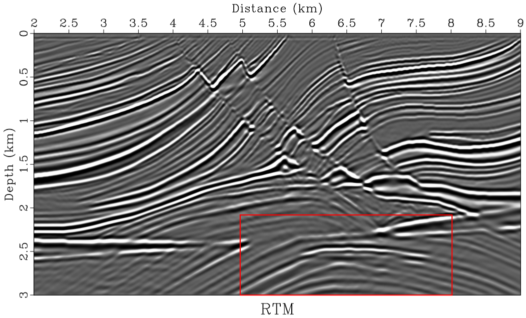


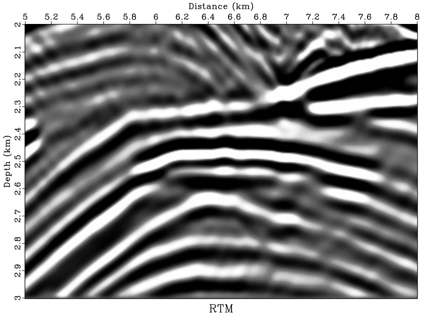

Kirchhoff




Kirchhoff

# Reverse-time migration



# Motivation

- The shortcomings of ray-theoretical depth migration motivated the development of less efficient, but more accurate wave-theoretical methods
- Modern PSDM algorithms based on finite-frequency wavefield extrapolation, such as one-way wave equation migration (Berkhout, 1980), and reverse-time migration (Baysal et al., 1983) are able to handle complex velocity fields
- However, the problem of automatically estimating the background velocity field over complex geological settings is still unsolved

# Review of wave equation migration velocity analysis (WEMVA)

- WEMVA is a kind of seismic tomography method based on linearized or non-linear inversion of seismic reflection data in the image-domain using wave theoretical methods (Chavent and Jacewitz, 1995; Biondi and Sava, 1999; Shen et al., 2003; Sava and Biondi, 2004; Shen and Symes, 2008; Mulder, 2008)

# Outline

## Acoustic reverse-time migration (RTM)

*Prestack depth migration = Wavefield reconstruction + Imaging condition*

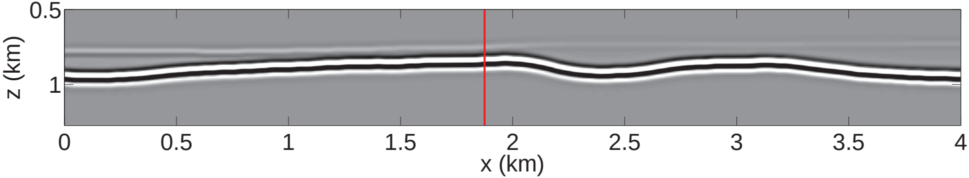
## Wavefield reconstruction in RTM

$$\left[\frac{1}{v_p^2(\mathbf{x})}\frac{\partial^2}{\partial t^2} - \nabla^2\right] w^s(\mathbf{x}, t; s) = f(\mathbf{x}, t; s)$$

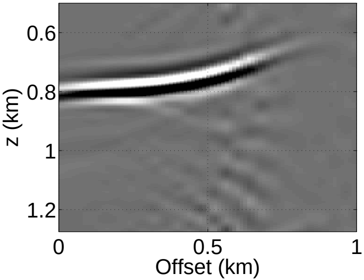
$$\left[\frac{1}{v_p^2(\mathbf{x})}\frac{\partial^2}{\partial t^2} - \nabla^2\right] w^r(\mathbf{x}, t; s) = d(\mathbf{x}, T - t; s)$$

## Imaging condition

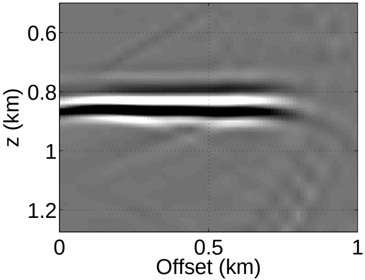
$$\mathcal{R}(\mathbf{x}; s) = \int_0^T w^s(\mathbf{x}, t; s) w^r(\mathbf{x}, T - t; s)$$




**Wrong velocities**




**Correct velocities**



# Wave equation migration velocity analysis by stack-power

## Stack-power

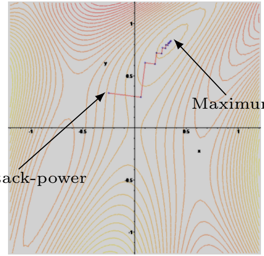
*Find a P-wave velocity model that maximizes the stack over sources of the depth migrated image*

Define $\mathcal{J}(\mathbf{v})$ as the stack of the migrated image. WEMVA is then the problem

$$\arg\max_{\mathbf{v}} \mathcal{J}(\mathbf{v}) = \sum_s \sum_{\mathbf{x}} \frac{\partial}{\partial x_3} \left[\mathcal{W}(\mathbf{x})\mathcal{R}(\mathbf{x}, \mathbf{v}; s)\right]^2$$

Solved using an iterative method

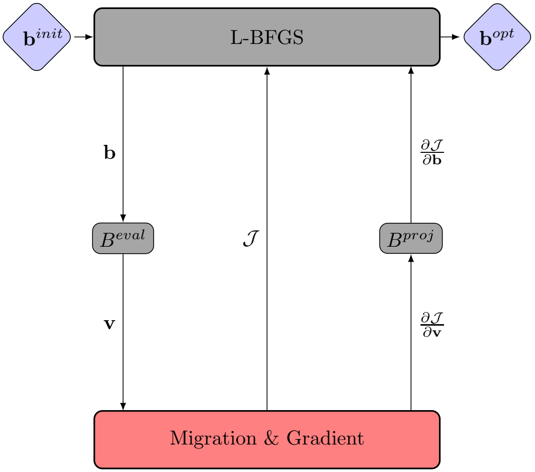
$$\mathbf{v}_{k+1} = \mathbf{v}_k + \alpha_k \mathbf{g}_k,$$




| | |
|---|---|
| $\mathbf{v}_k$ | model at iteration $k$ |
| $\mathbf{g}_k$ | gradient of $\mathcal{J}(\mathbf{v})$ at iteration $k$ |
| $\alpha_k$ | step length at iteration $k$ |

# Organization of WEMVA

- Using an initial model ($\mathbf{b}^{init}$), migrate the seismic data, and stack to form an image
- Evaluate $\mathcal{J}$ by computing the stack-power of the stacked image
- Using the stacked image compute the gradient $\partial\mathcal{J}/\partial\mathbf{v}$
- Finally, project the gradient in a tri-cubic B-spline basis



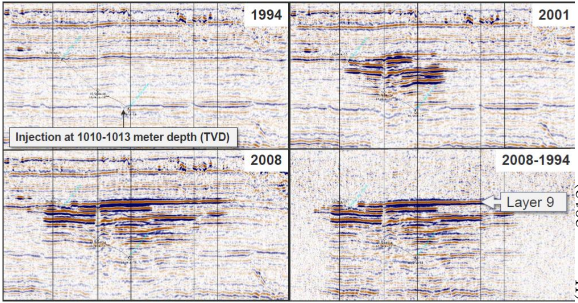
# 3D WEMVA implementation

## Major challenges

- Computational Cost (Combination of high frequencies and 3D Reverse-time migration requirements)
- Checkpointing problems (Partially solved by recomputation from the boundaries)
- Sensitivity to multiples (Solution has been to use 3D SRME. However, this method gives suboptimal results in poorly sampled shallow water NAZ datasets.)

# $CO_2$ injection in Utsira

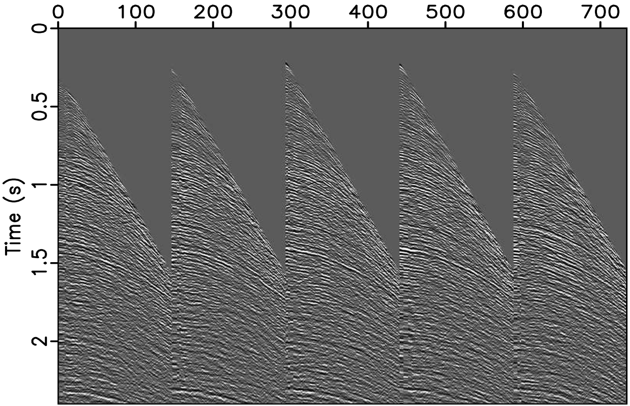
- $CO_2$ from the Sleipner field is stored in Utsira Formation, North Sea
- Reservoir unit is at 800-1100 m depth
- One $CO_2$ injector at $\sim$ 1012 meter
- Injected gas is $\sim$ 98% $CO_2$
- 15.3 Mt $CO_2$ have been injected (as of May 2014, $\sim$ 0.9 Mt per annum)




(Hagen, 2012)

# Sleipner 1994 data - pre-injection

- The geometry of the data consists in a minimum offset of 0.25 km and maximum offset of 1.7 km
- There are 5 cables. Crossline receiver interval is 100 meters and inline receiver interval is 12.5 m
- There are 1708 shots.The shooting pattern is flip-flop with a shot interval of 18.75 m
- Recording time 2.3 s
- Processing included multiple attenuation (3D SRME) and muting of refractions and wide-angle reflections
- We filter the frequencies to 30 Hz and use only 854 shots.

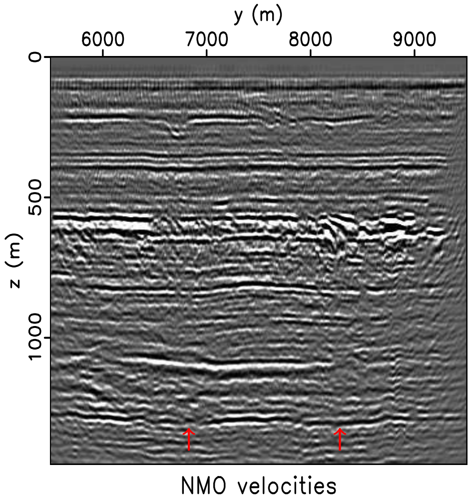


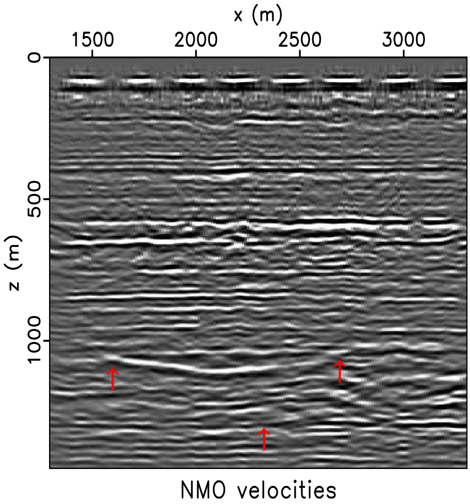

1994 Shot gather

# Workflow

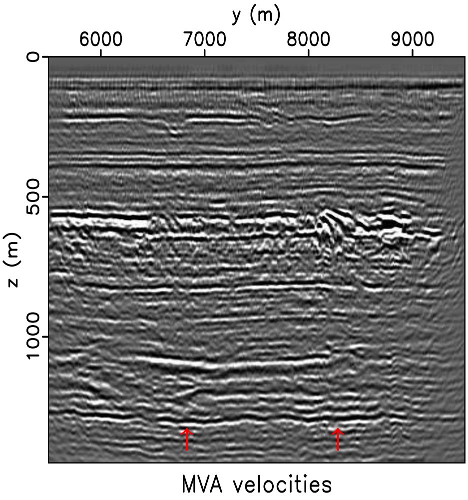
- Demultiple using SRME
- Binning
- Traditional velocity analysis to produce initial velocity model (NMO velocities)
- Low pass filter of data with high cut at 30 Hz
- Time gain ($t^{1.5}$ gave best results)
- WEMVA

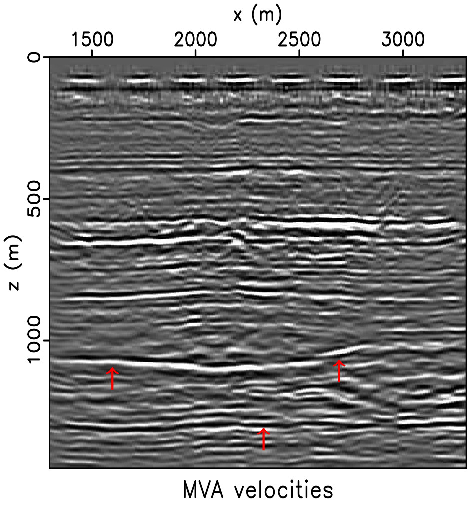
# Initial images



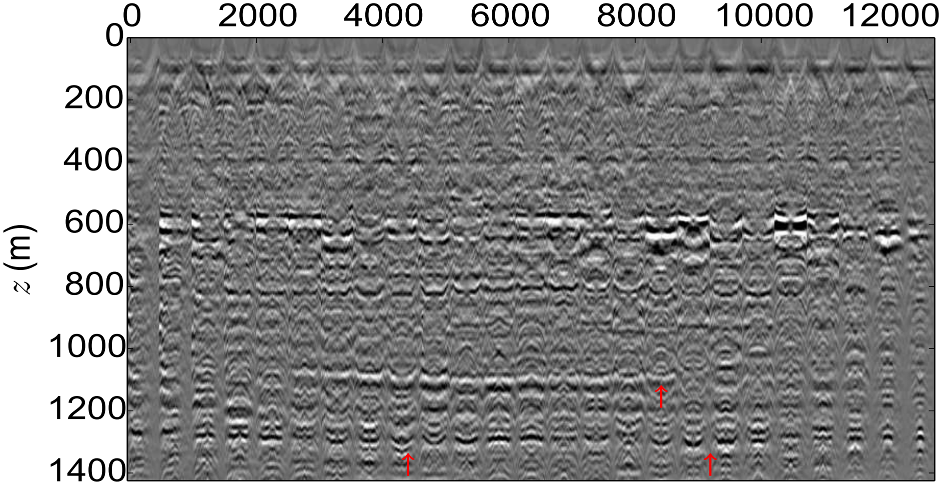



# Updated images after 2 iterations

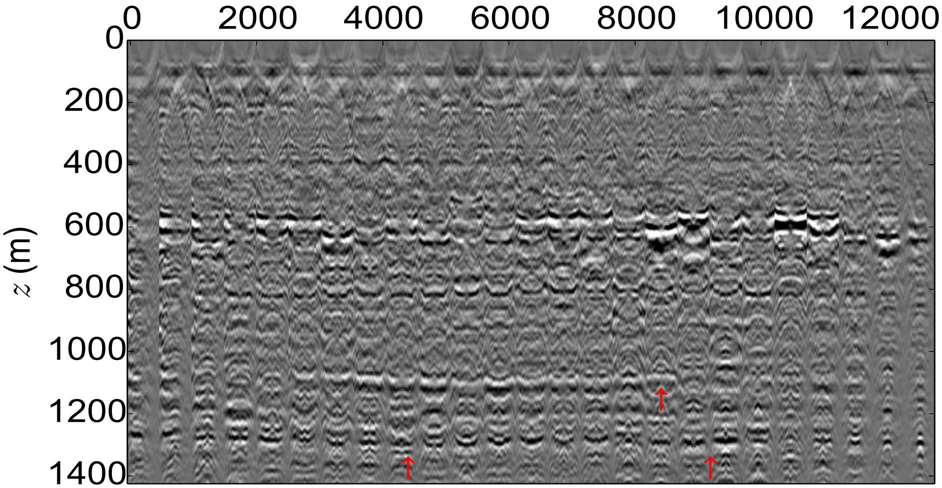


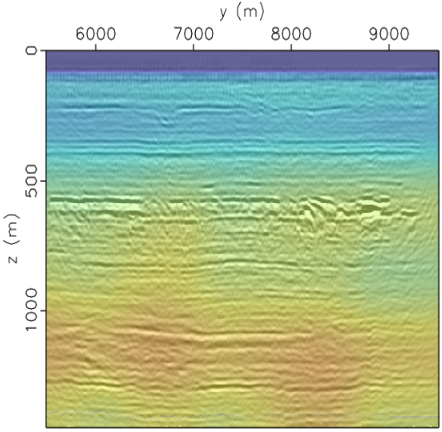
# Initial CIGs



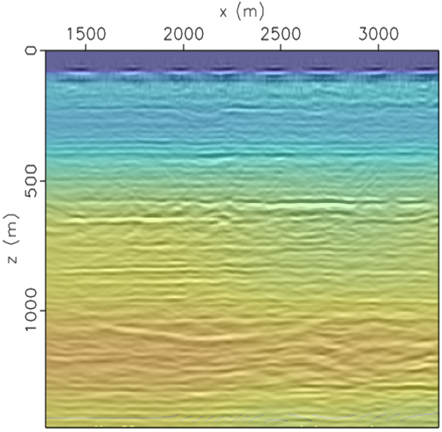
# Updated CIGs after 2 iterations



# NMO velocities

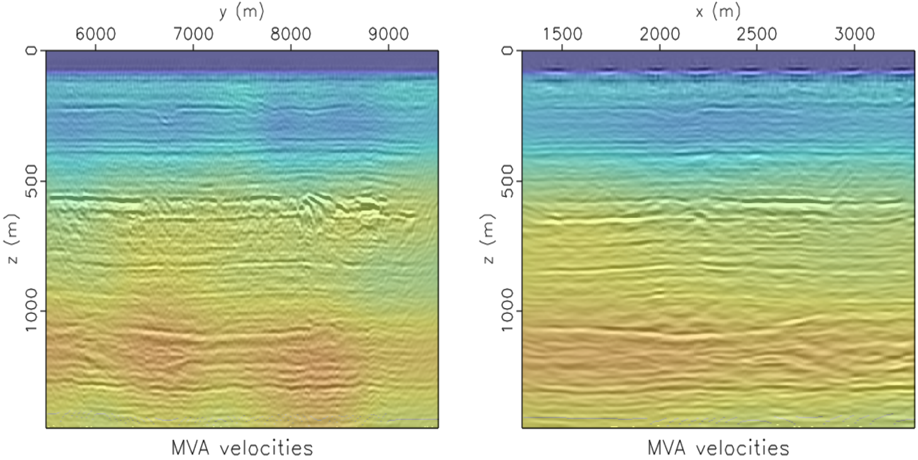



NMO velocities

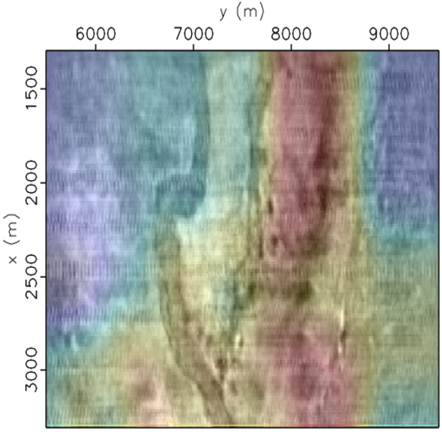



NMO velocities

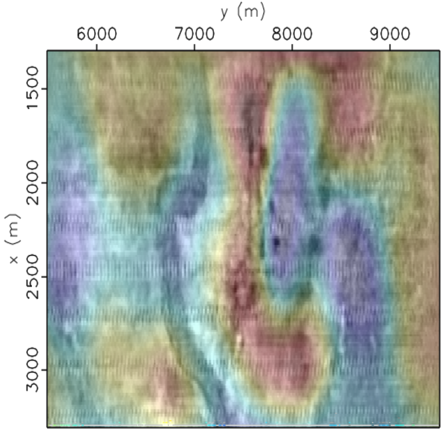
# MVA velocities after 2 iterations



# Depth Slice comparison



NMO velocities

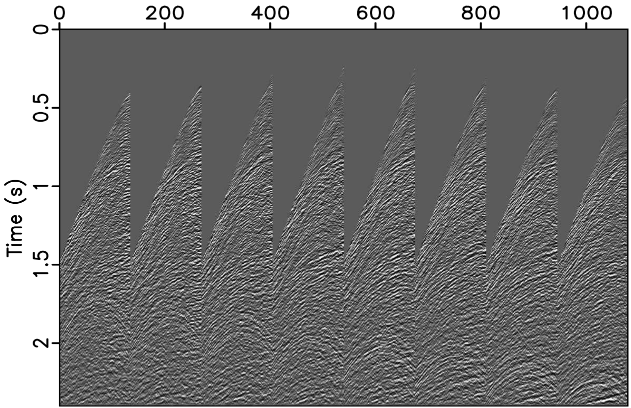


MVA velocities

# 2006 data

# Sleipner 2006 data

- The geometry of the data consists in a minimum offset of 0.15 km and maximum offset of 1.7 km
- There are 8 cables. Crossline receiver interval is 50 meters and inline receiver interval is 12.5 m
- There are 1419 shots.The shooting pattern is flip-flop with a shot interval of 18.75 m
- Recording time 2.3 s
- Processing included multiple attenuation (3D SRME) and muting of refractions and wide-angle reflections

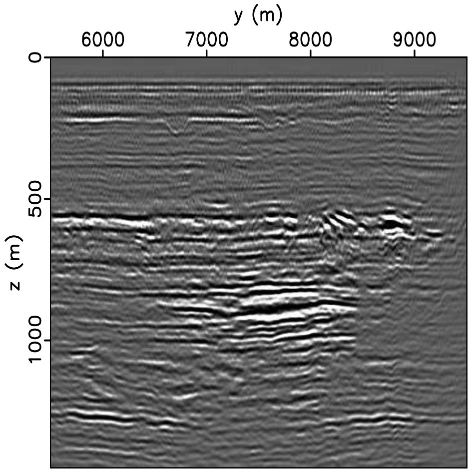



2006 Shot gather

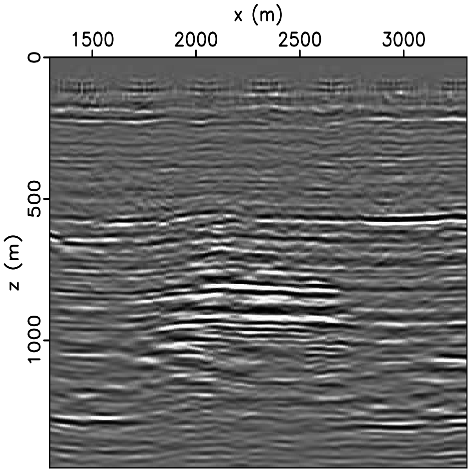
# Problems and issues

- Currently the velocity analysis is not converging
- The enhanced amplitudes of the reflections due to gas complicates the velocity analysis
- The region around the gas injection dominates the objective function
- Interbed multiples generated within the gas cloud can also cause problems for WEMVA
- One attempt to overcome the issues was to define a weighting function to counter the amplitude effects
- Another strategy was to mute the gradient such as to only allow updates at and around the gas injection volume

# Initial images

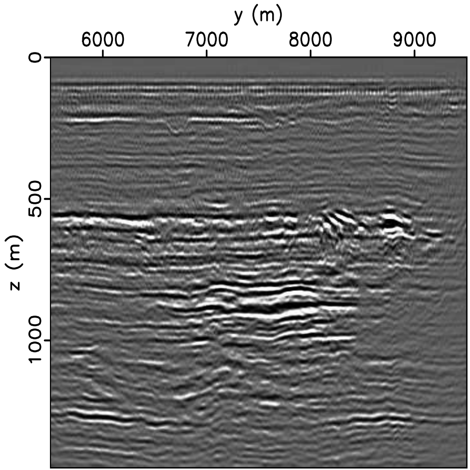



1994 velocities

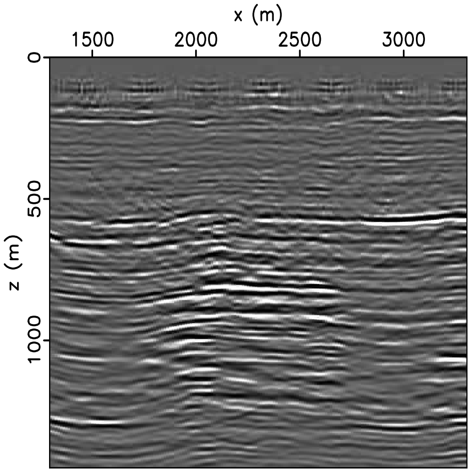



1994 velocities

# Updated images after 3 iterations

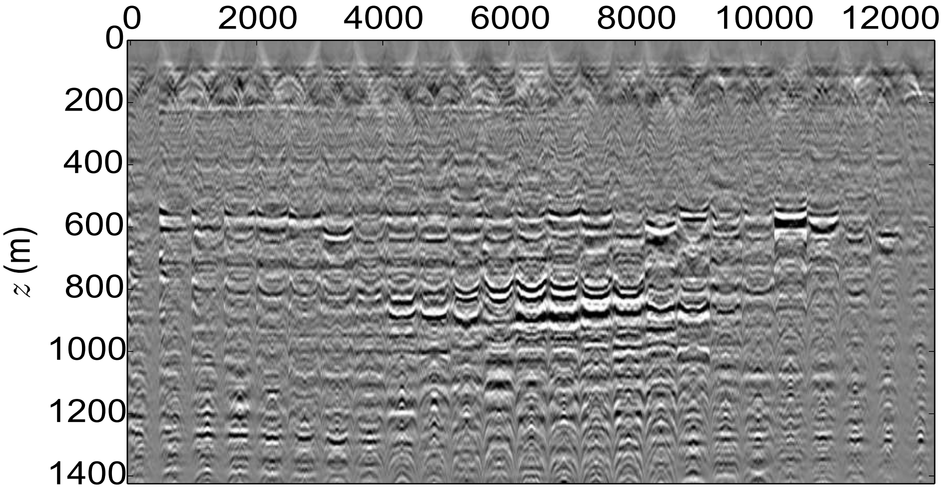



2006 velocities

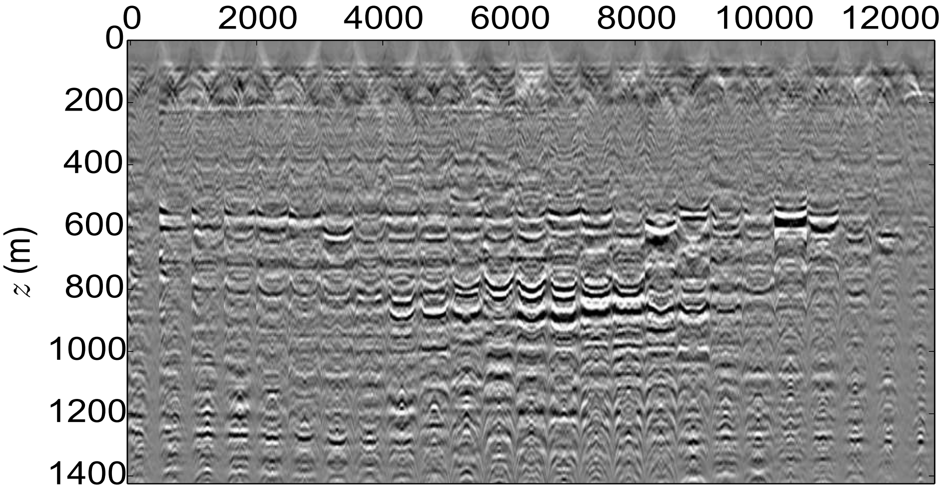



2006 velocities

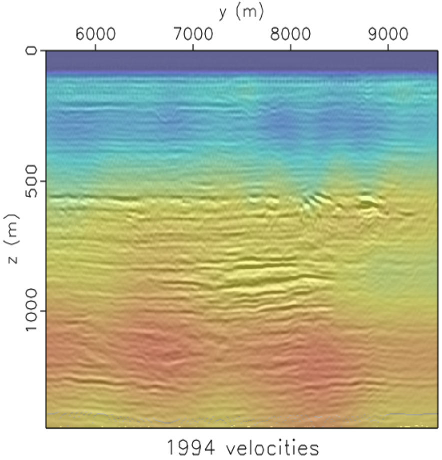
# Initial CIGs

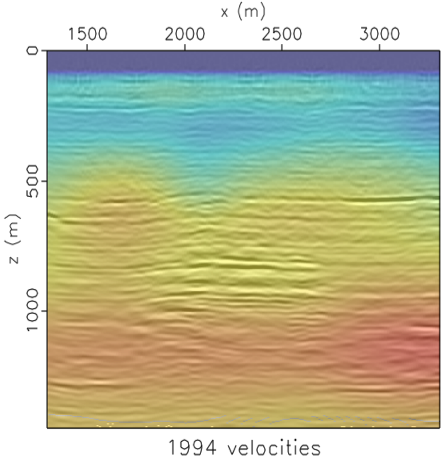


# Updated CIGs after 3 iterations

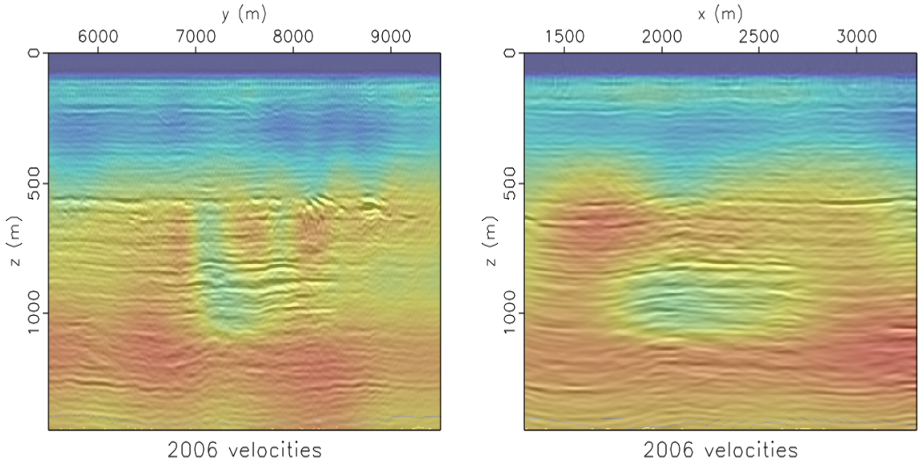


# NMO velocities



# MVA velocities after 2 iterations



# Conclusion

- We perform wave equation migration velocity to a 3D narrow azimuth survey at Sleipner
- The algorithm is based on maximization of stack-power of the depth migrated images constructed using reverse-time migration
- The method is applied to the 1994 and 2006 vintages of the 3D seismic data
- The method converges acceptably after 2 iterations for the 1994 data
- For the 2006 dataset, the method diverges, and is not able to acceptably improve the image under the Utsira formation
- Possible causes are the lack of longer offsets in the data, the poor scaling, and the presence of strong interbed multiples

# Acknowledgments

I acknowledge my colleages at the modeling and seismic imaging (MSIM) group at IPT for help and discussion. I also acknowledge the sponsors of the Rose consortium for financial support of this project.