IMMI: the role of well calibration in the context of high geological complexity

Sergio Romahn

Kris Innanen

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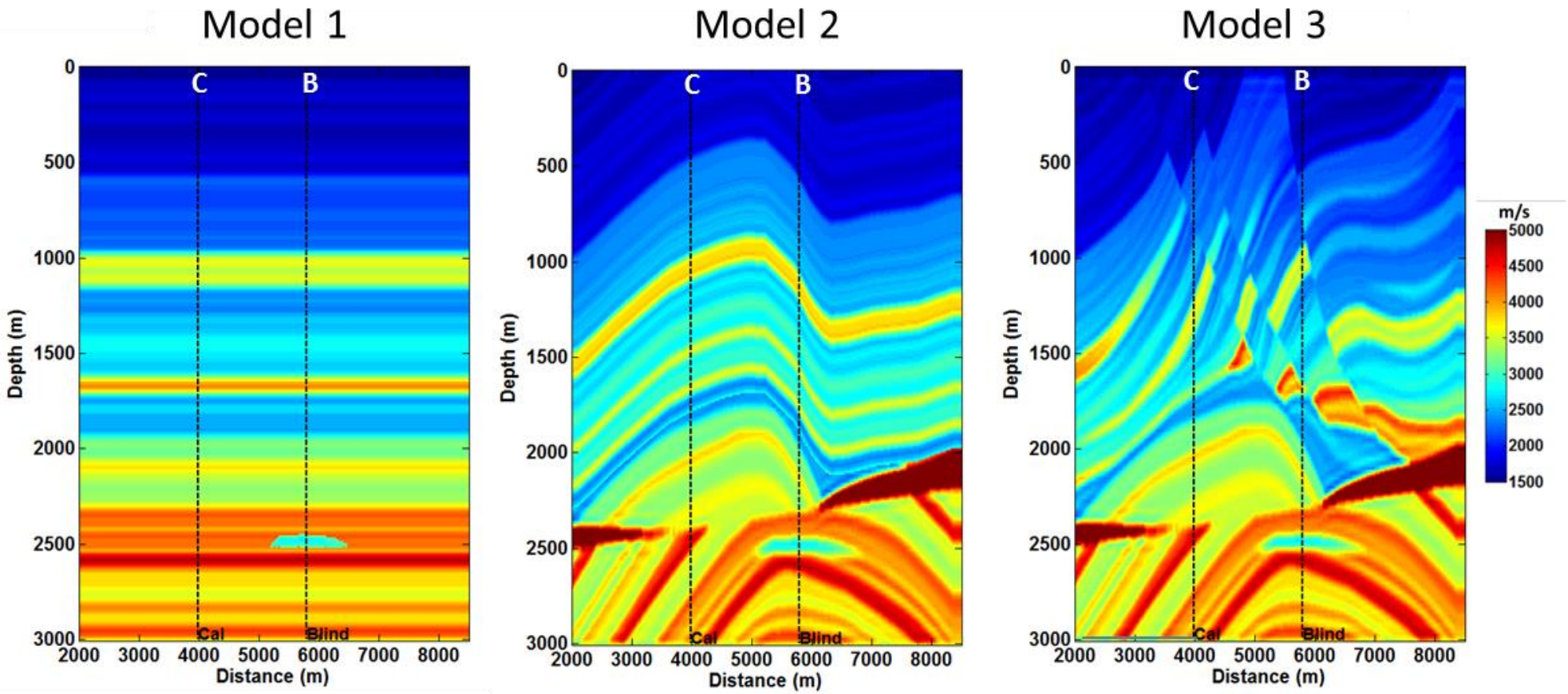
Outline

- Introduction
  - IMMI
  - Objective
- FWI process
- Well calibration
- Conclusions
- Future work

- IMMI was introduced by Margrave, Innanen, & Yedlin in 2012 (chapter 70, CREWES report).
- IMMI stands for iterative, modelling, migration and inversion, which can be seen as the cycle of FWI.
- IMMI proposes the incorporation of standard processing techniques into the process of FWI.
- Examples of IMMI's approach are the use of any migration method to obtain the gradient and the use of well velocity to calibrate it.

Objective

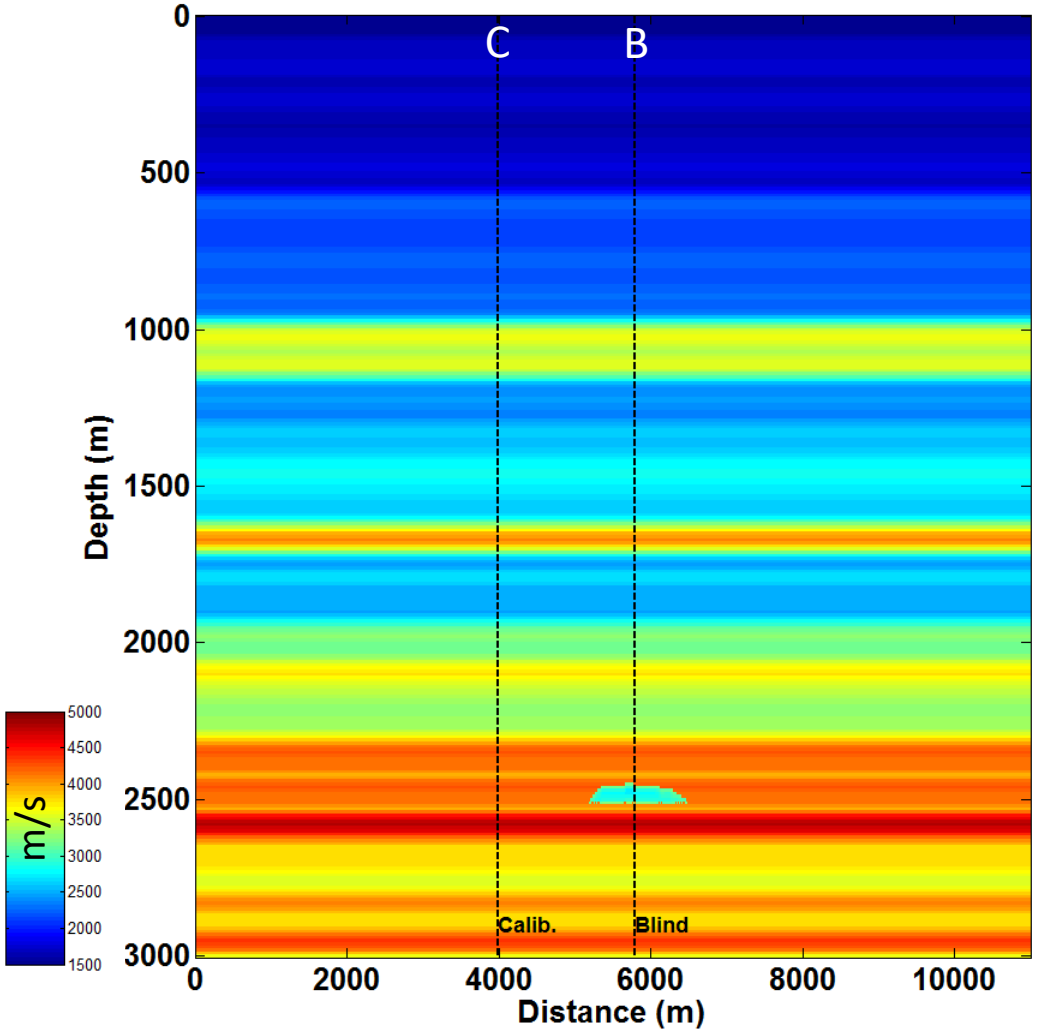
To evaluate the role of well calibration in the context of increasingly complex geology



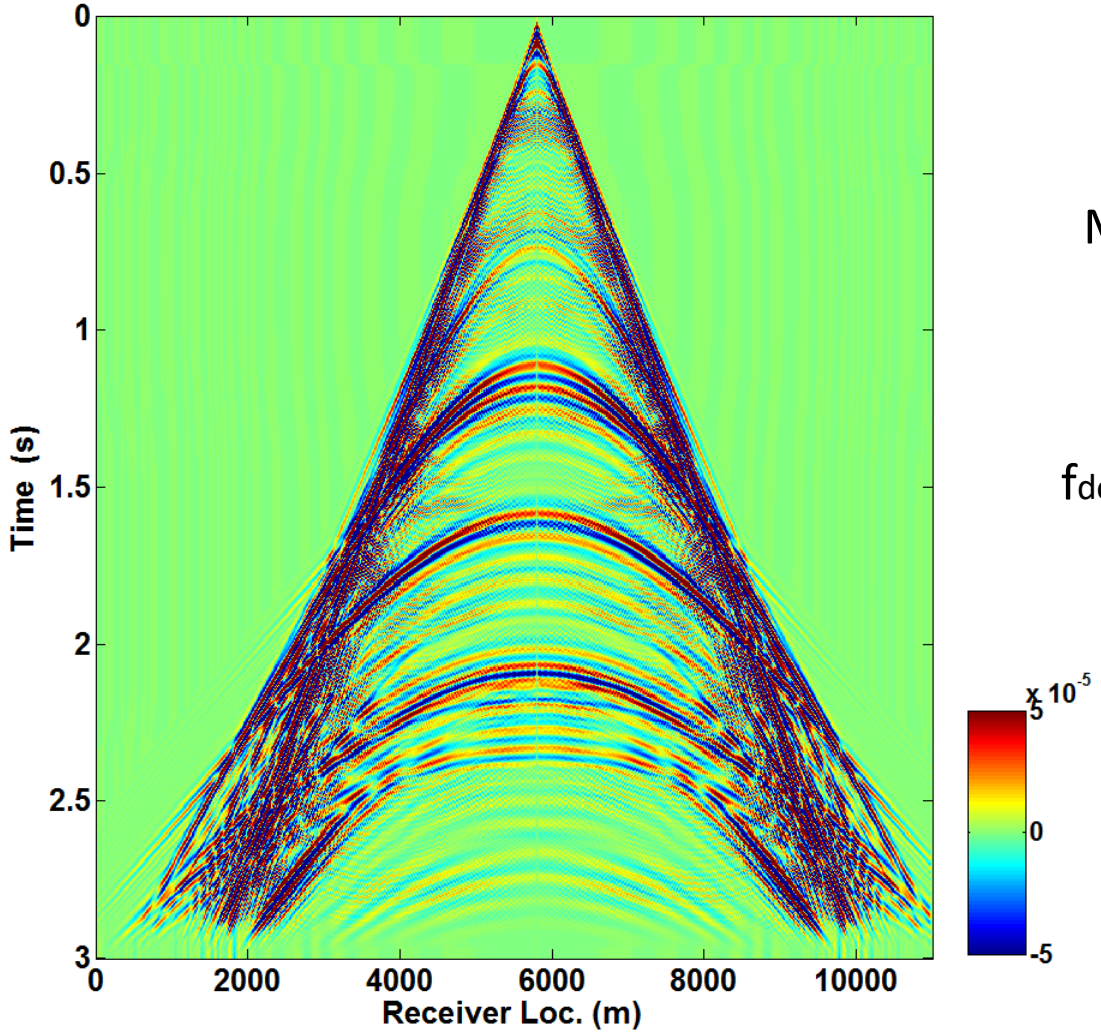
FWI process

Observed shots

Model 1



Observed shot

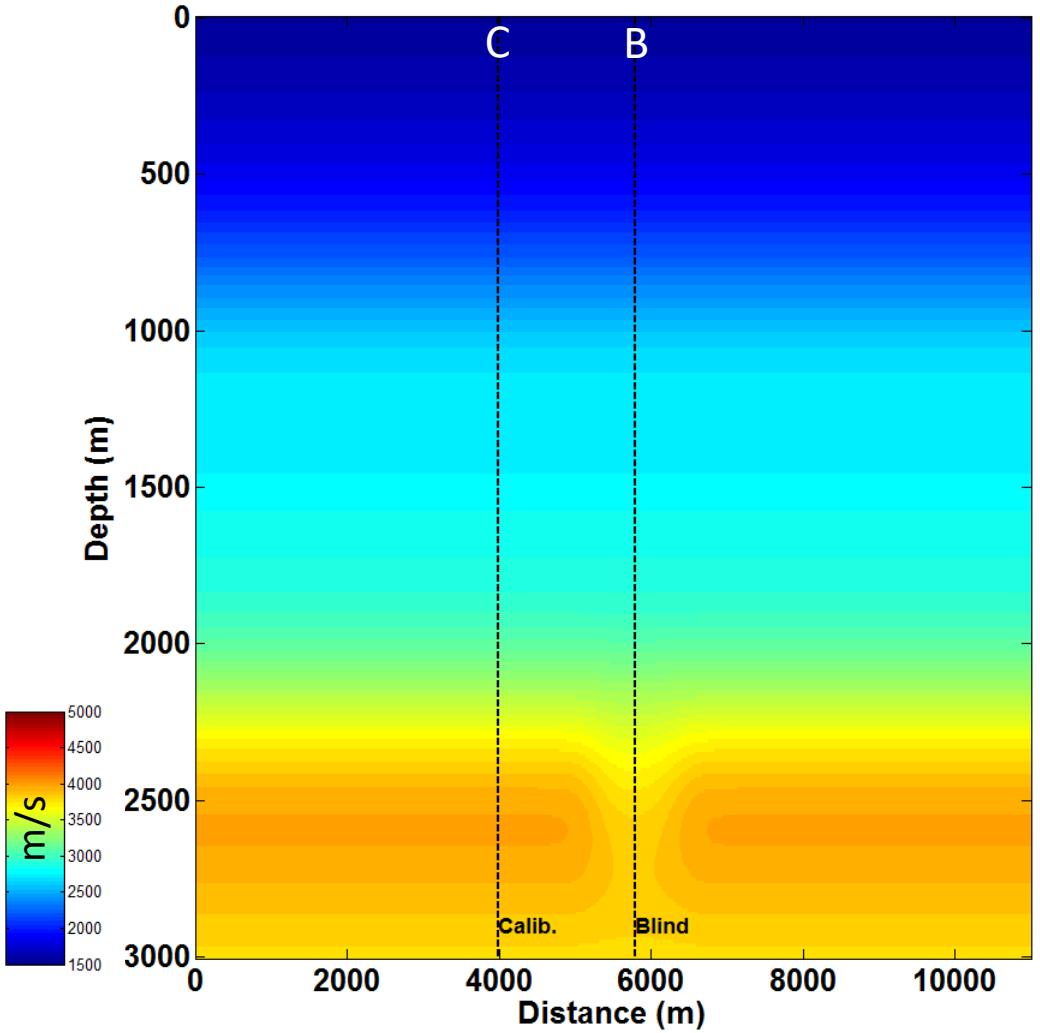


Minimum phase wavelet

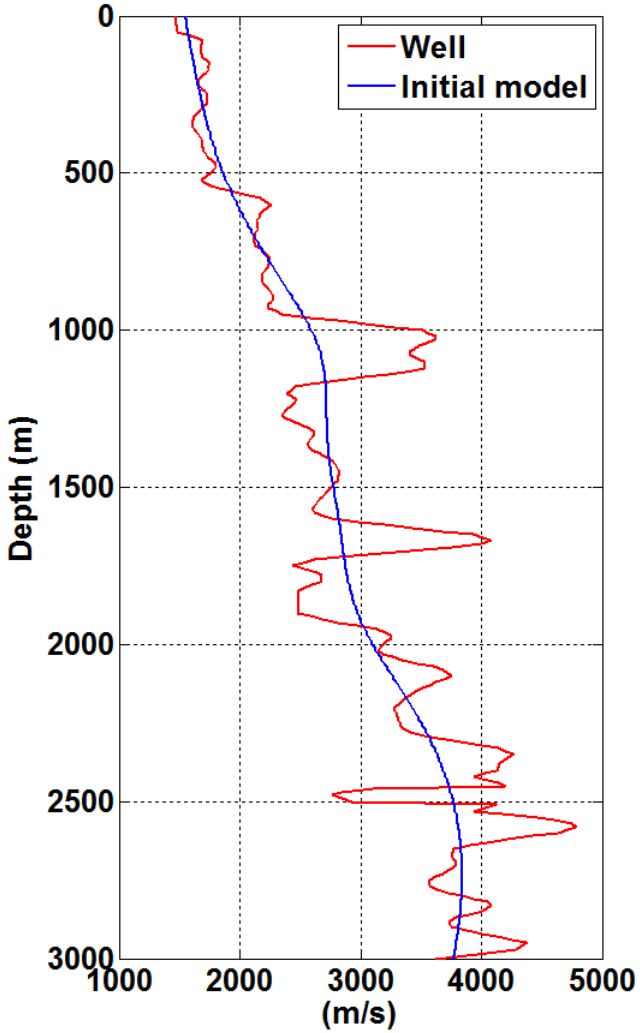
f_{dom} = 20 Hz

1st step: Modelled shots

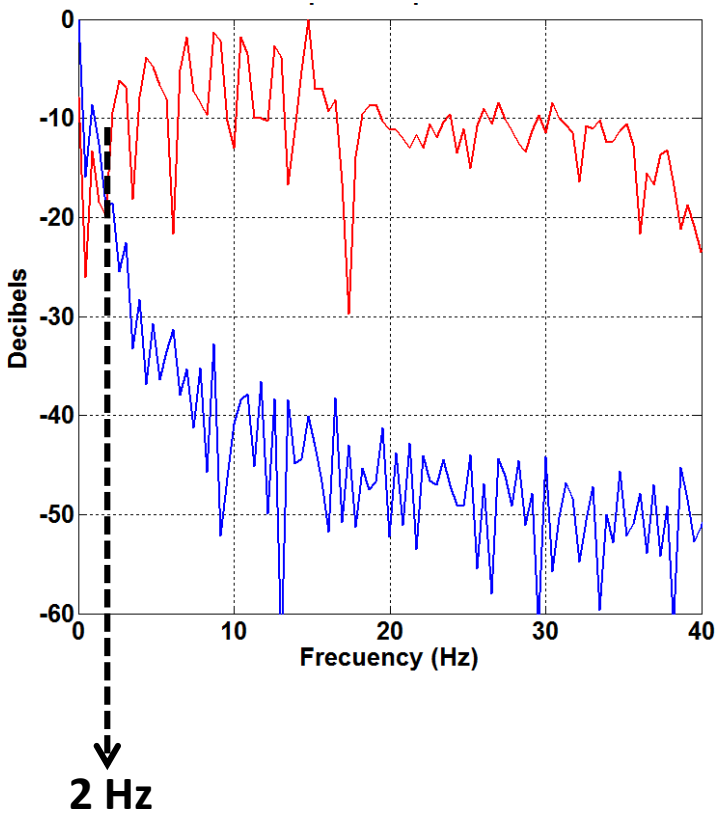
Initial model



Velocity in well B

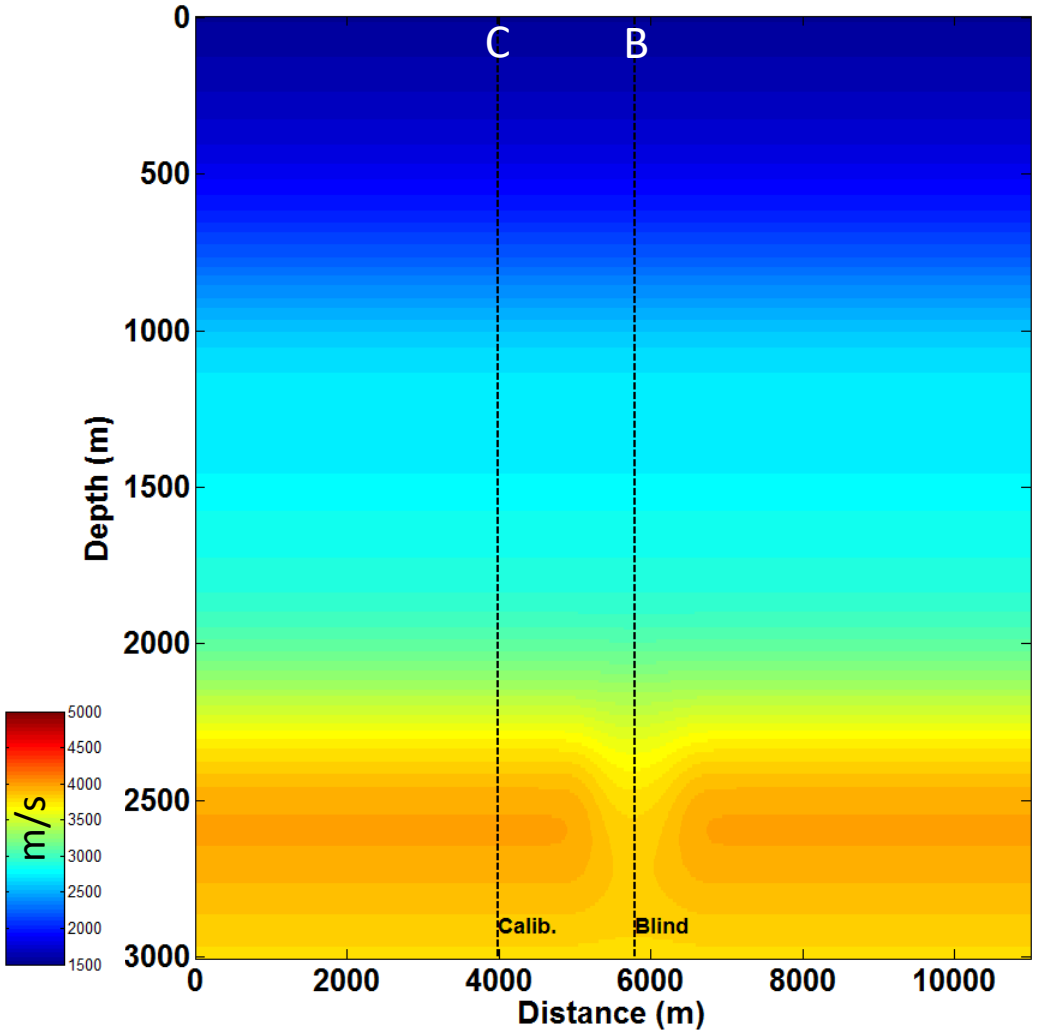


Reflectivity amplitude spectra

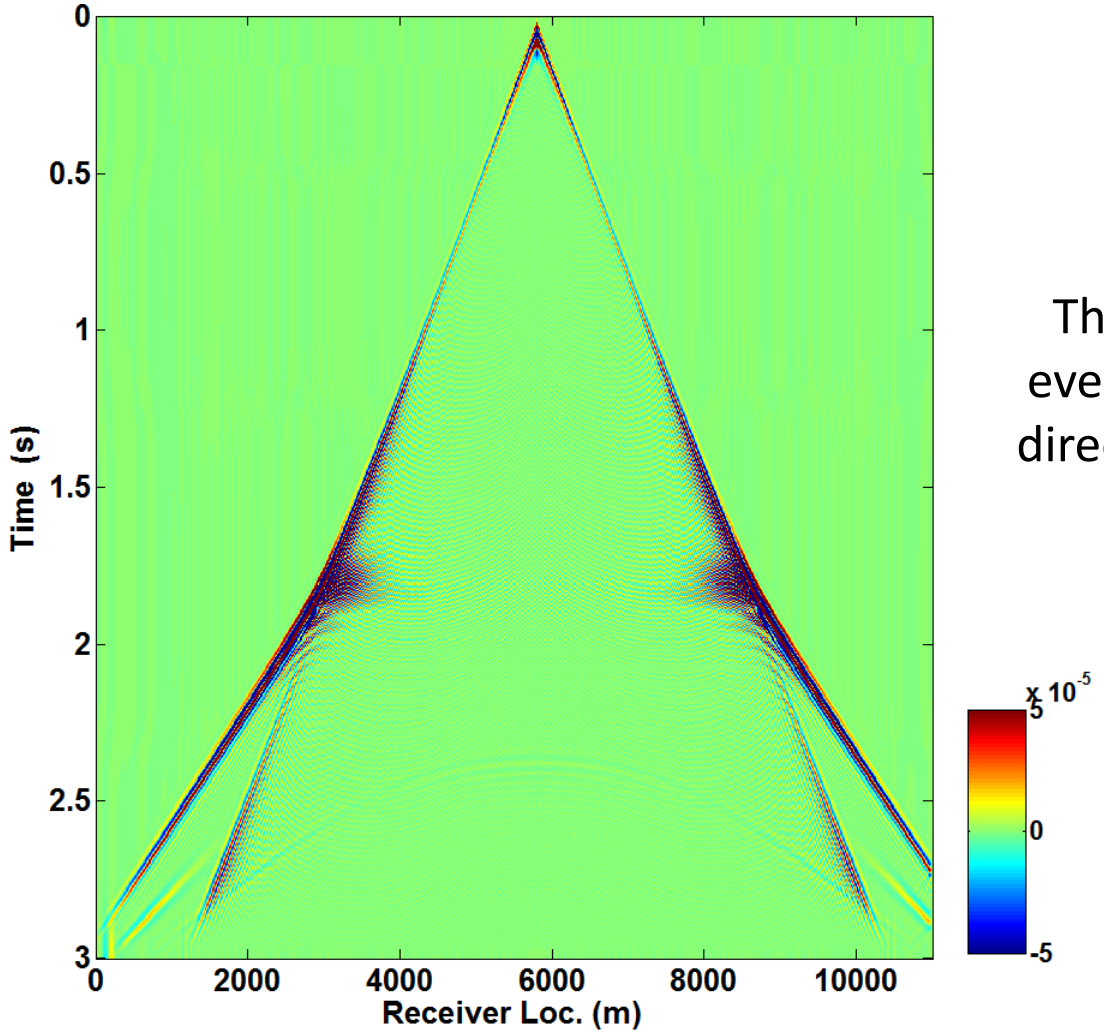


1st step: Modelled shots

Initial model



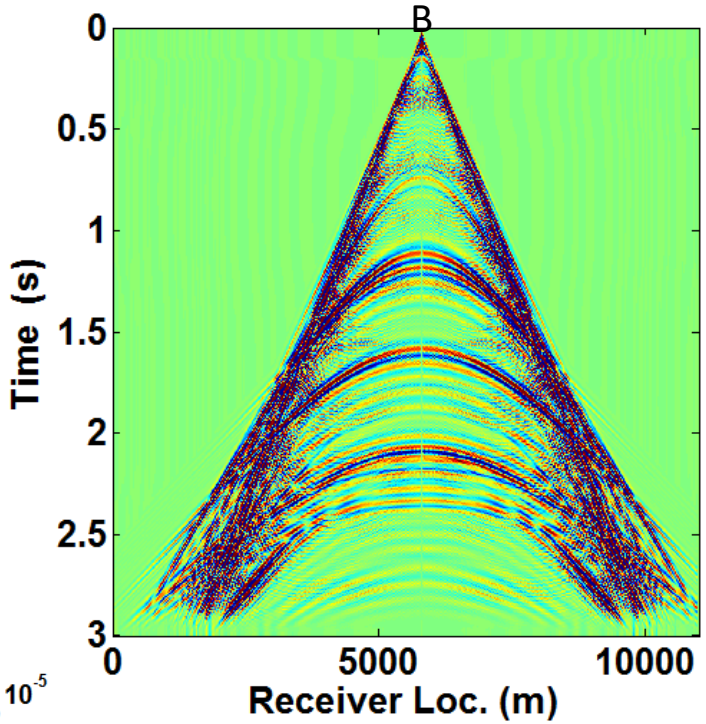
Modelled shot



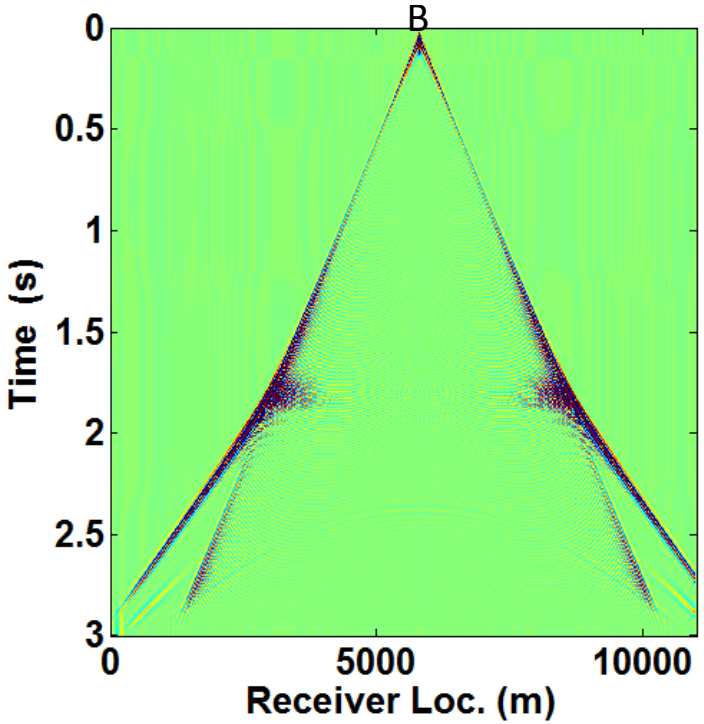
The main event is the direct arrival

1st step: Modelled shots

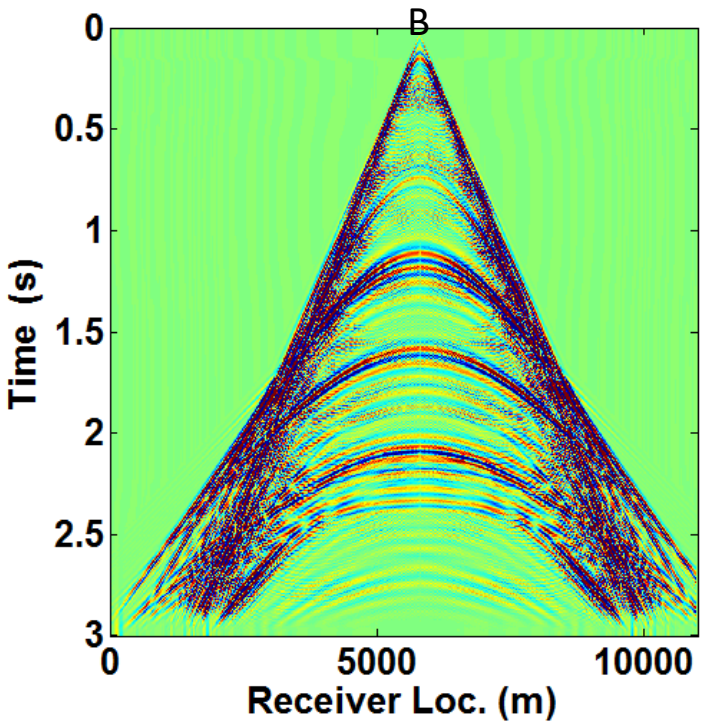
Observed shot

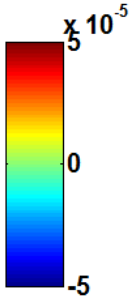


Modelled shot



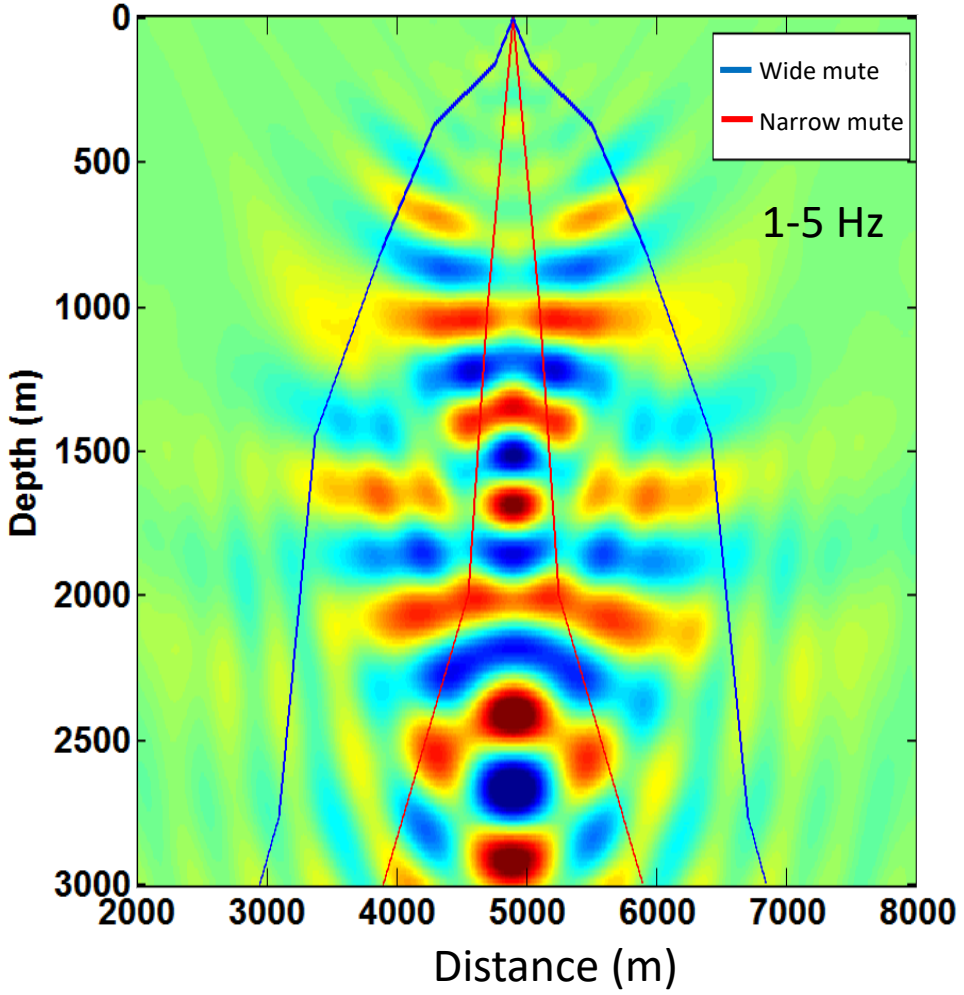
Data residual



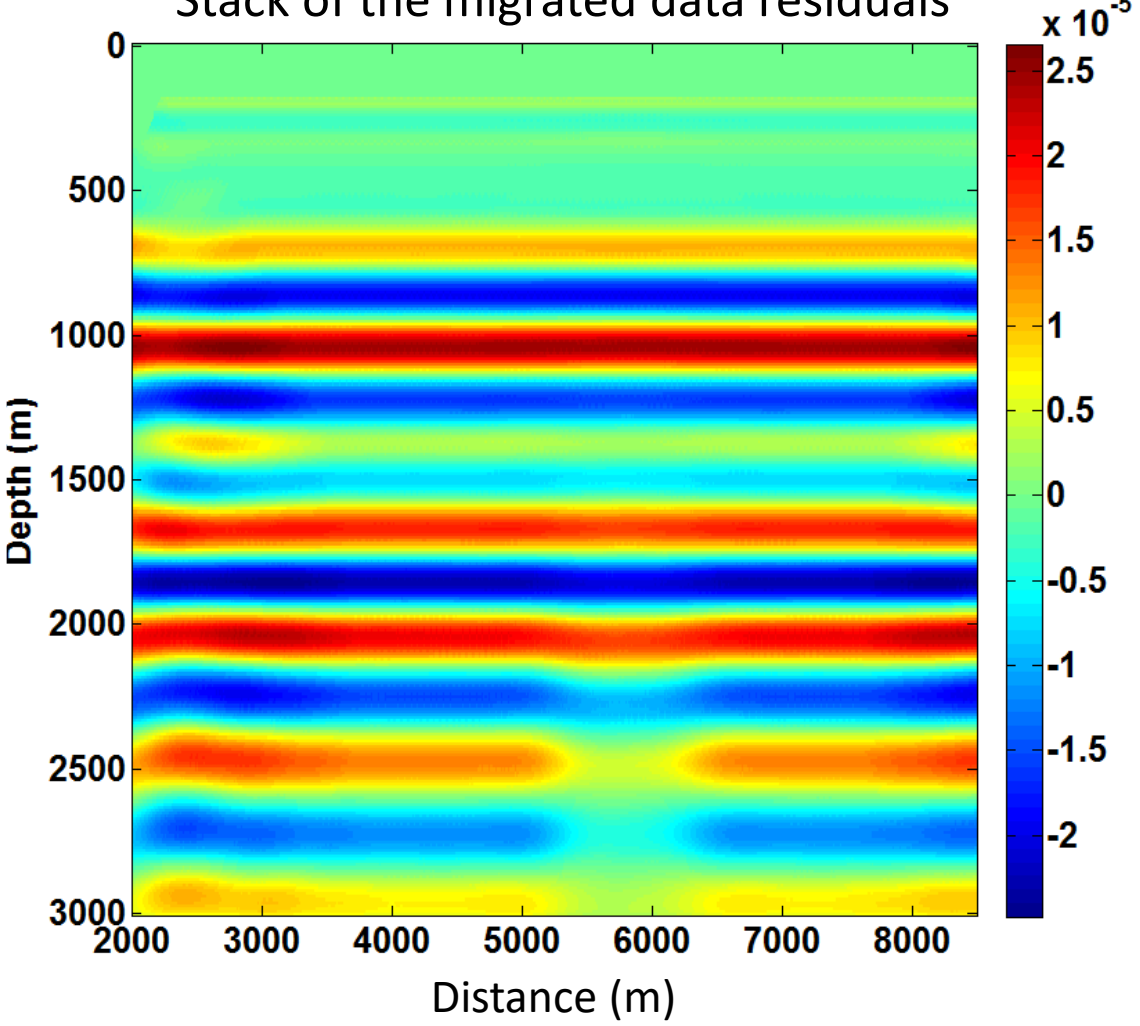


2nd step: Migrate and stack data residuals

Migration of the data residual

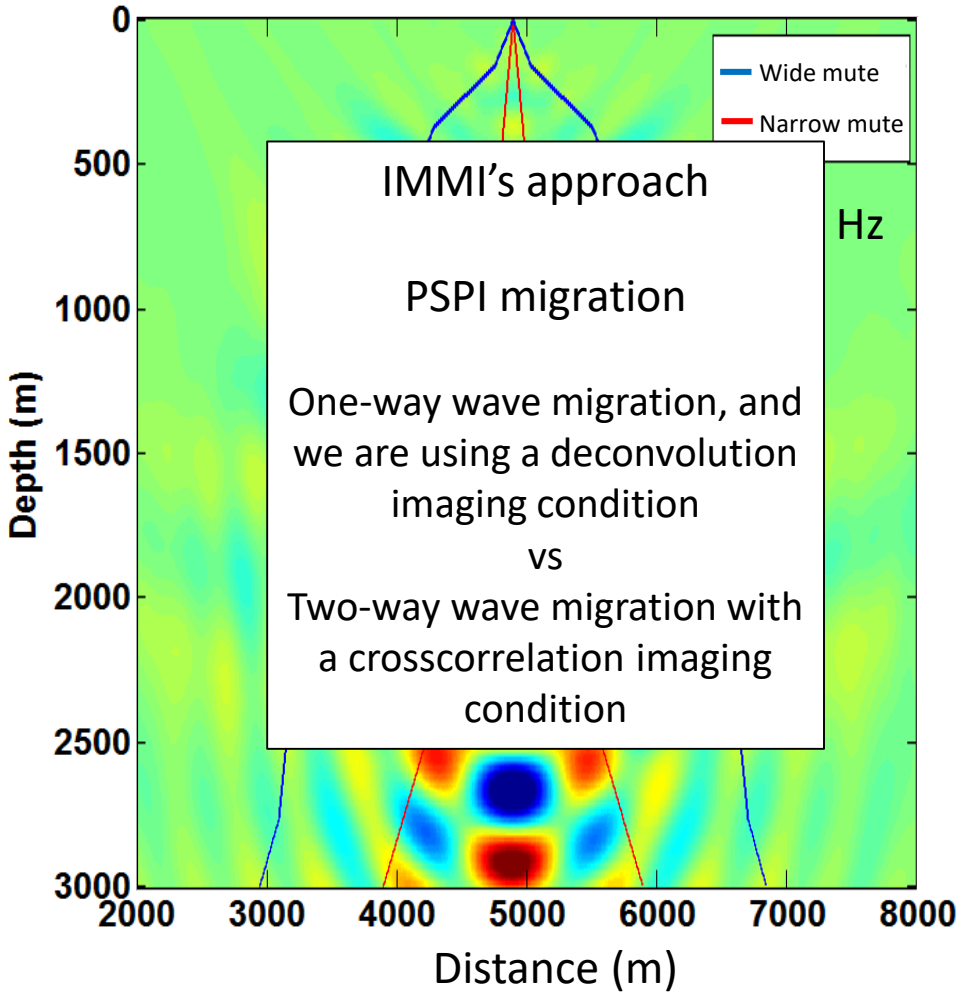


Gradient =
Stack of the migrated data residuals

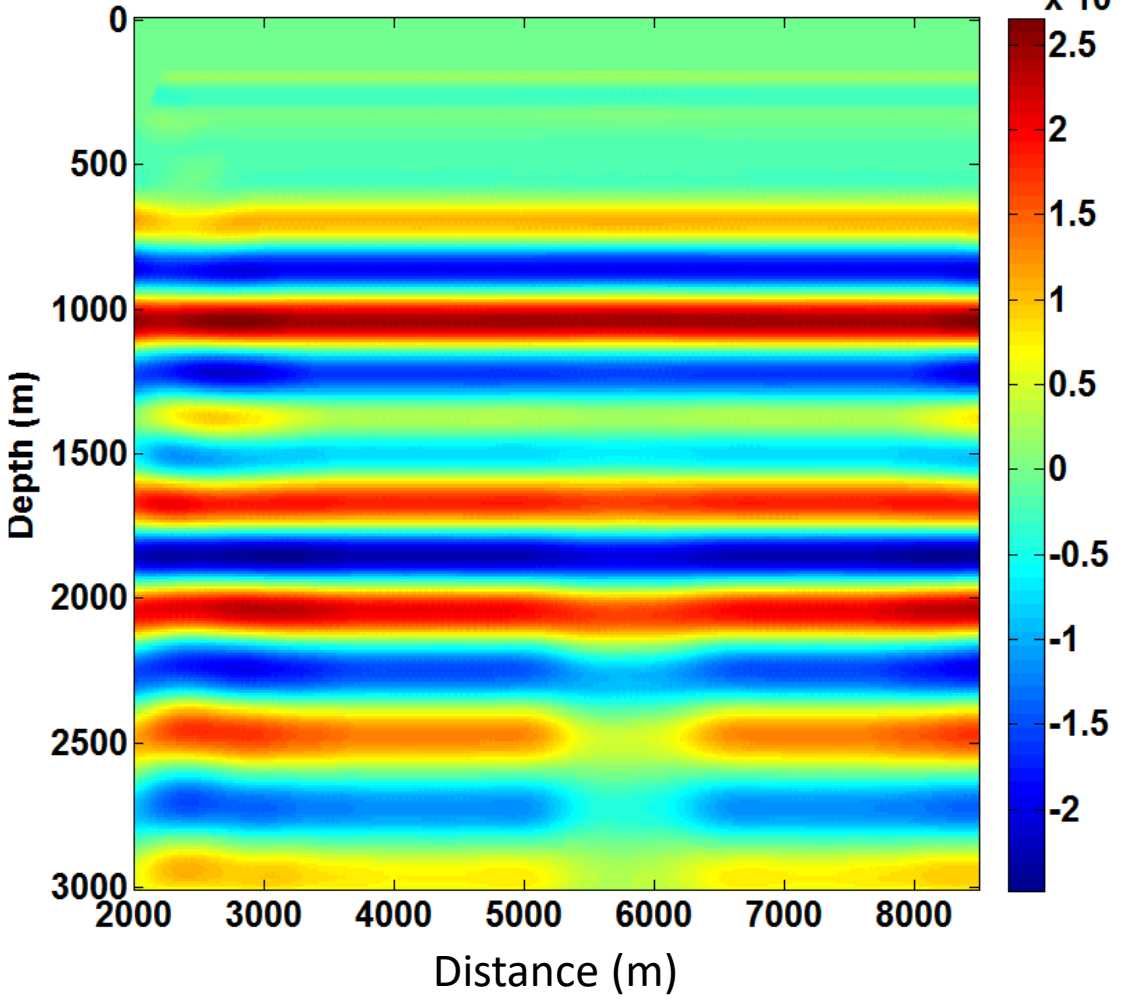


2nd step: Migrate and stack data residuals

Migration of the data residual



Gradient =
Stack of the migrated data residuals

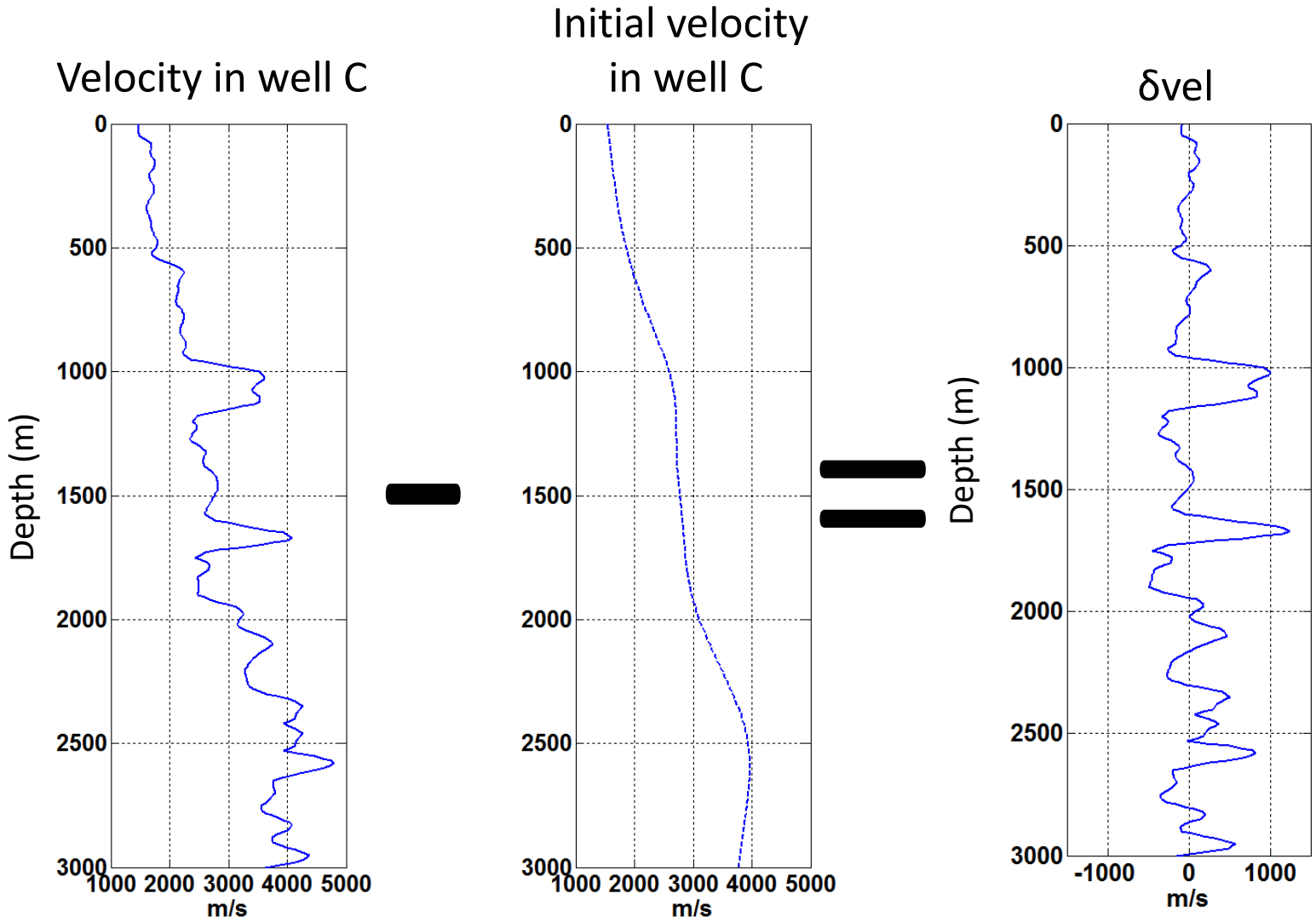


3rd step: Calibration of the gradient

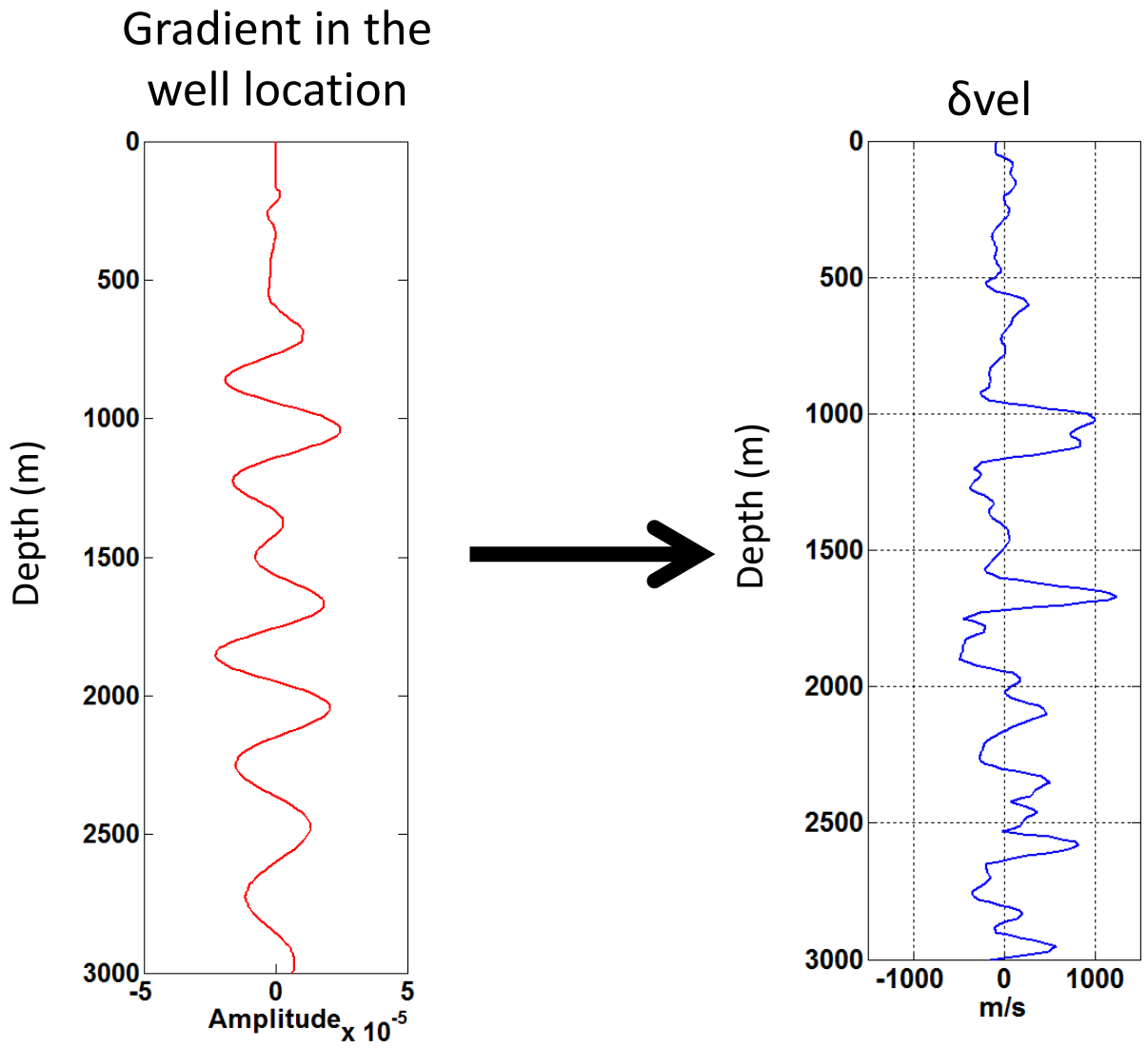
IMMI's approach

Well calibration
vs
Line search method or an approximation of the inverse Hessian matrix

3rd step: Calibration of the gradient



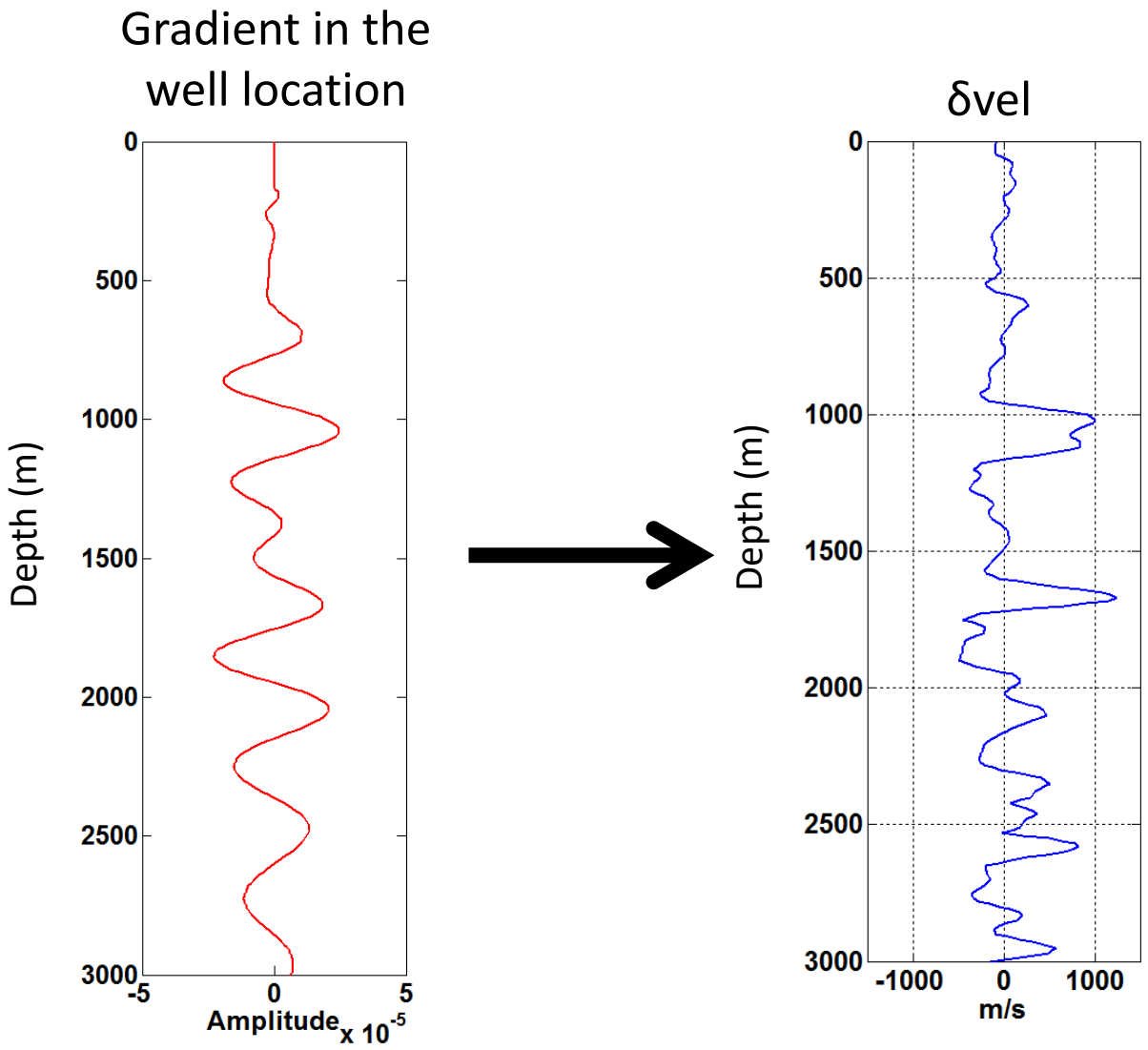
3rd step: Calibration of the gradient



3rd step: Calibration of the gradient

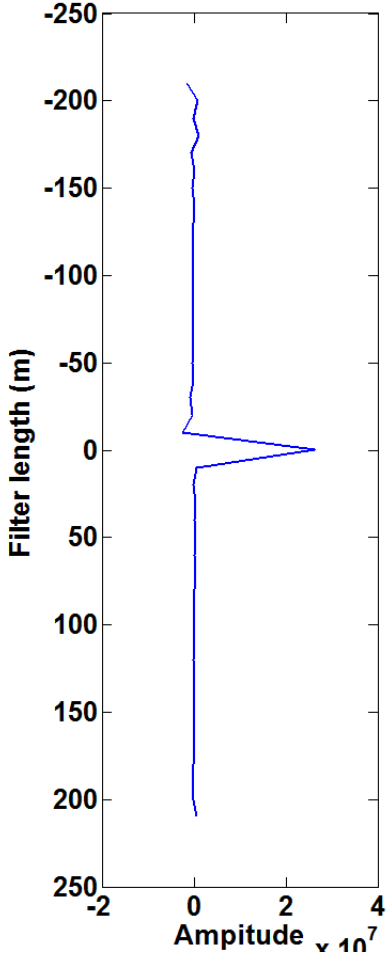
An Amplitude scalar **a** so that δvel – ag is mimimized by least squares

A phase rotation φ, so that, δvel and the calibrated gradient have a similar phase

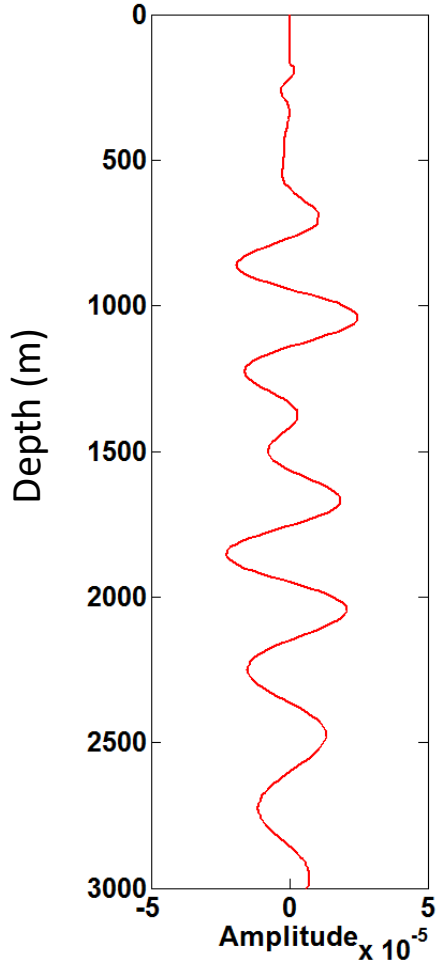


3rd step: Calibration of the gradient

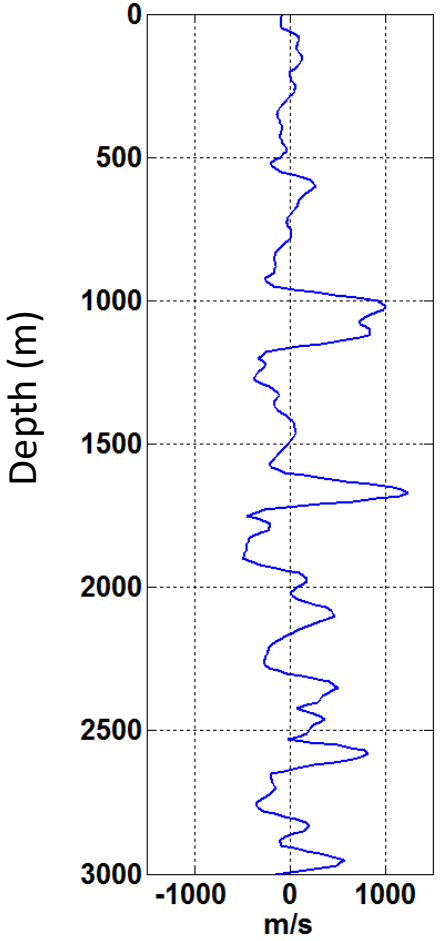
Match filter



Gradient in the well location

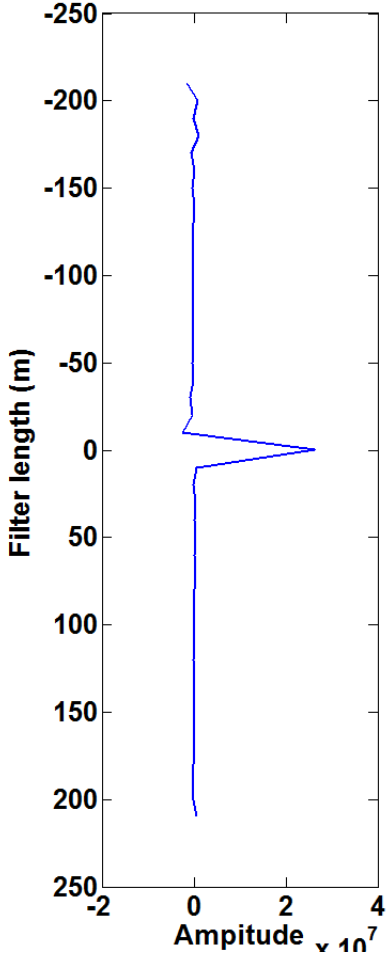


δvel

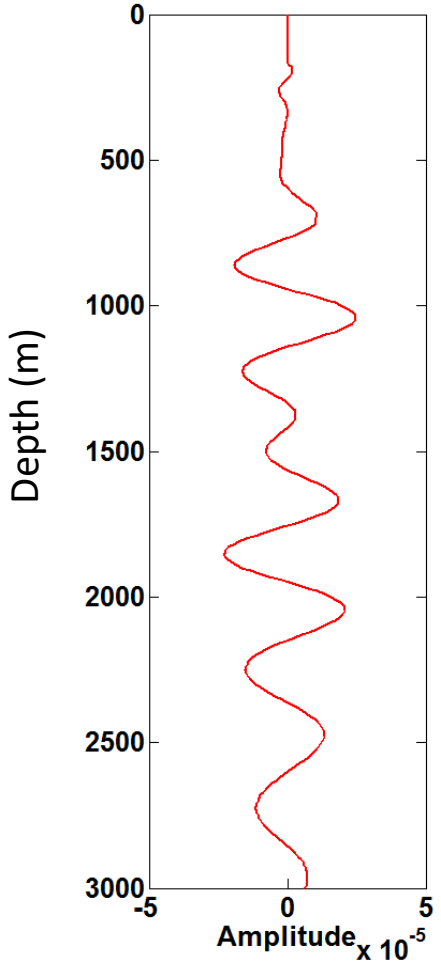


3rd step: Calibration of the gradient

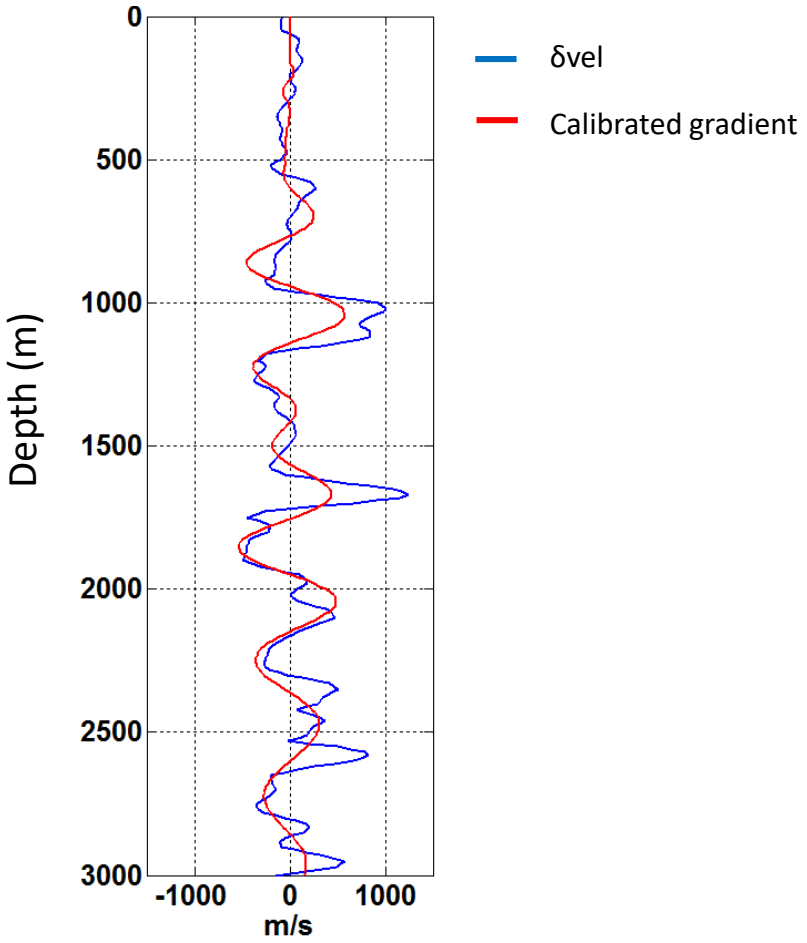
Match filter



Gradient in the well location

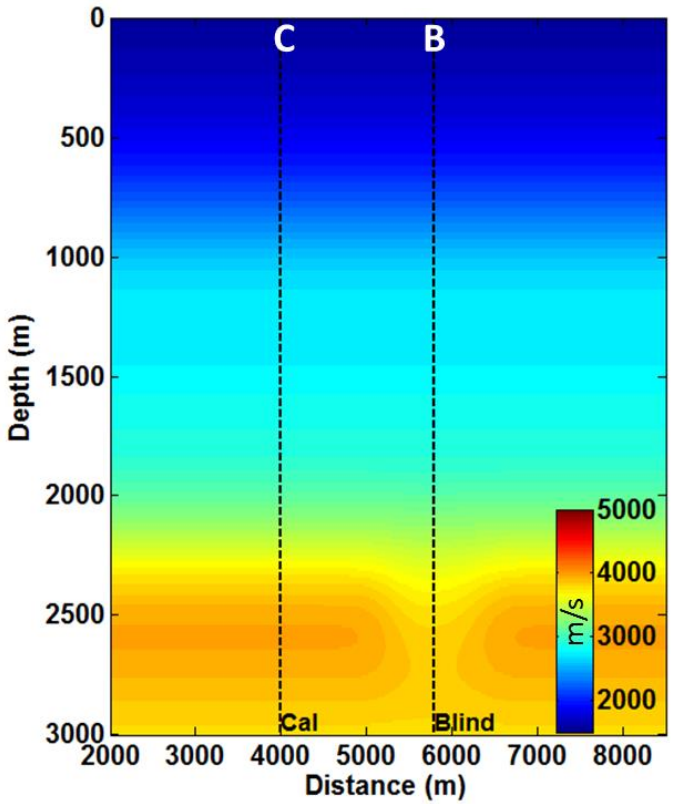


δvel and calibrated gradient



4th step: Updated velocity model

Initial model



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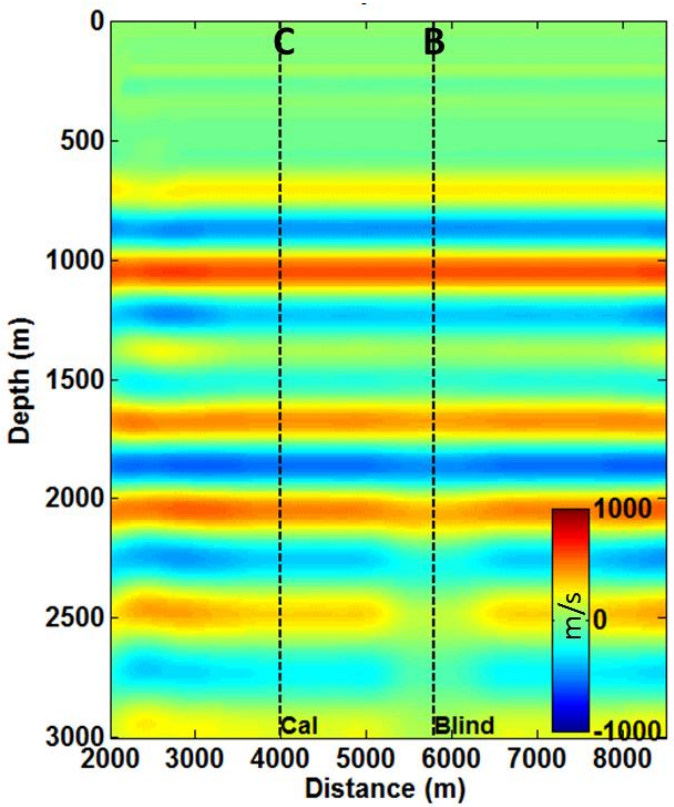
Velocity update



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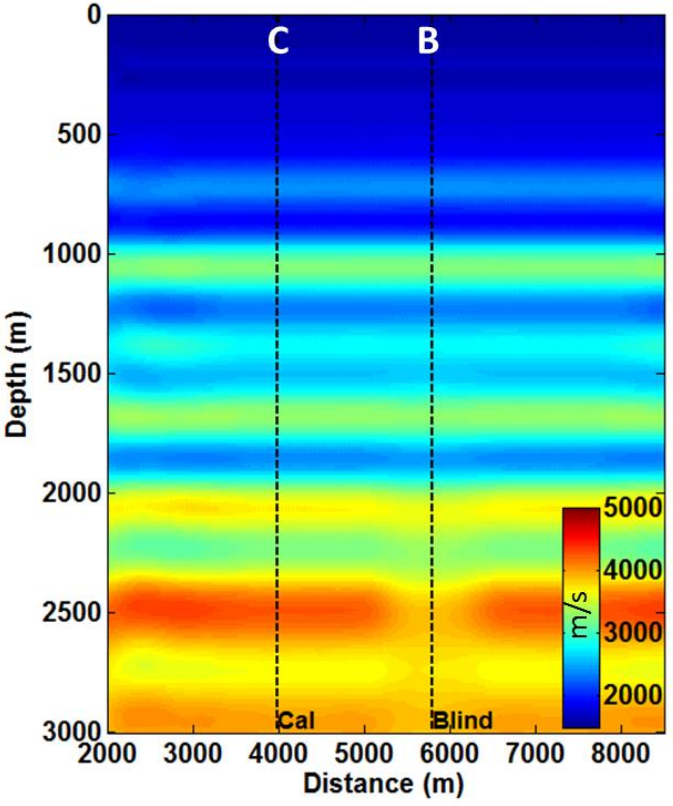
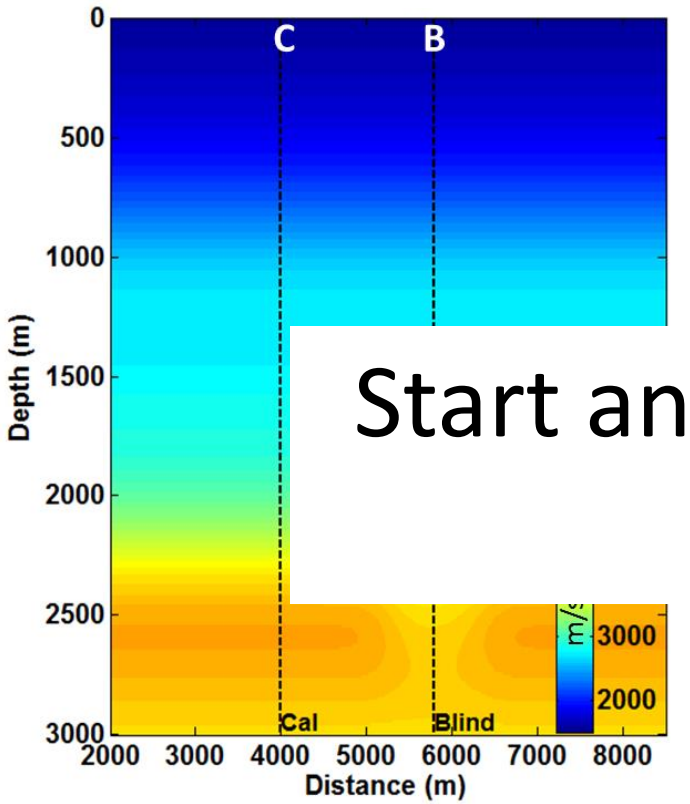
Inverted velocity model

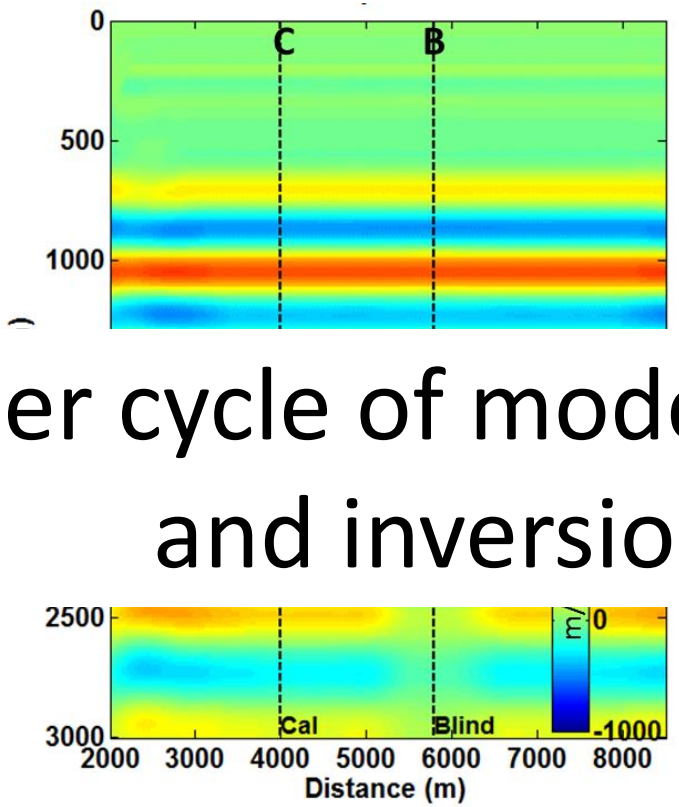


4th step: Updated velocity model

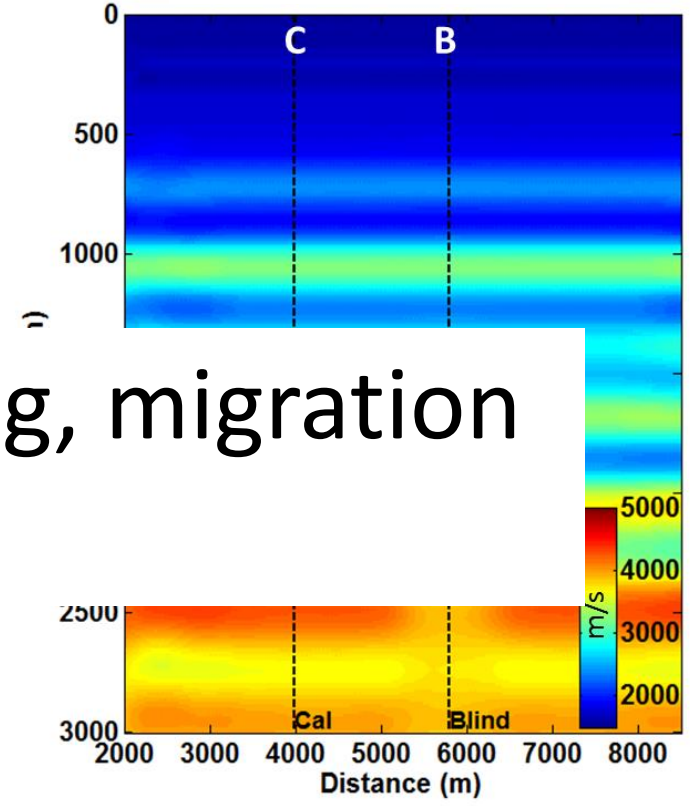
Initial model



Velocity update

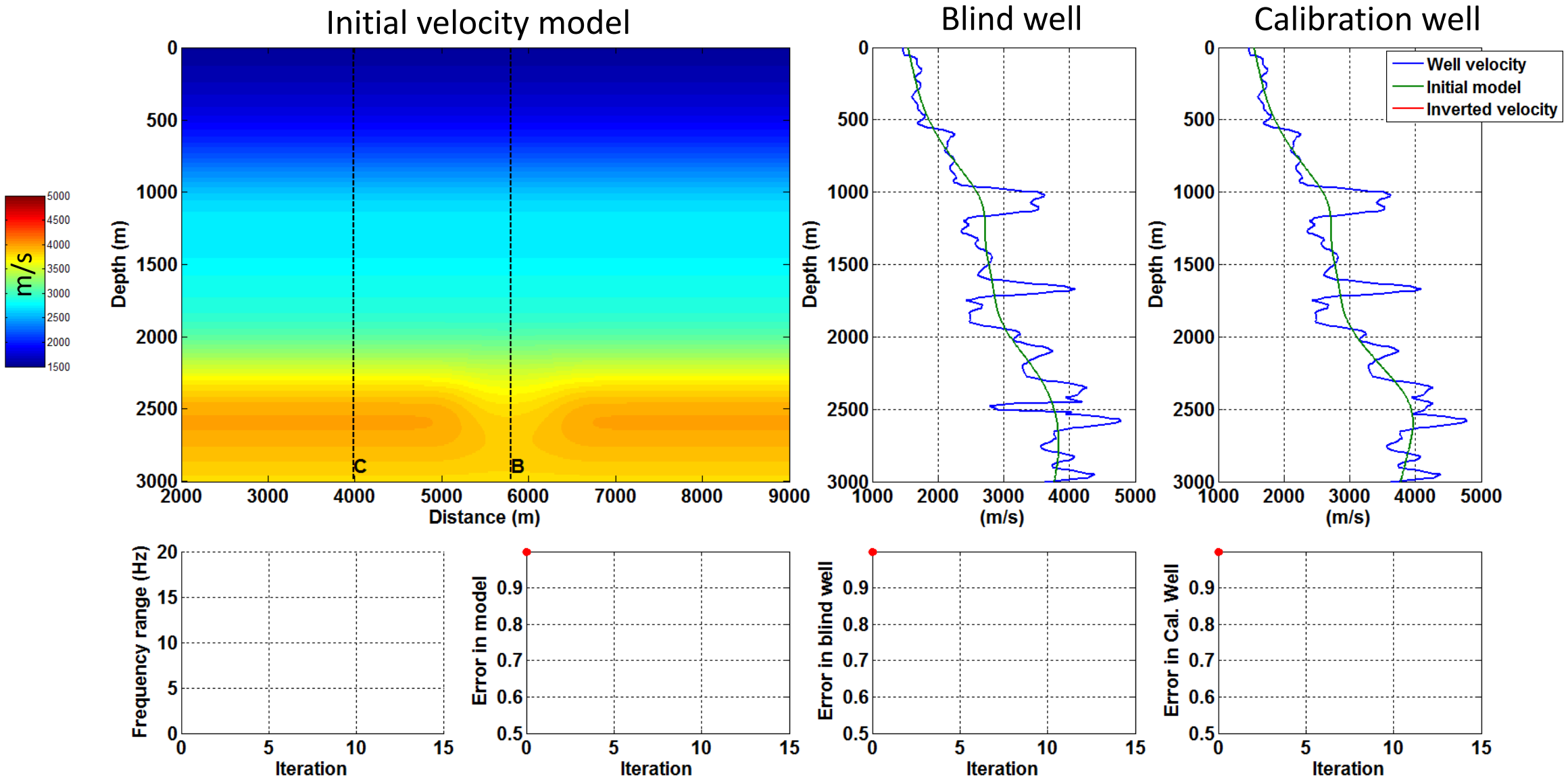


Inverted velocity model



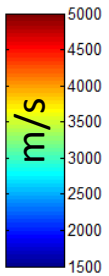
Start another cycle of modelling, migration and inversion

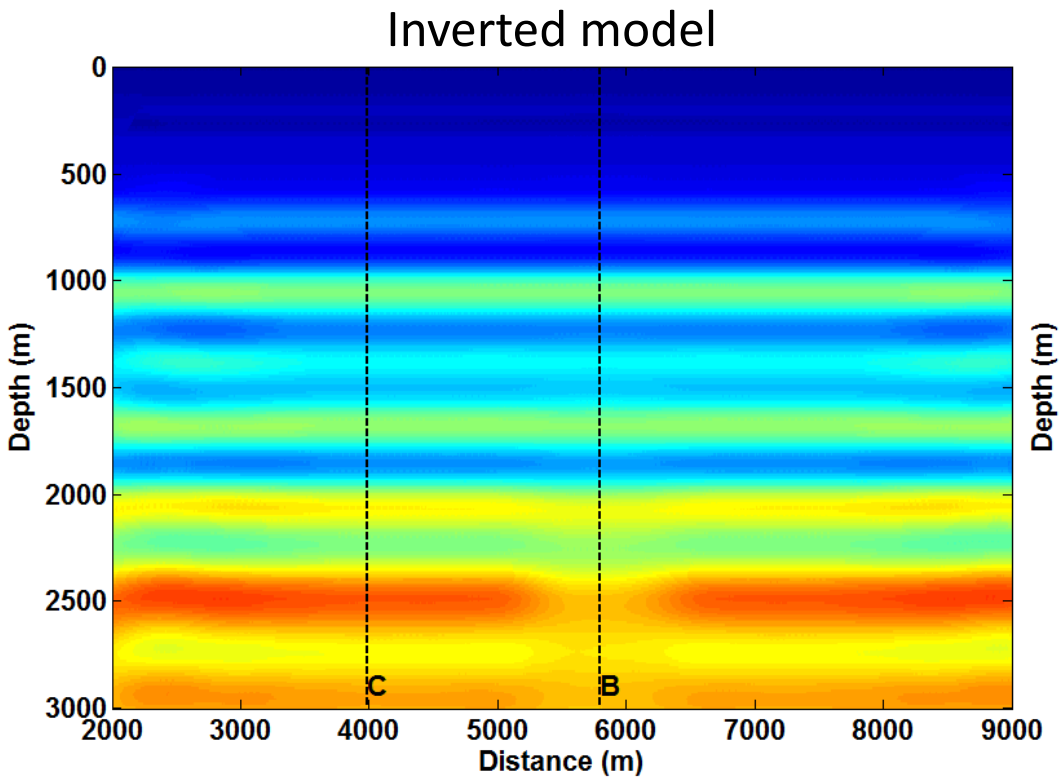
Evolution of the inverted model with more iterations

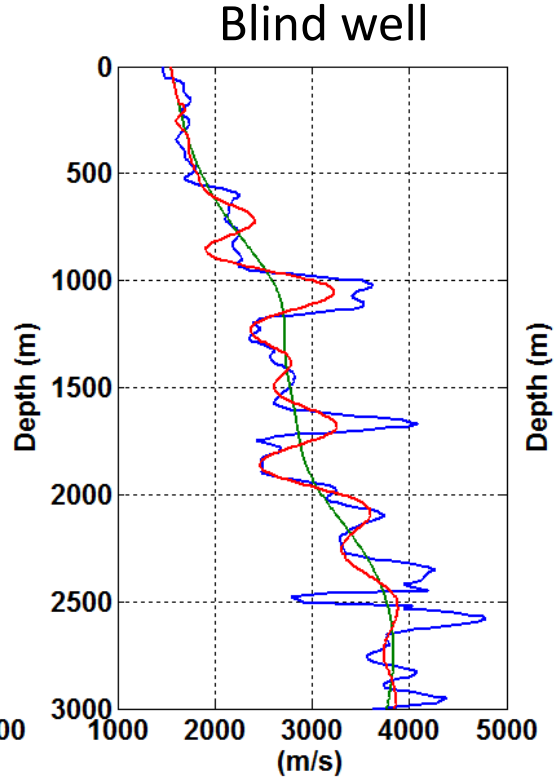


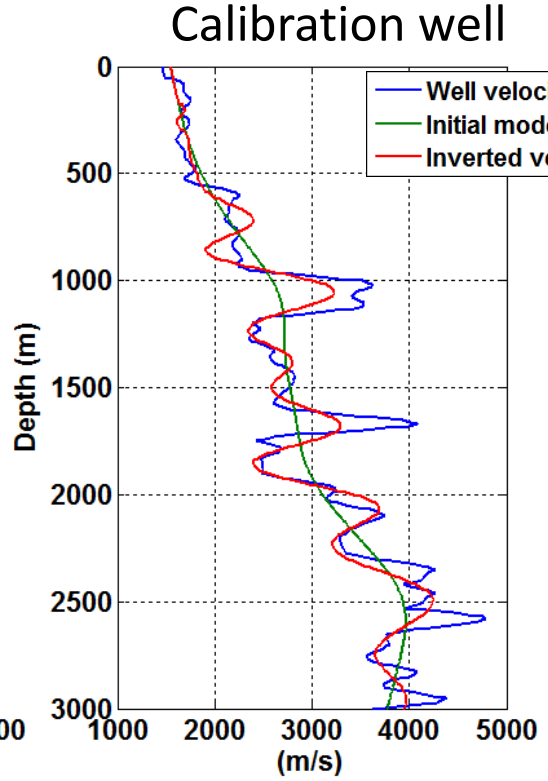
Evolution of the inverted model with more iterations

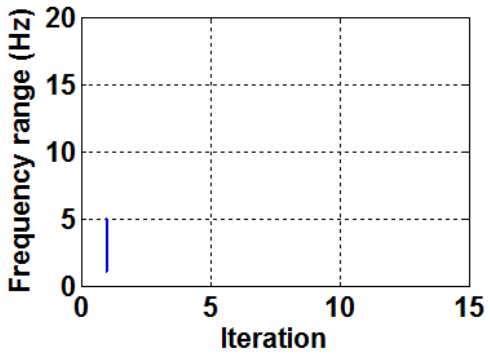
Iteration 1

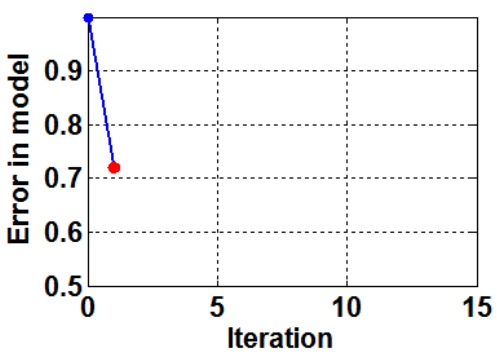


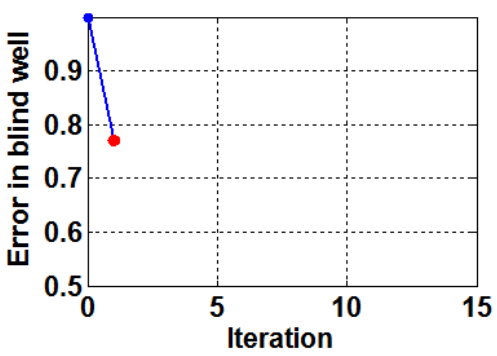


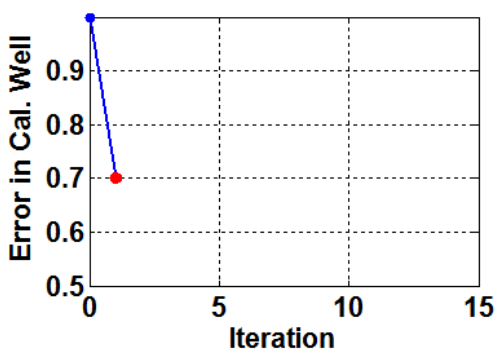






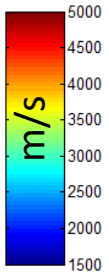


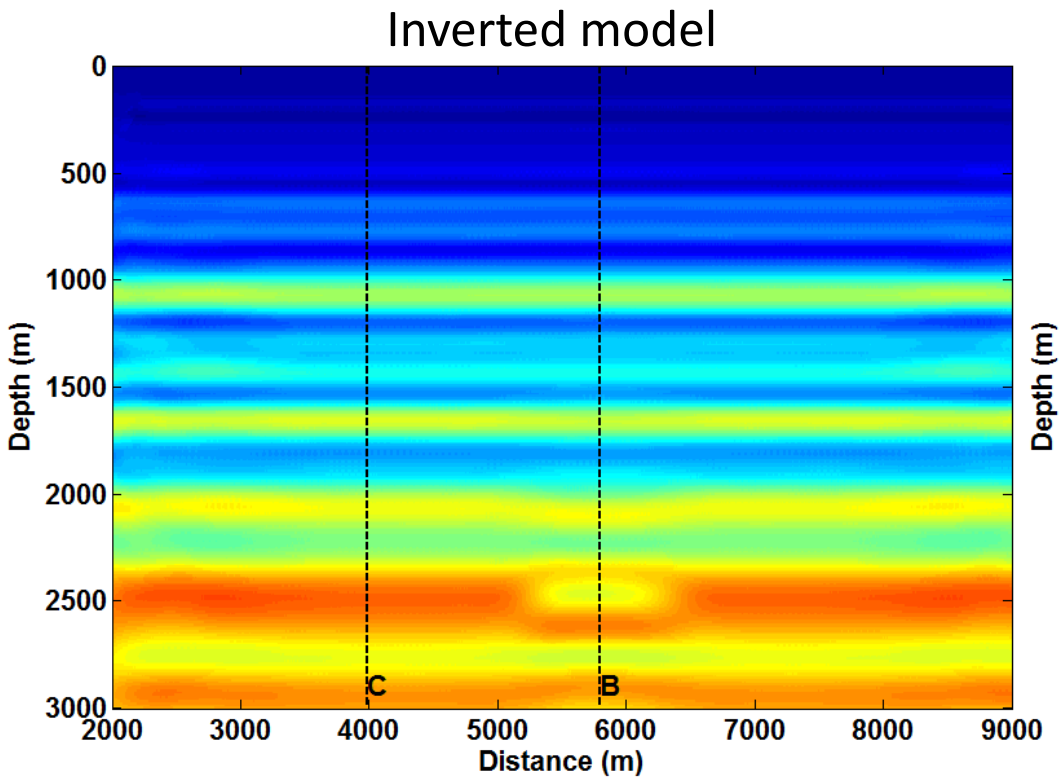


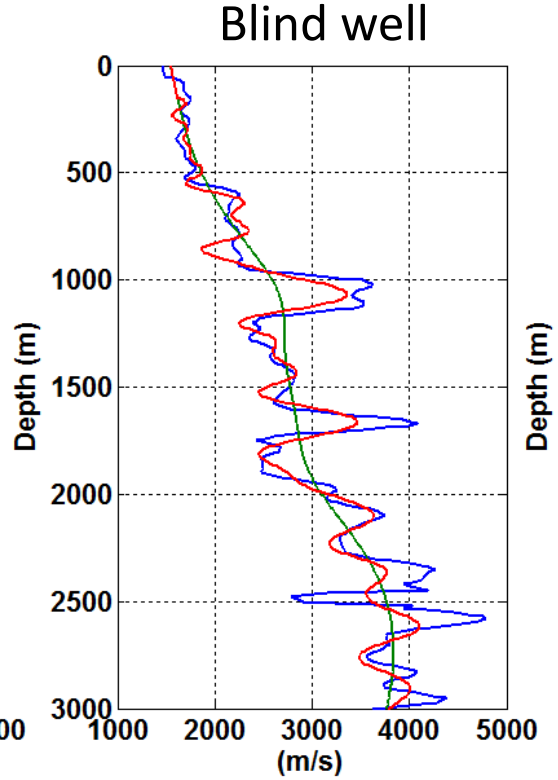


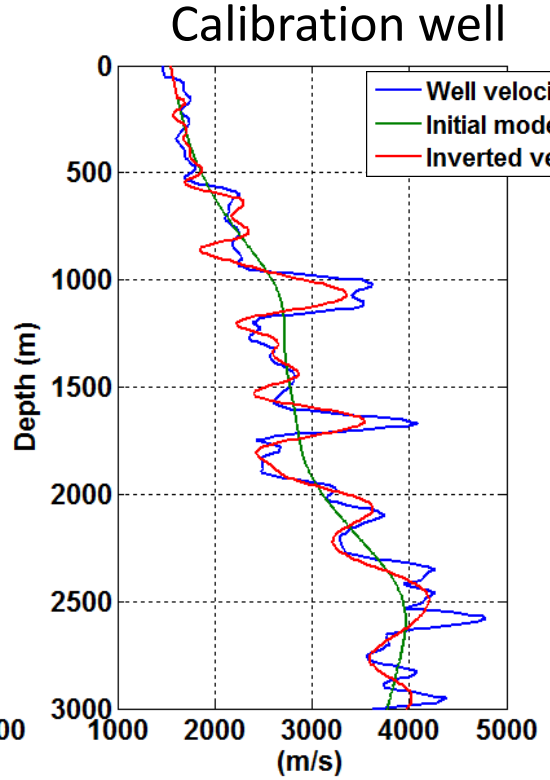
Evolution of the inverted model with more iterations

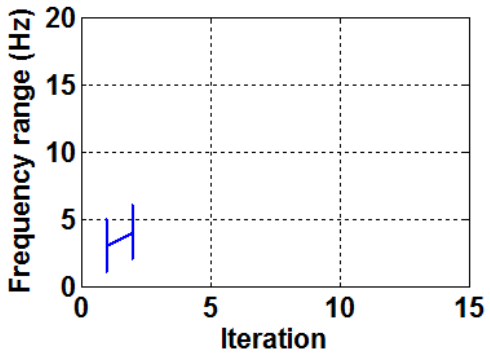
Iteration 2

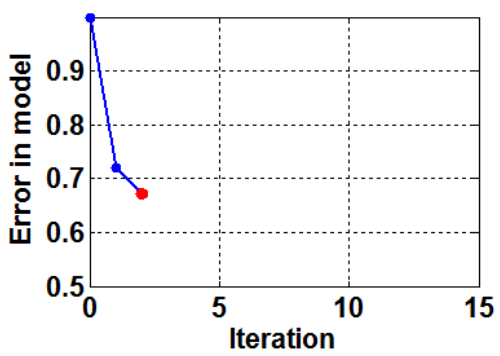


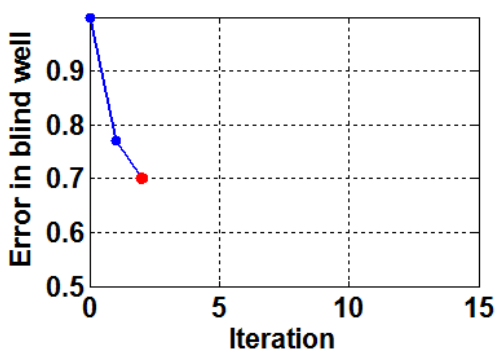


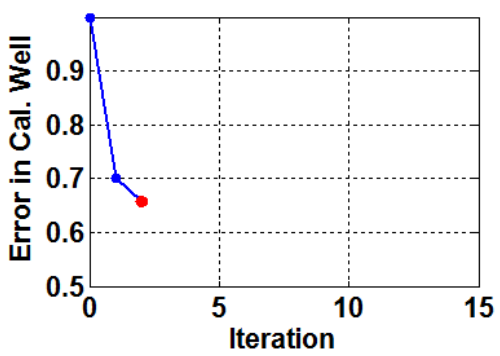






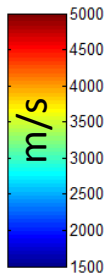


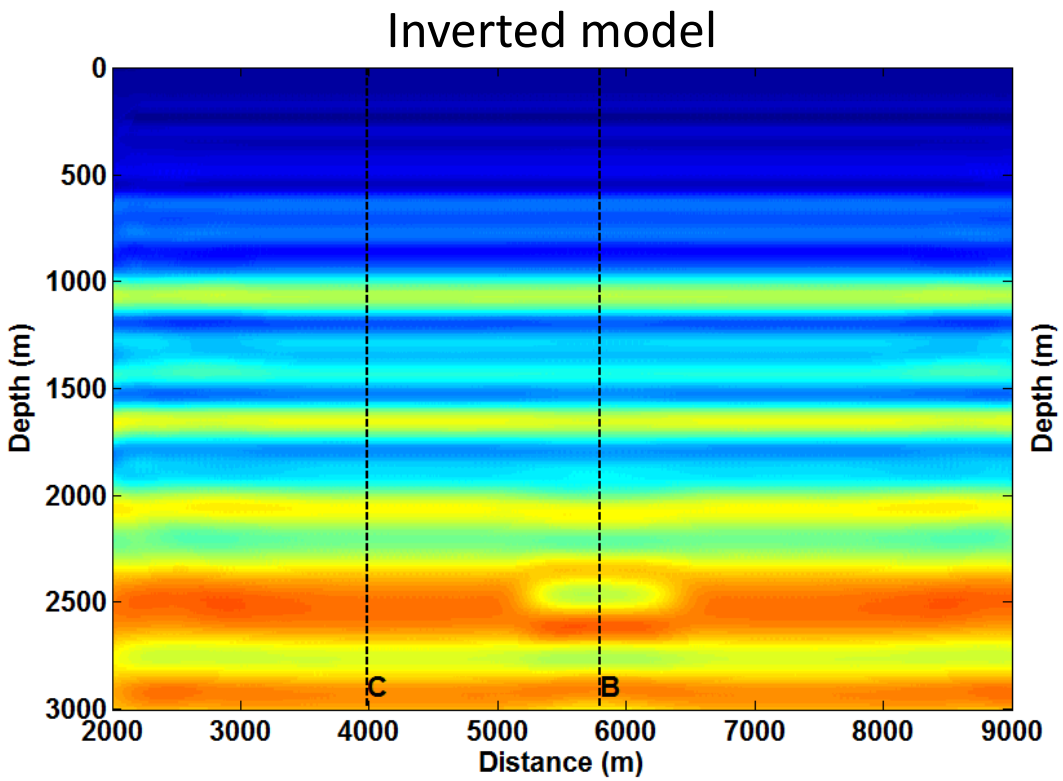


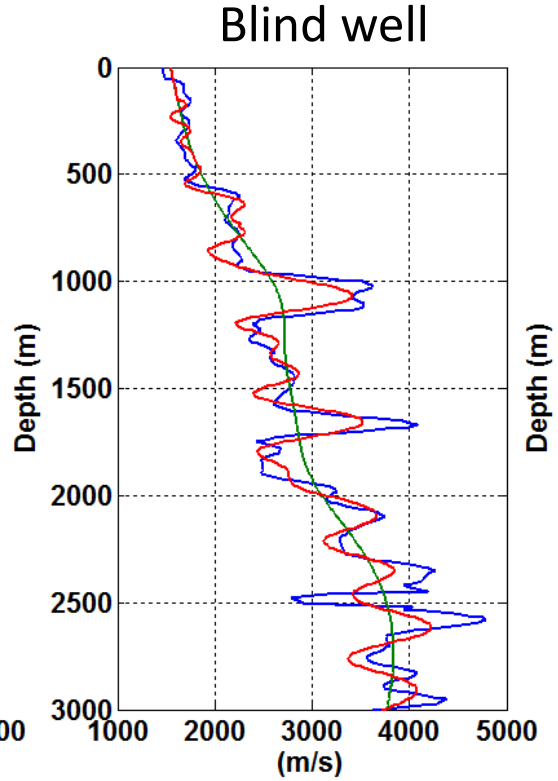


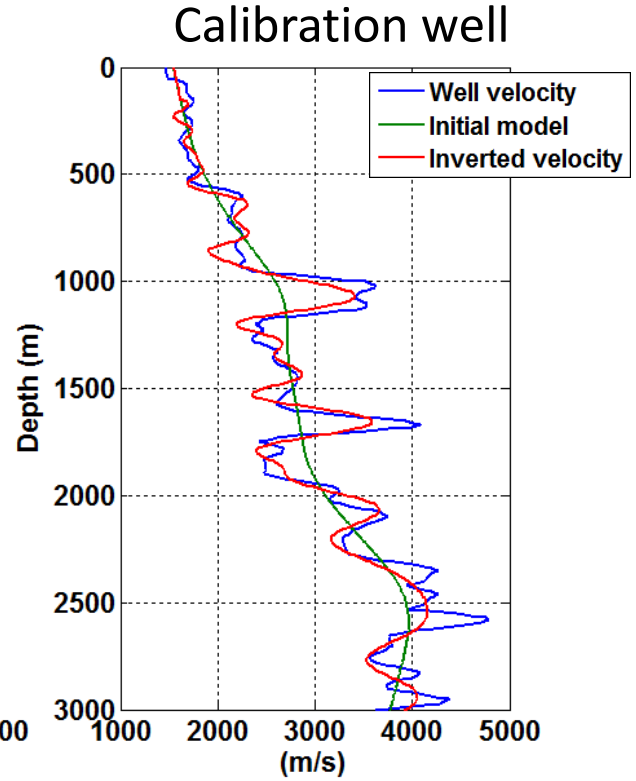
Evolution of the inverted model with more iterations

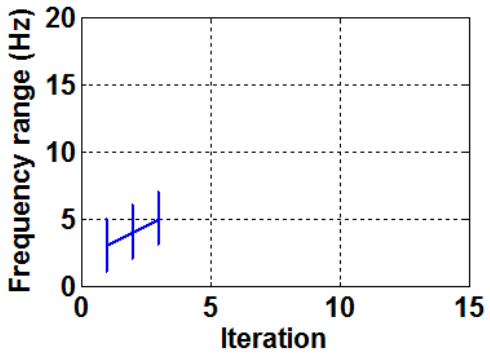
Iteration 3

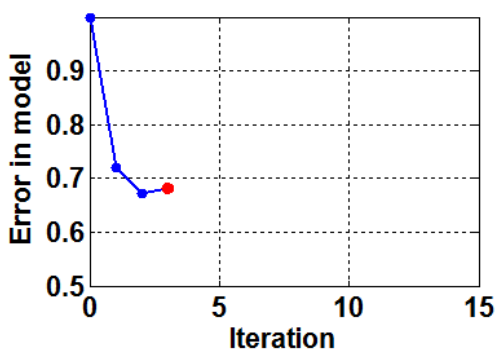


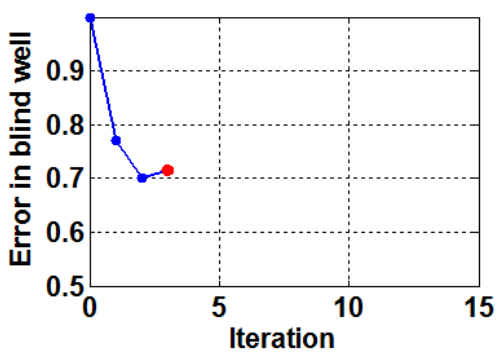


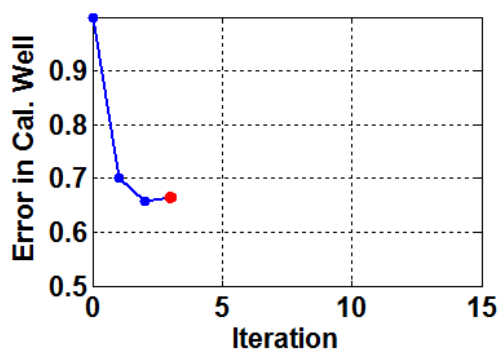






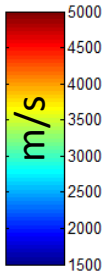


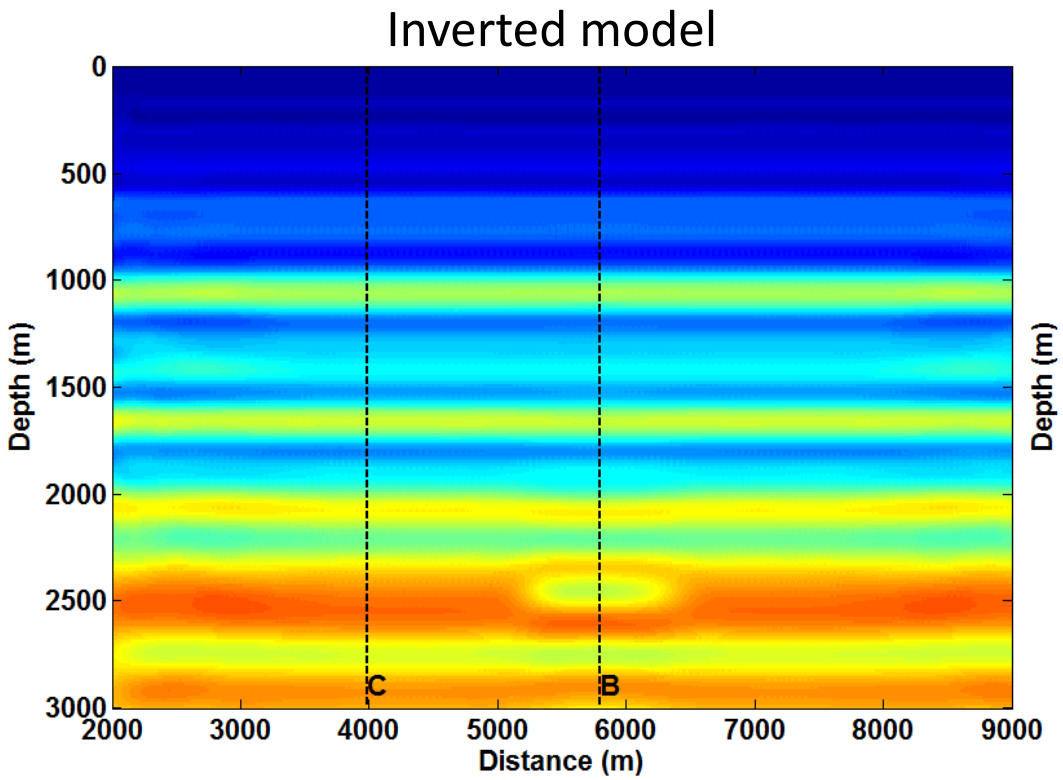


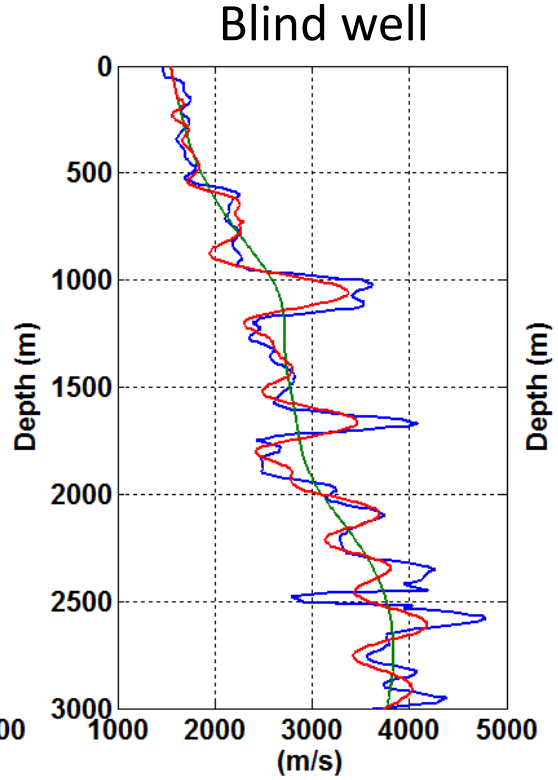


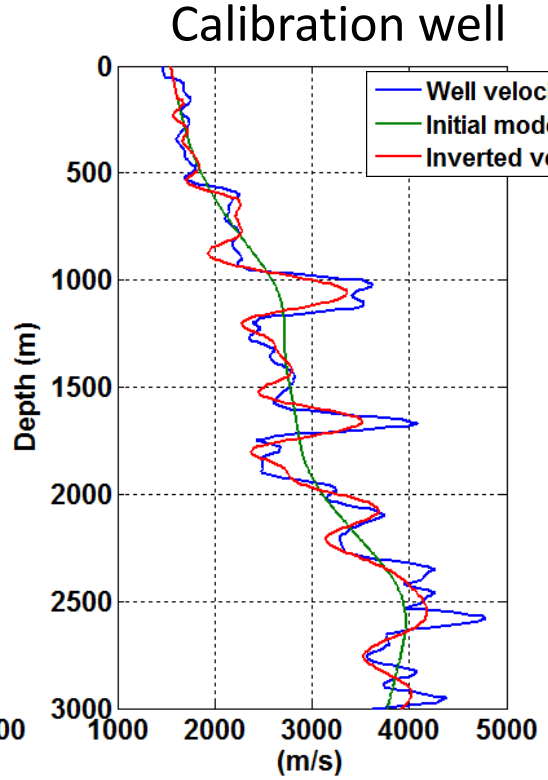
Evolution of the inverted model with more iterations

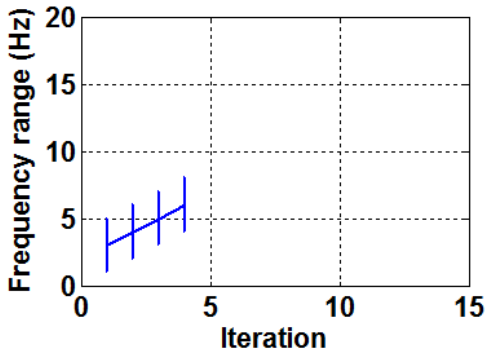
Iteration 4

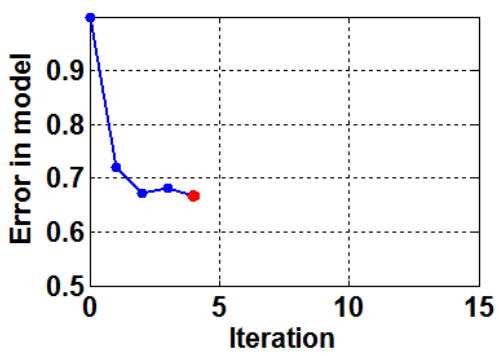


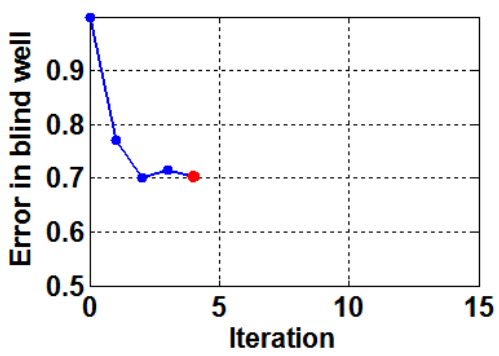


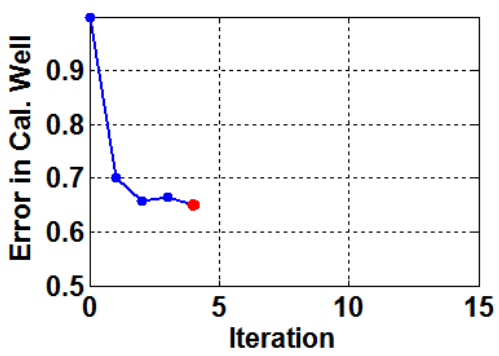






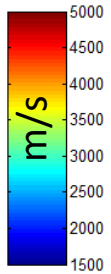


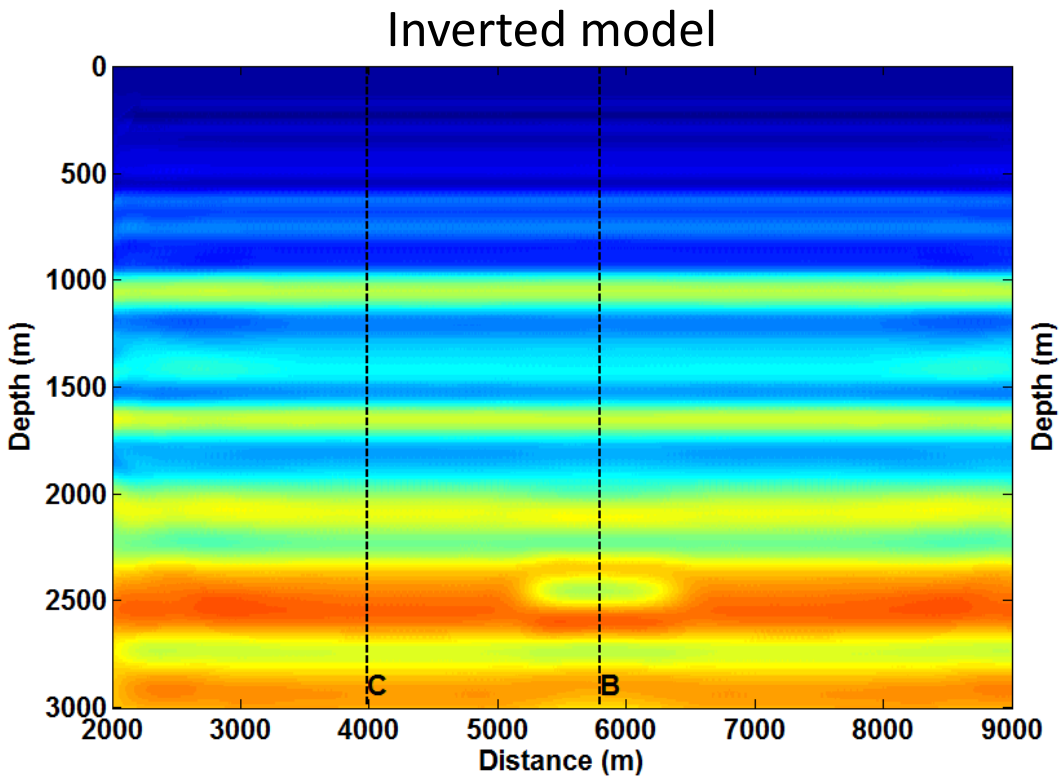


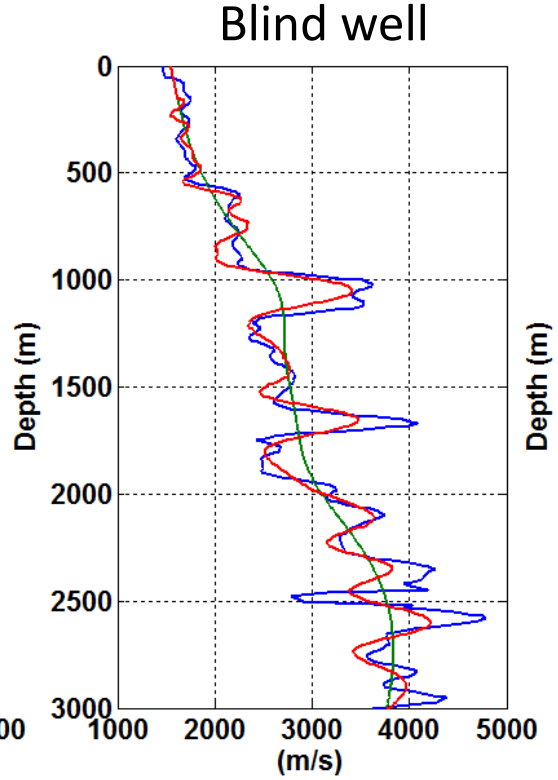


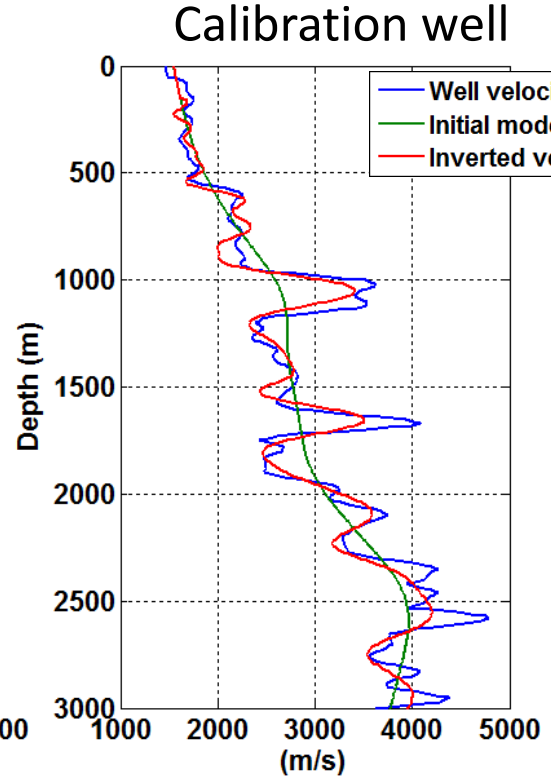
Evolution of the inverted model with more iterations

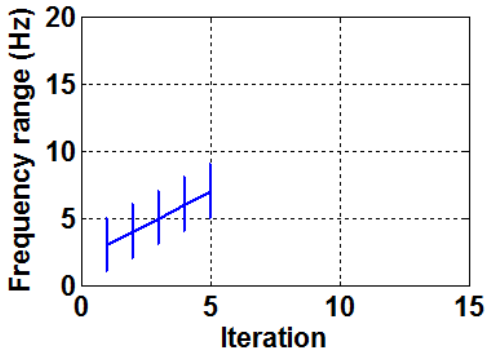
Iteration 5

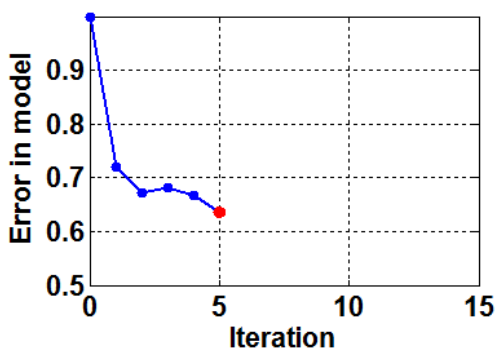


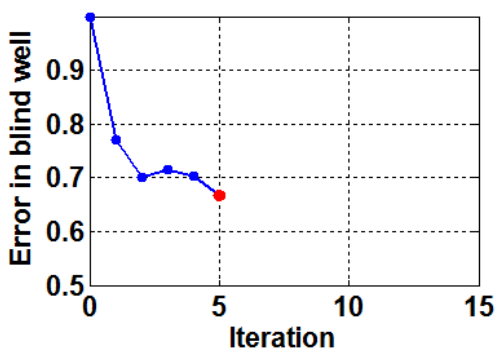


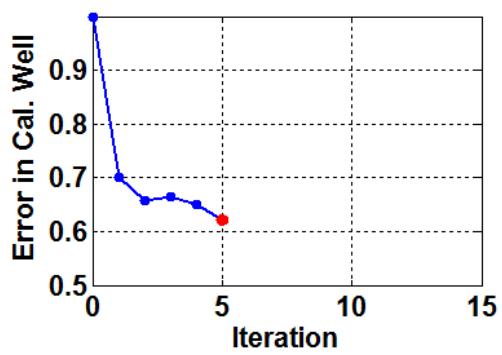






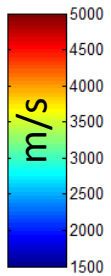


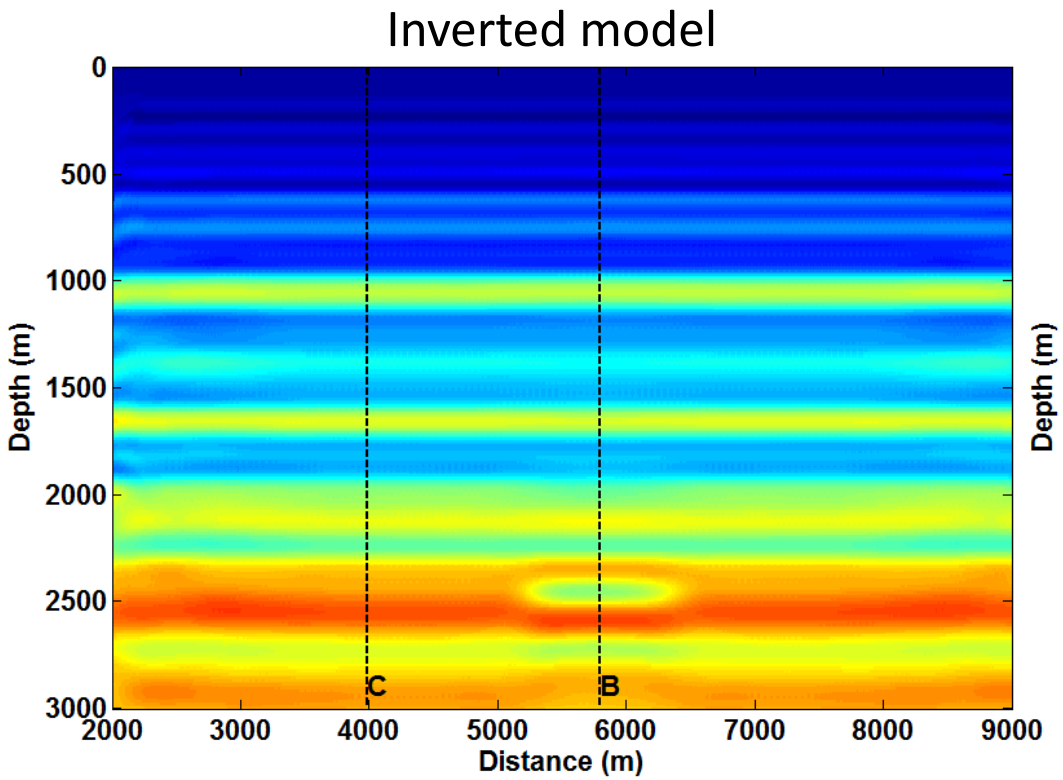


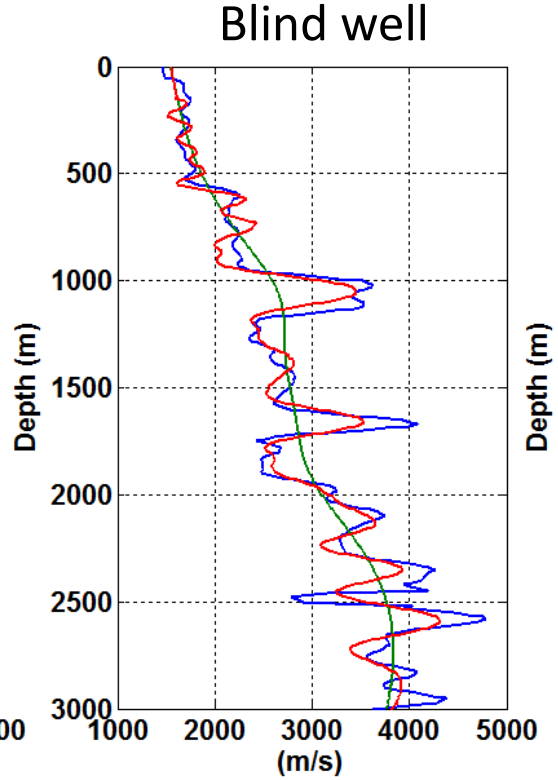


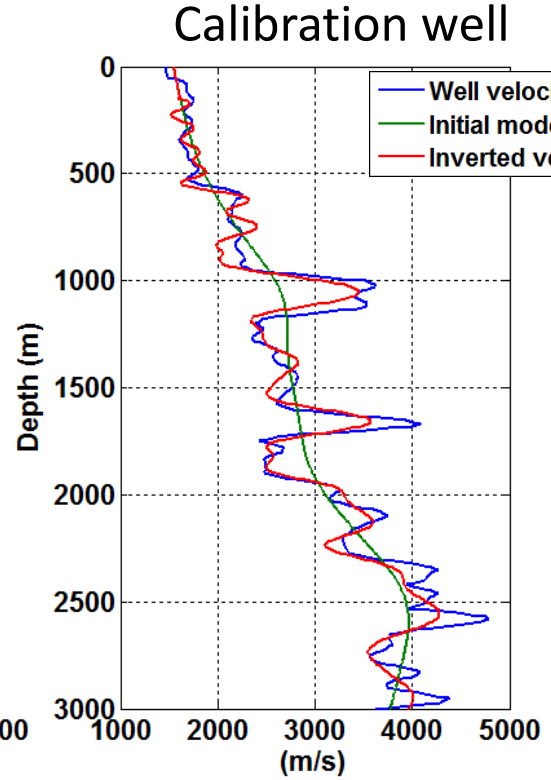
Evolution of the inverted model with more iterations

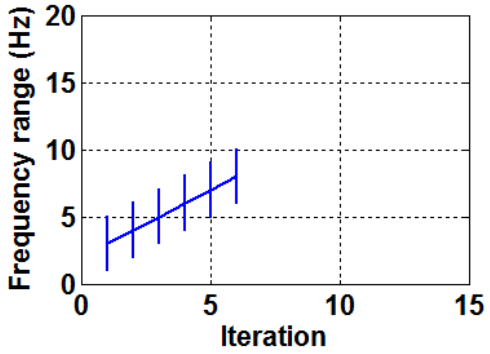
Iteration 6

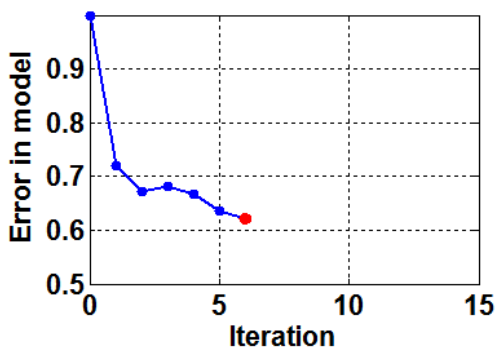


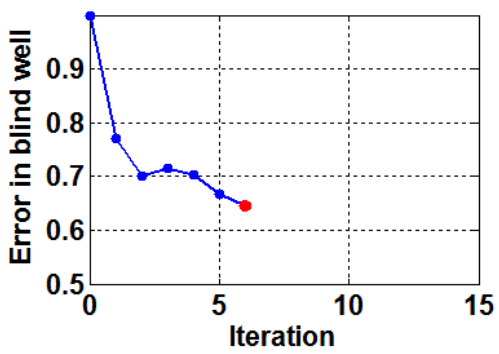


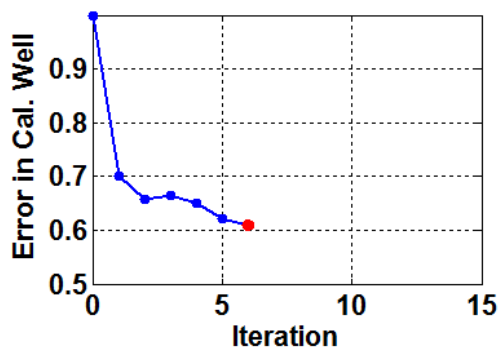






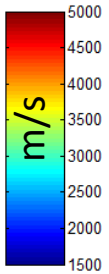


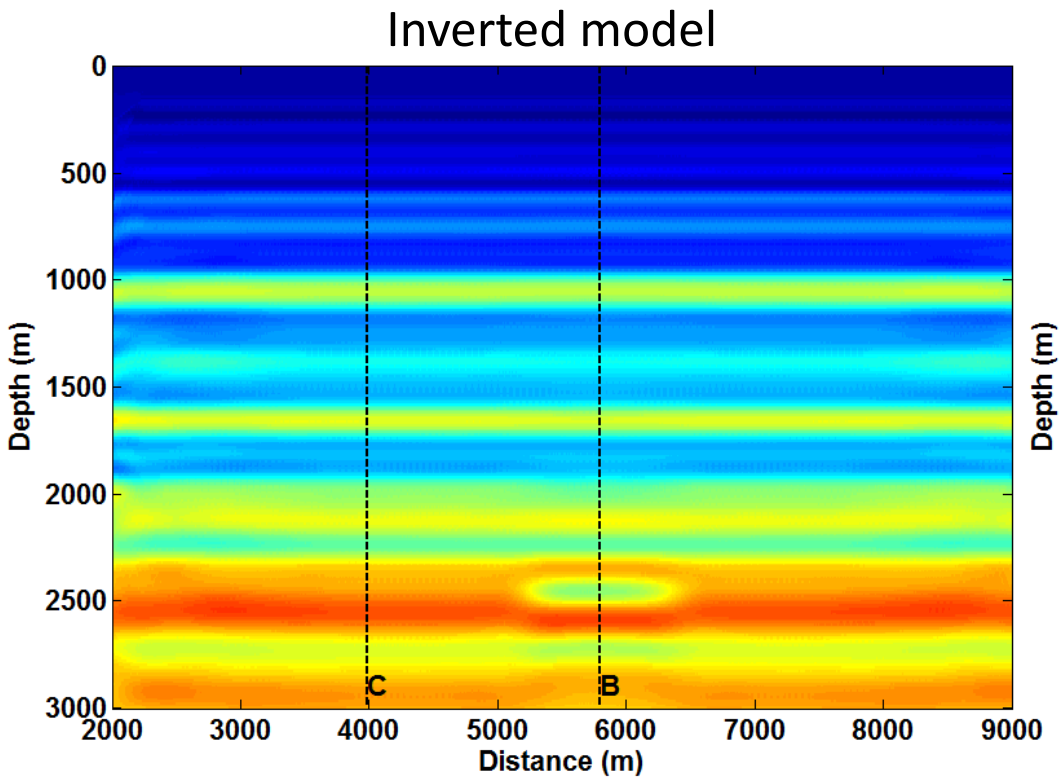


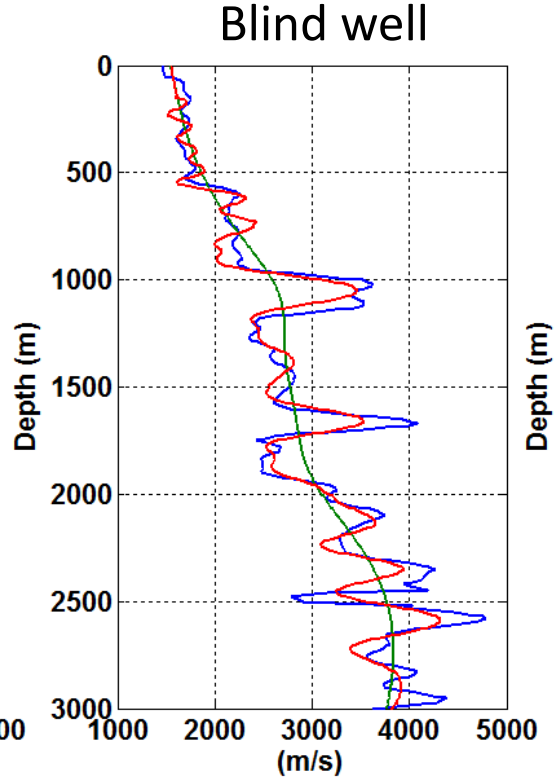


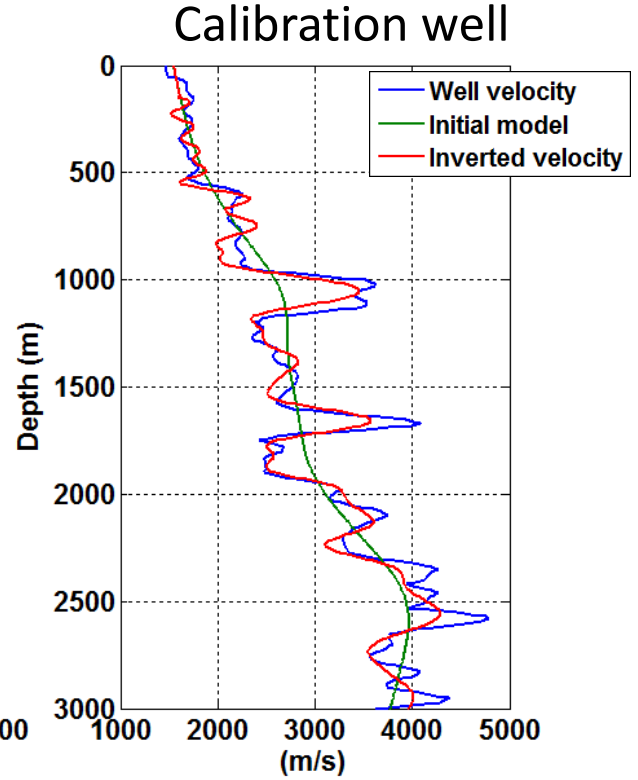
Evolution of the inverted model with more iterations

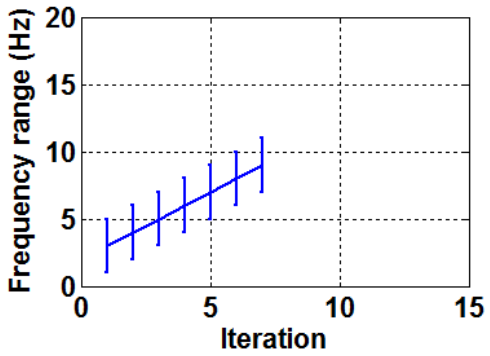
Iteration 7

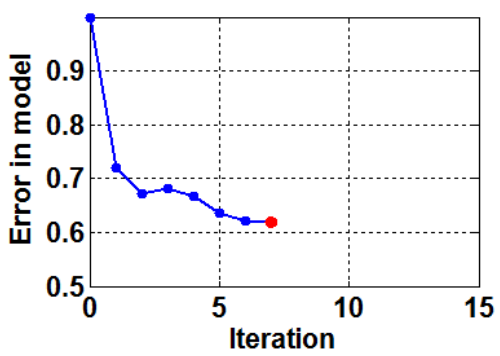


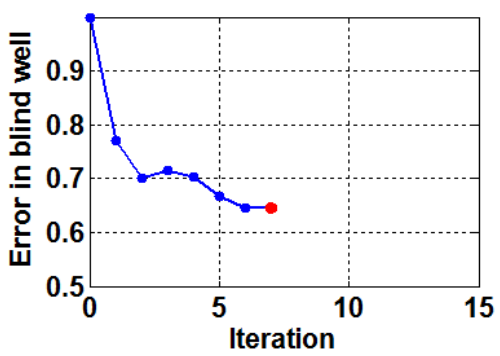


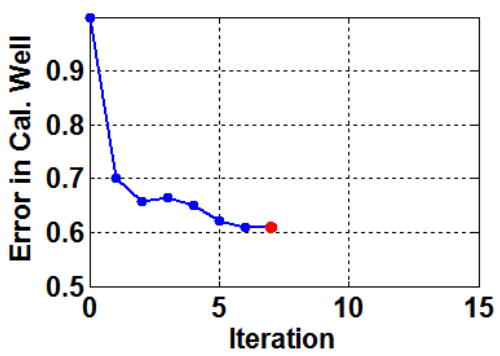






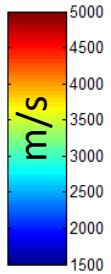


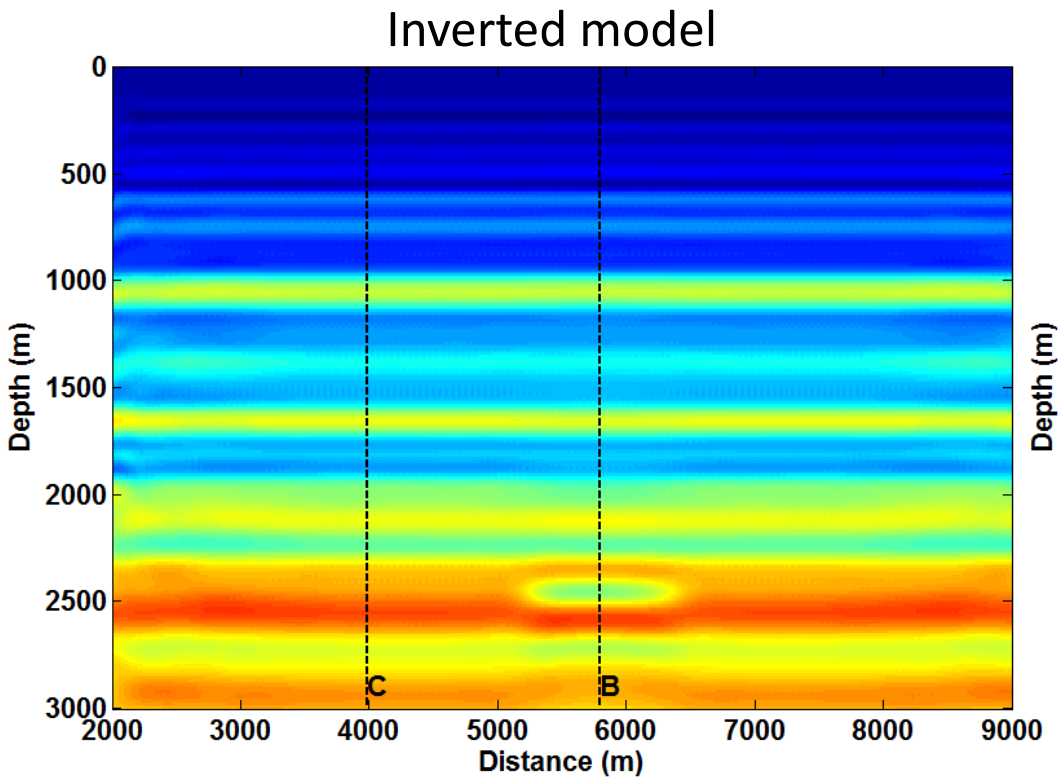


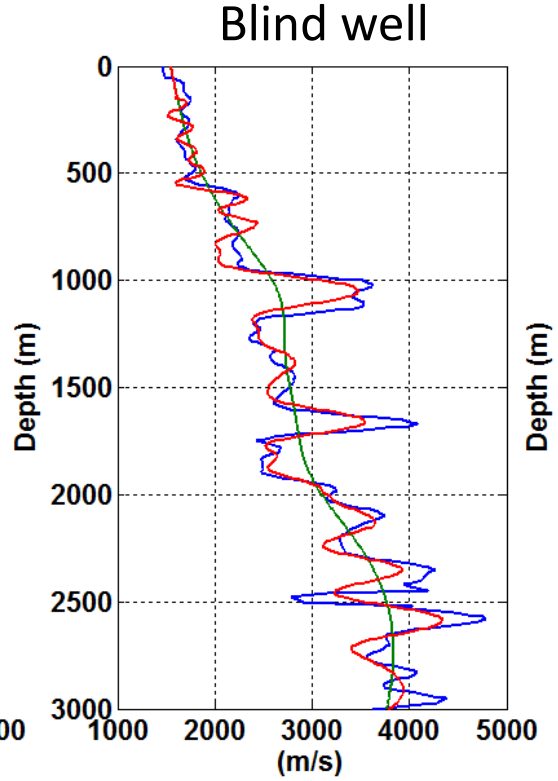


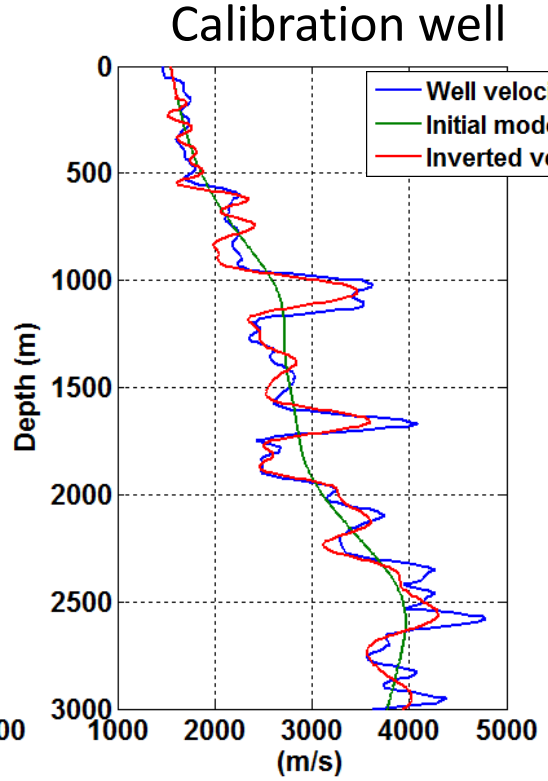
Evolution of the inverted model with more iterations

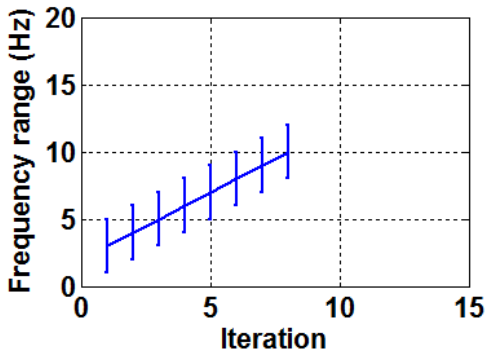
Iteration 8

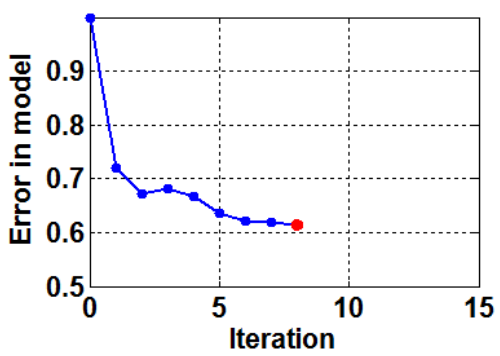


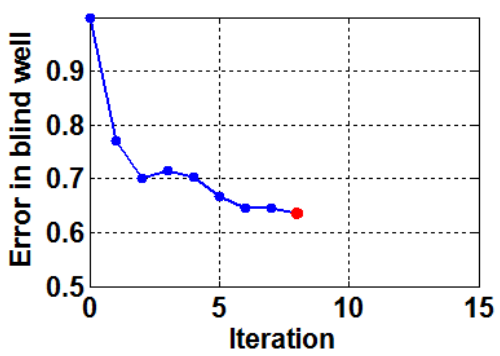


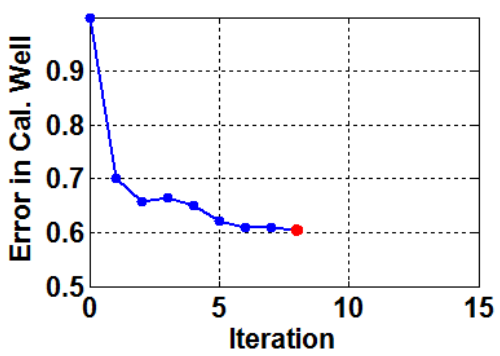






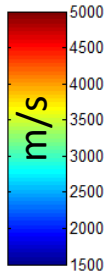


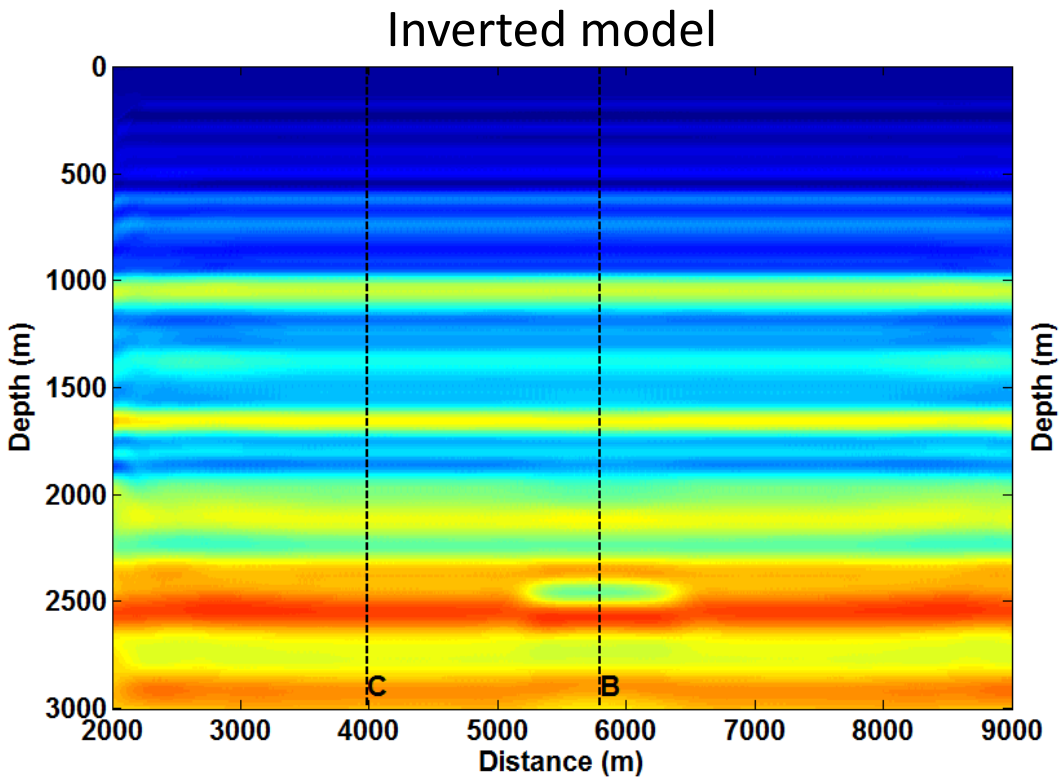


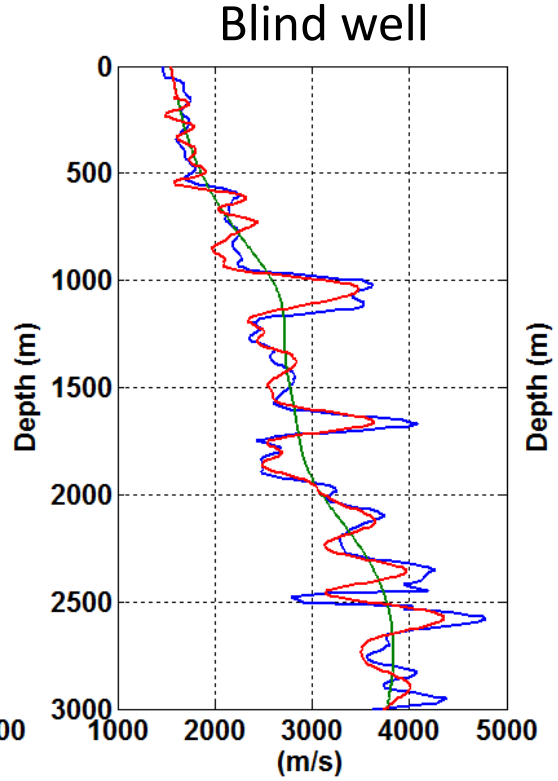


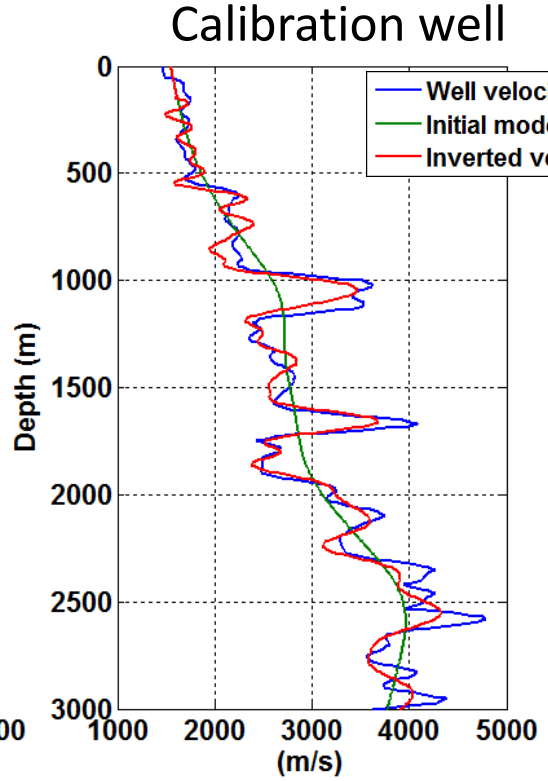
Evolution of the inverted model with more iterations

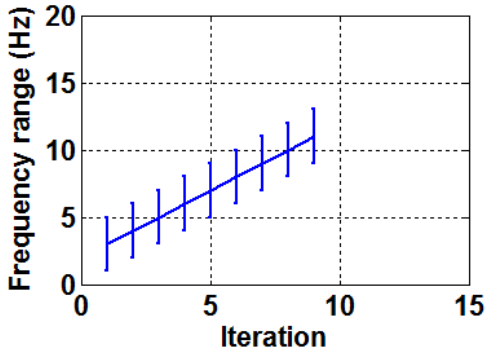
Iteration 9

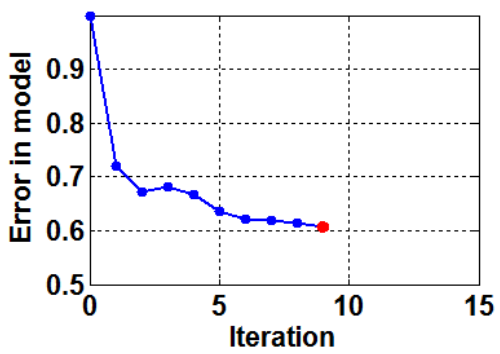


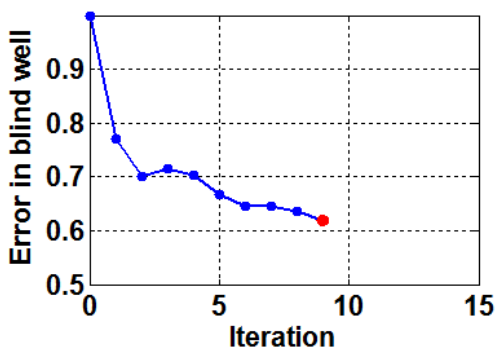


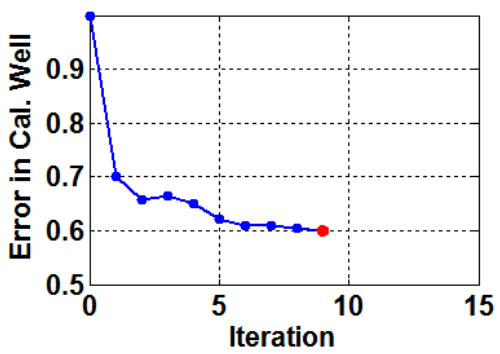






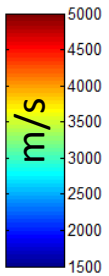


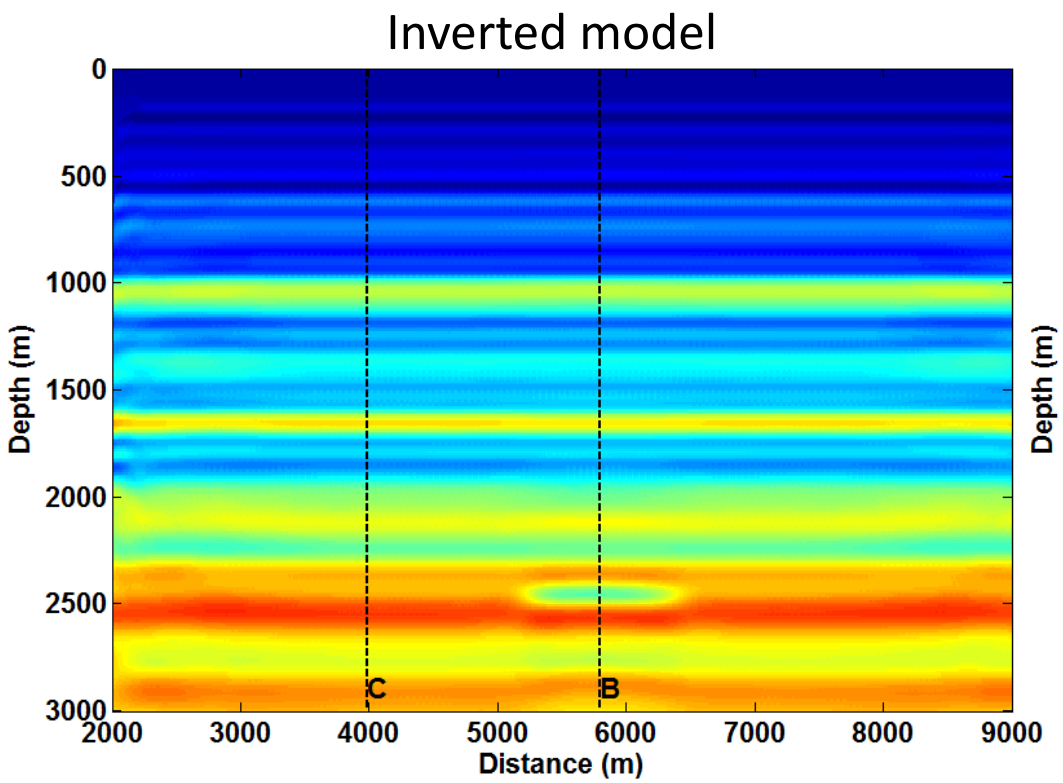


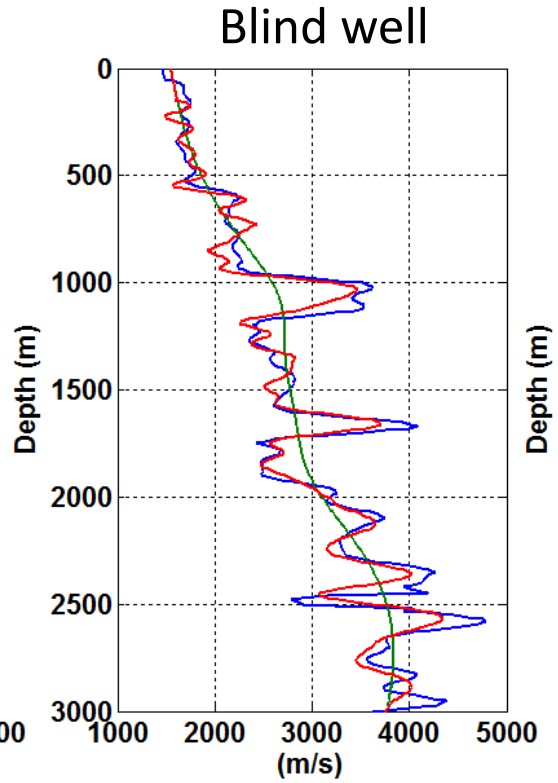


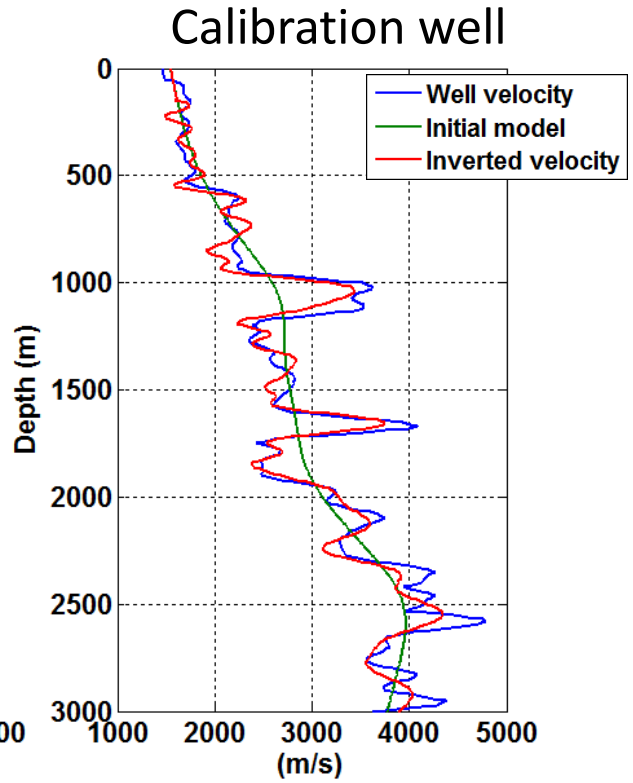
Evolution of the inverted model with more iterations

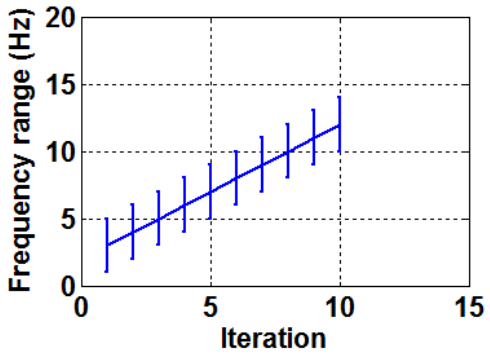
Iteration 10

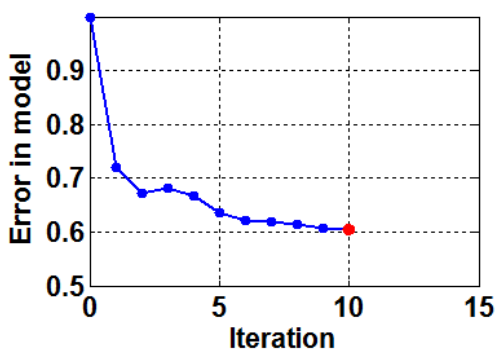


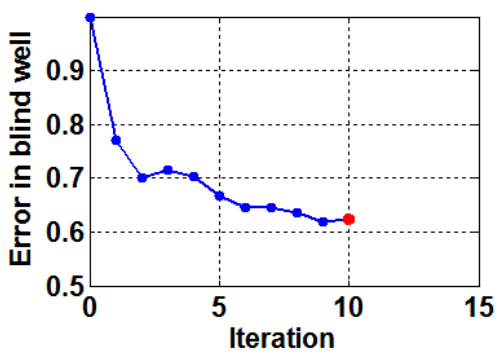


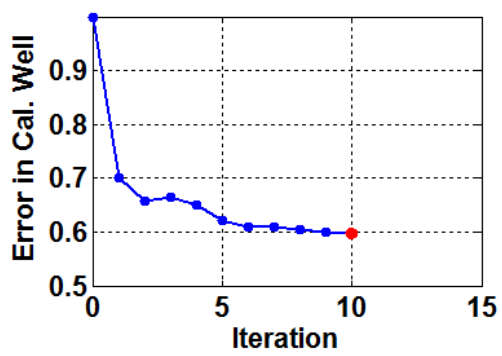






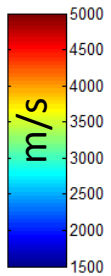


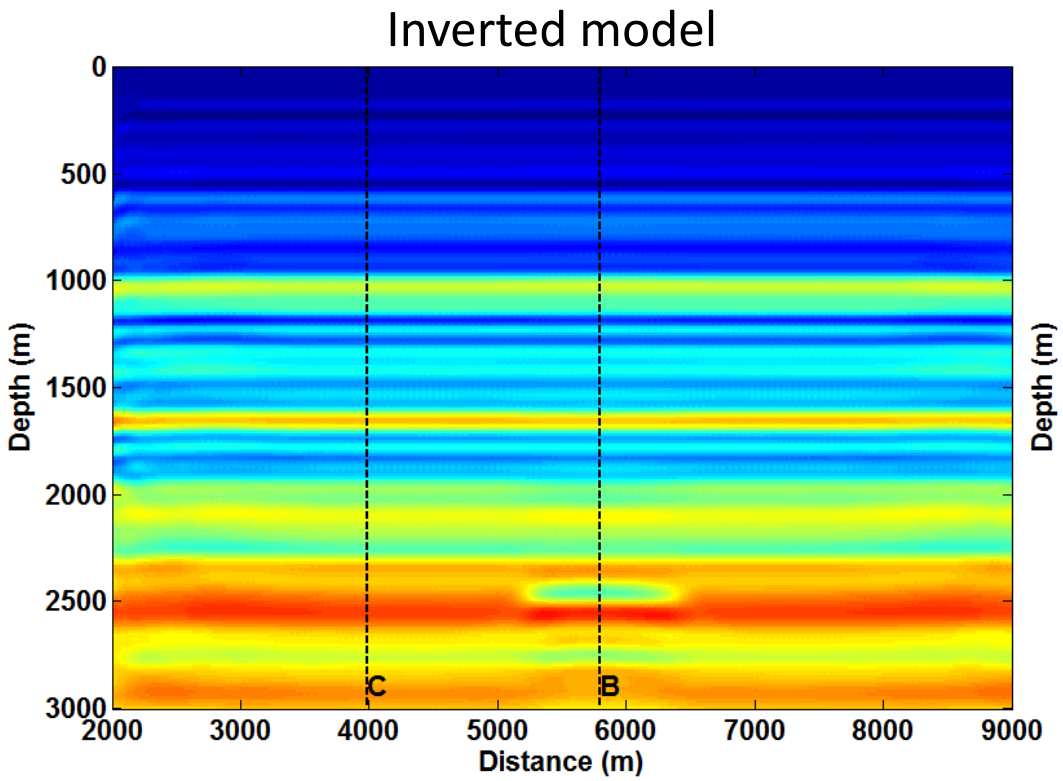


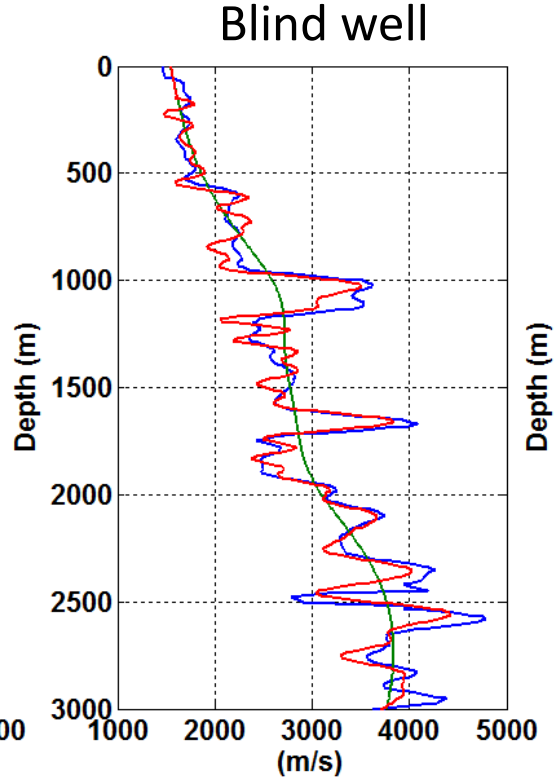


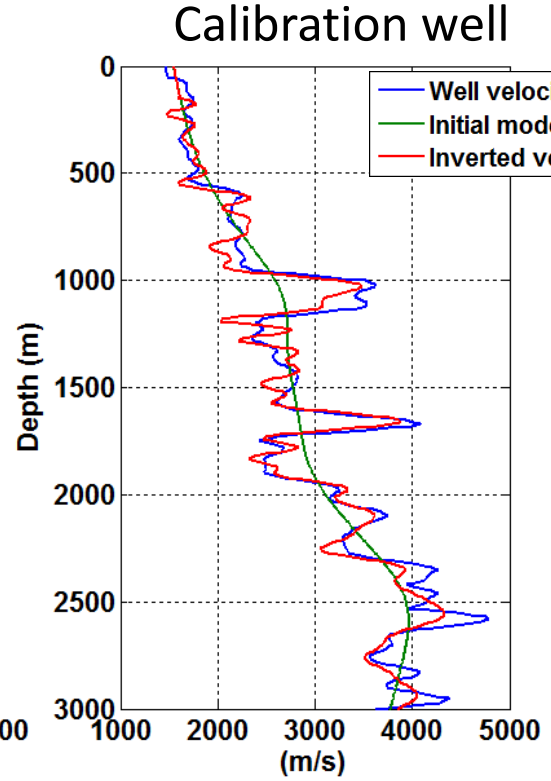
Evolution of the inverted model with more iterations

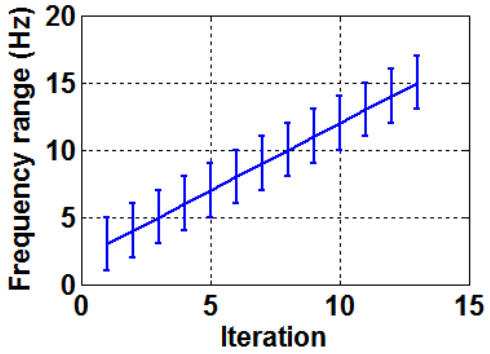
Iteration 13

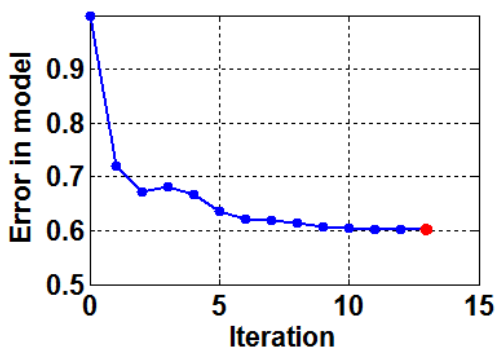


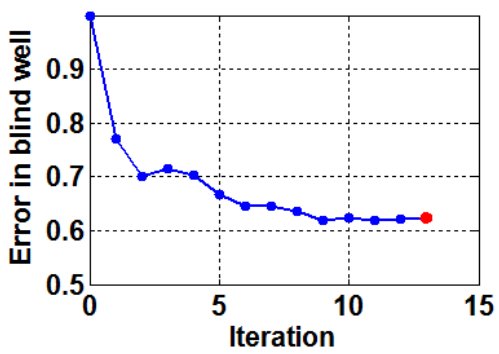


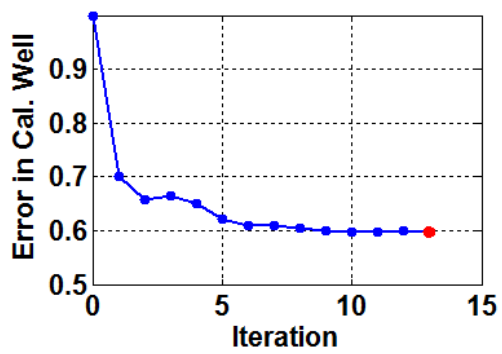






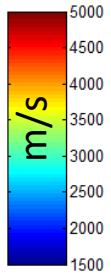


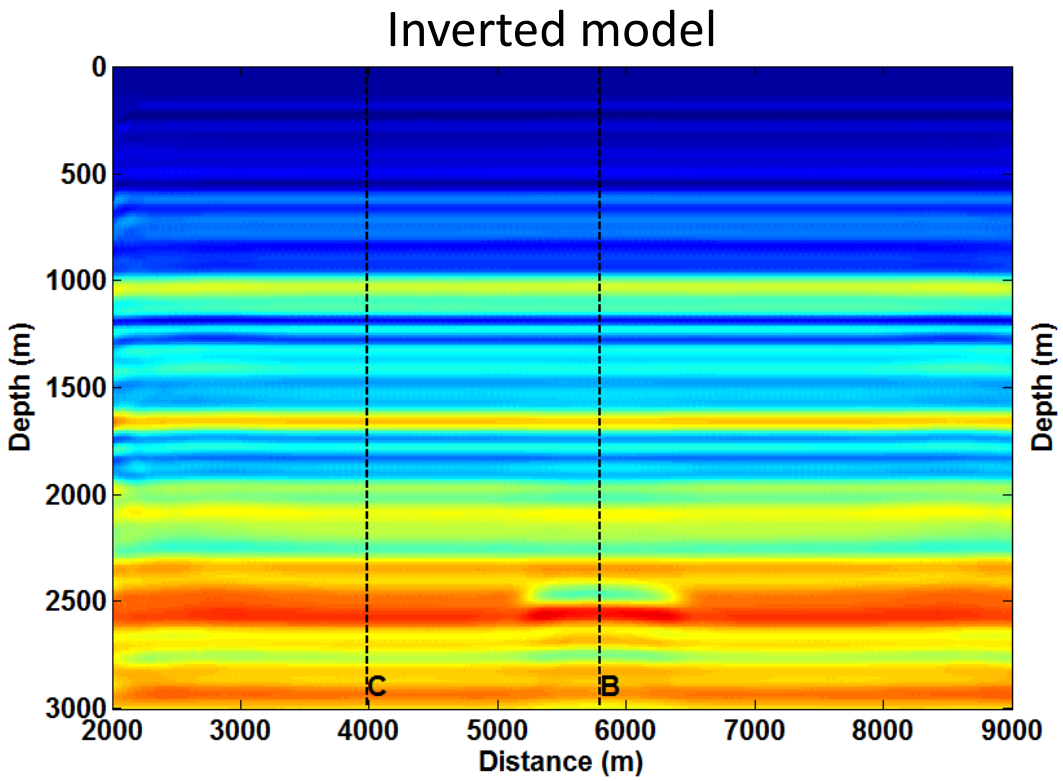


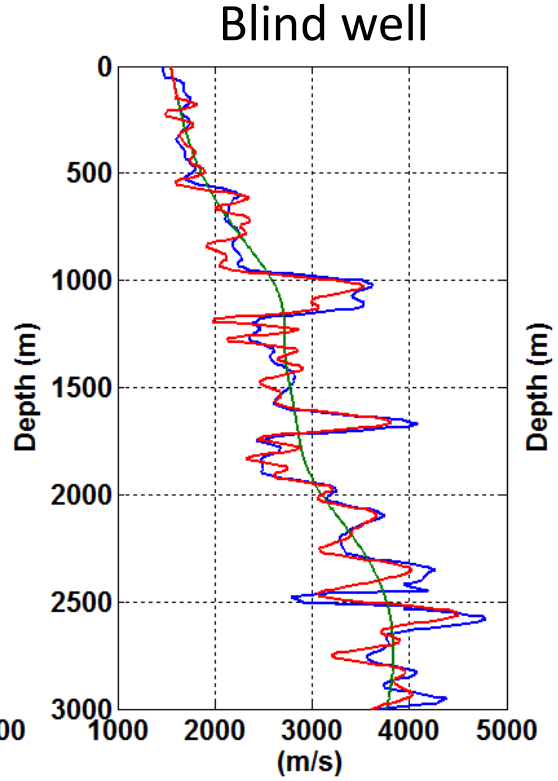


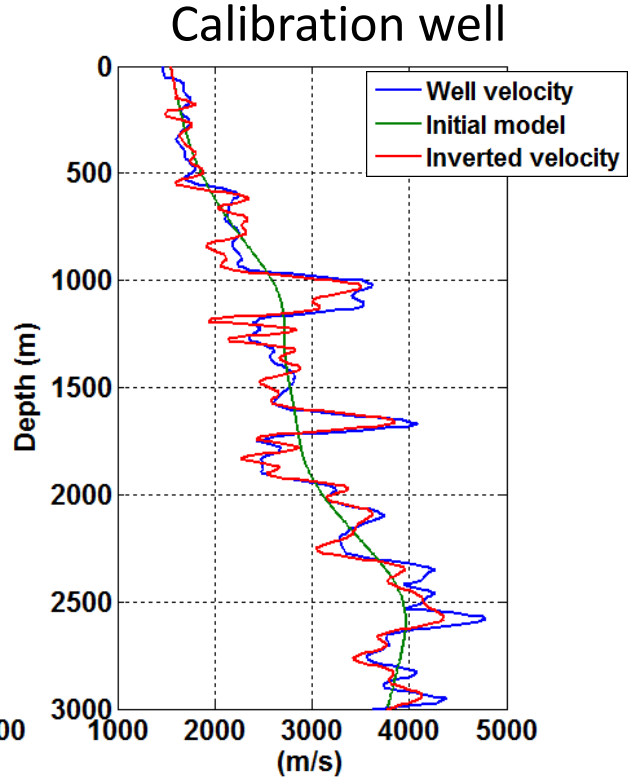
Evolution of the inverted model with more iterations

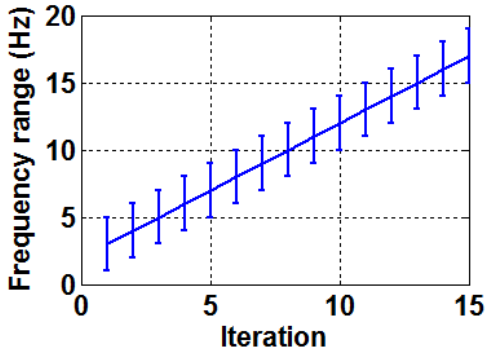
Iteration 15

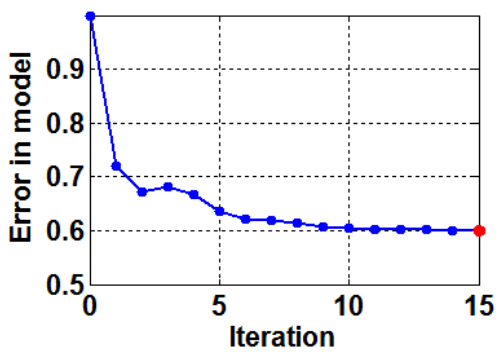


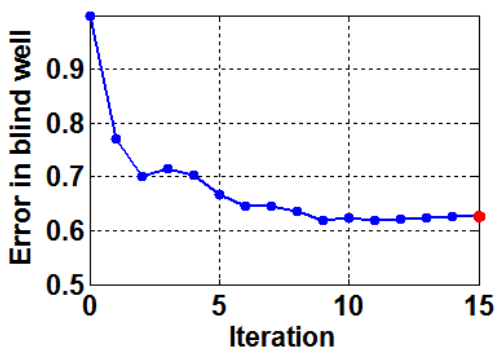


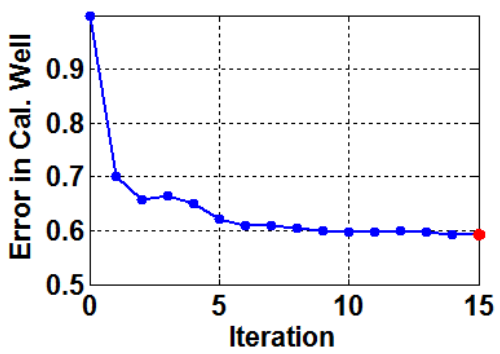






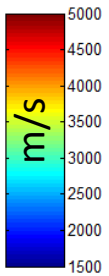


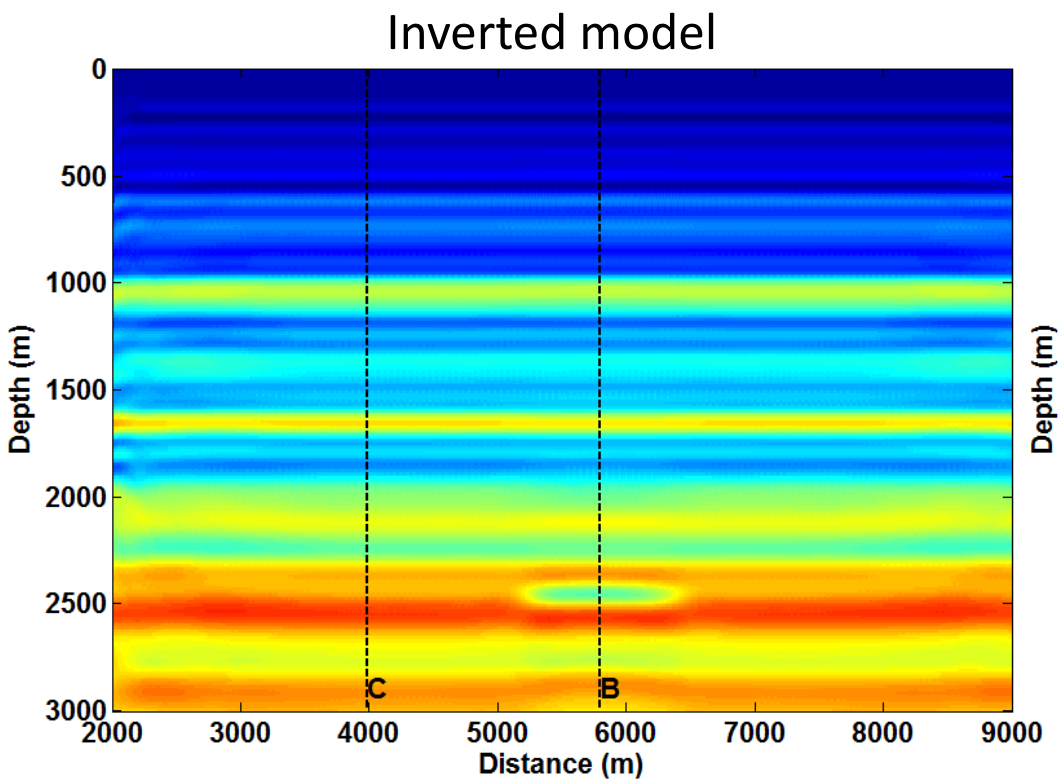


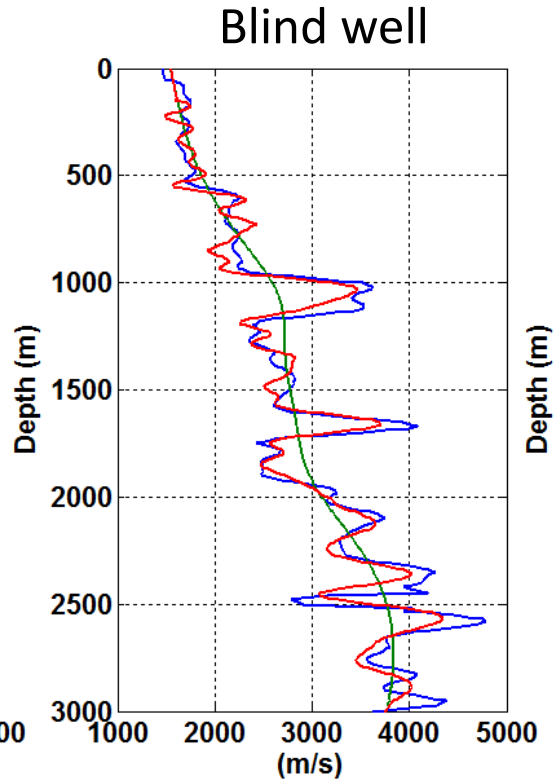


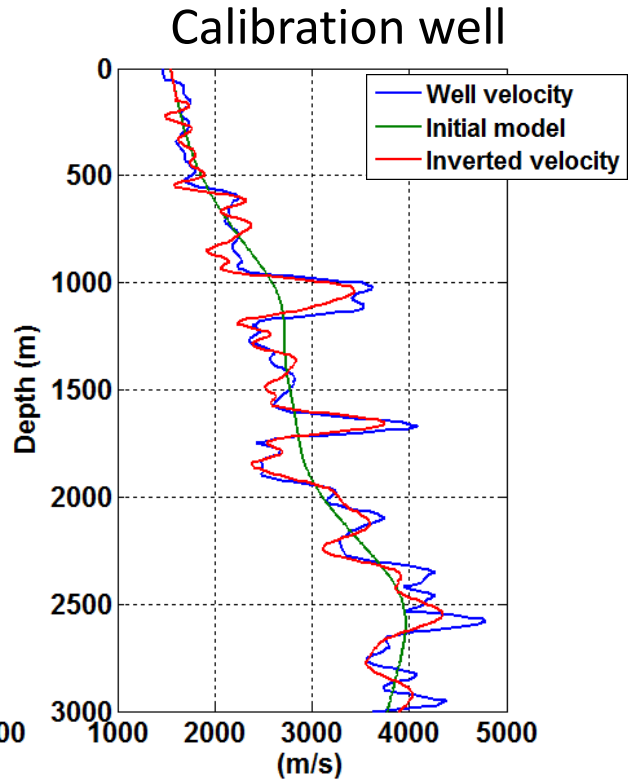
Evolution of the inverted model with more iterations

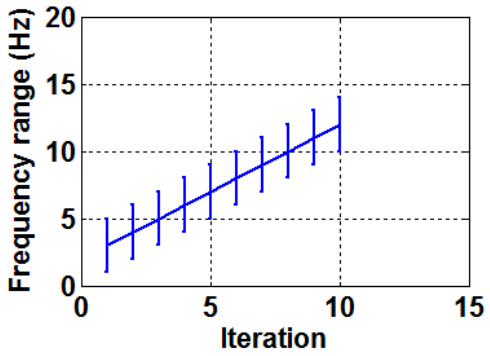
Iteration 10

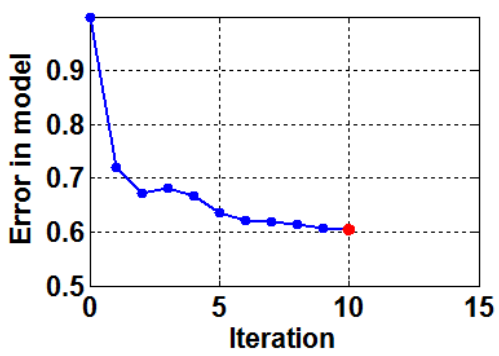


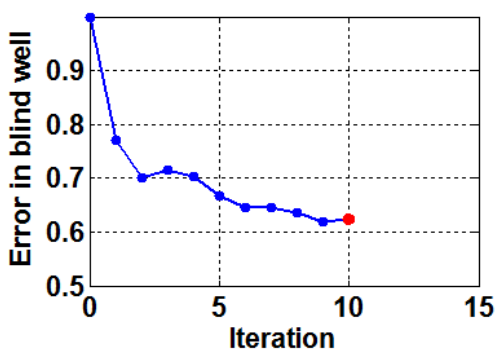


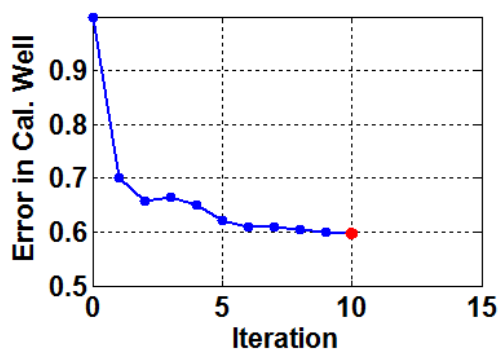






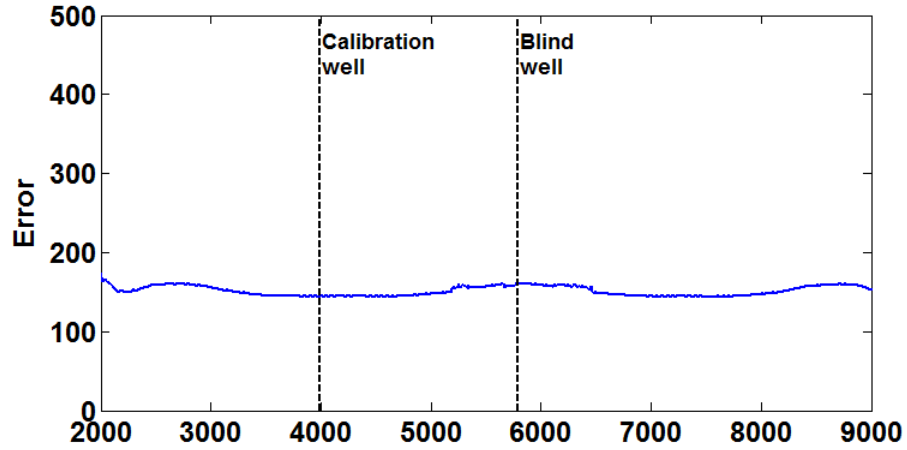




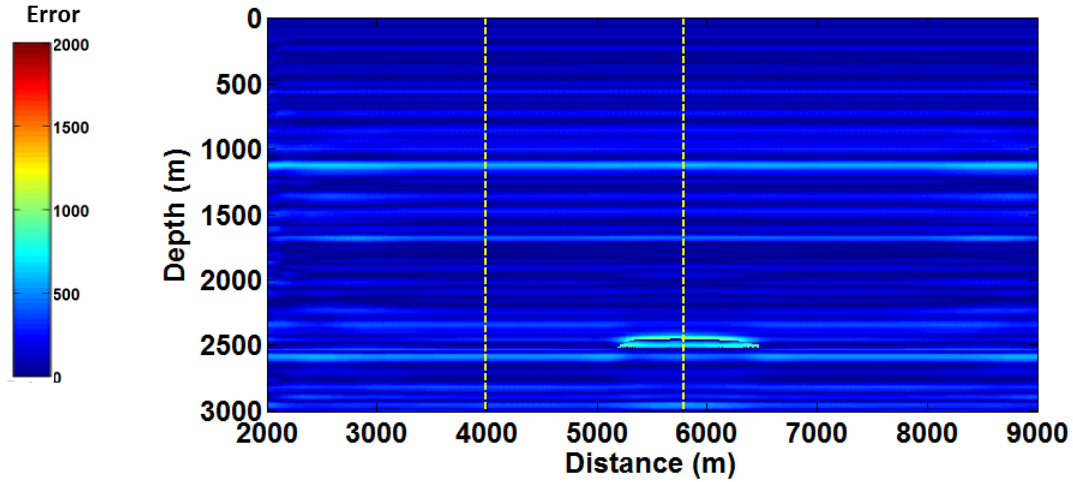


Spatial distribution of the error

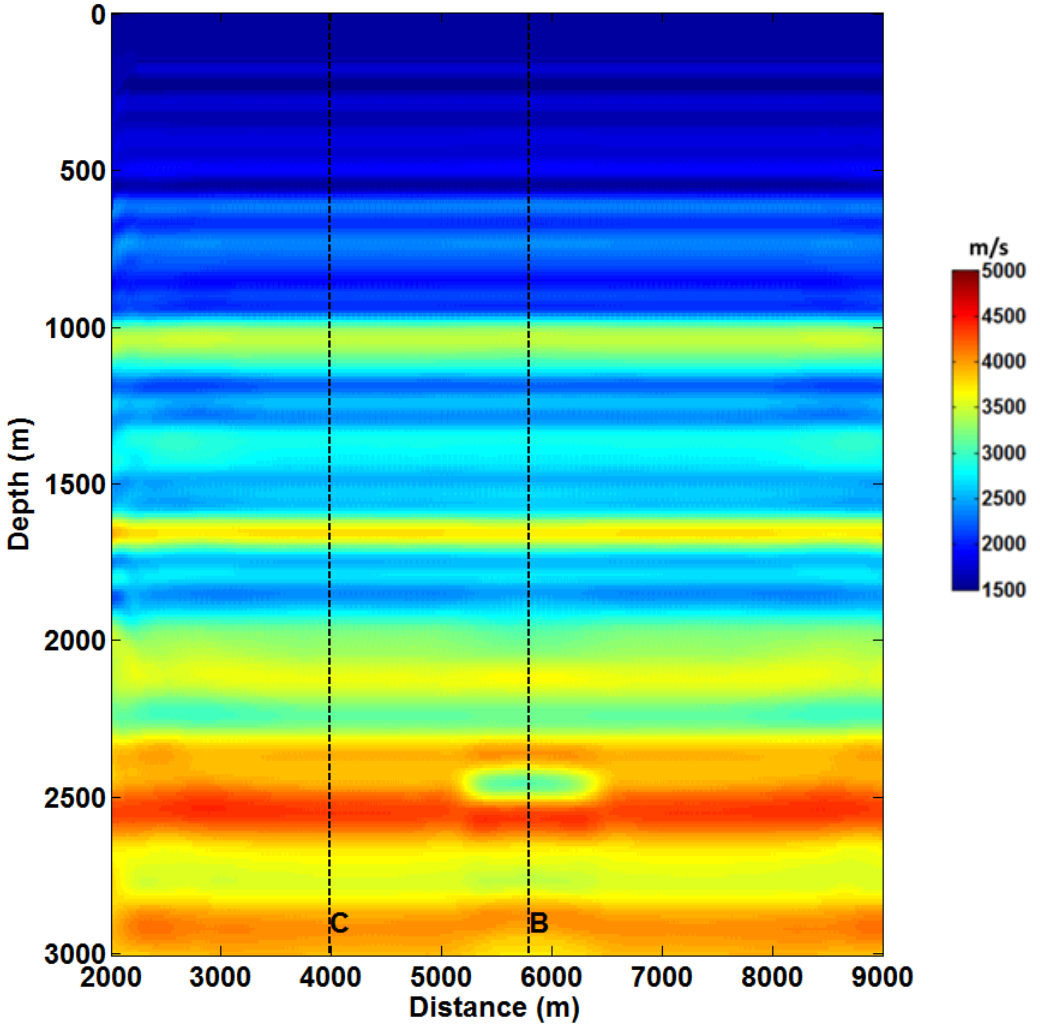
Horizontal distribution of the error



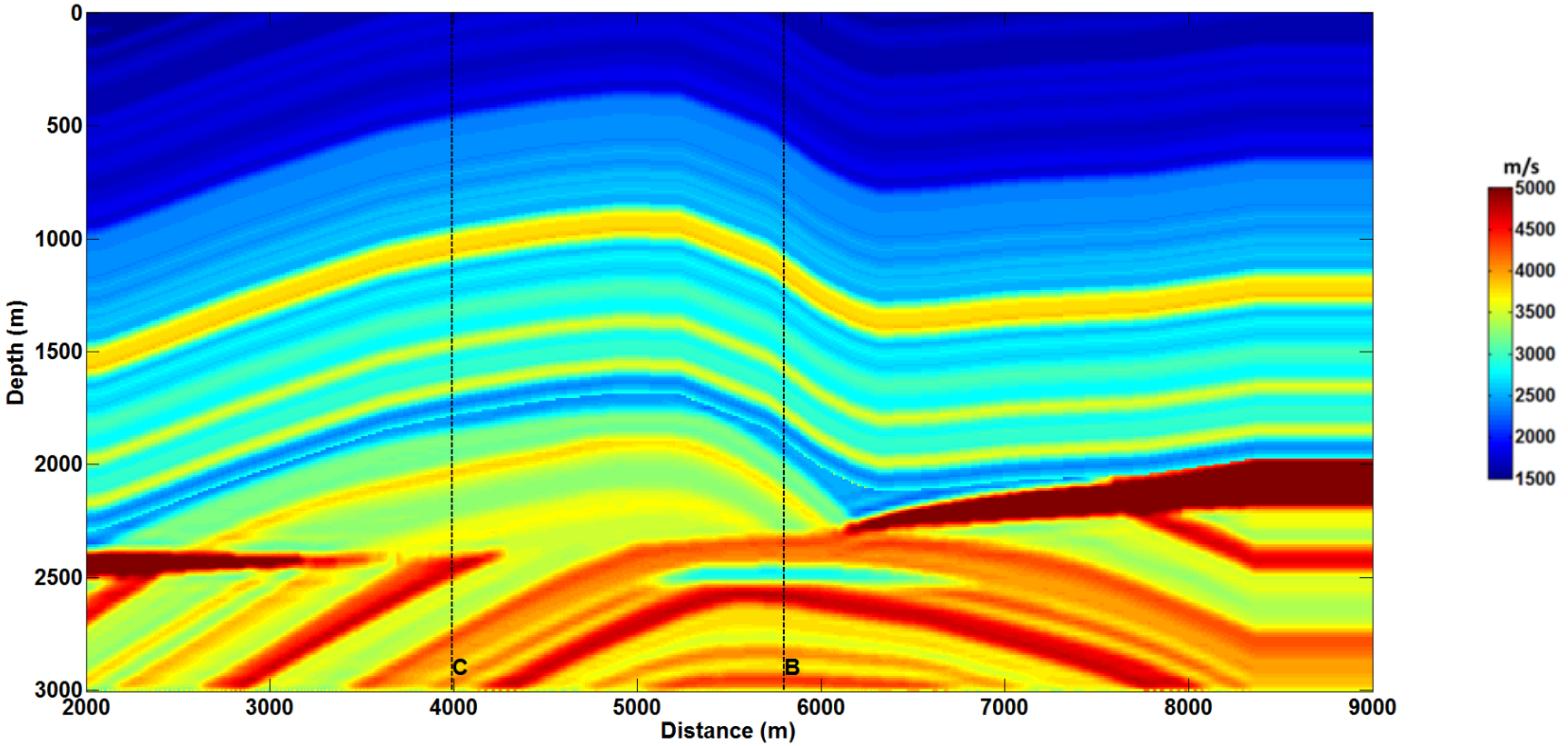
Spatial distribution of the error



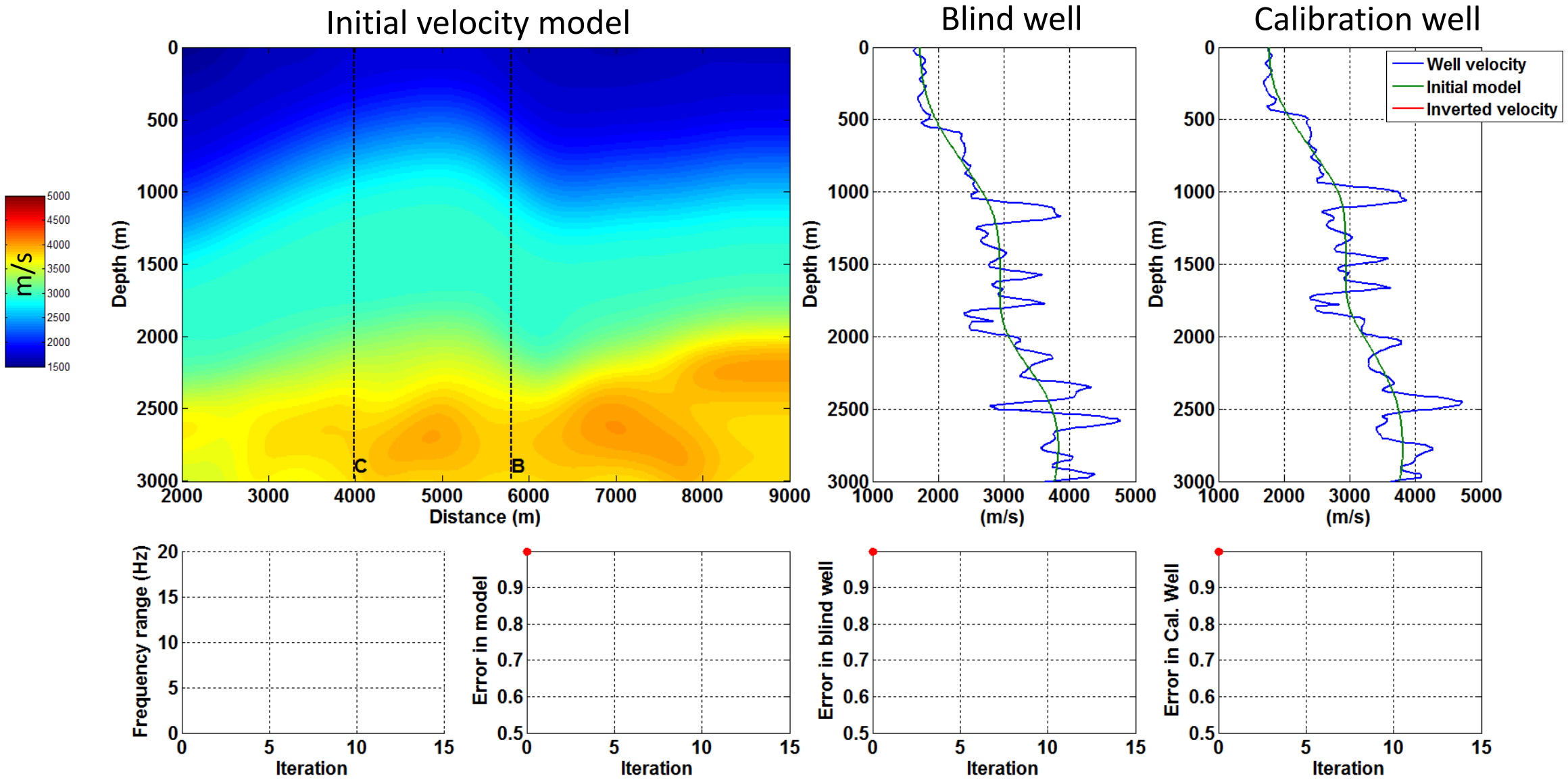
Inverted velocity model



Model 2

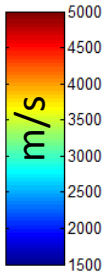

0
500
1000
1500
2000
2500
3000
Depth (m)
2000
3000
4000
5000
6000
7000
8000
9000
Distance (m)
C
B
m/s
5000
4500
4000
3500
3000
2500
2000
1500

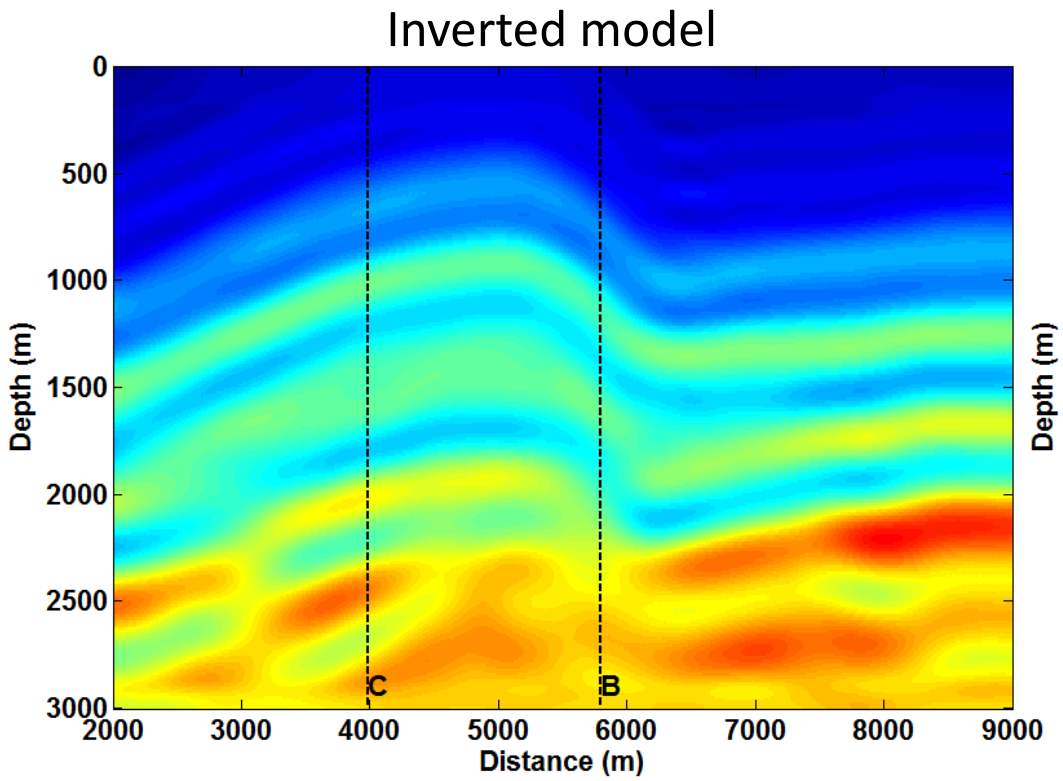
Evolution of the inverted model with more iterations

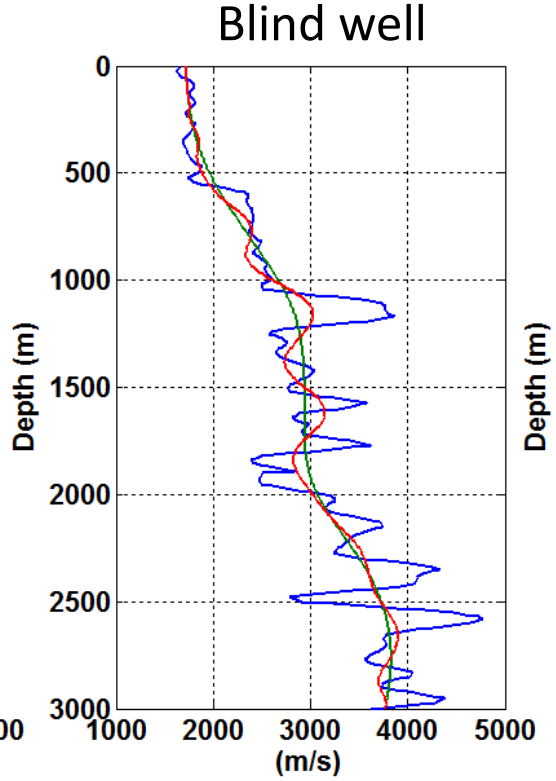


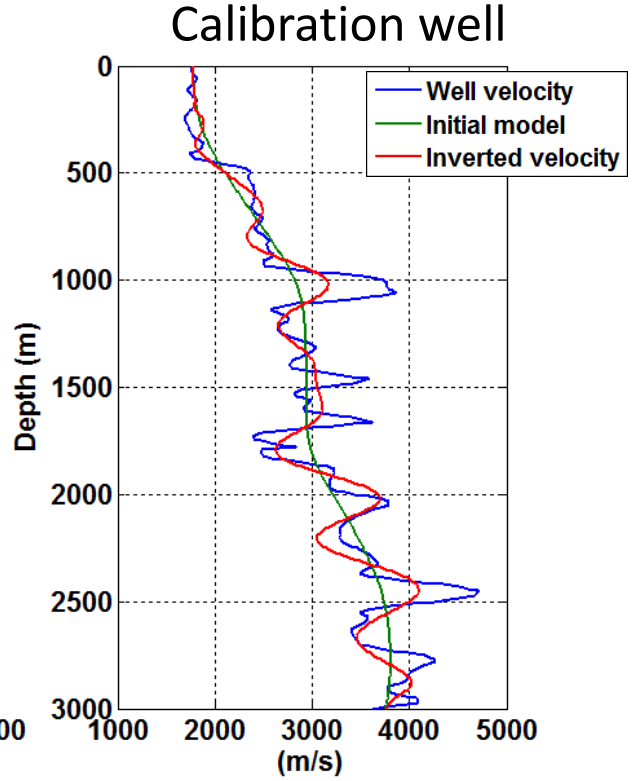
Evolution of the inverted model with more iterations

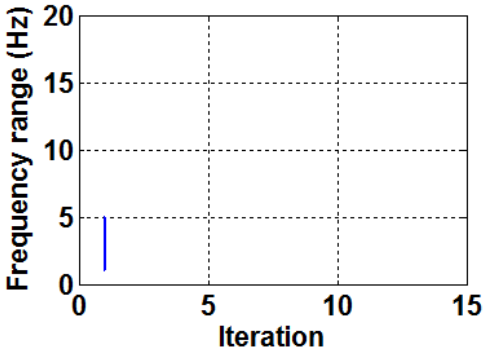
Iteration 1

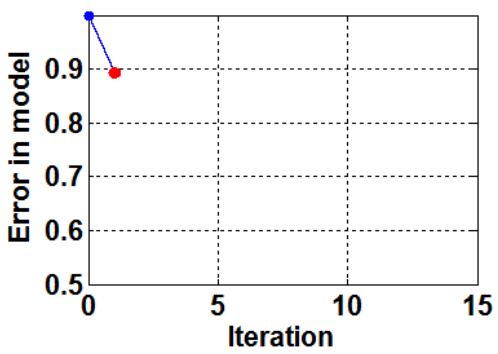


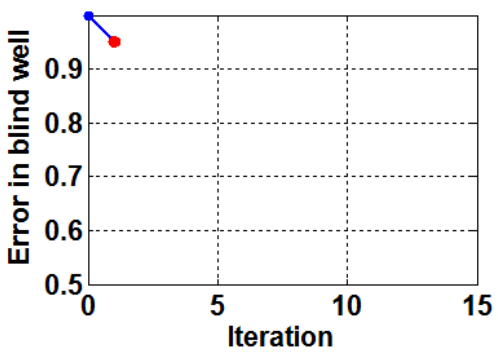


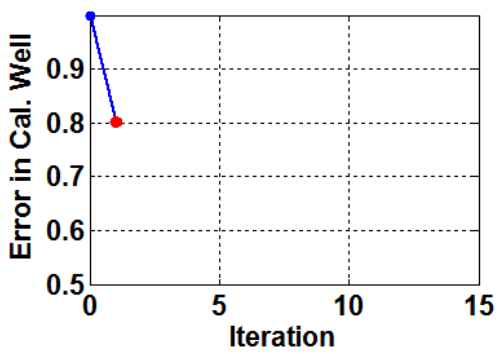






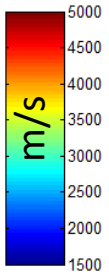


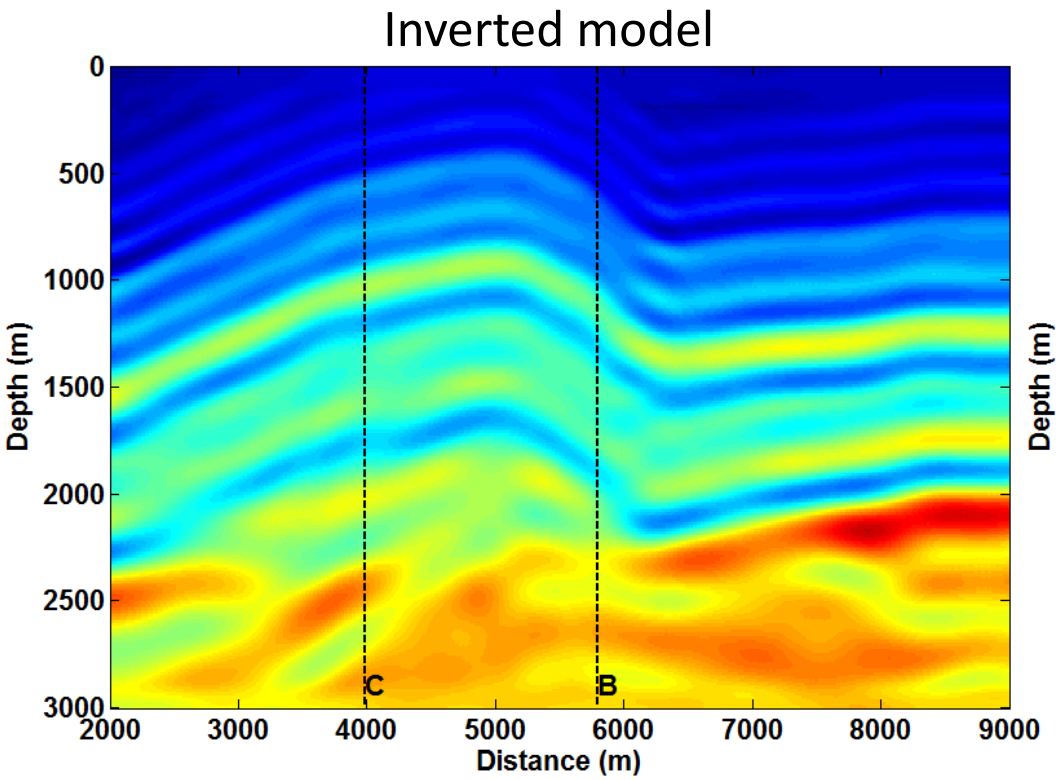


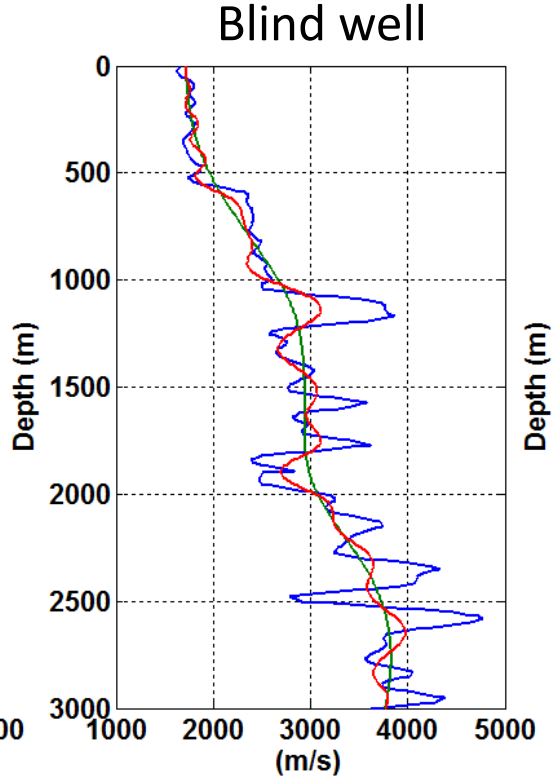


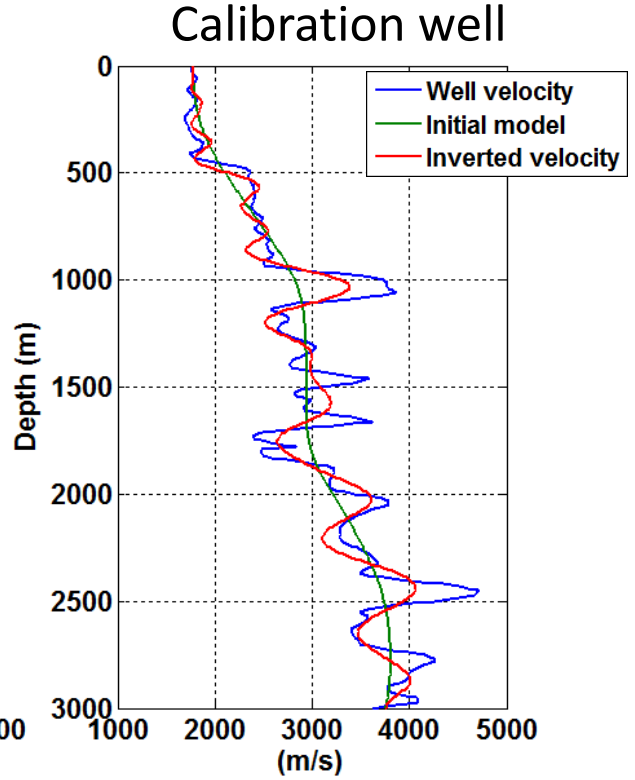
Evolution of the inverted model with more iterations

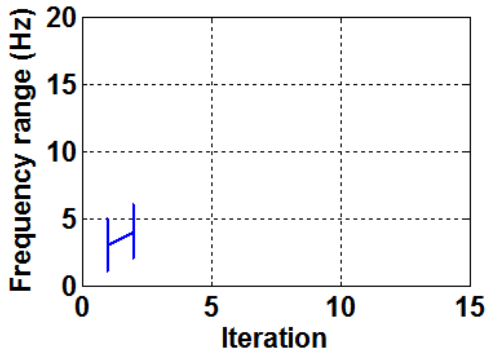
Iteration 2

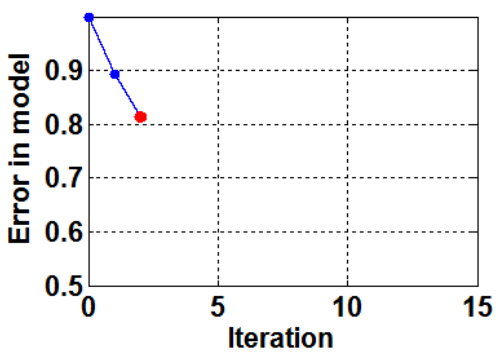


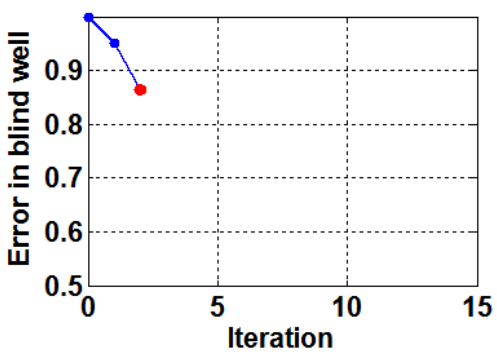


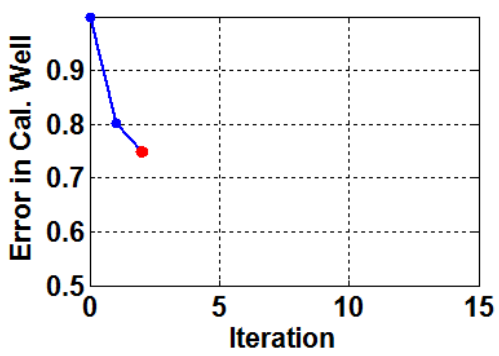






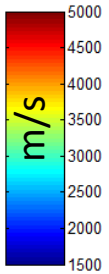


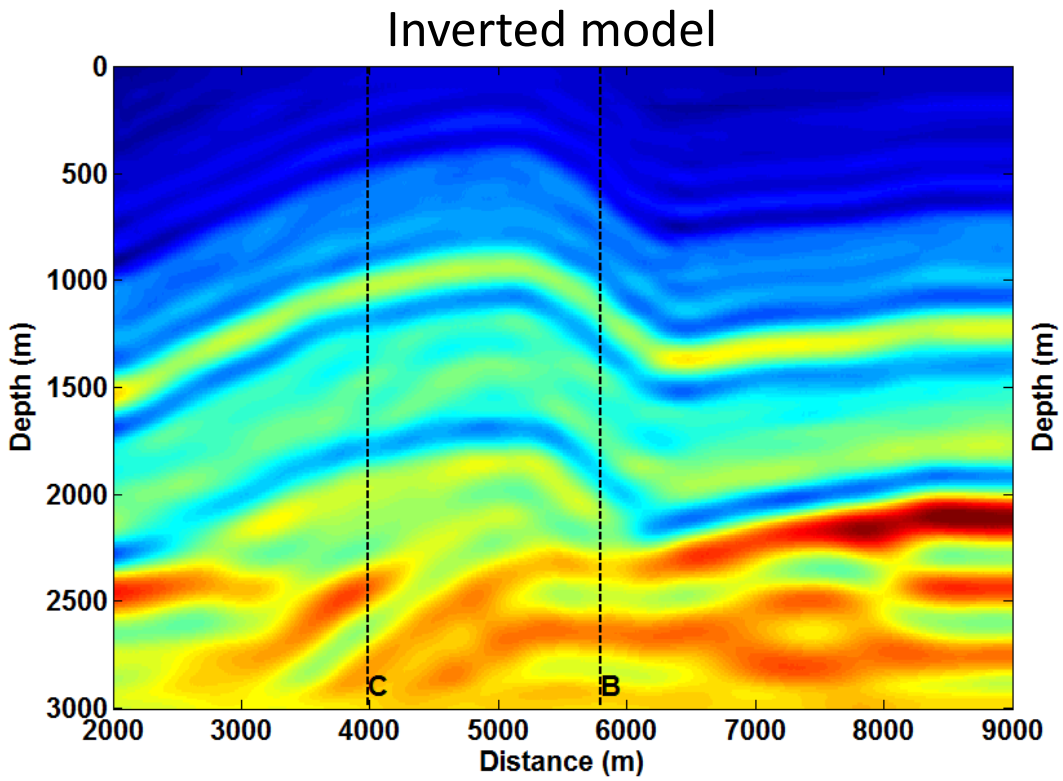


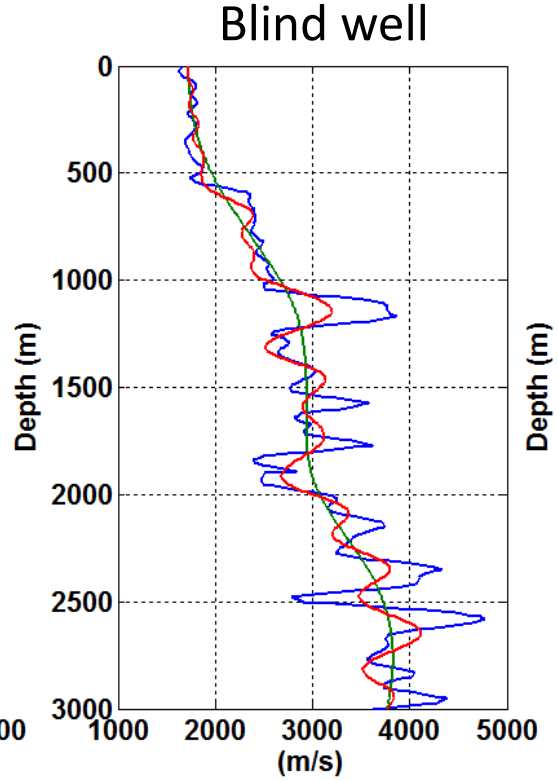


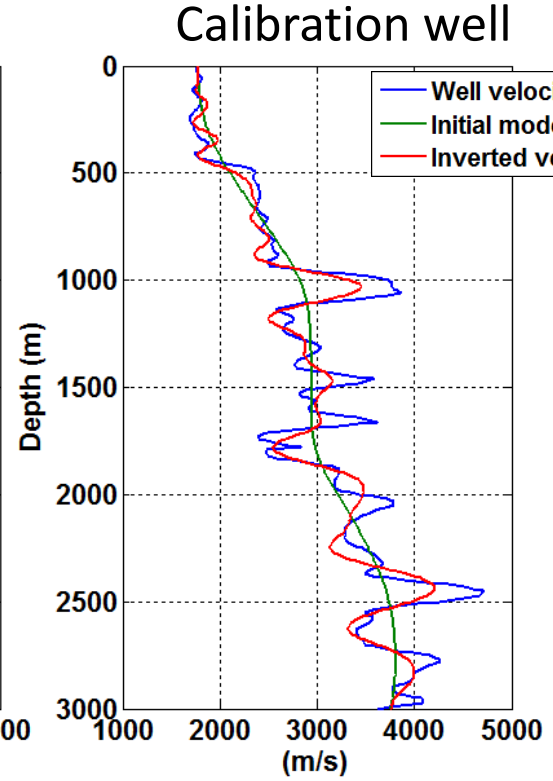
Evolution of the inverted model with more iterations

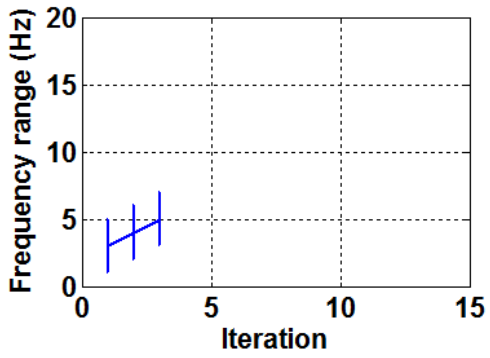
Iteration 3

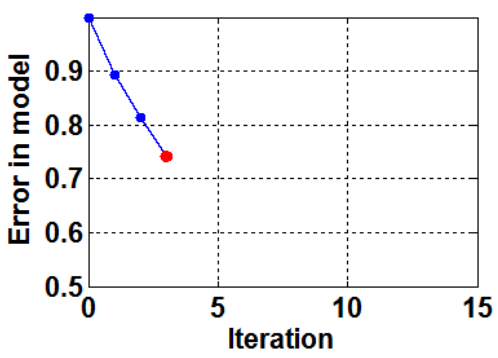


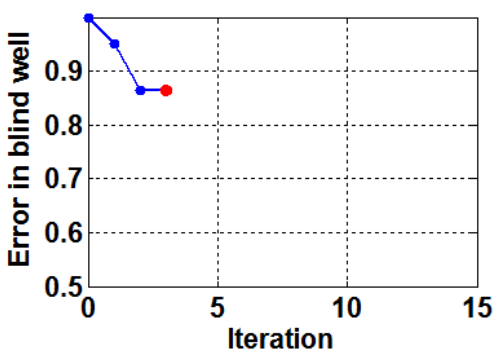


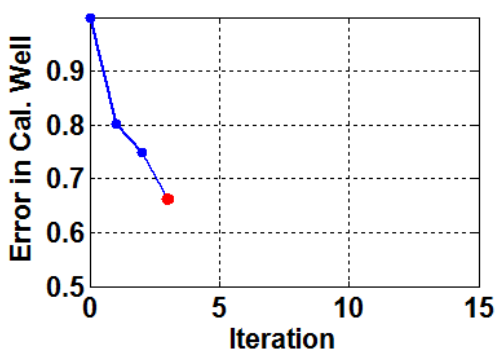






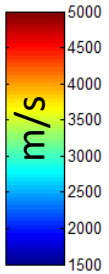


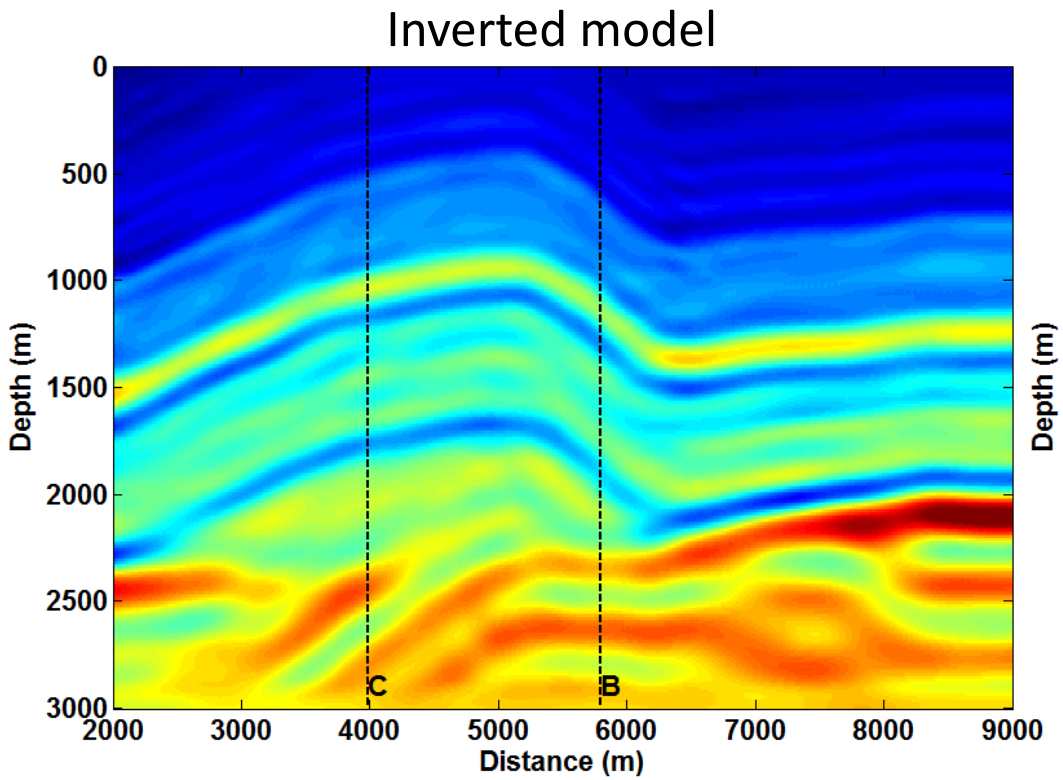


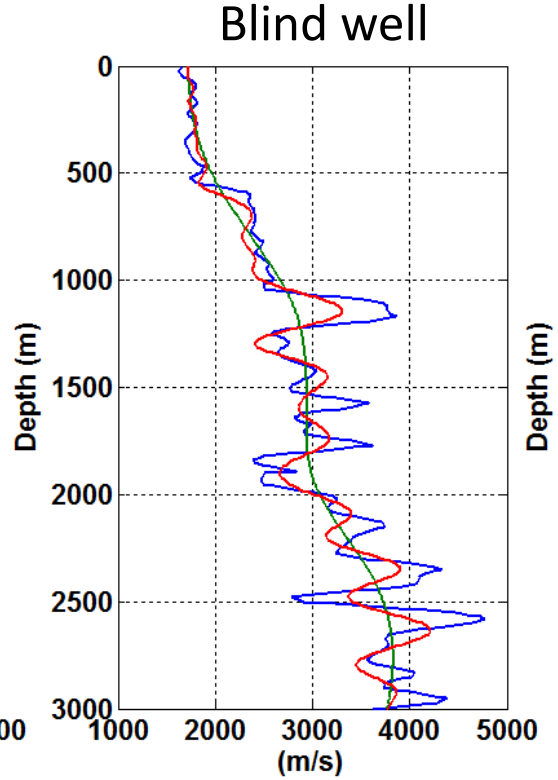


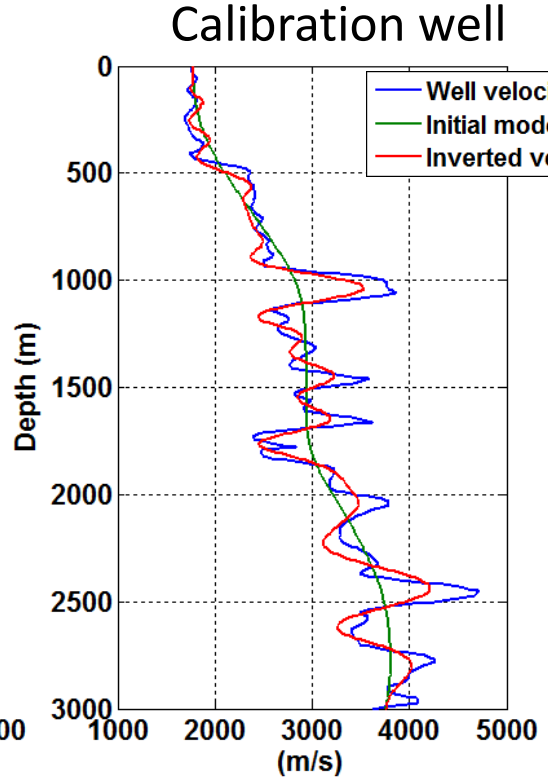
Evolution of the inverted model with more iterations

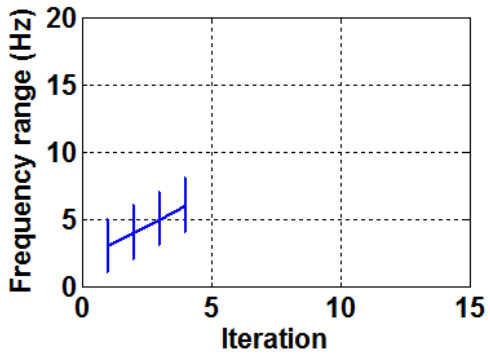
Iteration 4

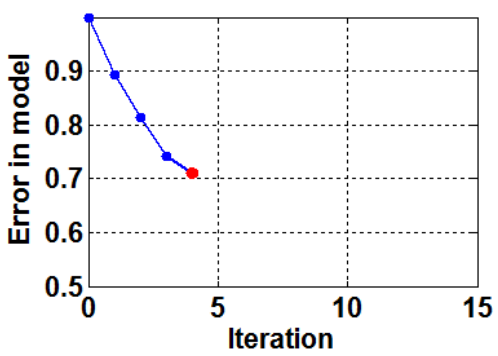


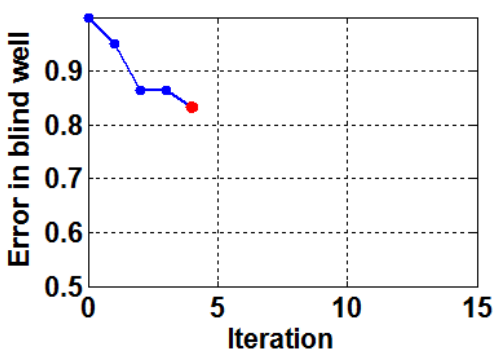


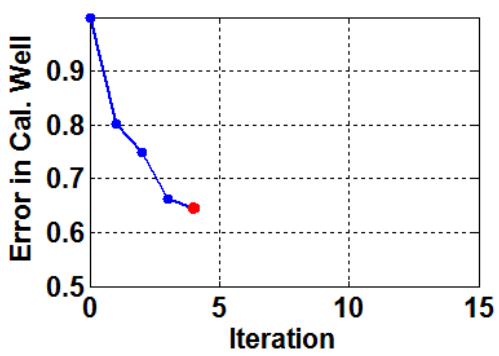






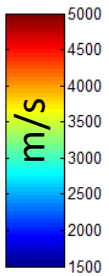


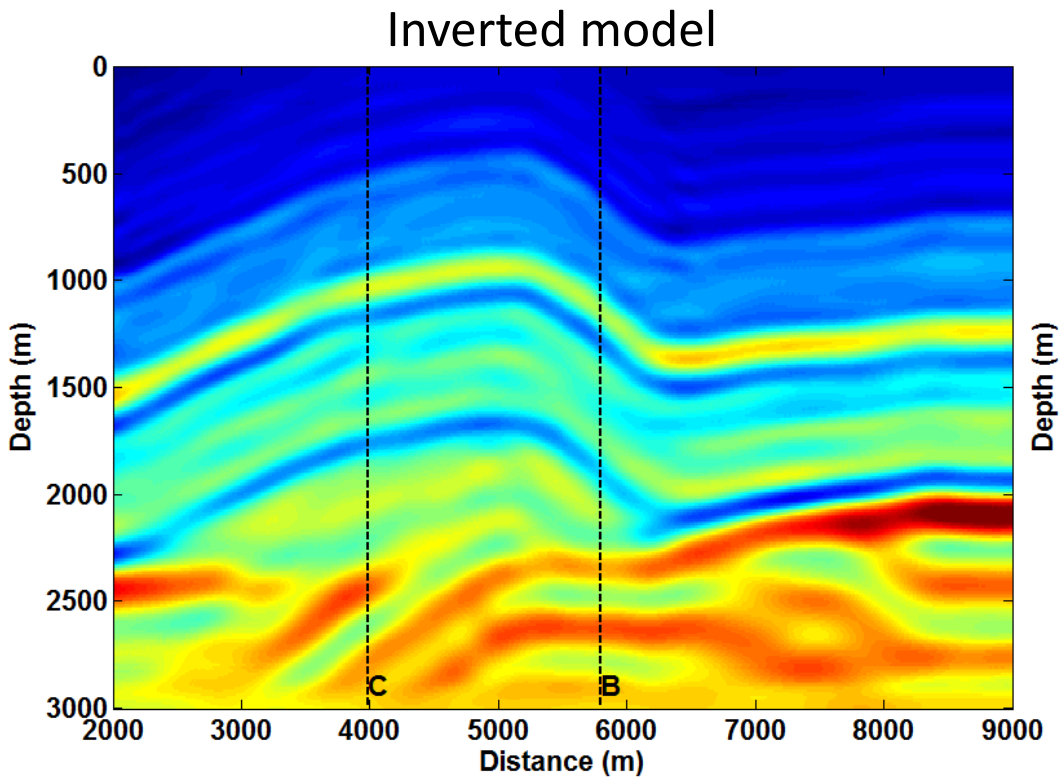


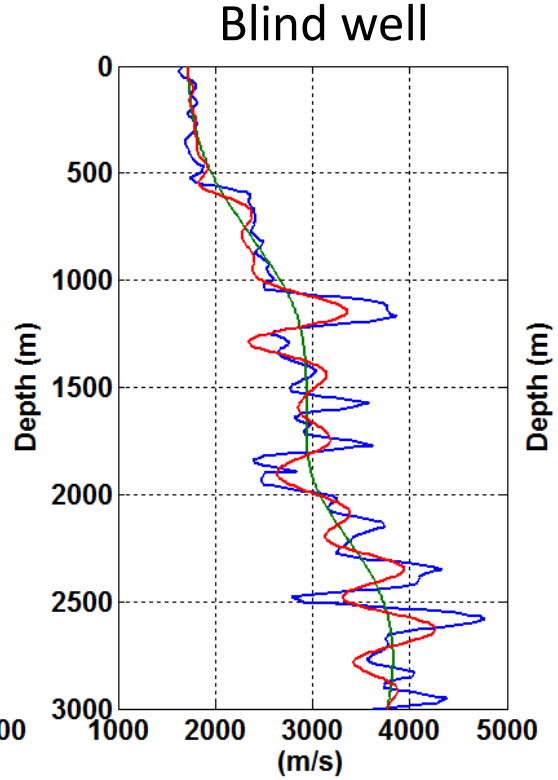


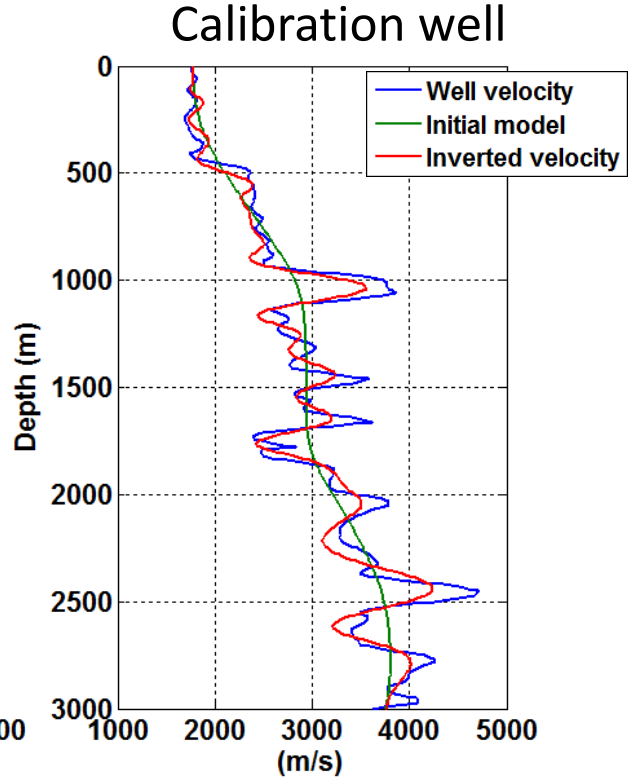
Evolution of the inverted model with more iterations

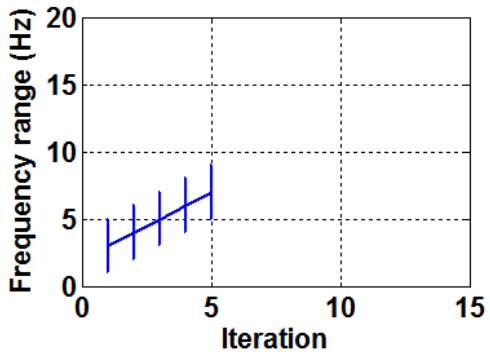
Iteration 5

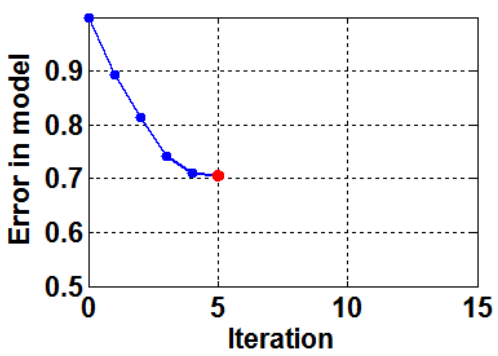


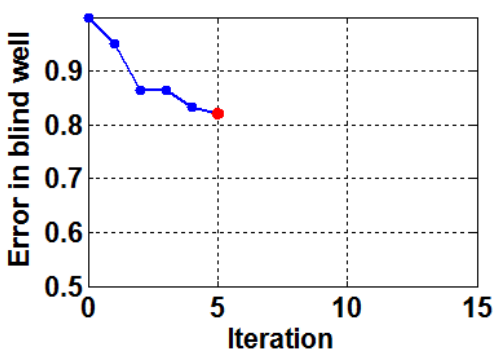


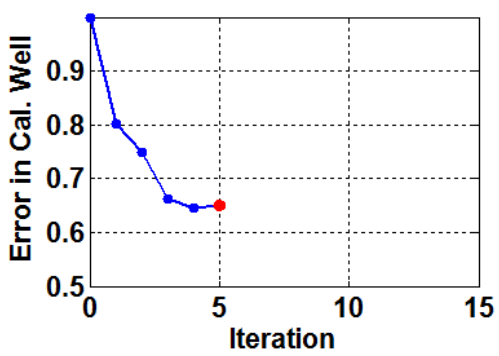






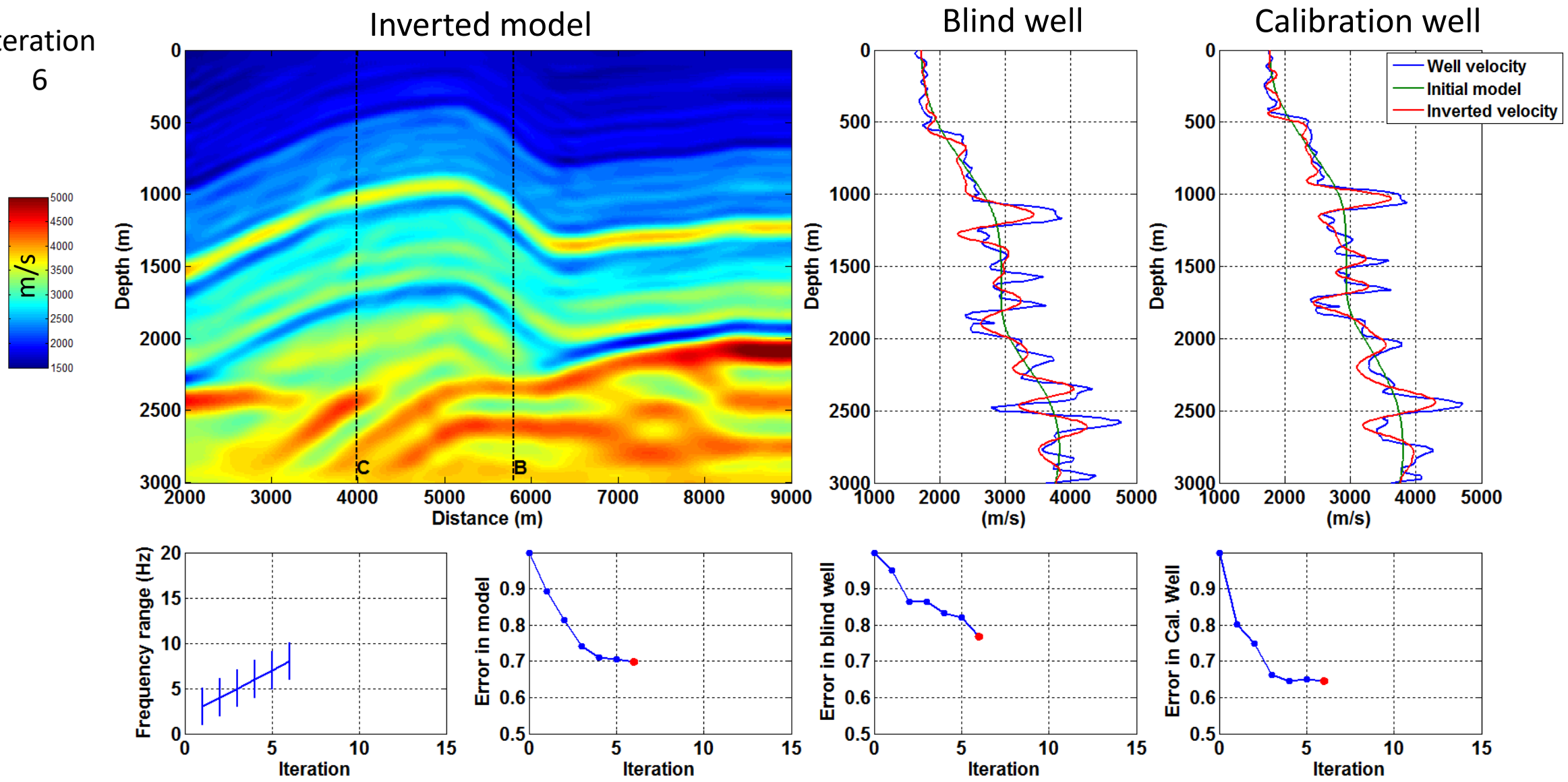






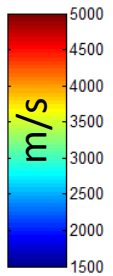
Evolution of the inverted model with more iterations

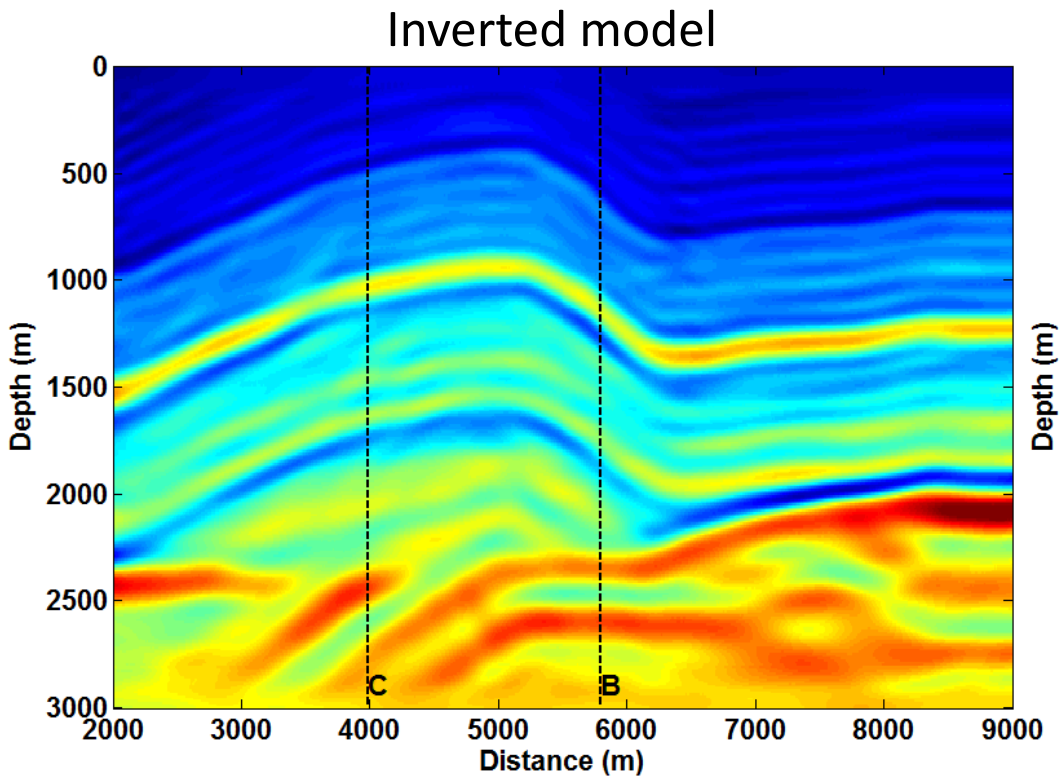
Iteration 6

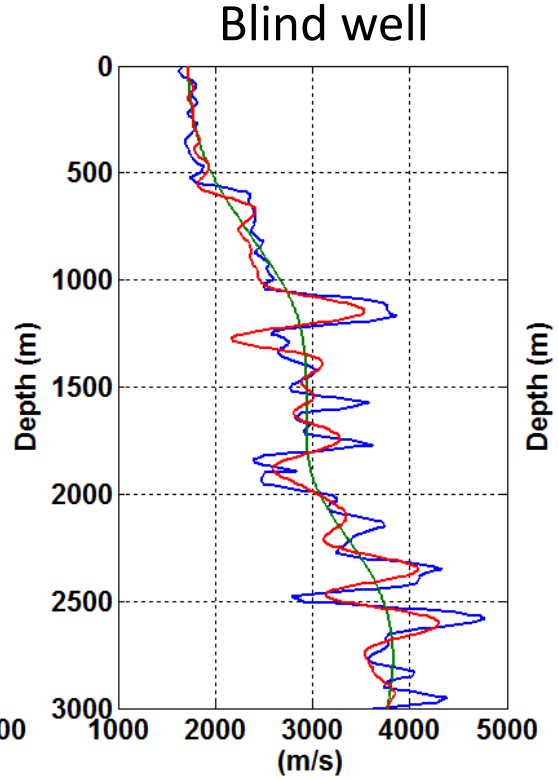


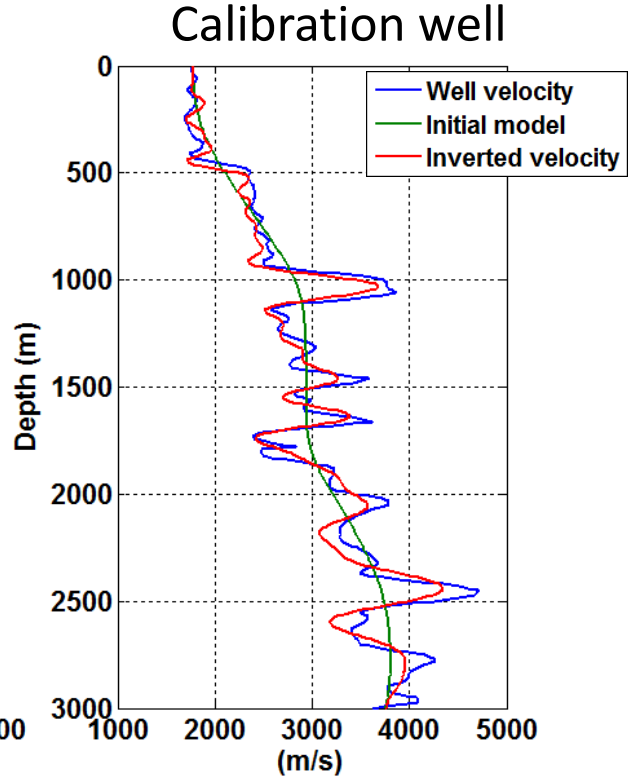
Evolution of the inverted model with more iterations

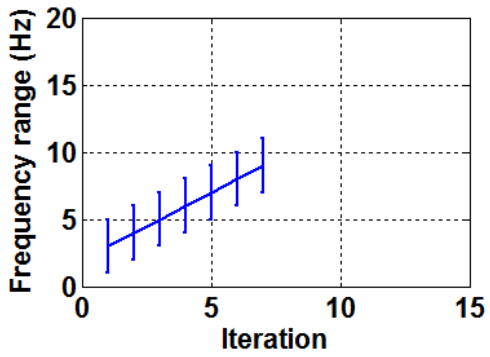
Iteration 7

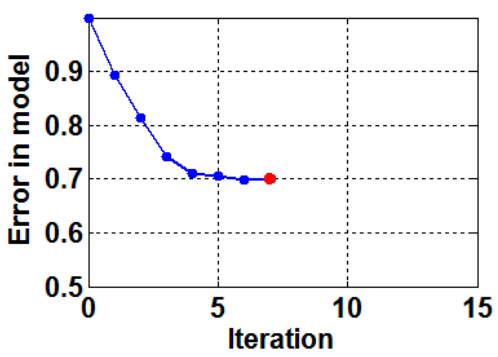


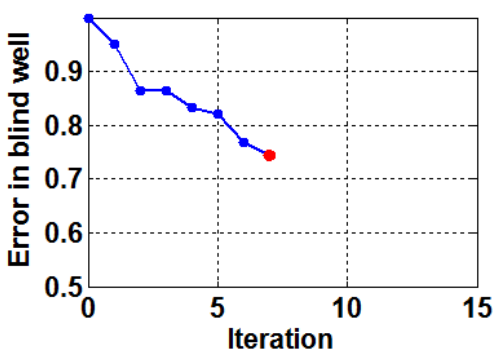


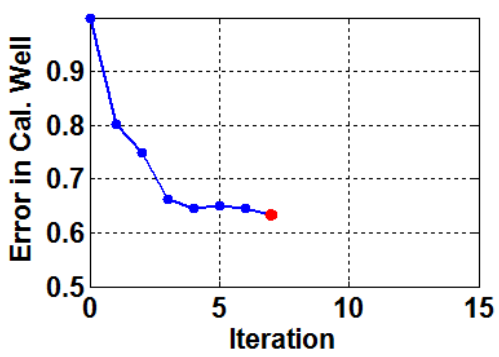






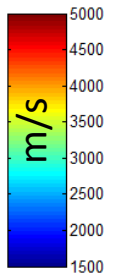


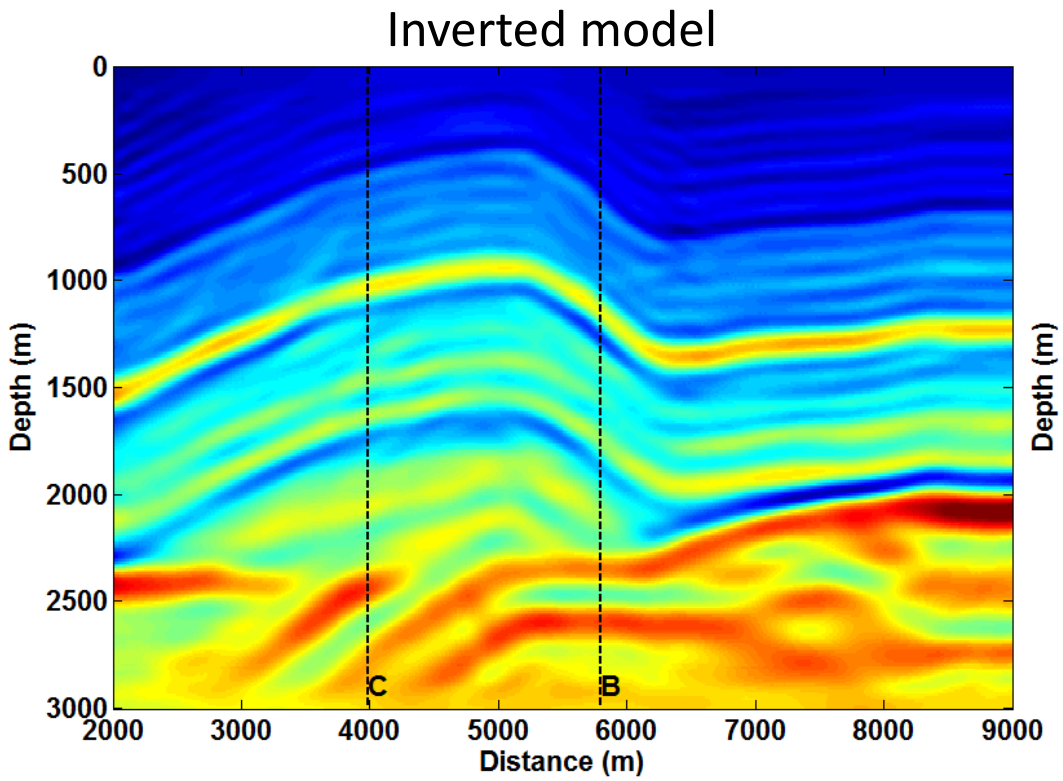


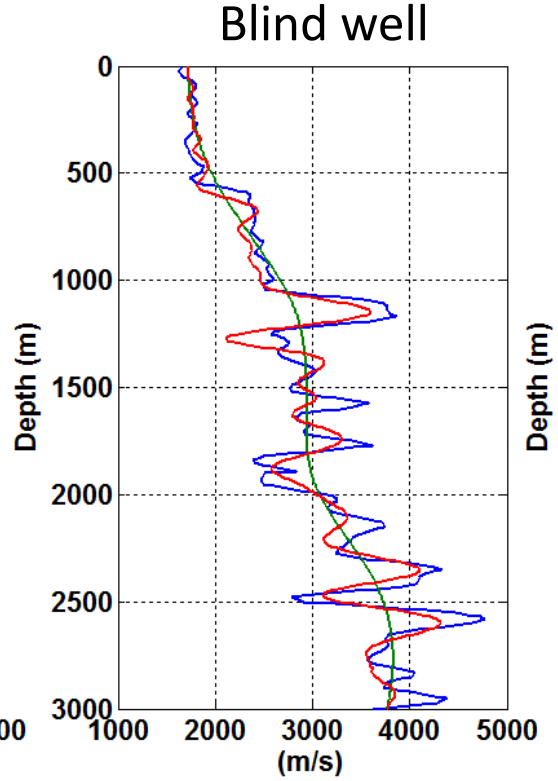


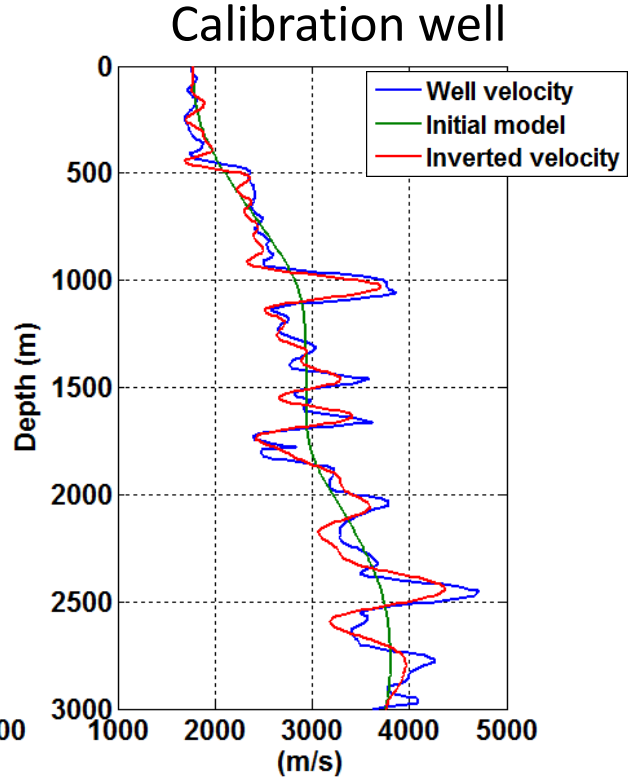
Evolution of the inverted model with more iterations

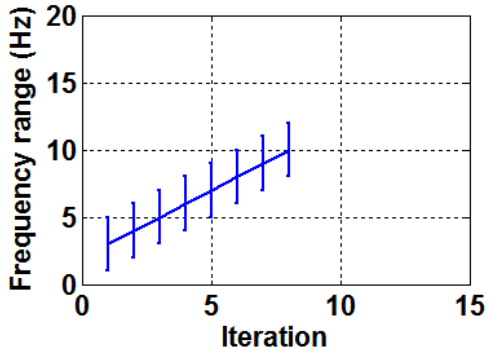
Iteration 8

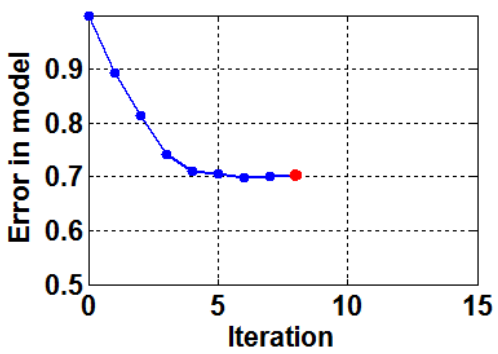


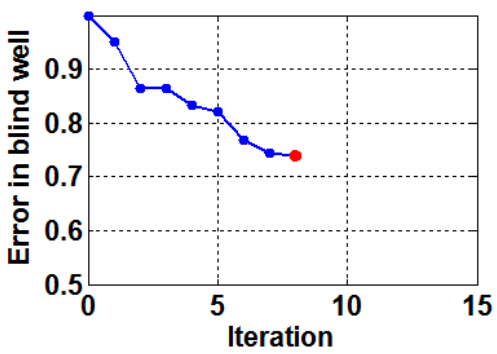


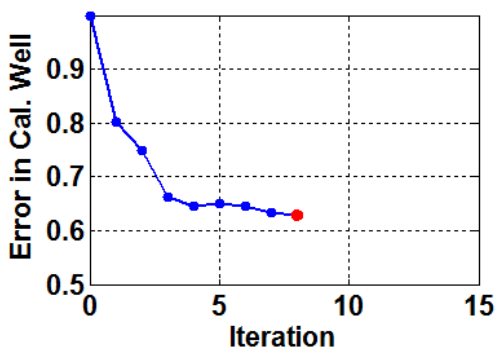






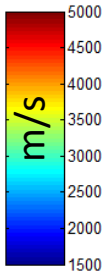


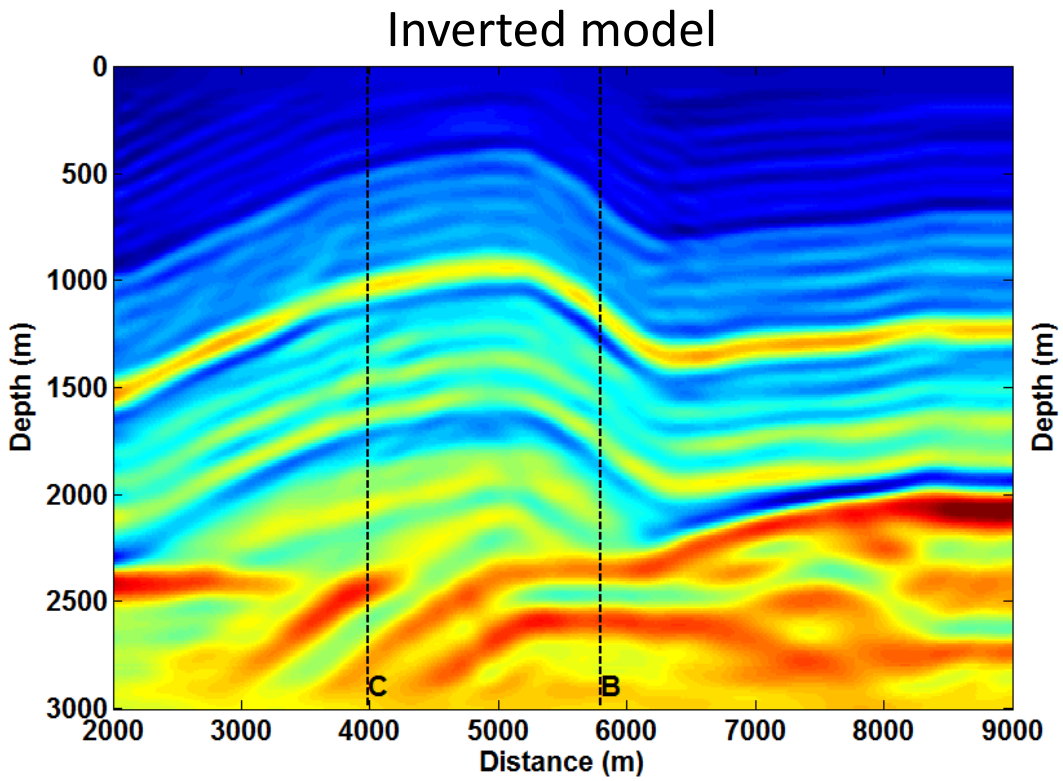


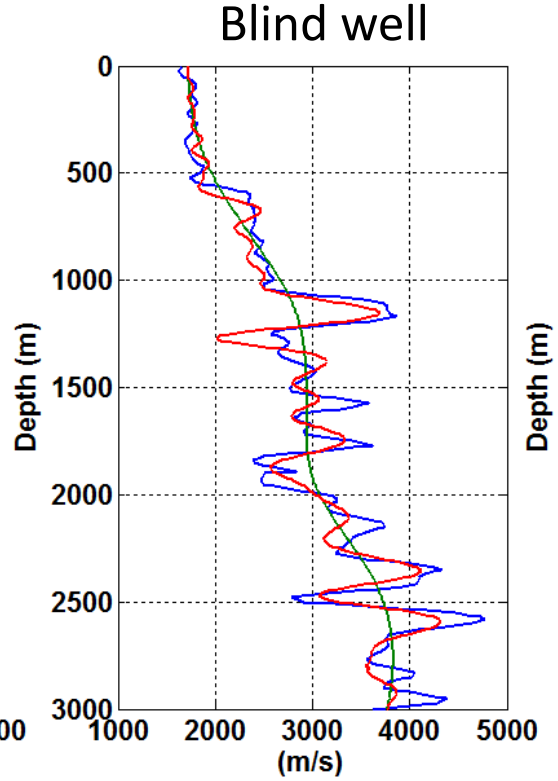


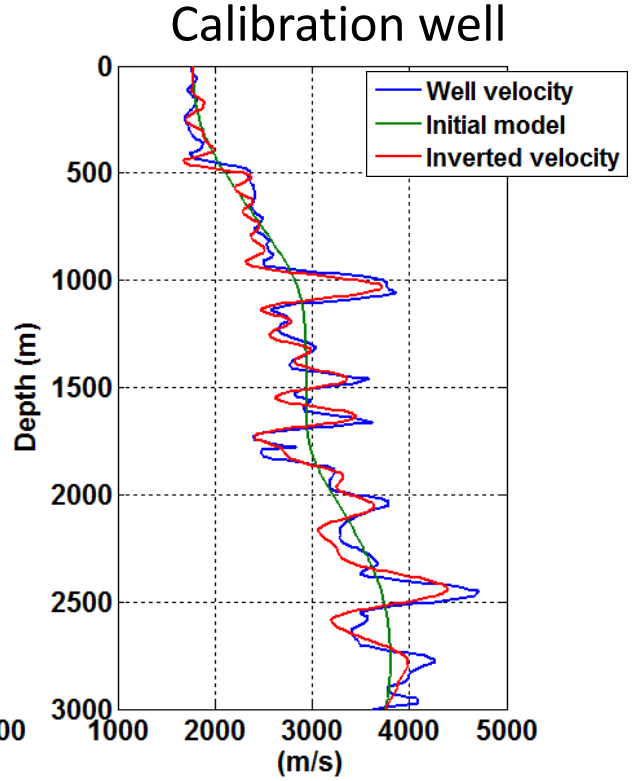
Evolution of the inverted model with more iterations

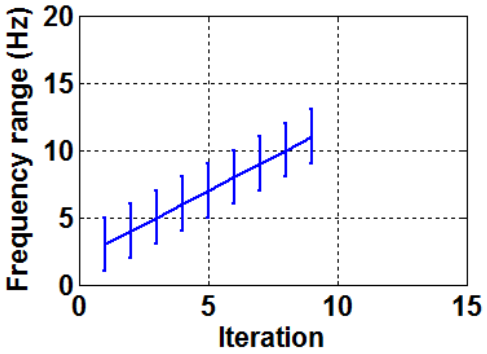
Iteration 9

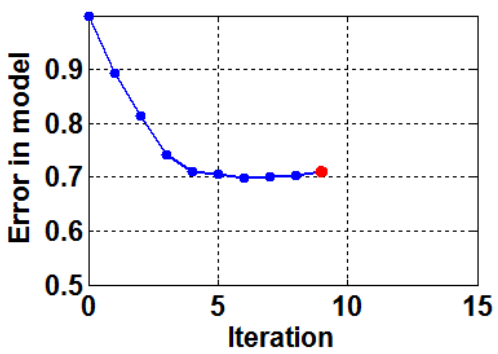


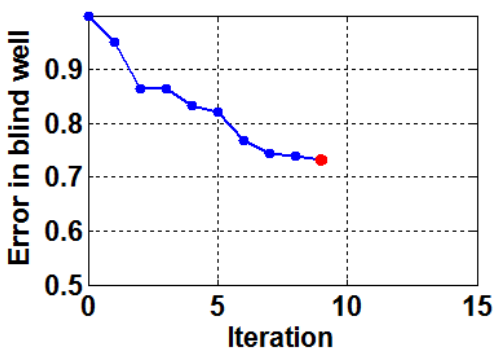


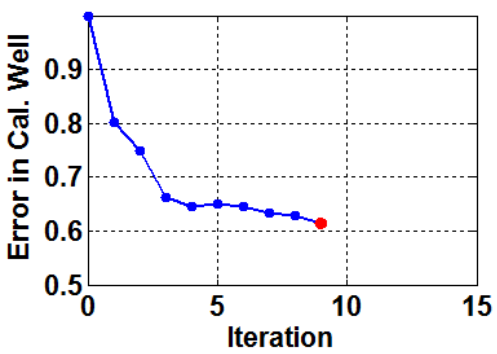






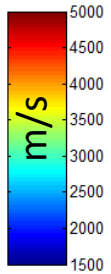


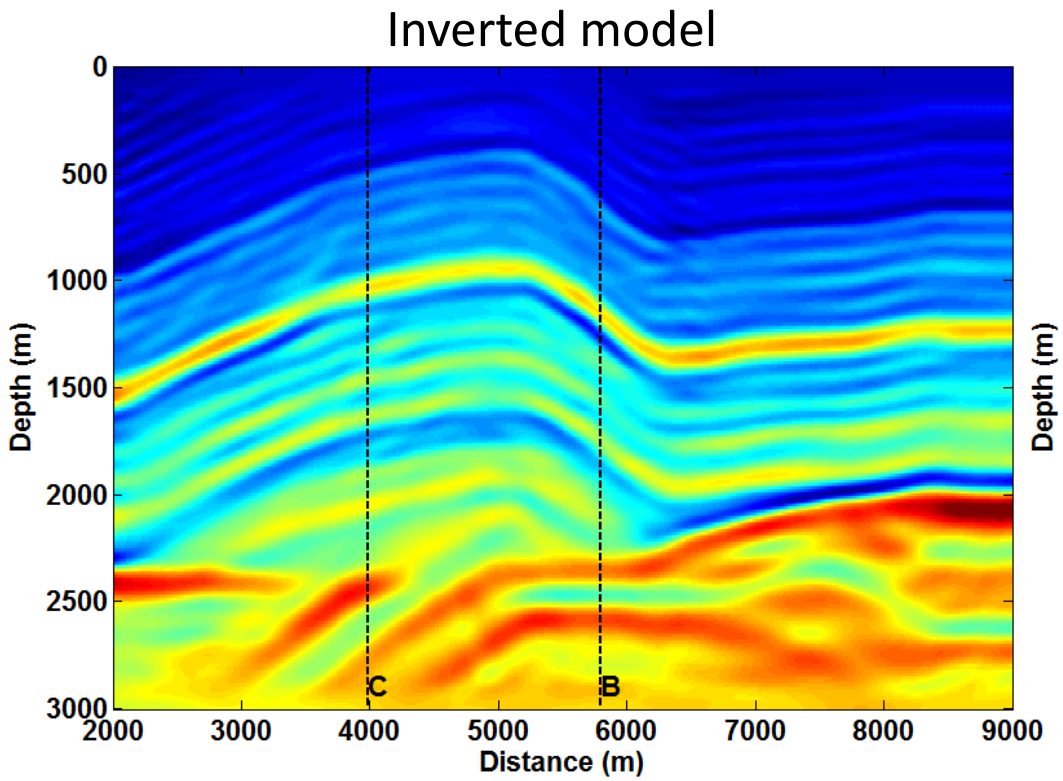


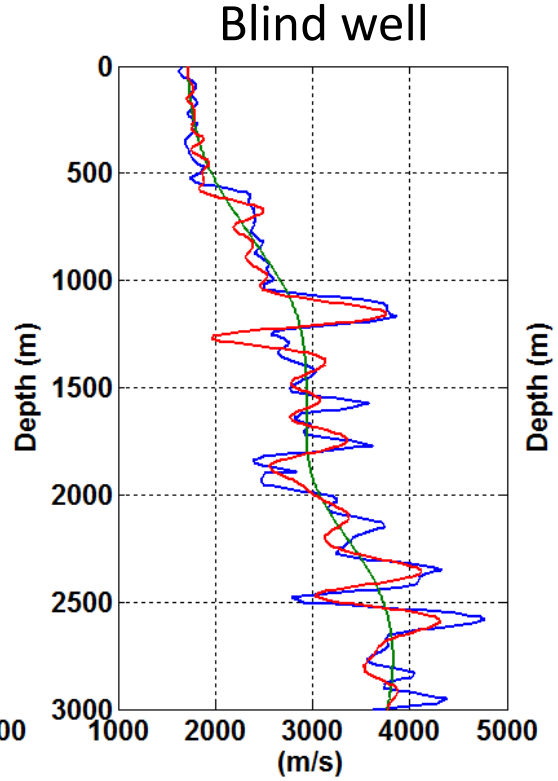


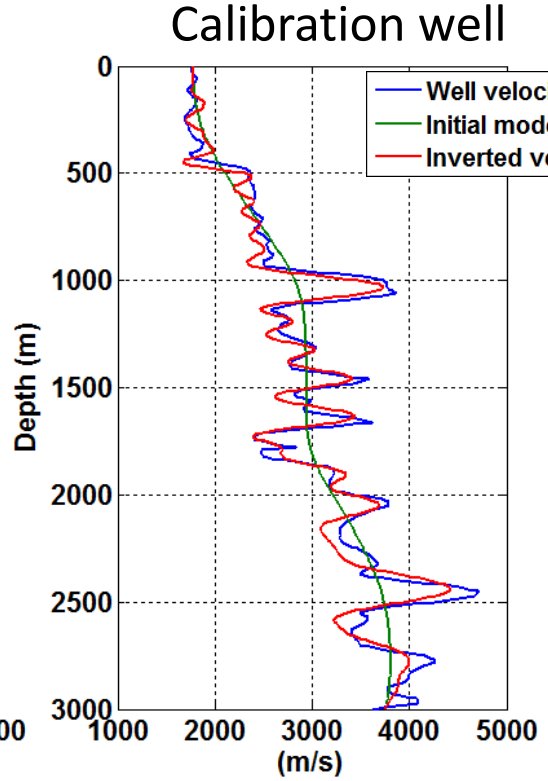
Evolution of the inverted model with more iterations

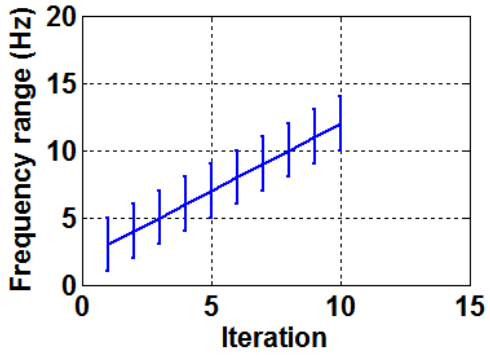
Iteration 10

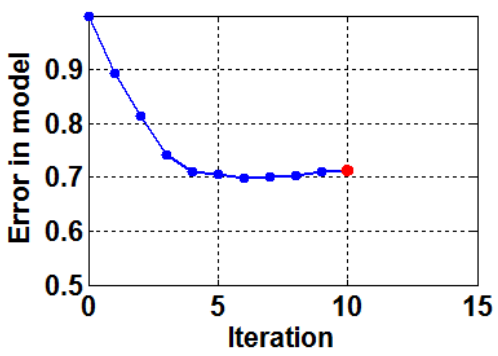


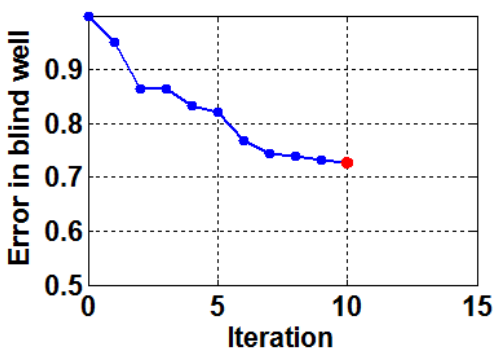


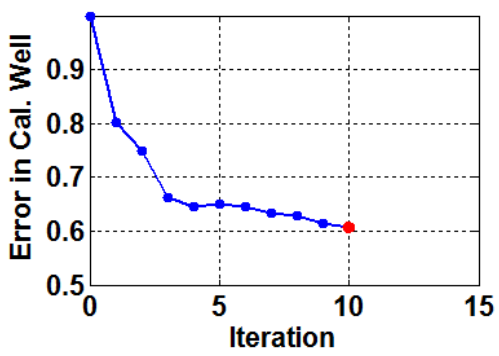






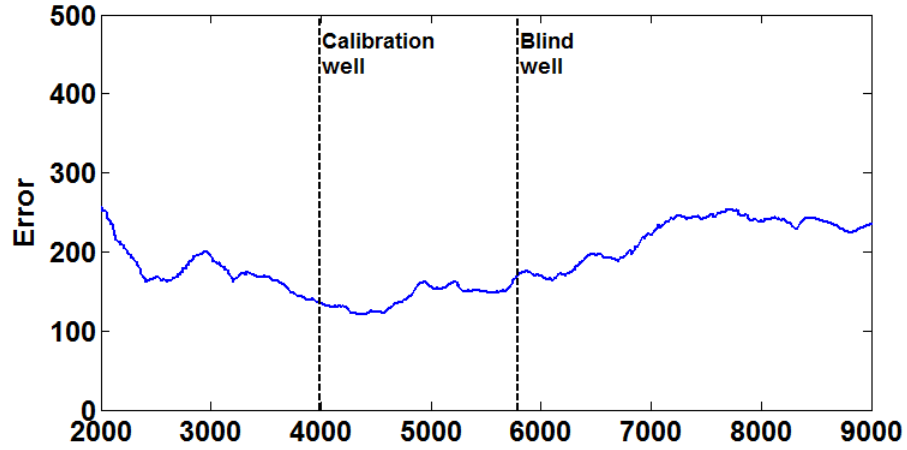




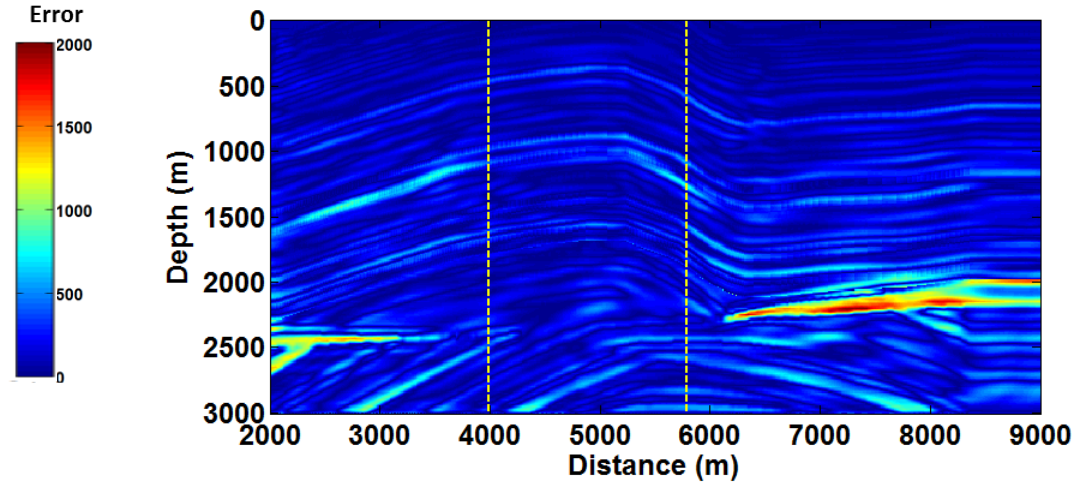


Spatial distribution of the error

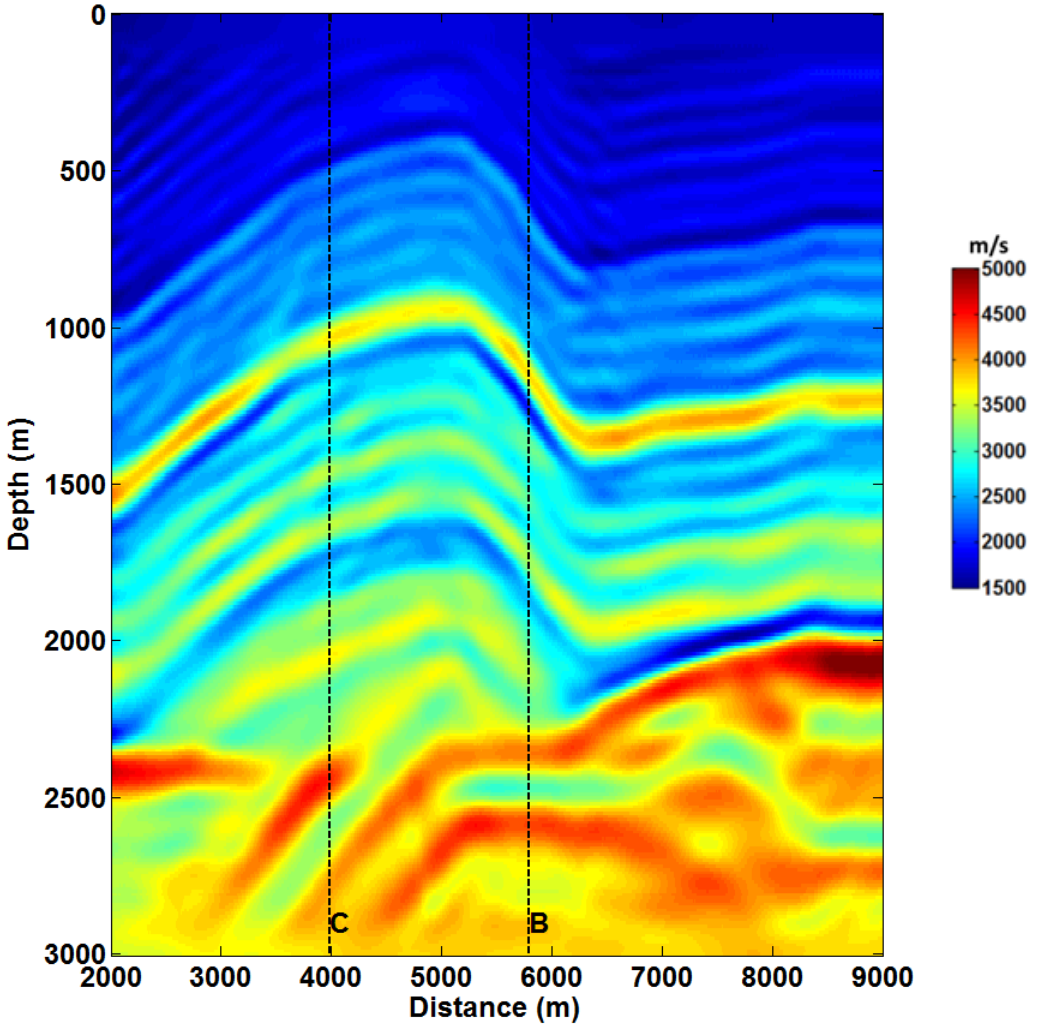
Horizontal distribution of the error



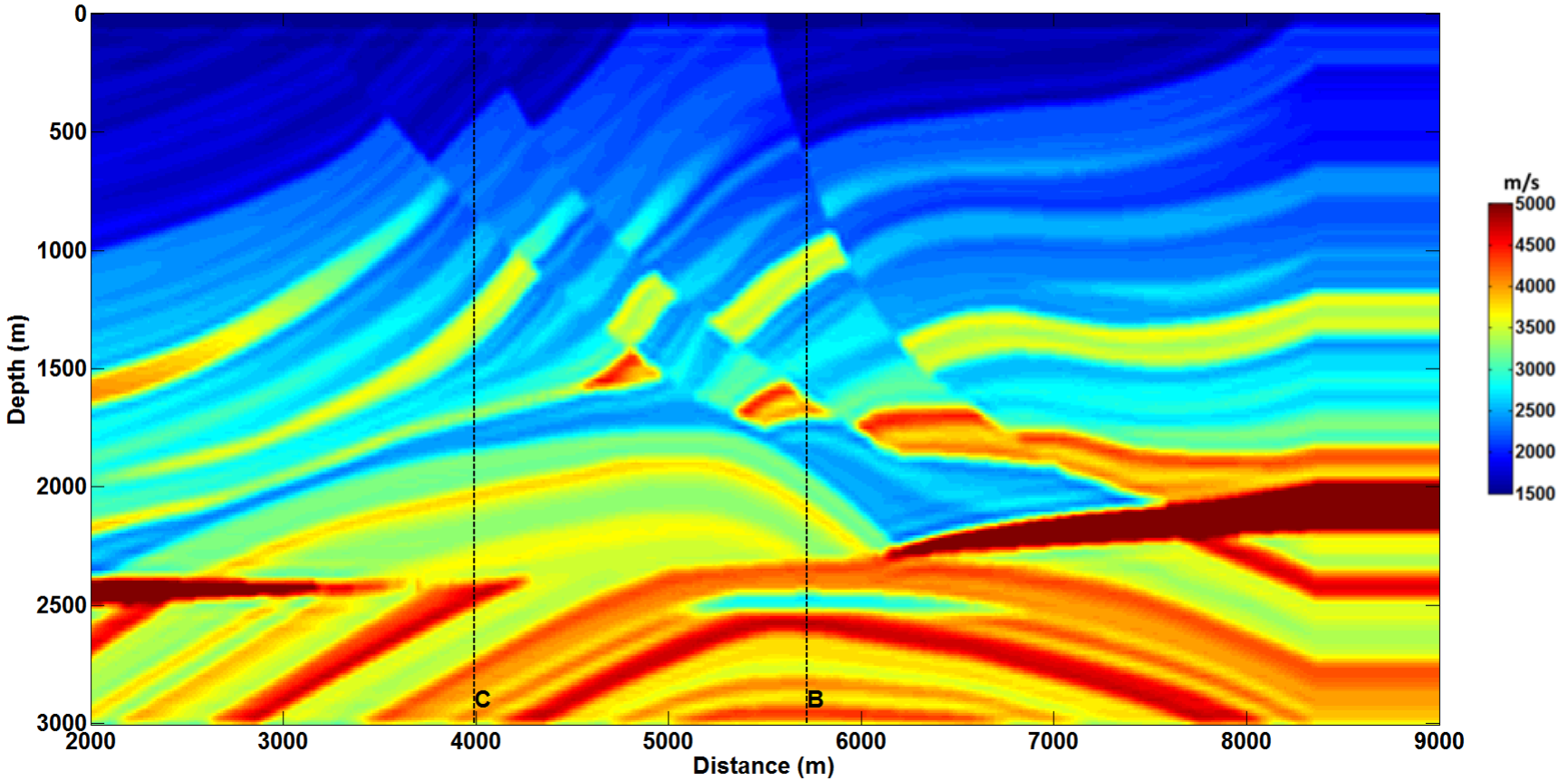
Spatial distribution of the error



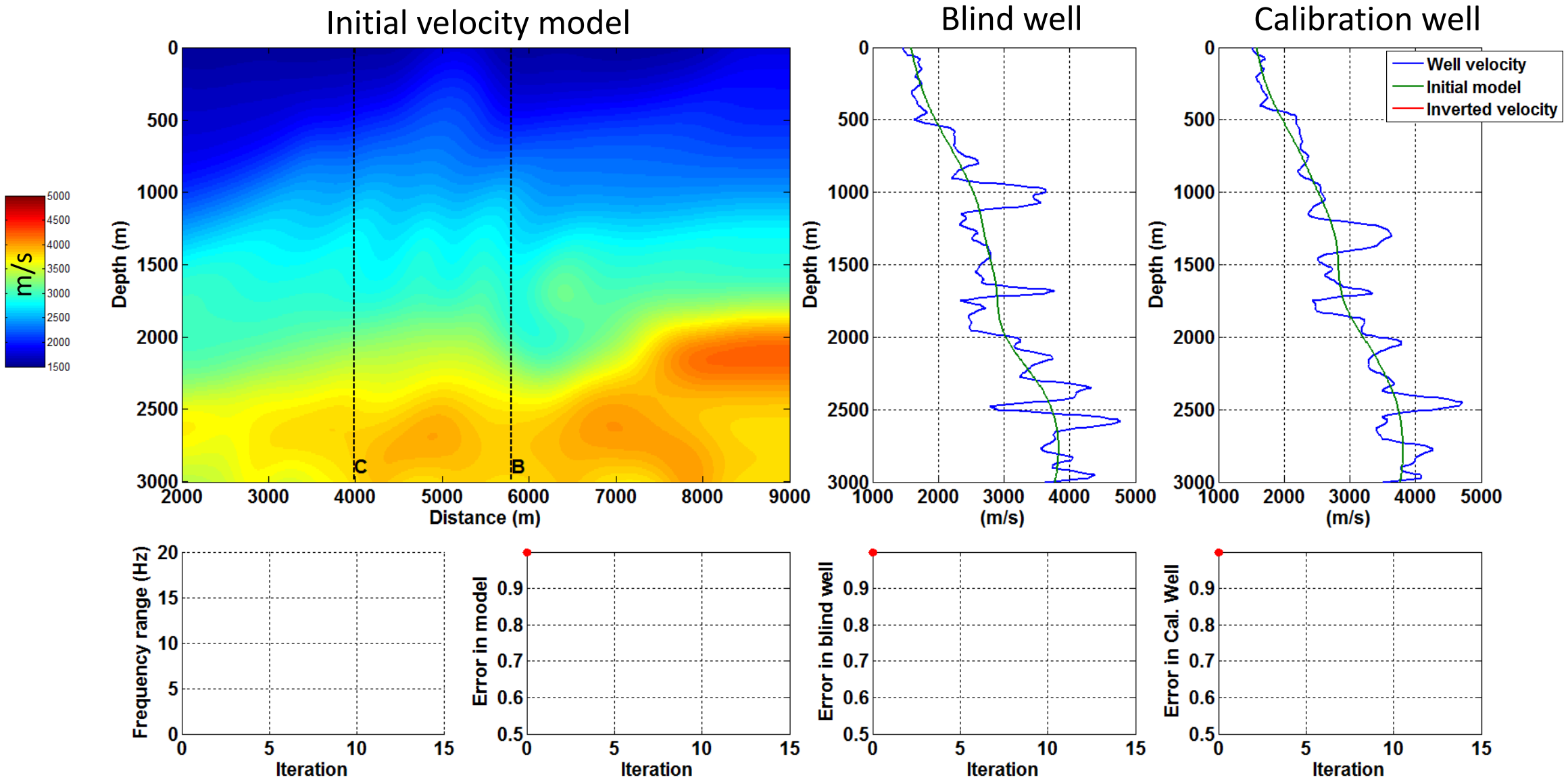
Inverted velocity model



Model 3

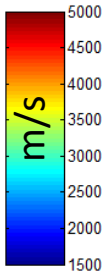

Depth (m)
0
500
1000
1500
2000
2500
3000
2000
3000
4000
5000
6000
7000
8000
9000
Distance (m)
C
B
m/s
5000
4500
4000
3500
3000
2500
2000
1500

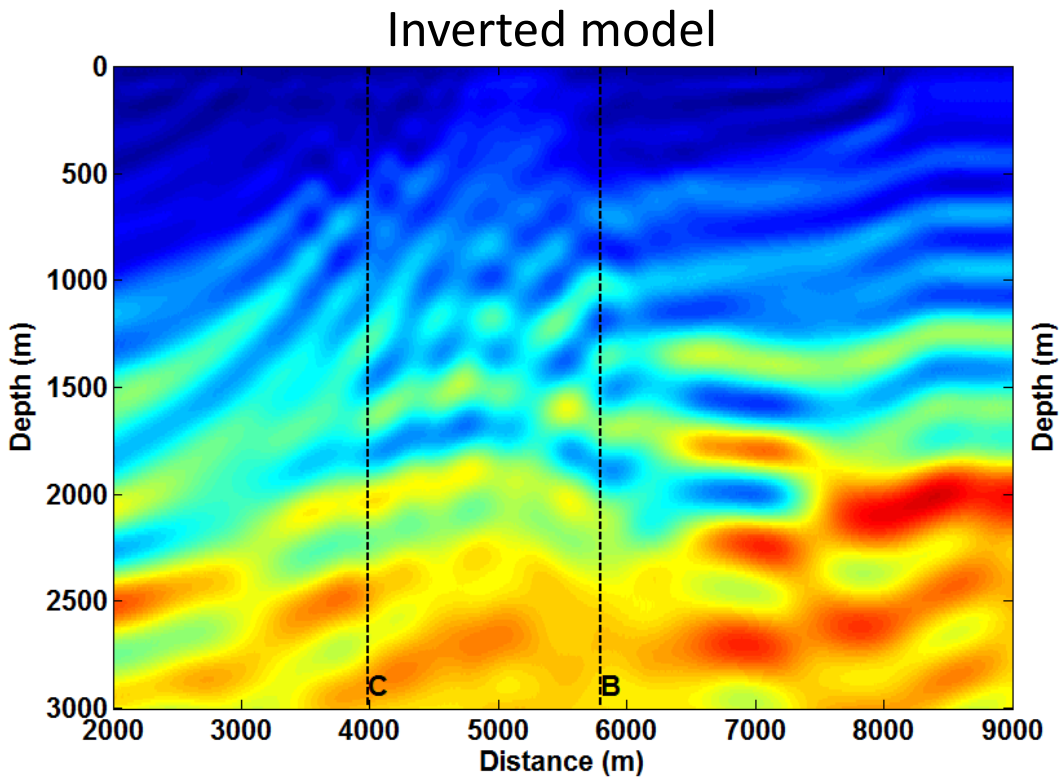
Evolution of the inverted model with more iterations

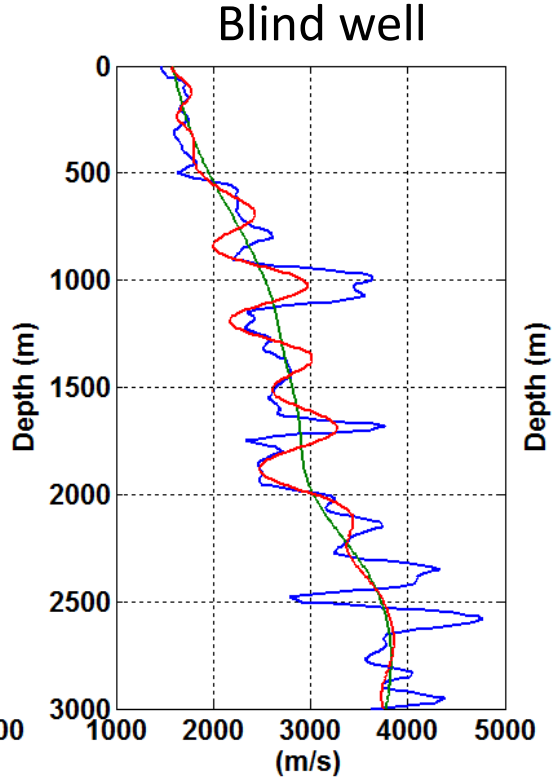


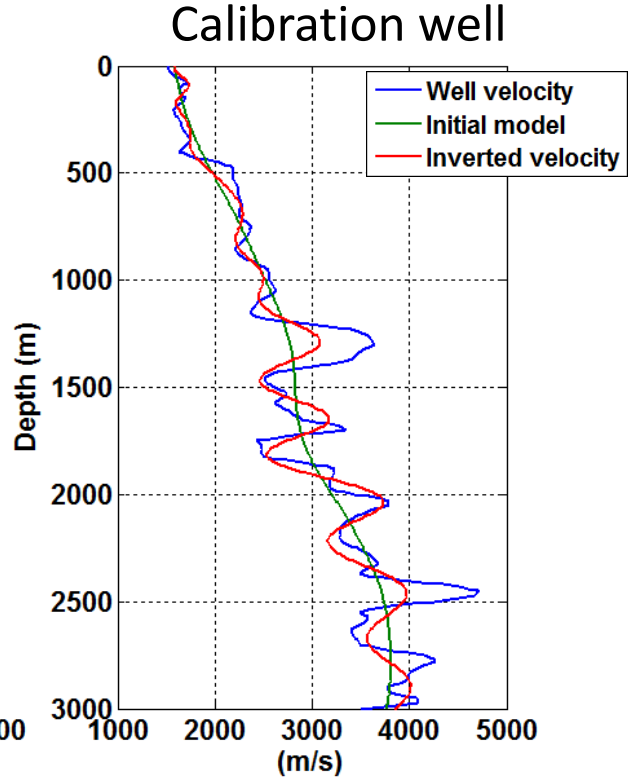
Evolution of the inverted model with more iterations

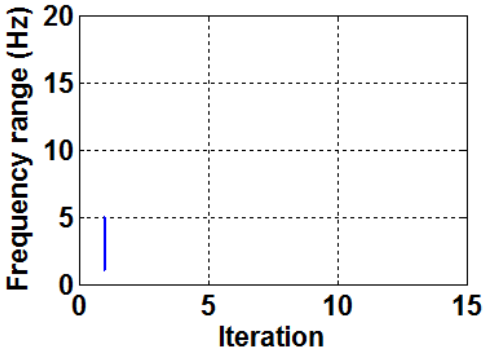
Iteration 1

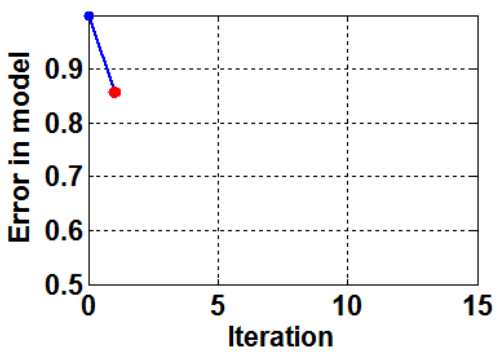


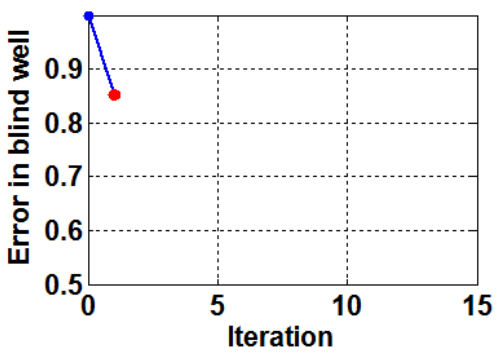


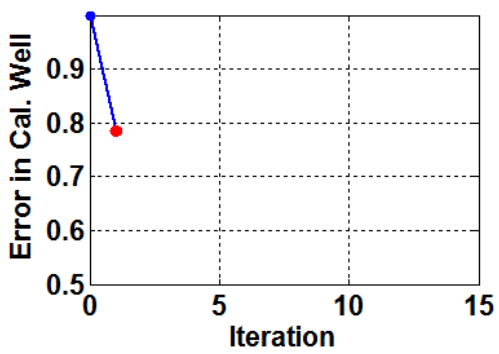






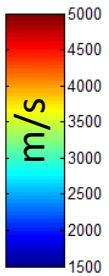


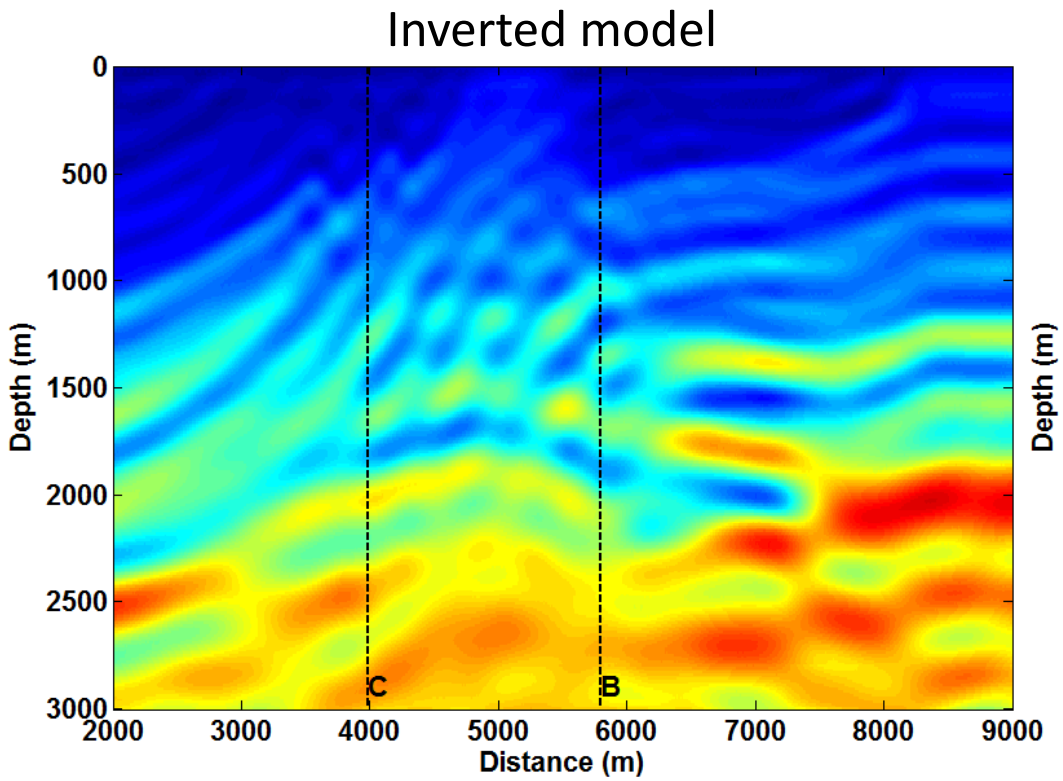


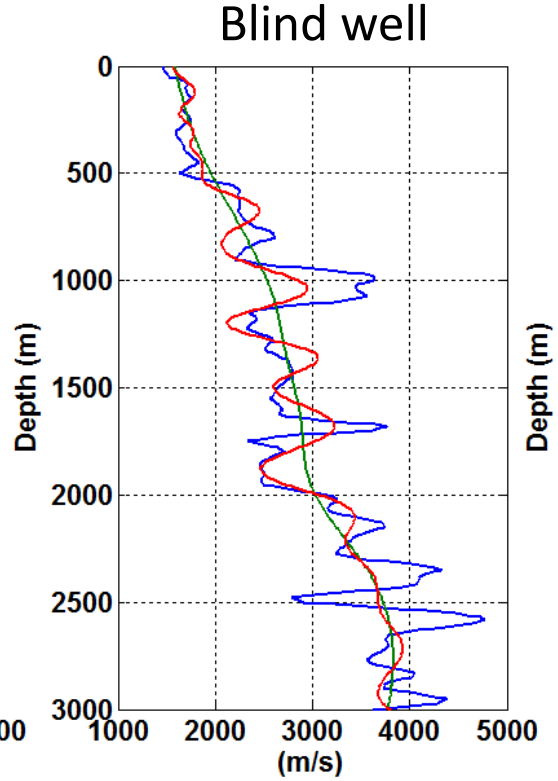


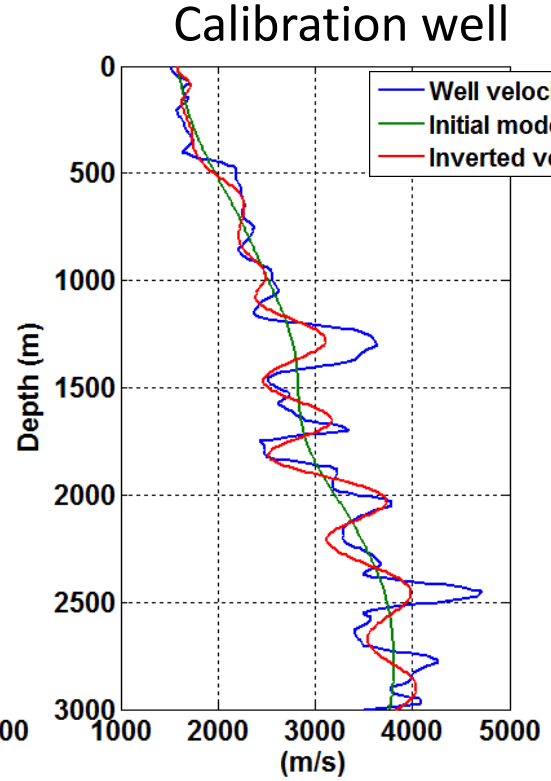
Evolution of the inverted model with more iterations

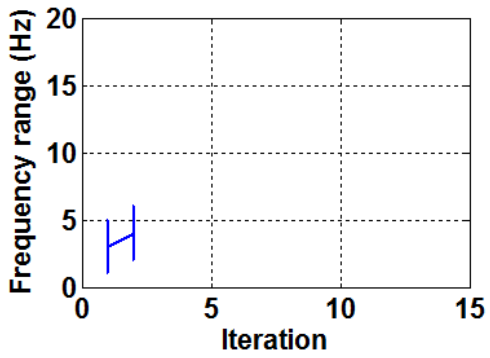
Iteration 2

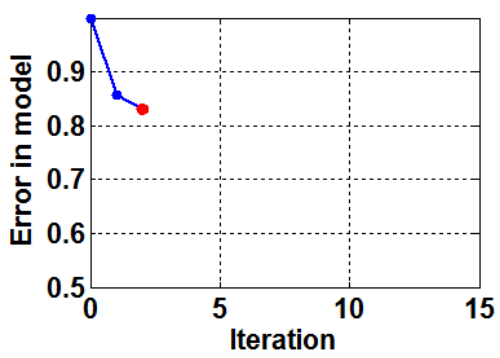


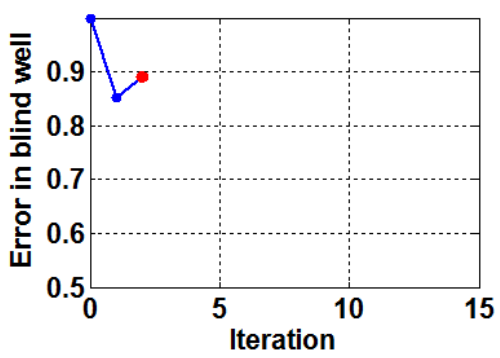


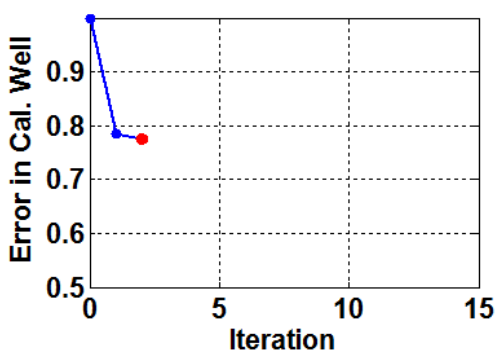






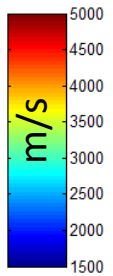


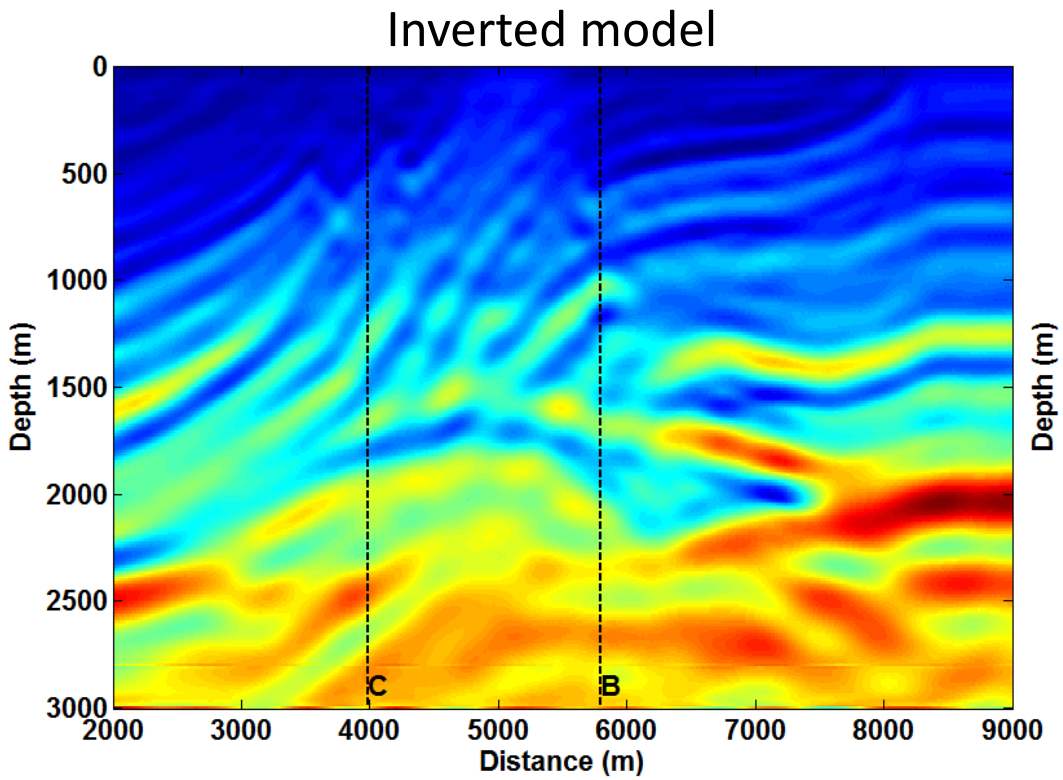


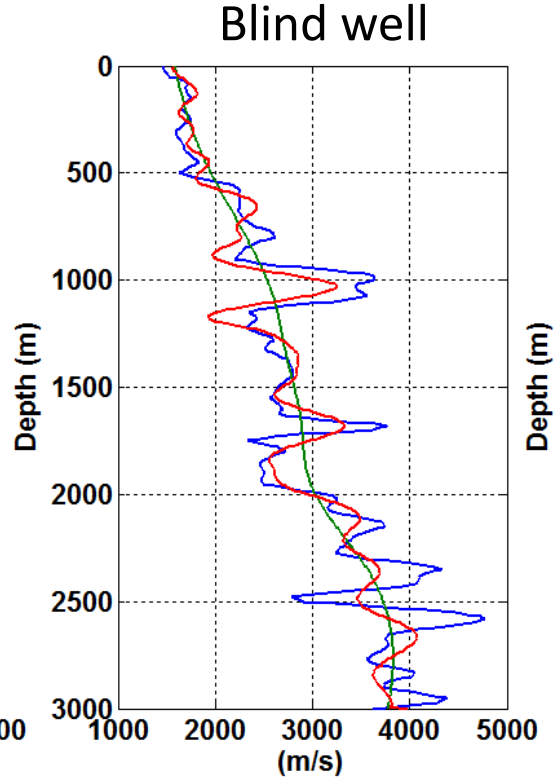


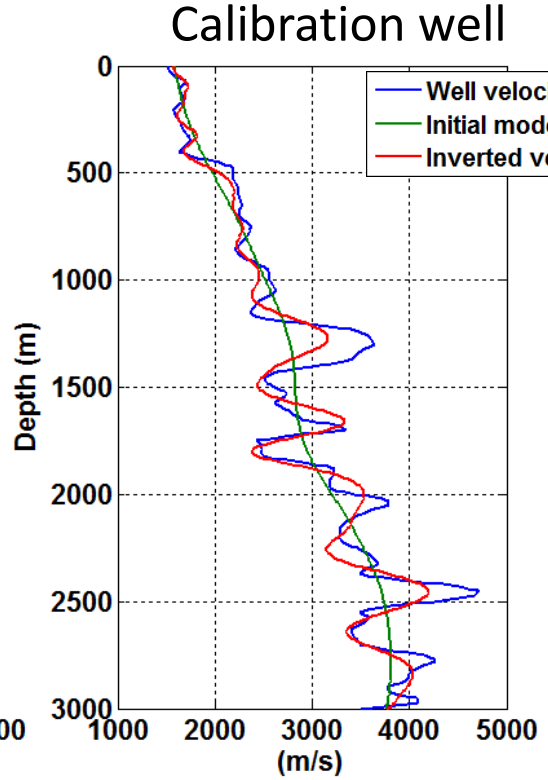
Evolution of the inverted model with more iterations

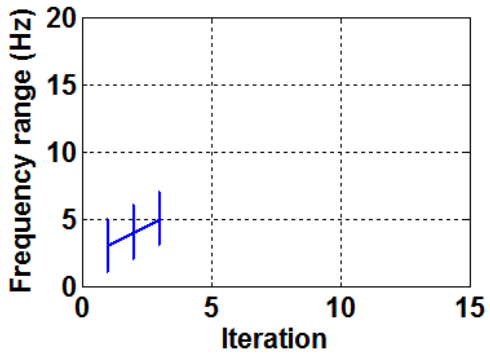
Iteration 3

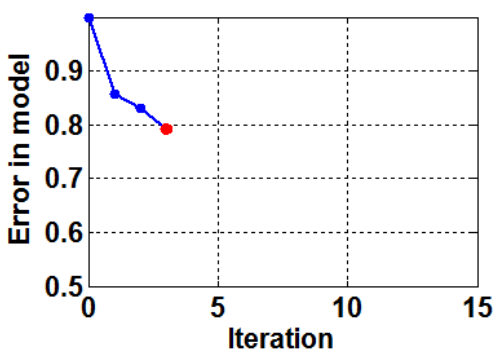


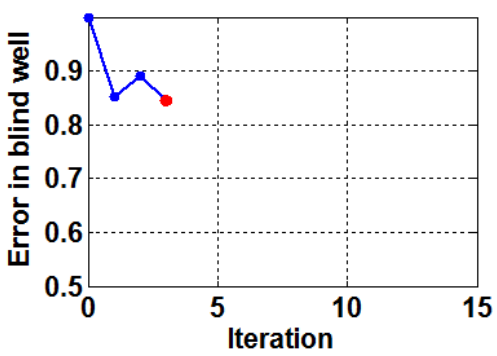


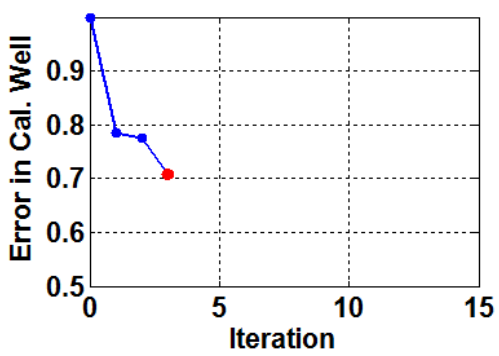






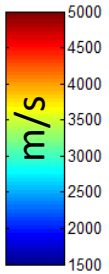


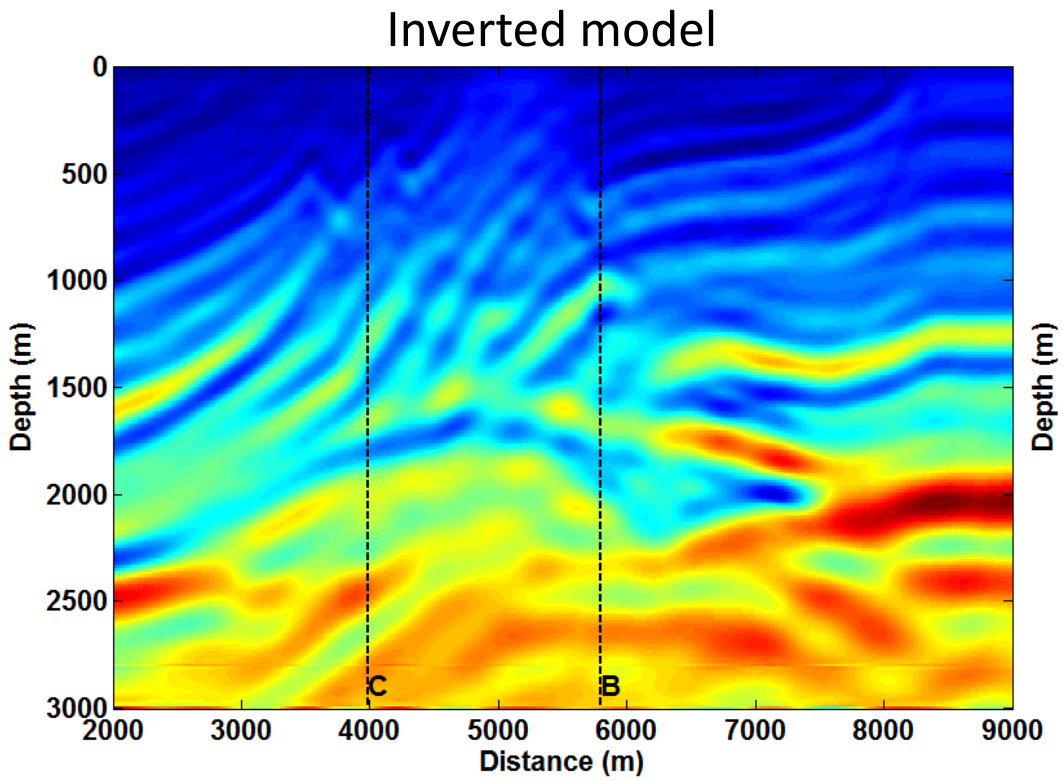


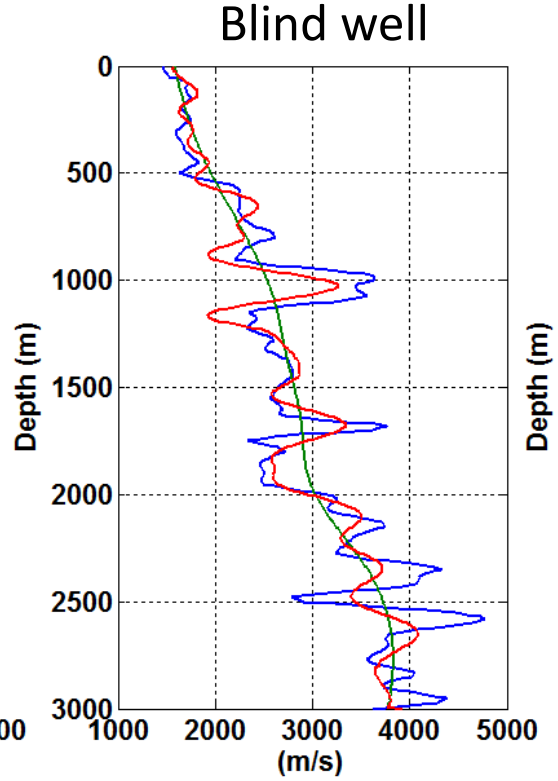


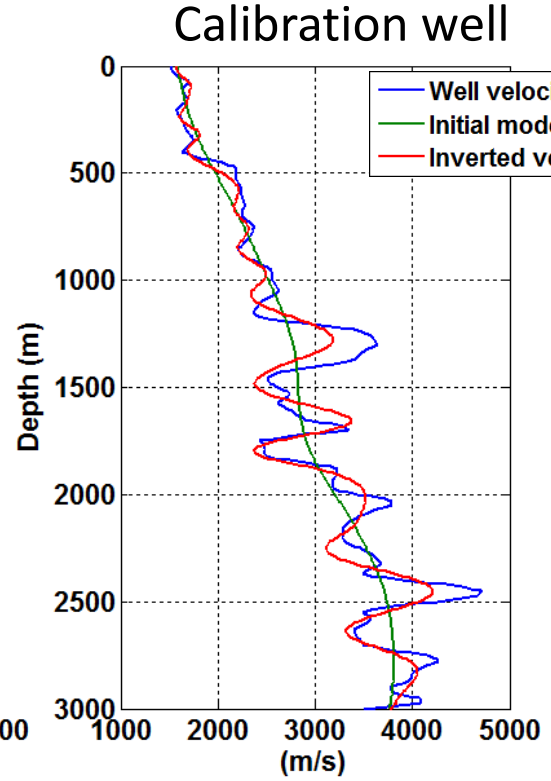
Evolution of the inverted model with more iterations

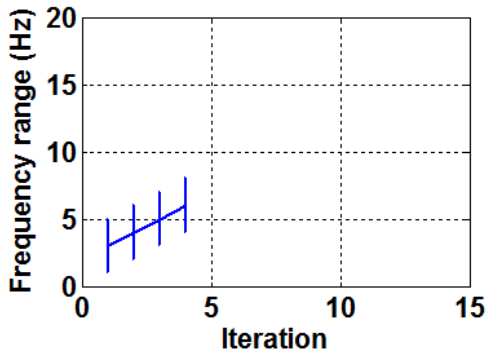
Iteration 4

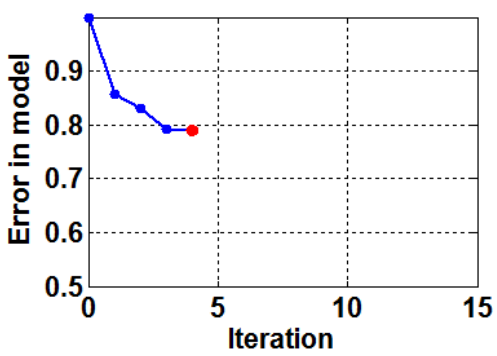


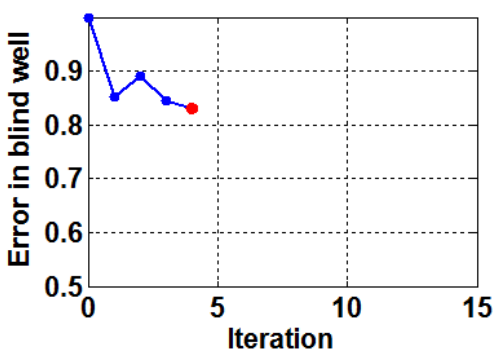


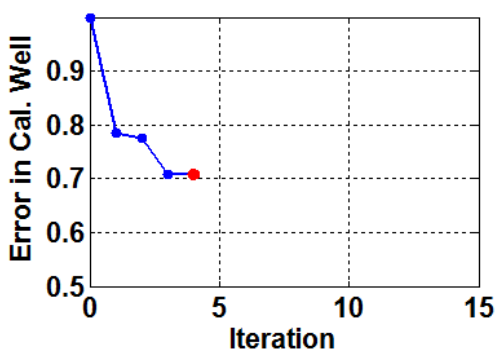






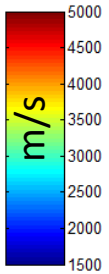


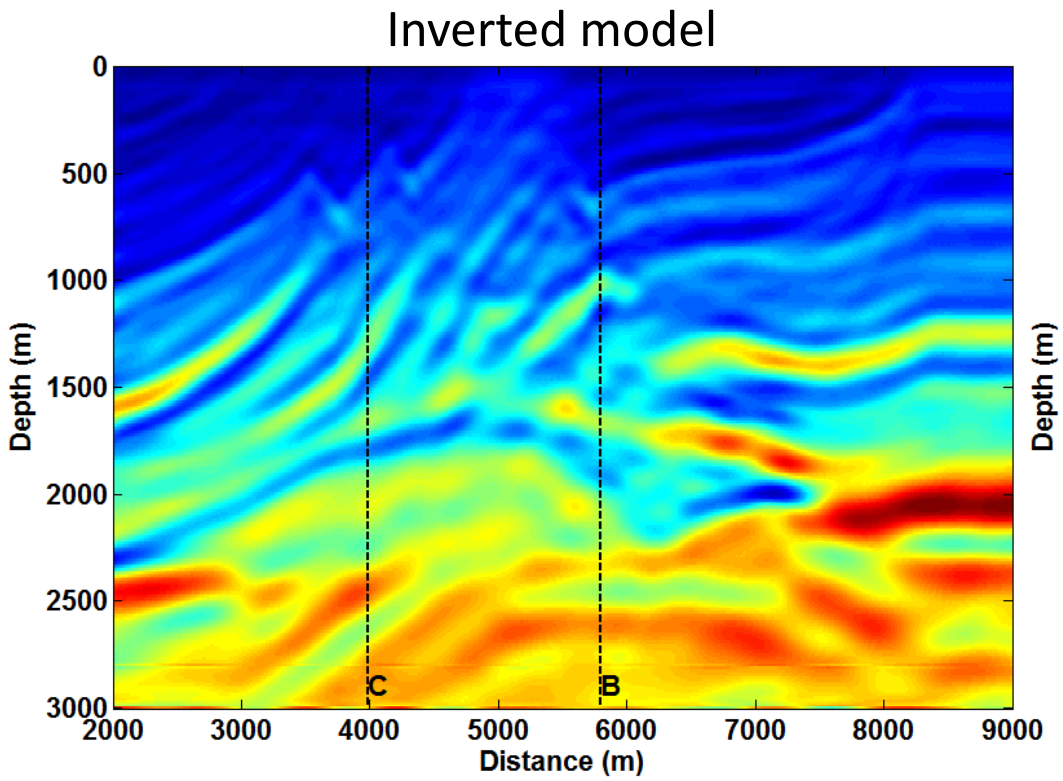


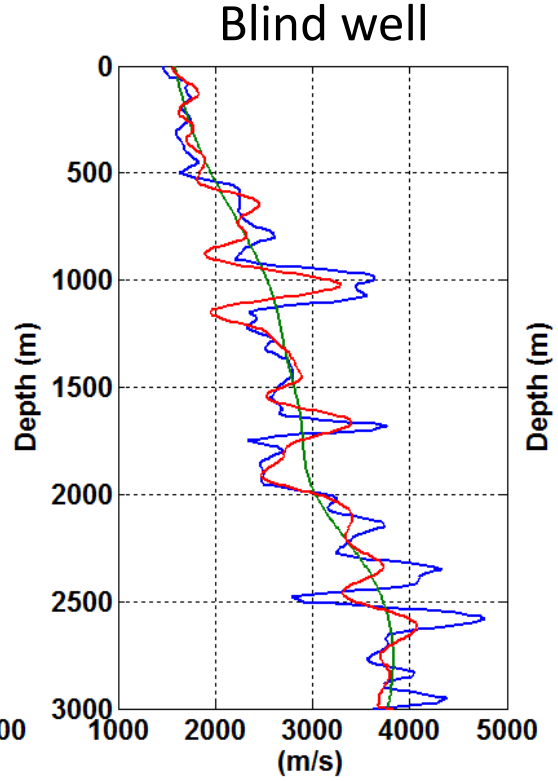


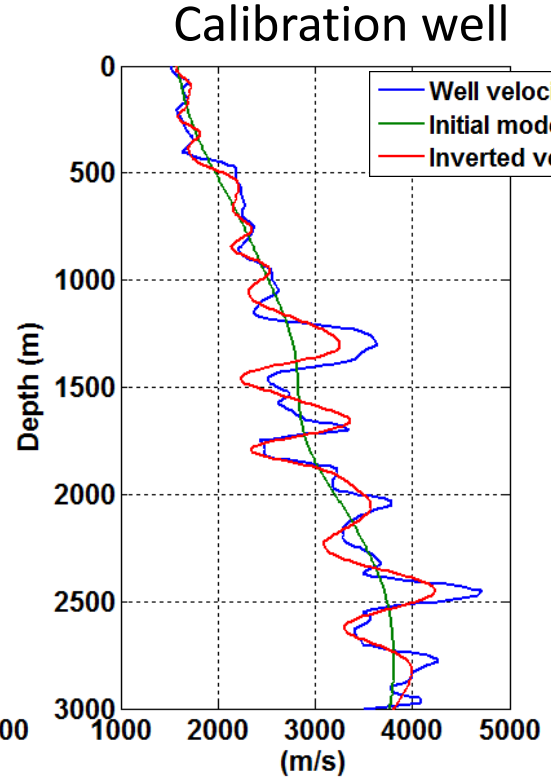
Evolution of the inverted model with more iterations

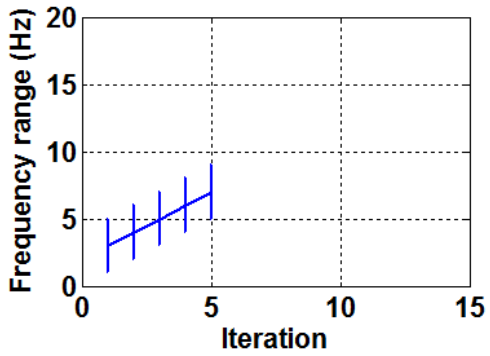
Iteration 5

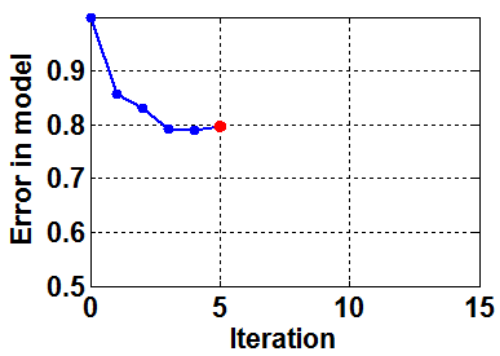


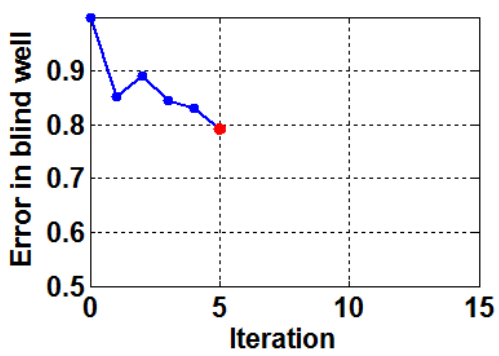


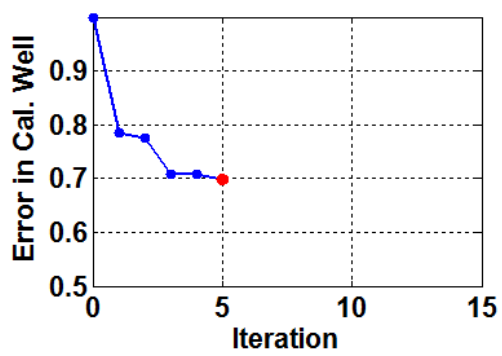






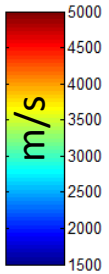


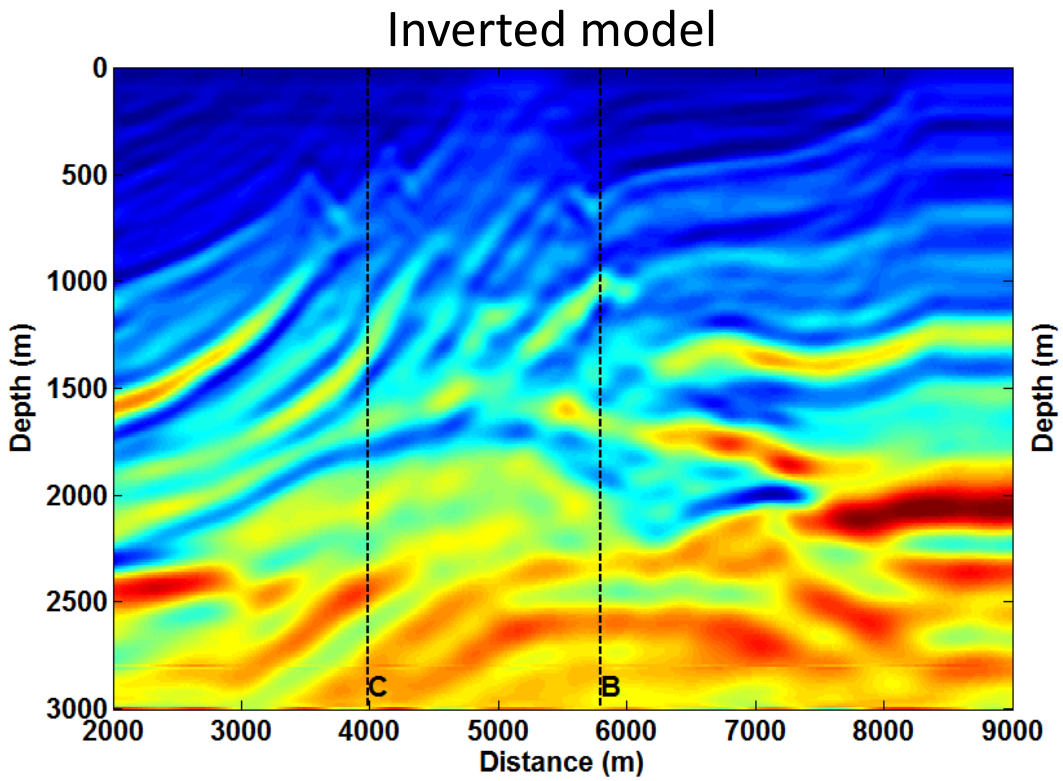


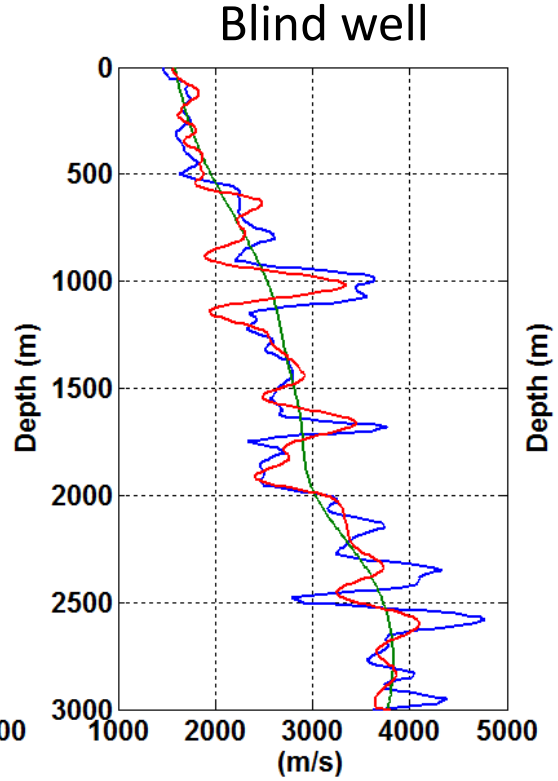


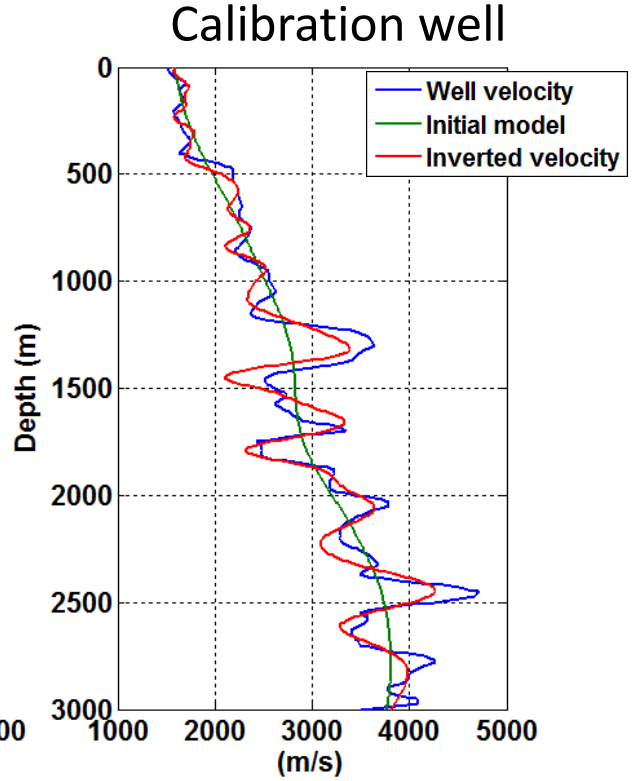
Evolution of the inverted model with more iterations

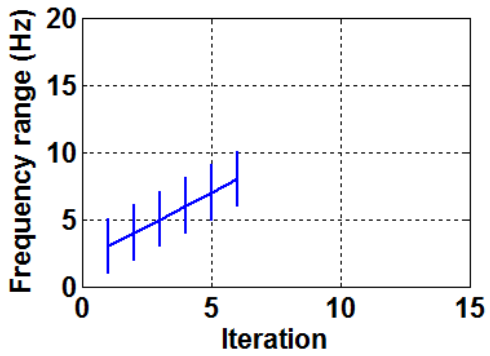
Iteration 6

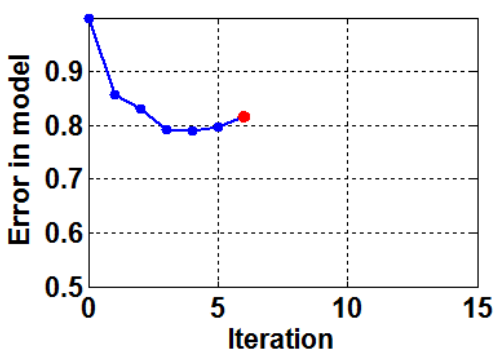


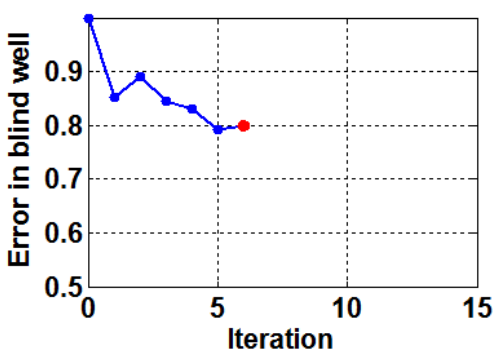


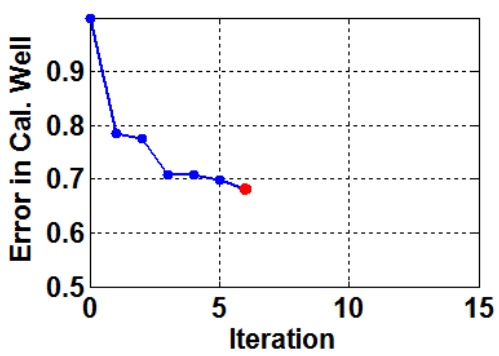






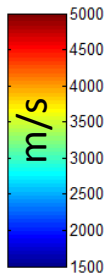


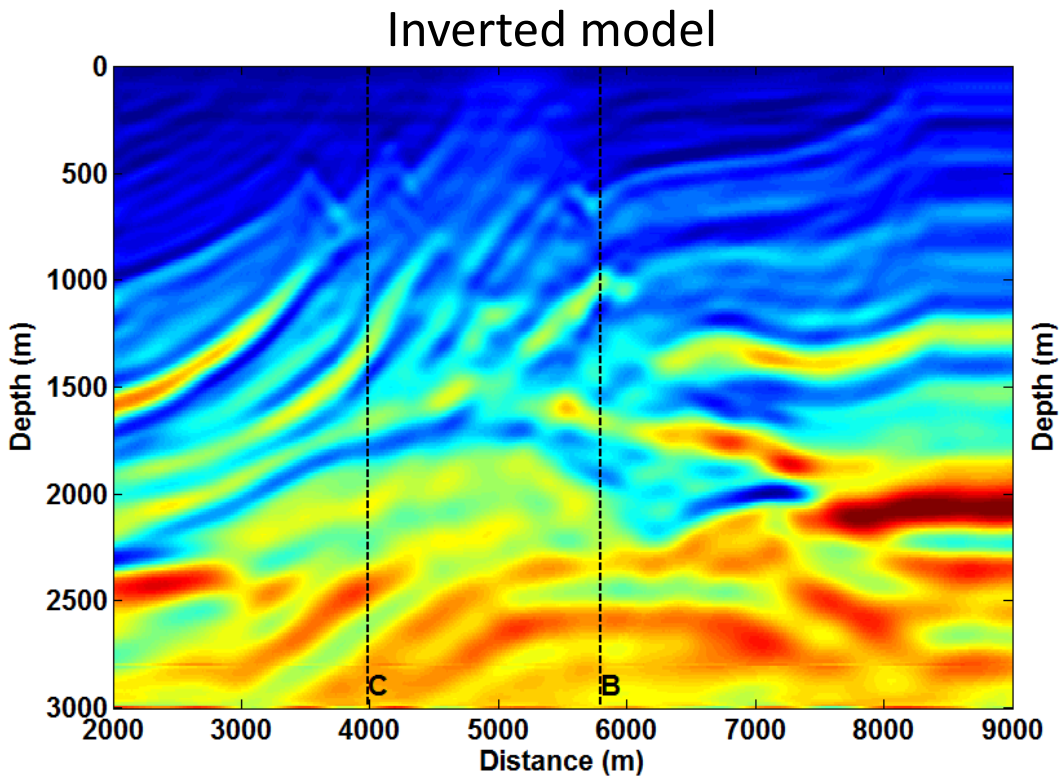


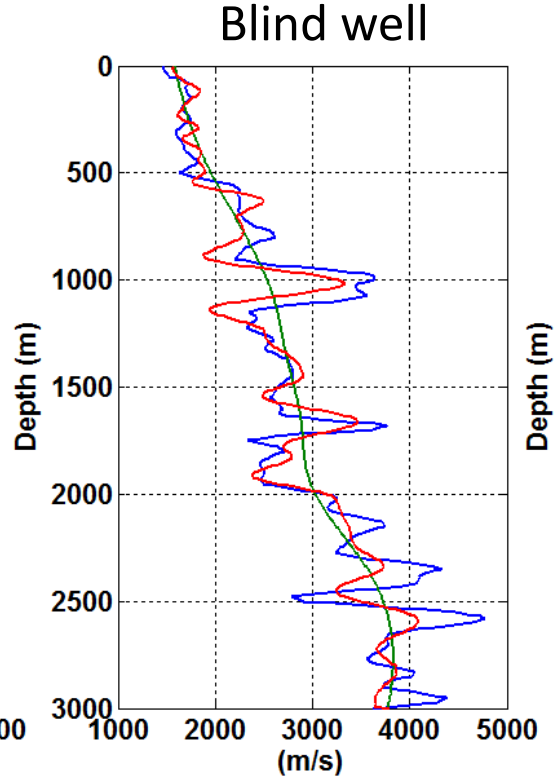


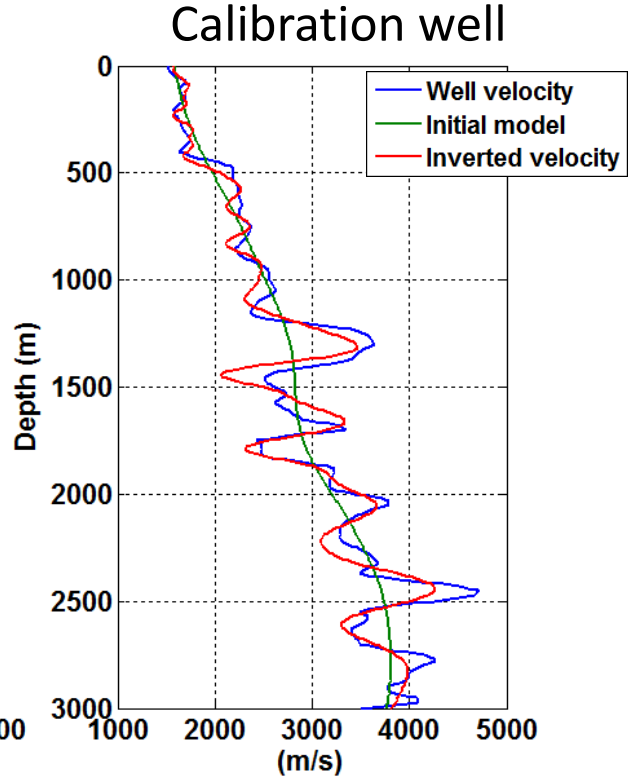
Evolution of the inverted model with more iterations

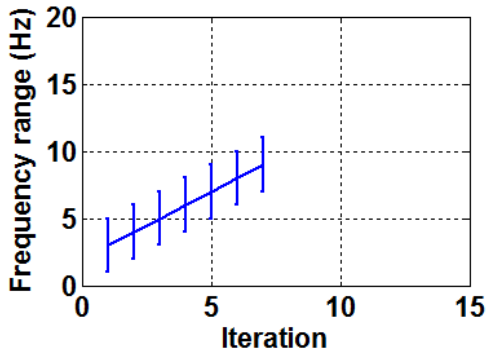
Iteration 7

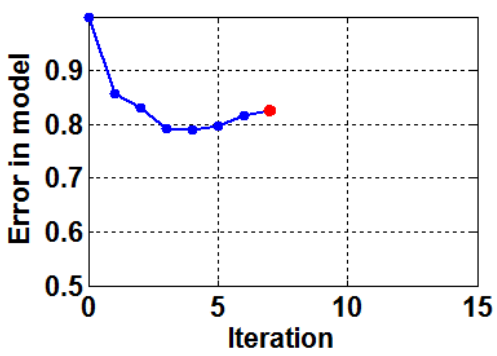


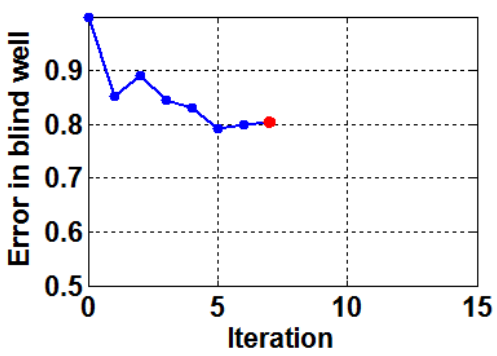


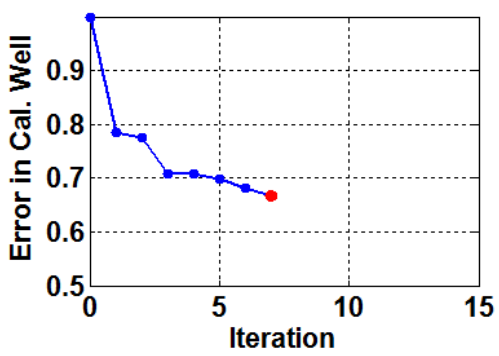






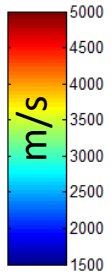


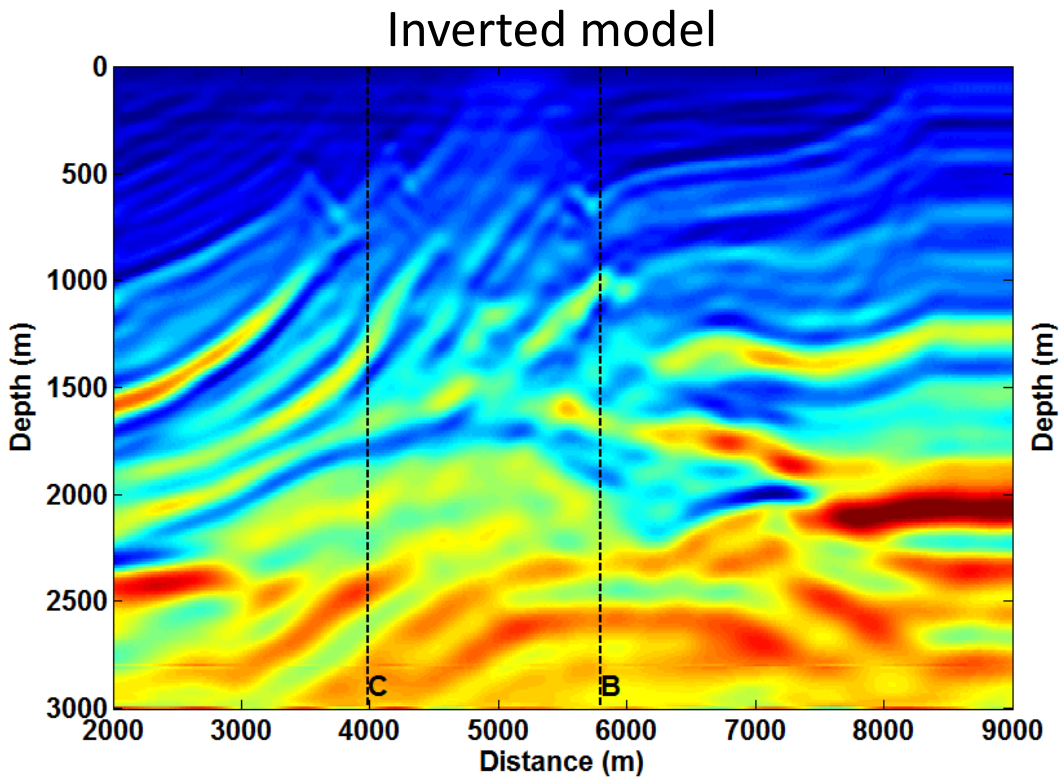


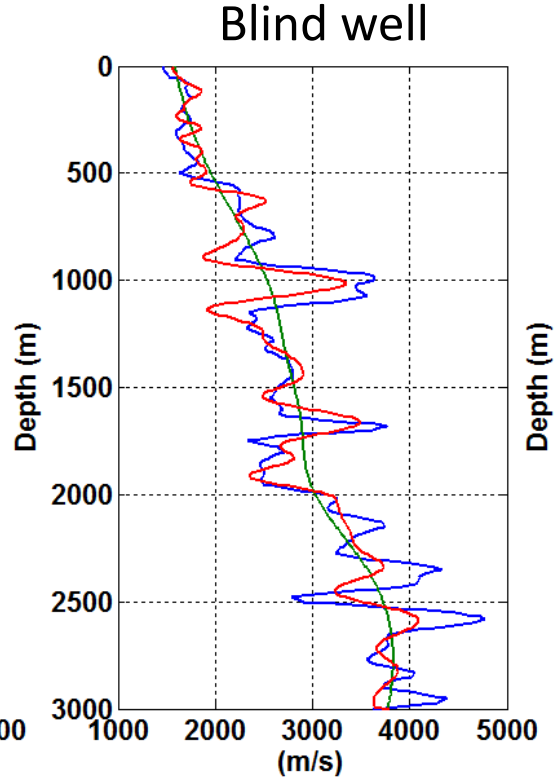


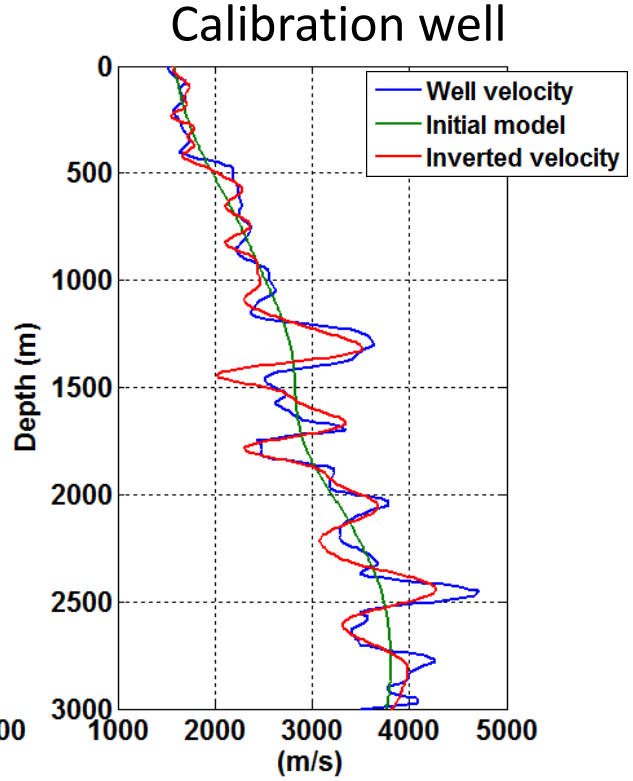
Evolution of the inverted model with more iterations

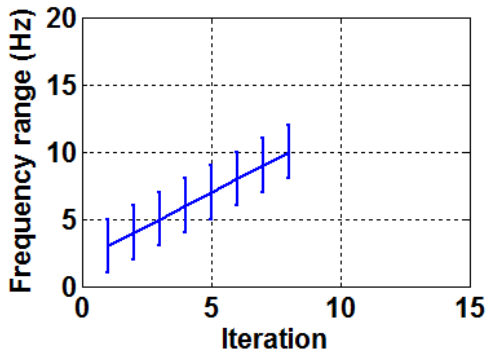
Iteration 8

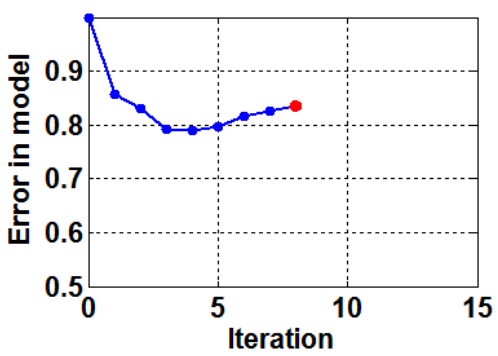


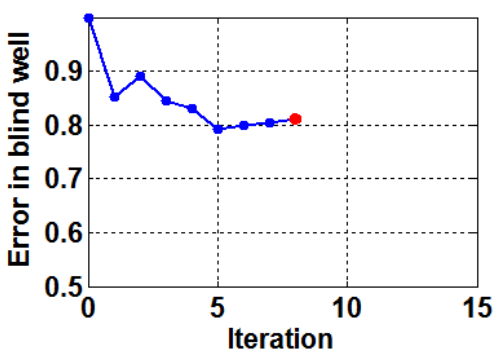


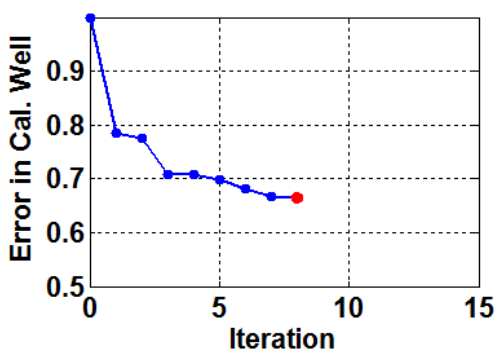






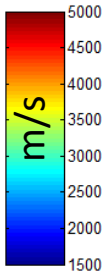


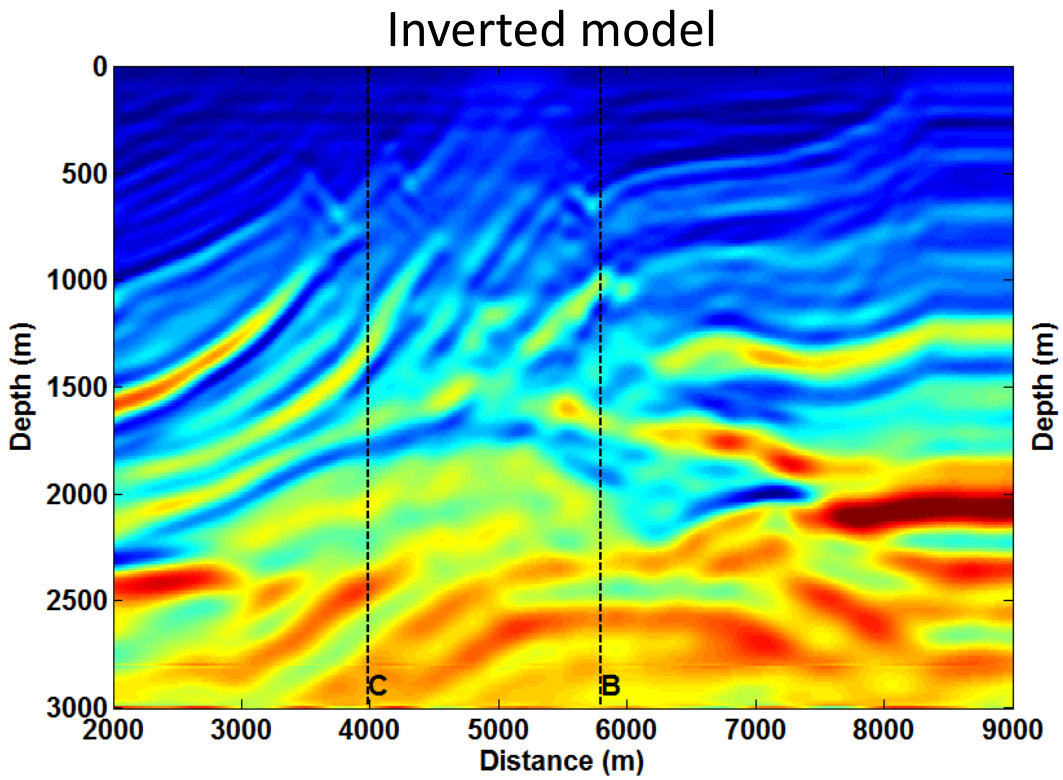


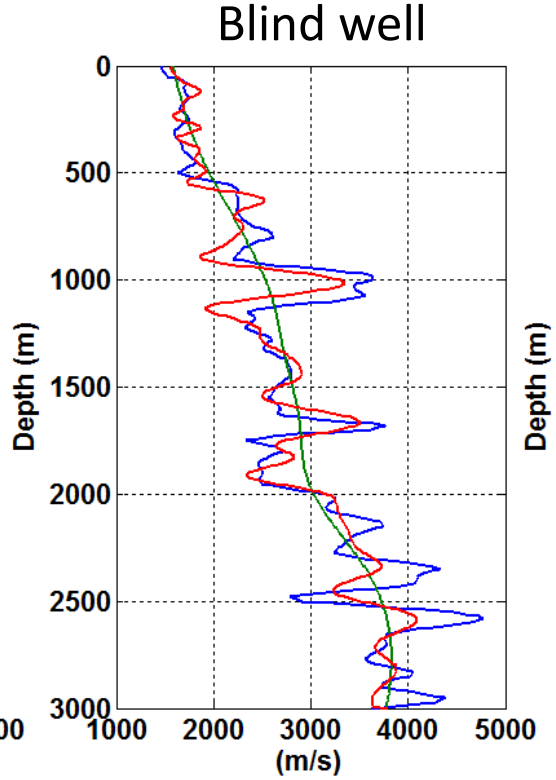


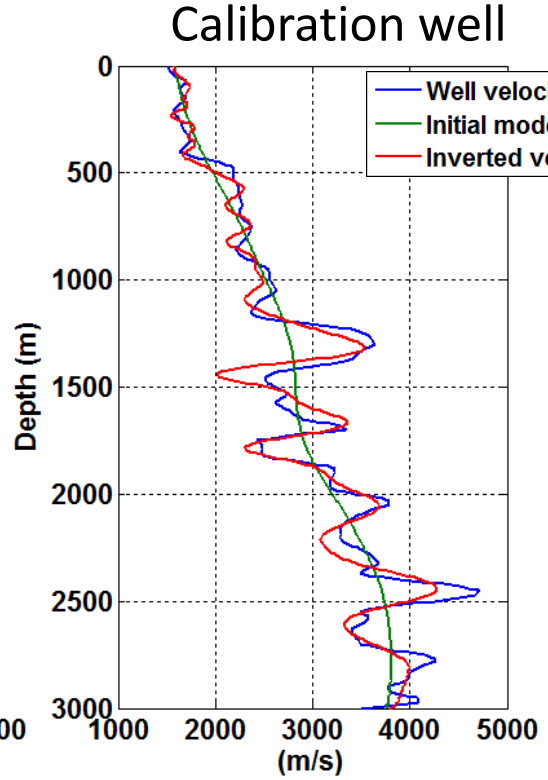
Evolution of the inverted model with more iterations

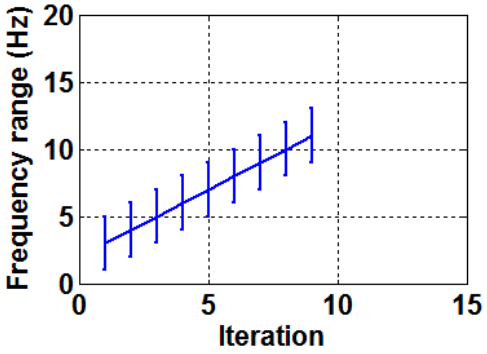
Iteration 9

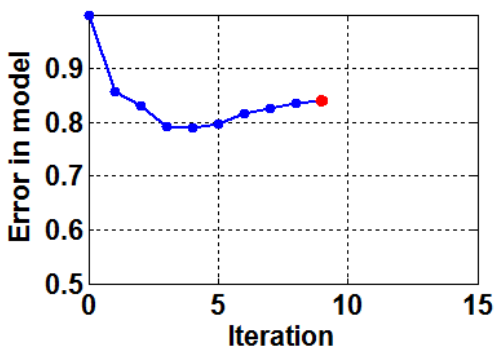


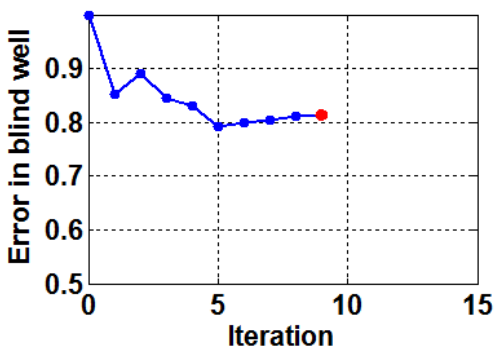


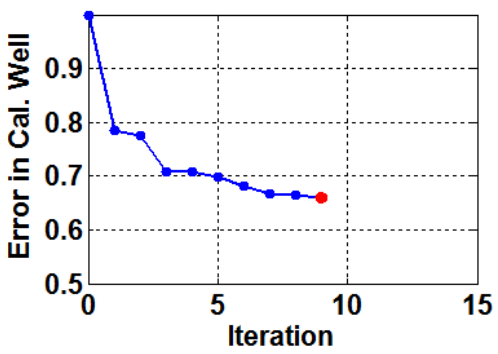






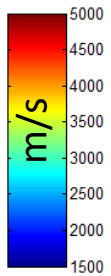




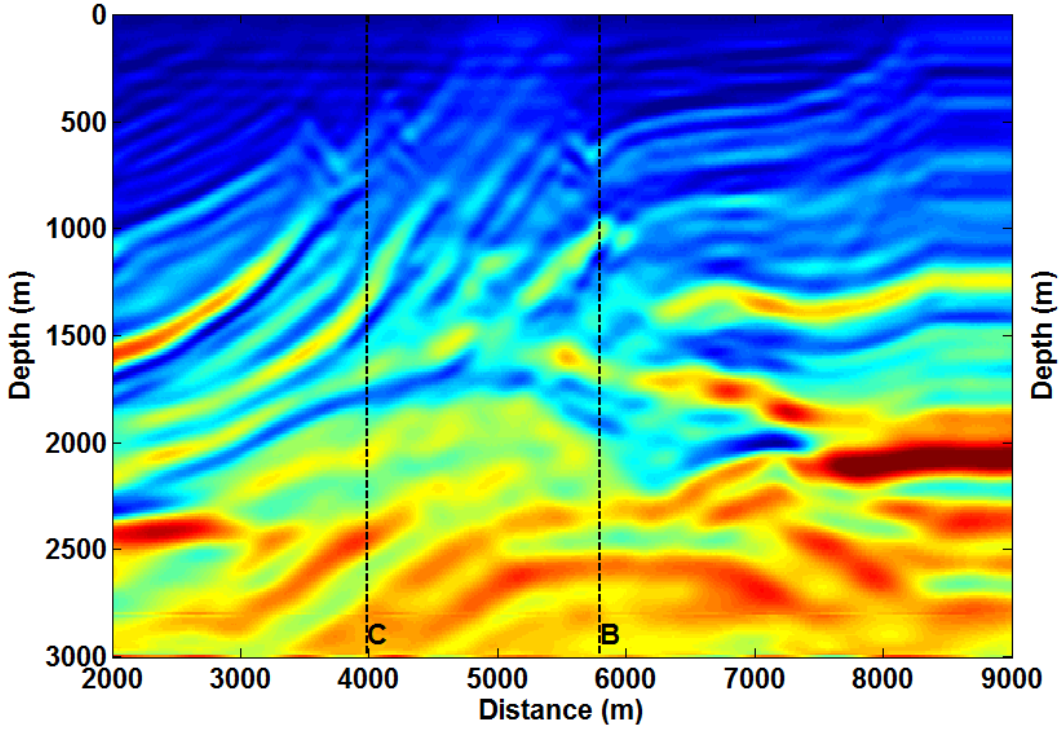


Evolution of the inverted model with more iterations

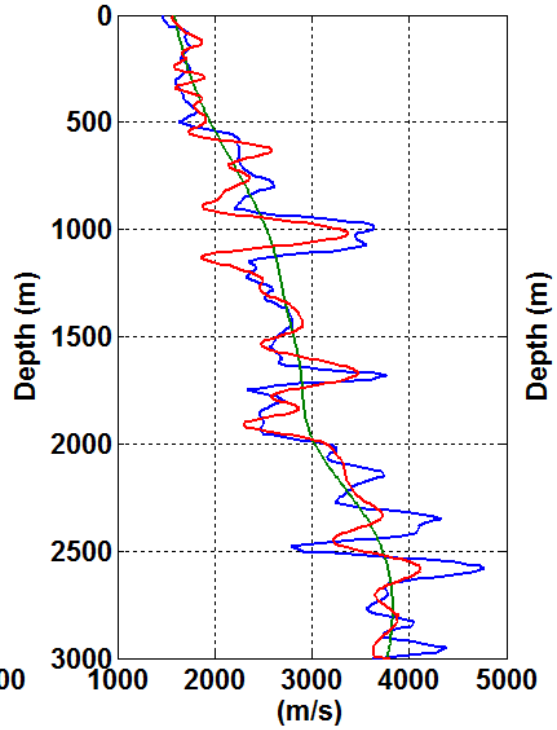
Iteration 10



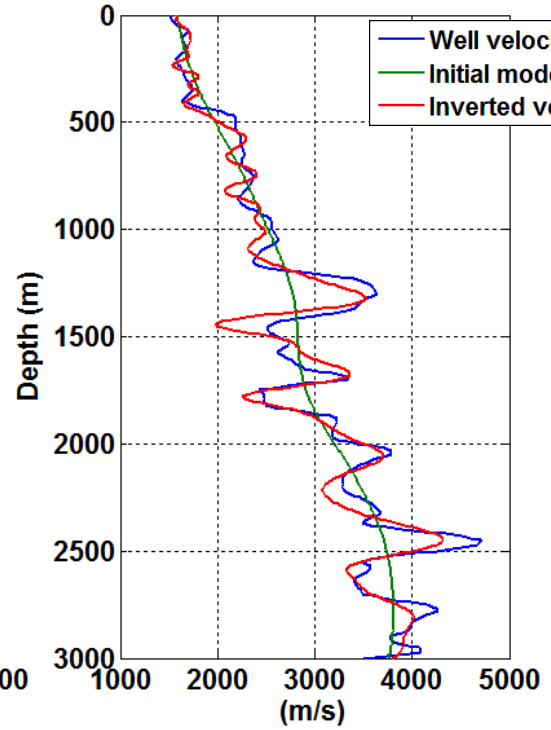
Inverted model

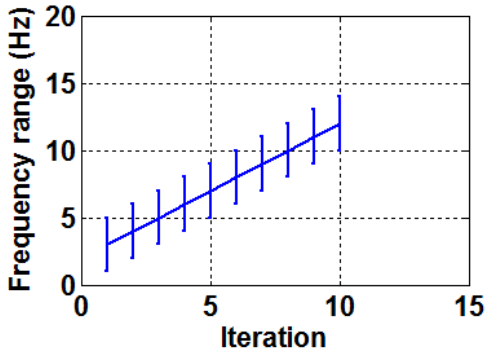


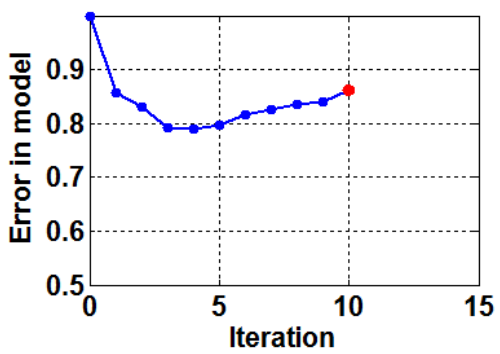
Blind well

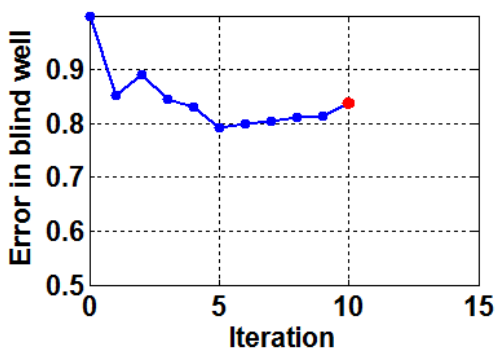


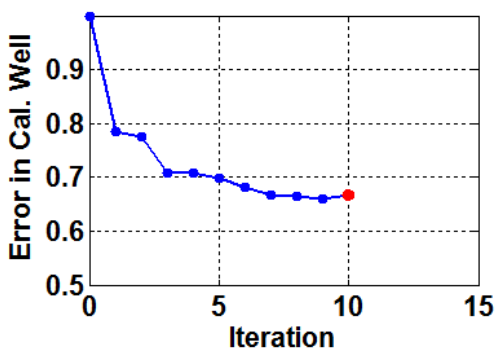
Calibration well





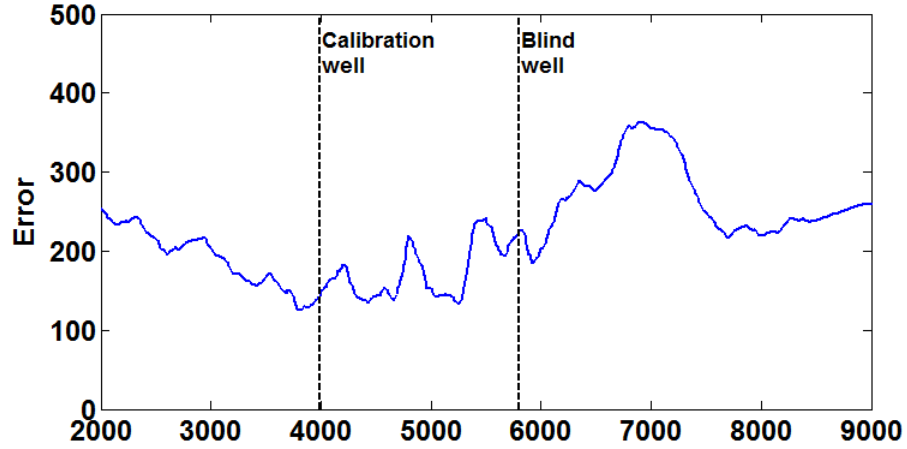




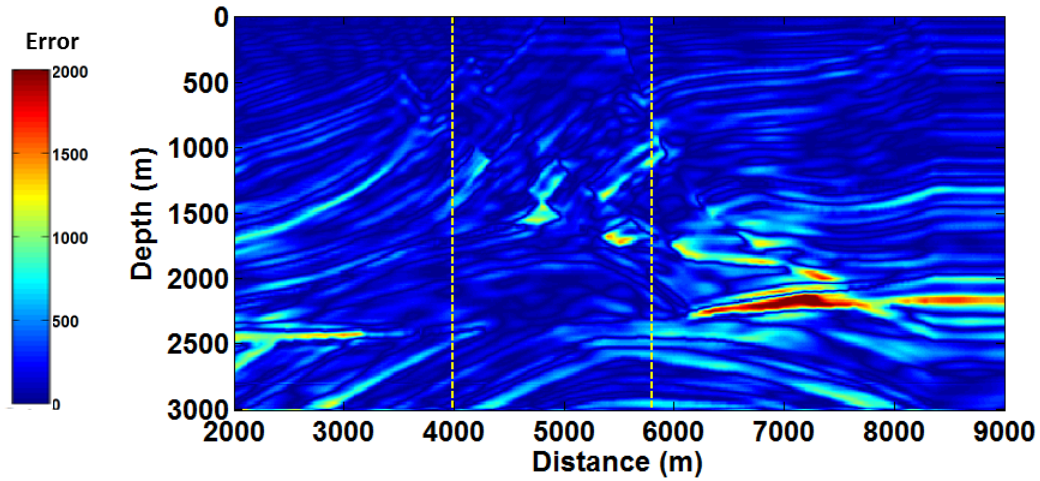


Spatial distribution of the error

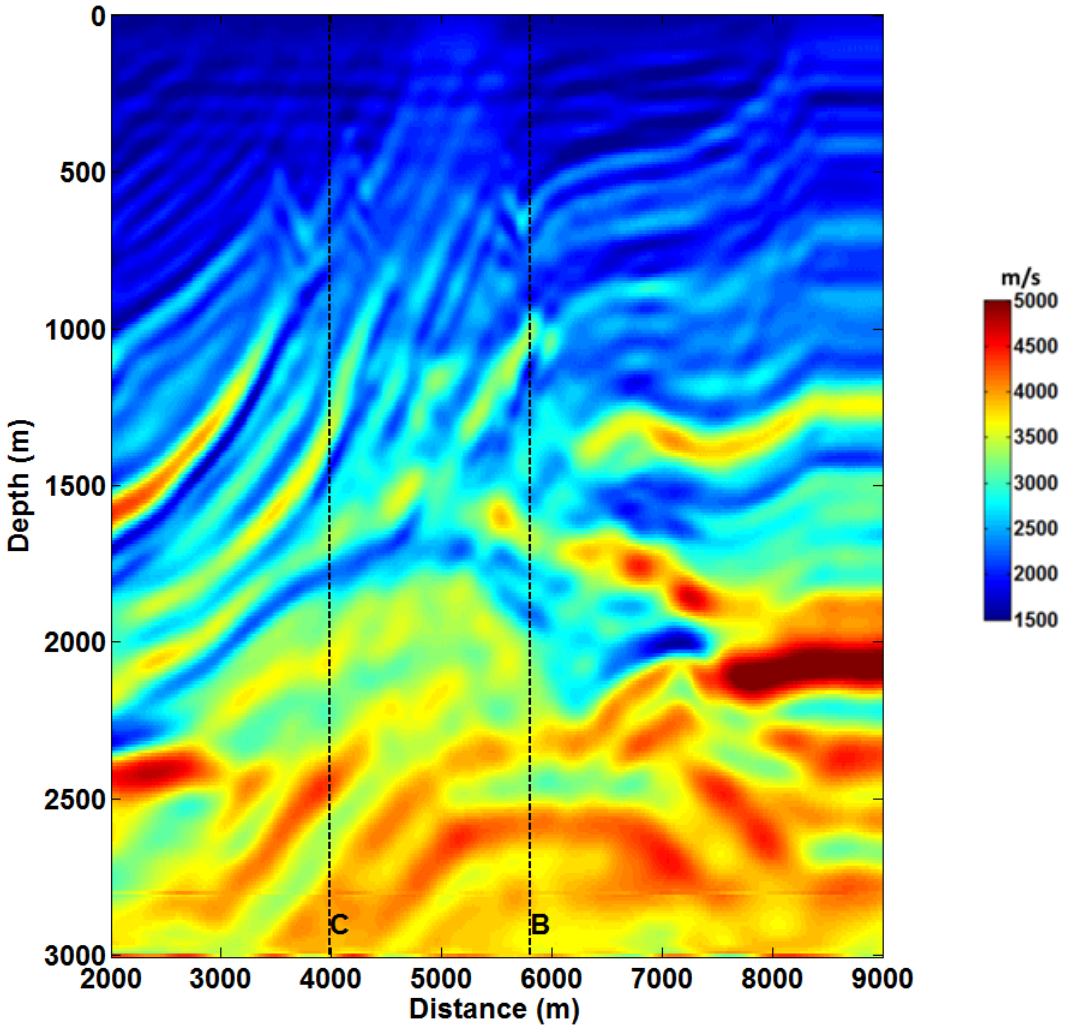
Horizontal distribution of the error



Spatial distribution of the error

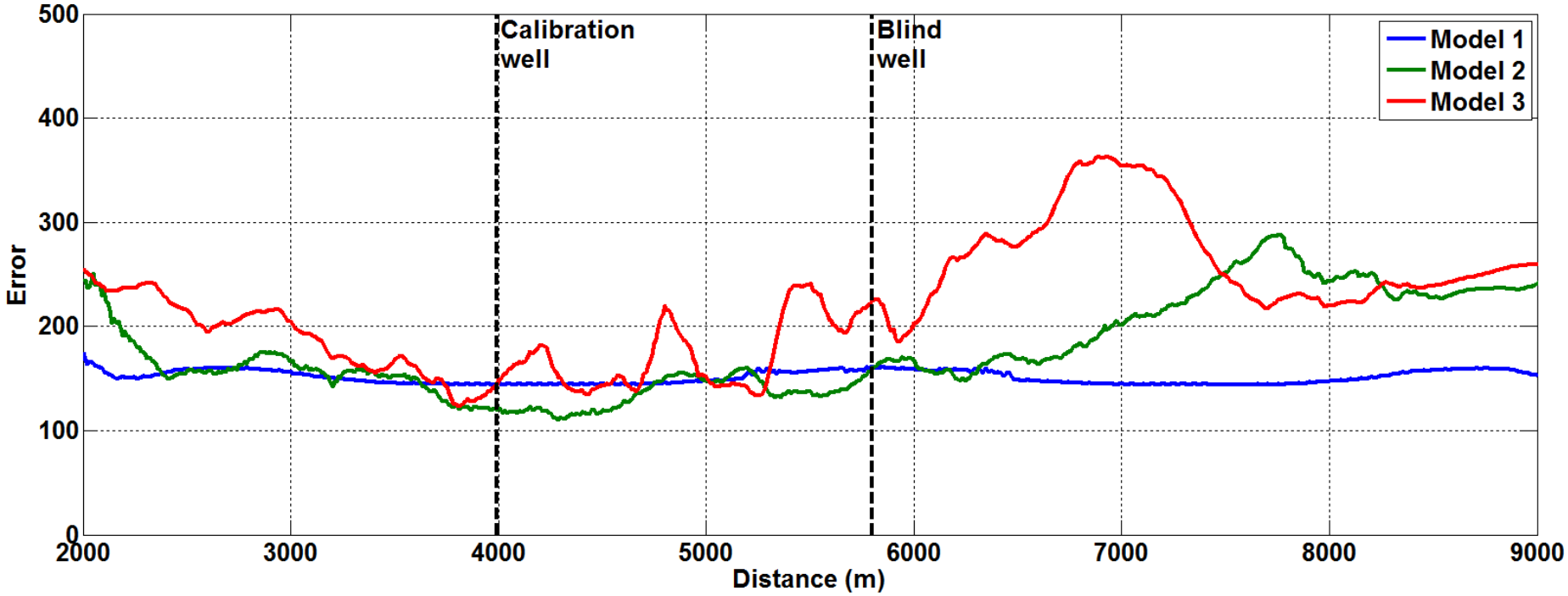


Inverted velocity model



Comparison of horizontal error

Models 1, 2, 3

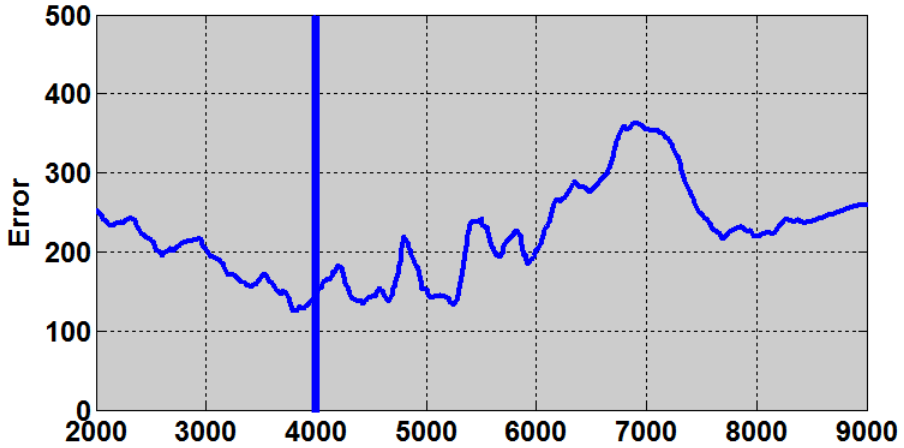


- We found a consistently low error in the well location even for the most complex model.
- Well calibration satisfactorily performs in the presence of moderate lateral velocity changes (Model 1 and 2).
- The error increases in the presence of high velocity contrasts.

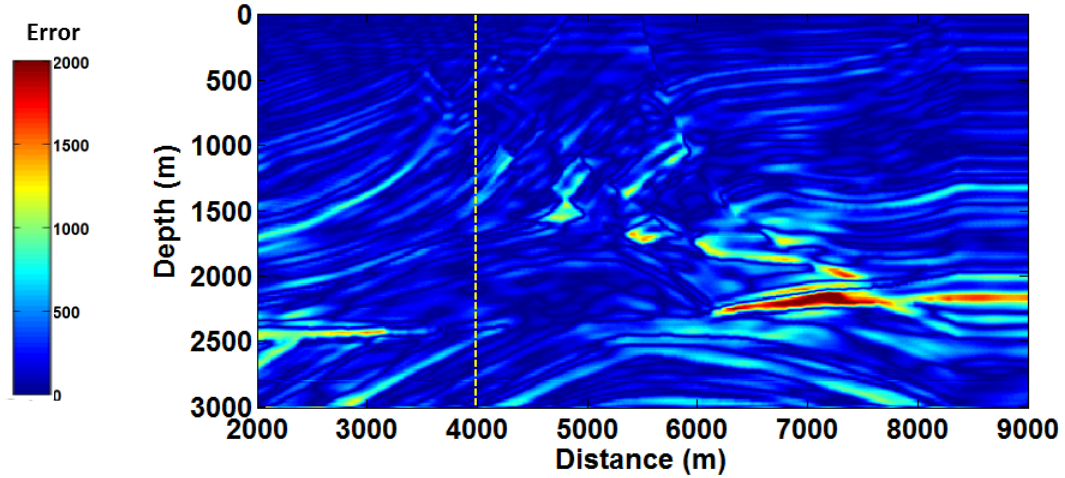
What if the calibration well is in another location?

Model 3

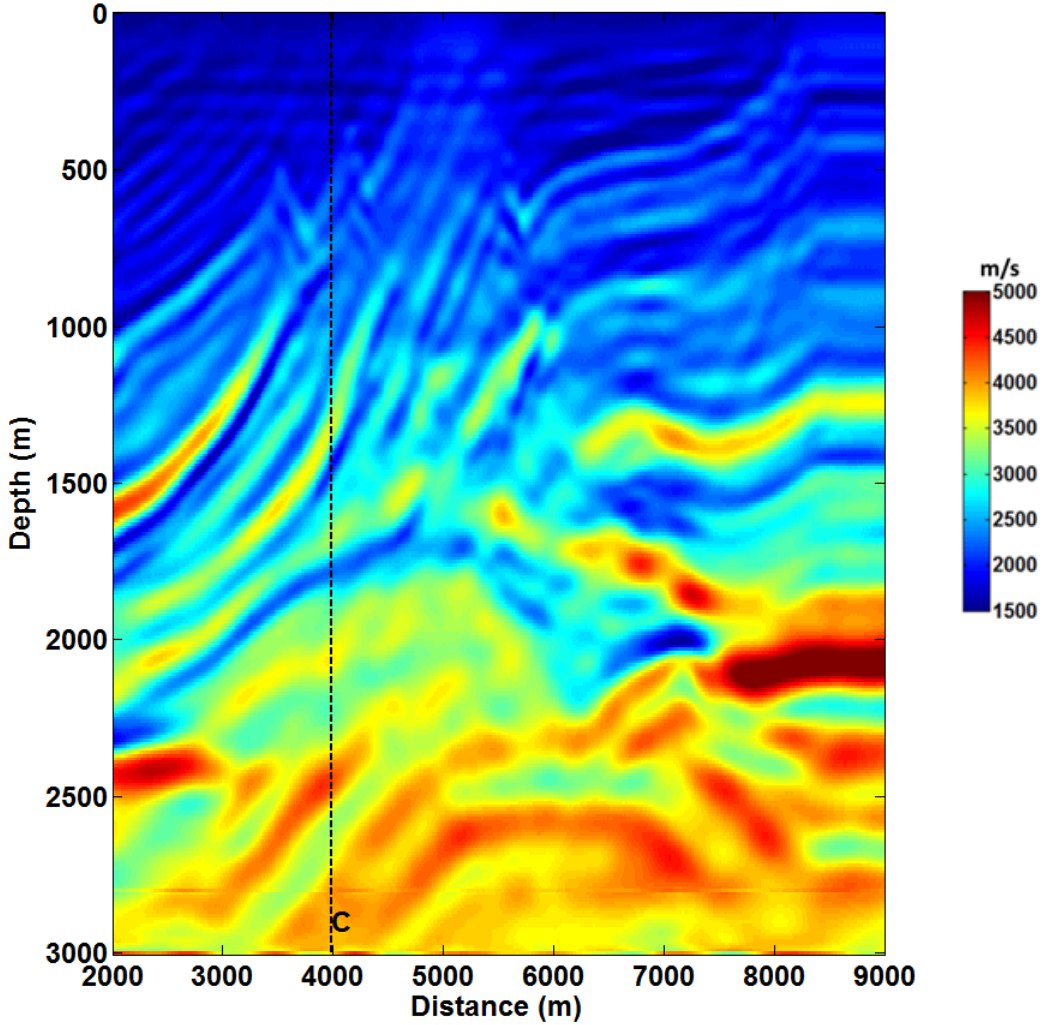
Horizontal distribution of the error



Spatial distribution of the error



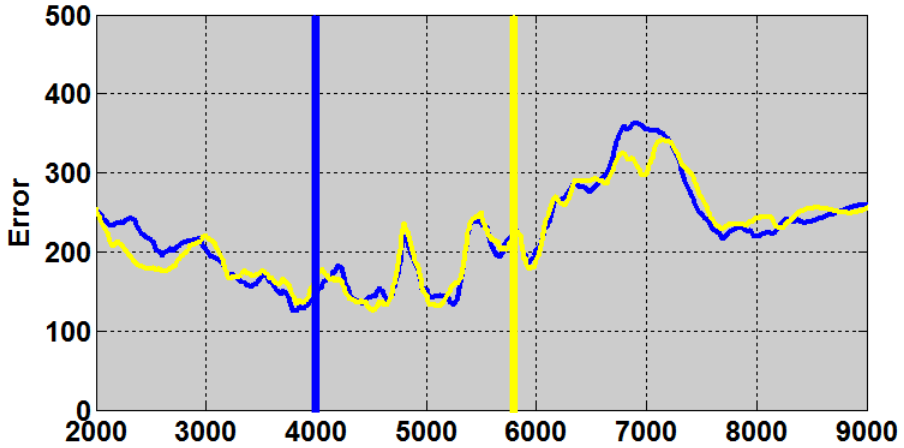
Calibration well at 4000 m



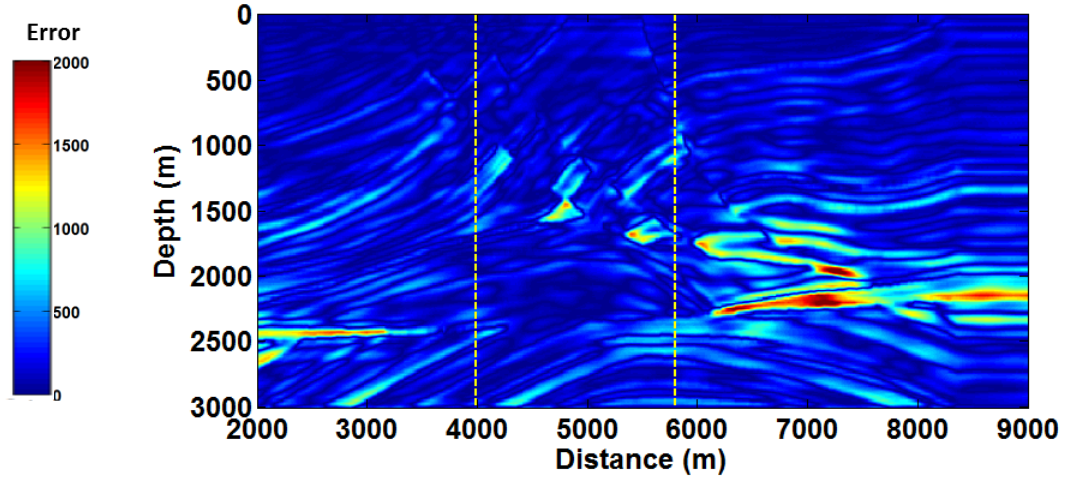
What if the calibration well is in another location?

Model 3

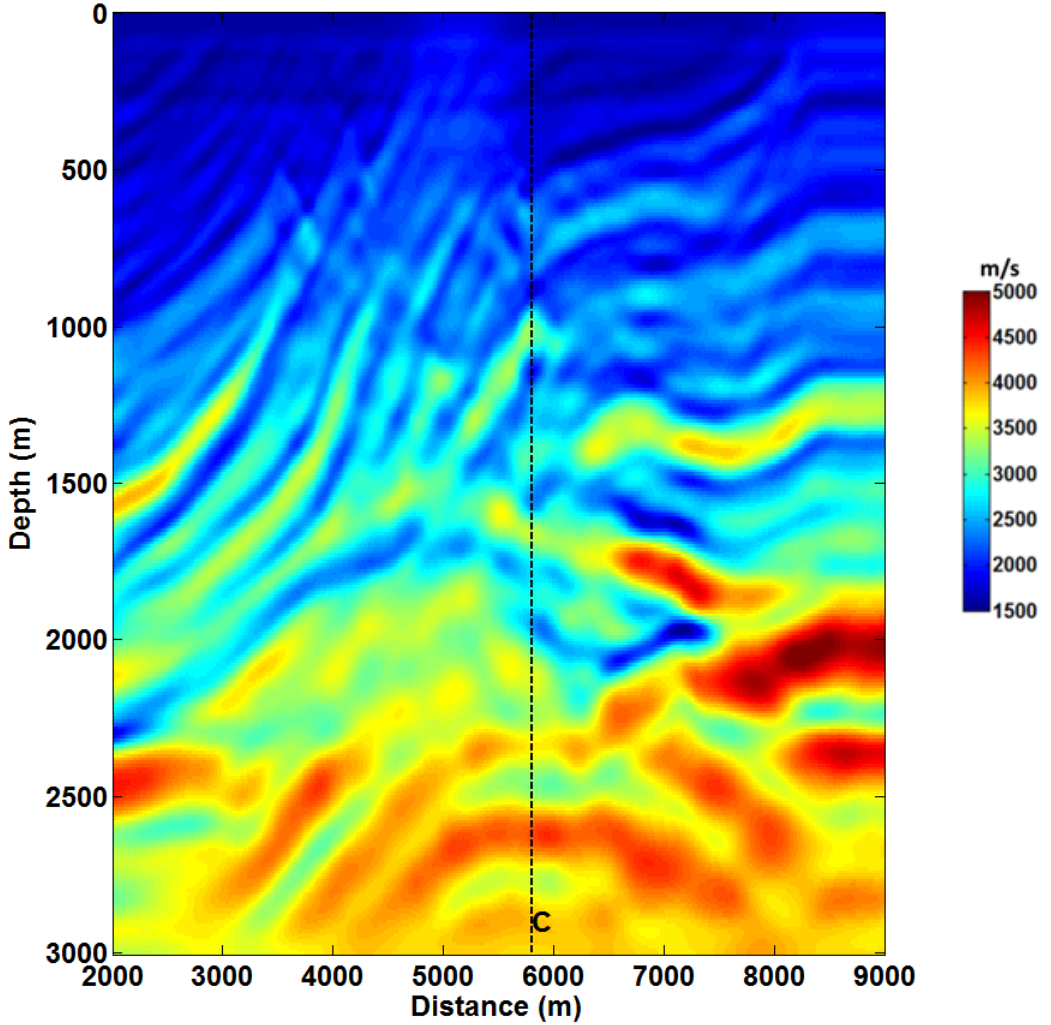
Horizontal distribution of the error



Spatial distribution of the error



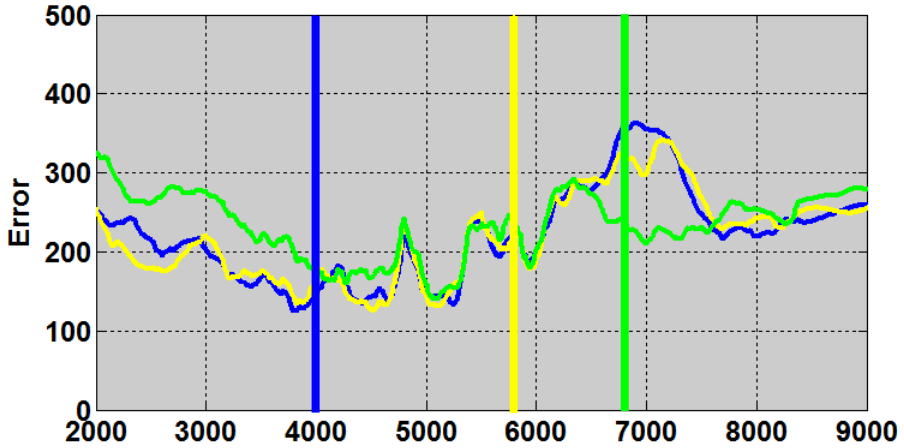
Calibration well at 5800 m



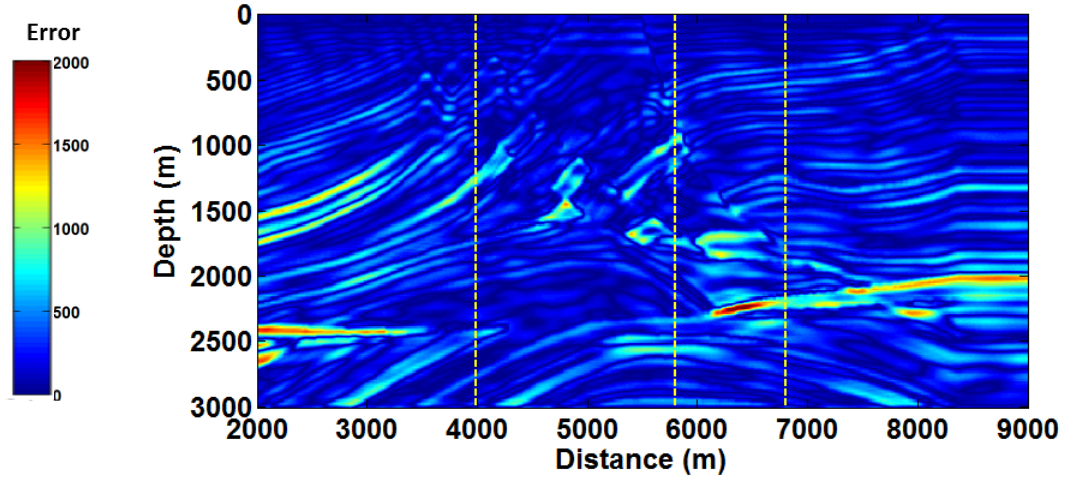
What if the calibration well is in another location?

Model 3

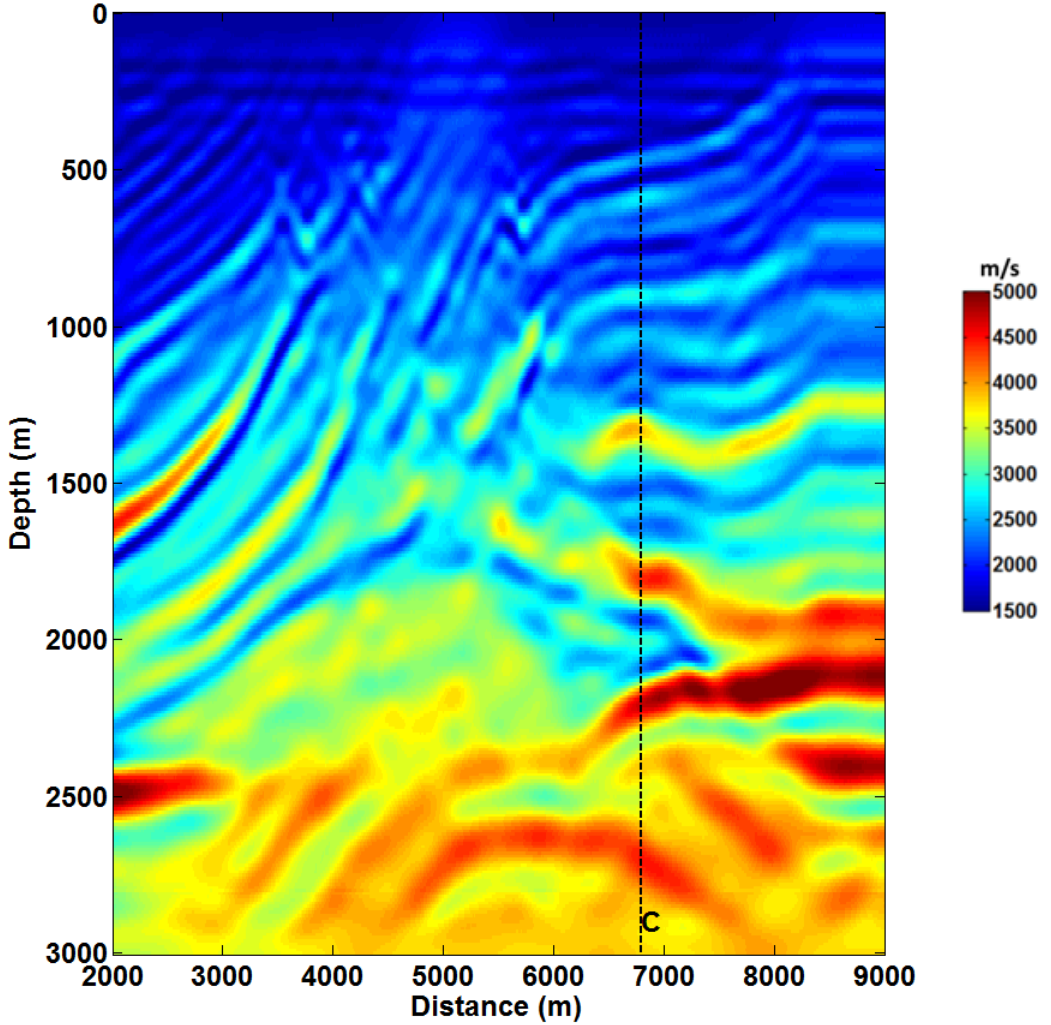
Horizontal distribution of the error



Spatial distribution of the error

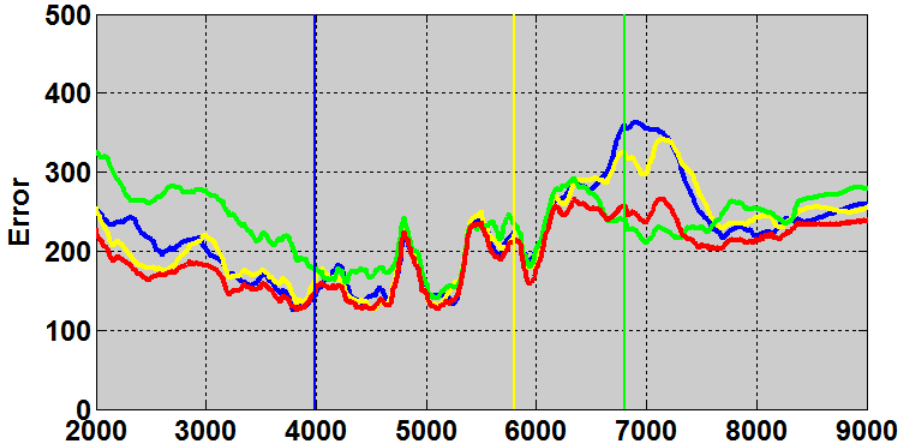


Calibration well at 6800 m

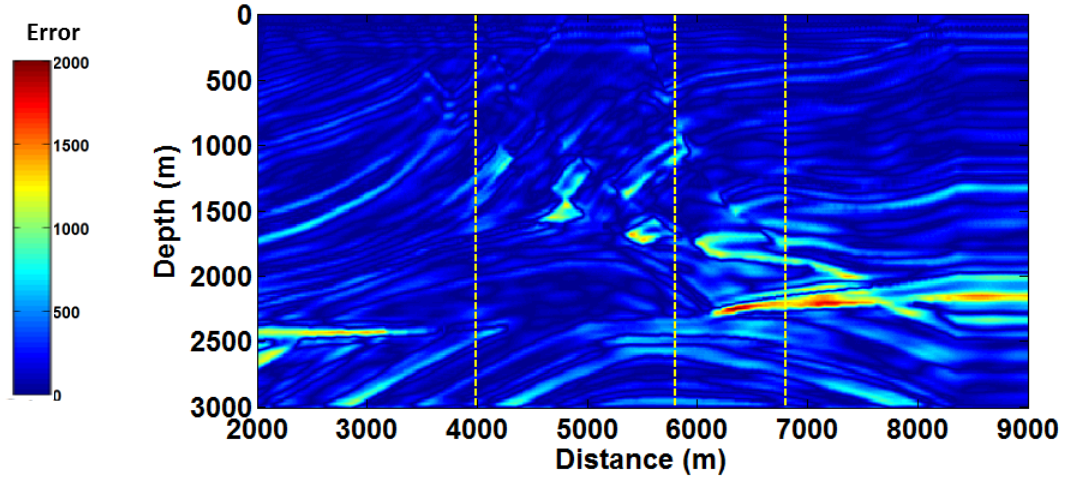


Using the three wells to obtain one match filter

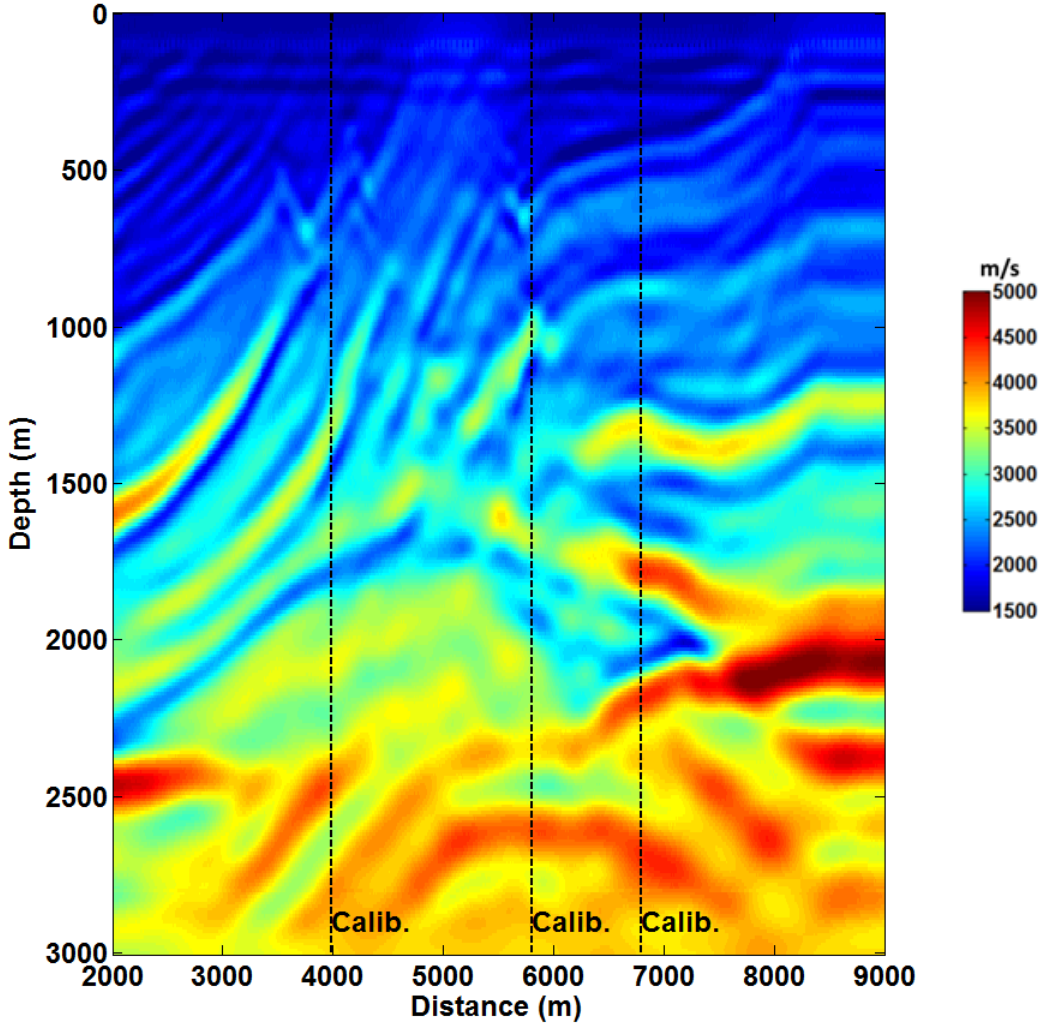
Horizontal distribution of the error



Spatial distribution of the error

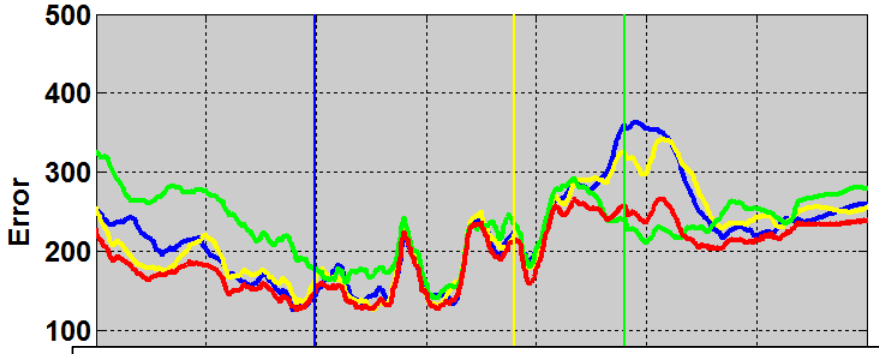


Average match filter

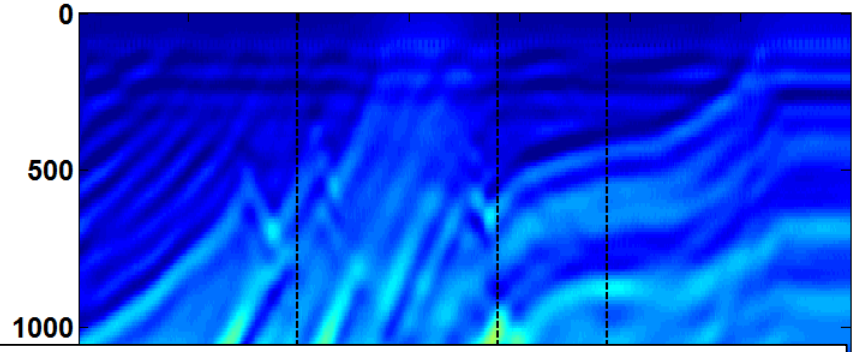


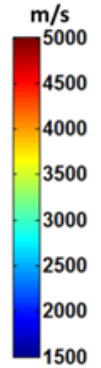
Using the three wells to obtain one match filter

Horizontal distribution of the error

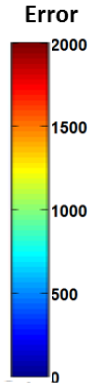


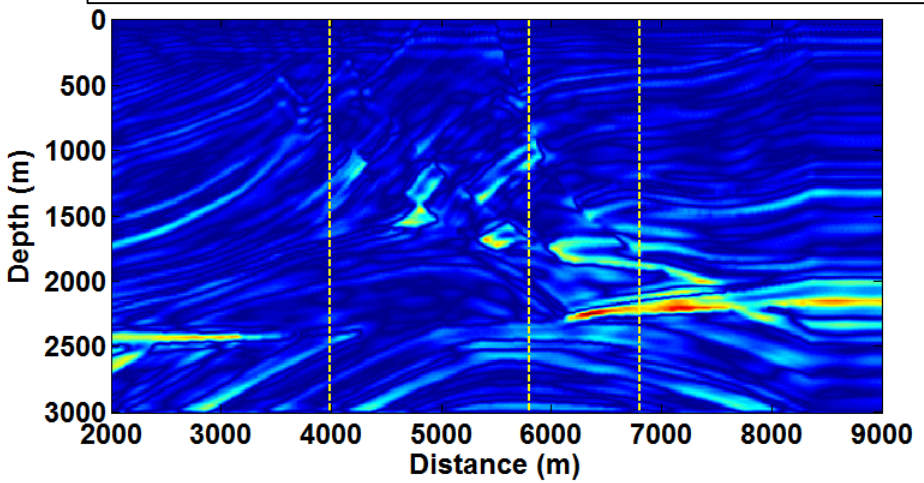
Average match filter

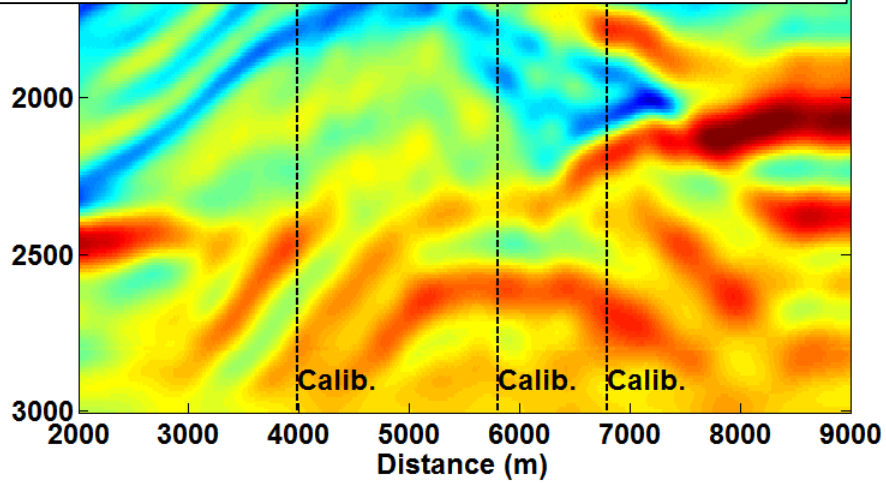




Well calibration works in high complex settings, if the well information is representative of the area of interest





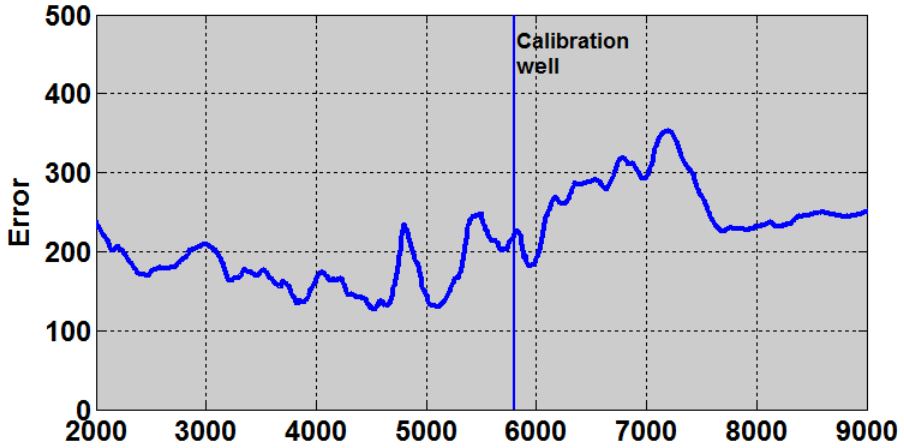


Varying depth interval

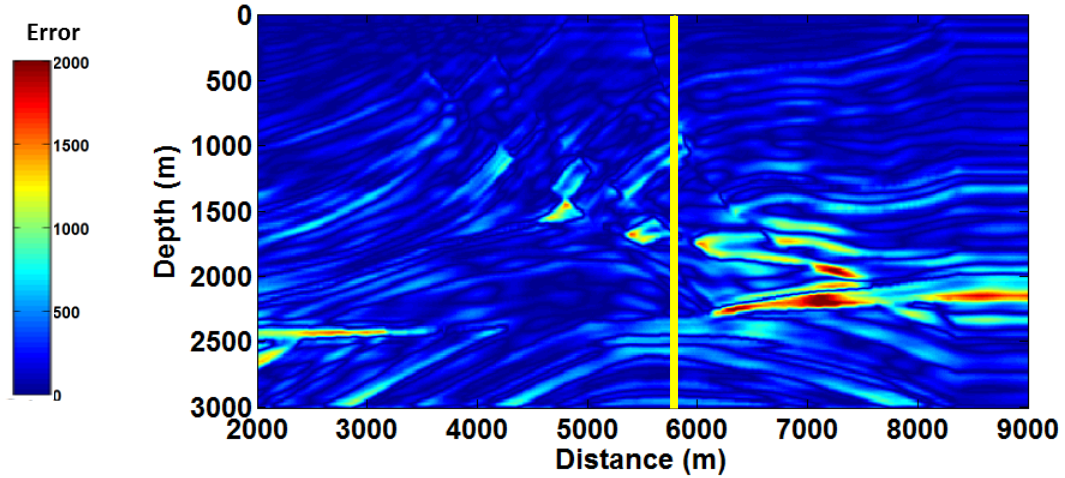
Depth interval (m)

0 – 3000

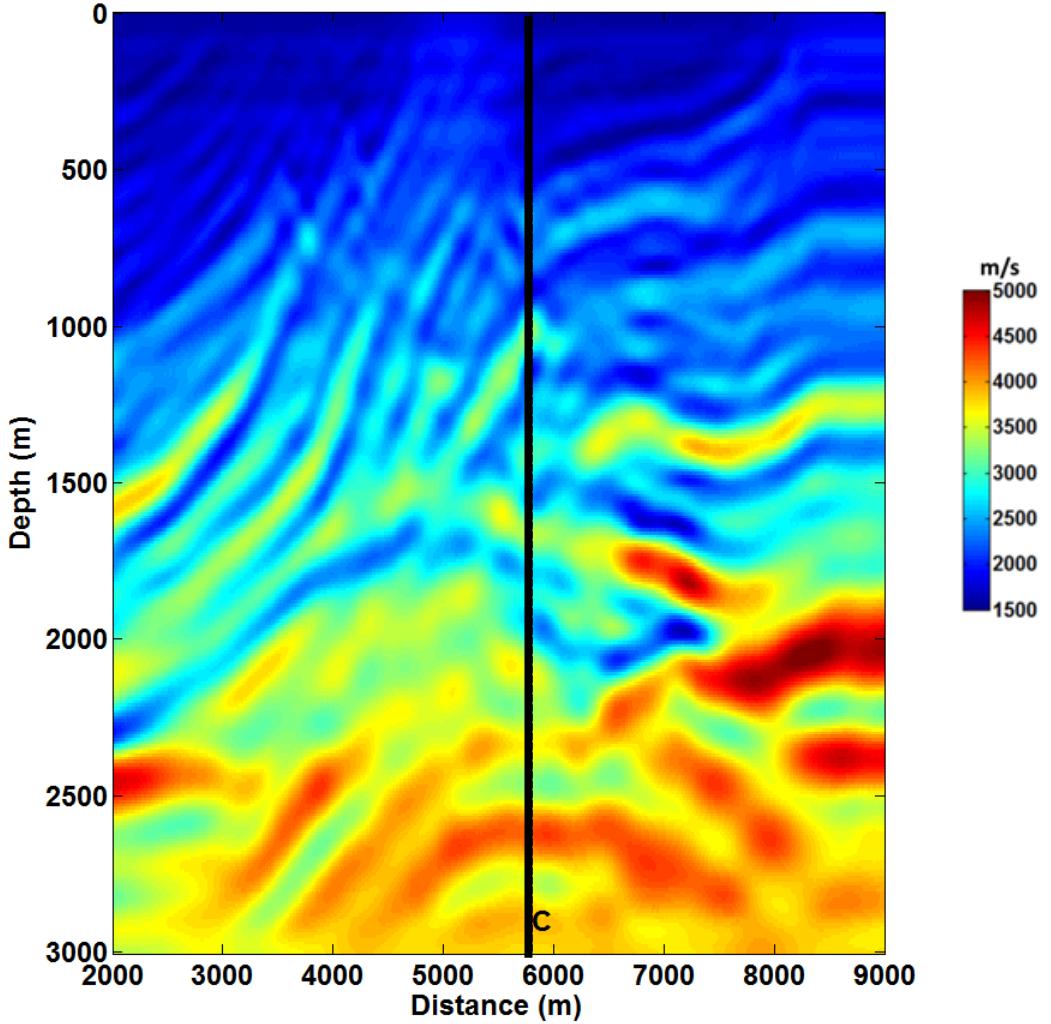
Horizontal distribution of the error



Spatial distribution of the error



From 0 to 3000 m



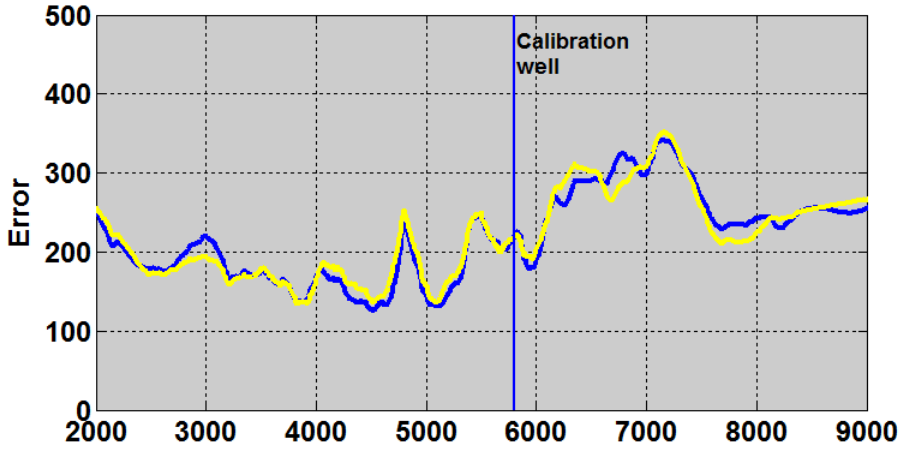
Varying depth interval

Depth interval (m)

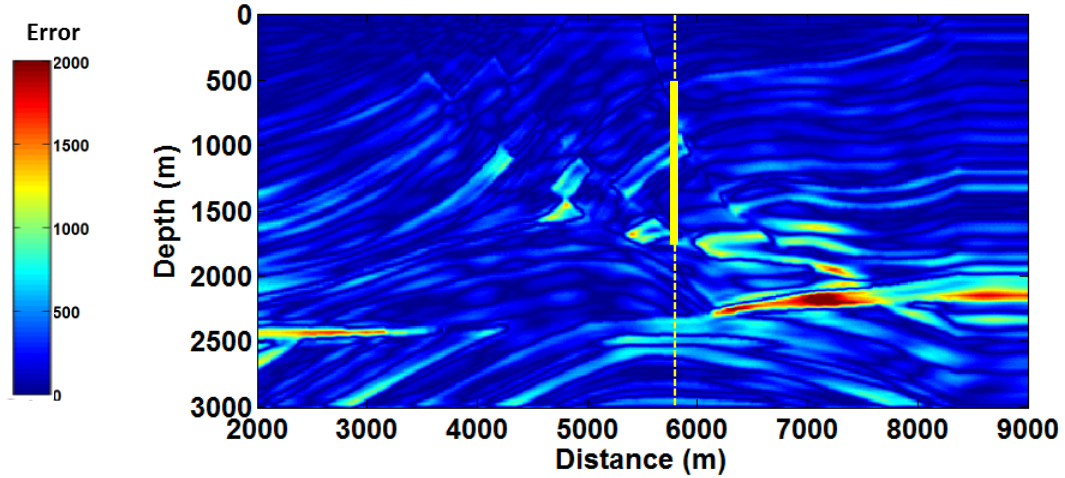
0 – 3000

500 – 1800

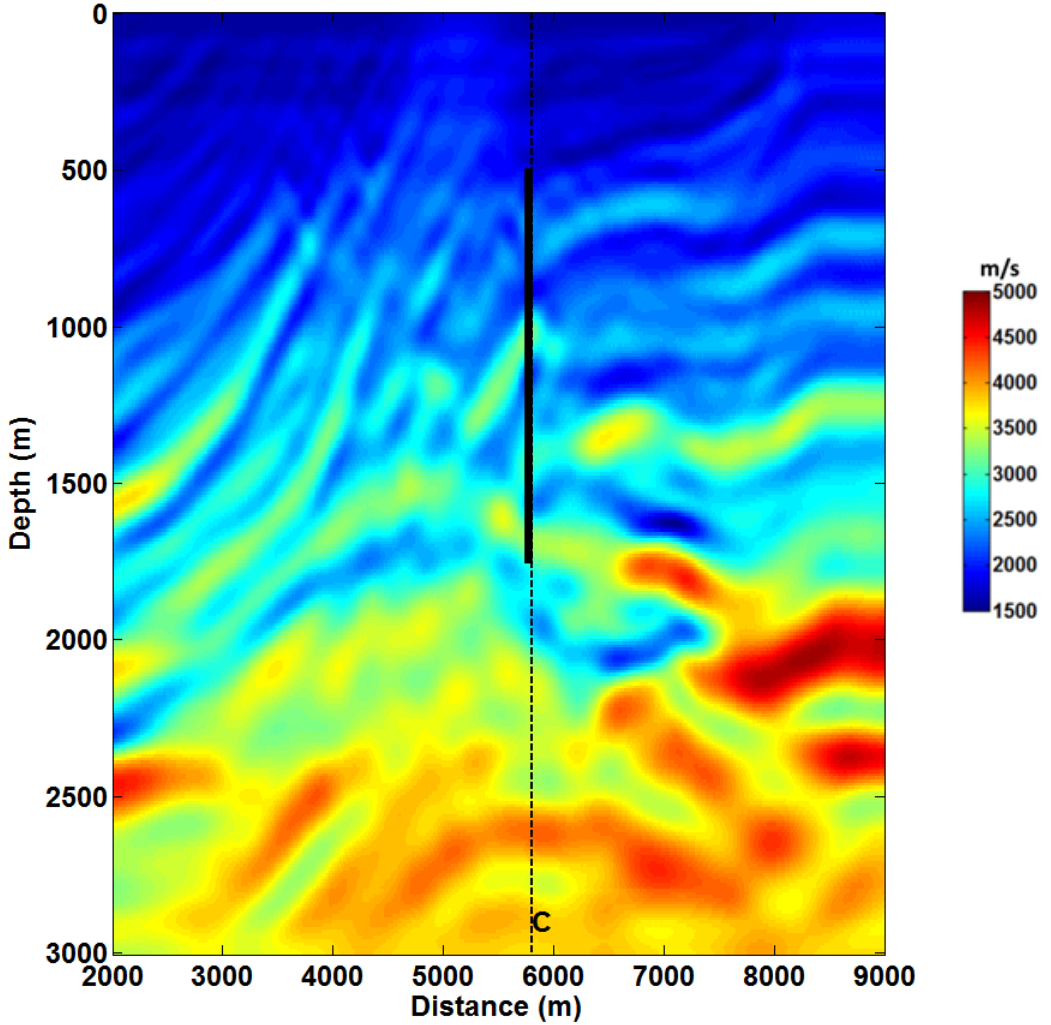
Horizontal distribution of the error



Spatial distribution of the error



From 500 to 1800 m

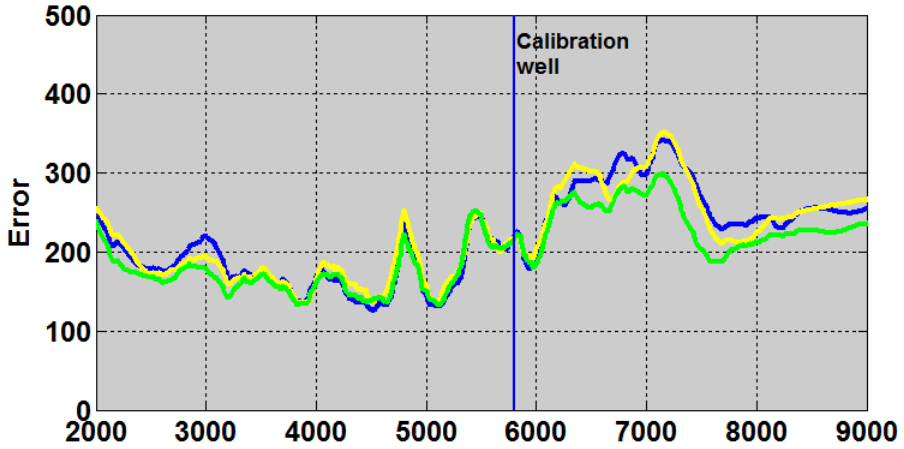


Varying depth interval

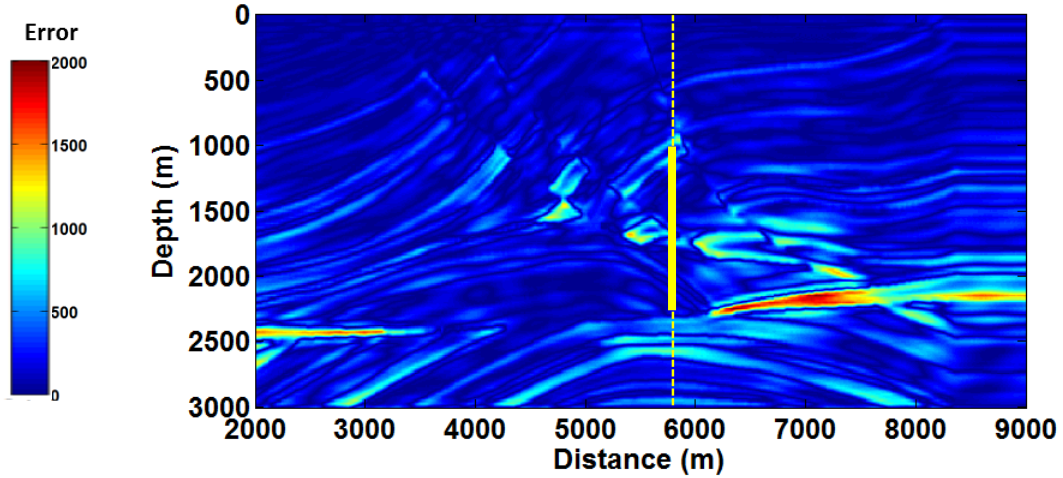
Depth interval (m)

0 – 3000
500 – 1800
1000 – 2300

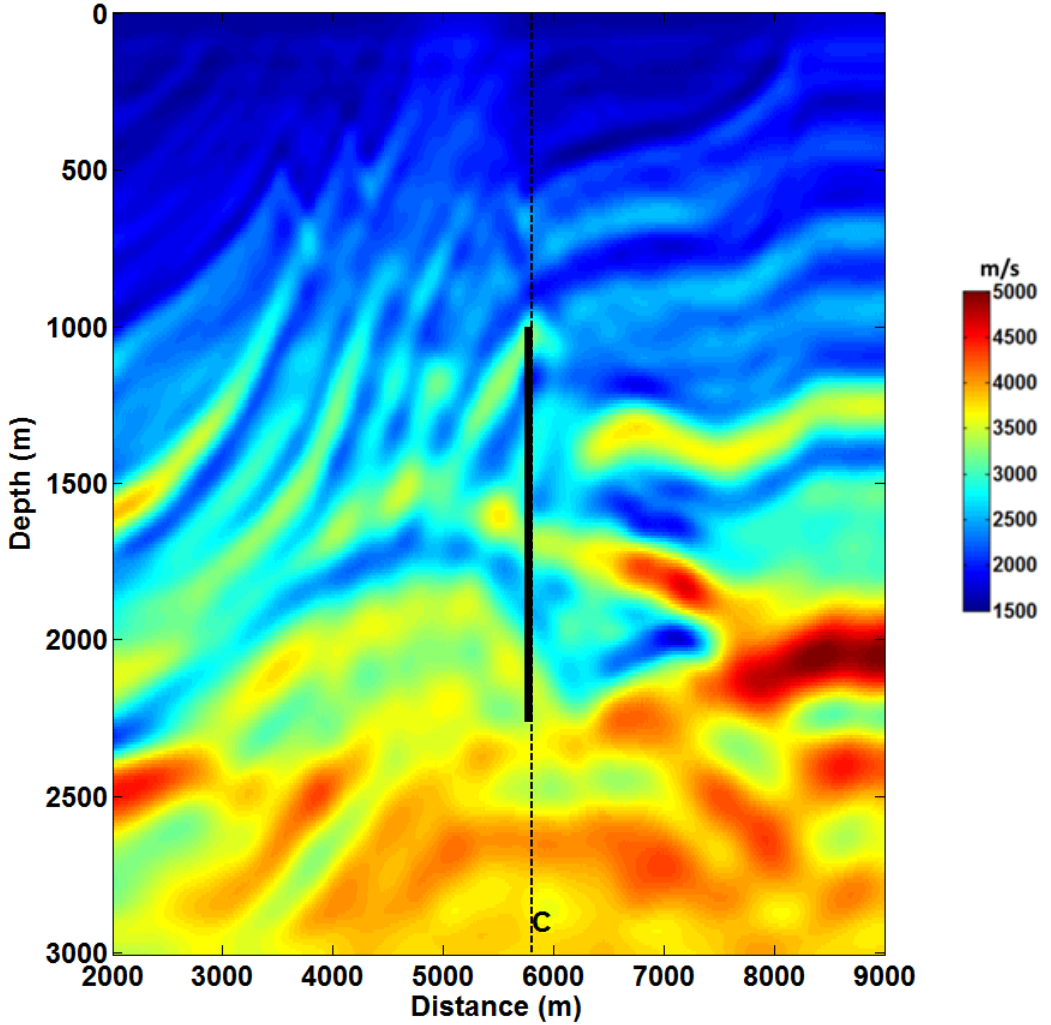
Horizontal distribution of the error



Spatial distribution of the error



From 1000 to 2300 m

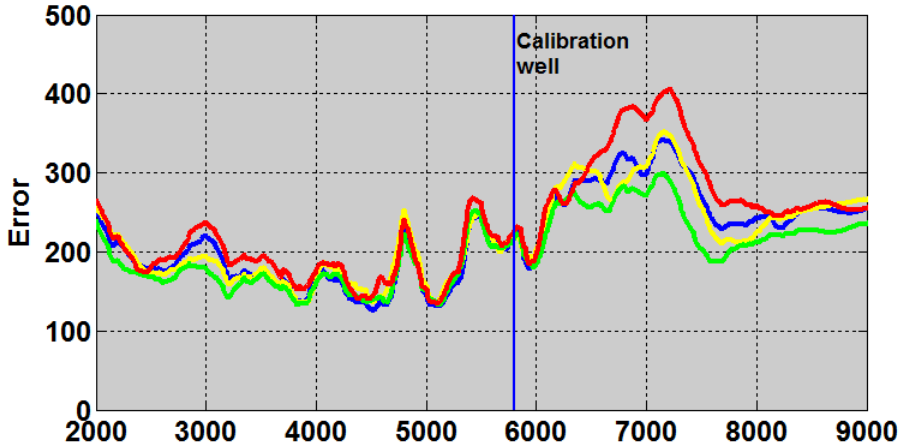


Varying depth interval

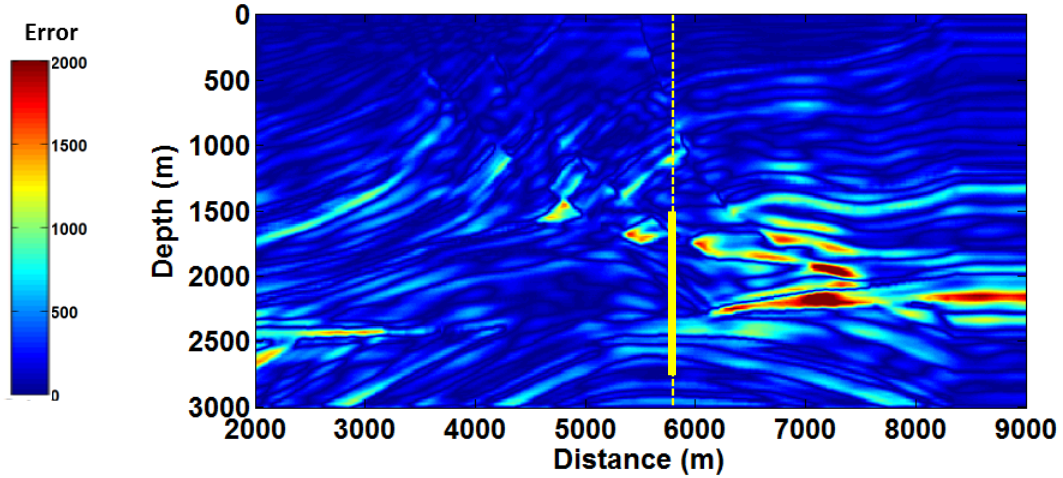
Depth interval (m)

- 0 – 3000
- 500 – 1800
- 1000 – 2300
- 1500 – 2800

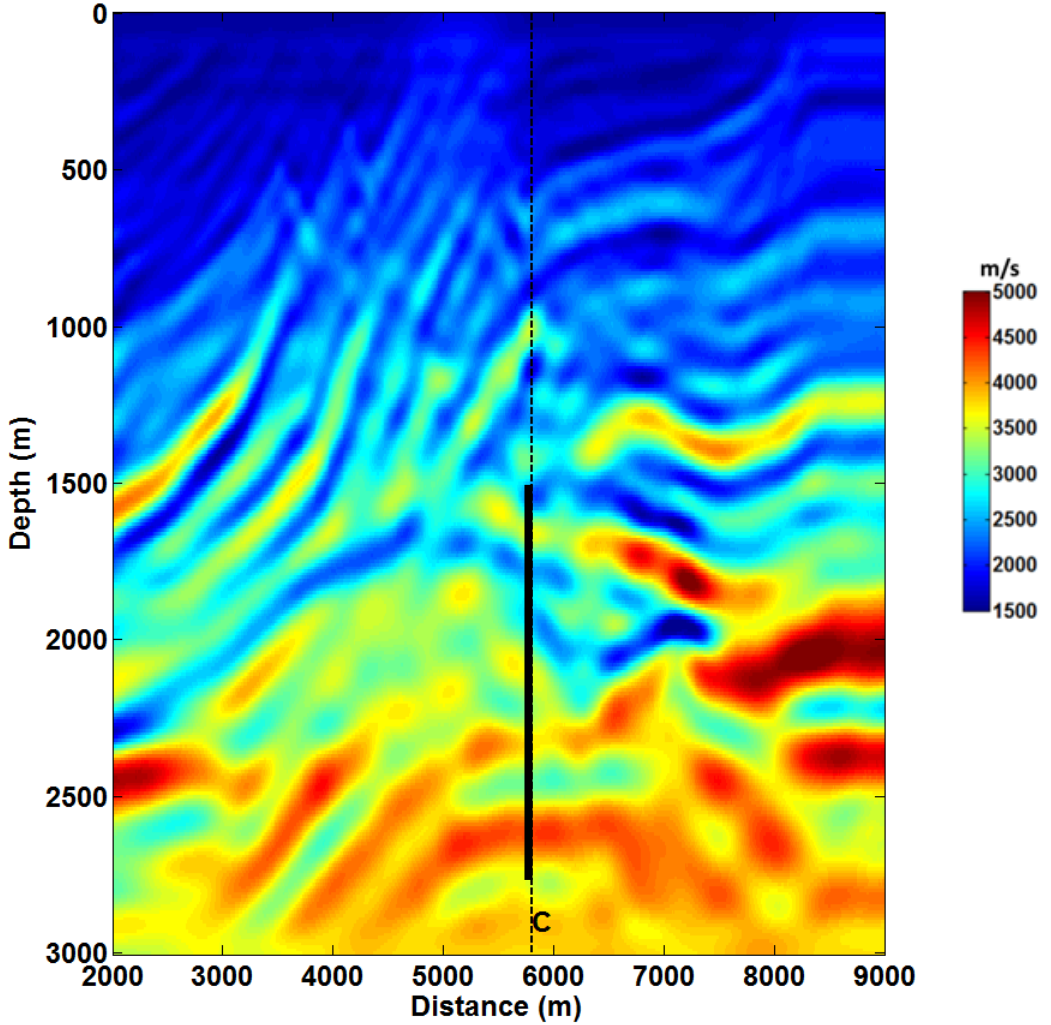
Horizontal distribution of the error



Spatial distribution of the error



From 1500 to 2800 m

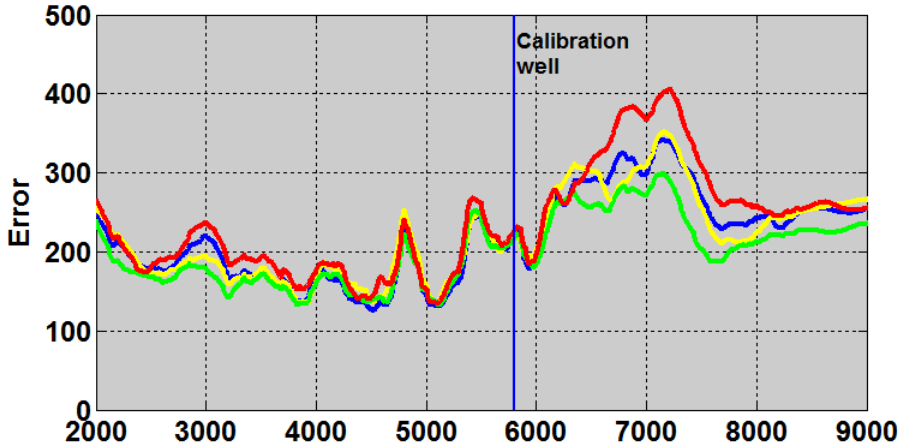


Varying depth interval

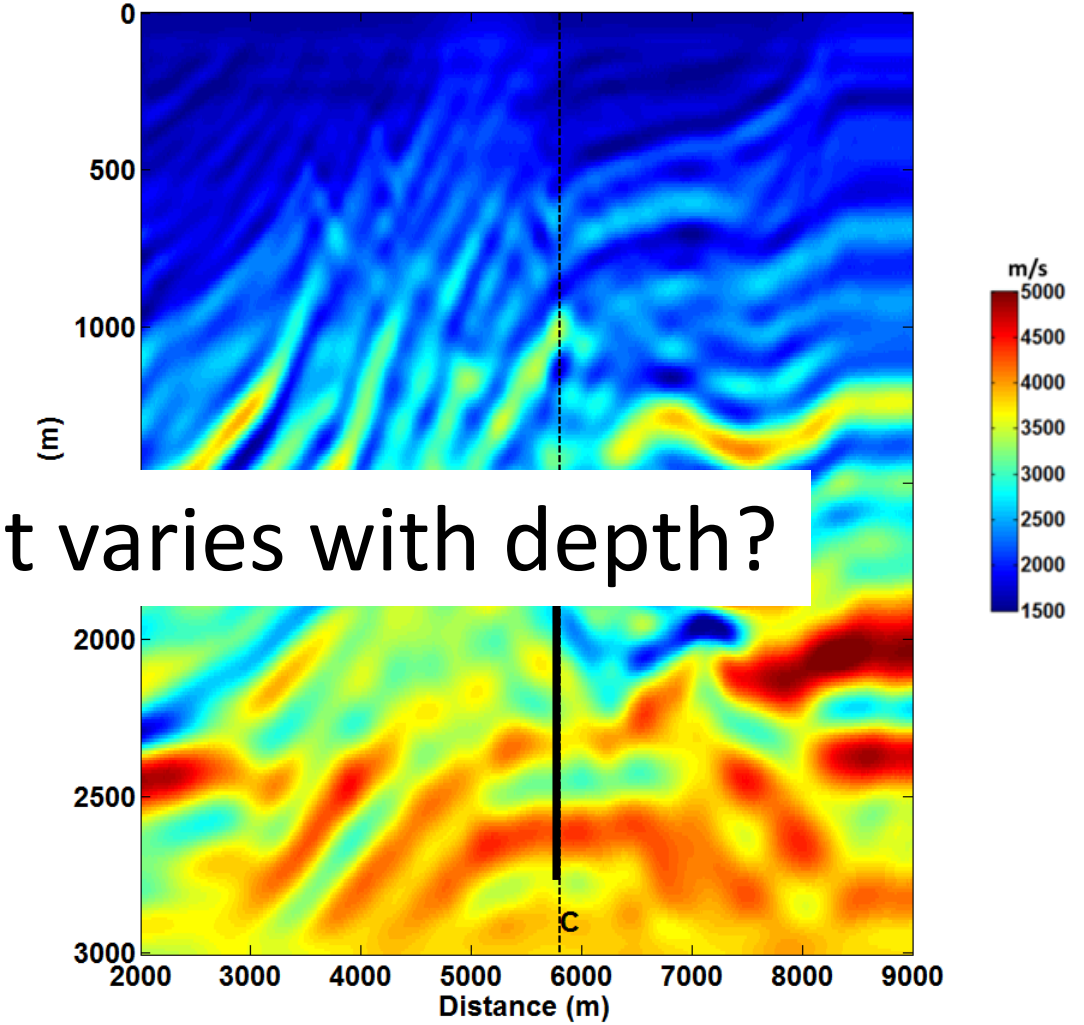
Depth interval (m)

- 0 – 3000
- 500 – 1800
- 1000 – 2300
- 1500 – 2800

Horizontal distribution of the error

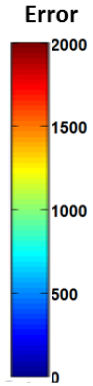


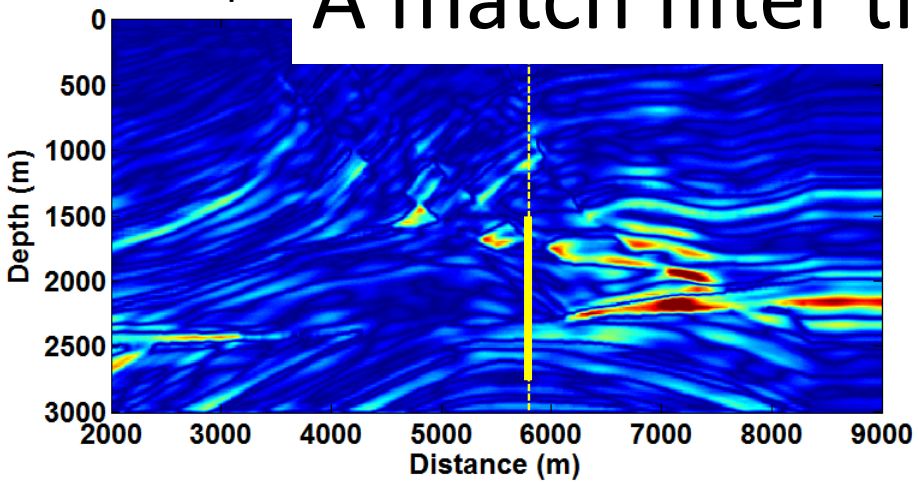
From 1500 -2800 m



Spat

A match filter that varies with depth?





Conclusions

- The gradient, calculated with a one-way wave migration method (PSPI) with a deconvolution imaging condition, points to the right direction in order to minimize the objective function in the FWI scheme.
- A scalar, estimated with well information, calibrates the gradient and produces suitable velocity perturbations to update the model. This was confirmed by consistently low errors in the well location even for the most complex model.
- Well calibration satisfactorily performs in the presence of moderate lateral velocity changes, such as in Model 1 and 2.
- Well calibration works in strong lateral velocity contexts, providing that the well is representative of the geology of the zone of interest.
- A match filter that varies both laterally and vertically may be a worthy option if we have multiple wells available and wide vertical coverage.

Future work

- We will address the elastic case. The goal will be, following IMMI's philosophy, to incorporate the knowledge and experience in AVO analysis and inversion into the FWI process.

- We will investigate how the integration of AVO information into the process of FWI can help finding a better scalar in a multi-parameter context.

Acknowledgements

Sponsors of CREWES for their support

NSERC through the grant CRDPJ 461179-13

PEMEX and the government of Mexico for funding this research

Acknowledgements

Thank you