Full-waveform inversion for large-scale problems: workflow, source encoding, and application

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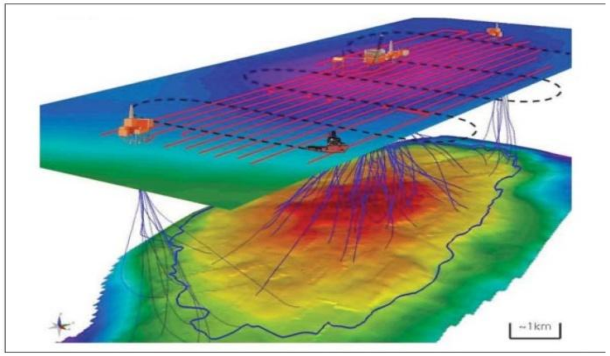
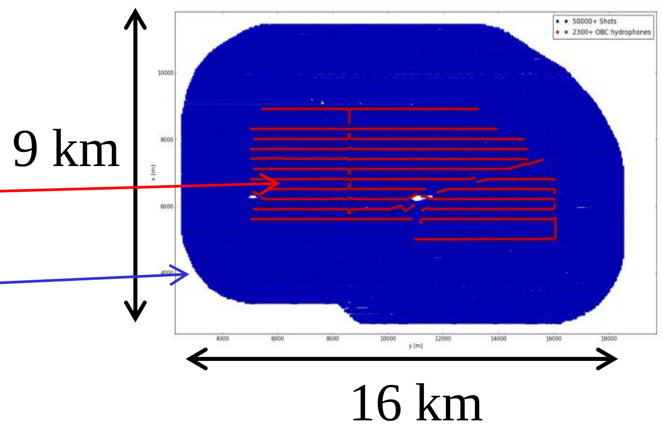
Towards FWI at the exploration scale



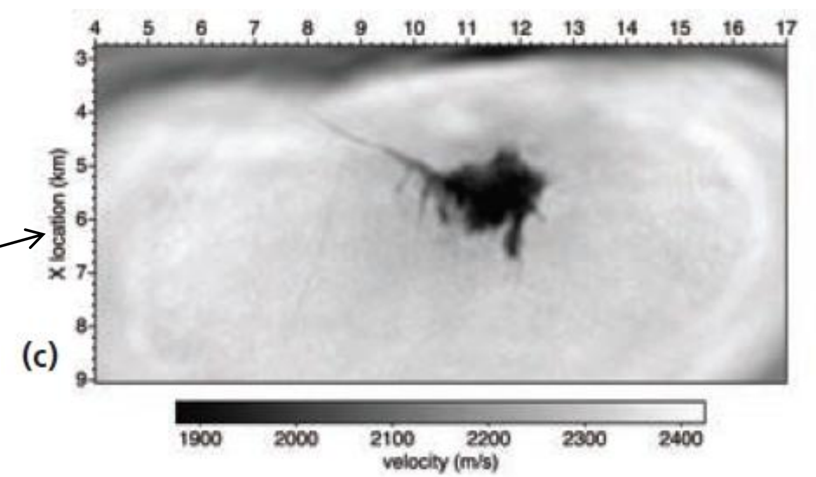
Gestel et al. (2008), TLE

- “Large-scale” FWI
  - Many sources/receivers
  - Automated workflow (Python)



- Valhall oilfield:
  - **2300 OBCs**
  - **50000 shots**
  - 50 m spacing
  - Many simulations
  - Much data processing (100+ GB)

- High-resolution tomographic image



Sirgue et al. (2010) First Break EAGE

FWI implementation

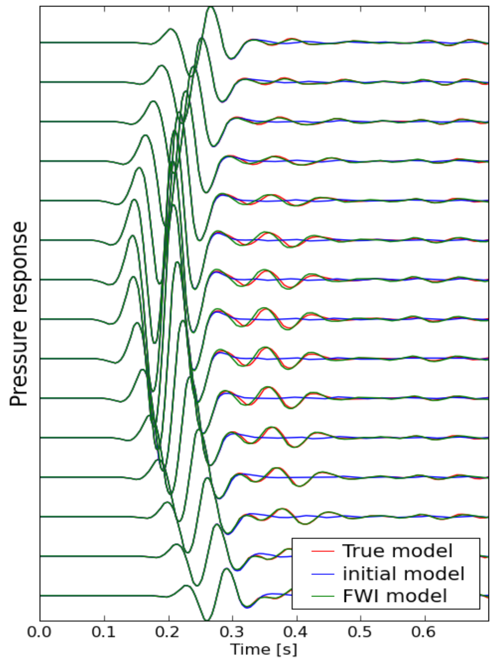
- Time-domain acoustic modeling
- SPECFEM3D spectral element code
- L_2-misfit
- Gradient descent
- Multi-scale through low-pass filtering

"Potential-formulation"

$$\kappa^{-1}\,\partial_t^2\phi = \nabla\cdot(\rho^{-1}\,\nabla\phi) + f,$$

$$p = -\kappa\,(\nabla\cdot\mathbf{s}) = -\partial_t^2\phi\,.$$

$$\mathbf{s} = \rho^{-1}\,\nabla\phi\,.$$



$$K_\kappa = -\kappa^{-1}\int_0^T \underline{\partial_t^2\phi^\dagger}(T-t)\,\underline{\partial_t^2\phi}(t)\,\mathrm{d}t,$$ Sensitivity kernel

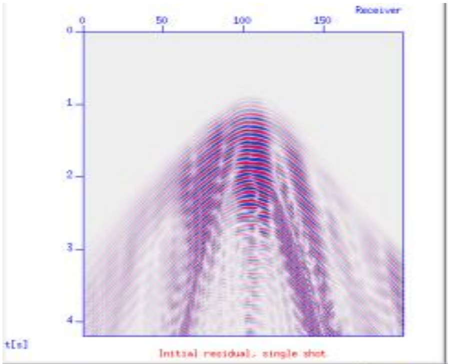
Adjoint wavefield — Forward wavefield

$$f^\dagger(\mathbf{x},t) = -\sum_i \partial_t^2\Delta p_i(T-t)\,\delta(\mathbf{x}-\mathbf{x}_i).$$ Adjoint source

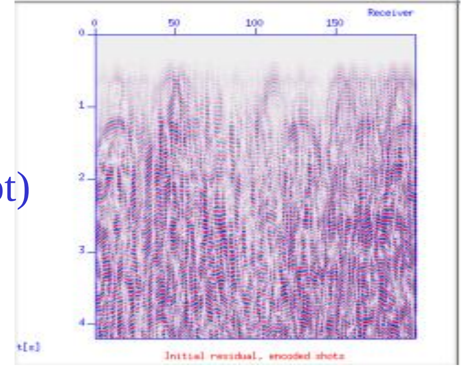
Encoded simultaneous-source (ESS)-FWI

- Capdeville et al. (2005, GJI); Krebs et al. (2009, Geophys.); Ben-Hadj-Ali et al. (2011, GJI)
- **Exploit linearity of wave equation over sources to reduce number of simulations**
- Easily applied with permanently installed receivers (e.g. OBC)
- "Cross-talk" noise introduced

1 shot



576 shots
(1 supershot)



	Simulated wave equation F u ~ modeled waveforms s ~ source m ~ current model	**Misfit functional** h d ~ data
Standard FWI N_S **events**	$F(u;m,s_n)=0$ $n \le N_S$	$h(u;m) = \frac{1}{2}\sum_{n=1}^{N_S}\left\Vert u(m,s_n)-d_n\right\Vert^2$
Encoded-source FWI **1 event**	$F(u;m,\sum_{n=1}^{N_S} c_n s_n)=0$ $c_n = \pm 1$ (random codes)	$\tilde{h}(u;m) = \frac{1}{2}\left\Vert \sum_{n=1}^{N_S} c_n u(m,s_n) - \sum_{n=1}^{N_S} c_n d_n \right\Vert^2$

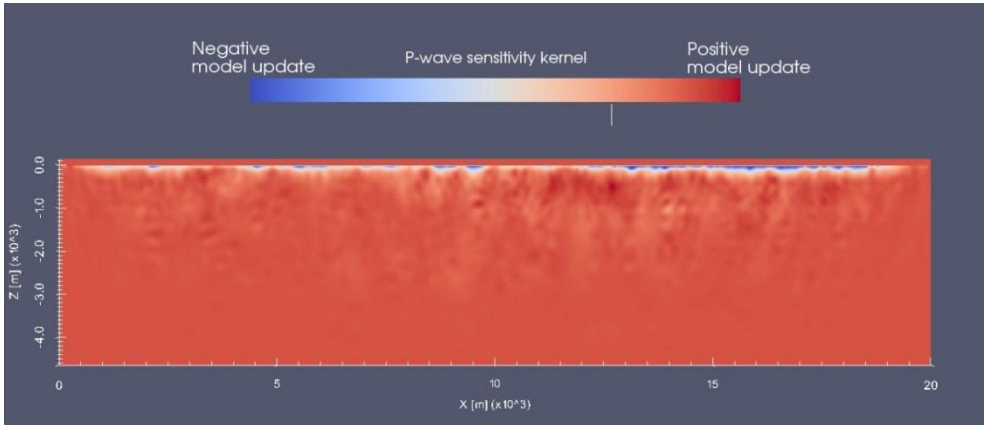
Inversion strategies

<u>Gradient clipping ("preconditioning")</u>

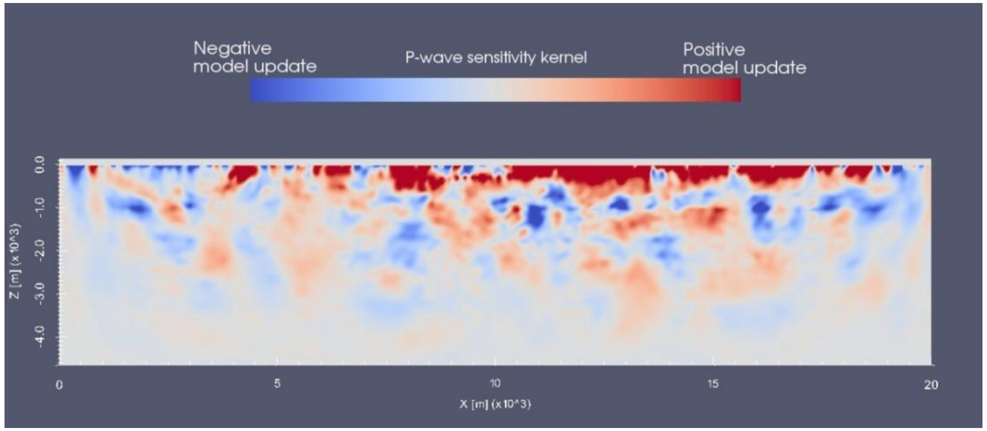
- Depth + iteration-dependent threshold
- Reduce sensitivity at surface
- Enhance sensitivity at depth

<u>Multi-scale modeling</u>

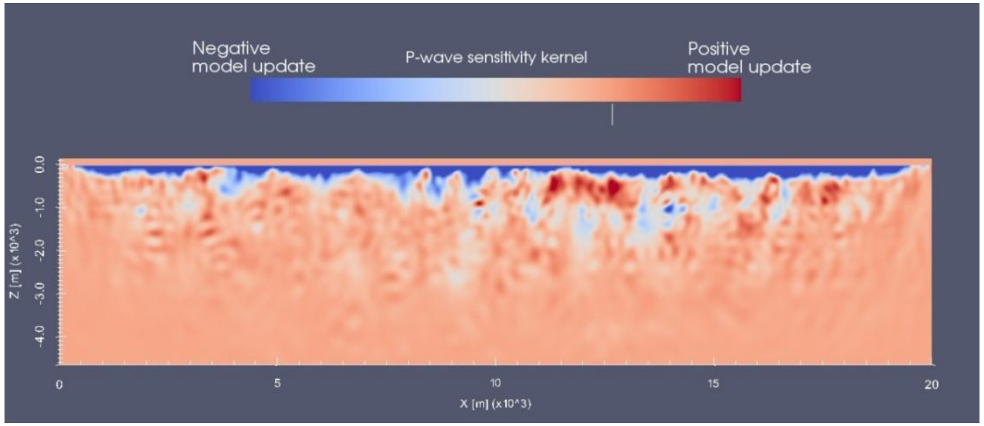
- Filter with increasing cutoff frequencies
- Time-windowing may not be possible with source encoding



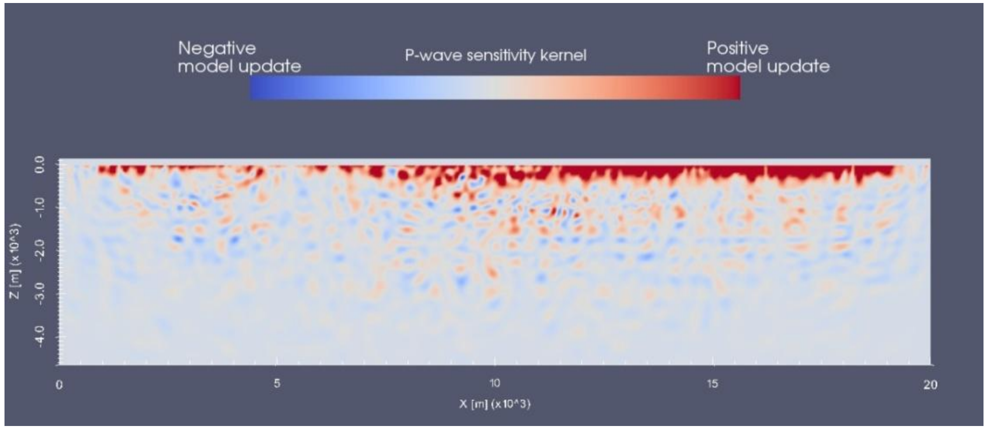
Raw (unclipped) gradient



Lowpass 1.0 Hz



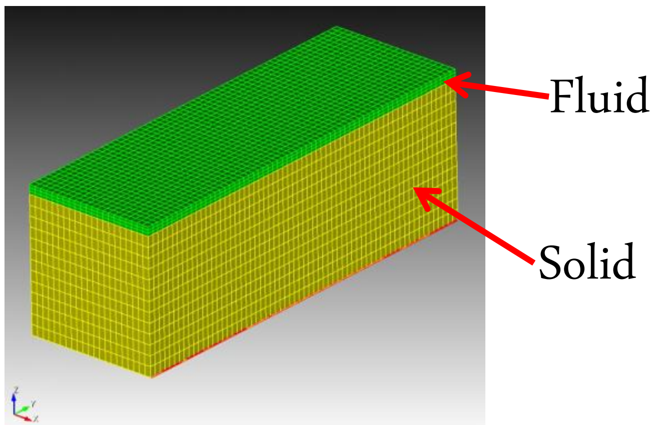
Clipped gradient



Lowpass 6.0 Hz

Why SPECFEM3D?

- High-accuracy SEM
- Forward + adjoint solves
- Fluid-solid interface support for elastic modeling



- Options for anisotropy, attenuation
- Scalable to many CPUs
- **Well-developed community code**

Why Python?

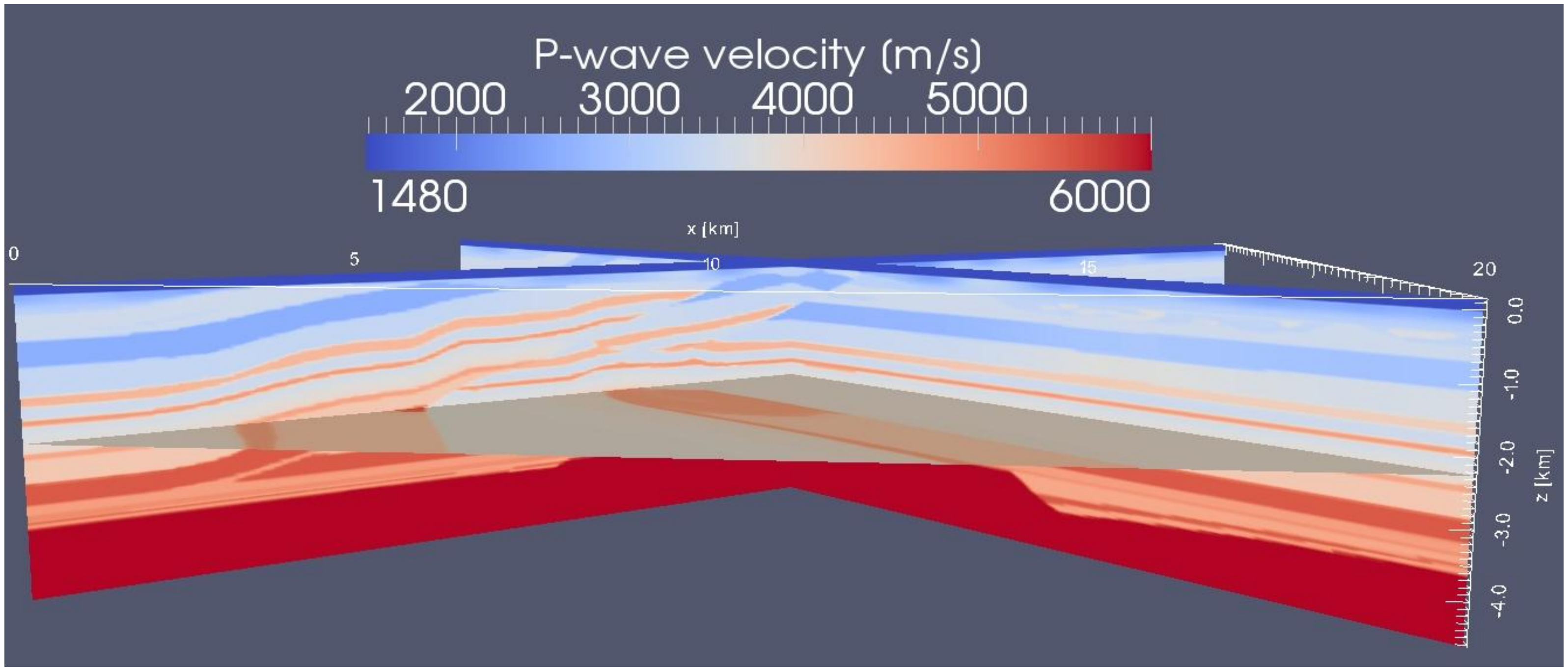
- Integrate heterogeneous workflow components

Python
- SPECFEM3D
- Seismic Unix
- Obspy libraries
- Shell scripts

- Obspy toolbox for data processing
- High-level / transparent code
- **Fast development**

```
>>> from obspy.core import read
>>> st=read("raw_data.SU")
>>> st.filter("lowpass",freq=3.0)
>>> st.write("filtered_data.SU")
```

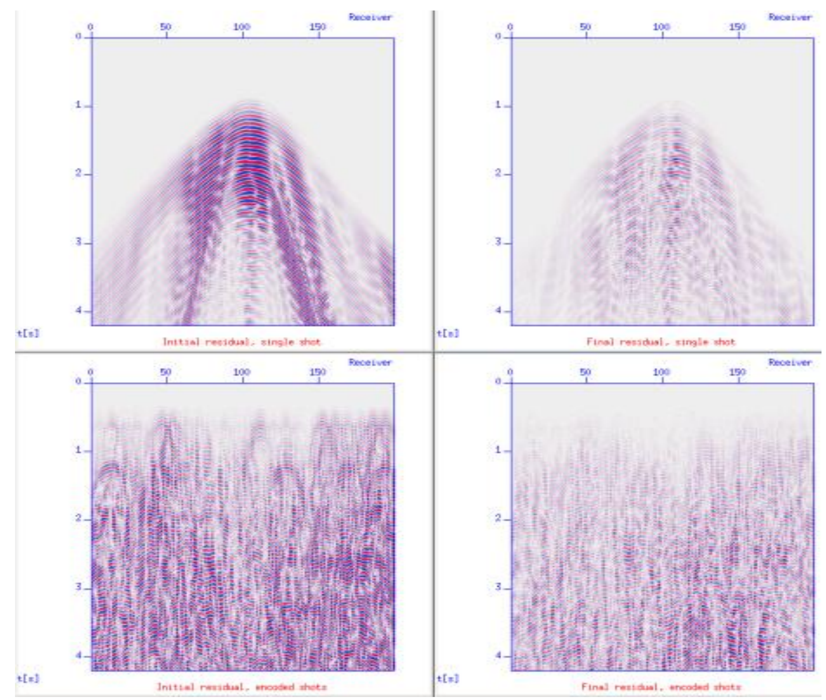
Synthetic Application [SEG/EAGE overthrust model]



- 3-D acoustic model
- 20 x 20 x 4.5 km^3 + water layer
- SEM edge length = 150 m
  - 550,000 elements
- 576 sources + 40,000 receivers
  - source/receiver reciprocity
- **One (!) supershot**
- 1.0 – 6.0 Hz
- 1 iteration ~ 80 CPU-hours
  - 130 total iterations

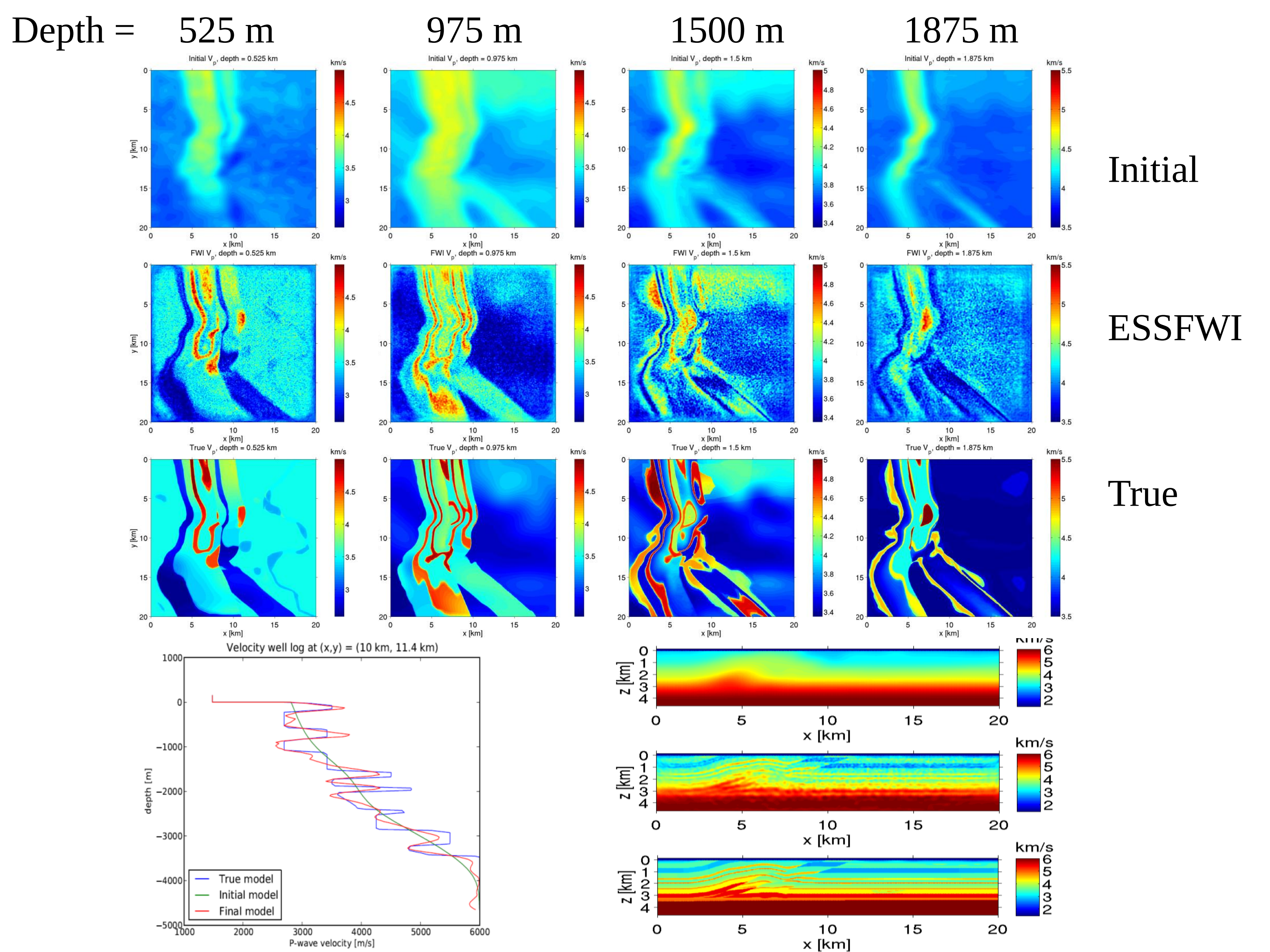
1 source

576 encoded sources



Initial misfit

Final misfit



Depth =
525 m
975 m
1500 m
1875 m
Initial
ESSFWI
True
Initial V_p, depth = 0.525 km
Initial V_p, depth = 0.975 km
Initial V_p, depth = 1.5 km
Initial V_p, depth = 1.875 km
FWI V_p, depth = 0.525 km
FWI V_p, depth = 0.975 km
FWI V_p, depth = 1.5 km
FWI V_p, depth = 1.875 km
True V_p, depth = 0.525 km
True V_p, depth = 0.975 km
True V_p, depth = 1.5 km
True V_p, depth = 1.875 km
km/s
x [km]
y [km]
Velocity well log at (x,y) = (10 km, 11.4 km)
True model
Initial model
Final model
depth [m]
P-wave velocity [m/s]
z [km]

Application to Valhall oilfield data

Valhall oilfield, North Sea

- 50,000 shots, 2300 receivers
- Ocean-bottom cable data (OBC)
- Permanently-recording system
- 2 surveys / year
- Acoustic FWI demonstrated
  (Sirgue et al., 2010)
- Time-lapse studies (“4-D seismic”)

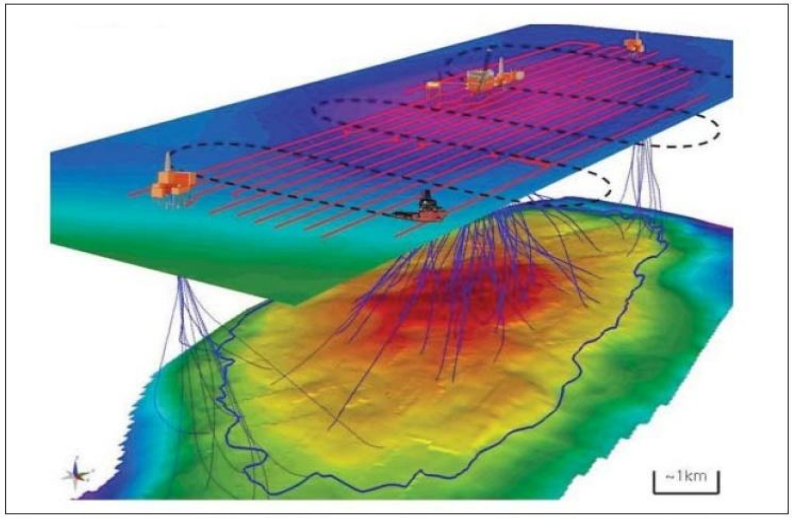
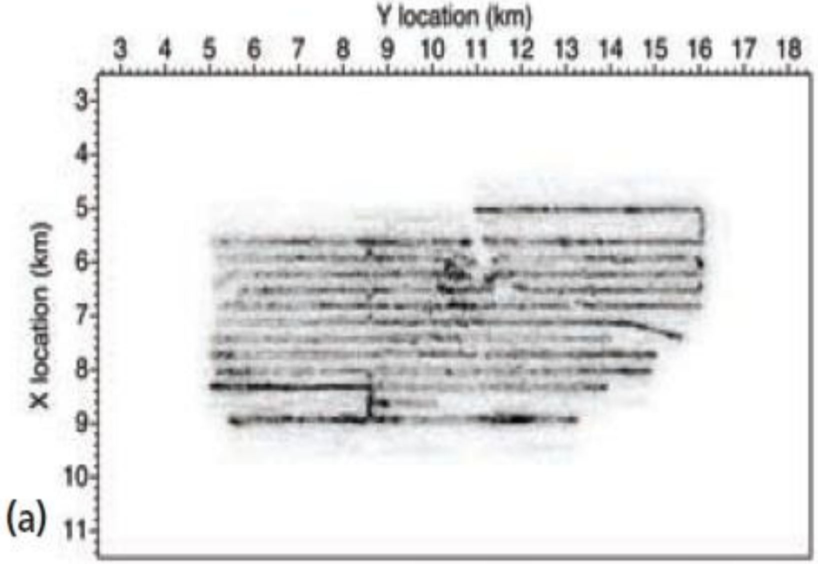


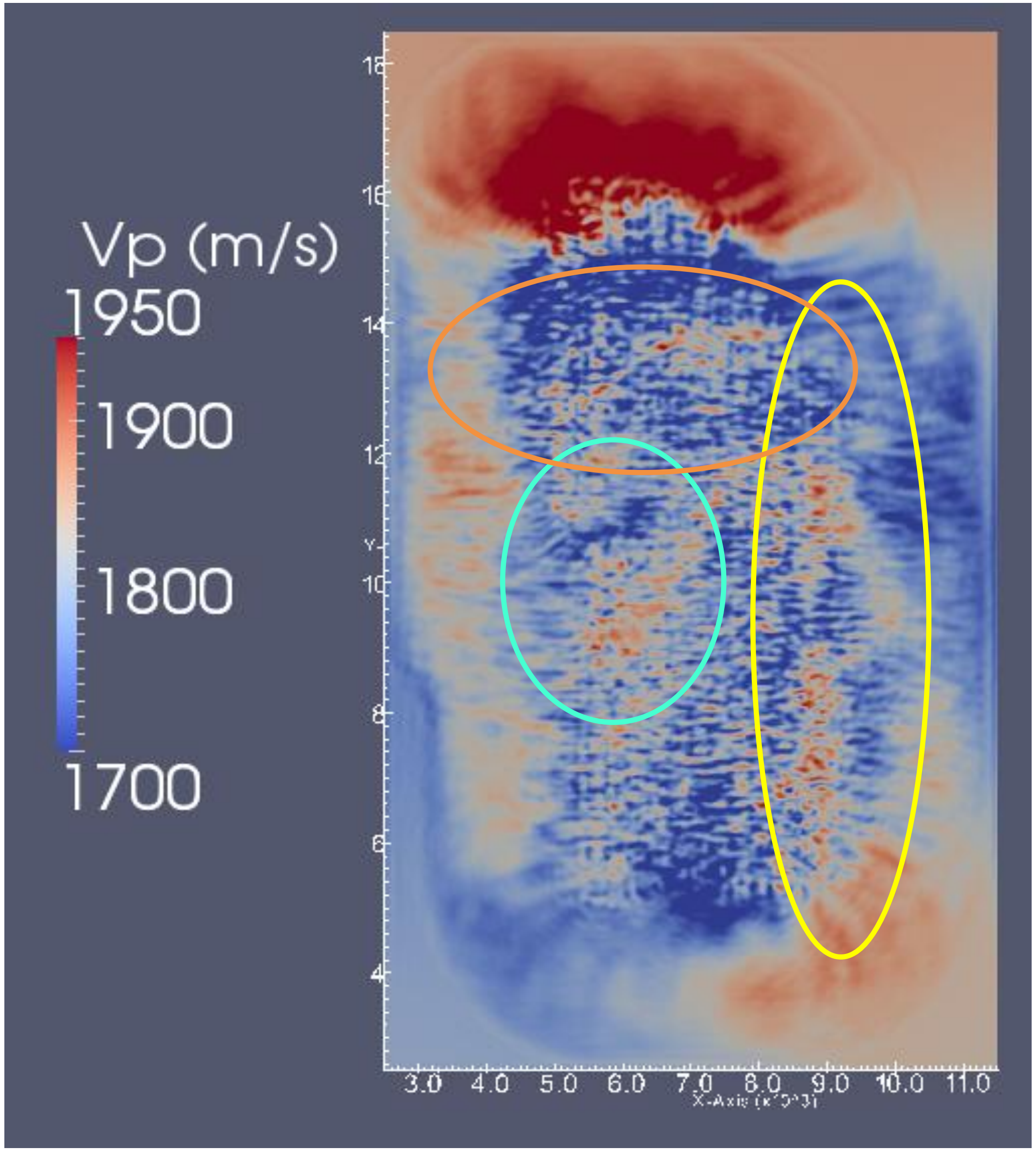
Figure 1. Overview of Valhall Field showing the layout of the geophone array at the sea floor (red lines), the top of the reservoir, the outline of the field (dark blue line), and the wells (thin blue lines).

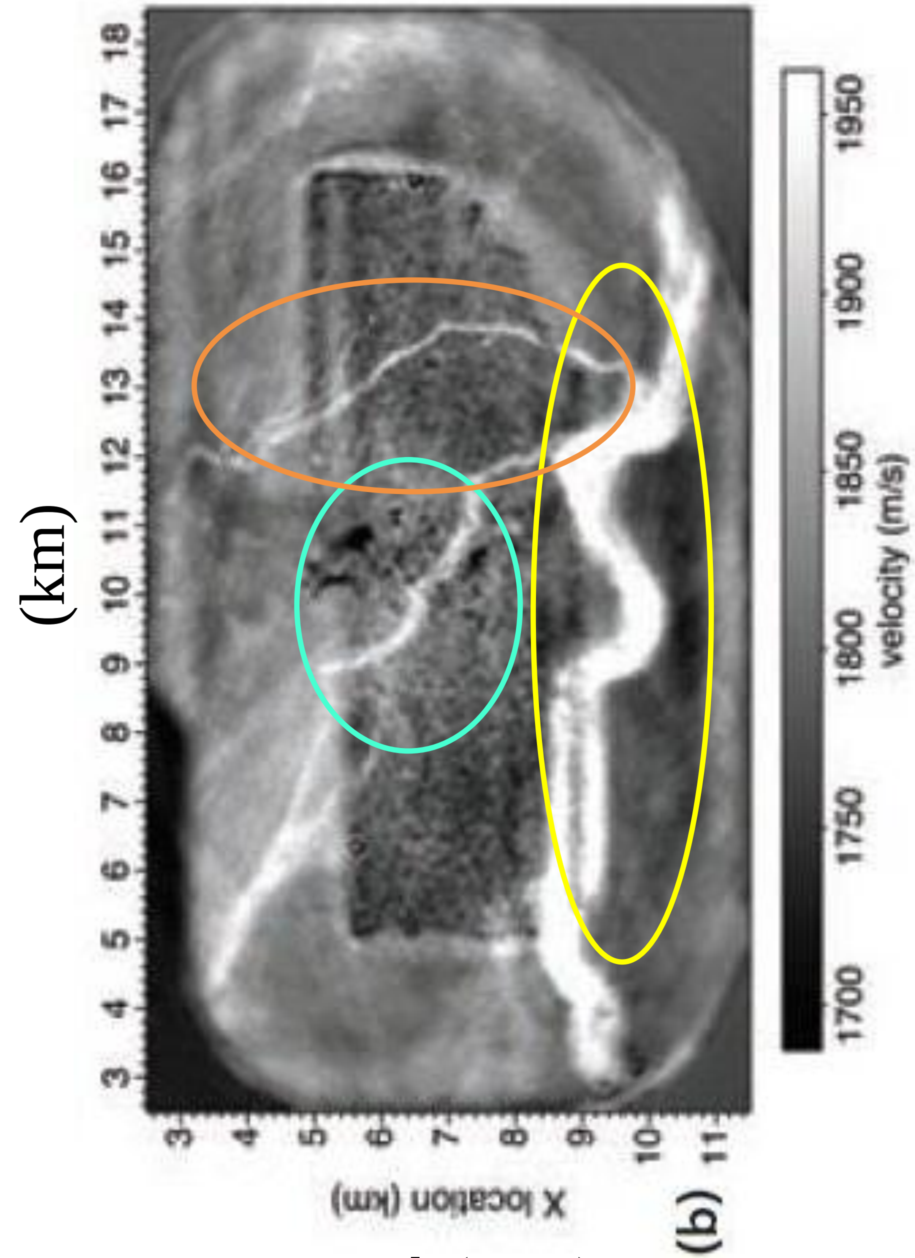
Gestel et al. (2008), TLE



Receiver array
(Sirgue et al., 2010, First Break EAGE)

Valhall: early results

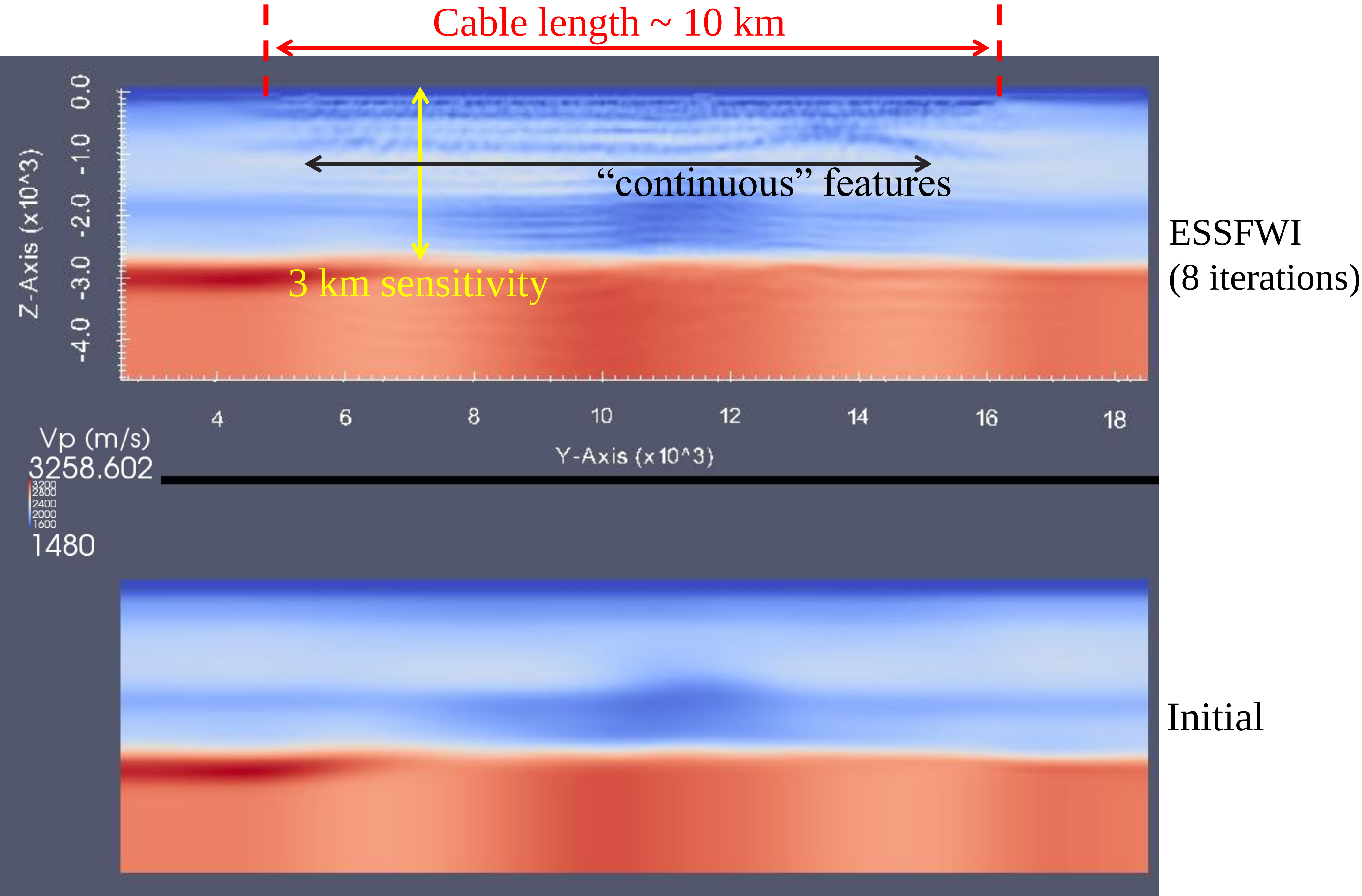




Sirgue et al. (2010)

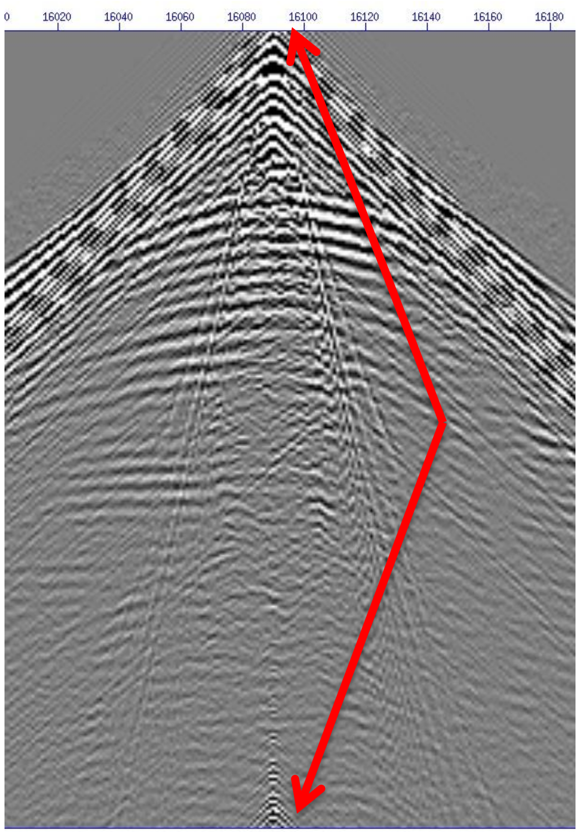
- ~200 m depth
- 10 supershots [~230 encoded shots / supershot]
- 8 ESSFWI iterations [~280 CPU-hour s/ iteration]

Valhall: early results



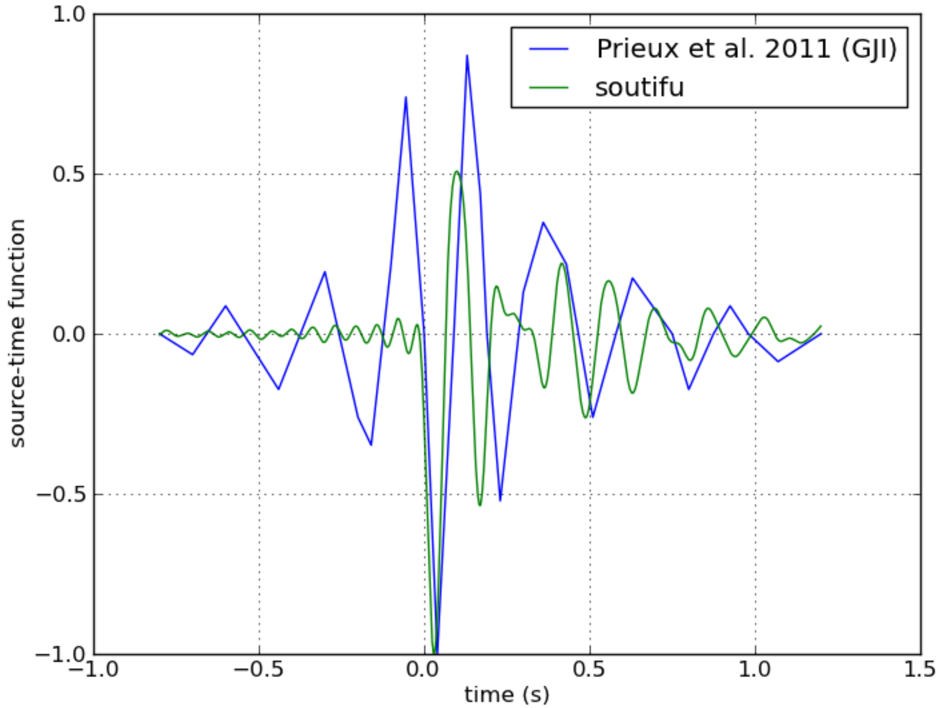
Source-time function inversion

- **soutifu** from TFSoftware (Thomas Forbriger)
- Weighted least-squares deconvolution



Common receiver data

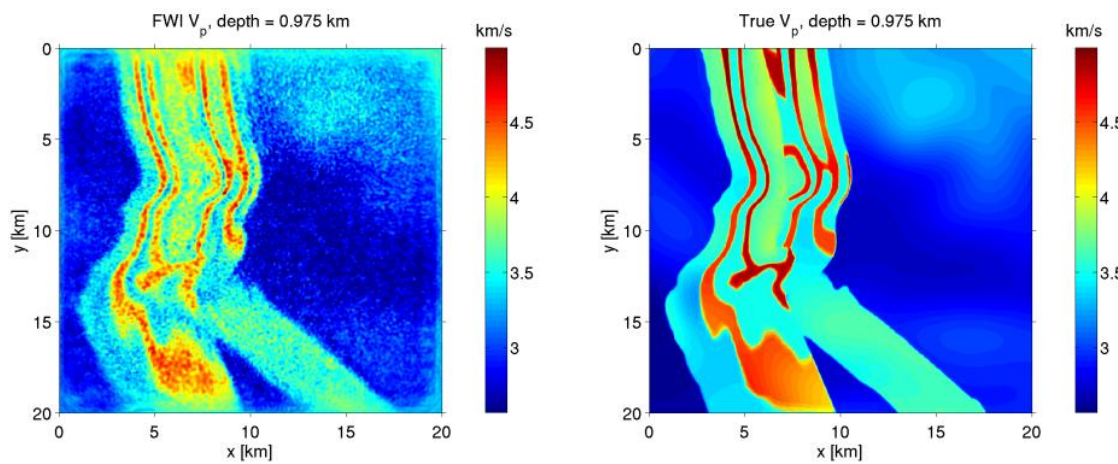
➢ Data processing steps are lumped into source function



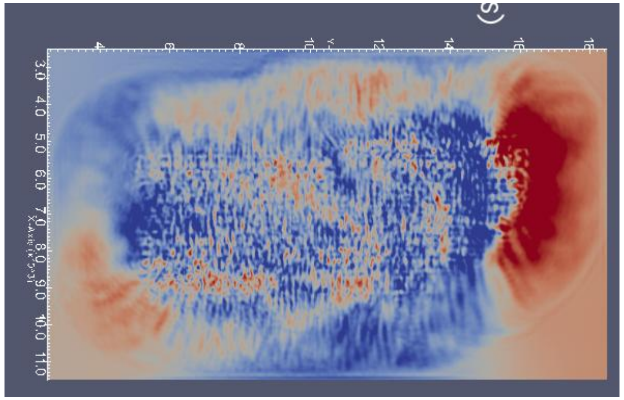
Computed source-time functions

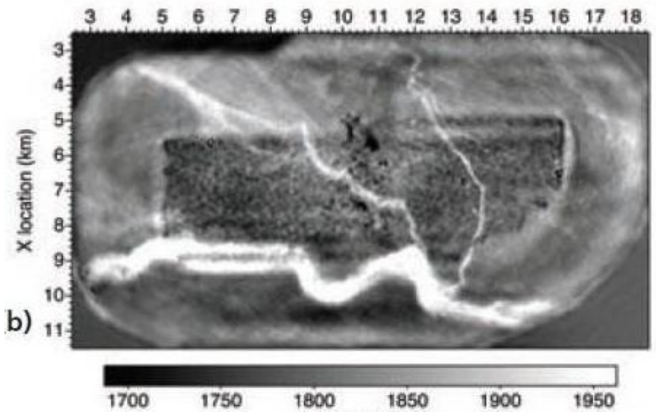
Summary

- ESSFWI: reduce # of sources to simulate for FWI
- Python-driven workflow + SPECFEM3D solver
- Obspy libraries
- Synthetic application
  - 1 supershot
  - Works great!



- Real-data application to Valhall oilfield
  - 10 supershots
  - Promising start





Inversion Workflow