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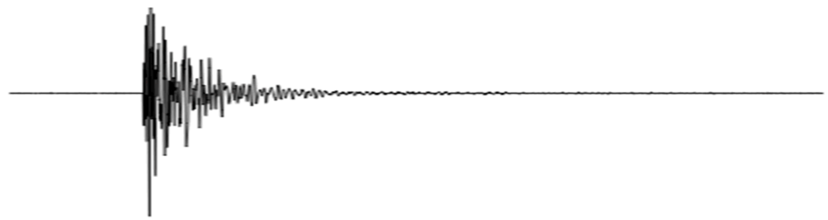

Full Waveform Inversion Methods for Source and Media Characterization Before and After SPE5

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

1. **Introduction**
   Source Physics Experiment shots and objectives

2. **Methods**
   Full waveform inversion for source and media

3. **Results**
   Acoustic, Elastic, and Anelastic physics
   Forward simulations and inversions

4. **Future work**
   Improvements to source model and velocity model
   Utilize different inversion techniques

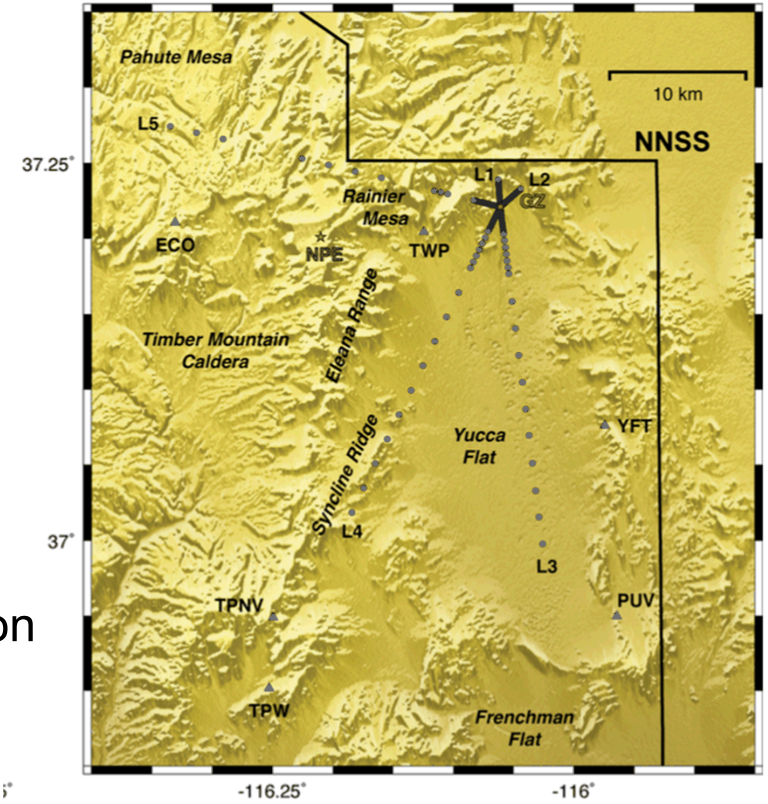
Source Physics Experiment (SPE)

Experimental setup:

- Granite Climax Stock at the Nevada Nuclear Security Site
- 100m spaced short-period geophone arrays, accelerometers, rotational sensors, and broadband sensors further out
- Varied yields and depth of burial

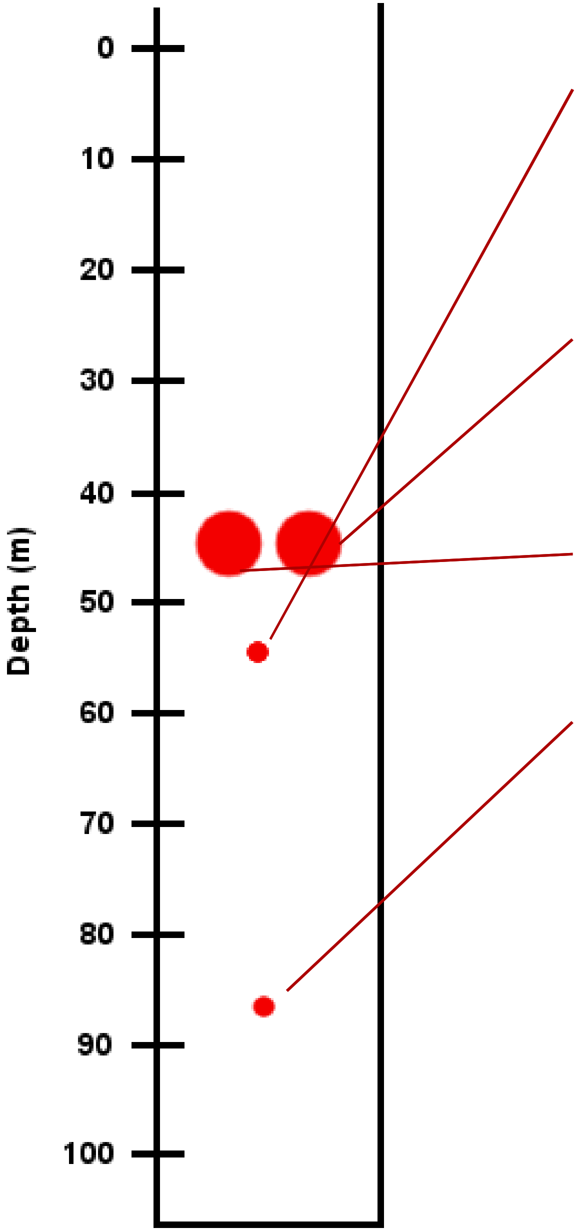
Goals:

- Improve existing models to allow discrimination of explosions in various conditions
- Impact of medium damage
- Mechanisms for S-wave generation



Mellors et al., 2011

First four shots of SPE4 lead to improved models and techniques



SPE1, May 3, 2011, 22:00:00
DOB 54.9m, W 87.9kg TNT

SPE2, Oct. 25, 2011, 19:00:00
DOB 45.7m, W 997kg TNT

SPE3, July 24, 2012, 18:00:00
DOB 45.8m, W 905kg TNT

SPE4prime, May 21, 2015, 18:36:00
DOB 87.2m, W 89.1kg TNT

SPE5, planned
Expected W: 5000kg TNT, DOB: a few meters shallower than SPE4prime

Full waveform inversion for source and medium

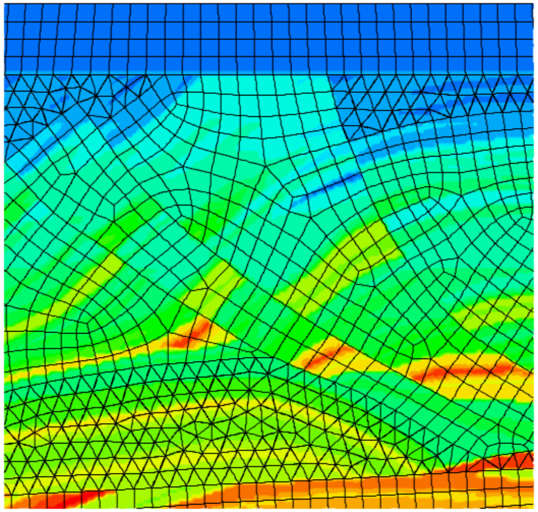
Code characteristics

Discontinous Galerkin method (DGM)
Unstructured meshes, local polynomial refinement
Different physics: **Acoustic, Elastic, Anelastic, Viscoanisotropic**
Time integration: **Runge-Kutta, TVD, Multistep, Backward Euler, Trapezoidal**
Numerical Fluxes: **Lax-Friedrichs, Steger-Warming, Riemann**
Trilinos toolkit

Why this method?

- Allows for inhomogeneous material variations within each element for realistic earth models

- Curved elements and hybrid meshes with both simple and complex elements to allow for better fit to subsurface topography



From Smith et al. SEG 2010
Unstructured Marmousi2 from Martin et al. 2006

Objectives

1. Source and medium inversion for SPE4prime
2. Use the results for SPE4prime to estimate station observations for SPE5

Progress

Forward modeling with Acoustic, Elastic, and Anelastic physics for each array and all numerical fluxes

Matched source amplitude, frequency content by comparing data and synthetics

Acoustic source inversions for SPE4prime – 2D and 3D

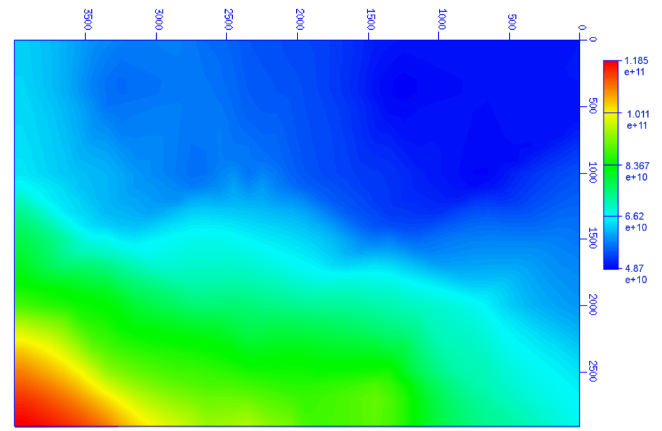
Lax-Friedrichs, Fourth-order Runge-Kutta, nonlinear optimization algorithm with gradient update using steepest descent with line search

Earth models

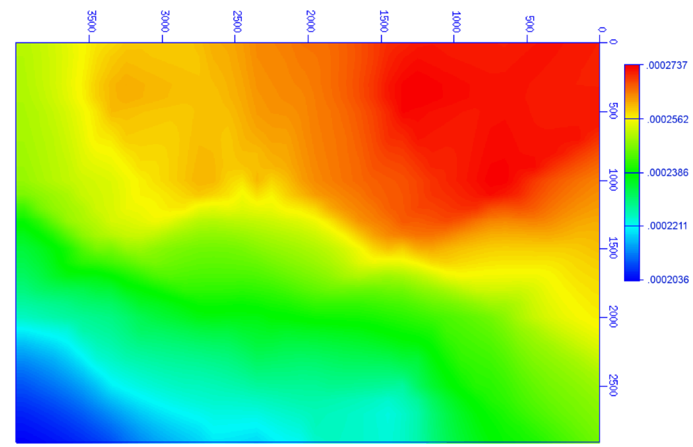
Initial starting model: 3D tomography model from Leiph Preston, 2 km spacing in horizontal directions

2D slices along each array
3D volume centered at source location

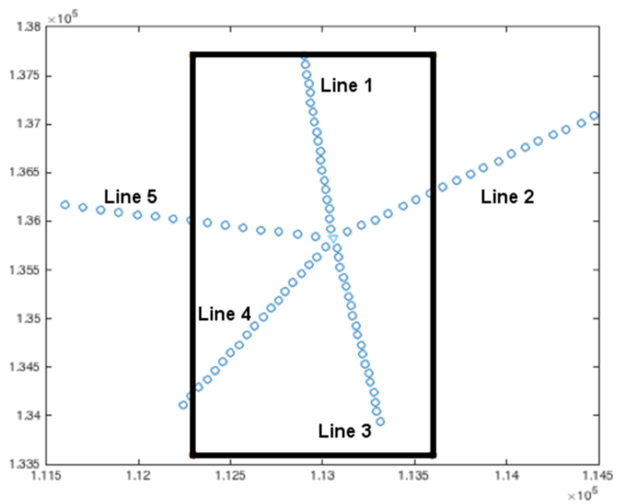
Alternative model tested: 3D model from LLNL (Pitarka et al. 2015; Wagoner 2014)



$\kappa=\rho V_p^2$ from vertical slice of 3D model



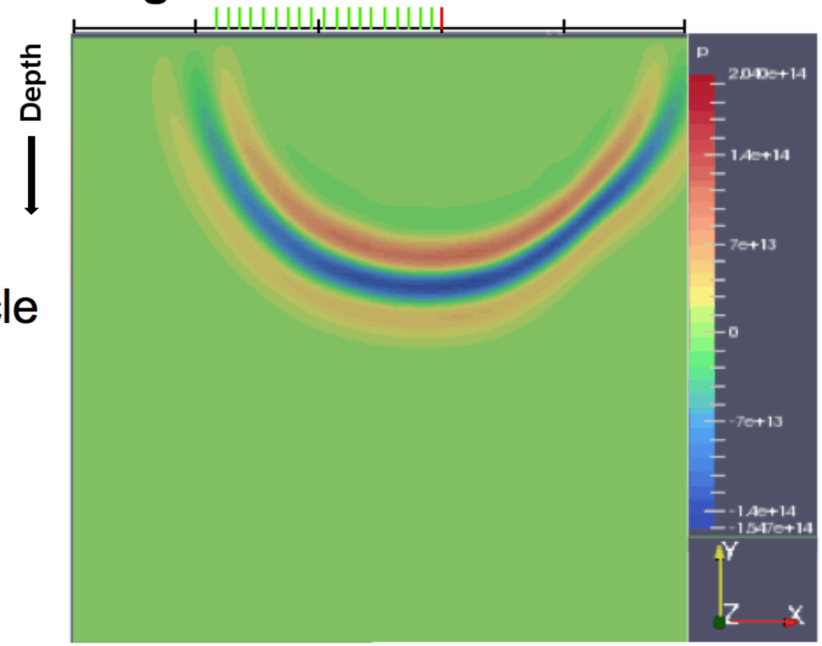
$v=1/\rho$ from vertical slice of 3D model



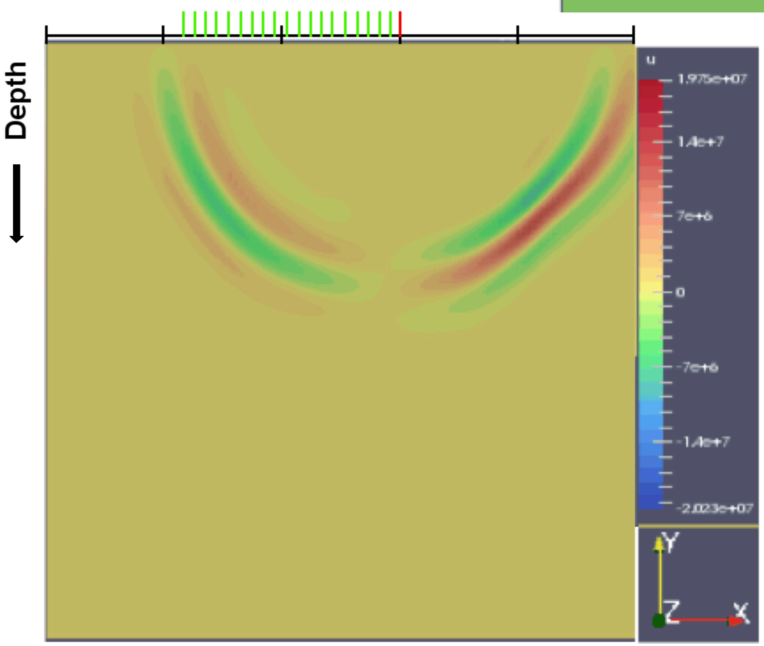
Acoustic Forward Modeling – Line 2

Vertical slice that includes Line 2

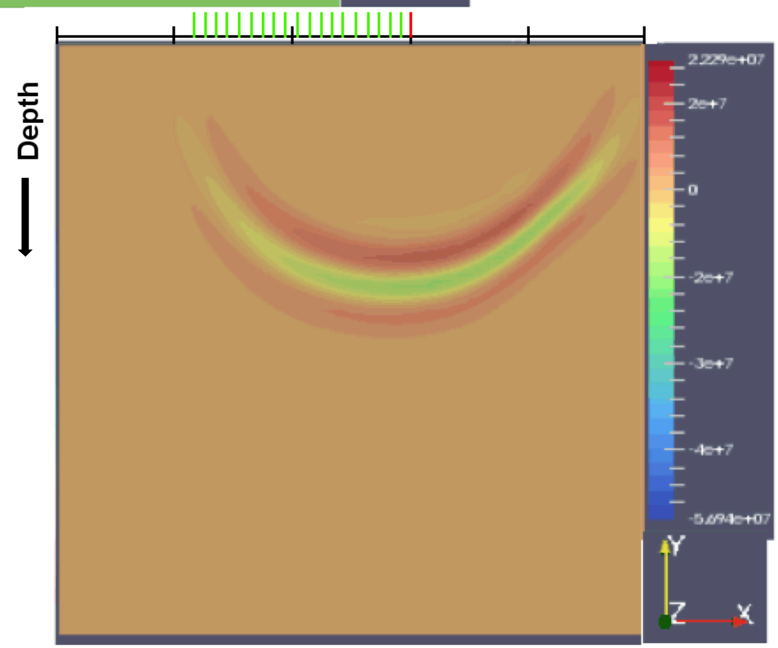
Pressure (p) and particle velocities (u,v)



p

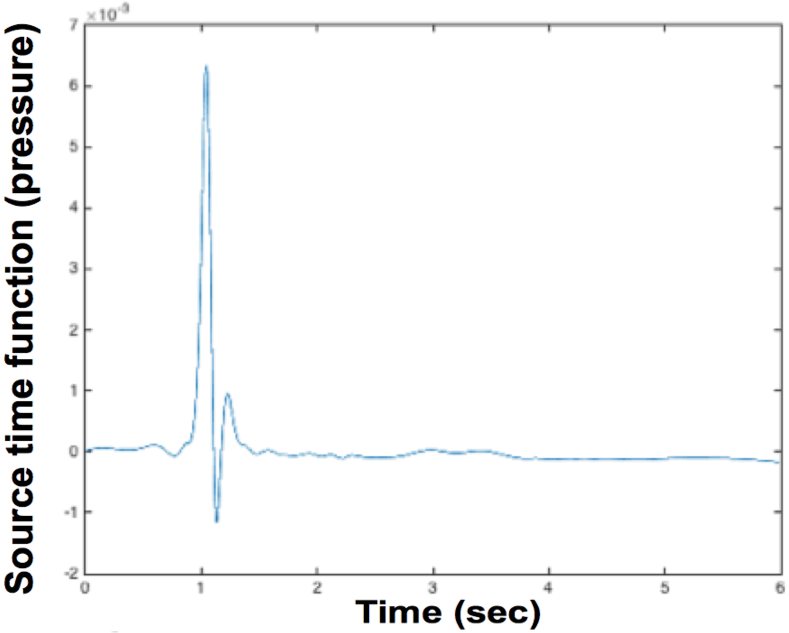


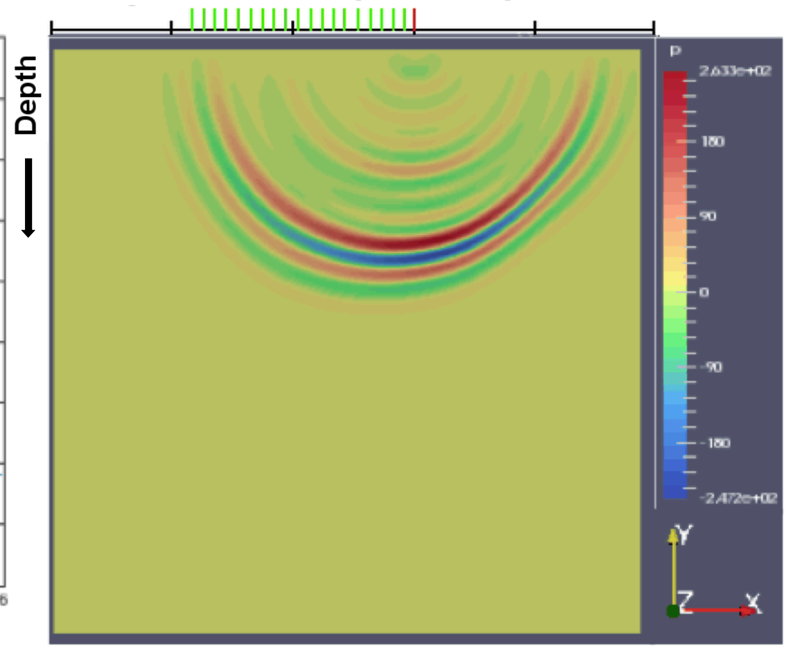
u

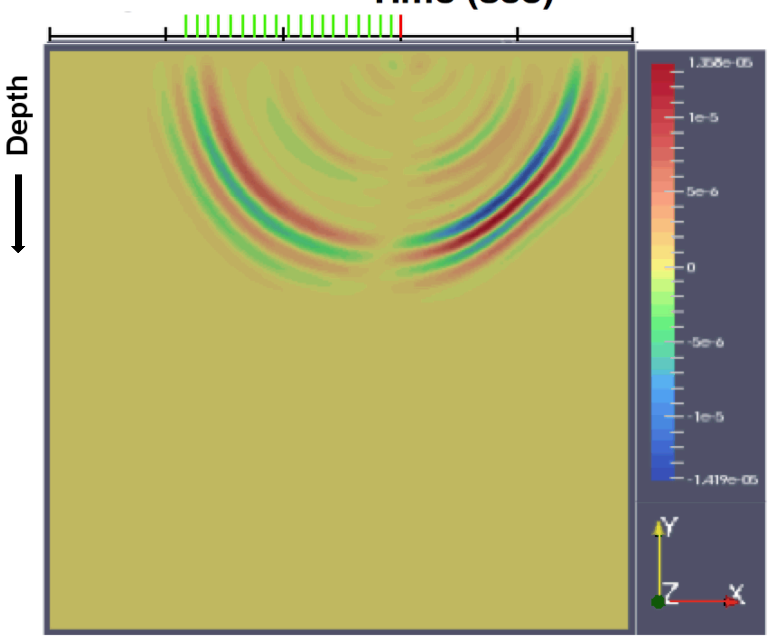


v

Inversion results: 2D Acoustic source inversion (Line 2)







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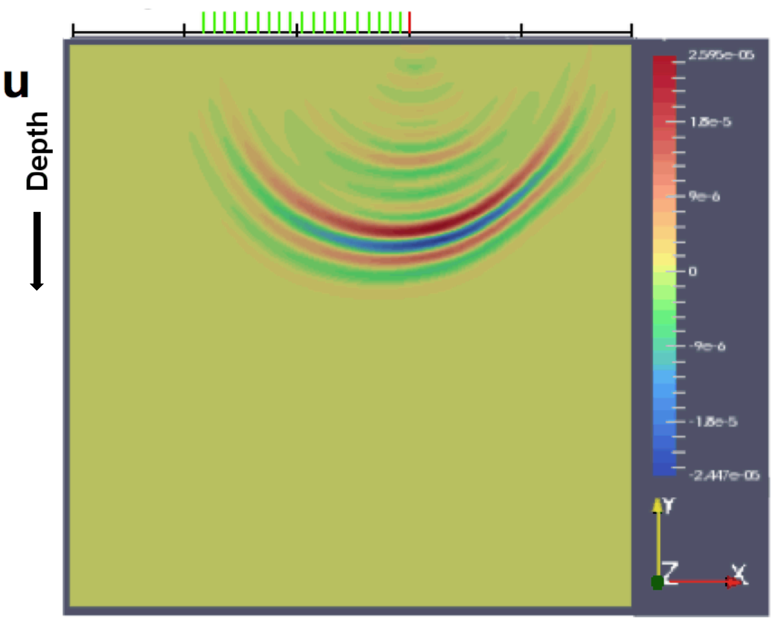
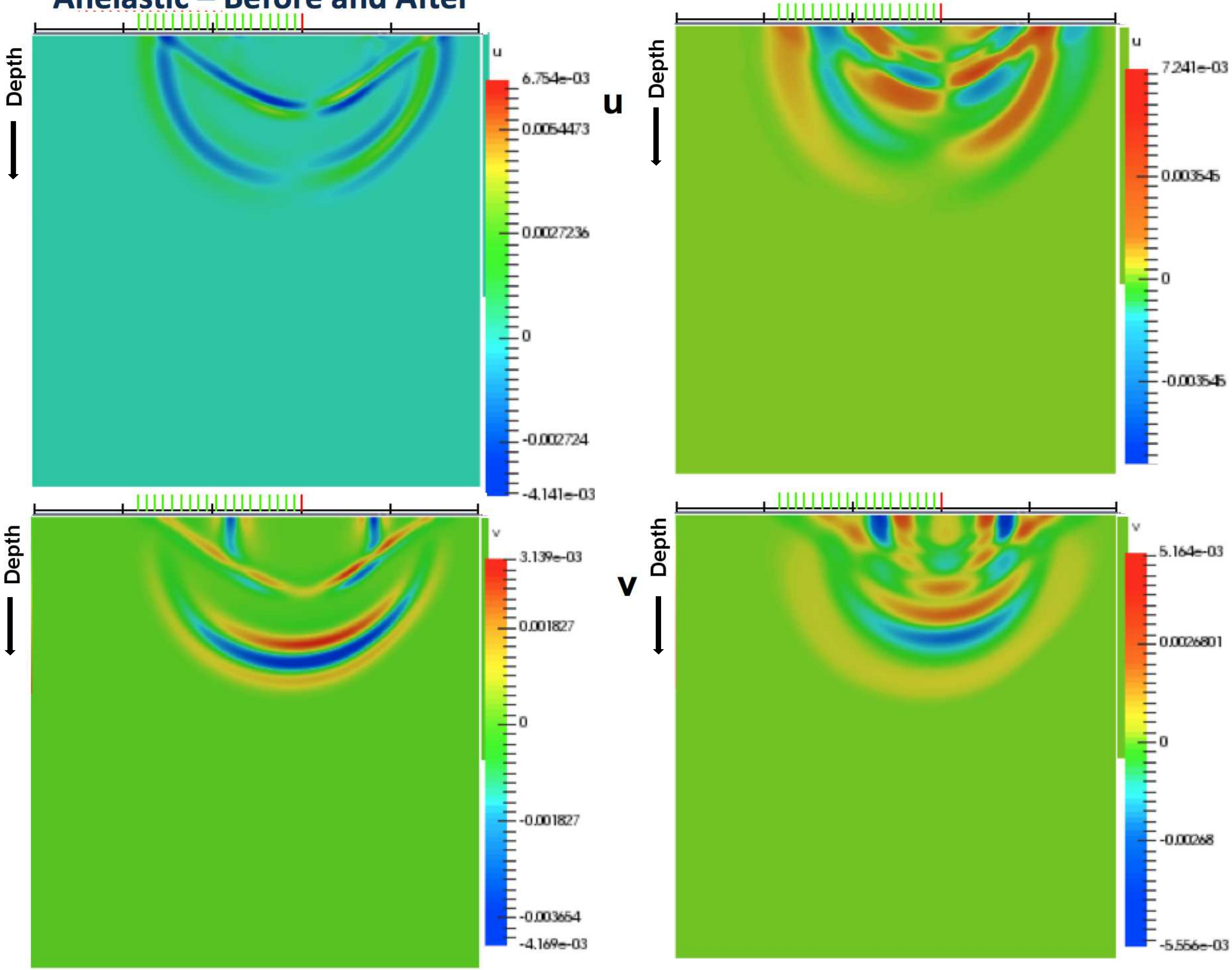


v

Anelastic – Before and After



Inversion results: 3D Acoustic source inversion, after 4 iterations

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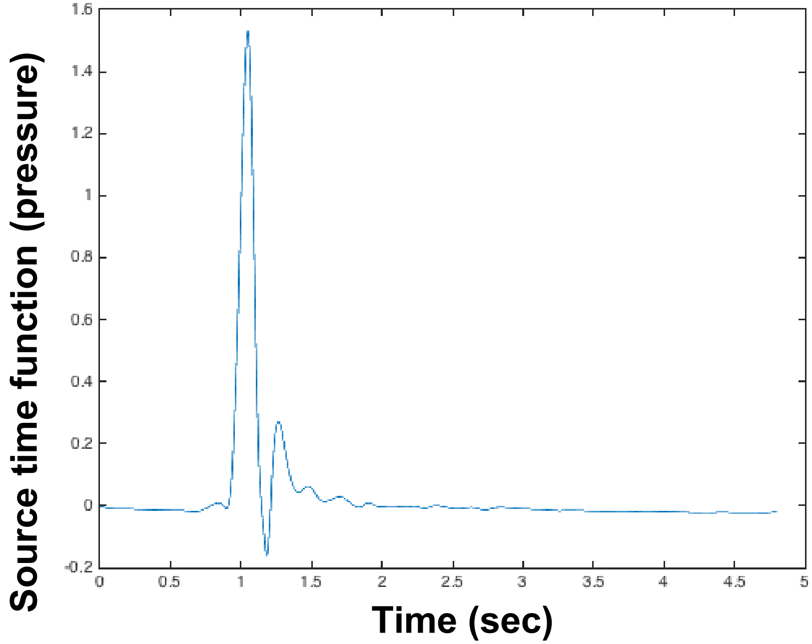

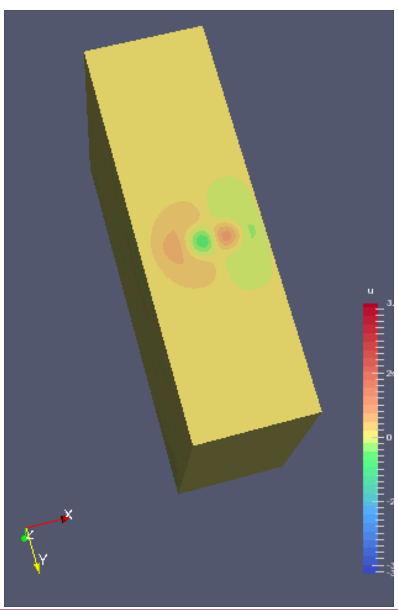

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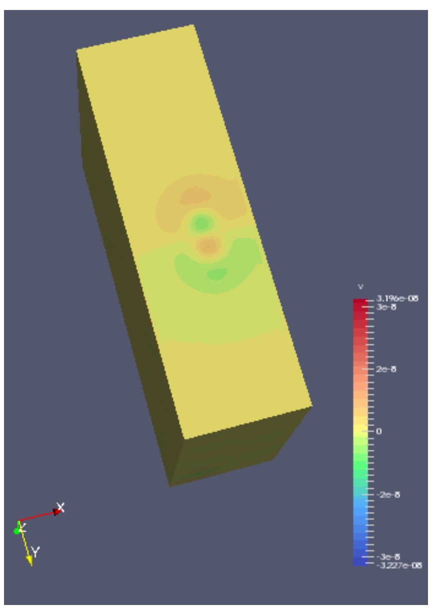
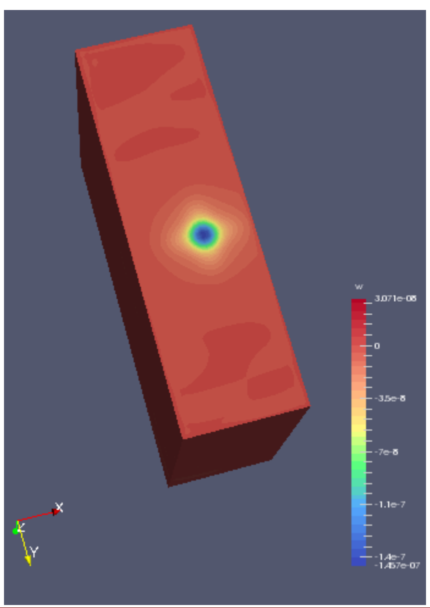
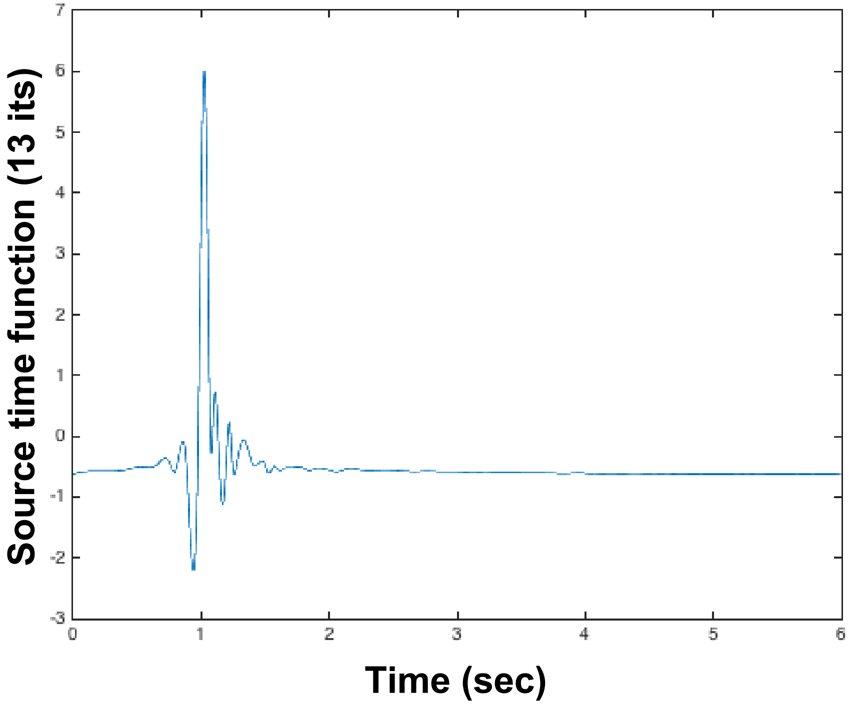


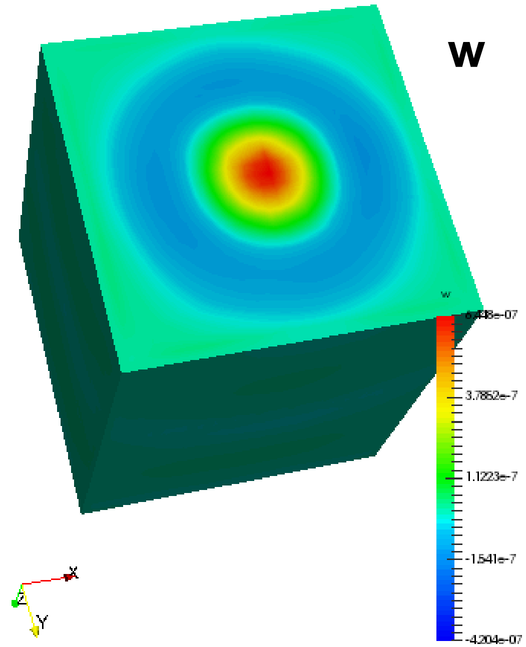
v



w

Inversion results: 3D Acoustic source inversion with velocity model from LLNL





Related papers:

Pitarka, A., R.J. Mellors, W.R. Walter, S. Ezzedine, O. Vorobiev, T. Antoun, J.L. Wagoner, E.M. Matzel, S.R. Ford, A.J. Rodgers, L. Glenn, & M. Pasyanos (2015). Analysis of Ground Motion from An Underground Chemical Explosion. Bulletin of the Seismological Society of America, Vol. 105, No. 5, pp. , Oct. 2015, doi: 10.1785/0120150066

Wagoner, J.L. (2014). Working toward a site-specific geomodel, Nevada National Security Site, RMR2014 Review of Monitoring Research for Ground-based Nuclear Explosion Monitoring Technologies, Albuquerque, New Mexico, 18 June 2014

Towards Predicting SPE5

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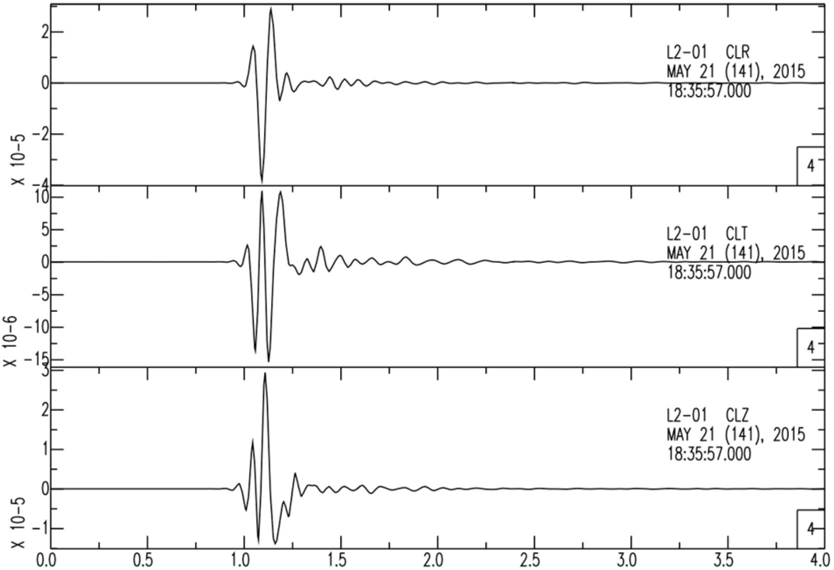
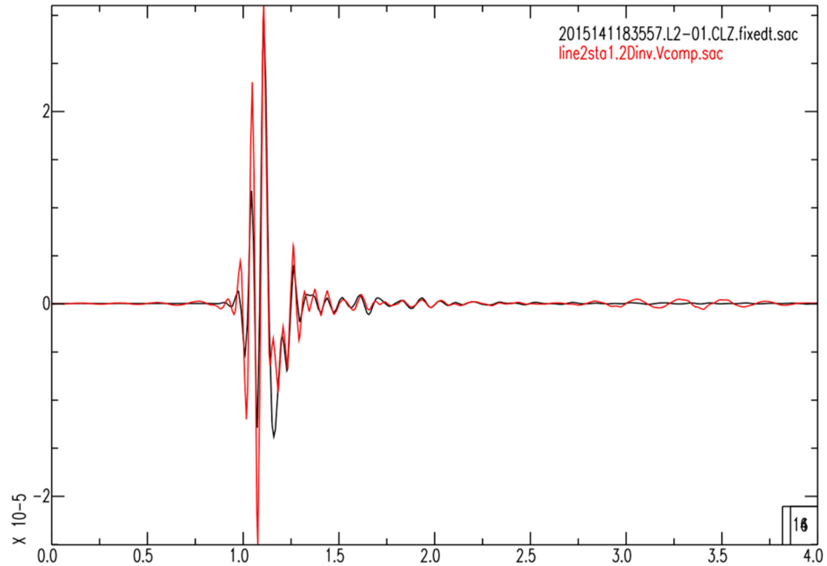
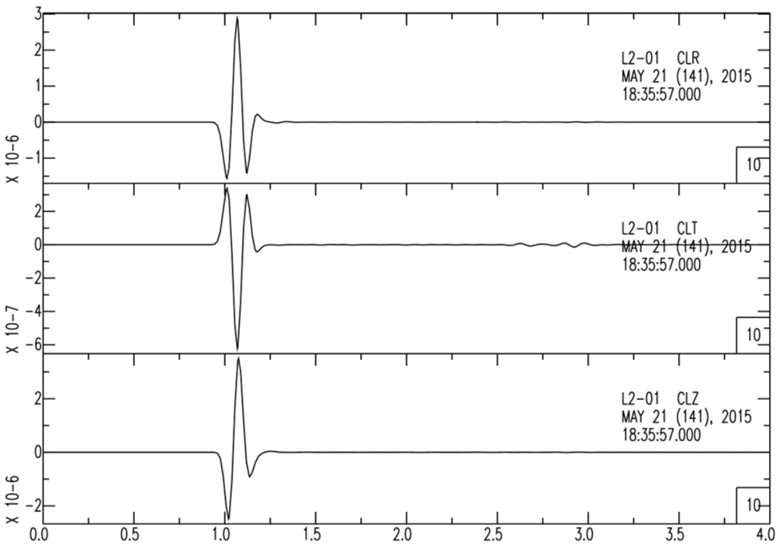
L2-01 Filtered data, fp = 10Hz



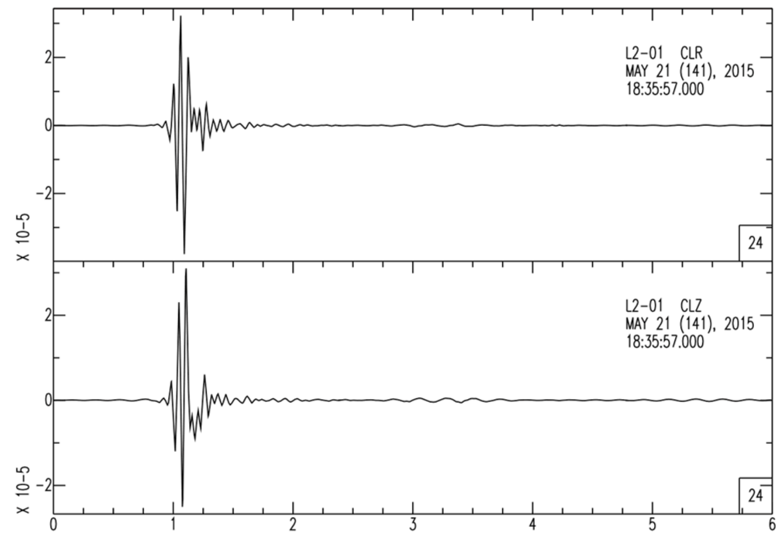
L2-01, CLZ synthetic fit to data (20 its)



Synthetics, before inversion (3D forward)



2D synthetics, after source inversion



Summary

- Similar source time functions obtained for both 2D and 3D Acoustic inversions for SPE5

- Increased complexity for simulations which include the new source function

- A better model for the source coupled with improvements in the velocity model will allow for predictions of observations of SPE5

Future Work

- Increase complexity of velocity model: medium inversions

- Perform inversions with Elastic, Anelastic, and Viscoanisotropic physics, different fluxes, time integration techniques

References:

Brocher, T. (2008). Key elements of regional seismic velocity models for long period ground motion simulations, J. Seismol, 12:217-221, doi 10.1007/s10950-007-9061-3

Graves RW, Pitarka A (2004). Broadband time history simulation using a hybrid approach. Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, paper no. 1098

Mellors, R.J., A. Rodgers, W. Walter, S. Ford, H. Xu, E. Matzel, S. Myers, N.A. Petersson, B. Sjogreen, T. Hauk, and J. Wagoner (2011). Pre-shot simulations of far-field ground motion for the Source Physics Experiment (SPE) Explosions at the Climax Stock, Nevada National Security Site: SPE2, Lawrence Livermore National Laboratory technical report, LLNL-TR-507132

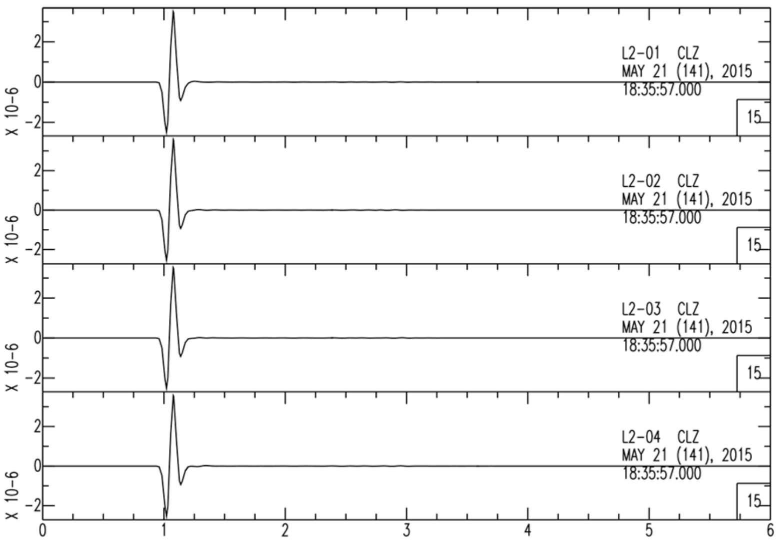
Martin, G.S., R. Wiley, and K.J. Marfurt (2006). Marmousi2: An Elastic Upgrade for Marmousi, The Leading Edge, 25, 156- 166

Smith, T.M., S.S. Collis, C.C. Ober, J.R. Overfelt, & H.F. Schwaiger (2010). Elastic Wave Propagation in Variable Media using a Discontinuous Galerkin Method, SEG Expanded Abstracts, 29:2982-2987

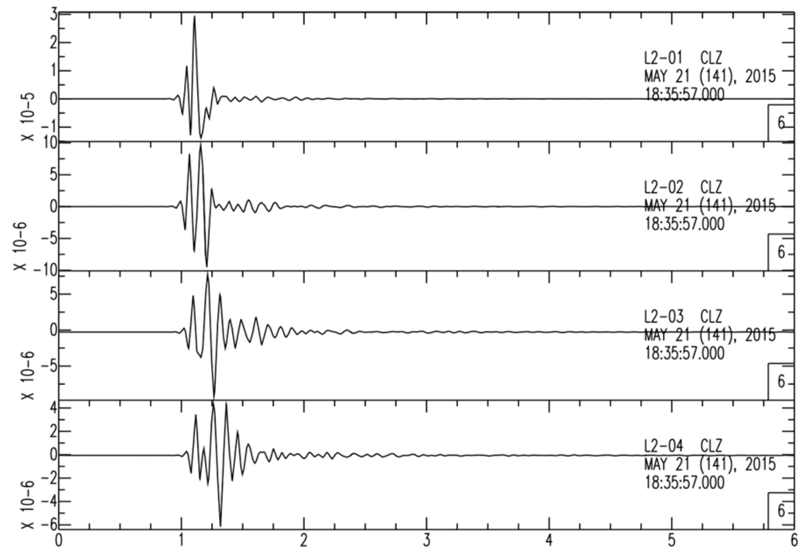
Backup Slides

Towards Predicting SPE5

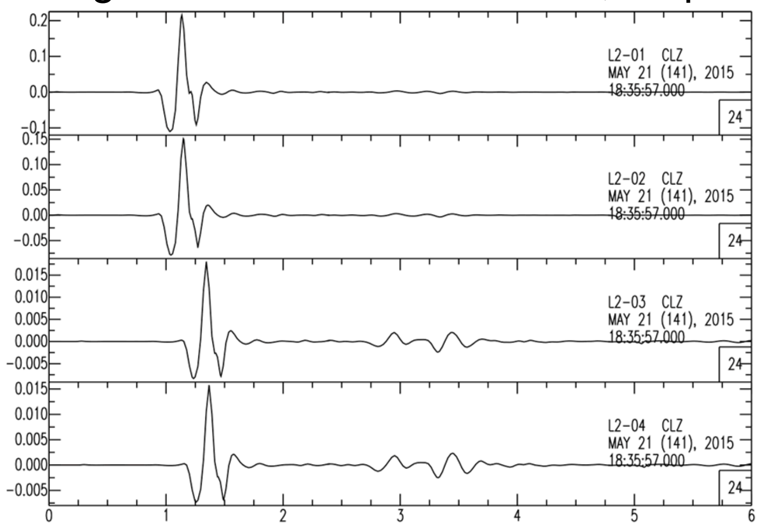
SPE4 synthetics before source inversion



L2 data



Using new source time function, amplitude expected for SPE5



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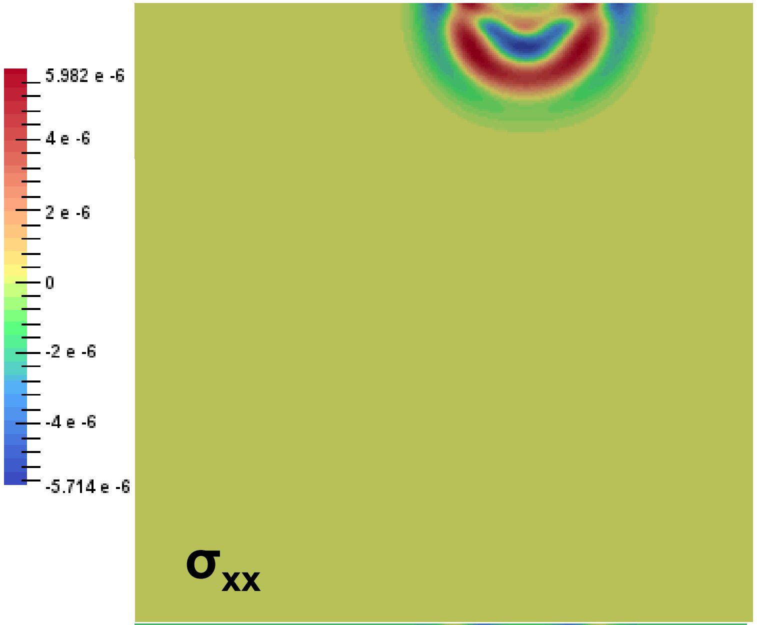
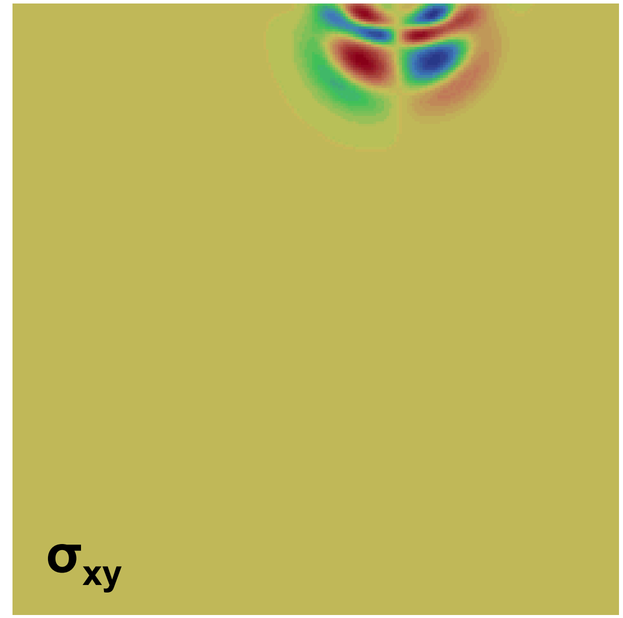
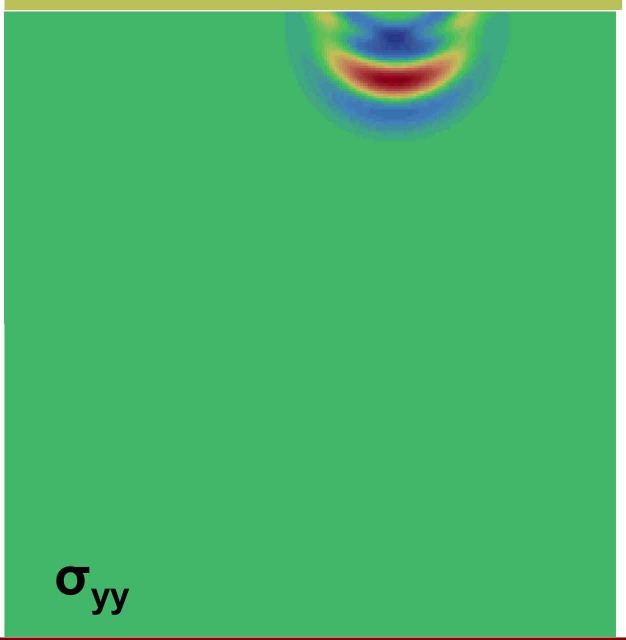
Example: Anelastic 2D Forward Modeling







- Line 2, 3.5 sec
- Includes attenuation
- Models for Qp, Qs

Brocher 2008, regression of Graves and Pitarka's (2004) values for 0.3 km/s < Vs < 5 km/s

- Observations for normal stresses and particle velocities are similar between all Lines for coarse velocity model

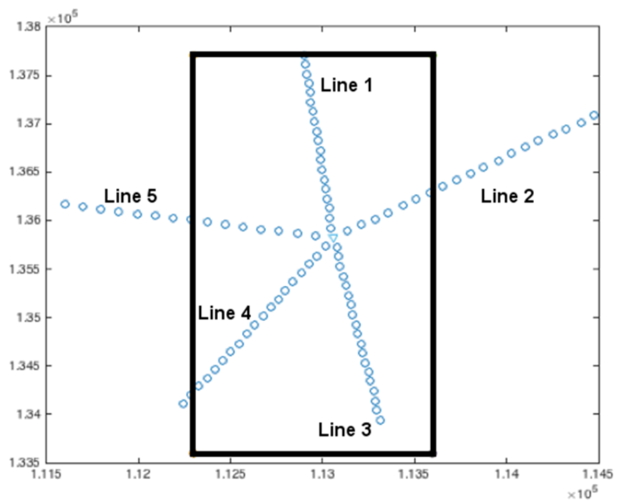
Earth models

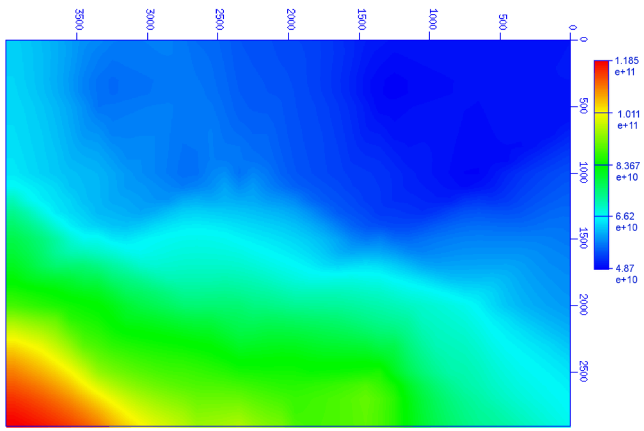
Different inversion parameterizations possible, physics dependent

V_p, V_s, ρ, Q_p, Q_s, $\kappa=\rho V_p^2$, $\mu=\rho V_s^2$, $v=1/\rho$, $\lambda=\kappa-2\mu$

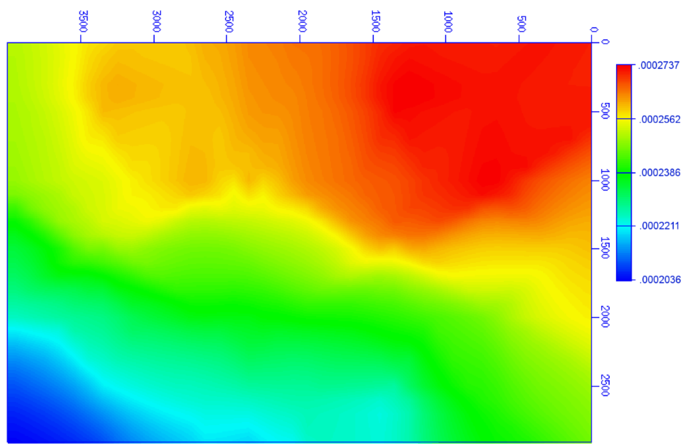
Initial starting model: 3D tomography model from Leiph Preston, 2 km spacing in horizontal directions

2D slices along each array
3D volume centered at source location





$\kappa=\rho V_p^2$ from vertical slice of 3D model



$v=1/\rho$ from vertical slice of 3D model