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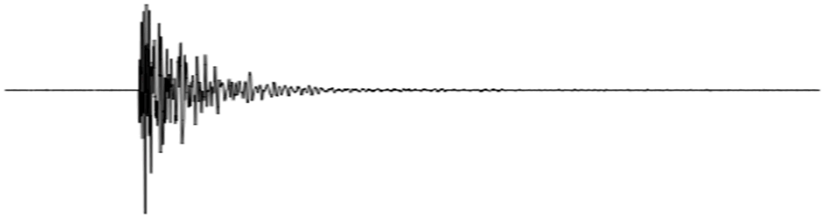

Full waveform source inversions for SPE data: results, challenges, and lessons learned

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

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- **Motivation and Objectives**
  - Source Physics Experiment (SPE)
- **Methodology**
  - Data sources and collection
  - Full waveform inversion code
  - Source inversions
- **Challenges overview**
- **Lessons Learned**
  - Including topography
  - Complex waveforms and simple velocity models
  - Filtering lessons: fit to raw data vs. fit to synthetics
- **Preliminary Results**
- **Conclusions and future work**

Motivation and Objectives

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- **Source Physics Experiment**
  - Series of chemical explosions at Nevada National Security Site conducted to advance our ability to detect and characterize explosions in a variety of complex media and different emplacement conditions

National Nuclear Security Administration

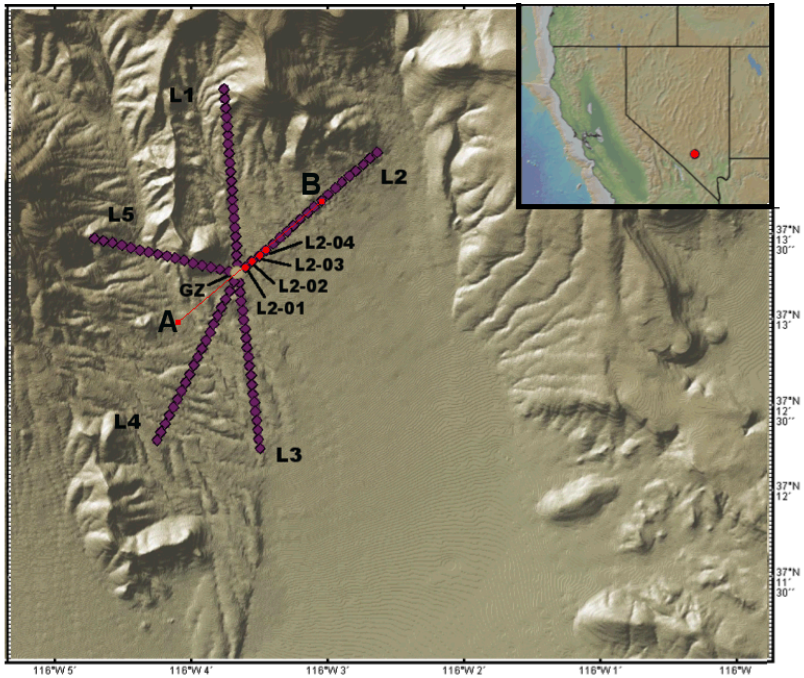
- **Scientific objectives**
  - Improve existing explosion models using physics-based numerical modeling techniques
  - Near-field and far-field investigations of explosive signature and impacts including S-wave generation and damaged zone

Nevada National Security Site

- **Experiment to date**
  - Four explosions in the same shot location in granitic geology. Differing yields and depths of emplacement.
  - Attempts are made to predict waveforms before each shot. Post-shot comparison with predictions allows for iterative model improvement
  - Next phase of experiment in Yucca Flats, alluvium geology

Methodology: Data Sources and Collection

SPE 1	SPE2	SPE3	SPE4prime	SPE5
3/3/2011	10/25/2011	7/24/2012	5/21/2015	Spring 2016
54.9m	45.7m	45.8m	87.2m	
W 87.9 kg	W 997 kg	W 905 kg	W 89.1 kg	



Well recorded in near and far field

Near field:
- triaxial accelerometers in azimuthally distributed boreholes at 10 m and 20 m distance

Far field:
- Five short-period geophone arrays with 100 m spacing, extending out to 2 km
- Accelerometers and rotational sensors at 1 km
- Accelerometers and broadband seismometers at more distant locations

Methodology: Full Waveform Inversion

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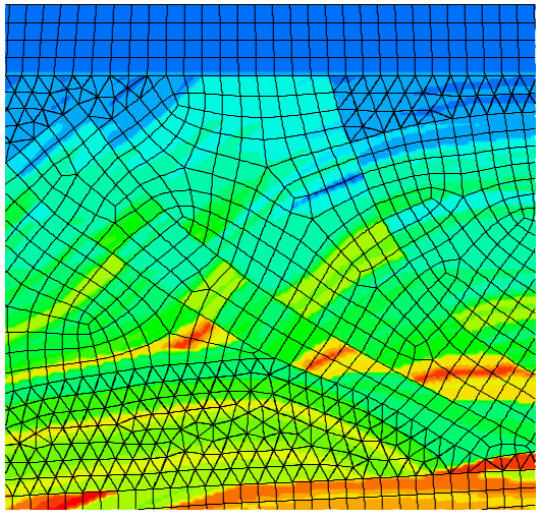
Code characteristics:

- Based on Discontinuous Galerkin method (DGM)
- Two or three dimensions
- Various physics available: Acoustic, Elastic, Anelastic, ViscoAnisotropic
- Various receivers available: Pressure, Velocity, Stresses
- Numerical fluxes: Lax-Friedrichs, Steger-Warming, Riemann
- Time integration: 4^{th} order Runge-Kutta
- Allows for unstructured meshes, local polynomial refinement, inhomogeneous material variation within an element
- Good material representation of discontinuous material interfaces at element boundaries
- Modal, nodal, or spectral elements
- Can invert for source or material properties (or both simultaneously)



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

Methodology: Source inversions

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	1 comp. Acoustic	1 comp. Elastic	2 comp. Acoustic	2 comp. Elastic	3 comp. Acoustic	3 comp Elastic
SPE2	✔	✔				
SPE3	✔	✔				
SPE4’	✔	✔	✔	✔	✔	In progress

- 2D source inversions: fits 1 or 2 velocity components (R, Z or Z only)
- 3D source inversions: fits 1 or 3 velocity components (R, T, Z or Z only)
- Including topography
- Testing four different simple velocity models
- Full waveforms or only direct arrivals
- Peak frequencies of 20Hz
- polynomial order, minimum 2
- Element size 25 m

Challenges

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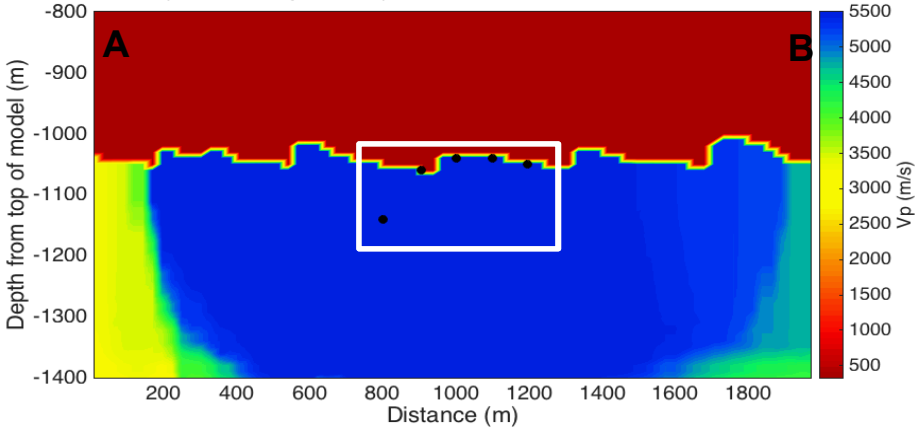
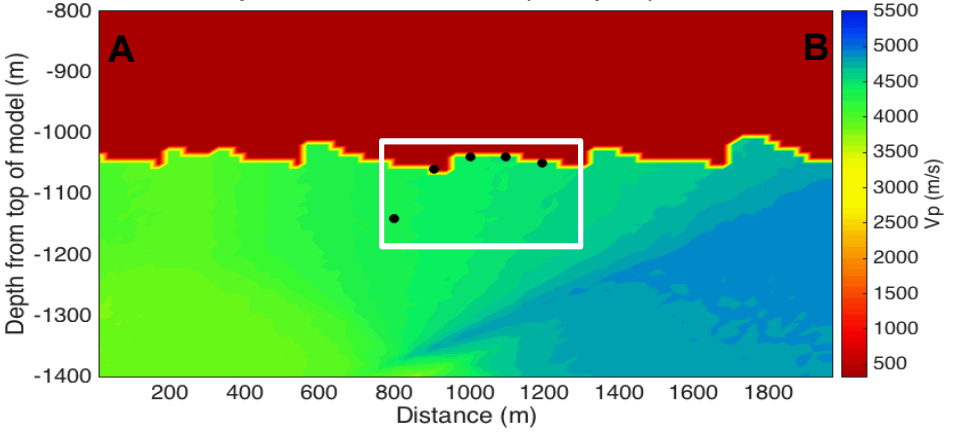
- Effects of topography on wave propagation and numerical handling of air/ground interface
- Smoothness and simplicity of velocity models
- Computational expensiveness of three-dimensional modeling
- Complex waveforms: Signals from shear waves, structural reflections, noise, etc. not accounted for in model are incorporated into fit for source time function
- Fitting direct arrivals only: trade-off between accurately representing phase and amplitude of raw data versus having a frequency content that can be well modeled numerically

Simple velocity models

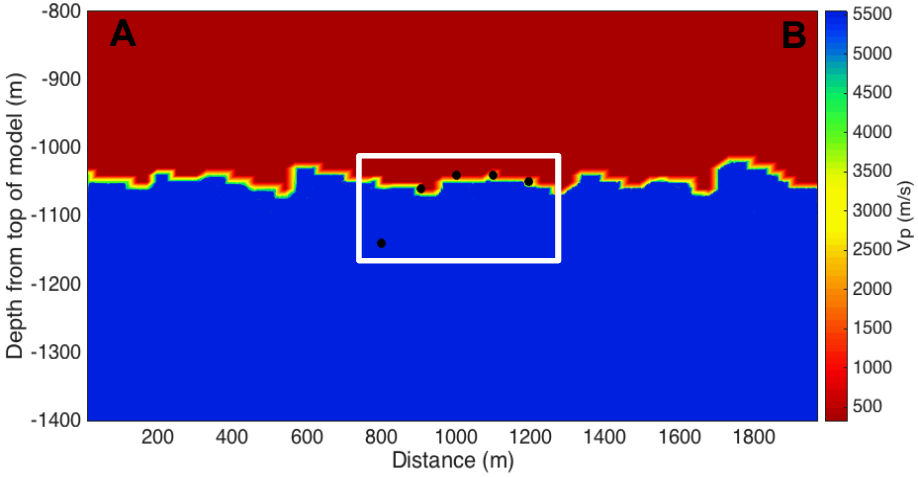
1. Shallow velocity data based on AWD surveys along arrays (“AWD”)



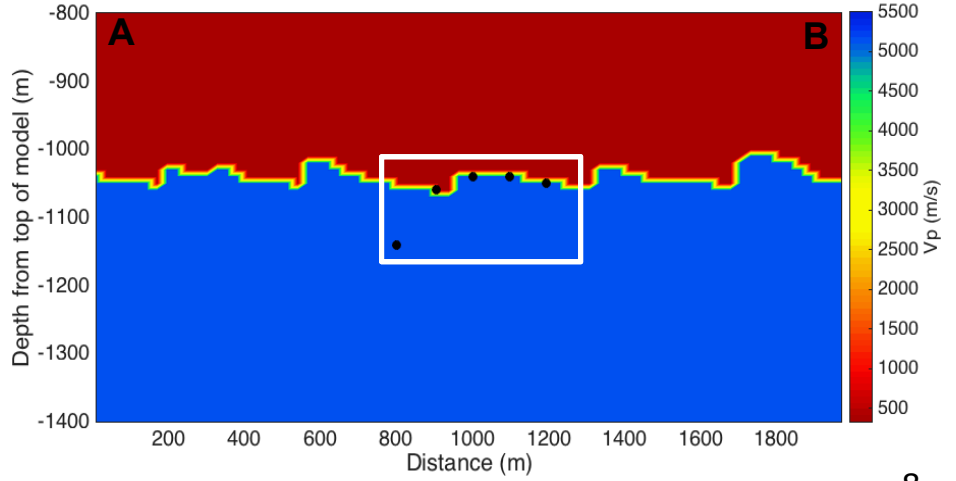
2. Based on 3D tomography (Leiph Preston, SNL), 2 km spatial resolution (“Leiph”)



3. Based on ambient noise (LLNL, Pitarka et al. 2015, Wagoner, 2014) (“LLNL”)



4. Simple homogenous half space with granitic properties (“Granite”)



Lessons learned: Topography

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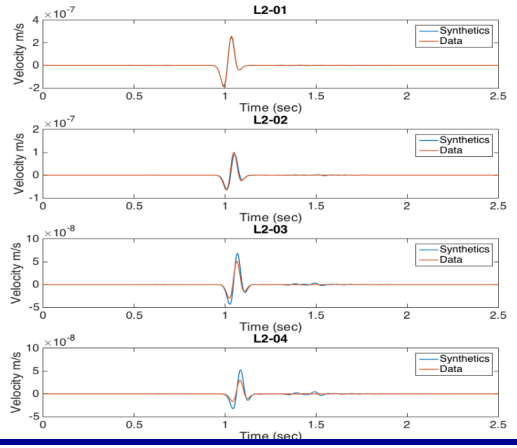
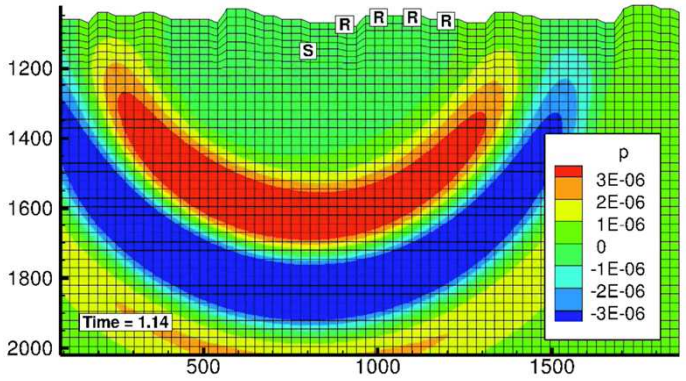
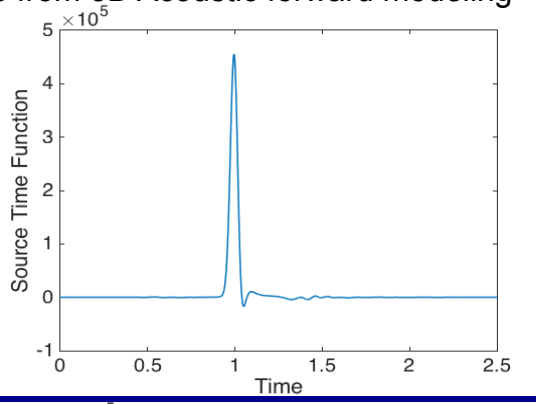
2D source inversions for synthetic Gaussian source from 3D Acoustic forward modeling

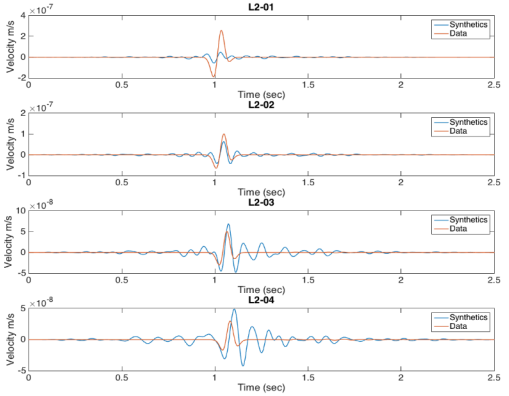
Acoustic

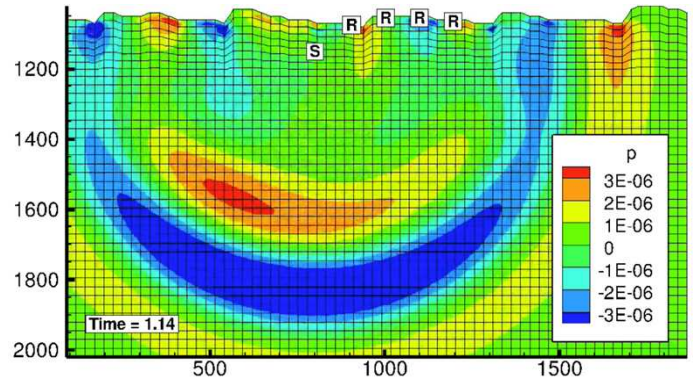


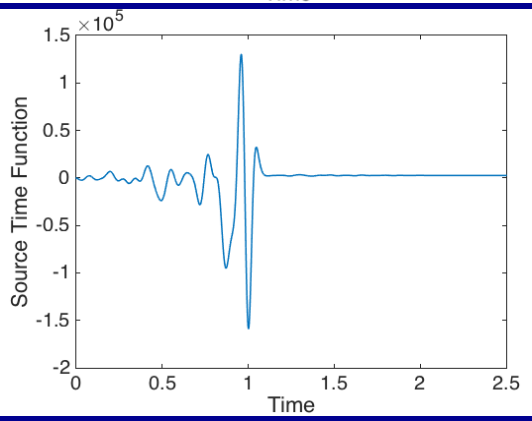




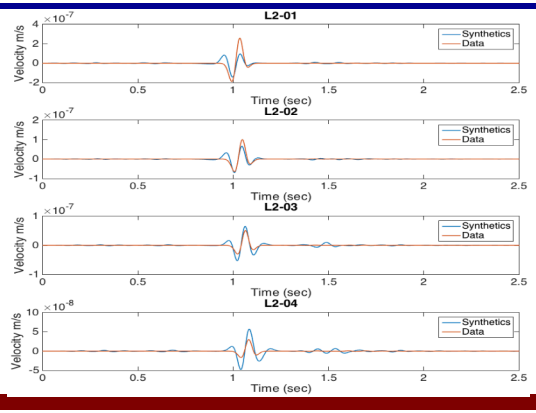
Elastic

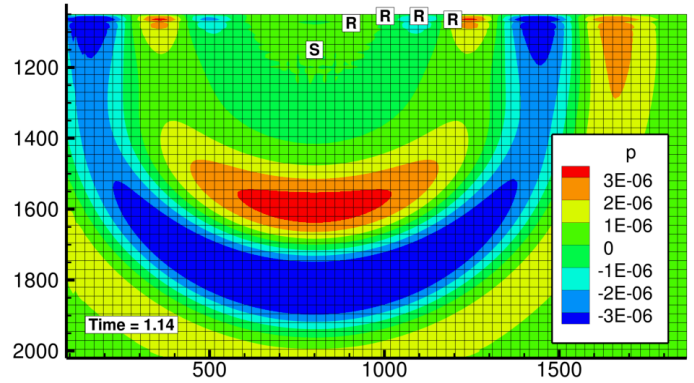


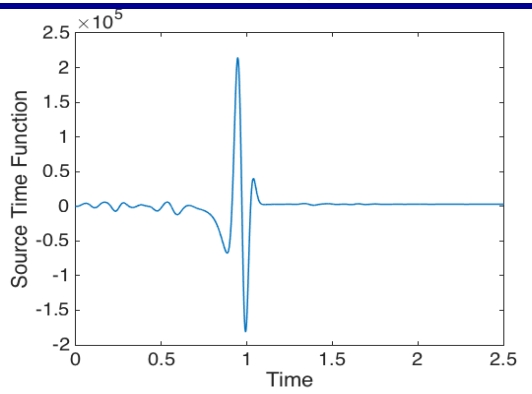




Elastic, Flat

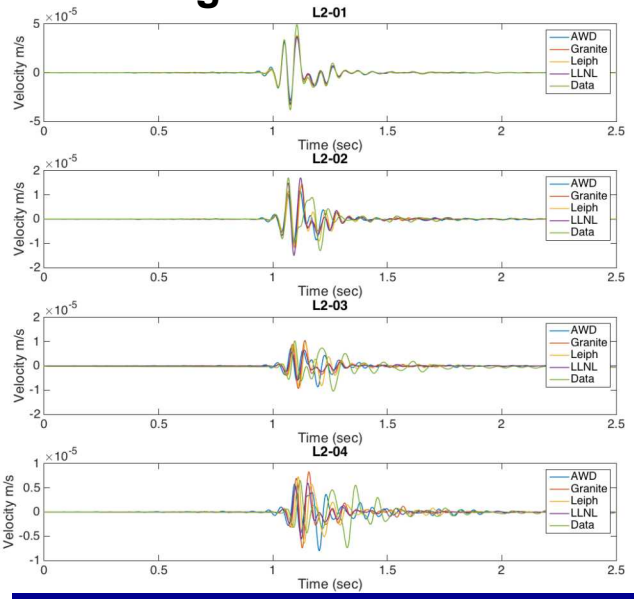


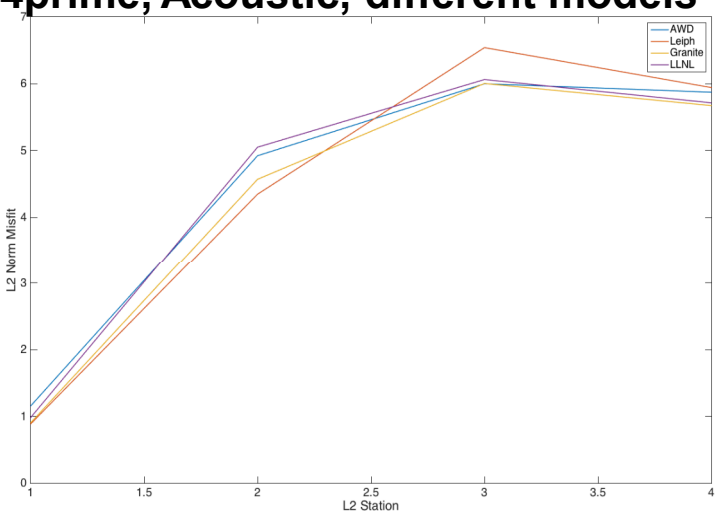


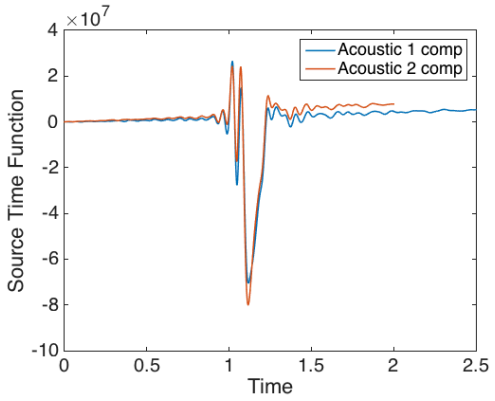


Lessons Learned: Complex waveforms and simple velocity models

Fitting full waveforms for SPE4prime, Acoustic, different models

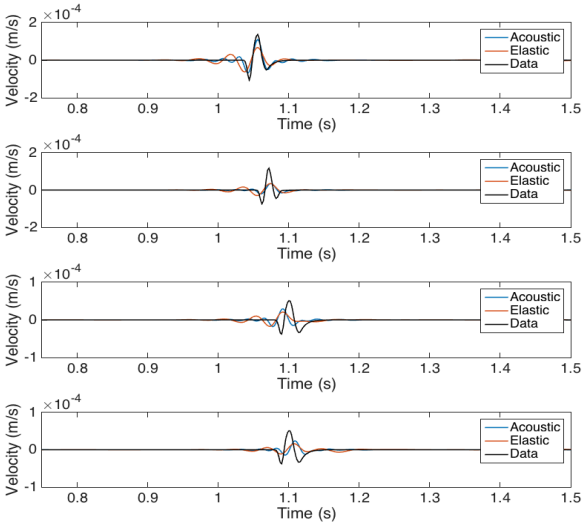


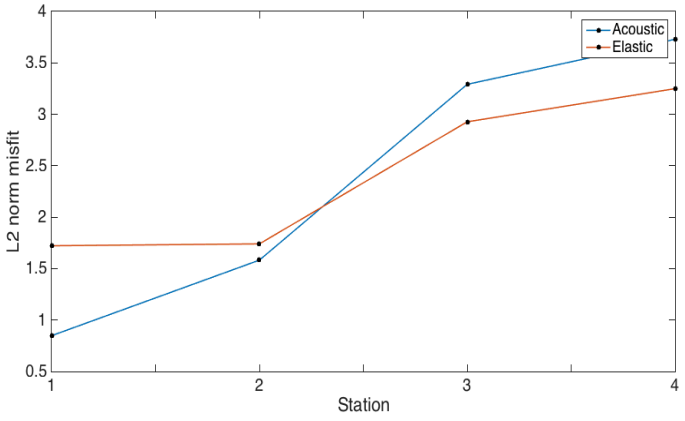


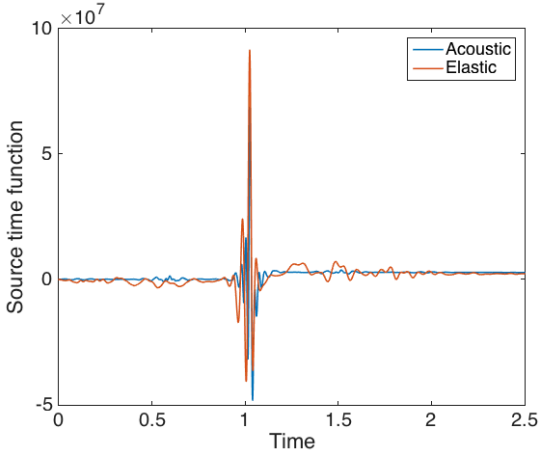


(AWD model)

Fitting direct arrivals only for SPE4prime, Acoustic and Elastic



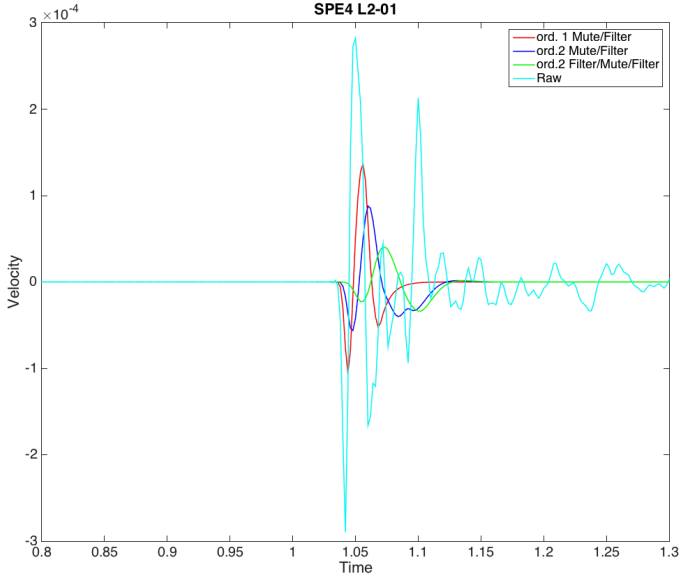


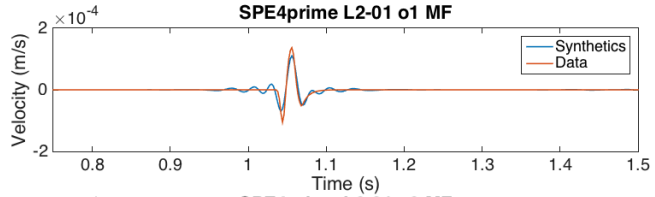


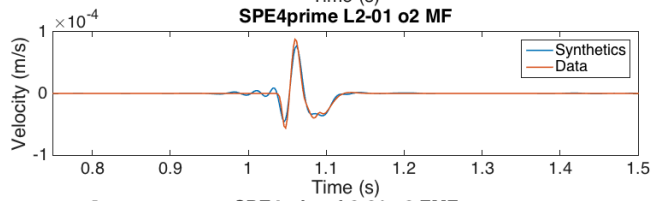
(Granite model)

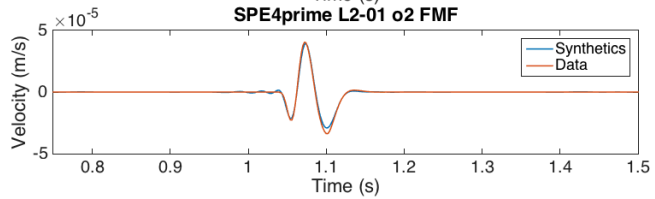
Lessons Learned: Filtering lessons

Comparison of SPE4prime raw data and muted first arrivals with different filtering



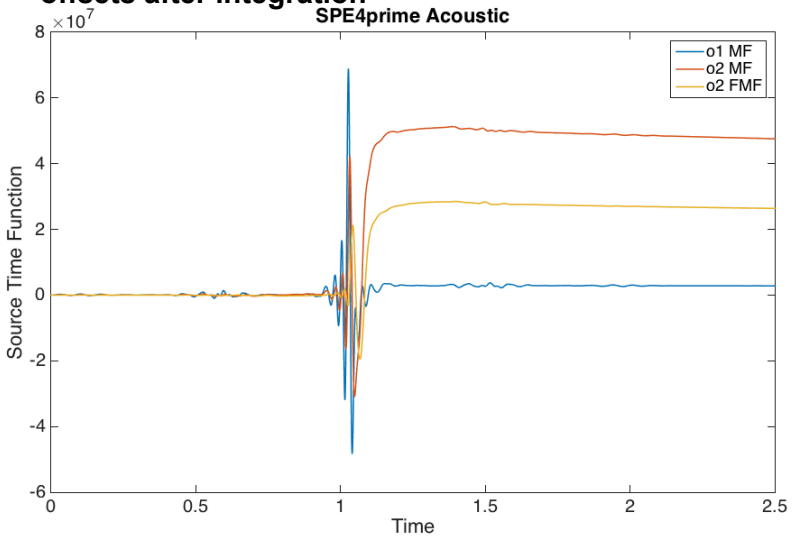




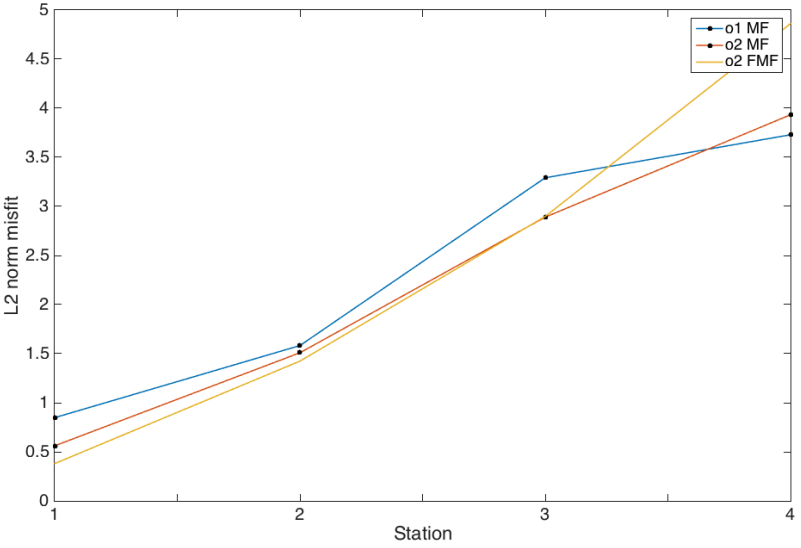


o1: 1st order butterworth filter
o2: 2nd order butterworth filter
MF: Mute, then filter
FMF: filter, mute, filter again

Small differences in input waveforms result in non-zero offsets after integration



Station fits are similar for different filtering methods



Preliminary Results: 2D Elastic and Acoustic results – SPE4prime

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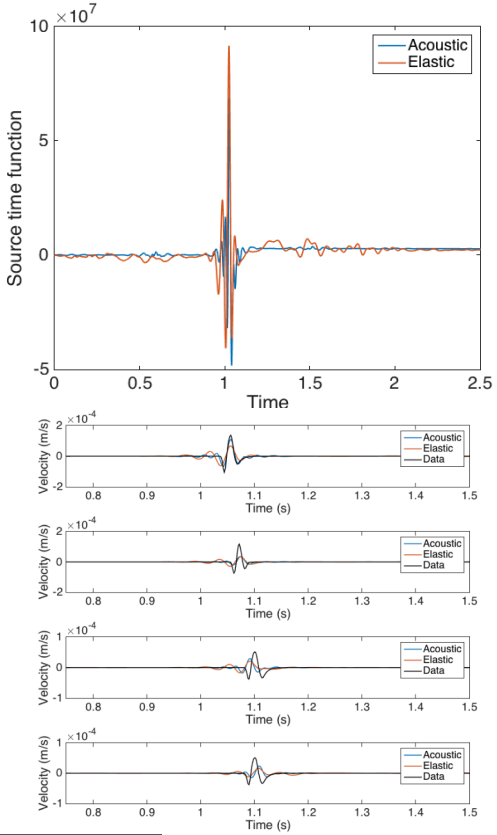
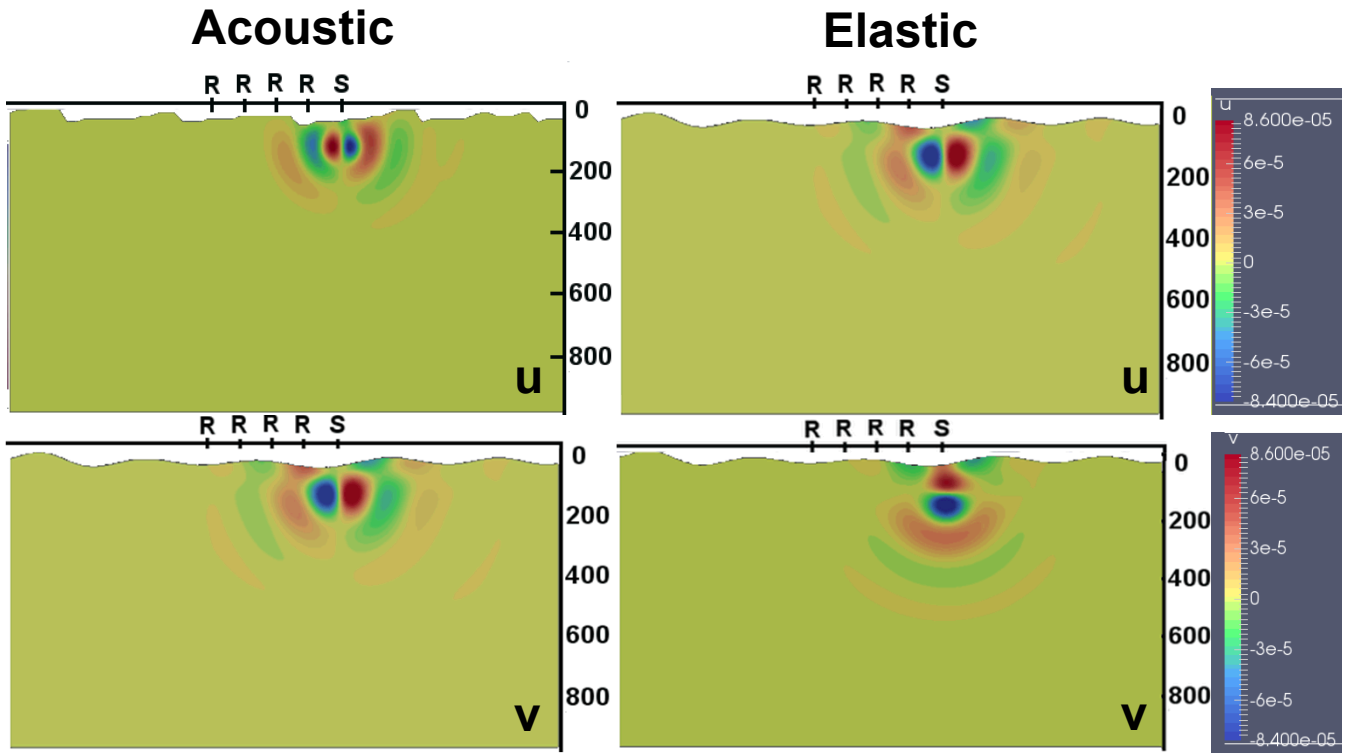
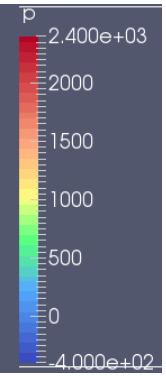
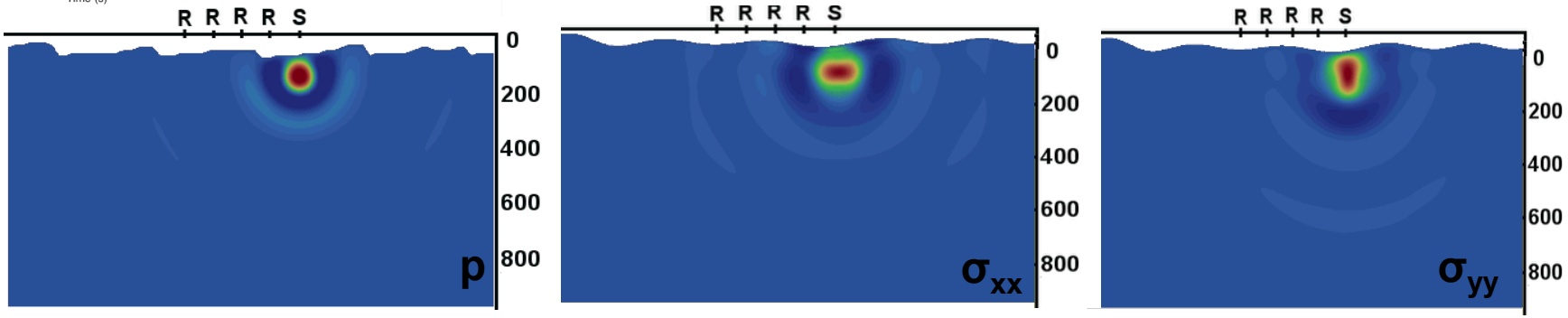




Above: horizontal and vertical particle velocity profiles





Acoustic pressure (p)

Elastic Stresses (σ) [p=-(1/2) tr(σ)]

Preliminary Results – increasing number of components fit

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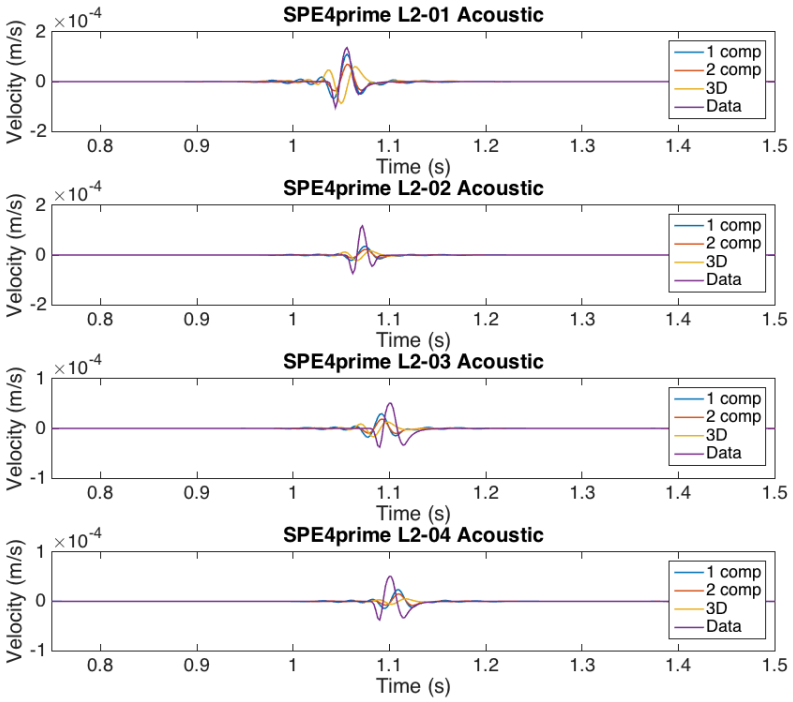
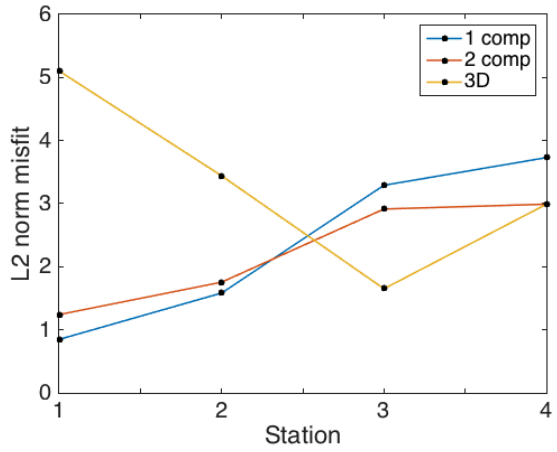
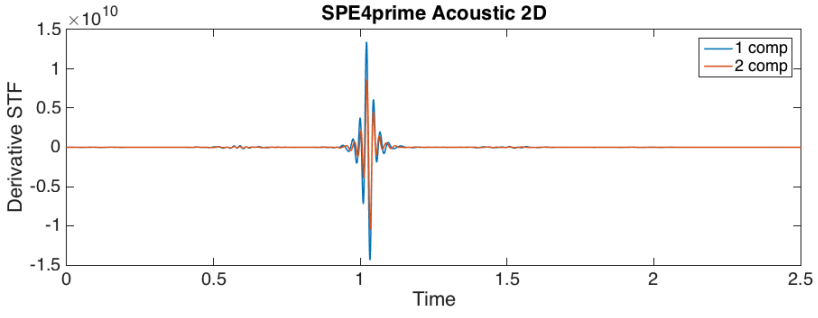
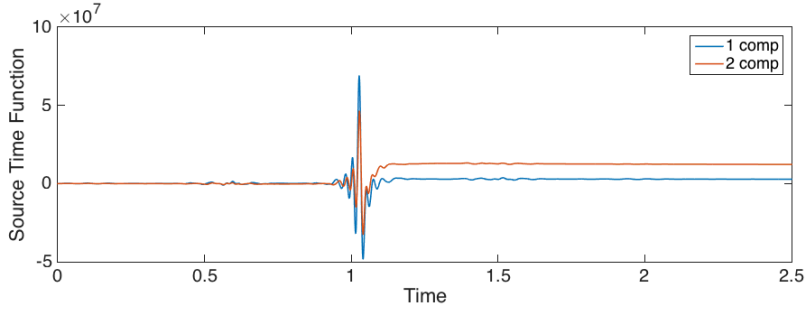
Station fits for 2D and 3D

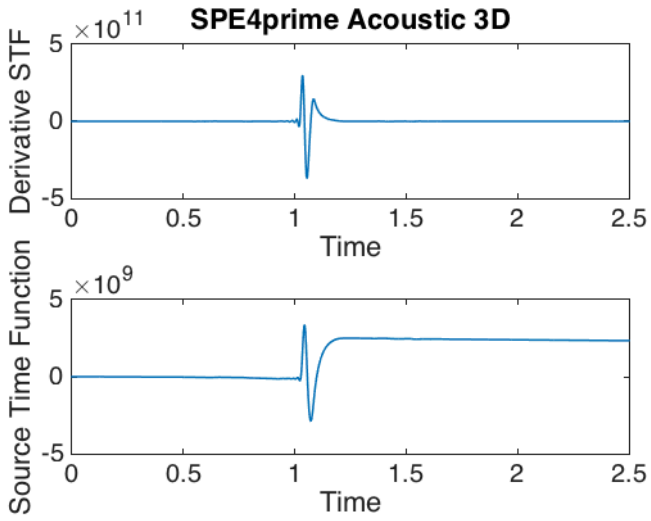




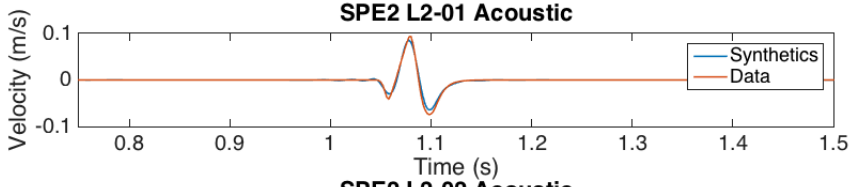
Source time functions for 2D and 3D

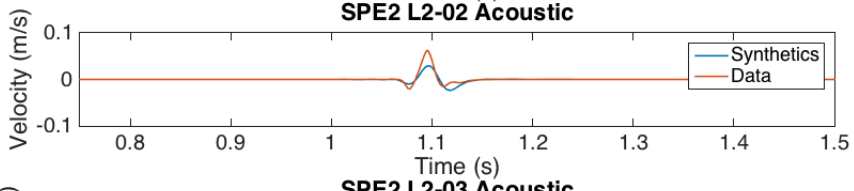


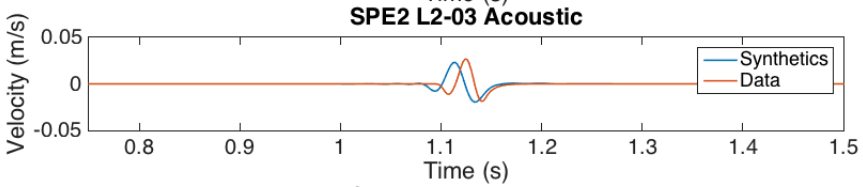


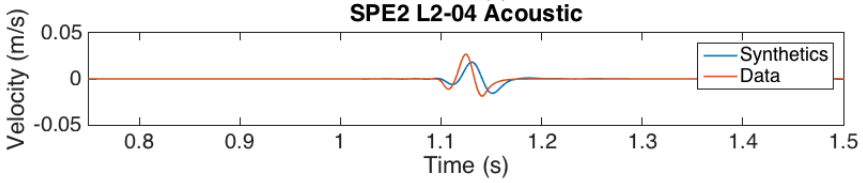


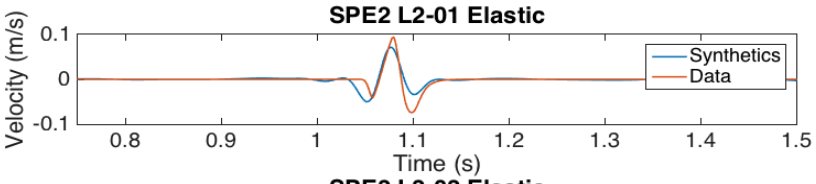
Preliminary Results – SPE2

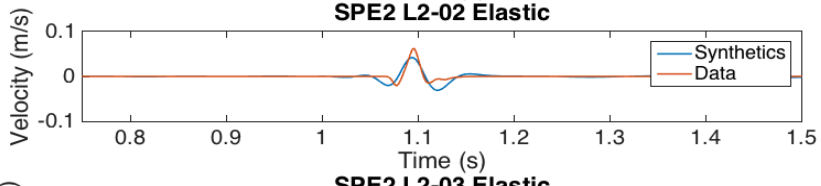


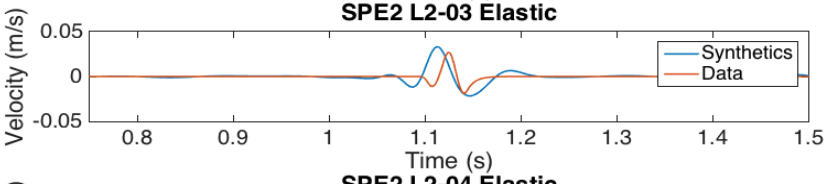


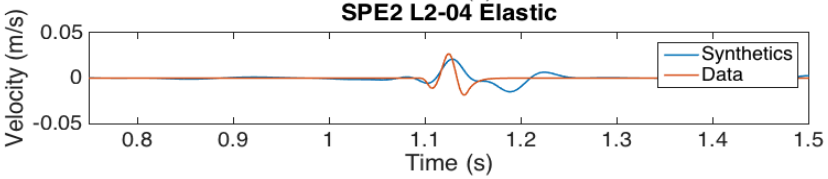


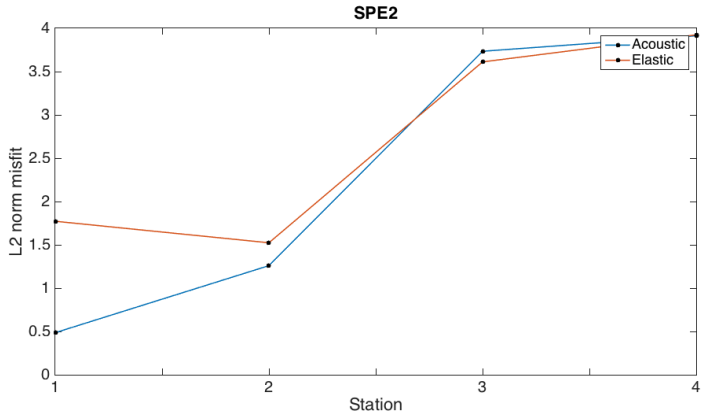


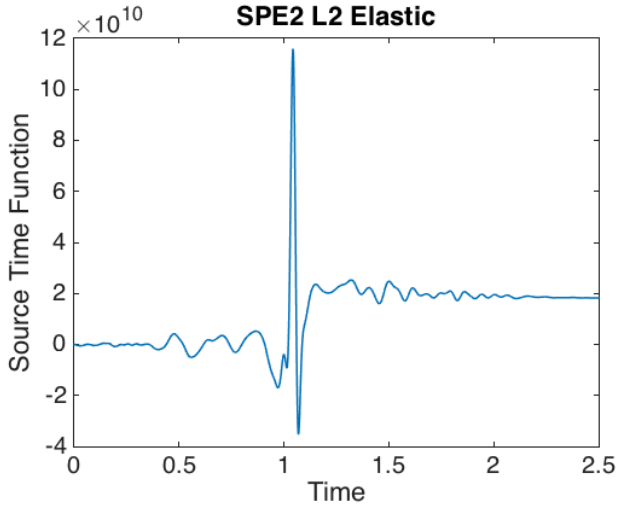




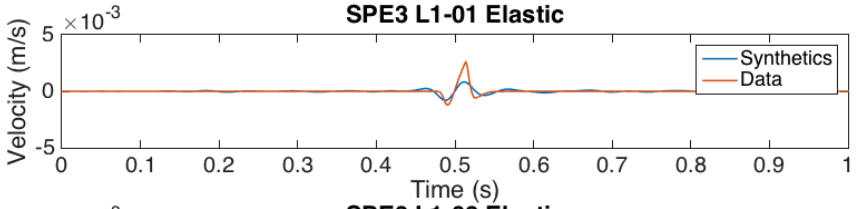


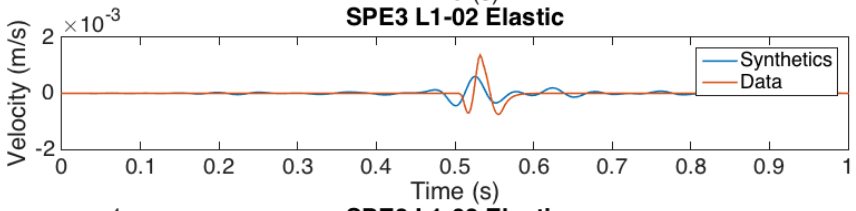


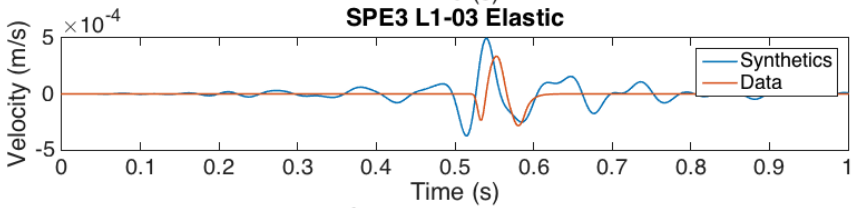


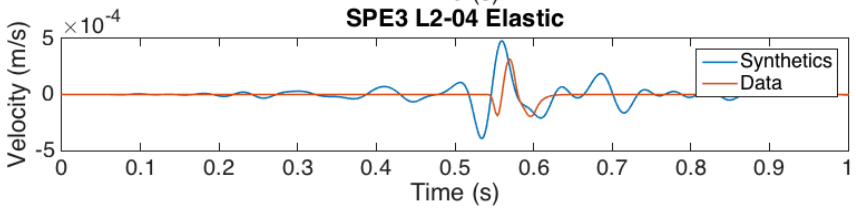


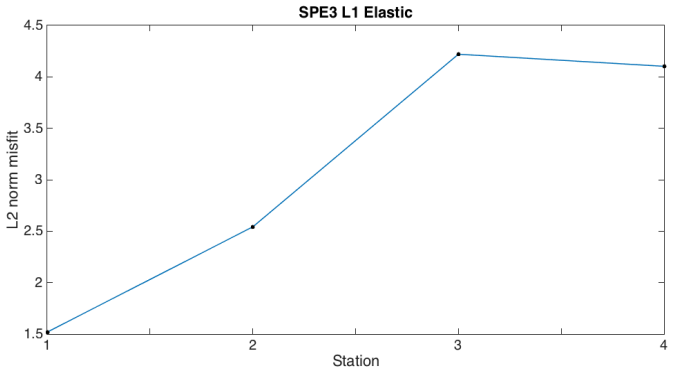
Preliminary Results – SPE3

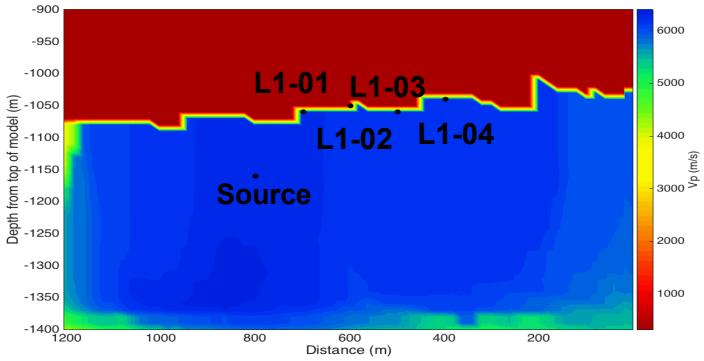




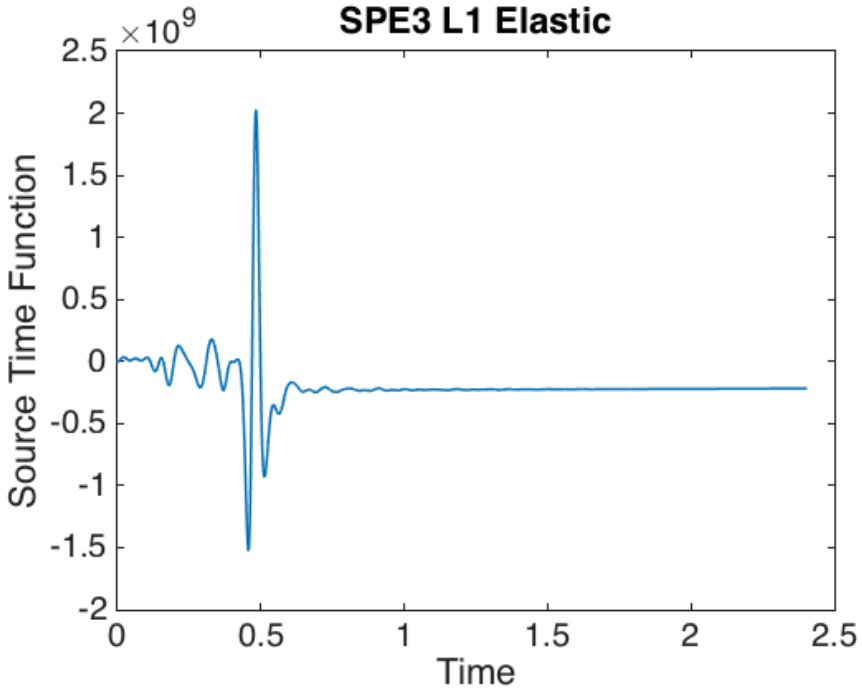




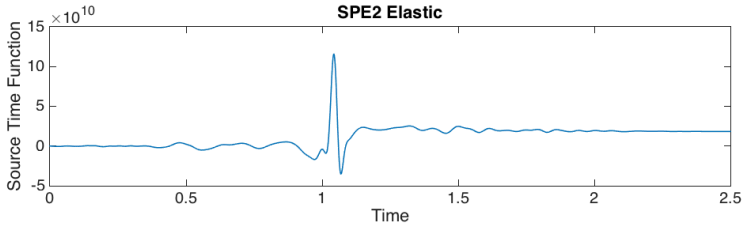


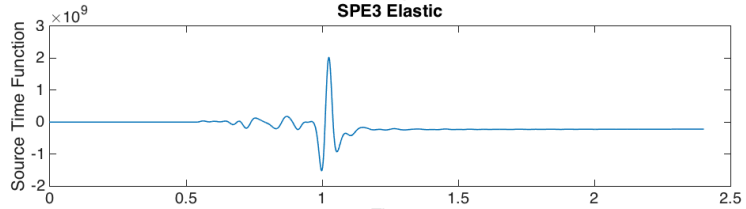


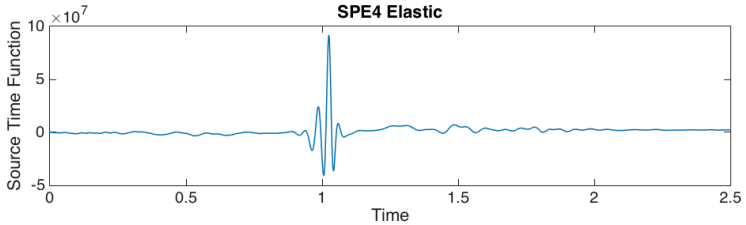
Line 1 velocity profile used for SPE3

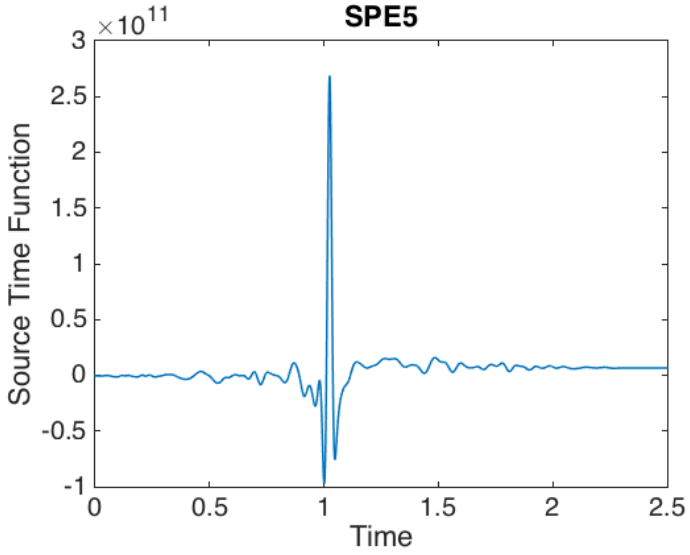


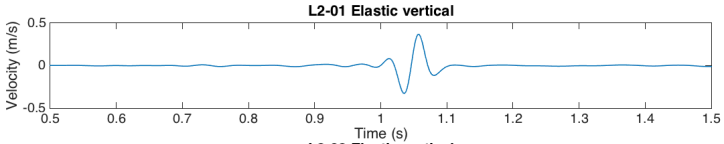
Preliminary Results – SPE5 predictions

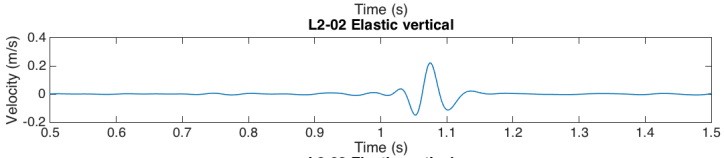


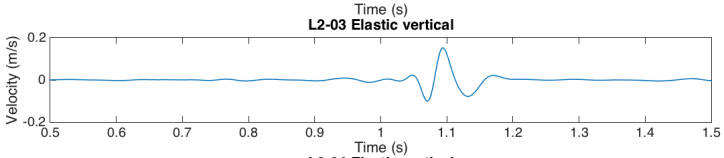


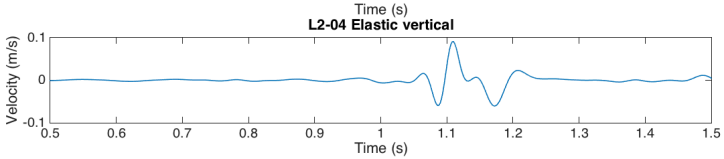


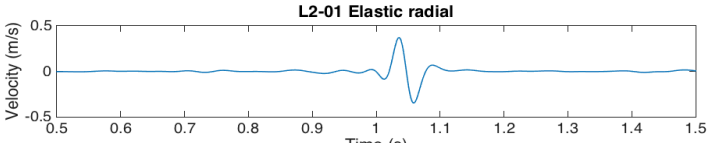


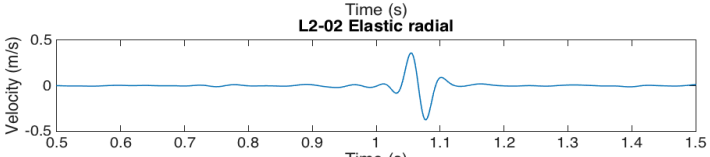


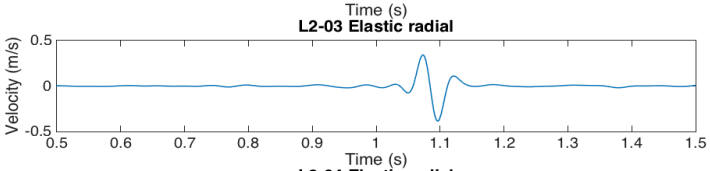


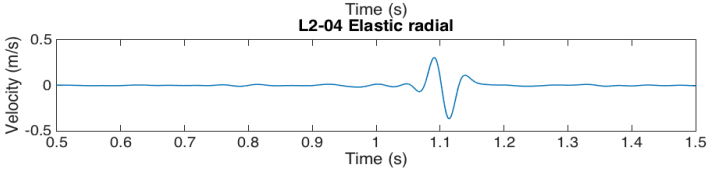












Conclusions and Future Work

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- Source inversions using direct arrivals produce possible source time functions for SPE2, SPE3, and SPE4prime that can be used as predictors of SPE5 source time function used for waveform predictions.

- Comparison of predictions and post-SPE5 waveforms will allow for improvement of models and methods

- Medium inversions and addition of complexity to velocity model will allow for inversions of more complex waveforms, higher frequencies, modeling of the damaged zone.

Backup Slides

References

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

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

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

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