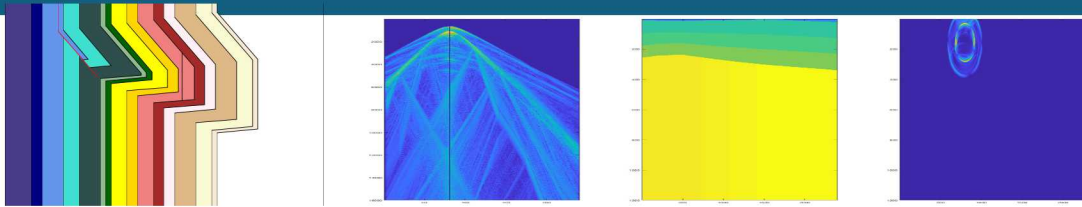
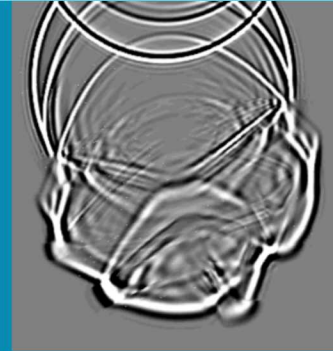


# Waveform Methods in GNEM Signal Propagation



PRESENTED BY

Nathan Downey





### Waveform Methods in GNEM Signal Propagation

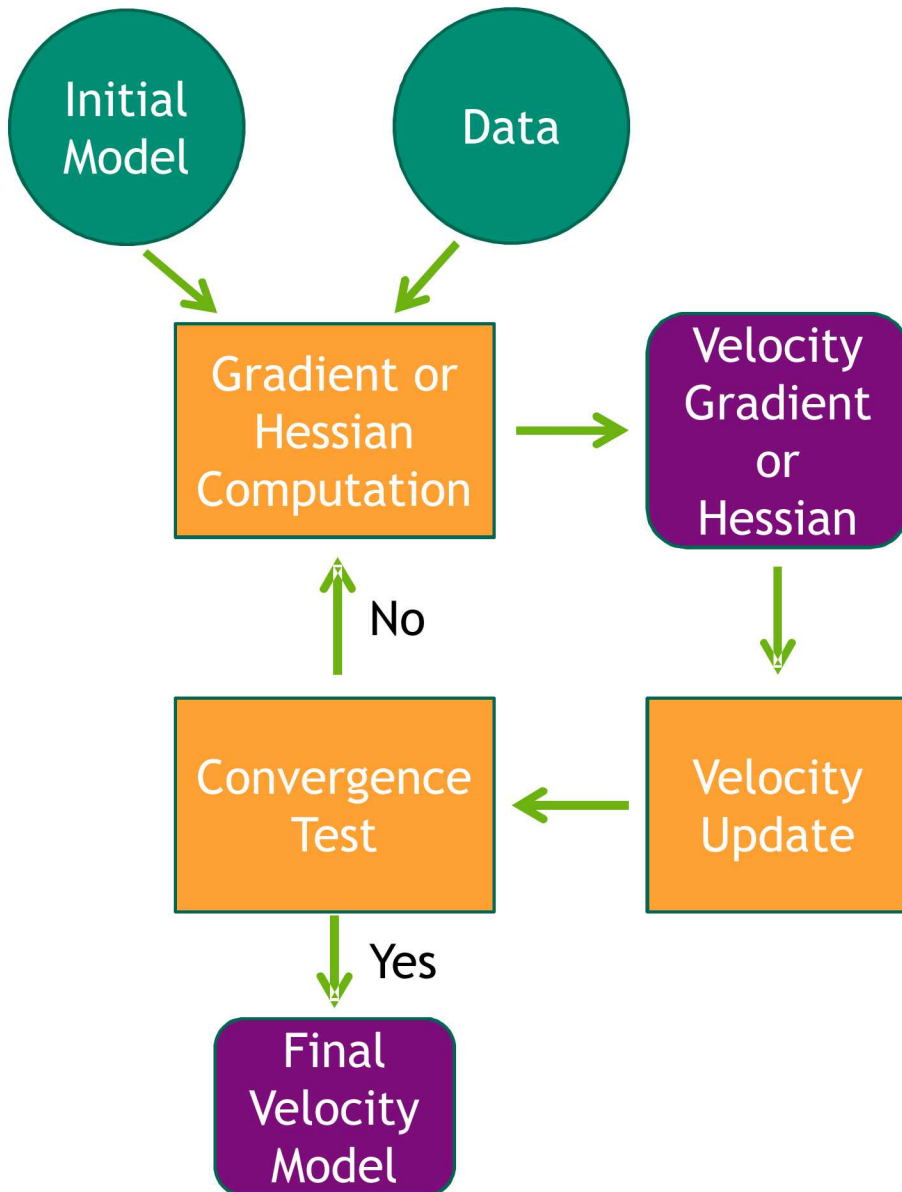
- SALSA3D works with travel times, which is good for event locations
- However when we work with the full recorded wavefield new applications can be investigated.
  - Discrimination
  - Event characterization
  - Effects of attenuation
- Here I will talk about the nascent efforts we have undertaken so far

## Background

Neill Symons requested that I pursue waveform methods for use in GNEM signal propagation in mid 2017

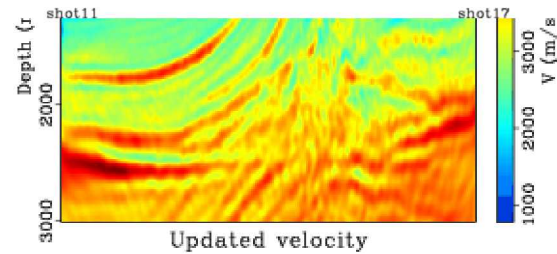
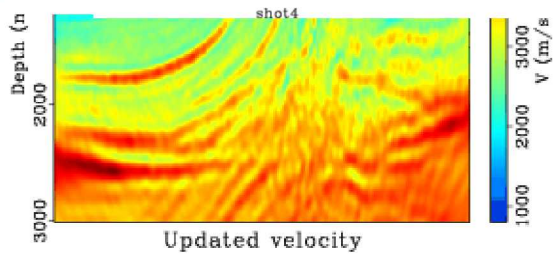
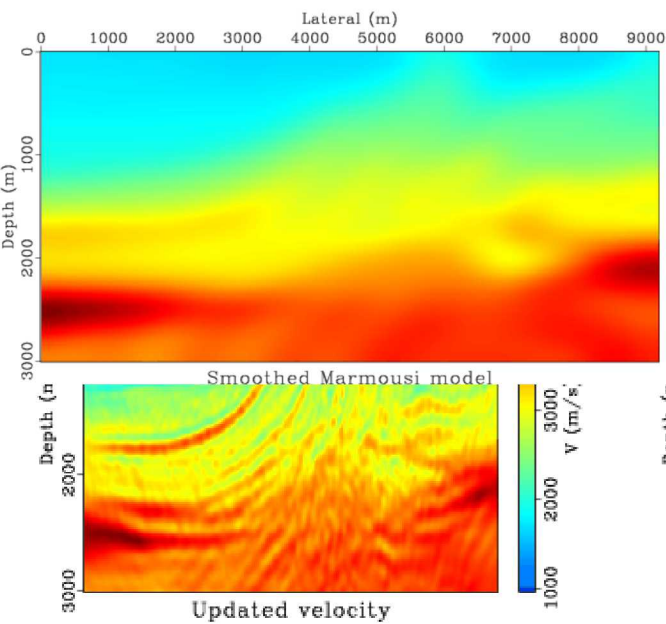
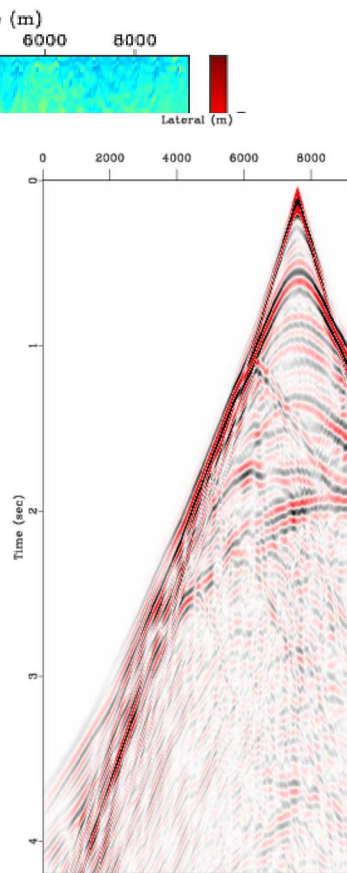
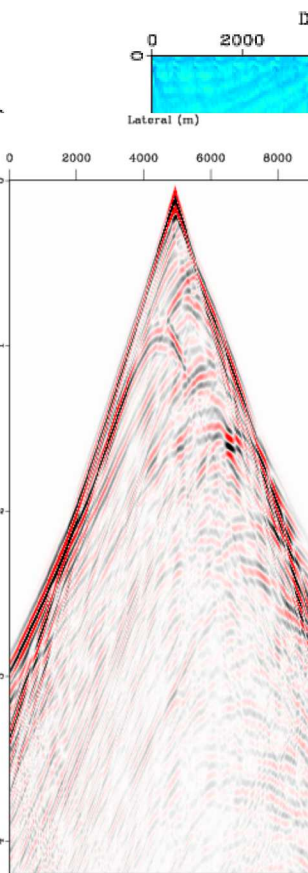
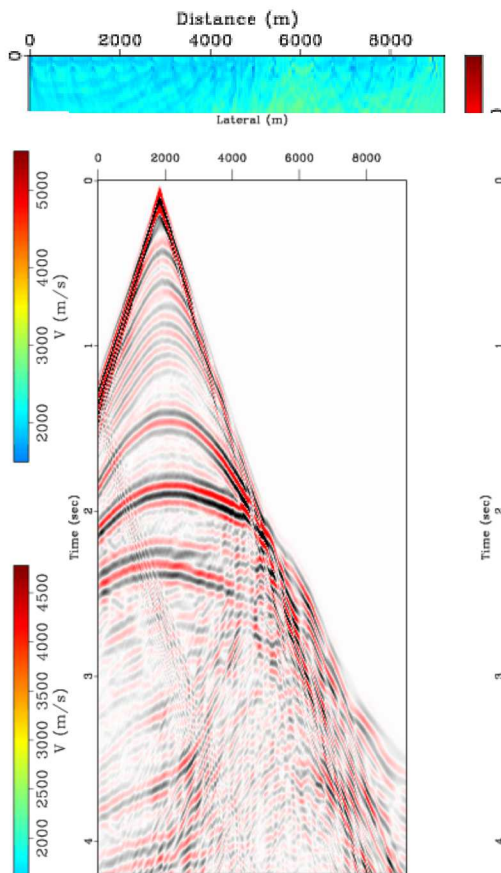
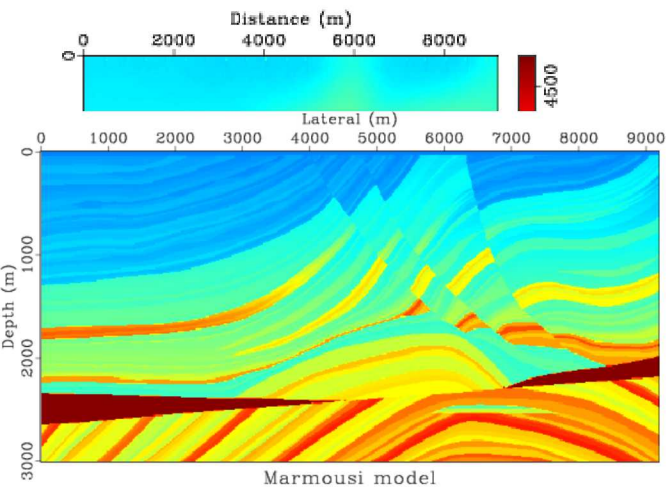
- Interested in leveraging a significant investment to develop seismic full-waveform inversion (FWI) software in Sandia's Computer Science Research Institute (CSRI)
- The developers of this software are located at Sandia providing us with easy access to support and allows us to work with the software directly
- Utilizing the FWI software within Sandia fosters cross-lab collaboration.

1. Full wavefield inversion at Sandia
  - Advantages and disadvantages
2. Computational challenges
  - Efficient simulators, 2D problems
3. Data coverage challenges
  - USArray data, 2D problems
4. Velocity model challenges
  - Use waveform modeling as a guide
5. Other waveform applications
  - Sensitivity of crustal phases, waveform (synthetic) catalogs

 Input Computation Output

- FWI is an iterative method to update a velocity model using a data residual (Ref: Tarantola, 1984)
- The required tools are
  1. Waveform simulator
  2. An optimization algorithm
- Algorithm dates to early 80's but became part of industry standard methods in early 2010's
- Many specialized tricks are required to get proper convergence

# 6 Introduction to FWI

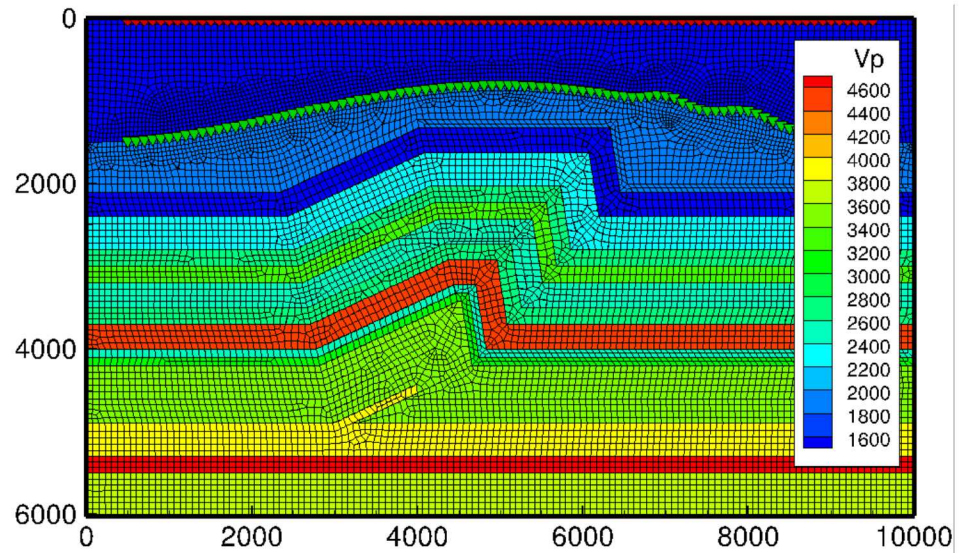
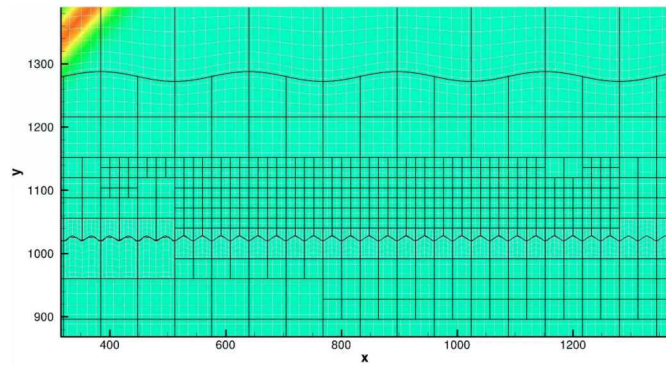
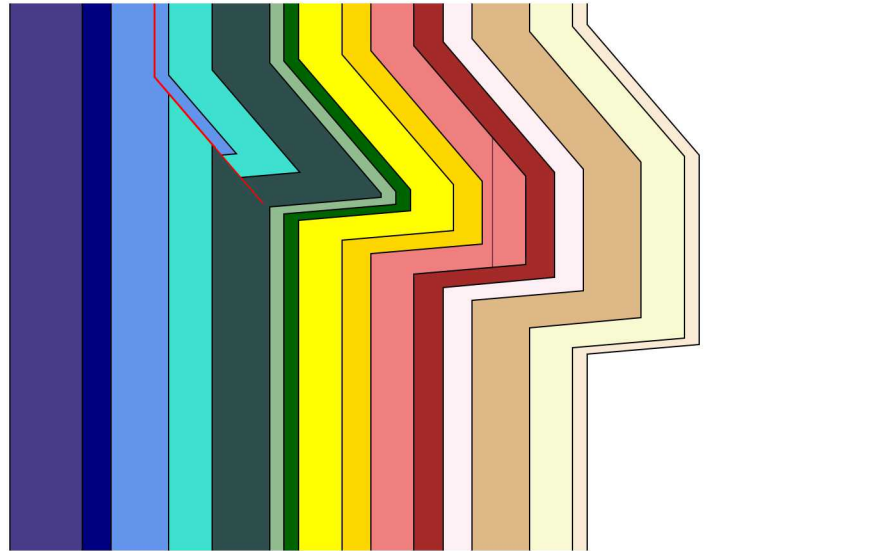
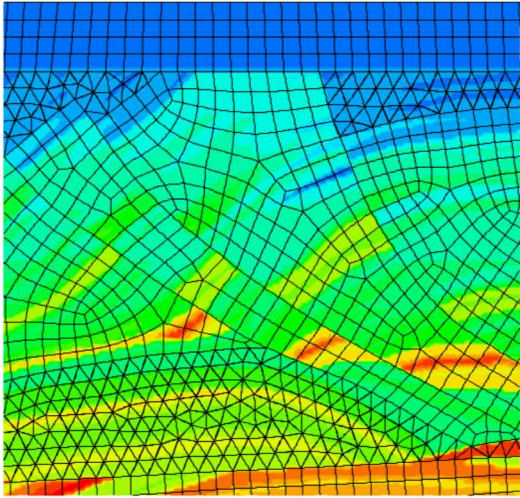


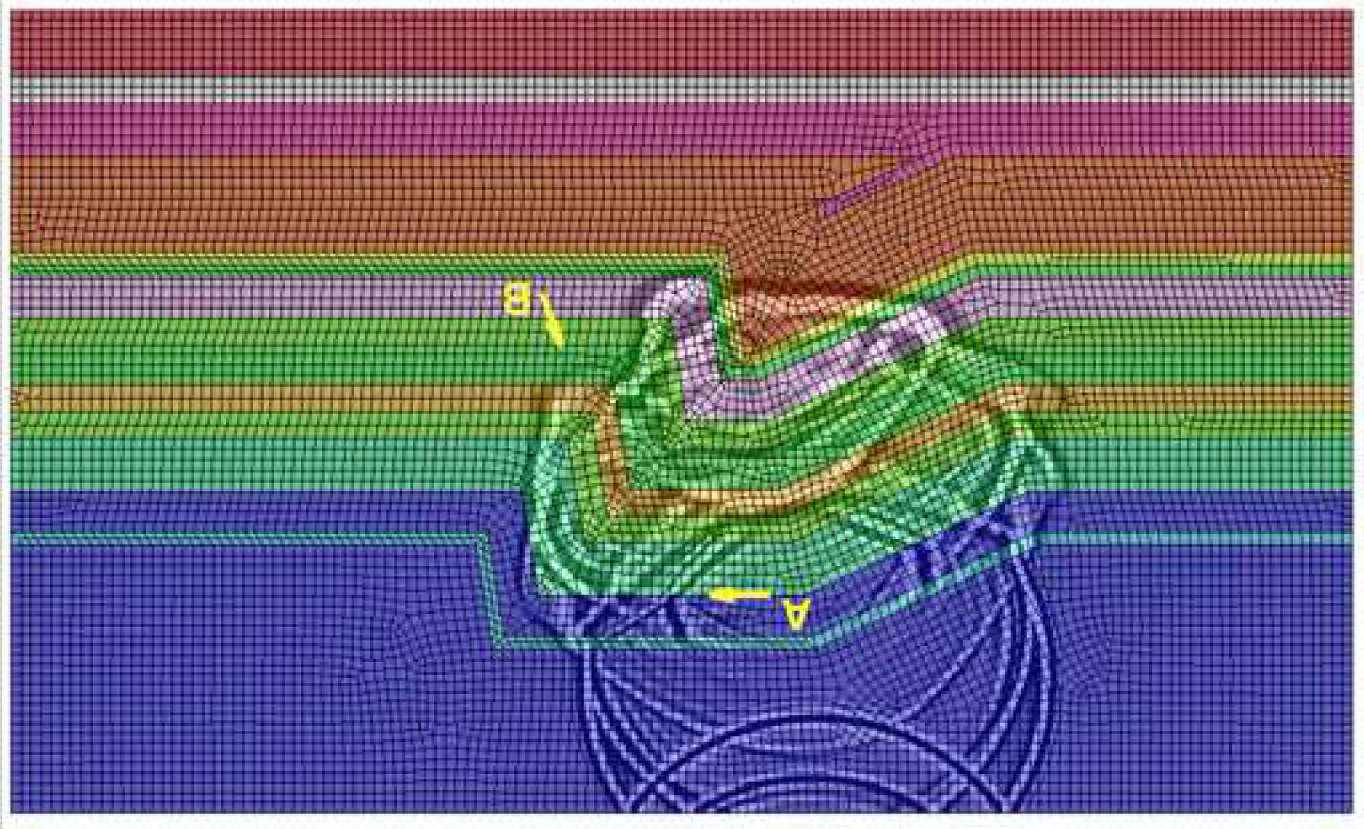
Sandia has developed an advanced industry-style FWI capability with unique features:

1. A waveform simulator that utilizes a discontinuous Galerkin (dG) finite element approach and is capable of predicting the response of an anisotropic attenuative medium
  - Advantages: Very flexible meshing capabilities, high fidelity for strong-contrast interfaces and multiply scattered waves, access to developers
  - Disadvantages: Computationally expensive, tuned to industry-sized problems
2. The use of an advanced optimization library, ROL (Rapid Optimization Library)
  - Capable of high-order methods, interior-point methods, many varieties of line search, ...
  - Provides methods for optimization under uncertainty
  - Sandia-developed and available as part of the Trilinos package



# dG Simulator Features





## 1. Computation

- Single simulation is expensive, need one per source, gradient computation costs 3x a single simulation, line search is 3-4x a single simulation
- Unfortunately dG is an expensive numerical method

## 2. Data Coverage

- Good coverage means crossing raypaths
- Successful industrial applications use GIANT datasets (6000 channels per source, ~ million sources)

## 3. Need an appropriate initial model

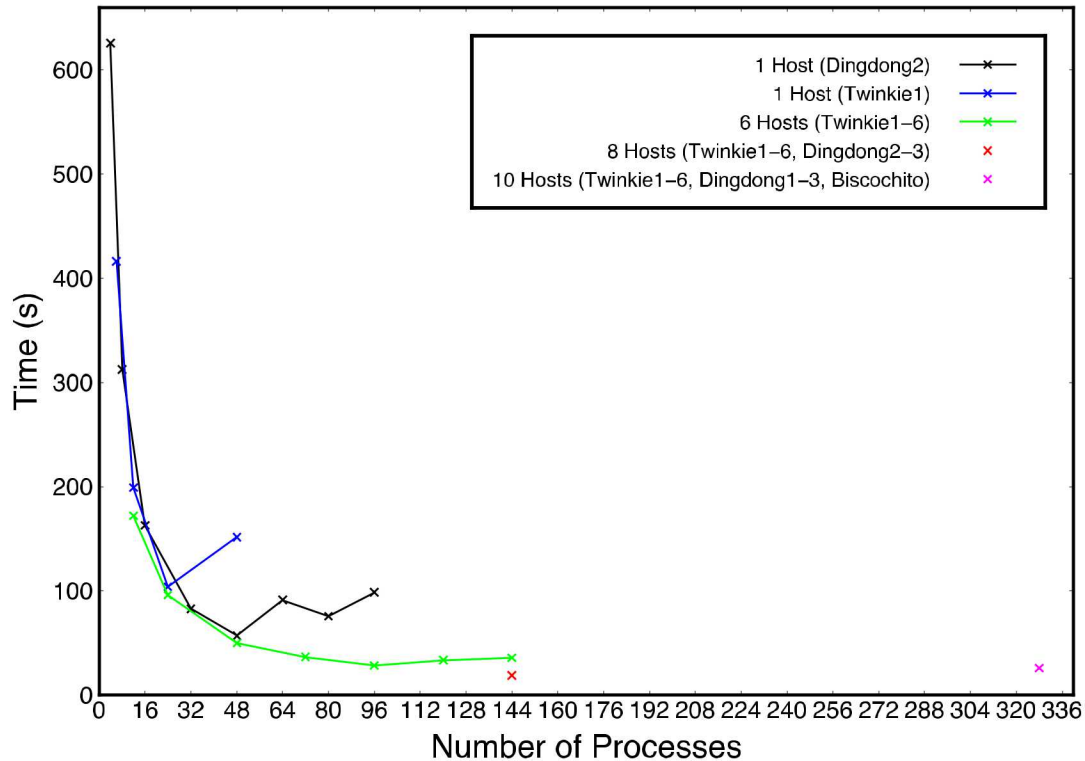
- Close enough to the true model to avoid a local minima
- Usually FWI requires a previous tomographic inversion to converge to “true” solution

Our dG-based simulator is designed for large industry-style problems

- Uses 1000's of cores, optimized for large CRAY-type supercomputer clusters

However it scales to the number of physical cores on the geocluster

### MPI Timing Tests on Geocluster



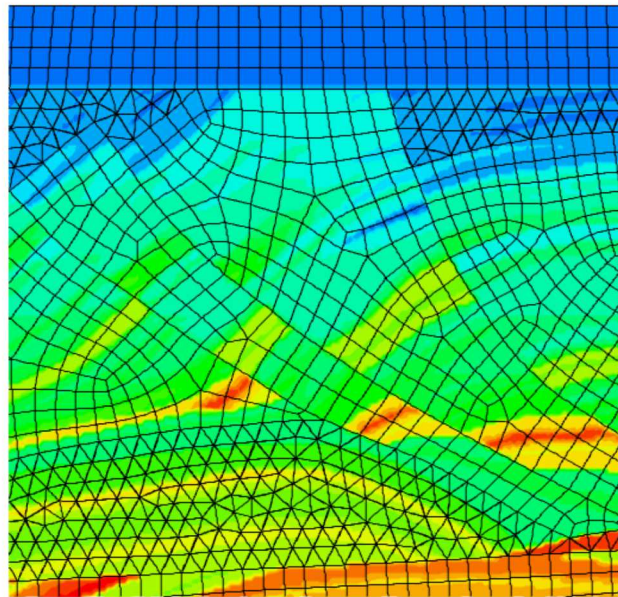
## Computational Challenges

Our dG-based simulator is not optimized for global/regional domains

- Spherical domains possible, but not tested
- Absorbing boundary conditions are rudimentary

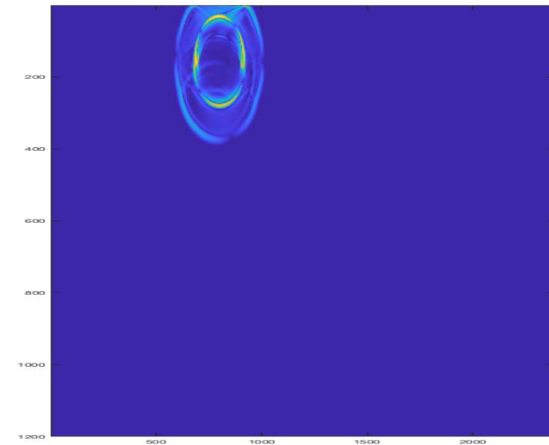
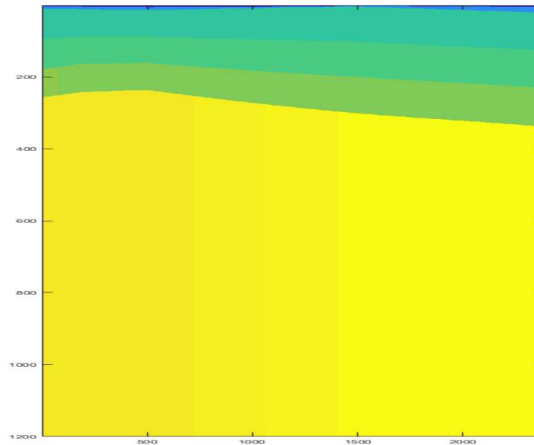
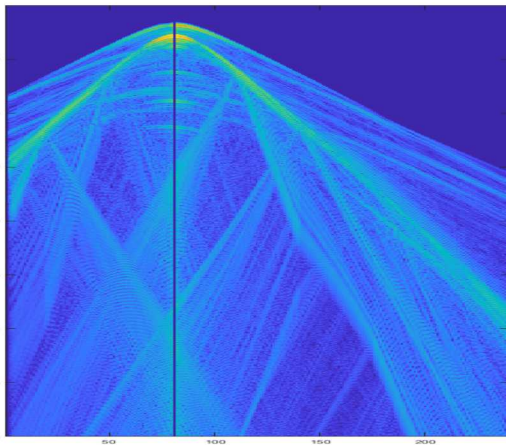
For early applications we are going to work with crustal propagation to near regional distances and we are in the early stages of implementing a PML (Perfectly-Matched Filter) formulation

- Theoretical analysis is complete, implementation details are currently being worked out



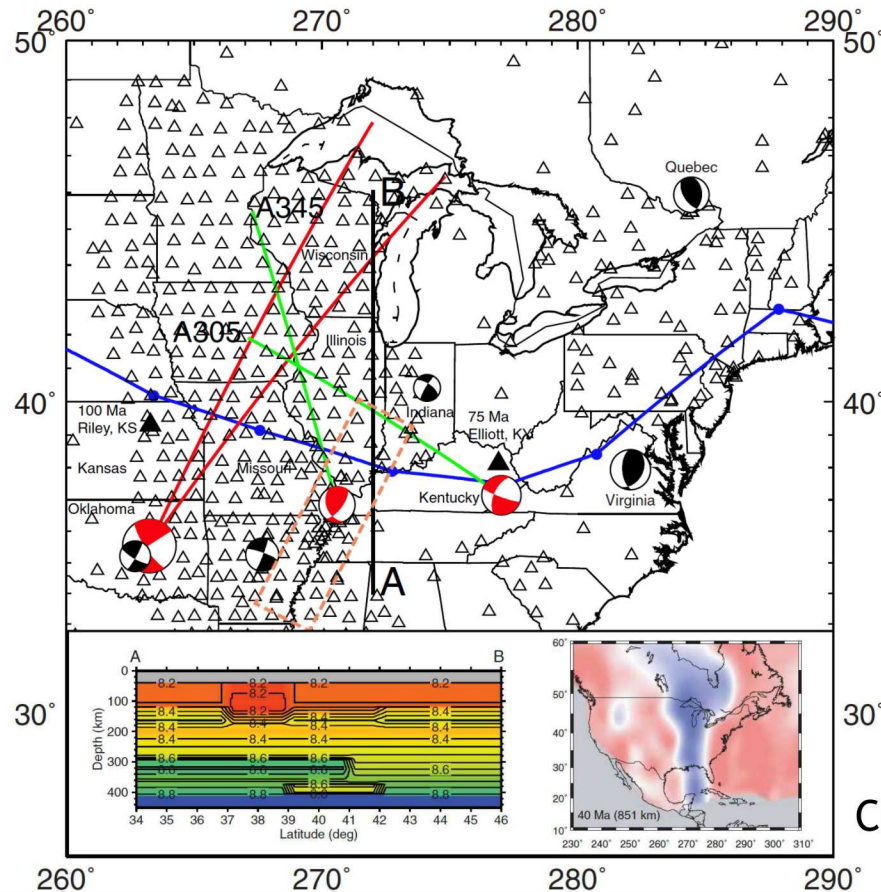
We have also obtained an alternative waveform simulator that uses GPU acceleration and approximation methods to simulate 3D wavefields in 2D

- This simulator has been used in several waveform modeling studies at regional and global scales
- Currently this simulator is in use by the LYNM project to help design a new method for the automatic identification and association of seismic events



Dense datasets are required that not only provide good coverage, but also include a large amount of non-redundant data

- The USArray provides large amounts of data from a variety of events that could be used in waveform inversion studies.



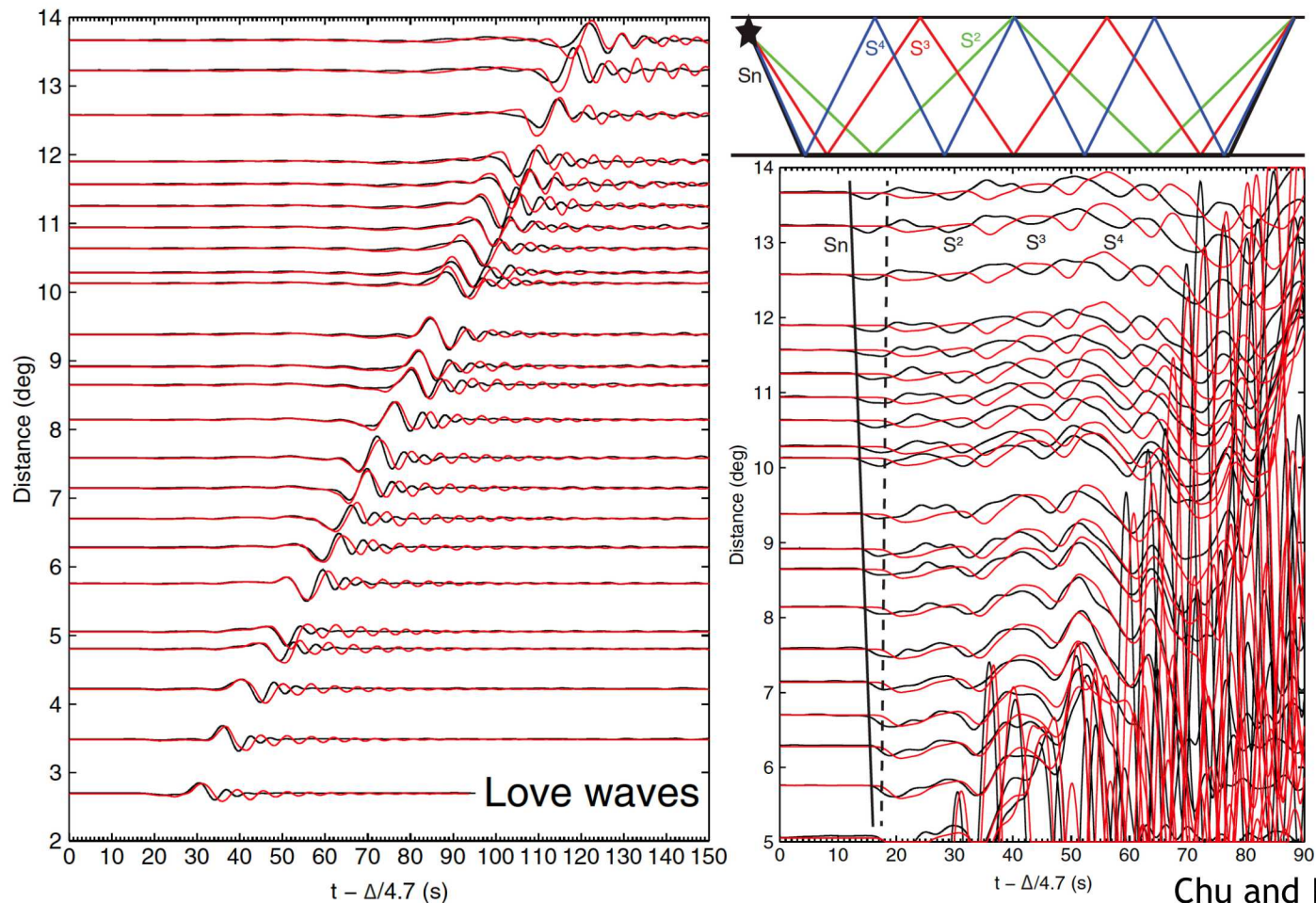
Dense datasets are required that not only provide good coverage, but also include a large amount of non-redundant data

- SALSA3D provides us a way to gather datasets that are well-resolved through its ability to compute resolution matrices
- One Possible workflow:
  1. Use SALSA3D to do a tomographic inversion of a regional dataset
  2. Examine model covariance to determine independence of the gathered dataset
  3. Supplement/modify dataset and repeat 1-2 until we are confident that waveform inversion has a good chance of success

## Initial Model Challenges

If the Initial Model for FWI is not close to the true Earth model it is very hard to avoid local minima in the inversion

- This is caused by the modeled data being aliased with respect to the observed data and can be avoided by inverting lowest frequencies first



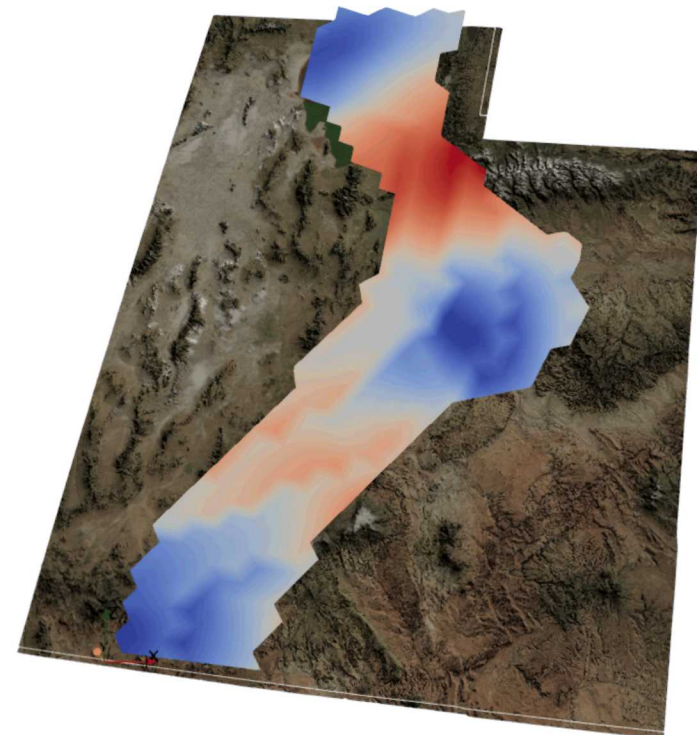
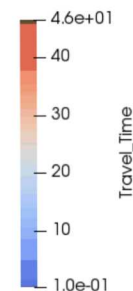
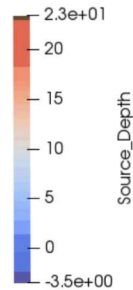
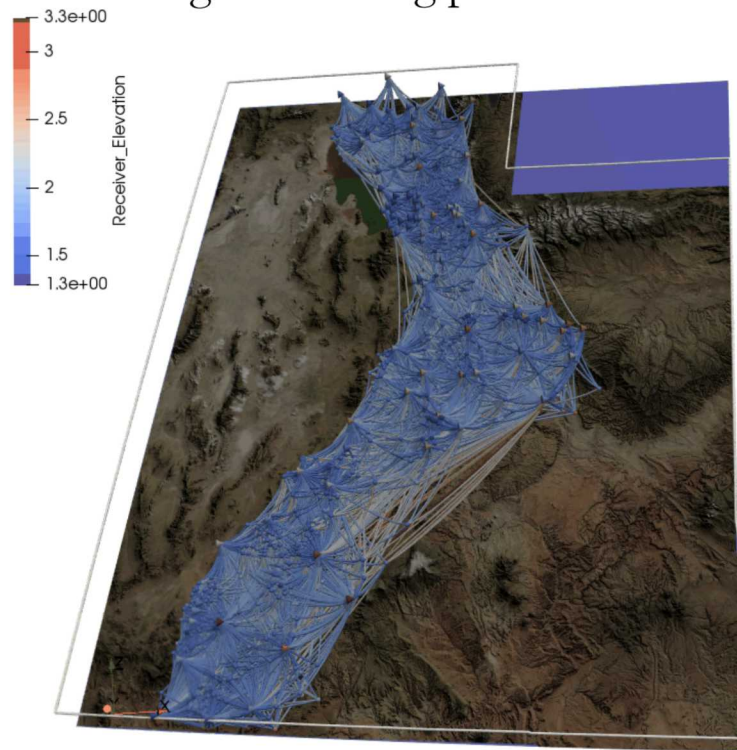
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SALSA3D provides us a way to obtain initial models.

- Regional inversions such as the one we are working on in Utah will provide a good starting point



## Other Applications of Waveform Modeling

1. Determining travel-time sensitivities for crustal phases for use in tomographic inversions
  - Pn, Pg, Lg, and other complicated phases
  - For use in regional/crustal tomographic inversions
2. Create catalogs of synthetic data for use in research and data analysis
  - Similar in scope to the Princeton Global Shakedown project but with a monitoring focus (Tromp et al. 2010)
  - This is already being utilized in the LYNM project

# Waveform Method Project Plan

## FY19:

1. Finish implementation of PML in dG simulator and begin regional phase modeling benchmarking
2. Complete SALSA3D inversion of Utah using additional data obtained from the University of Utah

## FY20:

1. Study sensitivities of crustal phase travel-times to changes in crustal velocity
2. Examine Utah inversion results to determine a location where waveform inversion has best chance of success. Select events from this dataset and examine data misfit