

## **Advanced Microseismic Monitoring Methods\***

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### **Abstract**

Microseismic monitoring is a widely used tool to map fracture propagation during hydraulic fracture stimulation. The capability to model, monitor, and measure the resulting fracture network is essential for optimal production. Using a sample dataset recorded from a set of surface sensors, we demonstrate the use of empirical matched filters to first detect low threshold events and then apply Bayesian-based location methods to yield locations along with robust error estimates. The error estimation is useful in relating the observed seismicity distribution to geologic models and distinguishing between features reflecting actual geologic structure as opposed to artifacts caused by sensor geometry and other sources of error. The velocity model is estimated using all available data and refined using Green's function derived from ambient noise. Next, we explore the use of full waveform modeling using adjoint methods to define the micro-seismic focal mechanism, which distinguishes between tensile and shear mechanisms in the underlying fractures. The results (locations and focal mechanisms) are compared with the known geology (such as lithologic changes and fracture orientations) of the site and with standard techniques (P/S amplitude ratio and first-motion focal mechanisms) to evaluate the validity of these methods.

# *Advanced microseismic monitoring methods*

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# Goals

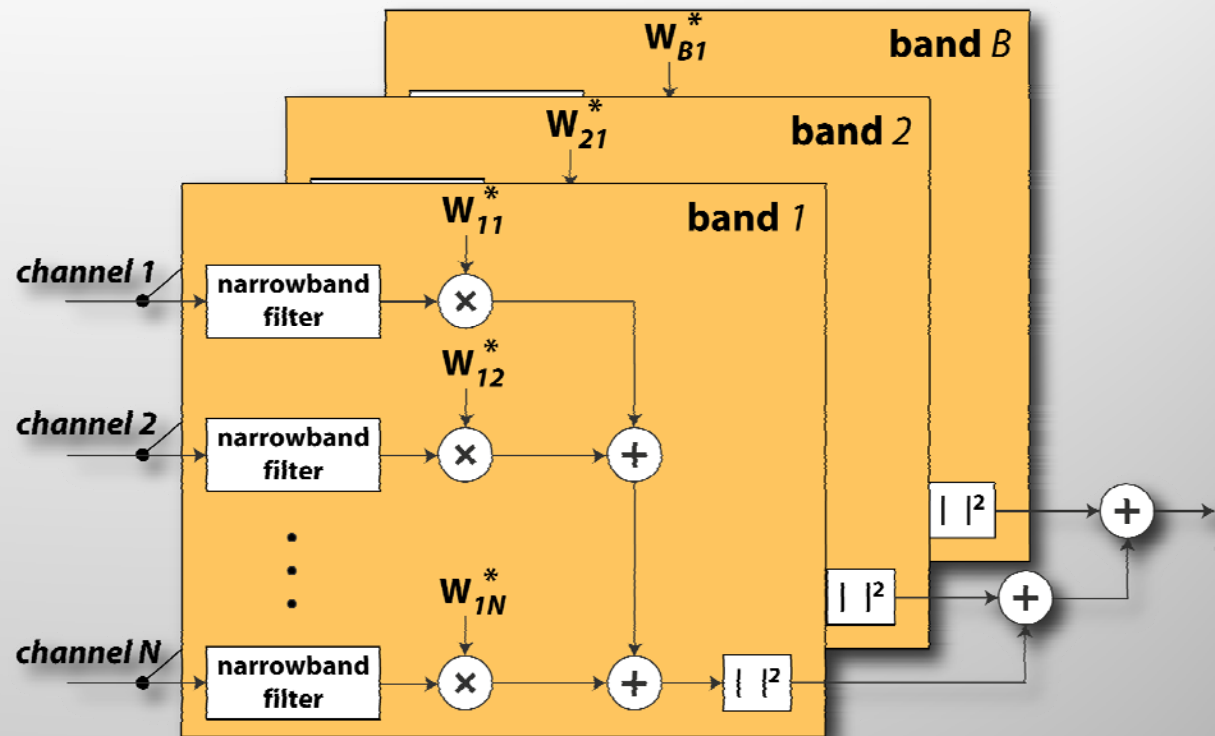
- Test use of algorithms developed for seismic monitoring to micro-seismic
- Investigate the use of Bayesian-based error estimates on micro-seismic locations
- Characterize focal mechanisms
- Compare with computational rock mechanics
- Current focus is geothermal; would like to test on other datasets.

# Overview

- Detection
  - Empirical Matched Field [see Wang et al., following]
  - Source-scanning
- Location
  - Bayesian-based location algorithm
  - Synthetic micro-seismic dataset
- Characterization
  - Velocity model from seismic interferometry
  - Adjoint full waveform inversion
- Incorporation into fracture model

# Detection

- Matched Field Processing
  - A non-traditional technique applies to a geothermal setting
  - Improved numbers of events
  - Better characterization of faults and fractures



See following talk by J. Wang for more details

# Location

- Observed lineaments in microseismic hypocenters can be used to infer faults and fractures
- Lineaments can also be created by errors in locations ('artifacts')
- Variety of algorithms for location; in this talk we focus on triangulation using P and S phases
- How to distinguish between artifacts and real structures?
  - Better error estimation
  - Focal mechanisms
- Test on synthetic and real datasets

# Location errors

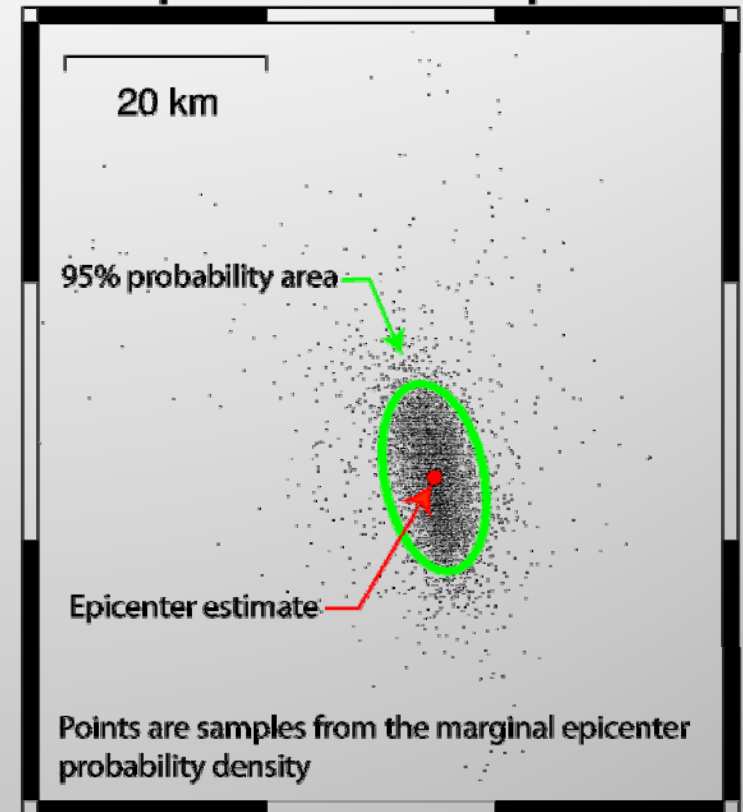
- Velocity model inaccuracies
- Measurement errors
- Compounded by station location and geometry
- Error estimates provided by most algorithms are poor
- Proper error estimates, in combination with other information, greatly assist interpretation



# Location algorithm

- Bayesian-based Monte Carlo location algorithm ('Bayesloc')
- Developed for regional/global monitoring and currently being adapted for micro-seismic
- Usually used to locate many events simultaneously; this leads to improved locations
- Provides estimated errors of locations and input measurements at each stations for all phases.
- Improved assessment of location uncertainty helps to confidently identify real seismicity patterns; can be automated
- Open-source C++ code; free!

## *A Posteriori* assessment of epicenter samples

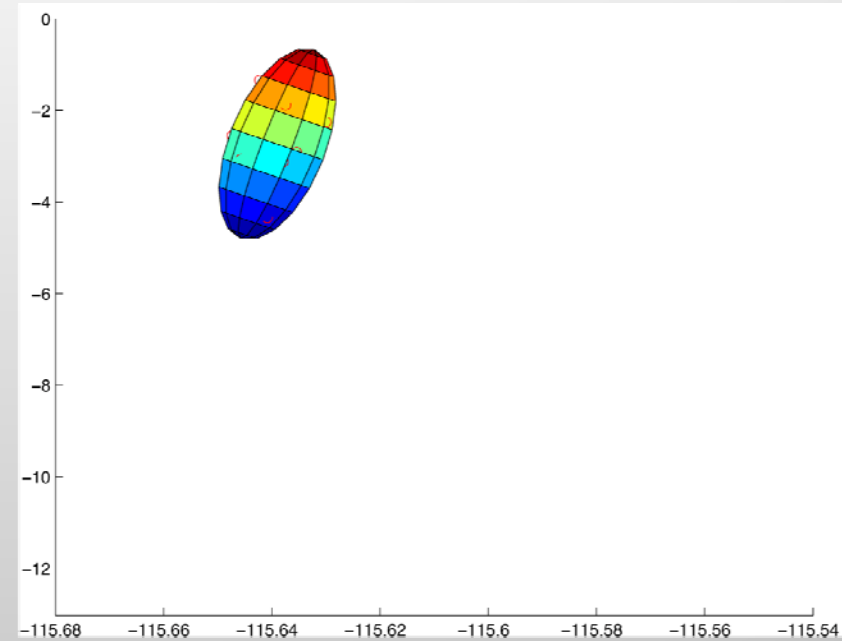
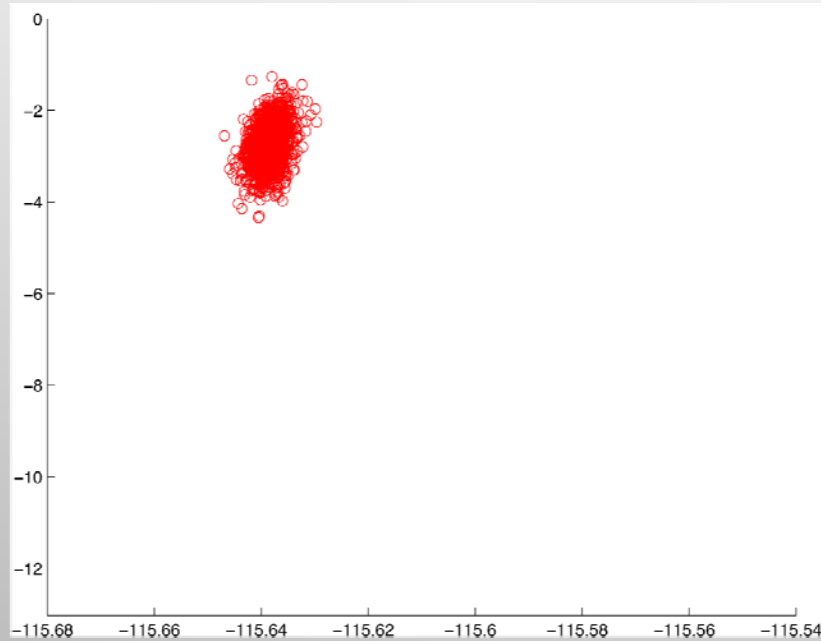


Shows probability of a single event by testing many possible locations (black dots)



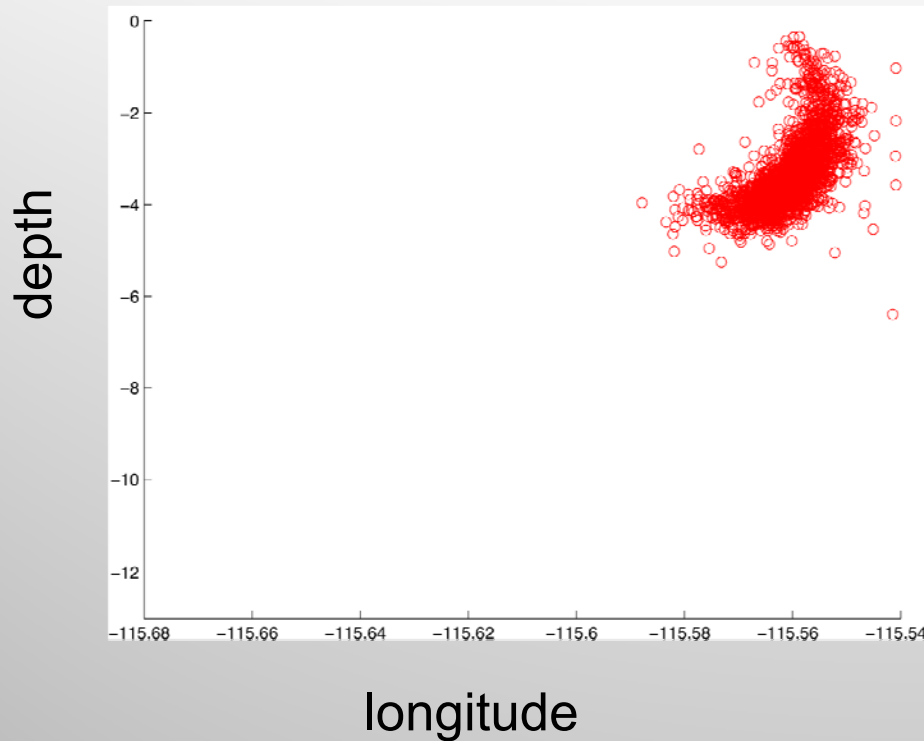
# Are location errors Gaussian?

Gaussian Representation (ellipsoid)



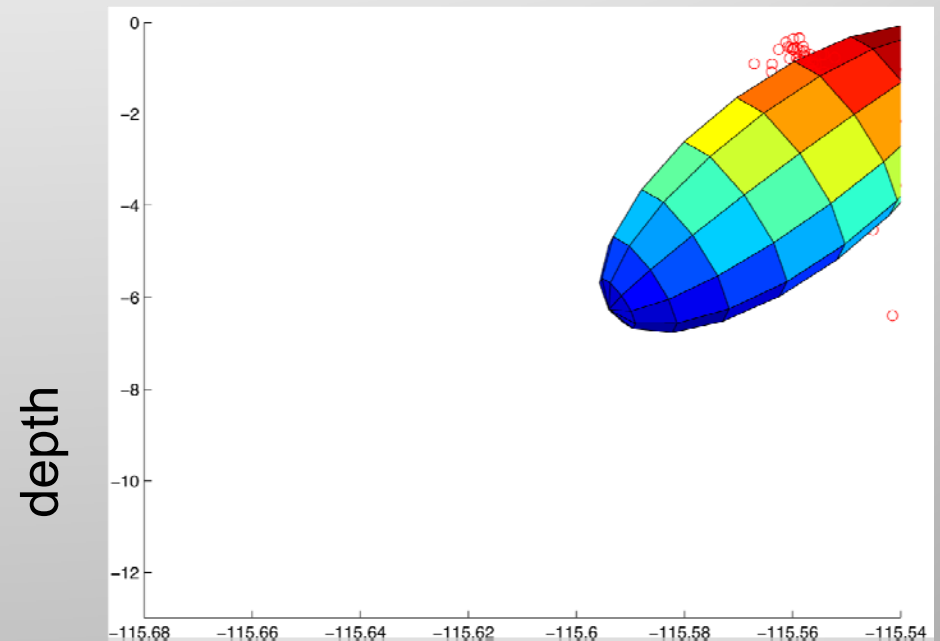
Sometimes...

# Example of non-Gaussian errors



Gaussian assumption of error may not always be appropriate  
Dependent on station geometry and velocity model

Possible locations for a single event that fit data at a 95% level



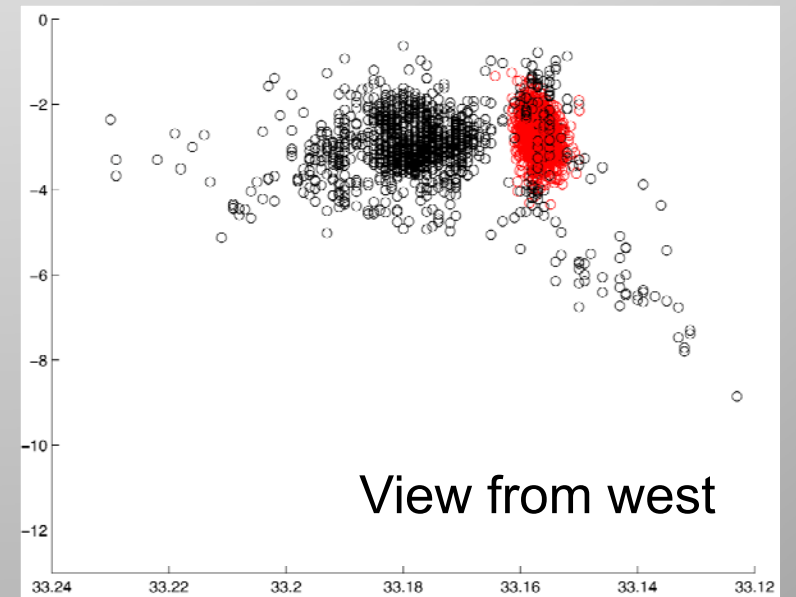
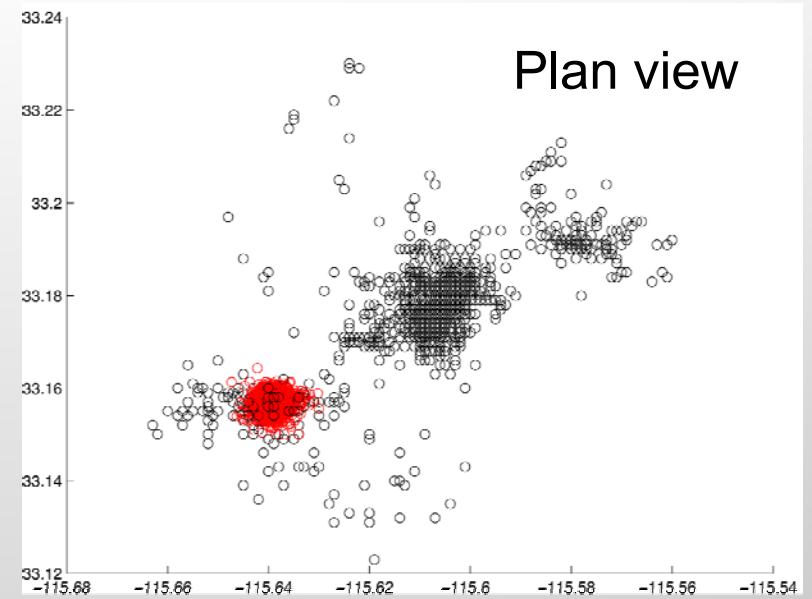
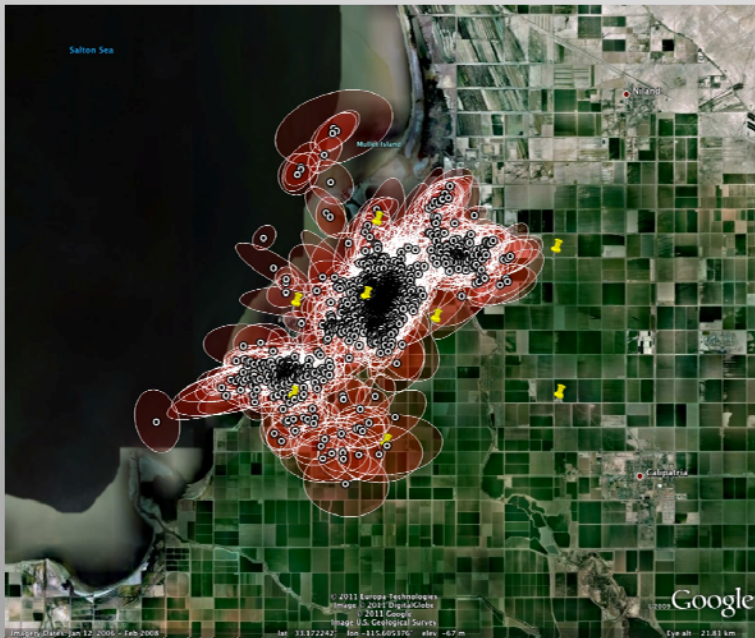
Gaussian best-fit to data at 95% level; poor representation of error

# Example: Identifying artifacts in micro-seismic locations

Salton Sea geothermal field  
(~3000 events; 5 minutes on desktop quad-core)

**Question:** Is apparent vertical structure (red) real?

**Answer:** Likely not; most events in red area have high measurement error and poor depth control

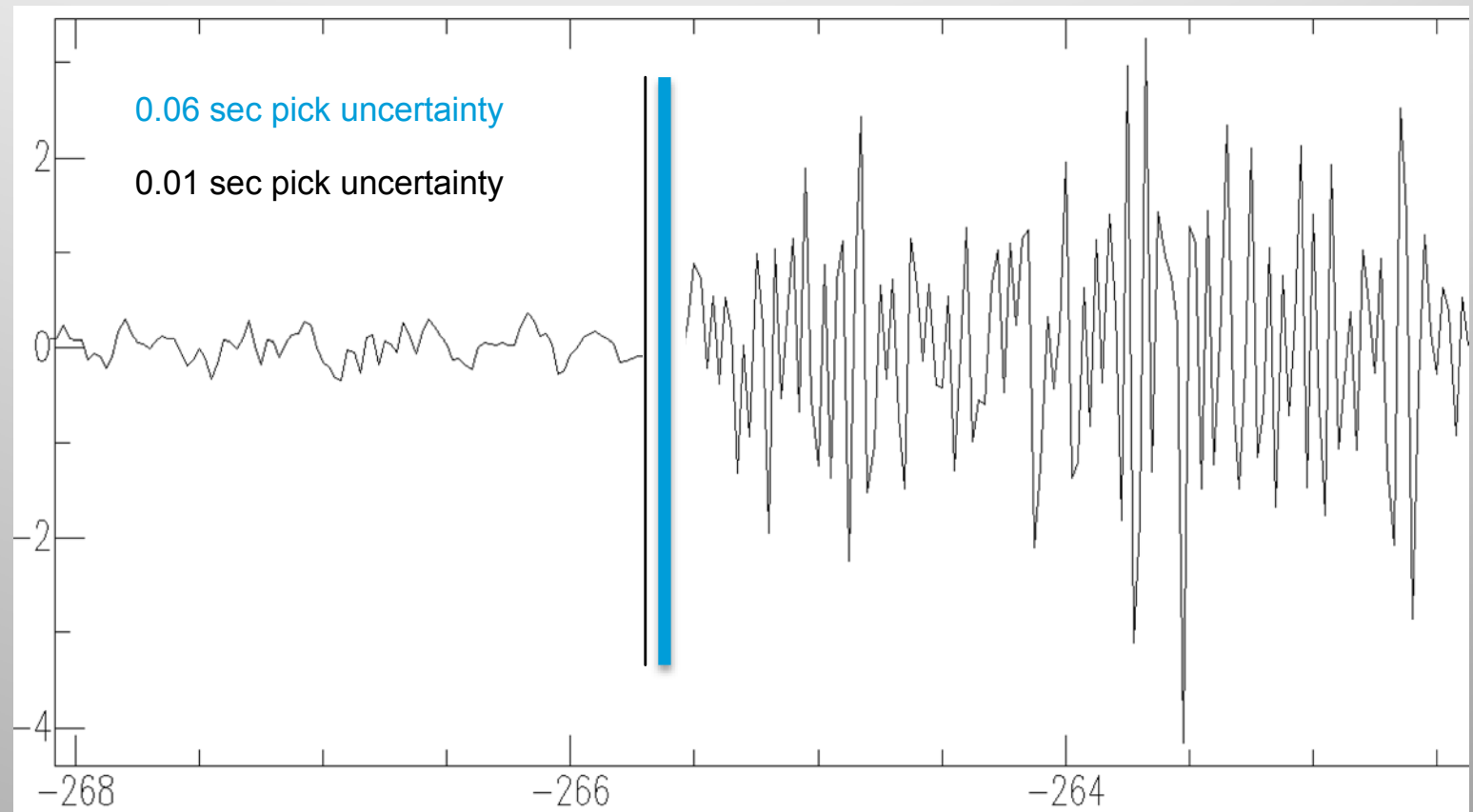


# Major source of errors

Average measurement uncertainty determined in Bayesloc

P = 0.06 sec  
S = 0.09 sec

Pick errors ~0.01 second are needed for >100 meter location accuracy (sample rate 100/sec).

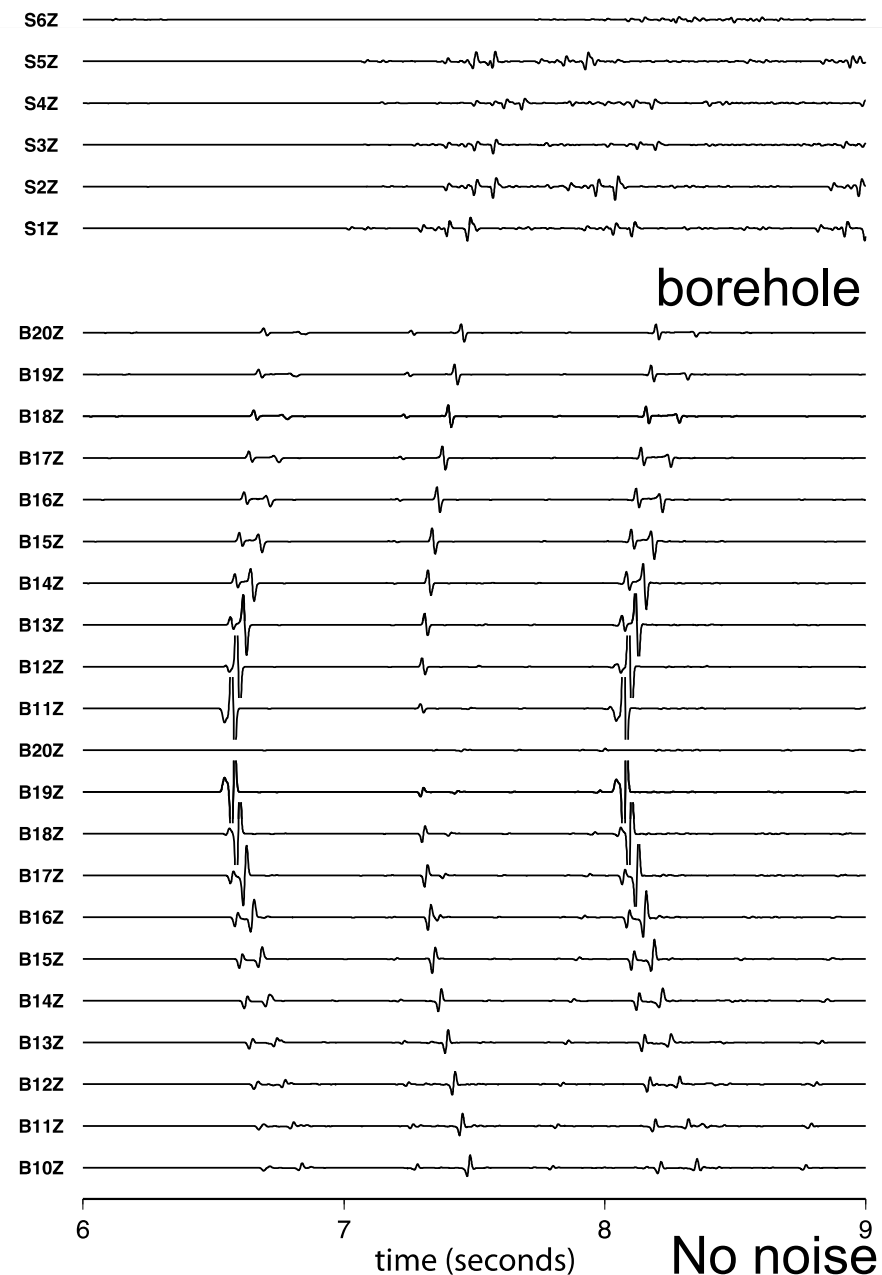
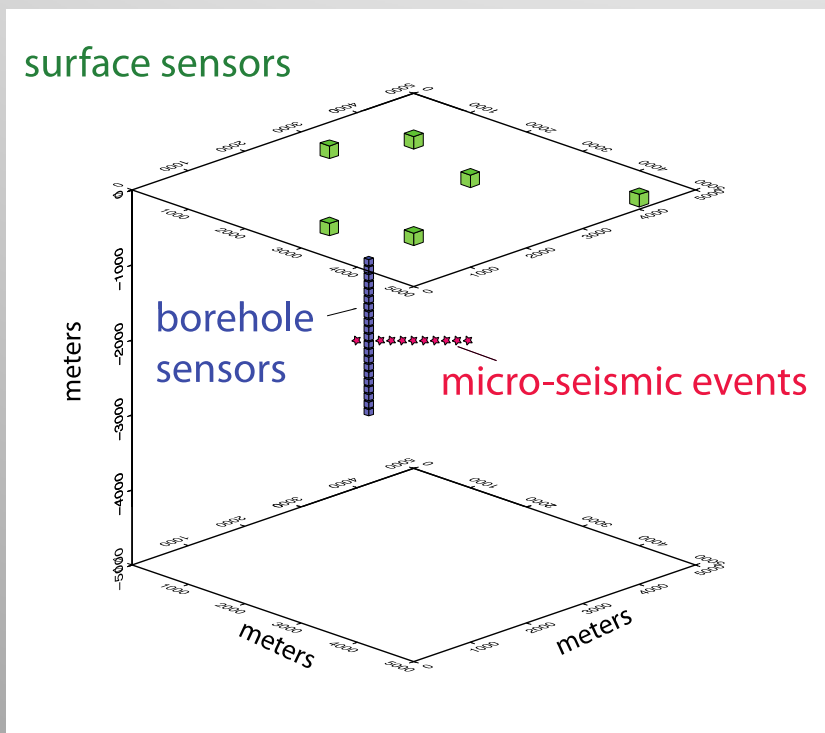


# Synthetic microseismic dataset

- 3D velocity variations
- Multiple events; full moment tensor representation
- Up to 72 Hz
- 5 km by 5 km by 5 km; 80 million points; 3D finite difference code
- Based on geothermal field
- Noise added afterwards

surface

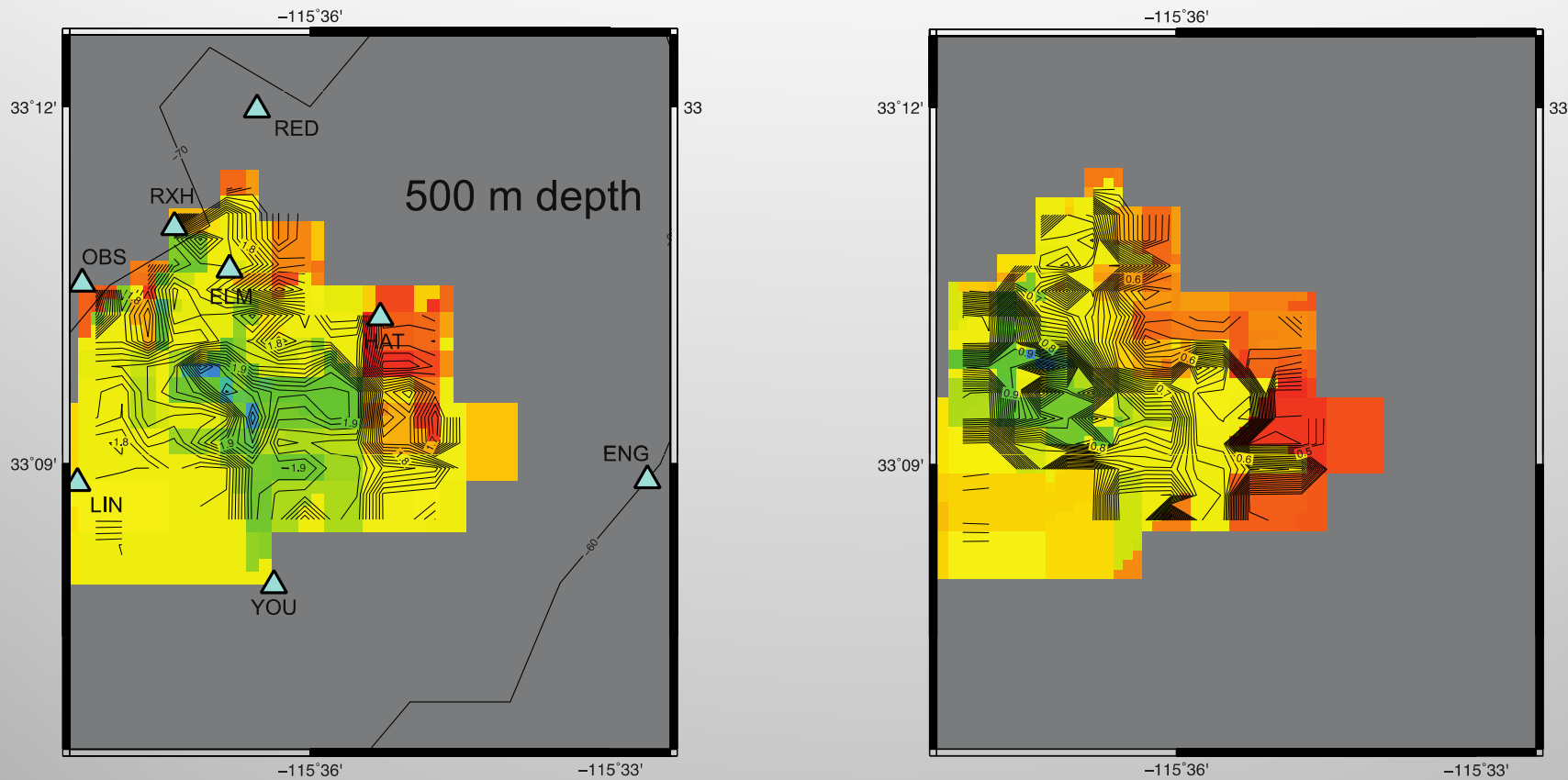
borehole



# Improve velocity model

- Seismic interferometry
- Powerful technique to estimate velocity structure (especially shallow)
- Use ambient noise field rather than active sources
- Requires continuous seismic data.
- More data; better model

# Example: Salton Sea



Variations in velocity of Salton Sea geothermal field based on seismic interferometry using 4.5 Hz geophones



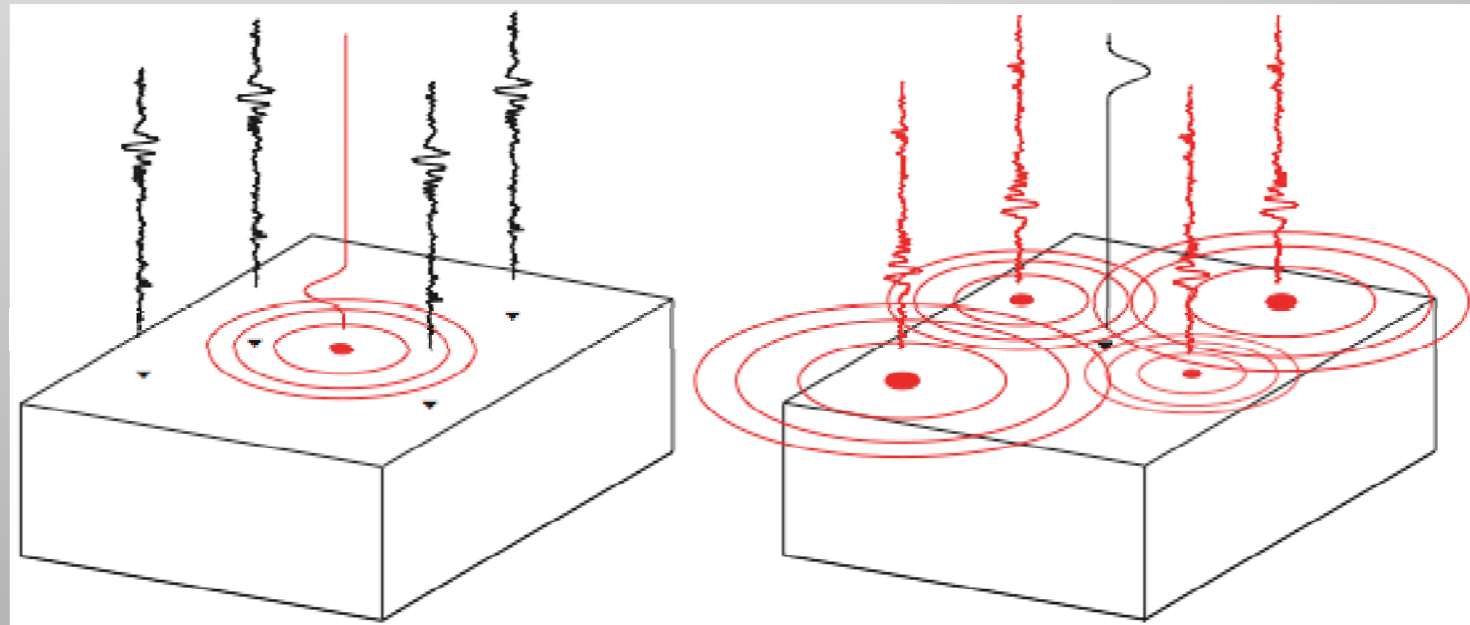
# Source characterization

- Infer orientation of fractures
- Determine focal mechanism/moment tensor
- Estimate energy release
  - Magnitude
  - Stress drop

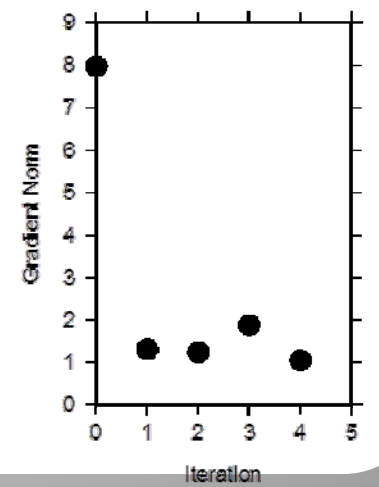
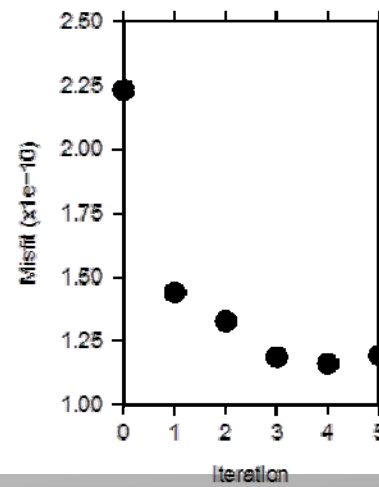
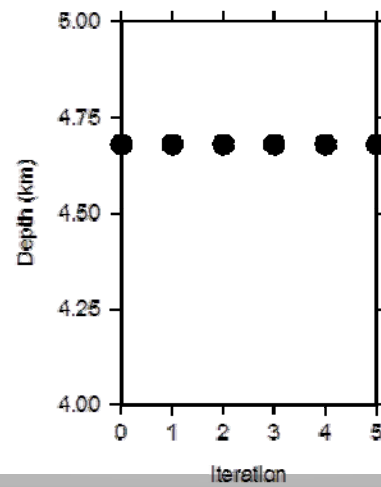
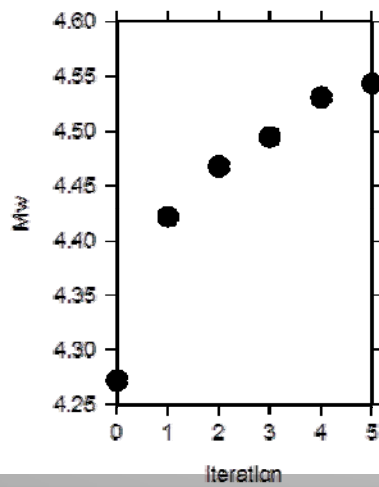
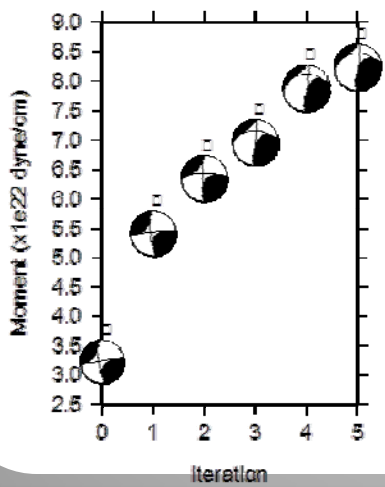
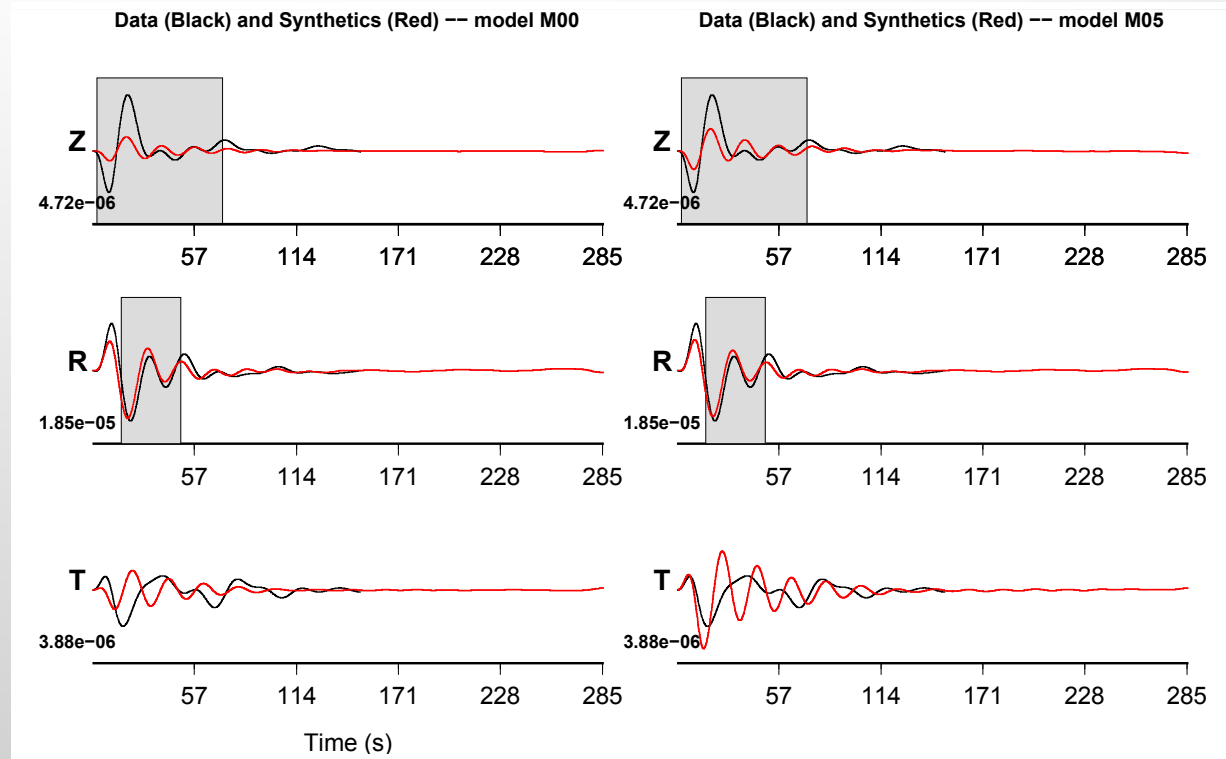
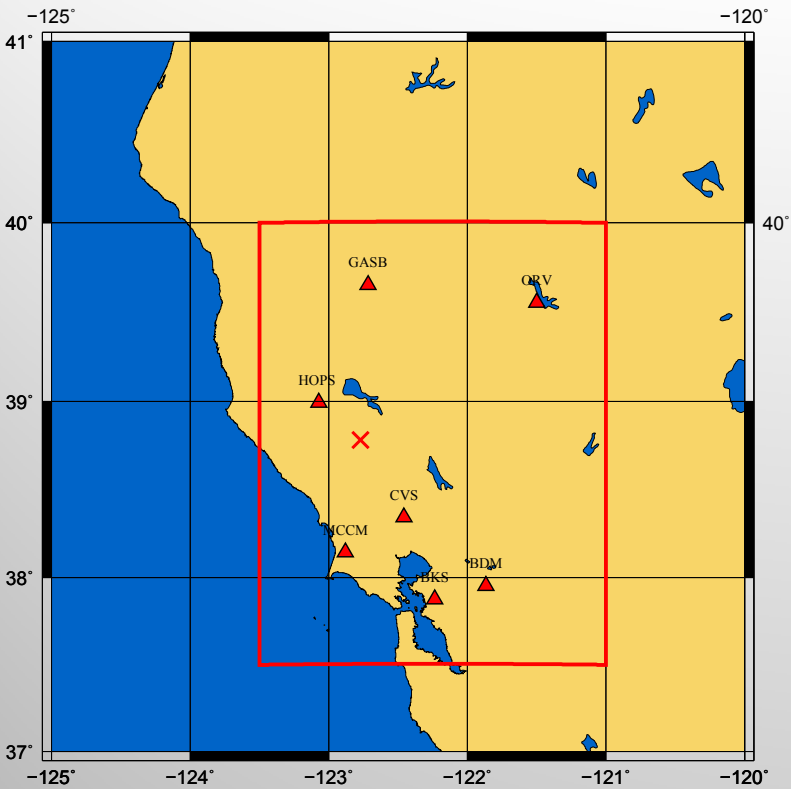
# Source characterization

- Infer orientation of faults and fractures
- Adjoint full waveform inversion
  - Proven at large scale; adapted for local scale & micro-seismic
  - Compares wavefield data and synthetics, uses differences to recover structural and source mechanism
  - High-frequencies are challenging

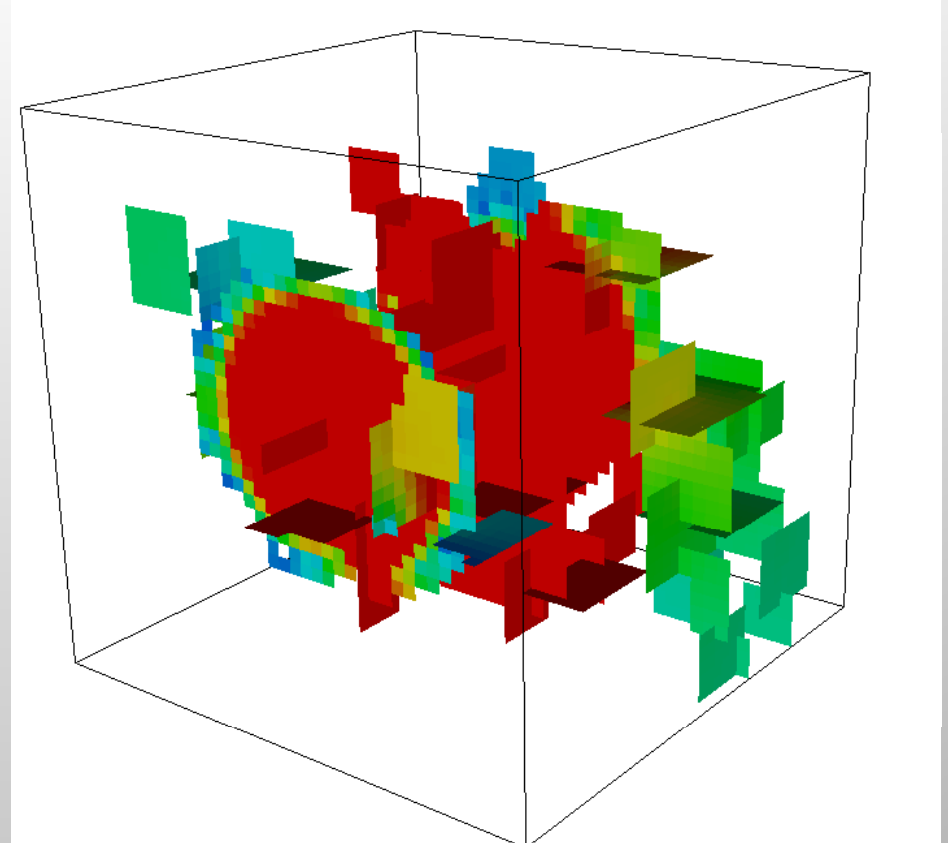
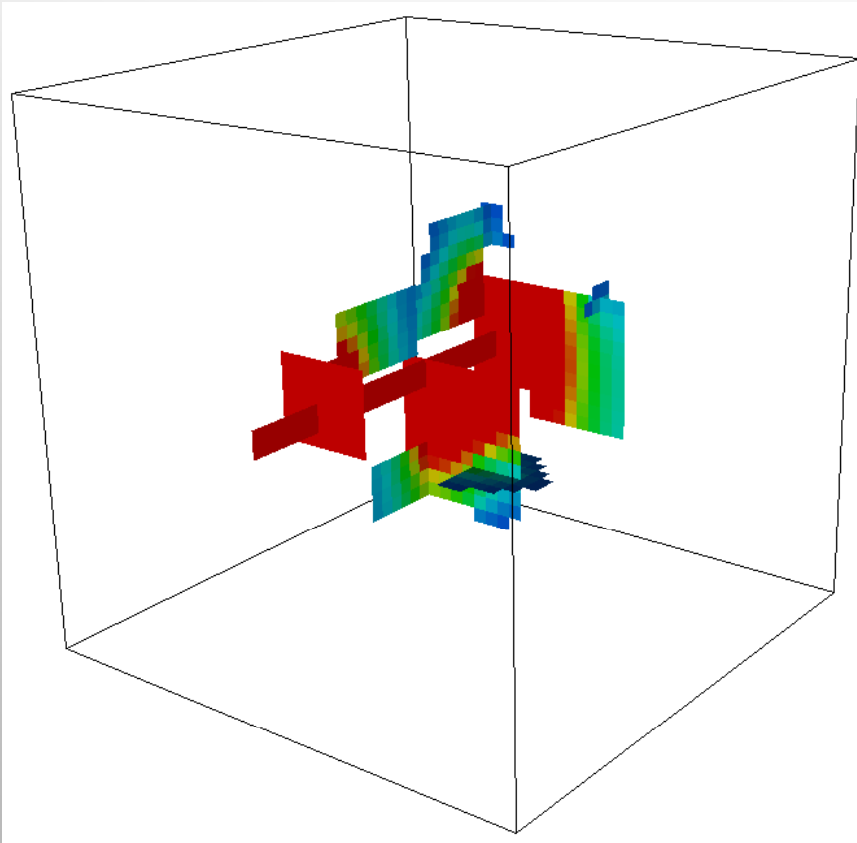
Adjoint source =  
back projection



# Example: the Geysers Geothermal field



# Fracture simulation: 3D



Objective:

- Fracture network modelled from fundamental rock physics
- Use microseismicity and sources to constrain fracture network

In progress

# Conclusions and next steps

- Accurate error estimation assist interpretation
- Seismic interferometry effective for velocity model
- Full waveform inversion for small events challenging
- Develop openly available 3D synthetic microseismic dataset for algorithm validation using 3D finite difference
- Merge location and source characterization with fracture modeling
- Datasets needed!
- Questions: [mellors1@llnl.gov](mailto:mellors1@llnl.gov)

Thank you for your time!