Monitoring and Modeling Fluid Flow in a Developing EGS Reservoir

April 24, 2013

Michael Fehler
Massachusetts Institute of Technology

Monitoring and Monitoring Fluid Flow

Relevance/Impact of Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Project Objective

Use Chevron's high-quality data from a long-term injection in the Salak geothermal field to better understand stress changes and permeability development during the fracture growth stage of an EGS development

Question

Why does seismicity appear to be propagating to significant depth below the injection zone?

Related Questions

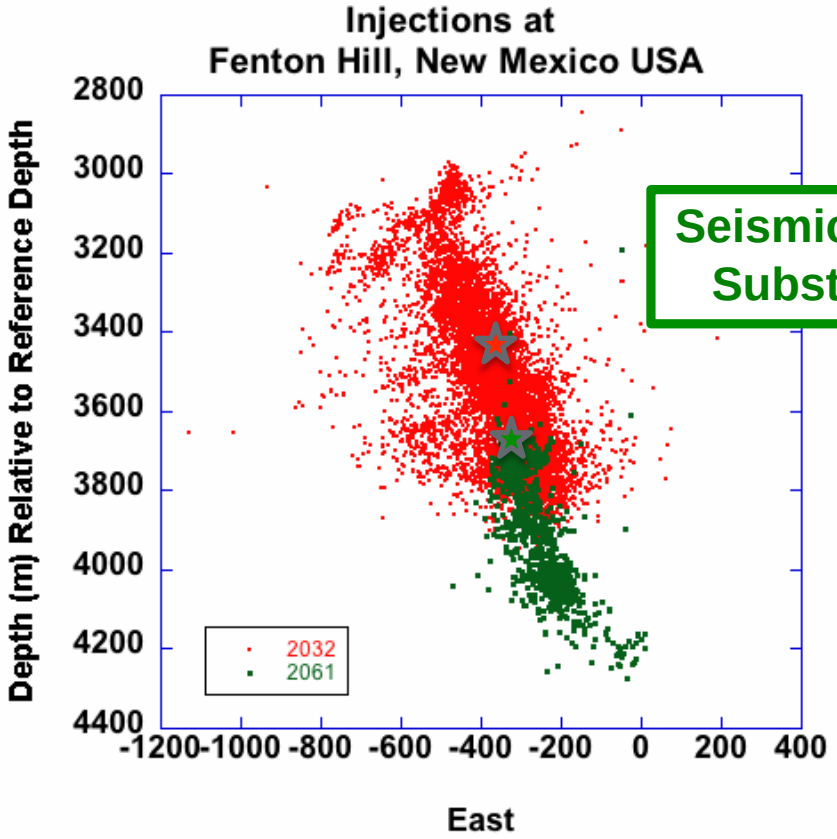
How well constrained are depths of the events?

How well can we do with a relatively sparse seismic network located on the surface (typical EGS monitoring)

Background

- Reliable reservoir models are essential to predict and improve performance of EGS system
  - Lifetime and production prediction essential for economic model
- Need to better understand how to optimize stimulation of geothermal reservoirs
- Seismic data provide best reservoir information at locations away from borehole
- What can we learn about geomechanics from seismic analysis coupled with reservoir simulation?

Scientific/Technical Approach

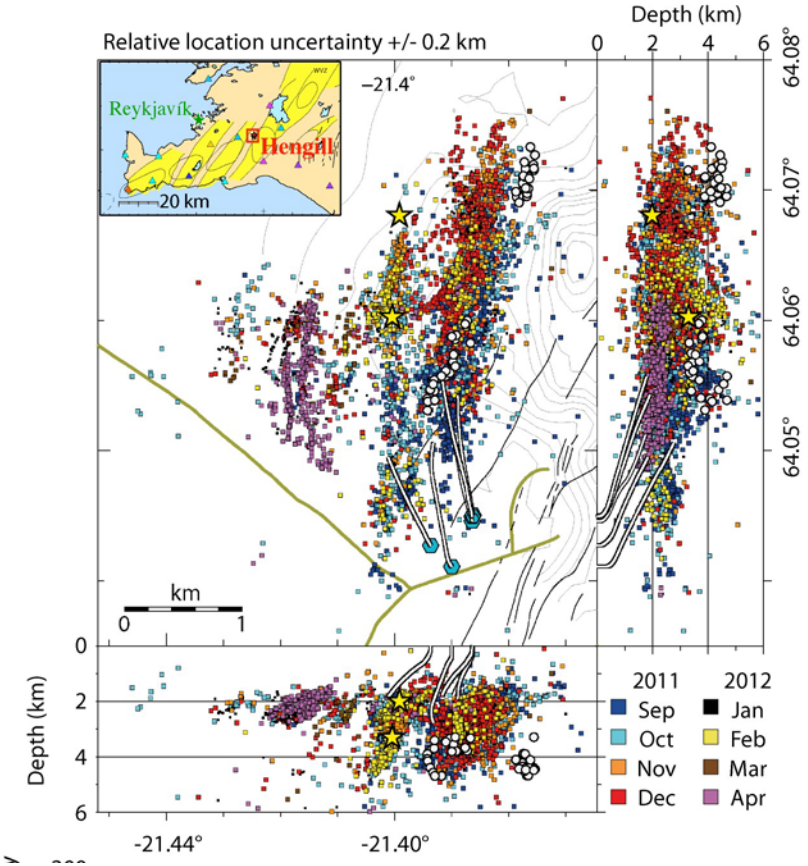


Seismic Energy Release During 2061 was Substantially Higher than During 2032

★ 2032 Injection zone, 21,600 m^3 injected

★ 2061 Injection zone, 5,600 m^3 injected

- Seismicity accompanying wastewater injection in Hengill geothermal field, Iceland
- Seismiciity extends downward from injection zone
  - Migration in time is also apparent



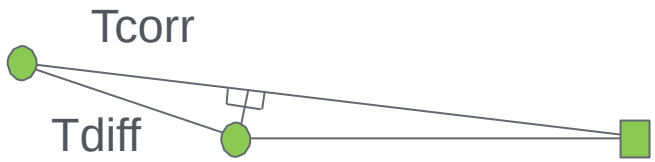
Hreinsdottir et al., 2012

Scientific/Technical Approach

- Seismic tomography
  - Event locations and velocity structure
- Focal mechanism determination
  - Planes of slip and constrain stress field
- Interferometry to constrain interevent travel times
  - Help evaluate location catalog resulting from tomography
- Estimation of Green's function for diffusion of seismic waves
  - Diffusion coefficient places bounds on multiple scattering of seismic waves and hence on heterogeneity (fractures) of reservoir

Seismic Interferometry for the Assessment of Event Location Accuracy

- Measure the traveltime delays at each station via crosscorrelation
- This gives a lower bound on the actual traveltimes



Tdiff > Tcorr

- Summing the correlated signals (interferometry) improves the reliability of this estimate and reduces its dependence on the velocity model

Relevance to Project Objectives:

- Tool to mitigate trade-off between locations & velocities
- Confidence in location of events and thus interpretation of results

Awibengkok (Salak) Geothermal Field, Indonesia

- Operated by Chevron
- Water-dominated system
- > 370 MWe

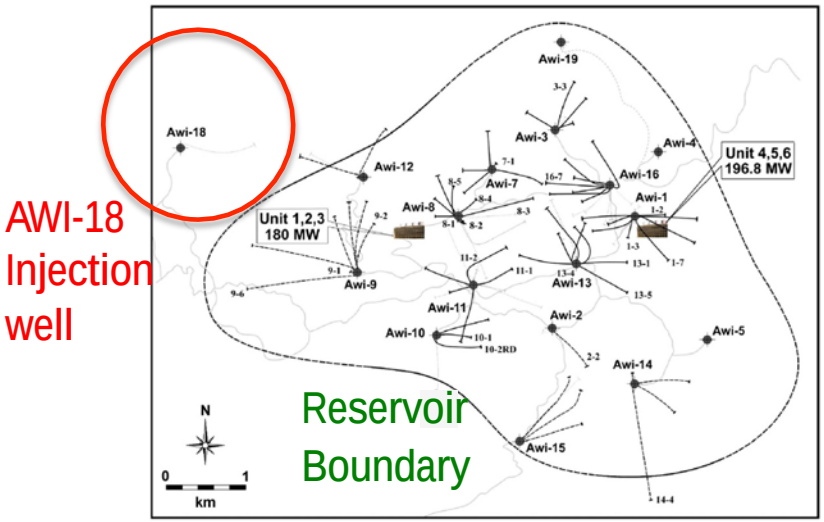


Figure modified from *J.A. Acuna et al. / Geothermics 37 (2008) 332–346*

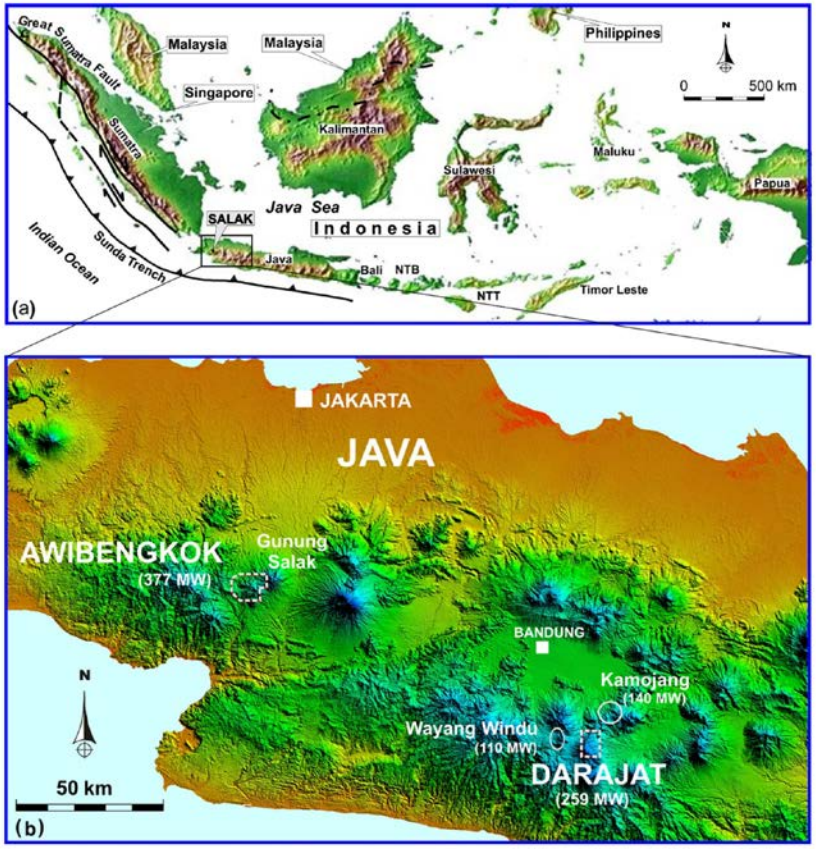
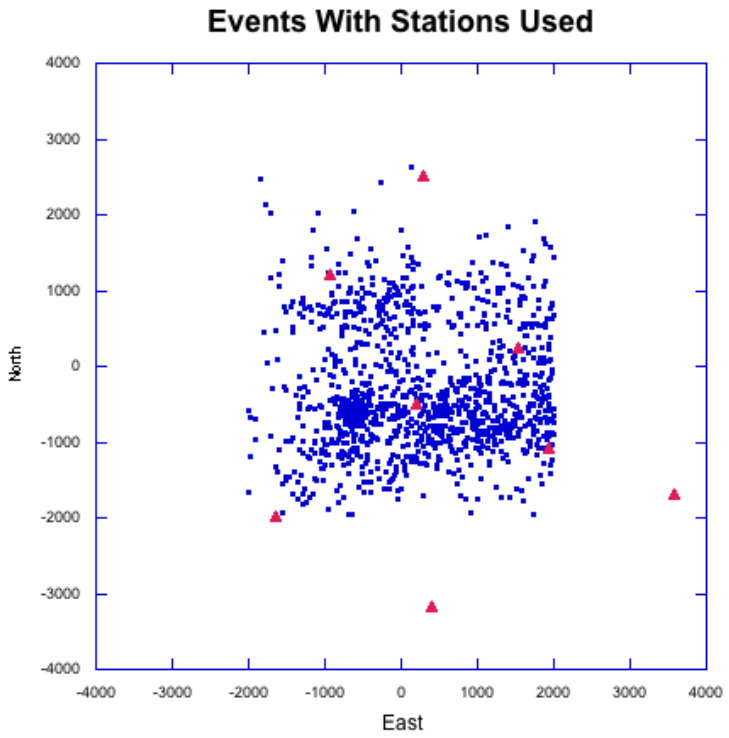


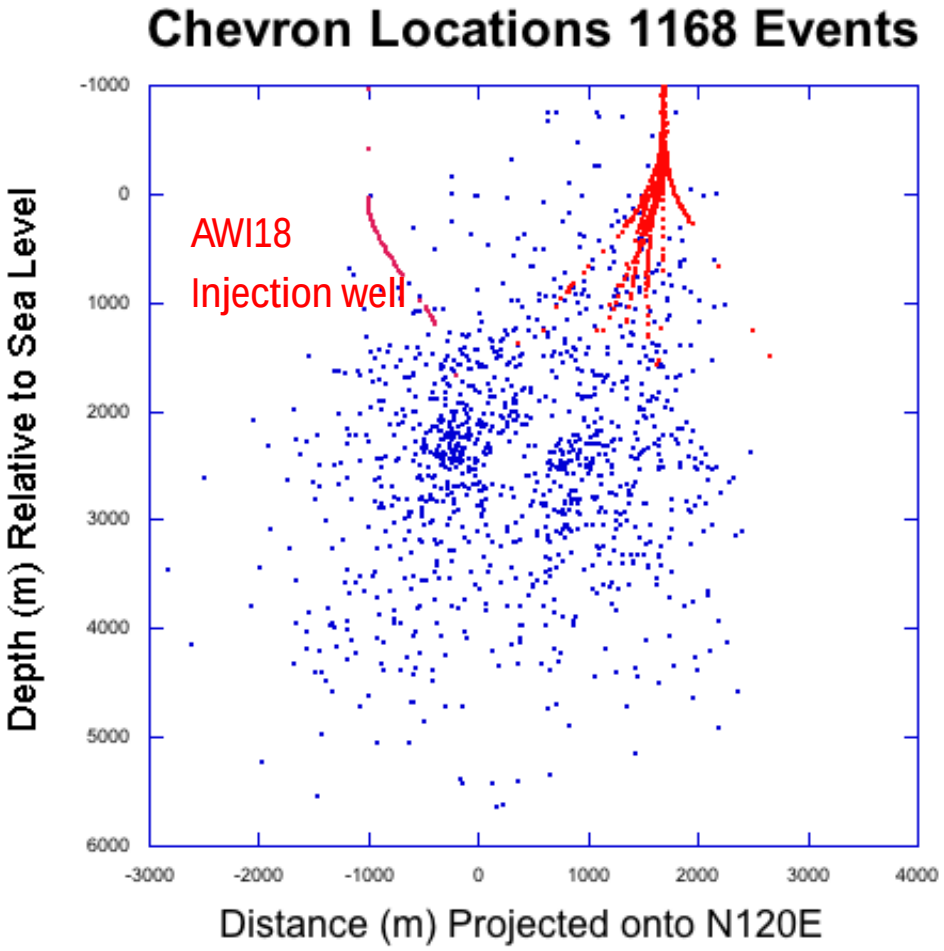
Figure from *J. Stimac et al. / Geothermics 37 (2008) 300–331*

Tomography Using Seismic Events Near Injections into the Salak Geothermal Field

- Questions are
  - how deep are events
  - relationship to injection
  - relationship to wellbore fractures and geology
- Apply tomography to events in region surrounding injection zone to get constraint on locations and thus on structure

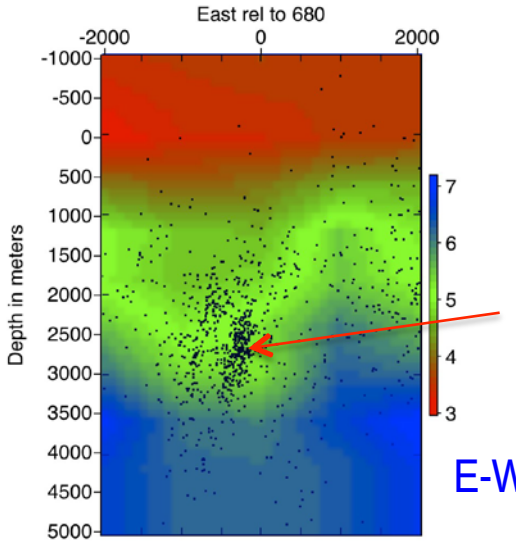


- Selected 1168 events in region near injection well
- Applied tomodd both with and without waveform cross correlation times
- Locations shown are projected onto N120^{o}E



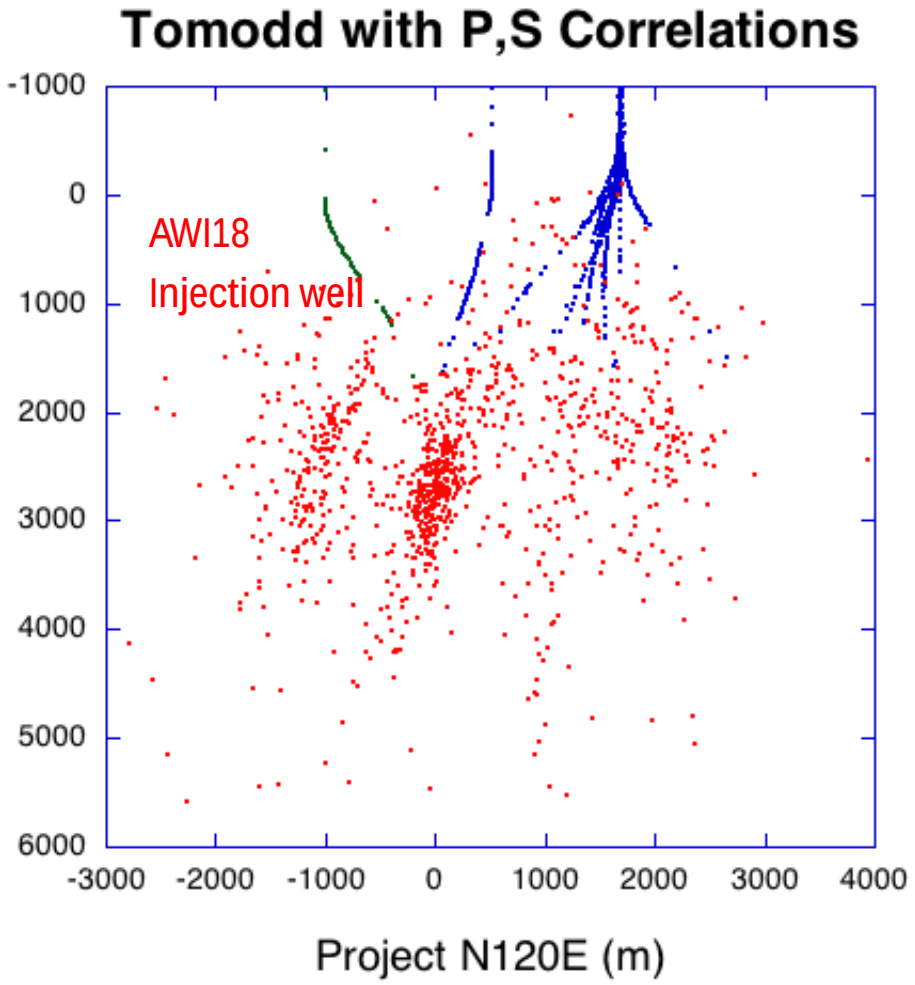
Projection is onto plane perpendicular to Muara fault

- Projection of locations onto vertical cross section trending N120°E
- Below is EW vertical cross-section through P



Events appear to fall along low-velocity trend

E-W Projection

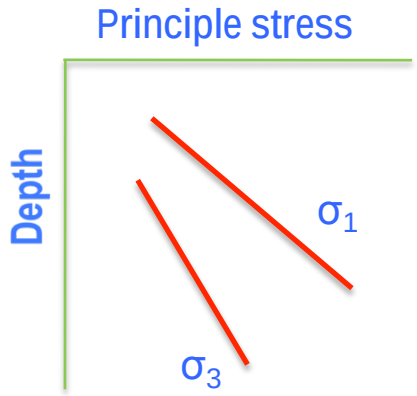


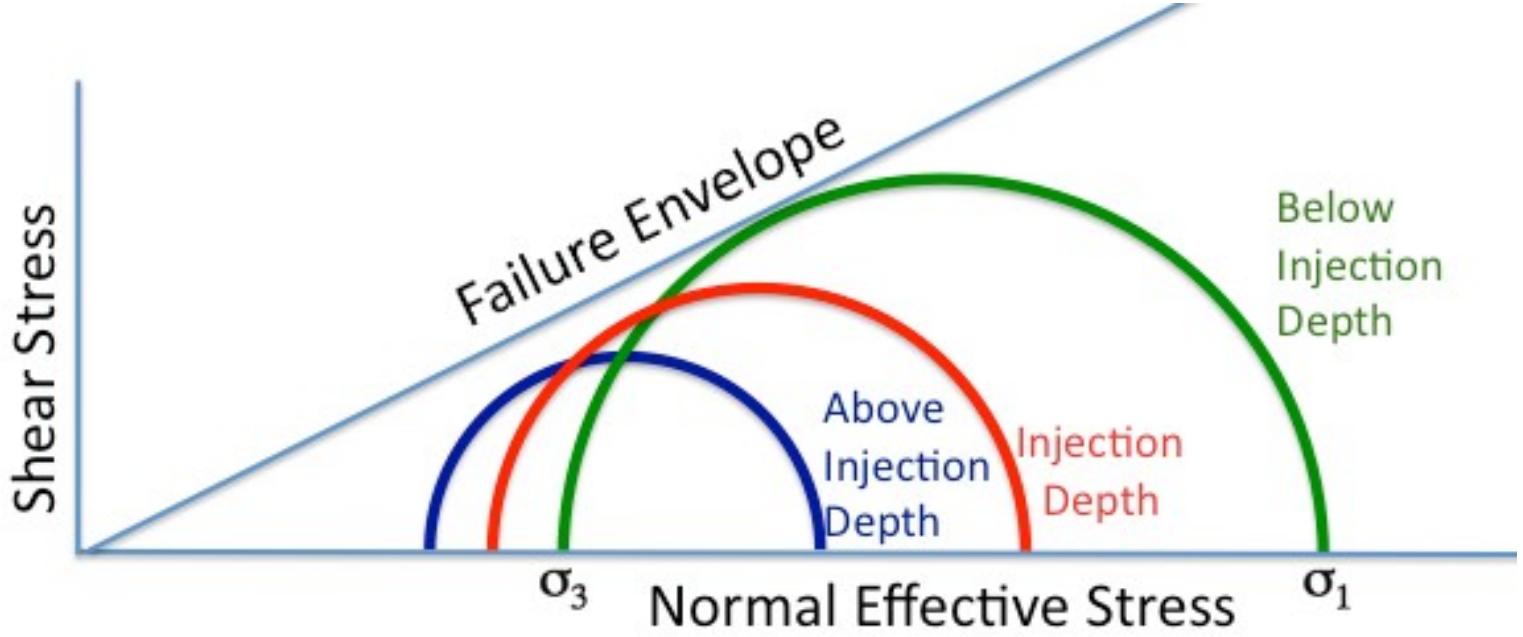
Projection is onto plane perpendicular to Muara fault

Why Seismicity Migrates Downwards

Stress Gradients

- Shear stress increases as difference in principle stresses increases
- If principle stresses have different gradients with depth, difference in principle stresses increases with depth and shear stress increases with depth
- Leads to increasing shear stress with depth and more likely failure with increasing depth
- Possible mechanism at Salak and Fenton Hill

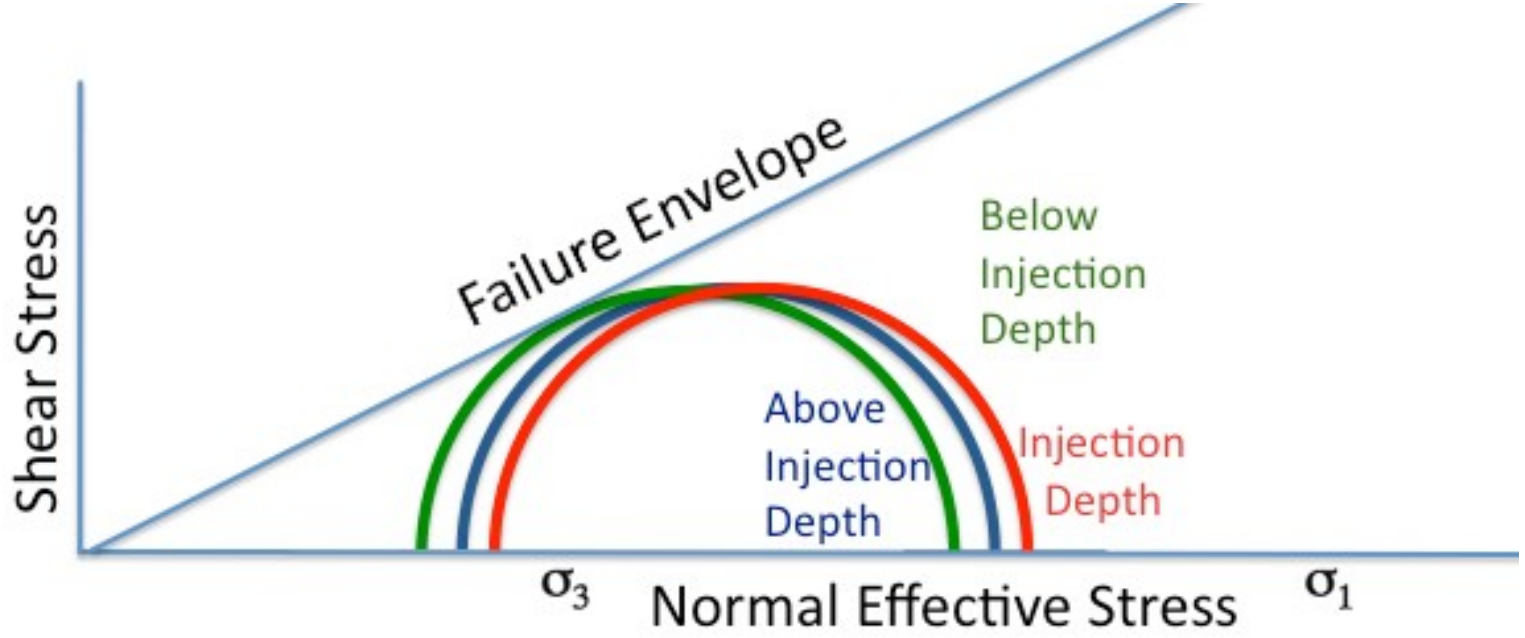




Why Seismicity Migrates Downwards

Temperature Gradient

- Cold water reduces effective stress
- Amount depends on water temperature relative to ambient
- Stress reduction is more below injection zone due to higher ambient temperature
- Depending on temperature gradient, effect of cold water is to shift Mohr envelope to failure envelope
- Rule of thumb: stress change due to 1 MPa pore pressure is equivalent to that from 5 degrees C temperature change



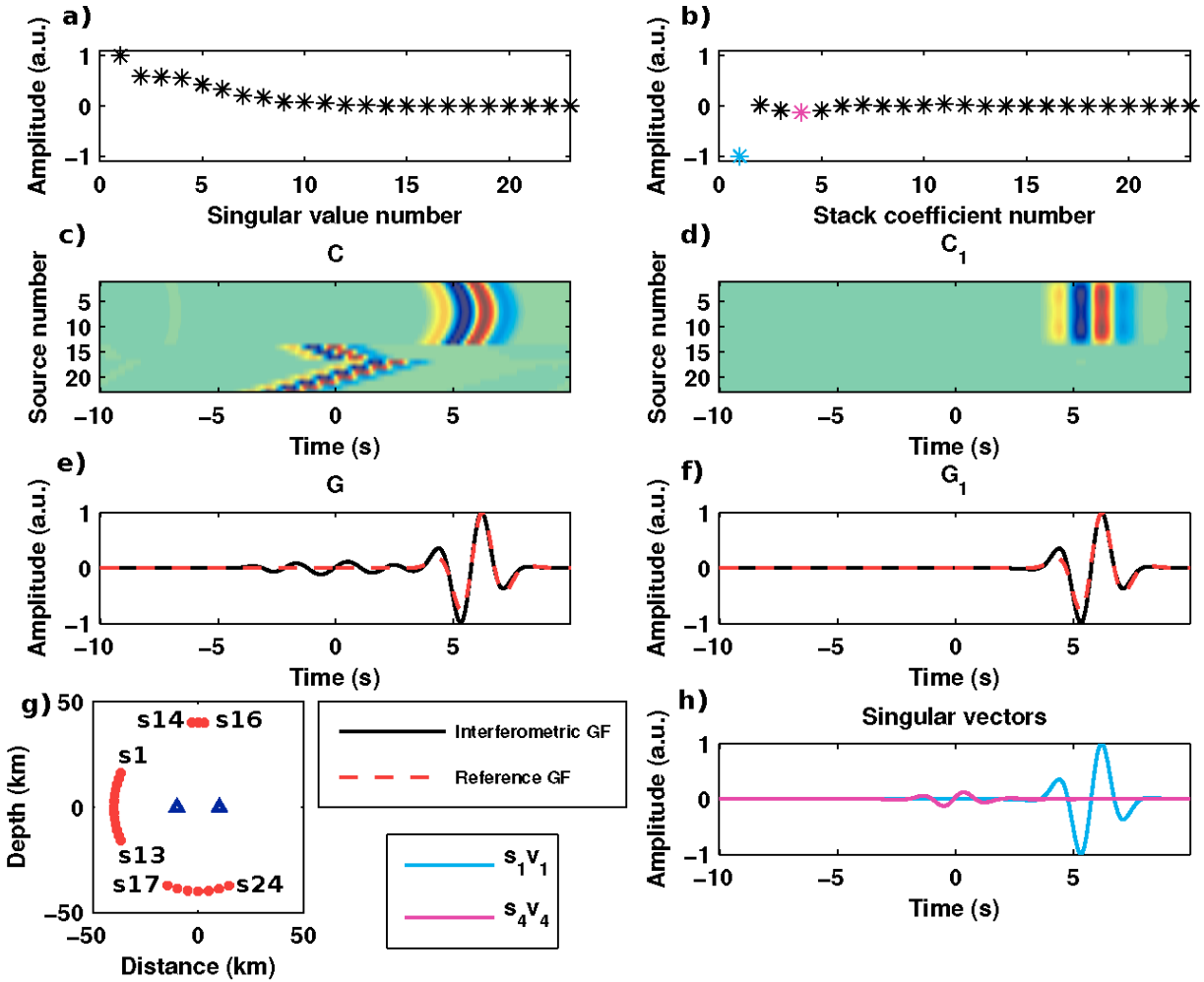
Seismic interferometry for the assessment of event location accuracy

- Compared three methods of location
- Completed and submitted paper on use Singular Value Decomposition to improve interferometric estimations and applied to field VSP dataset

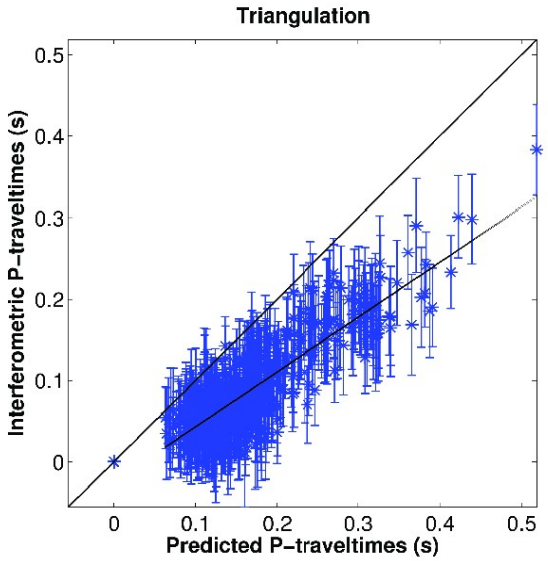
Challenges:

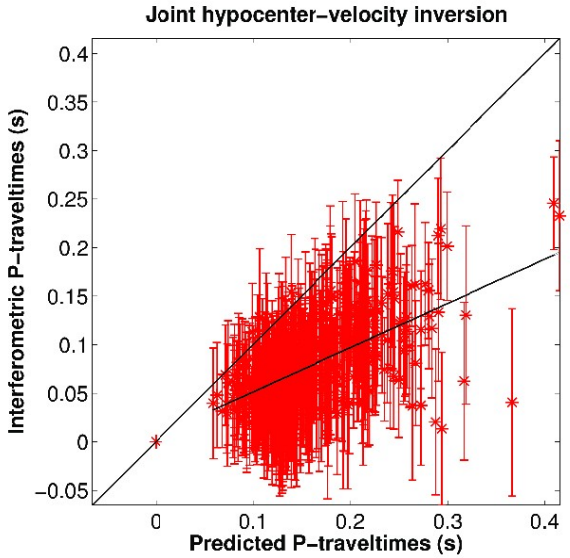
- Designing a fair comparison for each method
  - Using different models for each method
- Locating event pairs for which method is most likely to be accurate
  - Primarily events located roughly above one another

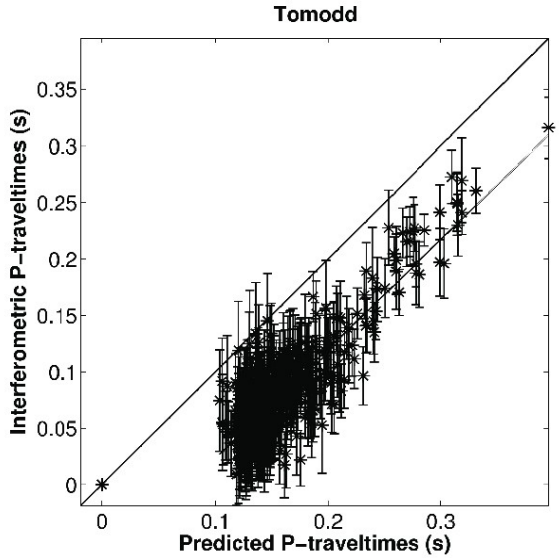
Benefits of Singular Value Decomposition in Interferometry



Using Interferometry to Compare Results of 3 Location Methods







Mandatory Summary Slide

- Salak data is a rich dataset for understanding EGS potential on the edge of a producing geothermal field
- Tomographic analysis provides significantly improved location catalog that
  - Shows events migrate downward from two injections
  - Events fall along approximately planar features that are parallel to nearby fault and parallel to fractures from well logs
- Interferometry provides us a way to test our event location catalog
- Project is technically complete but we will wrap up some loose ends and write papers

Project Management

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- The purpose of this slide is to provide some context for evaluating your project.
- Please prepare one overview slide containing the following information:

Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
2/1/09	2/1/13	2/1/9	2/1/13

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
708,633	450,000	1,158,633	1,148,633	1,100,701	10,000