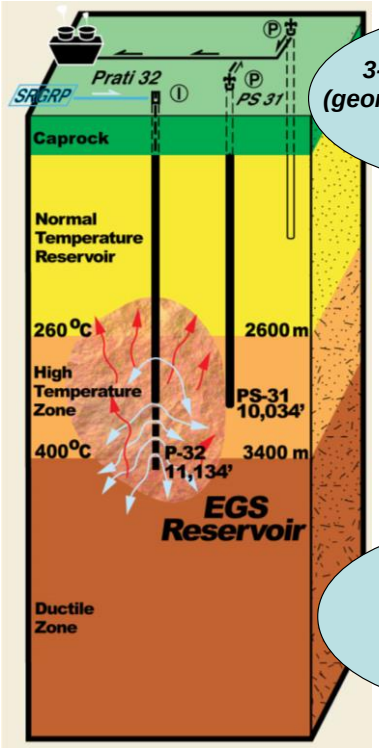
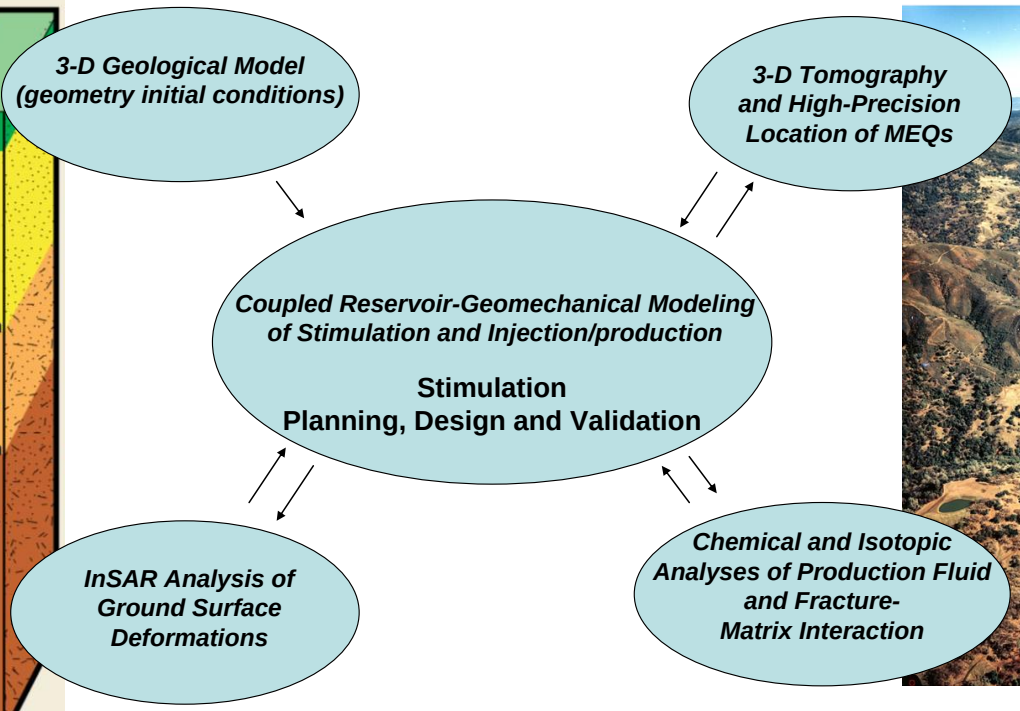
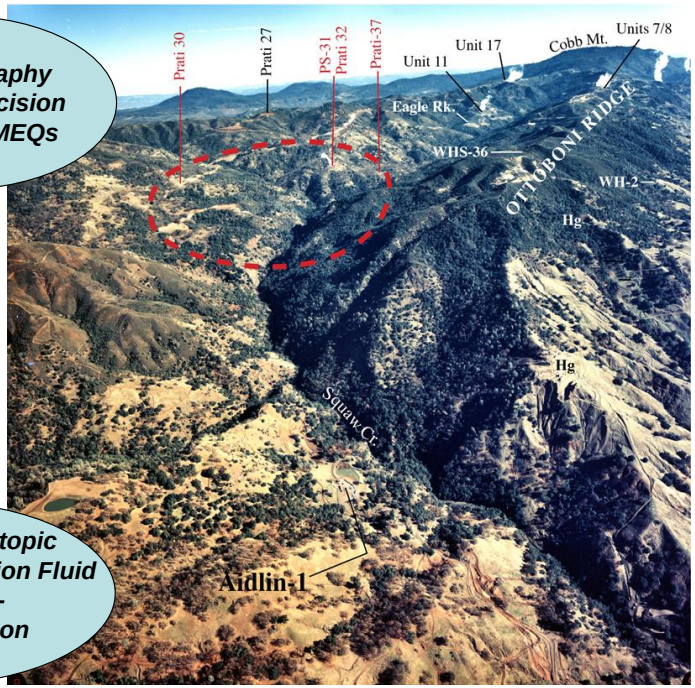
The EGS Concept:



Modeling and Monitoring:



The Site:



Modeling and Monitoring of the Northwest Geysers EGS Demonstration

Project Officer: Lauren Boyd

Total Project Funding: $ 1510K (2009-2014)

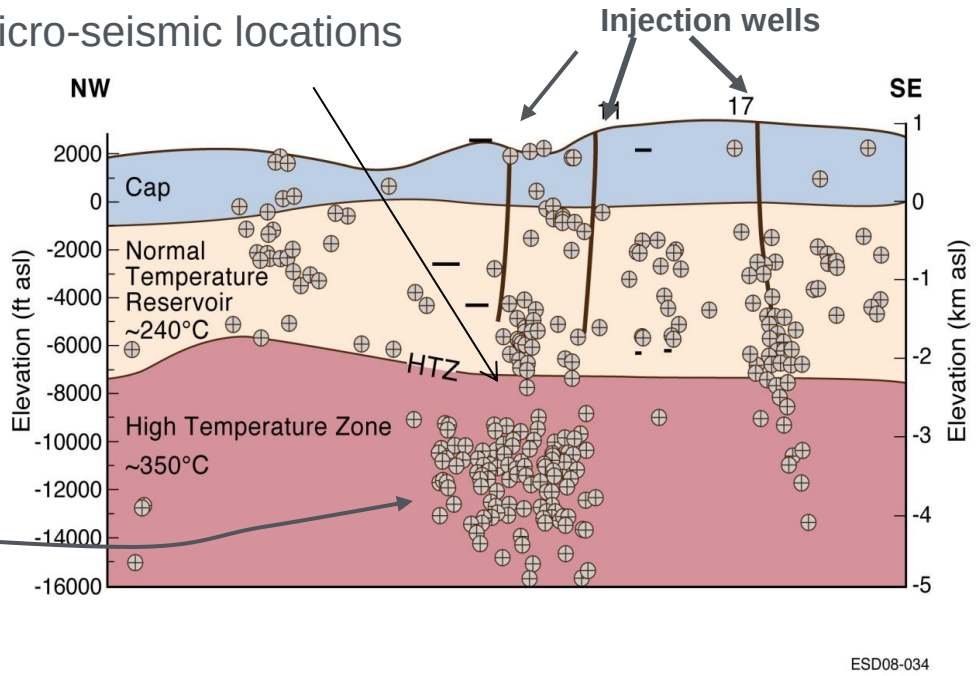
Jonny Rutqvist (Pi)

Pierre Jeanne, Pat Dobson, Don Vasco, Mack Kennedy…

Project Objectives

Create an Enhanced Geothermal System (EGS) by directly and systematically injecting cold water under low pressure into NW Geysers high temperature zone (HTZ)

Similar to “inadvertently” created EGS in the oldest Geysers production area to the southeast of the EGS demonstration area



Other technical objectives are:

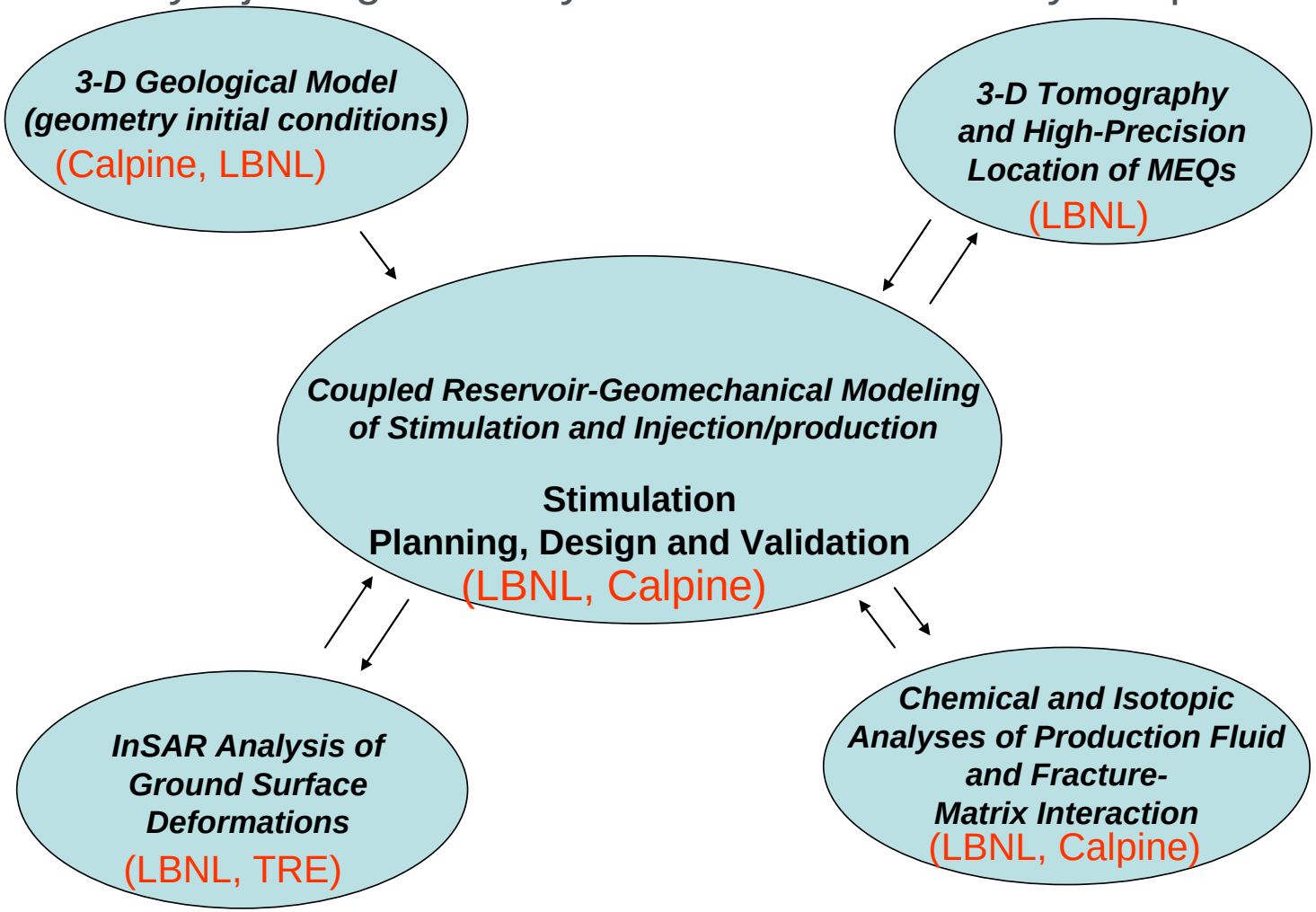
- To investigate how cold-water injection under low pressure affects fractured high temperature rock systems
- To investigate the technology to monitor and validate stimulation and sustainability of such an EGS

The NW Geysers EGS Demonstration Project Overview

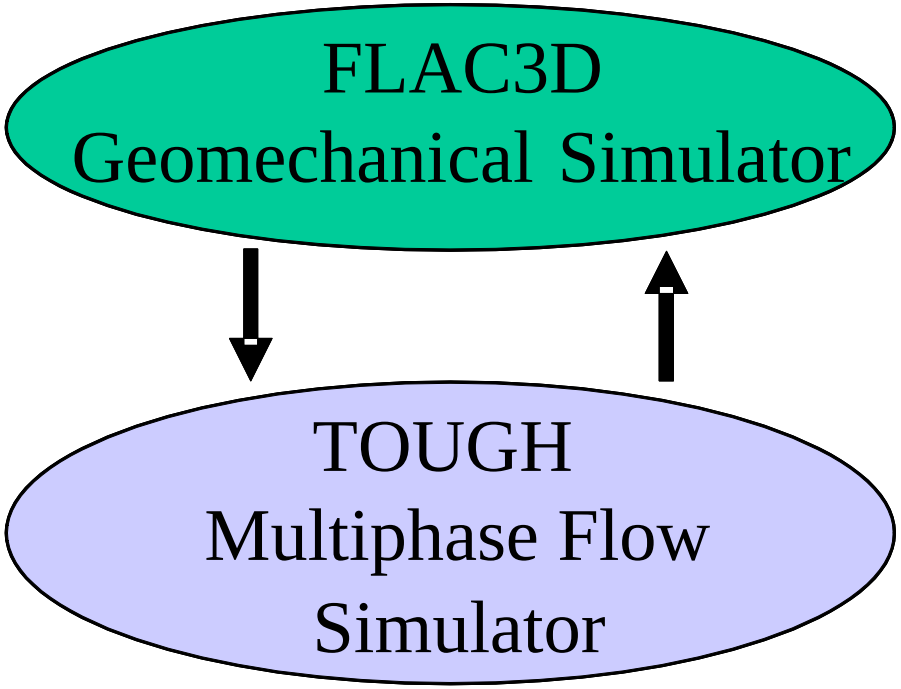
- Calpine Corporation manages field work and real-time monitoring using data from LBNL's seismic network
- LBNL performs modeling of stimulation and injection/production and analyze field data for planning, design and validation of the EGS stimulation
- **Timeline**:
  - Phase I Pre-stimulation phase started June 2009 (100% complete)
  - Phase II Stimulation phase along with injection October 2011 (100% complete); Final report delivered March 2015
  - Phase III Long-term monitoring and validation
- **Budget:**
  - LBNL's Modeling, field data collection (e.g. InSAR and. seismic tomography) for FY2009 to FY2014: $1510K (250 K per year)
  - LBNL's FY2015 work is financed by a carryover of about $240K from FY2014 used to support Calpine's Phase II final reporting, publication of Phase II results in journals, and completing geochemical sampling

Scientific/Technical Approach

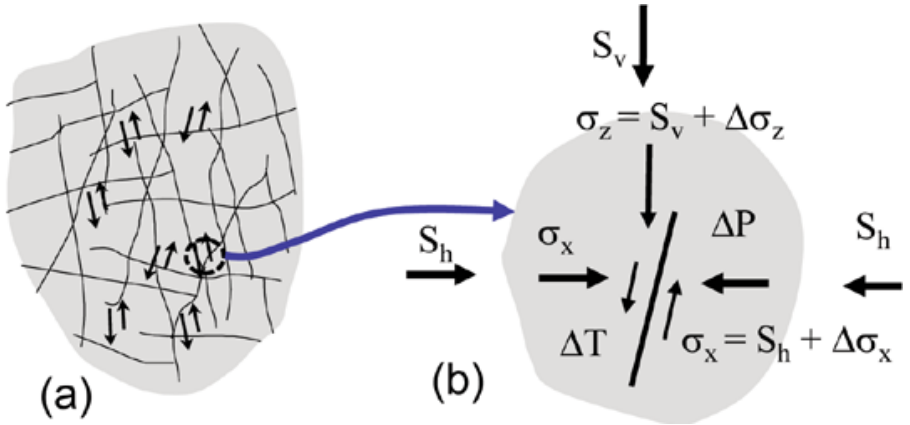
Integrated modeling and monitoring for design and validation of an EGS system created by injecting relatively cool water at relatively low pressure:



Geomechanical Modeling Approach



1) Use TOUGH and FLAC3D to calculate stress changes as a result of “cold” water injection
2) From stress changes calculated the likelihood of MEQ in different areas around the injection



The rock mass at The Geysers is near-critically stressed for shear failure: a small stress change can cause fracture shear and a microseismic event

Pre-Stimulation Model Prediction

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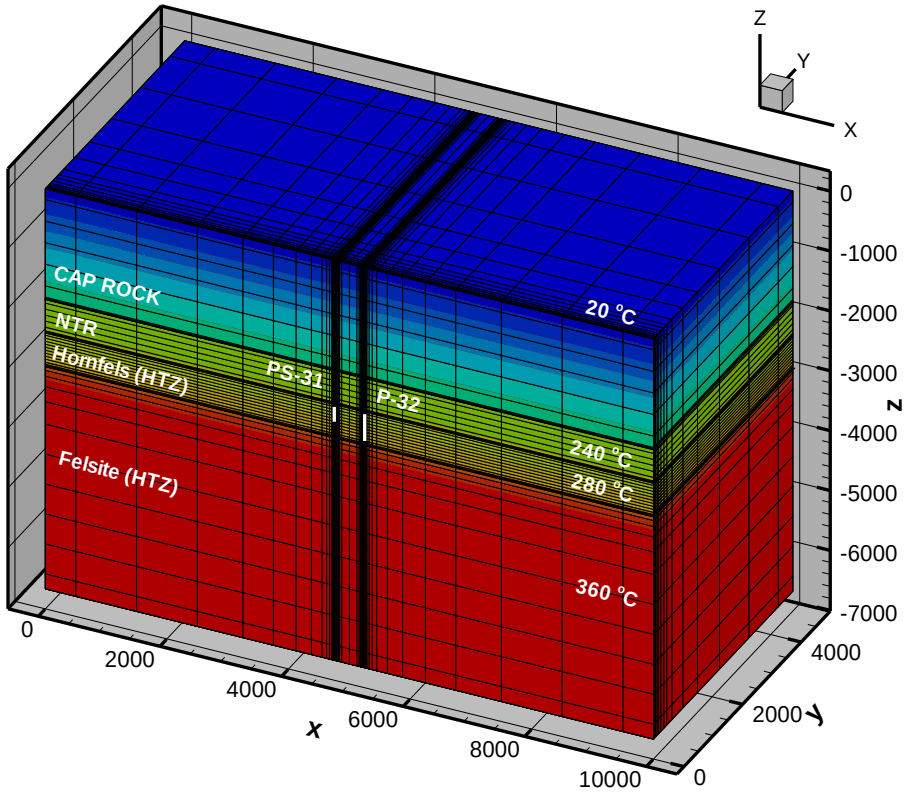
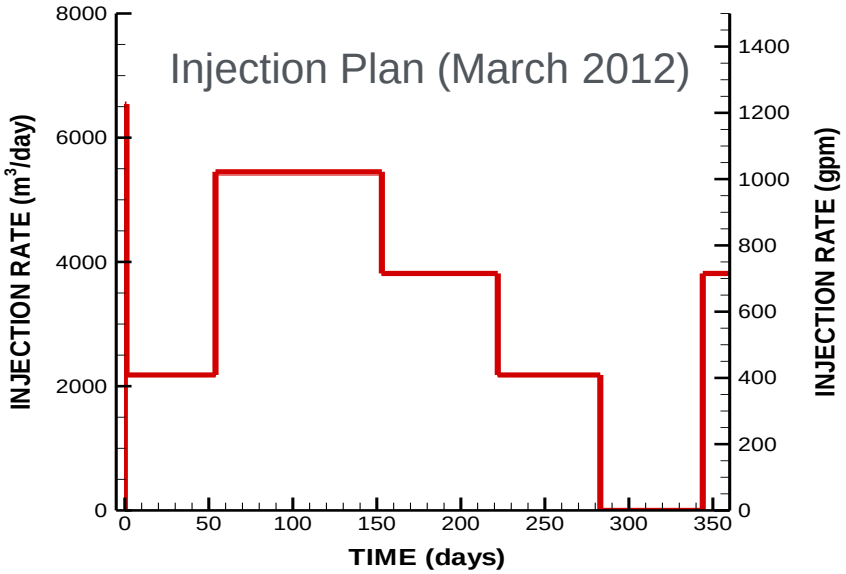
Model and Initial Temperature

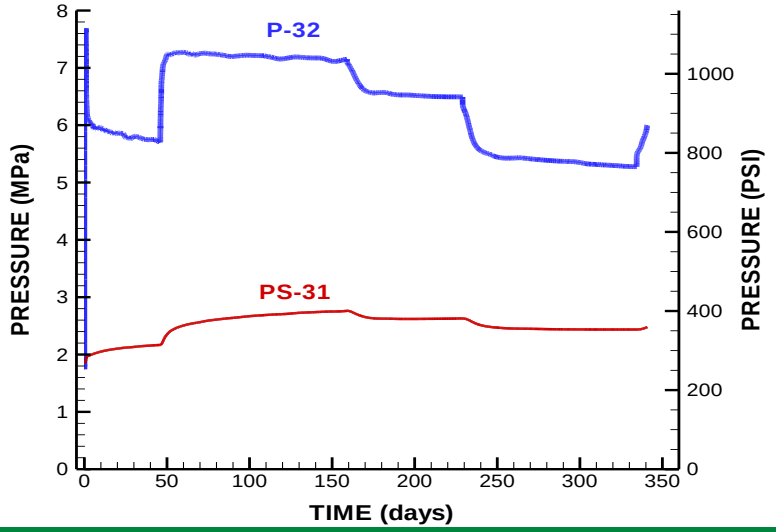


- Maximum downhole pressure 8 MPa < σ_3, (≥ 24 MPa)
- Staged injection and “gentle” progressive stimulation of the HTZ in steps

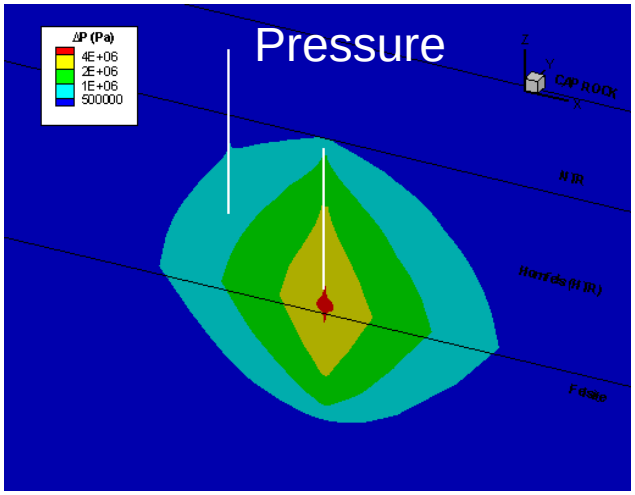
Injection Plan (March 2012)

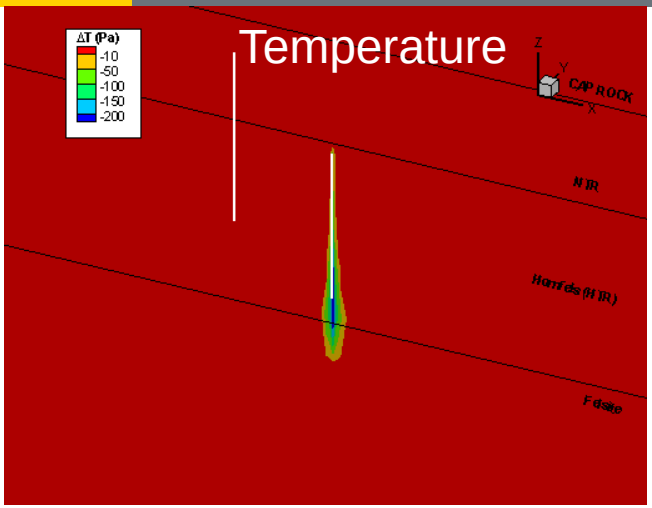


Calculated pressure

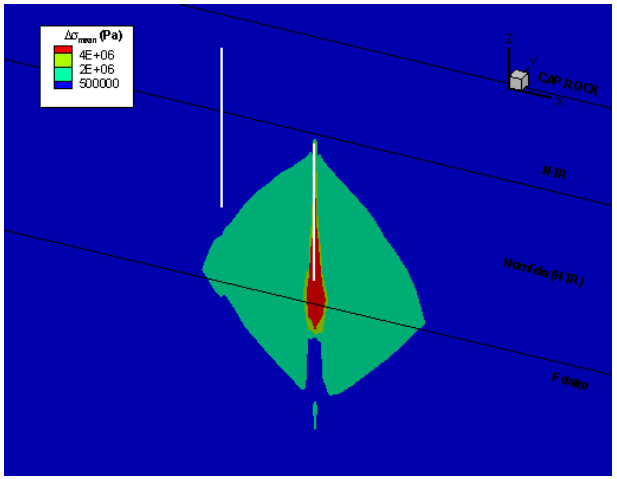


Pre-Stimulation Model Prediction

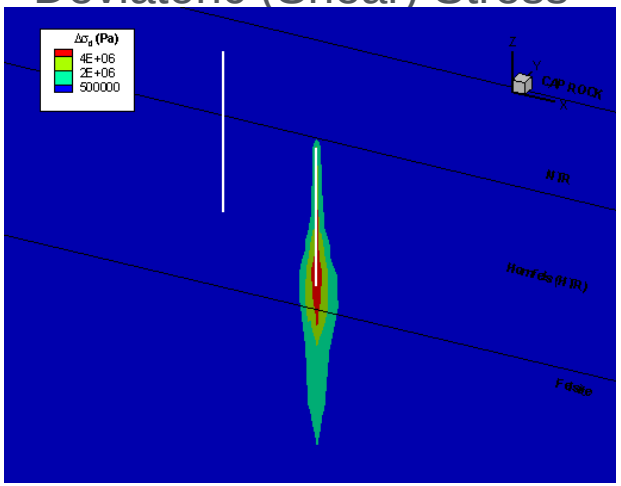




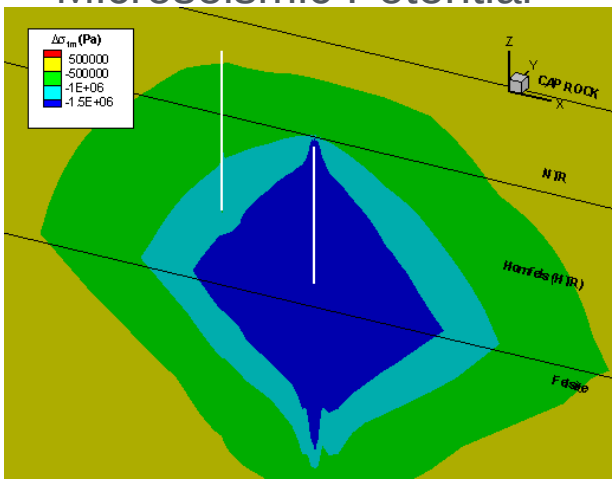
Mean Effective Stress



Deviatoric (Shear) Stress



Microseismic Potential



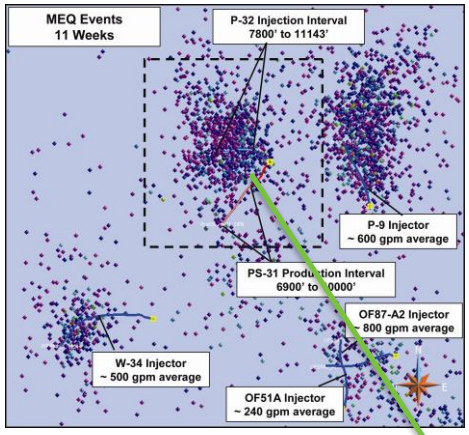
High microseismic potential by combined cooling contraction and pressure change

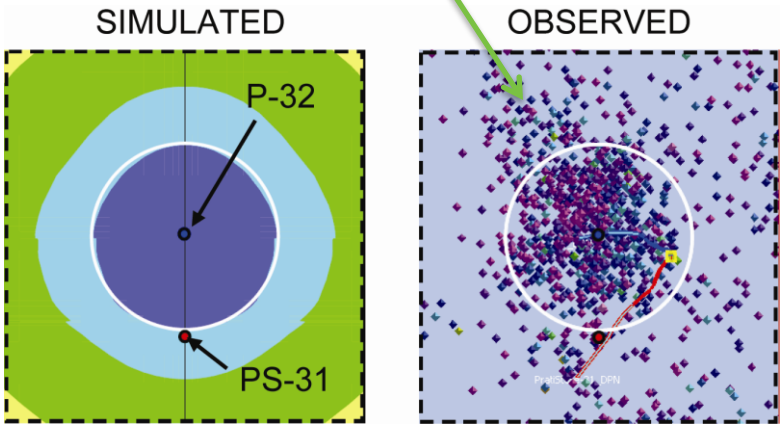
Stimulation zone (blue contour) extends to production well

Pre-Stimulation Model Prediction

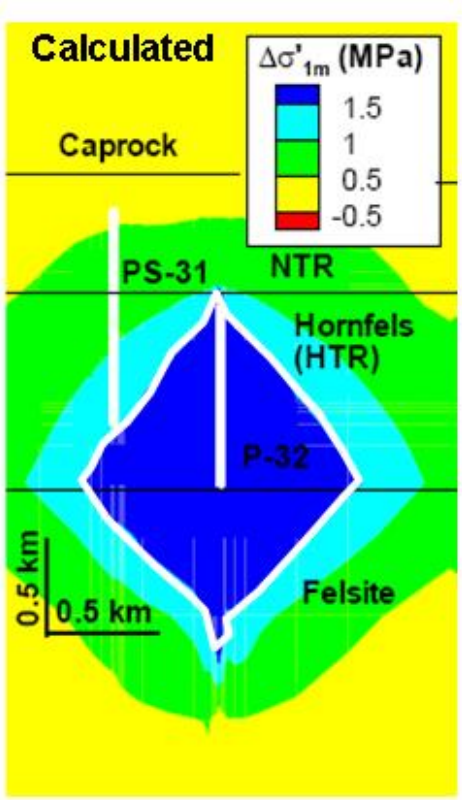
Predicted and observed extent of stimulation zone after 3 months of injection

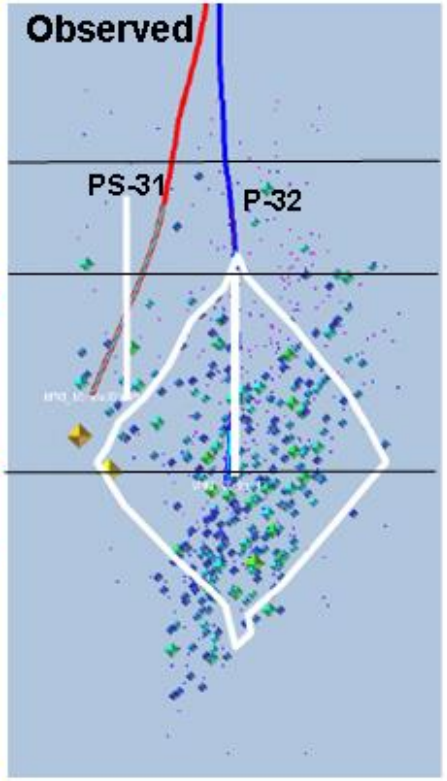
Horizontal cross-section





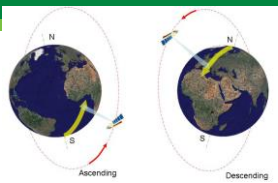
Vertical cross-section

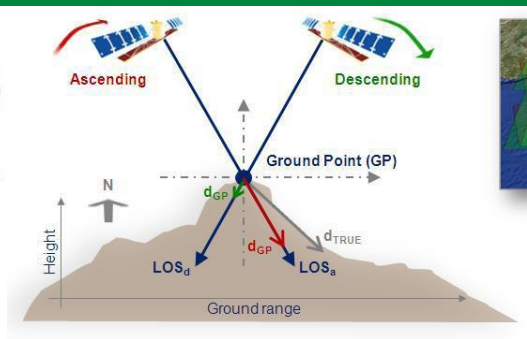


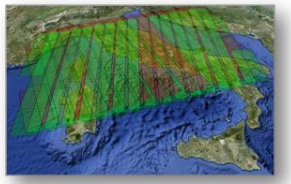


The extent of the stimulation zone reasonably predicted

InSAR Surface Deformation Monitoring







Ascending and Descending Geometry Acquisitions

Impressive resolution and coverage with new X-band data from TerraSAR-X data and COSMO-Skymed (compare to previous C-band data)

PSinSAR™ C-band results ERS data 1992-1999

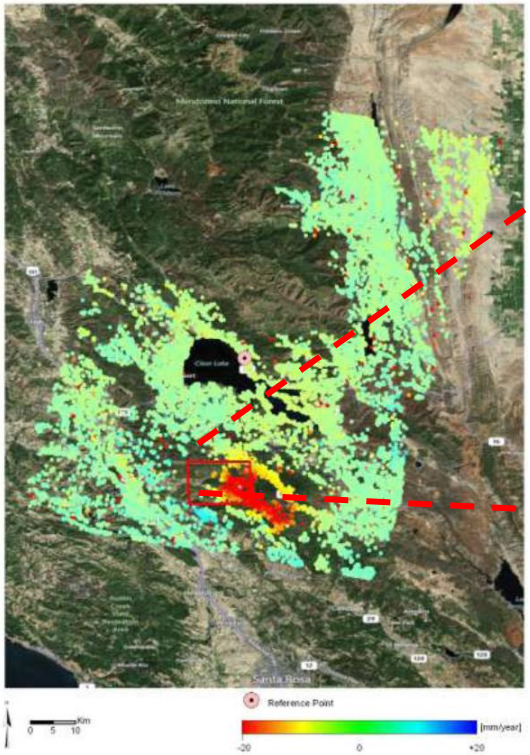


Figure 19: PSInSAR™ velocity map – C band results. ERS data 1992-1999.

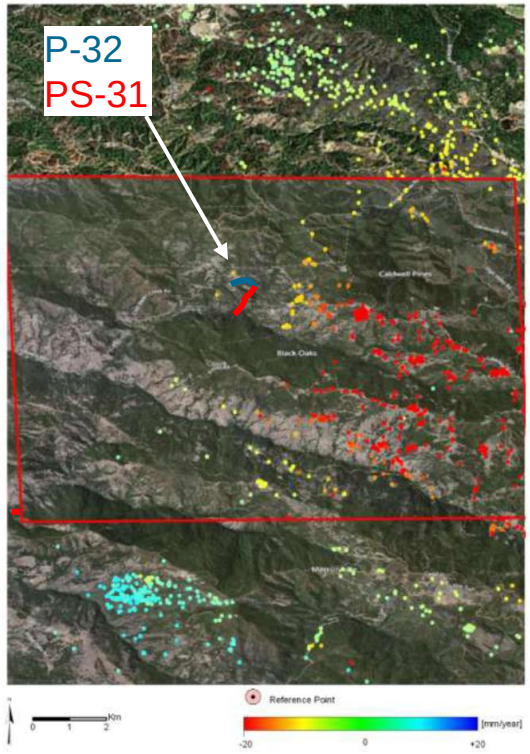


Figure 20: PSInSAR™ velocity map, close up – C band results. ERS data 1992-1999.

SqueeSAR™ X-band results TSX data May-Nov 2011

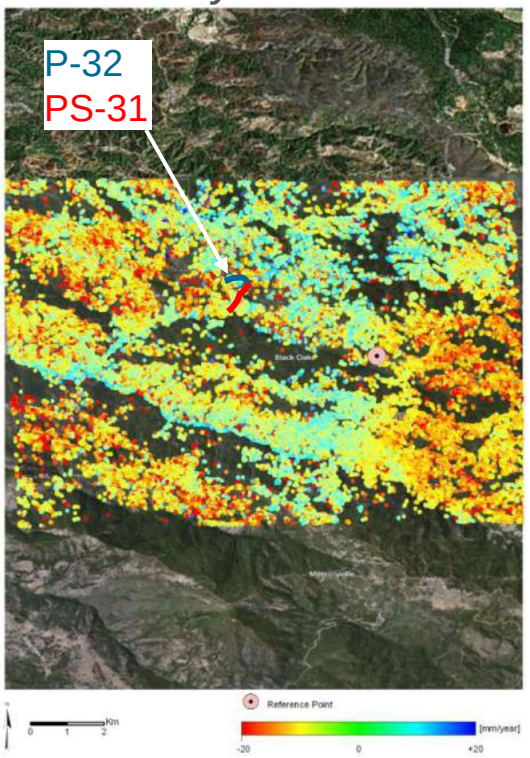
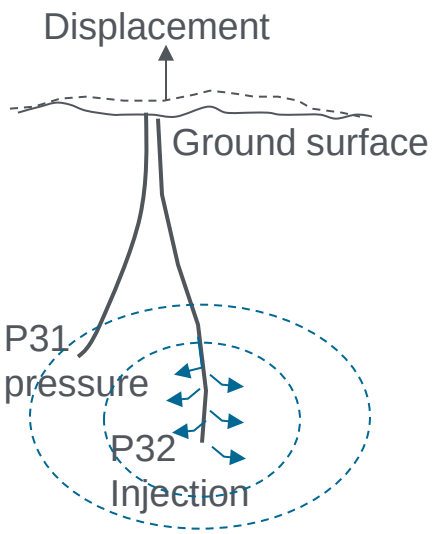
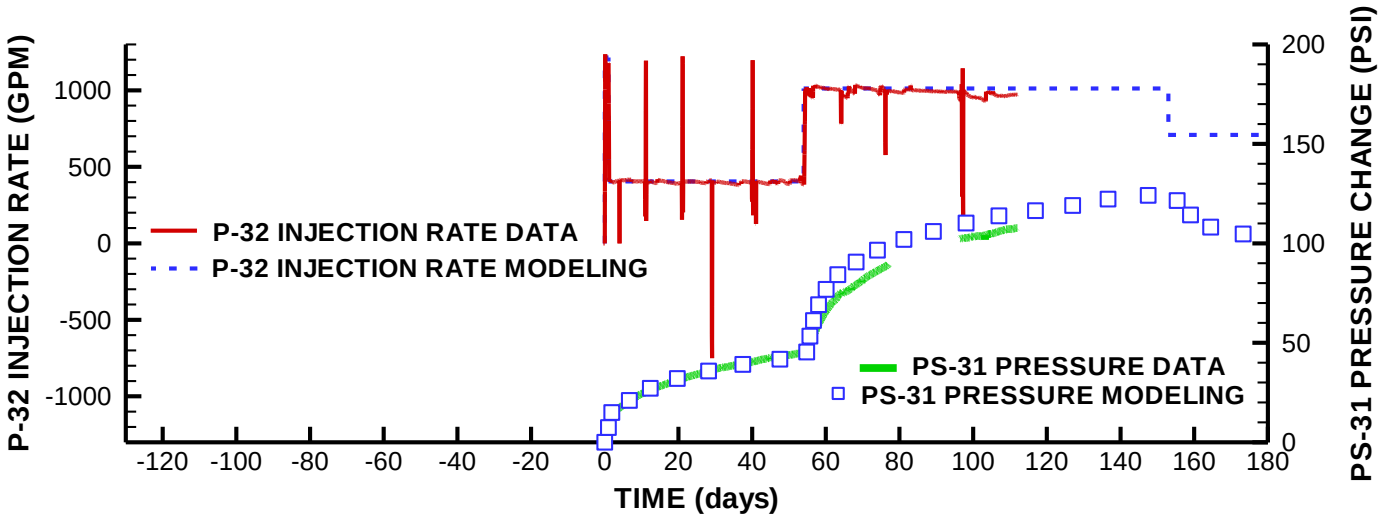
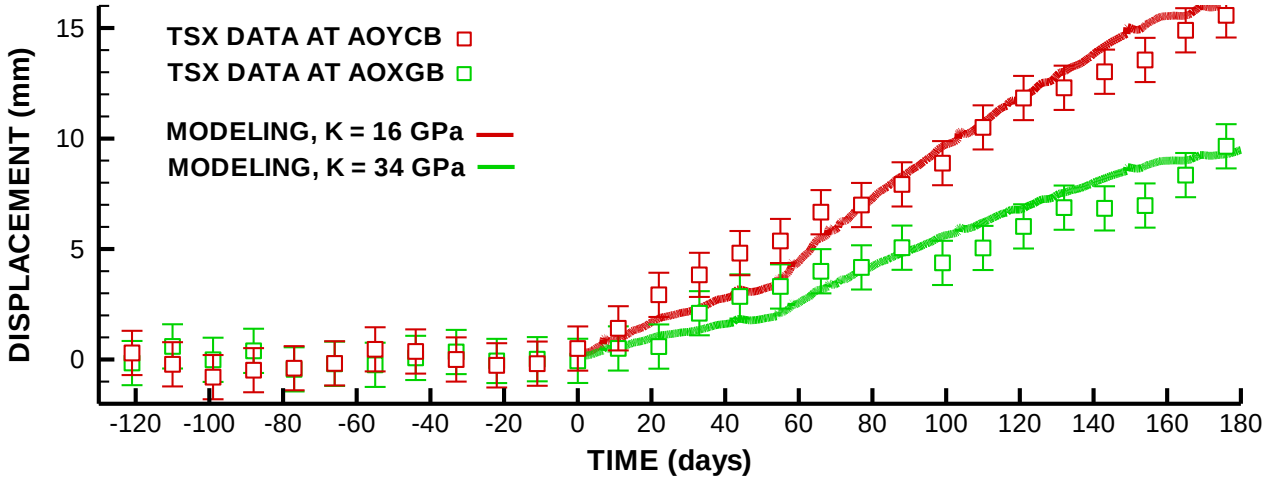


Figure 21: SqueeSAR™ velocity map – X band results. TSX data May 2011- December 2011.

Interpretative Modeling

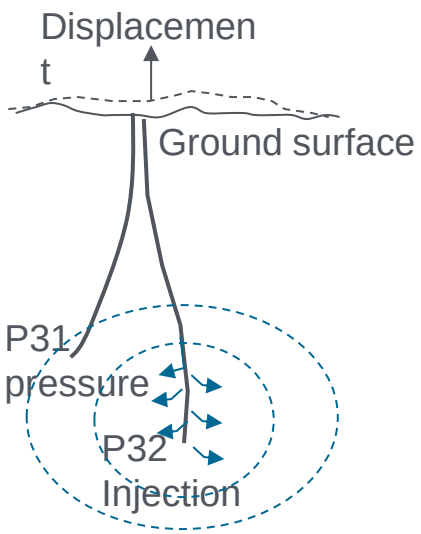


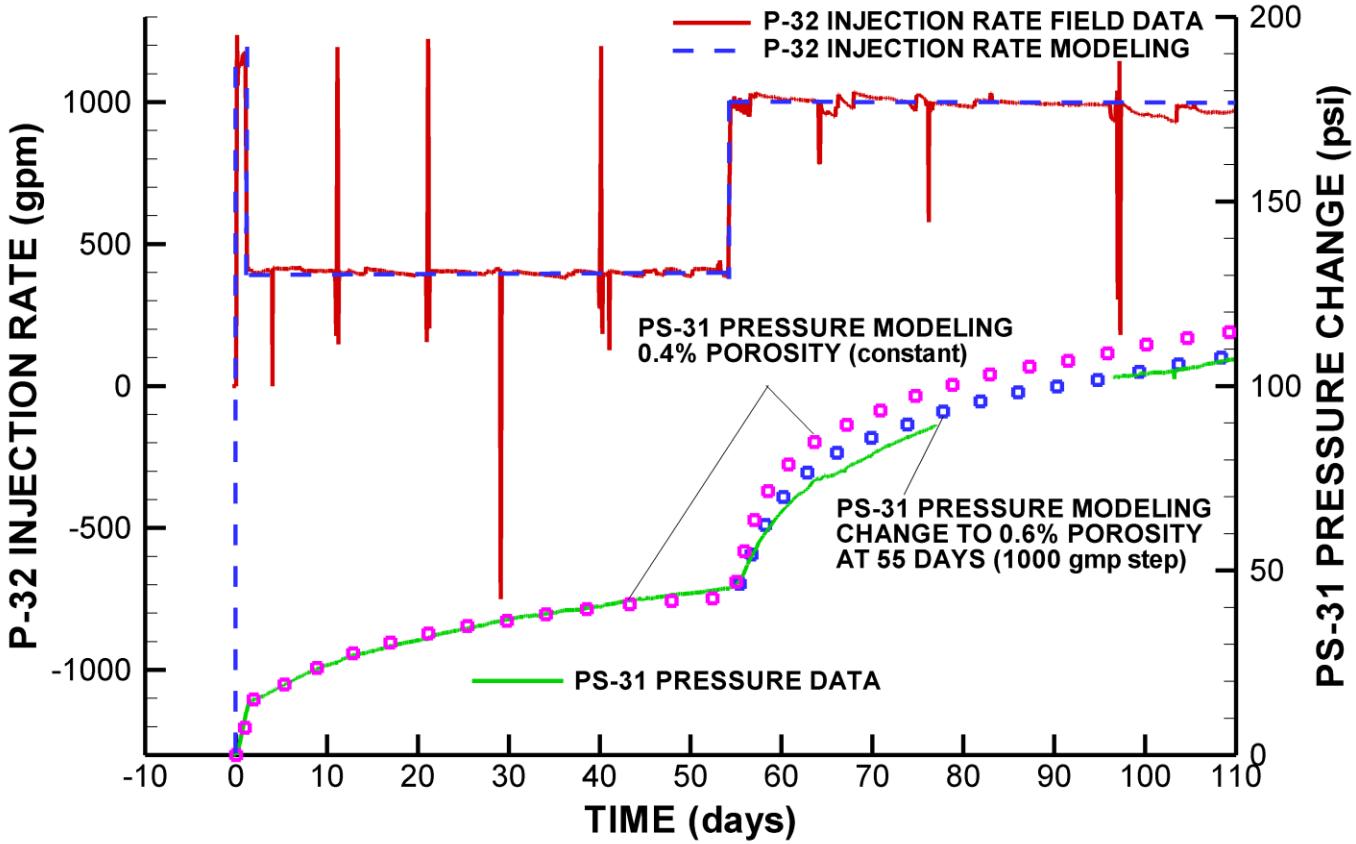




The comparison of model and observed responses was used to constrain hydraulic and mechanical model parameters

Interpretative Modeling



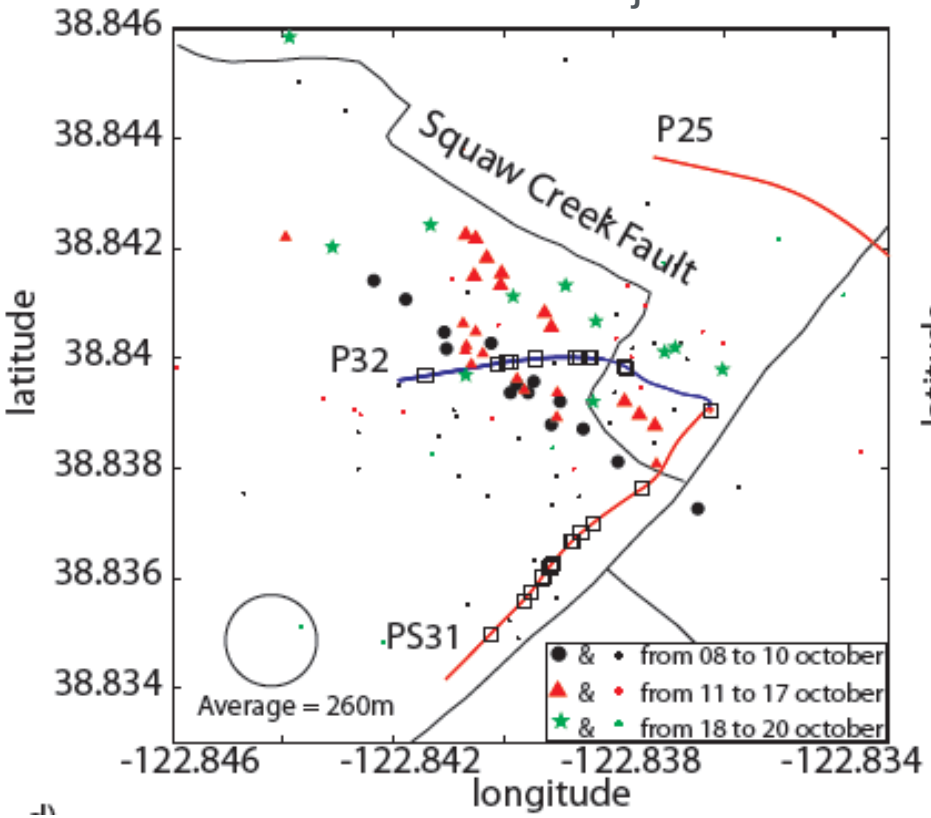


Pressure response at nearby PS-31 monitoring well indicates and increase in porosity from 0.4% to 0.6% (it is small but it is an increase by 50%)

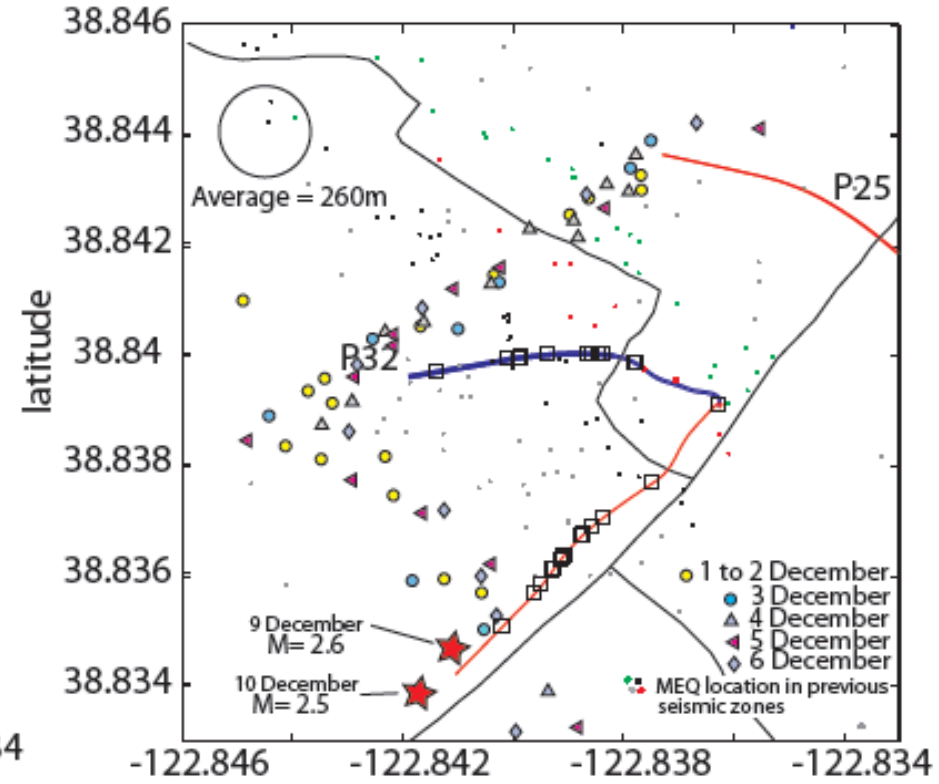
Identification of Shear-zone Network

Daily evolution of microseismicity after injection rate increase:

First 2 weeks of injection



Following increase to max rate



Indicates both permeable reservoir-crossing shear zones and impermeable reservoir bounding shear zones (also note correlation with steam entries)

Calibration of Shear Zone Network Hydraulic Properties

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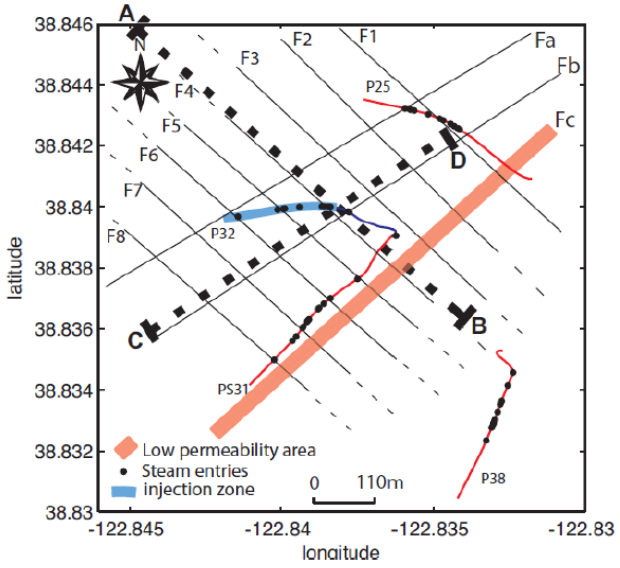
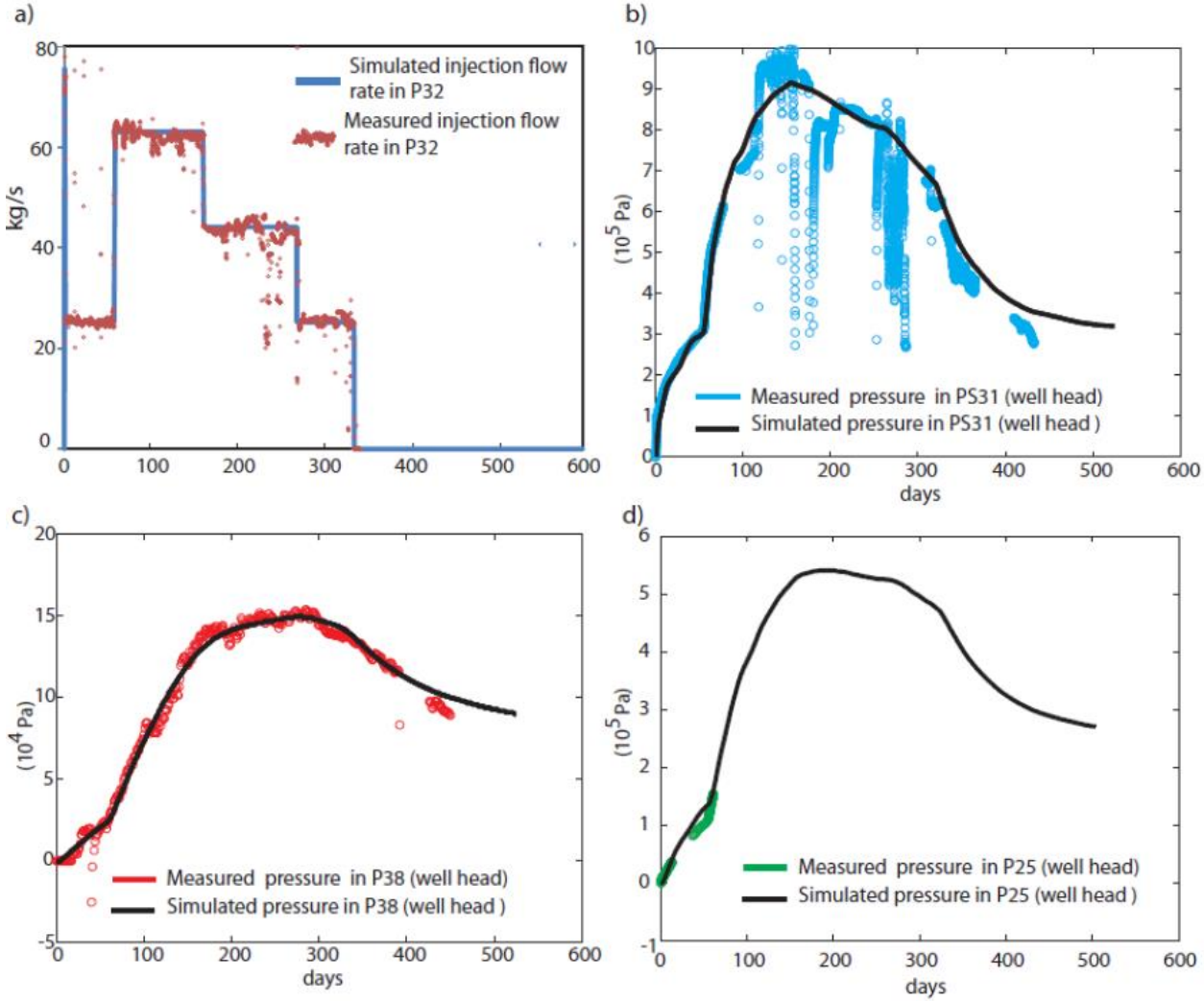
Shear-zone network



Compartmentalized system

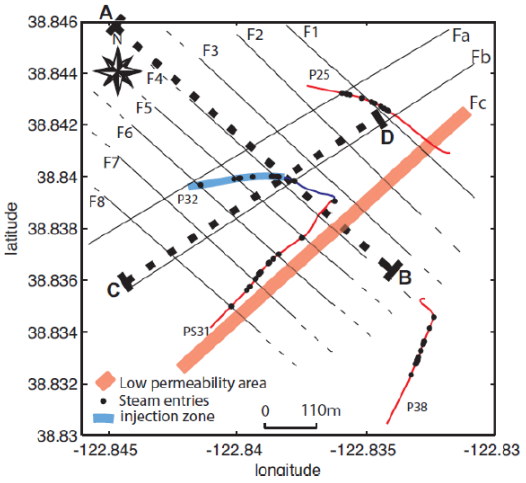
Permeability ranges..

Matching of well pressures



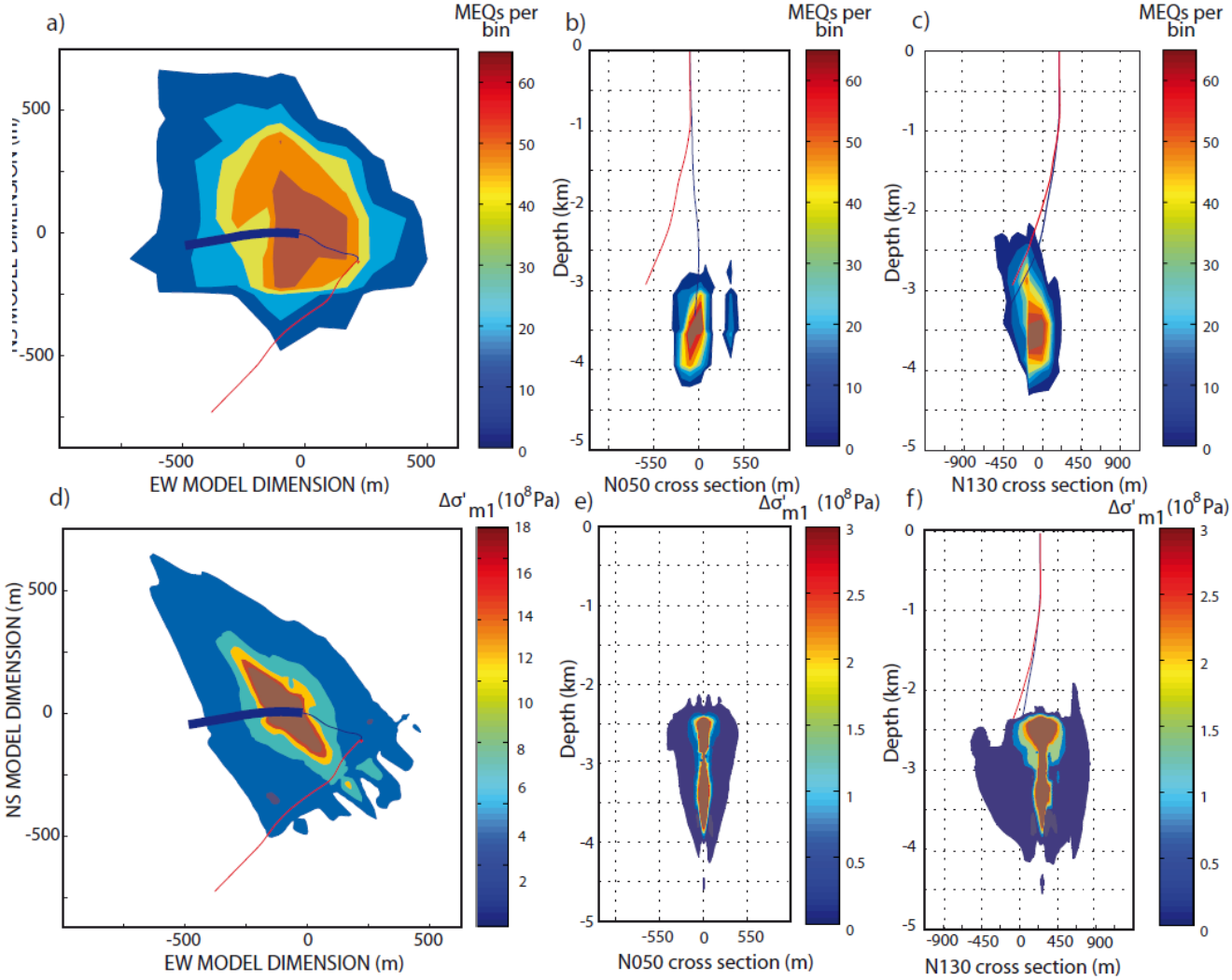
Observed and Modeled Compartmentalized Stimulation zone

Shear-zone network



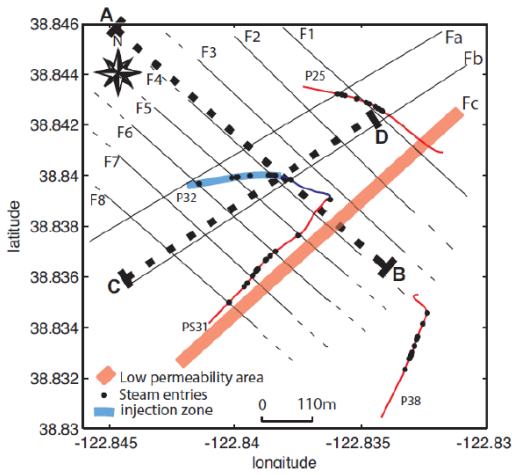
Compartmentalized system

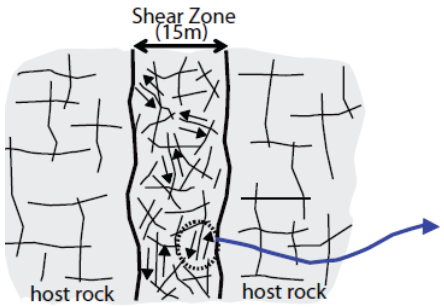
Observed seismicity (top) and modeled seismicity (bottom)

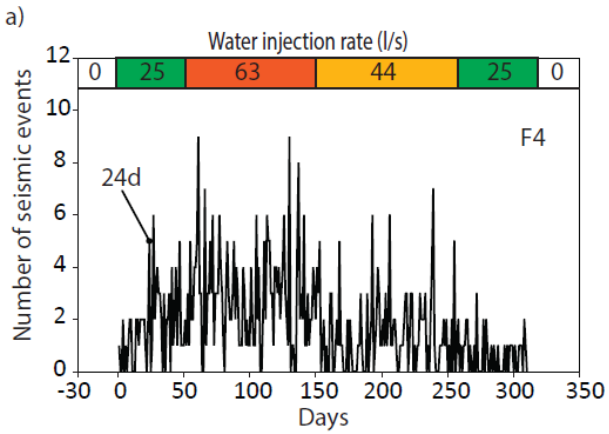


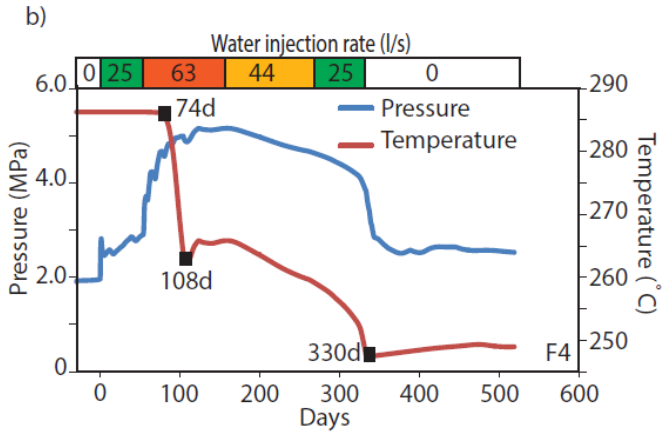
THM Induced Shear Activation of Fractures within Shear Zones

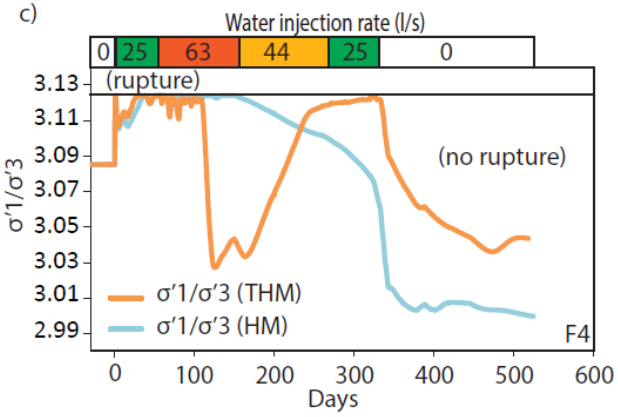
Elasto-plastic shear-zone modeling and microseismic activity (results at point located in F4 100 m from injection)

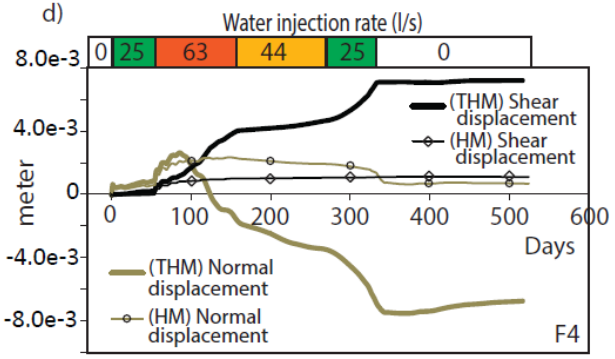








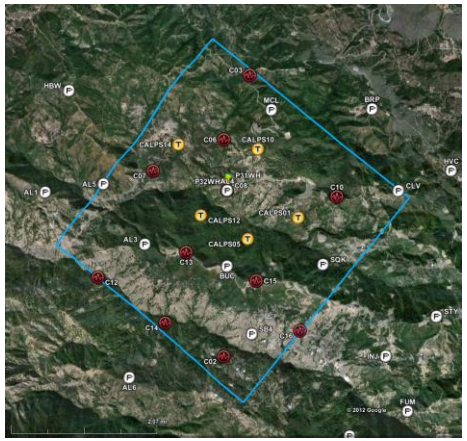




In this in this case, for a point close to injection, the shear activation is affected by both pressure and cooling effects in a rather complex response.

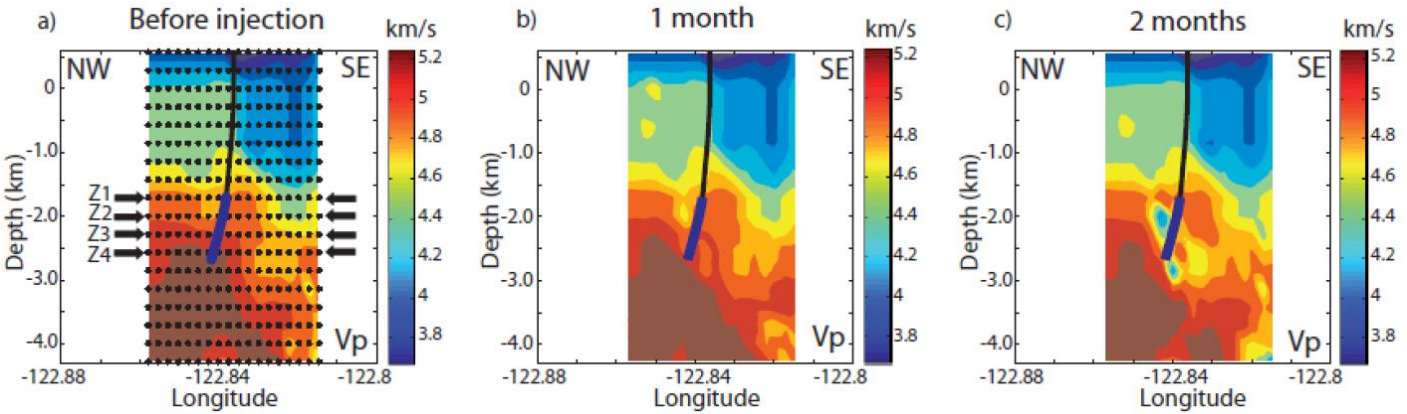
Seismic Tomography

23 surface stations within 5.7km X 6.0km area around the injection well

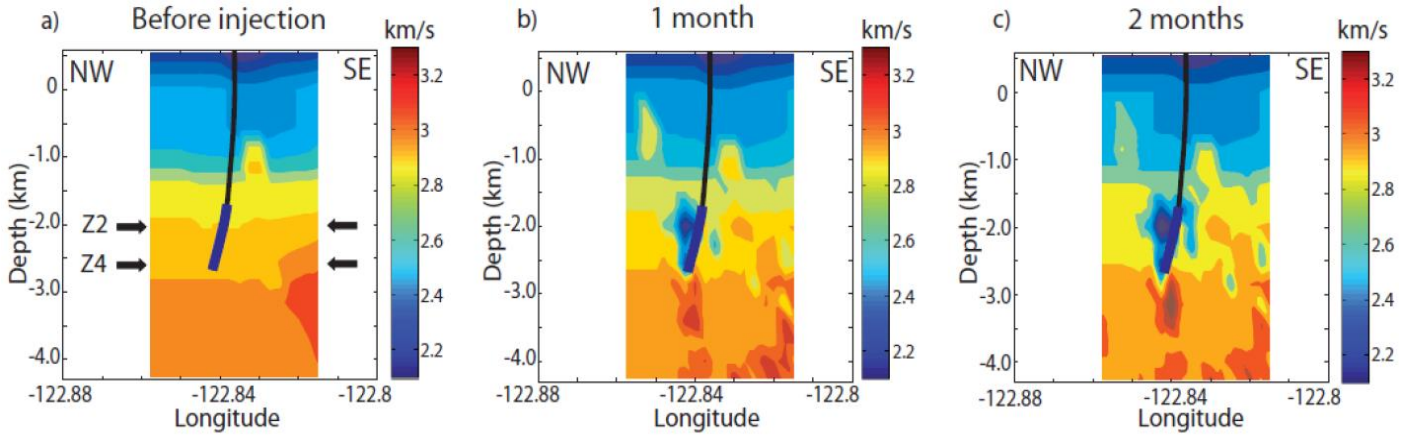


LBNL Geyser Stations
5 additional P-32
Test of ..

Evolution of the P-wave distribution



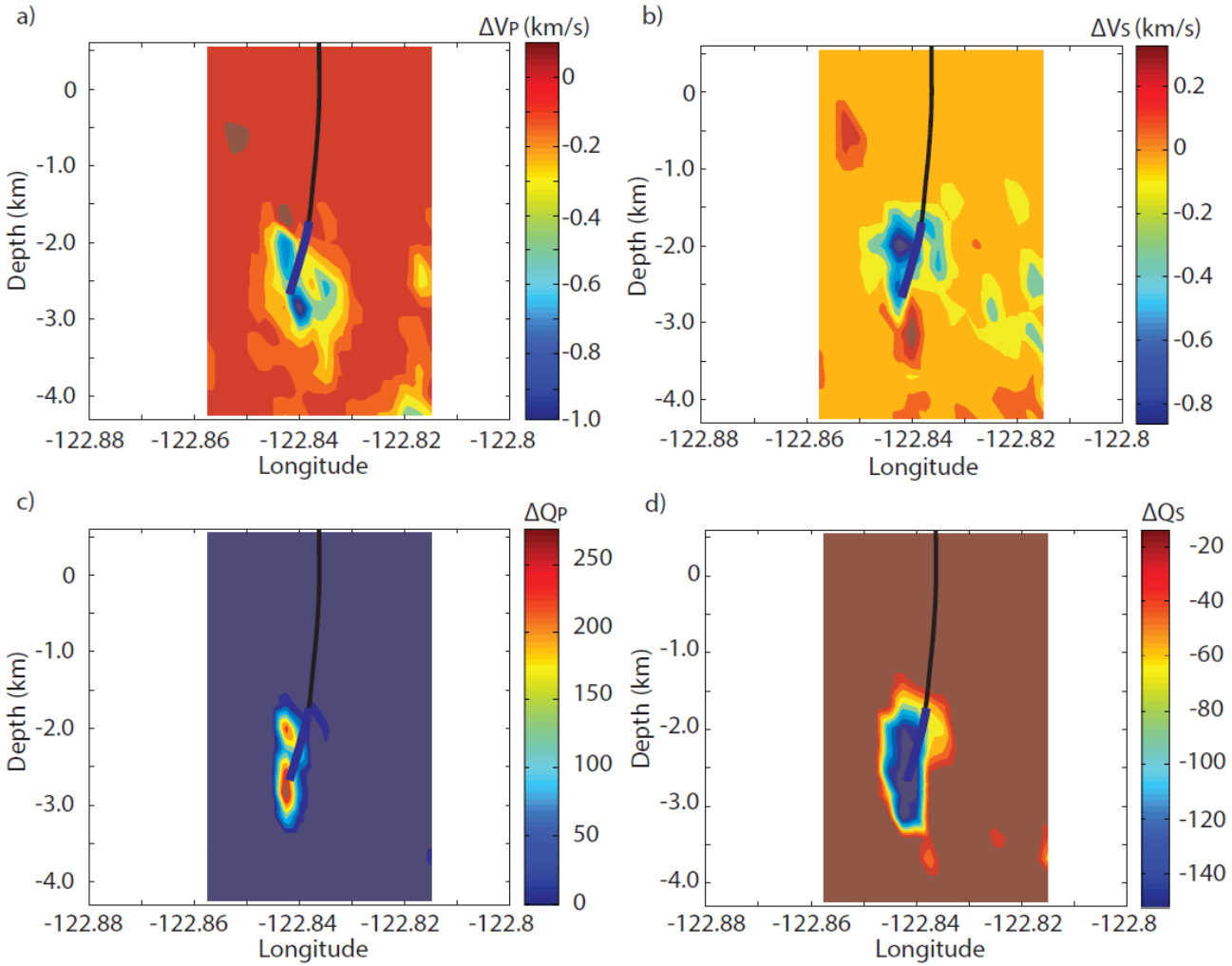
Evolution of the S-wave distribution



Anomaly in both P and S-wave velocity around injection well

Seismic Tomography

Distinct changes in velocity (ΔVp, ΔVs) and quality factor (ΔQp, ΔQs) before and 2 months after injection:



Reduction in P and S-wave velocity that could correspond to a reduction in dynamic modulus to 70% of original value

Increase in Qp correlates with a narrow liquid water zone ⇒ change from partially saturated to fully saturated pores?

Decrease in Qs widespread ⇒ related with shear damaged zone?

Accomplishments, Results and Progress

1) **Pre-stimulation modeling guided injection design for establishing an EGS encompassing the P-32/PS-31 injection/production pair**
2) **Pre-stimulation model prediction showed reasonable match with observed seismic cluster and reservoir pressure**
3) **Better than expected InSAR resolution in difficult terrain**
4) **Stimulation volume confirmed by high resolution seismic tomography**
5) **Identified microseismicity being caused by small but rapid pressure changes as well as near-well cooling effects confirming critically-stressed rock hypothesis**
6) **The integrated modeling/monitoring characterized properties of an EGS with reservoir-crossing and bounding shear zones.**
7) **The stimulation zone was characterized by substantial mechanical softening and porosity changes attributed to stimulation-induced shear failure**
8) **11 journal papers published 2013 to 2015**

In FY2015, provided critical input to the Phase II milestone report related to 1) estimated stimulation volume, 2) change in reservoir properties, 3) cause and mechanisms of induced seismicity, 4) evaluation of monitoring techniques.

Relevance/Impact of Research

The key to the success of making EGS a factor in the US energy mix is to learn how to effectively stimulate a rock mass on a kilometer scale and how to effectively design, predict, and monitor such a system:

- The technology of heat mining of these deep untapped resources below conventional hydrothermal systems is an innovative and unconventional EGS approach developed in this project
- The work investigates effective injection schemes that optimize stimulation caused by cooling shrinkage and pressure effects, while minimize the potential for notable earthquakes
- The technology developments and lessons learned in this project (related stimulation techniques, modeling and monitoring) will be directly applicable to EGS developments in any other fractured rock system where the goal is to stimulate an existing fracture network
- 11 journal publications have been produced associated with the NW Geysers EGS Demonstration in the past 2 years

Summary and Future Directions

The work to-date concludes Phase II of the Geysers EGS Demonstration Project (stimulation phase).

We have developed a 3D model of the system, including the P-32 and PS-31 injection/production well pair and the nearby production P-25 well.

The model could in the future be readily used to interpret system responses during production and long-term monitoring (Phase III of the project, once the PS-31 main production well is put back into production).

Ideally, with continued sustained injection, the stimulation will move progressively downwards for increasing heat mining deep within the high temperature reservoir and underlying felsite.

This could be verified with monitoring of microseismic evolution, reservoir pressure, repeated seismic tomography, and interpretive modeling of injection/production.