Induced Micro-earthquakes: Analysis for Reservoir Properities at The Geysers, California

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USC 2015

Purpose of this Project

Minimize costs and time to model and monitor reservoirs

Apply new developments that provide better resolution and information about reservoirs

- Inexpensive instrumentation
- Automated data processing
- Automated earthquake source parameters
- Double-difference tomography
- Apply rock physics interpretation
- Utilize sophisticated visualization

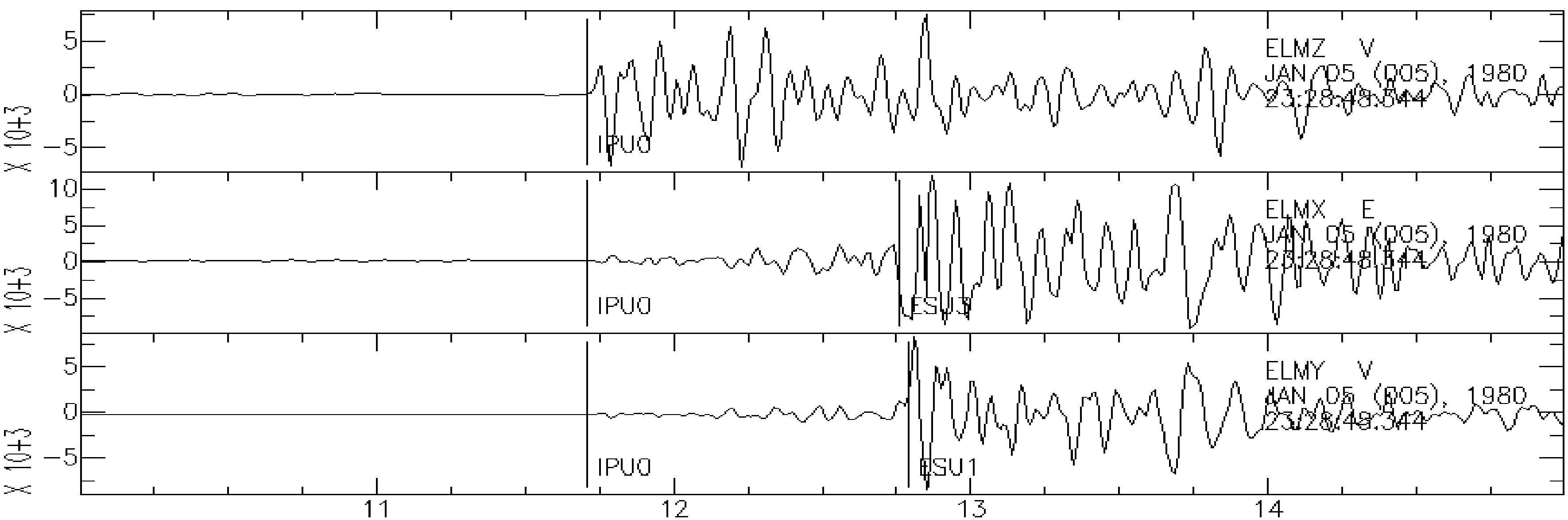
Approach

Extract as much information as possible from recordings of micro-earthquakes

- Obtain three-dimensional distribution of *Vp, Vs Qp, Qs* at small node spacing (~250 m) from
- Tomography
- Obtain elastic constants: Poisson's ratio, Lambda, Bulk and Young's moduli
- Obtain earthquake source parameters: location, magnitude, stress drop, moment tensor

3-component seismograms

• P & S-arrivals	→	Vp & Vs tomograpahy
• Pulse width		Qp & Qs "
S1,S2,P	→	anisotropy "
• Moment Tensor		crack orientations
• P & S spectra	→	stress drop, Mo



Tomography

- *Vp, Vs, Qp, Qs* from tomography
- Lambda, Bulk, and Young's moduli and Poisson's ratio from Vp, Vs & density

$$v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \qquad v_s = \sqrt{\frac{\mu}{\rho}} \qquad \frac{K}{\mu} = \frac{\left\{ V_p^2 - \frac{4V_s^2}{3} \right\}}{V_s^2}$$

Elastic Parameters

- *Poisson's ratio*: ratio of transverse strain to longitudinal strain
- *Bulk modulus*: measures the ratio of hydrostatic pressure to change in volume
- *Shear modulus*: ratio of shear stress to shear strain
- *Lambda (*λ): ratio longitudnal stress to transverse strain
- *Young's modulus*: is ratio of longitudinal stress to longitudnal strain

Rock Physics Interpretation

- Develop quantitative relationships between reservoir properties and *Vp, Vs, Qp, Qs, and elastic parameters*
- Utilize laboratory and well-log data
- Develop rock physics models of the reservoir
- Utilize 3D visualization software

Velocity and Q

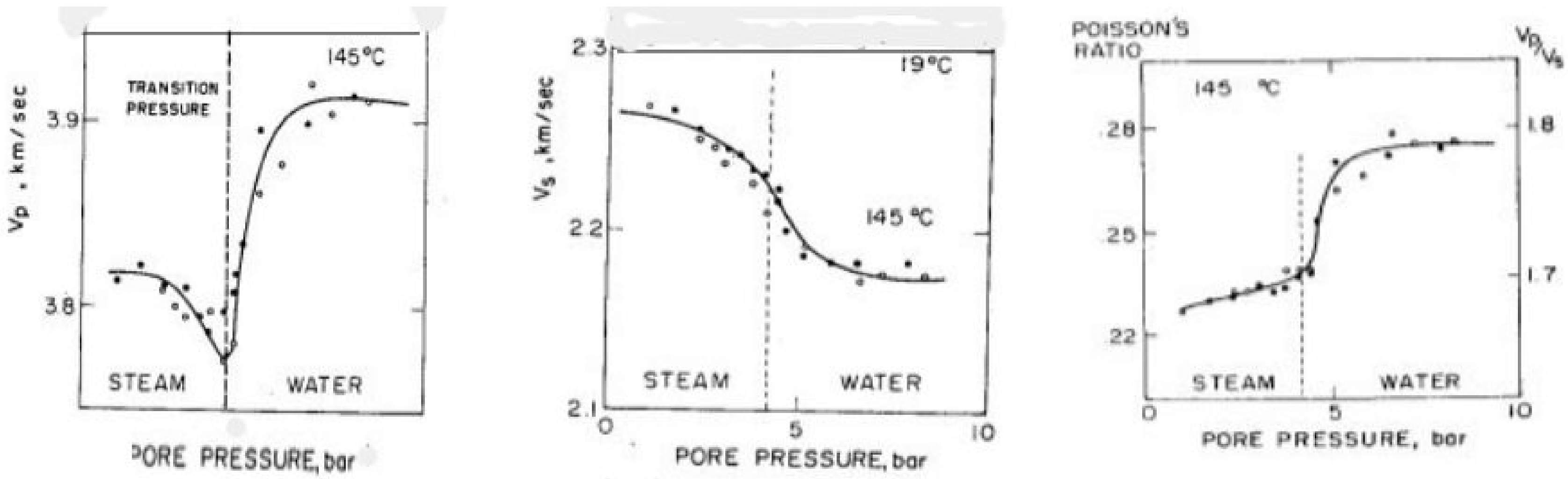
INTERPRETATION

Basic axioms of rock physics

- Increase of velocity and decrease in attenuation with depth
- Decrease in velocity and increase in attenuation due to fracturing
- Decrease in velocity due to alteration
- Extreme temperature gradient works to decrease velocity with depth
- Fluid saturation stiffens pores; affects P-wave velocity, but not S-waves
- Attenuation due to scattering from fractures or heterogeneities (extrinsic)
- Attenuation also due to fluid migration at a range of scales (intrinsic)
- Attenuation and Vp changes (in space or time) can indicate saturation
- In a fully saturated homogeneous medium only extrinsic attenuation
- Saturation increases the density of the material and decreases both P- and S-velocity
- Shear modulus is independent of fluid in the absence of geochemical reactions
- Viscosity, porosity and permeability affects the degree of attenuation
- Dilatency can cause expansion and permeability
- Variation in lithology observed in elastic constants
- Decrease in Poisson's ratio occurs as porosity
- Compaction and lithification preferentially eliminate small aperture pores

Laboratory Studies

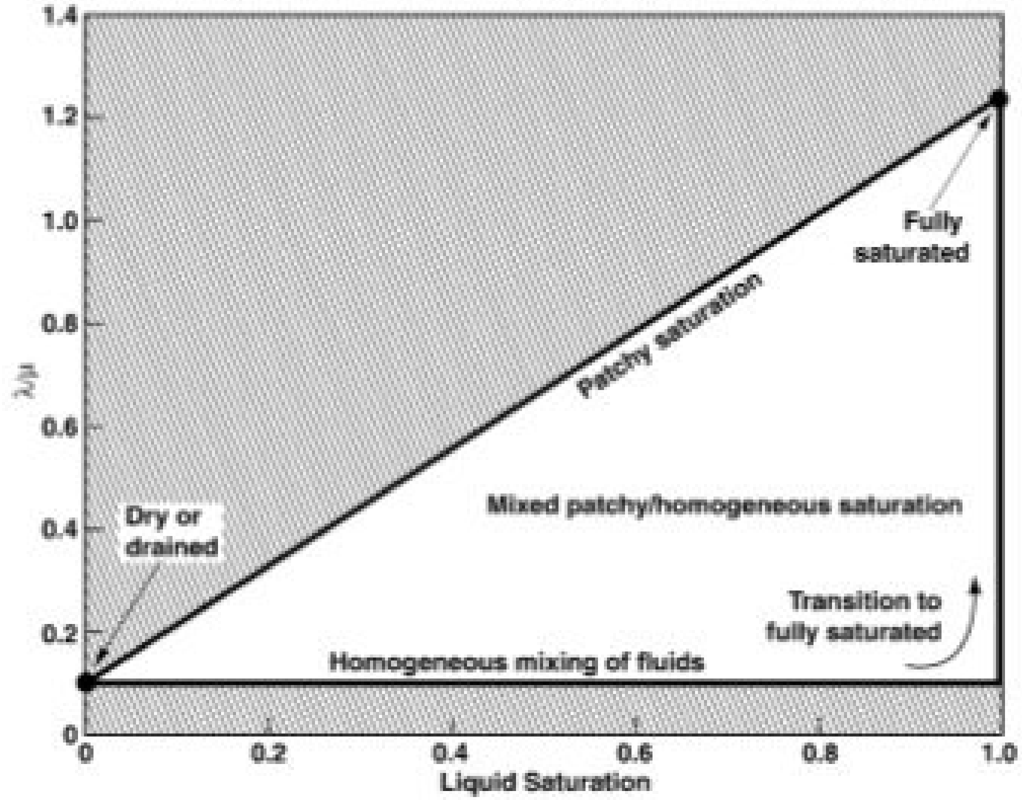
Laboratory study at constant confining pressure and temperature, but changes in saturation



Vp, Vs and Poisson's ratio from Ito et al., 1979

Laboratory Stucies

Effects of liquids on Lambda



From Berryman and Bonner, 2002

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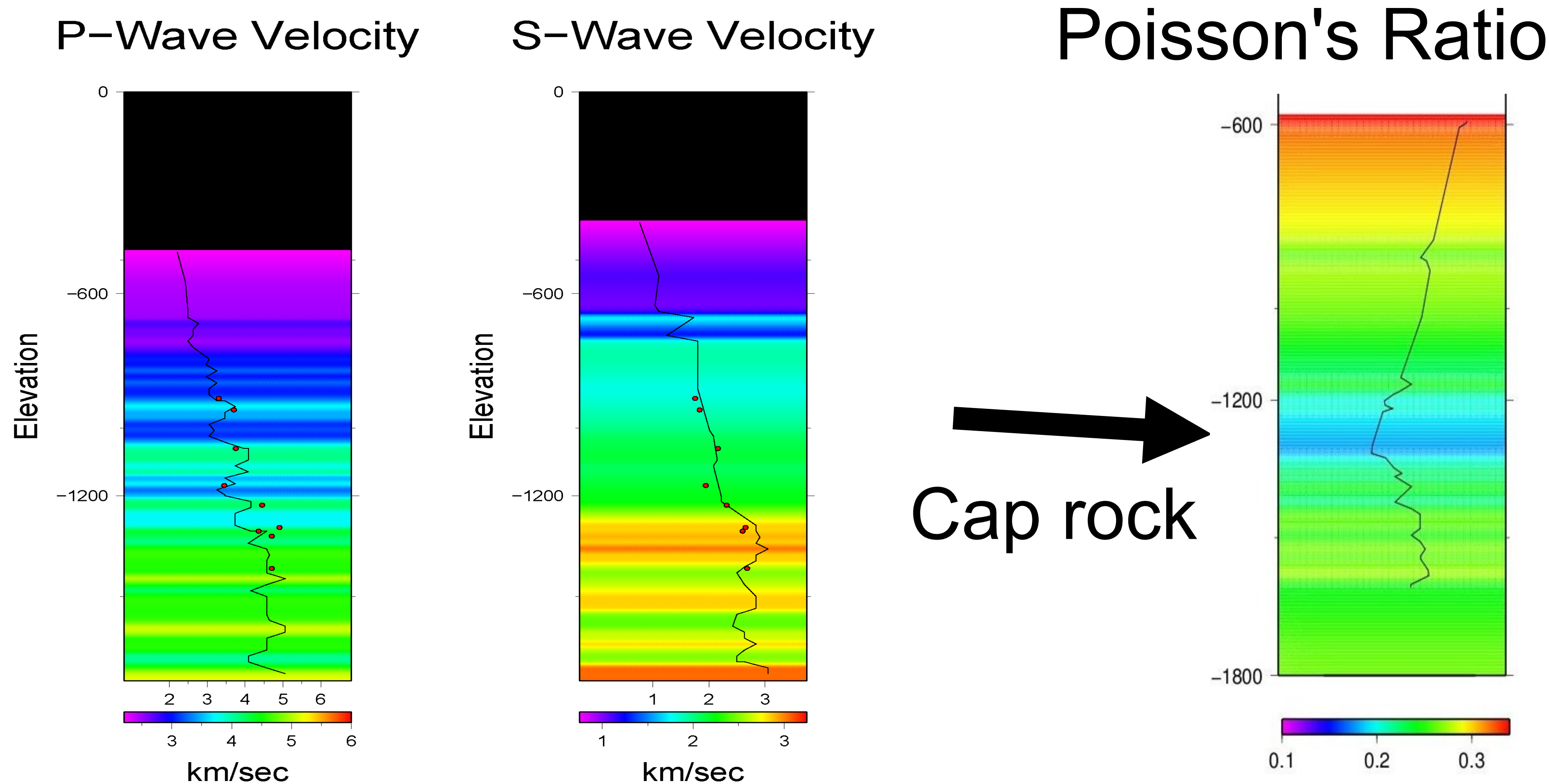
Observation

BERKELEY LAB

State 2-14 Well - Salton Sea



Interpretation (red flag)

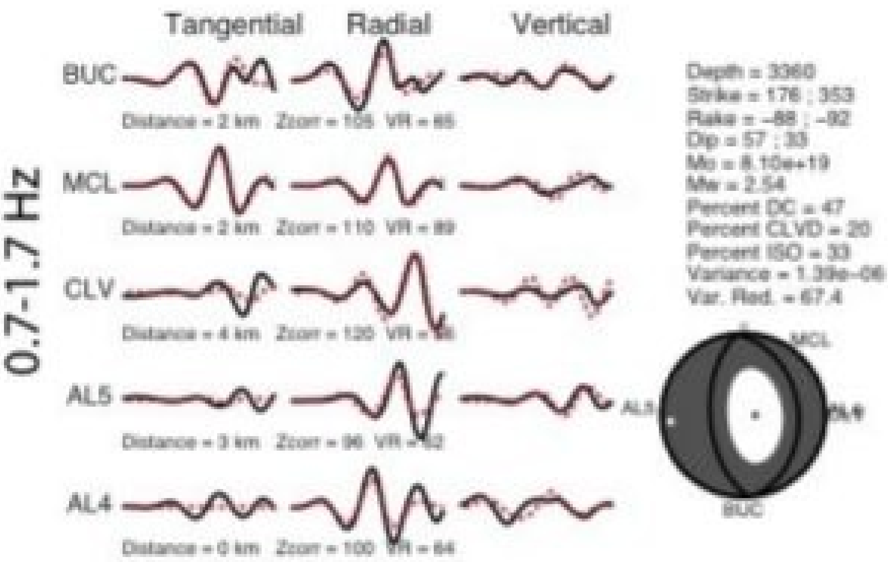
We observe a monotonic decrease in PR, whereas mechanical consideration would cause PR to increase (Bonner and Schock, 1982).

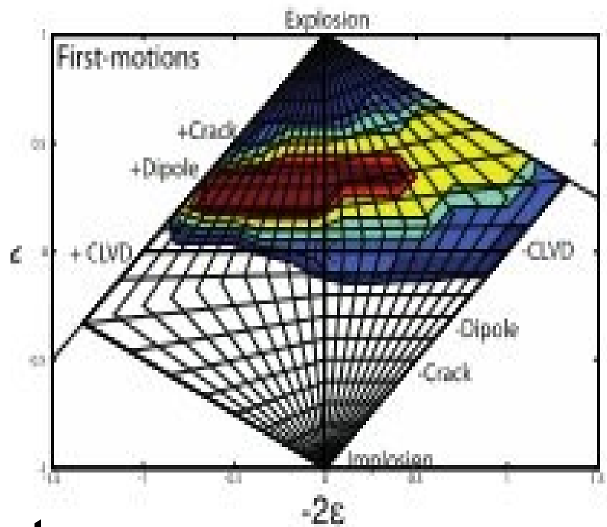
This observation is an indication that something besides the lithostatic load is causing this.

We hypothesize that geochemical alteration of the pores structure my explain this because of the systematic change in the pore shape from crack like to round.

Below, PR behaves “normally”, as the chemical alteration has completed the transition to “normal” rock

Moment Tensor Inversion

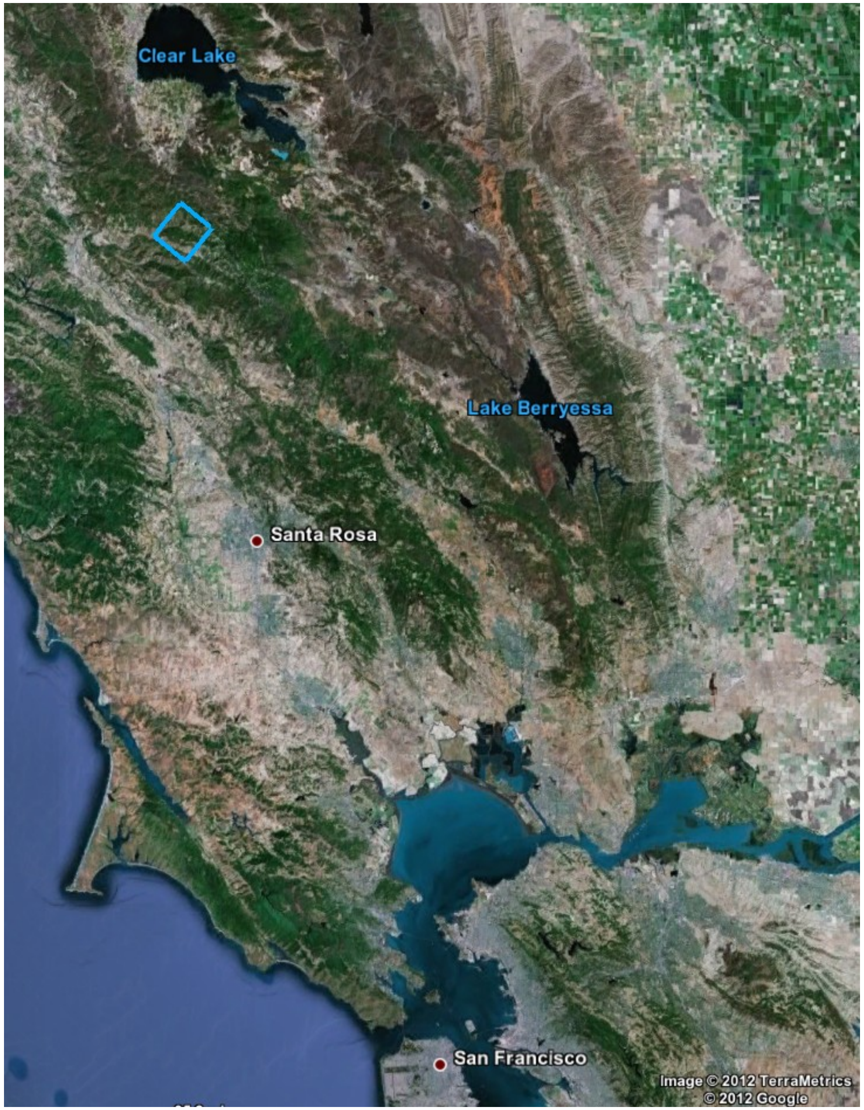


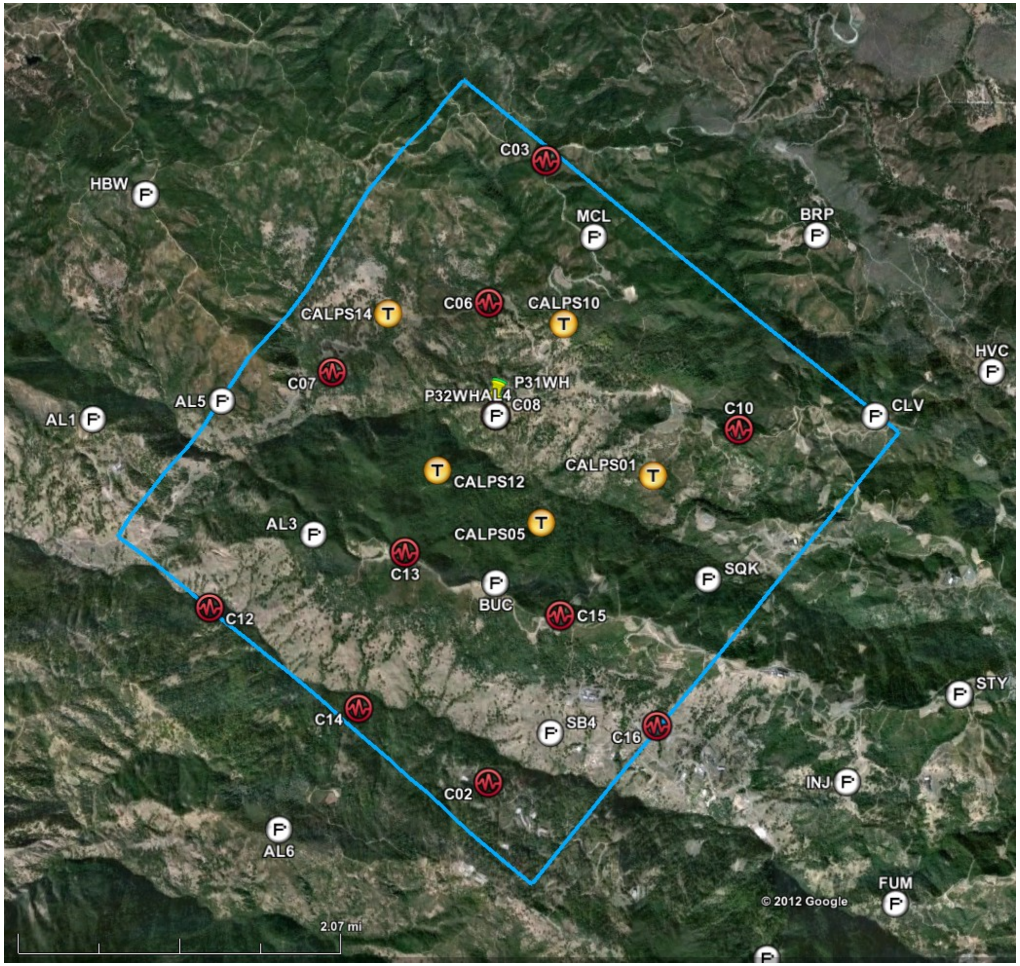


Uncertainty in Hudson Plot

High Density Network

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

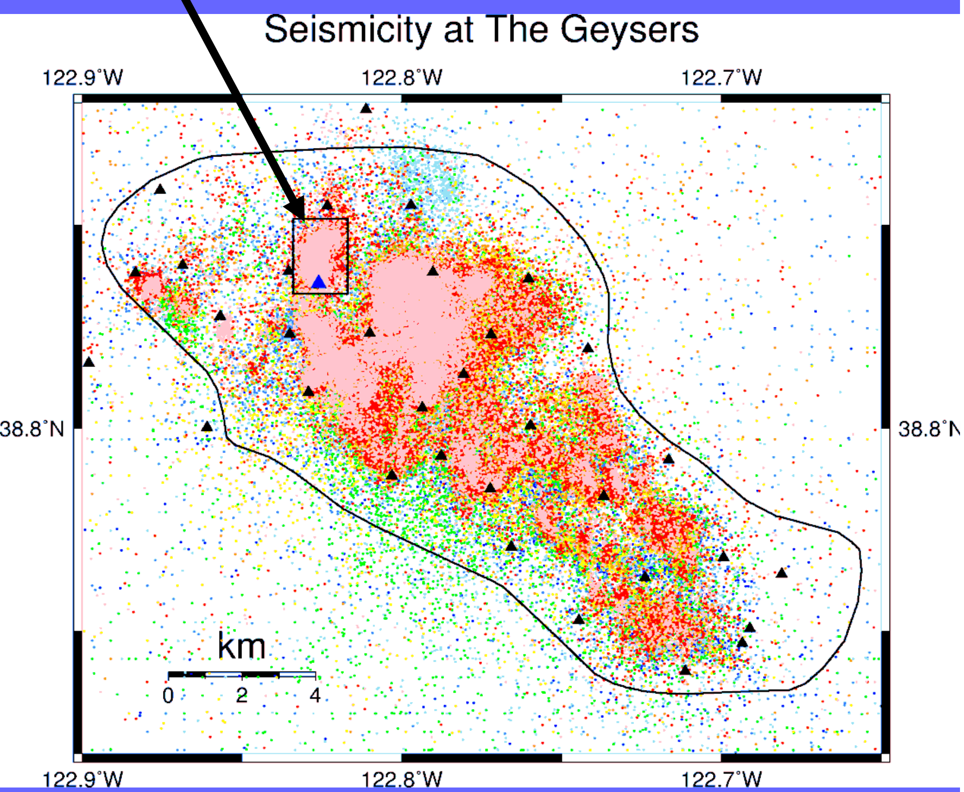


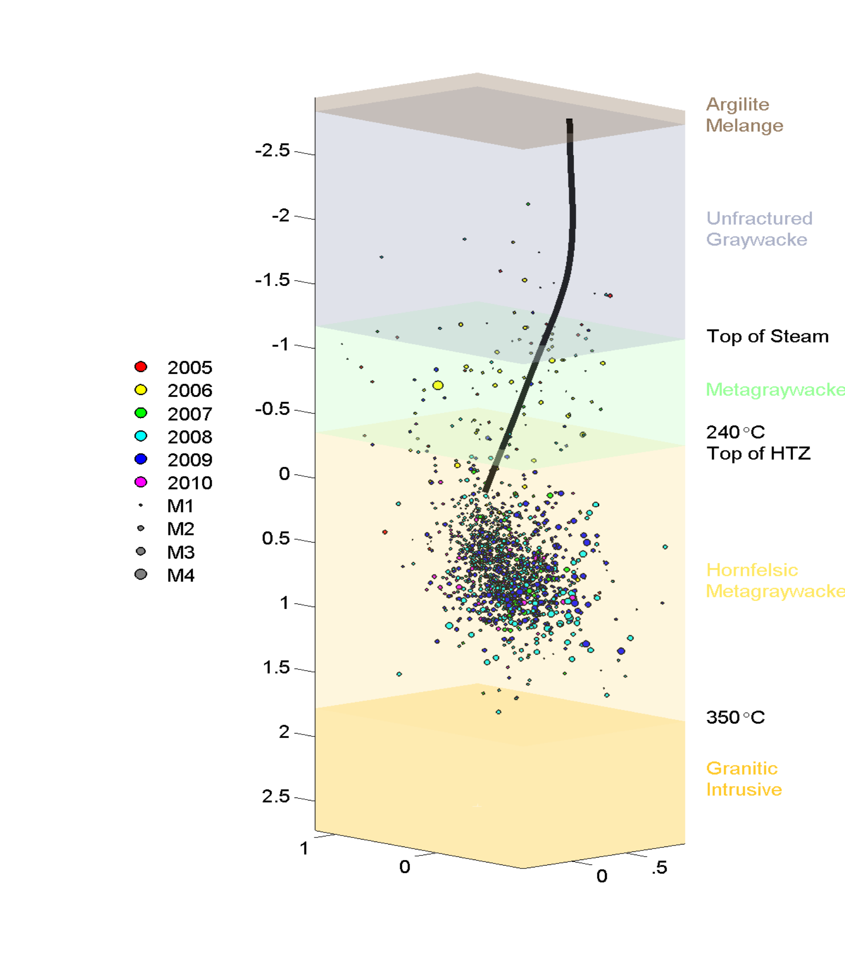


Prati-32 Injection Test

Injection into previous pristine, competent rock; below existing production zone

Well Prati 32





Data Recording

Buried sensors, pole mount.

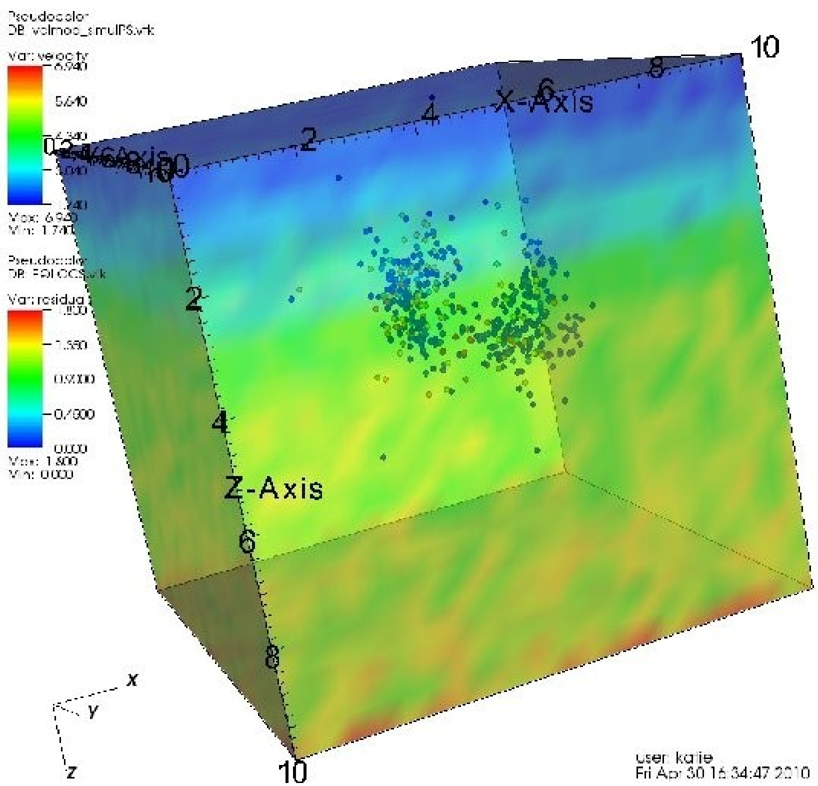
Internal sensors, base coupling plate, satellite antenna.

The recording system is low-cost, and designed to be easily deployed with little training. This will allow rapid deployment of large numbers of recording sites at minimal cost.

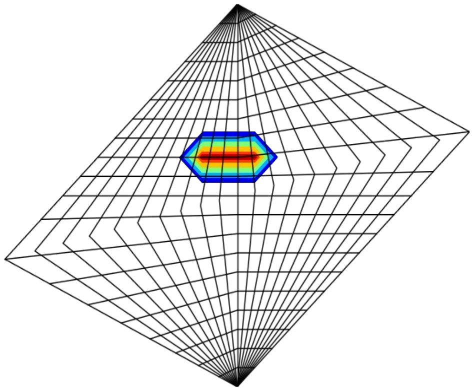
Recording System

- **4.5 Hz geophone sensors—external or inside system enclosure.**
- **Simple user interface—3 LEDs indicate system status.**
- **SD flash memory for data storage.**
- **Satellite transmission of status and event summaries is also available.**
- **18 bit dynamic range--sufficient to record $0.5 < M < 3.0$.**
- **GPS for self locating and timing.**
- **Powered by small 10-watt solar panel and 10 amp-hour gel cell.**

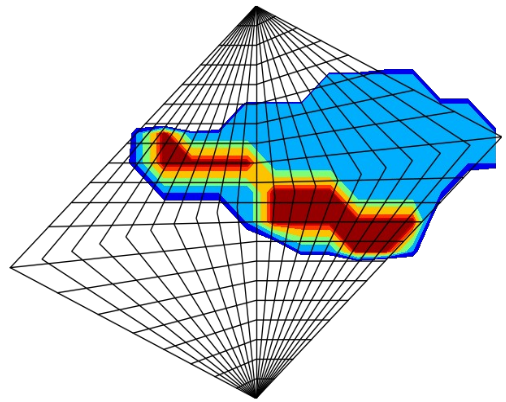
Automated Earthquake Parameters
Rapid Tomography - updated daily



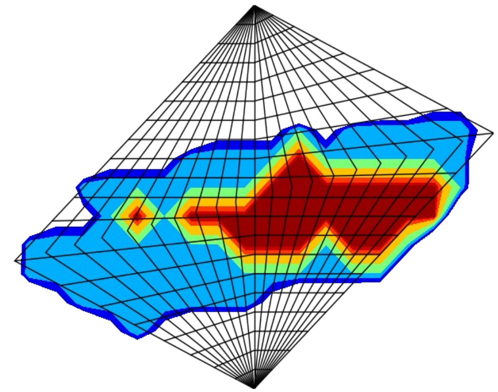
Moment Tensor solutions



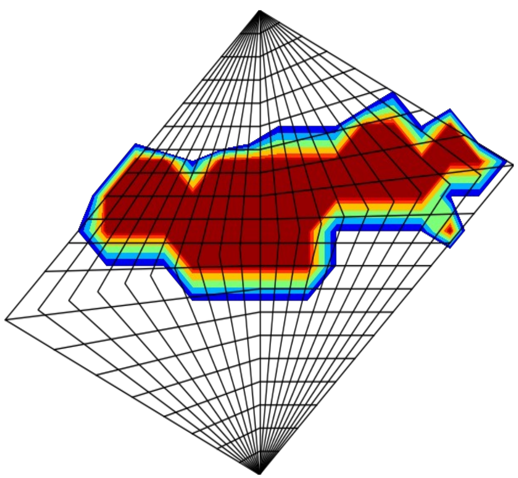
Double couple



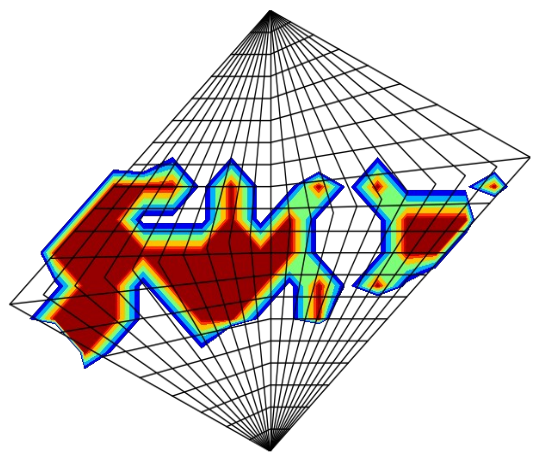
Crack closing



Crack closing



Crack



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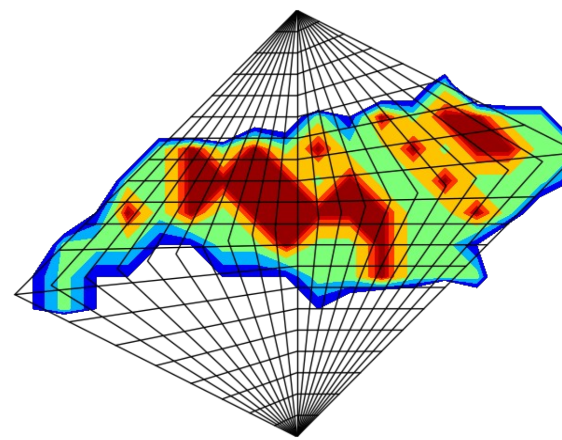
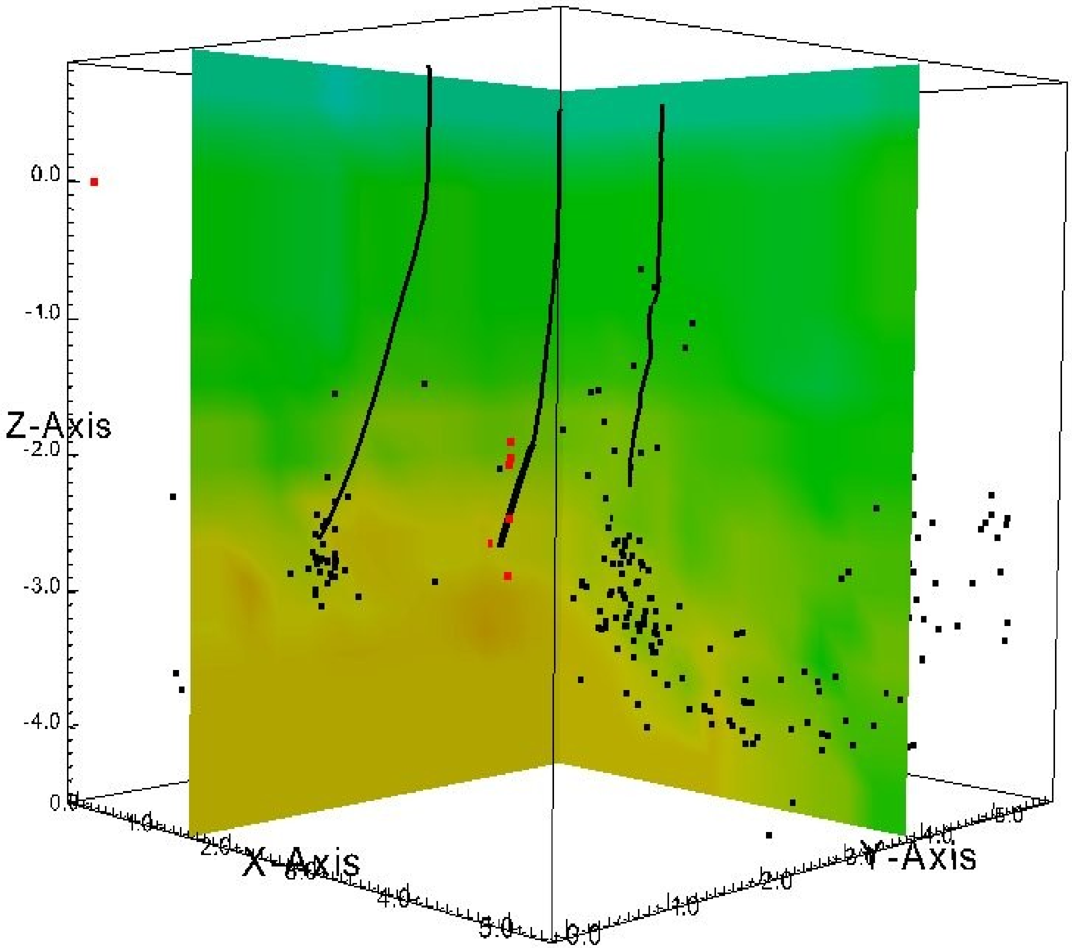
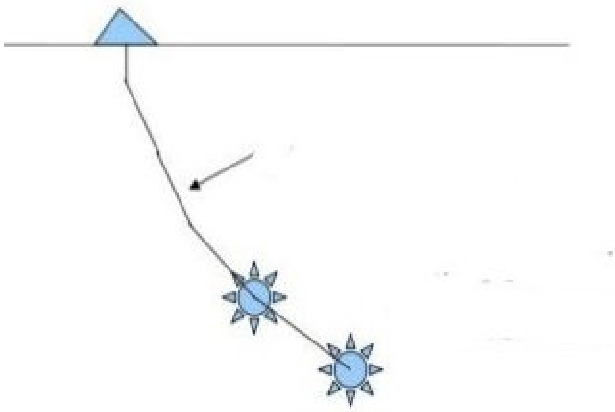


Crack

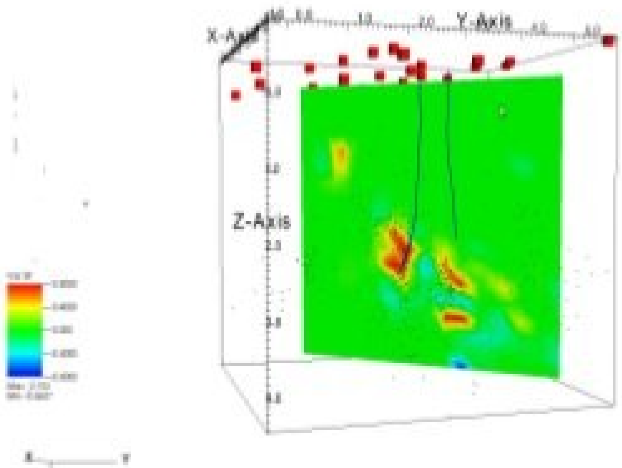
Validation of Tomography



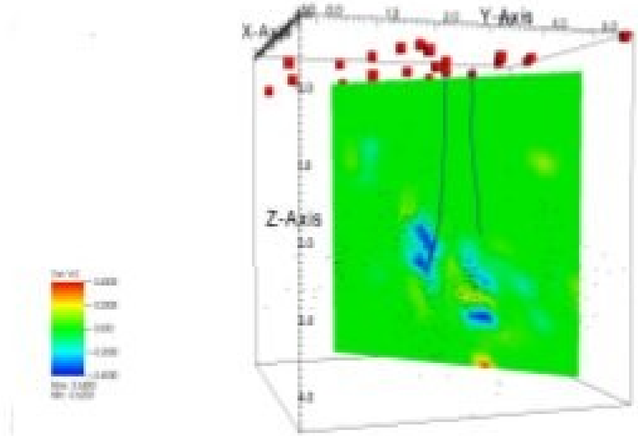


Overlapping ray paths used to constrain relative locations and tomography between events

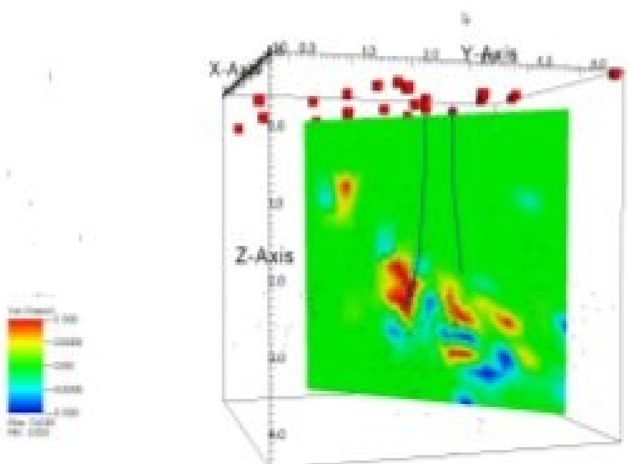
After one Month of Injection



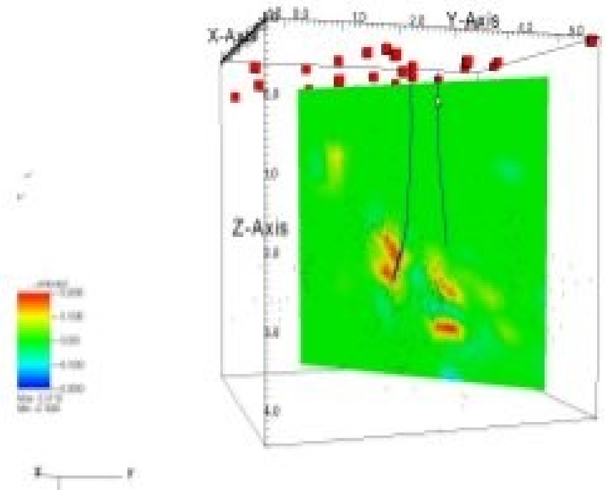
Bulk modulus



Vs



Poisson's ratio



Lambda

One Month After

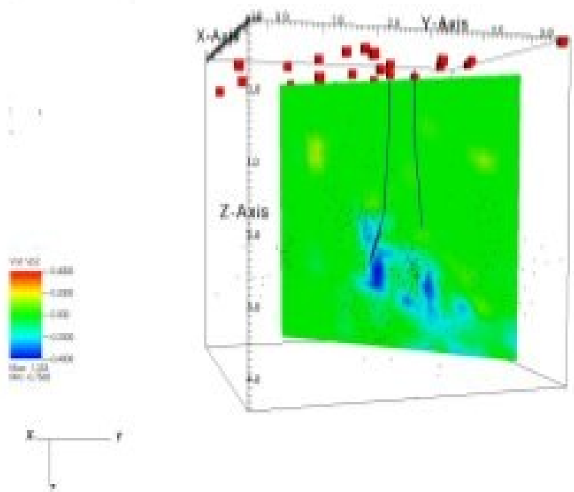
Bulk modulus, Poisson's ratio, and Lambda increased. *Qp* and *Vp* increased, while *Vs* and *Qs* decreased. We interpret this observation to indicate that there is fluid saturation along with fracturing around the well bottom. Fracturing would decrease *Vs* & *Vp*, but saturation would not affect *Vs*. Whereas, saturation would increase *Vp*, even with fracturing. Saturation and fracturing should have competing effect of intrinsic and extrinsic *Q*. Saturation should increase intrinsic *Qp* & *Qs*, but not affect extrinsic *Qs*. Lambda and Poisson's ratio increased, which is another indication of saturation.

One Month After

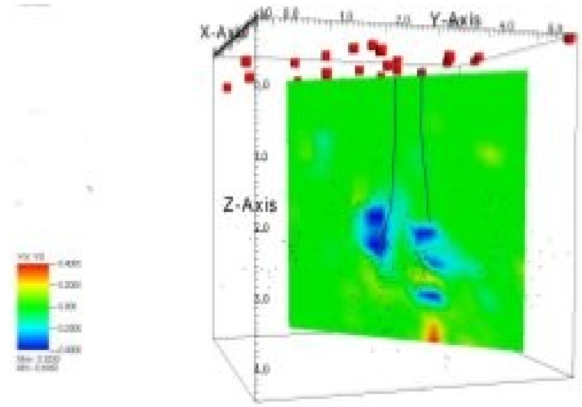
Saturation and fracturing should have competing effect of intrinsic and extrinsic *Q*

- There is very little pore fluids, so incrinsic Q is minimal
- Saturation should increase extrinsic *Qp,* but not affect extrinsic *Qs*

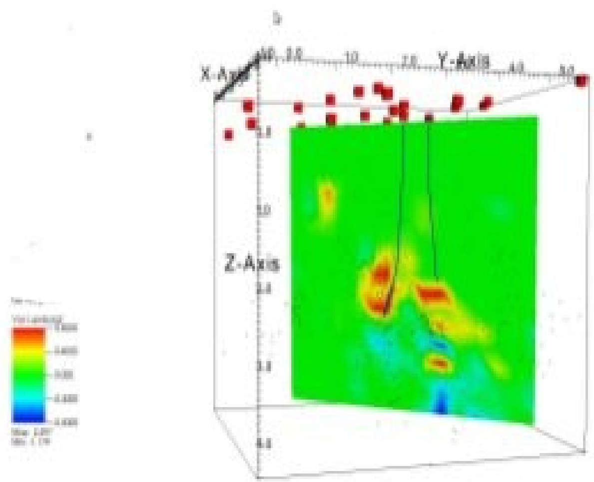
After Two Months of Injection



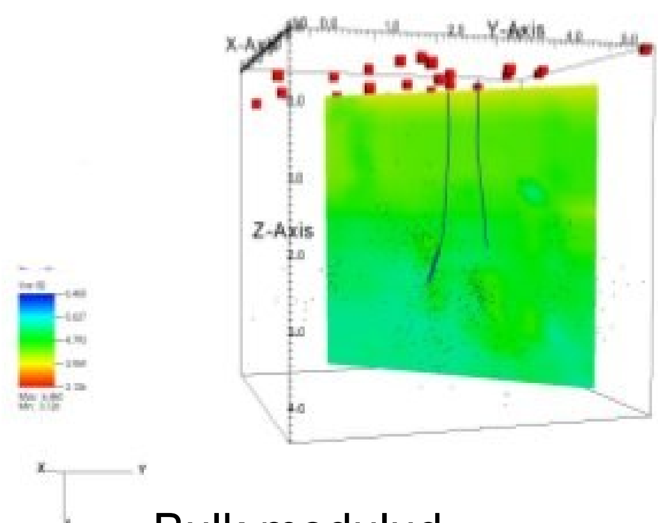
Vp



Vs



Lambda



Bulk modulud

Second Month After

- New anomalies have appread below the well bottom

-*Vp* is low and *Vs* remains low -->> steam with fracturing

- The old anomalies at the well bottom have not moved but increased in size

- We interpret these observations to indicate continued saturation around the well bottom, but with increased fracturing, and fracturing with steam below the well

Conclusions & Observations

- Improvements in data collection and processing can improve reservoir monitoring and modelling
- Reduced costs in labor and hardware for data collection
- Reduced time and labor for processing and analysis
- Allows for near-real time reservoir monitoring
- Micro-earthquake data can be used to provide a basis for rock physics interpretations in geothermal fields