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

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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 $V_p$, $V_s$, $Q_p$, $Q_s$ 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
- Pulse width
- Moment Tensor
- P & S spectra

Vp & Vs tomography

Qp & Qs

anisotropy

crack orientations

stress drop, Mo
• $V_p$, $V_s$, $Q_p$, $Q_s$ from tomography
• Lambda, Bulk, and Young's moduli and Poisson's ratio from $V_p$, $V_s$ & density

\[
v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad n_s = \sqrt{\frac{\mu}{\rho}} \quad \frac{K}{\mu} = \left\{ \frac{V_p^2 - \frac{4V_s^2}{3}}{V_s^2} \right\}
\]
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 longitudinal stress to transverse strain
- **Young's modulus**: is ratio of longitudinal stress to longitudinal strain
• Develop quantitative relationships between reservoir properties and $V_p$, $V_s$, $Q_p$, $Q_s$, and elastic parameters

• Utilize laboratory and well-log data

• Develop rock physics models of the reservoir

• Utilize 3D visualization software
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 study at constant confining pressure and temperature, but changes in saturation

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

Effects of liquids on Lambda

From Berryman and Bonner, 2002
State 2-14 Well
- Salton Sea

P-Wave Velocity

S-Wave Velocity

Poisson's Ratio

Cap rock
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 may 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
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

Seismicity at The Geysers
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

Crack

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

- There is very little pore fluids, so intrinsic $Q$ is minimal
- Saturation should increase extrinsic $Q_p$, but not affect extrinsic $Q_s$
After Two Months of Injection

Vp

Vs

Lambda

Bulk modulud
• New anomalies have appeared below the well bottom.  

\[-V_p\text{ is low and } V_s\text{ remains low} \implies\text{steam with fracturing}\]

• 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