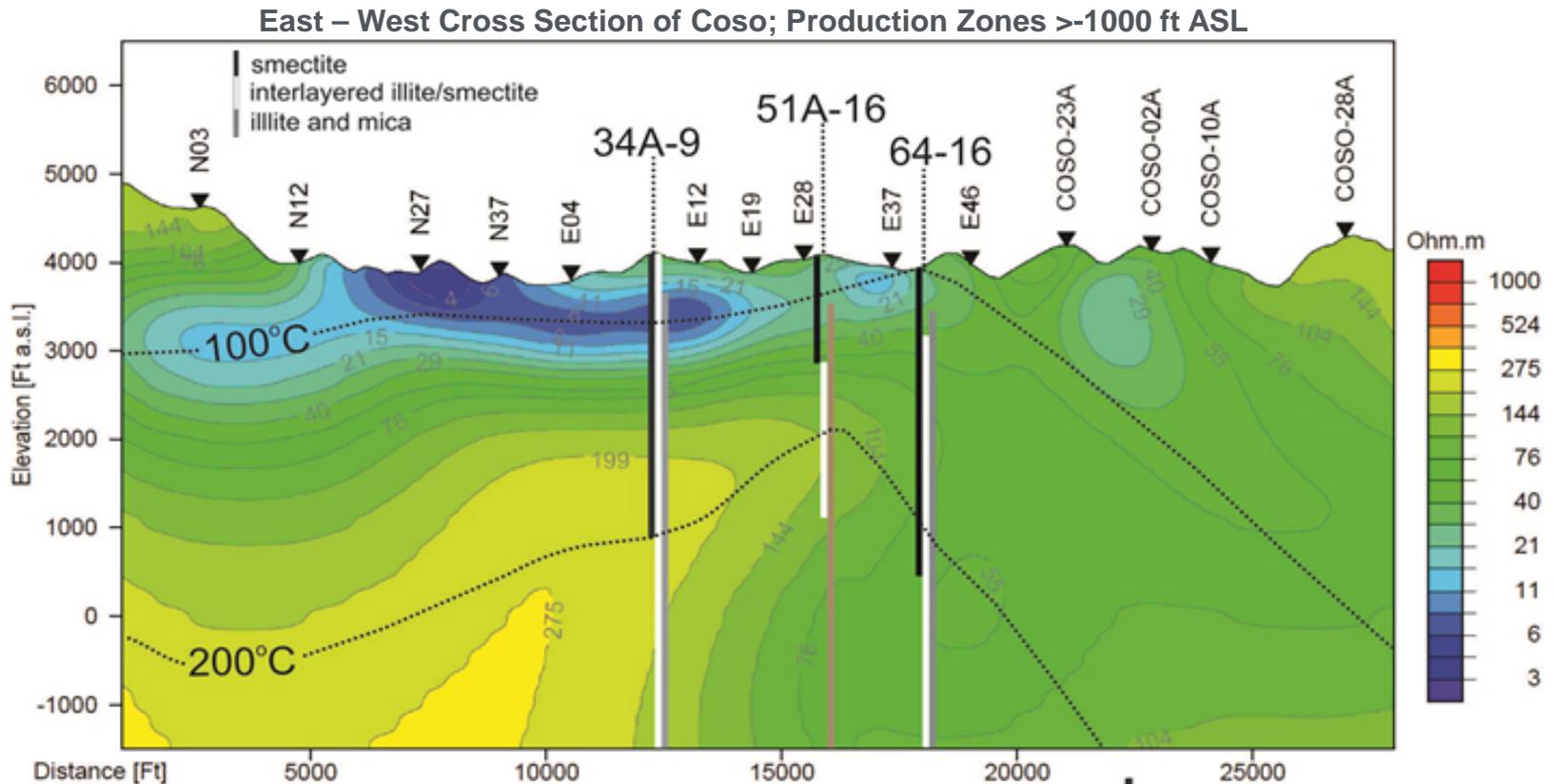


# Geothermal Technologies Program 2013 Peer Review



Innovative Computational Tools for Reducing  
Exploration Risk Through Integration of Water-  
Rock Interactions and Magnetotelluric Surveys

April 24, 2013

Principal Investigator:  
Joseph Moore

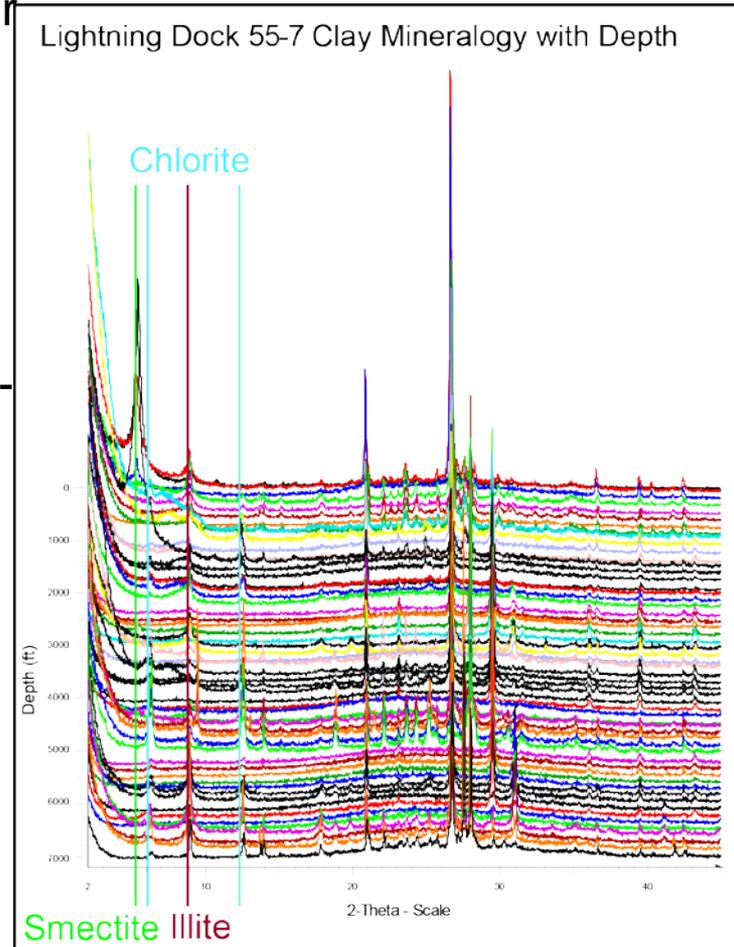
**Organization: University of Utah**

Track Name: Research and  
Development

**Objective:** Develop the framework to relate reservoir permeabilities with geochemical indicators of water-rock interactions and electrical resistivities as measured by MT surveys.

**Problem:** Locating zones of high permeability is a major challenge. MT is widely used but its relationship to permeability and its application to low- to moderate – temperature systems is not well established.

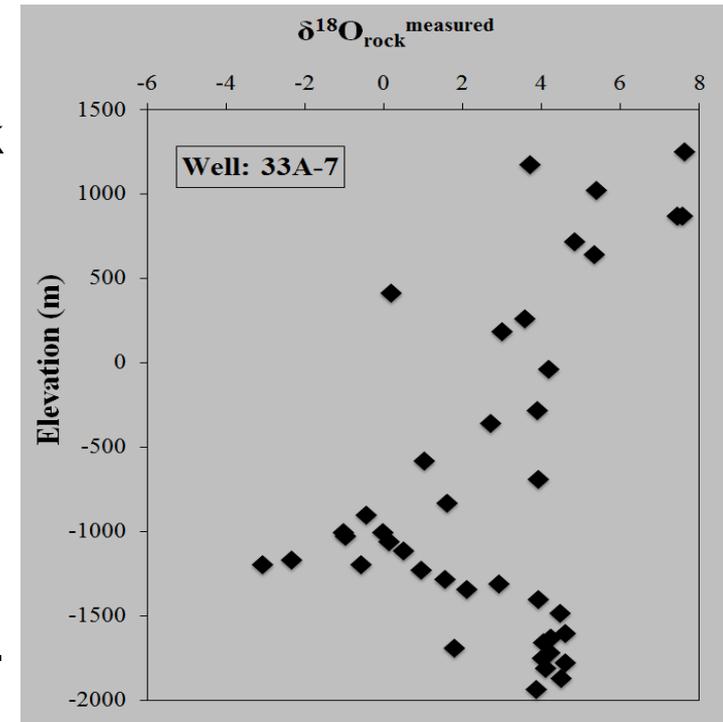
- **Impact:** Reduce exploration and development costs by reducing risk and number of wells drilled.
- **Innovative Aspects:** Application of geochemical indicators to low- to moderate temperature resources represents a novel approach to understanding reservoir characteristics.
- New geothermal scientists are being trained.



**Phase 1:** Establish methodology in 2 well characterized geothermal systems.

- Determine mineral distributions and isotope compositions.
- Evaluate geochemical indicators of water-rock interactions:
  - Isotopic ratios
  - Reaction progress
- Compare with downhole permeabilities
- Relate resistivities (from MT) to reservoir geometry and permeabilities.
- Develop framework to relate geochemical indicators to resistivity and permeability data.

**Phase 2:** Extend the procedures developed in Phase 1 to a geologically complex environment.



**33A-7, Coso geothermal field**

## Water:rock ratios (Taylor 1979)

$$W/R = \frac{\delta^{18}\text{O}_r^f - \delta^{18}\text{O}_r^i}{\delta^{18}\text{O}_w^i - \delta^{18}\text{O}_w^f}$$

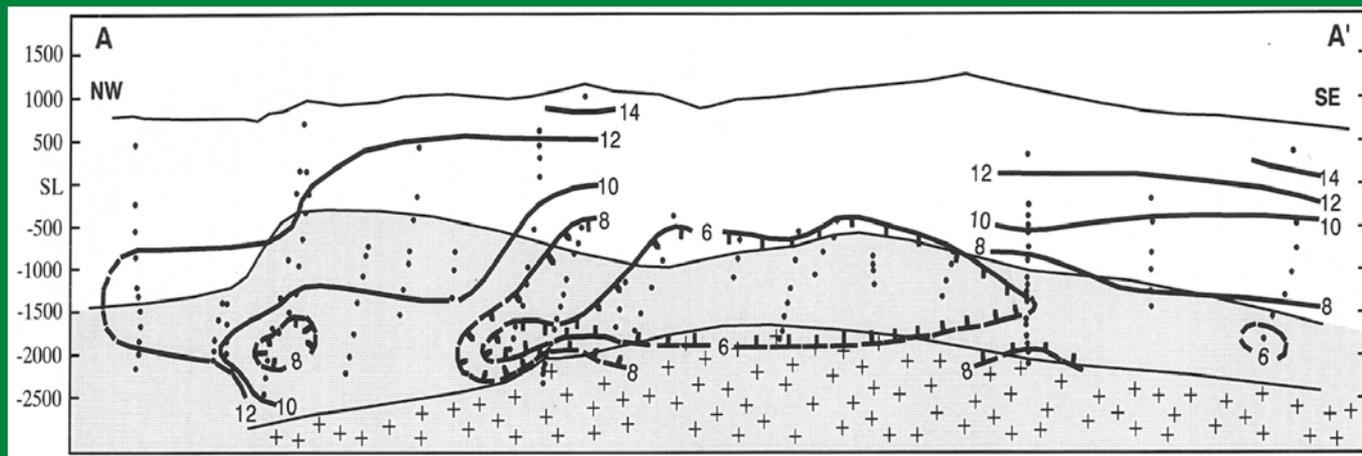
$\delta^{18}\text{O}_r^f$  is  $\delta^{18}\text{O}$  of measured sample

$\delta^{18}\text{O}_r^i$  is the initial  $\delta^{18}\text{O}$  of host-rock

$\delta^{18}\text{O}_w^i$  is the value of local meteoric water

$\delta^{18}\text{O}_w^f$  is the value of the reservoir fluid

### Whole-rock $\delta^{18}\text{O}$ values of The Geysers Geothermal System



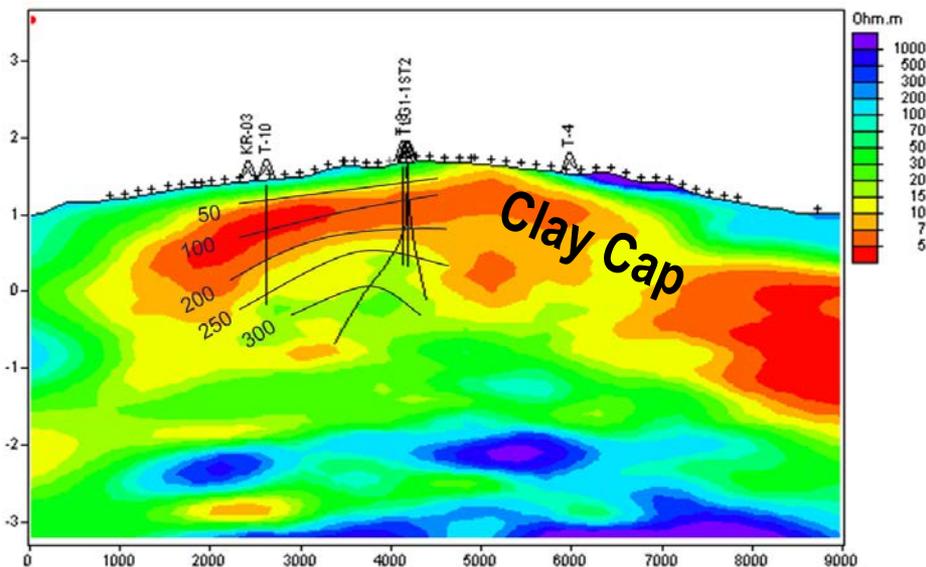
Moore and Gunderson, 1995

# Using Magnetotelluric Surveys to Map Permeability

MT surveys can be used to map:

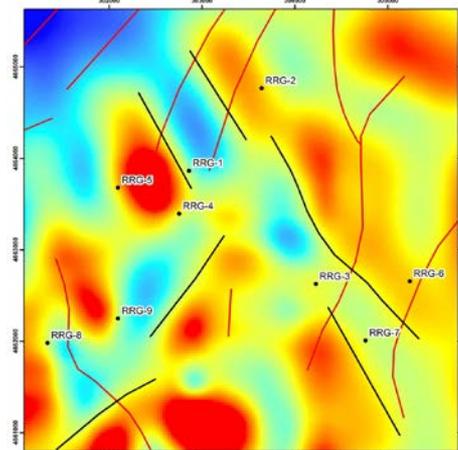
- Smectite and interlayered illite-smectite that forms at  $T < 225$  C (e.g. clay caps)
- Resistivity variations and relative degree of water saturation

## Karaha - Telaga Bodas, Indonesia

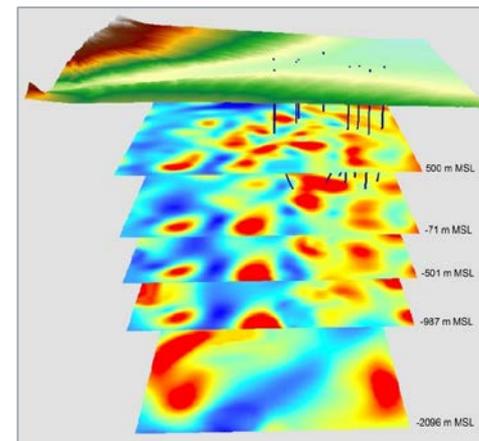


Ussher, 2007

## Raft River, Idaho

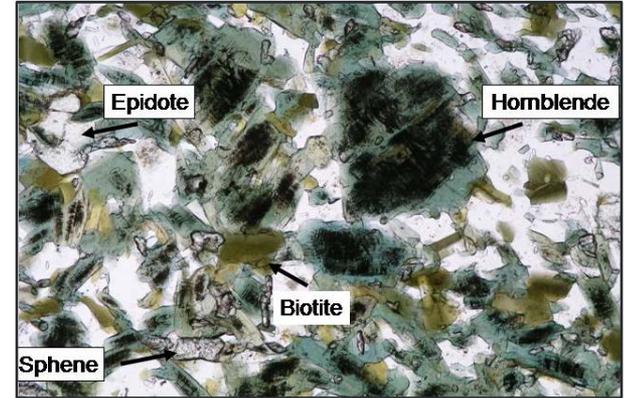


Magnetotelluric Log 10 Resistivity  
500m MSL Slice  
Value  
High : 3.11  
Low : -0.76  
— Fault inferred from MT data  
— Fault inferred from gravity data  
Coordinates: UTM Zone 12N, NAD83



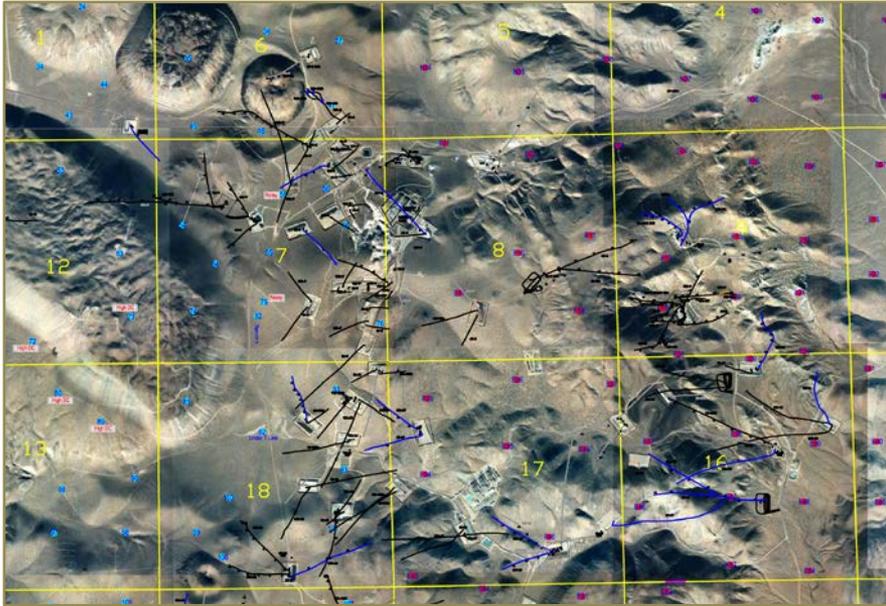
- We have not been faced with any technical challenges. All required data for Phases 1 and 2 have been obtained from our industry partners, Cyrq Energy and Terra-Gen Power, LLC.
- The project has progressed as planned.
- There have been no technical variances from the proposed program.

## Diorite (Coso reservoir rock)

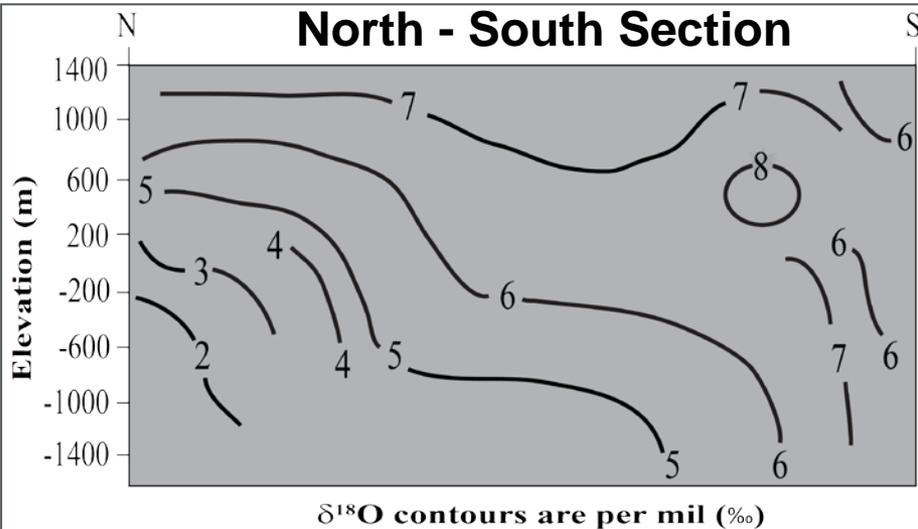
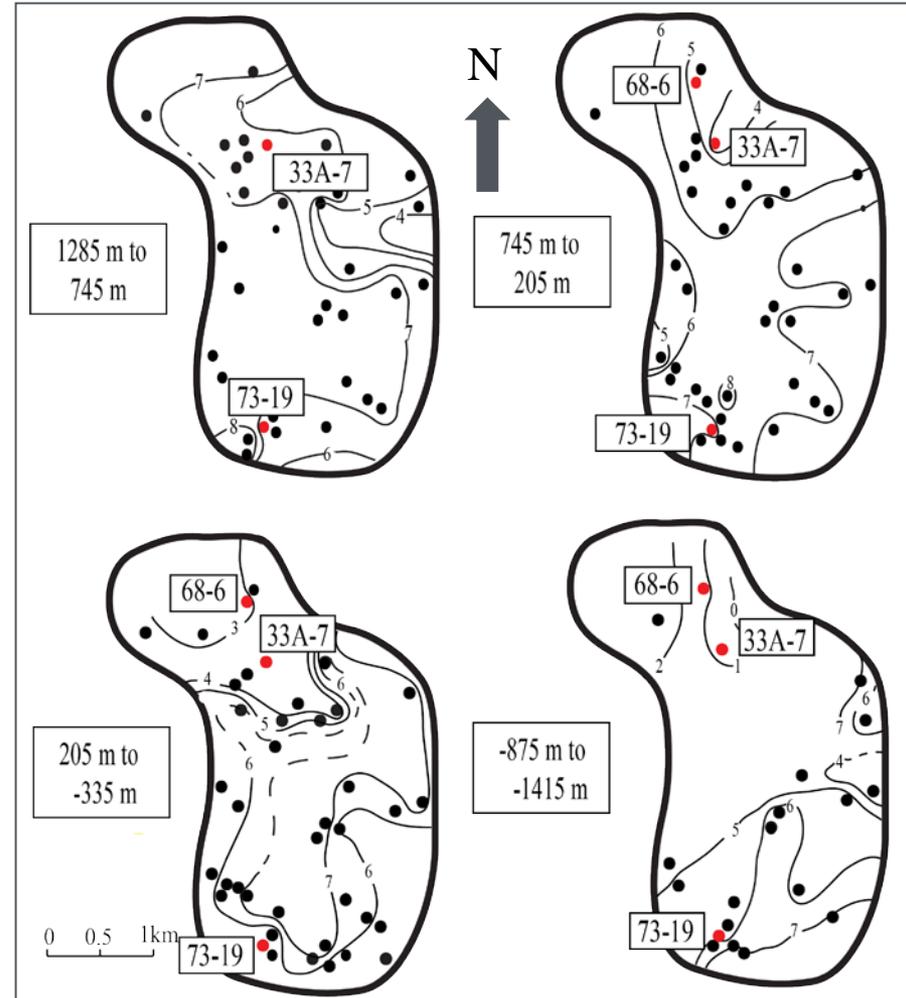


Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Acquire rock samples and data	Obtained all required samples and relevant data.	9/2012
Complete X-ray diffraction analyses	Completed X-ray analyses of 3 wells from Coso, 5 from Lightning Dock and 2 from Thermo. Additional analyses are in progress.	(3/2013)
Complete isotope analyses	Completed 85 analyses from Coso; additional isotopic analyses from Coso planned based on results. Remainder to be completed by 9/2013.	9/2012
Obtain MT data	3-D MT models have been obtained from Coso and Lightning Dock; MT model from Thermo anticipated.	6/2012

# Accomplishments, Results and Progress: Coso

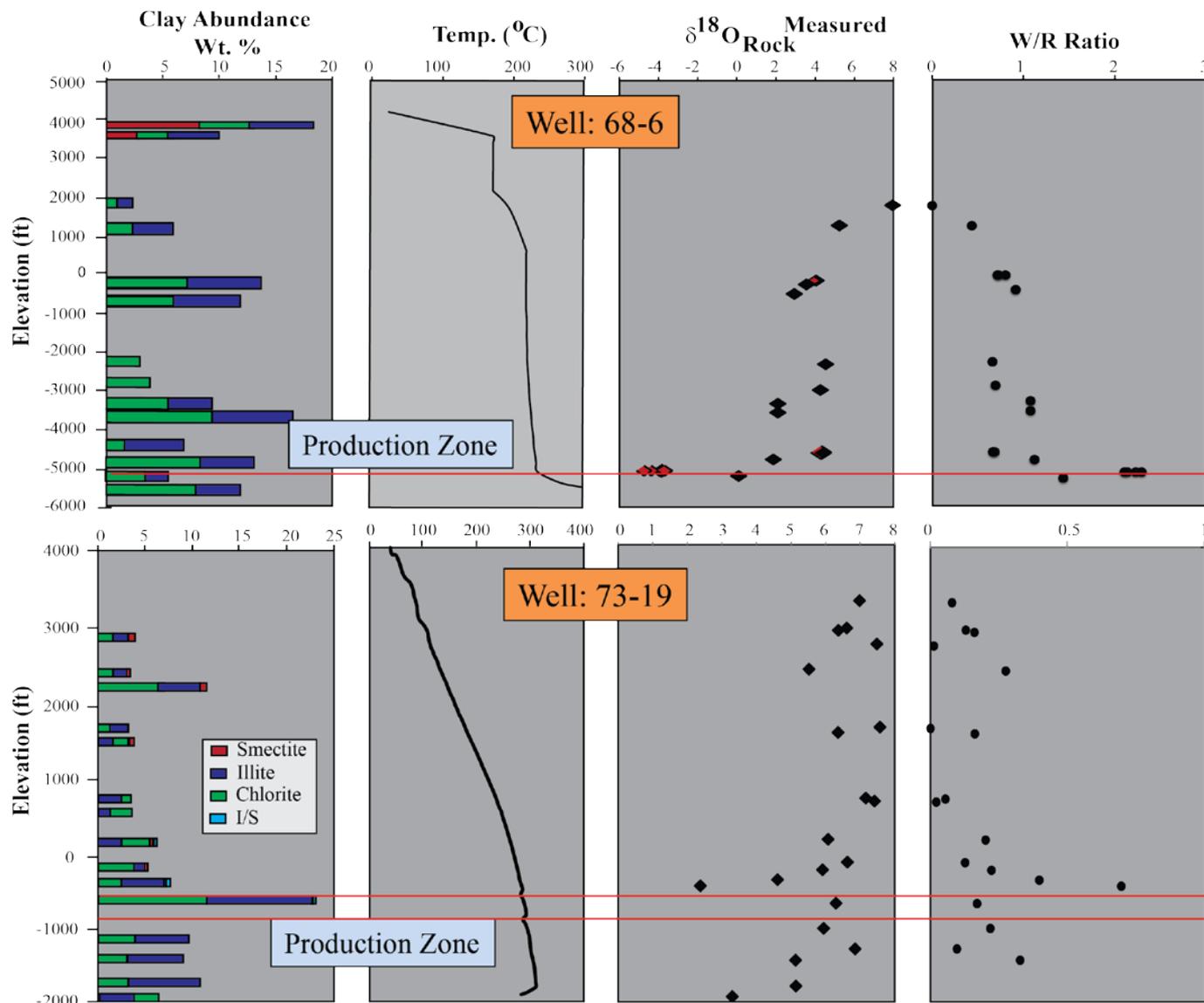


## Plan Maps of $\delta^{18}\text{O}$ Values



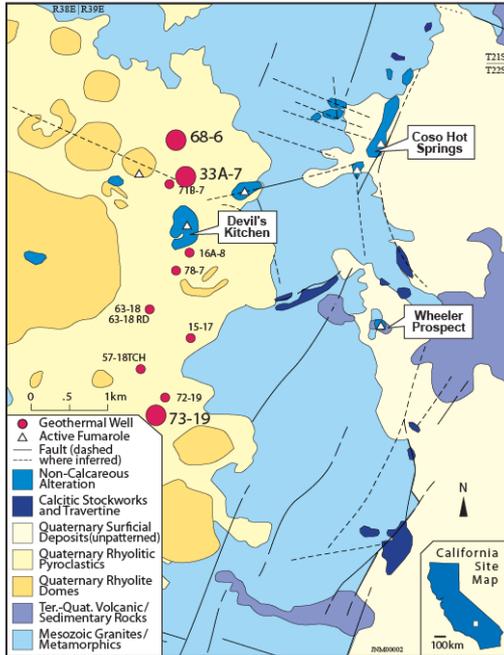
Data courtesy of Terra-Gen Power LLC.

# Accomplishments, Results and Progress: Coso



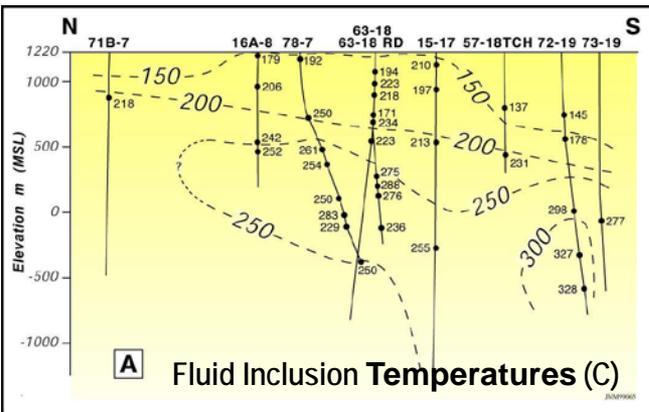
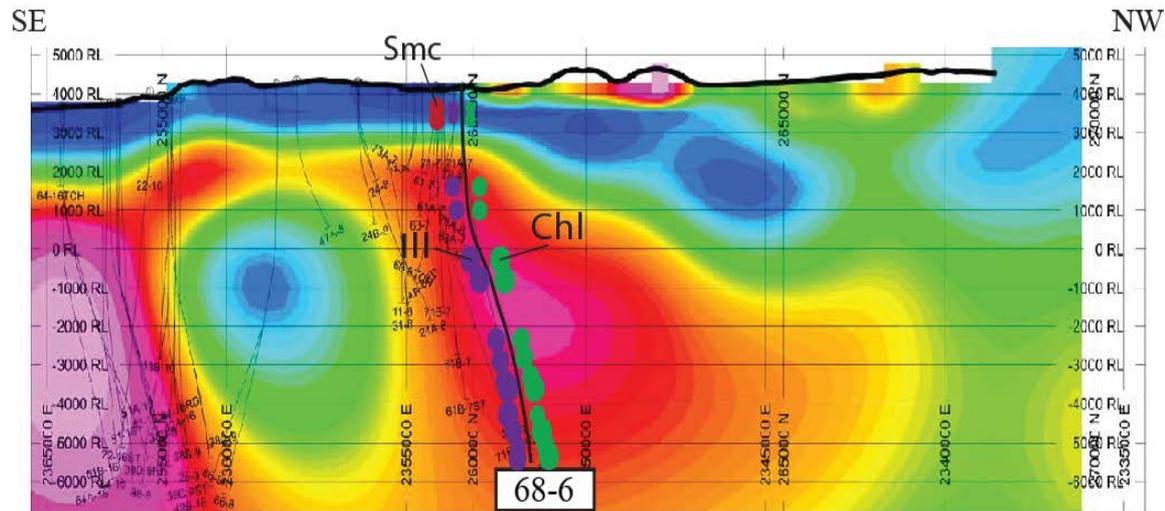
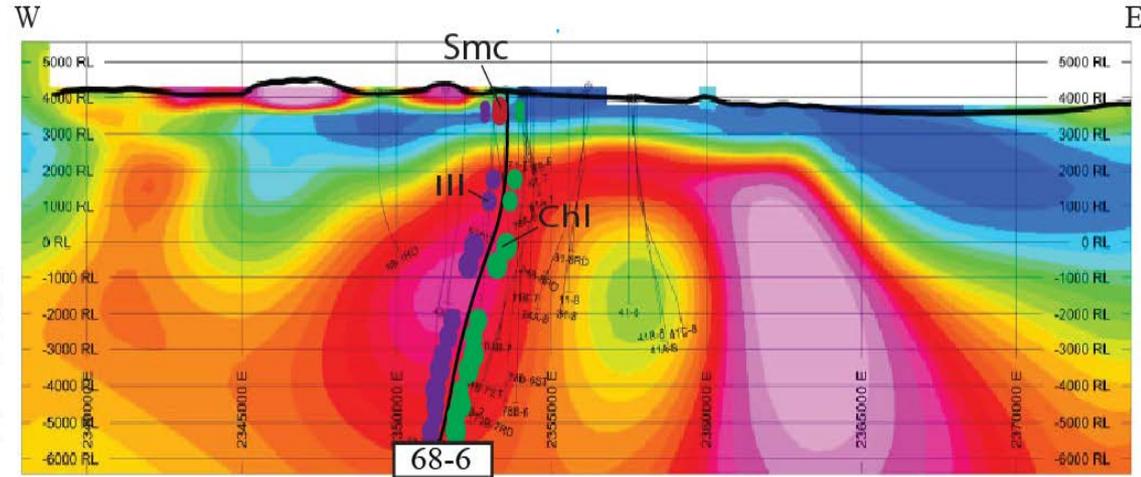
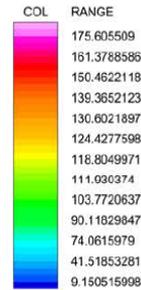
**Diorite**

# Accomplishments, Results and Progress: Coso

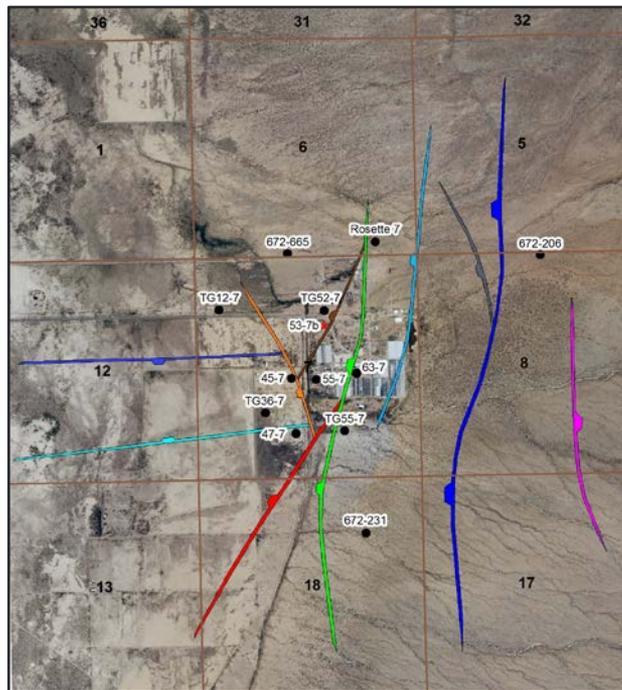


## Clay minerals in 68-6

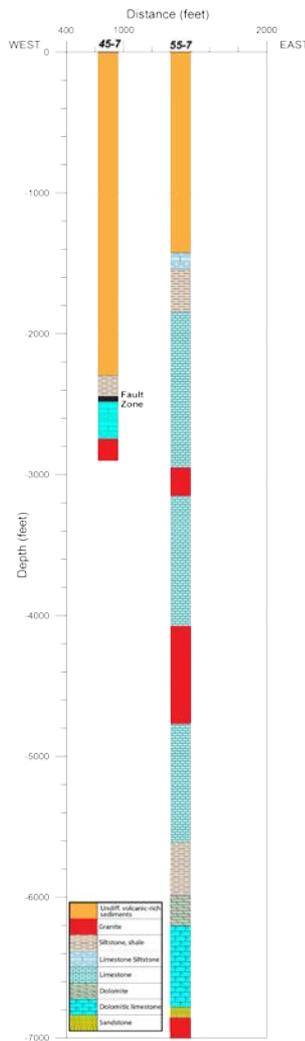
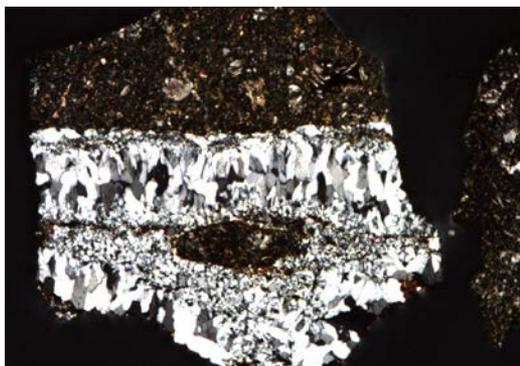
Resistivity  
(Ohm-m)



# Accomplishments, Results and Progress: Lightning Dock

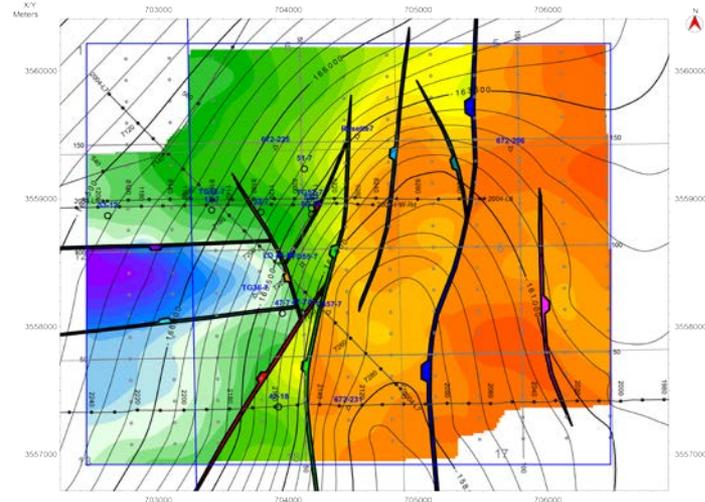


Quartz Vein in Alluvium

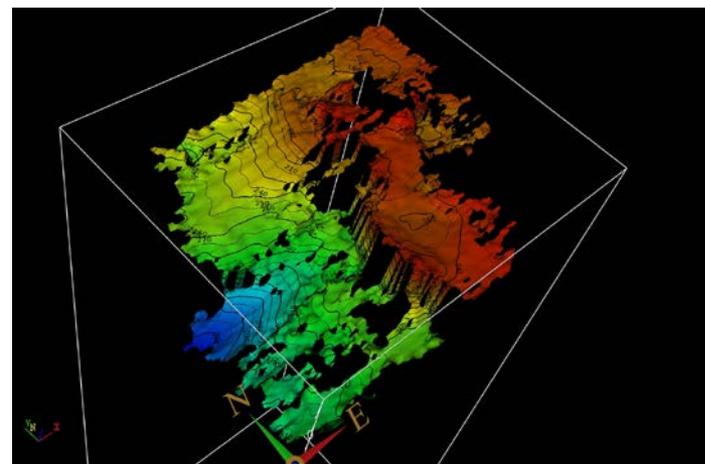


Reconstructed lithologic columns

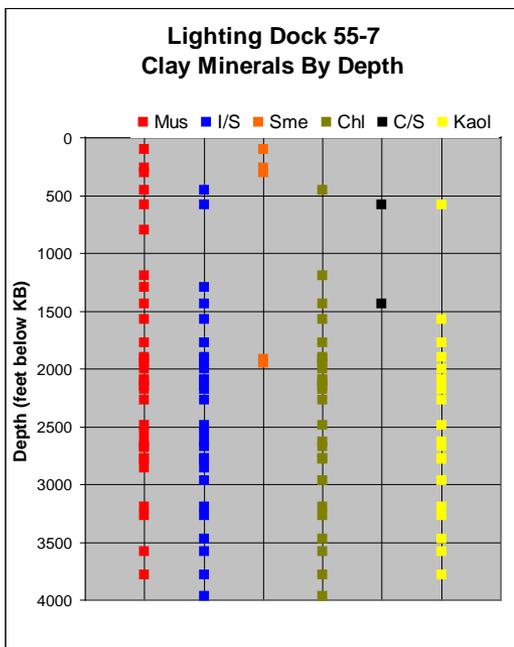
Bouguer Gravity Map



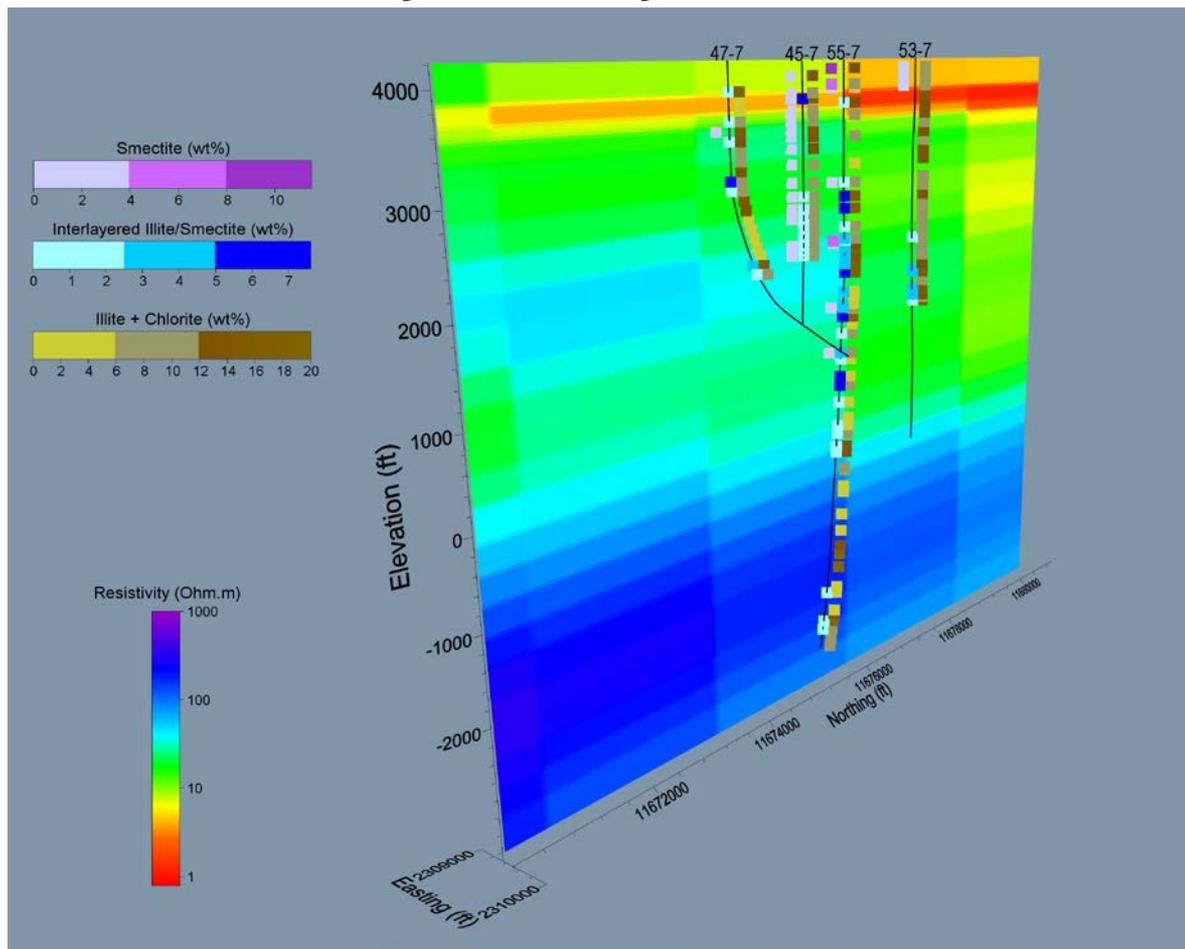
3-D Seismic Image



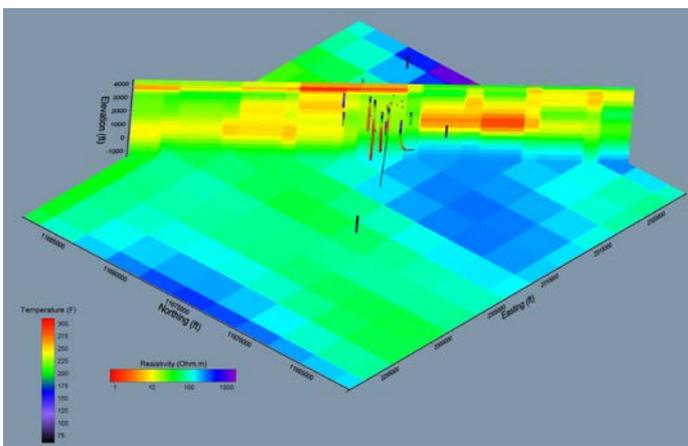
# Accomplishments, Results and Progress: Lightning Dock



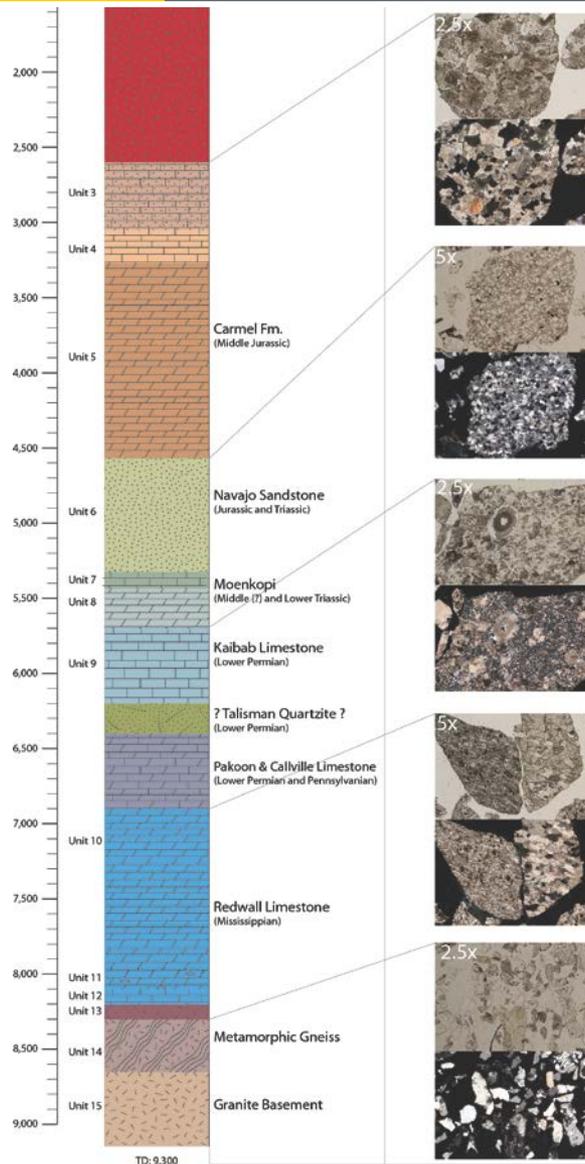
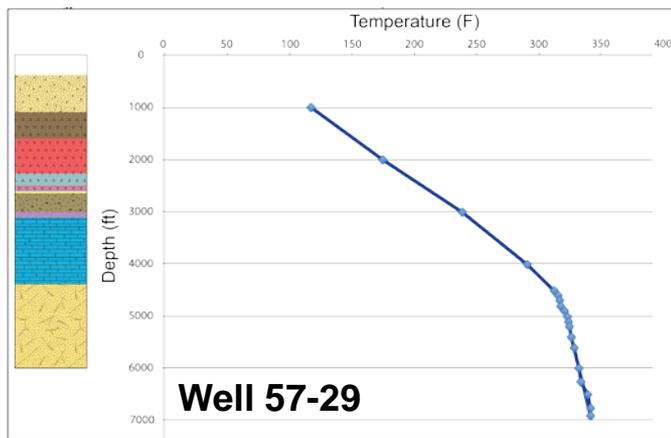
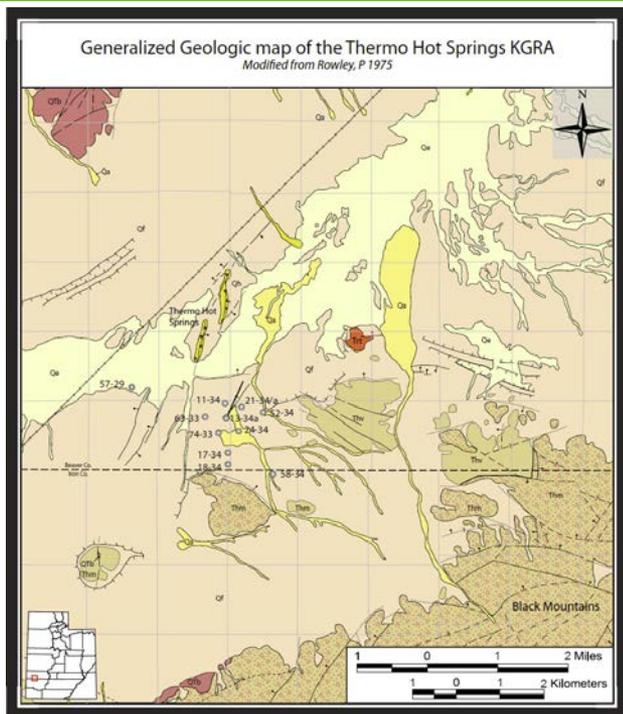
## Resistivity and Clay Distributions



## Temperatures (on Wells) and Resistivities



# Accomplishments, Results and Progress: Thermo Hot Springs



**Well 17-34**

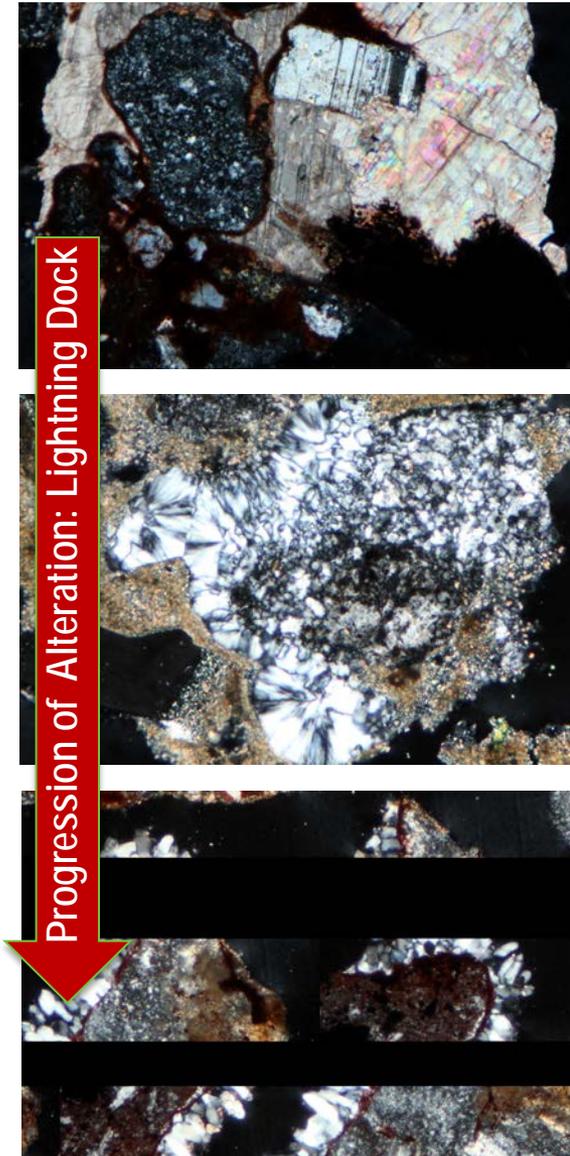
## Phase 1:

- Complete X-ray, petrographic and isotope analyses.
- Complete calculation of water-rock ratios and reaction progress.
- Conduct new isotopic analyses on injection zones at Coso.
- Integrate reservoir permeabilities, geochemical indicators of water-rock interactions and reservoir resistivities.
- Develop approach for Phase 2 (Go/No-Go decision point targeted for 9/2013)

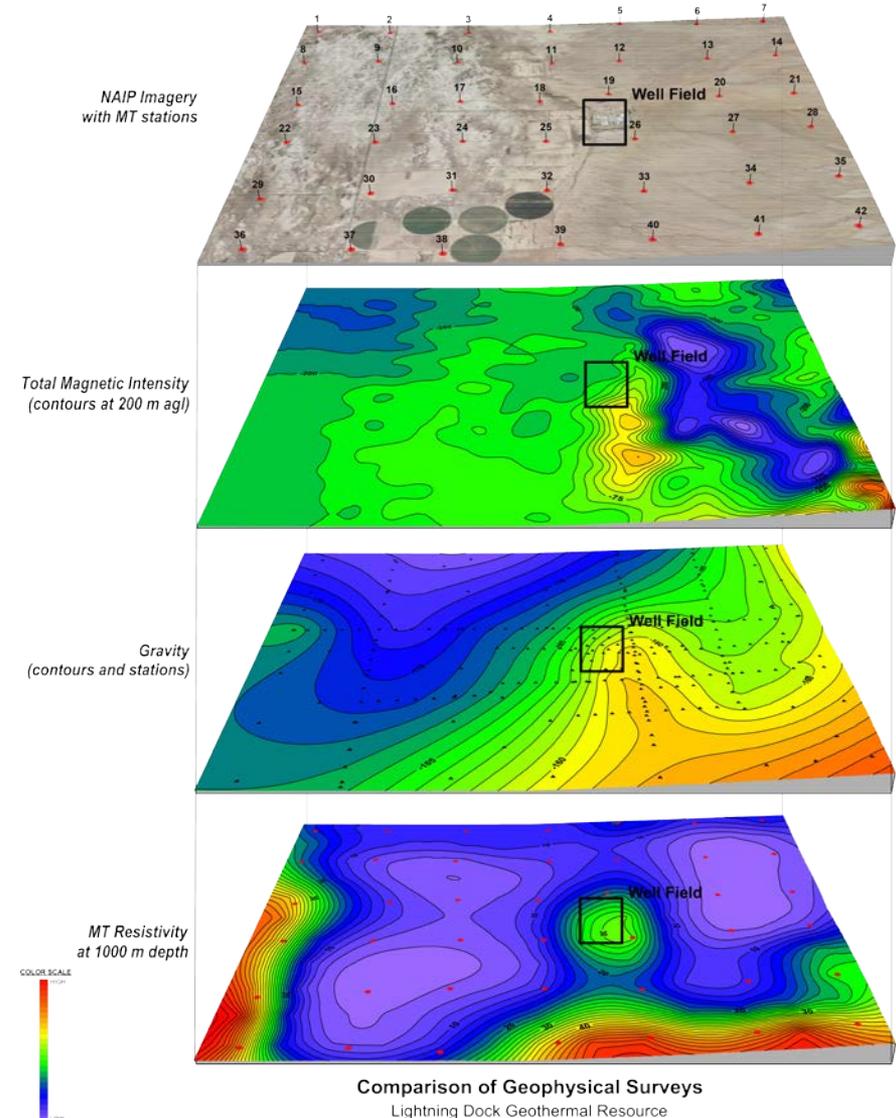
## Phase 2: Test model

- Use data and samples from the Coyote Canyon NV geothermal system. Required data and samples are in house.

No issues are anticipated in completing the project as proposed. The required data has been collected. Any unanticipated challenges will be reviewed with the Project Manager and a decision will be jointly made.



- All samples and data from Coso and Lightning Dock required for Phase 1 have been obtained by EGI. Additional samples from Thermo under study.
- Petrographic and X-ray analyses were completed on 3 wells from Coso, 5 wells from Lightning Dock and 2 wells from Thermo.
- 85 whole-rock isotope analyses have been obtained on 3 Coso wells.
- The Coso results support a relationship between permeability and water-rock ratios determined from isotopic data.
- 3-D interpretations of MT data are being analyzed for their relationship to permeability.
- 1 M.S. thesis completed on Thermo; 1 M.S. thesis underway on Coso.



Timeline:	Planned		Actual		Current	
	Start Date	End Date	Start Date	End Date (Phase 1)		
	9/30/2011	12/31/2014	12/01/2011	12/31/2013		

Budget:	Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	DOE Funding needed to Complete Phase 1 Work
		\$693,151	\$74,520	\$180,241	\$180,241	\$384,000

- Principal Investigator: Dr. Joseph Moore (EGI): oversees work and coordinates activities among team members and with the DOE; assumes overall responsibility for budget.
- Leveraging of funds: Cost share is being provided by the U. of Utah for student support and research. Cyrq Energy and Terra-Gen LLC are providing, at no charge, well, survey and analytical data.
- Integration with other projects: J. Moore and P. Wannamaker are part of other project teams investigating the applications of MT surveys and water-rock interactions in low- to moderate-temperature environments. This involvement allows cross fertilization of ideas and techniques.
- The project is progressing on schedule.