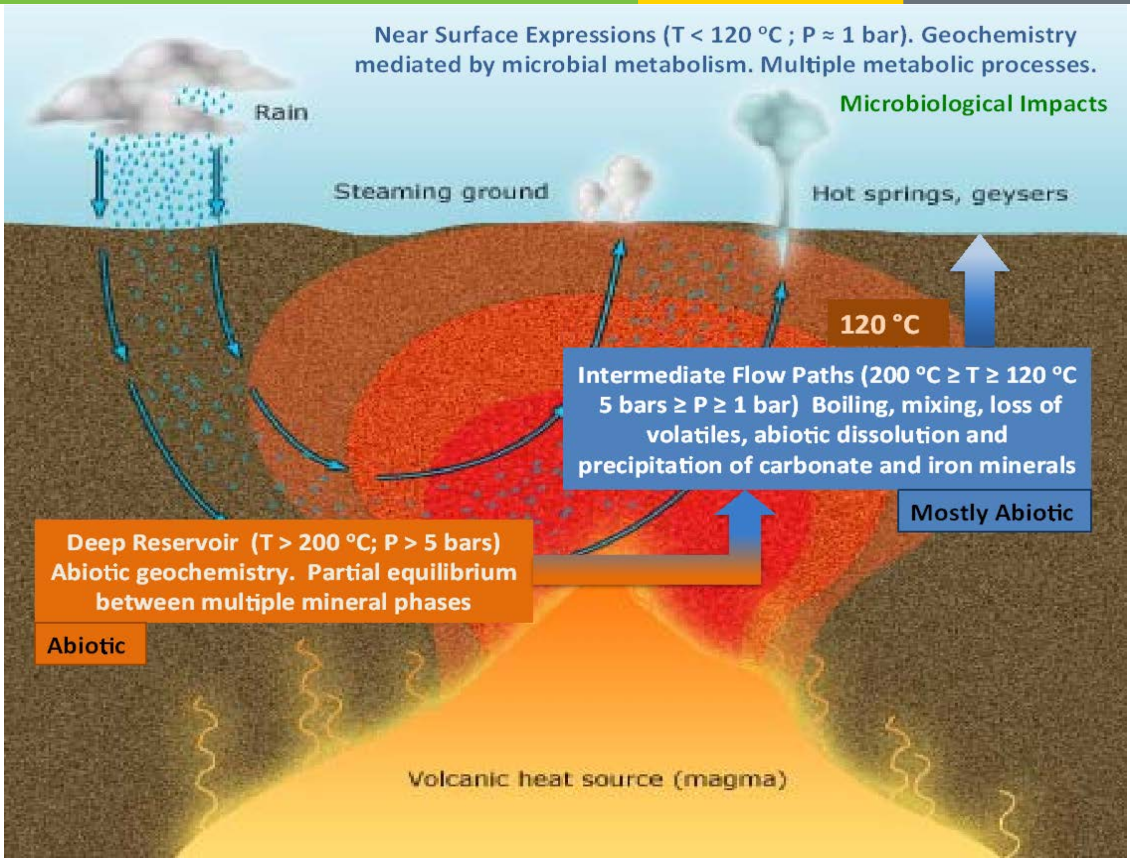

Improved Geothermometry Through Multivariate Reaction Path Modeling and Evaluation of Geomicrobiological Influences on Geochemical Temperature Indicators

Project Officer: Eric Hass

Total Project Funding: $999,000

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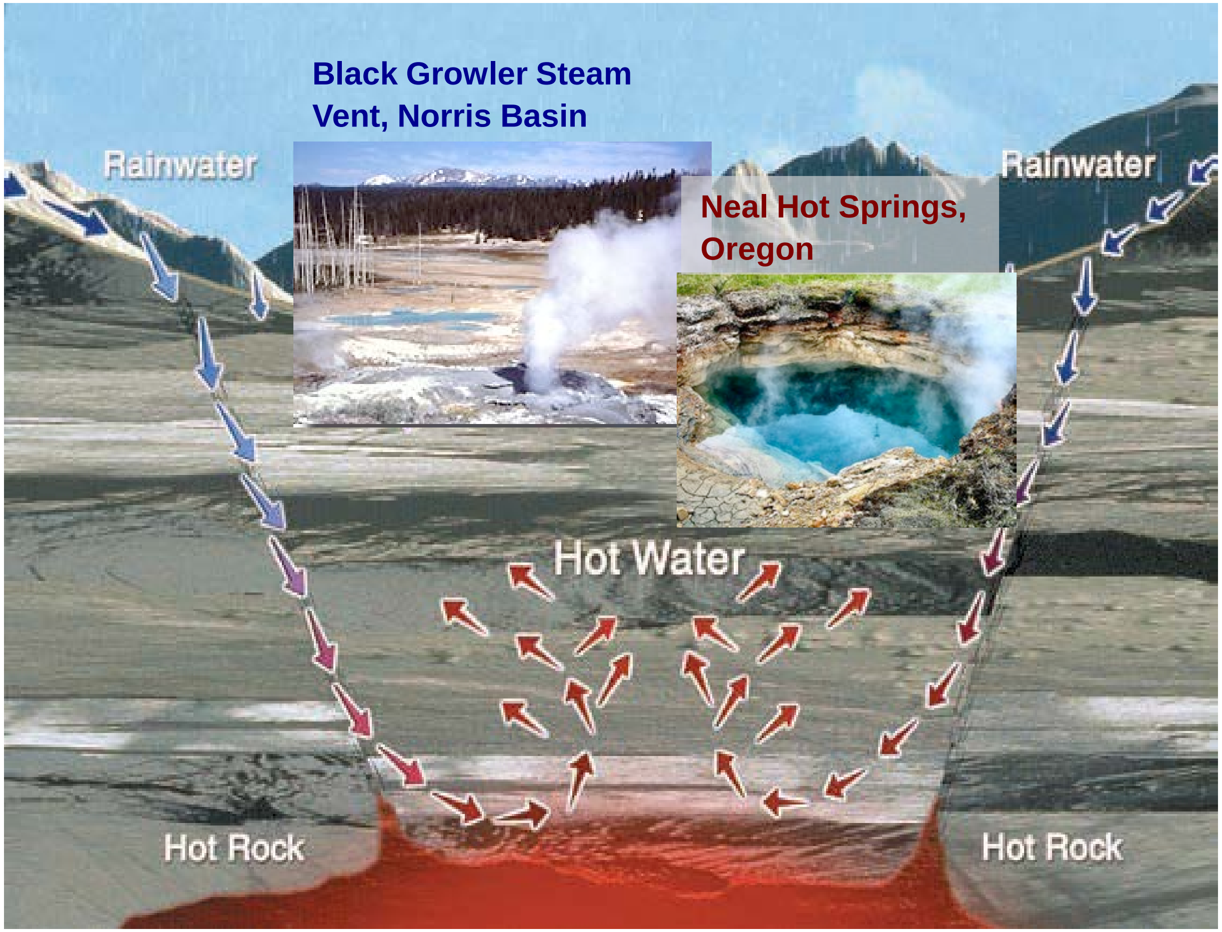
Geothermometry enables estimation of reservoir (subsurface) temperatures using chemical and/or isotopic composition of surface discharges

4. Warm surface water samples provide altered but recoverable record of deeper, high-T equilibrium
3. Mixing, precipitation, dissolution, degassing, microbiological effects, etc. alter solution during ↑ transport
2. Re-equilibration does not occur during rapid upward transport through fractures
1. Water-mineral equilibrium established in high-T recirculation zone



Relevance/Impact of Research

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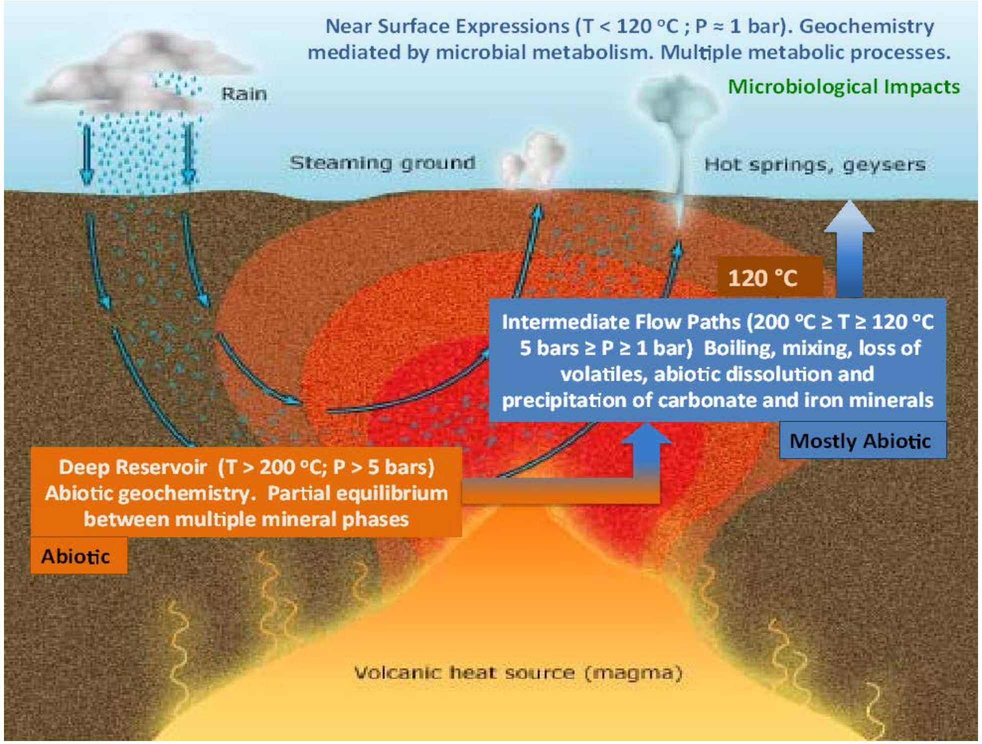
Objective: Predict reservoir temperature to within the DOE target of ±30°C using geothermometry

Challenges:

- Quantify the changes that occur in solution chemistry during upwelling
  - What processes are important?
  - What components change and by how much?
- Techniques to quantify changes rely on simplistic or untested assumptions and have not been validated against field and lab data
  - Uncertainty in temperature prediction is unknown.

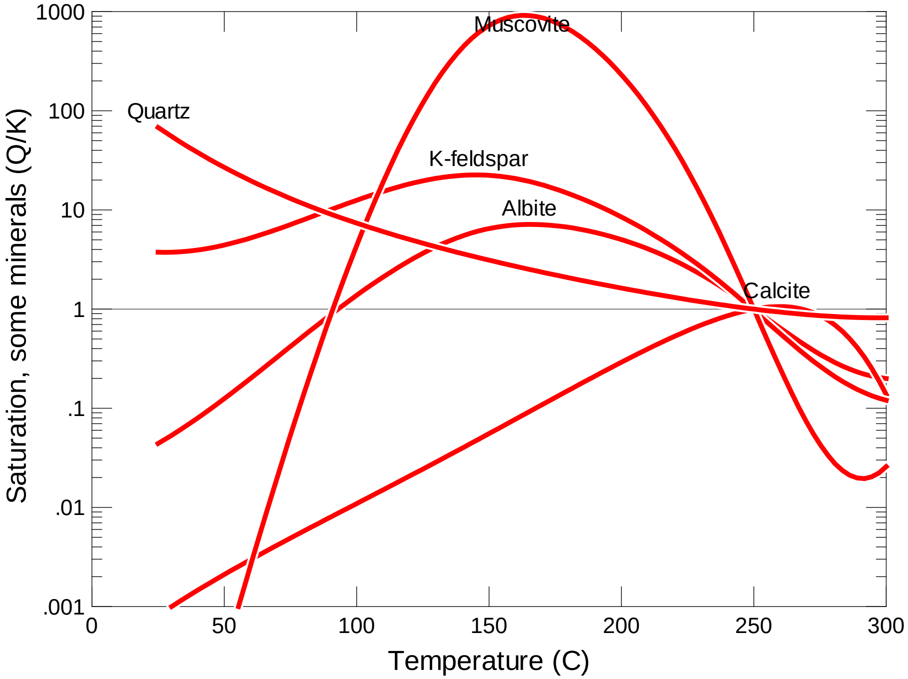
Three pronged approach

- Reduce uncertainty in temperature estimate via ***inverse simulation*** of reservoir geochemistry
- Validate the accuracy and robustness of geothermometry models through ***laboratory experiments***
- Determine if ***microbial activity*** is an important alteration mechanism



Inverse Simulation

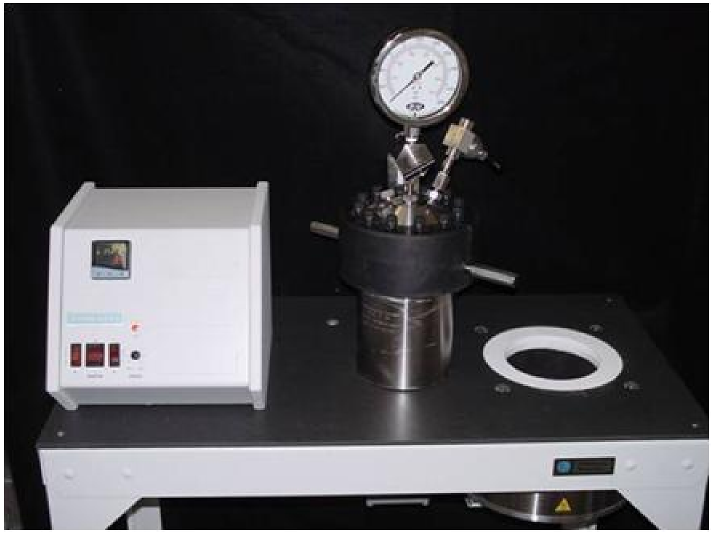
- Develop geochemical reaction path calculations that predict solution composition from initial conditions (e.g. T, P, mixing)
- Develop inverse parameter estimation approach for T, so that multiple forward calculations converge on a reliable solution
- Develop knowledge base to allow end users to select mineral suites from geologic province information
- Evaluate alternative optimization techniques
- Demonstrate tool in exploration setting



Scientific/Technical Approach

Laboratory Experiments

- Assess the relative importance of primary and secondary mineralogy to define solution composition
- Determine the influence of different cooling mechanisms, volatile loss, and fluid mixing histories on final water composition.
- Evaluate the role of fluid mixing and microbial activity (sulfur cycling) on fluid composition
- Evaluate the limitations of laboratory experiments for approximating field geochemical conditions for enhanced geothermal systems.



Microbial Activity

- At temperatures ≤ 121°C, microbial activity may become significant; large disequilibria at surface expressions provide abundant energy.
- Microbial metabolism can dramatically alter pH, Eh, solute concentrations.
- Develop methods to detect and estimate microbial activity in geothermal prospecting samples.
- Test methods on geothermal samples.
- Use these methods in laboratory/field studies to demonstrate that microbial activity can alter water composition sufficiently to impact temperature predictions.

Four Simulated Cases to Test Inverse Approach

1. **Open System**
   Cooled to 25^{o}C, at atmospheric pCO_2
2. **Effect on Analytical Errors**
   Cooled to 25^{o}C, at atmospheric pCO_2
   Random errors in analyses
3. **Deep Boiling**
   Water isothermally boiled until 15% water loss
   Mineral equilibrium maintained during boiling
   Water cools to 25^{o}C, at atmospheric pCO_2
4. **Flashing**
   Water isothermally boiled until 15% water loss
   No mineral reaction during boiling
   Water cools to 25^{o}C, at atmospheric pCO_2

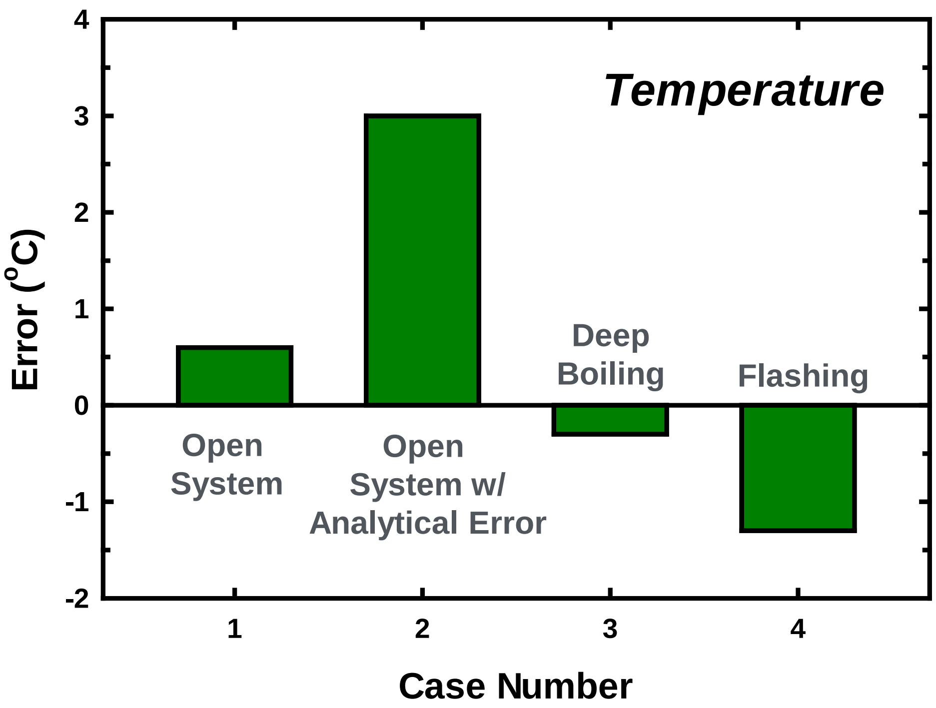
Objective Function: Minimize TSI

$TSI = \sum(SI_i/wt_i)^2$

SI_i = Saturation Index for i^{th} mineral

wt_i = Weighting factor for i^{th} mineral

Test Cases
Errors in Estimated Temperature



- **Multicomponent geothermometry performed well, provided**
  - Number of minerals considered is limited (phase rule)
  - Controlling mineral assemblage is reasonably known
  - Loss of volatile constituents is considered
  - Loss of water is considered
- **Multicomponent geothermometry approach more accurate than conventional geothermometers**
- **Preliminary results suggest goal of achieving estimates of reservoir temperature to within±30°C is feasible**

Progress – Lab Experiments

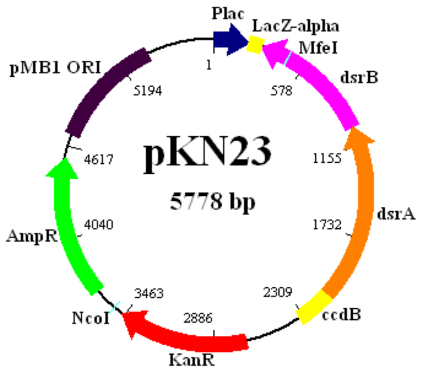
- Experimental research plan has been developed
  - Raft River Site
    - provide insight as to the appropriate mineral assemblages that should be considered in developing the inverse multivariate reaction-path geothermometer.
    - address the influence of "cooling" history on the composition of equilibrated reservoir fluids
  - Newberry Geothermal field
    - evaluate the ability of laboratory-scale experiments to simulate field-scale observations
  - Soda Springs
    - assess the impact sulfur metabolizing microbial communities could have on sulfur speciation and consequently on fluid chemistry

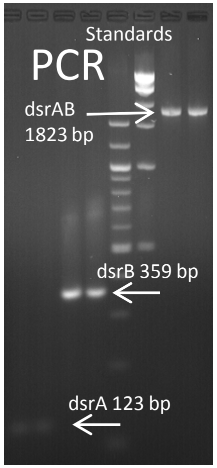
Utilizing genetic tools to assess sulfur cycling microbial activity

- S species prominent in geothermal systems
- Microbial S transformations alter pH, Eh and can dramatically alter water chemistry
- Quantifying genes specific to S cycling allows estimation of number of S transforming microbes in a sample and can be linked to activity

Progress to date

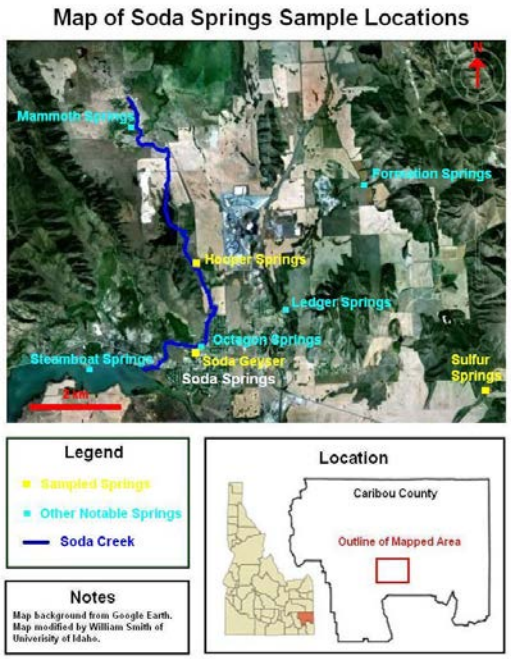
- Created a quantitative DNA standard (plasmid pKN23) containing genes specific to sulfate reducing organisms.
- Developed quantitative polymerase chain reaction (qPCR) assay for estimating gene abundance.
- Applied assay to samples from Soda Springs, ID, a blind geothermal system.

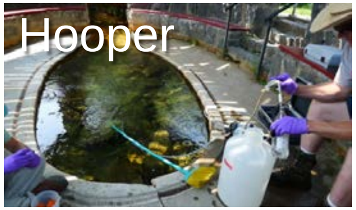




Construct of pKN23 plasmid standard (top), and results from PCR gel electrophoresis showing amplification of sulfate reducing genes *dsrA* and *dsrB* (bottom).

Progress – Microbiology





One of the genes specific to sulfate reducers

- Microorganisms, and sulfate reducers, present in all samples
- Sulfur Springs particularly high in biomass and sulfate reducers—*important role in modulating chemistry?*

	Cells (ml^{-1})	***dsrB*** **(ml^{-1})**
Geyser	9.3(3.1)E+4	3.1 (2.6)E+1
Hooper Springs	4.9(1.6)E+4	1.9(1.3)E+1
Sulfur Springs	8.5(3.4)E+7	9.0(3.4)E+5

Accomplishments, Results and Progress

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Develop sulfate-reduction gene assay	Completed sulfate-reduction gene assay technique	Sept. 2012
Develop prototype GTM	Completed conceptual approach, and prototype GTM, working on coupling Geochemists' Workbench and PEST	Jan. 2013
Publications	Presented two papers at Stanford Geothermal Workshop and one at AGU	Feb. 2013

- Simulation results of hypothetical geothermal systems and potential microbial influences on geothermometry chemical composition were presented at the Stanford Geothermal Workshop

Future Directions

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- Inverse Simulation
  - Complete coupling to inverse parameter estimation package
  - Compare against experimental results
- Laboratory Experiments
  - Begin laboratory experiments using Raft River mineral assemblage
- Microbial Activity
  - Develop additional assay techniques for microbial sulfur cycling
- Progress toward Commercialization
  - Use model to conduct calculations on samples collected by U.S. Geothermal, and from Newberry EGS demonstration site

Milestone or Go/No-Go	Status & Expected Completion Date
Develop sulfur-oxidation assay	Started, Jan. 2014
Evaluate effectiveness of GTM for known geothermal systems	Started, Jan. 2014
Determine utility of gene assays for quantifying alteration of geothermal fluids	Future, Jan. 2015
Evaluate effectiveness of GTM in EGS and exploration settings	Future, Jan. 2015

Summary

- Inverse Modeling of Alteration Processes
  - Developed a broadly applicable conceptual model that can be implemented using commercial software
  - Implemented forward simulation, developed a numerical approach for optimizing inverse calculations
  - Demonstrated potential for improved accuracy of temperature predictions
  - Developing automated link between parameter estimation package (PEST) and Geochemists Workbench
- Laboratory Experiments
  - Completed experiment plan
- Evaluation of Microbiological Effects
  - Developed qPCR assays that can be applied to geothermal systems
- Progress Towards Commercialization
  - Developed collaborations with three geothermal companies and with LBNL

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
1/1/12	1/1/15	1/1/12	1/1/15

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$995,000	$0	$422,000	$472,000	$426,500	$523,000

- Project is on schedule.
- Project is 50K overspent
  - Project management rebaselined research activities to complement those of LBNL
  - Implemented a more complete geothermometry inverse modeling method
  - Additional efforts were required to present results at Stanford Workshop
  - Milestones expected to be completed on schedule and in budget
- Initiated studies at:
  - Newberry EGS , Soda Springs, and Raft River sites

Thank you