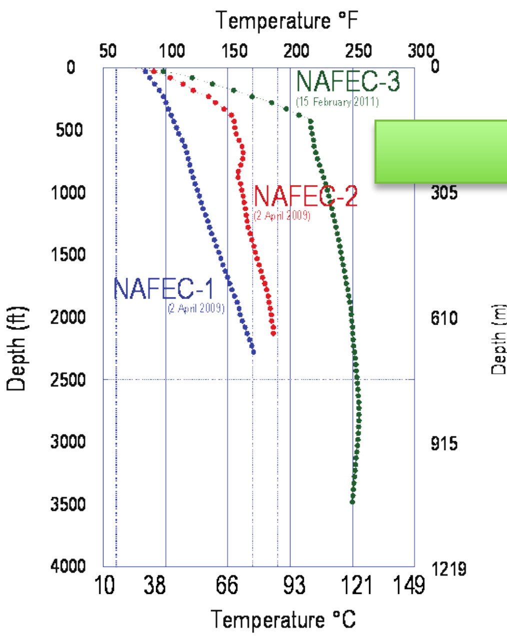
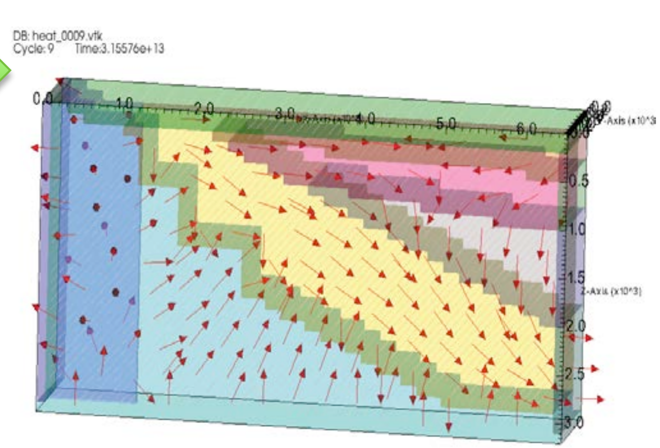
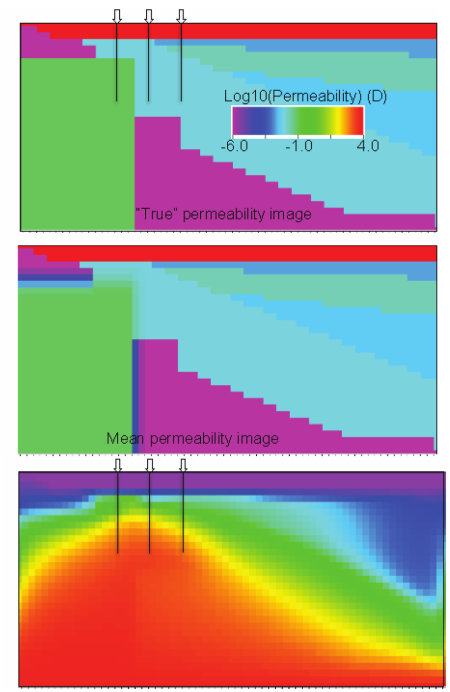
Subsurface permeability and temperatures



Data



Flow models



Stochastic Joint Inversion for Integrated Data Interpretation in Geothermal Exploration

Project Officer: Eric Hass

Total Project Funding:
$890,000

April 24, 2013

Mandatory slide

Principal Investigator: Robert J. Mellors
Lawrence Livermore National Laboratory

Track 1: Geophysics

Objectives:

- *Challenges, barriers, knowledge gaps, or problems*: **Improve interpretation of geothermal prospects by identifying useful temperature and flow fields at depth.**
- *Impact costs, performance, applications, markets, or other factors in geothermal energy development:* **Reduce costs in geothermal exploration and prospect evaluation by decreasing number of wells and improving risk assessment.**
- *Innovation:*
  - Joint stochastic inversion of multiple data sets with associated error estimate
  - Include fluid and heat flow modeling with geophysical constraints.
  - Test use of reduced order models and value of information.
- Relevance to GTP goals
  - Lower risks and costs of development and exploration
  - Lower levelized cost of electricity (LCOE) to 6 cents/kWh by 2020 by reducing exploration costs
  - Accelerate development of 30 GWe of undiscovered hydrothermal resources

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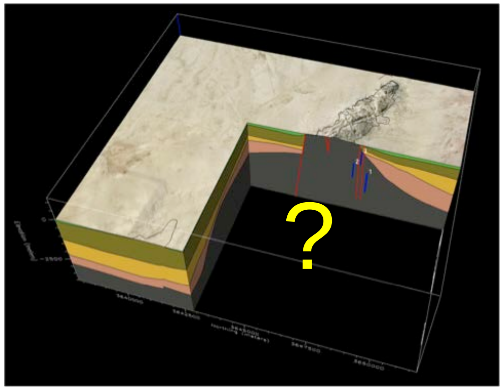
Relevance/Impact of Research



Produce better and more reliable predictive capabilities for fluid flow and temperature prior to significant drilling.

Use varied geophysical data combined with a flow model to reduce and predict uncertainties.

- Anticipated uses:
  - Hypothesis testing, risk assessment.
  - Identify likely areas for test production well
  - Identify key areas that, with additional datasets, might reduce uncertainty.
  - Compare a set of prospects among a portfolio.

Scientific/Technical Approach

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- General approach
  - Assemble multiple geophysical, thermal, and hydrologic data.
  - Integrate all data using joint inversion to constrain subsurface permeability and structure.
  - Find suite of models that match the data with associated likelihoods.
- Use specific prospect (Superstition Mountain) as initial test case
  - Data: Borehole temperature profiles, surface heat flow, MT survey
  - Markov Chain Monte Carlo staged joint inversion
  - 3D Thermal-hydrologic fluid flow (NUFT).
  - *a priori structural* model
- Team expertise (A. Ramirez, X. Yang, A. Tompson, M. Chen, J. Wagoner).
- Similar to Jardani and Revil, 2009; Chen et al., 2012; Ramirez et al., 2012

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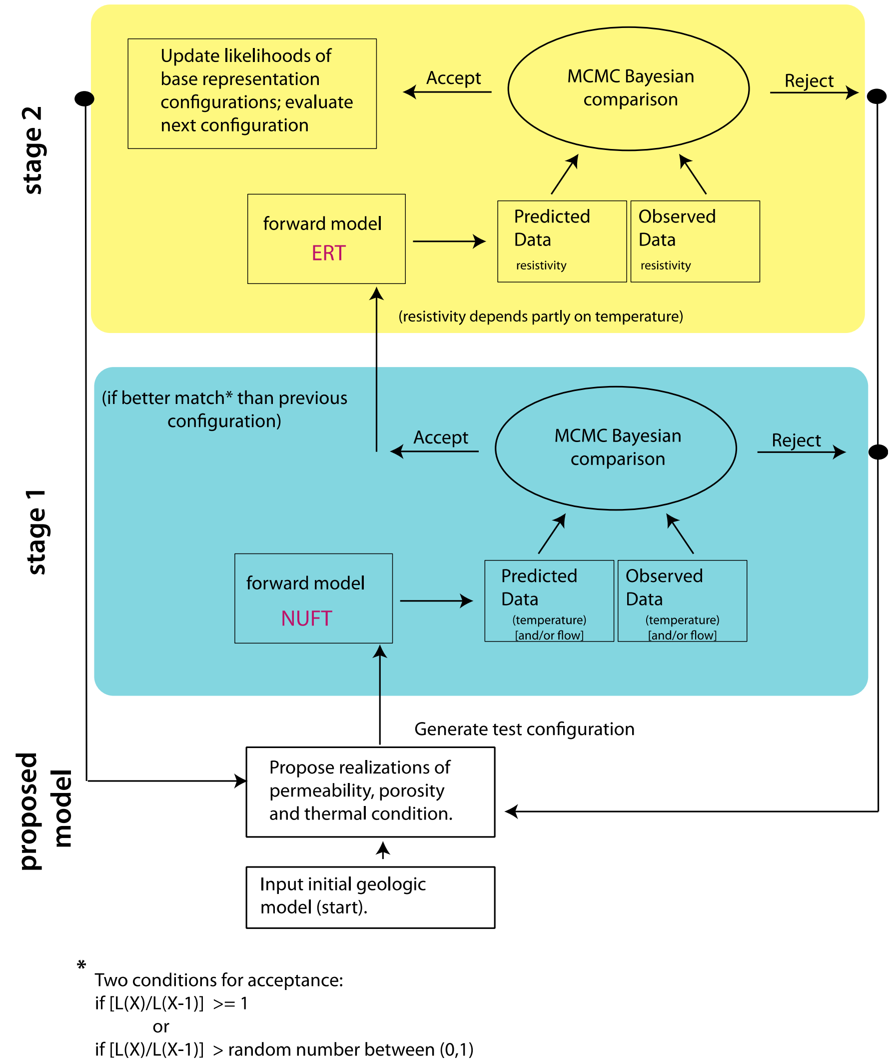
Scientific/Technical Approach

- Markov Chain Monte Carlo
- Efficient, flexible algorithm with Bayesian inference
- Incorporate multiple, disparate data sets
- Test thousands of possible models
- Cascaded stages of data sets to achieve joint inversion
- Produces a ranked range of possible solutions with associated uncertainty

1) Initial realization of model
2) Solve fluid and heat flow for equilibrium using NUFT; check fit to data
3) If acceptable, calculate resistivity and check fit.
If acceptable, save answer



Scientific/Technical Approach

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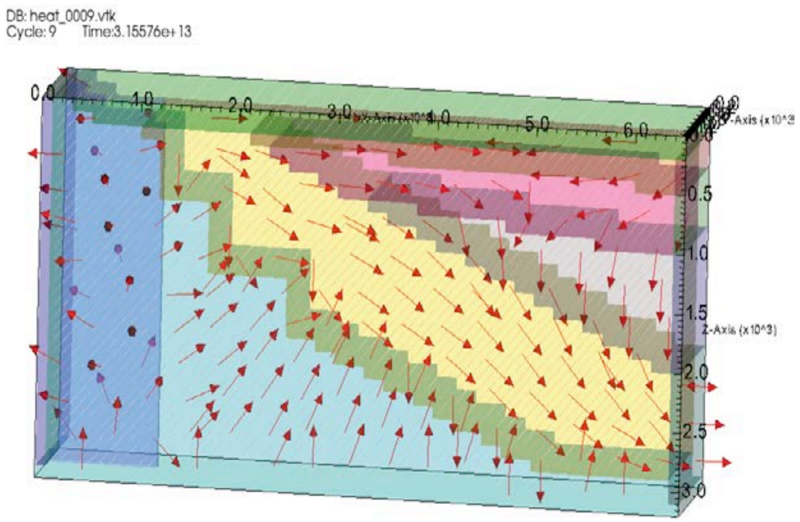
3D Thermal-hydrologic fluid flow (NUFT)

- 3D multi-phase fluid and thermal flow model
- Fixed temperatures of 27 at top and 150 C at bottom in all simulations
- Hydrostatic pressures defined at SW (slightly higher) and NE ends in all simulations

3D Resistivity code (Multi-bh)

- 3D finite difference resistivity code with rectangular elements
- Mesh for resistivity extends outside of NUFT boundaries
- Stage two of inversion

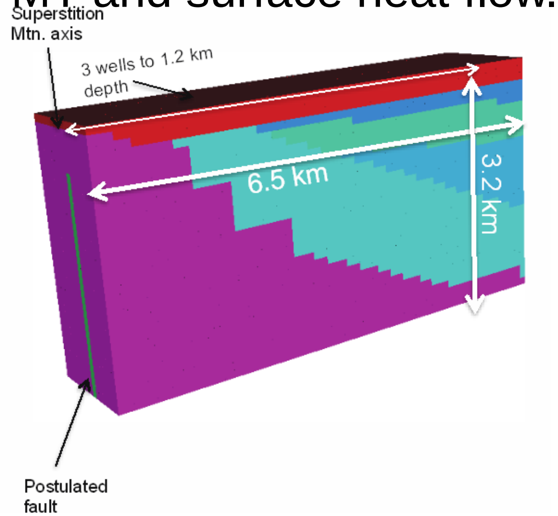
MT: adapting 2D code (in progress)

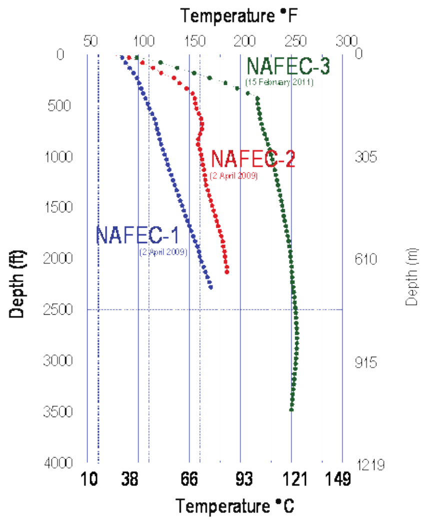


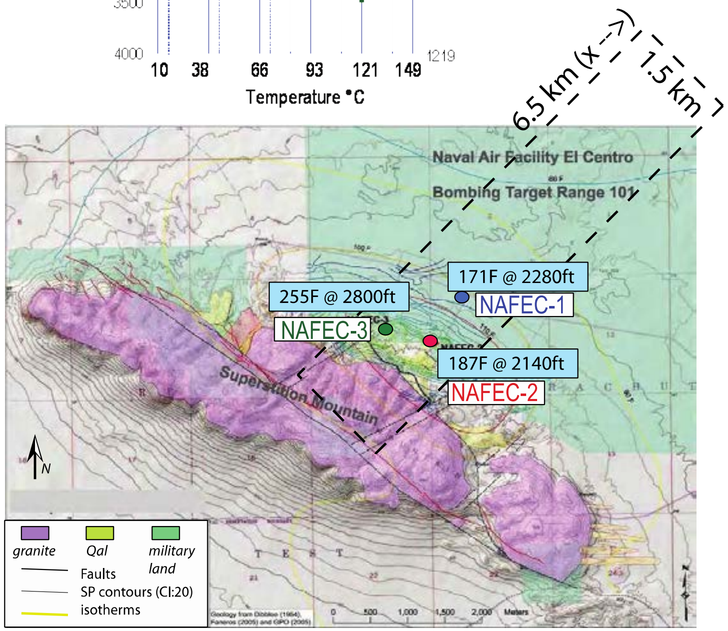
- A NUFT simulation is stage one of the inversion.
- Each model realization is defined by sampling fault dimensions, permeability, and other parameters from a-priori distributions.
- Inversion uses thousands of flow model realizations run to equilibrium and compared with observed data.
- Accepted models progress to stage two, where resistivity is calculated and compared.
- All models that pass both stages are saved as results and sorted by likelihood.

Application to prospect:

- Superstition Mountain in western Salton trough; under investigation by Navy geothermal program.
- Created 3D representation based on known and inferred structure. Includes highly permeable zone as possible fault.
- Use commercial modeling package (Earthvision) to generate mesh.
- Borehole thermal measurements available; also MT and surface heat flow.



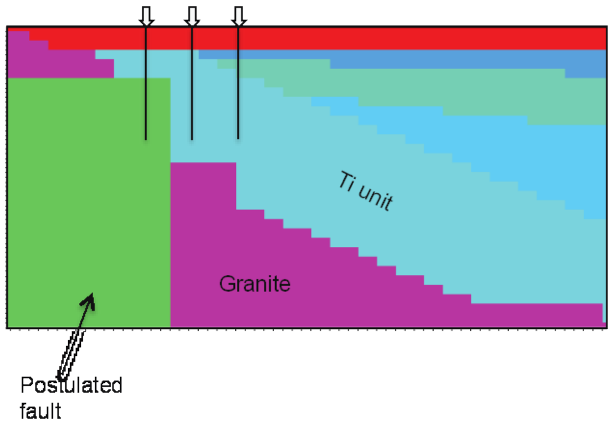


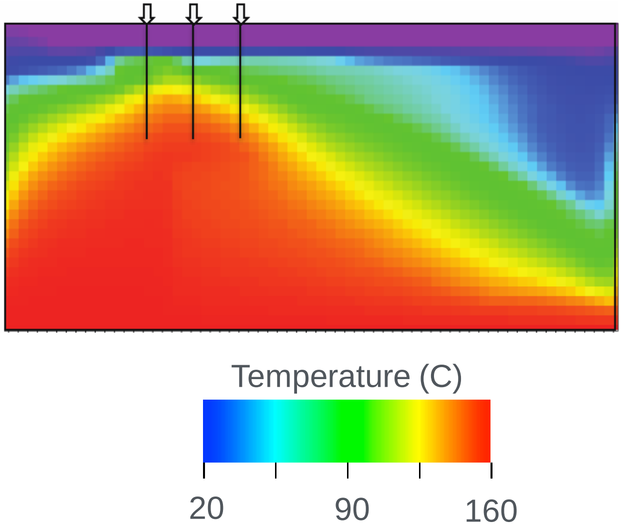


Test inversion algorithm with known (synthetic) data set [borehole measurements and surface resistivity].

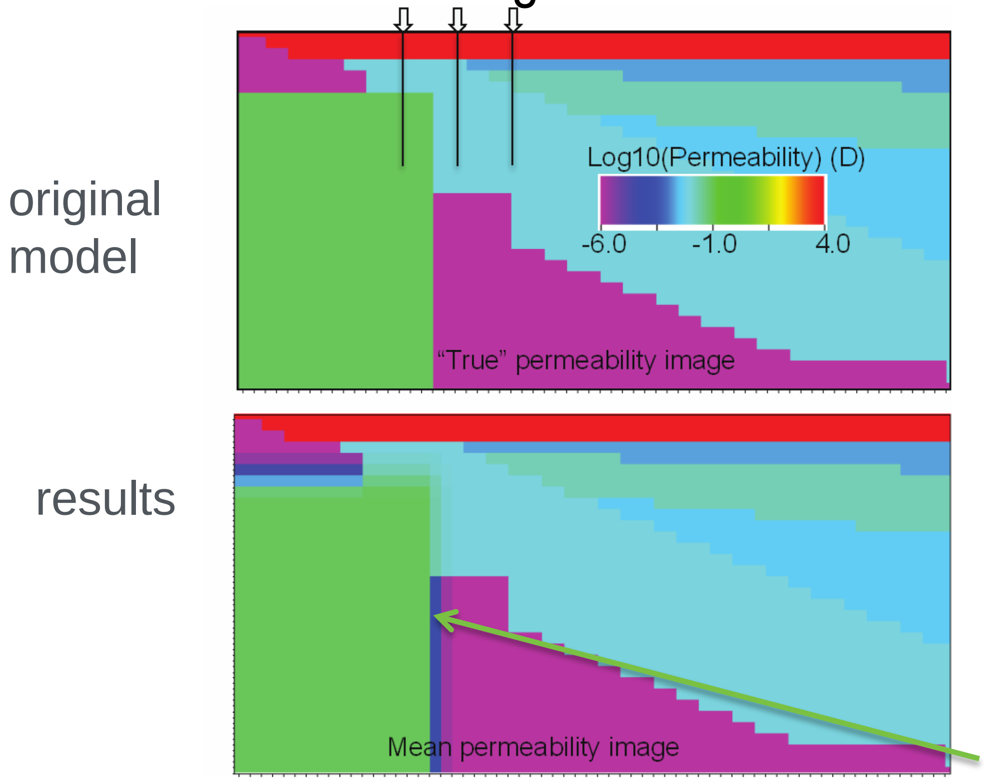
- Objective of inversion is to find models that match the observed temperature profile at each well along with geophysical data.
- 1000's of model realizations are tested.
- Both layer permeability and geometry of highly permeable zone (shown as green) varied for each realization.
- Choices of permeability and structure are drawn from a defined probability distribution; search guided by likelihood.
- The top 10% models are used to define the model and the estimated error.
- 5 Markov chains and approximately 5000 iterations.

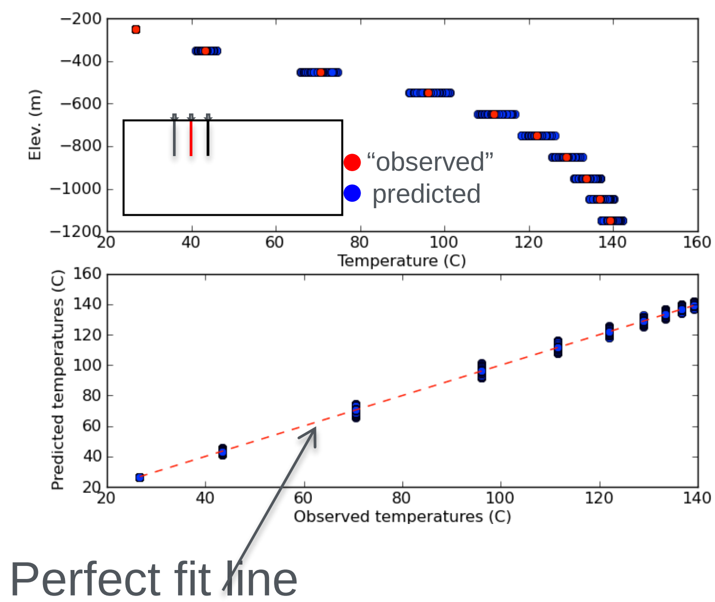
Results: Inversion matched original model used to generate synthetic data.





Cross section through 3D model





Represents fault size variation within the top 10% models

Original model, which included a highly permeable zone (green), was used to generate synthetic datasets; inversion of synthetic data yielded a set of possible models with variable geometries and permeabilities. The results show the mean permeability for the top 10% of the models. The 'fuzzy' area around the green represents the variance in fault zone geometry of the top 10% models. Models without a highly permeable zone did not produce an acceptable fit to the data.

Accomplishments, Results and Progress

- Accomplishments/Progress to date.
  - Procedure developed to create 3D model prospect; applied to Superstition Mountain.
  - Staged inversion framework constructed.
  - Forward codes (thermal/fluid and resistivity) tested and incorporated into inversion code with samplers.
  - Inversion conducted successfully (reproduces model) on synthetic dataset based on actual prospect.
  - Code capable of running 1000’s of realizations within a reasonable time (<20 hours).
  - Successfully tested inversion of borehole temperature data and can distinguish between two different hypothesis.
  - MT code adapted to inversion (in progress)

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
FY12. Develop and test forward codes (fluid flow; resistivity)	Completed	9/30/12
FY13 Link forward fluid flow/resistivity codes with inversion	Completed	3/01/13

Future Directions

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- Future plans (FY2014)
  - Complete majority of code development by Sept 2013.
  - Validate with known data set and results
  - Test alternate data sets and collaborating/transitioning with industry use.
  - Publication in peer-reviewed journal.
  - Test performance with more variables (e.g. boundary conditions)
  - Test reduced order models to improve performance and value of information to aid decision making.
  - Investigate adding variations in fluid chemistry to vary fluid resistivity and constraint on flow model.

Milestone or Go/No-Go	Status & Expected Completion Date
FY 13 inversion test; recover fluid flow and temperature distributions with synthetic data	Completed [without MT] scheduled 9/30/13
FY 13 add MT forward model	35% scheduled 9/30/13
FY 14 invert field data	50 % scheduled 3/30/13
FY 14 Invert alternate prospect(s)	scheduled 9/30/14

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Mandatory Summary Slide

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- Key points
  - Provide automated method to evaluate prospects and provide errors estimates; decrease evaluation time and reduce number of wells.
  - Use MCMC inversion combined hydrothermal and geophysical forward modeling codes to constrain geothermal prospect.
  - Flexible and robust; yields error estimate based on top 10% of acceptable models.
  - Inversion tested with synthetic data set (temperature, resistivity) based on an actual prospect and reproduces original model.
  - Initial tests with real data.
  - Need to add MT forward model and possibly gravity.
  - Will test on additional data sets in future in collaboration with industry.
  - Will investigate ways to improve efficiency such as reduced order models and constraints such as fluid chemistry.
  - On budget and on schedule.

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Data sharing

- All original data is owned by other groups.
- We plan to release our 3D models and results and submit to the geothermal database, as permitted by the owners of the data.
- Publications, unless under copyright, will be submitted to the geothermal database.

- We appreciate assistance from Steven Bjornstad and Andrew Sabin of the U.S. Navy geothermal program for providing access to data and insight on the Superstition Mountain prospect.

Optional slide- keep to one slide

Project Management

	FY2012				FY2013				FY2014			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1 Forward models			M*									
Task 2 Inversion developm ent						M*		M				
Task 3 Joint Inversion								M				M
Task 4 Managem ent												

* Denotes completed milestone

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
10/1/11	9/30/14	1/1/12	9/30/14

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$890	$0	$375	$373	$445	$517

Management activities

- Team at LLNL; periodic team meetings.
- Coordination by R. Mellors
- Reporting by R. Mellors

- On schedule with budget (within 5% anticipated) and on track with technical progress.
- Next step are interactions and engagement with industry to try new datasets and to develop into useful product.

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