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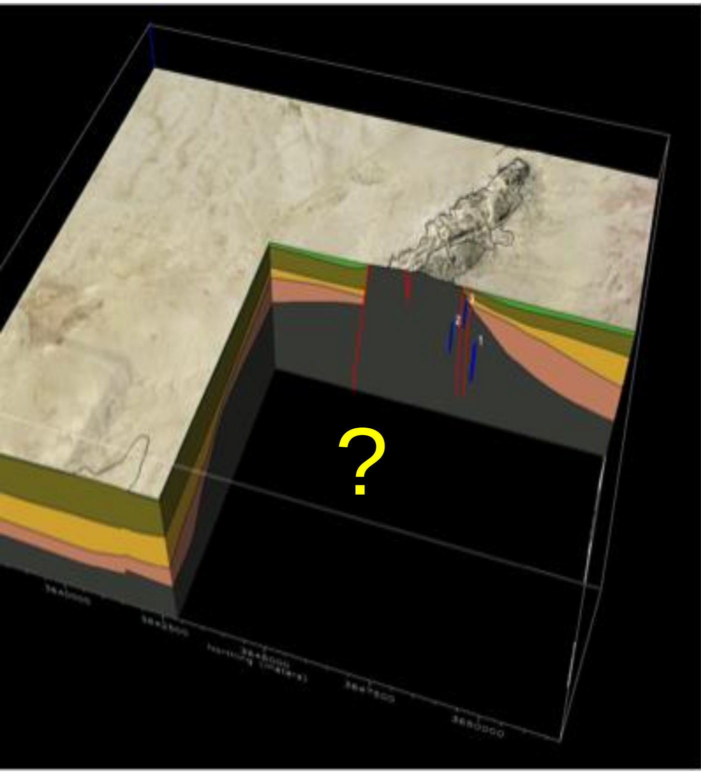

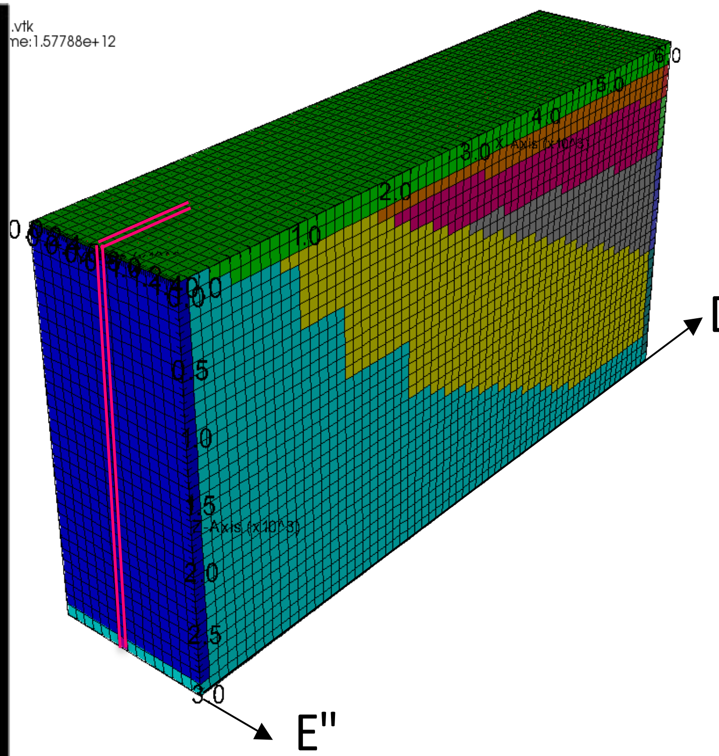

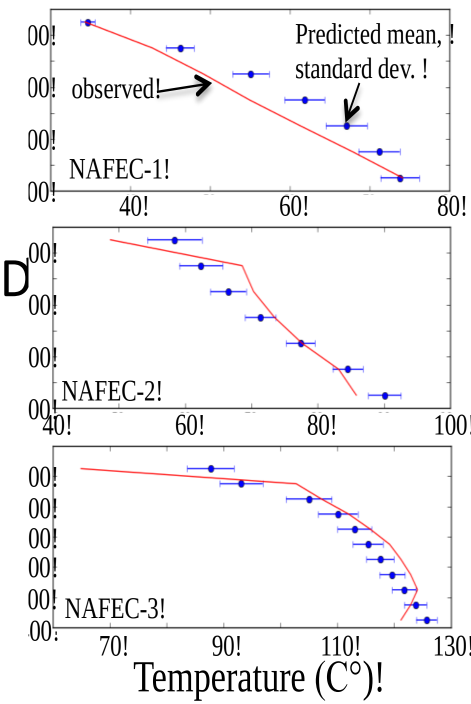

Stochastic Joint Inversion for Integrated Data Interpretation in Geothermal Exploration

Project Officer: Eric Hass

Total Project Funding: $930,000

May 11, 2015

Mandatory slide

Principal Investigator (always include)

Presenter Name (if not the PI)

Organization

HRC

Relevance/Impact of Research

Improve interpretation of geothermal prospects

- Improve success rate in finding economic resources and provide realistic risk estimates
- 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, heat flow, and resistivity (DC and MT) modeling into inversion
  - Used reduced order models in inversion to reduce computational effort and to evaluate sensitivity.
- Relevance to GTP goals
  - **Lower risks and costs of development and exploration**
  - Lower levelized cost of electricity (LCOE).
  - Accelerate development of undiscovered hydrothermal resources

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Scientific/Technical Approach

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1. Develop initial conceptual model (geology, hydrology, and geophysics) of prospect.
2. Define questions to be answered (e.g. hypotheses regarding flow paths, flow rates, or temperatures; optimal pumping locations) and parameters to be inverted (e.g. geometry, permeability)
3. Invert using Markov Chain Monte Carlo (MCMC) methodology and full numerical approach (THMC).
4. Use best solutions (e.g. top 10%) to answer question.
5. Utilize sensitivity analysis and reduced order models to better guide uncertainty assessments and streamline computational costs

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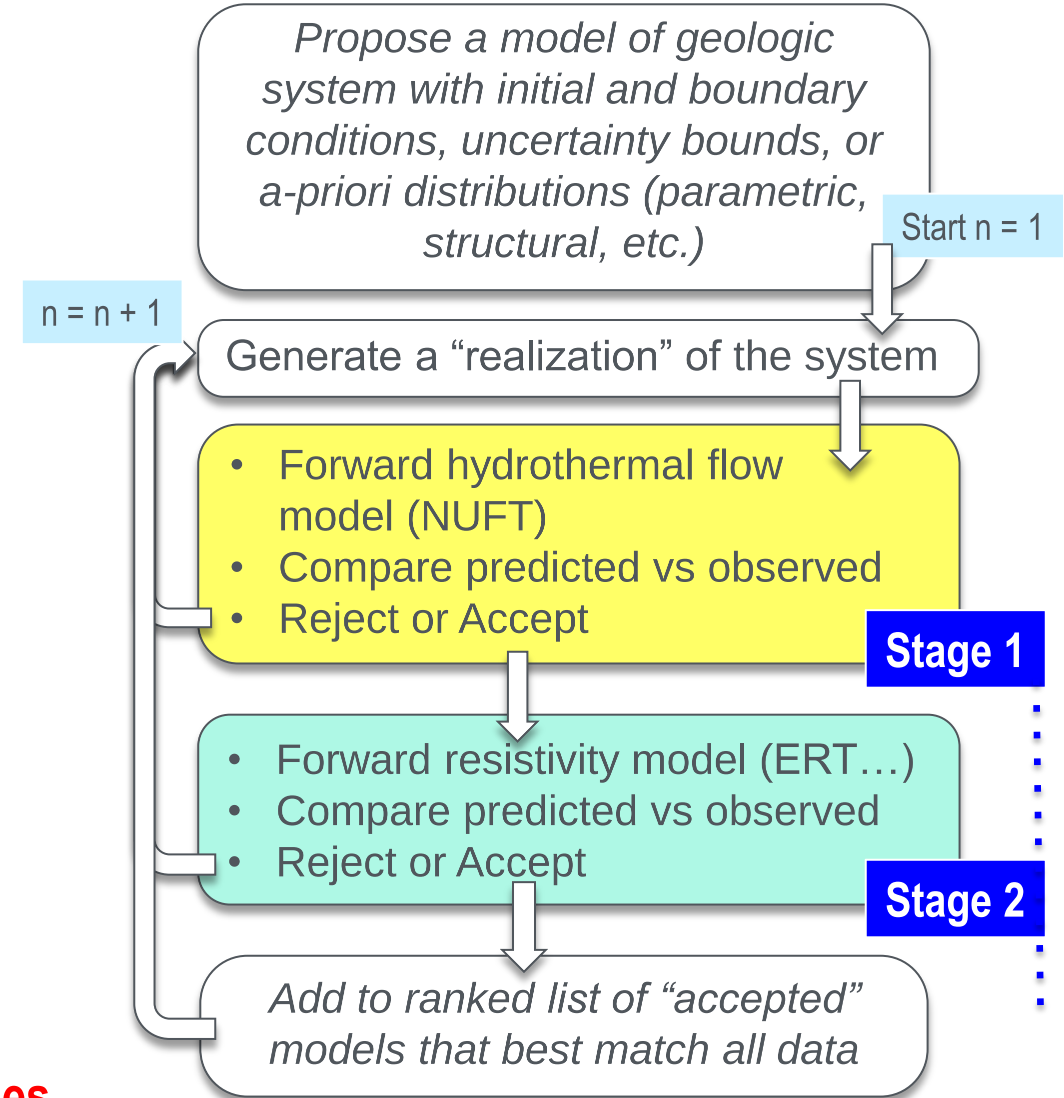
Scientific/Technical Approach

Basic Inversion Methodology

- Efficient, flexible algorithm with Bayesian inference
- Incorporate multiple, disparate data sets
- Test thousands of possible models, n = 1, 2, …. 10,000, ... N_{max}
- Cascaded stages of data sets to achieve joint inversion
- Produces a range of possible solutions with associated uncertainty
- "Acceptance" or "Rejection" based upon comparison of simulated and measured data
- Python framework with separate modules for THMC model and geophysics.
- Typically, 4 MCMC chains and at least 5,000 realizations per chain.
- Tested on synthetic data and then real data.



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Scientific/Technical Approach

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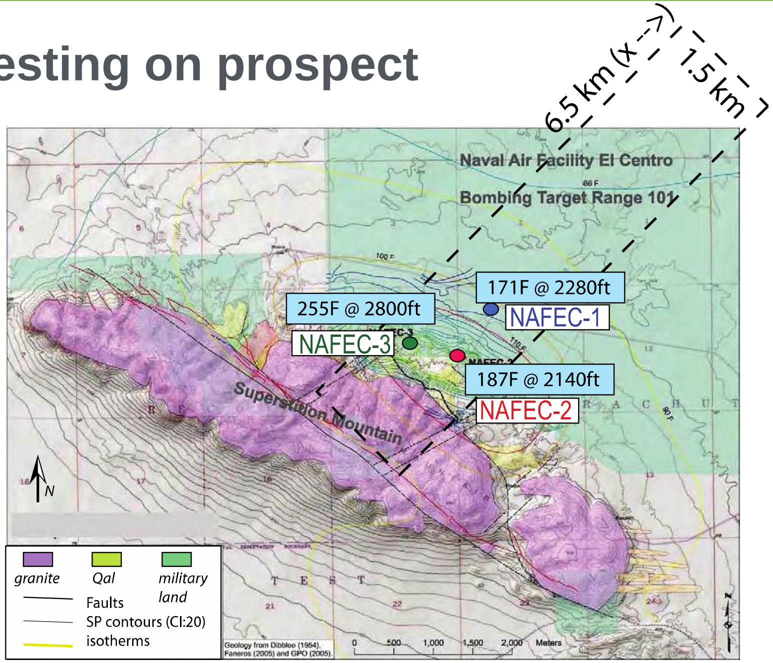
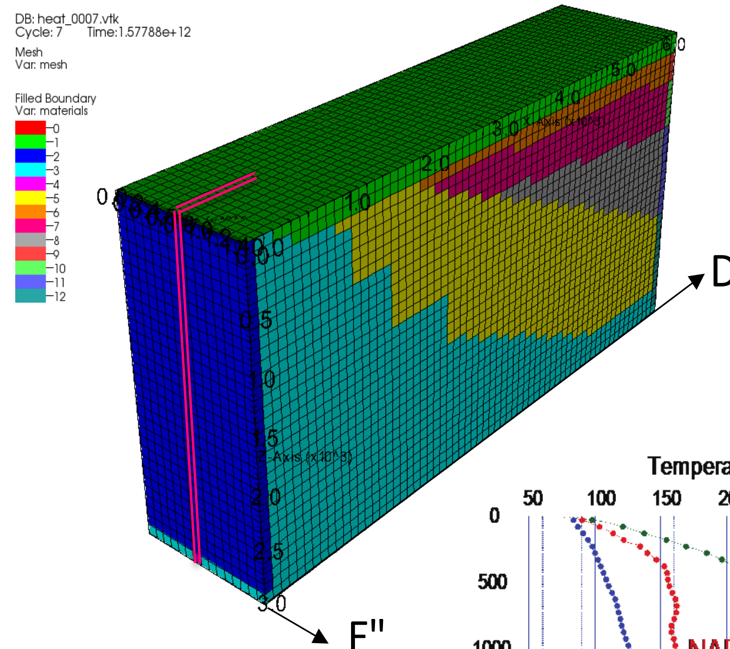
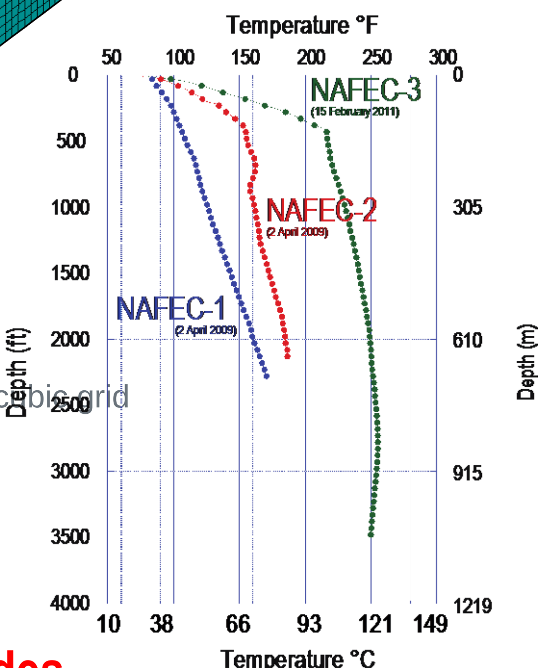
Testing on prospect





100-m cubic grid



- U.S. Navy geothermal prospect at Superstition Mtn
- Initial geological model developed in geological modeling program Earthvision.
- Slightly different mesh needed for THMC and MT.
- Want to match temperature profiles at three wells and MT.
- Allow length and width of postulated fault to vary and permeability in key layers.
- Use THMC code NUFT and MT code.

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Scientific/Technical Approach

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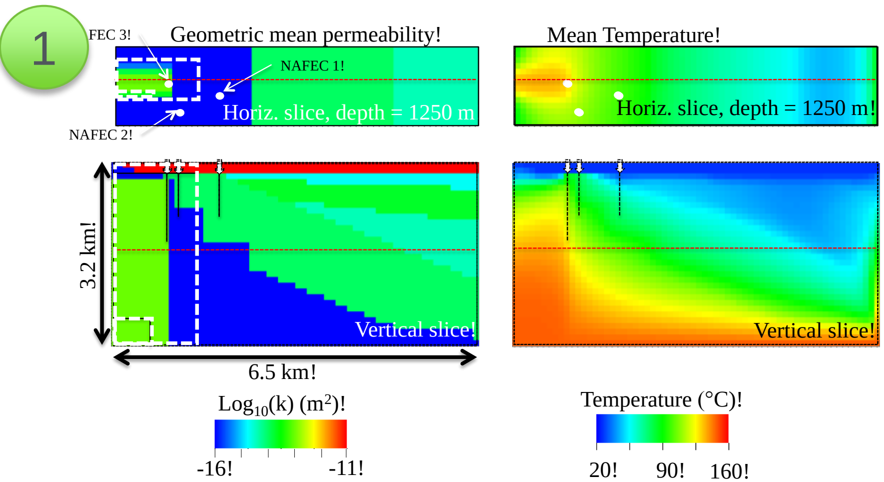
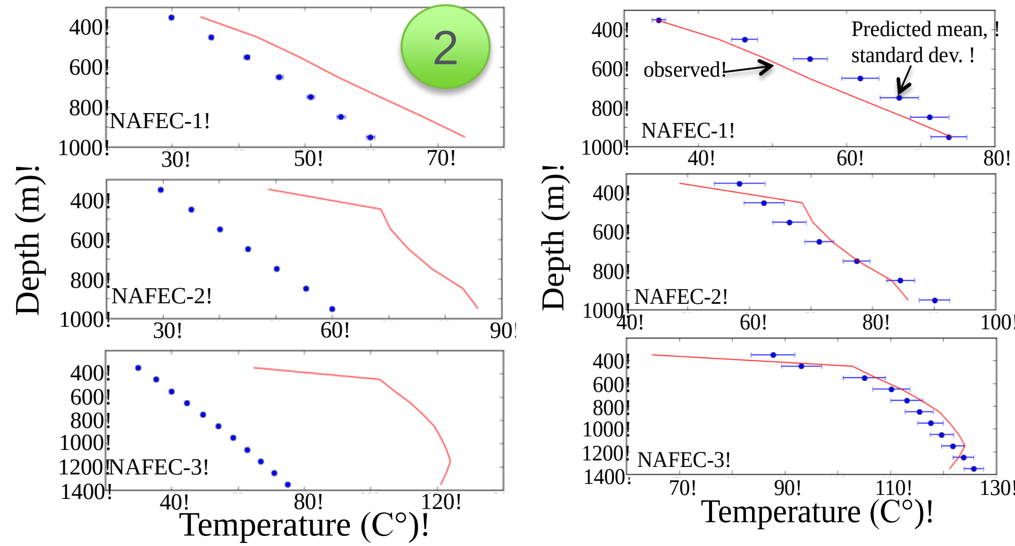


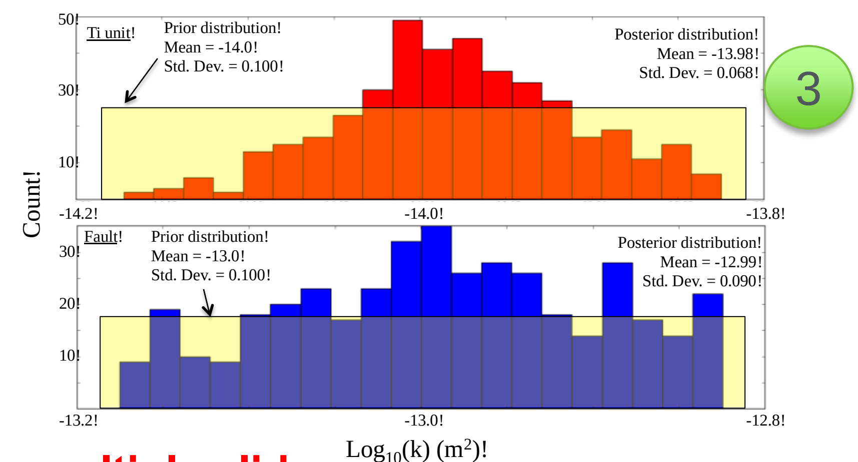


Without fault in analysis

With fault in analysis

Testing on prospect: results

1) Inversion yields 1000’s models; here we show the mean of the top 10% with permeability on left and temperature on the right. This model run has a high-permeability fault allowed to vary in size. Initial configuration shown by dashed lines.
2) If we run without a high-permeability fault, a suitable solution is not found (left). With a fault, a good fit to the data is found. MT in current implementation does not strongly constrain results.
3) The results yield posterior estimates of the distributions (shown as red or blue). Prior distribution is shown in yellow.



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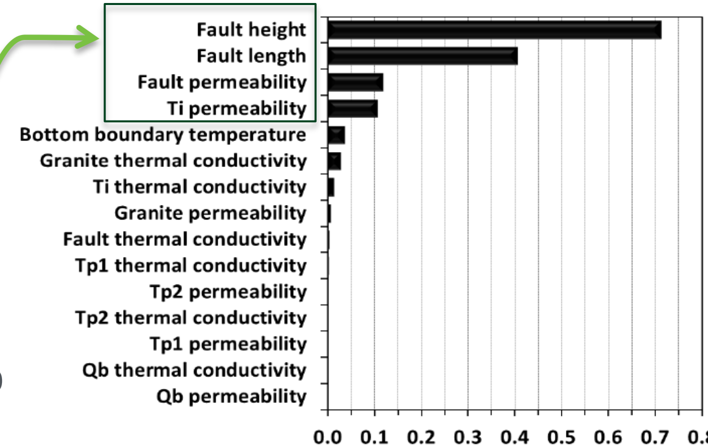
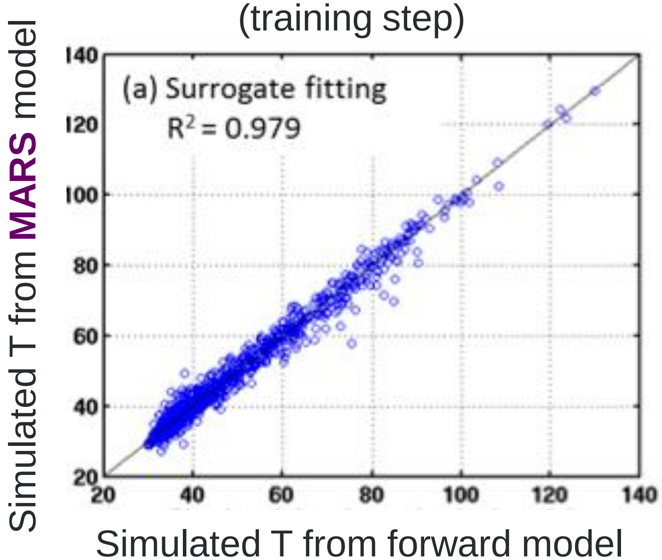
Surrogate Models and Sensitivity Analyses

- Forward (THMC) model runs can represent a significant computational burden, despite simplifications used for computational parsimony
- In addition, important parameters and variables and their uncertainties may be difficult to recognize or prioritize in advance:
- **Sensitivity Analyses** can be conducted beforehand to identify and rank important design variables, as an aid to expert judgment
- **Surrogate or "Lower Order" Models** can be developed and trained to efficiently approximate forward model solutions for both *Sensitivity Analyses* and *forward simulations in the MCMC loops*.
- We tested a Multivariate Adaptive Regressive Spline technique **(MARS)** to approximate the response of a high-fidelity model as a function of key variables.
- Much faster (100's of times) than running full numerical model with good accuracy.
- **Not in original SOPO, but successful for both sensitivity and forward model runs**
- See *Chen et al*., 2014, 2015.



Sobol' total sensitivity index

(training step)



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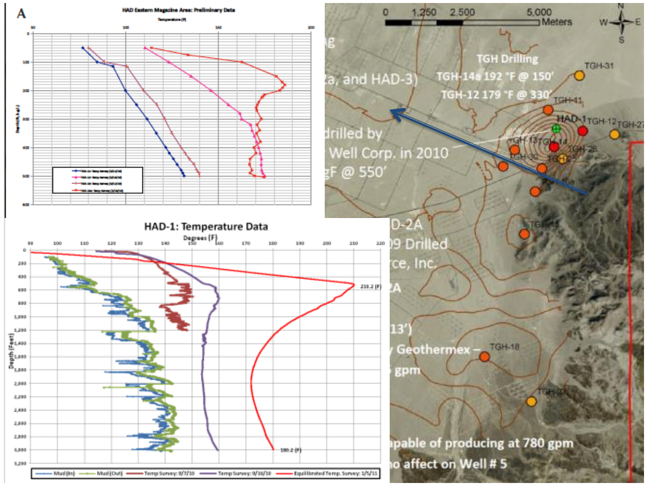
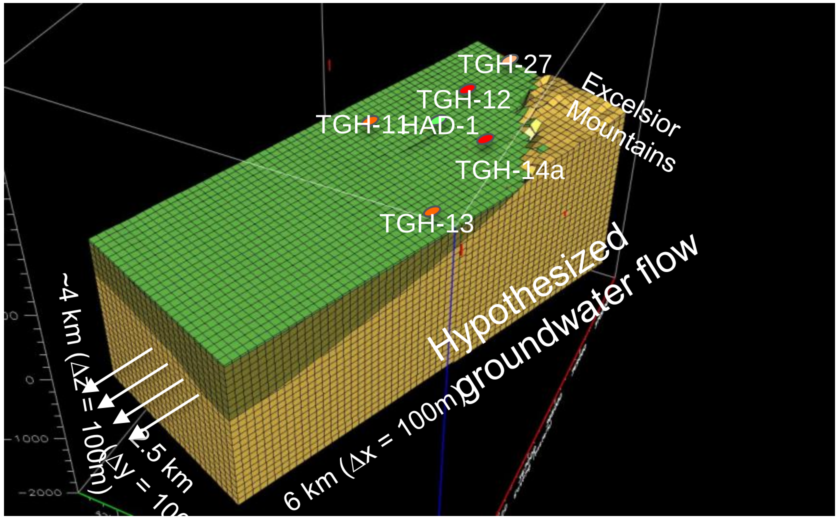
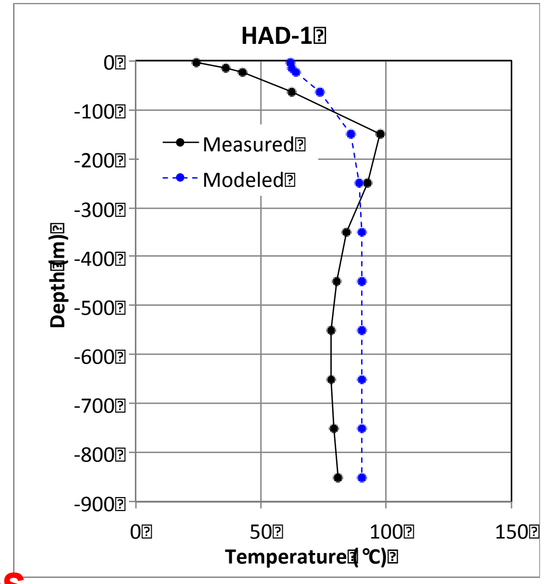




Testing on second prospect

- After code development and extensive testing on Superstition Mountain, we moved to a different prospect at Hawthorne, NV
- Test adaptability of code and framework.
- Validate results with flow tests.
- Modifications were more challenging than expected but complete now.
  - Required minor changes to code as well as input files.
  - Uses Earthvision input mesh
- Initial runs show reasonable match to temperature profiles.



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Accomplishments, Results and Progress

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- A stochastic joint inversion has been developed that include both fluid flow, heat flow, and geophysical information.
  - The stochastic inversion with THMC models and geophysics have been developed by a few other groups.
  - We do not know of other groups who also include reduced order models as an option to the stochastic inversion.
  - All proposed milestones were accomplished and on time except for the last milestone, which was delayed by 4 months.
  - A set of papers and conference proceedings have been published as part of this work.
  - Technical challenges included meshing the area to accommodate all algorithms a and assembling a team with the required expertise in numerical flow models, geophysics, geology, inversion, and geothermal.
- The successful inversion and the adaptation of the reduced order models for an actual prospect shows that this is an effective means of modeling prospects.

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Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 1: Forward models		
T1.A *Develop and test forward modeling codes*	Complete (THMC, DC res.)	**9/30/12**
T1.B *Add additional data type (likely MT or gravity).*	Complete. MT added.	**9/30/15**
Task 2 Inversion development		
T2.A *Incorporate forward codes into stochastic inversion*	Complete.	**3/30/13**
T2. B *Invert synthetic model*	Complete.	**9/30/13**
T3 Joint Inversion		
T3.A *Invert field data*	Complete. (Superstition Mtn)	**3/3/14**
T3.B *Invert data from a different target area.*	Complete.(Hawthorne)	**3/15/15**
Task 4. Reporting and publications		
Required reporting	Ongoing [final report].	
External (conferences and peer-reviewed publications).	2 peer-reviewed; 6 conferences.	

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Future Directions

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- We have developed a stochastic joint inversion and applied it to two prospects.
  - All technical milestones complete.
  - Added additional work using reduced order models.
  - Project will be complete on submission of final report (6/30/15).
  - We will seek ways to transition the technology to be usable by industry

Milestone or Go/No-Go	Status & Expected Completion Date
Submission of final report	In progress; 6/30/15
Additional peer-review paper submitted	In progress; 6/30/15

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Mandatory Summary Slide

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- A stochastic inversion has been developed to match temperature and geophysical data.
- Both geometry and permeability can be varies within a 3D volumes.
- Tested at two prospects, Superstition Mtn and Hawthorne.
- Added capability to develop reduced order models.
  - This achieved greatly reduced computational effort.
  - Sensitivity of variable also conducted.

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Additional Information

Peer-reviewed

- Chen, M., A. F. B. Tompson, R. J. Mellors, and A. Osman, **2015,** An efficient optimization of well placement and control for a geothermal prospect under geological uncertainty, Applied Energy Volume: 137 Pages: 352-363. DOI: 10.1016/j.apenergy.2014.10.036
- Chen, M., A. F. B. Tompson, R. J. Mellors, A. L. Ramirez, K. M. Dyer, X. Yang, and J. L. Wagoner, **2014**, An efficient Bayesian inversion of a geothermal prospect using a multivariate adaptive regression spline method, *Applied Energy*, (2014), pp. 619-627, DOI information: 10.1016/j.apenergy.2014.09.063

Abstracts and proceedings

- Mellors, R. J., A. F. B. Tompson, X. Yang, Mi. Chen, A. Ramirez, and J. Wagoner, **2015**, Stochastic Joint Inversion Modeling Algorithm of Geothermal Prospects , Fourtieth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 26-28.
- Tompson, A.F.B., R. J. Mellors, A. Ramirez, M. Chen, K. Dyer, X. Yang, J. Wagoner, and W. Trainor-Guitton, **2014**, Use of a Stochastic Joint Inversion Modeling Algorithm to Develop a Hydrothermal Flow Model at a Geothermal Prospect, AGU Fall meeting, San Francisco, CA, 15-19 dec
- Mellors, R. J., A. Tompson, K. Dyer, X. Yang, M. Chen, W. Trainor-Guitton, and A. Ramiriez, **2014**, Joint Inversion Modeling Algorithm of Geothermal Prospects, Proceedings of the 39th Stanford Geothermal Workshop, Feb. 24-26, Stanford, CA.
- Tompson, A.F.B., R. J. Mellors, A. Ramirez, M. Chen, K. Dyer, X. Yang, J. Wagoner, and W. Trainor-Guitton, **2013**, *Evaluation of a geothermal prospect using a stochastic joint inversion modeling procedure*, Geothermal Research Council, Sept. 29-Oct 2.
- Mellors, R. J., A. Ramirez, A. Tompson, M. Chen, X. Yang, K. Dyer, J. Wagoner, W. Foxall, and W. Trainor-Guitton, **2013**, *Stochastic Joint Inversion of a Geothermal Prospect*, Thirty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13.
- Ramirez, A. R. J. Mellors, A. F. Tompson, Mi. Chen; K. Dyer, J. L. Wagoner, X. Yang, W. Foxall, W. J. Trainor Guitton, **2012,** *Stochastic Joint Inversion Of A Geothermal Prospect*, V13A-2819, 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 Dec.

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