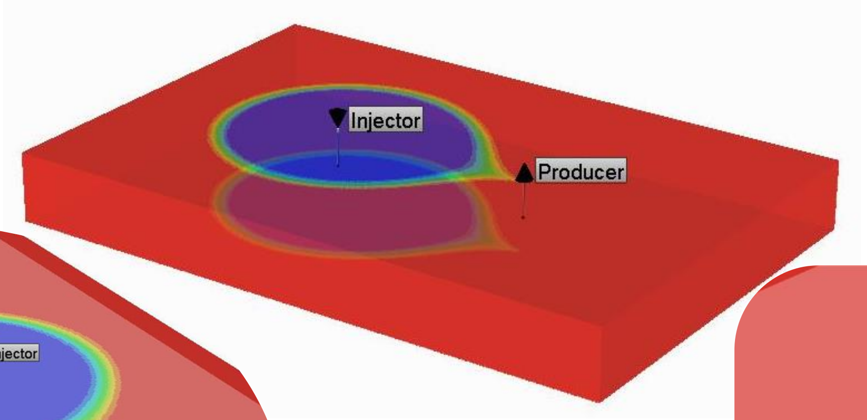

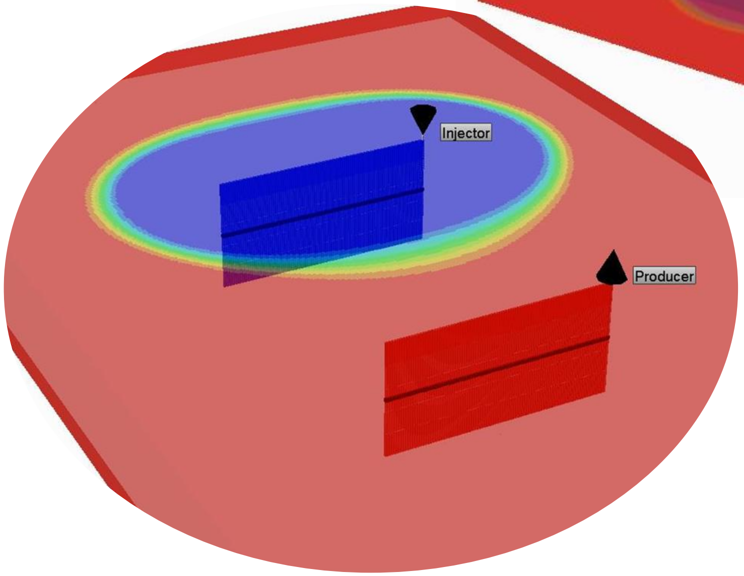

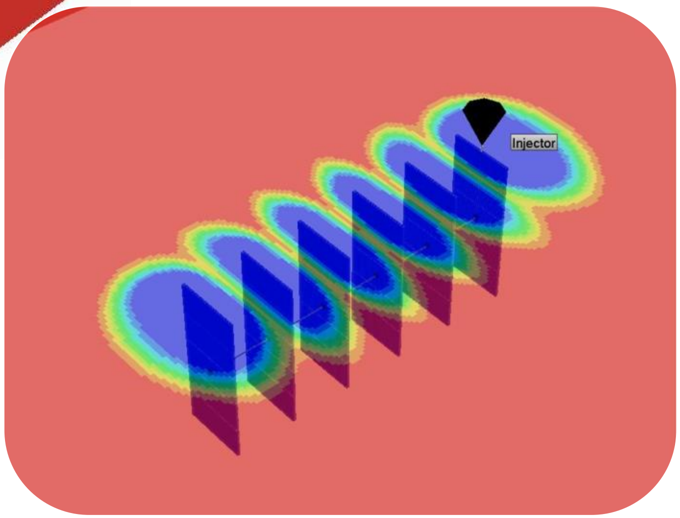

SURGE: Sedimentary Geothermal Feasibility Study

Project Officer: Eric Hass
Total Project Funding: $400k
May 11, 2015

Chad Augustine, NREL
Luis Zerpa, CSM
Presenter: Augustine and Zerpa

HRC: Reservoir Fracture Characterization & Fluid Imaging

Relevance/Impact of Research

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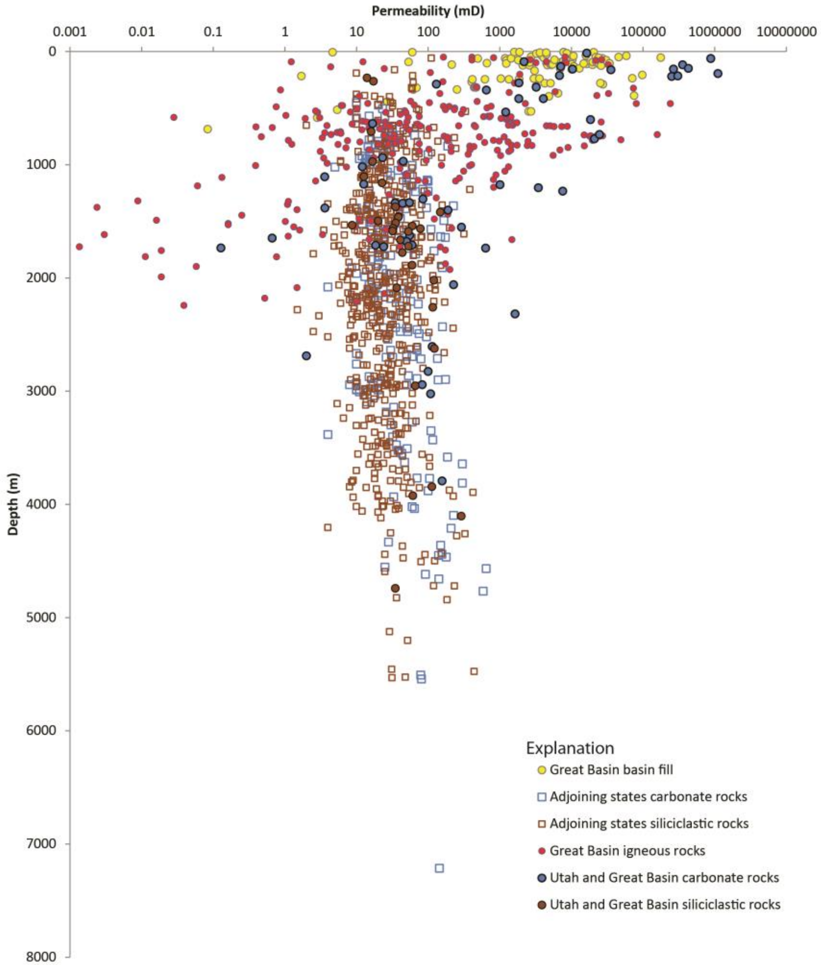
Objectives

Sedimentary geothermal: rely on natural matrix permeability of formation to circulate fluid through reservoir to recover thermal energy

- Heat recovery dominated by convective flow of fluid through rock matrix (not conductive flow of heat through rock to fracture)
- Requires highly-permeable sedimentary formations at depth
- However, permeability tends to decrease with depth (while temperature increases)



Permeability vs. depth for different rock lithologies in the Great Basin and adjoining regions (Kirby, 2012)

Objectives

Analyze feasibility of commercial geothermal projects from a sedimentary reservoir with low permeability that requires well productivity enhancement

- Use reservoir modeling to assess whether:
    1. the sedimentary formation can be modified using reservoir enhancement techniques, such as hydraulic fracturing, and/or long-reach horizontal completions, to increase well productivity to commercial levels, and
    2. to predict the thermal evolution and lifetime of the reservoir
- Evaluate well productivity enhancement options and determine the techniques and technologies required to create them.

Relevance/Impact of Research

Potential Impacts

- Greatly expand the size of the sedimentary geothermal resource potential by enabling utilization of low permeability reservoirs
- Spark the development of sedimentary geothermal projects, particularly in the basin studied
- By leveraging the project participants' close ties with the petroleum industry, this task could result in rapid dissemination and adoption of the technology by the petroleum industry and increase their participation and investments in the geothermal industry
- Success in this project would support GTO goal to drive industry deployment of a targeted 100+ GW of EGS

Scientific/Technical Approach

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1. Develop **analytical model of doublet system** in a sedimentary formation
   - Gain insight on the reservoir characteristics controlling reservoir lifetime and well productivity index
   - Use this analytical model to validate numerical reservoir models.
2. Develop and validate **numerical reservoir model for doublet system** in reservoir with homogenous properties. STARS CMG chosen as software model.
3. **Apply and evaluate well enhancement techniques** in reservoir with homogenous properties using numerical reservoir model.
4. Add and evaluate **impact of reservoir heterogeneities** using numerical reservoir model.
5. **Develop reservoir model of actual sedimentary formation** based on available data sets, and use numerical reservoir model to evaluate reservoir performance and impact of well enhancement techniques.
6. **Apply techno-economic models to estimate cost** of developing power generation projects, based on the modeling results, and evaluate their commercial feasibility.

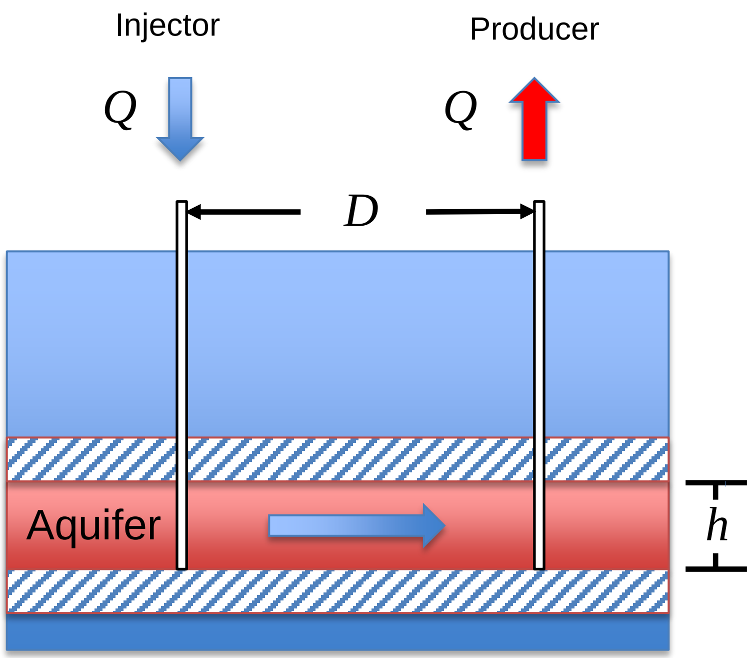
Analytical model of geothermal doublet system (Gringarten, 1979)

- Key parameters:
  - Injectivity/Productivity index (determines flow rates/ pumping requirements)
  - Thermal Breakthrough time (determines reservoir lifetime)
- Time for thermal breakthrough at production well:

$$\Delta t = \left[\phi + (1-\phi)\frac{\rho_r C_{p,r}}{\rho_w C_{p,w}}\right]\frac{\pi}{3}\frac{D^2 h}{Q}$$

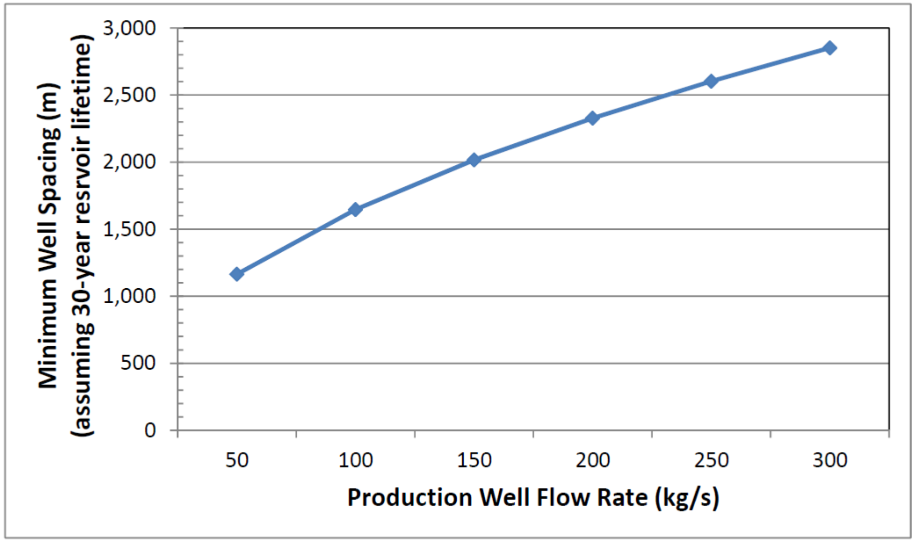
- Pressure difference between injection and production wells:

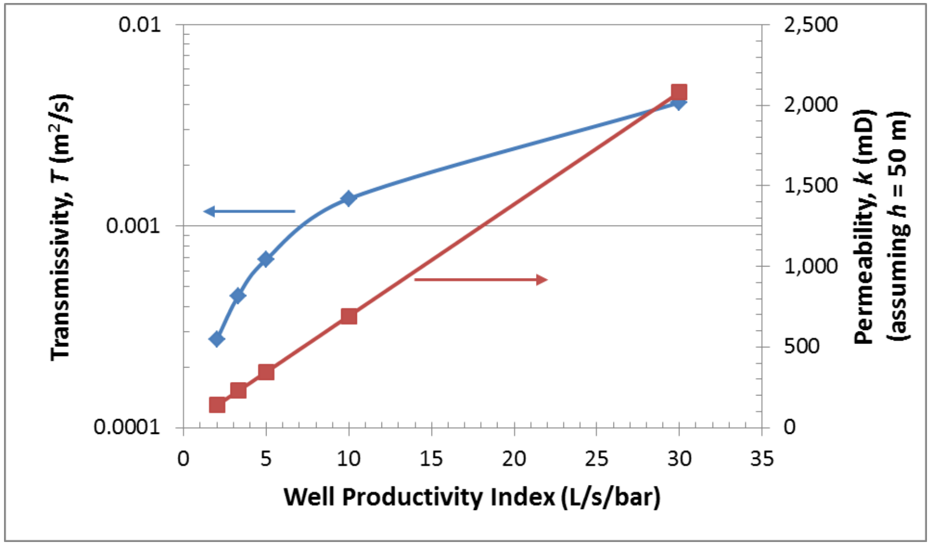
$$\Delta P = \frac{\mu Q}{\pi k h}\ln\left(\frac{D}{r_{well}}\right)$$



Parameter	Value
Porosity, ϕ	0.15
Reservoir thickness, h	50 m
Rock heat capacity, $\rho_r C_r$	2,770 kJ/m^3/^{o}C
Water heat capacity, $\rho_w C_w$	3,860 kJ/m^3/^{o}C
Water viscosity, μ_{avg}	2.18e-4 Pa-s
Well radius, r_{well}	0.108 m (8.5” diam.)
Reservoir lifetime, Δt	30 years

Analytical Model Results



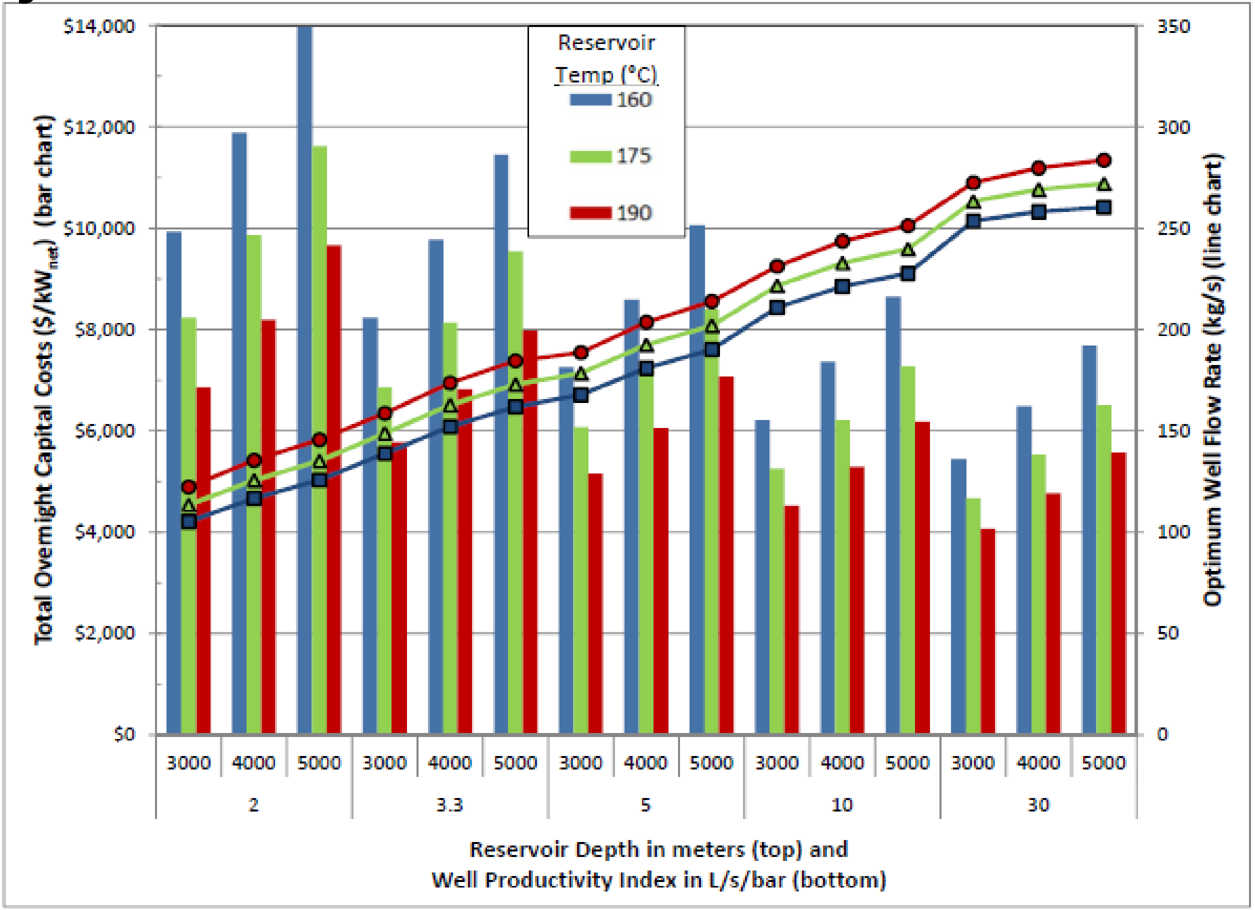


(from Augustine, 2014)

Well spacing on the order of 1-2 km required for doublet system for production well flow rates typically found at conventional hydrothermal power plants (independent of reservoir permeability) assuming 30-year reservoir lifetime

- Productivity index range studied requires reservoir permeabilities of hundreds to thousands of mD for the specified system performance
- Higher permeabilities needed than values of ~100 mD assumed in previous studies
- Assumes production well flow rate of 100 kg/s and reservoir height of 50 m

Cost Analysis Results



(from Augustine, 2014)

Modified GETEM to estimate costs of sedimentary systems as function of temperature, depth (well cost), and PI

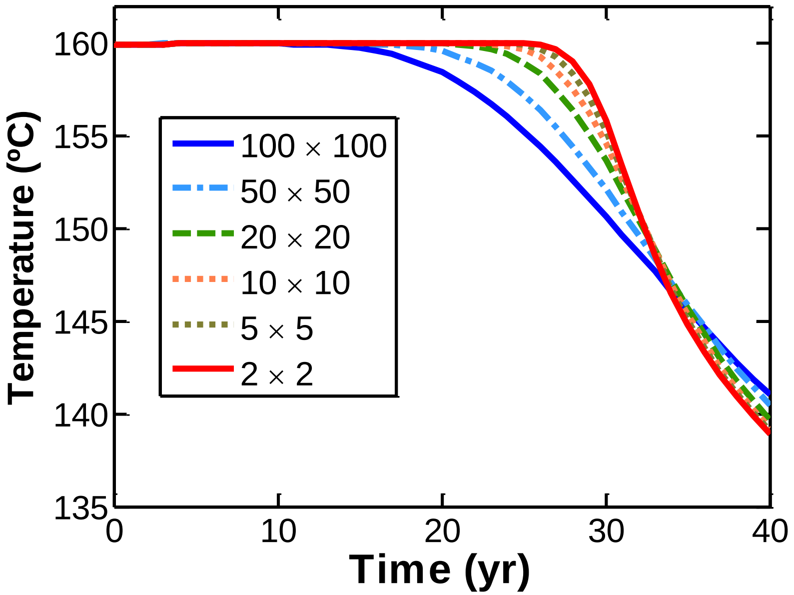
Numerical Model Validation

- Numerical solution for hydraulic behavior is not affected significantly by grid block size and time step used.
- Numerical solution for thermal behavior is affected by grid block size and boundary effects.
  - Found grid sizing, total reservoir size, and grid configuration that minimized numerical effects

Grid block size (m)	Thermal breakthrough time (yr)		Relative error (%)
	Analytical solution	Numerical solution	
100 x 100	30	19.0	36.6%
50 x 50	30	22.0	26.6%
20 x 20	30	25.0	16.6%
10 x 10	30	27.0	10.0%
5 x 5	30	28.0	**6.6%**
2 x 2	30	28.0	**6.6%**

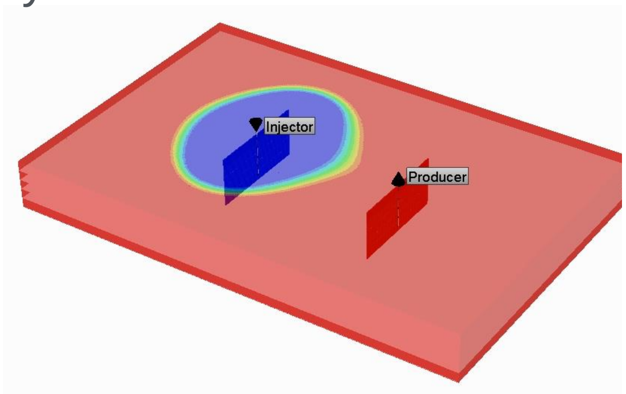
Well spacing = 1500 m Reservoir size = 34,500 x 33,000 m

Temperature at production well as function of time

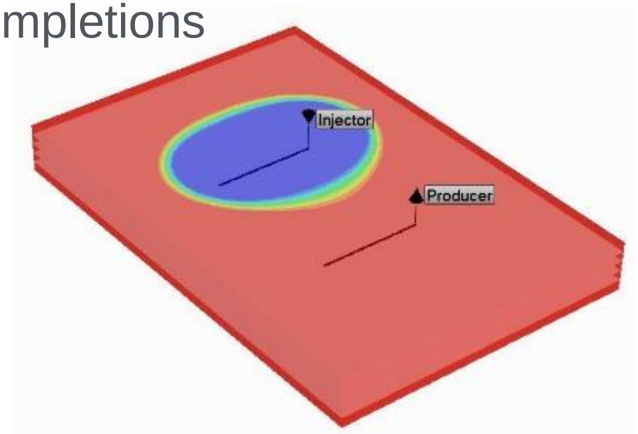


Four different well configurations were compared against the base case of vertical wells doublet

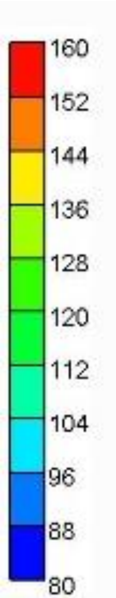
1. Vertical wells doublet with hydraulic fractures



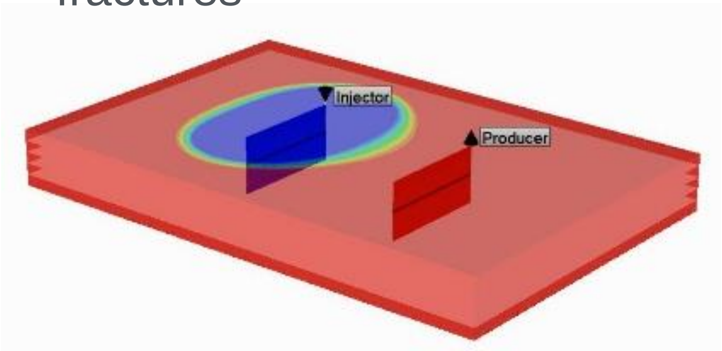
2. Horizontal wells with open-hole completions



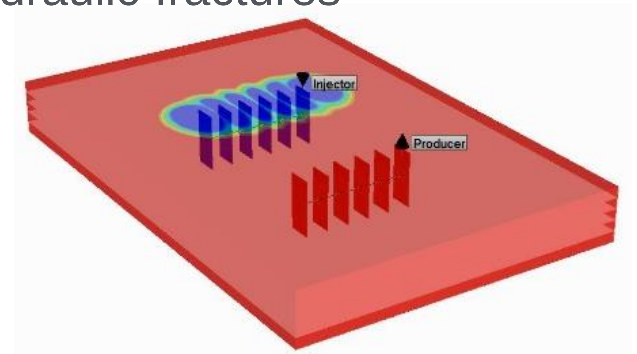
Temp. (ºC)



3. Horizontal wells with longitudinal fractures



4. Horizontal wells with multi-stage hydraulic fractures



Numerical Model Results – Well Enhancement

Well Configuration	Average reservoir pressure (kPa)	Bottomhole pressure injection well (kPa)	Bottomhole pressure production well (kPa)	Pressure drawdown, ΔP (kPa)	Productivity Index	
					Injector (l/s-bar)	Producer (l/s-bar)
Doublet	28,374	38,349	22,865	15,484	0.94	1.70
Vertical + hydraulic fracture	28,364	30,523	26,659	3,864	4.33	5.48
Horizontal open-hole	28,367	30,231	27,095	3,136	5.01	7.34
Horizontal with longitudinal fracture	28,368	29,956	27,241	2,715	5.88	8.29
Horizontal with multi-fracture	28,369	29,795	27,325	2,470	6.55	8.94

(from Cho et al., 2015)

Assumptions:

- 1,500 m well spacing
- Injection/Production Rate = 8068 m^3/day
- Permeability = 100 mD
- Reservoir Thickness = 50 m
- Horizontal Well Lengths = 1000 m

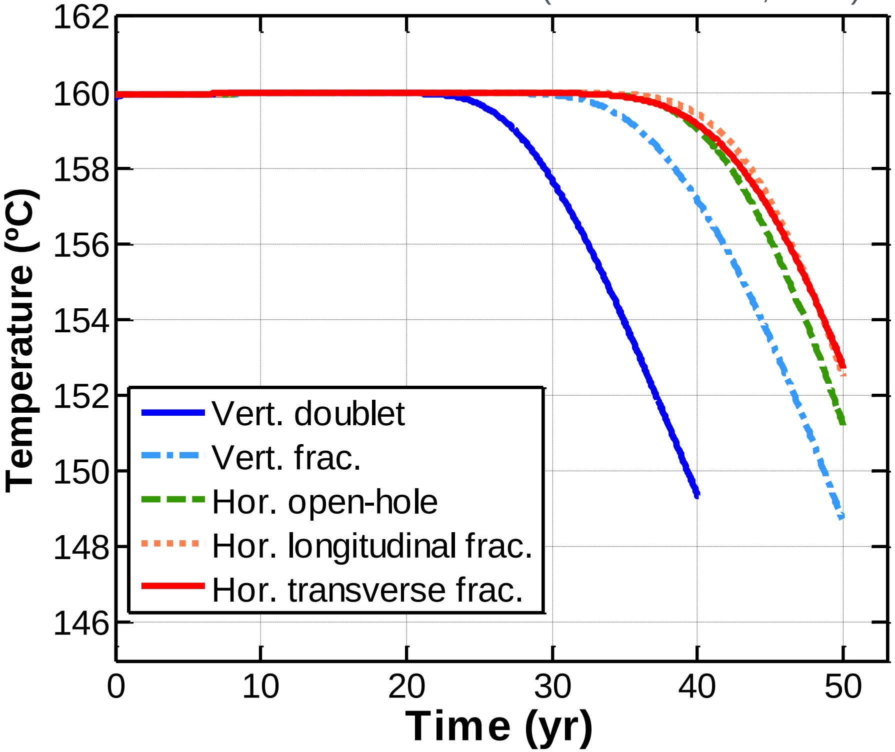
Note: 1,000 kPa = 145 psi

Reservoir hydraulic behavior is improved by the use of hydraulic fractures, and further improved by the use of horizontal wells

Numerical Model Results – Well Enhancement

Well Configuration	Thermal breakthrough time (yr)
Doublet	27
Vertical + hydraulic fracture	36
Horizontal open-hole	40
Horizontal with longitudinal fracture	42
Horizontal with multi-fracture	41

(from Cho et al., 2015)



- Horizontal wells with longitudinal fractures present the greatest improvement

Thermal breakthrough time is increased by the introduction of reservoir enhancement techniques

Accomplishments, Results and Progress

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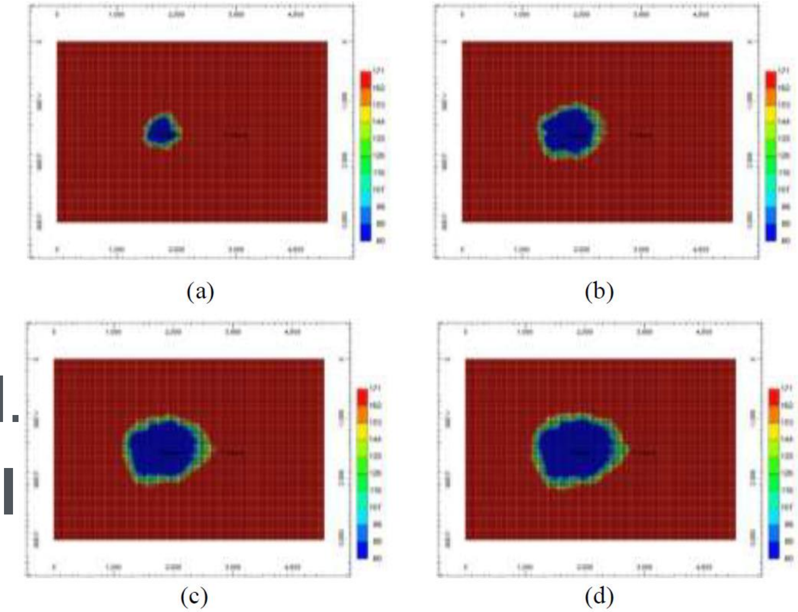
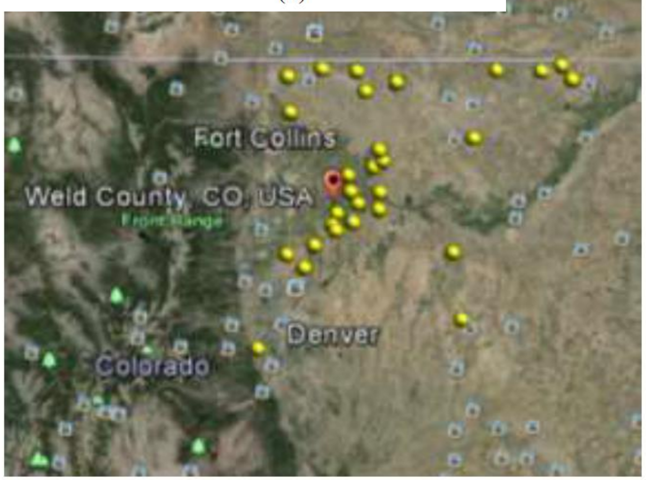
Original Planned Milestone/ Technical Accomplishment	Planned Date	Actual Date Completed
Participate in GTO-led workshop on sedimentary basin characterization	12/31/2013	11/5/2013
Go/No-Go decision of selection of sedimentary basin for feasibility study	1/31/2014	4/8/14
Complete initial reservoir modeling runs	3/31/14	10/21/14
Draft final results, including enhancement methods studied, identification of most-promising method, impact on reservoir performance	6/30/14	10/21/14
Complete FY14 draft report or paper summarizing project results	9/30/14	1/12/15

Challenges:

- Difficulties obtaining proper software license
- Numerical model validation more difficult than anticipated. Delayed modeling runs, but gave us more confidence in results.

1. Add and evaluate **impact of reservoir heterogeneities** using numerical reservoir model.
2. **Develop reservoir model of actual sedimentary formation** based on available data sets, and use numerical reservoir model to evaluate reservoir performance and impact of well enhancement techniques.





Location of wells in Wattenberg field

Future Directions

Milestone or Go/No-Go	Status & Expected Completion Date
Complete data gathering and pre-processing of well logs in Wattenberg Field, DJ Basin, Colorado	In progress. Undergraduate students digitizing data from 32 well logs. Expected completion April 2015
Complete preliminary 3D model of Wattenberg Field	In progress. Waiting on well logs. Expected Completion May 2015
Preliminary results of Wattenberg field sedimentary geothermal system performance	Performing runs to evaluate impact of reservoir heterogeneities to prepare for interpretation of actual reservoir model run results. 6/30/2015
Complete draft report summarizing Wattenberg Field results	9/30/2015

Beyond FY15…

- If modeling results are promising, would like to explore possibility of sedimentary geothermal demonstration project in Wattenberg field

Summary

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- Reservoir permeability requirements for commercially-viable sedimentary geothermal power generation systems are larger than previously expected. Despite this, reservoirs with commercially-viable characteristics that include reasonable permeabilities (low-hundreds of mD) have been identified.

- Numerical modeling shows that using well enhancement techniques such as hydraulically fracturing and drilling long horizontal segments can substantially increase well productivity (by a factor of ~5). This has the potential to greatly increase the number of sedimentary reservoirs that could developed into geothermal systems for electricity generation.

Publications and Presentations, Intellectual Property (IP), Licenses, etc.

- Augustine, C., 2014. "Analysis of Sedimentary Geothermal Systems Using an Analytical Reservoir Model." Geothermal Resources Council Transactions, v. 38, p. 641-647.

- Cho, J, 2014. “Feasibility Study of Sedimentary Enhanced Geothermal systems using reservoir simulation.” MS Thesis, Advisor: L. E. Zerpa, Colorado School of Mines.

- Cho, J., C. Augustine and L. E. Zerpa, 2015. "Validation of a Numerical Reservoir Model of Sedimentary Geothermal Systems Using Analytical Models." Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University, CA, January 26-28, 2015, p. 13.