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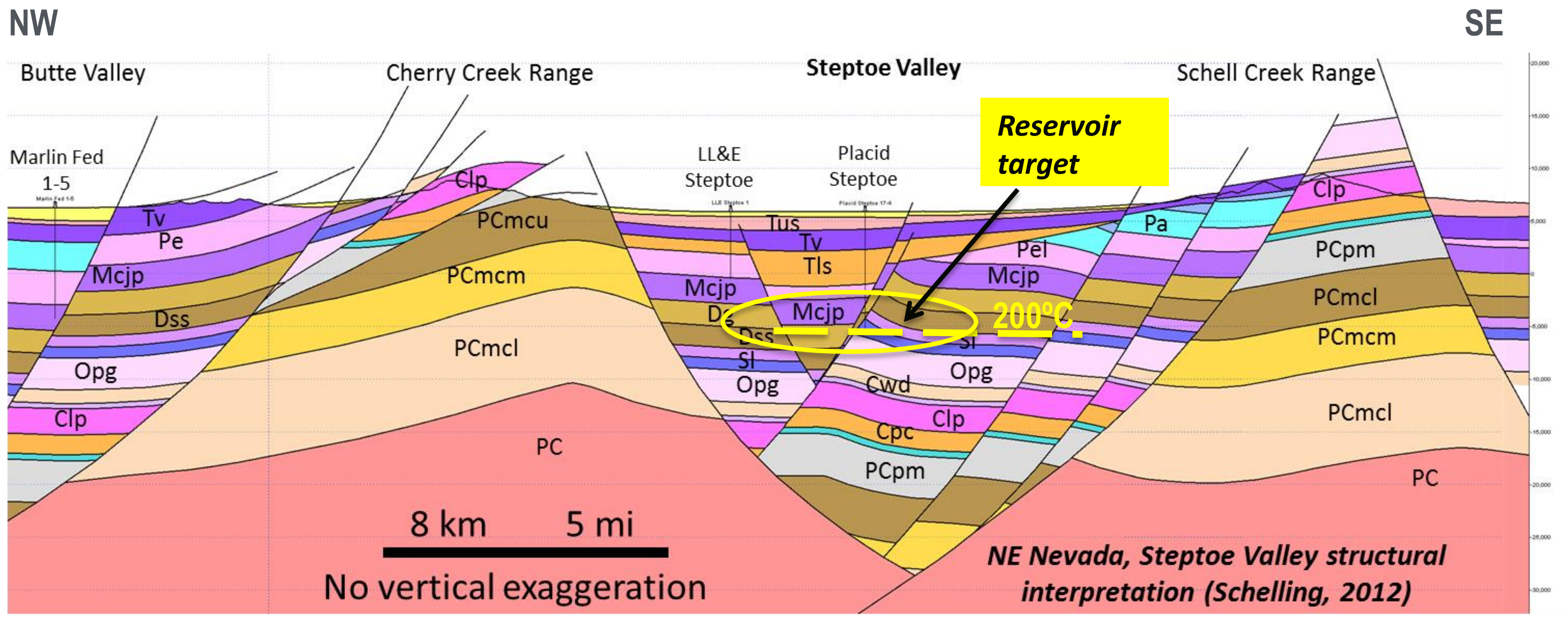

Novel Geothermal Development of Deep Sedimentary Systems in the U.S.

Project Officer: Bill Vandermeer

Total Project Funding: $xx

May 13, 2015

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Track Name: Track 3 EGS1

This presentation does not contain any proprietary confidential, or otherwise restricted information.

Relevance/Impact of Research (1)

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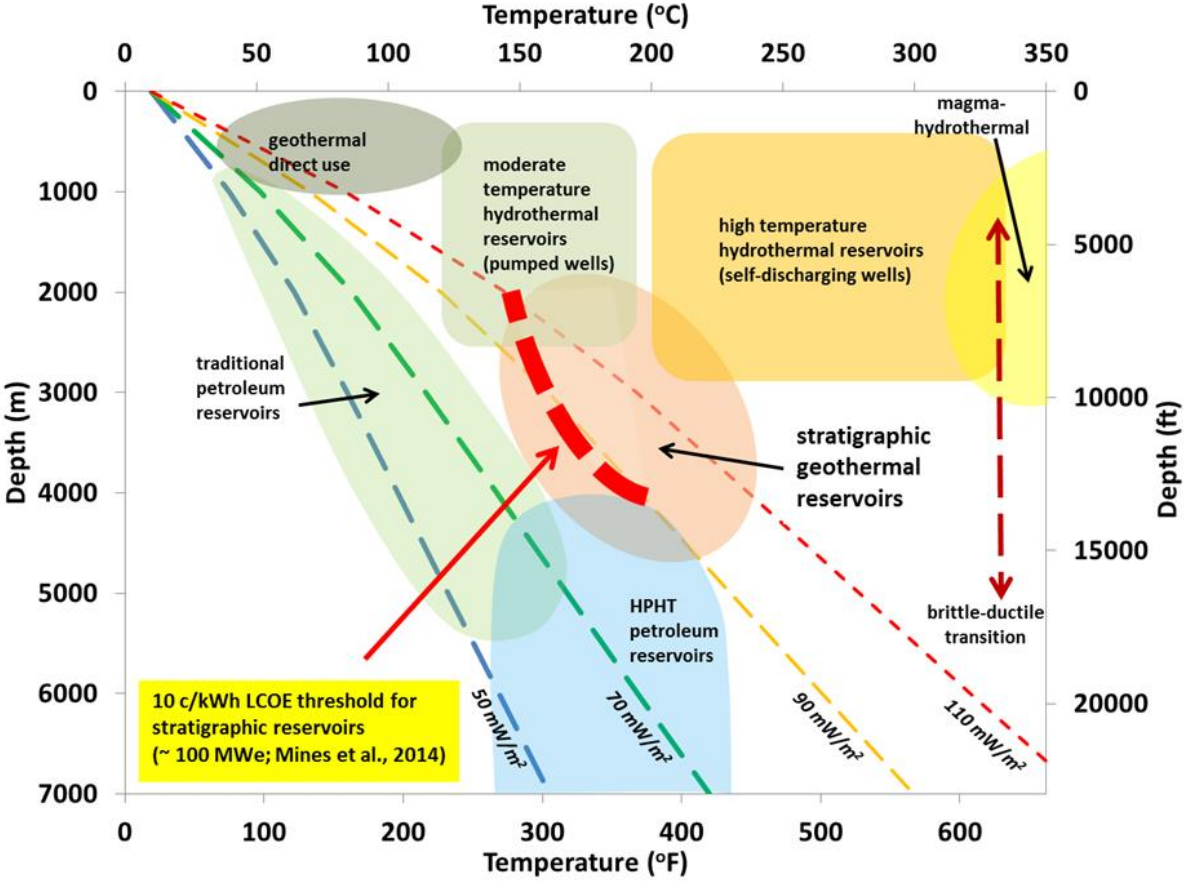
Objectives

- GWe growth in geothermal power in the U.S. requires power plants that are more than 100 MWe in size, which means reservoir volumes of ~ 10 km^3 for 30 year lifetimes
- Large areas of high (conductive) heat flow in the western U.S. have temperatures of more than 150ºC at 3 depth
- Sub-horizontal stratigraphic units at these depths with characteristically high permeability have potential as large reservoirs which can contribute to future growth in geothermal power generation.
- Although traditional EGS targets low permeability rock, it is possible early, large-scale EGS projects will focus on rocks with some natural permeability rather a totally impermeable mass of rock
- Deep stratigraphic “reservoirs” with moderate permeability offer a bridge to technology development of EGS.
- The vision here is for the application of technology developments (horizontal drilling and permeability enhancement) that have transformed the oil and gas industry to also transform the geothermal power industry.

Relevance/Impact of Research (2)

Prospective stratigraphic reservoirs are typically deeper than conventional hydrothermal reservoirs, and hotter than conventional petroleum reservoirs.

The insulating effects of basin fill mean temperatures beneath basins may be up to 50˚C higher than at the same depth beneath ranges. Where there is at least 2 km of basin fill, temperatures of 150 – 200˚C exist at 3 – 4 km depth beneath many basins with heat flows of 80 – 100 mW/m².



Stratigraphic reservoirs offer attractive targets for new power generation in the U.S.

Scientific/Technical Approach

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- **Phase 2 has five tasks**. Task 1 integrates a wide range of geoscientific data in prospective basins in the western U.S. to prioritize the most attractive development targets. Task 2 examines geochemical issues for production and injection. Task 3 optimizes reservoir performance and heat sweep models between injectors and producers by applying oilfield water sweep experience. Task 4 applies GETEM to investigate the economic impacts of drilling costs, reservoir temperature and productivity, and borefield strategy on the LCOE for 100 MWe power plants. Task 5 integrates the results and identifies possible proof-of-concept demonstration sites, and ensures data and reports are submitted to the national geothermal database.

- **Current work includes:**
  - analyzing data from oil exploration in the Great Basin (BHTs, wireline log data, surface geophysical surveys);
  - Investigating water geochemistry from stratigraphic reservoirs in hydrothermal systems for verification and simulation of thermodynamic equilibria
  - optimizing injection-production performance using the STARS simulator and typical petroleum reservoir models
  - economic modeling with GETEM modeling by Greg Mines, INL, has been completed
  - Integrating results, identifying the most attractive prospects, recommending exploration strategies, suggesting appropriate standard-of-practice guidelines for development, and ensuring all data and reports are submitted to the NGDS

Accomplishments, Results and Progress

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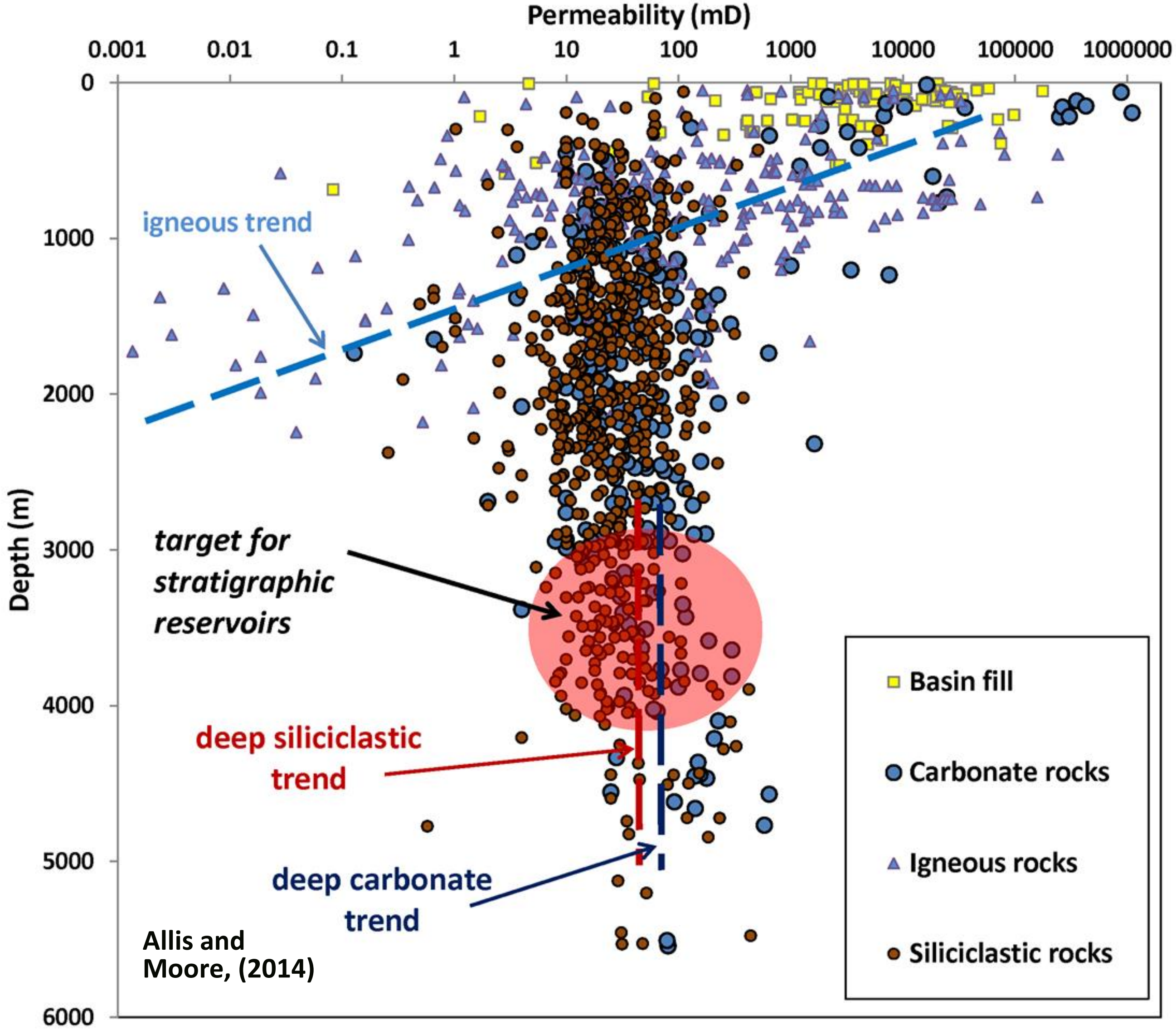
- No cost variances; a no-cost extension to 6/2016 has been requested; Phase 1 data submitted to NGDS
- Over 40 papers, presentations, and posters at national industry and scientific conferences, venues (see list with summary document)
- GRC best presentation awards in 2012 (Allis et al.: Stratigraphic reservoirs in the Great Basin – the bridge to development of enhanced geothermal systems), and in 2014 (Allis and Moore: Can deep stratigraphic reservoirs sustain 100 MW power plants?). This also won the best poster award at the 2014 GRC meeting
- In general, accomplishments exceed original expectations. Results point to many basins in the northern Great Basin having both the recommended thermal criteria (150 - 200 ºC at 3 - 4 km depth) and stratigraphic units with potentially good permeability within this depth range. Faulting within the basins will enhance the deep permeability. The economic models suggests temperatures between 180 and 200 ºC are optimal; pumps presently will not operate at higher temperatures.

Milestone or Go/No-Go	Status & Expected Completion Date
Task 1. Resource Characterization: Stratigraphic Reservoirs of the Western U.S.	Identifying at least 10 prospective basins in ID, CO, UT, and NV; completed by 6/16
Task 2. Fluids and Minerals: Issues for Production and Injection	Examining geochemical issues for production and injection; completed 6/16
Task 3. Optimizing reservoir performance and heat sweep models between injectors and producers	Numerical simulations using STARS simulator; Spencer Nich completes M. Chem. Eng. At U. of Utah on 6/15.
Task 4. Using GETEM to investigate the impacts of drilling costs, reservoir temperature and productivity, and borefield strategy	Task complete
Task 5. Integrating the results and identifies possible proof-of-concept demonstration sites	Significant progress on best site ranking ; priority task for last 12 months;

Accomplishments: The required permeability CAN be found!



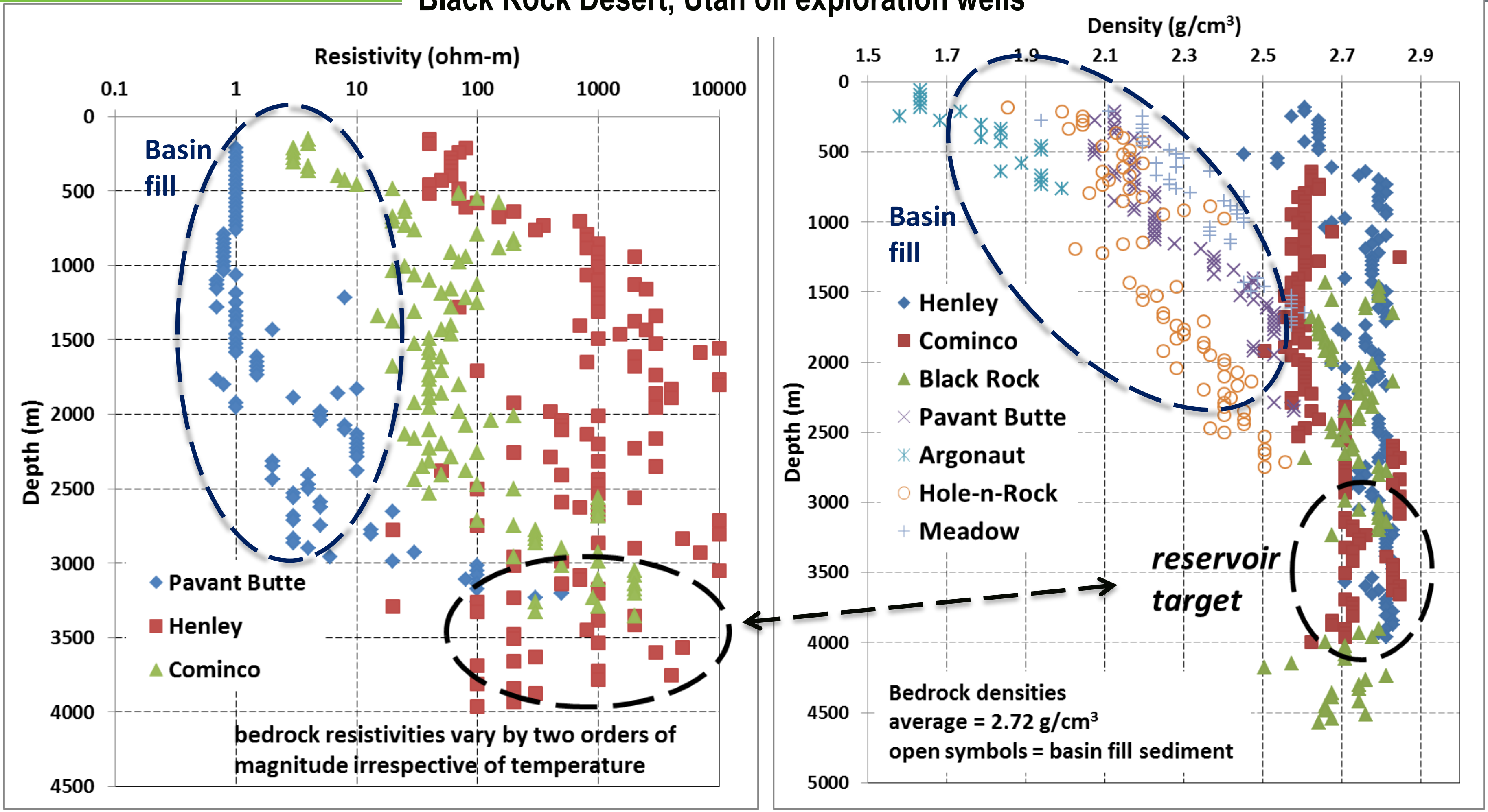
Compilation of permeability data from oil and gas database (GASIS) and groundwater databases (Kirby, 2012).

The graph shows that carbonate and clean siliciclastic reservoirs at 3 – 5 km could sustain good geothermal production wells.

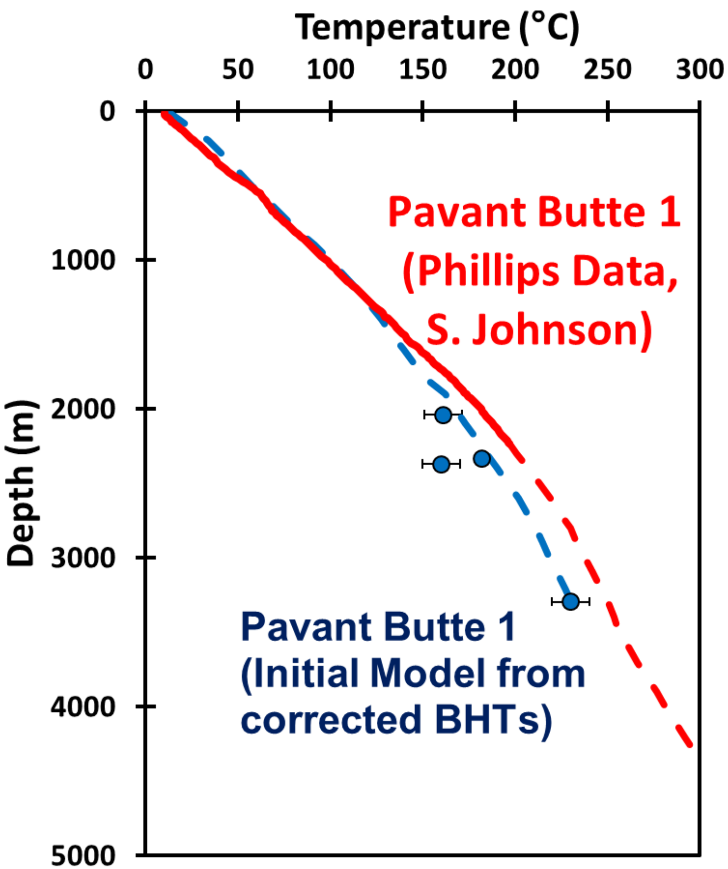
Igneous reservoirs look like a poor choice (unless active faulting?)

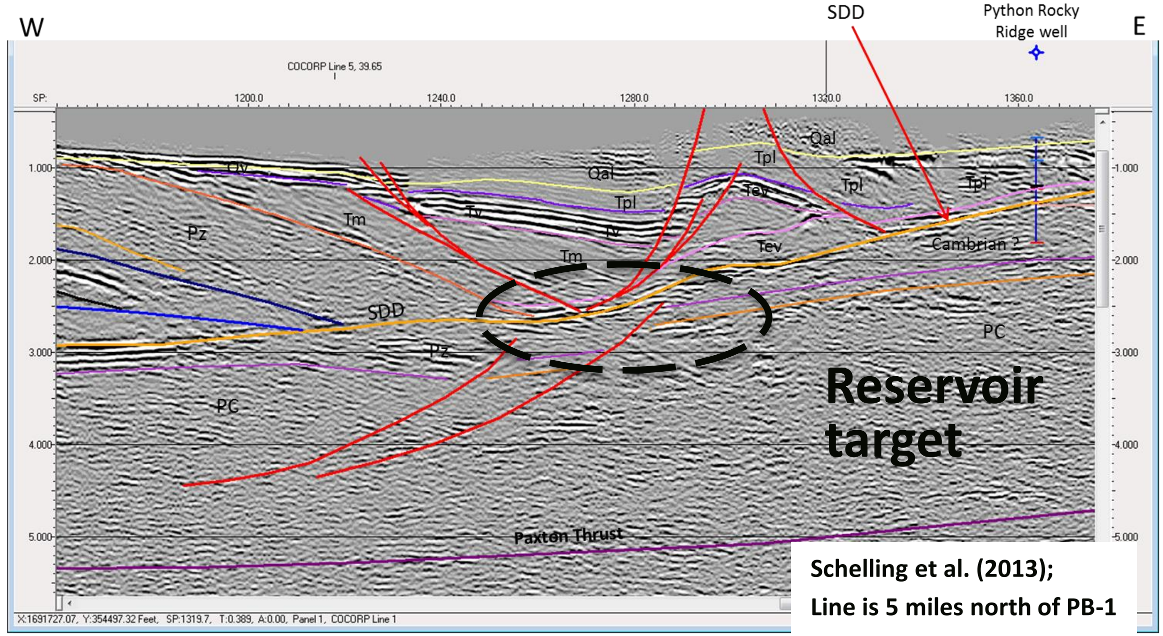
Accomplishments: Wireline log data critical for development strategies

Black Rock Desert, Utah oil exploration wells



When drilling wells to 3 – 4 km depth, geophysical wireline log data is an essential part of development optimization





Interpreted seismic line Utah Cocorp 1; Sevier Desert detail

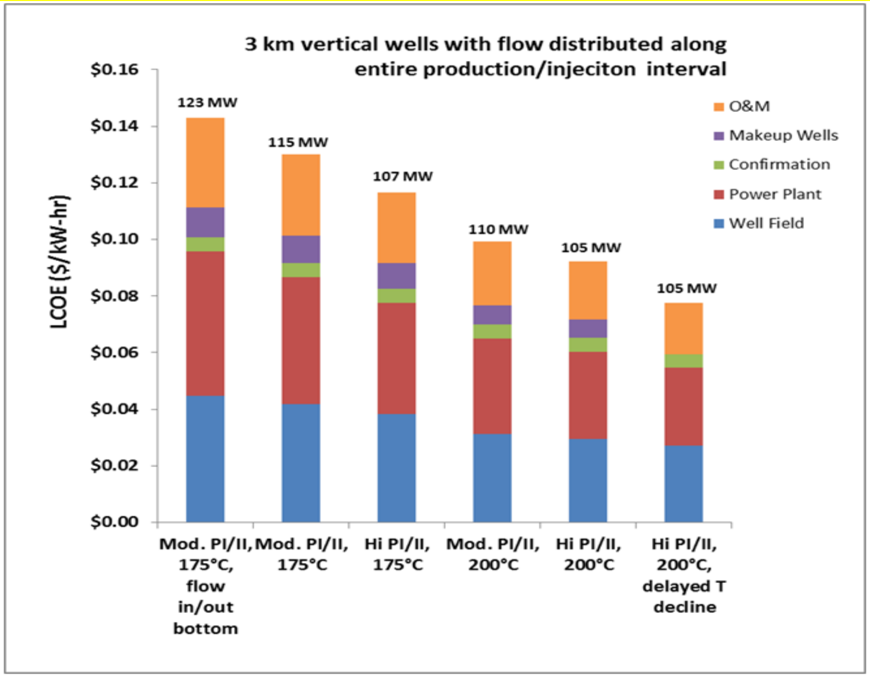
Legend

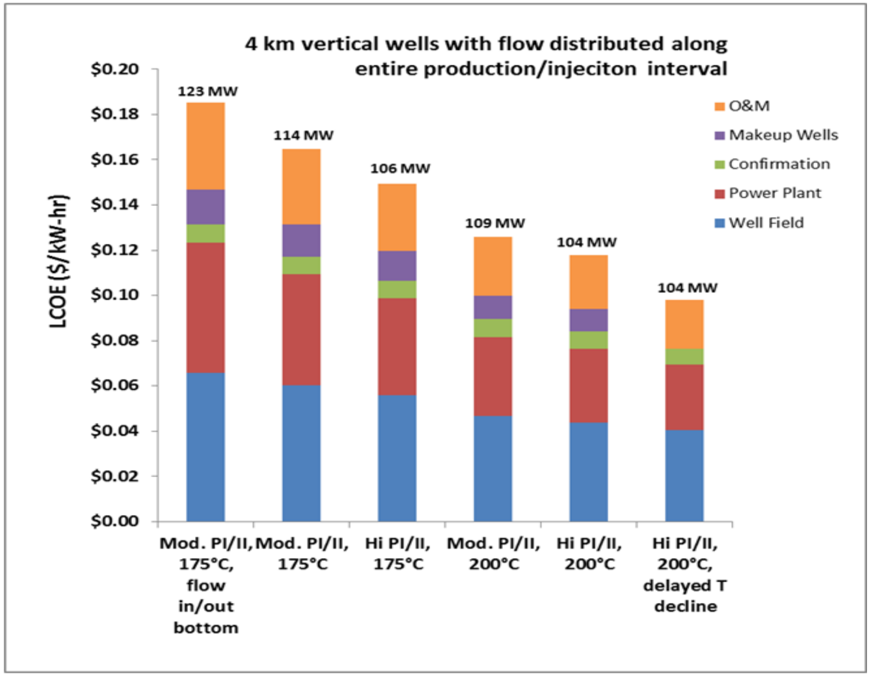
red lines = normal faults
black lines = thrust faults
purple line = Paxton Thrust
blue line = Pavant Thrust
orange line = Sevier Desert Detachment (SDD)
Qal = Quaternary alluvium
Qv = Quaternary volcanics
Pz = Paleozoic
PC = Precambrian
Tpl = Pliocene
Tv = Tertiary volcanics
Tm = Oligocene-Miocene
Tev = Tertiary (?) evaporites

Our project may have "found" the most attractive, undeveloped prospect in the Great Basin. Modern seismic reflection profiling is an important exploration tool for identifying structure and stratigraphy in prospective basins. Using sonic velocity logs in a nearby deep well is also important for seismic interpretation.

Accomplishments:

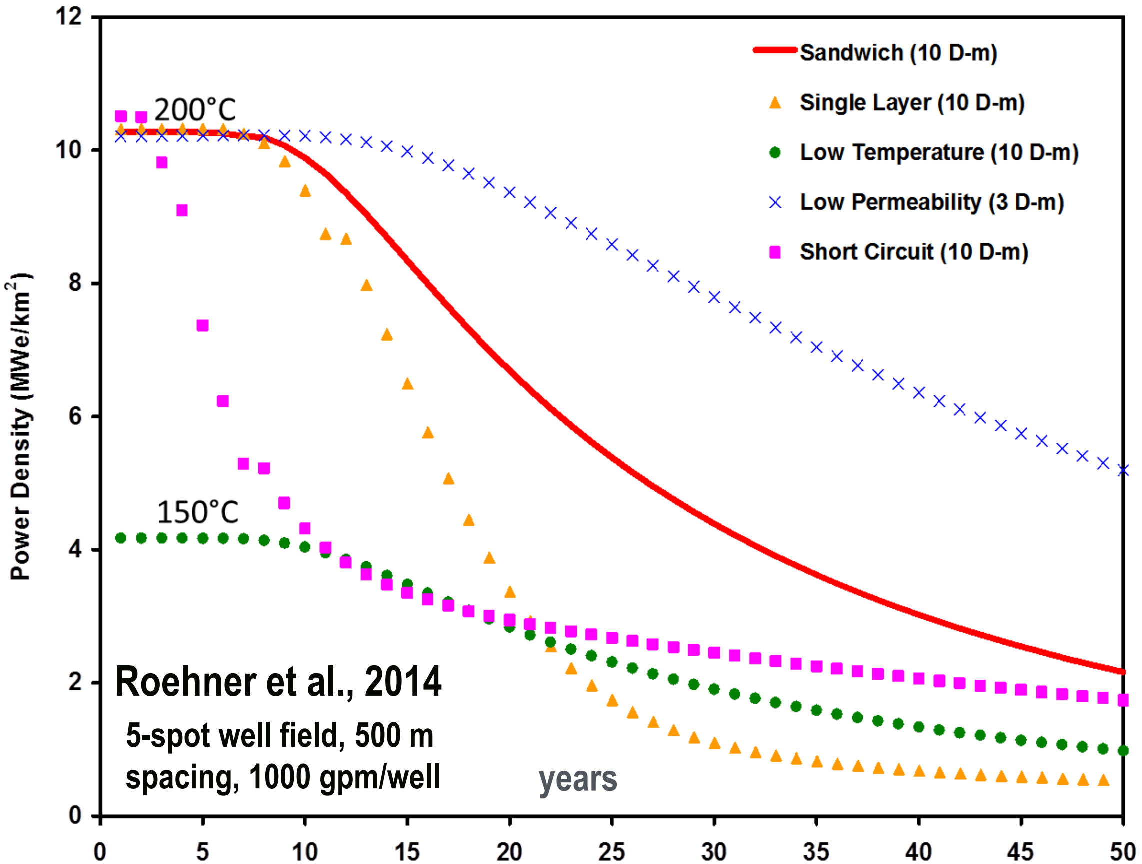
Wells at 3 – 4 km depth can have LCOEs of ~10c/kWh with ~ 100 MW power plants (150˚C @ 2 km reservoir depth ≈ 200̊C @ 4 km depth)

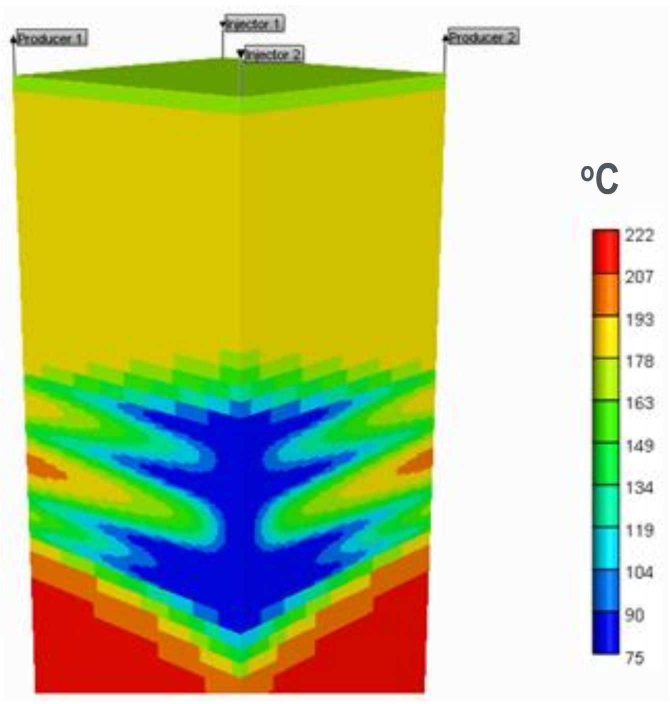




- Range of resource temperature & depth can impact LCOE by 2 to 4¢
- GETEM default is flow enters/leaves well at single entry point (bottom of well) – allowing for flow distribution along entire interval reduced LCOE by 1 to 2¢
- Delayed temperature decline increases early project revenue and avoids cost for makeup wells; LCOE lower by 1.5 to 2¢
- Higher PI/II has greater benefit for lower temperature resources

Mines et al., (2014)

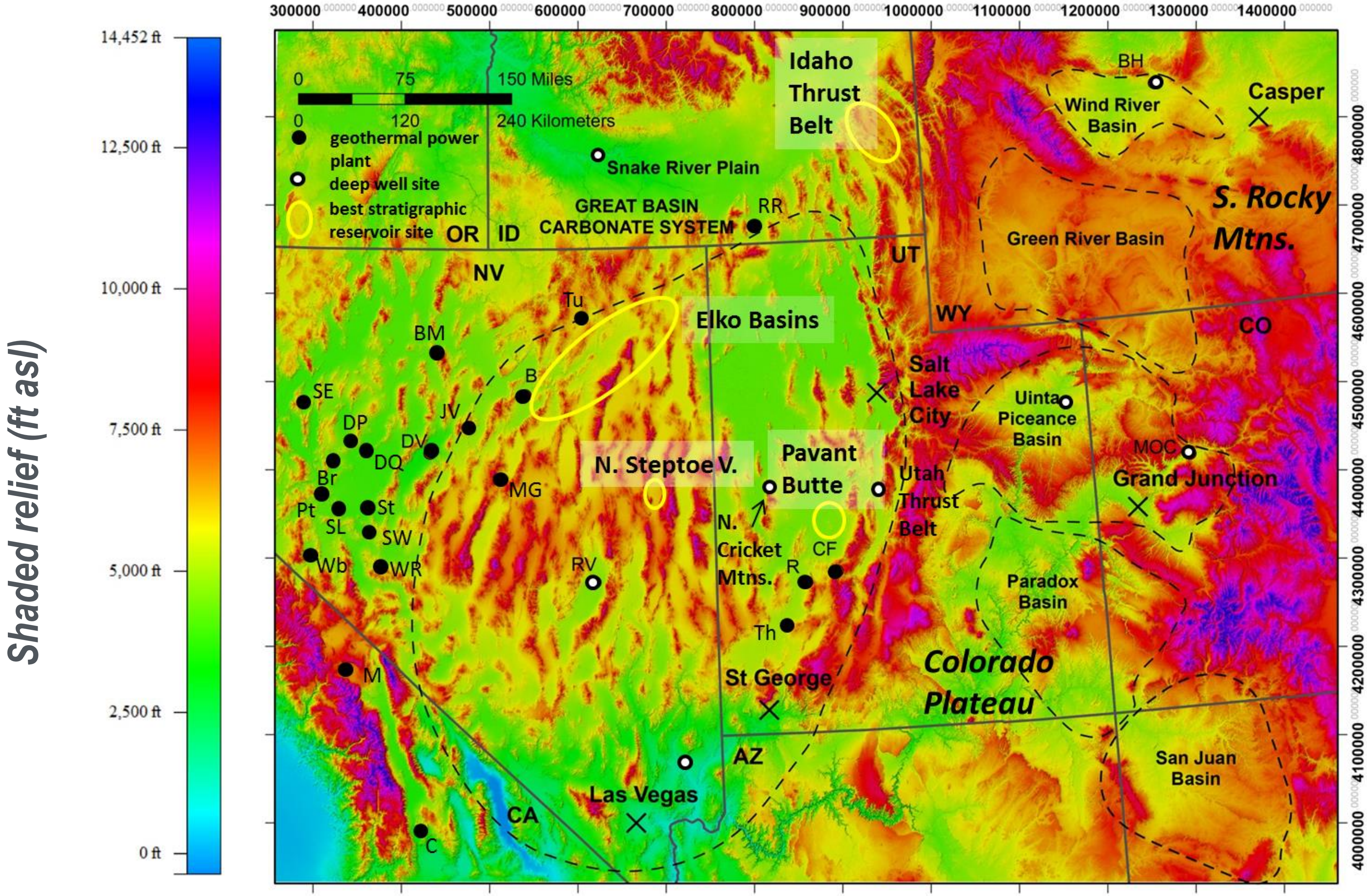




The rate of thermal decline is directly related to heat sweep efficiency. Injection fluid dispersing through several permeable layers significantly delays the thermal decline. The delay in thermal rundown is critical for capital investment timeline…

Even at 3 MWe/km^2, the scale of prospective basins (10^2 to 10^3 km^2) implies large-scale power potential

Accomplishments: our best four prospects!



Accomplishments: **our best four prospects**

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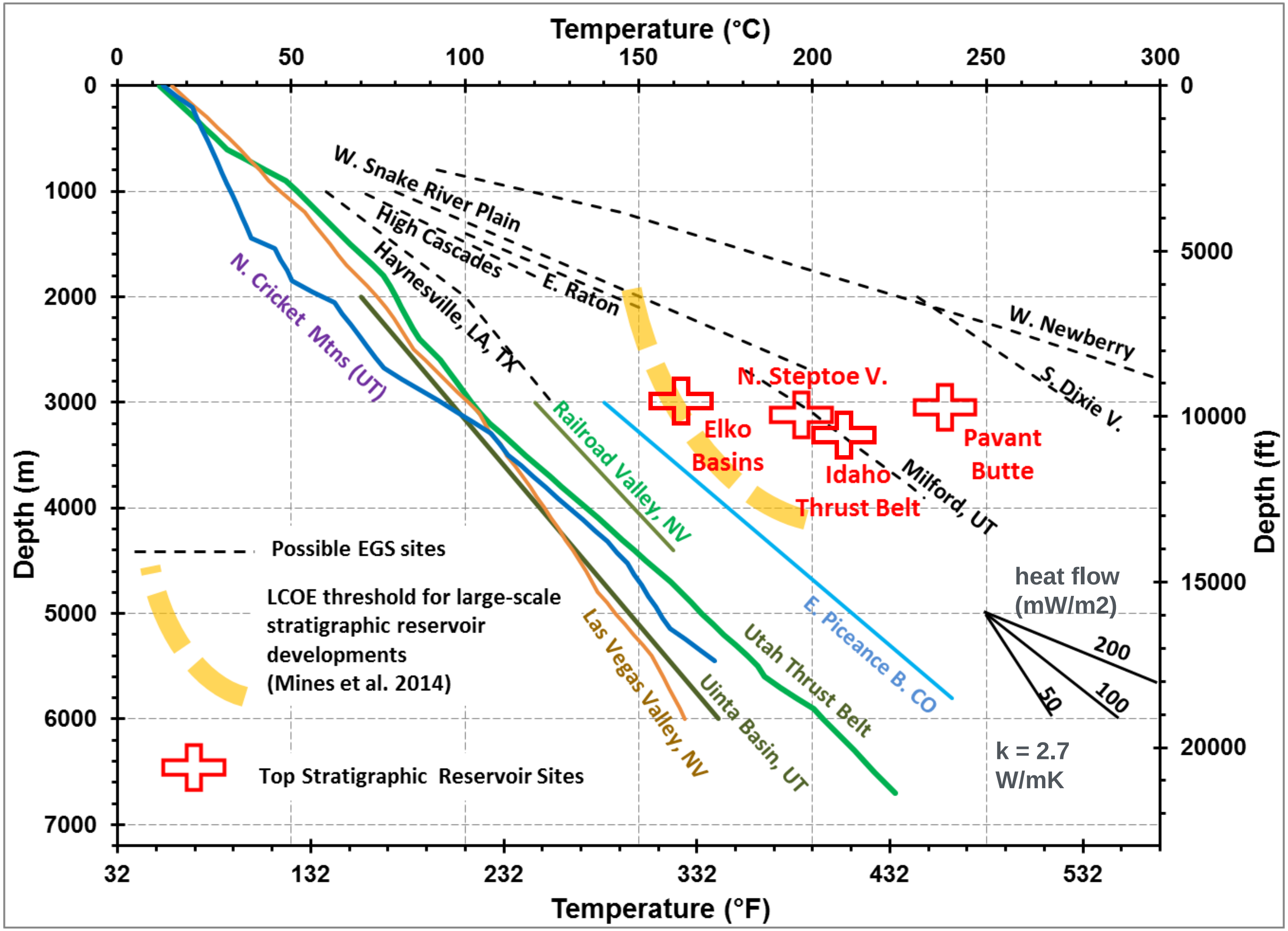

Future Directions

- Details of tasks for the remaining year of this project were covered in Slide 4 under "current work" and are linked to the milestone table on slide 5. All tasks will be completed by the requested end date of 6/30/2016.
- We already have a good idea of the likely basins on the "top-ten" list. Most are in the Great Basin, with varying amounts and quality of data supporting the ranking. A general conclusion is there is a lack of basic exploration data in most basins considered prospective, and a total lack of reliable thermal data in many basins we suspect should have high heat flow.
- Field campaigns, including heat flow, gravity, and resistivity surveys, and seismic reflection interpretation, are needed to further reduce development risk and attract industry investment. These are not cutting edge exploration techniques.
- It may be that industry will want assistance proving that the required well productivity can be obtained from horizontal wells in these stratigraphic formations at 3 – 4 km.
- The cost and feasibility of drilling horizontal legs at 3 km depth and at 150 - 200 ℃ remain uncertain. Technologies tested by FORGE will help.
- Deep stratigraphic reservoirs with their sub-horizontal permeability represent a type of geothermal system between hydrothermal systems with vertical, fault-dominated permeability, and EGS with little or no permeability. They show promise for growing U.S geothermal power capacity.

Summary

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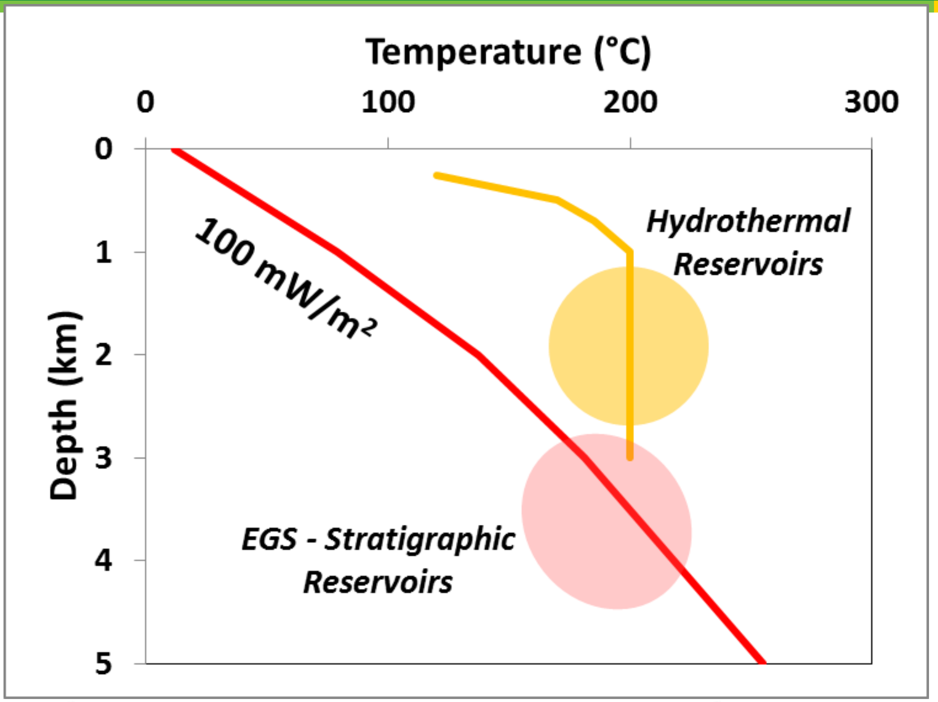
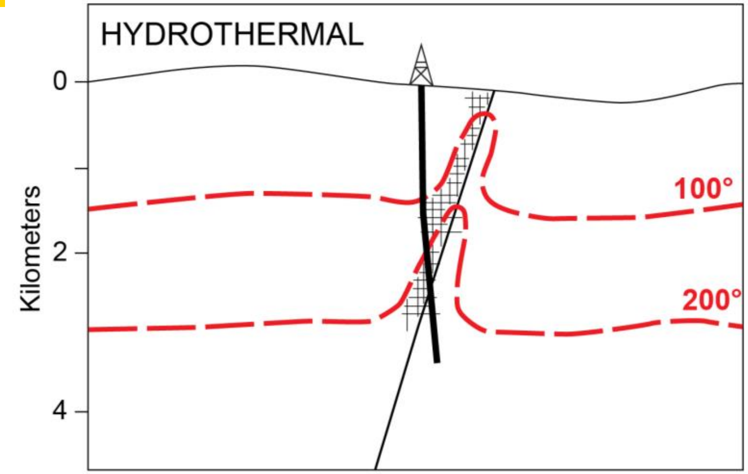
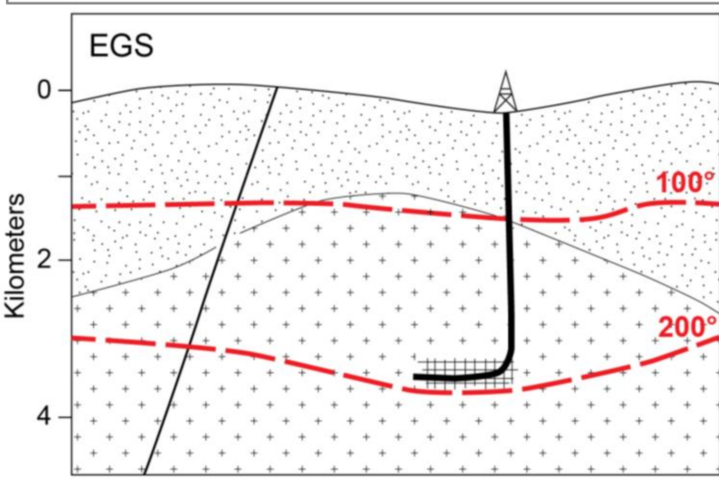
- The project is entering its final year with an emphasis on integration of results and recommendations for future work.
- Economic modeling of stratigraphic geothermal reservoirs indicates 100 MWe-scale developments can achieve LCOE's of ~ 10c/kWh if the initial reservoir temperature is close to 200℃ (the maximum temperature for pumps), and the reservoir is less than 4 km depth.
- Some stratigraphic units are known to be characteristically permeable, with petroleum well data indicating permeabilities in clean carbonates and siliciclastics in the range of 30 – 100 mD at 3 – 5 km depth. Horizontal or strongly deviated wells into these formation can yield the required high productivity (ideally at least 10 Darcy-m transmissivity).
- There is no evidence of overpressures in the Great Basin, and low risk of induced seismicity when there is no net fluid volume addition or loss to the reservoir with air-cooled binary power plants.
- Multiple reservoir-seal layers in a package over several hundred meters allow much more efficient heat sweep and delayed thermal rundown compared to one layer with high permeability.
- The standard of practice for geothermal drilling and reservoir development needs to evolve, with many insights applicable from recent development of tight oil and gas reservoirs. Modular wellfields accessing about 10 km^2 of reservoir from a single pad coupled with 30 MWe power plants are possible. A "stiletto" wellfield development strategy is recommended, with an initial vertical well extensively logged and followed with horizontal producers and injectors targeting the optimal stratigraphic reservoir intervals.

Final Thoughts

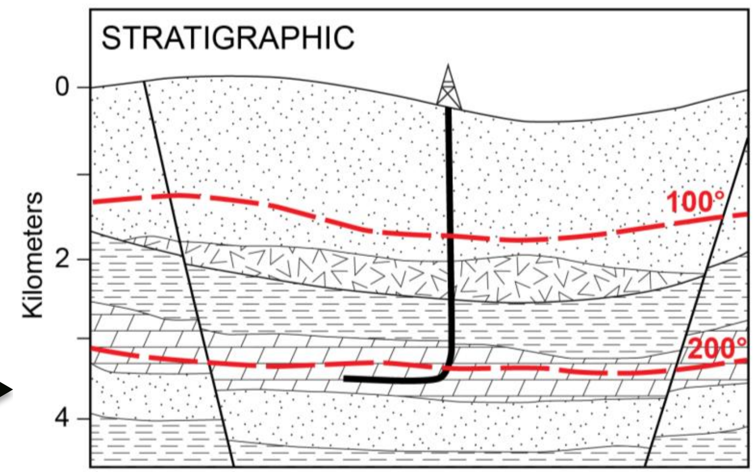




Is the next GWe going to be from another 20 - 50 of these?



Should EGS concepts be expanded?



Or from 5 of of these?

Thank you DOE-GTO for funding this project!

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Why is this not a serious exploration industry target today?