Design Requirements for Commercial Sedimentary Geothermal Projects

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Power Plays: Geothermal Energy in Oil and Gas Fields
Southern Methodist University
April 25-26, 2016

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

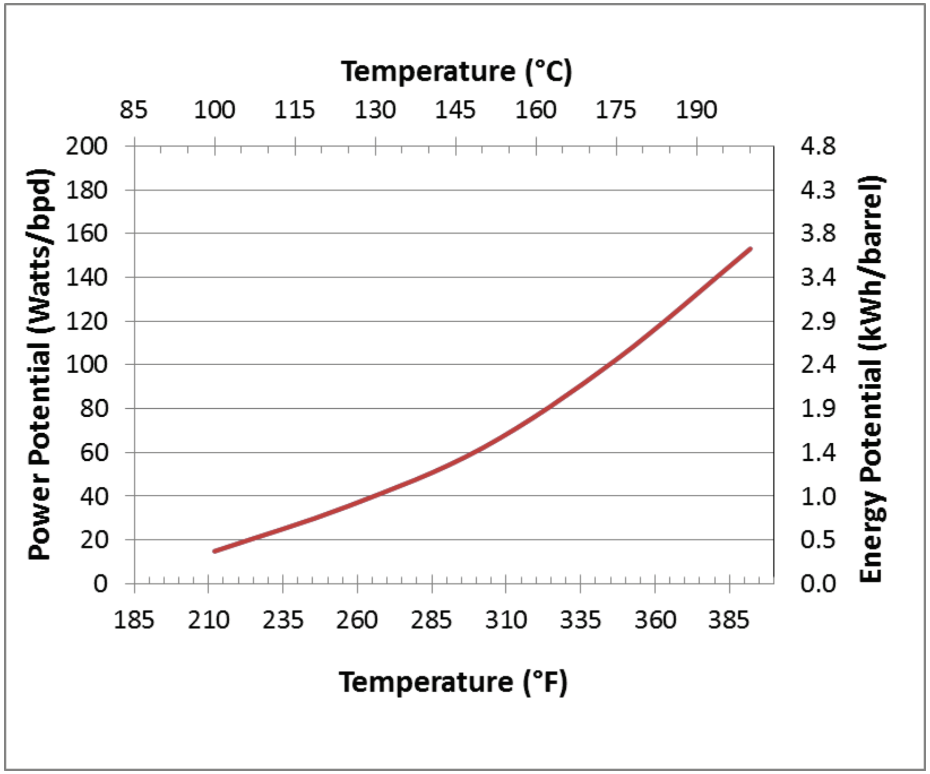
Geothermal vs. Petroleum – a Comparison

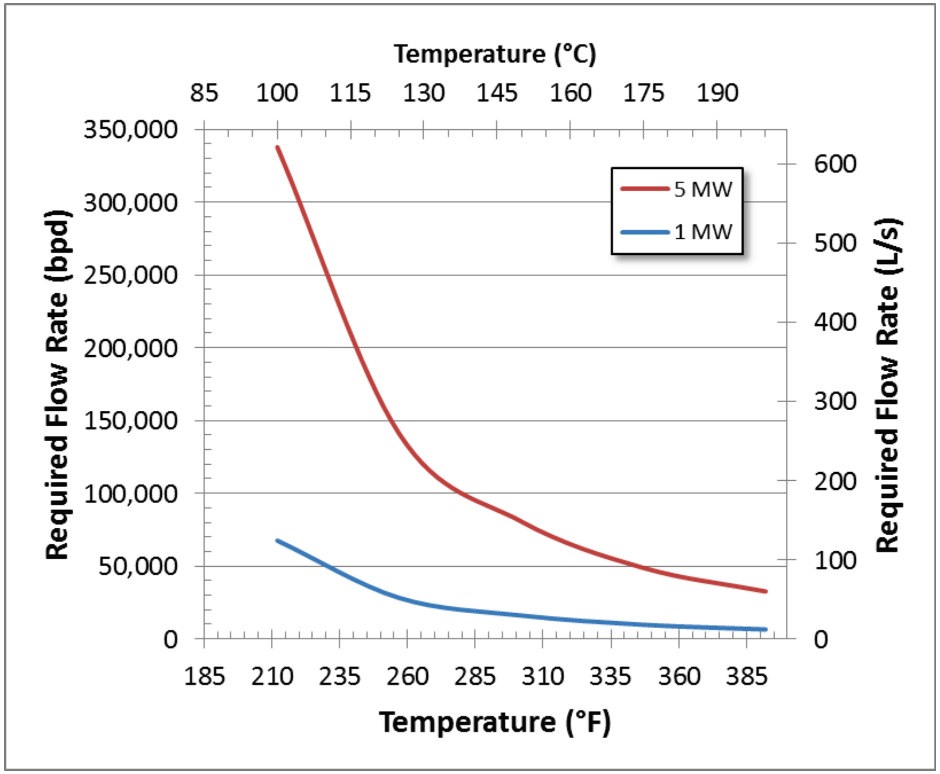
Petroleum		Geothermal
300-350°F is "Hot" (150-175°C)	**Temperature**	300-650+°F (150-350+°C)
5,000 bpd/well is "High Flow" (150 gal/min per well)	**Flow Rates**	50,000 bpd/well is *average* (1,500 gal/min per well)
Vertical and Long Reach Horizontal Onshore/Offshore 5"-7" diameter production interval	**Drilling**	Vertical/Deviated Onshore 8"-12" diameter bottom hole
High Initial Flow (months) Declining Rate (years)	**Production Profile/Timeframe**	Constant Production 20-30+ Years
Sedimentary	**Lithology**	Volcanic/Intrusive/Metamorphic
Stratigraphic/Structural	**Facies**	Complex Fault-Dominated
Petroleum (Oil & Gas) ~$40/barrel oil	**Recovered Product & Value**	Heat (Hot Water) ~$0.25/barrel hot water

Graphic by Chad Augustine, NREL

Temperature is important, but is not enough…

Need both Temperature AND Flow Rate for commercial power generation:





Electricity Generation vs. Temperature

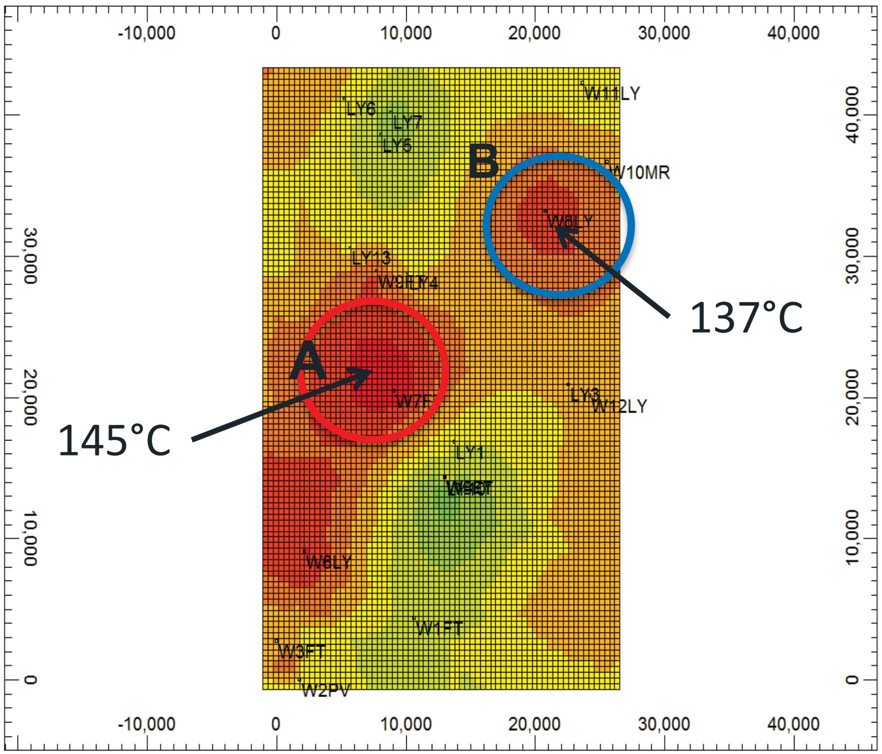
Flow Rate Requirements vs. Temperature

Adapted from Augustine and Falkenstern (2014), SPE-163142

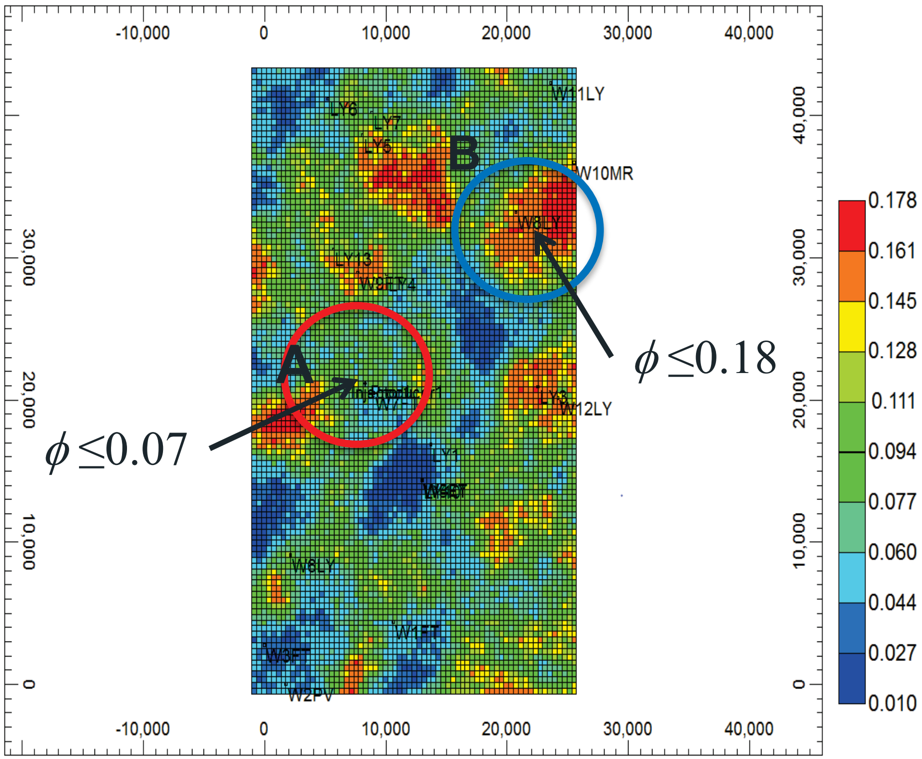
Which is a better sedimentary geothermal target?

- Areas A (red) and B(blue) both show elevated temperatures
- Area A has higher temperature…

- …but Area B has higher porosity (ϕ) and permeability (k): $\phi \sim \log(k)$
- **Area B is selected due to its higher porosity (higher permeability)**

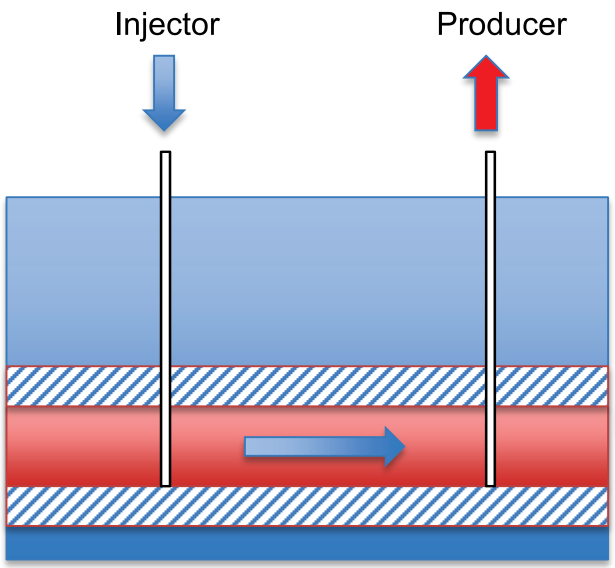


Temperature Distribution

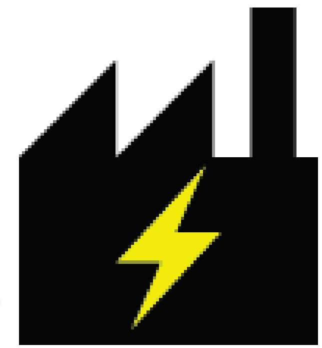


Porosity Distribution

Based on static reservoir model for Wattenberg Field built from well logs (Zhou, CSM Masters Thesis, 2016)



Sedimentary Geothermal Reservoir Requirements



Utility-Scale Electricity Generation

Temperature
- Resource quality
- Higher temperature = more power potential

Flow Capacity (*kh*)
- Resource recoverability
- Amount of geofluid that can be produced from well
- Formation permeability (*k*) and pay zone thickness (*h*)

Reservoir Volume
- Resource available
- Must be large enough to maintain production for project lifetime
- Areal Extent x Pay Zone Thickness

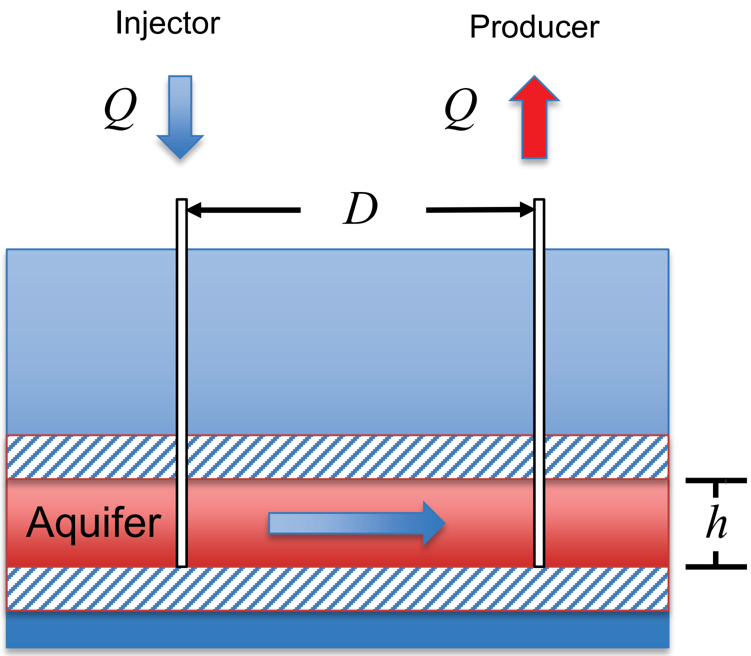
Sedimentary Geothermal Doublet – Analytic Model

- Time for **thermal breakthrough** at production well (Gringarten, 1979)

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

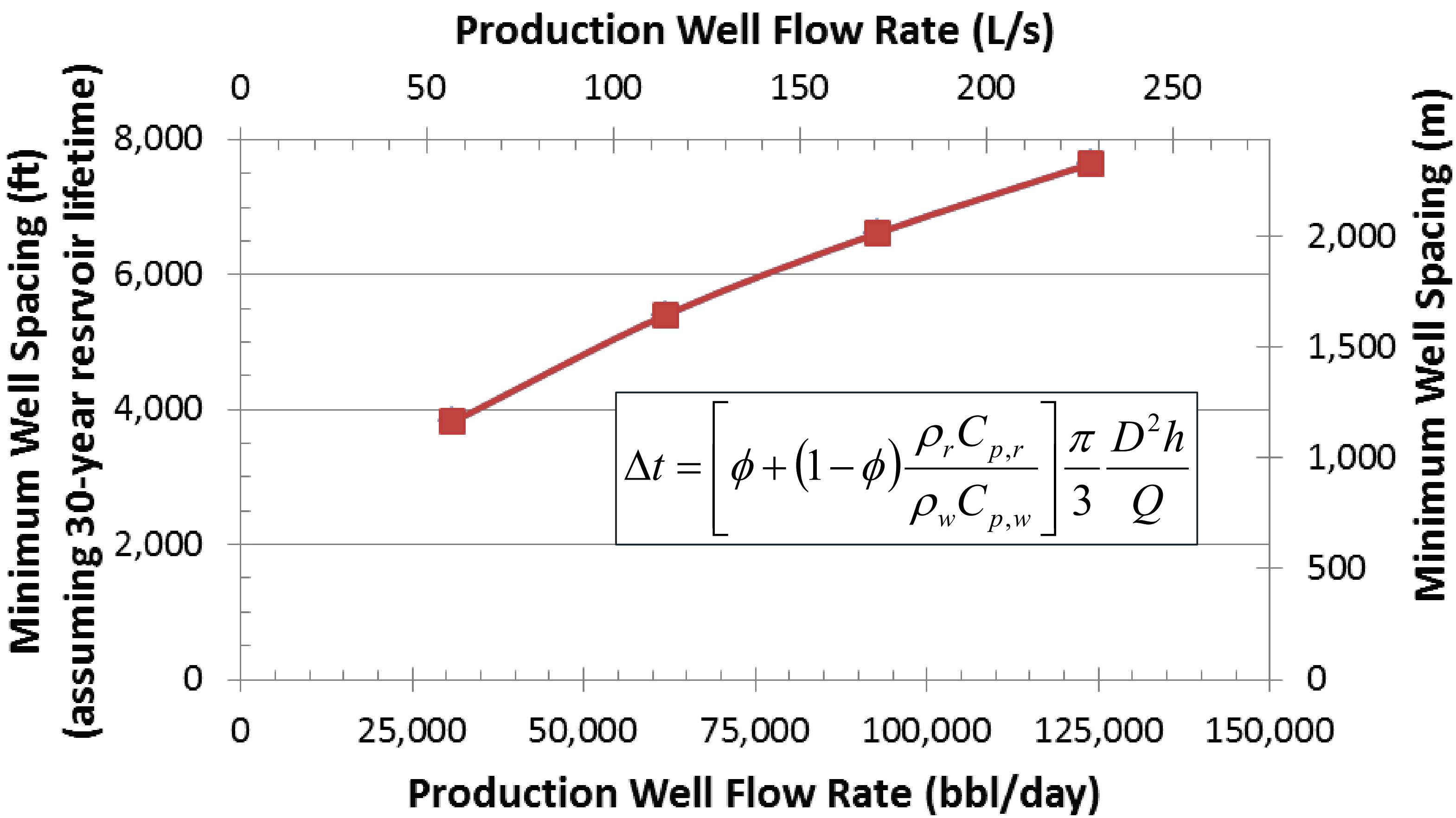
- **Pressure difference** between injection and production wells (Gringarten, 1979; Muskat, 1939)

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



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

Reservoir Lifetime and Well Spacing



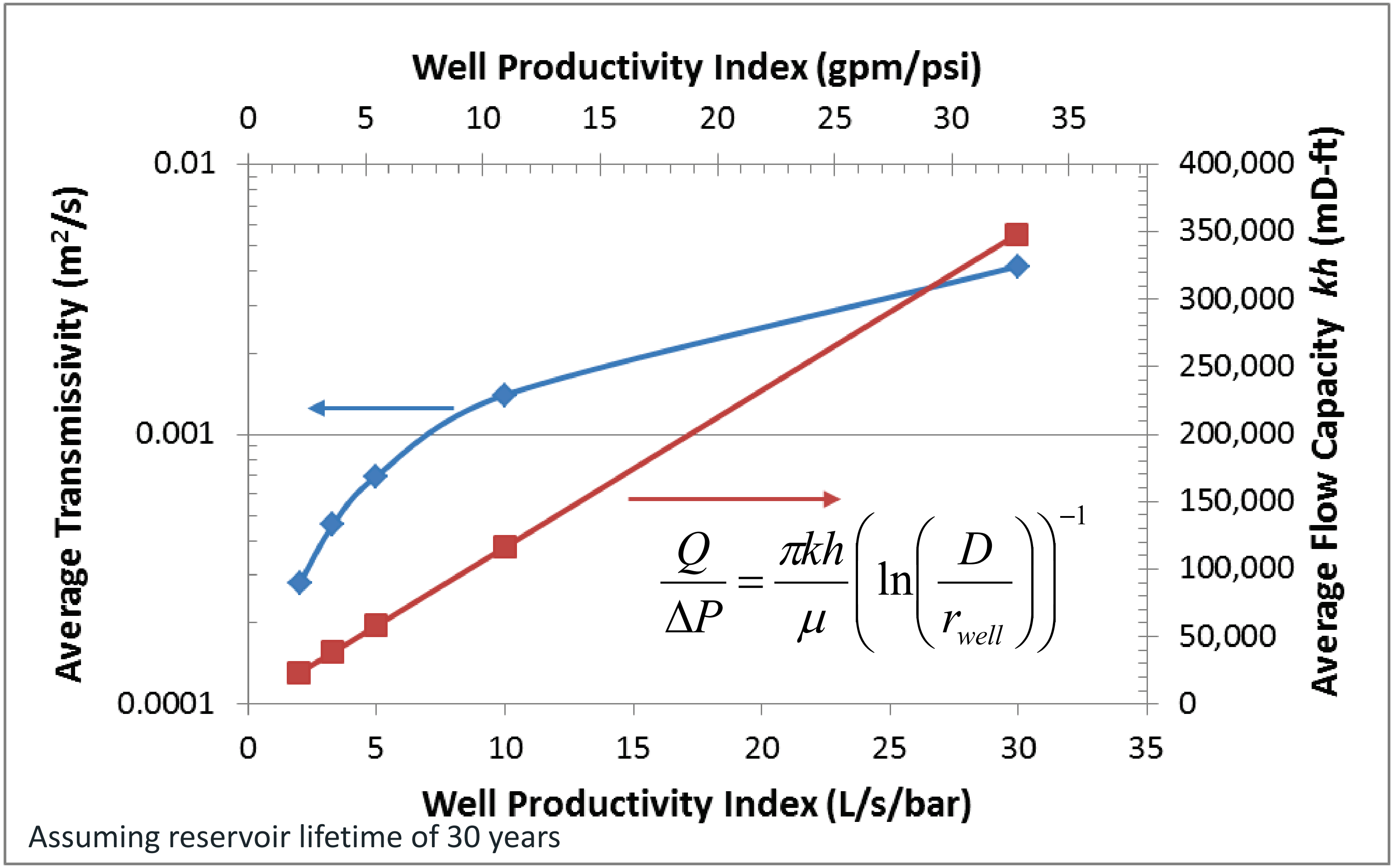
$$\Delta t = \left[\phi + (1-\phi)\frac{\rho_r C_{p,r}}{\rho_w C_{p,w}} \right] \frac{\pi}{3} \frac{D^2 h}{Q}$$

Assuming reservoir height of *h* = 50 m (165 ft)

Adapted from Augustine (GRC 2014)

- **Well spacing on the order of 4,000-6,000 ft (1-2 km)** required for doublet system for production well flow rates typically found at conventional hydrothermal power plants (independent of reservoir permeability)

Well Productivity



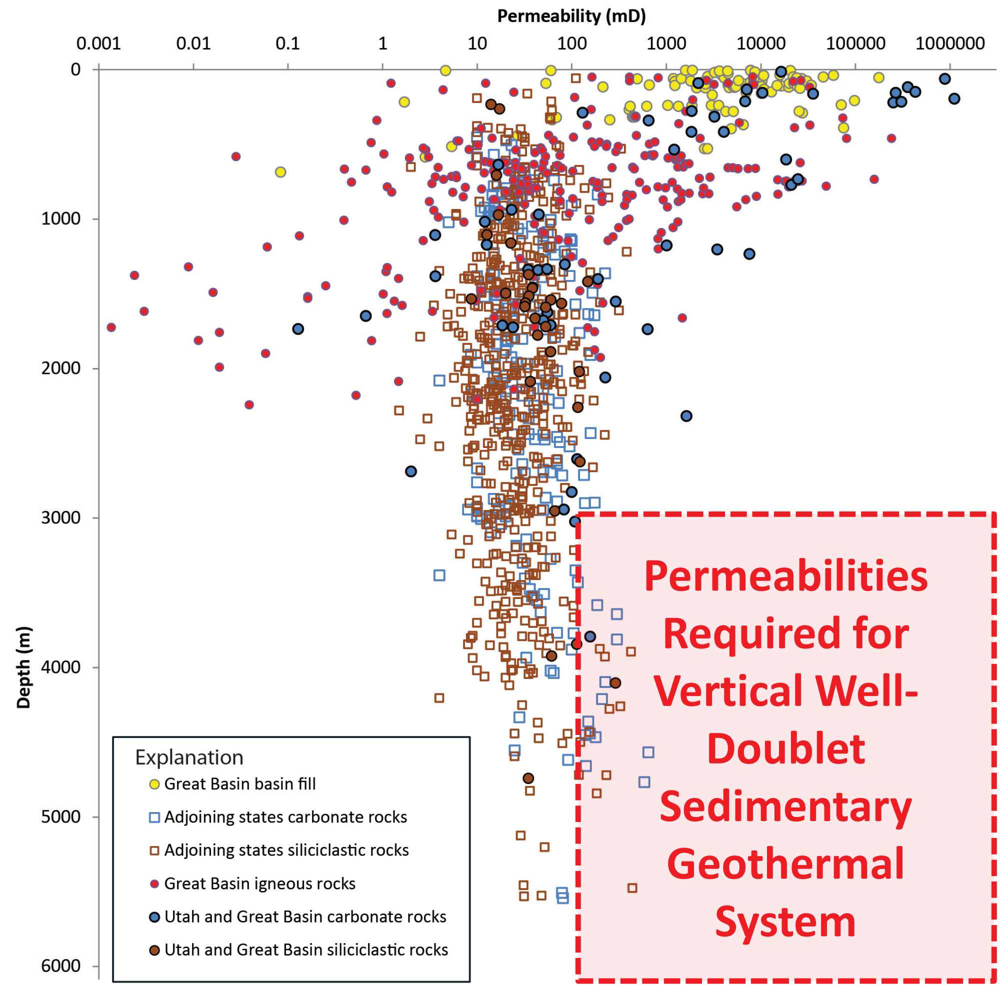
Adapted from Augustine (GRC 2014)

- Average required reservoir transmissivity/flow capacity vs. well productivity for a range of well spacings with 30-year reservoir lifetime
- Productivity index range studied requires **reservoir permeabilities of hundreds to thousands of mD** for the specified system performance

Sedimentary Geothermal Doublet – Analytic Model

Summary – "Ball Park" Reservoir Requirements

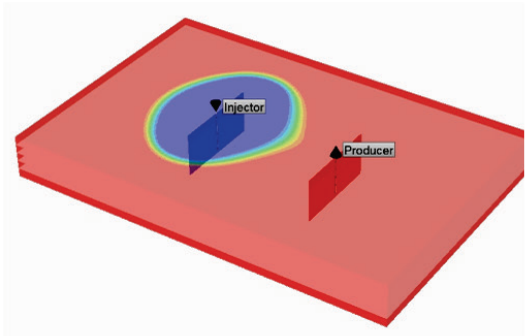
1. Well-doublet system reservoirs with life times of 30 years and well flow rates of 25,000-50,000 bpd (~50-100 L/s) **require a well spacing on the order of 3,000-6,000 ft**
2. **Relatively high permeabilities, on the order of hundreds or thousands mD,** required for commercially-viable vertical well doublet systems



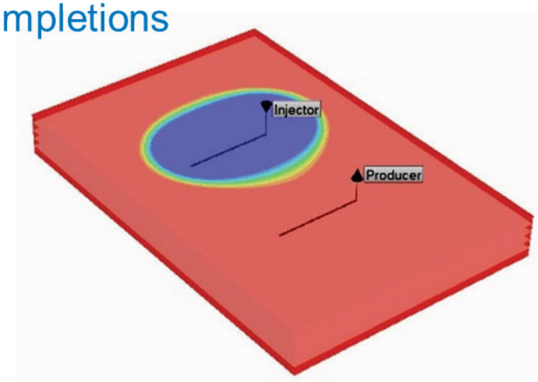
(from Kirby, 2012)

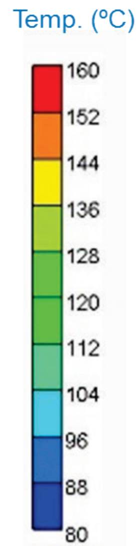
Can Reservoir Performance Be Improved?

1. Vertical wells doublet with hydraulic fractures

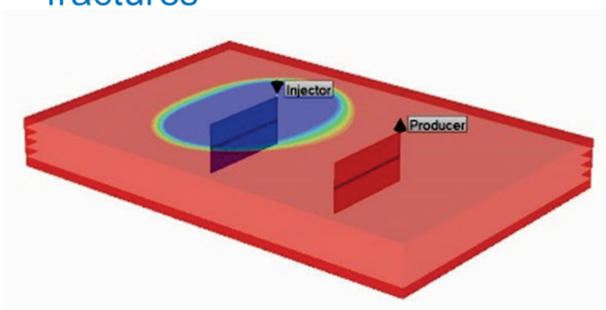


2. Horizontal wells with open-hole completions

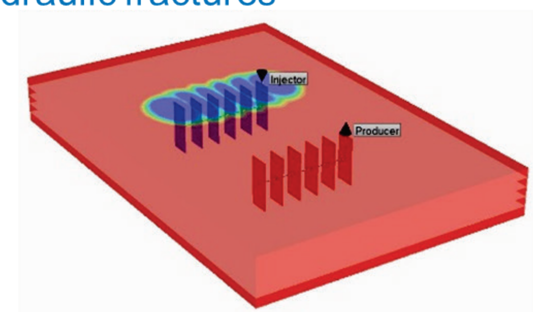




3. Horizontal wells with longitudinal fractures



4. Horizontal wells with multi-stage hydraulic fractures



Adapted from Cho et al. (Stanford 2015)

- **Studied impact of well-configurations on well productivity**
- **Found that use of horizontal wells and fracturing can increase well productivity by factor of 3-5**

Summary

1. **Need to speak the same language**
2. **Temperature is important, but is not the only factor**
   - Need large flow rates (ex. ~80,000 bpd @300°F for ~5 MW_e) → High reservoir permeability (100's to 1,000's mD) and thickness
   - Need long system lifetime (20-30 years)→ Large reservoir and well spacing (several thousand feet)
3. **Petroleum industry has knowledge and expertise to find and develop these systems**
   - In-depth knowledge of potential sedimentary basins
   - Improve reservoir performance with well design and enhancement techniques

Questions?

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This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

Special thanks to Dr. Luis Zerpa, Jae Kyoung Cho and Mengnan Zhou of the Colorado School of Mines Petroleum Engineering Department for their collaboration on this project.

Citations

Related Publications

- Augustine, C. (2014), "Analysis of Sedimentary Geothermal Systems Using an Analytical Reservoir Model." *Geothermal Resources Council Transactions*, 38, 641-647. Link
- Cho, J., Augustine, C. and Zerpa, L. E. (2015), "Validation of a Numerical Reservoir Model of Sedimentary Geothermal Systems Using Analytical Models." Fortieth Workshop on Geothermal Reservoir Engineering. Stanford University, CA, Stanford Geothermal Program, p. 13. Link
- Zerpa, L. E., Cho, J. and Augustine, C. (2015), "Assessing the Effect of Realistic Reservoir Features on the Performance of Sedimentary Geothermal Systems." *Geothermal Resources Council Transactions*, 39, 959-966. Link
- Zhou, M. (2016). *Optimization of Well Configuration for a Sedimentary Enhanced Geothermal Reservoir.* (M.S.), Colorado School of Mines, Golden, CO.

Additional References

- Augustine, C. and Falkenstern, D. (2014), "An Estimate of the Near-Term Electricity-Generation Potential of Coproduced Water From Active Oil and Gas Wells." SPE Journal, 19(3), SPE-163142-PA, 530 - 541. Link
- Kirby, S. M. (2012), "Summary of Compiled Permeability with Depth Measurements for Basin Fill, Igneous, Carbonate, and Siliciclastic Rocks in the Great Basin and Adjoining Regions." Open-File Report 602. Salt Lake City, Utah. Utah Geological Survey. Link