Design Requirements for Commercial Sedimentary Geothermal Projects

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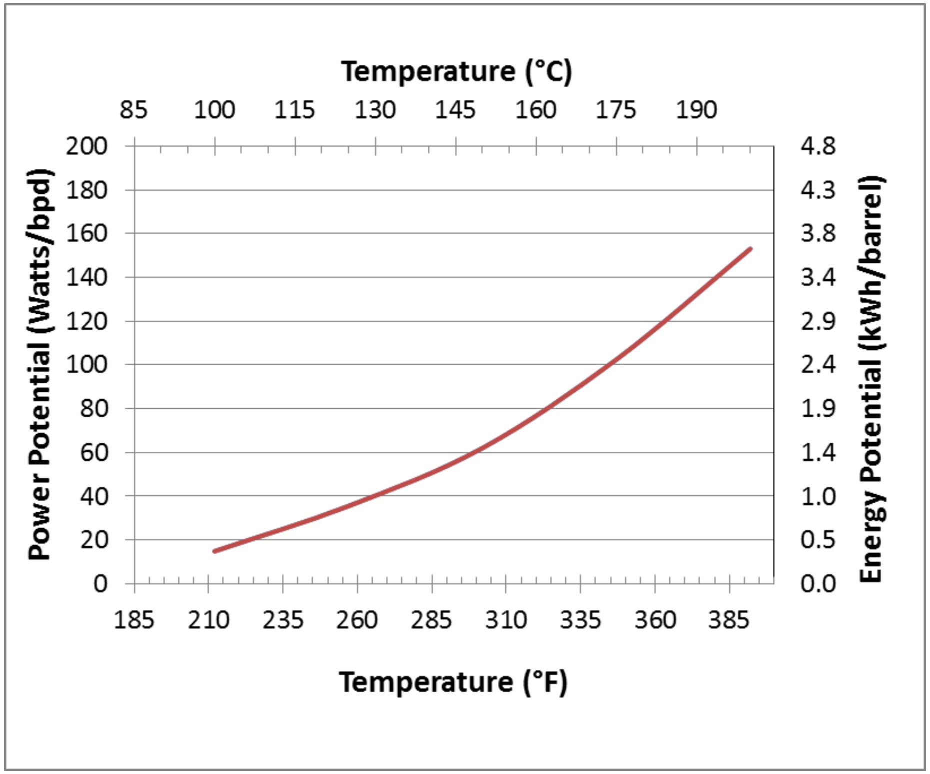
Geothermal vs. Petroleum – a Comparison

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

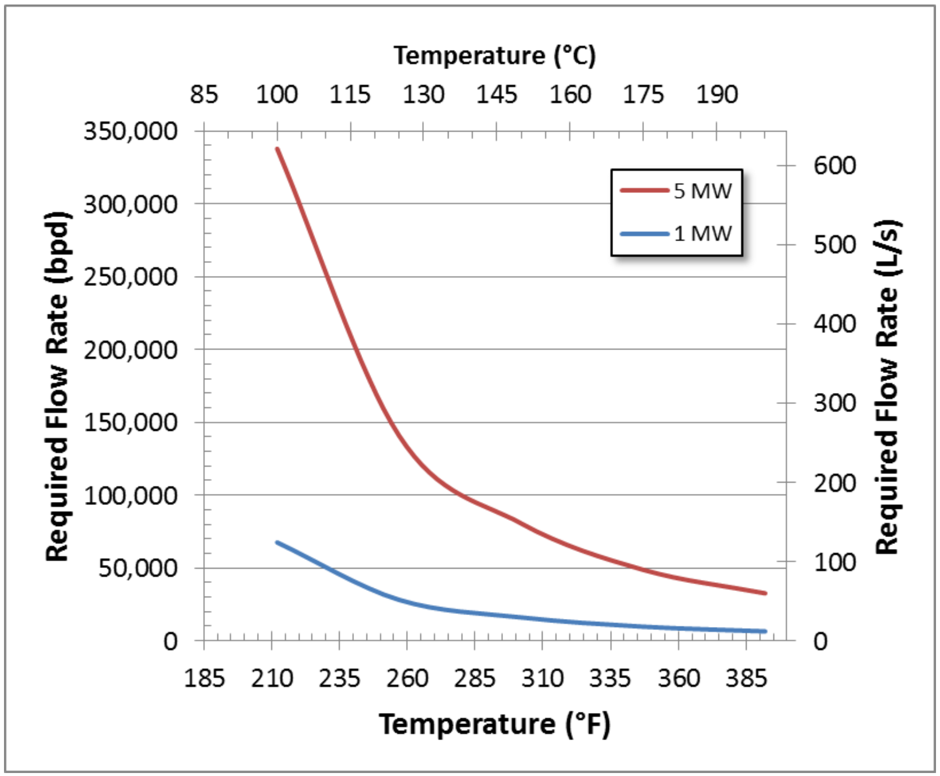
Graphic by Chad Augustine, NREL

Temperature is important, but is not enough…

Need both Temperature AND Flow Rate for commercial power generation:



Electricity Generation vs. Temperature

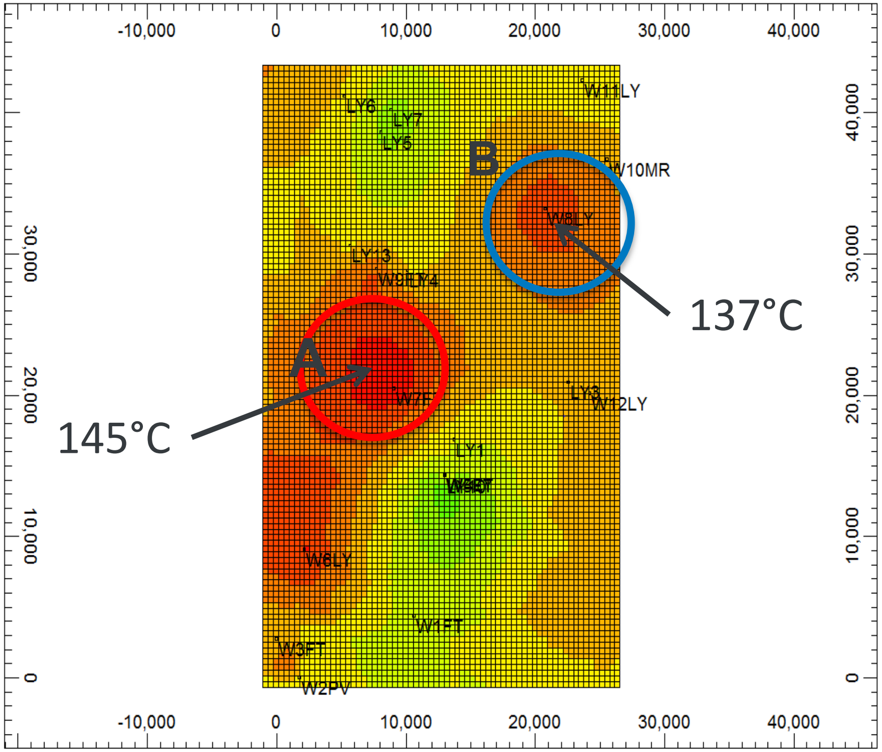


Flow Rate Requirements vs. Temperature

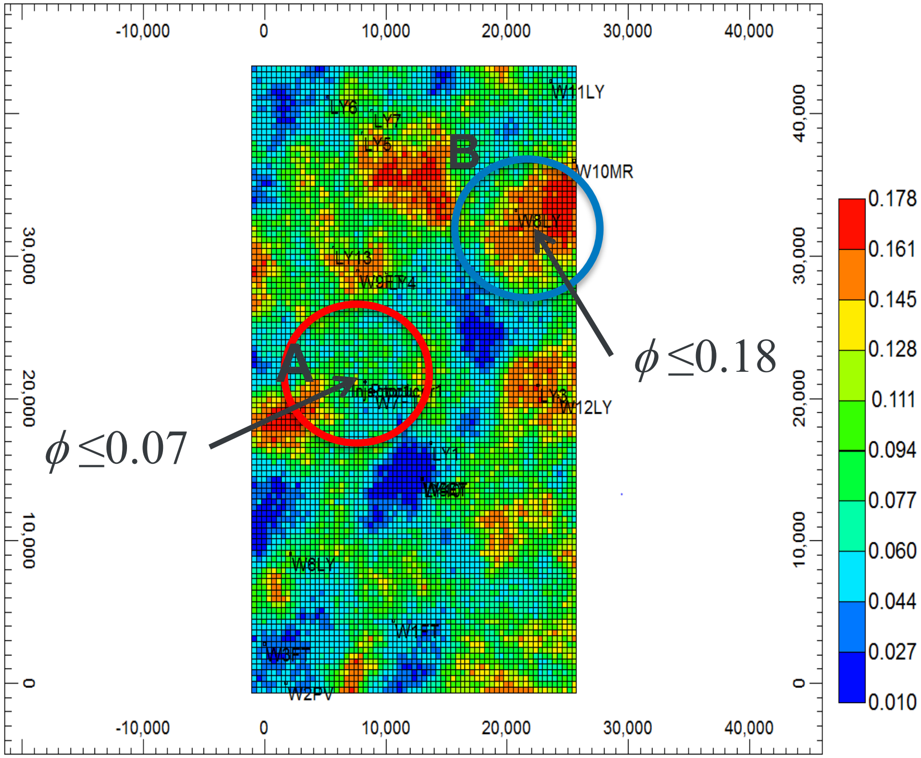
Adapted from Augustine and Falkenstern (2014), SPE-163142

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)**

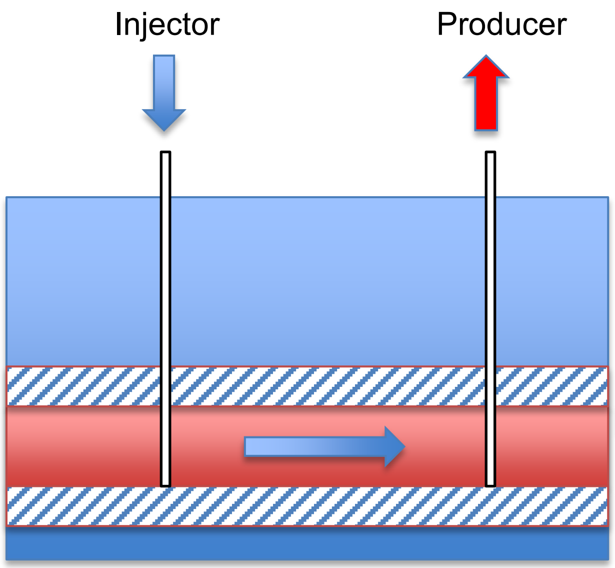


Temperature Distribution



Porosity Distribution

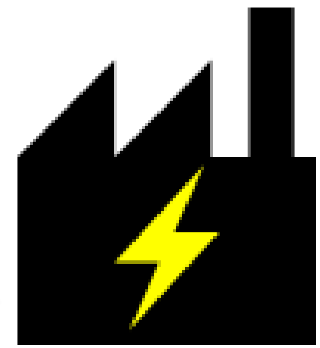
Based on static reservoir model for Wattenberg Field built from well logs (Zhou, CSM Masters Thesis, 2016)



Temperature

- Resource quality
- Higher temperature = more power potential

Sedimentary Geothermal Reservoir Requirements



Utility-Scale Electricity Generation

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

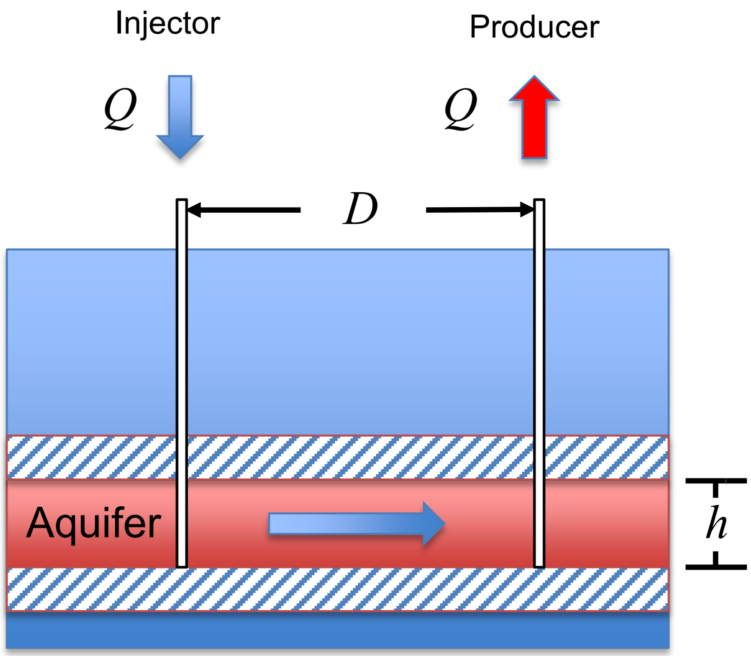
Sedimentary Geothermal Doublet – Analytic Model

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

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

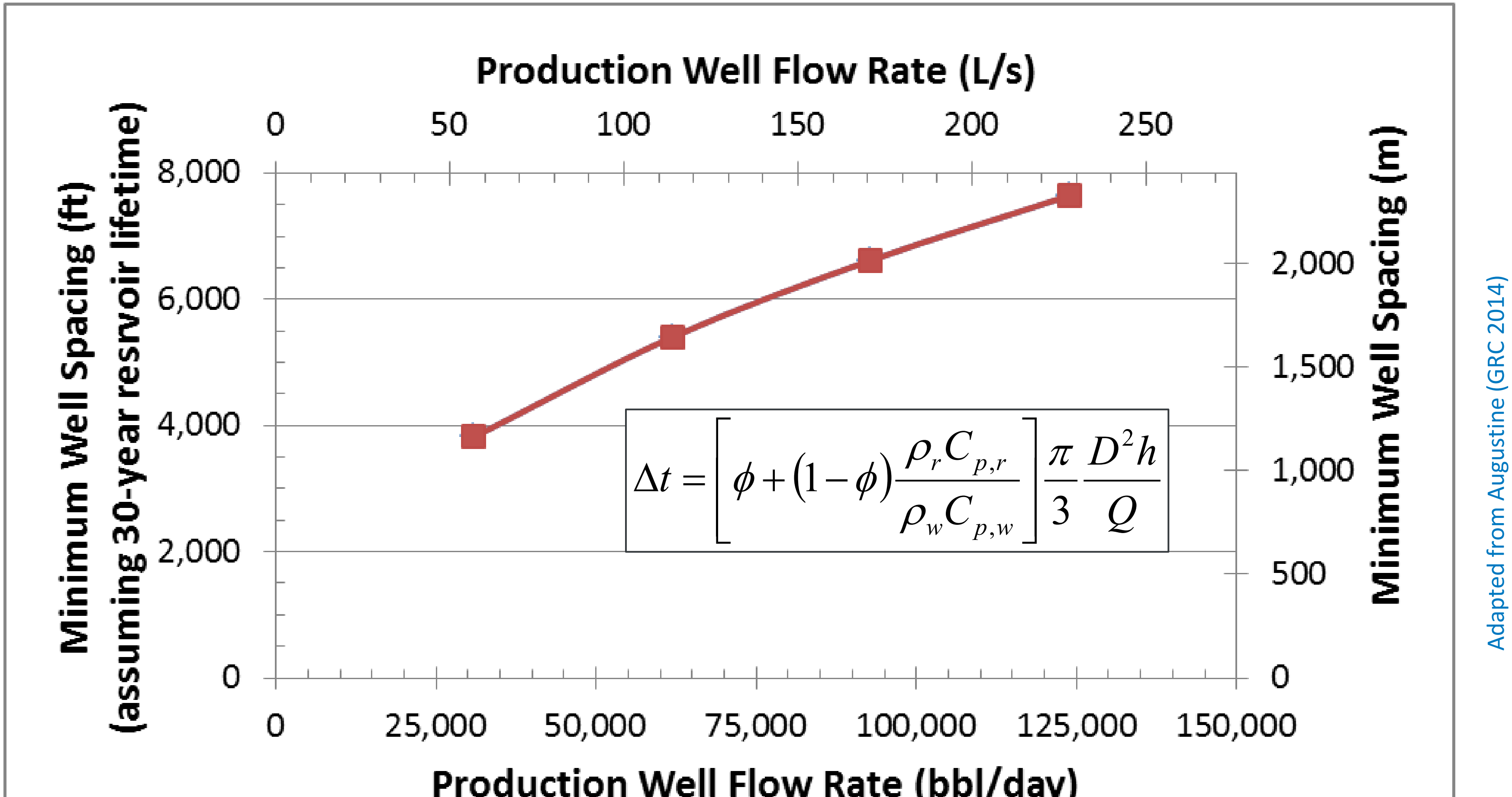
- **Pressure difference** between injection and production wells (Gringarten, 1979; Muskat, 1939)

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



Parameter	Value
Porosity, ϕ	0.15
Reservoir thickness, h	50 m
Rock heat capacity, $\rho_r C_r$	2,770 kJ/m³/°C
Water heat capacity, $\rho_w C_w$	3,860 kJ/m³/°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

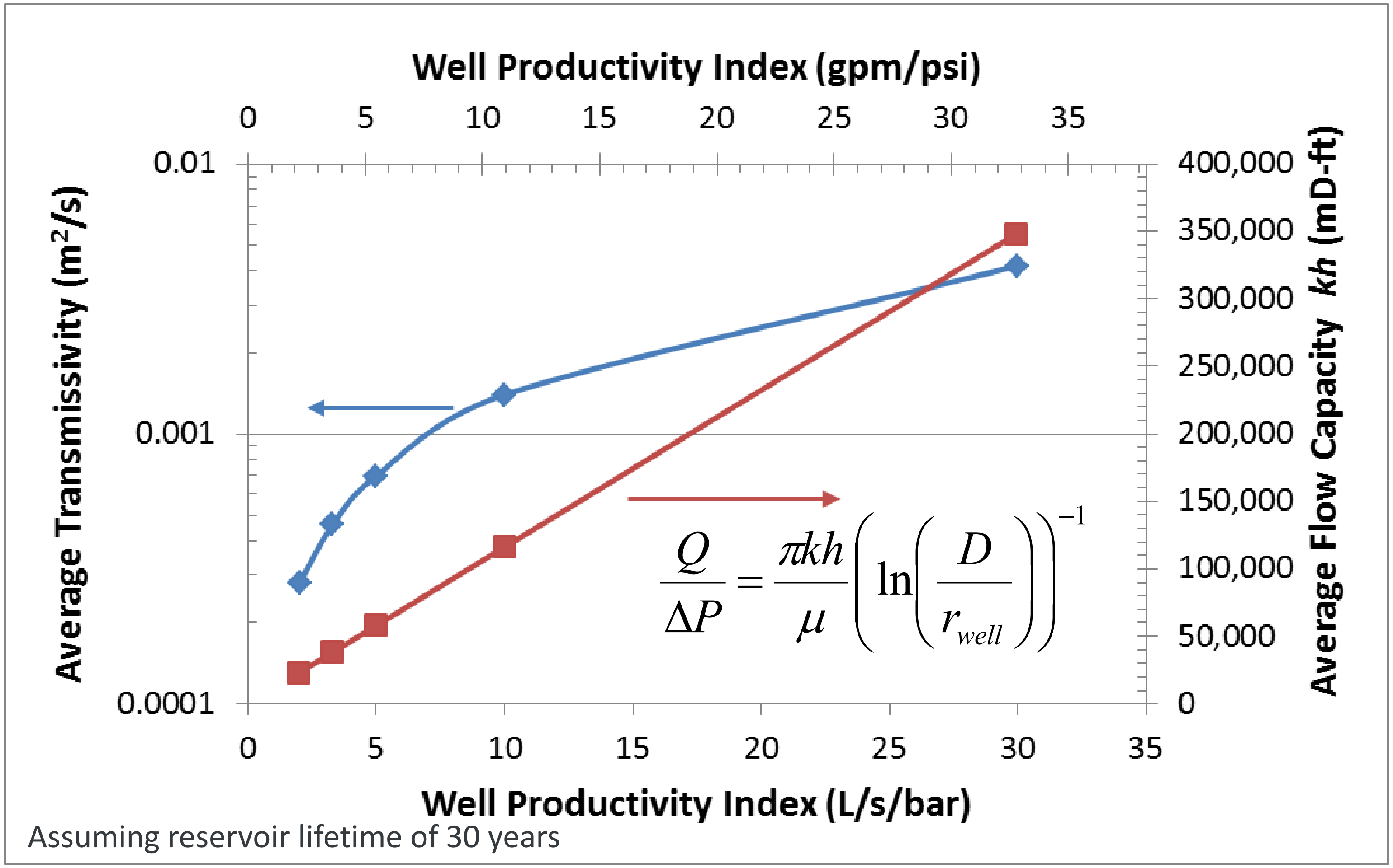
Reservoir Lifetime and Well Spacing



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

- **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



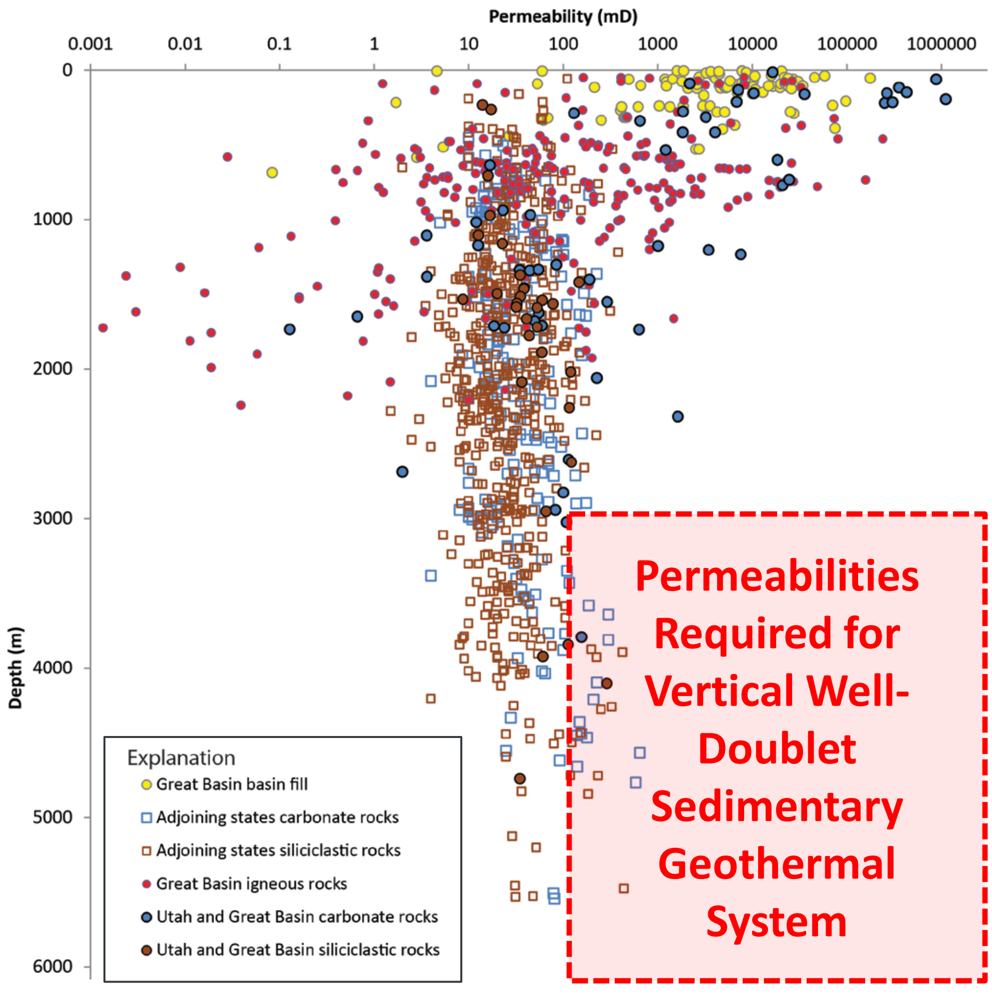
Adapted from Augustine (GRC 2014)

- 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

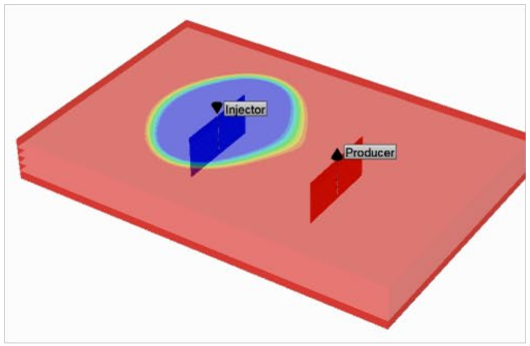
1. Well-doublet system reservoirs with life times of 30 years and well flow rates of 25,000-50,000 bpd (~50-100 L/s) **require a well spacing on the order of 3,000-6,000 ft**
2. **Relatively high permeabilities, on the order of hundreds or thousands mD,** required for commercially-viable vertical well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

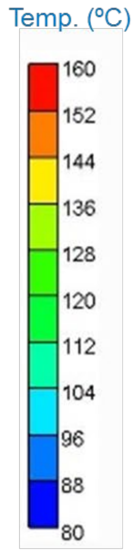


(from Kirby, 2012)

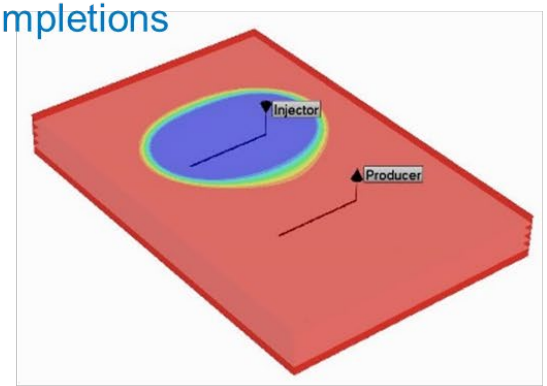
Can Reservoir Performance Be Improved?

1. Vertical wells doublet with hydraulic fractures

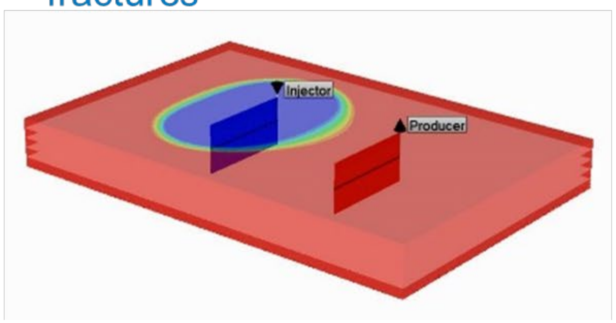




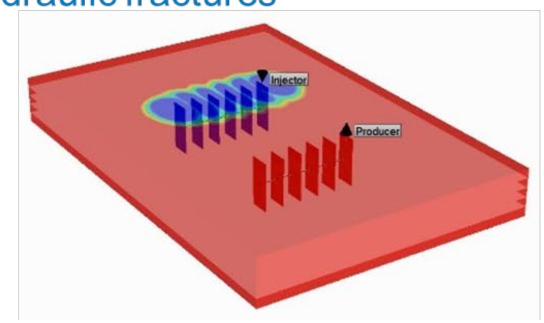
2. Horizontal wells with open-hole completions



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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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